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An engineering prototype of the Imaging Calorimeter for ACCESS (ICA)

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Abstract. The Imaging Calorimeter for ACCESS (Advanced Cosmic-ray Composition Experiment for Space Station) is one of several proposed concepts for the ACCESS calorimeter instrument designed to measure the spectrum of protons, helium and heavier nuclei up to ~10^{15} eV. This design utilizes a carbon target and high atomic number absorber sampled by thin layers of scintillating fibers. An engineering prototype detector was tested at CERN in August 2000 composed of 15 radiation lengths of interaction material with two types of readout: photomultiplier tubes and an image intensified CCD system. An overview of this prototype and its performance will be presented.

1 Introduction

The Advanced Cosmic-ray Composition Experiment for Space Station (ACCESS) is a mission concept in the preliminary stages of study by NASA. ACCESS will include two instruments: a transition radiation detector (TRD) and a calorimeter. ACCESS is designed to study cosmic rays up to an energy of 10^{15} eV. This energy range approaches the "knee" region of the cosmic-ray spectrum where a number of questions have arisen. ACCESS will be able to measure the spectra of protons, helium and elements through Z=28. These measurements will allow ACCESS to address several major questions including: the nature of the cosmic-ray acceleration process, the energy dependence of escape from the galaxy, and the source of the matter accelerated (Wefel and Wilson, 1999). The experiment has been specifically designed to take advantage of several characteristics offered by using the International Space Station as a platform. These advantages include having a long exposure time (4 years) and the ability to record and retrieve data at a later time. However, the experiment is limited, like all components of the space station, in size, weight, and power.

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There are several designs being developed for the calorimeter instrument on ACCESS including a hadron calorimeter utilizing BGO (Isbert et al., 1999), an imaging calorimeter using Si-W material (Bravar et al., 1999), a quartz calorimeter (Akchurin et al., 1997), and the concept that will be discussed in this paper, an imaging calorimeter using scintillating fibers (ICA; Parnell et al., 1999). ICA is an ultrathin sampling calorimeter composed of hodoscopic layers of X-Y planes of scintillating fiber ribbons. The scintillating fibers are 0.5 mm square in cross-section and emit scintillation light at a wavelength of ~420 nm. Lead is used as a converter material above each layer to stimulate the electromagnetic cascade with the fibers detecting the passage of the charged particles between the converter plates. The small fibers also allow for good angular resolution to determine the direction of arrival and mitigate the effects of backscatter in the instrument. At least one radiation length (r.l.) of carbon will be placed above the calorimeter to allow the cosmic rays to interact prior to reaching the fiber planes. The ICA study has included targets in front of the calorimeter up to 1 proton interaction length.

2 Beam Test Prototype Description

To test the design of ICA, a prototype calorimeter was constructed and tested. The prototype consists of twenty layers of orthogonal X-Y fiber planes (figure 1). Each fiber plane has an active area of 13 cm x 13 cm. The scintillating fibers are 0.5 mm in square cross-section and were manufactured at Washington University. The fibers have a thin single cladding that is only ~3% of the total width of the fiber. Each fiber layer was attached to an aluminum frame that could be tilted up to 42^{o} in the Y-direction so that the calorimeter could be tested for particles interacting at a number of different angles.

Lead sheets of 0.76 r.l. each were placed in front of each layer except for the first making a total of 14.5 r.l. in the entire calorimeter. Additionally, four 10 cm thick blocks of graphite (0.53 r.l. and ~0.25 proton interaction length each) could be placed in front of the calorimeter as target material. Between each of these blocks, a scintillator paddle could be inserted to determine if the shower had developed upstream.

The fiber planes measuring the Y position of the electromagnetic cascading particles were read out with two different devices. Each of these planes was coupled to a Phillips XP2020 photomultiplier (PMT). Each PMT signal was amplified by a low gain and a high gain channel of a pulse height analyzer. The high gain channel was used to calibrate the instrument using passage of protons through only the fibers. The low gain channel has a dynamic range of ~4000 MIPs (minimum ionizing particles). Both the X and Y fiber planes were read out with an image intensified CCD system (II-CCD). This system is composed of a Photek 80-40 mm reducing image intensifier coupled to a Photek MCP-340S image intensifier which is read out by a Thomson TH-7866 244 x 550 CCD array. Both of these readout systems are used to evaluate the performance of the calorimeter in a number of configurations.

The prototype calorimeter was tested at CERN in August 2000 with electrons of energies between 50 GeV to 250 GeV and protons of energies between 250 GeV to 350 GeV. A number of incident angles up to 42^{o} and several target configurations (0 cm to 40 cm of graphite) were tested at these energies.

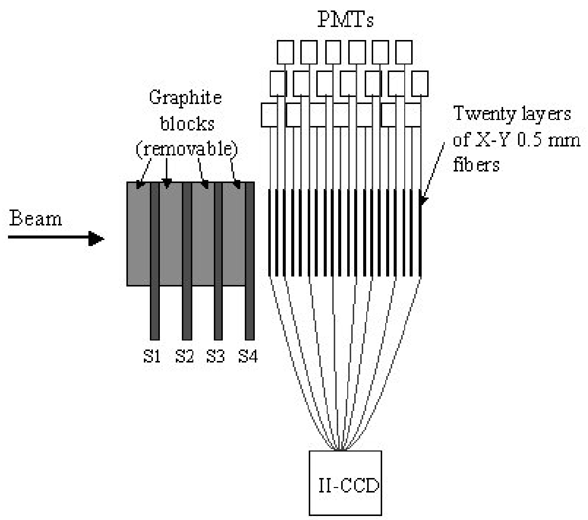

FIG. 1. Diagram of the beam test prototype instrument composed of 20 layers of scintillating fibers and read out with PMTs and an II-CCD system. The removable graphite targets and scintillators are shown in front of the instrument.

3 Scintillating Fiber Performance

The scintillating fibers used in the beam test prototype are composed of a polystyrene core with an index of refraction of 1.6 and are clad with a thin layer of acrylic with an index of refraction of 1.5 to light pipe the scintillation light to the readout device. The cladding layer of these fibers is only ~3% of the total fiber thickness (0.5 mm). This thin cladding allows for increased detection of passing particles as the probability of a particle passing only through the cladding material is small.

The scintillating fibers used have been shown to have a light output for a MIP producing 1.4 photoelectrons at a distance of 45 cm and 0.77 photoelectrons at a distance of 107 cm from the readout device. The attenuation length of the fibers is slightly over 1 m.

The scintillating fibers were laid out in tightly packed ribbons on aluminum frames and did not have an extramural absorber (EMA) covering the fibers. EMA is used to prevent crosstalk between fibers. Using the passage of protons that did not interact in the calorimeter, the detection efficiency for several fiber layers can be found by requiring a single MIP signal in the layers immediately in front of and behind the examined layer. The detection efficiency using the PMT readout system was found to be 80.3% for particles at normal incidence. This value is consistent with the photoelectron statistics of the light output.

4 Detector Performance

The detector performance has been examined for the August 2000 test at CERN for both protons and electrons with the PMT and II-CCD readouts. Data were taken to calibrate the twenty PMTs with 350 GeV protons passing through the fiber bundle in front of the II-CCD system. These protons did not pass through any target or converter material. These data were used to correct the gain differences in the twenty PMTs and calibrate the electronics on the signal of the passage of a relativistic proton through a fiber layer (~85 keV energy deposition). We are still in the process of correcting the II-CCD data. The data presented in this paper have been corrected for the dark frame build-up inherent in the CCD and normalized to the PMT signal. Mapping and gain corrections of the II-CCD system have not yet been applied. Gain variation across the CCD image is likely at least +/- 10%. Figure 2 shows the CCD image for the electromagnetic cascade for a 250 GeV electron at normal incidence with no target material present in front of the calorimeter. Figure 3 shows the CCD image of the resulting cascade from a 350 GeV proton at normal incidence with 20 cm of graphite in front of the calorimeter. The fiber layers are formatted on the CCD so that the Y-layers are the first 20 layers on the left

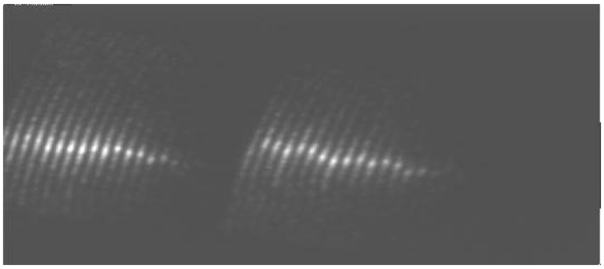

Fig. 2. CCD image of the cascade from a 250 GeV electron at normal incidence without a graphite target present.

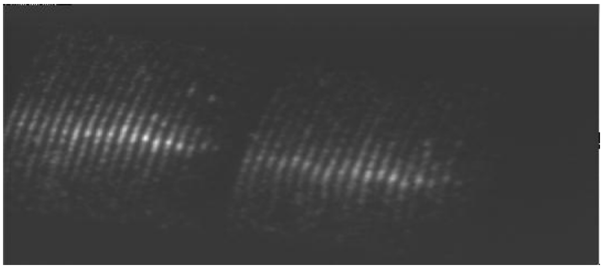

Fig. 3. CCD image of the cascade from a 350 GeV proton at normal incidence with 20 cm of a graphite target present.

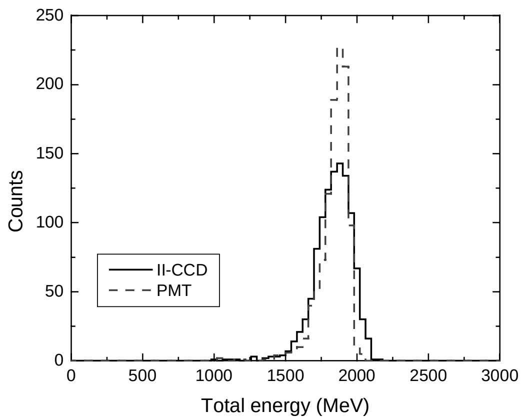

Fig. 4. Energy distribution for 150 GeV electron events at 23° incidence for both the II-CCD and PMT readout systems.

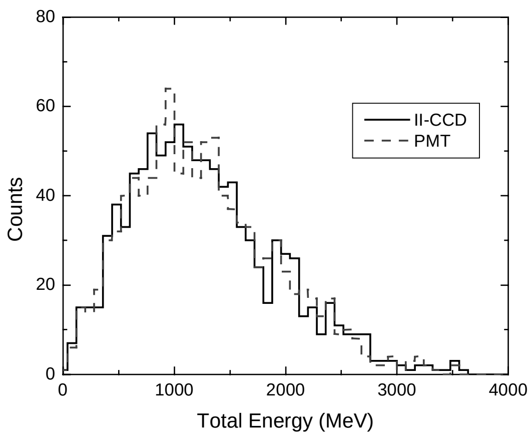

Fig. 5. Energy distribution for 350 GeV proton events at normal incidence with 20cm of carbon target material for both the II-CCD and PMT readout systems.

side of the image and the X-layers are the next 20 layers on the right. The layers are in reverse order with the front layer on the far right and the rear layer on the left.

The PMT and II-CCD readout systems give comparable energy resolution. Figure 4 shows the energy distribution for 150 GeV electron events at 23° incidence for both readout systems. Figure 5 shows the energy distribution for 350 GeV proton events at normal incidence with 20 cm of carbon target material. The II-CCD data have not had mapping and gain corrections applied. This effect is most noticeable for the electron events which is why the readout devices do not give the same energy resolution. The mapping/gain corrections will have little effect on the proton events and can be seen with similar resolution for these events.

The energy resolution for different calorimeter configurations, incident angles, and electron energies are given in Table 1. This resolution is given as a percentage of the root mean square of the distribution over the mean. The resolution for the II-CCD system compared to the PMT system is given.

Table 1. Energy resolution percentage for electrons of different energies with various target configurations and at different incident angles. The uncertainty is given in parentheses.

			Energy Resolution	
Energy	Angle	Target	PMT	CCD
50	0	0	9.4 (0.1)	--
150	0	0	7.9 (0.2)	11.7 (0.3)
150	23	0	5.9 (0.2)	7.2 (0.2)
150	23	20	5.2 (0.2)	6.5 (0.2)
150	23	40	5.8 (0.2)	7.1 (0.2)
250	0	0	8.0 (0.3)	8.2 (0.3)
250	28	20	6.2 (0.3)	7.6 (0.3)
250	42	0	10.3 (0.2)	10.6 (0.2)

5 Conclusions

The beam test prototype for ICA performed as expected. The results show that a sampling calorimeter composed of thin scintillating fibers with carbon target material has sufficient energy resolution for electron and proton-induced cascades. Detection efficiency is sufficient to image the resulting shower. Both the II-CCD readout system and the PMT readout system are adequate. Further analysis of the II-CCD system data with mapping and gain corrections should show similar resolution to the PMT system. The energy resolution for the 42 degree angle data is not as good due to the inability of the instrument to contain the shower in the lateral direction because of its small size. The energy resolution of the 23 degree angle data is better than that at normal incidence due to the increase in interaction material when traversing the detector at an angle and the slight improvement in detection efficiency of the scintillating fibers at an angle. The addition of target material does not have much effect on the energy resolution for the electron data as the cascade develops after several radiation lengths of material. The target material has a larger impact on the development of proton-induced cascades. The information gained from this test will help determine the configuration of the proposed ICA instrument.

The major advantage of the II-CCD system is the increase in position resolution of the shower in the calorimeter. A possible future readout device that would give position information and adequate gain to read out scintillating fibers is the position sensitive multianode photomultiplier tube which consists of 16 or 64 separate anodes (Rielage et al, 2001). Such a device could read out several fibers on each anode giving distinct position information for the shower over the PMTs used in this prototype detector.

Continued improvement in the fabrication of scintillating fibers with increased light output and less cladding material will increase the detection efficiency of future detectors. Scintillating fibers continue to be an attractive option as detectors in thin imaging calorimeters given the cost, weight and environmental conditions facing future cosmic-ray experiments.

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