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On-orbit performance of the ISS-CREAM SCD

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The Cosmic Ray Energetic And Mass for the International Space Station (ISS-CREAM) experiment is designed for precision measurements of energy spectra and elemental composition of cosmic rays. It was 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 with a total of 10,752 silicon pixels which have 1.37×1.57 cm^2 size each. Each layer is arranged in such a fashion that its active detection area of 78×74 cm^2 is free of any dead area. The SCD 4-layer configuration was chosen to achieve the best precision in measuring the charge of cosmic rays from proton to iron nuclei with a charge resolution of $0.1 - 0.3$e. We will present its on-orbit performance and operation status on the ISS since the launch.

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1. Introduction

The origin of cosmic rays, and their acceleration and propagation mechanisms, have remained unknown since their discovery a century ago. Various suborbital and space experiments have been studying cosmic rays of energies up to 10^{15} eV. The Cosmic Ray Energetic And Mass (CREAM) instrument, an Antarctic balloon-borne payload, was one of such suborbital experiments. It successfully completed seven flights between the years 2004 and 2017, and accumulated a total 191-day exposure. This made possible the discovery of an unexpected hardening in the energy spectra of cosmic rays at high energies [1]. However, high statistics data are required for the further investigation of this effect. Thus, ISS-CREAM was an obvious next step towards further investigation and exploration of cosmic rays with unprecedented statistics. The ISS-CREAM experiment adapts the detector concept and technology proven with the balloon-borne CREAM program.

2. ISS-CREAM instrument

The ISS-CREAM payload shown in Figure 1 is configured with a finely segmented four-layer Silicon Charge Detector (SCD) for charge measurements and a sampling tungsten/scintillator calorimeter (CAL) 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 the CREAM experiment. In addition, two new compact detectors were installed: Top/Bottom Counting Detectors (TCD/BCD) and a Boronated Scintillator Detector (BSD) [2]. In this paper, we present the SCD operation and its performance in space.

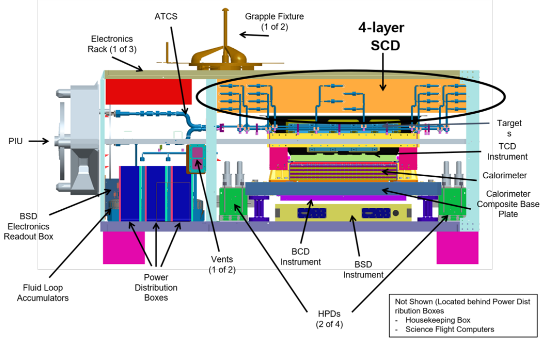


Figure 1: The ISS-CREAM payload

The SCD is located at top of the ISS-CREAM payload for the identification of cosmic rays and was built by SungKyunKwan University (SKKU) in Korea. The SCD consists of silicon pixel sensors and has a mass of 143 kg. Its outermost dimensions are 122.7 cm (length) × 81.7 cm (width) × 16.6 cm (height). The SCD has four layers, and the active area in each layer is 78 cm × 74 cm. Each of the four SCD layers have 2,688 channels for a total of 10,752 channels. The charge resolution for cosmic rays, from proton to iron nuclei, is $0.1 - 0.3e$ depending on energy and charge. The charge resolution was confirmed by CERN beam test in 2016 [3].

3. SCD operation in space

The ISS-CREAM payload was launched on Aug.15, 2017 (KST) at the Kennedy Space Center. It was transported to the International Space Station (ISS) on the SpaceX Dragon carrier. Three days after launch, the ISS-CREAM payload was successfully docked to the ISS and the SCD was turned on Aug. 22, 2017. For electronics power operation, each SCD layer is divided into 4 sections which are labeled Quadrant A to Quadrant D. Each quadrant consists of 6 ladders as shown in Figure 2.

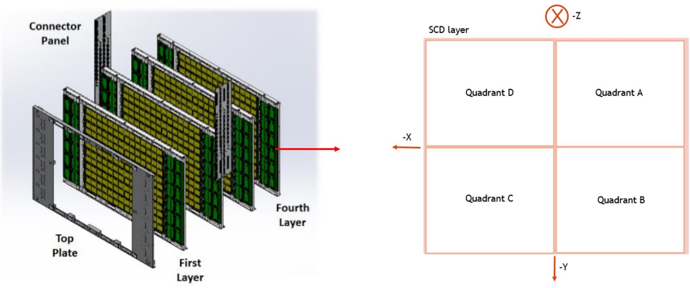


Figure 2: The ISS-CREAM SCD (left), the SCD quadrants (right)

3.1) Detector status

Figure 3 (left) shows the 4-layer SCD status after launch. The first and second (SCD1, SCD2) layers are working well during the on-orbit period since launch, though the first layer has 48 dead electronics channels. Initially, the third and fourth (SCD3, SCD4) layers had power problem. However, we found a stable power configuration on Aug. 2018. The fourth layer SCD4 was turned off and the third layer SCD3 was turned on for 75 percentage on-orbit period, because the power of three quadrants in SCD3 can stay normal for the operation. Thus, except dead channels in 3-layers, all channels work normal. Figure 3 (right) shows responses of cosmic rays together with two pre-launch tests on the ground in 16 channels of SCD1, which are quite similar for all channels.

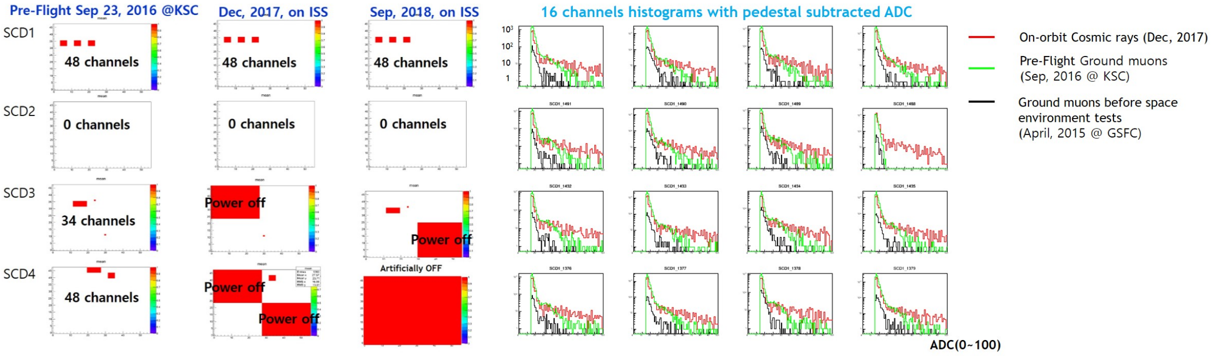


Figure 3: SCD dead channels and Power off quadrants (left). 16 channels responses to cosmic- ray particles in SCD1 (right)

3.2) Correlation of Temperature and Pedestal

The ADC pedestal value is closely correlated with temperature due to the nature of amplifier chips. Therefore, in order to increase physics data taking time, we calculated the pedestal ADC temperature dependence. Figure 4 (left) shows the correlation between temperature and the pedestal value. From the left figure, we can estimate the pedestal ADC value by a linear fit. For example, the pedestal value increased 18 counts with a temperature change of 1 ^{o}C. Figure 4 (right) compares the pedestal ADC value and the estimated ADC value by linear function. Comparing blue circle and red circle, the differences are within 5 ADC counts which is the nominal pedestal mean RMS value. So, the pedestal value is well estimated by temperature. We calculated the pedestal fluctuation within the error for one hour. Thus, the pedestal fluctuation is within the error during one hour. Therefore, we are taking the pedestal data every one hour, and can increase physics data taking time from this calibration.

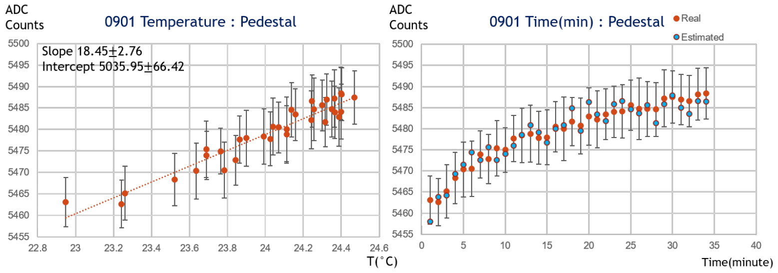


Figure 4: Relation of pedestal and temperature (left). Estimated pedestal values from linear function with respect to time are marked blue circle (right)

3.3) SAA operation

The South Atlantic Anomaly (SAA) is a region of reduced magnetic intensity where the inner radiation belt makes its closest approach to the Earth's surface. Satellites in low-Earth orbit pass though the SAA periodically, exposing them to several minutes of strong radiation each time, creating problems for scientific instruments [4]. Initially, to avoid radiation damage the instrument was turned off when the payload passed through the SAA since launch to end of Jul. 2018. Even though the SAA transition was less than several minutes out of ninety minutes per trajectory, we could turn on the detector only 1/3 for a day. Because, when the payload went into of the SAA orbit, we turned off the detector, which corresponds to 2/3 of total time for a day. Thus, to increase the data taking live-time, we studied radiation effect on silicon by referring the other experience. It was estimated that, silicon can survive up to 50-75kRad [5]. But, the ISS-CREAM payload helps protect from the radiation because it is covered by 3mm of aluminum. In the ISS-CREAM instrument system, the yearly amount of radiation exposure is estimated to be 37 rads for the SCD. Due to this calculation, it was decided that SAA operation could be tested carefully. Figure 5 shows cosmic ray events ADC and pedestal mean ADC value for all channels in SCD1, the red lines are SAA transit times. In middle plot, we can see many hits as expected because many radiation particles come into through the SAA at marked blue arrow. In right plot, the blue arrow is a pedestal run that overlapped with the SAA transit. This SAA operation test showed no adverse effect from the SAA transit. Because, there is no pedestal fluctuation. If the SCD was affected from the radiation, the pedestal mean value should be fluctuated by surface damage [6]. Therefore, all SCD data were continuously recorded since Aug. 2018 without power-off in the SAA.

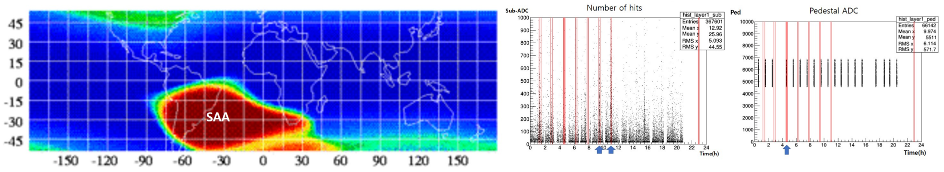


Figure 5: The SAA region (left), Cosmic ray hits in SCD1 (middle), Pedestal ADC mean value (right)

3.4) Channel Gain Calibration

The SCD is composed of 4 layers and each layer is composed of 24 ladders. Each layer has 2,688 channels, therefore, the total number of channels is 10,752. For good charge resolution, we should know the response of each channel. Therefore, an all channel gain calibration was done during the on-orbit period except for the powered off quadrants which are SCD4 and SCD3 quadrant B. We did a charge injection test by injecting charge numbers 2 to 20 for measuring all electronic channels responses. Charge was injected by a Digital Analog Conversion (DAC) signal into the SCD electronics channel. Gaussian distributions show different responses for all electronic channels for each charge as shown in Figure 6. The low and middle ranges correspond to the charge number 2 − 4 and the high range is 4 − 20. Each electronic channel was fit to a Gaussian distribution to find the mean value and standard deviation for each charge. We obtained each channel gain ratio and multiplied the gain factor to each channel. Figure 7 shows the electronics deviation for each injected charge. The channel gain correction is more effective for the low range charges. The reason is channel by channel variation becomes large when charge is small.

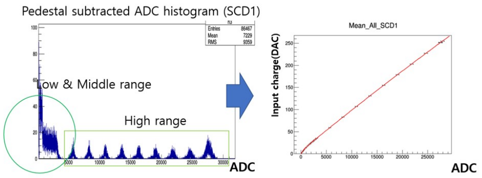
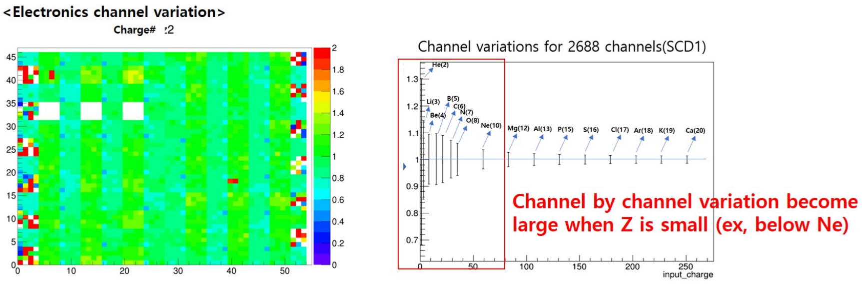


Figure 6: ADC value distribution by injected charge in SCD1 (left) . Charge injection response for each charge, error bar shows different response for all channels in SCD1 (right).



Channel by channel variation become large when Z is small (ex, below Ne)

Figure 7: Gain ratio for all electronic channels in layer1 when injected charge is helium (left). Each charge deviation for all electronic channels in layer1 (right).

4. Charge measurement

4.1) SCD tracking

The SCD is used to find cosmic ray tracks using three layers with four vectors which are positions and charge (x, y, z, Q). The charge is determined by SCD signal as a square of the incident charge(Z^2). Figure 8 shows an example of the SCD tracking method using a 3-dimensional linear function. First, a fit to a linear function using hits on SCD1 and SCD2 is done. Second, this is extended to SCD3 and find largest signal within searching area which is determined by projected pixel size to SCD3 using selected channels in SCD1 and SCD2. Third, compare these hits for charge consistence. If they satisfied the condition, then calculate direction of cosmic rays by fitting a linear function. It is tested with Chi-squared value. Currently, we are using Chi-square value less than 10 [7].

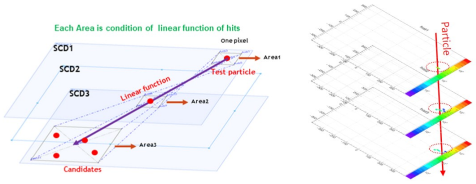


Figure 8: An example of SCD tracking

4.2) CAL tracking

The calorimeter (CAL) consists of 20 layers of tungsten plates and scintillator fibers that measure the cosmic ray energy, and can also provide trigger information and event tracking back to the SCD. Figure 9 shows an example CAL track using energy deposit in the detector. First, selecting 6 consecutive layer hits and at least 1 channel per layer has deposited energy greater than 45 MeV. Second, satisfying any of three physics trigger and searching maximum deposited energy in detector. Third, searching near 2 channels from maximum energy deposited channel and doing linear fit.

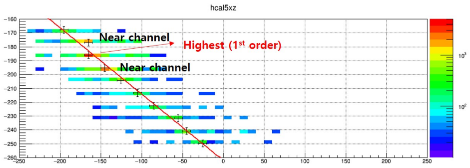


Figure 9: An example CAL tracking

4.3) Charge distribution

To get identification of the incident cosmic ray, we applied SCD and CAL cosmic ray tracking with 3 layers(SCD1, SCD2, SCD3). The SCD4 is not used because it was turned-off. The amount of charge obtained from the SCD allows to identify the incident particle. It is proportional to a square of the incident charge(Z^2) since it derives from the ionization energy loss. To determine the low charge which is the charge number smaller than 4 ($Z < 4$), we used CAL tracking method. Because, when the cosmic ray goes through the ISS-CREAM payload, it can interact with carbon target and making the secondary particles, mostly proton and helium. They can hit the SCD layers and can contribute to get incident particles with $Z < 4$. Thus, caused from back scattering particles, it is hard to find incident particles by SCD tracking only. Therefore, we are using CAL tracking for $Z < 4$. And for $Z > 4$, we are using SCD tracking so far, because the CAL trigger requires a high incident energy and event statistics are not enough for the charge calibration. Figure 10 (left) shows charge selection method using both tracking algorithm. To determine the charge, we selected largest SCD signal within selection area (10 × 10 pixels) from reconstructed track position. The selection area was determined from Monte Calro (MC) by 3-sigma region residual for reconstructed track position and incident position. And the right histogram is preliminary charge distribution. The preliminary data are from 308 days out of 540 days for $Z < 4$ using CAL tracking and 150 days out of 540 days for $Z > 4$. It will be updated after CAL calibration and studying charge change between SCD layers done.

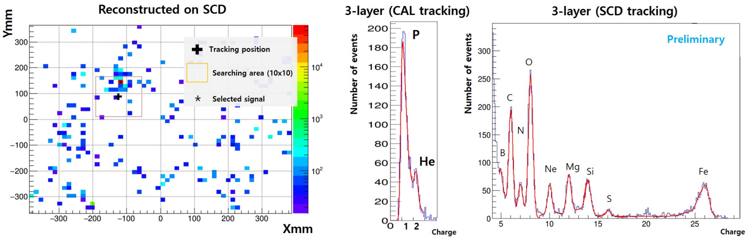


Figure 10: Proton and helium components obtained from the CAL tracking method. Distribution of the charge number greater than 4 obtained from the SCD tracking method (right). An example of charge determination (left)

4.4) Charge resolution

Figure 11 shows preliminary charge resolutions for different charges. Comparing before and after gain correction, we confirmed the charge resolution become better especially at the low charge range as we expected. In case of secondary products such as boron and nitrogen, charge peak become clearer and distinguishable from primary particles. The charge resolution for the proton, helium and boron are 0.15e, 0.16e and 0.15e which are similar to CERN beam test. And carbon, nitrogen and oxygen are 0.21e, 0.24 and 0.23, which satisfied NASA requirement for the charge resolution (< 0.3e) However, they are not reaching beam test result because of the SCD tracking. It will be improved soon after using CAL tracking with CAL calibration and studying charge change between SCD layers will be done. They are preliminary values yet.

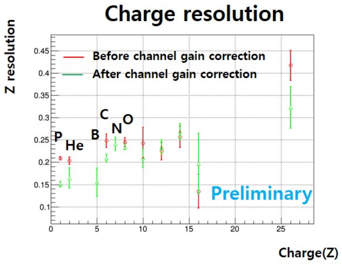


Figure 11: Charge resolution before and after gain correction

5. Summary

After integration at ISS, the SCD is working well as shown in charge distribution with the charge resolution. For the charges with Z < 4 , the charge resolutions are similar to CERN beam test. The charge resolutions satisfied the NASA requirement (< 0.3e). Now, we are working with the CAL calibration and studying particle interactions between SCD layers(charge changes). We expect to see the charge resolution improved with the works.

Acknowledgments

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