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The ISS-CREAM Silicon Charge Detector for identification of the charge of cosmic rays up to Z = 26

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The Cosmic Ray Energetics And Mass experiment for the International Space Station (ISS-CREAM) is a space-borne mission designed for the precision measurement of the energy and elemental composition of cosmic rays. It is scheduled to be launched and installed on the ISS in August 2017. The Silicon Charge Detector (SCD), placed at the top of the ISS-CREAM payload, consists of 4 layers. Each layer has 2688 silicon pixels and associated electronics arranged in such a fashion that its active detection area of 78 x 74 cm^2 is free of any dead area. The foremost goal of the SCD is to efficiently and precisely measure the charge of cosmic rays passing through it. The 4-layer configuration was chosen to achieve the best precision in measuring the charge of cosmic rays within the constraints on the mass, volume and power allotted to it. The amount of material used for its support structure was minimized as well to reduce the chance of interactions of the cosmic ray within the structure. Given the placement of the SCD, its 4-layer configuration and the minimal amount of material in the cosmic-ray trajectory, the SCD is designed to measure the charge of cosmic rays ranging from protons to iron nuclei with excellent detection efficiency and charge resolution. We present the design and fabrication of the SCD. It successfully underwent space environment tests including vibration and thermal-vacuum qualification. We present the performance of the SCD during these tests, as well as its charge-measurement performance on the ground using cosmic muons and heavy ions in a beam test at the European Organization for Nuclear Research.

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1. Introduction

The Antarctic balloon-borne experiment Cosmic Ray Energetics And Mass (CREAM) has successfully completed seven flights between the years 2004 and 2017, and collected data for a total of 191 days during these flights. It observed a discrepant hardening in the energy spectra of cosmic rays [1]. The International Space Station (ISS) is an ideal platform to further investigate the unexpected hardening as well as explore fundamental issues like the acceleration mechanism and the origin of energetic cosmic rays because of the high duty cycle of experiments on the ISS platform. Thus, the space-borne experiment ISS-CREAM stationed to be deployed to the ISS is an obvious next step towards further investigation and exploration of the outstanding issues with high-statistics. The ISS-CREAM experiment adapts the detector concept and technology proven with the balloon-borne CREAM experiment.

The ISS-CREAM payload is configured with a finely segmented four-layer Silicon Charge Detector for charge measurements and a sampling tungsten/scintillator calorimeter including a carbon target for energy measurements. These detectors have already demonstrated their capabilities to determine the charge and energy of cosmic rays from 10^{10} to 10^{15} eV for the proton to iron elemental range with excellent resolution. In addition, two new compact detectors are installed: Top/Bottom Counting Detectors (TCD/BCD) and Boronated Scintillator Detector (BSD). The configuration of the ISS-CREAM payload and details of its components are discussed elsewhere [2].

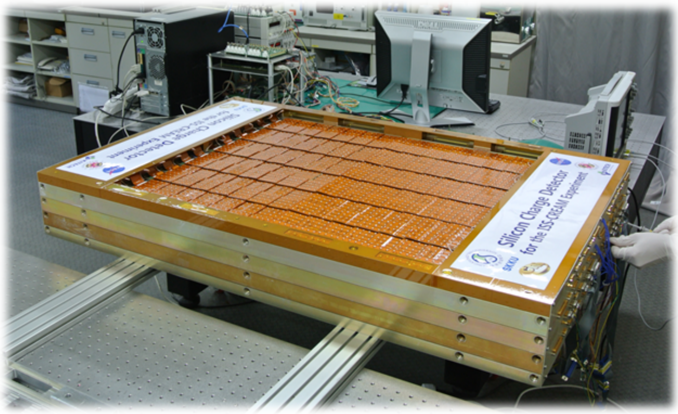

Figure 1: Overall view of the SCD.

2. Instrument Overview of the SCD

The SCD for the ISS-CREAM experiment consists of silicon pixel sensors, analog electronics, digital electronics and supporting mechanical structure. An overall view of the completed four-layer SCD is shown in Fig. 1. The mass of the SCD is 143 kg, and its outermost dimensions are 1227 mm (length) x 817 mm (width) x 166 mm (height). The SCD has four layers, and the active area in each layer is 782 mm x 736 mm. Each layer has 2688 channels and therefore the SCD has a total of 10752 channels. The power consumption of the SCD is 182.5 W. Details of the SCD building blocks mentioned above are described in the following subsections. The single layer

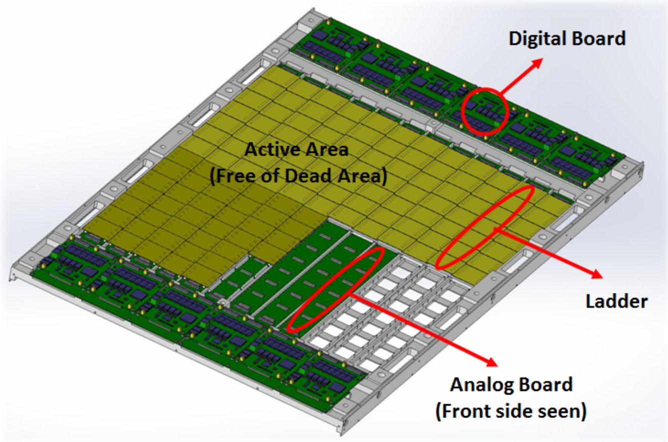

Figure 2: SCD single layer layout.

layout of the SCD is shown in Fig. 2. How the single layer of the SCD is built from these building blocks of the SCD and how the four-layer SCD is assembled are also explained in the following sections.

2.1 Silicon Sensor

Silicon pixel sensors in the ISS-CREAM SCD are fabricated on 525-μm thick silicon wafers. Each silicon sensor has 16 pixels, and is attached to a flexible printed circuit board for signal readout inter-connection. The process for fabricating such silicon sensors and completing the signal readout inter-connection is explained elsewhere [3]. Silicon sensors in general are known to be able to tolerate radiation level in space so that they exhibit no sign of degradation in their functionality even after many years of exposure to the radiation in space.

2.2 Analog Electronics

Analog electronics boards are equipped with CR1.4 ASIC chips which convert charge signals from silicon sensors to voltage signals [4]. The CR1.4 chips have been used in the calorimeter of the satellite-borne PAMELA experiment for nine years [5]. Therefore the radiation hardness of the CR1.4 chips has been proved by the space heritage of the PAMELA experiment. The front side of an analog board has connectors and mounting holes to accommodate seven silicon sensors while the backside of the board has seven CR1.4 chips.

2.3 Ladder

Seven silicon sensors are mounted onto the front side of an analog board to form a ladder. Note that the silicon sensors in the ladder slightly overlap each other so that there is no dead area along the length of the ladder. A ladder is a basic mechanical unit that populates the single layer structure of the SCD. Also a ladder is a basic electrical unit powered on/off and monitored. Various voltage, current and temperature sensors are installed in each ladder. The status and condition of the ladder are monitored by the slow control system (called housekeeping system) of the ISS-CREAM experiment which regularly reads voltage, current and temperature values from those sensors.

2.4 Digital Electronics

Digital electronics boards are equipped with ADC chips, radiation-hard Field Programmable Gate Array (FPGA) chips and various voltage regulators. Each digital board provides power for two ladders, configures and controls two analog boards in the ladders, and carries out digitization of analog signals from the two ladders. All electronics components in the digital boards are either radiation-hard or protected from a single event latch-up possible in space applications. The digital boards for the ISS-CREAM SCD have been modified from the ones for the balloon-borne experiment to accommodate radiation-hard components (in general larger than non radiation-hard components) and implement a protection measure against single event latch-ups for ADC chips while the functionality is kept unchanged. The digital boards are located off the active area as shown in Fig. 2 in order not to add material in the path of charged particles.

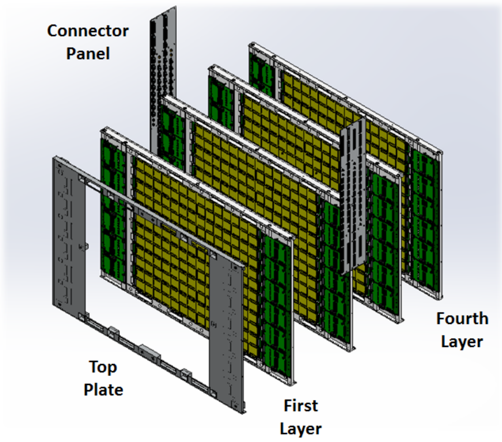

Figure 3: SCD layers along with top plate and connector panels.

2.5 Mechanical Structure and Assembly of the SCD

The supporting mechanical structure is designed in such a fashion as to minimize material in front of the silicon sensors and to guarantee effective heat conduction between major heat dissipating electronics components and mechanical structure. There are twenty four ladders and twelve digital boards installed in each SCD layer. The single layer layout is shown in Fig. 2 where all twelve digital boards are fully installed, but the ladders are not yet. The layout shows three completely empty slots with no ladders, three slots with only analog boards in place, and one slot with three silicon sensors removed. A ladder is a basic unit that populates the active area, and the silicon sensors are never removed from the analog board in the ladder once the ladder is mounted. Therefore, in the single layer layout of Fig. 2, the partial or full front sides of four analog boards (in green) are shown only for illustrative purpose to aid the reader's understanding.

Shown in Fig. 3 are the four SCD layers, top plate and two connector panels. The assembly order of the SCD is as follows: the fourth layer and the connector panels are assembled together first. Then the third layer is placed over the fourth layer, the second layer over the third layer, and the first layer over the second layer. Finally the top plate is placed over the first to complete the

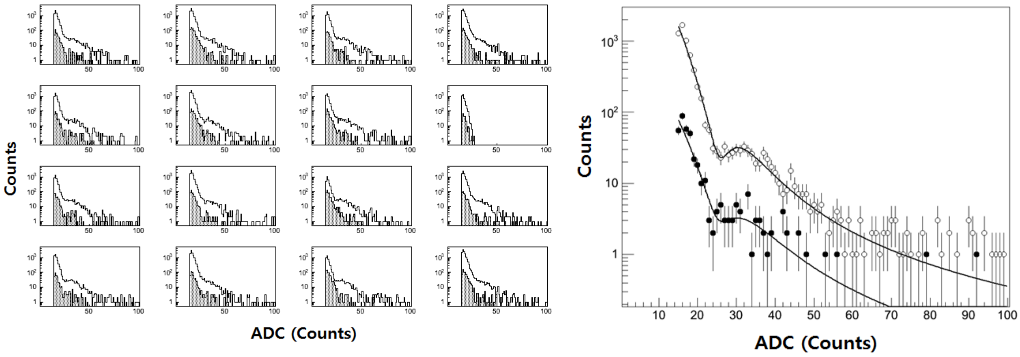

Figure 4: Left: muon signal distributions over the pedestal tail above the sparsification threshold observed in the 16 channels of one SCD sensor before (shaded) and after (unshaded) the space environment tests. Right: zoomed distributions of muon signals over pedestal tail detected in the thirteenth (at the fourth row and first column in the left figure) pixel. Open and solid circles represent the distributions obtained before and after the space environment tests, respectively. Each curve, a Gaussian and Landau combined function, is the best fit to the corresponding distribution.

SCD assembly. Note that the top plate is open at the active area to minimize the material in front of silicon sensors.

3. Performance of the SCD

The SCD has gone through space environment tests at the instrument level successfully, and then was delivered to NASA to be integrated into the ISS-CREAM payload. After the integration, the payload went through space environment tests at NASA facilities. Then the ISS-CREAM payload was delivered to the launch site, Kennedy Space Center, in August 2015 after all space environment tests. The functionality of the SCD in the payload was checked before and after each environment test with muon events triggered by the external scintillators placed at the top and bottom of the payload. The pedestal tail (above the sparsification threshold of 15 ADC counts) and muon signals, registered in 16 pixels of a silicon sensor in the SCD, are shown in the left of Fig. 4. Each shaded histogram in the left of Fig. 4 shows the distribution of pedestal tail plus muon signals in each pixel of the sensor from the data taken before the space environment tests, while the unshaded histogram shows the distribution from the data taken after all space environments tests. Before and after the space environment tests, muon data were taken for 4 hours and 22 hours, respectively. Obviously the statistics of the data taken before the environments tests were poor, but the number of pixels with muon signals observed remained the same before and after the space environment tests. Shown in the right of Fig. 4 are the zoomed distributions of pedestal tail plus muon signals detected in the thirteenth pixel where open and solid circles represent the distributions from data taken before and after the space environment tests, respectively. Each distribution was fitted with a Gaussian function with its mean fixed at zero for pedestal and a Landau function for muon signals. From the fits, the pedestal widths are 7.6 ± 0.3 and 6.8 ± 0.1 ADC counts, respectively, and the peak values of muon signals are 31.9 ± 2.5 and 31.4 ± 0.4 ADC counts, respectively. Therefore the peak of muon signals remained the same before and after the space environment tests. The signal to noise ratios measured with muons are 4.2±0.4 and 4.6±0.1, respectively. They remained statistically consistent before and after the space environment tests.

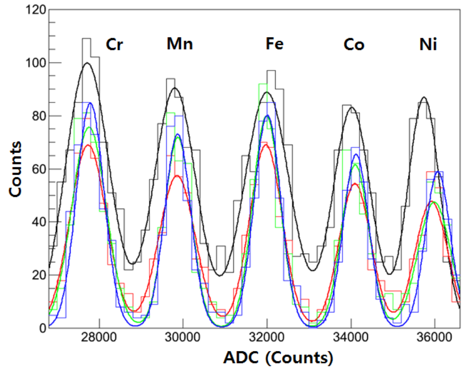

Figure 5: Distributions of the detector responses to heavy ions. The black, red, green and blue histograms are the distributions of single-layer response, double-layer, triple-layer and quadruple-layer average responses, respectively. Each distribution was fitted with a series of Gaussian functions representing the responses to Cr, Mn, Fe, Co and Ni ions, and each curve is the best fit to the corresponding distribution.

A heavy-ion beam, required to verify the capability of precision charge measurement of the SCD, became available at the European Organization for Nuclear Research (CERN) in November 2016. The heavy-ion beam was composed of secondary ions ranging from helium to zinc. A prototype instrument of a four-layer configuration using the same types of silicon pixel sensors and electronics installed in the SCD was exposed to the heavy-ion beam. The description of the beam test setup and the test result are found elsewhere [6]. The responses of pixels in layers of the prototype instrument to Cr, Mn, Fe, Co and Ni ions (i.e., the amounts of energy loss measured at the pixels) are shown in Fig. 5. Shown in black in Fig. 5 is the single-layer response to the four types of ions. Double-layer, triple-layer and quadruple-layer average responses to the ions are shown in red, green and blue in Fig. 5, respectively. The distribution of each response was fitted with a series of Gaussian functions as shown in Fig. 5. The resolution of the response to a particular ion is the RMS width of the Gaussian function which fits the response best. The resolutions of single-layer response, double-layer, triple-layer and quadruple-layer average responses to Fe ions, obtained from the corresponding fit functions, are 544±31, 389±19, 327±18 and 318±17 ADC counts, respectively. The Bethe-Bloch formula relates the mean energy loss ($< \frac{dE}{dx} >$) of the ions in a material to the charge (Z) of the ions as follows: $< \frac{dE}{dx} >= IZ^2$. Therefore the relation between the resolution of the energy loss ($\sigma_{dE/dx}$) and the charge resolution (σ_Z) is $\sigma_Z = \sigma_{dE/dx}/(2IZ)$. The charge resolutions (in charge unit) obtained using the value of I evaluated for Fe ions are 0.221±0.013 for single-layer response, 0.158±0.008 for double-layer average response, 0.133±0.007 for triple-layer average response and 0.129±0.007 for quadruple-layer average response, respectively. It is clearly demonstrated that the charge resolution improves as the number (i.e., the number of layers) for charge measurement increases as expected.

4. Conclusions

The SCD for the ISS-CREAM instrument was designed and manufactured to have the least amount of non-active material and the most active volume along the path of cosmic rays within the constraints on the mass, volume and power allotted to it. The charge resolution is expected to improve as the number of layers for charge measurement increases. The improvement was confirmed with the heavy ion beam test using the prototype detector. The electronics components used in the readout electronics of the SCD are all radiation-hard components. Therefore the SCD electronics as a whole is insusceptible to damage and single event latch-up caused by space radiation. The SCD completed the space environment (vibration and thermal-vacuum) tests successfully both at the instrument level and at the payload level. Therefore the SCD demonstrated that it will be able to withstand vibration and thermal-vacuum cycles during launch to the ISS and operation there. The ISS-CREAM instrument is scheduled to be launched and installed on the ISS in August 2017, and the SCD will carry out its primary mission of detecting and identifying cosmic rays with an excellent charge resolution.

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