Performance of a Dual Layer Silicon Charge Detector During CREAM Balloon Flight

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***Abstract*—The balloon-borne cosmic-ray experiment CREAM (Cosmic Ray Energetics And Mass) has completed two flights in Antarctica, with a combined duration of 70 days. One of the detectors in the payload is the SCD (Silicon Charge Detector) that measures the charge of high energy cosmic rays. The SCD was assembled with silicon sensors. A sensor is a 4×4 array of DC-coupled PIN diode pixels with the total active area of 21×16 mm^2. The SCD used during the first flight (December 2004–January 2005) was a single layer device, then upgraded to a dual layer device for the second flight (December 2005–January 2006), covering the total sensitive area of 779×795 mm^2. Flight data demonstrated that adding a second layer improved SCD performance, showing excellent particle charge resolution. With a total dissipation of 136 W for the dual layer system, special care was needed in designing thermal paths to keep the detector temperature within its operational range. As a consequence, flight temperatures of the SCD, even at diurnal maximum were kept below 38°C. The SCD mechanical structure was designed to minimize the possibility of damage to the sensors and electronics from the impacts of parachute deployment and landing. The detector was recovered successfully following the flight and is being refurbished for the next flight in 2007. Details of construction, operation, and performance are presented for the dual-layered SCD flown for the second CREAM flight.**

***Index Terms*—Balloon payload, charge measurement, cosmic rays, silicon sensors.**

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I. Introduction

DETAILED elemental spectra of cosmic rays in the energy range between 10^{12} and 10^{15} eV are necessary for testing theories about the origin and acceleration mechanism of the high-energy cosmic ray particles [1], [14], [2], [15], [3]. Existing measurements with limited statistics do not allow definite tests of theoretical models above about 10^{14} eV. Because of the small and rapidly decreasing flux with increasing energy the measurement of cosmic rays in the energy range requires long duration (longer than 600 m^2 -sr-days) operation of instruments in space.

The balloon-borne cosmic-ray experiment CREAM (Cosmic Ray Energetics And Mass) was designed with a challenging goal to perform a direct measurement of elemental spectra up to 10^{15} eV with high statistics, using multiple long-duration balloon flights over several years [4], [5]. Two balloon flights have been successfully performed, recording a combined duration of 70 days. The first flight (CREAM-I) was flown during December 2004 and January 2005. The second flight (CREAM-II) took place the following year during December 2005–January 2006.

The CREAM payload is equipped with detectors for energy and charge measurement of cosmic-ray nuclei. The SCD is an instrument dedicated to charge measurement using a silicon sensor array. For the CREAM-II flight the SCD was upgraded with new components to a dual layer device.

Other instruments in the CREAM-II payload are shown in Fig. 1. The detector configuration includes, from the top, a Timing Charge Detector (TCD) of segmented plastic scintillators, a Čerenkov detector (CD), the SCD, and a tungsten/scintillating fiber sampling calorimeter with a depth of 20 radiation lengths installed on carbon targets [6]. There is also a single layer detector, S3, between the target and the calorimeter. The coincidence signals from TCD and S3 are used for the trigger to take high statistics low energy data. The fast readout electronics of the TCD provides an additional charge measurement by rejecting delayed signals from back-scattered particles in the interaction of incoming cosmic rays with the calorimeter. The trigger for high energy cosmic rays are generated by requiring the presence of hits in at least 6 consecutive calorimeter layers out of the total 20 layers. The energy threshold of the trigger was set to be nearly 100% in the efficiency for showers of protons above 3×10^{12} eV during the second flight. In the following we discuss the construction and performance of the dual layer SCD for the CREAM-II flight.

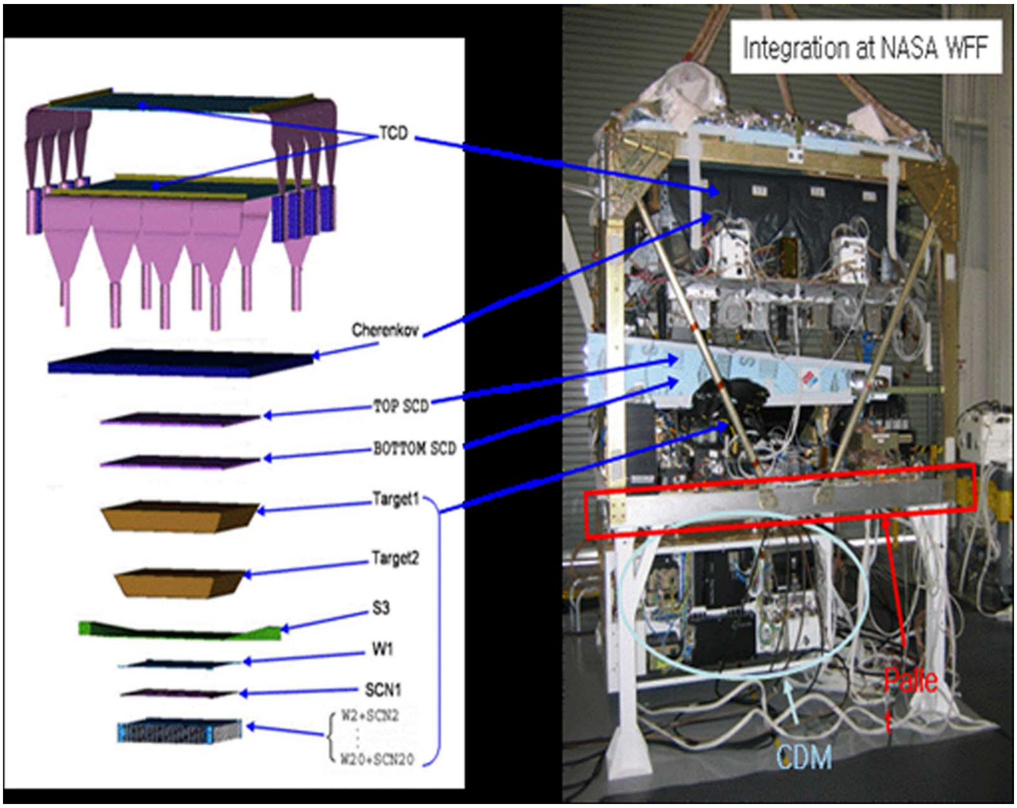

Fig. 1. Component detectors in the CREAM-II payload. The photo was taken in the middle of payload integration at the NASA Wollapse Flight Facility (WFF).

II. Dual Layer SCD

The SCD consists of silicon PIN diode [7] detectors in a large pixel array. The unit of the detector is a silicon sensor comprised of 16 pixels arranged in a 4 by 4 matrix, fabricated on a 5 inch, 380 μm thick wafer [8], [16], [9]. For the CREAM-II flight new sensors were produced with the same dimension (58×63 mm^2) and used in both layers. The typical sensor dark current was measured to be 3.5 nA at an operating bias of 100 V which is higher than full depletion voltage of the sensors with the thickness. In this way full depletion of all sensors is ensured against sensor-to-sensor variation of thickness and resistivity. 95% of the pixels show a dark current below 10 nA at the operation voltage.

The post-fabrication process was improved for the new sensors. First, the pixel wire bonding to the readout line was strengthened using double wires with vacuum cure of the bonding glue applied over the bond, completely preventing bonding failures during long term operation. The flexible PCB attached to the top of the sensor for signal readout was redesigned to add a ground area in the space between pixel readout lines, reducing readout noise and improving operation stability.

The sensor signal is provided by charge ionization produced in the depleted region by a cosmic ray passing through the sensor. The amount of ionization charge is proportional to the square of the charge of the incident particle because ionization is the major energy loss process of high energy particles with matter [10]. The signal is processed by a 16-channel Amplex CR1.4 ASIC chip [11] mounted on the front-end analog board. The integrated signal is converted to a held dc level for a channel when an external Track&Hold trigger is given. The outputs of the chip are then multiplexed onto a common output line.

The sensors are mounted on analog boards using two plastic spacers attached on the back side of each sensor with a slope of 1.24° with respect to the horizontal, allowing the sensors to overlap each other. In this way full coverage of a layer is obtained with no dead regions between sensors.

Equipped with 7 CR1.4 readout chips an analog board handles 7 sensor channels. The analog boards are installed on thermal straps made of aluminum plates with a thickness of 1 and 2 mm for the top and bottom layers, respectively. The plates provide a thermal path from the readout electronics to the frame. Fig. 2 shows the assembly of sensors with spacers, analog board, and thermal strap.

The digital electronics with 16 bit ADCs provides a fine resolution of the analog signal over the wide range from the proton to $Z = 28$ signals. The digital boards were redesigned into a more modular form, with each digital board handling two analog boards.

A total of 77 sensors were installed on 11 analog boards in a half layer with an extra sensor at a corner of the array handled by an additional analog board. 12 analog boards are connected to 6 digital boards for a half layer. All half layers in the top and bottom layers are identical in structure. The top layer was installed on the bottom layer, but rotated by 90°. In this way the active area covered by SCD sensors is 0.62 m^2, with the inner area of 0.52 m^2 (84%) covered by two layers of sensors. The total number of the sensors is 312 (78×4) which is a total of 4992 silicon pixels.

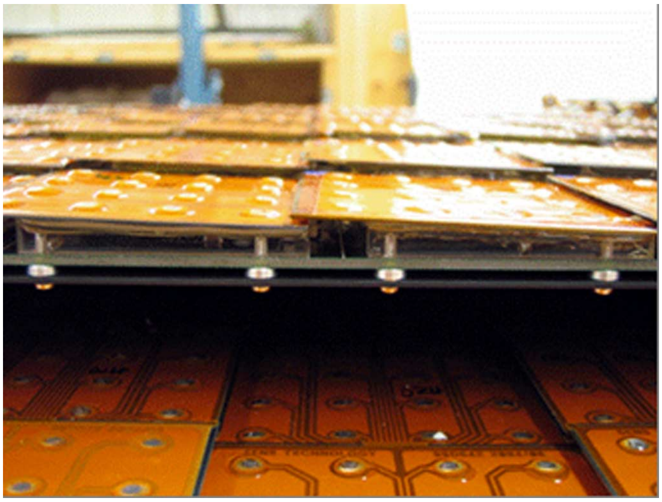

Fig. 2. Assembly of sensors, analog board, and thermal strap.

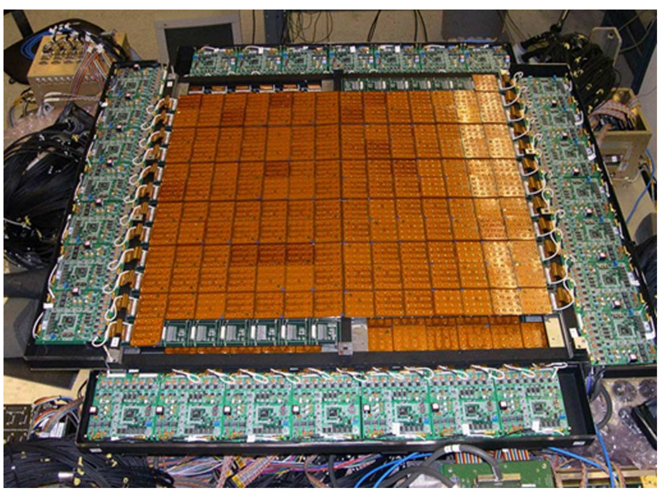

Fig. 3. Fully assembled dual layer SCD for CREAM-II flight. Total 312 sensors (a total of 4992 silicon pixels) shown in the central square are mounted on top of 48 analog boards. 24 digital boards are installed in four rectangular side wings. The top layer is parallel to the bottom one, but rotated about its central point by 90 degrees.

The mechanical structure was designed to allow stability of the whole system up to 10 g, considering the shock caused at parachute deployment. There is no mechanical support in the middle of the top and bottom layers that produces an insensitive region. The rectangular side wings on all four sides are used to install the digital boards. The overall SCD height was 97.5 mm and the gap between layers (from the top of bottom sensors to the bottom of top sensors) is 21 mm. The total weight is 56 kg. The fully assembled dual layer SCD for the CREAM-II flight is shown in Fig. 3.

The total power needed to operate the SCD is 136 W. It was a design issue to deal with the heat generated by the power consumption. Since the dark current of silicon sensors and the electronics noise are dependent on detector temperature, it was important to maintain that temperature below 40°C. Lacking significant convection at float altitude, the heat produced had to be dissipated through conduction and radiation. Accordingly, the aluminum heat plates under the analog boards were connected to the detector frame over a large area using conductive epoxy. Copper bars (with a 25×25 mm^2 cross section) were installed at two corners of the frame, leading to 300×300 mm^2 aluminum radiators viewing cold space to help remove heat from the SCD. Another thermal component, newly designed for the dual layer system was a reflective wedge installed over the top of the detector and viewing the coldest (anti-sun) direction (Fig. 4).

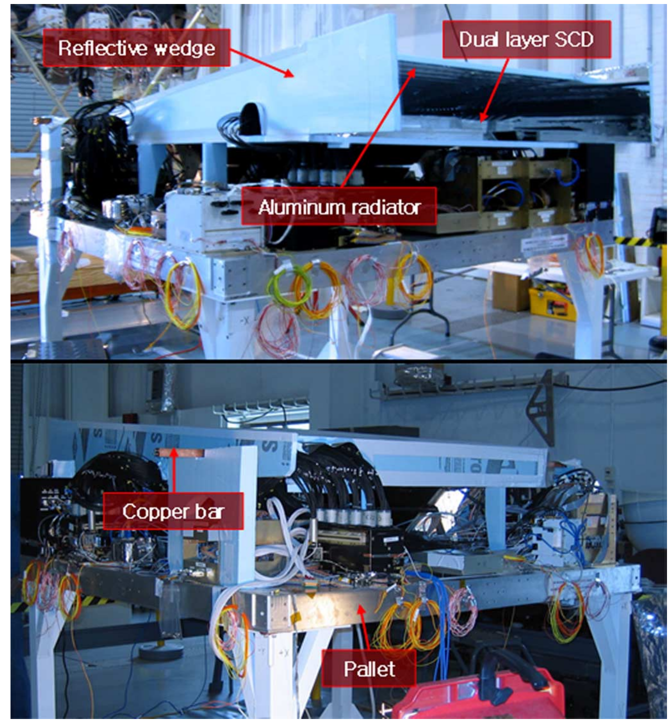

Fig. 4. Reflective wedge installed over the top of the SCD viewed from (a) sun side and (b) anti-sun side. The payload orientation was maintained in flight to keep the solar arrays pointed at the sun, and the radiative wedge opening away from it.

III. SCD Performance During Flight

After the launch from McMurdo station, the CREAM-II experiment remained at float for 28 days with two circumnavigations of the South Pole. Detector condition was monitored online during flight using 240 housekeeping channels including the temperatures, currents and voltage levels of the analog boards.

Fig. 5 shows the history of the balloon altitude, temperature of an analog board, and pedestal of a readout channel. The detector temperature and readout pedestal varied with the daily variation in altitude between 36 km and 40 km. During the flight detector temperature remained under 38°C.

Pedestal runs were taken every 5 minutes and downloaded for online monitoring of readout conditions. The readout noise level was kept low, at $\sim$5 ADC counts RMS width for most channels. The minimum charge signal $(\mathrm{Z} = 1)$ begins to appear above 35 ADC counts, implying a signal to noise ratio greater than 6. Fig. 6 shows the pedestal RMS of all channels of the top layer. The total fraction of dead and noisy channels was 1.7% throughout the flight.

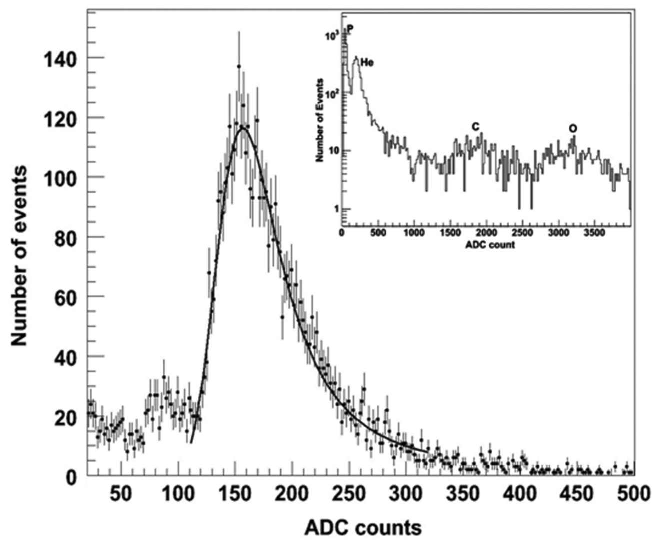

Fig. 5. History of the balloon altitude, the SCD temperature, and the electronics pedestals during flight. A strong correlation can be seen with the diurnal variation.

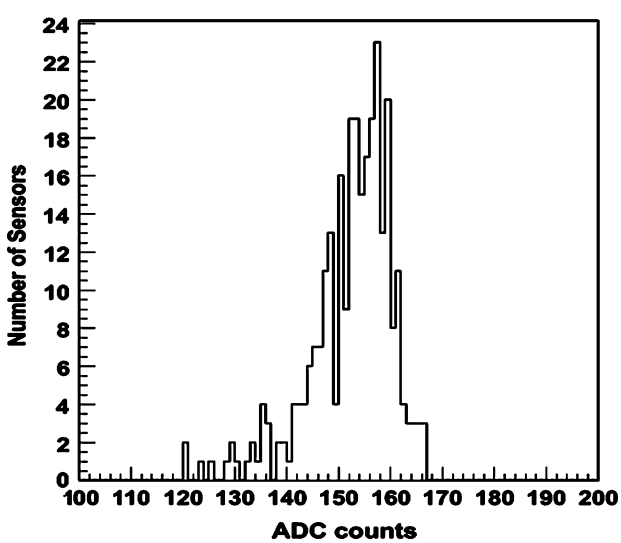

Fig. 6. Readout pedestal fluctuation of the top-layer channels during a pedestal run taken in flight. The color index is in unit of ADC counts. The singly-charged minimum ionizing particle (MIP) peak was measured at about 35 ADC counts above pedestal. The areas in the sides without color have no sensors installed.

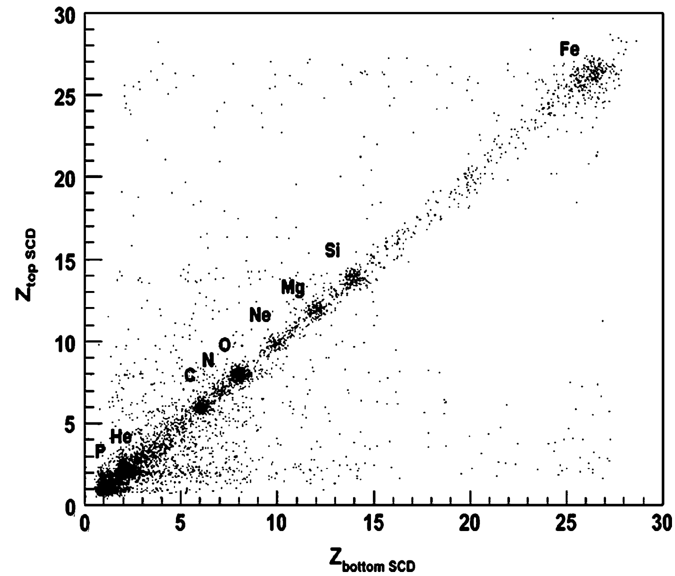

Fig. 7. Helium events for a sensor in the top-layer. The trigger condition of these events does not require calorimeter signals. Signals from other cosmic nuclei are shown in the top right plot from the data set taken with the calorimeter trigger.

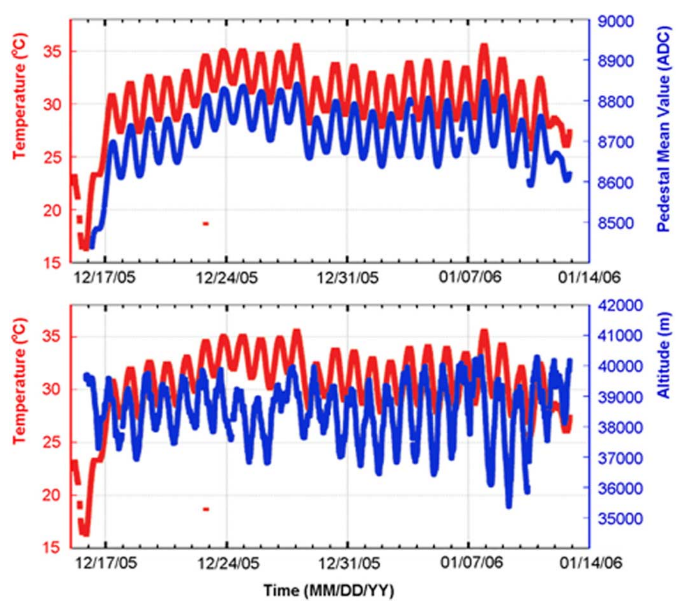

Fig. 8. Peak values of helium signal distributions (as shown in Fig. 7 for a sensor) from all sensors covered by the trigger.

One of the CREAM-II trigger conditions was to require the presence of hits in the TCD and S3 with a measured particle charge larger than that of a proton [12]. With this trigger condition, Helium-enriched data with high statistics were collected. These data were used for monitoring channel response. Fig. 7 shows the data for a sensor in the top layer along with a Landau curve fit. Signals were corrected for pedestal variation, as well as for the path length given by the angle of the particle track which is reconstructed with hits in TCD and both layers of the SCD. The width of the distribution was consistent with the result measured at a beam test with high-energy heavy ions, 0.10 (dZ/Z) for helium [13]. The constant widths measured in daily data sets shows this performance was maintained throughout the flight.

This monitoring scheme for the performance of the detector channels was applied to other sensors covered by the above trigger. Fig. 8 shows the peak variation has an RMS width of 8.1 ADC counts which means 5.3% variation in charge number, indicating most sensors operated well.

The data taken with the above trigger include low energy particles. Therefore, absolute charge calibration was carried out using flight data taken with the trigger for higher energy cosmic rays instead. The in-situ calibration is possible because there are clean peaks in the ADC spectrum corresponding to charge numbers of incoming cosmic rays. Conversion factors are obtained by comparing ADC values of the peaks with the square of the

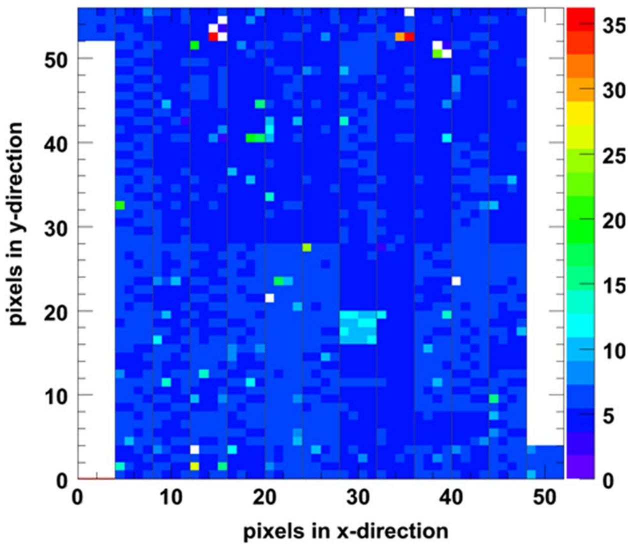

Fig. 9. Correlation between the top and bottom layer signals in events. High charge signals are clearly seen along with proton and helium nuclei.

charge numbers. A single conversion factor was enough for the entire range of the charge spectrum because of the good linearity of the detector response.

High energy cosmic ray events above were taken with a trigger based on calorimeter signals. With this trigger, low energy events, lacking significant shower activity in the 20 sampling layers are effectively rejected. The offline analysis of those events satisfying the trigger starts with the reconstruction of the shower axis. For events with a clear calorimeter shower, the shower axis is extrapolated to the planes of the top and bottom SCD layers, where one looks for hits in the region around the axis. Once such hits are found, the path length correction is made using the trajectory angle.

Fig. 9 shows signals from the top and bottom SCD layers in high energy event data. As mentioned, the signals from protons up to Fe nuclei were used to set the absolute scale of the charge measurement. Signals from high charge nuclei up to Fe can be clearly seen along the diagonal line in the figure, as can the high statistics proton and helium signals. The strong correlation between the two layers is further evidence of excellent SCD performance in the flight. The charge measurement of the dual-layered SCD is more reliable than the single layer SCD because we can select events that are correlated between the two planes. These appear on the diagonal of the figure. Signals seen in the off-diagonal section of the figure are secondary particles that are back-scattered from the target when a high energy cosmic ray produces a shower. The signals are effectively rejected with the dual layer system. Taking an average of correlated signals in the top and bottom detectors the charge resolution is improved by 10%.

After the flight, the SCD was safely recovered showing no damage to detector components in flight, at landing, or during the recovery. The SCD is ready for a third flight, planned to take place December 2007.

IV. Conclusion

The SCD is a space application of a large array of silicon PIN diode pixel sensors for charge measurement of high energy cosmic-rays. A new SCD, upgraded with a dual layer for the CREAM-II payload was successfully operated as designed during 28 days of balloon flight in Antarctica. Flight data show excellent performance of the detector throughout the flight. The signal correlation between the top and bottom layers is clearly seen for the range of cosmic ray protons to Fe nuclei.

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