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Simulated performance of the silicon tungsten calorimeter for ACCESS

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Abstract. The design of the Silicon Tungsten (Si-W) calorimeter for ACCESS was developed as an evolution of the Si-W imaging detectors currently used by the WiZard collaboration in balloon borne and spacecraft based cosmic ray experiments. We present a detailed analysis of this design and of its simulated performance for cosmic ray protons with energies from 100 GeV to 1,000 TeV.

1 Introduction

The Advanced Cosmic Ray Composition Experiment for the Space Station (ACCESS) is an experiment concept designed for installation as an attached payload to the ISS (Wefel *et al.*, 1999). The main scientific objective of ACCESS is the measurement of the energy spectra of individual elements from hydrogen to iron to energies of 10^{15} eV ('knee region'). The measurement of the electron spectrum in the TeV region, and the measurement of the abundances of higher -Z elements at moderate energies are the two secondary objectives of this experiment.

The current structure of ACCESS includes a transition radiation detector (TRD) to measure the energy of nuclei with $Z \geq 3$, and a hadronic calorimeter to measure protons, helium, lighter nuclei ($Z \leq 8$) and possibly electrons.

The scientific and technical requirements for the ACCESS calorimeter, detailed in the ACCESS Working Group formulation study report (AWG, 2000), can be summarized as:

1. Energy resolution (δE/E) of 40% or better for protons and helium.

2. Effective geometric factor for protons (i.e. geometric factor multiplied by the fraction of useful events, see e.g. Sullivan, 1971) of at least 0.5 m^2 sr.

3. Charge resolution of 0.2 charge units or better from Z=1 to Z=8.

4. Secondarily, ability to detect electrons with a rejection power for protons of 10^5 or better, δE/E better than 25%, and an effective geometric factor of at least 0.66 m^2 sr.

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The principal constraints are a maximum weight of 3,400 kg, a power limit of 300 W, and a data rate not in excess of 50 kbits/sec.

The final design of the ACCESS calorimeter has not been selected yet, and a number of different projects, all of them meeting these minimum requirements, are currently being evaluated.

2 Calorimetry in Space

Practical hadronic calorimeters for space applications are necessarily limited in absorber thickness in order to have both a reasonable mass and geometrical factor. A thin calorimeter must meet two basic requirements: the primary nucleus must undergo at least one inelastic interaction, and the energy resulting from this interaction must be measured with adequate resolution (Isbert *et al.*, 1999). Such a calorimeter should consist of a target section, to force the interactions, followed by an energy collecting section, to measure the energy of the hadronic showers. The energy resolution is governed by the thickness of the energy collector. Shower leakage from the bottom of such a thin calorimeter is one of the principal sources of fluctuations that limits the δE/E.

3 Si-W Calorimeter for ACCESS

A Si-W imaging calorimeter was used in the past (Barbiellini *et al.*, 1996; Golden *et al.*, 1996) as part of the NMSU/WiZard Balloon Borne Magnet Spectrometer. The same Si technology is now being employed for the spacecraft based cosmic ray detectors of the WiZard-RIM collaboration (Bakaldin *et al.*, 1997; Bonvicini *et al.*, 1999). The original WiZard Si-W calorimeter was designed as a particle identifier (for positrons

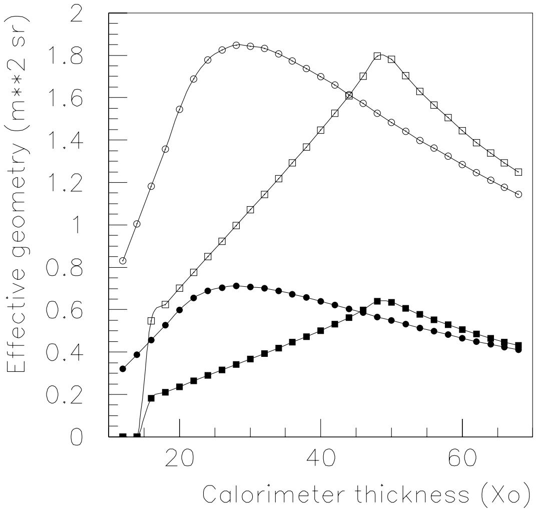

Fig. 1. Effective geometric factor vs. calorimeter thickness for protons (circles) and electrons (squares). 2,720 kg (open marks) and 1,156 kg (solid marks) configurations.

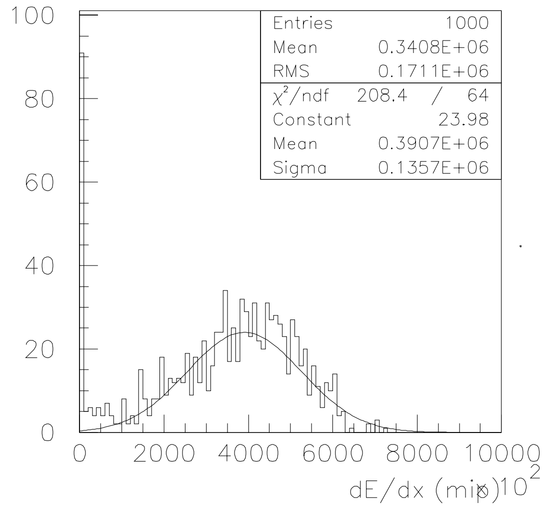

Fig. 2. Total dE/dx deposit for 10 TeV protons (raw data).

and antiprotons) and charge (dE/dx) measurer. The possibility of using a modified version of this detector as a hadronic calorimeter was analyzed previously in response to the NASA ultralong duration balloon program announcement (Bravar *et al.*, 1997). For ACCESS, the starting point for our design was a hadronic sampling calorimeter with Si microstrip detectors, which have been used in past and present instruments as the active material.

We considered a variety of absorbing materials (Al, Fe, Cu, Pb and W) and different shapes for the calorimeter structure. We studied the use of a low-Z material (carbon) for the target section in conjunction with a high-Z material for the energy collector. Finally, we chose a monolithic, square Si-W calorimeter, where both sections are made of tungsten. This material maximizes the effective geometric factor for a given mass and given δE/E. A carbon target would slightly improve the effective geometry ($\sim$15% increase), but would severely impair the ability to detect electrons. Tapering of the calorimeter sides, cylindric and conic structures slightly improve the effective geometry as well, but are disadvantageous from an engineering point of view.

The active Si planes are a mosaic of 8×8 cm^2 wide and 380 μm thick Si microstrip detectors (Bocciolini *et al.*, 1996). Each detector is divided into 32 Si microstrips, with a pitch of 2.4 mm each (PAMELA configuration Bonvicini *et al.*, 1999). The strips of adjacent detectors are daisy chained to each other, and the readout of the resulting long Si strip is performed at the edge of the Si plane. The strips of subsequent planes are oriented orthogonally to each other, providing double coordinate x-y readout. In order to meet the ACCESS power and data rate constraints, we assumed a 2 X_0 sampling for our calorimeter as a starting point. As expected, Monte Carlo simulations confirmed that δE/E for hadrons does not depend on the sampling frequency, while angular resolution and electron identification do.

Finally, we evaluated the effective geometric factor for protons and electrons for different thicknesses of our square Si-W sampling calorimeter, under the following conditions:

1. Total mass of the calorimetric material (Si layers with G10 substrate and W absorbers) is equal to 2,720 kg (i.e. 3,400 kg minus 20% contingency for structure and electronics).

2. Primary particle enters from top (to measure its charge), exits from either bottom or sides.

3. For protons: 20 X_0 of W and 3 Si planes are traversed by the track of the primary after the first interaction (to achieve the 40% δE/E, from our Monte Carlo results).

4. For electrons: 50 X_0 of W and 10 Si planes traversed by the primary electron (for electron identification purposes).

5. A descope option with a mass of 1,156 kg for the calorimetric material was also considered.

Results are shown in figure 1. We selected a thickness of 52 X_0 (i.e. 1.9 λ_I) for our Si-W calorimeter. This design achieves the required effective geometric factors for both protons and electrons, both in its full mass and descoped versions. The effective geometry for Z$\geq$2 nuclei is always larger than that of the protons.

In this final version, the full-mass Si-W calorimeter consists of 26 Si layers and 26 W absorbers, with an area of 88×88 cm^2 and an estimated height of 26 cm. Each Si layer is made of 11×11 Si microstrip detectors and has 352 readout channels.

4 Energy Resolution

The performance of the Si-W calorimeter was simulated with the Monte Carlo package GEANT 3.21 98A, linked to FLUKA

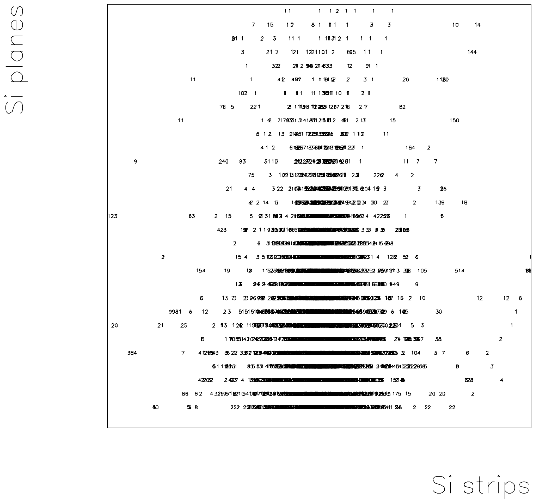

Fig. 3. Interaction pattern of a 1,000 TeV proton in the calorimeter.

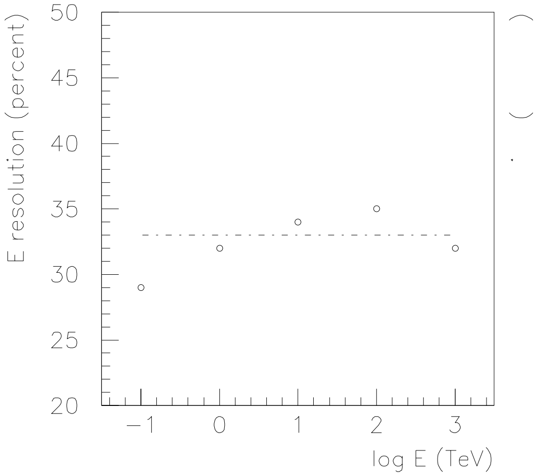

Fig. 4. δE/E vs. E for protons, 0.1 TeV to 1,000 TeV. Note: δE/E is $<$ 40% over the entire energy range.

for hadronic interactions (Brun *et al.*, 1992). 10 TeV protons were used for optimization studies (figure 2), and we simulated protons from 0.1 TeV up to 1,000 TeV (figure 3) for our final configuration. Figure 4 shows the energy resolution for raw proton data as a function of energy, obtained as the ratio σ/X_{mean} of the Gaussian fit to the dE/dx distributions at various energies (the 10 TeV fit is shown in figure 2). Our δE/E is nearly energy-independent, and we achieve δE/E$<$40% at all points.

We studied several software methods to improve the δE/E through offline analysis: e.g. elimination of the low energy peak in the dE/dx distribution by introducing a lower limit on the lateral spread of the shower, and use of the location of the Si plane with the maximum dE/dx deposit (function of the shower starting point) in conjunction with the total dE/dx. Such algorithms, while improving the δE/E, at least in the case of Monte Carlo events, require a much more demanding offline analysis.

Effects of different angles of incidence of the primary proton were also studied (0° to 60°), and finally we analyzed the energy dependence of the total dE/dx (raw data) vs. the energy of the incident particle. As already observed previously (Bravar et al., 1999), the total dE/dx deposit produces a non-linear response in the calorimeter. Vice-versa, the dE/dx around the shower core (5 Si strips around the trajectory of the primary) gives a linear signal (figure 5). The relationship between actual energy and dE/dx in our 52 X_0 Si-W calorimeter (i.e. the fitting function in figure 5) is:

$$log_{10}[dE/dx]\;(mip) = 4.5 + 1.0 \times log_{10}[E]\;(TeV) \qquad (1)$$

Monte Carlo simulations were also used to study the performance for alpha particles at 10 TeV/nucleon. We used both the superposition and minimum fragmentation models to represent nuclear interactions. In both cases, and under any selection conditions, the δE/E for alpha particles is better than the one for protons.

With respect to electrons, the performance of the ACCESS Si-W calorimeter is similar to the performance of ELO (Bravar *et al.*, 2001). δE/E is better than 10% at all energies.

5 Particle Identification

Originally, the ACCESS instrument complement included an element identifier module (ZIM) on top of the TRD, designed to measure the charge of cosmic ray particles. The ZIM was removed due to financial constraints, and at present the ACCESS calorimeter is required to perform the charge measurement of low-Z particles by itself.

Our current Si microstrip detectors, with a sensitivity of ∼0.1 mips, can easily determine the charge with high accuracy from the dE/dx deposit for Z≤8. However, at ACCESS energies, this measurement is highly affected by backscatter particles from the calorimeter, produced in the interaction of the cosmic ray. Therefore, we decided to add a dedicated charge detector, located 20 cm above the calorimeter, and study its performance in the presence of backscatter for 10 TeV protons.

The granularity of the Si-W calorimeter enables us to reconstruct the trajectory of the primary proton with great accuracy by fitting a straight line to the peaks of the lateral spread of the dE/dx deposits in each Si plane. The point at which the primary proton hits the charge detector can then be extrapolated. Our data show an average angular resolution of $\delta\theta$ = 15 mrad, and a position resolution in a plane 20 cm above the calorimeter of δx = 1 cm (figure 6).

Our charge detector design consists of 2 Si layers, interleaved with a thin tungsten shield (0.5 X_0 thick, to absorb low energy backscatter events). We considered three configurations for the Si layers: Si strips (identical to the ones in the calorimeter, with readout performed at the Si layer edge), an array of square Si pixels (area = 1 cm^2) and Si microstrips (2.5 mm × 8 cm, i.e. the layer is again a mosaic of Si microstrip detectors, but the microstrips of adjacent detectors are no longer daisy chained, and each one is read out indi-

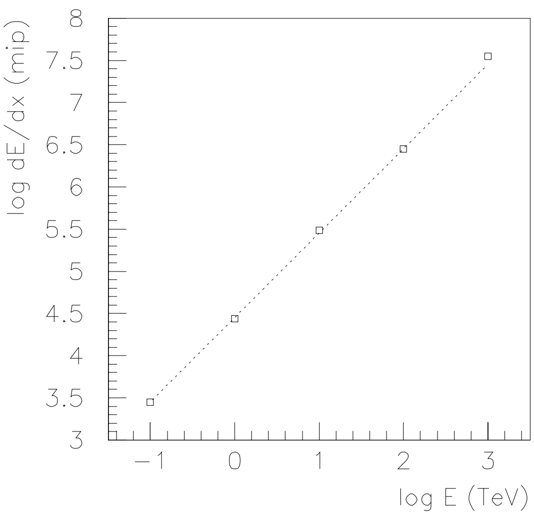

Fig. 5. dE/dx within 5 Si strips vs. initial energy of the proton, 0.1 TeV to 1,000 TeV.

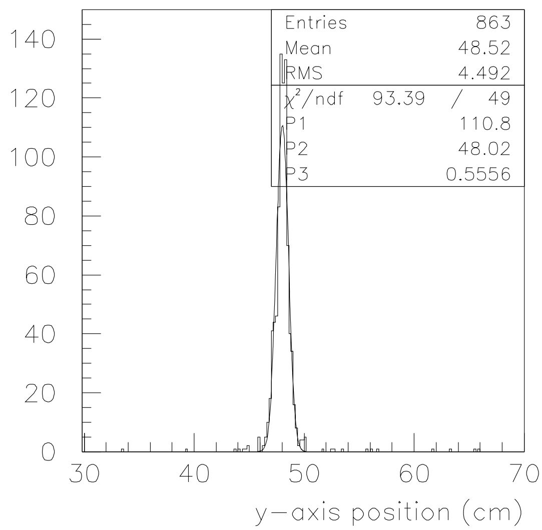

Fig. 6. Position resolution, δx, of the extrapolated point of impact in a plane 20 cm above the calorimeter.

vidually).

For each event, we then reconstructed its point of impact on the charge detector and considered the dE/dx deposits in both Si layers within a 1 cm circle around the reconstructed point of impact. The event was identified as a proton if the dE/dx deposit within this area in either Si layer was less than 2.5 mips.

Our conclusion is that two layers of Si strips do not provide a sufficient charge resolution, while both Si pixels and Si microstrips have an accuracy of better than 99% in the identification of 10 TeV protons. Although Si pixels are the most natural choice, Si microstrips are based on the same detector used in the calorimeter, making the overall design simpler.

As known, the intensity of backscatter increases with energy, and more Monte Carlo simulations are needed at the highest energies for ACCESS before deciding on the optimal design for the charge detector. However, our current simulations show only minimal differences in the intensity of the backscatter produced by a monolithic W calorimeter vs. a C target + W energy collector calorimeter.

The identification of electrons is described elsewhere (Bravar *et al.*, 2001). A rejection power for protons of 10^5 or better can be easily achieved by the Si-W calorimeter. An additional problem posed by ACCESS and not present in ELO is the rejection of gamma ray particles after they passed through the TRD.

6 Technical Aspects

Several options for the trigger of the ACCESS Si-W calorimeter have been considered. The use of an autotrigger scheme, similar to those utilized in space Si calorimeters (Bakaldin *et al.*, 1997), appears to be the most viable solution.

One of the major areas of concern of the Si-W design is the limited dynamic range of the currently available readout electronics (CR-1.4 chip Adams *et al.*, 1999). In order to measure the maximum dE/dx deposit in a single Si strip of a 1,000 TeV shower, and at the same time retain the 1 mip detection capability, the Si detectors for ACCESS should have a dynamic range of 1:10^7 to 1:10^8. Several solutions have been considered, including the use of different dynamic ranges for different Si planes, and the use of non linear preamplifiers, that would require an ASIC design.

The cost, power and data rate analyses show that the Si-W design (in its descope version, if necessary) meets all of the ACCESS requirements and fits within the estimated budget limits. Most of the technology employed for this design is based on detectors that have been already developed and whose performance and reliability are well known. This makes the Si-W design a simple and viable candidate for the ACCESS calorimeter.

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