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Charge determination of nuclei with the AMS-02 silicon tracker

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Abstract

The silicon tracker of the AMS-02 detector measures the trajectory in three dimensions of electrons, protons and nuclei to high precision in a dipole magnetic field and thus measures their rigidity (momentum over charge) and the sign of their charge. In addition, it measures the specific energy loss of charged particles to determine the charge magnitude. Ladders from the AMS-02 tracker have been exposed to ion beams at CERN and GSI to study their response to nuclei

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from helium up to the iron group. The longest ladder, $72 \times 496\,mm^2$, verified in the tests contains 12 sensors. Good charge resolution is observed up to iron.

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Keywords: AMS-02; Silicon tracker; Energy loss; Charge of nuclei

1. Introduction

The Alpha Magnetic Spectrometer (AMS) analyzes cosmic radiation of galactic and extra-galactic origins at an altitude of 400 km. A precursor flight on NASA Space Shuttle mission STS-91 took place in June 1998, using the prototype detector AMS-01. The AMS-01 detector consisted of a permanent magnet with silicon microstrip tracker planes, a time-of-flight system and two layers of a threshold Cherenkov counter. The tracker of the AMS-01 detector had $\sim 2.1\,m^2$ of silicon micro-strip sensors distributed on six layers. All sensors functioned successfully throughout the flight with noise levels comparable to those measured on the ground. The precursor flight demonstrated the successful adaptation of the silicon microstrip detector technology to a large area silicon detector in space. Details of the flight performance of the AMS-01 tracker can be found in Ref. [1]. The experiment took data during 10 days resulting in about 100 million triggers. Analysis of this wealth of data has already allowed a broad spectrum of physics results concerning both cosmic rays and the Earth's radiation belts [2]. Based on experience gathered during this first mission, a new detector, AMS-02 [3], with a broader scope is being built. An exploded view of this detector is shown in Fig. 1. The detector is manifested to be installed on the International Space Station (ISS) in 2008.

The new detector aims to extend the energy range of the spectrometer into the TeV region with improved particle identification capabilities. It is built around a spectrometer with a superconducting magnet and a silicon microstrip tracker, supplemented with a transition radiation detector, a time-of-flight system, a ring imaging Cherenkov detector and an electromagnetic calorimeter for particle identification. The main physics goals are the search for dark matter, the search for anti-helium and heavier anti-nuclei, the collection of data on the origin and propagation of cosmic rays as well as the observation of high-energy photons from diffuse and point sources.

The new design of the tracking detector for AMS-02 requires a total of 192 ladders which are arranged on eight layers. AMS-02 ladders consist of up to 15 double-sided silicon strip sensors. The junction side (or S-side) strips have an implementation pitch of 27.5 μm and a read-out pitch of 110 μm. The ohmic side (or K-side) strips have an implementation pitch of 104 μm and a read-out pitch of 208 μm. These read-out strips of the K- and S-sides are separately connected in different daisy-chains to front-end hybrid circuits. There are 640 read-out channels for the S-side and 384 read-out channels for the K-side. The front-end hybrid design is based on the VA-hdr9a readout chip: a high dynamic range chip developed on the basis of the VA and Viking chips [4]. Details of the tracker design and the production of the sensor and ladder can be found in Refs. [3,5].

2. Experimental setup

To study the AMS-02 ladder response to nuclei, six ladders were exposed to ion beams at CERN and GSI in October 2003. At CERN, a fragmentation beam was produced from a primary indium beam with 158 GeV/A impinging on a beryllium target. Secondary nuclei were selected according to the ratio of atomic mass (A) to atomic charge (Z). Two values were chosen, $A/Z = 2$ and $A/Z = 2.25$. Tests at GSI were made with boron and carbon beams at 0.8 GeV/A.

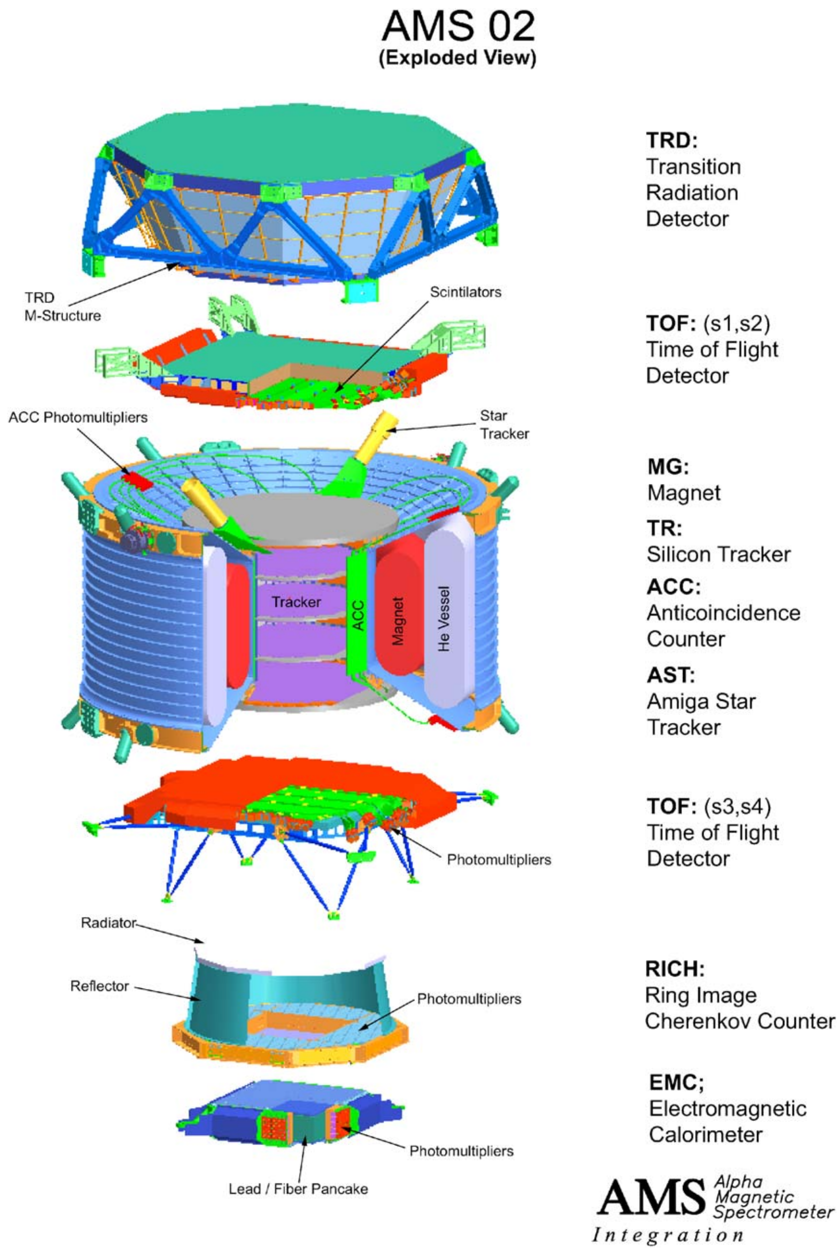

Fig. 1. Exploded view of the AMS-02 detector showing its main components. The detector is about 3 m in diameter, 3 m high and weighs close to 7 t.

The six ladders, five with 12 sensors and one with nine sensors, were selected from the flight hardware produced for AMS-02 and were instrumented with flight-like electronics. All ladders were orthogonal to the beam direction during tests. In addition, a prototype AMS-02 RICH detector [6,7] was placed behind the six ladders and was used to verify charges measured by ladders during the CERN run. A trigger to the data acquisition system based on a PC-computer was provided by using a scintillator beam telescope.

3. Analysis

The ionization energy generated by a charged particle crossing a silicon strip sensor is collected by a cluster of adjacent read-out strips. The first step in the analysis is to correct the signal from each channel with a common mode shift and pedestal. The common mode shift represents the mean of the uniform shift over all channels of a VA chip. Randomly triggered events after the common mode shift correction are used to determine the pedestal and noise value of each channel. The average value of the channel noise is about 2.5 ADC counts for the S-side and 3.0 ADC counts for the K-side.

Clusters are then selected using the following criteria:

- A cluster seed is found at channel i with the maximum signal on one side of a ladder. It is required to be greater than three times the channel noise.
- The contiguous neighboring channels with signal greater than 1.5 times their channel noise are included in the cluster. The average cluster width is about 2 channels for proton and goes up to about 14 channels for iron.
- The integral signal of a cluster is required to be larger than 15 ADC counts for the S-side and 20 ADC counts for the K-side, compared to typical values of 26 and 32 ADC counts for minimum ionizing protons.

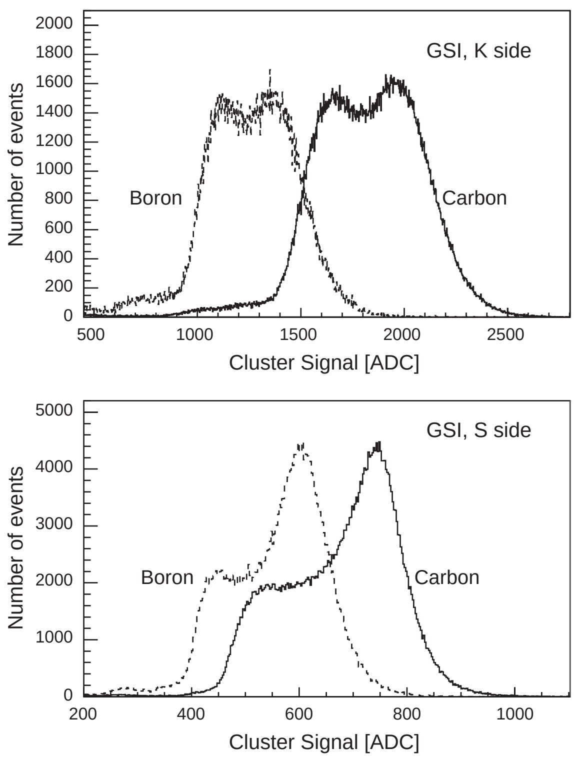

Fig. 2. Cluster signal distributions from the K- and S-sides of a single ladder in the GSI tests. All six ladders have similar distributions.

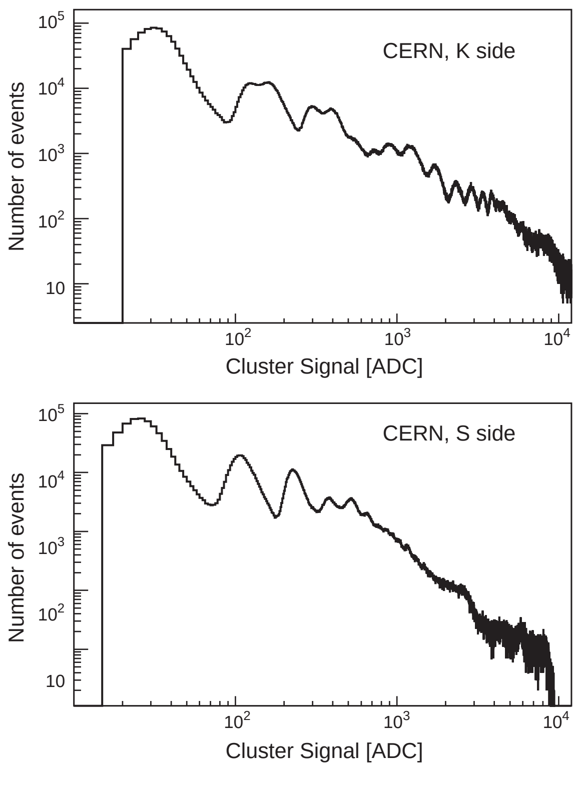

Fig. 3. Cluster signal distributions from the K- and S-sides of a single ladder in the CERN tests with $A/Z = 2.25$. All six ladders have similar distributions.

Fig. 2 shows the distributions of the boron and carbon integral cluster signal for the K- and S-sides of a single ladder from the GSI data. The distributions from all ladders are similar. A double-peak structure is observed for both sides and for both nuclei. The corresponding spectra of the CERN data with $A/Z = 2.25$ are shown in Fig. 3. A similar double-peak structure is observed. The difference in signal between two sides for $Z>2$ particles is due to the different strip layout and the different gain in front-end electronics.

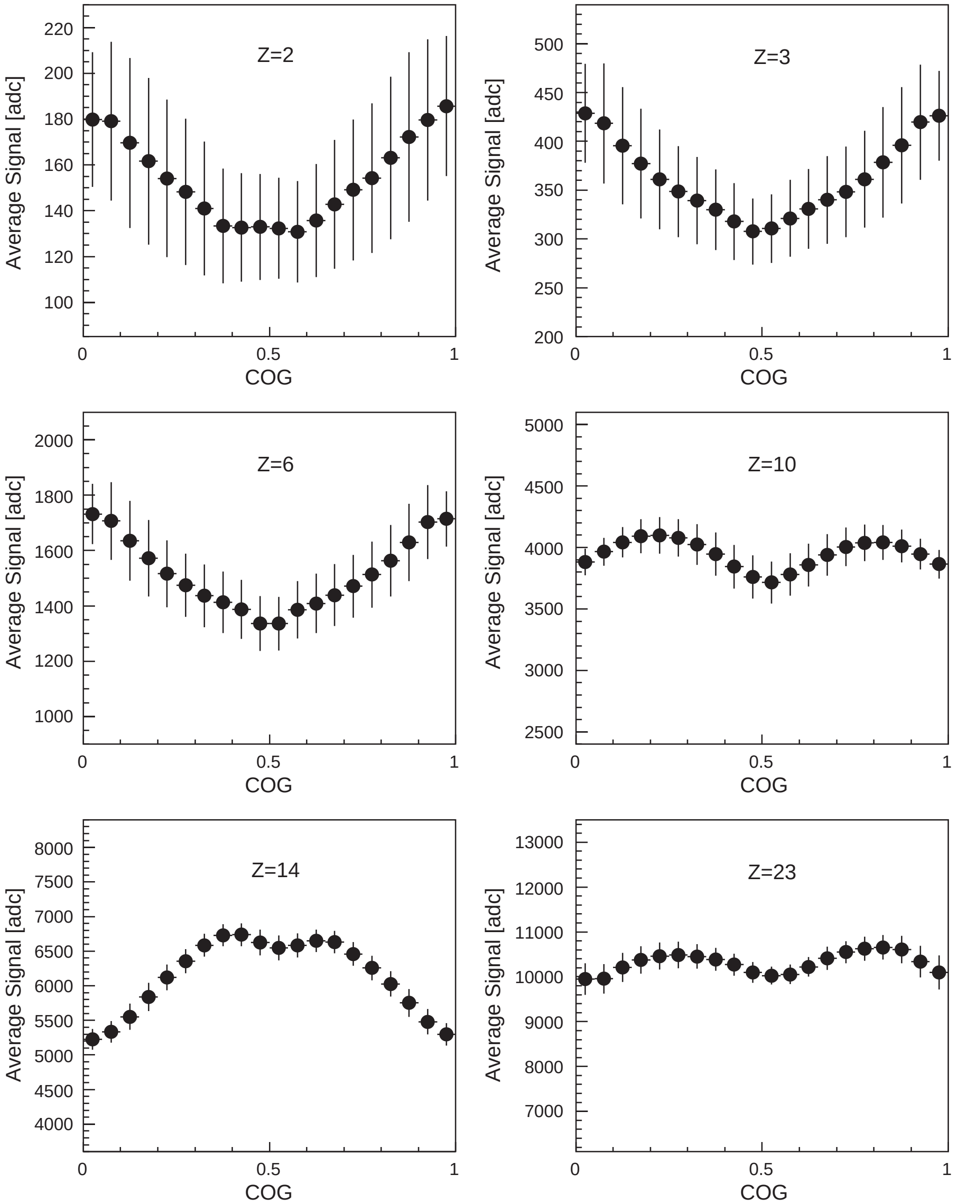

Fig. 4. Average cluster signal as a function of position relative to the read-out strip, COG, for selected nuclei from the K-side of a single ladder. All six ladders show a similar dependence. The error bars are the standard deviation of average cluster signals.

The integral cluster signal is found to depend on the impact location relative to the two nearest read-out strips. The shape of this dependence is also found to vary with the total energy deposited and hence with the nucleus charge. To improve the nuclei identification, the cluster signal has to be corrected according to this relative impact location and the total energy deposited. The cluster signal

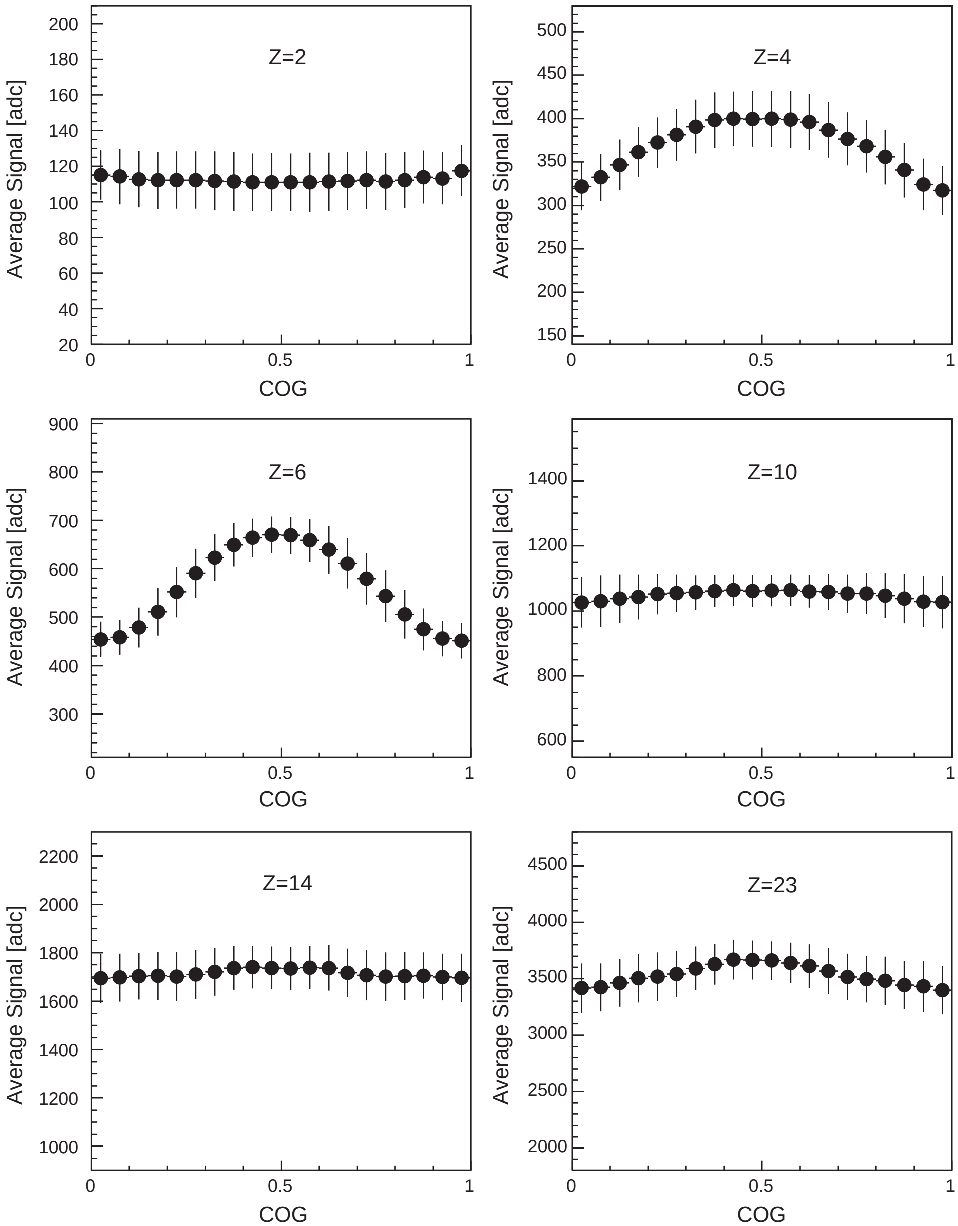

Fig. 5. Average cluster signal as a function of position relative to the read-out strip, COG, for selected nuclei with the S-side of a single ladder. All six ladders show a similar dependence. The error bars are the standard deviation of average cluster signals.

calibration is estimated first for the K-side with the following steps:

(A) Calibration factors for the K-side of ladders are obtained first from the helium sample of the CERN data. Helium is selected by cuts on the cluster signal. This first calibration factor is only dependent on the particle position, which is determined by the relative position of the cluster, COG. This quantity is defined as the distance of the cluster centre-of-gravity to the closest read-out strip in the left side, divided by the strip pitch. The correction is applied to the whole CERN data. The middle region of COG, $0.45 \leqslant \mathrm{COG} \leqslant 0.55$, is used as reference for the calculation of calibration factors.

(B) The corrected cluster signal of each ladder is transformed from ADC units to charge (Z) units to equalize gain differences between different read-out chips. Then the results from different ladders are combined to obtain the average charge value, $\bar{Z}$, using a truncated mean

$$\bar{Z} = \frac{1}{n-2}\left[\sum_{i=1}^{n} Z_i - (Z^{\mathrm{Max}} + Z^{\mathrm{Min}})\right]$$

$$n = 5, 6 \qquad (1)$$

where n is the number of ladders. Z^{Max} and Z^{Min} are the maximum and minimum charge values.

(C) This $\bar{Z}$ value is used to identify nuclei for individual ladders in order to re-estimate the calibration factor with both the COG and cluster signal dependence. The dependence on the cluster signal is estimated by a polynomial fit for each COG bin.

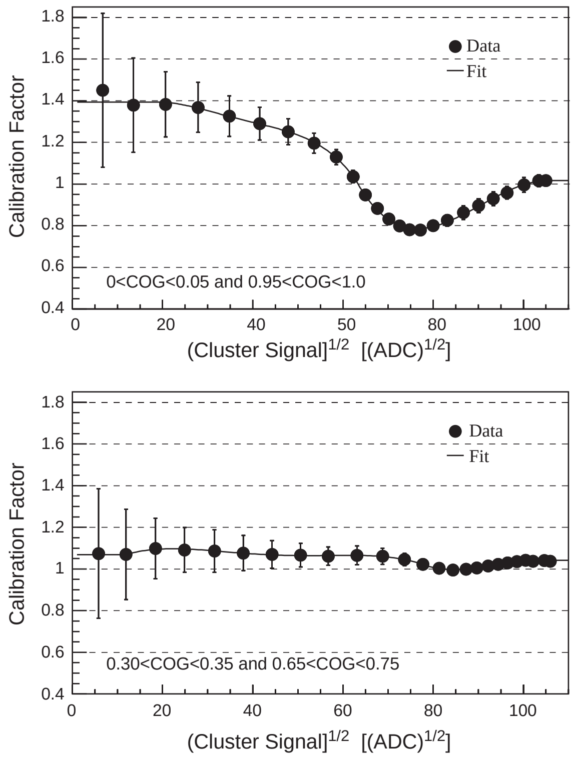

Fig. 6. Cluster signal dependence of the calibration factor from the K-side of a single ladder in two different COG regions. All six ladders show a similar dependence. The errors represent the standard deviation of the average cluster signals shown in Fig. 4.

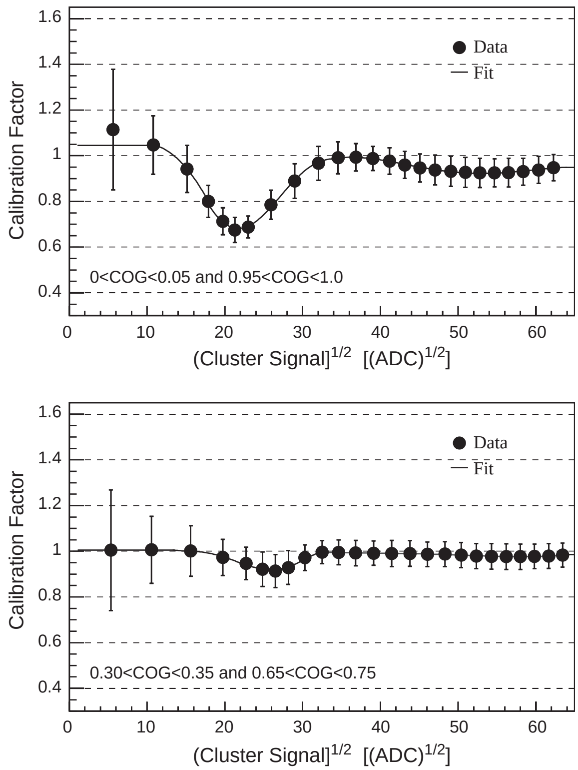

Fig. 7. Cluster signal dependence of the calibration factor from the S-side of a single ladder in two different COG regions. All six ladders show a similar dependence. The errors represent the standard deviation of the average cluster signals shown in Fig. 5.

(D) After applying the new calibration factor to the CERN data, steps (B) and (C) are repeated until there is no new nucleus identified.

The calibration factor to the cluster signal measured by the S-side of ladders is estimated by using the $\bar{Z}$ value from the K-side. Figs. 4 and 5 show the average cluster signal as a function of COG for different nuclei. The variation of the COG dependence on the cluster signal with different nuclei is clearly seen. This nucleus (cluster signal) dependence in the calibration factor to the cluster signal is also shown in Figs. 6 and 7 for two different COG bins. The nucleus dependence is similar between different COG bins, but the variation becomes smaller when the COG bin is close to 0.5.

The final corrected cluster signal distribution of a single ladder is shown in Fig. 8. The nucleus identification with the K-side is better than that from the S-side. With a single ladder, the nuclei can be identified up to silicon ($Z = 14$). Above silicon, the overlap between nuclei is significant because of saturation in the front-end electronics, which limits the maximum output of a read-out channel to about 3900 ADC counts. For the S-side, the overlap between nuclei is also significant from boron ($Z = 5$) to neon ($Z = 10$) due to the gain transition shown in Fig. 9. The measured cluster signals on the K- and S-sides of ladders are proportional roughly to Z^2. For the S-side, there are two linear regions with a factor of two difference in gain. For the K-side, the slope of the calibration curve changes around silicon because of the saturation effect. The S-side of ladders is not affected by saturation because of the lower overall gain.

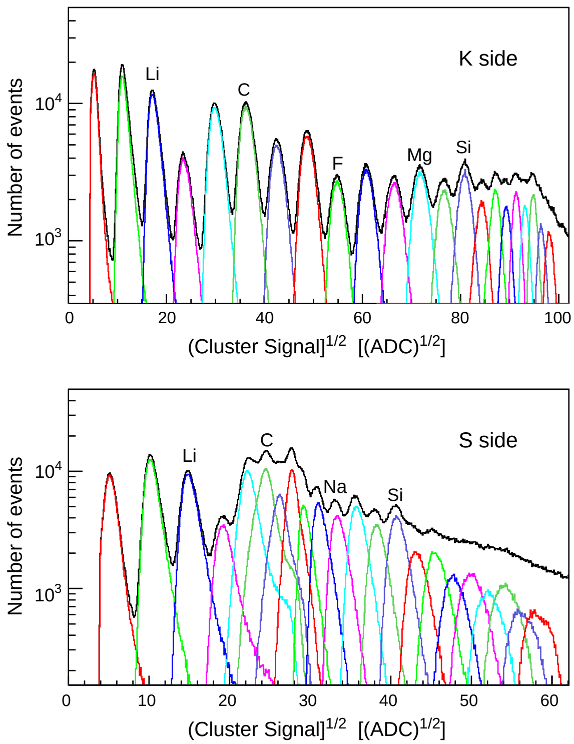

Fig. 8. Distributions of corrected cluster signal for the K- and S-sides of a single ladder. The contributions from individual nuclei are also shown. The distributions of all six ladders are similar.

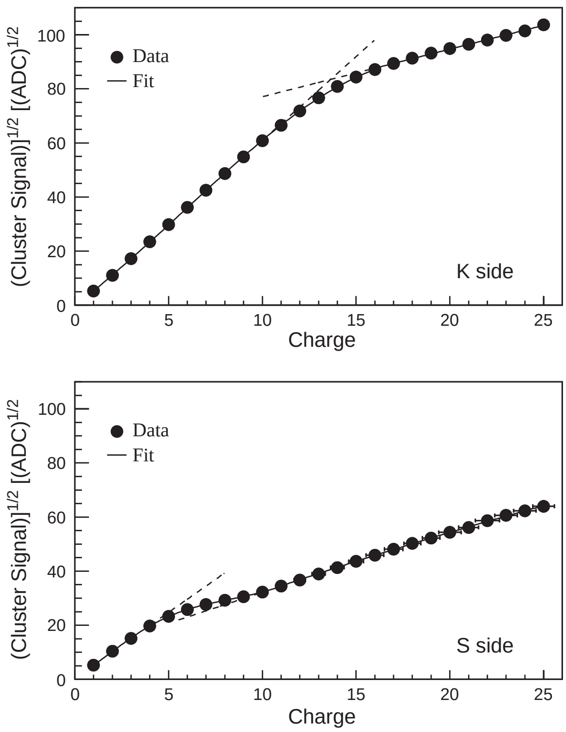

Fig. 9. Correlation between the charge and the corrected cluster signal for the K- and S-sides of a single ladder. The behaviour of all six ladders is similar.

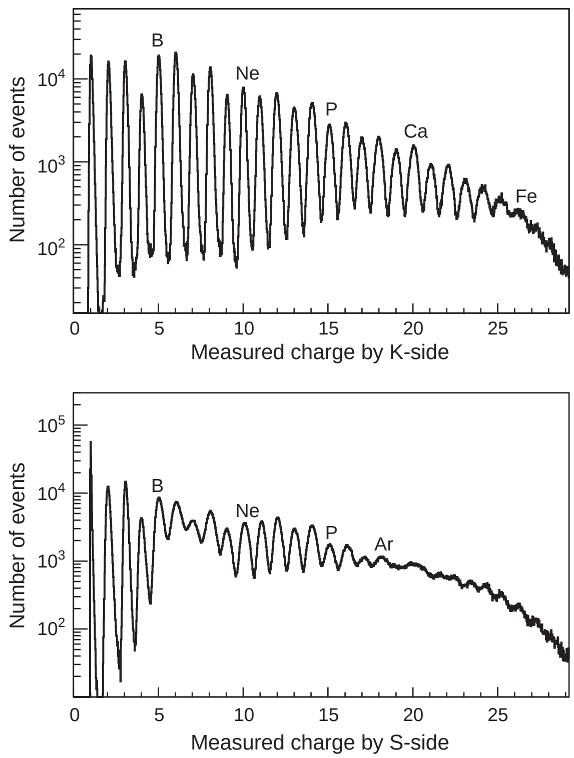

Fig. 10. Combined charge measurements of the K- and S-sides using all six ladders.

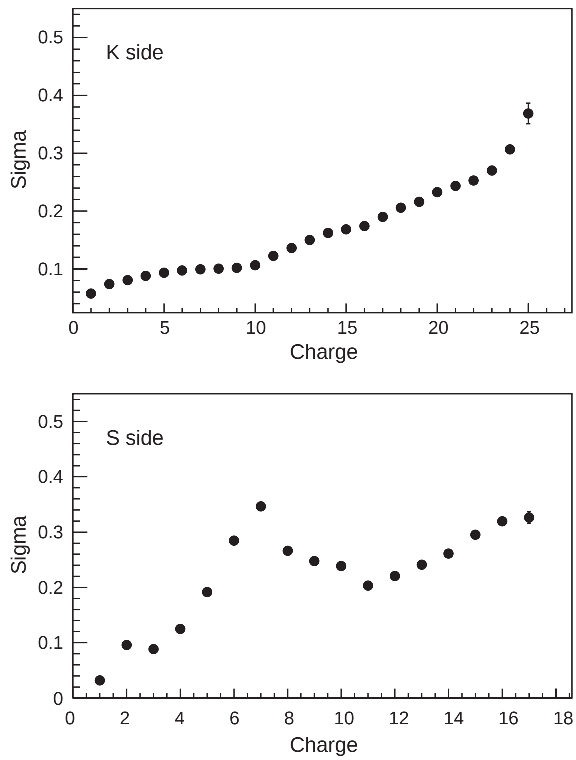

Fig. 11. Sigma of the Gaussian fits to the charge spectra of nuclei measured with the K- and S-sides of all six ladders.

The measured charge values from different ladders are combined for both the K- and S-sides by using the truncated mean described above. The results are shown in Fig. 10. With the combined results of six ladders, the nuclei can be identified up to iron ($Z = 26$) with the K-side and argon ($Z = 18$) with the S-side. The measured charge spectra are fitted with a Gaussian for each nucleus. The Gaussian width for each nucleus is plotted in Fig. 11. Fig. 12 shows the comparison of charge values measured from the AMS-02 RICH prototype and the K- and S-sides of tracker. A good correlation is observed up to iron for both sides of the ladders. The resolution of charge measurements from the K-side of the ladders is also comparable to the AMS-02 RICH prototype resolution. Nuclei can occasionally fragment in the beam line between the silicon ladders and the RICH prototype. In such cases, the measured charge value by the RICH prototype will be lower than the one measured by the silicon ladders. This effect is observed clearly in Fig. 12 although the fraction of these events is only a few percent. A detailed study on the identification of these ion fragmentation events in the RICH prototype is given in Ref. [7].

4. Conclusions

The performance of the AMS-02 silicon ladders in detecting a large range of nuclei has been measured. With six ladders, the nuclei can be identified from protons to irons ($Z = 26$). In the complete AMS-02 experiment, the silicon tracker includes eight layers of ladders.

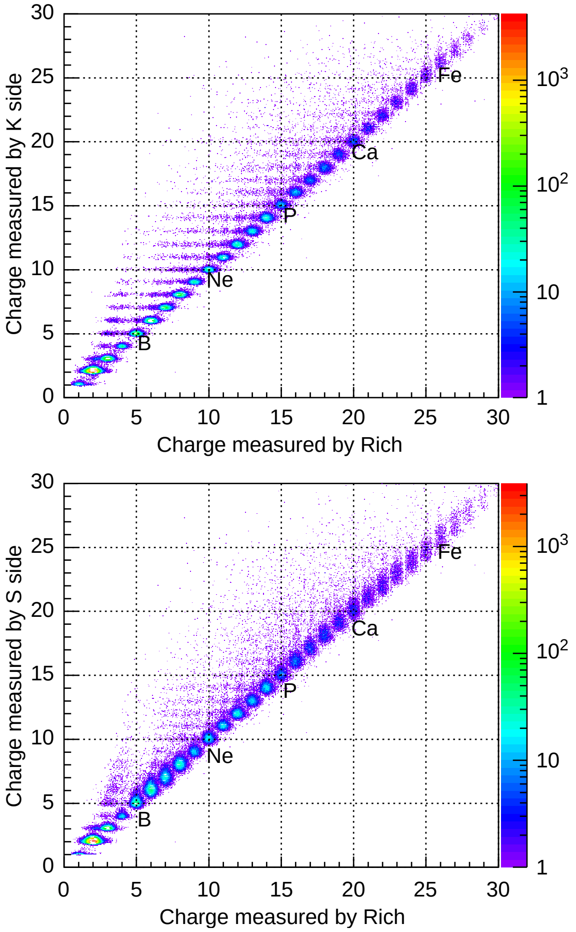

Fig. 12. Correlation of measured charge values from the RICH prototype with the K- and S-sides of the ladders.

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