



UNIVERSITÉ CATHOLIQUE DE LOUVAIN

École Polytechnique de Louvain

ICTEAM Institute

Antenna Group

Louvain-la-Neuve, Belgium

---

## Modeling and Design of a Connected Birdcage Coil for Ultra-High Field MRI

---

Farzad Jabbarigargari

Thesis presented for the Ph.D. degree in Engineering Sciences

### **Examining Committee**

Advisor: Christophe CRAEYE, UCLouvain, Belgium

Jury: Redha ABDEDDAIM, Fresnel Institute, France  
Jean-marc LAHEURTE, Gustave Eiffel University,  
France

Jean-Francois REMACLE, UCLouvain, Belgium

Secretary: Dimitri LEDERER, UCLouvain, Belgium

President: Laurent FRANCIS, UCLouvain, Belgium

January 23, 2023





“As you start to walk on the way, the way appears.”

*Molavi (Rumi)*

*To*  
*My parents*



# Acknowledgements

First and foremost, I am extremely grateful to my thesis advisor, Prof. Christophe Craeye, for giving me the opportunity to start a Ph.D on an exciting topic related to health. I greatly appreciate his invaluable advice, continuous support, patience, and motivation that inspired me in my academic research and daily life. I am thankful to Prof. Redha Abdeddaim for his guidance and advice during the M-Cube and M-One projects, that I was involved in during my PhD. I would also like to thank the members of my examination committee, Prof. Jean-marc Laheurte, Prof. Dimitri Lederer, Prof. Jean-François Remacle, and Prof. Laurent Francis, for their comments to improve this manuscript.

I would like to thank my former colleagues Donia Oueslati and Chan-Sun Park for our great collaborations during my PhD journey. I am especially thankful to Maxime Drouguet for his advice and help on the fabrications and measurements of the birdcages, besides all the discussions we had about global warming. Many thanks to Laetitia Niyonzima, Oumaima Mhadhbi, Husnain A. Kayani, and Valentin Sokolow, with whom I had a chance to share pleasant moments in the office. I'm thankful to Denis Tihon for organizing the group meetings, to Jean Cavillot for sharing his sportive attitudes, to Modeste Bodehou and Khaldoun Alkhalifeh for our sociological and cultural discussions, and to Vincent Kaschten for bringing a nice atmosphere to the lab.

I appreciate Souley Djadjandi, Benoît Hubert, and Pierre Gérard for putting up with my numerous requests for the birdcage measurements. I am also thankful to my colleagues from the Fresnel Institute and Multi-wave imaging, Clément Durochat, Pierre Jomin, Amira Trabelsi, Sajad Hosseinneshadian, Marc Dubios, Elodie Georget-Paris, Djamel Berrahou, and Jonathan Bartoli for all the collaborations we had during these years.

Tackling the challenges accompanied by studying abroad, especially during the COVID period, was easier for me, with love and support from my friends. I deeply want to thank my Iranian friends in ELEN, Mojtaba Razavian and Masoud Arash for sharing their non-academic thoughts and experiences. Many thanks to Esmaeil Isazadeh, Mehran Ghaffari, Sina Fardipour, and my Kung Fu ToA instructor Naser Nazarigargari, for being able to assist me in different ways while they were far away.

I want to thank my uncle Javad, an avionics engineer, for always being there for me, despite his occasionally nonsense ideas. Thanks to my cousins Vesal and Reza, who are stepping in for me by assisting my parents in dealing with issues related to digital life.

No words can express my gratitude to my family for their love and support. I'm truly indebted to my mother, for the perseverance she inculcated in me, and to my father, for always reminding me to be optimistic. I would like to thank my sister, Asieh, for taking care of our parents while I was away. Many thanks to Asieh and my brother (in-law), Mohammad, who were the main initiators of my interest in starting a PhD abroad. I always remember Mohammad's invaluable help with preparing visa-related documents. Last but not least, I want to thank my lovely niece Hannah for bringing joy and love into our family.

# Abstract

Magnetic Resonance Imaging (MRI) is a widely used imaging technique that has evolved over the past several years into a powerful and versatile medical diagnostic tool capable of providing images from inside human or animal bodies. Due to the high demand for high-resolution images with an improved signal-to-noise ratio (SNR), that would result in an early-stage diagnosis, research efforts in the MRI system design have been carried out.

Two types of magnetic fields called  $B_0$ , and  $B_1$  are the essential part of each MRI machine. The  $B_0$  field, also called the static magnetic field, is created by the superconducting electromagnets to polarize the magnetic moments of the hydrogen atoms inside the body. The  $B_1$  field, which is perpendicular to the  $B_0$  field and created by a radio-frequency (RF) coil, is responsible for homogeneously (uniformly) tilting the polarized magnetic moments, resulting in the procedure of obtaining the MRI images.

It has been shown that improving the SNR is feasible by increasing the strength of  $B_0$  field from low-field level to high-field (HF) or even ultra-high-field level (UHF). An increase in the strength of the  $B_0$  field requires high-frequency RF coils (from the Larmor equation); hence, special attention has been given to the RF coil design in HF MRI and beyond. Among the different surface and volume coils used for different purposes in MRI, the birdcage coil is a well-known volume coil as it can produce a very homogeneous  $B_1$  field inside its volume; however, its homogeneity degenerates

when the wavelength inside the phantom becomes comparable to the phantom size as a result of resonance.

The main part of this thesis has been devoted to the new design of the birdcage coil, called connected birdcage, to improve the magnetic field homogeneity in HF and UHF MRI applications. This achievement has been obtained by connecting the birdcage to its surround shield via some lumped elements. The connection between the birdcage and the shield follows the ladder model of a transmission line, which improves the coil's efficiency and provides more possibilities for optimizing the current distribution on the birdcage legs, directly impacting the magnetic field homogeneity.

A 3T connected birdcage coil has been designed, optimized, and fabricated for human head imaging. The preliminary results obtained in collaboration with Fresnel institute showed nearly homogeneous fields and paved the way for the use of the connected birdcage at 7T MRI.

To tackle the more obvious inhomogeneity due to the shortened wavelength at 7T MRI, vertically oriented floating loops have been introduced into the connected birdcage. Method of Moments (MoM) simulations validated with CST have shown that the floating loops not only improve the homogeneity in the volume of the connected birdcage but also can be implemented in a conventional birdcage for the same purpose. The 7T connected birdcage with floating loops has been fabricated, and some intermediate measurement results have been obtained.

Apart from the RF coil design, while analyzing the electromagnetic (EM) field distribution inside a piecewise homogeneous medium, a nesting approach based on computing some interaction matrices once and for all, has been used to reduce the MoM's computation time. However, finding the EM field distribution inside an inhomogeneous body in the MRI application has been accomplished through collaborative work by using a hybrid EM solver based on the combination of the finite element method (FEM) and the MoM.

# Contents

|                                                        |              |
|--------------------------------------------------------|--------------|
| <b>Acknowledgements</b>                                | <b>ii</b>    |
| <b>Abstract</b>                                        | <b>v</b>     |
| <b>Table of Contents</b>                               | <b>vii</b>   |
| <b>List of Figures</b>                                 | <b>xi</b>    |
| <b>List of Tables</b>                                  | <b>xxv</b>   |
| <b>Acronyms</b>                                        | <b>xxvii</b> |
| <b>1 Introduction</b>                                  | <b>1</b>     |
| 1.1 Principles of Magnetic Resonance Imaging . . . . . | 1            |
| 1.1.1 Radio-frequency (RF) Coil . . . . .              | 2            |
| 1.1.2 Relaxation . . . . .                             | 3            |
| 1.2 Techniques to Improve the SNR . . . . .            | 6            |
| 1.3 Transmitter and Receiver RF Coils . . . . .        | 7            |
| 1.4 RF Volume Coils . . . . .                          | 11           |
| 1.4.1 Axial Resonators . . . . .                       | 12           |
| 1.4.2 Transverse Resonator . . . . .                   | 12           |

|          |                                                                               |           |
|----------|-------------------------------------------------------------------------------|-----------|
| 1.4.3    | Inhomogeneity in the Loaded Birdcage Coil . . . . .                           | 22        |
| 1.4.4    | Dipolar-type of RF Coils . . . . .                                            | 24        |
| 1.5      | Use of Design Tools . . . . .                                                 | 26        |
| 1.6      | Goals of the Thesis . . . . .                                                 | 26        |
| 1.7      | Outline of the Thesis . . . . .                                               | 28        |
| <b>2</b> | <b>Method of moments in MRI applications</b>                                  | <b>31</b> |
| 2.1      | Introduction . . . . .                                                        | 31        |
| 2.2      | The Fields Equivalence Principle and the Method of Moments                    | 33        |
| 2.2.1    | Discretization and Basis Functions . . . . .                                  | 37        |
| 2.2.2    | Meshing of the Human Body Organs . . . . .                                    | 39        |
| 2.2.3    | Array Scanning Method . . . . .                                               | 40        |
| 2.2.4    | Nesting Approach . . . . .                                                    | 42        |
| 2.2.5    | Nesting Approach Validation for Concentric Media . .                          | 45        |
| 2.3      | MoM to Design a 3 Tesla Birdcage Coil . . . . .                               | 47        |
| 2.3.1    | Asymmetric Birdcage Coil . . . . .                                            | 50        |
| 2.4      | Conclusion . . . . .                                                          | 53        |
| <b>3</b> | <b>Connected Birdcage Coil</b>                                                | <b>55</b> |
| 3.1      | Introduction . . . . .                                                        | 56        |
| 3.2      | RF Magnetic Field Pattern . . . . .                                           | 58        |
| 3.3      | Connected Birdcage Coil . . . . .                                             | 65        |
| 3.4      | Optimized Connected Birdcage Coil . . . . .                                   | 69        |
| 3.4.1    | Robustness of the Connected Birdcage for Different<br>Phantom Radii . . . . . | 80        |
| 3.5      | Fabrication Process . . . . .                                                 | 81        |
| 3.6      | Conclusion . . . . .                                                          | 88        |
| <b>4</b> | <b>Birdcage Coil for Ultra-high Field MRI</b>                                 | <b>89</b> |
| 4.1      | Introduction . . . . .                                                        | 90        |
| 4.2      | Conventional Birdcage Coils for 7T MRI . . . . .                              | 93        |



|        |                                                                                                                          |            |
|--------|--------------------------------------------------------------------------------------------------------------------------|------------|
| 4.2.1  | Eight-leg Birdcage with Ports between Legs and the End ring . . . . .                                                    | 96         |
| 4.2.2  | Eight-leg Birdcage coil with Ports on the End ring . .                                                                   | 97         |
| 4.2.3  | Eight-leg Birdcage with Ports between the Birdcage and Shield . . . . .                                                  | 99         |
| 4.2.4  | Sixteen-leg Birdcage Coil with two Ports in the Middle of the Legs . . . . .                                             | 101        |
| 4.2.5  | Sixteen-leg Birdcage with Ports Between the Birdcage and Shield . . . . .                                                | 102        |
| 4.3    | Radially Oriented Vertical Loops used in the RF Coils . . . .                                                            | 104        |
| 4.4    | Eight-leg Conventional Birdcage with Floating Loops . . . .                                                              | 106        |
| 4.4.1  | Discussion Regarding the Impact of the Floating Loops on the Current Distribution of the Conventional Birdcage . . . . . | 111        |
| 4.5    | Eight-leg Connected Birdcage Coil for 7T MRI . . . . .                                                                   | 116        |
| 4.6    | Eight-leg Connected Birdcage with Floating Loops . . . . .                                                               | 118        |
| 4.7    | Field Distribution Inside the Voxel Family . . . . .                                                                     | 125        |
| 4.8    | Comparison Between the 16-leg Birdcage and CBCL . . . . .                                                                | 127        |
| 4.9    | Implementing the Floating Loops into the 3T CBC . . . . .                                                                | 131        |
| 4.10   | Receiver Loops with the CBCL Coil . . . . .                                                                              | 131        |
| 4.11   | Detuned CBCL . . . . .                                                                                                   | 134        |
| 4.12   | Fabrication of 7T Connected Birdcage with Floating Loops .                                                               | 137        |
| 4.12.1 | Measurement of the 7T CBCL . . . . .                                                                                     | 141        |
| 4.13   | Conclusion . . . . .                                                                                                     | 145        |
| 5      | <b>Finite Element-Boundary Integral method</b>                                                                           | <b>147</b> |
| 5.1    | Introduction . . . . .                                                                                                   | 148        |
| 5.2    | FEBI System of Equations . . . . .                                                                                       | 149        |
| 5.3    | Field Distributions Inside a Dielectric Sphere Illuminated by an Incident Plane Wave . . . . .                           | 152        |

5.4 FE-BI System of Equations in the Presence of a Birdcage  
Coil around the Phantom . . . . . 156

5.4.1 7T CBCL around Two Concentric Spheres . . . . . 158

5.5 7T CBCL around the Inhomogeneous Human Head . . . . . 159

5.6 Conclusion . . . . . 161

**6 Conclusions and Future Works 163**

6.1 Conclusions . . . . . 163

6.2 Future Works . . . . . 165

**7 List of Publications and Research Talks 167**

**Bibliography 183**

# List of Figures

|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |   |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---|
| 1.1 | (a) Nucleus is spinning around its own axis creates a magnetic moment as $m$ . (b) Nuclei spin around their own axis and are oriented in random directions when there is no applied magnetic field ( $B_0 = 0$ ). (c) Magnetic moments are precessing (with a frequency of $\omega_0$ ) out of phase around the axis of the applied magnetic field. (d) The net magnetization vector is aligned in the same direction as the applied $B_0$ field. (e) After applying the RF pulse, the magnetic moments are precessing in phase resulting in the rotation of the net magnetization vector. . . . . | 4 |
| 1.2 | Once the RF pulse is switched off, the transverse net magnetization vector returns to its initial position in the longitudinal direction while inducing signals on the receiver coil. . . . .                                                                                                                                                                                                                                                                                                                                                                                                      | 5 |
| 1.3 | (A) Represents the T1 relaxation, and (B) Represents the T2 relaxation [4]. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 5 |
| 1.4 | Impact of the applied magnetic field strength on the SNR. (a) 1.5T MRI machine. (b) 3T MRI machine [5]. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 6 |
| 1.5 | Effect of the element numbers on the receive mode on the SNR. (a) Two channel knee coil. (b) Sixteen channel knee coil [5]. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 7 |

|      |                                                                                                                                                                                                                                                                                                   |    |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 1.6  | A 10-channel transmit coil and 31-channel receive coil are combined in a transmit-only/receive-only configuration [10]. . .                                                                                                                                                                       | 8  |
| 1.7  | A 16-channel transceiver loop-dipole configuration. (b) Single element of loop-dipole with front and back views [11]. . .                                                                                                                                                                         | 8  |
| 1.8  | Three typical observation planes in the MRI applications [13].                                                                                                                                                                                                                                    | 9  |
| 1.9  | (a) Surface loop coil and the orientation of its magnetic field [18]. (b) Surface loop coil used in the Rx mode with its preamplifier [19]. . . . .                                                                                                                                               | 10 |
| 1.10 | Effect of the surface loop diameter on the penetration depth of the magnetic field [20]. . . . .                                                                                                                                                                                                  | 10 |
| 1.11 | Two types of current distributions that create homogeneous magnetic fields inside the coil. Left, uniformly distributed loop of currents. Right, sine-dependent line current [20]. . . .                                                                                                          | 11 |
| 1.12 | Orientation of the object being imaged inside the axial resonator (solenoid coil in this figure) [21]. . . . .                                                                                                                                                                                    | 12 |
| 1.13 | Saddle coils [22], [23]. . . . .                                                                                                                                                                                                                                                                  | 13 |
| 1.14 | Saddle coil in a combination with the surface loop [24]. . . . .                                                                                                                                                                                                                                  | 13 |
| 1.15 | (a) Uniform magnetic field inside an infinite cylinder can be obtained via axial surface current that varies like $\sin\phi$ around its axis. (b) Birdcage coil with variable currents on its legs to approximate the $J_0 \sin\phi$ current distribution [19]. . . . .                           | 14 |
| 1.16 | Different parts of the birdcage coil. Half of the siled is not shown to easily show the different parts. . . . .                                                                                                                                                                                  | 15 |
| 1.17 | Three different types of the birdcage coil. (a) High-pass. (b) Low-pass. (c) Band-pass; the excitation ports are not shown.                                                                                                                                                                       | 16 |
| 1.18 | Four differnt modes for an eight-leg birdcage. The desired mode is the red one when the current has one wavelength on the legs. The mode shown in black is a higher mode prodccing oposite currents on the adajecent legs, which result in the zero field at the center of the coil [13]. . . . . | 17 |

|      |                                                                                                                                                                                                                                                                                                                        |    |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 1.19 | Obtained from [29]: (a) an eight-leg birdcage coil. (b) Simplified equivalent circuit of a birdcage coil, consists of multiple unit cells. (c) The high pass or low pass unit cells due to the position of the capacitors. . . . .                                                                                     | 17 |
| 1.20 | Resonant modes of the LP and HP eight-leg birdcages. For the HP birdcage Co-Rotational (CR) mode corresponds to the resonance of the end-ring (The horizontal axis is the frequency range in MHz) [20]. . . . .                                                                                                        | 20 |
| 1.21 | Current amplitude in each leg (shown by small circles) and associated magnetic field distribution corresponding to each mode. The homogenous field distribution is obtained for the $k = 1$ mode [20]. . . . .                                                                                                         | 20 |
| 1.22 | (a) Linear and (b) quadrature excitation of a birdcage coil. . . . .                                                                                                                                                                                                                                                   | 21 |
| 1.23 | (a) A full body birdcage coil. (b) A birdcage coil dedicated to human head imaging (a mirror positioned on the top allows the patient to see the outside of the magnet bore) [19]. . . . .                                                                                                                             | 21 |
| 1.24 | $B_1^+$ Field distribution inside the birdcage coil surrounded by shield at 3T: (a) without phantom at 129 MHz. (b) With phantom at 131 MHz. One can see the inhomogeneity (hot spot in the center and dark spot on the top left) in the field distribution due to the loading of the birdcage with a phantom. . . . . | 22 |
| 1.25 | (a) TEM coaxial and microstrip elements. (b) An 8 channel TEM head coil with modified elements to improve the magnetic field homogeneity in the axis of the coil [32], [33]. . . . .                                                                                                                                   | 23 |
| 1.26 | (a) Two fractionated dipoles mounted on the PMMA. (b) 8 elements of the fractionated dipoles are placed on the volunteer body for the prostate imaging [38]. . . . .                                                                                                                                                   | 24 |
| 1.27 | (a) Dipole and (b) monopole antenna arrays for the human head imaging at 10.5T [41], [40]. . . . .                                                                                                                                                                                                                     | 25 |
| 1.28 | (a) Two elements of the microstrip transmission line (MTL) and dipole antenna. (b) 16-channel combined array of MTLs and dipoles [44]. . . . .                                                                                                                                                                         | 25 |

|      |                                                                                                                                                                                                                                                                                  |    |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 1.29 | A human brain image at 7T MRI; two circles show the destructive interference resulting in the dark regions with lower field values [47]. . . . .                                                                                                                                 | 27 |
| 2.1  | Schematic of an MRI scanner [49]. . . . .                                                                                                                                                                                                                                        | 32 |
| 2.2  | The equivalence currents are impressed on the surface $S$ to produce the same fields external to $S$ as do the original sources [50]. . . . .                                                                                                                                    | 34 |
| 2.3  | Geometry of the (a) RWG basis function. (b) Rooftop basis function. . . . .                                                                                                                                                                                                      | 38 |
| 2.4  | (a) Rooftop basis function on the feed point. (b) RWG basis function on the feed point. . . . .                                                                                                                                                                                  | 39 |
| 2.5  | (a) Surface mesh of the human head and other internal organs. (b) Surface mesh of a liver obtained from different layers of MRI images. . . . .                                                                                                                                  | 40 |
| 2.6  | Array Scanning Method: (a) A unit cell of the birdcage coil with a phantom. (b) A complete mesh of the birdcage coil with a phantom. . . . .                                                                                                                                     | 41 |
| 2.7  | A bowtie antenna is located around a piecewise homogeneous human head model. $x_1$ for the unknowns on the surface of the antenna, $x_2$ for the unknowns on the surface of the head, and $x_3$ for the unknowns on the surface of all the other organs inside the head. . . . . | 43 |
| 2.8  | Three concentric spheres and a bowtie antenna around them.                                                                                                                                                                                                                       | 46 |
| 2.9  | LaRa transponder and antennas. . . . .                                                                                                                                                                                                                                           | 46 |
| 2.10 | A bowtie antenna around a human head model, consisting of brain and the liquid around the brain. (b) Fields observation plane inside the brain is shown in blue (the brain model provided by Prof. Redha Abdeddaim). . . . .                                                     | 47 |
| 2.11 | Left to right, $x$ , $y$ and $z$ components of the $E$ field on the observation plane inside the brain shown in Fig. 2.10(b). . . .                                                                                                                                              | 47 |

|      |                                                                                                                                                                                                                                                                                                                                                    |    |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 2.12 | (a) Top view of a birdcage coil with a phantom; capacitors are shown in red and the excitation ports are shown in green. (b) 3D view of the birdcage coil, phantom, and the surrounding shield (one sector of the shield is hidden for the illustration purpose). . . . .                                                                          | 48 |
| 2.13 | (a) Scattering parameters of the 3T birdcage coil loaded with a cylindrical phantom obtained from MoM and CST simulations. The desired mode of the birdcage is at 127 MHz with MoM, and with CST it is at 131 MHz. $B_1^+$ field distribution on the transverse cut inside the phantom obtained from: (b) MoM at 127 MHz. (c) CST 131 MHz. . . . . | 52 |
| 2.14 | (a) Objective weighting matrix. (b) Obtained field map with the asymmetric birdcage at 280 MHz [66]. . . . .                                                                                                                                                                                                                                       | 53 |
| 3.1  | Main parts of an MRI scanner [91]. . . . .                                                                                                                                                                                                                                                                                                         | 58 |
| 3.2  | Transverse plane of an unloaded 3T birdcage. Field lines when: (a) the first port is excited. (c) Second port is excited. (e) Two ports are excited in the quadrature mode, resulting in the circular polarization. (b), (d), and (f) Show the contour form of the corresponding fields in (a), (c), and (e). . . . .                              | 59 |
| 3.3  | Two different shield radii are put around the unloaded 3T birdcage coil. $r_{obs}$ indicates the radius of the observation plane. (a) Shield radius is 15 cm. (b) Shield radius is 18 cm. . . . .                                                                                                                                                  | 60 |
| 3.4  | Current distributions on the legs for a 16-leg birdcage without shield with 40 cm height and 29 cm diameter. Currents are shown for the unloaded case and when the birdcage is loaded with different phantoms at: (a) 1.5T. (b) 4.7T [89]. . . . .                                                                                                 | 62 |
| 3.5  | The connections and the type of their loads for the CBC. . . . .                                                                                                                                                                                                                                                                                   | 65 |
| 3.6  | One sector of the connected birdcage. . . . .                                                                                                                                                                                                                                                                                                      | 66 |
| 3.7  | Top view of the connected birdcage. . . . .                                                                                                                                                                                                                                                                                                        | 66 |
| 3.8  | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution on the transverse cut inside the phantom obtained from MoM: (a) 3T conventional birdcage at 127 MHz. (b) 3T connected birdcage at 127 MHz. . . . .                                                                                                                                           | 68 |

|      |                                                                                                                                                                                                                                                                                                                                                                                            |    |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.9  | Current distributions with the linear excitation of the conventional birdcage. Induced currents on the additional rings are circulating in the opposite direction as the currents on the end ring. . . . .                                                                                                                                                                                 | 69 |
| 3.10 | (a) Sagittal cut view of a 3T conventional birdcage. (b) Sagittal cut view of a 3T conventional birdcage with additional top and bottom rings to the shield. $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution on the transverse cut obtained from CST for (c) conventional birdcage at 131 MHz. (d) Conventional birdcage with two additional rings on the shield at 129 MHz. . . . . | 70 |
| 3.11 | (a) Side view of the CBC with additional rings. (b) One sector of the CBC. (c) One sector of the CBC with additional rings (the additional rings are shown in cyan). . . . .                                                                                                                                                                                                               | 72 |
| 3.12 | (a) S - parameters obtained from MoM and CST simulations, where the frequency of the main mode is marked on the $S_{12}$ curve. $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution on the transverse cut inside the phantom obtained from: (b) MoM at 127 MHz. (c) CST at 126.4 MHz. . . . .                                                                                            | 73 |
| 3.13 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution on the transverse cut inside the phantom obtained from MoM at 127 MHz: (a) Conventional birdcage. (b) Connected birdcage. (c) Connected birdcage with the additional rings on the top and bottom. . . . .                                                                                                                            | 75 |
| 3.14 | Amplitude of the current distributions on the birdcage legs. . . . .                                                                                                                                                                                                                                                                                                                       | 76 |
| 3.15 | SAR distribution at 127 MHz: (a) Conventional birdcage with $SAR_{max} = 6.02$ W/kg. (b) CBC with $SAR_{max} = 3.07$ W/kg. . . . .                                                                                                                                                                                                                                                         | 76 |
| 3.16 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution on the three-quarter cuts on the top and bottom obtained from CST. (b) and (d) Connected birdcage at 126.4 MHz. (c) and (e) Conventional birdcage at 131 MHz. . . . .                                                                                                                                                                | 78 |
| 3.17 | $B_1^+$ field for the 1 W accepted power on the sagittal plane. (a) Conventional birdcage. (b) CBC. . . . .                                                                                                                                                                                                                                                                                | 79 |



|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |    |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.18 | S - parameters obtained from CST for different radii of the phantom for the CBC; 126.4 MHz is the desired resonance frequency of the birdcage for a phantom with 9.6 cm radius. .                                                                                                                                                                                                                                                                                                                                                                                                                         | 81 |
| 3.19 | Fabrication model: (a) Only supporting material. (b) Supporting material loaded with different copper parts. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 82 |
| 3.20 | Different layers of copper used to ease the soldering of the inductors. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 83 |
| 3.21 | Fabrication model of the CBC. (a) Middle cut view. (b) Top view of the CBC; one separable copper layer on the shield is not shown for illustration purposes. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                      | 84 |
| 3.22 | Different parts of the fabricated CBC fabricated in SIRRIS. (a) Supporting material. (b) Copper plates used for the shield, middle leg, additional rings on the top and bottom of the shield, the interlayer between the shield and the additional rings on the top and bottom of the shield to ease the soldering of the vertical inductors, and the tube used for the inner legs. (c) One sector of the additional ring on the top of the shield, covering the interlayer copper plate. (d) Assembled 3T connected birdcage; the two brown coaxial cables are shown for the excitation purpose. . . . . | 85 |
| 3.23 | The measured scattering parameters of the 3T CBC at UCLouvain. The main mode of the birdcage is at 125 MHz. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | 86 |
| 3.24 | (a) Measurement setup: the probe loop which measures the S21 can move in three different axis inside the coil to measure the chosen observation plane. (b) Observation plane, and corresponding results obtained from: (c) CST at 125.4 MHz. (d) Measurement at 125 MHz. . . . .                                                                                                                                                                                                                                                                                                                          | 87 |
| 4.1  | Inhomogeneity caused by the increased $B_0$ field [68]. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 90 |
| 4.2  | (a) pTx RF coil with 16-channel strip-line array for 7T head imaging. (b) 16×8 Butler matrix [76]. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 91 |
| 4.3  | (a) An unloaded birdcage coil with two observation planes at its center. (b) Loaded birdcage with a phantom. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 94 |

|      |                                                                                                                                                                                                                                                                                                          |     |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.4  | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ fields for the eight-leg conventional birdcage coil at 300 MHz. (b) Transverse middle cut with NSD = 0.3099. (c) Sagittal cut with NSD = 0.3731. . . . .                                                                                                              | 95  |
| 4.5  | (a) An eight-leg birdcage with the excitation ports between the end ring and legs. The corresponding $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distributions at 300 MHz on the: (b) transverse plane with NSD = 0.3162. (c) Sagittal plane with NSD = 0.3753. . . . .                                     | 96  |
| 4.6  | (a) An 8-leg birdcage coil with excitation ports on the end ring, and the corresponding $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distributions at 300 MHz on the: (b) transverse plane with NSD = 0.2549. (c) Sagittal plane with NSD = 0.2932. . . . .                                                  | 97  |
| 4.7  | Current distributions on the birdcage legs when the excitation ports are on the legs or on the end ring. . . . .                                                                                                                                                                                         | 98  |
| 4.8  | (a) An 8-leg birdcage coil with excitation ports between the birdcage and shield, and the corresponding $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution at 300 MHz on the: (b) transverse plane with NSD = 0.2579. (c) Sagittal plane with NSD = 0.3. . . . .                                      | 99  |
| 4.9  | (a) A 16-leg birdcage coil with two excitation ports in the middle of the legs. $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution for the 16-leg birdcage with the ports in the middle of two legs at 300 MHz. (b) Transverse plane with NSD = 0.2611. (c) Sagittal plane with NSD = 0.2825. . . . . | 102 |
| 4.10 | (a) A 16-leg birdcage coil with two excitation ports between the birdcage and shield. $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution at 300 MHz on the: (b) transverse plane with NSD = 0.2224. (c) Sagittal plane with NSD = 0.2272. . . . .                                                     | 103 |
| 4.11 | Combination of TEM and birdcage coils; vertical loops are part of the TEM coil since they are connected to the shield [116].                                                                                                                                                                             | 104 |
| 4.12 | Free element coil [118]. . . . .                                                                                                                                                                                                                                                                         | 105 |
| 4.13 | Vertical loops in combination with surface loops [119]. . . . .                                                                                                                                                                                                                                          | 105 |
| 4.14 | Side and top views of a single floating loop. . . . .                                                                                                                                                                                                                                                    | 106 |

|      |                                                                                                                                                                                                                                                                                                                                                                          |     |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.15 | Conventional birdcage with floating loops. (a) Top view. (b) 3D view without shield. . . . .                                                                                                                                                                                                                                                                             | 107 |
| 4.16 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distributions on the transverse plane inside the phantom at 300 MHz. (a) Conventional birdcage with NSD = 0.3009. (b) Conventional birdcage with floating loops with NSD = 0.2349. . . . .                                                                                                                                      | 107 |
| 4.17 | New design of the floating loops. (a) Side view and top view of the single element. (b) Birdcage coil with the new design of the floating loops. . . . .                                                                                                                                                                                                                 | 108 |
| 4.18 | Current distributions on the birdcage legs for: (a) conventional (normalized). (b) Conventional with extended floating loops. . . . .                                                                                                                                                                                                                                    | 109 |
| 4.19 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distributions at 300 MHz: (a), (c) and (e) are the transverse plane for the conventional, conventional with floating loops and conventional with extended floating loops. (b), (d) and (f) are the sagittal plane for the conventional, conventional with floating loops and conventional with extended floating loops. . . . . | 110 |
| 4.20 | Current distributions on the birdcage legs in the presence of the phantom for the conventional BC, conventional BC with floating loops and the ideal case. . . . .                                                                                                                                                                                                       | 111 |
| 4.21 | Instantaneous current flow in an eight-element birdcage coil for the main mode. All the currents are normalized to the maximum rung current, the magnetic field inside the coil is oriented away from the reader. [13]. . . . .                                                                                                                                          | 112 |
| 4.22 | (a) Instantaneous current paths on the birdcage and the extended floating loops. Current distribution on the extended floating loops close to the second leg is shown with a dotted rectangular: (b) Top view. (c) Bottom view. . . . .                                                                                                                                  | 114 |
| 4.23 | Magnetic field lines for the linear excitation. (a) Conventional BC. (b) Conventional BC with floating loops. (c) Conventional BC with the extended floating loops. The inner circle is the end ring and the outer circle is the shield. . . . .                                                                                                                         | 115 |

|      |                                                                                                                                                                                                                           |     |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.24 | (a) SAM inside the CBC. (b) Observation plane inside the SAM. (c) $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ distribution at 300 MHz for a chosen observation plane with NSD = 0.2294. . . . .                                    | 116 |
| 4.25 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution on the sagittal cut inside the birdcage at 300 MHz: (a) conventional birdcage with NSD = 0.3731. (b) CBC with NSD = 0.32. . . . .                                   | 118 |
| 4.26 | Side and top views of a single floating loop. Dimensions are listed in Table 4.8. . . . .                                                                                                                                 | 118 |
| 4.27 | CBC with floating loops. (a) Side view of one sector of the CBC with floating loops. (b) Top view of the complete mesh. Dimensions are listed in Table 4.8. . . . .                                                       | 119 |
| 4.28 | $B_1^+$ field on the observation plane with a radius of 11.5 cm for the unloaded birdcages. (a) <b>CBC</b> with NSD = 0.2107. (b) <b>CBCL</b> with NSD = 0.1066; the floating loops are shown in red. . . . .             | 120 |
| 4.29 | $B_1^+$ field distribution inside the coils for 1 W accepted power, when they are loaded with a SAM used in Fig. 4.24(a). (a) CBC. (b) CBCL. . . . .                                                                      | 122 |
| 4.30 | 7T connected birdcage with floating loops (CBCL) loaded with a cylindrical phantom. . . . .                                                                                                                               | 123 |
| 4.31 | Scattering parameters of the CBCL. The desired resonance frequency producing the homogeneous magnetic field is at 300 MHz. . . . .                                                                                        | 123 |
| 4.32 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution for the CBCL at 300 MHz on the (b) transverse plane with NSD = 0.2196. (c) Sagittal plane with NSD = 0.1897. . . . .                                                | 124 |
| 4.33 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distribution at 300 MHz on the sagittal plane for: (a) the connected birdcage (CBC) with NSD = 0.32. (b) Connected birdcage with floating loops (CBCL) and NSD = 0.1897. . . . . | 124 |

|      |                                                                                                                                                                                                                                                                                                                                  |     |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.34 | (a) The 8-leg birdcage with two ports in the middle of the legs is loaded Gustav model from the CST voxel family. (b) Sagittal cut of the voxel model. . . . .                                                                                                                                                                   | 126 |
| 4.35 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distributions for 1 W accepted power in the middle of the: (a) 8-leg birdcage coil with two excitation ports in the middle of legs at 298 MHz. (b) CBCL at 300 MHz. . . . .                                                                                                             | 126 |
| 4.36 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ for: (a), (b) The 16-leg birdcage. (c), (d) The 8-leg CBCL. . . . .                                                                                                                                                                                                                           | 128 |
| 4.37 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ inside the SAM at 300 MHz for the 16-leg birdcage on the left side, and the CBCL on the right side. . . . .                                                                                                                                                                                   | 130 |
| 4.38 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ at 3T obtained with CST. (a) Transverse plane for the CBC with NSD = 0.790 at 126.4 MHz. (b) Sagittal plane for the CBC with NSD = 0.2451 at 126.4 MHz. (c) Transverse plane for the CBCL with NSD = 0.0854 at 124 MHz. (d) Sagittal plane for the CBCL with NSD = 0.1813 at 124 MHz. . . . . | 132 |
| 4.39 | (a) Single element of the Rx loops. (b) Rx loops around the phantom. (c) CBCL with Rx loops. . . . .                                                                                                                                                                                                                             | 133 |
| 4.40 | $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$ field distributions for the 7T CBCL. (a) Rx loops are not detuned. (b) Rx loops are detuned. . . . .                                                                                                                                                                                          | 133 |
| 4.41 | Schematic view of the PIN diode in the forward and reverse biases. . . . .                                                                                                                                                                                                                                                       | 135 |
| 4.42 | Detuned CBCL. (a) Top view of the coil with the PIN diodes on the end rings. (b) PIN diodes are also used in series with the inductors. . . . .                                                                                                                                                                                  | 135 |
| 4.43 | (a) PIN diodes with reverse bias. (b) With forward bias; the main mode is at 297 MHz. . . . .                                                                                                                                                                                                                                    | 136 |

|      |                                                                                                                                                                                                                                                                                                                                                     |     |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.44 | (a) Middle cut view of the supports: red-colored support for the floating loops and greened-colored support for the rest of the configuration. (b) Middle cut view of the supports loaded with different parts of the coil. (c) Complete view of the coil in the presence of the supports. . . . .                                                  | 137 |
| 4.45 | Fabrication of the CBCL at SIRRIS. (a) Floating loops support. (b) Support for the shield and the inner legs (via clips). (c) Tubular legs used for the inner legs. (d) Copper plates used for the shield, top and bottom additional rings, middle legs, and the floating loops. . . . .                                                            | 139 |
| 4.46 | The two parallel plates represent the middle leg capacitor. (a) Side view. (b) Perspective view. . . . .                                                                                                                                                                                                                                            | 140 |
| 4.47 | (a) Only middle legs with the folded ends. (b) Fabricated 7T CBCL. . . . .                                                                                                                                                                                                                                                                          | 140 |
| 4.48 | Folded excited tubes toward to the floating loops may cause asymmetry in the S - parameters. (a) Top view of the position of two excitation ports. (b) Side view of the two tubes on the excitation position; on the soldered position these two tubes can be folded toward the floating loops and cause asymmetries in the S - parameters. . . . . | 141 |
| 4.49 | S - parameters from measurement, when all the components were soldered. . . . .                                                                                                                                                                                                                                                                     | 142 |
| 4.50 | (a) Measurement setup. (b) The carried out measurement for the simplified CBCL when the floating loops were removed. (c) CST simulation result for the vertical cut inside the coil. (d) Measurement result for the same cut at 242 MHz. . . . .                                                                                                    | 144 |
| 5.1  | An artificial surface around the object. . . . .                                                                                                                                                                                                                                                                                                    | 149 |
| 5.2  | A dielectric sphere and a plane wave propagating in the negative x direction. . . . .                                                                                                                                                                                                                                                               | 152 |
| 5.3  | First row is the MoM and second row is the CST results. . . . .                                                                                                                                                                                                                                                                                     | 153 |
| 5.4  | First row is the MoM and second row is the CST results. . . . .                                                                                                                                                                                                                                                                                     | 153 |

5.5 3D view of  $|Ex|$  field ( $x = 0$  plan perspective). (a) FE-BI method. (b) FEM. Figures are obtained from the FEBI system of equations assembled by Dr. Clément Durochat. . . . . 154

5.6 3D view of  $Ey$  field ( $x = 0$  plan perspective). (a) FE-BI method. (b) FEM. Figures are obtained from the FEBI system of equations assembled by Dr. Clément Durochat. . . . . 155

5.7 x componenet of the E field obtained from: (a) FEM. (b) FEBI with  $n \times \text{RWG}$  testing. (c) FEBI with  $\text{RWG} + n \times \text{RWG}$  testing. Figures are obtained from the FEBI system of equations assembled by Dr. Clément Durochat. . . . . 155

5.8 (a) A birdcage coil around a spherical phantom. (b) and (c)  $|E|$  on the  $x = 0$  observation plane obtained from FE-BI and MoM, respectively. (d) and (e)  $|E|$  on the  $z = 0$  observation plane obtained from FE-BI and MoM, respectively. The birdcage coil design and mesh have been provided by Farzad Jabbarigargari, and simulations have been carried out by Dr. Chan-Sun Park. . . . . 157

5.9 (a) Top view of the CBCL around two concentric spheres. (b)  $|E|$  field obtained from FEBI. (c)  $|E|$  field obtained from MoM. The birdcage coil design and mesh have been provided by Farzad Jabbarigargari, and simulations have been carried out by Dr. Chan-Sun Park. . . . . 158

5.10 Mesh of the heterogenous human head with four media: skin/muscles, skull, cerebro spinal fluid and brain. (a) Lateral cross section. (b) Skull mesh. (c) Front cross section. Meshes were provided by Dr. Clément Durochat. . . . . 159

5.11  $|E|$  field on the sagittal plane obtained from (a) FEBI. (b) CST. FEBI figures are obtained from the FEBI system of equations assembled by Dr. Clément Durochat and CST simulation has been carried out by Dr. Chan-Sun Park. . . . . 160

- 5.12  $|E|$  field on the coronal plane obtained from (a) FEBI. (b) CST. FEBI figures are obtained from the FEBI system of equations assembled by Dr. Clément Durochat and CST simulation has been carried out by Dr. Chan-Sun Park. . . . . 160



# List of Tables

|     |                                                                                                                                                                       |     |
|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 1.1 | Field discription due to the strength of the $B_0$ field [12]. . . .                                                                                                  | 8   |
| 3.1 | NSD for two observation plane with two different radii when the birdcage is surrounded with two different shield size. . .                                            | 61  |
| 3.2 | Dimensions of the CBC shown in Fig. 3.7. . . . .                                                                                                                      | 67  |
| 3.3 | Value of the loads shown in Fig. 3.6. . . . .                                                                                                                         | 67  |
| 3.4 | Value of the loads shown in Fig. 3.11 for the CBC with the additional top and bottom rings. . . . .                                                                   | 71  |
| 3.5 | NSD values for the conventional and connected birdcages on three transverse observation planes inside the phantom. . . .                                              | 77  |
| 3.6 | $B_1^+$ field value for the conventional and connected birdcages in the center of three observation planes inside the phantom for 1 W accepted power. . . . .         | 79  |
| 3.7 | Dimensions of the fabricated CBC. . . . .                                                                                                                             | 84  |
| 4.1 | NSD values for two observation planes, shown in Fig. 4.3(a), inside an unloaded conventional birdcage optimized for 3T and 7T. The birdcage has 13 cm radius. . . . . | 94  |
| 4.2 | NSD and $B_1^+$ values (for 1 W accepted power) in the center of the phantom for different port positions on the transverse and sagittal planes. . . . .              | 100 |

|      |                                                                                                                                                                                                                                                        |     |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.3  | NSD and $B_1^+$ values (for 1 W accepted power) in the center of the phantom for: 8-leg BC with ports in the middle of the legs (PML), 16-leg BC with ports in the middle of the legs (PML), and 16-leg BC with ports between the BC and shield (PBS). | 101 |
| 4.4  | Dimensions of the loop shown in Fig. 4.14.                                                                                                                                                                                                             | 106 |
| 4.5  | Dimensions of the loop shown in Fig. 4.17.                                                                                                                                                                                                             | 108 |
| 4.6  | Homogeneity comparison on the transverse and sagittal planes for: an eight-leg birdcage with two ports in the middle of the legs (BC), BC with floating loops, and BC with extended floating loops.                                                    | 109 |
| 4.7  | Lumped elements for the 7T connected birdcage. C1 and C2 are the end ring capacitors, and the position of the other parameters can be found in Fig. 3.11(a).                                                                                           | 117 |
| 4.8  | Dimensions of the floating loop and the connected birdcage shown in Fig. 4.27, and Fig. 4.26.                                                                                                                                                          | 119 |
| 4.9  | Lumped elements for the 7T connected birdcage with floating loops. C1 and C2 are the end ring capacitors, and the position of the other parameters can be found in Fig. 3.11(a).                                                                       | 120 |
| 4.10 | NSD of the $B_1^+$ filed for the available volume inside the unloaded CBC and CBCL with 28 cm heights and different radii.                                                                                                                             | 121 |
| 4.11 | NSD and $B_1^+$ values for 1 W accepted power on the observation plane in the center of the coils loaded with SAM shown in Fig. 4.29.                                                                                                                  | 122 |
| 4.12 | NSD for the volume inside the phantom at 7T (for the available volume inside the coil); all coils have 8 legs.                                                                                                                                         | 125 |
| 4.13 | NSD for the planes and volume inside the phantoms with two different radii for 16-leg birdcage and 8-leg CBCL, and $B_1^+$ values in the center of the phantoms for 1 W accepted power.                                                                | 129 |
| 4.14 | Dimensions of the fabricated CBCL, in which parameters can be seen in Fig. 4.44(b).                                                                                                                                                                    | 139 |

# Acronyms

|       |                                         |
|-------|-----------------------------------------|
| ASM   | Array Scanning Method                   |
| ABCs  | Absorbing Boundary Conditions           |
| BC    | Birdcage Coil                           |
| BEM   | Boundary Element Method                 |
| BP    | Band-Pass                               |
| CBC   | Connected Birdcage Coil                 |
| CBCL  | Connected Birdcage with Floating Loops  |
| CFIE  | Combined Field Integral Equation        |
| CST   | Computer Simulation Technology          |
| CT    | Computed Tomography                     |
| EFIE  | Electric Field Integral Equation        |
| EM    | Electromagnetic                         |
| FE-BI | Finite Element Boundary Integral Method |
| FEM   | Finite Element Method                   |
| FD    | Frequency Domain                        |
| FOV   | Field of View                           |
| HF    | High Field                              |
| HIS   | High Impedance Surface                  |
| HP    | High-Pass                               |
| LP    | Low-Pass                                |
| MFIE  | Magnetic Field Integral Equation        |

|      |                                       |
|------|---------------------------------------|
| MoM  | Method of Moments                     |
| MRI  | Magnetic Resonance Imaging            |
| MTL  | Microstrip Transmission Line          |
| NMR  | Nuclear Magnetic Resonance            |
| NSD  | Normalized Standard Deviation         |
| PA12 | Polyamide 12                          |
| PCB  | Printed Circuit Board                 |
| PBS  | Ports between the Birdcage and Shield |
| PMMA | Polymethyl Methacrylate               |
| PML  | Ports in the Middle of the Legs       |
| RF   | Radio Frequency                       |
| Rx   | Receive Coil                          |
| ROI  | Region of Interest                    |
| RWG  | Rao Wilton Glisson                    |
| Rx   | Receive Coil                          |
| SAM  | Specific Anthropomorphic Mannequin    |
| SAR  | Specific Absorption Rate              |
| SNR  | Signal-to-Noise                       |
| TEM  | Transverse Electromagnetic            |
| TD   | Time Domain                           |
| Tx   | Transmit Coil                         |
| UHF  | Ultra-High-Field                      |
| VNA  | Vector Network Analyzer               |

# Introduction

Nowadays, magnetic resonance imaging (MRI) is one of the dominant techniques that medical doctors or researchers use to get more information about human or animal bodies. While other imaging techniques like computed tomography (CT) and X-ray are based on ionizing radiation, MRI is a non-invasive method based on a strong magnetic field and radio waves. The main part of this thesis is devoted to designing the radio-frequency (RF) coils which are one of the essential parts of every MRI system. Moreover, efficient numerical techniques have been provided to analyze the electromagnetic fields distribution inside the body being imaged.

## 1.1 Principles of Magnetic Resonance Imaging

The image formation in the MRI technique is based on the presence of hydrogen atoms, which are parts of the water molecules inside the human. Hydrogen is the most used atom in MRI due to its abundance inside the body; however, different elements like fluorine, carbon, and sodium are also used for spectroscopy or imaging purposes [1]. To explain the principle of MRI, it is needed to look at the microscopic behavior of the hydrogen atoms under normal condition and when they are exposed to an external strong magnetic field. Each hydrogen nucleus spins around its axis and produces

a magnetic moment like  $m$ , as shown in Fig. 1.1(a) [2]. Under normal conditions, when there is no applied magnetic field, those magnetic moments of different protons are randomly oriented, as shown in Fig. 1.1(b). Considering an applied external static magnetic field, the randomly oriented magnetic moments will be aligned either in the parallel or anti-parallel direction with respect to the applied magnetic field, Fig. 1.1(c).

Given the applied static magnetic field  $B_0$ , the magnetic moments will precess along their axis. The precession frequency is proportional to the strength of the applied magnetic field with equation (1.1), and that frequency is called the Larmor frequency.

$$f_{Larmor} = \frac{\gamma B_0}{2\pi} \quad (1.1)$$

where  $\gamma$  is the gyro-magnetic ratio and has a value of 42.57 MHz/T [3]. Considering the precession of the nuclei in the presence of the  $B_0$  field the precession axis could be parallel or anti parallel to the  $B_0$  due to the energy state of each proton. One can imagine that lower-state protons are aligned in the direction and higher energy protons are aligned in the opposite direction. Given the above explanation the net magnetic vector of the magnetic moments ( $m$ ) as shown in Fig. 1.1(a) will be anyway parallel to the  $B_0$  field.

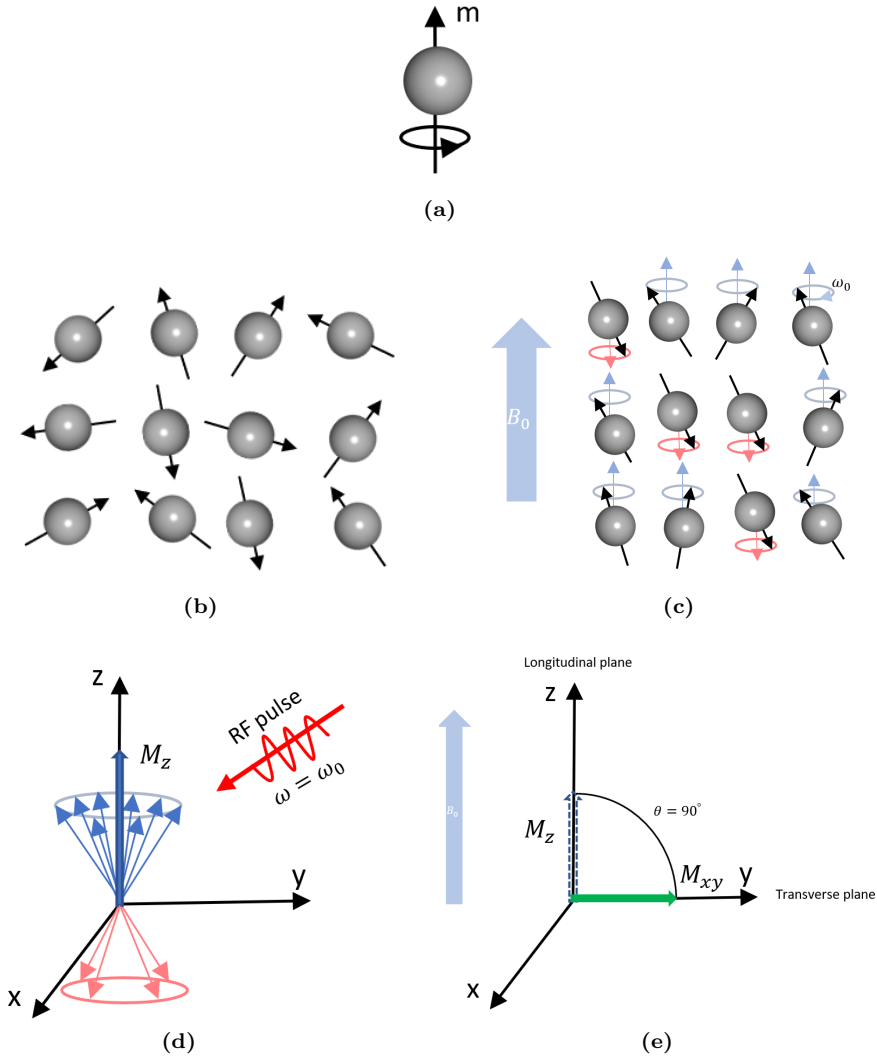
### 1.1.1 Radio-frequency (RF) Coil

Besides the static magnetic field ( $B_0$ ), the RF coil is the other important part of an MRI machine. The RF coils are responsible for producing another RF magnetic field called  $B_1$  in MRI applications. The  $B_1$  field is orthogonal to the  $B_0$  field and is produced by an RF coil that resonates at the Larmor frequency, providing the resonance condition. Hence, as a result of the RF pulse, firstly, some protons will move from a lower energy state ( magnetic moments oriented in the same direction as the  $B_0$  field) to a higher energy level (magnetic moments in the opposite direction as the  $B_0$  field). Secondly, the magnetic moments will precess in phase. As a consequence, the net magnetization vector will be rotated from the longitudinal direction ( $M_z$ ) to the transverse one ( $M_{xy}$ ), shown in Fig. 1.1(d) and Fig. 1.1(e). The

rotation angle depends on the strength of the  $B_1$  field and its duration. Once the RF coil is switched off, this rotated net magnetization vector, returning to its initial position on the longitudinal axis, will induce signals on the receiver coils and start making the image procedures.

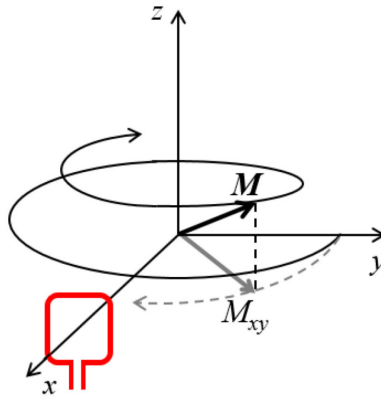
### 1.1.2 Relaxation

As mentioned earlier, by applying RF pulse, the hydrogen nuclei will spin in phase, and the net magnetic vector will be rotated into the transverse plane (xy plane). Once the RF pulse is switched off, after a while and due to interactions between nuclei, the magnetic moments will lose their phase coherence in the transverse plane, resulting in the decay of the net transverse magnetic vector ( $M_{xy}$ ). This relaxation is called T2 and corresponds to the time for  $M_{xy}$  to lose 63% of its maximal transversal magnetization obtained at the end of the excitation, as shown in Fig. 1.3. On the other hand, T1, or longitudinal relaxation, which is longer than T2, is related to the regrowth of the longitudinal net magnetic vector, corresponding to the inducing signals in the receiver system due to the energy transfer between the spin system and the surrounding environment. T1 is the time for  $M_z$  to recover 63% of its initial longitudinal magnetization  $M_z$  before the excitation. As a hint, T1 is shorter in fat than in water and varies between 500 to 1000 milliseconds for biological tissues, whereas T2 is faster in the liquid than in the solid.

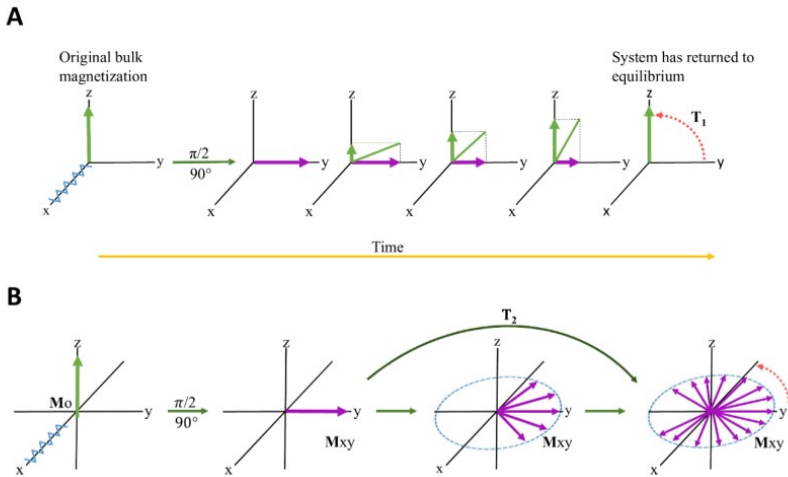


**Figure 1.1:** (a) Nucleus is spinning around its own axis creates a magnetic moment as  $m$ . (b) Nuclei spin around their own axis and are oriented in random directions when there is no applied magnetic field ( $B_0 = 0$ ). (c) Magnetic moments are precessing (with a frequency of  $\omega_0$ ) out of phase around the axis of the applied magnetic field. (d) The net magnetization vector is aligned in the same direction as the applied  $B_0$  field. (e) After applying the RF pulse, the magnetic moments are precessing in phase resulting in the rotation of the net magnetization vector.





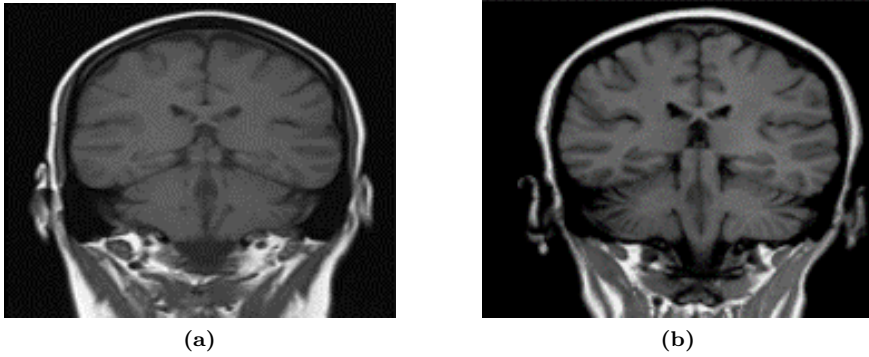
**Figure 1.2:** Once the RF pulse is switched off, the transverse net magnetization vector returns to its initial position in the longitudinal direction while inducing signals on the receiver coil.



**Figure 1.3:** (A) Represents the T1 relaxation, and (B) Represents the T2 relaxation [4].

## 1.2 Techniques to Improve the SNR

Over the last few decades, it has been proven that higher signal-to-noise (SNR) results in better spectral [6] and spatial resolution [7] images in a shorter time, ultimately providing more straightforward diagnosis. Among the different parameters, such as the magnetic characteristics of the tissue to be imaged that would impact the SNR value, from an MRI hardware point of view, the strength of the magnetic field ( $B_0$ ) and the type of the RF coils are essential to improve the SNR. Increasing the magnetic field's strength from low field to the extremely high field, as provided in Table 1.1, increases the amount of the aligned protons in the direction of the applied magnetic field; hence the amount of the produced signal or SNR will be improved; the impact of the strength of the magnetic field on the SNR is shown in Fig. 1.4. Besides the type of the RF coils (surface or volume coils) that results in different SNR values, the number of the elements during the reception also impacts the SNR, as shown in Fig. 1.5.



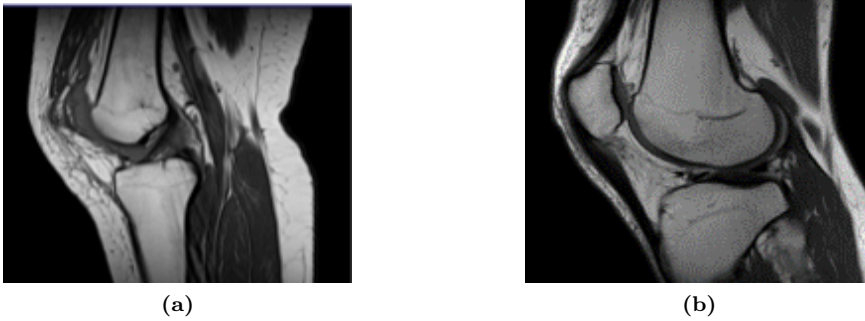
**Figure 1.4:** Impact of the applied magnetic field strength on the SNR. (a) 1.5T MRI machine. (b) 3T MRI machine [5].

Generally, relation between the spin magnetization and static magnetic field ( $B_0$ ) is expressed by equation below [8]:

$$M_0 = \rho_0 \frac{\gamma^2 \hbar^2}{4kT} B_0 \quad (1.2)$$

where  $\rho_0$  is the proton spin density,  $\gamma$  is the gyromagnetic ratio,  $\hbar$  is the Planck constant divided by  $2\pi$ ,  $k$  is the Boltzmann constant, and  $T$  is the absolute temperature (in Kelvin). However, there is no linear relation between the SNR and the  $B_0$  field since other factors like the thermal noise of the sample and electronic components noise should be taken into account while dealing with SNR; hence it has been measured that the relation between SNR and the  $B_0$  field can be expressed as:  $\text{SNR} \sim B_0^{1.65}$  [9].

Knowing that a higher magnetic field corresponds to the higher resonance frequencies for the magnetic moments and a higher resonance frequency for the RF coils, special attention to the RF coil designs has been given. The remainder of this chapter provides a brief overview of the principles of the RF coils and their different types.



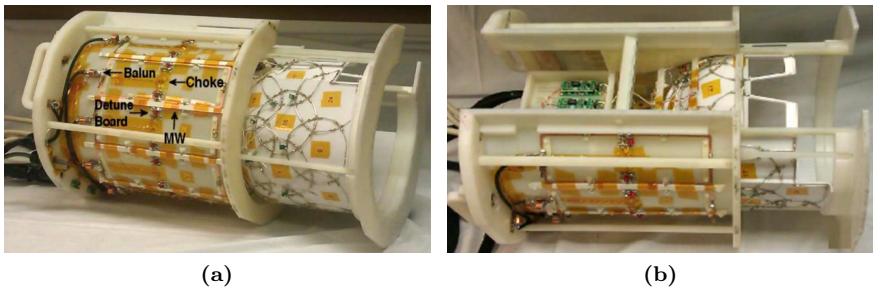
**Figure 1.5:** Effect of the element numbers on the receive mode on the SNR. (a) Two channel knee coil. (b) Sixteen channel knee coil [5].

### 1.3 Transmitter and Receiver RF Coils

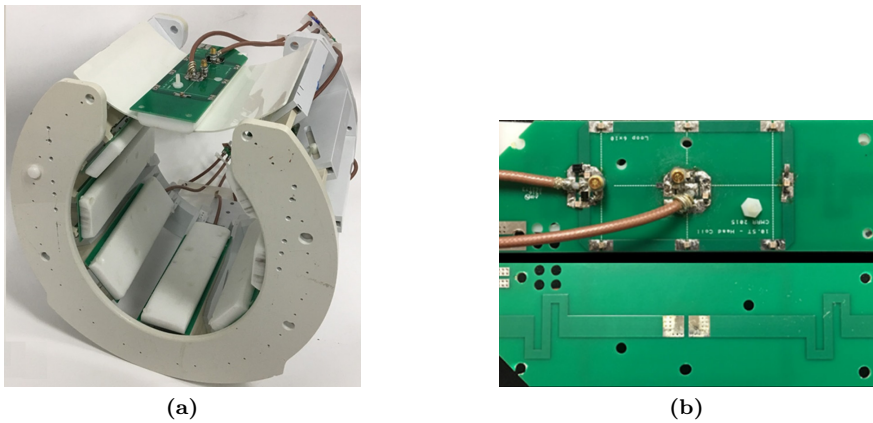
The nomination of RF coils in MRI applications comes from the fact that their resonance frequency, regardless of their type or function, corresponds to the RF range in the EM spectrum. RF coils could be categorized into the transmitter (Tx), receiver (Rx), or transceiver (both transmit and receive (Tx/Rx)). In the transmit mode, as mentioned in Section 1.1.1, the RF coils have been used to tip the net magnetization vector; however, in the receive mode, the RF coils are responsible for receiving the signals due to the relaxation of the excited spins.

**Table 1.1:** Field discription due to the strength of the  $B_0$  field [12].

| Field description | ( $B_0$ )       | Larmor frequency |
|-------------------|-----------------|------------------|
| Low               | 0.2- 0.5        | 8.5- 21.3 MHz    |
| Intermediate      | 0.5- 1.5        | 21.3- 63.9 MHz   |
| High              | 1.5- 4          | 63.9- 170.3 MHz  |
| Ultra high        | 4- 10.4         | 170.3- 400.2 MHz |
| Extremely high    | 11.7 and higher | >498.1 MHz       |



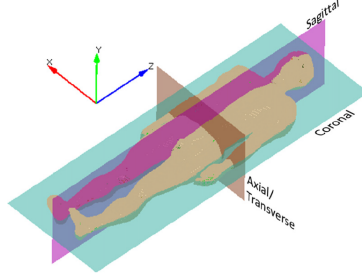
**Figure 1.6:** A 10-channel transmit coil and 31-channel receive coil are combined in a transmit-only/receive-only configuration [10].



**Figure 1.7:** A 16-channel transceiver loop-dipole configuration. (b) Single element of loop-dipole with front and back views [11].

The Tx and Rx coils could be used separately to obtain the best per-

formance in each devoted phase as shown in Fig. 1.25. However, there are some applications where one RF coil has been used to perform both tasks. Three typical observation planes that can be seen by positioning of the RF coils are shown in Fig. 1.8.



**Figure 1.8:** Three typical observation planes in the MRI applications [13].

The magnetic field due to the RF coil is called  $B_1$ . This linearly polarized magnetic field could be written as [14]:

$$\overline{B} = 2B_1 \cos(\omega t + \phi) \hat{x} \quad (1.3)$$

where  $\omega$  and  $\phi$  are the Larmor frequency and an arbitrary phase from the instruments, respectively. This field could be decomposed into the two circularly polarized fields as:

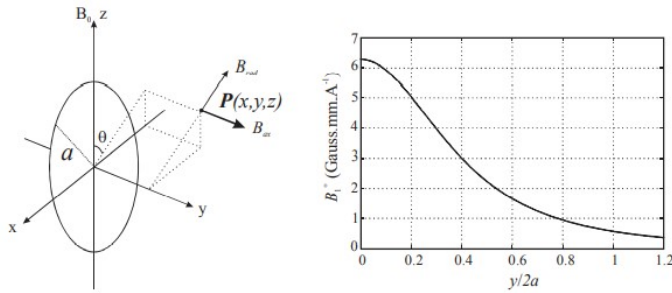
$$\overline{B} = B_1 [\cos(\omega t + \phi) \hat{x} - \sin(\omega t + \phi) \hat{y}] + B_1 [\cos(\omega t + \phi) \hat{x} + \sin(\omega t + \phi) \hat{y}] \quad (1.4)$$

The first term, also known as  $B_1^+$  is used for the excitation, as it rotates in the same direction as the spins. The second term which rotates in the opposite direction of the nuclear precession is  $B_1^-$ . According to the principle of reciprocity [15], the magnitude of the current induced in the receiver coil (when net magnetization vector is changing from transverse plane to the longitudinal one) is proportional to the magnitude of this field. In other words, the sensitivity of the receiver coil is proportional to its efficiency as a transmitter coil. In order to obtain the optimal performance in the Tx, Rx, or Tx/Rx mode, one can imagine that the RF coils should have the proper

topology due to the application, which can be categorized into the surface and volume coils. Surface coils with the shape of the flat rectangular or circular, shown in Fig. 1.9, mainly have been used in the Rx mode since they have higher receive sensitivity in the vicinity of the coil and low noise pick up as they couple to a limited tissue volume. However, surface coils can be used as a transmitter for more localized and topical applications (in the near field region, the magnetic field is the dominant field for the loop antennas [16], [17]). To increase the penetration depth of the magnetic field for the surface loop, we may increase the diameter of the loop, which will reduce the SNR, Fig. 1.10.



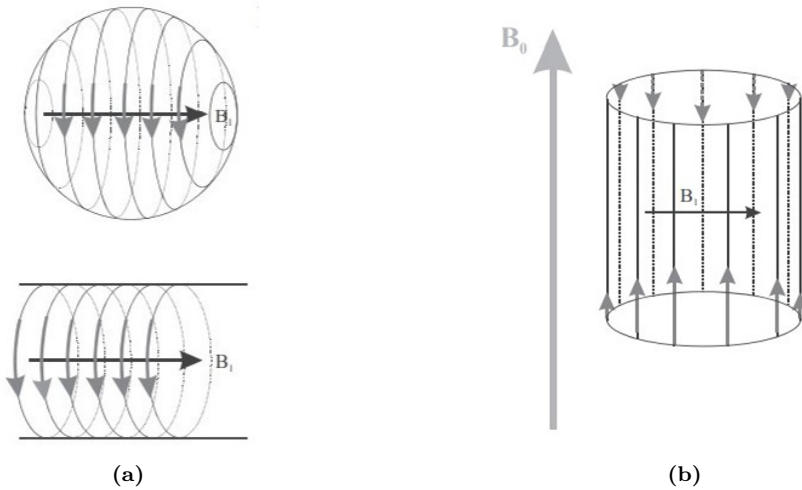
**Figure 1.9:** (a) Surface loop coil and the orientation of its magnetic field [18]. (b) Surface loop coil used in the Rx mode with its preamplifier [19].



**Figure 1.10:** Effect of the surface loop diameter on the penetration depth of the magnetic field [20].

## 1.4 RF Volume Coils

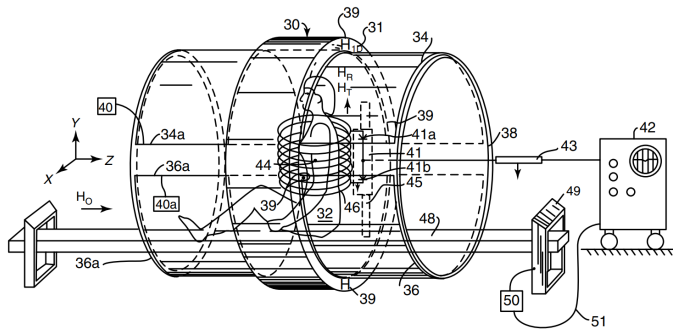
Compared to the surface coils, volume coils have a larger field of view (FOV) with a homogeneous field distribution. As comes from their names, these coils have been used to encompass a volumetric organ, such as the head or abdomen. We can consider two different current distributions to create a homogeneous magnetic field inside a volumetric resonator; either a uniformly distributed loop of currents on the surface of a sphere (could be a long solenoid) as shown in Fig. 1.11(a) or a sine-dependent line current distribution parallel to the cylinder axis as shown in Fig. 1.11(b). Due to the orientation of the magnetic field concerning the coils symmetry axis, volume coils can be divided into axial and transverse resonators [20].



**Figure 1.11:** Two types of current distributions that create homogeneous magnetic fields inside the coil. Left, uniformly distributed loop of currents. Right, sine-dependent line current [20].

### 1.4.1 Axial Resonators

In this category of the volume coil (like sphere or solenoid), the homogeneous magnetic field is oriented in the same direction as the coils axis, as shown in Fig. 1.12. The solenoid coil is the well-known axial resonator where the object being imaged is needed to be perpendicular to the main magnetic field  $B_0$ , which was the early idea in MRI imaging but nowadays, the axial resonators mainly are used in the Nuclear Magnetic Resonance (NMR) spectroscopy.



**Figure 1.12:** Orientation of the object being imaged inside the axial resonator (solenoid coil in this figure) [21].

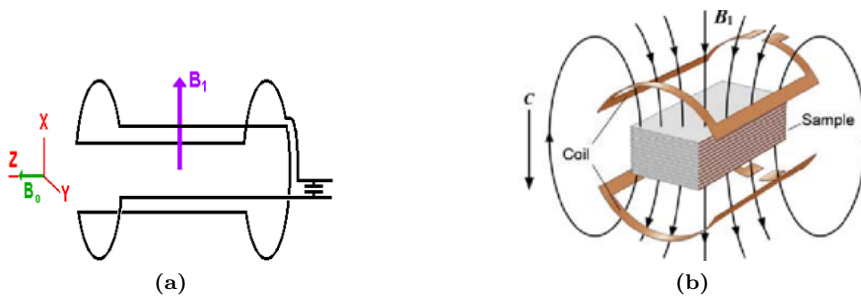
### 1.4.2 Transverse Resonator

The dominant property of the transverse resonators is their perpendicular  $B_1$  field concerning the coil symmetry axis, making them the best candidate for human head imaging. Some of the well-known transverse coils are reviewed hereunder.

#### Saddle Coil

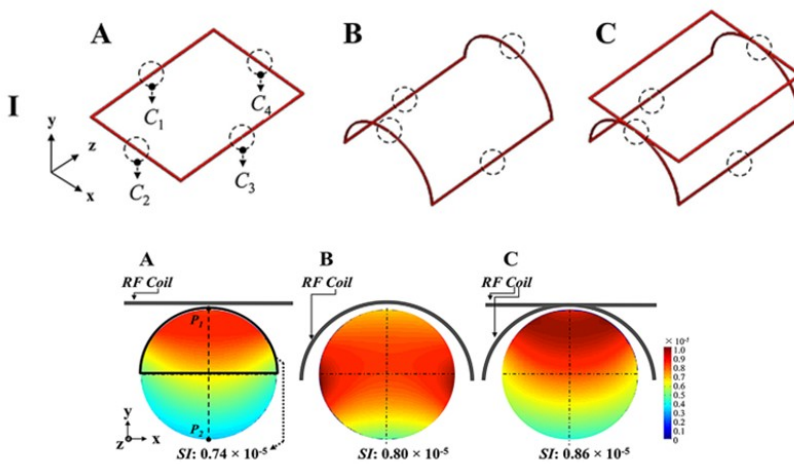
The saddle coil consists of two loops either connected in series or two free elements so that the corresponding magnetic field is perpendicular to the  $B_0$  field, Fig. 1.13. One loop is located on the back side of the head, and the other one is just in front of it with a constant distance to create a uniform magnetic field.





**Figure 1.13:** Saddle coils [22], [23].

Saddle coils could be used with the surface coils to increase the SNR; this idea has been implemented for a half-saddle coil and a square loop for small animal imaging, see Fig. 1.14 .



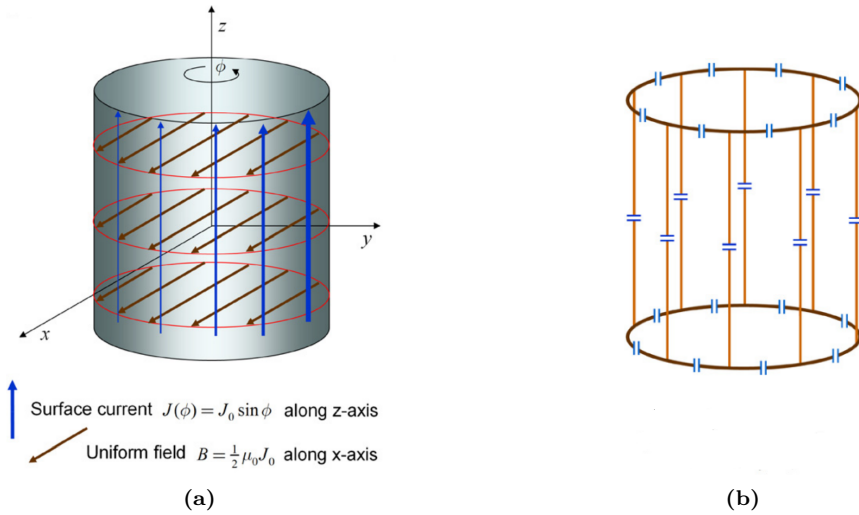
**Figure 1.14:** Saddle coil in a combination with the surface loop [24].

### Birdcage Coil

The most well-known and most used volume coil is the birdcage coil. This coil got this name since its topology looks like the traditional cage for birds. This coil was first introduced in 1985 by C. Hayes [25] for an MRI machine at 1.5 T. The principle of the birdcage coil comes from the fact that an infinitely long cylinder carrying a surface current parallel to its axis and varying like  $\sin\phi$  around its axis, generates a uniform transverse magnetic field inside the cylinder [19], shown in Fig. 1.15(a).

As any static magnetic field in free space satisfies the Maxwell equations, considering a cylinder with axial surface current  $\vec{J}$  and applying the boundary condition as  $\hat{n} \times \vec{H} = \vec{J}$  ( $\hat{n}$  is the normal vector to the surface), then the axial surface current ( $J_s(\phi)\hat{z}$ ) will be a function of  $\sin\phi$ , as shown in Fig. 1.15(a).

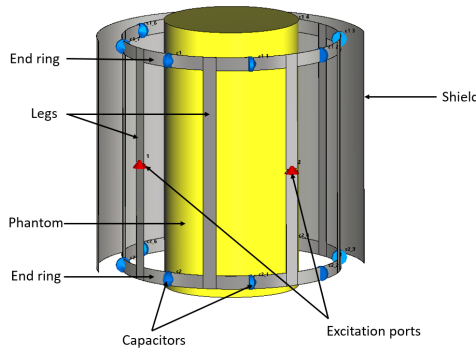
The birdcage coil, shown in Fig. 1.15(b), tries to approximate the above-mentioned theory by having equally spaced current-carrying vertical legs to replace the cylinder body.



**Figure 1.15:** (a) Uniform magnetic field inside an infinite cylinder can be obtained via axial surface current that varies like  $\sin\phi$  around its axis. (b) Birdcage coil with variable currents on its legs to approximate the  $J_0 \sin\phi$  current distribution [19].

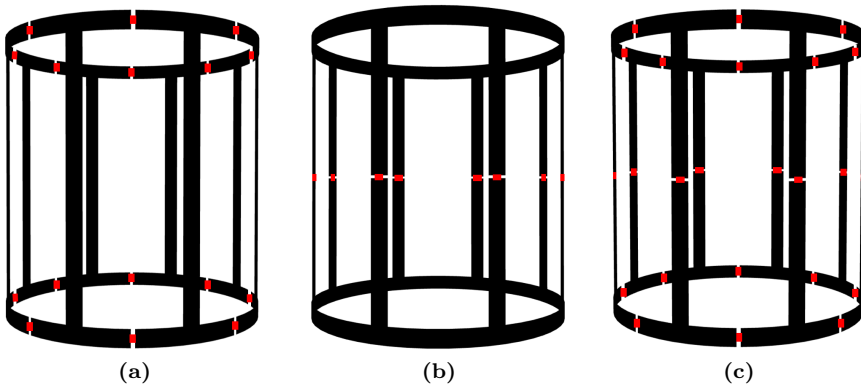
The vertically oriented legs are terminated to two end rings on the top and the bottom. The natural inductances that come from these current-carrying conductive elements, together with lumped capacitors that could be positioned on the legs or on the end rings, create an LC network with several resonance frequencies.

For a birdcage coil with  $N$  (even) number of legs, each leg is positioned with  $\frac{2\pi}{N}$  rotation with respect to the previous leg. An eight-leg birdcage coil with two end rings and surrounded by a metallic shield is shown in Fig. 1.16. Shield is used to avoid unwanted interactions between the birdcage and the outside environment.



**Figure 1.16:** Different parts of the birdcage coil. Half of the shield is not shown to easily show the different parts.

Concerning the position of the lumped capacitors, three different topologies for the birdcage coil have been considered so far [26]. The low-pass (LP) birdcage, in which the capacitors are located on the legs. If the capacitors are located on the end rings, that birdcage is called high-pass (HP). Whereas for the band-pass (BP) birdcage, capacitors are on the legs and the end rings; these three types of the birdcage coil are shown in Fig. 1.17. HP birdcages are preferred for the UHF MRI, whereas LP birdcages are used in the low-field MRI because the homogeneous mode of the LP birdcage occurs in the lower frequencies compared to the HP birdcage with the same size, and BP birdcages, depending on the application can be used in both higher or lower frequencies.

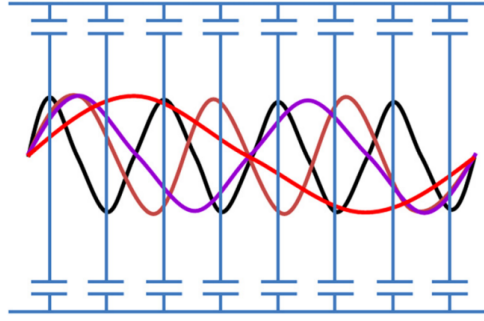


**Figure 1.17:** Three different types of the birdcage coil. (a) High-pass. (b) Low-pass. (c) Band-pass; the excitation ports are not shown.

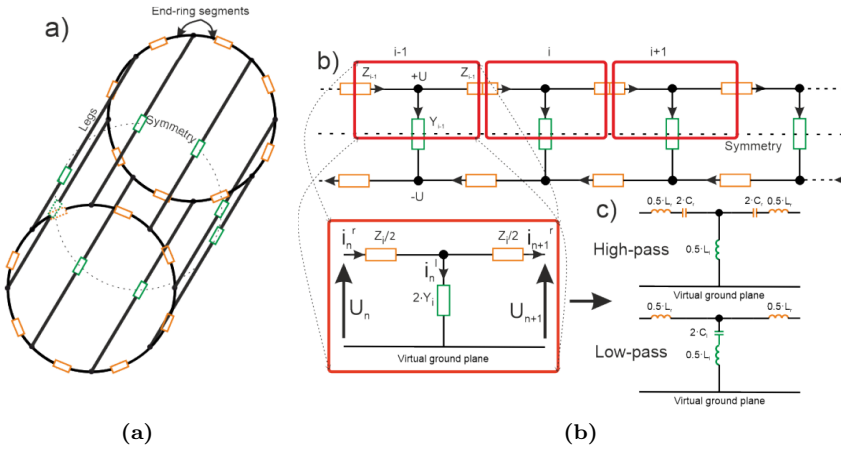
It has been shown that a birdcage coil with  $N$  number of legs can have maximum  $N/2+2$  resonances.  $N/2$  comes from the number of closed current loops within the birdcage, and 2 corresponds to the resonances due to the current flowing through the end rings [27], [28]. In [29], the author analyzed the birdcage coil as a transmission line. A unit cell or leg described by a transfer or ABCD matrix by considering a birdcage as a periodical network of LC network [29]. This implies that each unit cell of a birdcage can be defined with the a characteristic impedance and a phase shift.

The desired resonance of the birdcage among the several resonances, is when the current on the legs has only one wavelength (or a total phase shift of  $2\pi$  for the current around the legs), shown in Fig. 1.18. This mode in combination with a mode rotating in the opposite direction (a combination of  $e^{j\phi}$  and  $e^{-j\phi}$  modes, which provide the desired  $\sin\phi$  current distribution), provide a very homogeneous field inside the birdcage, and its the only resonance frequency producing a non-zero transverse magnetic field at the center of the birdcage, see Fig. 1.21(a), [13].

In [29], the author considered an eight-leg birdcage as a transmission line (TL), composed of a periodic arrangement of unit cells, see Fig. 1.19.



**Figure 1.18:** Four different modes for an eight-leg birdcage. The desired mode is the red one when the current has one wavelength on the legs. The mode shown in black is a higher mode producing opposite currents on the adjacent legs, which result in the zero field at the center of the coil [13].



**Figure 1.19:** Obtained from [29]: (a) an eight-leg birdcage coil. (b) Simplified equivalent circuit of a birdcage coil, consists of multiple unit cells. (c) The high pass or low pass unit cells due to the position of the capacitors.

Fig. 1.19, shows three unit cells with  $Y$  representing the leg admittance and  $Z$  the end ring segment impedance. Considering modes wherein the current directions are opposite on the end rings, the middle transverse plane could be considered as a virtual ground plane. Then a unit cell can be simplified as shown in Fig. 1.19(b) with a lumped parallel admittance  $2Y_i$

on the leg and two lumped series impedance  $Z_i/2$  on the end ring [29].

This periodic structure can be described by the transfer or ABCD matrix, which allows one to obtain the characteristic impedance and the phase shift induced by a unit cell. The transfer matrix  $T_i$  of a unit cell, is a  $2 \times 2$  complex matrix that links the input voltage and current  $(U_n, I_n)$  to the output voltage and current  $(U_{n+1}, I_{n+1})$  through [29]:

$$\begin{pmatrix} U_{n+1} \\ I_{n+1} \end{pmatrix} = T_i \cdot \begin{pmatrix} U_n \\ I_n \end{pmatrix} \quad (1.5)$$

From the schematic the and the relation between the input and output voltages and currents, the transfer matrix of the  $i^{th}$  unit cell can be written as [29]:

$$T_i = \begin{pmatrix} 1 + Z_i Y_i & -\frac{Z_i^2 Y_i + 2Z_i}{2} \\ -2Y_i & 1 + Z_i Y_i \end{pmatrix} \quad (1.6)$$

In the case of a high pass unit cell,  $Z_i$  and  $Y_i$  are given by [29]:

$$Z_i = \frac{1}{i\omega C_{r,i}} + i\omega L_{r,i}, \quad Y_i = \frac{1}{i\omega L_{l,i}} \quad (1.7)$$

And, for a low pass unit cell they read [29]:

$$Z_i = i\omega L_{r,i}, \quad Y_i = \frac{1}{i\omega L_{l,i} + \frac{1}{i\omega C_{l,i}}} \quad (1.8)$$

With  $C_{r,i}$  end ring capacitance for a high pass, and  $C_{l,i}$  leg capacitance for a low pass birdcages.  $L_{r,i}$ , and  $L_{l,i}$  are the end ring and leg effective inductances. The effective inductance of the ring or leg number  $m$  that takes into account the mutual coupling between conductors is given by [29]:

$$L_m^{r,l} = \hat{L}_m^{r,l} + \sum_{n=0, n \neq m}^{N-1} M_{nm}^{r,l} \cos(2\pi k \frac{n-m}{N}) \quad (1.9)$$

where  $\hat{L}^{r,l}$  is the self-inductance of a ring or leg number  $m$ ,  $M_{nm}$  is the mutual inductance between two thin an parallel wires,  $k$  is the mode number and  $N$  is the total number of unit cell.

The phase shift induced by a unit cell can be obtained by computing the eigenvalues of the matrix  $T_i$ , as follows [29]:

$$\delta\phi_i = \cos^{-1}(1 + Z_i Y_i) \quad (1.10)$$

The phase shift  $\delta\phi_i$  corresponds to the phase of the nodes (between the cells), and as for the main mode of the birdcage the total phase shift of  $2\pi$  is needed, then having  $N$  number of legs, implies  $\delta\phi_i = \frac{2\pi}{N}$ .

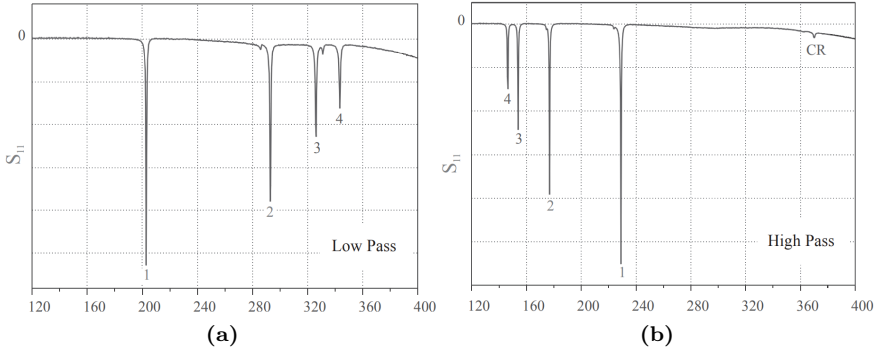
The characteristic (Bloch) impedance which is the ratio between the voltage and currents at the nodes of unit cells, can be determined from eigenvector analysis of the transfer matrix as follows [29]:

$$Z_b^i = \frac{1}{2} \sqrt{Z_i^2 + \frac{2Z_i}{Y_i}} \quad (1.11)$$

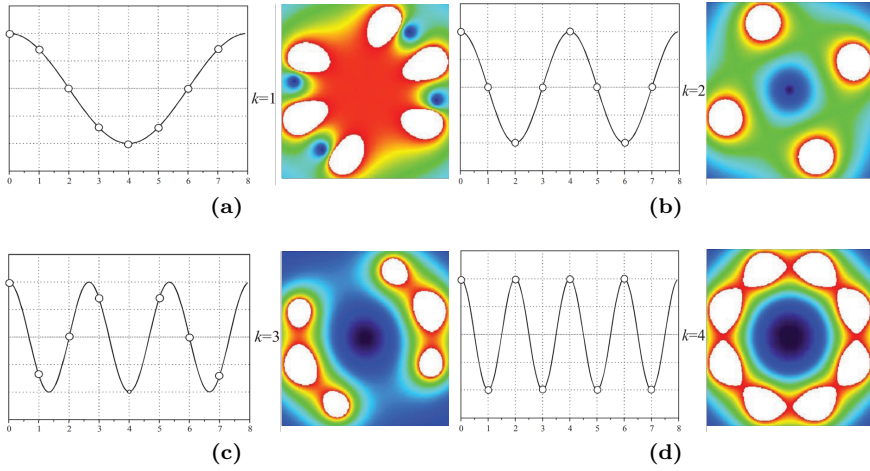
For a conventional birdcage as all the cells are identical, the characteristic impedance is set the same for each unit cell.

Knowing the induced phase shift by a unit cell and the characteristic impedance, one enables can compute the end ring capacitance and the leg inductance for a high pass birdcage [29].

For illustration purpose, resonant modes of an eight-leg LP and HP birdcage coils are shown in Fig. 1.20, when the coil is matched to  $50 \Omega$ . As shown, the fundamental mode ( $k = 1$ ), is the first mode for the LP birdcage, and for the HP birdcage is the mode before the end ring mode (end ring mode is indicated as Co-Rotational (CR) mode). The corresponding current distributions in the legs and associated field distributions for each mode are shown in Fig. 1.21.



**Figure 1.20:** Resonant modes of the LP and HP eight-leg birdcages. For the HP birdcage Co-Rotational (CR) mode corresponds to the resonance of the end-ring (The horizontal axis is the frequency range in MHz) [20].



**Figure 1.21:** Current amplitude in each leg (shown by small circles) and associated magnetic field distribution corresponding to each mode. The homogenous field distribution is obtained for the  $k = 1$  mode [20].

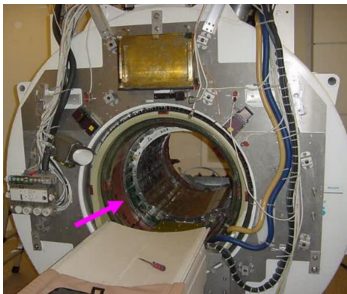
Birdcage coils are typically driven in the quadrature mode to produce the circular polarization. As shown in Fig. 1.22, in that configuration two ports are located  $90^\circ$  apart spatially and electrically. Such an excitation improves the SNR by a factor of  $\sqrt{2}$  [30].





**Figure 1.22:** (a) Linear and (b) quadrature excitation of a birdcage coil.

The birdcage coil can be used for whole-body imaging, which needs to be inserted into the MRI bore, shown in Fig. 1.23(a). In this case, a metallic shield again inserted into the bore separates the birdcage coil from the rest of the MRI and keeps the proper isolation from unwanted interactions. Also, as shown in Fig. 1.23(b), a birdcage coil can be dedicated to human head imaging. This thesis focuses on the birdcage coil for head imaging at 3T and 7T MRI.



(a)

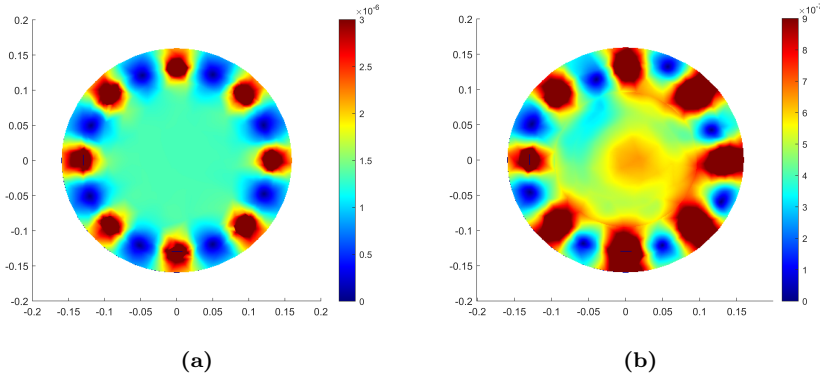


(b)

**Figure 1.23:** (a) A full body birdcage coil. (b) A birdcage coil dedicated to human head imaging (a mirror positioned on the top allows the patient to see the outside of the magnet bore) [19].

### 1.4.3 Inhomogeneity in the Loaded Birdcage Coil

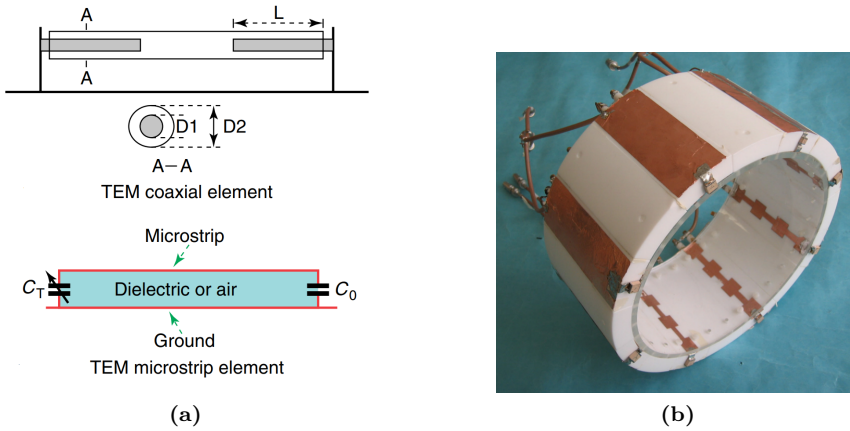
The homogenous magnetic field produced by a birdcage is affected by several parameters, which will be discussed in Chapter 3. However, the main reason for the inhomogeneity is the shortened wavelength, which happens more obviously at high frequencies. The shortened wavelength creates standing waves inside the phantom and also inside the MRI tunnel, or within the cavity created by the shield. Corresponding to a constructive and destructive pattern for the fields distribution. Inhomogeneity in the MRI community refers to the bright and dark spots in the field distribution inside the dielectric phantom. Fig. 1.24 shows an unloaded and loaded birdcage with phantom. One can see that for the unloaded case, a very homogeneous magnetic field inside the coil is achievable. However, the inhomogeneity is evident when the coil is loaded with a phantom. Proposing new designs for the birdcage to improve its homogeneity is the main goal of this thesis.



**Figure 1.24:**  $B_1^+$  Field distribution inside the birdcage coil surrounded by shield at 3T: (a) without phantom at 129 MHz. (b) With phantom at 131 MHz. One can see the inhomogeneity (hot spot in the center and dark spot on the top left) in the field distribution due to the loading of the birdcage with a phantom.

### Transverse Electromagnetic Resonator (TEM)

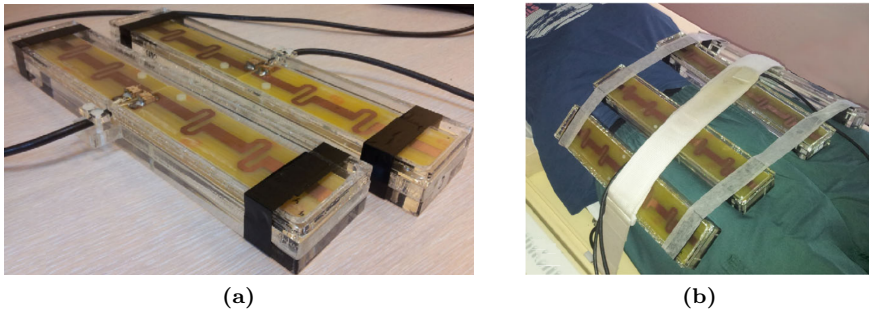
The TEM coil, proposed by Vaughan et al. in 1994 [31], is another type of volume coil that has been used for high field and ultra high field MRI. The TEM coil consists of a number of  $N$  transmission line elements like coaxial or microstrip elements connected to shield through capacitors, shown in Fig. 1.25(a). For the TEM coil with coaxial elements, the gap between two inner conductors is used to tune the element resonance frequency to the desired one; whereas, for the microstrip transmission, capacitors at the end of the line are used for the tuning [32]. Having no endings makes the resonance path shorter than the birdcage coil; on the other hand, each element can be tuned independently, providing more freedom in optimizing the coil to improve the magnetic field homogeneity. As shown in Fig. 1.25(b) the traditional rectangular shaped microstrip line elements are modified into multi-section alternating impedance element to improve the magnetic field homogeneity along the coil length [33], [34].



**Figure 1.25:** (a) TEM coaxial and microstrip elements. (b) An 8 channel TEM head coil with modeified elements to improve the magnetic field homogeneity in the axis of the coil [32], [33].

#### 1.4.4 Dipolar-type of RF Coils

Besides the LC resonators introduced above, other types of RF coils based on dipole antennas have been proposed by researchers. Dipole antennas in the UHF MRI have been used for imaging of deeply located organs [35], [36], [37]. Further improvement in the safety of the dipoles has been reported in [38], [39], where fractionated dipoles (each arm of the dipole is segmented and interconnected with capacitors or inductors) are used to reduce the specific absorption rate (SAR), see Fig. 1.26.



**Figure 1.26:** (a) Two fractionated dipoles mounted on the PMMA. (b) 8 elements of the fractinated dipoles are placed on the volunteer body for the prostate imaging [38].

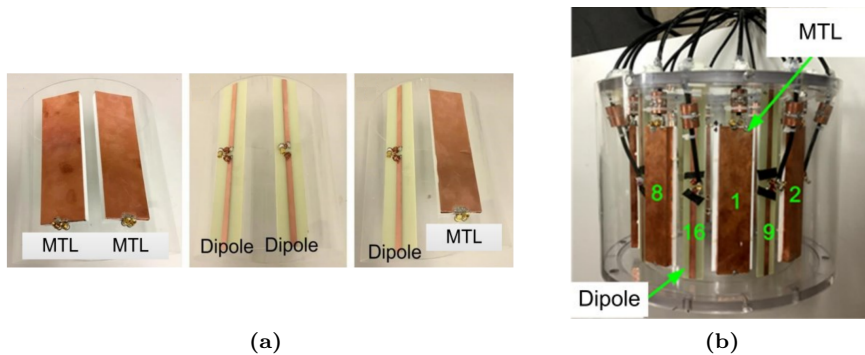
As shown in Fig. 1.27, radiative antenna arrays consisting of 16-channel dipole [40], and 8-channel monopole antennas [41], also have been used for human head imaging at 10.5T. Combinations of dipoles and loops also have been proposed in the MRI applications to provide more degrees of freedom in manipulating the near field distribution through the different properties of dipoles and loops [17], [42], [43].

Besides the dipole antenna array that mentioned above, an array of microstrip transmission lines (MTL) can also be used in the MRI applications. However, by increasing the number of channels to improve the SNR, for instance from 8 channel to 16 channel, mutual coupling between two neighbor elements would be stronger, resulting in the reduced transmission efficiency and the SNR in the reception mode. Knowing that for the MTL, the EM

fields are confined between the strip and the ground, its  $B_1^+$  field is mainly located close to the coil, so the penetration depth is low. In contrast, dipoles are radiative elements, and their  $B_1^+$  field is penetrated through the phantom. Hence, as shown in Fig. 1.28, it has been proposed to use the MTL elements in combination with the dipole to reduce the coupling between two elements within an RF array [44].



**Figure 1.27:** (a) Dipole and (b) monopole antenna arrays for the human head imaging at 10.5T [41], [40].



**Figure 1.28:** (a) Two elements of the microstrip transmission line (MTL) and dipole antenna. (b) 16-channel combined array of MTLs and dipoles [44].

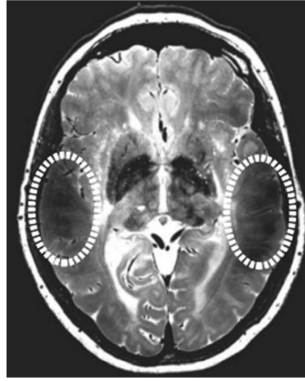
## 1.5 Use of Design Tools

Numerical methods are accurate in MRI applications, either in analyzing the EM field distributions inside the body or designing the RF coils. However, due to the complexity of the MRI system, fast and efficient methods have gotten more attention. In this thesis, an in-house method of moments (MoM) code developed in C++ and MATLAB has been used to design the birdcage coil. Given the axial symmetry of the birdcage coil, a fast and accurate technique, the array scanning method (ASM), has been applied in the MoM code to exploit that symmetry and to efficiently reduce the computation time. On the other hand, using the open-circuit pattern concept [45], the MoM code allows us to compute the full-MoM impedance matrix once and for all and to optimize the lumped elements value without rerunning the whole computation. The commercial EM software, Microwave CST Studio Suite [46], has been utilized to validate the design of the birdcage coils and to see the magnetic field distribution inside the specific anthropomorphic mannequin (SAM) and the human head model in the voxel family of the CST commercial software. The CST voxel family provides a set of inhomogeneous human body models that can be used for more realistic simulations while loading the birdcage with the voxel models. In the fabrication procedure, the impact of the supporting material used to guarantee the mechanical stability of the coils, is simulated by using the MoM and CST together.

## 1.6 Goals of the Thesis

The main objective of this thesis is to design a new birdcage coil for HF and UHF MRI applications. The birdcage coil is a well-known coil that has been used in the human body and mainly in head imaging. It has been proven that the SNR of the MRI images increases by increasing the strength of the static magnetic field, which corresponds to the higher Larmor frequency, so it is necessary to use high-frequency RF coils. The inhomogeneity as shown in Fig. 1.27, i.e., bright and dark spots in the magnetic field distribution happens when the birdcage coil is loaded with a phantom and the wavelength inside the phantom becomes comparable or even smaller than

the phantom size, resulting in the standing waves with constructive and destructive interference. However, this problem worsens by increasing the strength of the static magnetic field and the resonance frequency of the RF coils.



**Figure 1.29:** A human brain image at 7T MRI; two circles show the destructive interference resulting in the dark regions with lower field values [47].

A new birdcage coil has been designed and fabricated to overcome the aforementioned inhomogeneity issues. The novelty of this design, is the physical connection between the birdcage coil and its shield with some lumped elements [48], which makes sense to call this design as the connected birdcage. Besides the new birdcage design, two different numerical techniques have been studied. In the first one, an efficient method has been used in the method of moments solver to observe the field distribution inside the piecewise homogeneous media, whereas in the second one, a hybrid method that combines the finite element method and method of moments is studied. Thanks to this hybrid method, the efficiency of the FEM in solving the EM equation inside heterogeneous media and the efficiency of the MoM in the scattering problems such as the interaction between the body and the antenna is feasible.

## 1.7 Outline of the Thesis

The main part of this thesis is devoted to the new designs of the radio-frequency (RF) coils at high field and ultra-high-field magnetic resonance imaging (MRI). Besides, numerical techniques have been proposed to efficiently analyze the electromagnetic (EM) field distribution inside the imaged object. Hereunder a brief description of each chapter is given.

**Chapter 1** introduced the principles of magnetic resonance imaging while explaining its different parts; special attention is given to the RF coils.

**Chapter 2** explains the concepts of the Method of Moments in the MRI application, providing more details on the techniques for an efficient design of the RF coils and analysis of the field distribution inside the piecewise homogeneous media.

**Chapter 3** discusses the homogeneity concept of the RF transmitter coils at high-field MRI by reviewing the techniques that have been used to improve the magnetic field homogeneity for a given cut inside the human body, along with the methods that can be applied for the local homogeneity improvement by creating a secondary magnetic field in the vicinity of the region of interest. Then, significant attention is given to the new design for the birdcage coil, named connected birdcage. Simulation and fabrication techniques with the measurement results for the 3T connected birdcage coil that have been carried out in collaboration with the Fresnel institute in Marseille are provided in this chapter.

**Chapter 4** introduces new designs for the conventional birdcage and the connected birdcage based on the radially oriented floating loops. It has been shown that the floating loops improve the magnetic field homogeneity in the available volume inside the birdcages. This chapter also includes a comparative study between this new designs and other conventional birdcages to point out the main advantages of this newly designed coil. The new coil based on the connected birdcage and floating loops has been fabricated for UHF (7T) MRI, and the measurement results are provided.

**Chapter 5** is related to a hybrid electromagnetic solver, which combines the finite element method (FEM) and the boundary integral method (MoM).



This hybrid method uses FEM to find the fields distribution within an inhomogeneous body while it uses MoM to compute the interaction between the body and a surrounding antenna. Special attention is given to the articulation between the two methods at the surface of the body. This work has been carried out in collaboration with Dr. Clément Durochat from the Multiwave imaging company and Dr. Chan-Sun Park from UCLouvain.

**Chapter 6** concludes the thesis and provides some perspectives to improve the homogeneity of the field at UHF MRI.



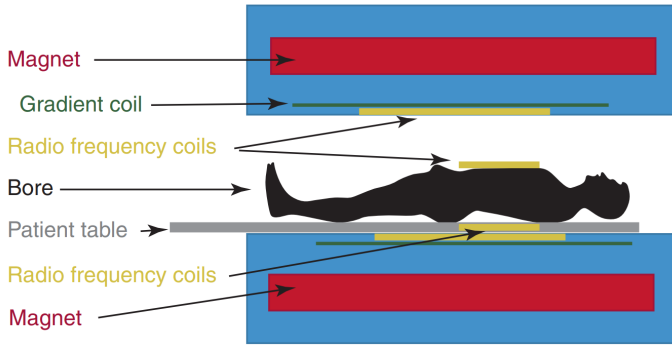
# CHAPTER 2

## Method of moments in MRI applications

This chapter presents numerical techniques used in the thesis to analyze the EM field inside the body and MRI antenna design. Using numerical methods is essential since solving the Maxwell equation for MRI system, including complex structures like the human body, would not reach a precise solution with analytical techniques. Section 2.1 provides an introduction regarding the numerical methods in the MRI application. Section 2.2 gives an overview of the method of moments, followed by the reviewing array scanning method and its application in the design and analysis of the RF coils. This section also presents the nesting approach, enabling us to efficiently use the MoM code to analyze the EM field distribution inside the object being imaged in the MRI scanner. In Section 2.3 a birdcage coil has been designed and analyzed with the MoM code and the results are validated using a commercial software.

### 2.1 Introduction

The goal consists of determining the distribution of electromagnetic fields in the UHF MRI for a given distribution of materials as shown in Fig. 2.1



**Figure 2.1:** Schematic of an MRI scanner [49].

(human body, supporting structures, MRI tunnel, and antennas themselves) and a given excitation of the antennas. The field representation looked for allows one to check (i) that magnetic fields have the proper homogeneity so as to allow imaging with a homogeneous signal-to-noise ratio, (ii) that the electric field does not reach too high values so as to avoid a too high Specific Absorption Rate (SAR) and (iii) that the power provided by the generators does not get reflected towards them (impedance matching). Generally, a key tool consists of solving Maxwell equations to find electric and magnetic fields everywhere within the structure. A simulation method is named full wave when the geometrical discretization of the surfaces and volumes (e.g., meshing into elementary triangles or tetrahedra) only limits the accuracy. In this area, four categories of methods can be determined based on two orthogonal classifications: (i) time-domain versus frequency-domain and (ii) integral-equation approaches versus differential equations. The first description concerns the fact that fields are represented as a function of time or as a superposition of harmonics. The second one concerns the fact that fields are explicitly written as radiated by sources distributed over certain surfaces or volumes or, alternatively, as satisfying locally the relations between their derivatives versus space (and also the time in the non-harmonic case), which directly corresponds to solving Maxwell equations in their most traditional form. A priori, one cannot express preferences between those four categories of methods. The choice is essentially application-driven; for instance the integral-equation approaches are preferred when the media are piece-

wise homogeneous, which is true in general for man-made objects, such as antennas, MRI tunnels and metamaterials, and is only partially true for the human body. Since the goal of this thesis is strongly focused on the coils, one may prefer to use integral-equation approaches, provided that a sufficiently good approximation exists as a collection of homogeneous objects. For the purpose of MRI qualification, this may be sufficient if the body is divided into a few components, such as brain, bones, lungs, muscles, etc.

## 2.2 The Fields Equivalence Principle and the Method of Moments

As mentioned earlier, analyzing the EM fields distribution within the human body inside the MRI system is crucial in improving the quality of MRI images and guaranteeing the safety of under imaging patients. The time-varying fields and their inter-relationships were presented in a set of Gauss's, Faraday's, Ampere's Laws and extended by Maxwell. They were then compactly reformulated in time-harmonic form as follows:

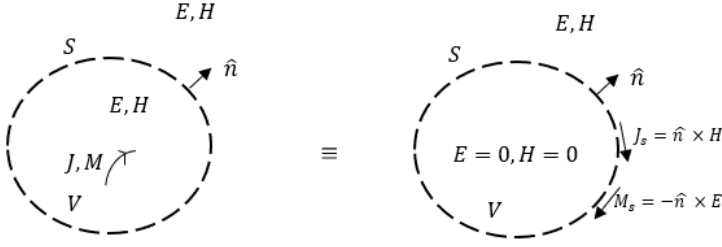
$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H} \quad (2.1a)$$

$$\nabla \times \mathbf{H} = \mathbf{J} + j\omega\epsilon\mathbf{E} \quad (2.1b)$$

$$\nabla \cdot \mathbf{E} = \frac{1}{\epsilon}\rho \quad (2.1c)$$

$$\nabla \cdot \mathbf{H} = 0 \quad (2.1d)$$

From Faraday's law (2.1a), a changing magnetic field creates a circulating electric field, and from Ampere's law (2.1b) a changing electric field creates a circulating magnetic field, such that this process continues and the propagation of electromagnetic waves happens. Electromagnetic equivalence theorems are useful for simplifying solutions to many problems, as they offer physical insight into the behavior of electromagnetic fields [50]. Let us consider electric and magnetic sources inside a surface  $S$ , enclosing volume  $V$ , radiating  $E$  and  $H$  fields everywhere. A problem equivalent to the original problem external to  $S$  can be considered as the original fields exist external to  $S$ , but zero fields exist inside the  $S$ , Fig. 2.2. To support



**Figure 2.2:** The equivalence currents are impressed on the surface  $S$  to produce the same fields external to  $S$  as do the original sources [50].

these fields, boundary conditions on  $S$ , imply that there must exist electric and magnetic surface currents  $J_s$  and  $M_s$  on  $S$ ; they must correspond to

$$J_s = \hat{n} \times H \quad (2.2)$$

$$M_s = -\hat{n} \times E \quad (2.3)$$

where  $\hat{n}$  is the normal vector to the surface  $S$  that points outward, while  $E$  and  $H$  are the electric and magnetic fields along the boundary  $S$ . The fields equivalence principle is the heart of Method of Moments (MoM) simulation. MoM is a technique to solve the linear equations in the form of the

$$L(f) = g \quad (2.4)$$

where  $L$  is a linear operator,  $g$  is the known excitation, and  $f$  is the unknown function that needs to be determined.

The unknown function  $f$  (which is the equivalent electric or magnetic surface currents ( $J$  and  $M$ ) in the MoM) could be approximated as a superimposition of the Rao-Wilton-Glisson (RWG) [51] basis functions as follow:

$$f = \sum_n \alpha_n f_n \quad (2.5)$$

where  $\alpha_n$  are unknown constants, and  $f_n$  are called the basis functions.

Substituting (2.5) into (2.4), the linear operator  $L$  yields

$$\sum_n \alpha_n L(f_n) = g \quad (2.6)$$

Consider an inner product between a basis function  $f_n(\mathbf{r}')$  and a testing or weighting function  $w_m(\mathbf{r})$  as

$$\langle w_m, f_n \rangle = \int_{w_m} w_m(\mathbf{r}) \cdot \int_{f_n} f_n(\mathbf{r}') d\mathbf{r}' d\mathbf{r} \quad (2.7)$$

Implementing the inner product with the testing functions  $w_m$  in (2.6), reads

$$\sum_n \alpha_n \langle w_m, L(f_n) \rangle = \langle w_m, g \rangle \quad (2.8)$$

This can be written in  $N \times N$  matrix form as

$$[Z_{mn}][\alpha_n] = [g_m] \quad (2.9)$$

where,

$$[Z_{mn}] = \begin{bmatrix} \langle w_1, L(f_1) \rangle & \langle w_1, L(f_2) \rangle & \cdots \\ \langle w_2, L(f_1) \rangle & \langle w_2, L(f_2) \rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \quad (2.10)$$

$$[\alpha_n] = \begin{bmatrix} \alpha_1 \\ \alpha_1 \\ \vdots \end{bmatrix} \quad [g_m] = \begin{bmatrix} \langle w_1, g \rangle \\ \langle w_2, g \rangle \\ \vdots \end{bmatrix} \quad (2.11)$$

The unknown constants  $\alpha_n$  can simply be calculated by matrix inversion of the non-singular  $Z_{mn}$ , such that

$$[\alpha_n] = [Z_{mn}]^{-1}[g_m] \quad (2.12)$$

By knowing the value of the constants, the unknown function  $f$  can be

computed from (2.5). In this thesis, the Galerkin's method [52] is used in choosing the testing functions, which means that the set of testing functions is chosen to be the same as the set of basis functions.

The matrix  $Z$  (MoM impedance matrix) that describes the equations has entries that correspond to reactions between basis and testing functions. For instance:

$$Z_{mn} = \int_S \vec{E}\{J_n\} \cdot \vec{J}_m dS \quad (2.13)$$

where  $\vec{E}\{.\}$  should be regarded as an integral operator, i.e. the electric field radiated by the electrical current  $\vec{J}_n$ , and when that radiated field is computed the integral over  $S$  appears. However more details and proofs regarding the radiated electric and magnetic fields due to the electric and magnetic currents could be found in [52], but the compact format of these radiated fields are provided hereunder.

Let us consider the Green's function of an isotropic homogeneous medium of permittivity  $\varepsilon$  and permeability  $\mu$  as

$$G(r, r') = \frac{e^{-jk_0 R}}{4\pi R} \quad (2.14)$$

with  $k_0 = \sqrt{\omega^2 \varepsilon \mu}$  the wavenumber inside the medium and  $R = |\mathbf{r}' - \mathbf{r}|$ , with the observation point  $\mathbf{r}$  and the source point  $\mathbf{r}'$ . Then the electric field due to the electric  $\vec{J}$  and magnetic  $\vec{M}$  currents distribution equals to

$$\begin{aligned} E\{J, M\}(r) = & -jk_0 \eta_0 \int G(r, r') J(r') dV(r') \\ & - \frac{j\eta_0}{k_0} \int \nabla(G(r, r')) \nabla' \cdot J(r') dV(r') \\ & - \int \nabla(G(r, r') \times M(r')) dV(r') \end{aligned} \quad (2.15)$$

where  $\eta_0 = \sqrt{\frac{\mu}{\varepsilon}}$  is the impedance of the medium. Similarly, the magnetic



field generated by the the electric  $\vec{J}$  and magnetic  $\vec{M}$  currents reads

$$\begin{aligned} H\{J, M\}(r) = & -\frac{jk_0}{\eta_0} \int G(r, r') M(r') dV(r') \\ & -\frac{j}{k_0 \eta_0} \int \nabla(G(r, r')) \nabla' \cdot M(r') dV(r') + \int \nabla(G(r, r') \times J(r')) dV(r') \end{aligned} \quad (2.16)$$

Hence, injecting (2.16) and (2.15) into (2.13) would result in the  $Z$  matrix.

### 2.2.1 Discretization and Basis Functions

Discretization of surfaces and subsequent decomposition of unknown functions into basis functions is the core of surface-integral equation solvers in electromagnetic. Depending on the type of EM solvers, surface or volumetric basis functions could be considered. In the MoM solver since the unknowns are the surface electric and magnetic currents distribution, the surface basis functions are needed. Basis functions could be defined locally; they are then non zero only in a part of the domain. They can also be defined globally; they are then non-zero over the whole domain. Rao-Wilton-Glisson (RWG) and rooftop are two famous types of basis functions defined locally (sometimes name "elementary" basis functions), their geometries are shown in Fig. 2.3. In this thesis the RWG basis functions have been used to mesh both the metallic RF coil and the dielectric phantom. In those cases, the Gmsh [53] mesh generator has been used. The definition of the RWG basis functions is given hereunder:

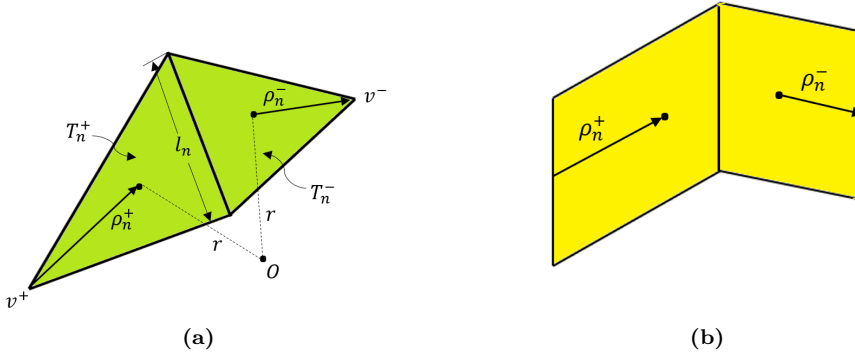
$$\mathbf{f}_n(\mathbf{r}) = \begin{cases} \frac{l_n}{2A_n^+} \rho_n^+, & \mathbf{r} \text{ in } T_n^+ \\ \frac{l_n}{2A_n^-} \rho_n^-, & \mathbf{r} \text{ in } T_n^- \\ 0, & \text{otherwise} \end{cases} \quad (2.17)$$

where,  $l_n$  is the length of the common edge of the two triangles, and  $A_n$  is the area of the triangular facet. The  $\rho_n^+$  and  $\rho_n^-$  vectors corresponding to

their position in the  $T_n^+$  or  $T_n^-$  triangles are defined:

$$\begin{aligned}\rho_n^+ &= v^+ - r \\ \rho_n^- &= r - v^-\end{aligned}\tag{2.18}$$

rooftop basis functions are rarely used in this thesis and are only exploited representing the feeding nodes.

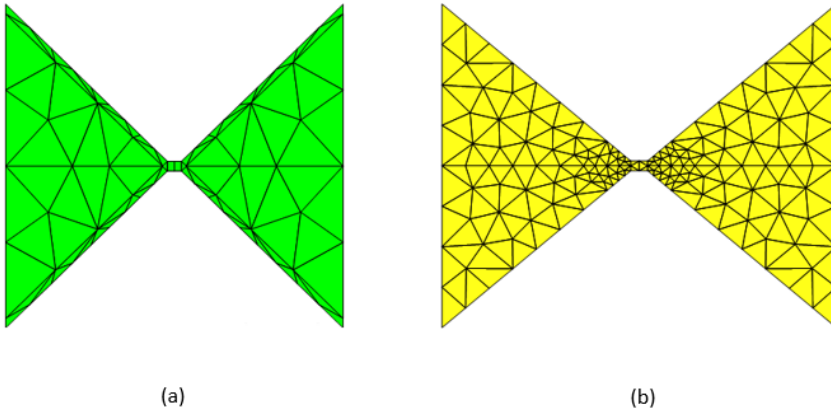


**Figure 2.3:** Geometry of the (a) RWG basis function. (b) Rooftop basis function.

An example of two mentioned different basis functions is provided on the feed point of a bowtie antenna, shown in Fig. 2.4. The delta-gap generator with a  $50\ \Omega$  source impedance is considered as the excitation for the bowtie antenna. The delta-gap generator is defined as a voltage discontinuity between two infinitely close conductors. A Dirac-delta type function then models the electric field in the gap. After testing of those field by a function that overlaps the gap, the excitation vector in (2.8) then has zeros in all entries except for the overlapping testing function, where the entry equals to:

$$E_x = -w_g V_0\tag{2.19}$$

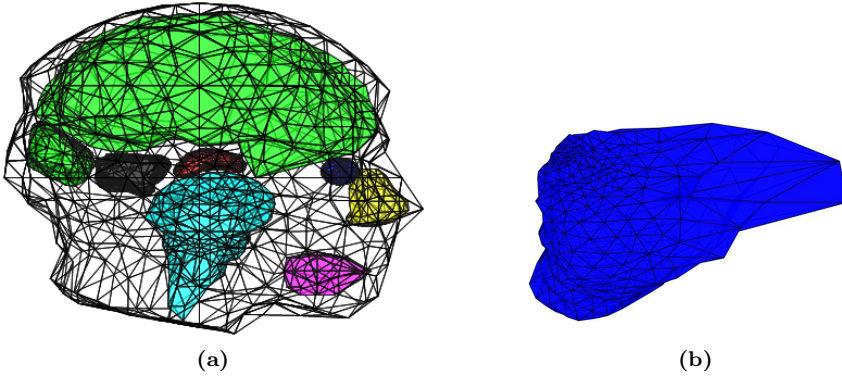
where  $w_g$  and  $V_0$  are the width of the gap and the voltage applied to the gap, respectively.



**Figure 2.4:** (a) Roftop basis function on the feed point. (b) RWG basis function on the feed point.

### 2.2.2 Meshing of the Human Body Organs

In this thesis, to mesh the RF coils and spherical or cylindrical phantoms, the Gmsh mesh generator has been used [53]. However, to obtain the surface mesh of the human head or other internal organs, a surface meshed sphere or ellipse is transformed into a cloud of the points (that can be obtained from a volume mesh or a 3D model) on the organs' surface. Using this technique, the surface meshes of the human head with some internal organs by implementing this technique have been obtained, shown in Fig. 2.5(a) (Thibaut Letertre from Institute Fresnel provided 3D models of the internal organs [54]). This method can also be used when there are MRI images from different cuts of an organ. For instance, 18 MRI images from different layers of a liver (provided by Jean Léger from UCLouvain) were contoured, and by detecting those contours and accumulating them via MATLAB routines, a cloud of the points was obtained, enabling us to transform a meshed vertical ellipse to a mesh representing a liver as shown in Fig. 2.5(b).

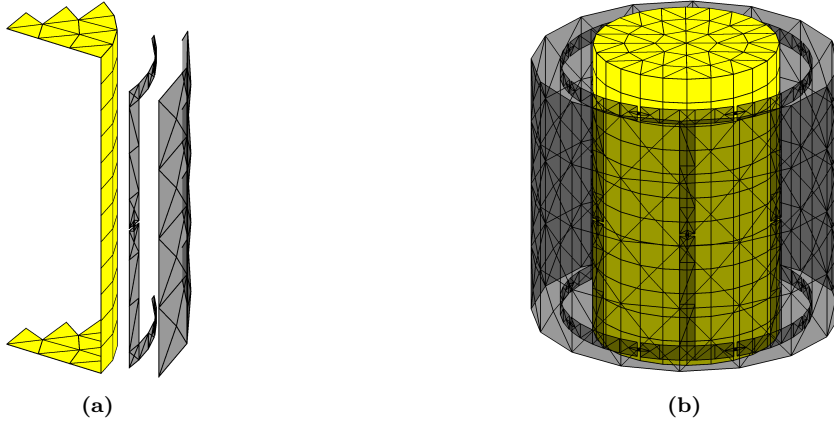


**Figure 2.5:** (a) Surface mesh of the human head and other internal organs. (b) Surface mesh of a liver obtained from different layers of MRI images.

### 2.2.3 Array Scanning Method

For MRI scanners having axial symmetry, as shown in Fig. 2.6, a fast and accurate technique can be applied to exploit that symmetry. In this example, the birdcage coil has 8 legs and the phantom is a cylinder; thus, the full structure has a 8-fold symmetry, i.e. it can be divided into 8 similar sectors. Such setup, sometimes called discrete volumes of revolution [55], are truly infinitely periodic with respect to the revolution angle. Thus, periodic boundaries can be applied to accelerate the simulation, resulting in exactly the same solution as the approach not exploiting symmetry. In this section, we will apply the Array Scanning Method (ASM) [56], [57], [58], for the analysis of MRI antennas exploiting their azimuthal symmetry.

Analyzing the large array of antennas or metamaterials with periodic excitation has been done with the ASM [55]. In the case of the non-periodic excitation, such as the birdcage coil with two excited ports, the ASM could be used by decomposing the non-periodic excitation into a sum quasi-periodic excitations, allowing one to analyze the response of a periodic structure to a non-periodic excitation. By quasi-periodic we here mean that the currents are the same in all sectors, except for a phase shift corresponds to a multiple  $2\pi/N$ . Considering an infinite linear array of elements with just one element (antenna) excited and the others passively terminated, the current



**Figure 2.6:** Array Scanning Method: (a) A unit cell of the birdcage coil with a phantom. (b) A complete mesh of the birdcage coil with a phantom.

on any element can be computed as:

$$I(k) = \frac{1}{(2\pi)} \int_0^{2\pi} I^\infty(\theta) e^{-ik\theta} d\theta \quad (2.20)$$

with  $I(k)$  the total current on the  $k$ -th element,  $i$  the imaginary unit and  $I^\infty(\theta)$  the current on the element 0 for the infinite array solution with phase shift of  $\theta$  between consecutive element [58]. In the case of the discrete volumes of revolution and considering the periodic excitation of period  $2\pi$  with respect to the revolution angle, the current on element  $k$  can be obtained as:

$$I(k) = \frac{1}{N} \sum_{p=0}^{N-1} I^\infty(\theta_p) e^{-ik\theta_p} \quad (2.21)$$

The method of moments based analysis of an array of antennas usually requires the solution of a problem of  $(N \times M)$  by  $(N \times M)$  system of equations,  $N$  being the number of antennas and  $M$  the number of basis functions per antenna (here per sector in the symmetrical structure). Applying the ASM, the system of equations is decomposed into  $N$  independent systems of equation of size  $(M \times M)$ , that can be solved separately. It leads to an acceleration of the filling time by factor  $N$  and of the solution time by a factor  $N^2$ .

### 2.2.4 Nesting Approach

In traditional computation techniques once a new mesh of the antenna has been obtained, everything should rerun to compute the effect of this change in the field distribution of the desired internal organ. To avoid this, it is proposed to precompute some matrices once and for all. Here it is assumed that the body is a collection of homogeneous domains. This approach is sufficient to estimate the homogeneity of magnetic fields, as well as the maximum electric field. To this end, thanks to relatively intense pre-computations, it is possible to update the fields at the antenna level and in the body within seconds. The idea consists of avoiding re-computation of all equivalent currents inside the body everytime the antenna is modified (it could be either change in the dimensions of the antenna or the position of the antenna with respect to the body or any change in the lumped elements within the antenna or coil). This is done by focusing on the equivalent currents on the outer surface of the body. It shares with [59], [60], the idea of using surface equivalence to hide details outside a given area, and using some precomputed matrices in solving integral equations [61].

Beyond this, a direct link will be established between currents on the body surface and observable fields inside any organ, though specifically defined matrices. As shown in Fig. 2.7, if  $x_1$ ,  $x_2$  and  $x_3$  correspond to the unknowns on the antenna, on the surface of the head and on surfaces inside the head respectively, the matrix of the system of equations has the following structure:

$$\begin{pmatrix} Z_{11} & Z_{12} & 0 \\ Z_{21} & Z_{22} & Z_{23} \\ 0 & Z_{32} & Z_{33} \end{pmatrix}$$

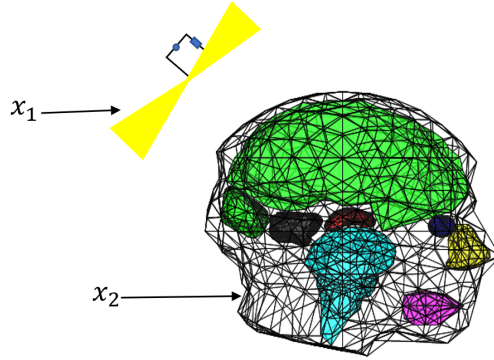
Where  $(Z_{ij})$  is a block of the impedance matrix that links sources on interface  $j$  and fields on interface  $i$ . The two off-diagonal zeros are due to the fact that there is no direct interaction between equivalent currents located on the antenna and on surfaces inside the body (because of the equivalence principle, see Section 2.2). If unknowns relative to the latter are eliminated

(but not omitted), the matrix of the new system of equations reads:

$$\begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z'_{22} \end{pmatrix}$$

Where the new matrix standing for interactions between basis functions on the surface of the body is given by:

$$Z'_{22} = Z_{22} - Z_{23}Z_{33}^{-1}Z_{32} \quad (2.22)$$



**Figure 2.7:** A bowtie antenna is located around a piecewise homogeneous human head model.  $x_1$  for the unknowns on the surface of the antenna,  $x_2$  for the unknowns on the surface of the head, and  $x_3$  for the unknowns on the surface of all the other organs inside the head.

The fields inside the body can also be obtained by elimination from the fields on the surface of the head. Let us now denote by  $x_2$  the fields on the surface of the head, by  $x_3$  the equivalent currents on the surface of the brain and by  $x_4$  the field on all other internal organs. It is interesting to notice that there is no direct interaction between  $x_1$  on one side and  $x_3$  and  $x_4$  on the other side (i.e. the corresponding matrices are zero), which simplifies calculations a little bit. Knowing that there are no sources inside the head,

the corresponding interactions can be written as:

$$Z_{32}x_2 + Z_{33}x_3 + Z_{34}x_4 = 0 \quad (2.23)$$

$$Z_{42}x_2 + Z_{43}x_3 + Z_{44}x_4 = 0 \quad (2.24)$$

From which  $x_3$  is obtained as follows:

$$x_3 = -(U - Z_{33}^{-1}P_{34}Z_{43})^{-1}Z_{33}^{-1}(Z_{32} - P_{34}Z_{42})x_2 \quad (2.25)$$

$$= P_{32}x_2 \quad (2.26)$$

with  $P_{34} = Z_{34}Z_{44}^{-1}$ . The matrix in the above equation can be computed once and for all. To obtain fields inside a given organ, one then just needs to left-multiply the currents  $x_3$  by a matrix that provides the fields on a number of testing functions (with all three orientations) inside that organ, Let us name it  $Q_{30}$ , and that matrix can directly left-multiply  $P_{32}$ . That product, denoted here as  $X$ , can also be pre-computed once and for all. Then, whenever a new value of  $x_2$  is obtained (e.g. because the antenna design has changed), it just needs to be left-multiplied by matrix  $X$  to provide the fields inside the organ.



### 2.2.5 Nesting Approach Validation for Concentric Media

Consider an antenna around three concentric spheres with different properties, as shown in Fig. 2.8; the matrix of the system of equations is:

$$\begin{pmatrix} Z_{11} & Z_{12} & 0 & 0 \\ Z_{21} & Z_{22} & Z_{23} & 0 \\ 0 & Z_{32} & Z_{33} & Z_{34} \\ 0 & 0 & Z_{43} & Z_{44} \end{pmatrix}$$

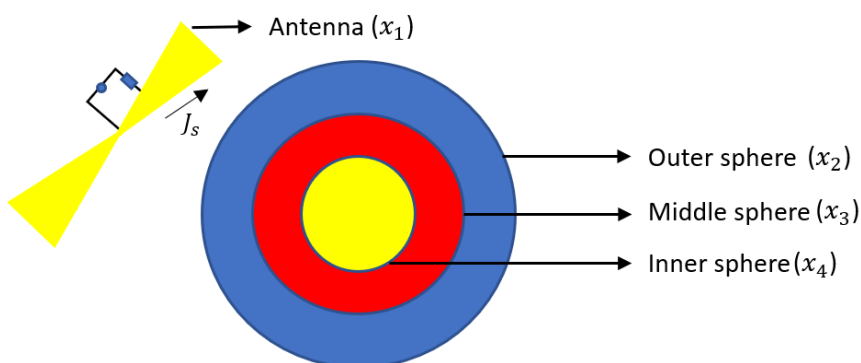
Zeros indicate that there is no direct interaction between the equivalent currents located on the antenna and middle and inner spheres, which is also true for the interaction between the outer sphere and the inner sphere. By considering the third and fourth rows of the above matrix, the surface current distribution on the inner sphere  $x_4$  can be obtained from the current distribution on the surface of the outer sphere  $x_2$  as follows

$$x_4 = (U - Z_{44}^{-1} Z_{43} Z_{33}^{-1} Z_{34})^{-1} (Z_{44}^{-1} Z_{43} Z_{33}^{-1} Z_{32}) x_2 \quad (2.27)$$

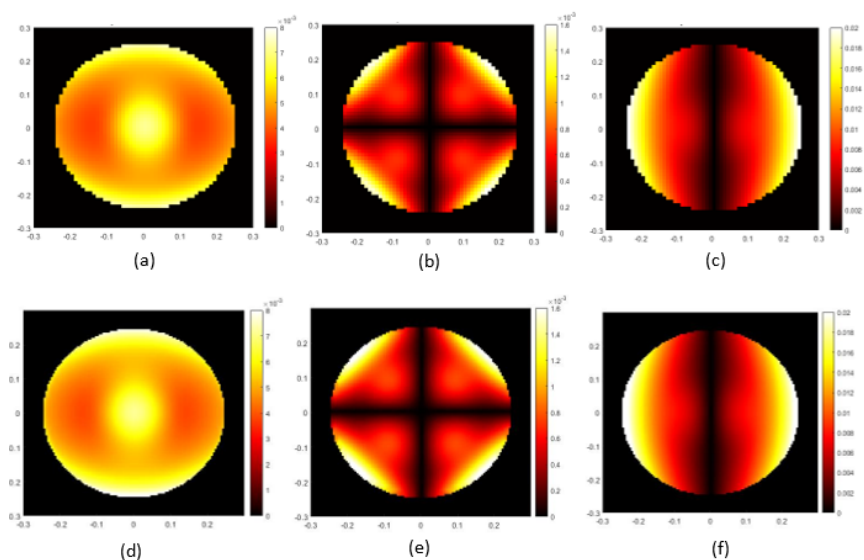
$$= P_{34} x_2 \quad (2.28)$$

Thanks to this nesting approach the  $P_{34}$  matrix is computed once and for all, and whenever the antenna mesh is changed, the computation time will be smaller since we do not need to recompute this matrix.

For the validation, three spheres with the permittivities of 5-0.25i, 42-60i, and 61-70i, and with a radius of 50 cm, 40 cm and 25 cm, are considered for the outer, middle, and inner spheres respectively. Fig. 2.9 shows the three different components of the electric field obtained with MoM and CST inside the inner sphere with a radius of 25 cm at 150 MHz. In this example the nesting approach may allow us to deal with matrices of size of the order of  $4.000 \times 4.000$  instead of  $16.000 \times 16.000$ , thereby achieving a time saving of the order of 16 or more (filling time goes like the square of number of unknowns, while solving time goes like the cube [52]).



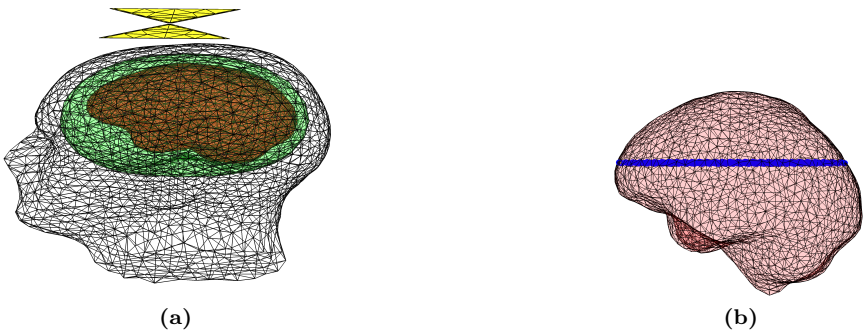
**Figure 2.8:** Three concentric spheres and a bowtie antenna around them.



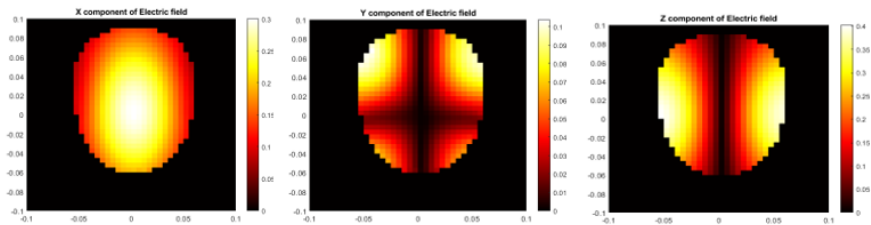
**Figure 2.9:** First row: x, y, and z components of the E field computed with MoM. Second row: x, y, and z components of the E field computed with CST.

In another example, as shown in Fig. 2.10(a), a bowtie antenna is positioned on the top of a human head model with three different media and

the same EM properties used for the three spheres in the previous example. Fig. 2.11 shows the three components of the electric field for the chosen cut within the brain (the blue plane shown in Fig. 2.10(b)) at 150 MHz.



**Figure 2.10:** A bowtie antenna around a human head model, consisting of brain and the liquid around the brain. (b) Fields observation plane inside the brain is shown in blue (the brain model provided by Prof. Redha Abdeddaim).

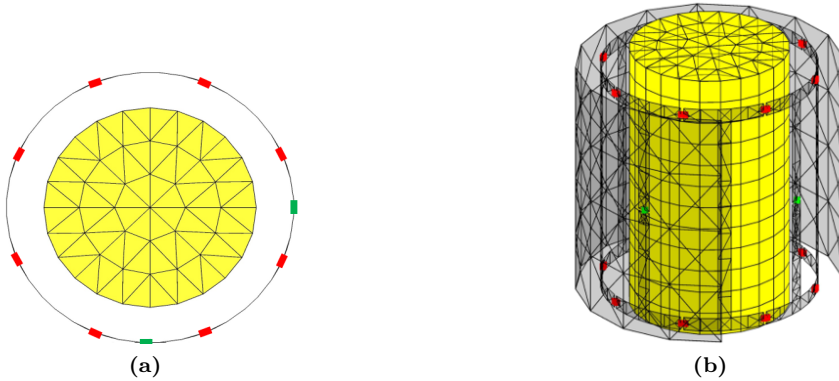


**Figure 2.11:** Left to right, x, y and z components of the E field on the observation plane inside the brain shown in Fig. 2.10(b).

### 2.3 MoM to Design a 3 Tesla Birdcage Coil

As mentioned in Chapter 1, a birdcage coil is an LC resonator in which the proper resonance frequency and the optimized current distributions on the legs can be obtained by optimizing the lumped capacitor values. In this section, an eight-leg high pass birdcage coil for 3T MRI (Larmor frequency = 127 MHz), has been designed and analyzed with the help of the in-house

method of moments code [62]. The results in terms of fields distribution and S - parameters have been validated with commercial software (CST) in the frequency domain (FD). This high pass coil has a diameter of 26 cm, and its height is 28 cm. A metallic shield with a diameter of 32 cm and a height of 28 cm is used around the coil to avoid any unwanted interactions between the coil and the surrounding environment. The end-rings and legs width is set to 1.6 cm. Two excitation ports  $90^\circ$  apart with  $90^\circ$  phase shift are used in the middle of two legs to provide the circular polarization, shown in Fig. 2.12. The lumped capacitors are shown in red, and two excitation ports are shown in green. In order to model the lumped elements (ports, capacitors and inductors), a delta-gap model is used [63]. Using the delta-gap model, the lumped elements are modelled using basis functions that bridge the infinitesimal gap separating different conductive parts of the geometry. The current flowing along these basis functions depend on the voltage that builds up across the gap and the impedance of the lumped elements (see Section 2.2.1)



**Figure 2.12:** (a) Top view of a birdcage coil with a phantom; capacitors are shown in red and the excitation ports are shown in green. (b) 3D view of the birdcage coil, phantom, and the surrounding shield (one sector of the shield is hidden for the illustration purpose).

A dielectric cylindrical phantom with relative permittivity and conductivity equal to 61 and 0.8 S/m respectively, has been used inside the coil

to represent the human body. This phantom has a diameter of 19.2 cm, and its height is 32 cm. In the figure above, one sector of the shield has been removed on purpose to be able to clearly show the different parts of the coil. As mentioned earlier, numerical methods in optimizing the RF coils are necessary while they are loaded with a dielectric phantom. The in-house method of moments code has been used in combination with particle swarm optimization (PSO) [64], to optimize the lumped element values based on the open-circuit embedded element pattern [45] (the optimization is carried out in collaboration with Dr. Chan-Sun Park). In MoM, once the impedance matrix ( $Z_{mom}$ ) is obtained, the open-circuit embedded element pattern can be computed once for all the ports; however, in CST, one needs to calculate the open circuit pattern for each port, which requires multiple calculations.

Optimizing the lumped elements enables one to tune the birdcage resonance frequency to the desired Larmor frequency; it also helps to improve the homogeneity of the magnetic field, decreases the peak value of the SAR, and provides good impedance matching on the ports of a birdcage coil. The optimization algorithm is mainly based on the generation of the homogeneous  $B_1^+$  field on the transverse plane of the phantom. This homogeneous magnetic field distribution is associated with a homogeneous electric field distribution, resulting in the lower peak values for SAR. The cost function that has been used in the thesis to design the birdcage coils is considered as the normalized standard deviation (NSD) of the  $B_1^+$  for a given cut inside the phantom,

$$NSD(B_1^+) = \frac{Std(B_1^+)}{Mean(B_1^+)} \quad (2.29)$$

where

$$Std(B_1^+) = \sqrt{\frac{\iint (|B_1^+(r)| - Mean(B_1^+))^2 dS}{S}} \quad (2.30)$$

$$Mean(B_1^+) = \frac{\iint (|B_1^+(r)|) dS}{S} \quad (2.31)$$

and  $S$  is the area of the transverse plane inside the phantom that needs to be optimized for the homogeneous field distribution (the transverse or horizontal plane can be seen in Fig. 1.8). Once the cost function is defined,

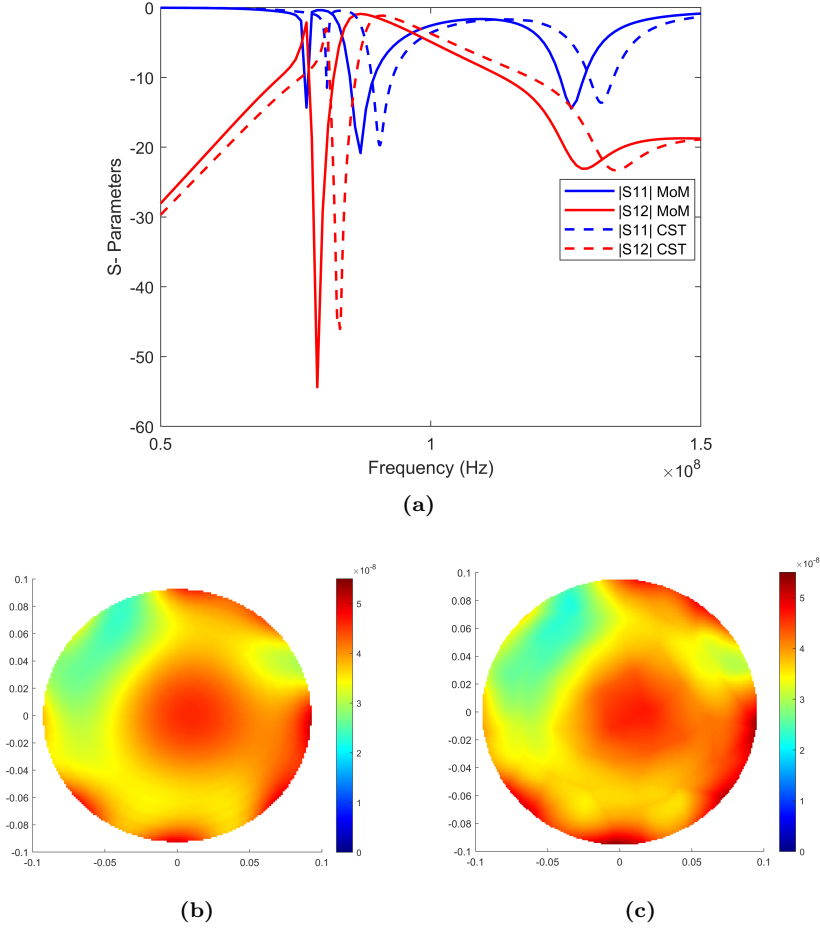
a set of candidate solutions is generated randomly and simulated. The cost function associated to each solution of the set is estimated, providing a measure of their quality. To improve the quality of the candidate solutions, the PSO algorithm treats each solution as a particle moving in the solution space, i.e. a  $N$  dimensional space,  $N$  corresponding to the number of lumped elements. At each iteration, each particle's movement is affected by its local best known position, but is also guided toward the best known positions in the whole solution space, as found by the other particles. This leads the swarm of particles to move toward the optimum solutions. The MoM code combined with the PSO method, is used to optimize the capacitors in the eight-legs birdcage coil. The scattering parameters computed with the MoM code and the CST is shown in Fig. 2.13(a). The slight shift in the desired resonance frequency of this coil which is 127 MHz with MoM and 131 MHz with CST, comes from the fact that each software uses a different method to solve the Maxwell equations. The  $B_1^+$  field distributions obtained from MoM and the frequency domain solver in CST for the middle cut inside the cylindrical phantom are shown in Fig. 2.13(b), and Fig. 2.13(c). These validated results confirm the accuracy of the accelerated method, such as ASM, and the optimization algorithm (PSO). This software package based on the MoM then is used in Chapter 3 and Chapter 4, to design and optimize new birdcage coils for 3T and 7T MRI.

### 2.3.1 Asymmetric Birdcage Coil

The birdcage coil optimized with the MoM code in the previous section is symmetric, meaning that the value of the capacitors used in each sector is the same. However, after computing the open-circuit embedded element pattern [45], and during the optimization, the lumped elements could be optimized asymmetrically, resulting in 16 different capacitors for an eight-leg birdcage. This asymmetrical configuration can be used to shape the field distribution inside the birdcage for specific applications in MRI. For instance, when it is needed to focalize the field distribution on the desired part of an organ (such as functional MRI or fMRI [65]).

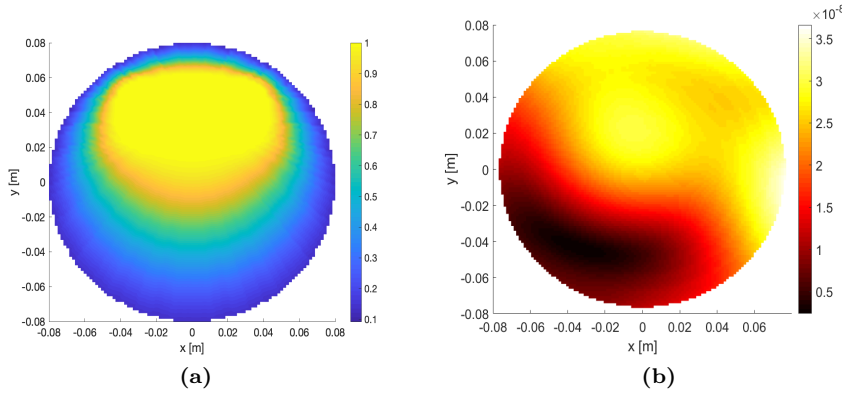
Two master students: Thomas Clerbois and Antoine Rampelbergh, in

the frame of their master thesis [66], tried to use an asymmetric birdcage and optimize the capacitors to produce the expected field shape with the asymmetric birdcage. For instance, an objective weighting matrix defined as an ellipse, shown in Fig. 2.14(a), resulted in a field map with the asymmetric birdcage shown in Fig. 2.14(b), which demonstrates the possibility of field shaping with the asymmetric birdcage. It should be noted that the main cause of the differences between the goal function and the obtained field, is the existence of only two excited ports. Increasing the number of active channels would provide additional flexibility in the field shaping, but it would need complex hardware.



**Figure 2.13:** (a) Scattering parameters of the 3T birdcage coil loaded with a cylindrical phantom obtained from MoM and CST simulations. The desired mode of the birdcage is at 127 MHz with MoM, and with CST it is at 131 MHz.  $B_1^+$  field distribution on the transverse cut inside the phantom obtained from: (b) MoM at 127 MHz. (c) CST 131 MHz.





**Figure 2.14:** (a) Objective weighting matrix. (b) Obtained field map with the asymmetric birdcage at 280 MHz [66].

## 2.4 Conclusion

Numerical methods are accurate enough to analyze the EM field distribution inside the body or to design the RF coils. MoM is an efficient solver among different solvers since unknowns are limited to the surface of the piecewise homogeneous media. Through the Nesting approach, MoM solvers can be accelerated in analyzing the EM field distribution inside the body by computing some matrices once and for all. Computing some matrices once, would result in  $N$  times small matrices, corresponding to time-saving of the order  $N^2$  in filling and  $N^3$  in solving. On the other hand, the MoM solver in the design of the RF coils can also be accelerated by exploiting the symmetry of the birdcage coil through the array scanning method (ASM), and can be efficiently optimized by combining the computed open-circuit embedded element pattern with the optimization algorithms such as the particle swarm optimization (PSO). This would result in the optimized lumped element (C, L) values to provide the resonance condition of the LC network at the appropriate Larmor frequency with a homogeneous magnetic field inside the birdcage, which corresponds to the ideal sinusoidal current distribution on the legs.

The following chapters discuss the causes of the inhomogeneities as well as the techniques to improve the homogeneity at HF and UHF MRI.



# CHAPTER 3

## Connected Birdcage Coil

This chapter introduces a new birdcage coil to improve the magnetic field homogeneity inside the dielectric phantom. Having the physical connections between the birdcage and the surrounding shield is the main feature of this new coil to obtain the optimized current distributions on the legs, resulting in a homogeneous field distribution inside the phantom.

In the introduction, a summary of the available techniques to improve the homogeneity of the magnetic field created by the RF coils is provided. Section 3.2 discusses the effective parameters in the RF magnetic field distribution. Section 3.3 explains the design of the connected birdcage to show the positions and types of connections between the birdcage and the shield. This section also shows the simulation results of a 3T connected birdcage coil, in which the improvement in the homogeneity of the magnetic field is compared with a 3T conventional birdcage. Further improvement in the homogeneity and reduction in the maximum value of the specific absorption rate (SAR) is obtained in Section 3.4, where an optimized design is implemented for the connected birdcage. In Section 3.5 the fabricated 3T connected birdcage coil is described. This section also provides the measurements carried out in collaboration with the Fresnel institute in terms of the S - parameters and the field distributions.

### 3.1 Introduction

Due to the higher SNR value in UHF MRI, precious information regarding the human body and, most importantly, about the brain can be obtained. This motivated several studies to tackle the inhomogeneity of the  $B_1^+$  field due to the shortened wavelength inside the body at UHF MRI [47]. Improving the homogeneity of  $B_1^+$ , called shimming, is generally categorized into two methods named passive and active shimming. Regarding passive shimming, it has been shown that high-permittivity dielectric pads based on chemical components like  $BaTiO_3$  [67], between the body and the transmitter coil (or even on the body) could create a secondary magnetic field in parts with lower magnetic field values created by the main RF transmitter [68] [69]. This compensation technique results in a uniform MRI image; however, the expiry time and bulkness of these pads are the main challenges in clinical applications. In [70], an artificial dielectric slab based on printed circuit boards (PCBs) and using the etched periodic structures of small square metal is presented to overcome issues with the expiry time of the chemical components used in the dielectric pads. However, unlike the dielectric pads that have mainly been used in the axial direction of the birdcage to increase the intensity of the magnetic field for the temporal lobes imaging, the artificial dielectric slab in this direction can not interact with the local magnetic field produced by the birdcage, hence would not increase the strength of the RF field. Another approach to redistribute the magnetic field inside the birdcage coil based on the inclusion of metallic rods is reported in [71]. The homogeneity improvement in the temporal and cerebellum regions in brain imaging is accessible with this technique while properly spacing the metallic rods on the human head.

In active shimming or RF shimming, the idea is to replace the entire  $B_1^+$  field created by a single transmitter with multiple  $B_1^+$  subfields created by independent transmitters with different phases and amplitudes to shift away the low-intensity field region from the region of the interest [72], [73], [74], [75]. One can imagine having different RF pulse shapes besides the variable phases and amplitudes; this technique is called parallel transmission (pTx) [73], [76]. Due to the controllable amplitude, phase,

and RF pulse shape of each transmitter, the pTx technique is quite efficient in improving the homogeneity of the magnetic field at UHF MRI. However, the system's complexity because of the additional boundary conditions (that might impact the matching of the system) [76], and the SAR issues due to the superpositioning of the fields generated by several transmitters [77], together with obtaining the Food and Drug Administration (FDA) approval [78], are the main challenges of pTx systems in clinical applications.

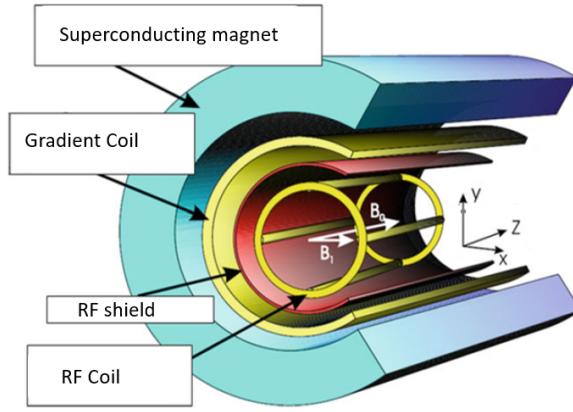
Similar to the pTx, one can imagine multiple scanning by changing the position of the RF coil with respect to the body to improve the homogeneity of the magnetic field. This technique requires multiple scans, and increasing the scan time corresponds to a higher risk to the body due to the increased thermal heating as more power dissipation happens within the body's tissues [79]. The heating effect is more dominant at higher frequencies as the RF field distribution is less uniform [80].

Besides the homogeneity, the penetration depth of the  $B_1^+$  field caught the attention in the RF coil designs. The RF shield used around the coil to minimize the interactions between the coil and the surrounding environment could cause additional coupling, loss, shift in the resonance frequency, and reduce the penetration depth of the  $B_1^+$  inside the phantom, since the induced currents on the shield are out of phase with the currents on the RF coil [81], [82]. In [83] it has been reported that the induced currents on the shield could be reduced by using a high impedance surface (HIS). The HIS is the practical version of the perfect magnetic conductor, which ideally suppresses the surface current. In other words, using a HIS would improve the coil's efficiency, where the efficiency is defined as the amplitude of the circular polarized transmit magnetic field created by the coil in the region of interest ROI ( $B_1^+$ ) for a given power accepted by the coil from a transmitter [84].

This chapter presents a new method to improve the performance of the birdcage coil. The electrical connection between the birdcage and shield is the unique feature of this new design, resulting in the improved magnetic field homogeneity and reducing the maximum value of the SAR. The robustness of the coil behavior for different sizes of the phantom is another

essential feature of this new coil. This new birdcage is patented in the antenna group at UCLouvain in the framework of the M-Cube project [48]. The following section reviews the effective parameters in the RF magnetic field distribution.

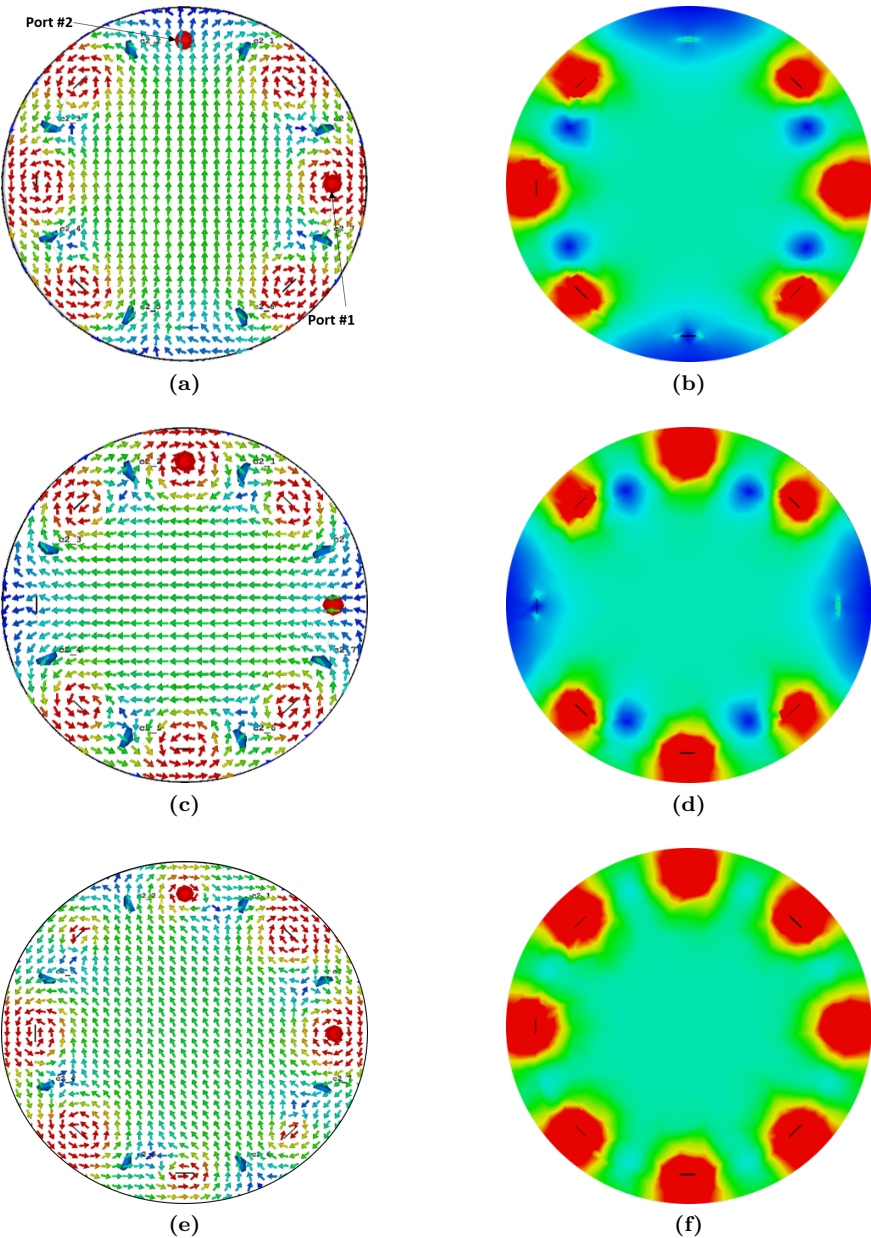
### 3.2 RF Magnetic Field Pattern



**Figure 3.1:** Main parts of an MRI scanner [91].

As mentioned earlier, the presence of the RF shield is essential in any MRI machine to protect the volume inside the RF coil from the outside, such that no additional noise will be introduced in the receiving. Also, the RF shield prevents undesired interaction between the RF coil and the gradient coil. However, during the fabrication of an MRI scanner, considering the size of the MRI bore, the spacing between the RF coil and gradient coil introduces constraints on the size of the shield.

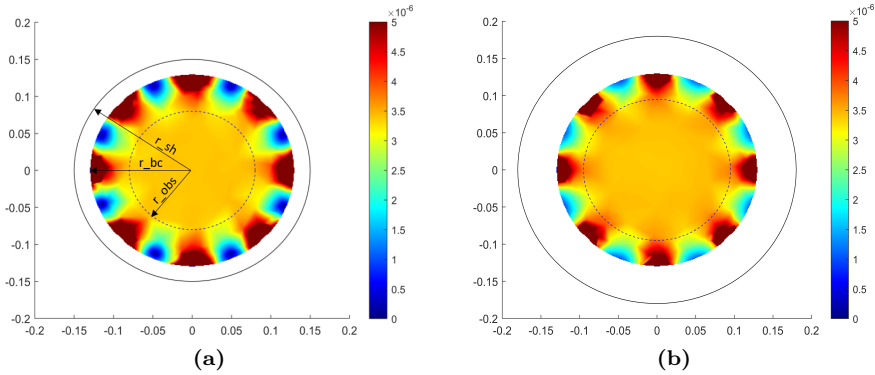
A drawback of the metallic shield is that the currents in the birdcage induce out-of-phase eddy currents on the shield [85]. The fields produced by these eddy currents interact constructively in the region between the birdcage legs and the shield which can be seen as the red spots in Fig. 3.2, and destructively in the center of the coil.



**Figure 3.2:** Transverse plane of an unloaded 3T birdcage. Field lines when: (a) the first port is excited. (c) Second port is excited. (e) Two ports are excited in the quadrature mode, resulting in the circular polarization. (b), (d), and (f) Show the contour form of the corresponding fields in (a), (c), and (e).

The constructive interference around the legs reduces the overall homogeneity in the available volume inside the birdcage, and the destructive interference reduces the strength of the  $B_1$  field per unit current, which reduces the efficiency [86], [87]. In [88], it has been reported that the overall homogeneity in the available volume within the birdcage decreases when the shield gets closer to the birdcage, or the shield height becomes longer than the birdcage.

As shown in Fig. 3.3, the  $B_1^+$  field distribution for a 3T birdcage coil with 13 cm radius in the presence of the shield with two radii of 15 cm and 18 cm is provided. It shows the impact of the shield dimension on the homogeneity of the magnetic field in the available region inside the birdcage. These simulations are carried out without a phantom to avoid the inhomogeneity due to the presence of the phantom.



**Figure 3.3:** Two different shield radii are put around the unloaded 3T birdcage coil.  $r_{obs}$  indicates the radius of the observation plane. (a) Shield radius is 15 cm. (b) Shield radius is 18 cm.

For each shield radius, the normalized standard deviation ( $NSD = SD/Avg$ ) of the  $B_1^+$  field is computed on two different observation planes. The NSD values in Table 3.1, indicates that putting the shield far away from the birdcage provides a more homogeneous area inside the birdcage; however, considering the dimensions of the MRI bore during the fabrication of each MRI machine, a certain distance between the birdcage and shield needs to



be considered.

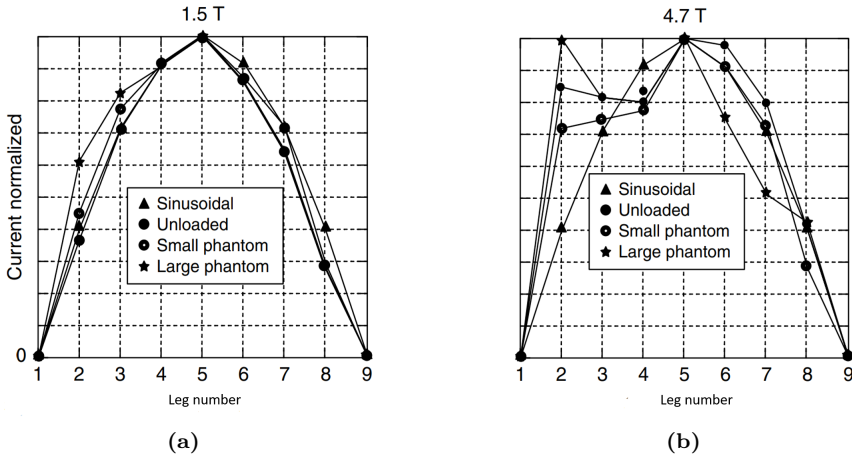
**Table 3.1:** NSD for two observation plane with two different radii when the birdcage is surrounded with two different shield size.

| Shield radius    | $r_{obs} = 12$ cm | $r_{obs} = 9$ cm |
|------------------|-------------------|------------------|
| $r_{sh} = 15$ cm | NSD= 0.2793       | NSD= 0.0317      |
| $r_{sh} = 18$ cm | NSD= 0.1614       | NSD= 0.0185      |

Besides the impact of the shield on the performance of the birdcage, loading the birdcage with a phantom also impacts the performance of the coil. As mentioned in Chapter 1, the birdcage coil with a current distribution as  $J_0 \sin\phi$  provides a homogeneous magnetic field distribution inside the coil. However, this desired current distribution on the legs is disturbed when the birdcage is loaded with a phantom. This distortion gets even worse at higher frequencies [89].

As shown in Fig. 3.4(a), at lower field strengths, like 1.5T, the unloaded birdcage could have a current distribution close to the ideal sinusoidal distribution. Loading with a small cylindrical shape phantom changes the current distribution; however, loading with a bigger and octagonal phantom significantly distorts the current distributions on the legs due to the increased interaction between the birdcage and the phantom [89]. At 4.7T, where the free space wavelength is around 150 cm, for a birdcage coil with a height of 40 cm, the legs would be around the quarter wavelength, and the birdcage would act like an antenna rather than a resonator [89], which is an essential concern in designing the long birdcage coils for the whole body applications. As shown in Fig. 3.4(b), the current distributions on the birdcage (with 40 cm height) are distorted even when it is not loaded with a phantom, and severe distortion can be seen when it is loaded [89]. The multi-port excitations method for the birdcage has been proposed to overcome the distortion in the current distribution at high frequencies [90]. However, using multiple excitations, when it comes to the MRI application, requires additional care regarding the interactions between the coaxial cables to keep the proper level of safety and SNR.

Besides the homogeneity and transmission efficiency, the specific absorption rate (SAR) is also a crucial criterion in MRI applications, which is related to safety and it should be kept low to avoid the heating of the organ under imaging. The presence of the metallic shield increases the SAR level since the reflected field from a metallic shield add to the field inside the load [82].



**Figure 3.4:** Current distributions on the legs for a 16-leg birdcage without shield with 40 cm height and 29 cm diameter. Currents are shown for the unloaded case and when the birdcage is loaded with different phantoms at: (a) 1.5T. (b) 4.7T [89].

In [82], a metamaterial absorber shield has been proposed to be used as the shield at 7T and 9.4T with dipole and loop coils to absorb the incident EM wave. Hence, because of the limited reflection, 32% improvement in the efficiency and 22% reduction in the SAR has been reported. However, due to its rigid design, it can not be used with the birdcage coil.

Another method to improve the performance of the birdcage is based on the perfect magnetic conductor (PMC) shield instead of the perfect electric conductor (PEC) shield [86], [87]. PMC implies that the tangential component of the magnetic field is zero at the boundary. Therefore, unlike the PEC, induced currents on the PMC are in phase with the currents on the

coil, and the E field produced by them will constructively interfere with the fields produced by the coil, resulting in the increased amount of the field generated by the unit current [86]. At high frequency one can consider that PMC shield increases the efficiency of the magnetic field in the center of the coil (zero on the surface and maximum near the center). In [86], a birdcage coil with the split ring resonators (SRRs) shield has been proposed. SRRs behave as artificial magnetic conductors (AMCs) to provide high magnetic conductivity. However, in that paper, it is reported that using an AMC prevents the azimuthal propagation mode around the birdcage that forms the desired sinusoidal current distribution on the legs, see Section 1.4.2. As the authors explained, this comes from the increased magnitude of the RF fields per unit current, which increases the load resistance and results in a stronger loss in the phantom as the energy propagates in the azimuthal direction. However, it is reported that when the birdcage is not loaded or it is loaded with a small phantom the azimuthal mode can propagate in the presence of the AMC shield [86], [87].

Besides all the above-mentioned parameters that impact the RF field, the electromagnetic properties of the body under imaging also play an important role in the RF field distribution inside the body. The skin depth ( $\delta$ ), which is defined as the depth where the current density is just  $1/e$  (about 37%) of the value at the surface, is related to the angular frequency ( $\omega$ ), permeability ( $\mu$ ), and conductivity ( $\sigma$ ), through  $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$  [91]. An increase in the frequency and conductivity results in the reduced skin depth [12]. As different organs in the human body show different conductivities at a given frequency, then some organs may have deeper skin depth than others [92], [93]. For instance, at 7T MRI, for the human brain with an average conductivity of 0.55 S/m, the skin depth is 39.18 mm, whereas, for the torso with an average conductivity of 1 S/m, the skin depth is 29.1 mm. It corresponds to high field values (bright spot) in the center of the head for head imaging and low field values (dark spot) in the center of the body for torso imaging [94] (the EM properties of the body for different frequencies can be found in [95]).

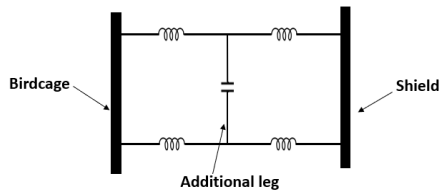
Despite all the mentioned constraints, the birdcage coil is still the best choice for body, and head imaging in clinical applications for 1.5T and

3T [96], as a 14% inhomogeneity with a 3T commercial birdcage head coil is an acceptable value for medical applications [77]. However, still some studies are going on to improve the magnetic field homogeneity of the birdcage coil at 3T [97].

The section above tried to summarize issues such as the current distortion on the birdcage legs due to the presence of a phantom or the metallic shield's impact on the coil's performance, with a summary of the available techniques in the literature to tackle the above-mentioned issues. In the following section, a new design for the birdcage coil is presented to improve the performance of the coil by reducing the inhomogeneity to 8.47% and decreasing the maximum SAR value by 49%.

### 3.3 Connected Birdcage Coil

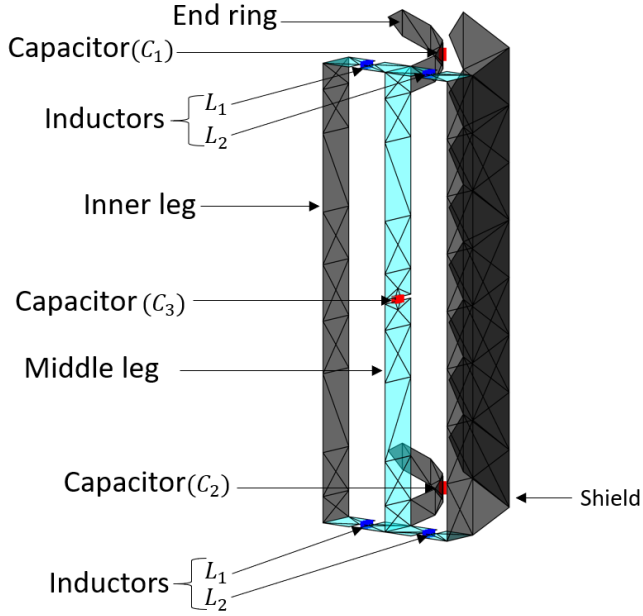
The new birdcage coil, called connected birdcage (CBC), will be introduced in this section. The main feature of the CBC is the connection between the birdcage and the shield. The connection types follow the ladder model of a transmission line, shown in Fig. 3.5, and act as an impedance bridge. The phase velocity is smaller in that transmission line than in free space, so that despite the short distance the low impedance on the shield (short circuit) is seen from the birdcage legs as a high impedance (ideally open circuit), which improves the matching of the coil and enhances the coil's efficiency. The additional leg shown in Fig. 3.5, is intended to be loaded with a lumped capacitor, which in combination with the inductors that connect the birdcage to the shield, creates the ladder model of transmission line. This type of connection provides more freedom to optimize the phase and the amplitude of the current distributions on the birdcage legs, so to be as closer to the optimal sinusoidal current distributions, resulting in a homogeneous magnetic field distribution in the center of the coil. In the rest of the thesis, for simplicity reasons, the additional leg will be called the middle leg, and the leg closer to the center of the coil will be named the inner leg.



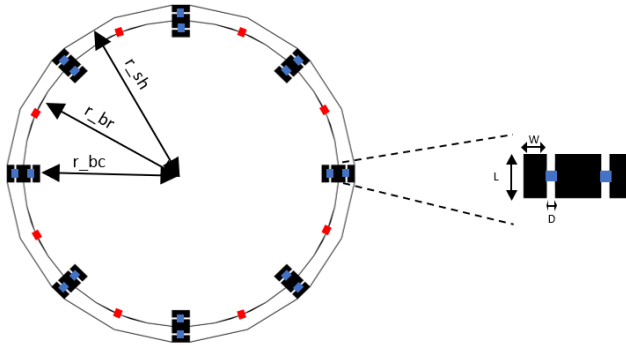
**Figure 3.5:** The connections and the type of their loads for the CBC.

Different parts of the CBC can be seen in Fig. 3.6, where the black parts show the parts that are also available in the conventional birdcage; the additional leg and the connections between the birdcage and the shield are shown in cyan. The lumped capacitors and inductors are shown in red and blue, respectively. Two excitation ports with a phase difference of  $90^\circ$  are placed in the middle of the two inner legs to provide circular polarization.

A top view of the CBC is shown in Fig. 3.7. The dimensions and the lumped element values are listed in Table 3.2, and Table 3.3, respectively.



**Figure 3.6:** One sector of the connected birdcage.



**Figure 3.7:** Top view of the connected birdcage.

**Table 3.2:** Dimensions of the CBC shown in Fig. 3.7.

| Parameter | Values  |
|-----------|---------|
| $r_{sh}$  | 16 cm   |
| $r_{br}$  | 14.5 cm |
| $r_{bc}$  | 13 cm   |
| $L$       | 1.6 cm  |
| $W$       | 6.3 mm  |
| $D$       | 2.4 mm  |

**Table 3.3:** Value of the loads shown in Fig. 3.6.

| Parameter | Values  |
|-----------|---------|
| $C_1$     | 11.3 pF |
| $C_2$     | 11.3 pF |
| $C_3$     | 3.75 pF |
| $L_1$     | 31.7 nH |
| $L_2$     | 87.4 nH |

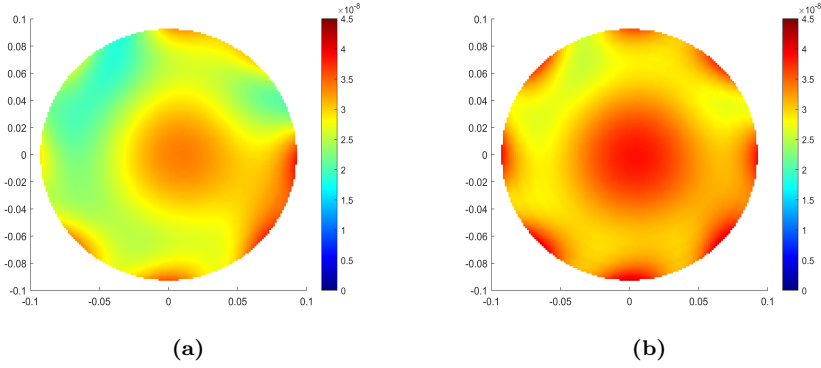
This CBC with a 28 cm height is placed around a dielectric phantom with a radius of 9.6 cm and a height of 32 cm. The relative permittivity and conductivity of the phantom are set to 61 and 0.86 S/m, respectively.

To have a better view of the performance of the CBC, a comparative study between the 3T CBC and the 3T conventional birdcage (with the dimensions provided Section 2.3) has been conducted, in which two coils are loaded with the above-mentioned phantom. The  $B_1^+$  fields normalized to the square root of the maximum SAR value are shown in Fig. 3.8 for two coils. The  $B_1^+$  fields normalized to the square root of the maximum SAR value, is called SAR efficiency in the MRI community [82]. SAR is a quantity related to safety aspects of MRI; it is defined as the power per unit mass absorbed by tissues when exposed to the RF field. It is given by

$$SAR = \frac{\sigma |E|^2}{2\rho} \quad (3.1)$$

where  $\sigma$  and  $\rho$  are the conductivity and the mass density of the tissue respectively and  $|E|$  is the magnitude of the electric field in the phantom.

Improvement in the homogeneity of the fields can be seen in Fig. 3.8, where the NSD of the fields is improved from 0.148 for the conventional birdcage to 0.105 for the CBC.

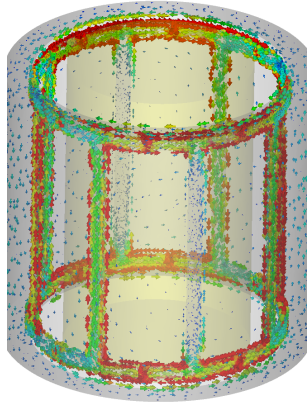


**Figure 3.8:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution on the transverse cut inside the phantom obtained from MoM: (a) 3T conventional birdcage at 127 MHz. (b) 3T connected birdcage at 127 MHz.



### 3.4 Optimized Connected Birdcage Coil

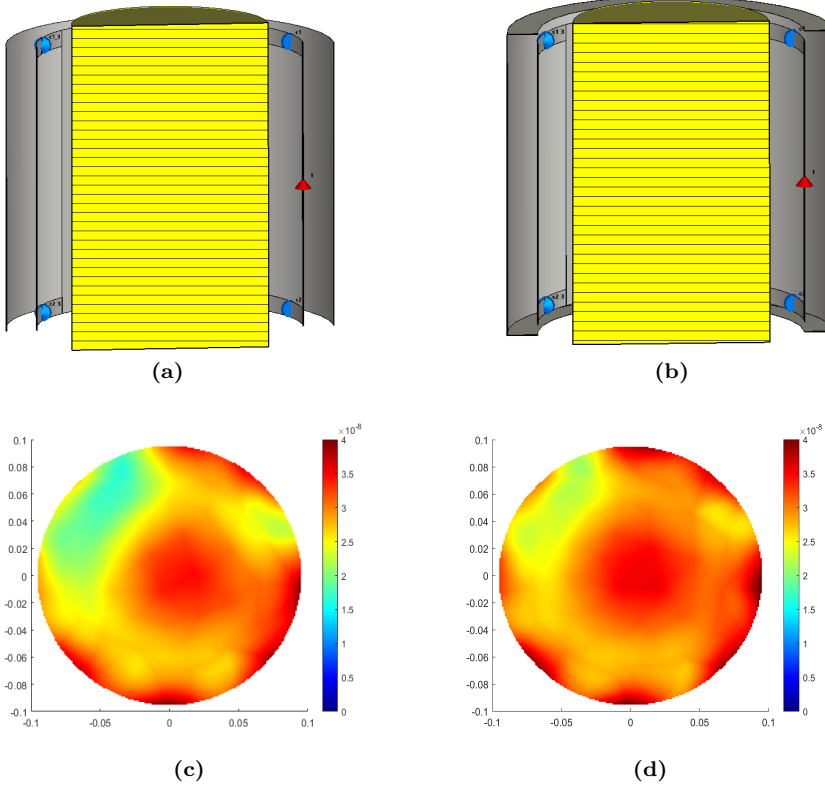
For the conventional birdcage, the flowing currents in the legs can only return from the end rings of the birdcage; thus, the end ring currents induce an additional transverse field at the center of the coil. In the loaded birdcage with the phantom, this contribution from end rings increases the  $B_1^+$  inhomogeneity in the middle of the coil [98]. It has been shown that adding extra rings on the top and bottom of the shield could reduce the impact of the currents on the end ring [98]. As shown in Fig. 3.9, the induced currents on the additional rings circulate in the opposite direction as the currents on the end ring and partially cancel out the undesired effect of the end ring currents on the homogeneity of the  $B_1^+$  field [98].



**Figure 3.9:** Current distributions with the linear excitation of the conventional birdcage. Induced currents on the additional rings are circulating in the opposite direction as the currents on the end ring.

Performance of a conventional birdcage in the presence of the additional rings on the shield is provided hereunder to give an insight into the impact of the additional rings. However, in the rest of the thesis, when it is referred to a conventional birdcage, it is a birdcage with a typical cylindrical shield without the additional rings. As shown in Fig. 3.10(b), for the conventional birdcage described in Section 2.3, the shield height is increased 1 cm on

its top and bottom and two rings are added into two ends of the shield. Additional rings start from the same radius as the end rings to avoid the reduction of the accessibility to inside the coil. With the same capacitors used for the conventional birdcage, the resonance frequency for the birdcage with additional rings on the shield, 2 MHz shifted downwards. Field distributions for a conventional birdcage and conventional birdcage with two additional rings on its shield is shown in Fig. 3.10, as expected, the field homogeneity improved in the presence of the additional rings by 27%.

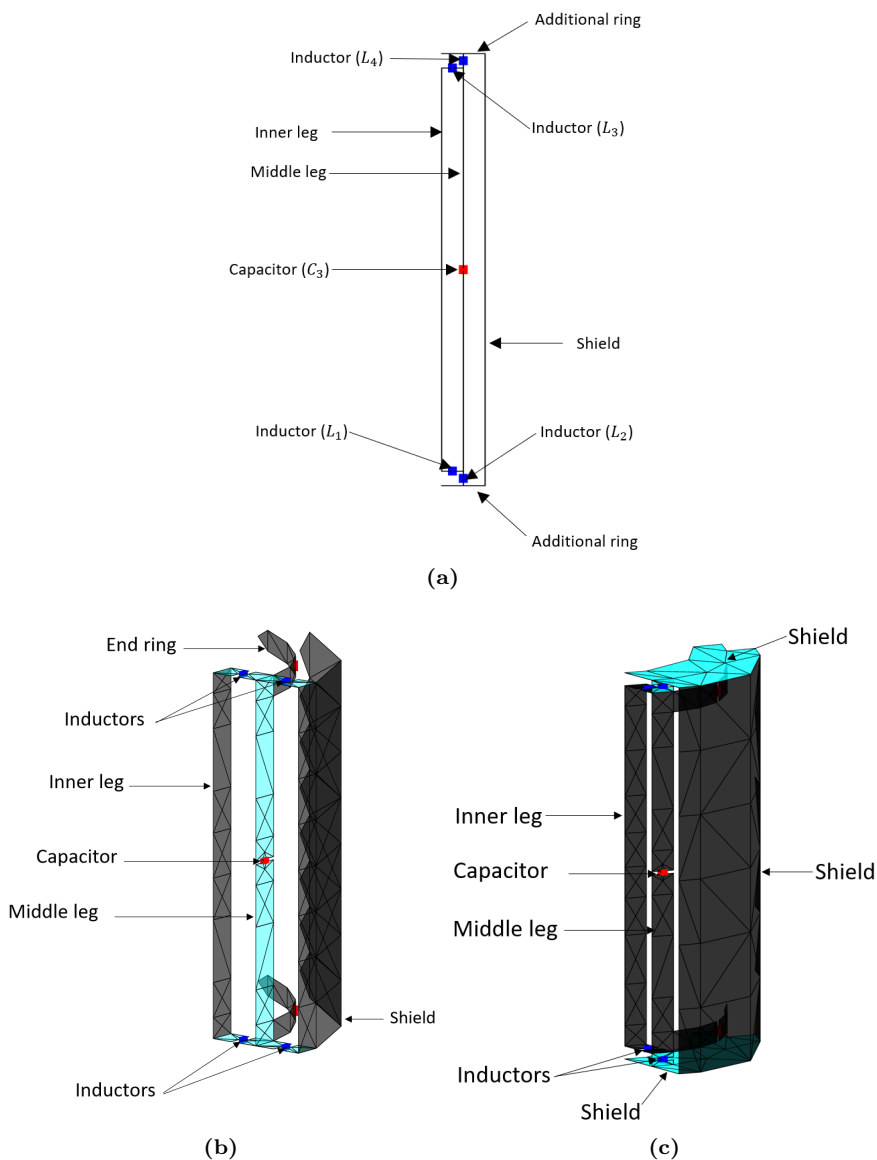


**Figure 3.10:** (a) Sagittal cut view of a 3T conventional birdcage. (b) Sagittal cut view of a 3T conventional birdcage with additional top and bottom rings to the shield.  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution on the transverse cut obtained from CST for (c) conventional birdcage at 131 MHz. (d) Conventional birdcage with two additional rings on the shield at 129 MHz.

For the CBC, due to the connections between the birdcage and shield, most of the currents return through the shield. Hence the contribution of the end rings in the  $B_1^+$  field in the middle of the coil is limited. Further improvement in the magnetic field homogeneity for the CBC has been obtained by adding copper rings on the top and bottom of the shield (like the technique applied for the conventional birdcage). A side view of the proposed design is shown in Fig. 3.11(a), where the additional rings cover the birdcage till the inner legs of the CBC. Also, the horizontally inductor-loaded connections between the birdcage and shield are changed to the vertical connections. The lumped element values for this configuration are shown in Table 3.4; C1 and C2 are the end ring capacitors, and the position of the other components is shown in Fig. 3.11(a).

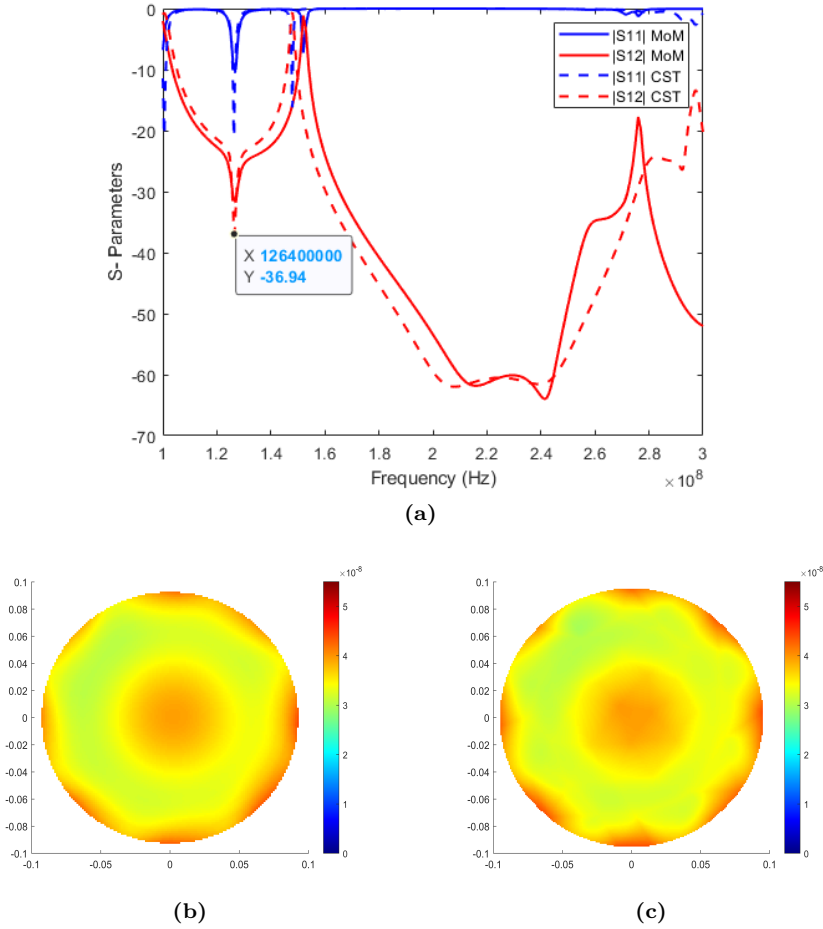
**Table 3.4:** Value of the loads shown in Fig. 3.11 for the CBC with the additional top and bottom rings.

| Parameter | Values  |
|-----------|---------|
| $C_1$     | 5.73 pF |
| $C_2$     | 5.73 pF |
| $C_3$     | 1.24 pF |
| $L_1$     | 147 nH  |
| $L_2$     | 181 nH  |



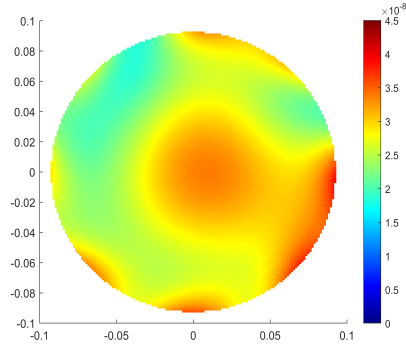
**Figure 3.11:** (a) Side view of the CBC with additional rings. (b) One sector of the CBC. (c) One sector of the CBC with additional rings (the additional rings are shown in cyan).

The S - parameters and field distributions on the transverse plane for the middle cut of the CBC coil with additional rings are shown in Fig. 3.12, where the MoM and CST results show a pretty good agreement.

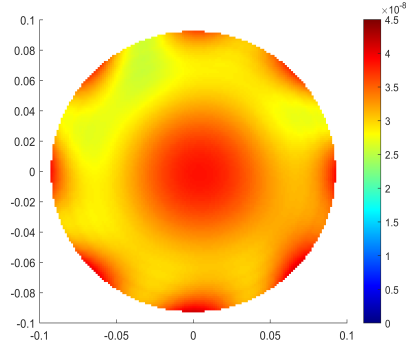


**Figure 3.12:** (a) S - parameters obtained from MoM and CST simulations, where the frequency of the main mode is marked on the  $S_{12}$  curve.  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution on the transverse cut inside the phantom obtained from: (b) MoM at 127 MHz. (c) CST at 126.4 MHz.

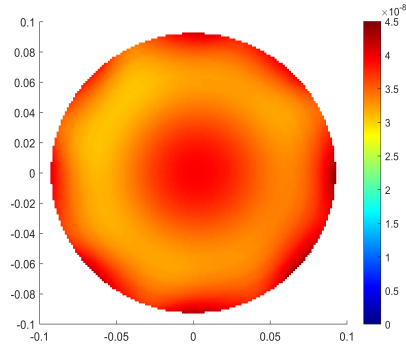
The field distributions for the conventional birdcage, CBC , and CBC with additional rings for the same phantom, same cut, and the same available region inside the three coils are shown in Fig. 3.13. Where an improvement of 43% in the homogeneity of the fields is obtained, in other words, the SD/Avg factor is improved from 0.148 for the conventional birdcage to 0.0847 for the CBC with additional rings. Current distributions on the birdcage legs are shown in Fig. 3.14, where the connected birdcage with the additional rings shows closer behavior to the ideal sinusoidal current distributions than the conventional birdcage. In the rest of the thesis, for simplicity, the CBC with additional rings will be called CBC.



(a)



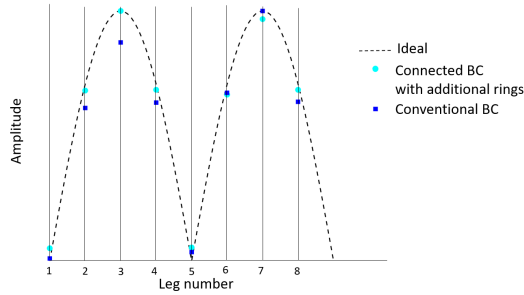
(b)



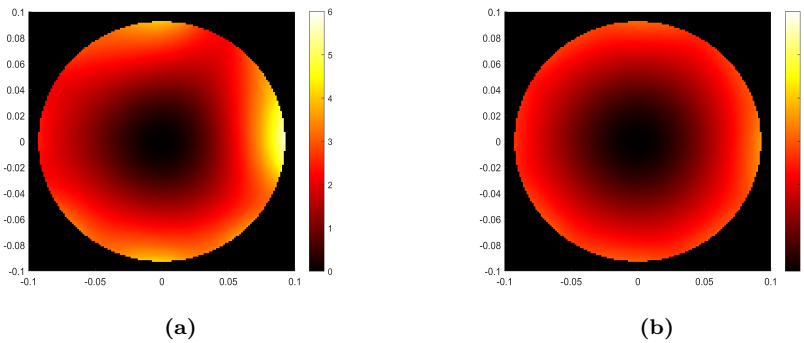
(c)

**Figure 3.13:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution on the transverse cut inside the phantom obtained from MoM at 127 MHz: (a) Conventional birdcage. (b) Connected birdcage. (c) Connected birdcage with the additional rings on the top and bottom.

In [90], it is shown that, if the current distributions in the linear excitation do not follow the sinusoidal form, then for the circular polarization, the fields produced by two ports, depending on the geometrical shape and the material properties of the phantom, can add up constructively or destructively, which could increase the SAR value. Hence, as shown in Fig. 3.14, the optimized current distribution for the CBC, improves the magnetic and the electric field homogeneity, resulting in a lower value for the maximum SAR. The SAR distributions for the conventional birdcage and the CBC for a phantom with a density of  $1 \text{ kg/m}^3$  are shown in Fig. 3.15, where an improvement by 49% is obtained in the maximum SAR value.



**Figure 3.14:** Amplitude of the current distributions on the birdcage legs.



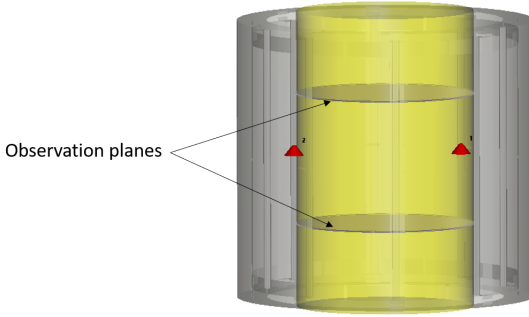
**Figure 3.15:** SAR distribution at 127 MHz: (a) Conventional birdcage with  $\text{SAR}_{\max} = 6.02 \text{ W/kg}$ . (b) CBC with  $\text{SAR}_{\max} = 3.07 \text{ W/kg}$ .



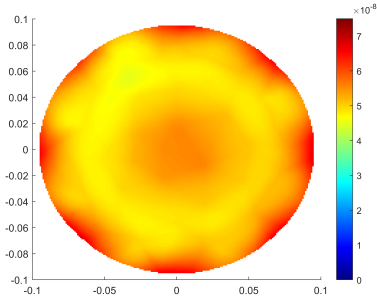
Since the birdcage coil is a volume RF coil, the  $B_1^+$  distributions for the different cuts inside the phantom are shown in Fig. 3.16. Thanks to the symmetric excitation (in the middle of the coil), the field distributions on both three-quarter sides of the conventional and the CBC are pretty much the same. It is worth mentioning that due to the lower maximum SAR values on these cuts, the higher values for the normalized fields are obtained compared to the middle cut values. The NSD values for the middle cut, three-quarter on the top and bottom for the conventional birdcage and the CBC are summarized in Table 3.5.

**Table 3.5:** NSD values for the conventional and connected birdcages on three transverse observation planes inside the phantom.

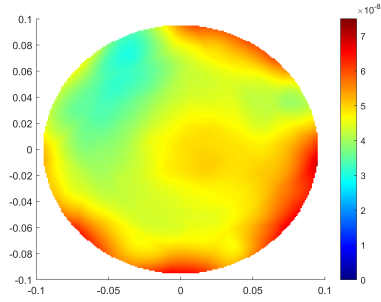
| Birdcage     | $z = 0$        | $z = 7 \text{ cm}$ | $z = -7 \text{ cm}$ |
|--------------|----------------|--------------------|---------------------|
| Conventional | NSD = 0.148 cm | NSD = 0.1608       | NSD = 0.1599 cm     |
| Connected    | NSD = 0.0847   | NSD = 0.0783       | NSD = 0.0797        |



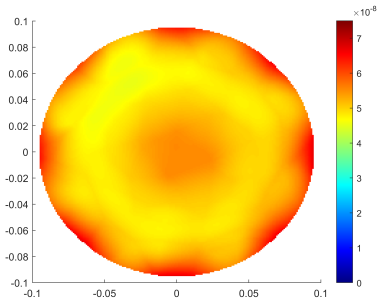
(a)



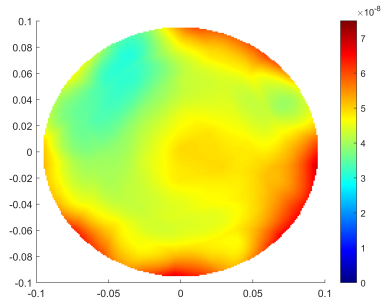
(b)



(c)



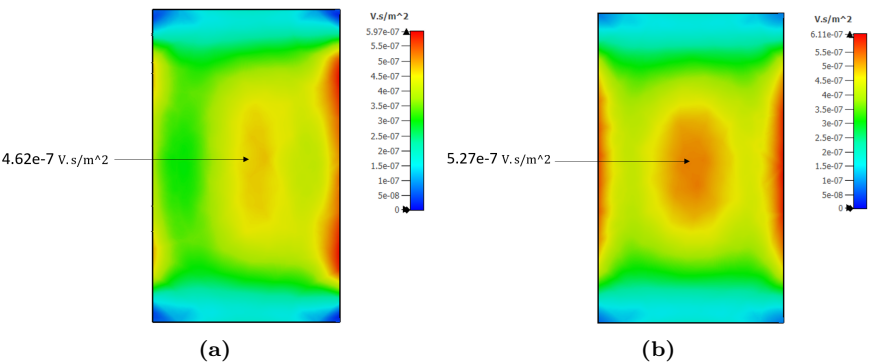
(d)



(e)

**Figure 3.16:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution on the three-quarter cuts on the top and bottom obtained from CST. (b) and (d) Connected birdcage at 126.4 MHz. (c) and (e) Conventional birdcage at 131 MHz.

Transmit efficiency for a given accepted power and the input impedance is another factor in comparing the performance of the RF coils. In the MRI community, the coil is more efficient if it can deliver more power to the center of the phantom [32]. The  $B_1^+$  field distributions on the sagittal cut for the conventional BC and the CBC are shown in Fig. 3.17. These fields are shown when each coil has 1 W accepted power. As indicated, the CBC shows better efficiency compared to the conventional BC, which can be explained by the transmission line type connection between the birdcage and shield (the increased parallel impedance from the shield as it is seen from the birdcage).



**Figure 3.17:**  $B_1^+$  field for the 1 W accepted power on the sagittal plane. (a) Conventional birdcage. (b) CBC.

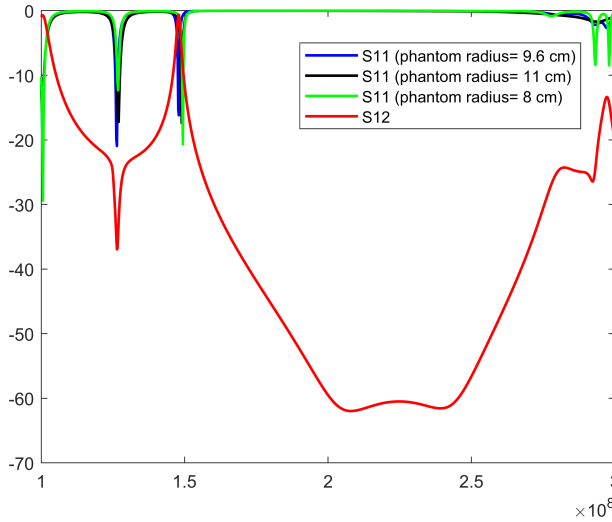
The values of the  $B_1^+$  field in the center of three transverse planes with different heights for the conventional BC and the CBC are provided in Table 3.6.

**Table 3.6:**  $B_1^+$  field value for the conventional and connected birdcages in the center of three observation planes inside the phantom for 1 W accepted power.

| Birdcage     | $z = 0$                              | $z = 7 \text{ cm}$                   | $z = -7 \text{ cm}$                  |
|--------------|--------------------------------------|--------------------------------------|--------------------------------------|
| Conventional | $B_1^+ = 0.46 \text{ } \mu\text{T}$  | $B_1^+ = 0.431 \text{ } \mu\text{T}$ | $B_1^+ = 0.438 \text{ } \mu\text{T}$ |
| Connected    | $B_1^+ = 0.527 \text{ } \mu\text{T}$ | $B_1^+ = 0.449 \text{ } \mu\text{T}$ | $B_1^+ = 0.451 \text{ } \mu\text{T}$ |

### 3.4.1 Robustness of the Connected Birdcage for Different Phantom Radii

Low-pass, high-pass, and band-pass birdcage coils show different sensitivities when loaded with a dielectric phantom. In low-pass birdcages, the presence of the phantom would reduce the resonance frequency since the stray capacitors through the phantom would be in parallel with those on the coil [32]. For the high-pass birdcage, as a result of loading, there will be an interaction between the coil and the phantom, which would induce additional currents on the legs [89]. This corresponds to increased resonance frequency because of the leg's reduced inductance [32]. However, for the band-pass coil, choosing the proper ratio between the capacitors on the legs and rings would reduce the coil's sensitivity to the loading [32]. In this sense, as for the CBC, capacitors are used in the legs and the end rings; this coil shows quite robust behavior for the different radii of the phantom. This property of the CBC could be attractive in the MRI measurements since there will be no need for tuning circuits while measuring different phantoms, which usually are used in conventional birdcages. The  $S$  - parameters for the CBC when it is loaded with three different radii of the phantom are shown in Fig. 3.18, in which tiny variations around the resonance frequency of the 3T MRI (127 MHz) indicate the robustness of the CBC. A significant advantage of the CBC over the coil with an artificial magnetic conductor (AMC) shield is the robustness of the CBC for various phantom sizes. As indicated in Section 3.2, the performance of a birdcage coil with an AMC shield depends on the size of the phantom (for big phantoms, the azimuthal mode providing the sinusoidal current on the legs can not propagate around the birdcage with an AMC shield due to the increased loss in the phantom).



**Figure 3.18:** S - parameters obtained from CST for different radii of the phantom for the CBC; 126.4 MHz is the desired resonance frequency of the birdcage for a phantom with 9.6 cm radius.

### 3.5 Fabrication Process

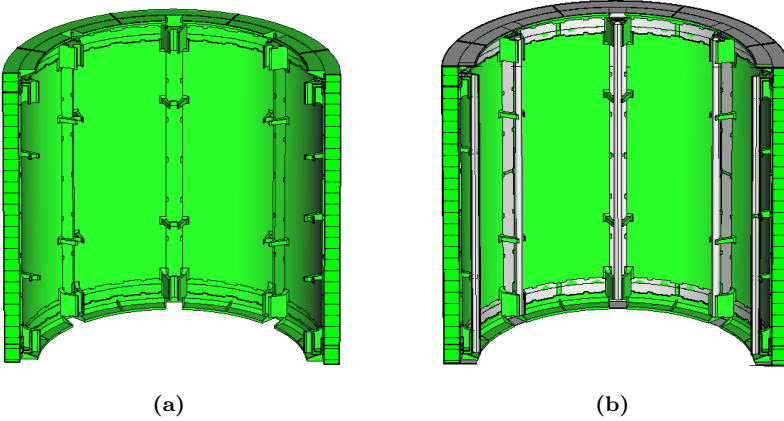
The 3T CBC coil for human head imaging has been fabricated in collaboration with SIRRIS (UCLouvain subcontractor in the MCube project). Due to the availability of the components in the market and the mechanical stability of the birdcage, several adjustment iterations were done with SIRRIS to set the final dimensions for the fabrication. Polyamide 12 (PA 12) proposed by the manufacturer is used for the mechanical stability of the design. To facilitate the excitation of the CBC with a coaxial cable, tubed-shaped legs are used in the position of the inner legs. The tube's diameter is set to half the width of the rectangular-shaped leg to provide the same inductance per unit length.

As shown in Fig. 3.19, the green colored supporting material holds the end ring, legs, and covers the inner side of the shield. Also, several embedded clips are used to keep the tubed-shaped inner legs of the CBC. The effect of the supporting material on the coil performance is simulated using CST [46],

by considering the dielectric constant and the filling factor ( $FF$ ) of 3.6 and 18% for PA 12, which would result in an effective relative permittivity ( $\varepsilon_{eff}$ ) of 1.46 from Equation (3.2)

$$\varepsilon_{eff} = \varepsilon \times FF + (1 - FF) \quad (3.2)$$

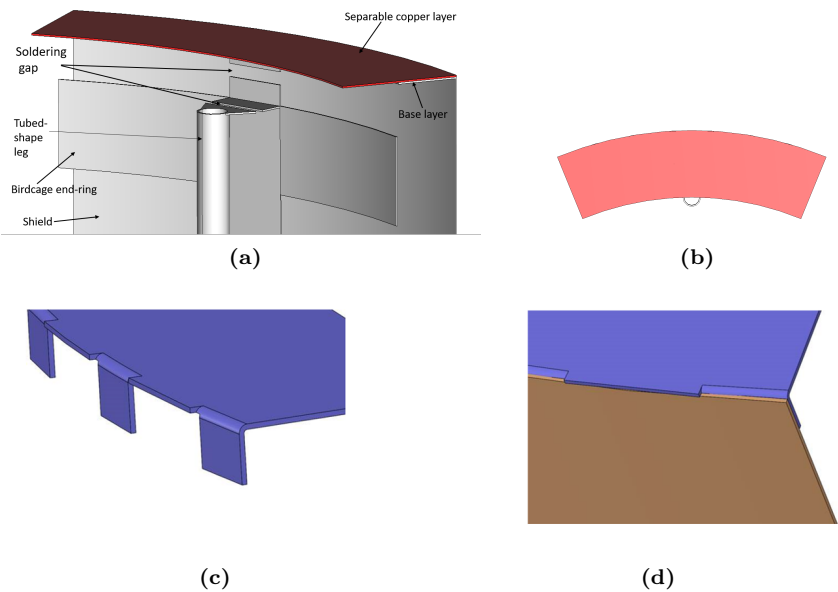
The presense of the supporting material in the coil results in a down-shift in the resonance frequency, which requires new optimizations to tune (around 15 MHz) the resonance frequency. At this level, optimizing only the lumped elements for the given dimension of the coil resulted in values for the capacitors and inductors that were unavailable on the market, which required optimizations on the coil dimensions to find the available components. As shown in Fig. 3.20(a), a separable layer of copper is used on the shield to be detached during the soldering; afterward, this layer would be connected to the shield via copper tape.



**Figure 3.19:** Fabrication model: (a) Only supporting material. (b) Supporting material loaded with different copper parts.

The base layer on the bottom of the separable layer is glued to the shield through the teeth-like connections, shown in Fig. 3.20(c) and Fig. 3.20(d), and extended to the position of the vertical inductor to provide the soldering

edge for the corresponding component.

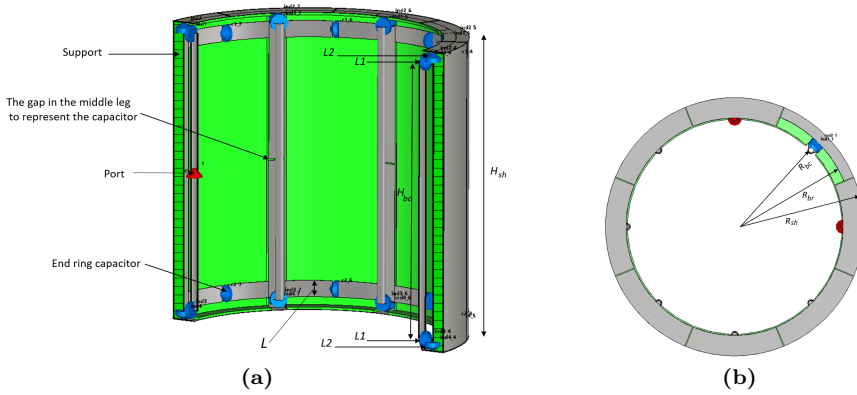


**Figure 3.20:** Different layers of copper used to ease the soldering of the inductors.

5 pF capacitors are used on the end-rings, and a 1.2 mm gap is placed in the center of the middle leg to represent the small capacitance value that could not be found on the market. 78 nH and 470 nH inductors are used for the horizontal L1 and the vertical L2 connections respectively. All the used lumped elements have the non-magnetic property to avoid any interaction with the magnetic field.

The other important aspect that should be considered in the design of the RF coil is the creation of the eddy currents on the copper plates as the result of the changes in the gradient coils. The latter are used in any MRI machine to provide the possibility of obtaining the MRI images from the desired part of the body. The presence of eddy currents could cause artifacts in the MRI images; hence, slots are recommended to be used on the shield or any copper plates used in the RF coils. The final fabrication model of the 3T CBC with eight segments on the shield is shown in Fig. 3.21(b), and

the corresponding dimensions are listed in Table 3.7. To keep the continuity of the shield, 1 nF capacitors are soldered on the slots (eight capacitors on each slot). The visualized version of all the described steps consisting of the supporting material, different copper segments, and finally, the assembled CBC with two coaxial cables on the ports are shown in Fig. 3.22.

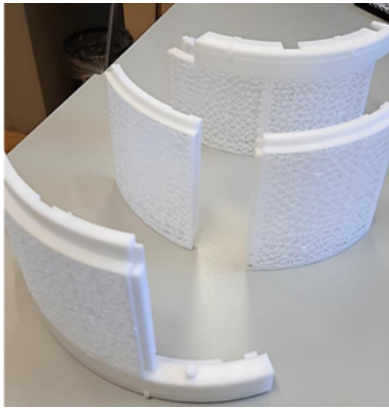


**Figure 3.21:** Fabrication model of the CBC. (a) Middle cut view. (b) Top view of the CBC; one separable copper layer on the shield is not shown for illustration purposes.

**Table 3.7:** Dimensions of the fabricated CBC.

| Parameter | Values  |
|-----------|---------|
| $H_{sh}$  | 29 cm   |
| $R_{sh}$  | 15.4 cm |
| $R_{br}$  | 14.2 cm |
| $R_{bc}$  | 13 cm   |
| $H_{bc}$  | 27 cm   |
| $L$       | 1.6 cm  |





(a)



(b)



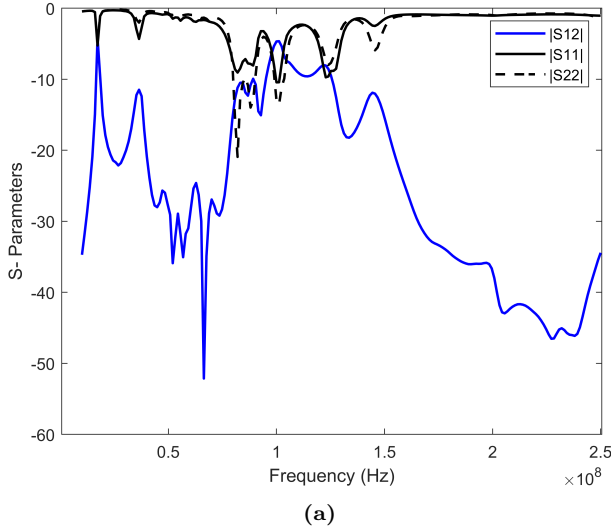
(c)



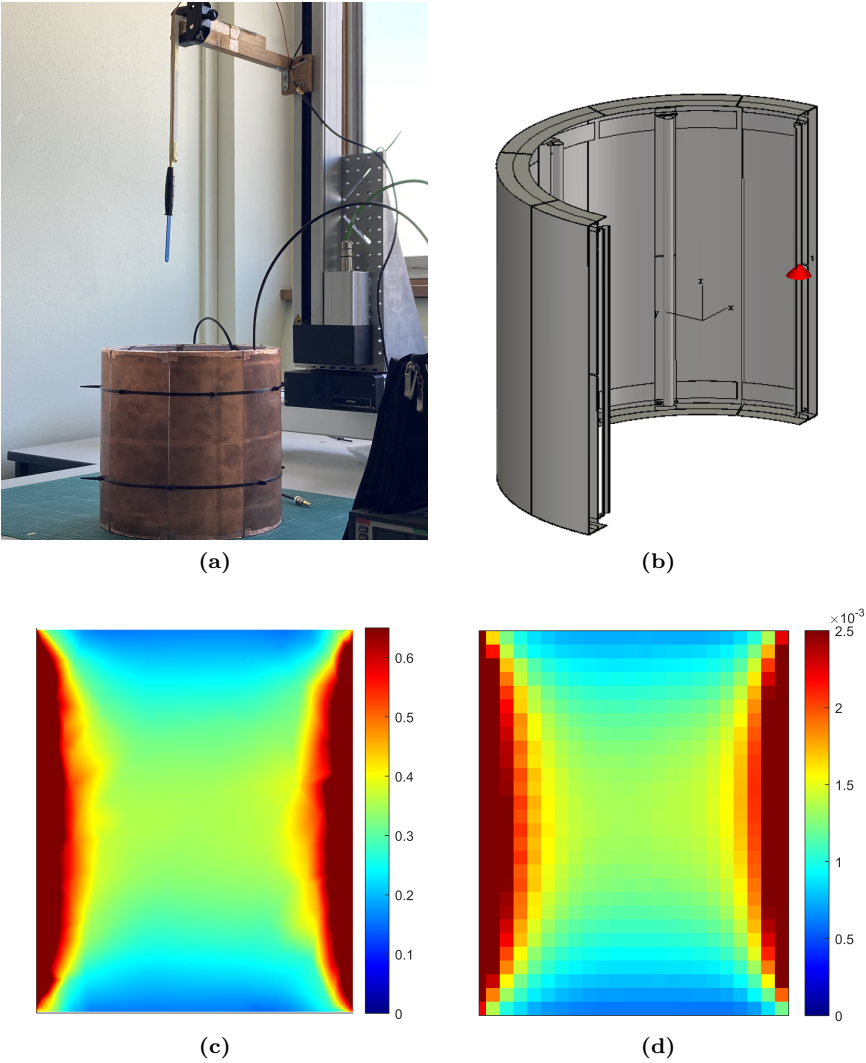
(d)

**Figure 3.22:** Different parts of the fabricated CBC fabricated in SIRRIS. (a) Supporting material. (b) Copper plates used for the shield, middle leg, additional rings on the top and bottom of the shield, the interlayer between the shield and the additional rings on the top and bottom of the shield to ease the soldering of the vertical inductors, and the tube used for the inner legs. (c) One sector of the additional ring on the top of the shield, covering the interlayer copper plate. (d) Assembled 3T connected birdcage; the two brown coaxial cables are shown for the excitation purpose.

After the fabrication of 3T CBC, two coaxial cables shown in Fig. 3.22(d) were used for the excitation, and small PCBs were used for soldering the tiny inductors on the birdcage. The carried out S - parameters measurement at UCLouvain is shown in Fig. 3.23, where the presence of six resonances confirms the maximum number of  $N/2+2$  resonances that can be obtained from a birdcage coil. By having an acceptable level of the symmetry for both ports, the field measurements have been carried out in collaboration with the Fresnel institute in Marseille. To measure the expected symmetrical behavior of the field distributions inside the birdcage, the first port of the birdcage is connected to the first port of the vector network analyzer (VNA), and the birdcage's second port is terminated with  $50\ \Omega$  load. A measurement probe connected to the second port of the VNA is used to measure the different components of the interactions between the port and the position of the probe(S21). Fig. 3.24(d) shows the absolute value of the y component of the S21 on the vertical plane inside the coil measured at 125 MHz, which has a good agreement with the CST simulation at 125.4 MHz shown in Fig. 3.24(c).



**Figure 3.23:** The measured scattering parameters of the 3T CBC at UCLouvain. The main mode of the birdcage is at 125 MHz.



**Figure 3.24:** (a) Measurement setup: the probe loop which measures the S21 can move in three different axis inside the coil to measure the chosen observation plane. (b) Observation plane, and corresponding results obtained from: (c) CST at 125.4 MHz. (d) Measurement at 125 MHz.

### 3.6 Conclusion

This chapter presented a novel birdcage coil to improve the homogeneity of the magnetic field inside the phantom with the help of the connections between the birdcage and the shield as well as introducing a capacitor-loaded additional leg. Further optimization has been obtained by using two additional rings on the top and bottom of the shield to reduce the undesirable contribution of the birdcage's end rings to the  $B_1^+$  field in the middle of the coil. The proposed coil has an inhomogeneity of just 8.5%, which results in a 49% homogeneity improvement compared to commercially available 3T birdcages with around 14% inhomogeneity. However, 8.5% inhomogeneity with one-channel birdcage coil compared to a 6% inhomogeneity<sup>1</sup> from multichannel (pTx) RF coils with a complex design, is a remarkable achievement. The fabrication procedure went to its end, and the preliminary measurement results showed a good agreement between simulation and measurement.

Chapter 4 is focused on the birdcage coils for Ultra-High field (7T) MRI. This chapter introduces a new design for a 7T conventional birdcage based on floating loops. The floating loops are also implemented into a 7T connected birdcage, resulting in an improved magnetic field homogeneity on both transverse and sagittal planes.

---

<sup>1</sup>Mentioned by Prof. Redha Abdeddaim on November 29, 2022.

# CHAPTER 4

## Birdcage Coil for Ultra-high Field MRI

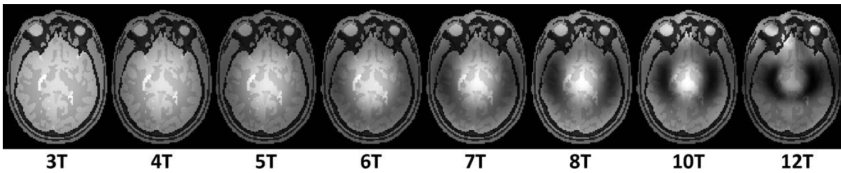
This chapter presents a new design for the birdcage coil at 7T MRI. This design is based on the optimized connected birdcage coil described in Chapter 3 with additional vertical floating loops. The presence of the floating loops improved the magnetic field homogeneity on both transverse and sagittal planes inside the phantom. The idea of the floating loops also is implemented for an eight-leg conventional birdcage coil, and homogeneity improvement for the conventional birdcage is also reported.

Section 4.1 provides an introduction to the UHF MRI while providing a summary of its benefits and challenges. In Section 4.2, field distributions for an eight-leg conventional birdcage coil are shown; followed by a study of the impact of the feeding points and the number of the birdcage legs on the fields homogeneity. The concept of the radially oriented vertical loops in the RF coils is provided in Section 4.3. In Section 4.4 the floating loops are implemented into the conventional birdcage. The performance of the connected birdcage at 7T MRI is reported in Section 4.5. Section 4.6 implements the vertical floating loops in the connected birdcage. Section 4.7, provides the simulation results for the realistic human head model (voxel

model). In Section 4.8, a comparative study is carried out between a sixteen-leg birdcage coil and the eight-leg connected birdcage with floating loops. Section 4.9 considers the possibility of using the floating loops for the 3T connected birdcage developed in Chapter 3. Section 4.10 presents the impact of the received array on the birdcage coil performance, and detuning of the connected birdcage coil with floating loops to avoid any interaction with the received array in the receive mode is provided in Section 4.11. Finally, the fabricated 7T connected birdcage coil with floating loops and its measurement procedures are reported in Section 4.12.

## 4.1 Introduction

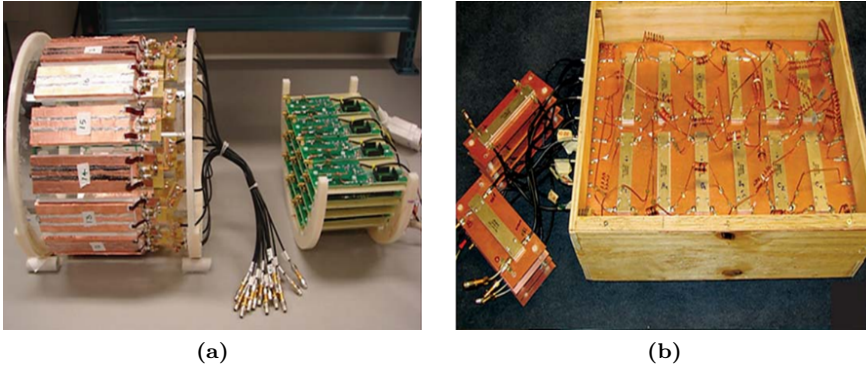
An increase in the strength of the static magnetic field ( $B_0$ ) provides a higher signal-to-noise ratio (SNR) [99], improves the spatial resolution [100], and could increase the spectral resolution [6]. On the other hand, an increased  $B_0$  field is accompanied by challenges like decreased penetration rate, higher RF power requirement [101], [102], and most notably, the reduced wavelength inside the body [47], [103]. The shortened wavelength would cause standing waves inside the body, resulting in bright and dark spots in the MRI images. This can be seen in Fig. 4.1, as the strength of the  $B_0$  field increases from 3T to 12T [68]. Besides the techniques that have been reviewed in Chapter 3 to locally increase the intensity of the fields in the regions with destructive interference (shown with dark spots), in [104], it is shown that the mechanically asymmetric birdcage coil could also improve the homogeneity of the magnetic field at 4.7T MRI.



**Figure 4.1:** Inhomogeneity caused by the increased  $B_0$  field [68].

The parallel transmission mentioned in Section 3.1, could be used in

UHF MRI applications, as it provides not only the optimization of the amplitude of the RF pulses, it also uses different RF pulse shapes (forms). Having tailored RF pulses from multiple transmitters, enables one the use the constructive and destructive interference from the RF waves to improve the homogeneity inside the body [105], [76], [74]. Although the parallel transmission technique is employed for research purposes at UHF MRI applications [106], [41], it comes with costly requirements. Since, it not only requires a separate RF amplifier to deliver the required power to the elements, see Fig. 4.2, it also needs an appropriate software implementation to generate and control the outgoing RF pulse for each channel. In addition, pTx is associated with a significant SAR risk due to the superposition of the fields produced by each transmitter, which is one of the ongoing studies by other researchers to confirm pTx safety in clinical applications (pTx scanners are still waiting for FDA approval [78]).



**Figure 4.2:** (a) pTx RF coil with 16-channel strip-line array for 7T head imaging. (b) 16×8 Butler matrix [76].

In [107], an inhomogeneity of 42% is reported in for a 7T birdcage coil when it is loaded with a head-shaped water phantom. Whereas in [108], a 29% deviation on the axial plane inside the head is reported with an

eight channel dipole transmit array in 7T head imaging, where the phase of each dipole is adjusted such that, the constructive interference happens in the center of the brain. This chapter aims to make the birdcage coil more homogeneous so that it can be used in 7T head imaging as a safe and simpler alternative to the pTx scanner.

The homogeneity improvement obtained with the connected birdcage coil in Chapter 3, encouraged using this coil at UHF. This chapter introduces a new design for a 7T conventional birdcage based on floating loops. It is shown that the presence of the floating loops improves the currents on the birdcage legs to be closer to the optimal sinusoidal current distribution and enhances the magnetic field homogeneity in the overall volume inside the 7T conventional birdcage. The floating loops are also implemented into a 7T connected birdcage, and an improvement in the homogeneity is reported.

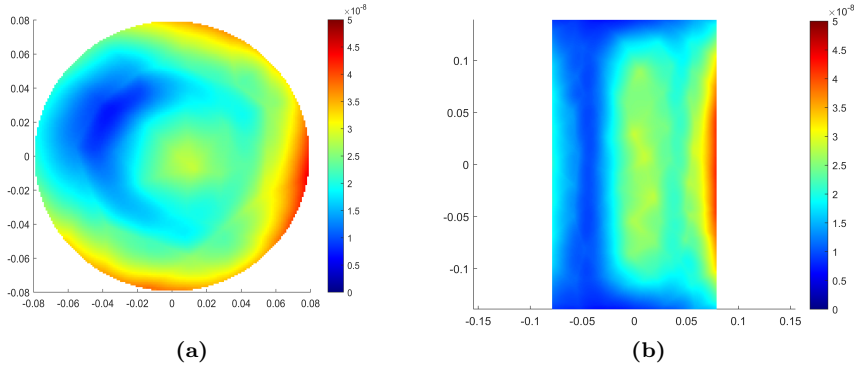


## 4.2 Conventional Birdcage Coils for 7T MRI

An eight-leg 7T conventional birdcage coil with two excitation ports in the center of two legs is considered a reference coils for all the designs presented in this Chapter. This 7T coil has a radius of 13 cm, and its height is 28 cm. The legs width is 1.6 cm, and sixteen capacitors with a value of 1.1 pF are used on the end rings. A metallic shield surrounds the coil with a radius of 16 cm and the same height as the birdcage. These dimensions were also used for the 3T conventional birdcage in Chapter 3, even though each coil requires different capacitor values to be tuned for the desired resonance frequency. As mentioned in Section 3.2, the desired sinusoidal current distribution on the birdcage legs is distorted with an increased frequency. This distortion can be explained as a standing wave pattern due to the interference of fields from different conductive elements in the coil [94]. This means that even for an unloaded birdcage (without phantom), the homogeneity inside the coil decreases as the frequency increases. Two observation disks with R1 and R2 radii inside an unloaded birdcage are shown in Fig. 4.3(a). The birdcage is differently optimized for 3T and 7T MRIs, and the corresponding NSD are summarized in Table 4.1. As can be seen, on the observation plane with a radius of 9 cm, an unloaded 3T birdcage shows 67% more homogeneity than the 7T birdcage on the same observation plane, indicating a severe current distortion on the birdcage legs at UHF MRI.

This 7T coil is loaded with a dielectric phantom with a radius of 8 cm and a height of 32 cm, shown in Fig. 4.3(b). The phantom's relative permittivity and conductivity are set to 45.3 and 0.87 S/m to represent the human head properties at 300 MHz. Field distributions on the transverse and sagittal planes are shown in Fig. 4.4. At 300 MHz ( 7T MRI) the wavelength inside the phantom is 14.8 cm, which is comparable to the phantom's diameter (16 cm) [103]. Hence a significant inhomogeneity as a result of the standing waves is obvious.



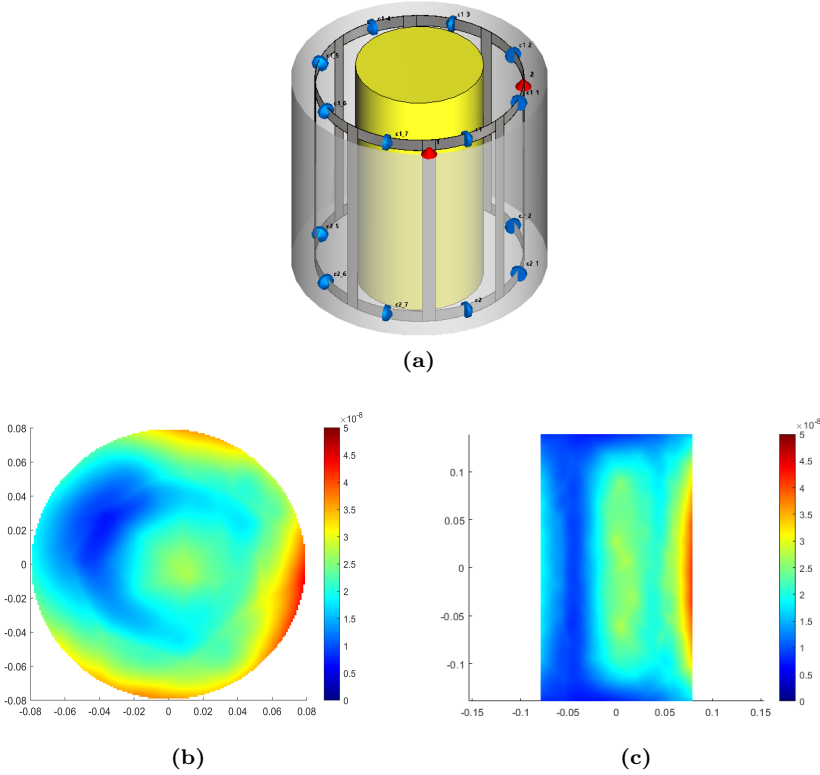


**Figure 4.4:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  fields for the eight-leg conventional birdcage coil at 300 MHz. (b) Transverse middle cut with NSD = 0.3099. (c) Sagittal cut with NSD = 0.3731.

However, as mentioned in Section 3.2, the current distortion on the birdcage legs due to the loading is severe at UHF MRI and on its own decreases the homogeneity of the  $B_1^+$  field. Several studies have considered different feeding points for the RF coils and their impact on the homogeneity at UHF MRI [109], [110], [111], [112]. Indeed if changing the position of the feeds improves the current distribution on the legs, (to be closer to the ideal sinusoidal distribution), it would enhance the homogeneity of the  $B_1^+$  field. In the following subsections, possible positions of the excitation ports and the corresponding field distributions are briefed for an eight-leg birdcage coil.

### 4.2.1 Eight-leg Birdcage with Ports between Legs and the End ring

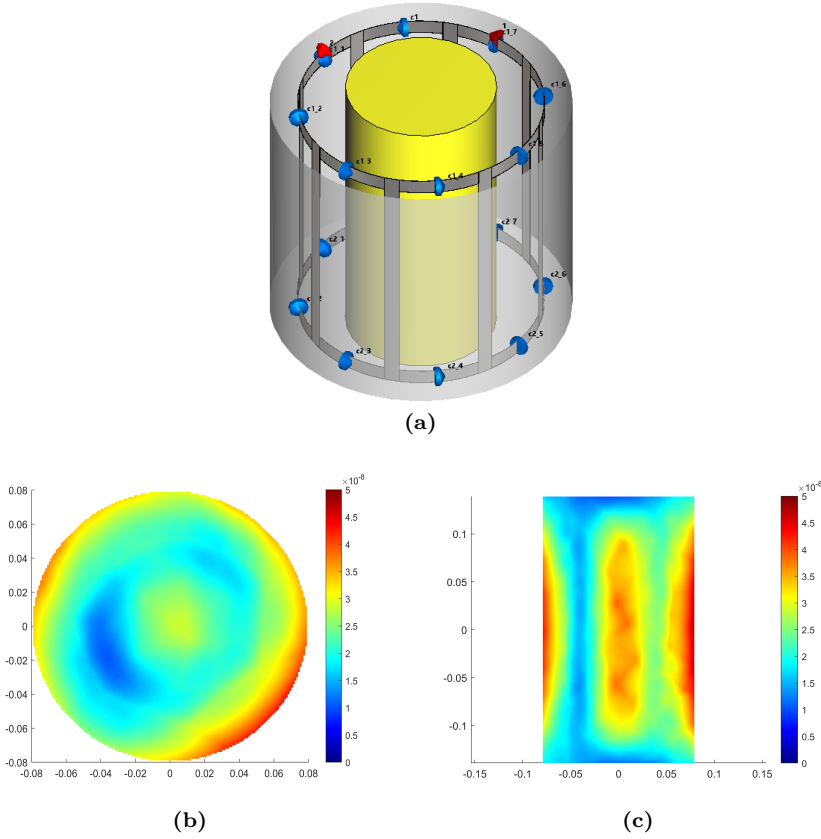
A birdcage coil could be excited as shown in Fig. 4.5(a), where two excitation ports are located on the junction points between two legs and the end ring. The corresponding field distributions on the two planes are shown in Fig. 4.5. It is worth mentioning that, in this case, the current distributions on the legs are pretty similar to the current distributions in Section 4.2, as the maximum and minimum of the current are on the position of the legs, resulting in pretty similar NSD values for the field distribution.



**Figure 4.5:** (a) An eight-leg birdcage with the excitation ports between the end ring and legs. The corresponding  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distributions at 300 MHz on the: (b) transverse plane with NSD = 0.3162. (c) Sagittal plane with NSD = 0.3753.

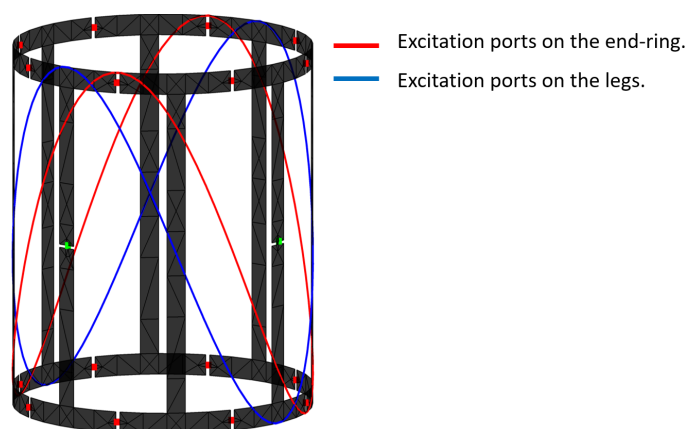
### 4.2.2 Eight-leg Birdcage coil with Ports on the End ring

As shown in Fig. 4.6(a), a high pass 7T birdcage with excitation ports on the end rings is designed and fields distributions for two two inside the phantom are shown in Fig. 4.6. Considering the NSD values, 18% and 21% improvements on the transverse and sagittal planes, respectively, are obtained compared to the case where the ports are in the middle of the legs.



**Figure 4.6:** (a) An 8-leg birdcage coil with excitation ports on the end ring, and the corresponding  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distributions at 300 MHz on the: (b) transverse plane with NSD = 0.2549. (c) Sagittal plane with NSD = 0.2932.

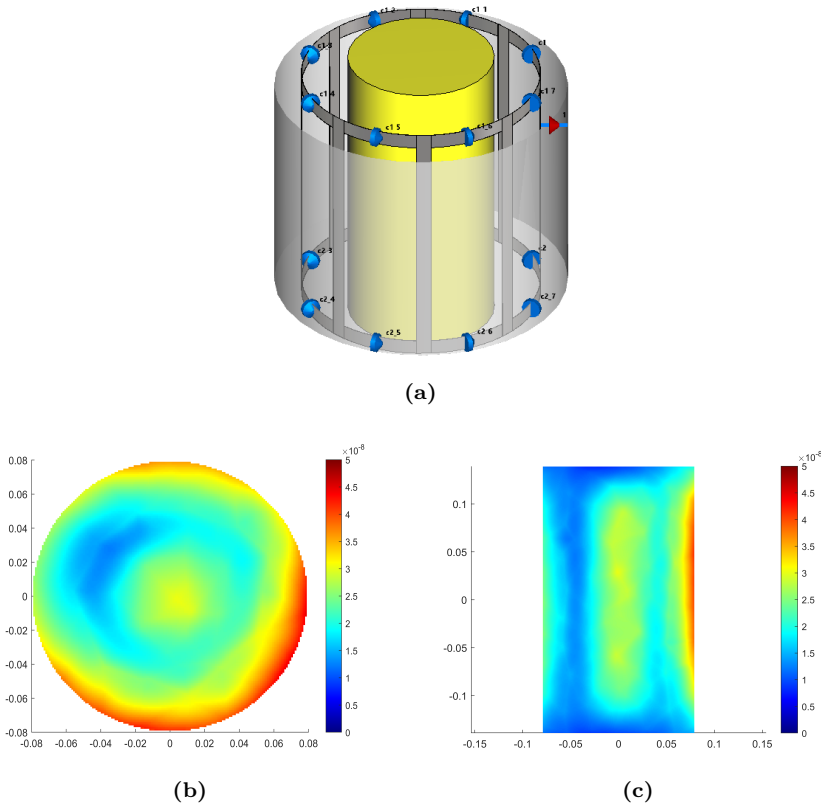
The possible explanation for the homogeneity improvement is that when the ports are located on the end ring, all the legs participate in producing the magnetic field. In other words, despite the case when the ports are on the legs, the minimum current is not on the position of the leg; the current distributions for both cases can be seen in Fig. 4.7.



**Figure 4.7:** Current distributions on the birdcage legs when the excitation ports are on the legs or on the end ring.

### 4.2.3 Eight-leg Birdcage with Ports between the Birdcage and Shield

A birdcage with excitation ports between the birdcage and shield is shown in Fig. 4.8(a). Compared to the configuration described in Section 4.2, this type of excitation could improve the homogeneity on the transverse plane by 17%, and 20% on the sagittal plane. The field homogeneity improvement can be explained by the limited currents on the end rings, see Section 3.4, as the birdcage is connected to the shield via the excitation ports.



**Figure 4.8:** (a) An 8-leg birdcage coil with excitation ports between the birdcage and shield, and the corresponding  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution at 300 MHz on the: (b) transverse plane with NSD = 0.2579. (c) Sagittal plane with NSD = 0.3.

The NSD values and the  $B_1^+$  value in the center of the phantom for 1 W accepted power, when the two excitation ports are placed in the different parts are summarized in Table 4.2. Considering the possibilities mentioned above for the port position, even though the asymmetrical excitations, like the ports on end rings or between the birdcage and the shield, provide improved homogeneity, they result in the top-bottom asymmetric field distribution. The asymmetric field distribution can be interpreted as the locally increased SAR value and tissue damage. Hence, to keep the symmetrical field distribution and predictable SAR value, the birdcage coil with the excitation ports in the middle of the legs is considered the reference birdcage in the rest of the thesis.

**Table 4.2:** NSD and  $B_1^+$  values (for 1 W accepted power) in the center of the phantom for different port positions on the transverse and sagittal planes.

| Port positions (8-leg BC)       | Transverse | Sagittal | $B_1^+$ in the center |
|---------------------------------|------------|----------|-----------------------|
| In the middle of the legs       | 0.3099     | 0.3731   | 0.338 $\mu$ T         |
| Between legs and end ring       | 0.3162     | 0.3753   | 0.337 $\mu$ T         |
| On the end ring                 | 0.2549     | 0.2932   | 0.326 $\mu$ T         |
| Between the birdcage and shield | 0.2579     | 0.3      | 0.315 $\mu$ T         |

Besides the position of the excitation ports that impact the field distribution, one can imagine increasing the number of legs to improve the homogeneity. The field distribution for 16-leg birdcages is included in the following sections to give an idea of the impact of the leg numbers on the homogeneity improvement.

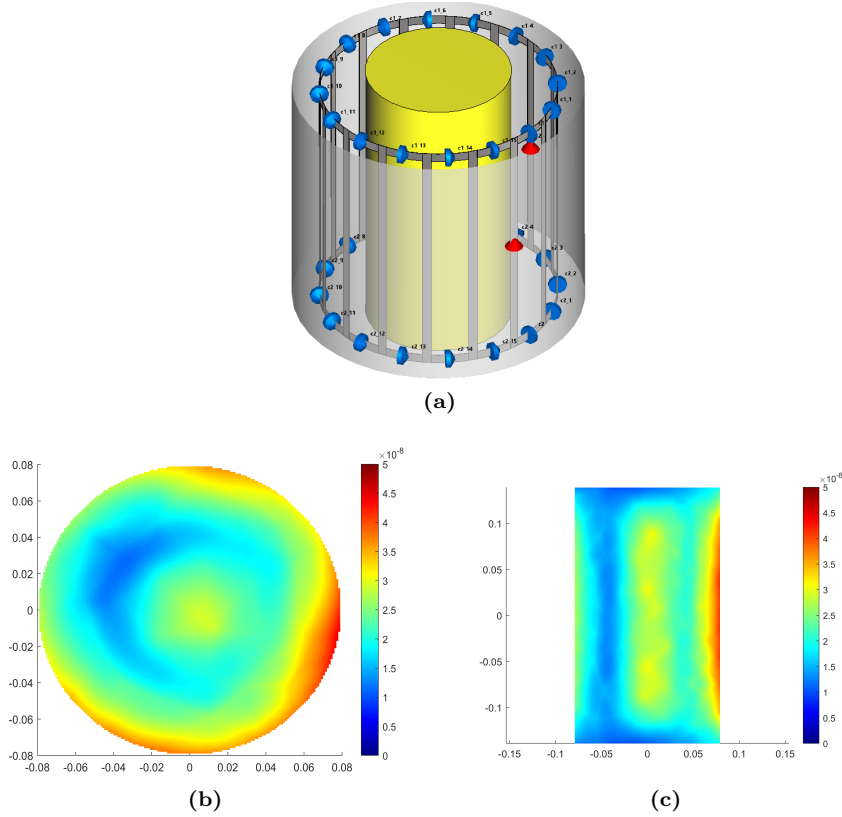


#### 4.2.4 Sixteen-leg Birdcage Coil with two Ports in the Middle of the Legs

It has been shown that, increasing the number of legs improves the magnetic field homogeneity for the birdcage coil loaded with a phantom. In other words, a birdcage coil with a larger number of legs provides a continuous sinusoidal current distribution explained in Section 1.4.2; hence the effect of the current fluctuations will be limited. A birdcage coil with 8, 12, 16, 32, 64, and 128 legs is imaginable, but due to the fabrication, tuning, and matching limits, a birdcage coil with 16 legs is the maximum number that can be fabricated [113], [114], [115]. As shown in Fig. 4.9(a), a sixteen legs birdcage coil with 1 cm leg width, a diameter of 26 cm, a height of 28 cm, and capacitor values of 4.4 pF, is designed for the 7T MRI. Two excitation ports are used in the middle of the legs, and a shield with a diameter of 32 cm and a height of 28 cm is put around the coil. The birdcage is loaded with a cylindrical phantom described in Section 4.2. As shown in Fig. 4.9(b), and Fig. 4.9(c) the homogeneity factor on the transverse and sagittal planes for the sixteen-leg birdcage coil are improved compared to the eight-leg birdcage mentioned in Section 4.2. As explained before, this improvement can be explained by the increased number of the legs participating in the ideal sinusoidal current distribution around the birdcage. However, as shown in the previous sections, the homogeneity for a birdcage could be improved as the position of the ports change. Hence, the following paragraphs, provides a 16 leg birdcage with two ports between the birdcage and shield (like the case shown for an eight-leg birdcage in Section 4.2.3)

**Table 4.3:** NSD and  $B_1^+$  values (for 1 W accepted power) in the center of the phantom for: 8-leg BC with ports in the middle of the legs (PML), 16-leg BC with ports in the middle of the legs (PML), and 16-leg BC with ports between the BC and shield (PBS).

| Birdcage type   | Transverse | Sagittal | $B_1^+$ in the center |
|-----------------|------------|----------|-----------------------|
| 8-leg BC (PML)  | 0.3099     | 0.3731   | 0.338 $\mu$ T         |
| 16-leg BC (PML) | 0.2579     | 0.3      | 0.343 $\mu$ T         |
| 16-leg BC (PBS) | 0.2224     | 0.2272   | 0.31 $\mu$ T          |

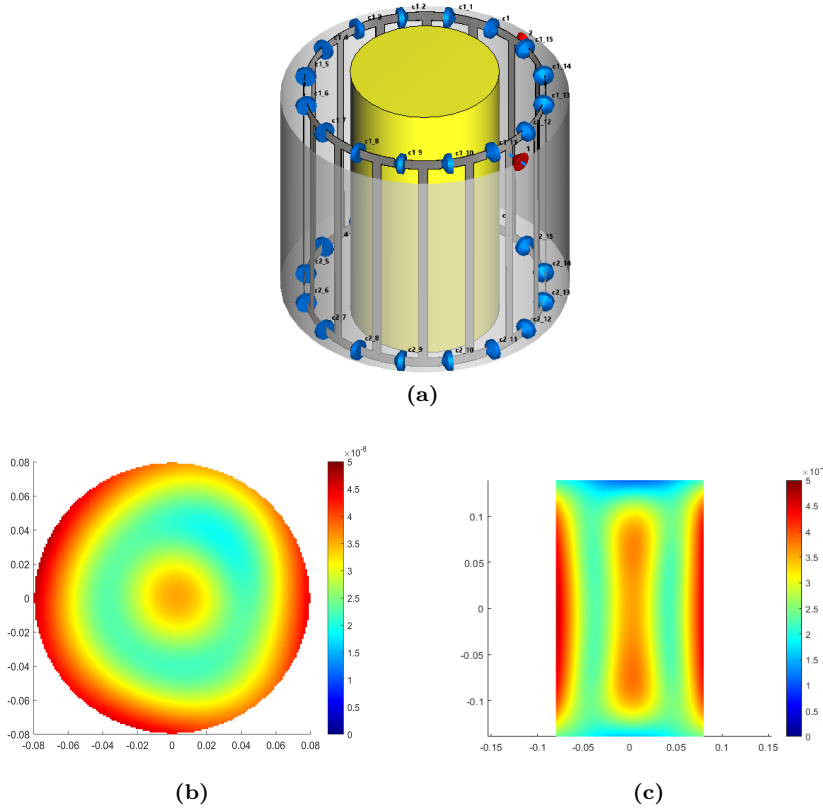


**Figure 4.9:** (a) A 16-leg birdcage coil with two excitation ports in the middle of the legs.  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution for the 16-leg birdcage with the ports in the middle of two legs at 300 MHz. (b) Transverse plane with NSD = 0.2611. (c) Sagittal plane with NSD = 0.2825.

#### 4.2.5 Sixteen-leg Birdcage with Ports Between the Birdcage and Shield

As shown for the eight-leg birdcage in Section 4.2.3, for the 16-leg birdcage (with the same dimensions as the previous section and the capacitors values of 4.5 pF), two ports are placed between the birdcage and the shield, see Fig. 4.10(a). The field distributions inside the phantom for this birdcage shown in Fig. 4.10(b) and Fig. 4.10(c). Thanks to this type of the excitation which limits current distribution on the end rings (see Section 4.2.3) and increased number of legs, this 16-leg birdcage shows substitutional improve-

ment compared to the 8-leg birdcage. The comparison between the 16-leg birdcages with different type of the excitations and the 8-leg conventional birdcage is provided in Table 4.3.



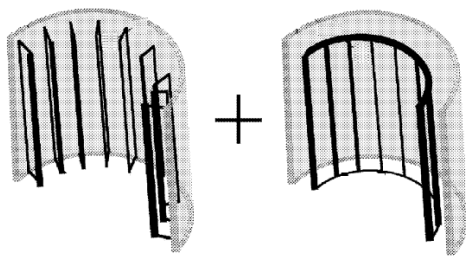
**Figure 4.10:** (a) A 16-leg birdcage coil with two excitation ports between the birdcage and shield.  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution at 300 MHz on the: (b) transverse plane with NSD = 0.2224. (c) Sagittal plane with NSD = 0.2272.

This sixteen-leg birdcage shows the best homogeneity among the conventional birdcages reported in this chapter. However, since this thesis seeks to enhance the homogeneity of the eight-leg birdcage to maintain the structure's simplicity; hence these 16-leg birdcages are not considered reference cases for this thesis.

Up to this point, every possible way to boost a 7T conventional birdcage's performance by changing the port positions and adding more legs has been studied. As the goal is to use eight legs and keep the top-bottom symmetry, the next sections propose a new technique based on the radially oriented vertical loops (floating loops) to be added to the eight-leg birdcage and improve its homogeneity. The following sections first present the literature review on the radially oriented vertical loops used for different applications in the MRI community, then presents the design details for the birdcage coils based on the floating loops.

### 4.3 Radially Oriented Vertical Loops used in the RF Coils

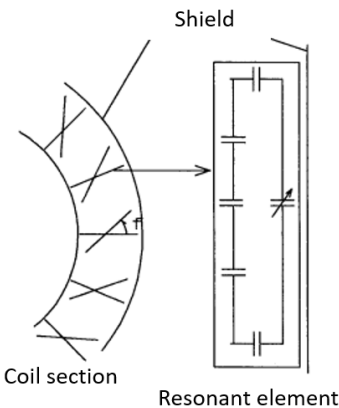
The patent and literature review revealed that radially oriented vertical loops have been used in RF coils for different purposes. In [116], [117], a combination of the birdcage and TEM coils have been proposed to create a dual frequency coil, in which radially oriented loops connecting to the shield are used as the TEM coil, Fig. 4.11 represents the configuration of this combined coil.



**Figure 4.11:** Combination of TEM and birdcage coils; vertical loops are part of the TEM coil since they are connected to the shield [116].

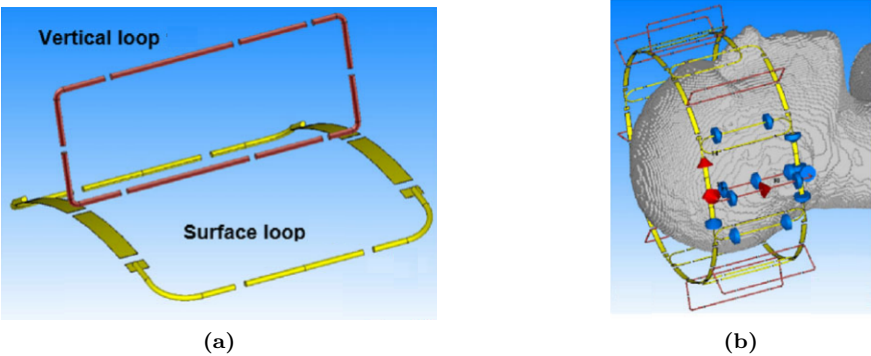
In [118], an array of individually tuned and inductively coupled resonant elements are used to easily tune each element, even asymmetrically, to manipulate the field distributions, and improve the magnetic homogeneity

when a specific part of the body is being imaged. One sector of this design is shown in Fig. 4.12.



**Figure 4.12:** Free element coil [118].

In [119], vertical loops are combined with the surface loops (without any intersection) to increase the number of receiver elements in the transceiver configurations and improve the SNR, see Fig. 4.13. The vertical loops are active only in the receive mode and are detuned during the transmission to avoid interference with the surface loops.



**Figure 4.13:** Vertical loops in combination with surface loops [119].

4.4 Eight-leg Conventional Birdcage with Floating Loops

Fig. 4.14 shows a single element of floating loops. These floating loops are vertically oriented and positioned between two consecutive legs of the birdcage, where they are radially extended from the position of the legs to the shield. The dimensions of a single loop is provided in Table 4.4, and the position of the floating loops within the birdcage is shown in Fig. 4.15. The birdcage dimensions are the same described in Section 4.2 with 1 pF capacitor on its end rings. The capacitor used between the second and third floating loops has 35 pF value, which is obtained through the optimization, and two other capacitors have 1 nF value (a big capacitor value) to keep the continuity between the two floating loops.

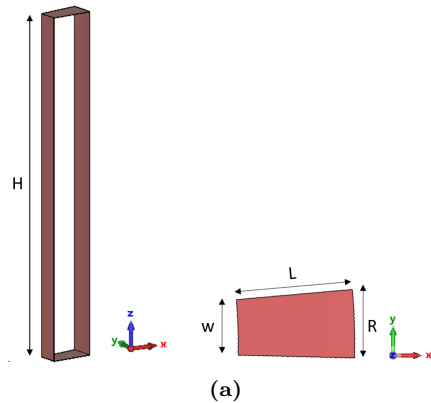
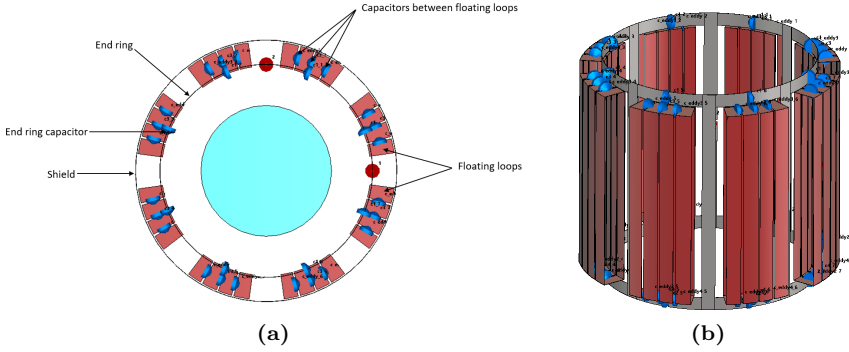


Figure 4.14: Side and top views of a single floating loop.

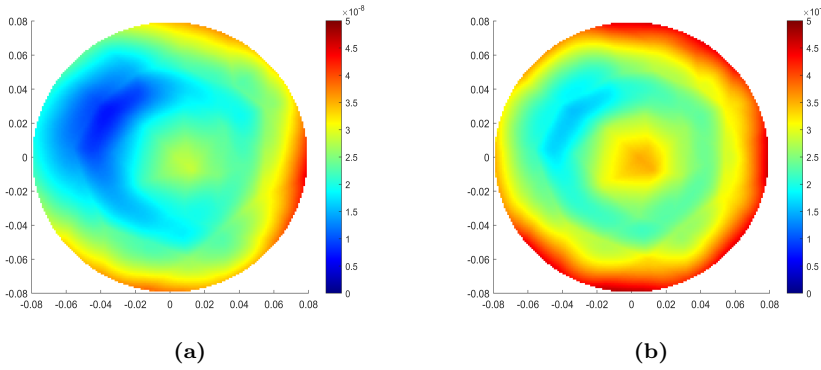
Table 4.4: Dimensions of the loop shown in Fig. 4.14.

| Parameters | Value (cm) |
|------------|------------|
| H          | 24.48 cm   |
| L          | 2.9 cm     |
| W          | 1.33 cm    |
| R          | 1.72 cm    |



**Figure 4.15:** Conventional birdcage with floating loops. (a) Top view. (b) 3D view without shield.

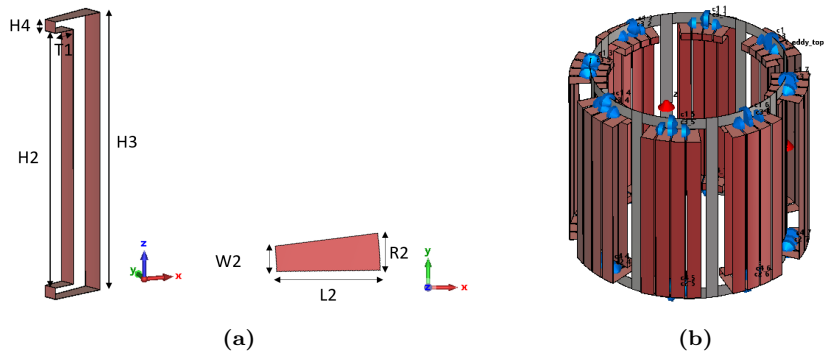
As shown in Fig. 4.16, a 24% improvement in the homogeneity of the magnetic field is obtained on the transverse cut, since the NSD value improved from 0.3099 for the conventional birdcage to 0.2349 for the conventional birdcage with floating loops.



**Figure 4.16:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distributions on the transverse plane inside the phantom at 300 MHz. (a) Conventional birdcage with NSD = 0.3009. (b) Conventional birdcage with floating loops with NSD = 0.2349.

Further enhancement in the homogeneity is obtained by increasing the width of the floating loop only on its two ends (extended floating loops) to keep the available volume in the rest of the coil, shown in Fig. 4.17.

Extending the floating loops in the axial direction of the birdcage improves the uniformity of the current distribution on the legs, which results in the homogeneity improvement on the sagittal plane.



**Figure 4.17:** New design of the floating loops. (a) Side view and top view of the single element. (b) Birdcage coil with the new design of the floating loops.

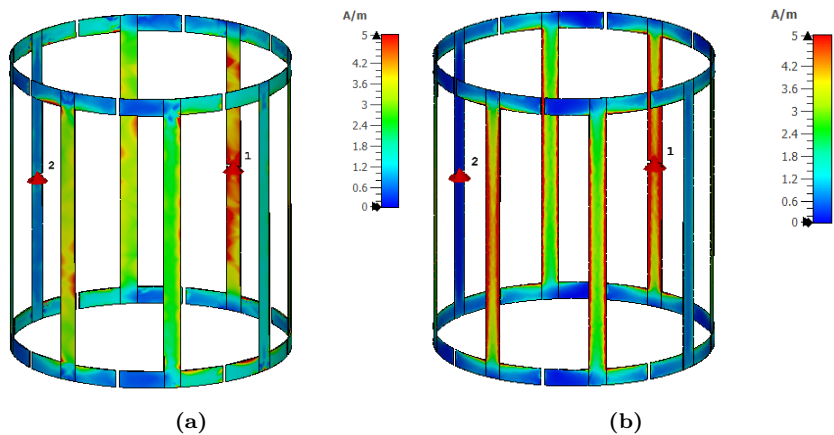
**Table 4.5:** Dimensions of the loop shown in Fig. 4.17.

| Parameters | Value (cm) |
|------------|------------|
| H3         | 24.32 cm   |
| H2         | 22.26 cm   |
| H4         | 1.03 cm    |
| T1         | 2.05 cm    |
| L2         | 4.94 cm    |
| W2         | 1.2 cm     |
| R2         | 1.72 cm    |

The current distributions on the legs for the conventional birdcage and conventional birdcage with the extended floating loops are shown in Fig. 4.18. Field distributions on the transverse and sagittal planes for the conventional birdcage, conventional birdcage with floating loops, and conventional birdcage with extended floating loops on their ends are shown in Fig. 4.19. 28% improvement on the transverse plane is obtained corresponding to the



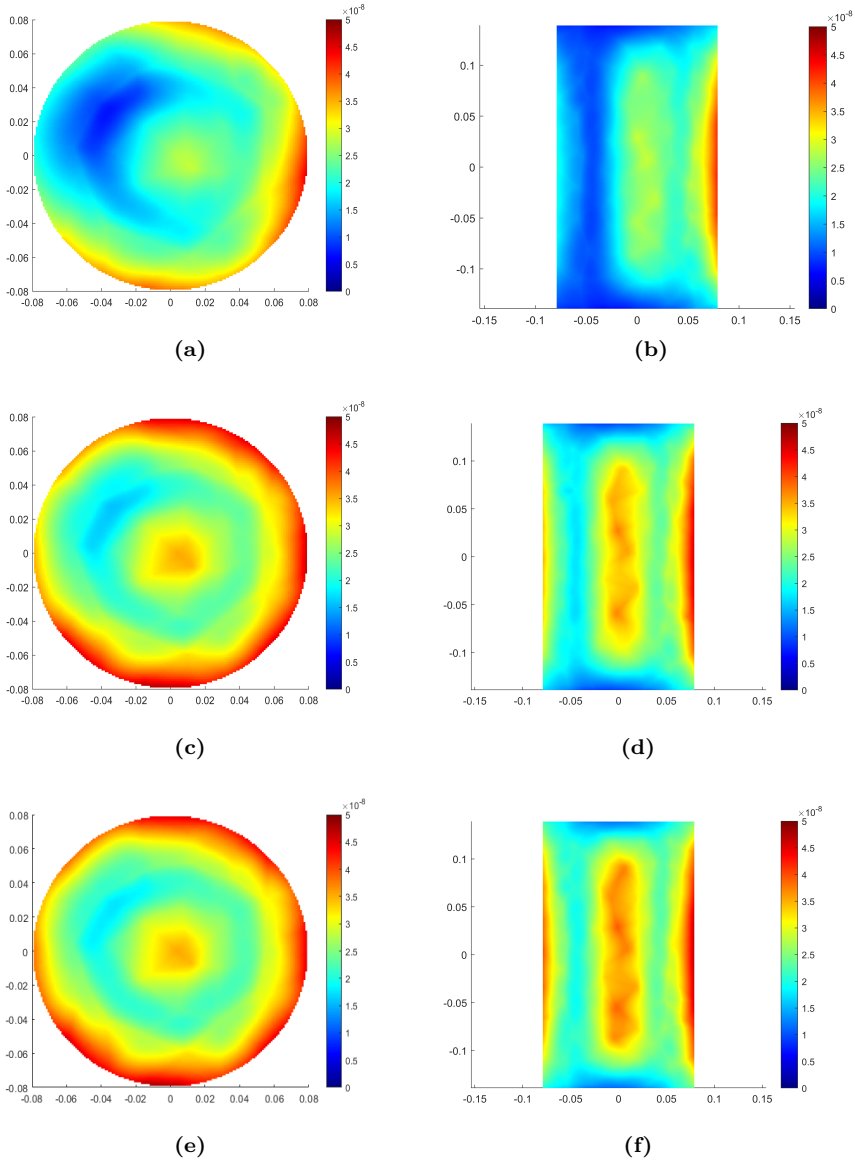
reduced NSD from 0.3099 to 0.2228, and 36% improvement on the sagittal plane is obtained due to reduced NSD from 0.3731 to 0.2398. The NSD values on the transverse and sagittal planes for three different coils are summarized in Table 4.6.



**Figure 4.18:** Current distributions on the birdcage legs for: (a) conventional (normalized). (b) Conventional with extended floating loops.

**Table 4.6:** Homogeneity comparison on the transverse and sagittal planes for: an eight-leg birdcage with two ports in the middle of the legs (BC), BC with floating loops, and BC with extended floating loops.

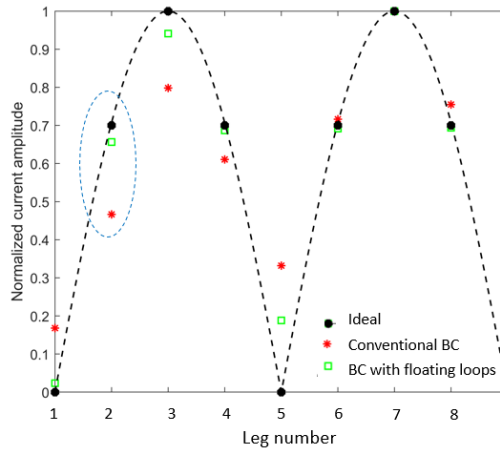
| Birdcage                        | Transverse plane NSD | Sagittal plane NSD |
|---------------------------------|----------------------|--------------------|
| BC                              | 0.3099               | 0.3731             |
| BC with floating loops          | 0.2349               | 0.2659             |
| BC with extended floating loops | 0.2228               | 0.2398             |



**Figure 4.19:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distributions at 300 MHz: (a), (c) and (e) are the transverse plane for the conventional, conventional with floating loops and conventional with extended floating loops. (b), (d) and (f) are the sagittal plane for the conventional, conventional with floating loops and conventional with extended floating loops.

#### 4.4.1 Discussion Regarding the Impact of the Floating Loops on the Current Distribution of the Conventional Birdcage

As explained in Section 3.2, the current distributions on the legs are disrupted at higher frequencies due to the strong coupling between the birdcage and phantom [89]. The current distribution on the legs of the 7T conventional birdcage when only one port is excited are shown with red asterisks in Fig. 4.20. The leg numbering starts with the leg that has a port but it is not excited, and counts counter-clockwise. One can see that, compared to the ideal case, the currents on the legs do not follow the sinusoidal distribution, which is the main reason for the inhomogeneity in the field distribution shown in Section 4.2.

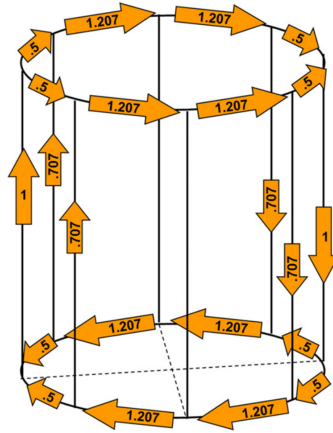


**Figure 4.20:** Current distributions on the birdcage legs in the presence of the phantom for the conventional BC, conventional BC with floating loops and the ideal case.

The following paragraphs provide an explanation for the homogeneity improvement obtained in the presence of the floating loops.

Considering the ideal sinusoidal current distribution on the birdcage legs, the instantaneous current follows the arrows shown in Fig. 4.21. It can be seen the maximum current appears on the end rings [13], and as explained in Section 3.4, the axial magnetic field produced by the end ring current

can reduce the transverse magnetic field homogeneity produced by the legs. In Section 3.4, it was shown that adding rings on the top and the bottom of the shield partially cancels out the impact of the end ring currents and improves the homogeneity.

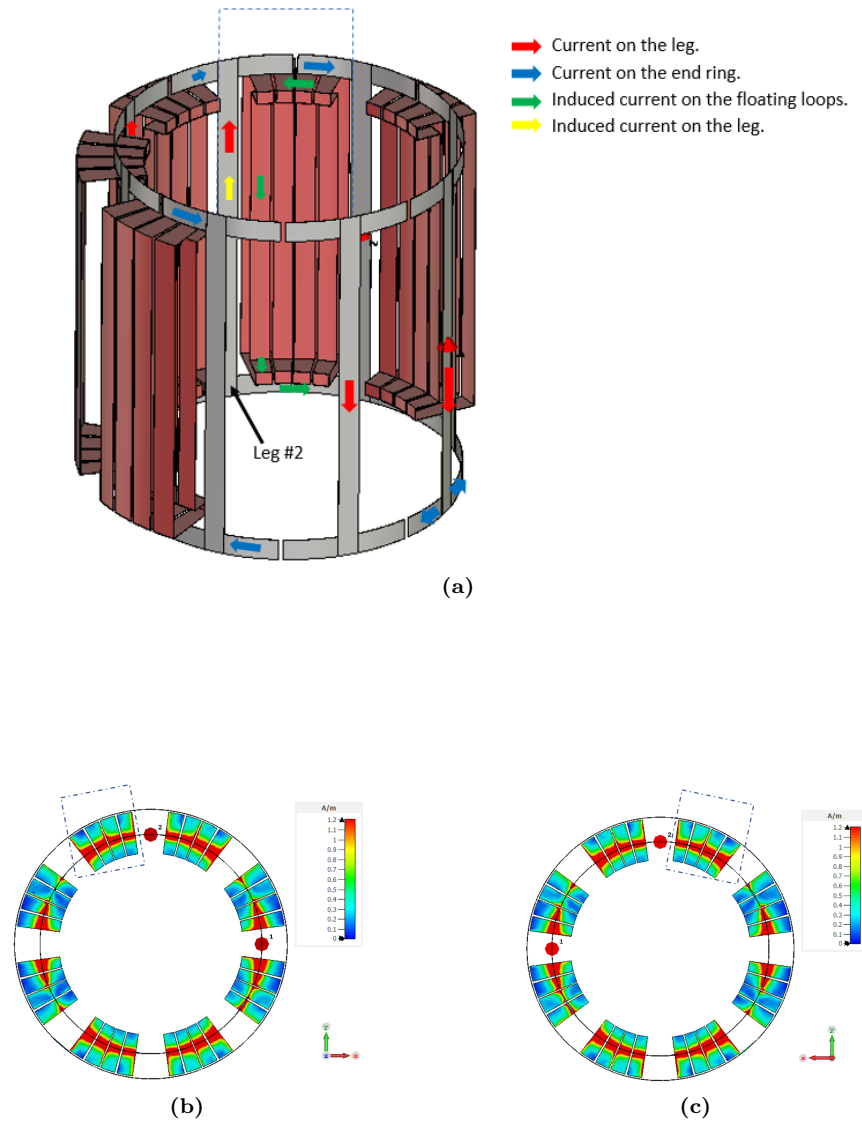


**Figure 4.21:** Instantaneous current flow in an eight-element birdcage coil for the main mode. All the currents are normalized to the maximum rung current, the magnetic field inside the coil is oriented away from the reader. [13].

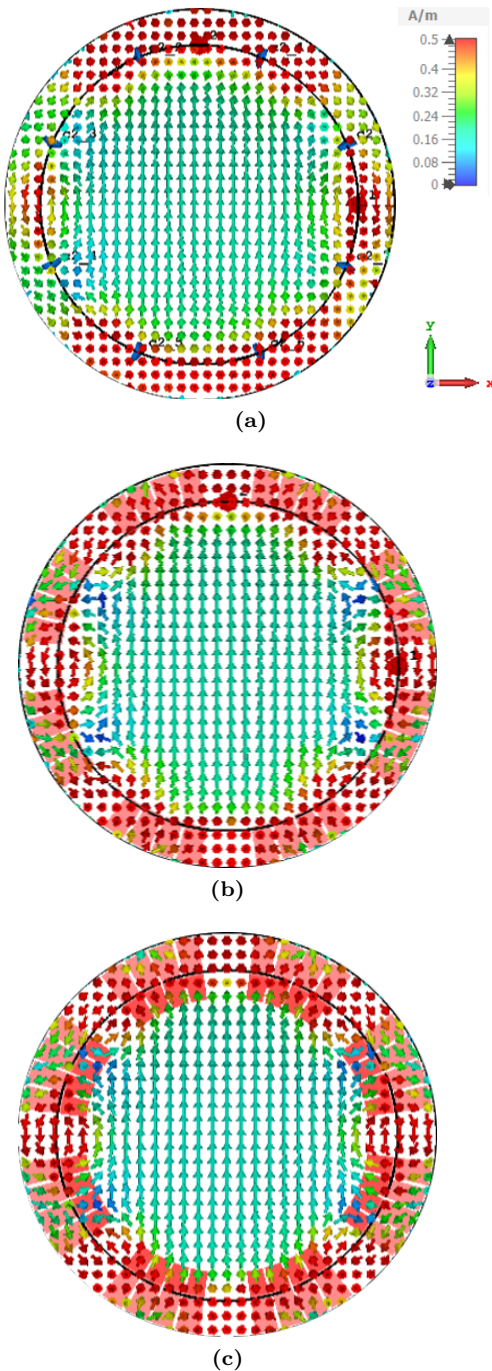
As shown in Fig. 4.22, the floating loops are placed close to the end rings, and this proximity induces currents on the floating loop. The induced currents on the floating loops flow opposite to the currents on the end rings, and they cancel out the impact of the end ring current and improve the transverse homogeneity. Thanks to the loops, the induced currents can circulate vertically, improving the homogeneity on the sagittal (vertical) plane. The surface current distribution on the floating loops from the top and bottom view can be seen in Fig. 4.22(b) and Fig. 4.22(c), where it is clear that the maximum induced currents on the floating happens on the parts of the end rings with higher current value (see Fig. 4.21).

It is worth mentioning that extending the floating loops on their ends

increases their effective surface in such a way that the magnetic field produced by the end rings (mainly in the  $Z$  direction) is canceled out. This impact can be seen in Fig. 4.23, where for a given cut close to the end ring, the magnetic field lines are more homogeneous for the conventional BC with the extended floating loops, as the  $Z$  component of the magnetic field is partially canceled out close to the parts of the end rings with higher current density (Fig. 4.23, top and the bottom of the end ring).



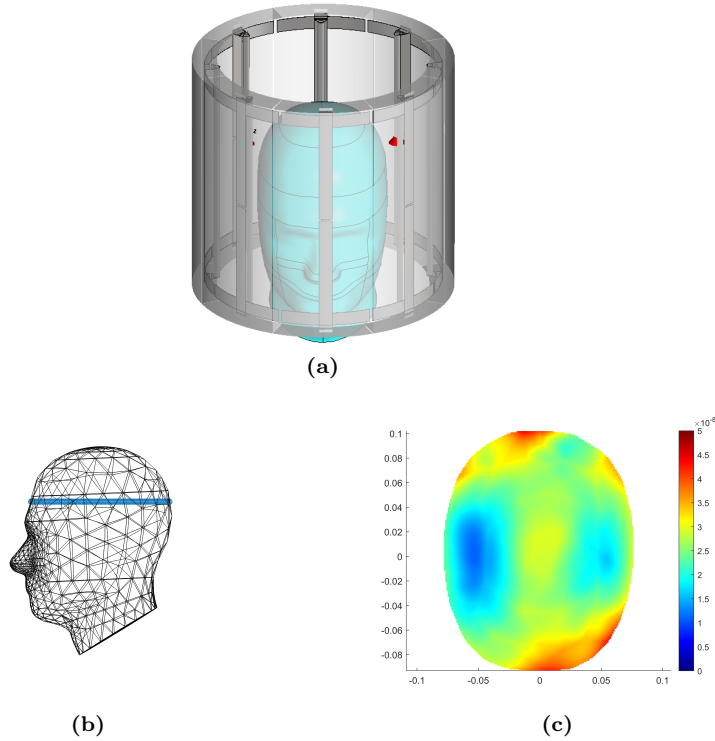
**Figure 4.22:** (a) Instantaneous current paths on the birdcage and the extended floating loops. Current distribution on the extended floating loops close to the second leg is shown with a dotted rectangular: (b) Top view. (c) Bottom view.



**Figure 4.23:** Magnetic field lines for the linear excitation. (a) Conventional BC. (b) Conventional BC with floating loops. (c) Conventional BC with the extended floating loops. The inner circle is the end ring and the outer circle is the shield.

### 4.5 Eight-leg Connected Birdcage Coil for 7T MRI

Given the promising results, including patents, obtained during the M-Cube project, another EU project (M-One project) started to study the CBC performance at UHF MRI among others. Since the M-One project aims to improve the homogeneity of the coil devoted to the human head imaging, the CBC is simulated when it is loaded with a specific anthropomorphic mannequin (SAM), shown in Fig. 4.24(a). This 7T CBC has the same design and dimensions as the 3T CBC described in Section 3.4. New optimizations are carried out for the lumped elements (inductors and capacitors) to tune the resonance frequency of the CBC to 300 MHz (7T MRI). The lumped element values obtained through the optimization are shown in Table 4.7.



**Figure 4.24:** (a) SAM inside the CBC. (b) Observation plane inside the SAM. (c)  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  distribution at 300 MHz for a chosen observation plane with NSD = 0.2294.

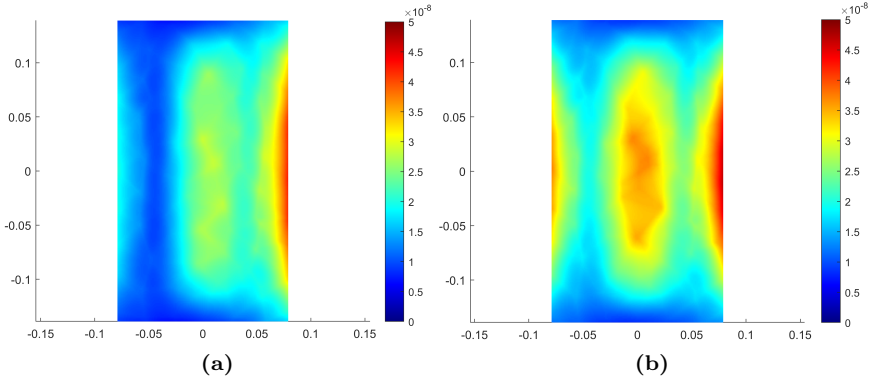


**Table 4.7:** Lumped elements for the 7T connected birdcage.  $C_1$  and  $C_2$  are the end ring capacitors, and the position of the other parameters can be found in Fig. 3.11(a).

| Parameter | Values  |
|-----------|---------|
| $C_1$     | 0.6 pF  |
| $C_2$     | 0.6 pF  |
| $C_3$     | 0.1 pF  |
| $L_1$     | 0.55 nH |
| $L_2$     | 52.8 nH |

Relative permittivity and conductivity of the SAM are set to 45.3 and 0.87 S/m, and two feeding points are symmetrically placed on two sides of the SAM to provide the symmetrical excitation (rather than putting one port on the back and the other port on the side of the SAM [13]). The observation plane is shown in Fig. 4.24(b), and the corresponding field distribution is shown in Fig. 4.24(c). As mentioned earlier, the inhomogeneity due to the shortened wavelength is quite obvious at 7T, even for the CBC.

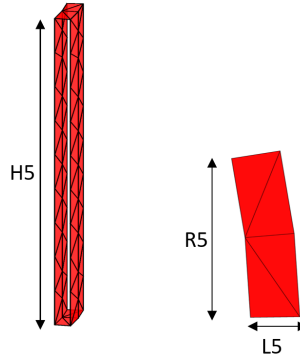
For a cylindrical phantom with the same electromagnetic properties as the SAM, the field distribution on the sagittal plane inside the phantom for the conventional birdcage described in Section 4.2 and the CBC are shown in Fig. 4.25. The homogeneity is improved compared to the conventional birdcage; however, further improvements could be obtained on both transverse and sagittal planes by introducing the floating loops into the CBC. The following section provides more details regarding the implementation of this new feature.



**Figure 4.25:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution on the sagittal cut inside the birdcage at 300 MHz: (a) conventional birdcage with NSD = 0.3731. (b) CBC with NSD = 0.32.

## 4.6 Eight-leg Connected Birdcage with Floating Loops

The floating loops introduced to the CBC look like the ones added to the conventional birdcage, but with shorter heights and different positions. In the CBC, the floating loops are placed between the middle and inner legs of the CBC. A single element of the floating loops is shown in Fig. 4.26.



**Figure 4.26:** Side and top views of a single floating loop. Dimensions are listed in Table 4.8.

Four floating loops are used in each sector of the CBC, resulting in 32 elements of the floating loops all around the birdcage, shown in Fig. 4.27. Dimensions of a floating loop and the CBC are listed in Table 4.8 and the lumped element values for the CBC can be found in Table 4.9. In the rest of the thesis the connected birdcage coil with floating loops will be called CBCL.



**Figure 4.27:** CBC with floating loops. (a) Side view of one sector of the CBC with floating loops. (b) Top view of the complete mesh. Dimensions are listed in Table 4.8.

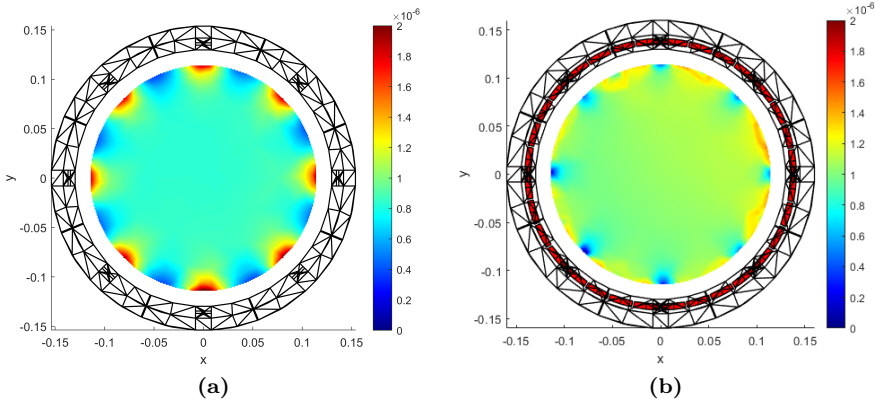
**Table 4.8:** Dimensions of the floating loop and the connected birdcage shown in Fig. 4.27, and Fig. 4.26.

| Parameters | Value (cm) | Parameters | Value (cm) |
|------------|------------|------------|------------|
| H5         | 16.8       | $H_{sh}$   | 30         |
| R5         | 2.3        | $R_{bc}$   | 13         |
| L5         | 0.6        | $R_{br}$   | 14.5       |
| $H_{bc}$   | 28         | $R_{sh}$   | 16         |

**Table 4.9:** Lumped elements for the 7T connected birdcage with floating loops. C1 and C2 are the end ring capacitors, and the position of the other parameters can be found in Fig. 3.11(a).

| Parameter | Values  |
|-----------|---------|
| $C_1$     | 9.86 pF |
| $C_2$     | 9.86 pF |
| $C_3$     | 1.01 pF |
| $L_1$     | 17.1 nH |
| $L_2$     | 12.9 pH |

An observation disk with a radius of 11.5 cm at the middle height, is chosen inside the unloaded CBC and CBCL with a radius of 13 cm to demonstrate the improved homogeneity attained as a result of the floating loops. The hot spots for the CBC shown in Fig. 4.28(a) are the points close to the inner legs, whereas the dark spots between two consecutive legs come from the fact that the magnetic field lines on those spots are in the opposite direction and somehow cancel out each other.



**Figure 4.28:**  $B_1^+$  field on the observation plane with a radius of 11.5 cm for the unloaded birdcages. (a) CBC with NSD = 0.2107. (b) CBCL with NSD = 0.1066; the floating loops are shown in red.

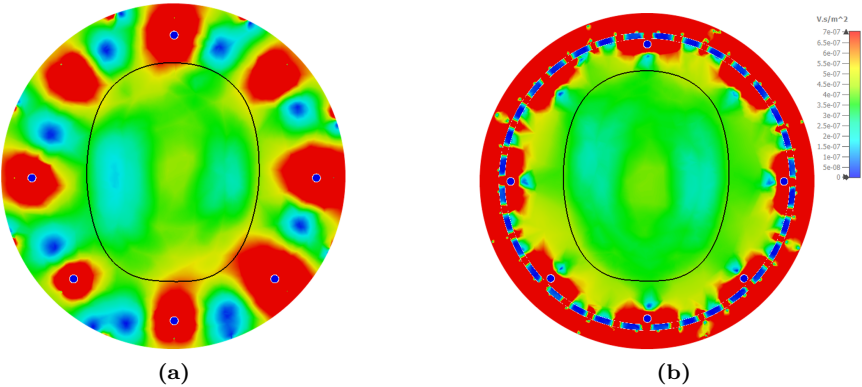
On the other hand, as seen in Fig. 4.28(b), the regions between two consecutive legs for the CBCL filled by the floating have a higher field

value. This phenomenon spreads the loops field azimuthally and so improve the homogeneity. This can be interpreted as the floating loops acting as additional legs, participating in the desired sinusoidal current distribution explained in Section 1.4.2 to create the homogeneous magnetic field. The NSD values show 49% improvement with CBCL on this observation plane with 11.5 cm radius. As the birdcage coil is a volume coil, analyzing the NSD inside its volume is also important; hence, for the unloaded case, the NSD comparison for different volumes inside the CBC and the CBCL is provided in Table 4.10. The NSD values indicate that, for the unloaded case the 7T CBCL shows a 34% homogeneity improvement (on average) compared to the 7T CBC.

**Table 4.10:** NSD of the  $B_1^+$  filed for the available volume inside the unloaded CBC and CBCL with 28 cm heights and different radii.

| Birdcage | radius = 11.5 cm | radius = 9 cm | radius = 5 cm |
|----------|------------------|---------------|---------------|
| CBC      | NSD = 0.3248     | NSD = 0.2243  | NSD = 0.2048  |
| CBCL     | NSD = 0.1835     | NSD = 0.1541  | NSD = 0.1494  |

Let us consider a case when the CBC and the CBCL are loaded with the SAM used in Fig. 4.24(a). As discussed in Section 3.2, there are constructive interference on the spaces between the legs and shield due to the out-of-phase induced currents on the shield. Fig. 4.29(a) depicts these constructive interference for the CBC in the space between the shield and the eight legs. On the other hand, for the CBCL shown in Fig. 4.29(b), the aforementioned constructive interference are visible across the spaces between the floating loops and the shield, demonstrating that the floating loops perform as additional legs to contribute to the ideal sinusoidal current distribution. As shown in Table 4.11, a 40% homogeneity enhancement is achieved for the middle-cut transverse observation plane inside the SAM with the CBCL. As mentioned earlier, the constructive interference in the region between the floating loops and shield correspond to the destructive interference in the center of the coil ( because of the out-of-phased induced currents on the shield).



**Figure 4.29:**  $B_1^+$  field distribution inside the coils for 1 W accepted power, when they are loaded with a SAM used in Fig. 4.24(a). (a) CBC. (b) CBCL.

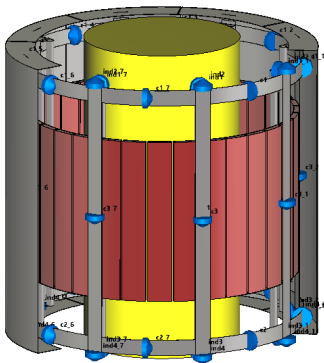
However, the destructive interference in the center of the CBCL does not appear to have much of an effect on the  $B_1^+$  in the center of the CBCL because of the common mode currents on the floating loops (indicated by a very weak field inside the floating loops shown in Fig. 4.29(b)). In other words, in the center of the CBCL, the common mode currents on the floating loops somehow cancel out the impact of the current on the shield (unlike the floating loops used for the conventional birdcage, for the CBC, the floating loops could also be used as two parallel strips (without making a loop); however, for the fabrication proposes using them in a loop shape provides more mechanical stability).

**Table 4.11:** NSD and  $B_1^+$  values for 1 W accepted power on the observation plane in the center of the coils loaded with SAM shown in Fig. 4.29.

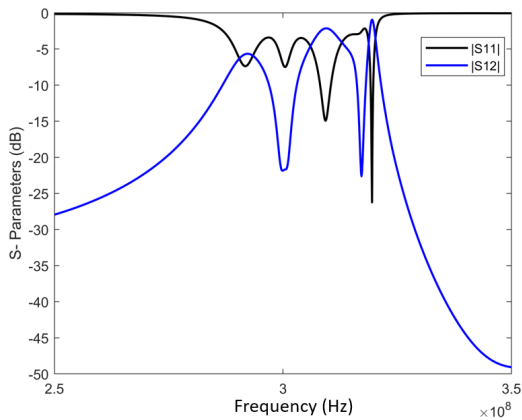
| 7T Birdcage | NSD    | $B_1^+$       |
|-------------|--------|---------------|
| CBC         | 0.2294 | 0.427 $\mu$ T |
| CBCL        | 0.1354 | 0.417 $\mu$ T |

The CBCL is loaded with the same cylinder phantom used in Section 4.2, and resulting S-parameters are shown in Fig. 4.31. The desired resonance frequency of this coil happens at 300 MHz (close to the Larmor frequency

of the 7T MRI, 297.2 MHz).

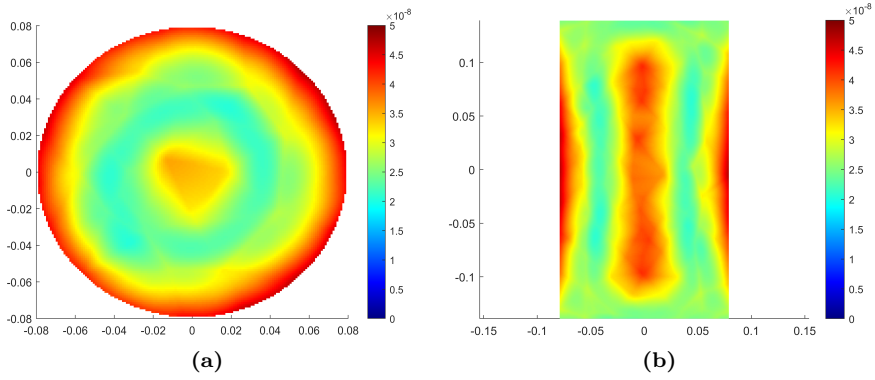


**Figure 4.30:** 7T connected birdcage with floating loops (CBCL) loaded with a cylindrical phantom.

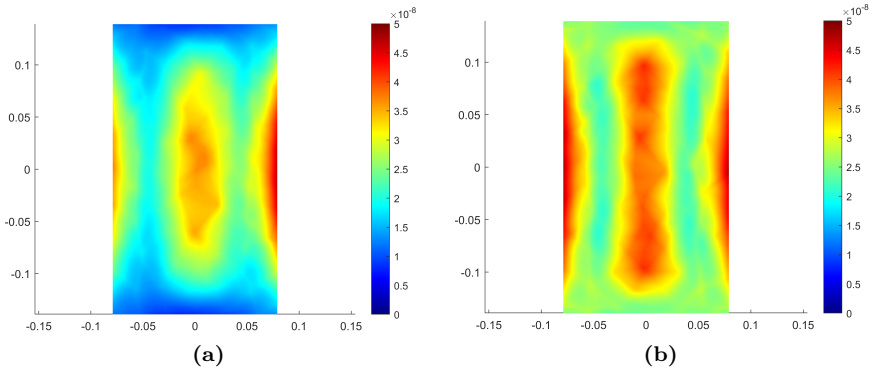


**Figure 4.31:** Scattering parameters of the CBCL. The desired resonance frequency producing the homogeneous magnetic field is at 300 MHz.

Field distributions on the transverse and sagittal planes inside the phantom for the CBCL are shown in Fig. 4.32(a), and Fig. 4.32(b). A substantial improvement (40%) in the homogeneity of the sagittal plane is obtained with the CBCL compared to the CBC, see Fig. 4.33.



**Figure 4.32:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution for the CBCL at 300 MHz on the (b) transverse plane with NSD = 0.2196. (c) Sagittal plane with NSD = 0.1897.



**Figure 4.33:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distribution at 300 MHz on the sagittal plane for: (a) the connected birdcage (CBC) with NSD = 0.32. (b) Connected birdcage with floating loops (CBCL) and NSD = 0.1897.

Table 4.12 summarizes the NSD values for the cylindrical phantom in the available volume inside the conventional birdcage, conventional birdcage with floating loops, connected birdcage and connected birdcage with floating loops. As can be seen the connected birdcage with floating loops (CBCL), provides the best homogeneity in its volume. This newly designed



CBCL shows 29% improvement on the transverse plane, 49% improvement on the sagittal plane, and 42% improvement in the volume, compared to the reference 8-leg conventional birdcage.

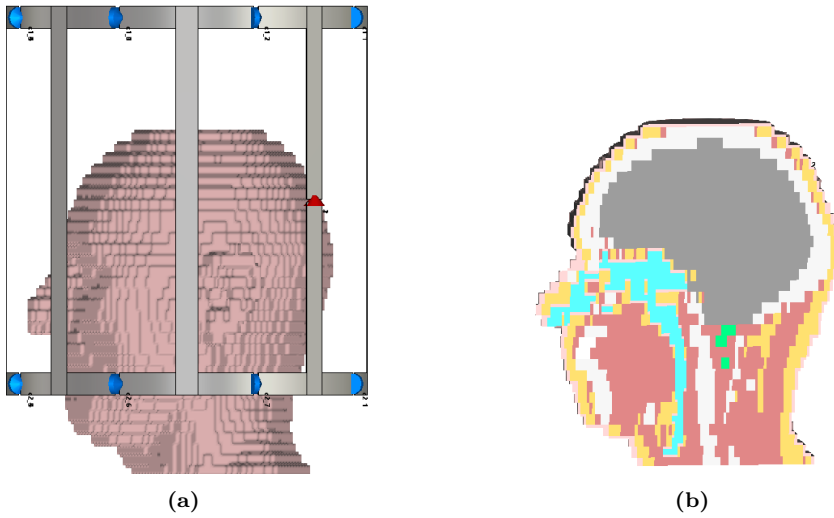
**Table 4.12:** NSD for the volume inside the phantom at 7T (for the available volume inside the coil); all coils have 8 legs.

| Birdcage               | Volume NSD |
|------------------------|------------|
| BC                     | 0.3487     |
| BC with floating loops | 0.2421     |
| CBC                    | 0.3367     |
| CBCL                   | 0.2019     |

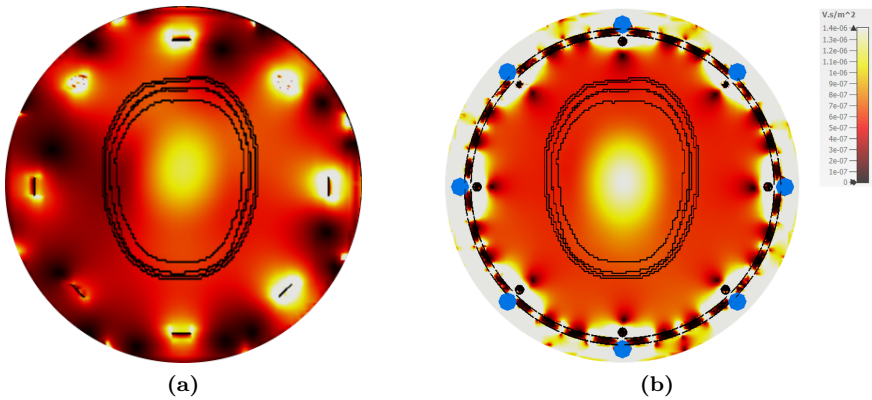
In the following section, the performance of the proposed CBCL and the 8-leg conventional birdcage is compared when these two coils are loaded with a realistic human head model in CST.

4.7 Field Distribution Inside the Voxel Family

So far, all the performed simulations were for the homogeneous cylinder phantom or SAM. A realistic simulation in the presence of an inhomogeneous human head model, see Fig. 4.34, is carried out for the eight-leg conventional birdcage coil described in Section 4.2, and the CBCL, when they are loaded with the Gustav voxel model in CST [46]. The CST voxel family is a group of eight human model voxel data sets created from eight persons of different gender, age, and stature. The Voxel family provides realistic properties of the human body, and the voxel resolution chnges for the different voxel family members ( $2.08\times2.08\times2\text{ mm}^3$  and  $2.08\times2.08\times8\text{ mm}^3$  are two available voxel sizes for the Gustav head model).



**Figure 4.34:** (a) The 8-leg birdcage with two ports in the middle of the legs is loaded Gustav model from the CST voxel family. (b) Sagittal cut of the voxel model.



**Figure 4.35:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distributions for 1 W accepted power in the middle of the: (a) 8-leg birdcage coil with two excitation ports in the middle of legs at 298 MHz. (b) CBCL at 300 MHz.

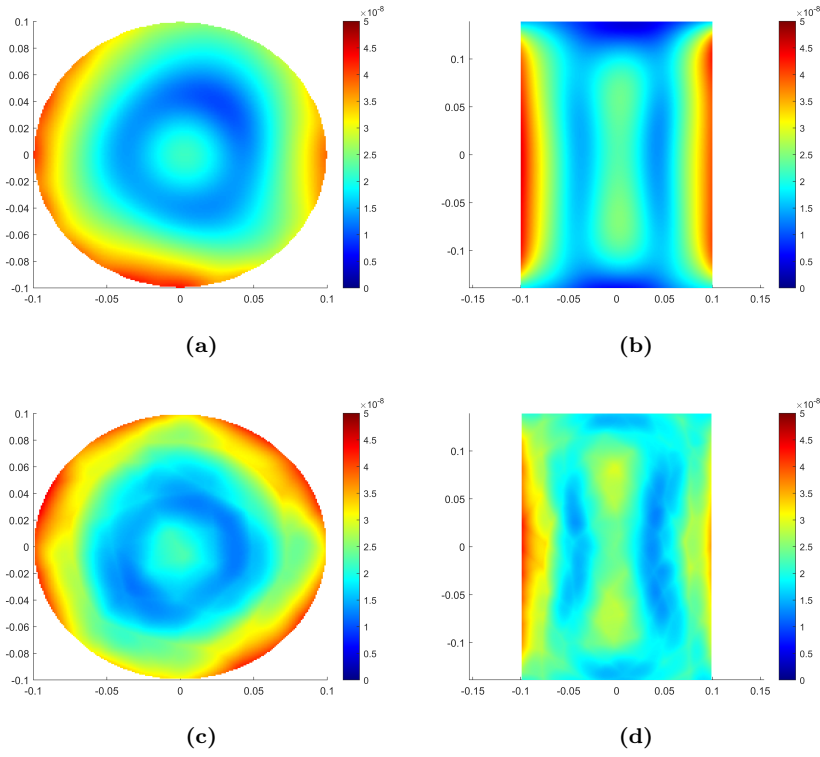
Two excitation ports of the birdcages are placed symmetrically with respect to the voxel model (located at  $-45^\circ$  and  $+45^\circ$  away from the back of the

head to ensure the similar loading condition seen from the two ports [13]), and the time domain (TD) solvers in CST have been used for the simulations. The  $B_1^+$  field distributions on the transverse plane for both coils are shown in Fig. 4.35, in which the improvements in the homogeneity of the  $B_1^+$  field can be seen where the region with slightly dark color for the conventional birdcage is changed to the symmetrical distribution for the CBCL.

## 4.8 Comparison Between the 16-leg Birdcage and CBCL

As shown in Section 4.2.5, the best homogeneity among conventional birdcages is provided by a 16-leg birdcage with two excitation ports between the birdcage and shield. Since this thesis aims to enhance the performance of the 8-leg birdcage, that 16-leg is not considered as the reference coil. However, it is worth comparing the performance of the CBCL with that 16-leg birdcage. To this end, the 16-leg birdcage and the eight-leg CBCL coils are loaded with a 10 cm radius cylinder phantom (the phantom radius is changed from 8 cm in the previous sections to 10 cm for this comparison). Field distributions on the traverse and sagittal planes for two coils are shown in Fig. 4.36. Thanks to the floating loops, which help to spread the currents in the vertical direction, the eight-leg CBCL shows 34% more homogeneity on the sagittal plane compared to the 16-leg birdcage. The homogeneity comparison between the CBCL and 16-leg birdcage, for two phantoms with different radii on the transverse and sagittal planes as well as the volumes inside the birdcages are summarized in Table 4.13; as can be seen, the CBCL provides 21% more homogeneity on the volume for a phantom with 10 cm radius and 14 cm height, compared to the 16-leg birdcage.

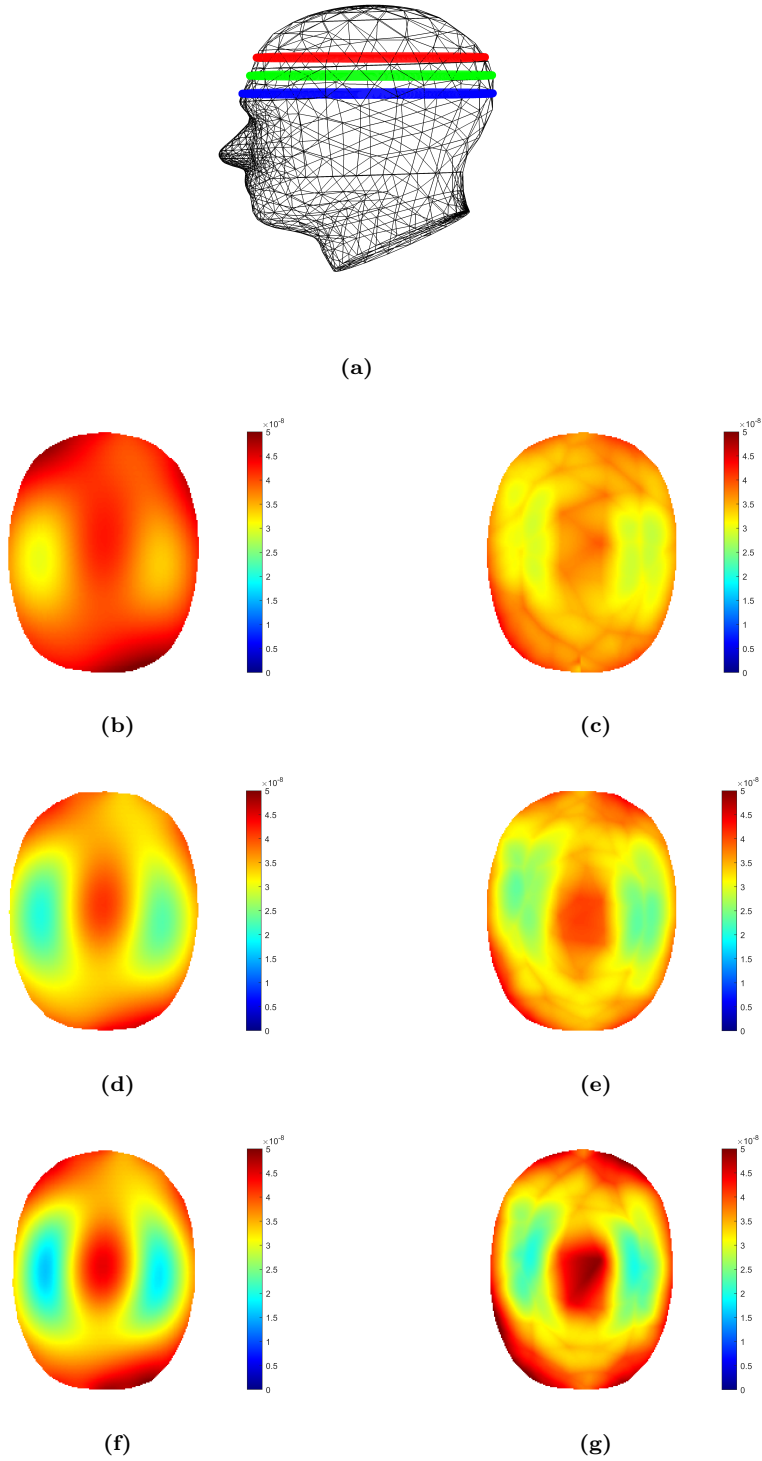
Another comparison between two coils is made for the field distributions on three different heights of the observation plane inside the SAM, as shown in Fig. 4.37. 0.096, 0.1530, and 0.2118 NSD values on the red, green, and blue planes with the 16-leg birdcage are improved to 0.0848, 0.1354, and 0.1979 with the CBCL, indicating the homogeneity improvement.



**Figure 4.36:**  $\frac{B_1^+}{\sqrt{SAR_{Max}}}$  for: (a), (b) The 16-leg birdcage. (c), (d) The 8-leg CBCL.

**Table 4.13:** NSD for the planes and volume inside the phantoms with two different radii for 16-leg birdcage and 8-leg CBCL, and  $B_1^+$  values in the center of the phantoms for 1 W accepted power.

| Observation planes/volumes        | 16-leg birdcage | 8-leg CBCL    |
|-----------------------------------|-----------------|---------------|
| Transverse plane (r = 8 cm)       | 0.2224          | 0.2196        |
| Sagittal plane (r = 8 cm)         | 0.2196          | 0.1897        |
| Volume (r = 8 cm, h = 14 cm)      | 0.2236          | 0.2019        |
| Transverse plane (r = 10 cm)      | 0.3354          | 0.3261        |
| Sagittal plane (r = 10 cm)        | 0.3632          | 0.2402        |
| Volume (r = 10 cm, h = 14 cm)     | 0.3513          | 0.2772        |
| $B_1^+$ in the center (r = 8 cm)  | 0.31 $\mu$ T    | 0.327 $\mu$ T |
| $B_1^+$ in the center (r = 10 cm) | 0.176 $\mu$ T   | 0.193 $\mu$ T |



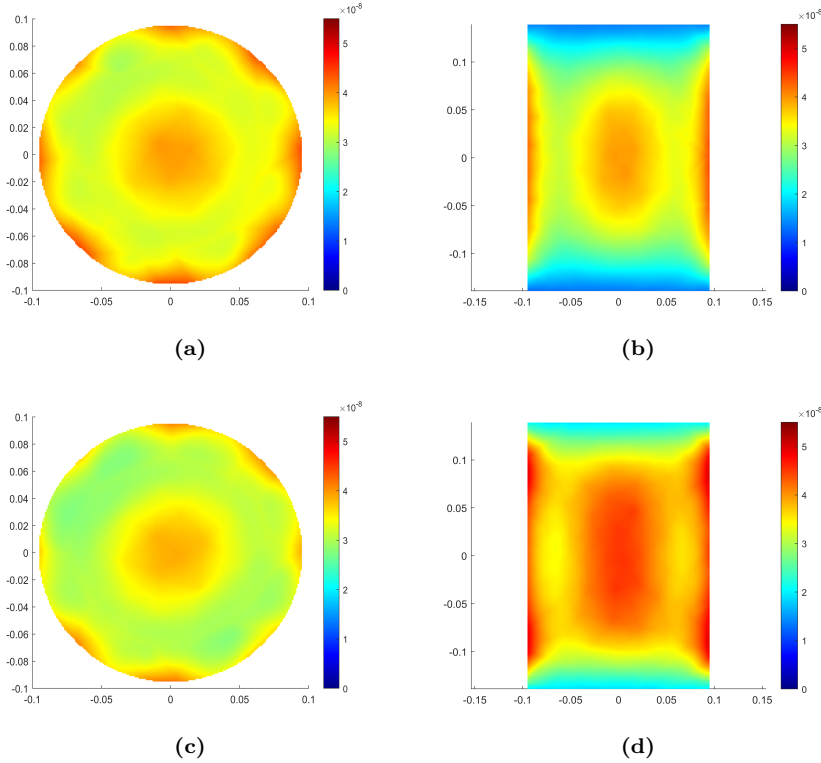
**Figure 4.37:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  inside the SAM at 300 MHz for the 16-leg birdcage on the left side, and the CBCL on the right side.

## 4.9 Implementing the Floating Loops into the 3T CBC

The 3T CBC developed in Section 3.4 shows  $NSD = 0.2451$  on the sagittal plane, indicating less homogeneity compared to the transverse plane with  $NSD = 0.0845$  ( $NSD = 0.0854$  is obtained from the MoM, from CST it is 0.790). Knowing the homogeneity improvement on the sagittal plane that can be obtained with the floating loops, encouraged us to implement them in the 3T CBC designed in Section 3.4. Floating loops with the dimensions shown in Fig. 4.14 are implemented in the 3T CBC (with the same dimensions as Table 3.2), and new optimization was carried out for the lumped element values, resulting in  $C1 = C2 = 6.9$  pF,  $C3 = 0.35$  pF,  $L1 = L3 = 128$  nH, and  $L2 = L4 = 187$  nH ( $C1$  and  $C2$  are the top and bottom end ring capacitors; the other lumped element positions can be found in Fig. 3.11(a)). Field distributions on the transverse and sagittal planes inside the cylindrical phantom with the properties described in Chapter 3 are shown in Fig. 4.38; considering the  $NSD$  values, 26% improvement on the sagittal plane is obtained for the 3T connected birdcage with floating loops.

## 4.10 Receiver Loops with the CBCL Coil

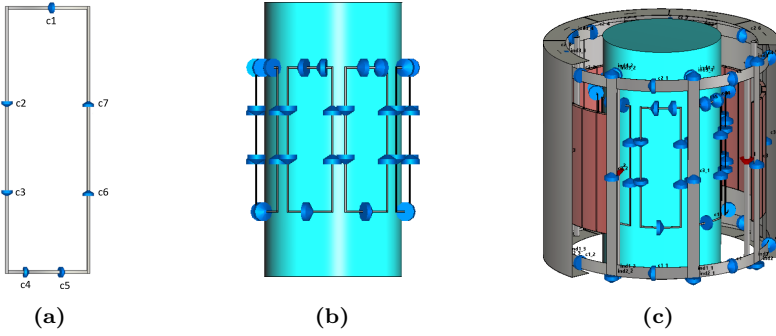
Birdcage coils have been mainly used in the transmit mode since they can produce a quite homogeneous magnetic field in the desired volume. On the other hand, in an MRI scanner, it is necessary to properly capture the emitted signals from the hydrogen atoms after they were energized using the RF transmitter coil. To do so birdcage coils could also be used in the reception mode, but as the received signals are weak, noise may impact the quality of the signal. Hence, receiving surface loops (Rx) with the possibility of close positioning to the phantom are used in the receive mode to pick up the signals from the protons during the relaxation time [120]. Using a birdcage coil on the transmit mode and surface loops on the receive mode requires additional care to avoid any unwanted interaction between Tx and Rx coils.



**Figure 4.38:**  $\frac{B_1^+}{\sqrt{SAR_{Max}}}$  at 3T obtained with CST. (a) Transverse plane for the CBC with NSD = 0.790 at 126.4 MHz. (b) Sagittal plane for the CBC with NSD = 0.2451 at 126.4 MHz. (c) Transverse plane for the CBCL with NSD = 0.0854 at 124 MHz. (d) Sagittal plane for the CBCL with NSD = 0.1813 at 124 MHz.

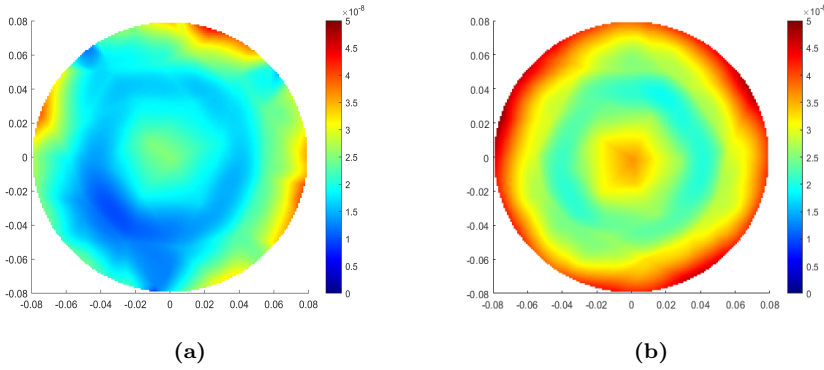
In other words, when the birdcage is working at the Larmor frequency, the working frequency of the Rx loops should be moved away from that Larmor frequency; this process is called detuning, and like the detuning of the Rx loops on the transmit mode, detuning of the birdcage is also required during the receive mode, which it is explained in Section 4.11. Detuning not only guarantees the proper performance of the coils on each mode, it also guarantees the safety of the pre-amplifier loaded circuits that are essential for each receiver coil.





**Figure 4.39:** (a) Single element of the Rx loops. (b) Rx loops around the phantom. (c) CBCL with Rx loops.

The Rx loops have been slightly idealized, in the form of rectangular frames (5.6 x 17 cm), with inserted capacitors, shown in Fig. 4.39(a). Fig. 4.39(b) shows the cylinder used as a phantom and the Rx loops.



**Figure 4.40:**  $\frac{B_1^+}{\sqrt{(SAR_{Max})}}$  field distributions for the 7T CBCL. (a) Rx loops are not detuned. (b) Rx loops are detuned.

Fig. 4.40(a) shows the  $B_1^+$  field distribution on the transverse plane inside the phantom when the Rx loops are not detuned. The creation of the dark spots in the field distribution shows the importance of the Rx detuning to avoid the degeneration of the homogeneity on the Tx mode. On the other

hand, as shown in Fig. 4.40(b), when the Rx loops are sufficiently detuned (by changing the capacitor values embedded in the Rx loops), the Rx loops don't impact the performance of the birdcage coil; in other words, the NSD changes from 0.2196 in the case when there are no Rx loops to 0.2214 when the detuned Rx loops are placed around the phantom.

### 4.11 Detuned CBCL

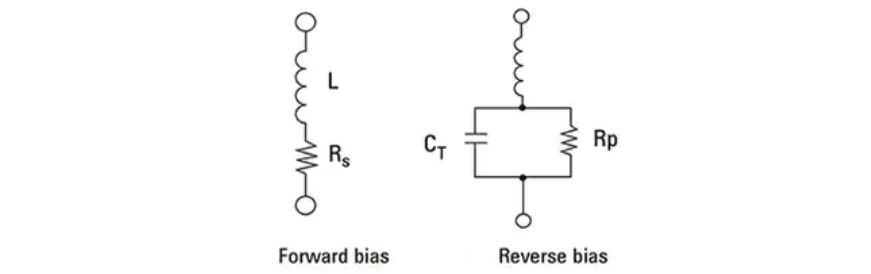
As mentioned earlier, the birdcage coil could be used in both transmit and receive modes; however, due to its lower reception sensitivity, the Rx loop array is recommended to be used in the receive mode.

Hence in the reception mode, the birdcage coil needs to be detuned to avoid any interaction between the birdcage and the Rx loops array. In this sense, thanks to the recommendations from our colleagues in the M-One consortium, PIN diodes are used as the RF switches for detuning and tuning the birdcage. The equivalent circuit of a PIN diode for the forward and reverse biases are shown in Fig. 4.41. When a PIN diode is added to an LC network, depending on the type of bias, the L and C in the PIN diode's schematic can alter the resonance frequencies of the LC network, such as a birdcage coil. This property of the PIN diodes enables us to detune the birdcage in the receive mode.

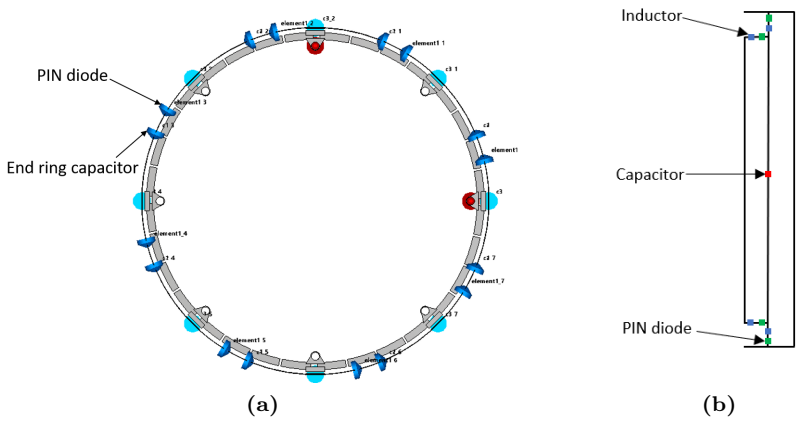
In the conventional birdcage, the PIN diodes usually are used on the two end rings between two consecutive legs to shift the resonance frequency of the birdcage quite far away from the Larmor frequency. Implementing the same idea in the CBCL, resulted in a value of around -1 dB for the reflection coefficient, meaning that somehow the birdcage may still interact with the Rx loops array at the Larmor frequency. Hence, PIN diodes are also used in the connections between the middle and inner legs and also at the connection between the middle leg and the shield to detune the CBCL properly, as shown in Fig. 4.42.

The scattering parameters for the CBCL when the PIN diodes have reverse and forward biases are shown in Fig. 4.43. As shown in Fig. 4.43(a) around the Larmor frequency for 7T (297.2), the CBCL shows a very flat behavior for S11 (-0.036 dB), indicating almost no interference with the Rx

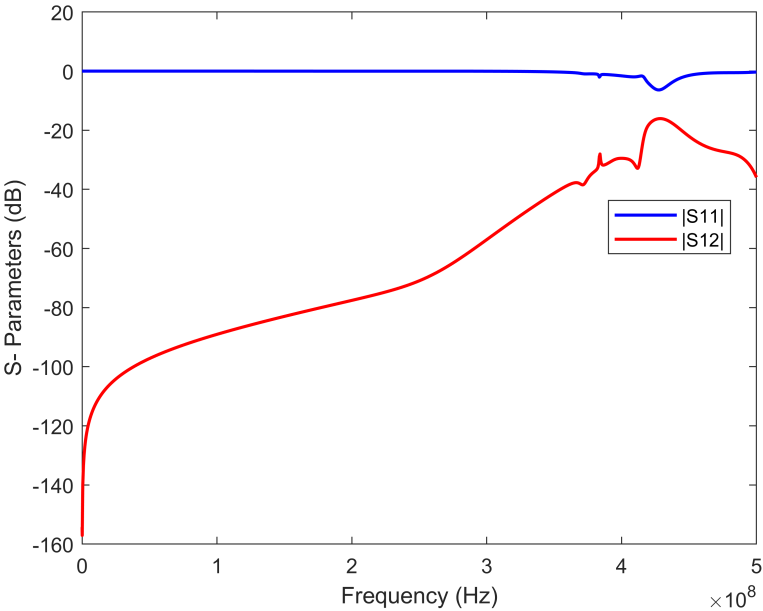
loops array. For the forward bias, Fig. 4.43(b), the S-parameters are similar to the case with no PIN diode.



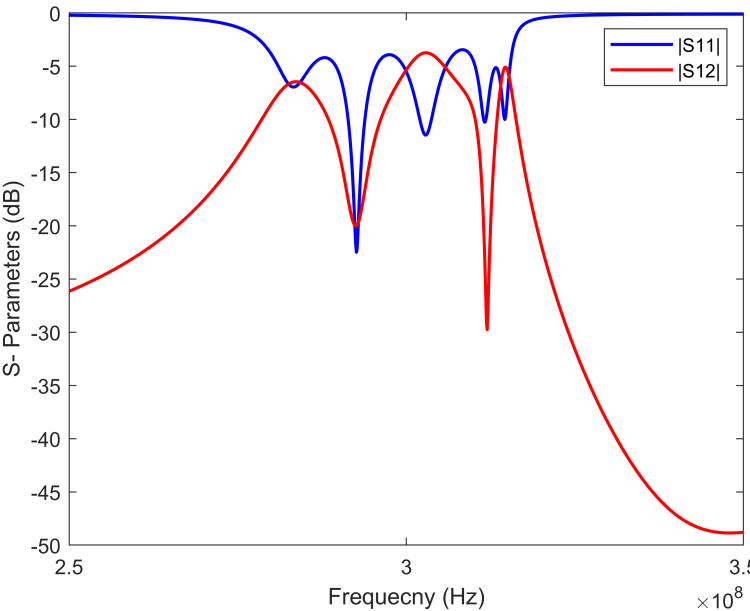
**Figure 4.41:** Schematic view of the PIN diode in the forward and reverse biases.



**Figure 4.42:** Detuned CBCL. (a) Top view of the coil with the PIN diodes on the end rings. (b) PIN diodes are also used in series with the inductors.



(a)

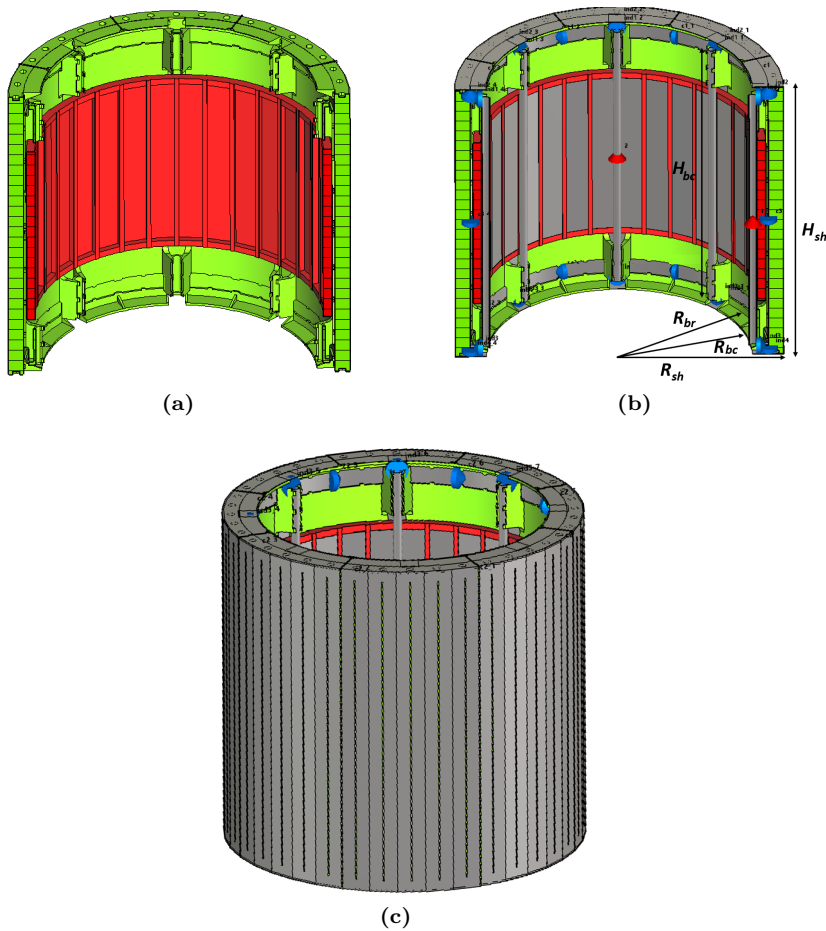


(b)

**Figure 4.43:** (a) PIN diodes with reverse bias. (b) With forward bias; the main mode is at 297 MHz.

### 4.12 Fabrication of 7T Connected Birdcage with Floating Loops

To fabricate the 7T CBCL, pretty much the same steps as those followed in the fabrication of the 3T CBC in Chapter 3, needed to be made here.



**Figure 4.44:** (a) Middle cut view of the supports: red-colored support for the floating loops and green-colored support for the rest of the configuration. (b) Middle cut view of the supports loaded with different parts of the coil. (c) Complete view of the coil in the presence of the supports.

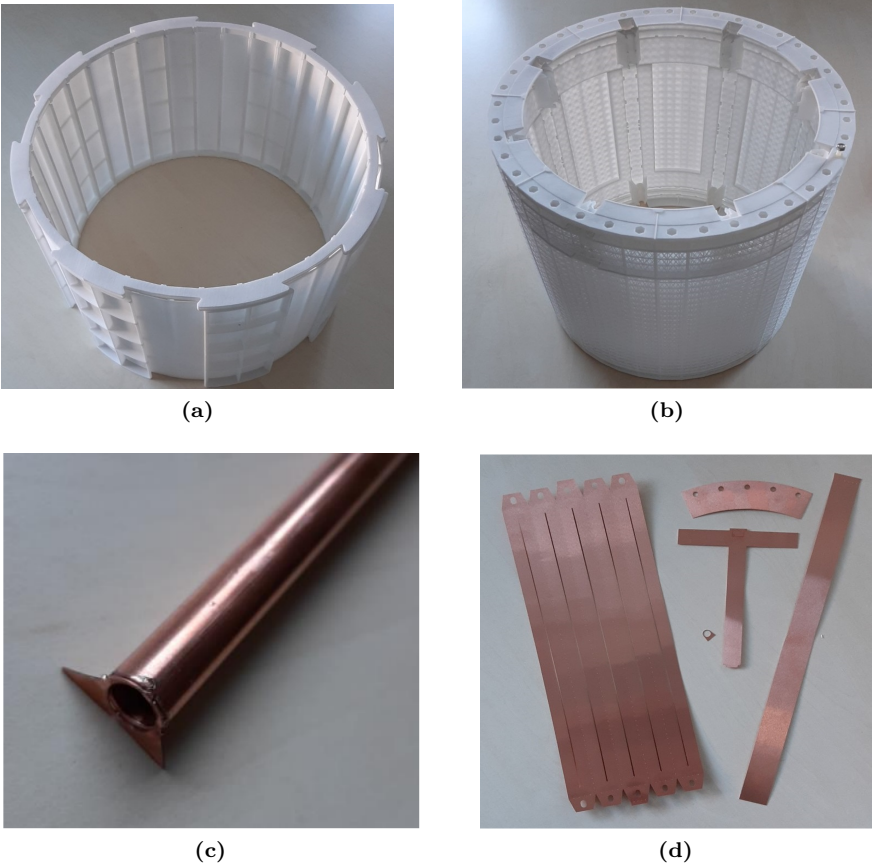
Regarding the mechanical stability of the configuration, two different support materials are used. As shown in Fig. 4.44, the green-colored support medium is aimed to hold the shield, the end rings, the inner legs, and the middle legs via some clips, whereas the red-colored support is intended to keep in place the floating loops between the middle and the inner legs of the CBC. The filling factor of 14.5% is assumed in equation (3.2) to consider the support materials impact in the simulation of the coil's resonance frequency. The fabricated supports are shown in Fig. 4.45(a) and Fig. 4.45(b). As mentioned in Chapter 3, tubular legs are used for the inner legs to ease the excitation of the coil via the coaxial cables; one of the tubes is shown in Fig. 4.45(c).

A copper plate with 0.3 mm thickness is used in the fabrication of the parts with the dimensions that are indicated in Fig. 4.44(b), and are listed in Table 4.14. Also copper strips with 1.6 cm width are used on the end rings and the middle legs, and the floating loop's height, length, and width are set to 16.8 cm, 5 cm, and 5 mm. The optimized values for the end ring capacitor, middle leg capacitor, horizontal inductor, and vertical inductor are 12 pF, 0.8 pF, 25 nH, and 0.6 nH, respectively. However, the component values can be changed during the measurement to tune the coil to the Larmor frequency. Since the value of the middle leg capacitors is small, two parallel plates with a length of 1 cm and a width of 2 mm, are designed at the end of the two legs to create the corresponding capacitance, the simulation model is shown in Fig. 4.46, and the fabricated one can be found in Fig. 4.47(a).

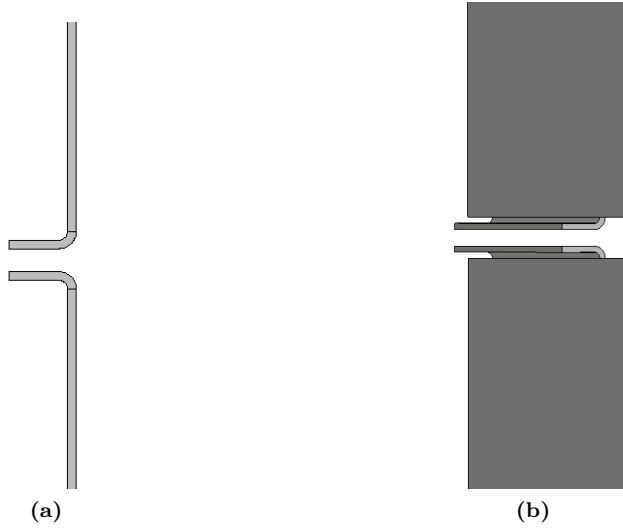
As done with the fabricated 3T CBC, the cylindrical shield is segmented into eight parts, and four slots are implemented within each segment to avoid the creation of eddy currents; one sector of the shield can be seen in Fig. 4.45(d). As shown in Fig. 4.47(b), five holes are used on the each sector of the shield and on the additional top and bottom rings to connect the shield to those rings via screws that are terminated on the shield support.

**Table 4.14:** Dimensions of the fabricated CBCL, in which parameters can be seen in Fig. 4.44(b).

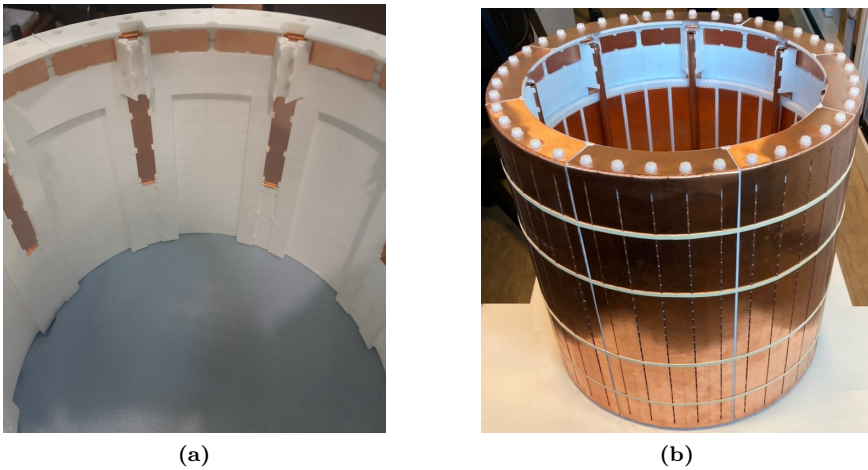
| Parameter | Values  |
|-----------|---------|
| $H_{sh}$  | 30 cm   |
| $R_{sh}$  | 16 cm   |
| $R_{br}$  | 14.5 cm |
| $R_{bc}$  | 13 cm   |
| $H_{bc}$  | 28 cm   |



**Figure 4.45:** Fabrication of the CBCL at SIRRIIS. (a) Floating loops support. (b) Support for the shield and the inner legs (via clips). (c) Tubular legs used for the inner legs. (d) Copper plates used for the shield, top and bottom additional rings, middle legs, and the floating loops.



**Figure 4.46:** The two parallel plates represent the middle leg capacitor. (a) Side view. (b) Perspective view.

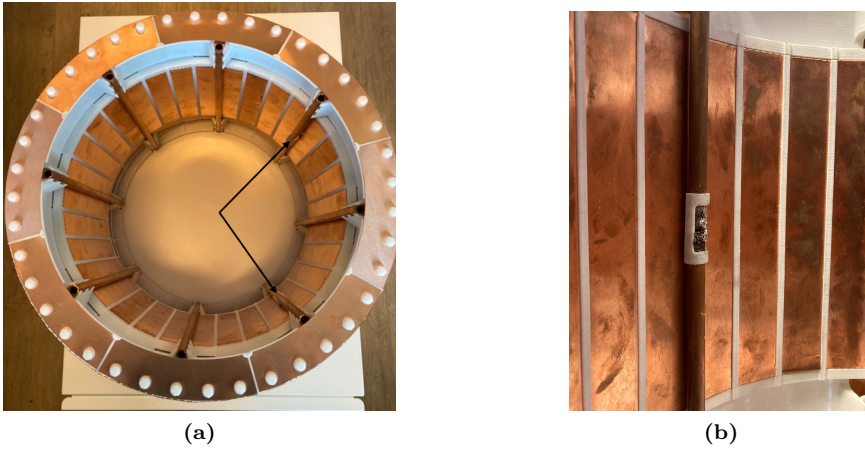


**Figure 4.47:** (a) Only middle legs with the folded ends. (b) Fabricated 7T CBCL.



### 4.12.1 Measurement of the 7T CBCL

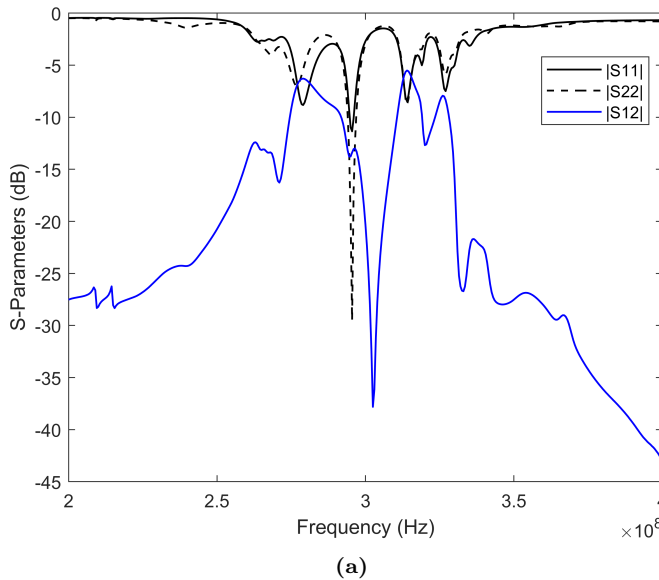
It is worth mentioning that so intense efforts have been made for the 7T CBCL measurement, which was started by soldering the tiny components (inductors) on the copper plate. Due to the small size of the components, small PCBs were used for soldering the components on the PCBs, then soldering the PCBs on the birdcage. After soldering the components, S - parameters measurements were carried out. Obtaining the symmetric S11 and S22 required checking the equal distance between the tubes and the floating loops on the port positions since the excitation tubes were potentially foldable toward the floating loops in their center, which could cause asymmetry in the S-parameters, positions of that foldable points are shown in Fig. 4.48. Soldering 1nF capacitors between each sector of the shield to create a continuous shield at radio frequencies was another essential step in obtaining the symmetric S - parameters (in some preliminary tests, instead of soldering the capacitors, aluminium foil was used to cover the shield and create the continuity of the shield).



**Figure 4.48:** Folded excited tubes toward to the floating loops may cause asymmetry in the S - parameters. (a) Top view of the position of two excitation ports. (b) Side view of the two tubes on the excitation position; on the soldered position these two tubes can be folded toward the floating loops and cause asymmetries in the S - parameters.

After obtaining the symmetric S-parameters, shown in Fig. 4.49(a), the field distribution measurement was carried out in collaboration at Institute Fresnel in Marseille. Several measurements were carried out, but the expected symmetric field distribution was not obtained. After checking the quality of the soldering, one possible reason for the asymmetric results was the asymmetry in the air-gapped capacitors on the middle legs since the folding sign was visible on one of the ports; hence, to reassure about the quality of the fabrication, the coil was sent back to SIRRIS.

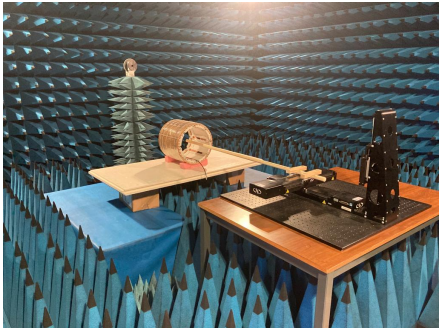
The next round of the field measurement was started at UCLouvain with the measurement setup that can be found in Fig. 4.50(a), where for simplicity, the CBCL was measured without any soldered component to check the symmetrical behavior of the configuration. During these measurements, it was noticed that touching the coaxial cables used either for the excitation or the probe causes a huge asymmetry in the field distributions, to overcome this issue, which is known as the common mode current, a set of ferrites bars is put around the coaxial cables.



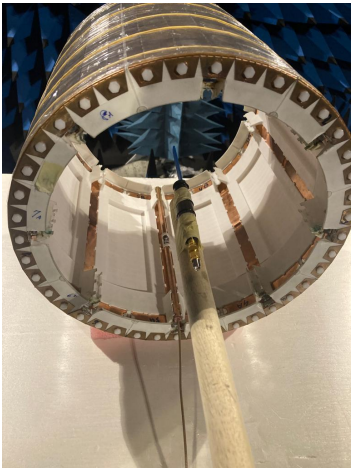
**Figure 4.49:** S - parameters from measurement, when all the components were soldered.

Hence, several measurements have been done with the added ferrites and simplified design of the CBCL. The simplified version refers to the measurements that have been carried out for each part of the CBCL without any soldered components. For instance, a measurement was done while the coil opened, and the floating loops were taken out; this configuration can be seen in Fig. 4.50(b). In another simplified measurement, again without the floating loops, the air-gaps in the middle legs were short-circuited to make the configuration truly symmetric to be able to expect a symmetric behavior in the field distributions. Besides, a measurement has been carried out only for the floating loops while the excited tube is put inside them.

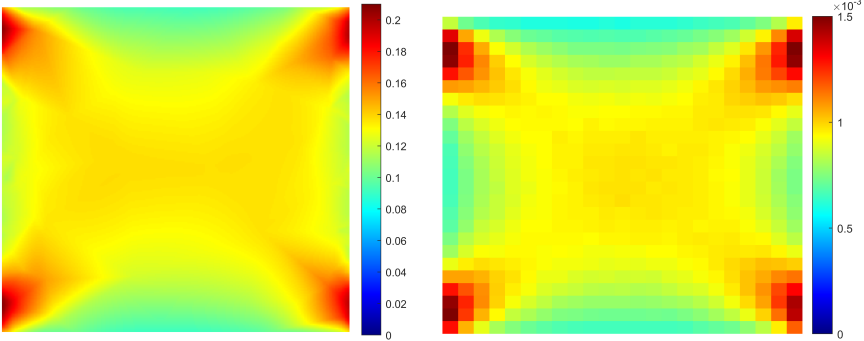
Another measurement was carried out when only one excitation port is used with floating loops, and the end ring capacitors are soldered without any soldered inductor. A CST simulation was carried out for the same configuration; as shown in Fig. 4.50(c), and Fig. 4.50(d) there is a pretty good agreement between the measurement and the simulation for the vertical cut in the middle of the CBCL. However, by adding the inductors the field distribution appears to be quite asymmetric at some frequencies, and this issue is the subject of the further investigation.



(a)



(b)



(c)

(d)

**Figure 4.50:** (a) Measurement setup. (b) The carried out measurement for the simplified CBCL when the floating loops were removed. (c) CST simulation result for the vertical cut inside the coil. (d) Measurement result for the same cut at 242 MHz.

## 4.13 Conclusion

This chapter proposed new designs for 7T birdcage coils based on the floating loops. The floating loops were implemented into the 8-leg conventional birdcage, and 30% homogeneity improvement was obtained in the available volume inside the birdcage. Also, the floating loops were introduced to the 7T connected birdcage (called CBCL), resulting in 40% homogeneity improvement in the available volume inside the connected birdcage. Generally speaking, the 7T CBCL showed 42% homogeneity improvement in the volume compared to the 8-leg conventional birdcage. In comparison with an eight-channel dipole transmit array reported in [108] with 29% deviation on the axial plane for human head imaging, the 8-leg CBCL showed 22% deviation for a cylinder phantom with the EM properties similar to human head at 300 MHz. However, for the fabricated birdcage, the field distribution appears to be quite asymmetric at some frequencies, and this issue is the subject of further investigation.



# CHAPTER 5

## Finite Element-Boundary Integral method

In this chapter, a hybrid electromagnetic solver is implemented for MRI applications. As mentioned in Chapter 2, the MoM is a very efficient solver dealing with piecewise homogeneous media such as RF transmit and receive coils. However, in real MRI applications, where an inhomogeneous human body is positioned inside the MRI tunnel, the finite element method (FEM) is preferred among other EM numerical solvers. In this chapter, a hybrid method based on the combination of the FEM and MoM called the Finite Element Boundary Integral method (FE-BI) is used to analyze the field distributions inside the body. This achievement has been obtained in close collaboration with Dr. Clément Durochat from Multiwave imaging company, which has been active on the FEM computation, and Dr. Chan-Sun Park from UCLouvain on the MoM computation.

Section 5.1 provides an introduction to the FE-BI. Section 5.2 presents the coupling process between FEM and MoM and the assembled system of equations. The first application of the FE-BI is implemented in Section 5.3, to find the field distribution inside a dielectric sphere diffracting an incident plane wave. The impact of the RF coil around the phantom in the FE-BI

system of equations is described in Section 5.4. Finally, Section 5.5 uses the FEBI method to find the field distribution inside an inhomogeneous model of the human head surrounded by the 7T coil developed in Chapter 4.

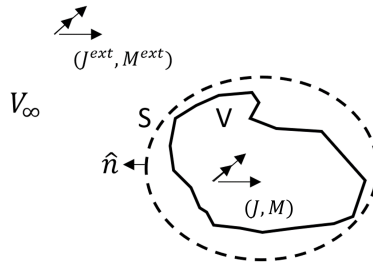
## 5.1 Introduction

The Finite Element Boundary Integral (FE-BI) [121] method, is a hybrid numerical method that shows excellent performance in analyzing complex structures in which various materials are mixed, by coupling the Method of Moments (MoM) with the Edge Finite Element Method (edge FEM) [122]. Even though one can consider the possibility of the volumetric MoM [123] in solving inhomogeneous problems, compared to the surface MoM, it requires volume meshes resulting in more unknowns. FE-BI hybridization is intended to combine the capability of the edge FEM on one side to accurately deal with irregularly shaped objects and inhomogeneous materials, yielding an accurate and natural description of a vector field with discontinuities in 3D, and on the other side the strengths specialized in the highly efficient scattering analysis of the MoM for the rest of the computational domain. It is thus possible to obtain an important gain in CPU time in the analysis of the inhomogeneous complex structure. At the same time, truncation errors generated by absorbing boundary conditions (ABCs) of the edge FEM can be alleviated through rigorous and clear boundary conditions in MoM, giving also a significant improvement on the computation accuracy.



## 5.2 FEBI System of Equations

Consider an arbitrary-shaped inhomogeneous medium with electromagnetic properties as  $\varepsilon_r$  and  $\mu_r$ , illuminated by an external incident field  $E^{inc}$  and  $H^{inc}$ , and excited by an internal source  $J_{src}$ . To implement the FEBI method in this electromagnetic problem, the volume consisting of the object is enclosed by a fictitious surface in order to divide the problem into an internal and an external region. The reasoning below follows the one described in [121].



**Figure 5.1:** An artificial surface around the object.

The fields in the interior region satisfy the vector wave equation through the equation below

$$\nabla \times \frac{1}{\mu_r} \nabla \times \mathbf{E} - k_0^2 \varepsilon_r \mathbf{E} = ik_0 z_0 \mathbf{J} \quad (5.1)$$

where  $E$  denotes the electric field,  $\varepsilon_r$  and  $\mu_r$  are the electromagnetic parameters,  $k_0$ ,  $z_0$  and  $\mathbf{J}$  respectively stand for the free-space wavenumber, impedance and an internal source.

For the exterior region, the fields satisfy the Electric Field Integral Equation (EFIE) and Magnetic Field Integral Equation (MFIE):

$$\begin{aligned} \mathbf{E} &= \mathbf{E}^{inc} - \mathcal{L}(\mathbf{J}) + \mathcal{K}(\mathbf{M}) \\ \mathbf{H} &= \bar{\mathbf{H}}^{inc} - \mathcal{K}(\mathbf{J}) - \mathcal{L}(\mathbf{M}) \end{aligned} \quad (5.2)$$

where  $\mathbf{J}$  and  $\mathbf{M}$  are respectively the unknown surface electric and magnetic currents and  $\mathcal{L}$  and  $\mathcal{K}$  are integral operators are defined as follows [121]:

$$\begin{aligned}\mathcal{L}(v) &\equiv ik_0 \oint_S [\mathcal{I}_d + \frac{\nabla \nabla \cdot}{k^2}] \frac{e^{-ik_0 R}}{4\pi R} \mathbf{v}(\mathbf{r}') dS' \\ \mathcal{K}(v) &\equiv \oint_S \mathbf{v}(\mathbf{r}') \times \nabla \frac{e^{-ik_0 R}}{4\pi R} dS'\end{aligned}\quad (5.3)$$

with  $\mathcal{I}_d$  the identity operator, and  $R = |r - r'|$  the distance between the observation point and the source point.

To couple edge FEM and MoM equations on conforming meshes, the unknown current densities and fields can be expanded as [121]:

$$\mathbf{J} = \sum_{j=1}^{N_S} H_j^S T_j \quad (5.4)$$

$$\mathbf{M} = - \sum_{j=1}^{N_S} E_j^S T_j \quad (5.5)$$

$$\mathbf{E} = \sum_{j=1}^{N_S} E_j^S \Phi_j + \sum_{j=1}^{N_I} E_j^I \Phi_j \quad (5.6)$$

$$\tilde{\mathbf{H}} = \sum_{j=1}^{N_S} \tilde{H}_j^S \Phi_j \quad (5.7)$$

where  $T_j$  and  $\Phi_j$  denote the Rao-Wilton-Glisson functions (RWG) from MoM and the edge basis functions from FEM, respectively;  $N_S$  and  $N_I$  are the number of degrees of freedom (DOFs) on and inside  $S$ ; and  $E_j^S$ ,  $E_j^I$ , and  $\tilde{H}_j^S$  are the unknown coefficients.

The corresponding coupled system of equations is given by [121]:

$$\begin{bmatrix} K^{II} & K^{IS} & 0 \\ K^{SI} & K^{SS} & B \\ 0 & P & Q \end{bmatrix} \begin{pmatrix} E^I \\ E^S \\ H^S \end{pmatrix} = \begin{pmatrix} b^I \\ b^S \\ b^{inc} \end{pmatrix} \quad (5.8)$$

where  $K^{II}$ ,  $K^{IS}$ ,  $K^{SI}$ ,  $K^{SS}$ ,  $B$  block-matrices and  $b^I$  and  $b^S$  vectors, represent those to be calculated by the edge FEM, and  $P$  and  $Q$  block-matrices and  $b^{inc}$  vector are those generated by MoM. The corresponding block-matrices and vector in FEM can be obtained through the equations below [121]:

$$K_{ij}^{XY} = \int_V \left[ \frac{1}{\mu_r} (\nabla \times \Phi_i^X) \cdot (\nabla \times \Phi_j^Y) - k_0^2 \varepsilon_r \Phi_i^X \cdot \Phi_j^Y \right] dV \quad (5.9)$$

$$B_{ij} = ik_0 \oint_S n \cdot (\Phi_i^S \times \Phi_j^S) dS \quad (5.10)$$

$$b_i^X = -ik_0 \int_V \Phi_i^X \cdot z_0 \mathbf{J} dV \quad (5.11)$$

For the MoM part, to prevent the internal resonance problem, the Combined Field Integral Equation (CFIE) is used, formulated by testing the EFIE with  $T_i^E$ , testing the  $n \times$  MFIE with  $T_i^M$  and mixing the two resulting matrix equations. Hence in the global FE-BI system of equations,  $P$ ,  $Q$  block matrices are expressed as [121]:

$$P_{ij} = \alpha \oint_S (n \times T_i^E) \cdot \left[ \frac{1}{2} T_j + n \times \tilde{K}(T_j) \right] dS + \beta \oint_S (n \times T_i^M) \cdot \mathcal{L}(T_j) dS \quad (5.12)$$

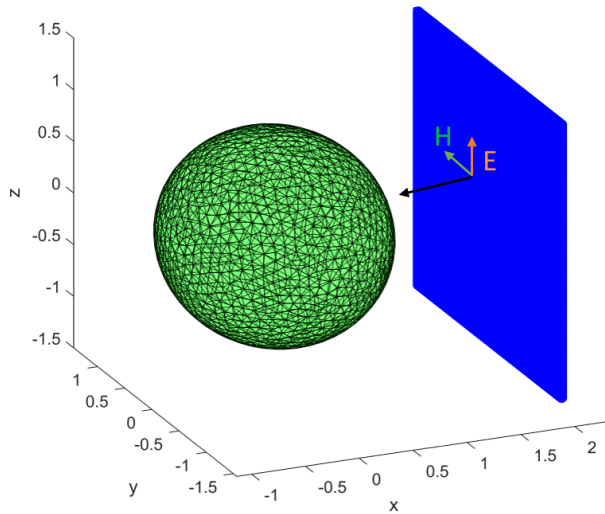
$$Q_{ij} = \beta \oint_S T_i^M \cdot \left[ \frac{1}{2} T_j + n \times \tilde{K}(T_j) \right] dS + \alpha \oint_S T_i^E \cdot \mathcal{L}(T_j) dS \quad (5.13)$$

$$b_i^{inc} = \alpha \oint_S T_i^E \cdot E^{inc} dS + \beta \oint_S S T_i^M \cdot (n \times \tilde{H}^{inc}) dS \quad (5.14)$$

$\tilde{K}$  is the principal value of the operator  $\mathcal{K}$ , and the combination factors are  $\alpha = \beta = -2ik_0$ .

### 5.3 Field Distributions Inside a Dielectric Sphere Illuminated by an Incident Plane Wave

To implement the FE-BI method, an electromagnetic problem consisting of a dielectric sphere illuminated by an incident plane wave is considered the first test case. The geometry is represented in Fig. 5.2, where the plane wave is initialized in the air and propagates towards a sphere with a radius of 1 m and  $\epsilon_r = 5-0.25i$ . In the FE-BI sense, the interior region is represented by the sphere, and the exterior region by the surrounding air.



**Figure 5.2:** A dielectric sphere and a plane wave propagating in the negative x direction.

Before using the FE-BI method, only the MoM solver is used to find the EM field distributions on the  $x = 0$  observation plane (done by Farzad Jabbarigargari). The MoM results validated with CST for x, y, and z components of the E field are shown in Fig. 5.3 and in Fig. 5.4, the same validation is carried out for the three components of the magnetic field.

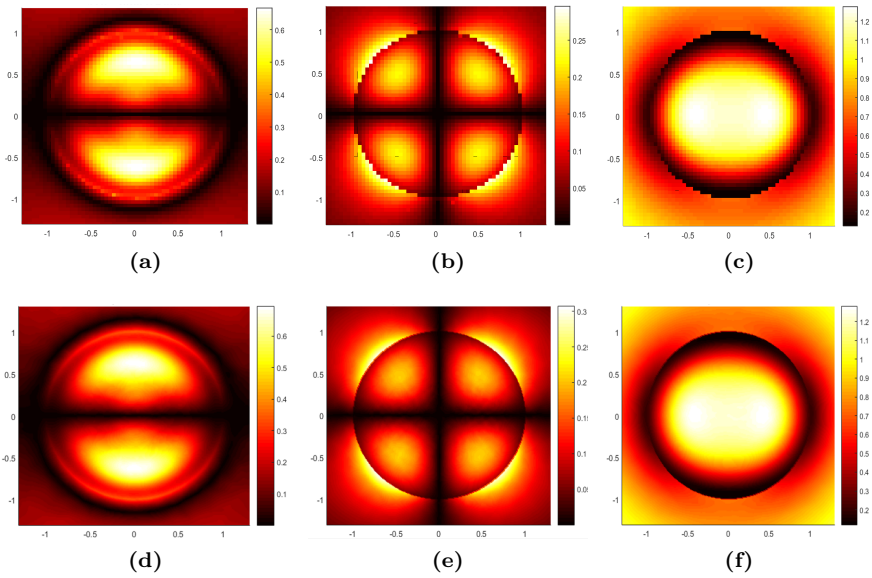


Figure 5.3: First row is the MoM and second row is the CST results.

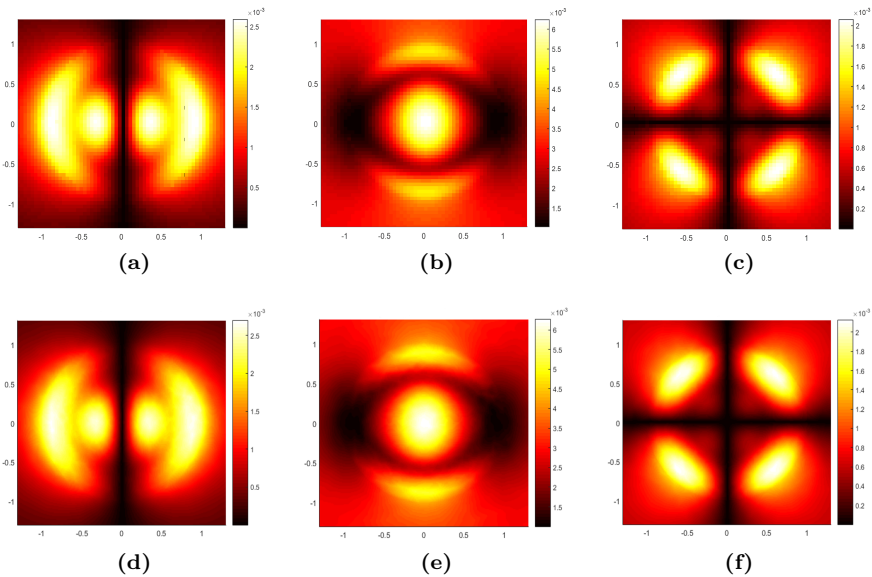


Figure 5.4: First row is the MoM and second row is the CST results.

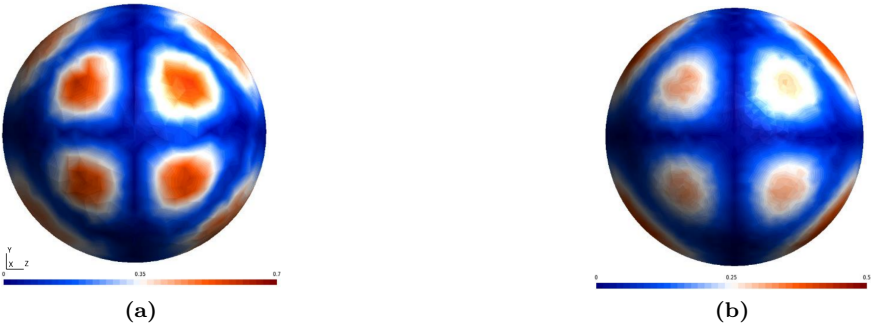
Regarding the implementation of the FE-BI method, FEM method uses the vectorial and high-order polynomial basis functions. Having the advantage of high-order edge finite elements [122], [124] provides flexibility and a much-improved accuracy level. On the other hand for the  $P$ ,  $Q$  and  $b^{inc}$  matrices are computed with considering the RWG basis and testing functions. To complete the FE-BI system of equations, all the block-matrices corresponding to the MoM are computed at UCLouvain in collaboration with Dr. Chan-Sun Park, and Dr. Clément Durochat from the Multiwave imaging company computed other block-matrices related to FEM computation. After assembling the whole matrices, 3D views of the  $x$  and  $y$  components of the  $E$  field obtained with FEM and FE-BI are shown in Fig. 5.5 and Fig. 5.6, where the correspondence in the field distributions between FEM and FE-BI ensures the proper assembly of the MoM and FEM; however, some differences between the two solvers are noticeable.



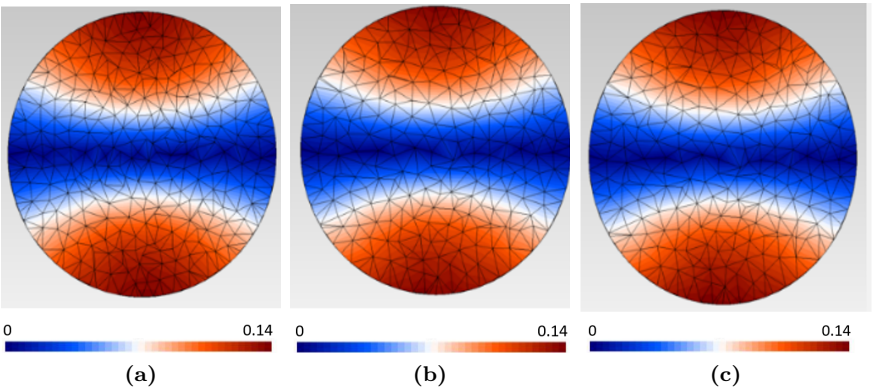
**Figure 5.5:** 3D view of  $|Ex|$  field ( $x = 0$  plan perspective). (a) FE-BI method. (b) FEM. Figures are obtained from the FEBI system of equations assembled by Dr. Clément Durochat.

This inaccuracy comes from the fact that the CFIE integral equation form is used in FE-BI to prevent the spurious interior resonance problem. However, the RWG testing function used in conventional MoM is classified as a divergence-conforming function, and when it is used for testing the  $n \times K$  operator in CFIE, the accuracy is greatly reduced. The accuracy of the FE-BI is improved by implementing the curl-conforming function or quasi-curl-conforming function, where two types of testing functions, including

the  $n \times \text{RWG}$  and  $n \times \text{RWG} + \text{RWG}$ , were implemented in the MoM by Dr. Chan-Sun Park at UCLouvain.



**Figure 5.6:** 3D view of  $E_y$  field ( $x = 0$  plan perspective). (a) FE-BI method. (b) FEM. Figures are obtained from the FEBI system of equations assembled by Dr. Clément Durochat.



**Figure 5.7:**  $x$  componentet of the E field obtained from: (a) FEM. (b) FEBI with  $n \times \text{RWG}$  testing. (c) FEBI with  $\text{RWG} + n \times \text{RWG}$  testing. Figures are obtained from the FEBI system of equations assembled by Dr. Clément Durochat.

The improved accuracy in the same test case by implementing the new testing functions can be seen in Fig. 5.7, where there is a good agreement between the FE-BI method and FEM results.

## 5.4 FE-BI System of Equations in the Presence of a Birdcage Coil around the Phantom

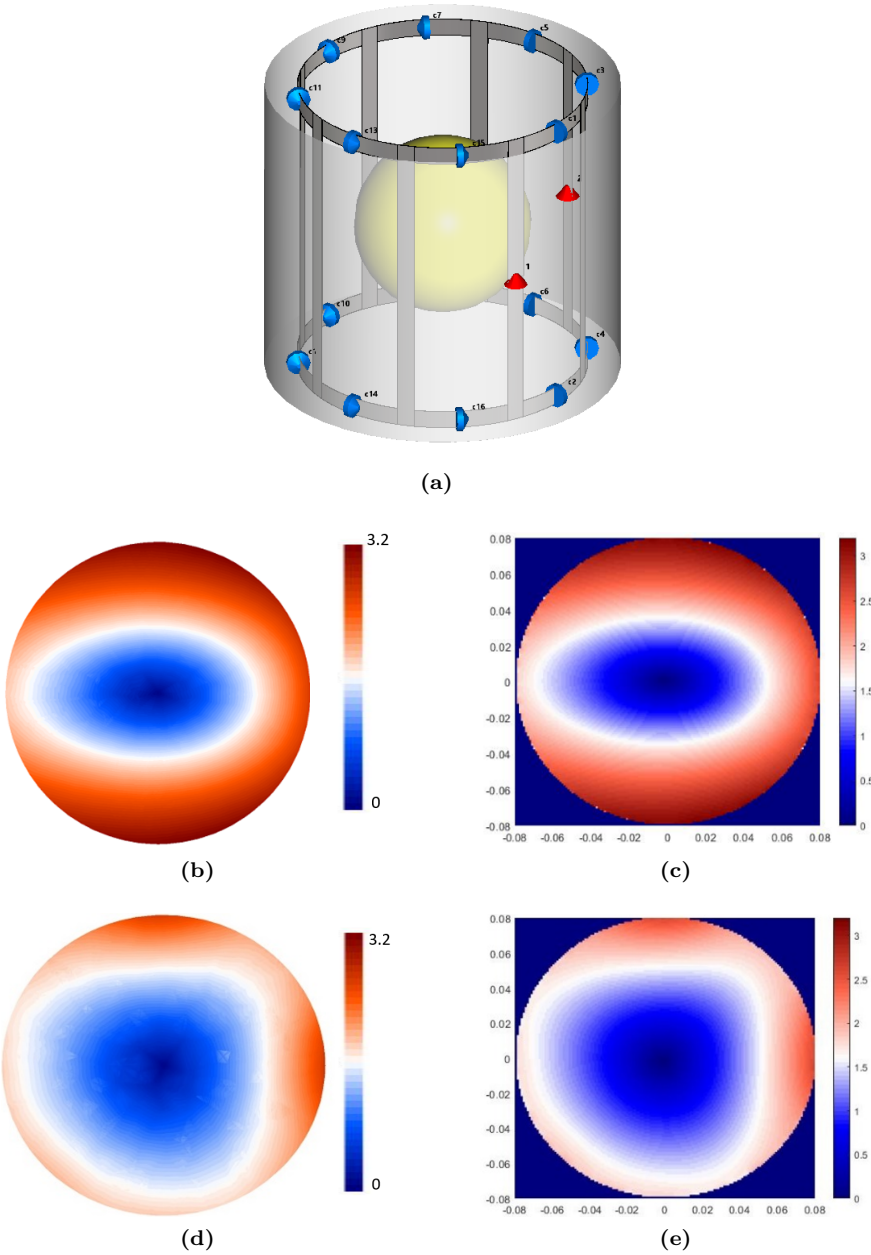
The system of equations mentioned in equations (5.8) does not allow including an antenna. Hence the FE-BI global system of equations has to be augmented to include the antenna interaction with the phantom. In this sense, the new system of equations implemented by Dr. Chan-Sun Park reads as:

$$\begin{bmatrix} K^{II} & K^{IS} & 0 & 0 \\ K^{SI} & K^{SS} & B & 0 \\ 0 & P & Q & A \\ 0 & P' & Q' & A' \end{bmatrix} \begin{pmatrix} E^I \\ E^S \\ H^S \\ H^{ant} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ b_{ant} \end{pmatrix} \quad (5.15)$$

$$\begin{aligned} P_{ij} &= \oint_{ph} \mathbf{T}_i^{RWG} \cdot \left( \frac{1}{2} \hat{\mathbf{n}} \times \mathbf{T}_j^{ph} - \tilde{K}(\mathbf{T}_j^{ph}) \right) dS + \frac{1}{\eta} \oint_{ph} \mathbf{T}_i^{nRWG} \cdot \mathcal{L}(\mathbf{T}_j^{ph}) dS \\ Q_{ij} &= \oint_{ph} \mathbf{T}_i^{nRWG} \cdot \left( -\frac{1}{2} \hat{\mathbf{n}} \times \mathbf{T}_j^{ph} + \tilde{K}(\mathbf{T}_j^{ph}) \right) dS + \frac{1}{\eta} \oint_{ph} \mathbf{T}_i^{RWG} \cdot \mathcal{L}(\mathbf{T}_j^{ph}) dS \\ A_{ij} &= \oint_{ph} \mathbf{T}_i^{nRWG} \cdot \left( -\frac{1}{2} \hat{\mathbf{n}} \times \mathbf{T}_j^{ant} + \tilde{K}(\mathbf{T}_j^{ant}) \right) dS + \frac{1}{\eta} \oint_{ph} \mathbf{T}_i^{RWG} \cdot \mathcal{L}(\mathbf{T}_j^{ant}) dS \\ P'_{ij} &= \oint_{ant} \mathbf{T}_i^{RWG} \cdot \left( \frac{1}{2} \hat{\mathbf{n}} \times \mathbf{T}_j^{ph} - \tilde{K}(\mathbf{T}_j^{ph}) \right) dS \\ Q'_{ij} &= \frac{1}{\eta} \oint_{ant} \mathbf{T}_i^{RWG} \cdot \mathcal{L}(\mathbf{T}_j^{ph}) dS \\ A'_{ij} &= \frac{1}{\eta} \oint_{ant} \mathbf{T}_i^{RWG} \cdot \mathcal{L}(\mathbf{T}_j^{ant}) dS \end{aligned} \quad (5.16)$$

As shown in Fig. 5.8(a), an eight-leg birdcage coil is placed around a dielectric sphere with a radius of 8 cm and  $\varepsilon_r = 20$ . The FE-BI method is used to plot the E-field distributions at 150 MHz on two different cuts inside the sphere. The MoM results are also provided to verify the new system of equations presented in Equation 5.15.

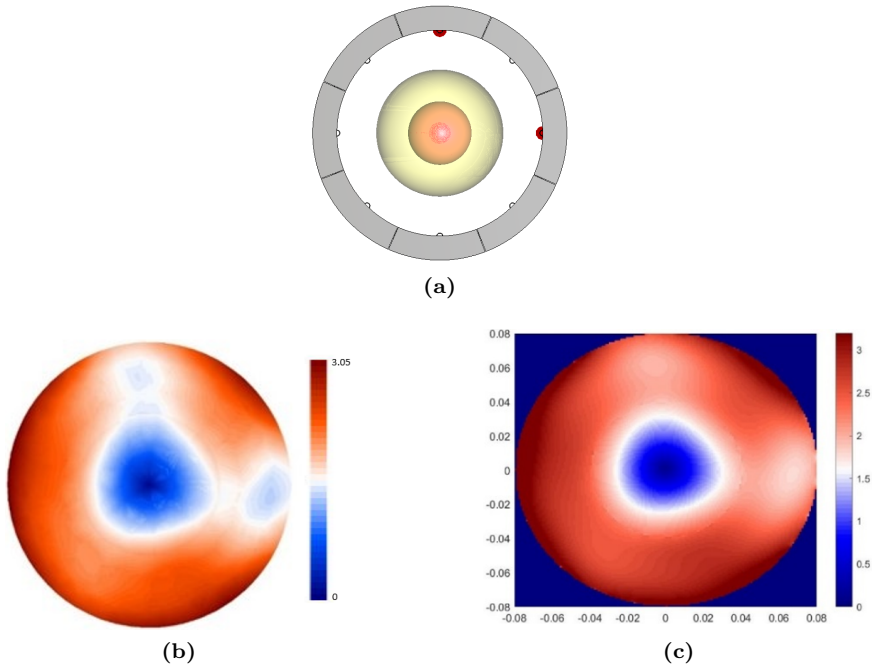




**Figure 5.8:** (a) A birdcage coil around a spherical phantom. (b) and (c)  $|E|$  on the  $x = 0$  observation plane obtained from FE-BI and MoM, respectively. (d) and (e)  $|E|$  on the  $z = 0$  observation plane obtained from FE-BI and MoM, respectively. The birdcage coil design and mesh have been provided by Farzad Jabbarigargari, and simulations have been carried out by Dr. Chan-Sun Park.

### 5.4.1 7T CBCL around Two Concentric Spheres

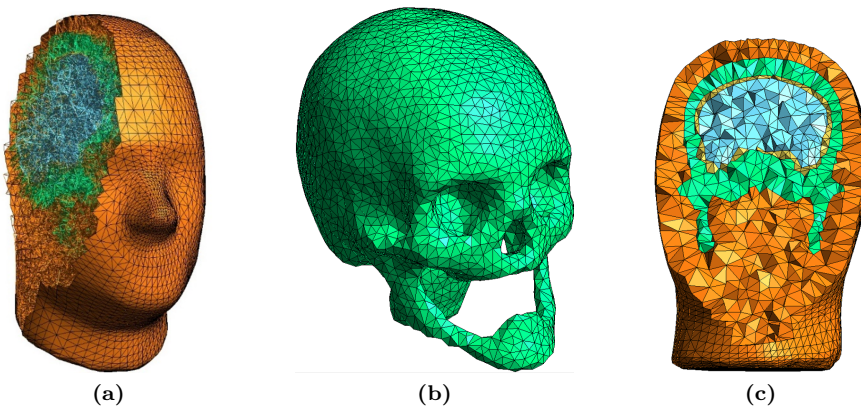
The FEBI method is used to find the electric field distributions inside two concentric spheres with different properties in the presence of the 7T CBCL (see Section 4.6) around the two spheres. The outer sphere has 8 cm radius and  $\varepsilon_r = 52.98 - 94.96i$  (average value for skin/muscles), and the inner sphere has 4 cm radius with  $\varepsilon_r = 18.3 - 17.89i$  (corresponding to skull). The absolute value of the E field obtained from MoM and FEBI on the  $z = 0$  observation plane is shown in Fig. 5.9. The small differences between full MoM and FE-BI are expected, since the two methods use different algorithms, especially in heterogeneous media (treated as piecewise-homogeneous media by MoM).



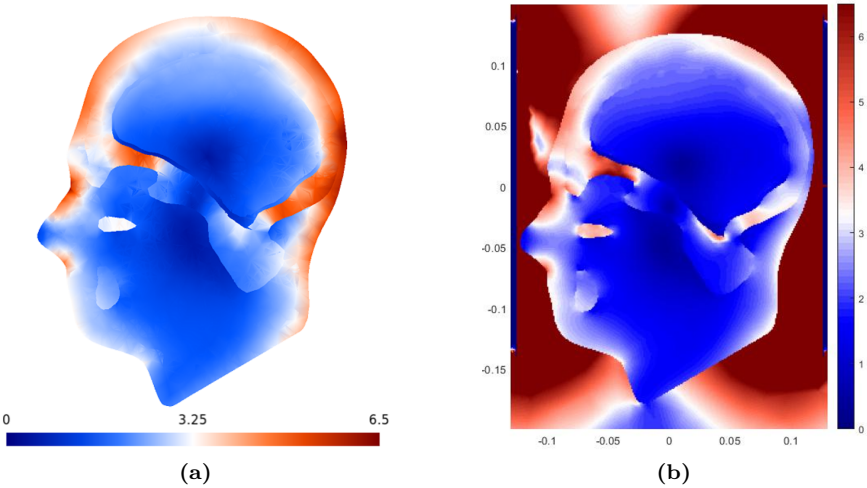
**Figure 5.9:** (a) Top view of the CBCL around two concentric spheres. (b)  $|E|$  field obtained from FEBI. (c)  $|E|$  field obtained from MoM. The birdcage coil design and mesh have been provided by Farzad Jabbarigargari, and simulations have been carried out by Dr. Chan-Sun Park.

## 5.5 7T CBCL around the Inhomogeneous Human Head

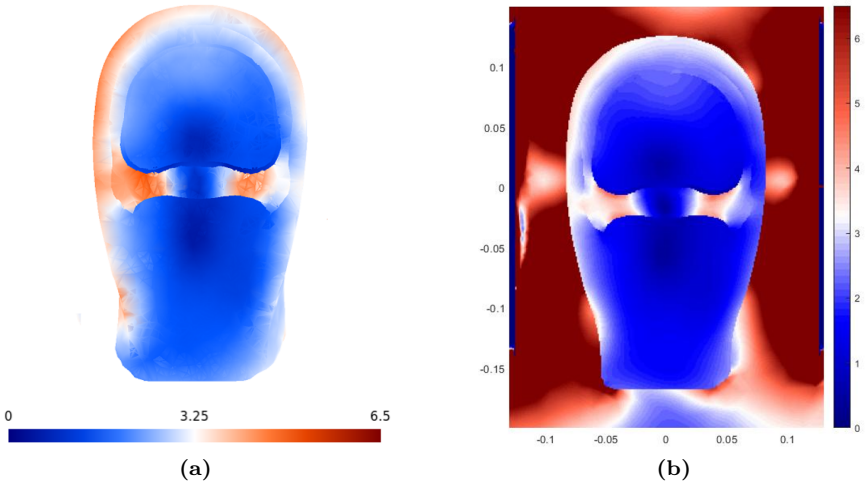
The main goal of the FE-BI method is to efficiently treat the EM problem in an inhomogeneous media. Hence in this section, a heterogeneous model of the human head, including the skin/muscles, the skull, the Cerebro Spinal Fluid, and the brain with  $\varepsilon_r = 52.98 - 94.96i$ ,  $\varepsilon_r = 18.3 - 17.89i$ ,  $\varepsilon_r = 72.73 - 266.94i$ ,  $\varepsilon_r = 51.9 - 66.34i$  [95], respectively, is used in the presence of the 7T CBCL coil, to analyze the field distributions inside the head with the FE-BI method. The absolute value of the E field on two different cuts inside the head, obtained with FE-BI and CST are shown in Fig. 5.11 and Fig. 5.12. The level of agreement between two solvers reassures the proper implementation of the FE-BI system of equations.



**Figure 5.10:** Mesh of the heterogeneous human head with four media: skin/muscles, skull, cerebro spinal fluid and brain. (a) Lateral cross section. (b) Skull mesh. (c) Front cross section. Meshes were provided by Dr. Clément Durochat.



**Figure 5.11:**  $|E|$  field on the sagittal plane obtained from (a) FEBI. (b) CST. FEBI figures are obtained from the FEBI system of equations assembled by Dr. Clément Durochat and CST simulation has been carried out by Dr. Chan-Sun Park.



**Figure 5.12:**  $|E|$  field on the coronal plane obtained from (a) FEBI. (b) CST. FEBI figures are obtained from the FEBI system of equations assembled by Dr. Clément Durochat and CST simulation has been carried out by Dr. Chan-Sun Park.

## 5.6 Conclusion

The Finite-Element method (FEM) is particularly well suited to inhomogeneous media such as the human head, while the Method-of-Moments (MoM), or equivalently BEM (Boundary Element Method), is well suited to piecewise homogeneous media, such as antennas. The BEM only requires meshing of surfaces and hence does not require the introduction of absorbing boundary conditions on the envelope of the computational domain. The FEBI approach [125], hence consists of articulating both methods at the surface of the head. This has been made possible through a close cooperation between Multiwave, which had developed a FEM software and UCLouvain which had developed a BEM software. This articulation required the development of new matrices providing the interaction between basis functions at the surface of the head. In this way, the volume mesh is limited to the inside of the head, while surface meshes are used on the surface of the head and on the surface of the antennas. This reduces the number of unknowns and to a large extent decouples the optimization of the antennas from the computation of the fields inside the head. However, the main issue with this coupled method is the constraints on the number of unknowns due to the available computer memory while solving the assembled (FE-BI) system. A further development could be obtained by getting a matrix from FEM part that fully represents the effects of the scattering by the inhomogeneous body, from the perspective of the outer world (coil, MRI tunnel, etc).



# CHAPTER 6

## Conclusions and Future Works

### 6.1 Conclusions

Among the different imaging methods that are used to get images from inside the human or animal body, MRI is a non-invasive and safe method that started from low field like 1.5T, and it has been moving toward UHF MRI systems like 7T, 9.4T, and 11.7 due to the higher SNR that could be obtained from these systems.

RF coils are essential parts of each MRI system since they are responsible for transmitting and receiving the RF signals due to their design and characteristics; hence, the transmitter RF coils design is crucial at HF and UHF MRI to create a very homogeneous field distribution in the transmit mode.

This thesis mainly focused on the design, fabrication, and measurements of the birdcage coils for HF and UHF MRI (3T and 7T). The core of both designs comes from the idea of the connected birdcage, where the birdcage is physically connected to the shield via some lumped elements. Besides the connection between the birdcage and the shield that is made by lumped inductors, additional legs loaded with the capacitors are introduced into the design. This geometry provides a transmission line type connection to optimize the current distributions on the legs, which results in homogeneous

magnetic field distributions in the available volume inside the coil.

For the 3T connected birdcage coil, it has been shown that the undesired impact of the end ring currents could be limited by introducing additional rings on the top and the bottom of the shield. The optimized 3T connected birdcage was fabricated in collaboration with SIRRIS, and the field distribution measurements were carried out at the Fresnel institute. Validation at the field distribution level revealed positive.

The connected birdcage was extended for UHF MRI while introducing vertical floating loops between the inner and middle legs of the connected birdcage. It has been shown that the presence of floating loops improves the homogeneity of the magnetic field on the transverse and sagittal planes. The idea of the floating loops has been applied to the conventional birdcage, and improvements in the current distributions are obtained, resulting in an improved magnetic field homogeneity in the volume of the coil. The 7T connected birdcage coil with floating loops has been fabricated, and preliminary measurements have been carried out. An asymmetry in the field distribution has been observed at some frequencies, requiring more measurements to determine the source of those asymmetries. Besides the design, fabrication, and measurement, which are the main parts of this thesis, two sections of the thesis were devoted to the numerical method to analyze the field distributions inside the human body in the presence of the RF coil. The MoM code developed in the lab has been used for piecewise homogeneous media, while accelerating the computation by utilizing a nesting approach and by computing some matrices once and for all.

Considering the inhomogeneity of the human head while using numerical methods to analyze the EM field distributions, the FEM is an efficient method since it uses the volume meshes, despite the surface mesh used in the MoM solvers. However, the FEM implies not only meshing of all the surrounding environment but also creates some inaccuracy while applying the corresponding boundary conditions. Hence, a hybrid EM solver combining the MoM and FEM has been implemented in the MRI application through a close collaboration between the M-ONE consortium partners to get advantages of the FEM for the interactions in a heterogeneous body and MoM solver for the interaction between the body and RF coils.



A summary of the original contributions is given below:

1. A technique to accelerate the MoM computation in the piecewise homogeneous media [Chapter 2]
2. An optimized design for the 3T connected birdcage [Chapter 3]
3. A new design for the 7T connected birdcage and 7T conventional birdcage [Chapter 4]
4. Collaboration in implementing a hybrid numerical method combining Finite Element and Integral Equation approaches [Chapter 5]

## 6.2 Future Works

This work has opened new perspectives on improving the magnetic field homogeneity in MRI applications. Hereunder, we propose some possible achievements that can be obtained using each contribution of the thesis. Due to the objectives of the projects (M-Cube and M-ONE), the birdcage coils only for human head imaging have been designed and fabricated. The proposed designs could be considered a good candidate for the whole-body RF coil since the proposed coils show better homogeneity for a bigger phantom and the robustness of the connected birdcage coil for different phantom sizes. In this thesis, the main attention was given to homogeneity improvement over the entire cut; however, at UHF MRI, the local improvement in homogeneity is another important topic that has gotten particular attention during the last few years. As shown in Chapter 2, an asymmetric birdcage coil design can be used to shape the magnetic field; it would be interesting to use an asymmetric design of the floating loops to be able to manipulate field distributions locally. An intelligent birdcage coil could be another interesting research topic. Depending on the application, that birdcage coil can be adapted via its variable lumped elements or rotatable floating loops. Hence, this coil can either provide a local magnetic field improvement through the asymmetric configuration or improve the homogeneity on a given plane with the symmetric design. However, this goal could be challenging because of the limited availability of non-magnetic lumped elements or a proper mechanical design to tilt the floating loops individually. Using the hybrid

FE-BI method with the above-proposed designs might also be efficient to further manipulate the EM field distribution inside the human body.

# CHAPTER 7

## List of Publications and Research Talks

### Patent

- P1.** **F. Jabbarigargari**, C. Craeye, C.-S. Park, “An improved Birdcage coil with floating loops,” a patent is in process.

### Journal Paper

- J1.** C.-S. Park, D. Tihon, **F. Jabbarigargari**, R. Abdeddaim, C. Craeye “Radially extended 3D birdcage antenna for MRI with loop-type legs and connection to the shield,” under review in *IEEE Access*, submitted on 15 June 2022.

### Conference Papers

- C1.** **F. Jabbarigargari**, C.-S. Park, D. Oueslati, D. Tihon, C. Durochat, T. Letertre, P. Sabouroux and C. Craeye, “ A nesting approach for the numerical analysis of MRI birdcage antennas in the presence of the human head,” *2020 14th European Conference on Antennas and*

*Propagation (EuCAP)*, Denmark (online), 2020, pp. 1-5.

- C1. T. Clerbois, A. Rampelbergh, **F. Jabbarigargari**, C.-S. Park, R. Abdeddaim, C. Craeye, “ Asymmetric use of 8-legged Conventional Birdcage,” *2023 17th European Conference on Antennas and Propagation (EuCAP)*
- C4. V. Sokolow, **F. Jabbarigargari**, P. Fisette, C. Craeye “Scanning GNSS-R Beams from Cubesats Using Sequentially Rotated Deployable Dipoles,” *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*, Brussels, 2021, pp. 8538-8541.

# Bibliography

- [1] C.-H. Choi, S.-M. Hong, J. Felder, and N. J. Shah, “The state-of-the-art and emerging design approaches of double-tuned rf coils for x-nuclei, brain mr imaging and spectroscopy: A review,” *Magnetic resonance imaging*, vol. 72, pp. 103–116, 2020.
- [2] R. W. Brown, Y.-C. N. Cheng, E. M. Haacke, M. R. Thompson, and R. Venkatesan, *Magnetic resonance imaging: physical principles and sequence design*. John Wiley & Sons, 2014.
- [3] M. A. Bernstein, K. F. King, and X. J. Zhou, *Handbook of MRI pulse sequences*. Elsevier, 2004.
- [4] A.-H. Emwas, K. Szczepski, B. G. Poulson, K. Chandra, R. T. McKay, M. Dhahri, F. Alahmari, L. Jaremko, J. I. Lachowicz, and M. Jaremko, “Nmr as a gold standard method in drug design and discovery,” *Molecules*, vol. 25, no. 20, p. 4597, 2020.
- [5] <https://www.mrimaster.com>.
- [6] R. Gruetter, S. A. Weisdorf, V. Rajanayagan, M. Terpstra, H. Merkle, C. L. Truwit, M. Garwood, S. L. Nyberg, and K. Ugurbil, “Resolution improvements in vivo 1h nmr spectra with increased magnetic field strength,” *Journal of magnetic resonance*, vol. 135, no. 1, pp. 260–264, 1998.

- [7] A. G. Webb and C. M. Collins, "Parallel transmit and receive technology in high-field magnetic resonance neuroimaging," *International Journal of Imaging Systems and Technology*, vol. 20, no. 1, pp. 2–13, 2010.
- [8] E. Moser, F. Stahlberg, M. E. Ladd, and S. Trattnig, "7t mr from research to clinical applications," *NMR in Biomedicine*, vol. 25, no. 5, pp. 695–716, 2012.
- [9] R. Pohmann, O. Speck, and K. Scheffler, "Signal-to-noise ratio and mr tissue parameters in human brain imaging at 3, 7, and 9.4 tesla using current receive coil arrays," *Magnetic resonance in medicine*, vol. 75, no. 2, pp. 801–809, 2016.
- [10] I. R. Connell, K. M. Gilbert, M. A. Abou-Khousa, and R. S. Menon, "Design of a parallel transmit head coil at 7t with magnetic wall distributed filters," *IEEE transactions on medical imaging*, vol. 34, no. 4, pp. 836–845, 2014.
- [11] M. K. Woo, R. L. Lagore, L. DelaBarre, B.-Y. Lee, Y. Eryaman, J. Radder, A. Erturk, G. Metzger, P.-F. van de Moortele, K. Ugurbil *et al.*, "A 16-channel transceiver loop+ dipole antennas head array for human head imaging at 10.5 t," in *2017 International Conference on Electromagnetics in Advanced Applications (Iceaa)*. IEEE, 2017, pp. 1649–1652.
- [12] R. H. Caverly, "Rf aspects of high-field magnetic resonance imaging (hf-mri): Recent advances," *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, vol. 3, no. 2, pp. 111–119, 2018.
- [13] C. M. Collins, *Electromagnetics in magnetic resonance imaging: physical principles, related applications, and ongoing developments*. Morgan & Claypool Publishers, 2016.
- [14] D. G. Nishimura, *Principles of magnetic resonance imaging*. Stanford Univ., 2010.

- [15] D. Hoult, "The principle of reciprocity in signal strength calculations a mathematical guide," *Concepts in Magnetic Resonance: An Educational Journal*, vol. 12, no. 4, pp. 173–187, 2000.
- [16] J. I. Agbinya, *Wireless power transfer*. CRC Press, 2022.
- [17] M. Manteghi and A. A. Y. Ibraheem, "On the study of the near-fields of electric and magnetic small antennas in lossy media," *IEEE Transactions on antennas and propagation*, vol. 62, no. 12, pp. 6491–6495, 2014.
- [18] B. Gruber, M. Froeling, T. Leiner, and D. W. Klomp, "Rf coils: A practical guide for nonphysicists," *Journal of magnetic resonance imaging*, vol. 48, no. 3, pp. 590–604, 2018.
- [19] R. Ansorge and M. Graves, *The physics and mathematics of MRI*. Morgan & Claypool Publishers, 2016.
- [20] J. Mispelter, M. Lupu, and A. Briguet, *NMR probeheads for biophysical and biomedical experiments: theoretical principles and practical guidelines*. World Scientific Publishing Company, 2015.
- [21] R. Damadian, "Apparatus and method for nuclear magnetic resonance scanning and mapping," Tech. Rep., 1988.
- [22] J. P. Hornak, "The basics of mri," <http://www.cis.rit.edu/htbooks/mri>, 2006.
- [23] A. Samila, "Simulation of magnetic field topology in a saddle-shaped coil of nuclear quadrupole resonance spectrometer," *Progress In Electromagnetics Research Letters*, vol. 56, pp. 67–73, 2015.
- [24] K.-N. Kim, J.-H. Seo, S.-D. Han, P. Heo, G. H. Im, and J. H. Lee, "Development of double-layer coupled coil for improving s/n in 7 t small-animal mri," *Scanning*, vol. 37, no. 5, pp. 361–371, 2015.
- [25] C. E. Hayes, W. A. Edelstein, J. F. Schenck, O. M. Mueller, and M. Eash, "An efficient, highly homogeneous radiofrequency coil for whole-body nmr imaging at 1.5 t," *Journal of Magnetic Resonance (1969)*, vol. 63, no. 3, pp. 622–628, 1985.

- [26] S. F. Ahmad, Y. C. Kim, I. C. Choi, and H. D. Kim, "Recent progress in birdcage rf coil technology for mri system," *Diagnostics*, vol. 10, no. 12, p. 1017, 2020.
- [27] J. Jin, *Electromagnetic analysis and design in magnetic resonance imaging*. Routledge, 2018.
- [28] M. C. Leifer, "Resonant modes of the birdcage coil," *Journal of Magnetic Resonance*, vol. 124, no. 1, pp. 51–60, 1997.
- [29] A. Nikulin, "Volume rf coils based on metamaterials for ultra-high field magnetic resonance imaging," Ph.D. dissertation, Université Paris science and letters, 2020.
- [30] C.-N. Chen, D. Hoult, and V. Sank, "Quadrature detection coils a further sqrt(2) improvement in sensitivity," *Journal of Magnetic Resonance (1969)*, vol. 54, no. 2, pp. 324–327, 1983.
- [31] J. T. Vaughan, H. P. Hetherington, J. O. Otu, J. W. Pan, and G. M. Pohost, "High frequency volume coils for clinical nmr imaging and spectroscopy," *Magnetic Resonance in Medicine*, vol. 32, no. 2, pp. 206–218, 1994.
- [32] J. T. Vaughan and J. R. Griffiths, *RF coils for MRI*. John Wiley & Sons, 2012.
- [33] C. E. Akgun, L. DelaBarre, S.-M. Sohn, C. Snyder, G. Adrian, K. Ugurbil, J. T. Vaughan, and A. Gopinath, "Novel multi-channel transmission line coil for high field magnetic resonance imaging," in *2009 IEEE MTT-S International Microwave Symposium Digest*. IEEE, 2009, pp. 1425–1428.
- [34] S.-M. Sohn, L. DelaBarre, A. Gopinath, and J. T. Vaughan, "Rf head coil design with improved rf magnetic near-fields uniformity for magnetic resonance imaging (mri) systems," *IEEE transactions on microwave theory and techniques*, vol. 62, no. 8, pp. 1784–1789, 2014.
- [35] A. J. Raaijmakers, J. Lagendijk, D. W. Klomp, B. van den Bergen, C. Possanzini, P. R. Harvey, and C. A. van den Berg, "Boosting b1



- efficiency for rf transmit surface elements by a radiative antenna design,” in *Proc. Intl. Soc. Mag. Reson. Med.*, vol. 17, 2009, p. 4764.
- [36] A. Raaijmakers, O. Ipek, D. Klomp, C. Possanzini, P. Harvey, J. Lagendijk, and C. Van den Berg, “Design of a radiative surface coil array element at 7 t: the single-side adapted dipole antenna,” *Magnetic resonance in medicine*, vol. 66, no. 5, pp. 1488–1497, 2011.
- [37] A. Raaijmakers, P. Luijten, and C. van den Berg, “Dipole antennas for ultrahigh-field body imaging: a comparison with loop coils,” *NMR in Biomedicine*, vol. 29, no. 9, pp. 1122–1130, 2016.
- [38] A. J. Raaijmakers, M. Italiaander, I. J. Voogt, P. R. Luijten, J. M. Hoogduin, D. W. Klomp, and C. A. van den Berg, “The fractionated dipole antenna: A new antenna for body imaging at 7 t esla,” *Magnetic resonance in medicine*, vol. 75, no. 3, pp. 1366–1374, 2016.
- [39] I. Zivkovic, C. A. de Castro, and A. Webb, “Design and characterization of an eight-element passively fed meander-dipole array with improved specific absorption rate efficiency for 7 t body imaging,” *NMR in Biomedicine*, vol. 32, no. 8, p. e4106, 2019.
- [40] M. K. Woo, L. Delabarre, M. Waks, J. Lee, R. L. Lagore, S. Jungst, A. Grant, Y. Eryaman, K. Ugurbil, and G. Adriany, “Comparison of 16-channel asymmetric sleeve antenna and dipole antenna transceiver arrays at 10.5 tesla mri,” *IEEE transactions on medical imaging*, vol. 40, no. 4, pp. 1147–1156, 2020.
- [41] M. K. Woo, L. DelaBarre, M. T. Waks, Y. W. Park, R. L. Lagore, S. Jungst, Y. Eryaman, S.-H. Oh, K. Ugurbil, and G. Adriany, “Evaluation of 8-channel radiative antenna arrays for human head imaging at 10.5 tesla,” *Sensors*, vol. 21, no. 18, p. 6000, 2021.
- [42] Y. Eryaman, B. Guerin, R. Kosior, E. Adalsteinsson, and L. L. Wald, “Combined loop+ dipole arrays for 7 t brain imaging,” in *Proc 21st Annual Meeting ISMRM, Salt Lake City*, 2013, p. 48.
- [43] G. C. Wiggins, B. Zhang, M. Cloos, R. Lattanzi, G. Chen, K. Lakshmanan, G. Haemer, and D. Sodickson, “Mixing loops and electric

- dipole antennas for increased sensitivity at 7 tesla,” in *Proceedings of the 21st Annual Meeting of ISMRM*, 2013, p. 2737.
- [44] M. Lu, S. Sengupta, J. C. Gore, W. A. Grissom, and X. Yan, “High-density mri rf arrays using mixed dipole antennas and microstrip transmission line resonators,” *IEEE Transactions on Biomedical Engineering*, 2022.
  - [45] C. Craeye and D. González-Ovejero, “A review on array mutual coupling analysis,” *Radio Science*, vol. 46, no. 02, pp. 1–25, 2011.
  - [46] CST, *CST Studio Suite Electromagnetic and Multiphysics Software*, Dassault Systèmes, 2021.
  - [47] Ö. Ipek, “Radio-frequency coils for ultra-high field magnetic resonance,” *Analytical Biochemistry*, vol. 529, pp. 10–16, 2017.
  - [48] C. Craeye, C.-S. Park, and D. Tihon, “improved birdcage antenna,” 2021.
  - [49] A. Delantoni and K. Orhan, “Atlas of dentomaxillofacial anatomical imaging,” 2022.
  - [50] R. F. Harrington, *Time-harmonic electromagnetic fields*. McGraw-Hill College, 1961.
  - [51] S. Rao, D. Wilton, and A. Glisson, “Electromagnetic scattering by surfaces of arbitrary shape,” *IEEE Transactions on antennas and propagation*, vol. 30, no. 3, pp. 409–418, 1982.
  - [52] R. F. Harrington and J. L. Harrington, *Field computation by moment methods*. Oxford University Press, Inc., 1996.
  - [53] C. Geuzaine and J.-F. Remacle, “Gmsh: A 3-d finite element mesh generator with built-in pre-and post-processing facilities,” *International journal for numerical methods in engineering*, vol. 79, no. 11, pp. 1309–1331, 2009.
  - [54] T. Letertre, “Study of the electromagnetic behavior of materials as a function of temperature to model the impact of heating generated by

- air friction on an aircraft during high-speed flight,” Ph.D. dissertation, Aix-Marseille, 2019.
- [55] M. A. Carr, J. Volakis, and D. Ross, “Acceleration of free space discrete body of revolution codes by exploiting circulant submatrices,” *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 9, pp. 1319–1322, 2002.
- [56] A. Roederer, “Etude des réseaux finis de guides rectangulaires à parois épaisses,” *L’onde Electrique*, vol. 51, pp. 854–861, 1971.
- [57] B. Munk and G. Burrell, “Plane-wave expansion for arrays of arbitrarily oriented piecewise linear elements and its application in determining the impedance of a single linear antenna in a lossy half-space,” *IEEE transactions on antennas and propagation*, vol. 27, no. 3, pp. 331–343, 1979.
- [58] F. Capolino, D. R. Jackson, and D. R. Wilton, “Fundamental properties of the field at the interface between air and a periodic artificial material excited by a line source,” *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 1, pp. 91–99, 2005.
- [59] A. Van De Water, B. De Hon, M. Van Beurden, A. Tijhuis, and P. De Maagt, “Linear embedding via greens operators a modeling technique for finite electromagnetic band gap structures,” *Physical Review E*, vol. 72, no. 5, p. 056704, 2005.
- [60] M.-K. Li and W. C. Chew, “Wave field interaction with complex structures using equivalence principle algorithm,” *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 1, pp. 130–138, 2007.
- [61] A. A. Kucharski, “Efficient solution of integral-equation based electromagnetic problems with the use of macromodels,” *IEEE transactions on antennas and propagation*, vol. 56, no. 5, pp. 1482–1487, 2008.
- [62] X. Dardenne, “Method of moments simulation of infinite and finite periodic structures and application to high-gain metamaterial antennas,” Ph.D. dissertation, UCLouvain, 2007.
- [63] R. S. Elliot, *Antenna theory and design*. John Wiley & Sons, 2006.

- [64] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proceedings of ICNN'95-international conference on neural networks*, vol. 4. IEEE, 1995, pp. 1942–1948.
- [65] <http://fmri.ucsd.edu/Research/whatisfmri.html>.
- [66] T. Clerbois and A. Rampelbergh, "Metamaterial antennas for medical imaging," 2022.
- [67] M. Dubois, L. Leroi, Z. Raolison, R. Abdeddaim, T. Antonakakis, J. De Rosny, A. Vignaud, P. Sabouroux, E. Georget, B. Larrat *et al.*, "Enhancement of transmit and receive efficiencies with hybridized meta-atom in 7t head coil," in *International Society for Magnetic Resonance in Medicine 27th Annual Meeting*, vol. 27, 2019, p. 1491.
- [68] A. Webb, "Dielectric materials in magnetic resonance," *Concepts in magnetic resonance part A*, vol. 38, no. 4, pp. 148–184, 2011.
- [69] Z. Raolison, R. Abdeddaïm, M. Dubois, L. Leroi, L. Neves, F. Mauconduit, S. Enoch, N. Malléjac, P. Sabouroux, A.-L. Adenot-Engelvin *et al.*, "Evaluation of a new long-lasting silicon carbide based dielectric pad for ultra-high field mri," in *Proceedings of the International Society for Magnetic Resonance in Medicine, Paris, France*, 2018.
- [70] V. Vorobyev, A. Shchelokova, I. Zivkovic, A. Slobozhanyuk, J. D. Baena, J. P. Del Risco, R. Abdeddaim, A. Webb, and S. Glybovski, "An artificial dielectric slab for ultra high-field mri: Proof of concept," *Journal of Magnetic Resonance*, vol. 320, p. 106835, 2020.
- [71] M. Dubois, L. Leroi, Z. Raolison, R. Abdeddaim, T. Antonakakis, J. De Rosny, A. Vignaud, P. Sabouroux, E. Georget, B. Larrat *et al.*, "Kerker effect in ultrahigh-field magnetic resonance imaging," *Physical Review X*, vol. 8, no. 3, p. 031083, 2018.
- [72] W. Grissom, C.-y. Yip, Z. Zhang, V. A. Stenger, J. A. Fessler, and D. C. Noll, "Spatial domain method for the design of rf pulses in multicoil parallel excitation," *Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine*, vol. 56, no. 3, pp. 620–629, 2006.

- [73] O. Kraff and H. H. Quick, “7t: Physics, safety, and potential clinical applications,” *Journal of Magnetic Resonance Imaging*, vol. 46, no. 6, pp. 1573–1589, 2017.
- [74] P. Ullmann, S. Junge, M. Wick, F. Seifert, W. Ruhm, and J. Hennig, “Experimental analysis of parallel excitation using dedicated coil setups and simultaneous rf transmission on multiple channels,” *Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine*, vol. 54, no. 4, pp. 994–1001, 2005.
- [75] W. A. Grissom, “Improving high-field mri using parallel excitation,” *Imaging in Medicine*, vol. 2, no. 6, p. 675, 2010.
- [76] L. L. Wald and E. Adalsteinsson, “Parallel transmit technology for high field mri,” *Magnetom Flash*, vol. 40, no. 1, p. 2009, 2009.
- [77] J. Nistler, “Homogeneity improvement using a 2 port birdcage coil,” *Proc. ISMRM 2007*, vol. 1063, 2007.
- [78] G. Ophem, A. van der Kolk, K. M. Bloch, A. J. Colon, K. A. Davis, T. R. Henry, J. F. Jansen, S. E. Jones, J. W. Pan, K. Rössler *et al.*, “7t epilepsy task force consensus recommendations on the use of 7t mri in clinical practice,” *Neurology*, vol. 96, no. 7, pp. 327–341, 2021.
- [79] F. G. Shellock, “Radiofrequency energy-induced heating during mr procedures: a review,” *Journal of Magnetic Resonance Imaging*, vol. 12, no. 1, pp. 30–36, 2000.
- [80] Medicines and H. P. R. Agency, “Safety guidelines for magnetic resonance imaging equipment in clinical use,” 2015.
- [81] N. I. Avdievich, G. Solomakha, L. Ruhm, A. Henning, and K. Scheffler, “Unshielded bent folded-end dipole 9.4 t human head transceiver array decoupled using modified passive dipoles,” *Magnetic resonance in medicine*, vol. 86, no. 1, pp. 581–597, 2021.
- [82] H. Chen, L. Guo, M. Li, A. Destruel, C. Liu, E. Weber, F. Liu, and S. Crozier, “Metamaterial-inspired radiofrequency (rf) shield with reduced specific absorption rate (sar) and improved transmit efficiency

- for uhf mri,” *IEEE Transactions on Biomedical Engineering*, vol. 68, no. 4, pp. 1178–1189, 2020.
- [83] Z. Chen, K. Solbach, D. Erni, and A. Rennings, “Improved b 1 distribution of an mri rf coil element using a high-impedance-surface shield,” in *2015 German Microwave Conference*. IEEE, 2015, pp. 111–114.
- [84] K. Lezhennikova, C. Simovski, R. Abdeddaim, R. Balafendiev, and S. Glybovski, “Extending a birdcage coil for magnetic resonance imaging of a human head with an artificial magnetic shield,” *Photonics and Nanostructures-Fundamentals and Applications*, vol. 43, p. 100890, 2021.
- [85] H. Ochi, E. Yamamoto, K. Sawaya, and S. Adachi, “Analysis of a magnetic resonance imaging antenna inside an rf shield,” *Electronics and Communications in Japan (Part I: Communications)*, vol. 77, no. 1, pp. 37–45, 1994.
- [86] C. van Leeuwen, B. Steensma, S. Glybovski, M. Lunenburg, C. Simovski, D. Klomp, C. van den Berg, and A. Raaijmakers, “Potential reduction of peripheral local sar for a birdcage body coil at 3 tesla using a magnetic shield,” *Frontiers in Physics*, p. 532, 2021.
- [87] K. Lezhennikova, R. Abdeddaim, A. Hurshkainen, A. Vignaud, M. Dubois, P. Jomin, D. Berrahou, A. Raaijmakers, N. Avdievich, I. Melchakova *et al.*, “Constructive near-field interference effect in a birdcage mri coil with an artificial magnetic shield,” *PHYSICAL REVIEW APPLIED Phys Rev Applied*, vol. 13, p. 064004, 2020.
- [88] C. M. Collins, S. Li, Q. X. Yang, and M. B. Smith, “A method for accurate calculation of b1 fields in three dimensions. effects of shield geometry on field strength and homogeneity in the birdcage coil,” *Journal of Magnetic Resonance*, vol. 125, no. 2, pp. 233–241, 1997.
- [89] T. S. Ibrahim, R. Lee, B. A. Baertlein, Y. Yu, and P.-M. L. Robitaille, “Computational analysis of the high pass birdcage resonator: finite difference time domain simulations for high-field mri,” *Magnetic resonance imaging*, vol. 18, no. 7, pp. 835–843, 2000.

- [90] T. S. Ibrahim, R. Lee, B. A. Baertlein, A. Kangarlu, and P.-M. L. Robitaille, "Application of finite difference time domain method for the design of birdcage rf head coils using multi-port excitations," *Magnetic resonance imaging*, vol. 18, no. 6, pp. 733–742, 2000.
- [91] Z. N. Chen, D. Liu, H. Nakano, X. Qing, and T. Zwick, *Handbook of antenna technologies*. Springer Publishing Company, Incorporated, 2016.
- [92] Q. X. Yang, J. Wang, X. Zhang, C. M. Collins, M. B. Smith, H. Liu, X.-H. Zhu, J. T. Vaughan, K. Ugurbil, and W. Chen, "Analysis of wave behavior in lossy dielectric samples at high field," *Magnetic resonance in medicine: an official journal of the international society for magnetic resonance in medicine*, vol. 47, no. 5, pp. 982–989, 2002.
- [93] K. Uğurbil, P.-F. Van de Moortele, A. Grant, E. J. Auerbach, A. Ertürk, R. Lagore, J. M. Ellermann, X. He, G. Adriany, and G. J. Metzger, "Progress in imaging the human torso at the ultrahigh fields of 7 and 10.5 t," *Magnetic Resonance Imaging Clinics*, vol. 29, no. 1, pp. e1–e19, 2021.
- [94] P.-M. L. Robitaille, "Ultra high field magnetic resonance imaging: a historical perspective," in *Ultra high field magnetic resonance imaging*. Springer, 2006, pp. 1–17.
- [95] <https://www.fcc.gov/general/body-tissue-dielectric-parameters>.
- [96] E. Moser, E. Laistler, F. Schmitt, and G. Kontaxis, "Ultra high field nmr and mri the role of magnet technology to increase sensitivity and specificity," *Frontiers in Physics*, vol. 5, p. 33, 2017.
- [97] S. L. Sokol, Z. A. Colwell, S. K. Kandala, M. F. Imani, and S.-M. Sohn, "Flexible metamaterial wrap for improved head imaging at 3 t mri with low cost and easy fabrication method," *IEEE Antennas and Wireless Propagation Letters*, vol. 21, no. 10, pp. 2075–2079, 2022.
- [98] W. Liu, C. M. Collins, P. J. Delp, and M. B. Smith, "Effects of end-ring/shield configuration on homogeneity and signal-to-noise ratio in a birdcage-type coil loaded with a human head," *Magnetic Resonance*

- in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine*, vol. 51, no. 1, pp. 217–221, 2004.
- [99] D. I. Hoult and R. Richards, “The signal-to-noise ratio of the nuclear magnetic resonance experiment,” *Journal of Magnetic Resonance (1969)*, vol. 24, no. 1, pp. 71–85, 1976.
- [100] E. Yacoub, A. Shmuel, J. Pfeuffer, P.-F. Van De Moortele, G. Adriany, P. Andersen, J. T. Vaughan, H. Merkle, K. Ugurbil, and X. Hu, “Imaging brain function in humans at 7 tesla,” *Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine*, vol. 45, no. 4, pp. 588–594, 2001.
- [101] P. A. Bottomley and W. A. Edelstein, “Power deposition in whole-body nmr imaging,” *Medical physics*, vol. 8, no. 4, pp. 510–512, 1981.
- [102] C.-N. Chen, V. Sank, S. Cohen, and D. Hoult, “The field dependence of nmr imaging. i. laboratory assessment of signal-to-noise ratio and power deposition,” *Magnetic resonance in medicine*, vol. 3, no. 5, pp. 722–729, 1986.
- [103] V. Taracila, L. S. Petropoulos, T. P. Eagan, and R. W. Brown, “Image uniformity improvement for birdcage-like volume coils at 400 mhz using multichannel excitations,” *Concepts in Magnetic Resonance Part B: Magnetic Resonance Engineering: An Educational Journal*, vol. 29, no. 3, pp. 153–160, 2006.
- [104] H. Song, K.-N. Kim, and D. Hernandez, “Simulation design of incremental leg tapered birdcage coil for head imaging at 4.7 t mri,” *Applied Sciences*, vol. 11, no. 5, p. 2064, 2021.
- [105] F. Padormo, A. Beqiri, J. V. Hajnal, and S. J. Malik, “Parallel transmission for ultrahigh-field imaging,” *NMR in Biomedicine*, vol. 29, no. 9, pp. 1145–1161, 2016.
- [106] I. A. Elabyad, M. Terekhov, D. Lohr, M. Bille, M. Hock, and L. M. Schreiber, “A novel antisymmetric 16-element transceiver dipole antenna array for parallel transmit cardiac mri in pigs at 7 t,” *NMR in Biomedicine*, p. e4726, 2022.



- [107] K. Setsompop, V. Alagappan, B. Gagoski, T. Witzel, J. Polimeni, A. Potthast, F. Hebrank, U. Fontius, F. Schmitt, L. L. Wald *et al.*, “Slice-selective rf pulses for in vivo b inhomogeneity mitigation at 7 tesla using parallel rf excitation with a 16-element coil,” *Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine*, vol. 60, no. 6, pp. 1422–1432, 2008.
- [108] K. Lakshmanan, G. Carluccio, J. Walczyk, R. Brown, S. Rupprecht, Q. X. Yang, M. T. Lanagan, and C. M. Collins, “Improved whole-brain snr with an integrated high-permittivity material in a head array at 7t,” *Magnetic resonance in medicine*, vol. 86, no. 2, pp. 1167–1174, 2021.
- [109] A. V. Nikulin, A. Vignaud, N. I. Avdievich, D. Berrahou, J. de Rosny, and A. Ourir, “Open birdcage coil for head imaging at 7t,” *Magnetic Resonance in Medicine*, vol. 86, no. 4, pp. 2290–2300, 2021.
- [110] T. S. Ibrahim, R. Lee, B. A. Baertlein, A. M. Abduljalil, H. Zhu, and P.-M. L. Robitaille, “Effect of rf coil excitation on field inhomogeneity at ultra high fields: a field optimized tem resonator,” *Magnetic resonance imaging*, vol. 19, no. 10, pp. 1339–1347, 2001.
- [111] N. S. Yadav, I. Kochar, T. K. Bhuiya, and R. Harsh, “Rf transmit/receive quadrature fed body birdcage coil for a 1.5 t mr system,” in *2018 2nd International Conference on Electronics, Materials Engineering & Nano-Technology (IEMENTech)*. IEEE, 2018, pp. 1–7.
- [112] T. Herrmann, J. Mallow, C. Bruns, J. Stadler, and J. Bernarding, “Improved b1 homogeneity for in vivo application of the birdcage coil architecture at 7 t ultra-high field mri,” *MAGMA*, vol. 28, p. S454, 2015.
- [113] J.-H. Seo, S.-D. Han, and K.-N. Kim, “Investigation of the b1 field distribution and rf power deposition in a birdcage coil as functions of the number of coil legs at 4.7 t, 7.0 t, and 11.7 t,” *Journal of the Korean Physical Society*, vol. 66, no. 12, pp. 1822–1826, 2015.

- [114] J. Mispelter and M. Lupu, "Homogeneous resonators for magnetic resonance: A review," *Comptes Rendus Chimie*, vol. 11, no. 4-5, pp. 340–355, 2008.
- [115] P. Boisssoles and G. Caloz, "Magnetic field properties in a birdcage coil," *archives-ouvertes. fr*, 2006.
- [116] A. S. Peshkovsky, "Dual-tuned tem/birdcage hybrid volume coil for human brain and spectroscopy," Jul. 3 2008, uS Patent App. 11/966,796.
- [117] S. Saha, "Hybrid birdcage-tem radio frequency (rf) coil for multinuclear mri/mrs," Oct. 11 2011, uS Patent 8,035,384.
- [118] H. Wen, A. S. Chesnick, and R. S. Balaban, "The design and test of a new volume coil for high field imaging," *Magnetic resonance in medicine*, vol. 32, no. 4, pp. 492–498, 1994.
- [119] N. Avdievich, I. Giapitzakis, A. Pfrommer, T. Borbath, and A. Henning, "Combination of surface and vertical loop elements improves receive performance of a human head transceiver array at 9.4 t," *NMR in Biomedicine*, vol. 31, no. 2, p. e3878, 2018.
- [120] K. Lakshmanan, M. Cloos, R. Brown, R. Lattanzi, D. K. Sodickson, and G. C. Wiggins, "The loopole antenna: A hybrid coil combining loop and electric dipole properties for ultra-high-field mri," *Concepts in Magnetic Resonance Part B, Magnetic Resonance Engineering*, vol. 2020, 2020.
- [121] J. Guan, S. Yan, and J.-M. Jin, "An accurate and efficient finite element-boundary integral method with gpu acceleration for 3-d electromagnetic analysis," *IEEE transactions on antennas and propagation*, vol. 62, no. 12, pp. 6325–6336, 2014.
- [122] J.-C. Nédélec, "A new family of mixed finite elements in r3," *Numerische Mathematik*, vol. 50, no. 1, pp. 57–81, 1986.
- [123] I. P. Georgakis, I. I. Giannakopoulos, M. S. Litsarev, and A. G. Polimeridis, "A fast volume integral equation solver with linear basis functions for the accurate computation of em fields in mri," *IEEE*

- Transactions on Antennas and Propagation*, vol. 69, no. 7, pp. 4020–4032, 2020.
- [124] M. Bonazzoli, V. Dolean, F. Hecht, and F. Rapetti, “An example of explicit implementation strategy and preconditioning for the high order edge finite elements applied to the time-harmonic maxwell’s equations,” *Computers & Mathematics with Applications*, vol. 75, no. 5, pp. 1498–1514, 2018.
- [125] J.-M. Jin, *The finite element method in electromagnetics*. John Wiley & Sons, 2015.
- [126] F. Rapetti and A. Bossavit, “Whitney forms of higher degree,” *SIAM Journal on Numerical Analysis*, vol. 47, no. 3, pp. 2369–2386, 2009.
- [127] P. Boissoles and G. Caloz, “Accurate calculation of mutual inductance and magnetic fields in a birdcage coil,” *Preprint IRMAR*, pp. 06–07, 2006.
- [128] G. Giovannetti, L. Landini, M. F. Santarelli, and V. Positano, “A fast and accurate simulator for the design of birdcage coils in mri,” *Magnetic Resonance Materials in Physics, Biology and Medicine*, vol. 15, no. 1, pp. 36–44, 2002.
- [129] Y. C. Kim, H. D. Kim, B.-J. Yun, and S. F. Ahmad, “A simple analytical solution for the designing of the birdcage rf coil used in nmr imaging applications,” *Applied Sciences*, vol. 10, no. 7, p. 2242, 2020.
- [130] J. Tropp, “The theory of the bird-cage resonator,” *Journal of Magnetic Resonance (1969)*, vol. 82, no. 1, pp. 51–62, 1989.
- [131] J. C. Watkins and E. Fukushima, “High-pass bird-cage coil for nuclear-magnetic resonance,” *Review of scientific instruments*, vol. 59, no. 6, pp. 926–929, 1988.
- [132] R. Pascone, B. Garcia, T. Fitzgerald, T. Vullo, R. Zipagan, and P. Cahill, “Generalized electrical analysis of low-pass and high-pass birdcage resonators,” *Magnetic resonance imaging*, vol. 9, no. 3, pp. 395–408, 1991.