A Silicon-Tungsten Imaging Calorimeter for ACCESS

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Abstract

A Silicon-Tungsten (Si-W) Imaging Calorimeter has been developed and flown by the WiZard collaboration in balloon borne and spacecraft based cosmic ray payloads. We analyze the expected performance of such a calorimeter concept for the ISS based ACCESS experiment as a possible alternative to the baseline design.

1 Introduction:

The scientific goals of the Advanced Cosmic ray Composition Experiment for the Space Station (ACCESS) are the measurement of the energy spectra of individual elements from hydrogen through iron to energies of approximately 10^{15} eV ('knee' region) and the measurement of the abundances of individual elements from iron to bismuth at moderate energies (see e.g. the Penn State web page). The current design of the ACCESS detector system includes three components: an element identifier module (ZIM) that measures the charge of cosmic ray particles from Z=1 to Z=83, a TRD to measure the energy of nuclei with $Z\geq3$, and a calorimeter intended to measure the energy of protons, helium and the lighter Z>2 nuclei. The definitive design of the calorimeter has not yet been determined.

A Si-W Imaging Calorimeter was flown in past cosmic ray payloads (Barbiellini et al. 1996, Golden et al. 1996, Hof et al. 1996, Boezio et al. 1997) as part of the NMSU/WiZard Balloon Borne Magnet Spectrometer. The same Si technology is now being employed for the satellite based cosmic ray detectors of the WiZard-RIM collaboration: NINA (Bakaldin et al. 1997) was launched in September 1998 and PAMELA (Adriani et al. 1999) is currently in an advanced development phase.

The original WiZard Si-W calorimeter was designed primarily as a particle identifier (used in paticular to identify positrons and antiprotons) and charge (dE/dX) measurer. The possibility of using a modified version of this detector as a hadronic calorimeter was previously analyzed in response to the NASA long duration '100 day' balloon program announcement (Bravar et al. 1997). In this paper we explore the option of using a Si-W Imaging Calorimeter as the third component of the ACCESS detector system.

2 ACCESS calorimeter overview:

The primary objective of the ACCESS calorimeter is the measurement of the energy spectra of protons and helium. The required performance can be summarized in an energy resolution $\delta E/E$ of better than 40% up to 10^{15} eV and a minimum effective collecting power (geometrical factor (Sullivan 1971) scaled by the fraction of useful events) of 0.5 $m^2 \cdot sr$. The ability to identify electrons up to an energy of a few TeV is also a desired, although not required, feature.

Several constraints are imposed on this calorimeter, the main one being its mass limit. This limit is not clearly fixed yet. For study purposes, however, we are currently assuming a maximum mass allocation of 2,730 kg for the basic calorimetric material.

Clearly, it is not possible to build a calorimeter that provides a full longitudinal containment of the hadronic shower and meets the above mass and collecting power specifications. The required $\delta E/E$ can be achieved by employing a thin calorimeter, a few nuclear interaction lengths (λ_I) in thickness. Such a calorimeter can be composed of two parts: a target section (to generate the hadronic shower) and an energy collecting section (to measure the energy released by this shower) that would ideally contain at least the shower maximum. The thickness of the target determines the fraction of useful events (i.e. the fraction of events that start their shower in this section) but also (due to the mass limit) the geometrical factor, while the energy resolution is directly related to the thickness of the energy collector. Longitudinal energy leakage from the bottom of such a calorimeter is one of the principal sources of fluctuations that limit the achievable $\delta E/E$ value.

3 Si-W calorimeter for ACCESS:

For our analysis, we considered a monolithic 2.0 λ_I thick Si-W calorimeter made of 30 sensitive Si detector layers interleaved with 29 equally thick W absorbers (the thickness of each absorber being 0.65 cm $\approx$ 0.07 $\lambda_I \approx$ 1.9 X_0 radiation lengths). In other words, both the target and the energy collector have exactly the same structure.

For the Si layers, we assumed the basic structure used in the past and present WiZard calorimeters (Bocciolini et al. 1996). Each Si layer is obtained as a mosaic of 8x8 cm^2 Si microstrip detectors. Each detector is 380 μm thick and is divided into 32 Si microstrips with a pitch of 2.4 mm. The strips of each detector are daisy chained longitudinally to the ones of the adjacent detectors to form a single Si strip whose readout is performed from the border of the sensitive layer. The mass limit fixes the area of the Si layers to 88x88 cm^2, equivalent to a mosaic of 11x11 Si detectors with a total of 352 readout channels. The strips of subsequent Si layers are oriented orthogonally to one another, providing alternating double coordinate (x-y) readout. In addition to being space qualified, this technology offers several advantages, including low cost, no known saturation effects, high linearity of the signal response, the ability to accurately detect 1 mip energy deposits, in flight auto calibration capability and high granularity (ability to provide an accurate topology of the interaction pattern).

For the absorbing layers, we investigated several low-Z and high-Z materials. Finally, we decided to use tungsten primarily because of collecting power issues. Optimization studies show that the very best effective collecting power can be achieved by using a low-Z material target followed by a high-Z energy collector (the ideal choice being carbon + uranium). A monolithic tungsten calorimeter (target and energy collector both made of tungsten rather than low-Z target + high-Z collector) has a slightly worse collecting power (around 20% lower) but offers several advantages over the low-Z target option: ability to accurately identify electrons, better determination of the starting point and longitudinal topology of the hadronic shower and better uniformity of the calorimeter response regardless of the depth at which the interaction occurs.

The weight of our calorimeter design is within the maximum limit, the power consumption is estimated to be slightly higher that 100 W and the effective collecting power for an isotropic flux is 1.18 $m^2 \cdot$ sr (the geometrical factor being 1.36 $m^2 \cdot$ sr).

4 Expected performance:

The expected performance of the above calorimeter design was investigated through Monte Carlo simulations. Our code was based on the GEANT 3.21-98a + FLUKA package (Brun et al. 1992). The simulations included protons in the energy range 0.1 TeV - 100 TeV and electrons at 0.1 TeV and 1 TeV, with all events entering the calorimeter at a 0^0 zenith angle. Effects connected to detector response (dynamic range, noise, dead area...) were not included in our code and simulations of low-Z nuclei have not been performed yet. The capabilities of most Monte Carlo codes at very high energies are not completely understood. Therefore some inaccuracies in our results might be possible, although unlikely.

The primary goal of the proton simulations was to determine the energy resolution at various energies and the energy response of the calorimeter as a function of incident energy. We investigated different ways of associating the visible energy (energy released in the sensitive layers of the calorimeter) to the incident energy of the proton. First we considered the energy deposit (dE/dX) distributions in all the Si layers without making any selection on the Monte Carlo protons, achieving a $\delta E/E$ value larger than 50%. We were then able to obtain a $\delta E/E \approx 40\%$ by excluding the protons that do not interact in the target section of the calorimeter. Subsequently we considered the dE/dX distributions of only those protons that interact on top of the calorimeter (Fig. 1). This choice gives $\delta E/E \approx 25\%$ at all energies but allows us to analyze only a very limited fraction of the total number of events. It is significant to note that the energy resolution in our broad energy range (0.1 TeV - 100 TeV) is nearly independent of the incident energy. This is probably due to the fact that higher incident energies correspond to both lower intrinsic $\delta E/E$ values and larger longitudinal leakage from the calorimeter bottom (due to deeper shower maximum).

We then analyzed separately the dE/dX distributions of protons interacting at different depths of the target section and obtained a separate $\delta E/E$ value for each of these samples. We estimated an average $\delta E/E$ (obtained as the mean of the single $\delta E/E$ values weighted by the fraction of events interacting at each of the different depths of the target section) of around 30%, again independent of incident energy.

We are currently investigating an algorythm to improve the above energy resolution by introducing a correction function to the dE/dX deposit. When a proton interacts deeper than the top few layers of the calorimeter (but within the target section), its dE/dX is corrected by a quantity that depends on the number of the Si plane where the shower maximum occurs and on the dE/dX deposit in the Si layers adjacent to this plane. This algorythm is still under development, however the first results provide an average $\delta E/E$ of about 25% (close to the resolution we have for the events interacting on top) for all of the events interacting in the target section (i.e. almost 70% of the total number of events with 0^0 zenith angle) (Fig. 2).

When we consider the total dE/dX in the whole calorimeter, the relation between the visible energy to the incident energy is non-linear. We are able to obtain good linearity if we consider only the energy deposited within 1 Si strip of the track of the primary particle (in other words, we are considering only the core of the hadronic shower), as shown in Fig. 3. Such a choice does not affect the $\delta E/E$ value at high energies (although we get a slightly worse $\delta E/E$ at low energies). Using only the core dE/dX also eliminates the problem of lateral leakage correction and border effects in proton tracks that are close to the lateral surfaces of the calorimeter.

Using our Monte Carlo code, we obtain a $\delta E/E \approx 4\%$ for electrons at 1 TeV. However, the main challenge is the separation of electrons from protons. Due to the overwhelming abundance of protons, a proton/electron rejection power of 10^5 is needed to assume an accurate electron selection. Our calorimeter design has a thickness of 55 X_0 (i.e. 2.0 λ_I of W). The longitudinal profiles of electromagnetic and hadronic showers in such a deep (from the electromagnetic standpoint) calorimeter are shown in Fig. 4. From our Monte Carlo samples, by simply introducing a cut on the 'tail' of the hadronic showers at high calorimeter depths, we can achieve a rejection power of better than 10^3 (this value is currently limited only by available statistics). Several studies (including our own work on our Monte Carlo data) show that a rejection power of at least 10^3 can be obtained independently in a high-Z imaging calorimeter by considering the topology of the shower in the Si layers at low detector depths. Therefore we can reasonably expect to obtain the 10^5 rejection power figure with the calorimeter alone, without any external aid e.g. from the TRD.

5 Conclusions:

The study presented in this work is far from complete and several points require further investigation. We are currently considering the possibility of supplementing our Si sampling layers with Scintillating Fibers for optimum calorimeter performance and beam tests to confirm our Monte Carlo results are planned in the near future. It appears that a simple Si-W sampling calorimeter can meet and exceed all of the ACCESS requirements and specifications. The Si technology that we considered for our analysis is already space qualified and can provide significant cost reductions over other detector options.

References:

Adriani, O. et al. 1999, Proc. 26th ICRC, Salt Lake City, USA

Bakaldin, Y. et al. 1997, Astrop. Phys. **8**, 109

Barbiellini, G. et al. 1996, A&A **309**, L15

Bocciolini, M. et al. 1996, Nucl. Instr. Meth. **A370**, 403

Boezio, M. et al. 1997, ApJ **487**, 415

Bravar, U. et al. 1997, Proc. 25th ICRC, Durban, South Africa, **4**, 93

Brun, R. et al. 1992, CERN GEANT 3 User's Guide, CERN, Geneva, DD/EE/84-1

Golden, R.L. et al. 1996, ApJL **457**, L103

Hof, M. et al. 1996, ApJL **467**, L33

Penn State ACCESS web page: http://access.phys.psu.edu/frames/home_frame.html

Sullivan, J.D. 1971, Nucl. Instr. Meth. **95**, 5

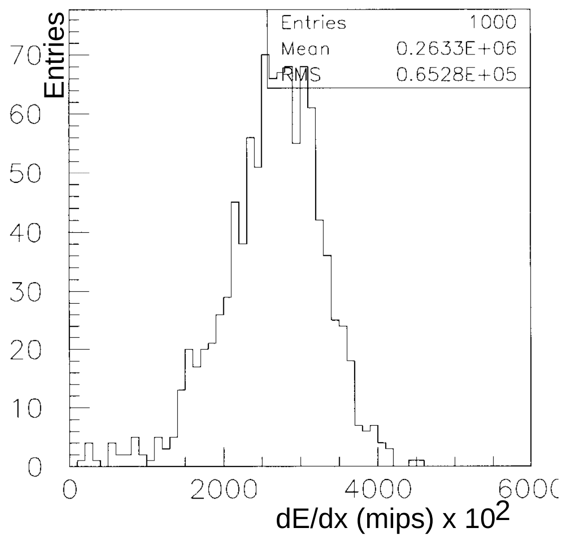

Figure 1: dE/dx distribution for 10 TeV protons interacting on top of the calorimeter

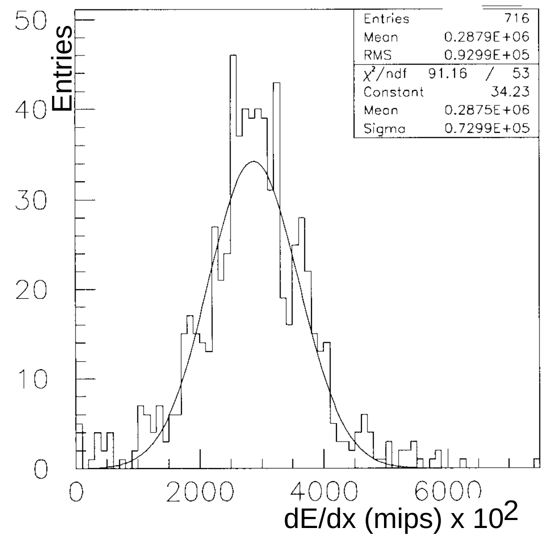

Figure 2: Corrected dE/dx distribution for 10 TeV protons interacting anywhere in the target section of the calorimeter

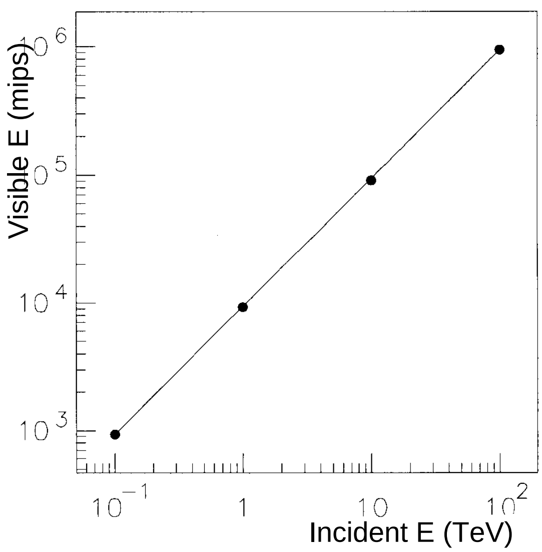

Figure 3: Incident energy vs. visible energy: energy response function of the calorimeter for dE/dx deposits within 1 Si strip of the track of the primary proton

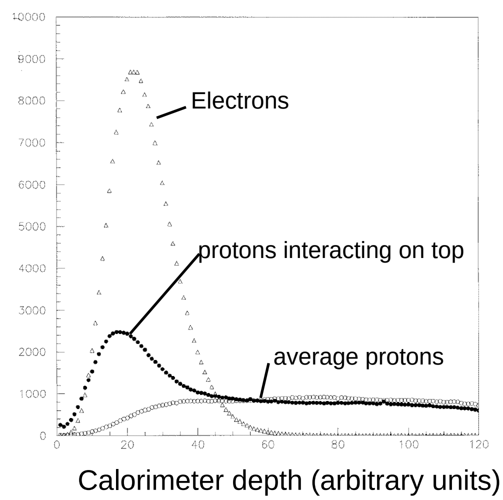

Figure 4: Longitudinal profile of showers in a 20 λ_I, 55 X_0 calorimeter for 1 TeV protons and electrons