A Guide for ACCESS Design Considerations

Opher Ganel, Eun-Suk Seo, Jian-Zhong Wang, Jayoung Wu

Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742, USA

Abstract. The Advanced Cosmic-ray Composition Experiment for the Space Station (currently under study) will include a thin calorimeter to measure the energy of cosmic ray nuclei from H to Fe. The calorimeter will provide the only energy measurement for H and He nuclei, crucial for two high priority objectives, searching for the existence of a ‘knee’ in the proton spectrum and studying the energy dependence of the H to He ratio. Particles scattered backward from hadronic interactions in the calorimeter will impact the performance of detectors above the calorimeter. The energy reach required by the physics goals requires a flexible, scalable trigger system to discard out-of-geometry and low-energy events. In this paper we provide a guide to some design considerations arising from the effects of back-scatter and the expected event rates.

INTRODUCTION

The baseline design of ACCESS (Fig. 1) includes a Charge Identification Module (ZIM) capable of resolving individual nuclei (H – U), a Transition Radiation Detector (TRD) for velocity measurement, and a calorimeter for energy measurement of nuclei from H to Fe. The TRD and calorimeter will provide cross-calibration for each other for Z ≥ 3 nuclei that penetrate the TRD and interact in the calorimeter.

The calorimeter section is comprised of a silicon charge detector (Si), a carbon target interleaved with several pairs of crossed scintillator-strip trigger planes, and a Bismuth Germanate (BGO) calorimeter with laterally oriented crystals in crossed layers. The 1 interaction length (λ_{int}) thick target will force nuclear interaction in more than 63% of incident protons and in greater percentages of heavier nuclei. Calorimetry is the only practical method to measure the energy of H and He nuclei at high energies. This measurement is crucial for searching for a proton spectral break hinted at by existing data (Asakimori et al., 1993) and the spectral index difference between protons and He nuclei that may indicate different acceleration mechanisms.

When a high-energy proton (or nucleus) enters the calorimeter module it soon undergoes a nuclear interaction, generating a large number of secondary particles (mostly π^+, π^−, and π^0) that carry off a large fraction of its energy. The π^0’s decay almost immediately into photon pairs and initiate electromagnetic (EM) showers or cascades (large collections of electrons, positrons, and photons). The surviving primary and charged secondaries continue on into the calorimeter. Some of these energetic charged hadrons will interact again, and fractions of their energy are also transferred to EM cascades. Most of the energy carried by charged hadrons will leak out the bottom of the calorimeter. The energy measured is predominantly the EM fraction produced in the first interaction(s).

Most high-energy shower particles have a ‘forward’ momentum component relative to the incident trajectory, but there is a large number of lower energy particles moving ‘backwards’. These are mostly MeV-range photons and electrons from the isotropic component of EM cascades and neutrons produced in hadronic interactions (see Fig. 2). Signals from some of these particles will overlay that of the primary particle in the ZIM and the calorimeter’s Si detector, making charge measurement more challenging. Indeed, this is a rather widely-accepted explanation for misidentification of protons as He nuclei in past experiments (Ellsworth et al., 1977). Figure 1 shows the tracks of shower particles resulting from the interaction of a simulated, vertically incident 1 TeV proton in ACCESS. Backward traveling particles can be seen impinging on all detectors above the calorimeter.
BACK-SCATTERED PARTICLES

GEANT/FLUKA 3.21 (Brun et al., 1984, Arino et al., 1987) simulations of vertically incident protons has been used to study back-scattered particles, in order to understand the factors that affect them, and to assess the effectiveness of some design strategies to minimize their impact on the measurements. Figure 2 shows energy spectra of back-scattered photons, neutrons, electrons, positrons, charged pions, protons, and kaons for 1 TeV protons.

Energy Deposit in Top Scintillator Layer

Figure 3 plots the dependence of mean back-scattered energy deposit density $D$ (in MeV), in the top scintillator layer (Fig. 1) on the distance from the incident proton trajectory $R$ (in cm). $D$ is the energy deposited in a $1 \times 1$ cm$^2$ area of a 2 cm thick scintillator, and is given for incident protons with kinetic energies of 1 TeV (circles), 10 TeV (squares), and 100 TeV (triangles) interacting in the carbon target. The functional forms of the empirical fit lines (solid, dashed, and dotted, respectively) are given by Eq. 1.

$$
D(1 \text{ TeV}) = 0.019 \times 10^{-R/37},
$$

$$
D(10 \text{ TeV}) = 0.040 \times 10^{-R/44},
$$

$$
D(100 \text{ TeV}) = 0.100 \times 10^{-R/51}. \tag{1}
$$
From Eq. 1 we see that a 2 x 2 cm² pixel of 2 cm thick scintillator at the point of incidence of a 100 TeV proton would measure, on average, a total deposit of 0.4 MeV. The same pixel, located 10 cm away would measure, on average, a total deposit of 0.25 MeV. Close to the trajectory, D increases roughly two-fold for a ten-fold increase in proton energy. Further from the proton’s point of incidence, D decreases, but its energy dependence increases.

Figure 4 shows the total back-scattered energy $E_d$, deposited in the 2 cm wide central strip of the top scintillator layer traversed by the simulated protons, as a function of incident proton energy $E_p$, (in GeV). $E_d$ is given in units of the mean energy deposited by minimum ionizing particles (MIP). Shown are the mean (circles), and top percentile (squares) values. Equation 2 gives the functional forms of the fits depicted by the solid and dashed lines, respectively. Extrapolating to 1000 TeV, the fits predict that the average proton event will have a back-scattered energy deposit in the 2 cm wide top scintillator central strip equivalent to 4.7 MIP and the top percentile of such back-scattering will be equivalent to 15 MIP. Nearly 50% of all 1000 TeV protons will be misidentified.

$$\log[E_d \text{ (mean)}] = 1.7 + 0.395 \log (E_p),$$

$$\log[E_d \text{ (top 1%)}] = -0.186 + 0.396 \log (E_p) - 0.0279 \log(E_p)^2.$$ (2)

Segmentation of Charge Detector

As previously demonstrated (Seo et al., 1996), a segmented detector is much less prone to back-scatter problems. Figure 5 shows the simulated back-scattered energy deposit, $E_\text{n}$, (in MIP units), integrated over a circular area, as a function of the circle’s radius (R), for 1 TeV (solid line), 10 TeV (dashed line), and 100 TeV (dotted line) incident protons. The curves show (e.g.) that on average back-scattered particles will deposit 3 MIP units in a 100 cm² area near the point of incidence of a 100 TeV proton. For a 4 cm² area, this deposit will be less than 0.1 MIP.

As the integrated energy deposit decreases with decreasing ‘pixel’ size, so does the probability of having one or more back-scattered particles in the same pixel as the primary. Figure 6 shows the fraction of misidentified protons, as a function of proton energy, for 2 x 2 cm² pixels (empty circles), 2 cm strips (full circles), 10 x 10 cm² pixels (empty triangles), 10 cm strips (full triangles), and without segmentation (empty diamonds). As can be seen, the fraction is 1 – 2% for 1 – 100 TeV, with 2 x 2 cm² pixels. Extrapolating to 1000 TeV, one can estimate the fraction will be 3 – 5% for the small pixels. The narrow strips and the larger pixels extrapolate to about 50%, while the wide strips and unsegmented detector are expected to misidentify virtually all protons at 1000 TeV.

From Figs. 5 and 6 it is clear that fine detector segmentation reduces the effect of back-scatter. The increased numbers of channels in finely segmented detectors however, make them more complex and expensive. A typical strip-detector might have hundreds of channels, whereas pixel detectors have thousands of channels. The optimal charge detector would have the minimal channel number required to achieve the measurement objectives. From Fig. 6 we see that a 2 x 2 cm² pixel size would serve for identifying protons over the planned ACCESS energy range.
The Effect of Discarding the Carbon Target

Suggestions have been made that discarding the carbon target would benefit certain physics measurements (e.g., primary electrons). Such a configuration would suffer several significant drawbacks for measuring nuclei. The effective geometry factor will be reduced by 20%, the energy resolution will be degraded (Ganel et al., 1998), and the back-scatter effect will increase. Two configurations have been simulated: the baseline ACCESS design with a 1 $\lambda_{\text{int}}$ carbon target, and an alternative design with a 1 $\lambda_{\text{int}}$ BGO 'target' instead. The density $D$ (in MeV/cm$^2$) of back-scattered energy in a 1 x 1 cm$^2$ area of the top scintillator with carbon (circles) and without carbon (squares) is compared in Fig. 7. Equation 3 gives the form of the (solid and dashed, respectively) fit lines. Near the simulated proton trajectory, the density is 4 times higher for the alternative design.

$$D (\text{carbon}) = 0.032 \times 10^{R/18}, \quad D (\text{no carbon}) = 0.183 \times 10^{R/13} \quad (3)$$

The Effect of Spatial Separation

Figure 8 displays the simulated back-scattered energy density $E_d$ (in MeV/cm$^2$), in a 10 x 10 cm$^2$ area of a 2 cm thick scintillator, with carbon (circles) and without carbon (squares), for 1 TeV protons, as a function of target to scintillator separation $S$ (in cm). From Eq. 4, which describes the (solid and dashed, respectively) fit lines for a
scintillator, we find that immediately above the target, at the Si detector, 2 MeV (0.5 MIP) is deposited with the baseline design compared to 11 MeV (2.75 MIP) for the alternative design without carbon. Mid-way up the TRD the values are reduced to 0.1 MeV and 0.22 MeV, respectively, and mid-way up the ZIM, 0.025 MeV and 0.05 MeV. With no carbon one must lift the charge detector 15 cm above the BGO to reduce the back-scattered energy deposit in a 10×10 cm² pixel to that in a pixel of the same size located immediately above a carbon target. A detector 60 cm above the carbon would need to be moved an additional 40 cm, to 100 cm above a BGO “target”.

\[
E_d (\text{carbon}) = \frac{600}{S + 18}, \quad E_d (\text{no carbon}) = \frac{1100}{S + 10}
\]

Note that the above energy deposits are for a scintillator at various locations and not the ZIM or TRD signals. The latter may be estimated from the energy spectra provided in Fig. 2. Note also that in some fraction of events the first interaction will occur in the ZIM or the TRD, and the effects of back-scattered particles on the ZIM will be greater.

**TRACKING AND TARGET SCINTILLATOR DESIGN**

To measure the charge of the incident particle one must correctly identify which pixel recorded its passage. To do so, the target scintillators and calorimeter must be constructed in such a way that track reconstruction is accurate enough to extrapolate to the incident position in the correct pixel. One can pick the pixel with the highest signal within the “circle of confusion” (a circle around the reconstructed track, with a radius equal to 3σ in the extrapolation uncertainty) as the one which has recorded the signal from the primary. To take full advantage of tracking precision the pixel size should be smaller than the diameter of the “circle of confusion”.

The details of shower development make the accuracy with which the measured shower axis represents the incident trajectory strongly energy dependent, with uncertainty increasing significantly for decreasing proton energies below 100 GeV. The long extrapolation distance needed up to the Si matrix (50 cm from the top of the BGO), or worse yet, to the ZIM module at the top of ACCESS (170 cm) magnify the effect of trajectory reconstruction errors.

At high energies, the measured shower core lies along the primary trajectory, but, as detailed above, many more back-scattered shower particles confuse the charge measurement, so excellent resolution is needed. Previously (Seo et al., 1996), a calorimeter-based algorithm was illustrated, providing an answer to this tracking requirement. The algorithm reproduced the proton trajectory to within a few mm in the BGO, but accurately extrapolating up to the Si position, especially below 100 GeV, was more difficult. Utilizing information from the target scintillators and the Si matrix, in addition to the BGO calorimeter energy deposit pattern, significantly improves the tracking accuracy. As scintillator hits are far less energy dependent than calorimeter signals, so is the accuracy of such a combined scheme. The resolution was shown (Ganel and Seo, 1998) to be better than 3 mm at 1 TeV and 4 mm at 100 TeV, with five layers of 1 cm wide scintillator strips and a Si detector with 2×1.5 cm² pixels.

Figure 9 plots the extrapolation resolution at the top of the target as a function of scintillator strip-width. The resolution is roughly proportional (slope of 0.31) to strip-width over the range studied. As the figure shows, 1 cm wide strips provide a circle of confusion similar in area to pixels of 2×2 cm². We intend to study whether narrower scintillator elements (e.g. fibers) would allow even better resolution. There are, however, practical limits having to do with readout-channel cost, power requirements, minimal required light yield, and increased attenuation. Simulations show that for half the proton events, the information provided by 1 cm wide scintillator strips below and above the target allows few-mm accuracy (Ganel and Seo, 1998). Unfortunately, flagging events in this category may not be possible. Additional layers interleaved in the target reduce the fraction of events where tracking accuracy is not improved from 50% with 2 layers to 1 – 2% with 5 layers. Scintillator layers high in the stack, where a low hit density makes correct identification of the primary track easier, offer the greatest improvement.

**FIGURE 9.** Simulated BGO + scintillator extrapolation resolution at top of target vs. strip width for 1 TeV protons.

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TRIGGER

For every order of magnitude increase in energy the cosmic ray flux is reduced by a factor of 50 – 100. Thus, to collect 10 protons above $10^{15}$ eV (over 1000 days) would imply several hundred billion protons above $10^9$ eV. Including out-of-geometry and heavy nucleus events, the event rate would exceed 75 kHz and the data volume 3,000,000 Terabytes. High-Z nuclei traversing the ZIM at all energies would exacerbate the problem even further. To be viable ACCESS needs a trigger system that selects more than 95% of in-geometry events above 1 TeV, while rejecting out-of-geometry and low-energy events sufficiently to keep data rate and volume acceptable. The trigger should be able to keep background events to no more than 50% of the data, and low-energy events to less than 90%. This would keep the data volume below 0.1 Terabyte and the event rate at about 1 Hz. Another crucial requirement of calorimeter/TRD trigger performance is to minimize the energy-dependence of its efficiency. All energy spectra measured by the experiment would be systematically in error if such dependence were not correctly accounted for.

No single selection scheme will work with near 100% efficiency over the wide energy range needed, while rejecting events at lower energy. Such trigger performance requires a combination of several selection schemes. The trigger system must be flexible and allow several thresholds (preferably more than three) for the highest sensitivity of any detector element. The system must include adjustable pre-scaling separately for each selection, and permit different sensitivities for calibration data (e.g. pass-through protons). Thresholds at lower sensitivities will allow separate flagging of the most interesting (highest energy) events. The trigger should include at the very least three scintillator layers above the calorimeter and the calorimeter itself. If the trigger cannot include the calorimeter (e.g. if it is read out by image-intensified CCD’s), additional trigger scintillators must be inserted in and below the calorimeter stack. ZIM triggers with different charge thresholds and pre-scaling factors should be OR’ed with the calorimeter/TRD triggers. Overlap between the ZIM triggers will allow inter-calibration and absolute abundance measurement.

CONCLUSIONS

Our simulations show that back-scattered particles will significantly affect measurements of the primary particle in detectors above the calorimeter. We have estimated the energy density and integrated energy deposits as a function of proton energy, distance from proton trajectory and vertical separation from the target. Finer segmentation and greater separation between detectors and the calorimeter module can limit this effect. Greater segmentation would, of course, increase cost and complexity. Greater separation would reduce the geometry factor. Discarding the carbon target would increase the back-scatter problem, unless the charge detector is moved 15 cm upward, and the TRD and ZIM are moved 35 cm upward. Tracking precision will also be important for overcoming overlay of back-scatter with the primary. This requires as many layers as practical of finely segmented scintillators, preferably positioned as high in the stack as possible and still be compatible with trigger needs. The energy range of interest for the calorimeter and TRD and the low energy threshold of the ZIM will make the ACCESS trigger both extremely important and challenging. We have presented some initial thoughts on how such a trigger might be implemented.

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REFERENCES