Proceedings of ICRC 2001: 2243 © Copernicus Gesellschaft 2001

ICRC 2001

An imaging calorimeter for ACCESS-concept study

T. A. Parnell[1], J. H. Adams[2], R. W. Binns[3], M. J. Christl[2], J. H. Derrickson[2], W. F. Fountain[2], L. W. Howell[2], J. C. Gregory[1], P. L. Hink[3*], M. H. Israel[3], R. M. Kippen[1], G. N. Pendleton[1*], Y. Takahashi[1], and J. W. Watts[2]

[1]University of Alabama in Huntsville, Huntsville, AL 35899
[2]NASA/Marshall Space Flight Center, AL 35812
[3]Washington University, St. Louis, MO 63130
[*]former affiliation

Abstract. A mission concept study to define the "Advanced Cosmic-ray Composition Experiment for Space Station (ACCESS)" was sponsored by the National Aeronautics and Space Administration (NASA). The ACCESS instrument complement contains a transition radiation detector and an ionization calorimeter to measure the spectrum of protons, helium, and heavier nuclei up to ~10^{15} eV to search for the limit of S/N shock wave acceleration, or evidence for other explanations of the spectra. Several calorimeter configurations have been studied, including the "baseline" totally active bismuth germanate instrument and sampling calorimeters utilizing various detectors. The Imaging Calorimeter for ACCESS (ICA) concept comprises a carbon target and a calorimeter using a high atomic number absorber sampled approximately each radiation length (rl) by thin scintillating fiber (SCIFI) detectors. The main features and options of the ICA instrument configuration are described in this paper. Since direct calibration is not possible over most of the energy range, the best approach must be decided from simulations of calorimeter performance extrapolated from CERN calibrations at 0.375 TeV. This paper presents results from the ICA simulations study.

1 Introduction

The Imaging Calorimeter for ACCESS (ICA) is a "mission concept" design study to define a sampling calorimeter for proton and helium spectral measurements up to the "knee" (~3 PeV in the all-particle cosmic ray spectrum) (ICA Home Page). In ACCESS, energy measurements on heavier nuclei would be made in concert with a transition radiation detector above the calorimeter. The collecting power, energy range, and energy resolution of the calorimeter ideally should be sufficient to detect a predicted break in the proton and helium spectra near 100 TeV. (Lagage,1983). Accurate measurements of the spectra of all elements Z=1-28 over wide energy ranges would test source models for cosmic rays (Biermann,1994).

Correspondence to: T. Parnell
Thomas.Parnell@MSFC.NASA.GOV

The ACCESS calorimeter would have a mass allocation of 2700kg and a maximum exposure time of 3 years. These constraints, along with the low fluxes at high energies, dictate a thin calorimeter with a maximum practical geometry–efficiency factor. A calorimeter that rapidly develops and absorbs the first interaction electromagnetic cascade was selected for ICA. This "ultra thin" approach has heritage in emulsion chambers (Burnett,1986), and more recently the SOFCAL instrument (Christl 1996,1999).

The configuration for the ICA study was a sampling calorimeter employing thin (~0.5mm) scintillating fiber detectors in hodoscopic X,Y planes, spaced each radiation depth or less in the calorimeter. The main components are a carbon target with up to one proton interaction length thickness and lead or tungsten plates, 0.5 to 1 rl thick, with a total depth of 25-60 rl. The concept study included an extensive series of GEANT-FLUKA simulations of energy resolution from 0.1 to 1000 TeV and tests with a small ICA model with protons and electrons at CERN. Results from the CERN tests are also presented at this conference.

Figure 1 shows a schematic of the ICA configuration. Geometry-efficiency factor calculations for various target and calorimeter depths which meet the ACCESS mass constraint show that the ICA configuration can achieve geometry-efficiency factor of >2 m^2-sr with or without a carbon target. These calculations include particles with up to 68° zenith angle and which interact anywhere in the target. The calculations also included events that interact in the calorimeter which have a residual path length of >25 rl in the calorimeter. With a proton spectral index of 2.7 changing to 3.1 above 100 TeV more than 50 protons would be detected above 500 TeV in 3 years.

In order to explore the full imaging capability of ICA and its potential benefits in data analysis, it is necessary to simulate each element of the detector system including target, absorbers, and each fiber (including the non-scintillating cladding). The ICA detector geometry was modeled in GEANT (Brun et al, 1984) and interaction/cascade simulations were performed in GEANT/FLUKA (Watts 1999, Lee 2000). The simulation results reported here were performed for calorimeters of 25 rl and 60 rl below a carbon target of $0.7\lambda_p$. Since the number of detector elements and array sizes are so large the area of the simulated calorimeter has been confined to 30 x 30 cm, although a Space Station ICA would have an area of ~ 1 m^2. Typical simulation data output array sizes of 50 megabytes resulted from each "event." The simulations were run on the Silicon Graphics Power Challenger and the Silicon Graphics Orion 2000 computers at MSFC.

2 Design Features of ICA

Thin (0.5mm) square scintillator fibers were selected as the detector for the ICA studies. This is the thinnest practical SCIFI detector with adequate optical attenuation characteristic (~1m) and light output (> 80% detection efficiency for relativistic singly charged particles). Thin detectors introduce the least dilution of the high Z absorber and allow the physically thinnest calorimeter. They also give the best "point back" angular resolution from the cascade to the pixelated primary charge detectors above the target, facilitating reduction of back-scattered particle effects on primary particle identification. Smaller fibers result in less photo-cathode area, which reduces the cost and complexity of the readout system. Sampling within the cascade with high resolution (Watts 1999,Parnell 2000) could find use in analysis of flight data, such as improved separation of primary electrons from proton events.

The 0.5mm square fibers used in the ICA simulation study have a polystyrene based scintillating core with a 6% total thickness acrylic cladding which was included in the GEANT geometry. The simulations used hodoscopic XY planes of fibers at 0.5 rl depth for the first 3 rl, and at each following rl.

The ICA study assumed image intensifier-CCD cameras (IICCD) as the principal candidate for its imaging device, since it is the presently available technology with the best combination of image resolution and record of successful application. A combination of IICCDS and photo-multiplier tubes on the opposite ends of the fibers would result in wide dynamic range and individual fiber imaging.

3 Major conclusions from the ICA simulation effort

3.1 Summary of results for the energy resolution for vertically incident protons:

The cascades for protons vertically incident on the instrument were simulated for a set of events at 0.1, 1, 10, 100, 1000, and 5000 TeV. The number of events simulated was 985, 1000, 527, 272, 50 and 20. Respectively. Events were selected that interacted anywhere in a 0.7 λ_p graphite target. The energy deposition in each plane of fibers (the "transition curve") was averaged for the set of events at each energy. At 5000 TeV the average transition curve peaks at 20 radiation lengths. These simulations show that 25 radiation lengths is an adequate depth for a calorimeter in the ICA design and for the anticipated energy range from a 3 year mission. Details of these simulations are contained in Watts (1999) and Parnell (2000).

3.2 Summary of results on the three-dimensional shower behavior (lateral profiles):

Because of the output format for the ICA simulations the lateral shower profiles are available to a granularity of 0.5 mm each radiation length along the shower. The lateral shower profiles show a significant central peak until well beyond shower maximum. A significant shower core is expected from consideration of the angles of pions produced in the first interaction (the rapidity distribution), and relativistic effects on subsequent pair production and bremsstrahlung. The narrow central core has consequences for calorimeter design. For example the application of the Moliere radius applies only for the average behavior of the entire cascade depth (Watts 1999, Parnell 2000).

3.3 Primary track reconstruction and point-back accuracy:

The fitting of simulated cascade profiles to reconstruct the primary track, and "point-back" to the primary charge detector has been done for sets of vertically incident protons at 1 TeV. The reconstructed tracks are within 1 mm sigma of the incident particles track for primary energies of 1 TeV and above at the top of the calorimeter. The reconstructed tracks are within 6 mm sigma of the incident primary path at a plane 1 cm above the top of the target (the position of a primary charge detector plane). This is 28cm above the top of the calorimeter. The fitting of simulated cascade profiles to reconstruct the primary track, and "point-back" to the primary charge detector has also been done for sets of isotropically incident protons at 100 GeV, 1 TeV, and 10 TeV. The reconstructed tracks are within 6 mm, 2 mm, and 0.5 mm sigma of the incident particles track for the respective energies at the top of the calorimeter. The reconstructed tracks are within 2 cm, 1 cm, and 2 mm sigma of the incident primary track for the respective energies at a plane 1 cm above at the top of the target (28 cm above the calorimeter). The point-back accuracy improves with the primary energy since the increased number of cascade particles "smoothes" the lateral profiles.

3.4 Summary of the results on deposited energy measures, and energy resolution:
The energy resolution has been studied for several measures or indicators of the deposited energy sampled by the fibers. The traditional measure is the total energy deposited in all fibers by the particle cascade, which we designate ΔE. Another measure we have investigated is the maximum energy deposited in any layer of the calorimeter as determined by a Greisen-parameter fit to the longitudinal shower development curve (energy deposited in each fiber layer). Still another was the maximum energy deposited in any single fiber in the calorimeter. For ΔE the energy resolution determined by the dispersion of the energy deposit for approximately 1000 events at each energy was 40% over the energy range from 0.1 to 1000 TeV for a 25 rl calorimeter. For the other measures the energy resolution was considerably worse at low energies, but only slightly worse at 100 TeV and above. For the event statistics simulated in these runs, the shapes of the energy deposition distributions were approximately Gaussian (Watts 1999, Parnell 2000).

3.5 Summary of results for the electron-proton separation (events interacting in the target):
In addition to the incident proton simulations incident electrons have been simulated at 1 and 10 TeV. These simulations include the 0.7 mfp carbon target, unlike most other ACCESS electron simulations that are incident on a high-Z calorimeter. For these electron events the lateral dispersion in energy deposition in fibers was calculated for the first three radiation lengths and compared with the dispersion calculated for protons with energies 10 times the electron energy (Watts,1999). Approximately one proton out of a thousand has a lateral spread that is as narrow as the average electron event. This result is comparable with experimental results reported from an experiment at CERN(Tamura,1999) which used a calorimeter without a target.

3.6 Summary of calculations to define the exposure factors needed to detect a spectral break :
A simple power law model consisting of a single spectral index α_1 is believed to be an adequate description of the galactic cosmic ray (GCR) proton flux at energies below 10^{13} eV, with a transition at knee energy E_k to a steeper spectral index $\alpha_2 > \alpha_1$ above E_k. A maximum likelihood procedure was developed for estimating these three spectral parameters of the broken power law energy spectrum from assumed detector geometry, resolution and exposure (Howell,2001). The statistical properties of the parameters were investigated with repeated "experiments". The estimation procedure will be generalized for application to future cosmic ray data. These estimates and their surrounding statistical uncertainty can be used to derive the requirements in energy resolution, calorimeter size, and energy response of a proposed calorimeter for ACCESS. For example, when the"true"spectral index change is 0.3 and the knee location is assumed to be at 100 TeV, the ICA baseline detector (1m^2 for 3 yr exposure) detected the spectral break for each of 1000 simulated missions. The distribution of estimated spectral indices above and below the break were clearly separated and the break energy was "measured" with a mean of 100.2 TeV and standard deviation of 24 TeV. However, if the assumed break is increased beyond 200 TeV, the ability to "detect" spectral changes rapidly degrades.

4 Conclusion

A study of a lead/tungsten and scintillating fiber calorimeter for ACCESS was performed with an extensive series of GEANT/FLUKA simulations and tests with a small calibration unit at CERN. Results from the CERN calibration, limited to 250 and 350 GeV for protons and 150 and 250 GeV for electrons, are reported in a separate conference paper. The study confirmed that the ICA concept meets the performance criteria for ACCESS in energy resolution (≤40%) and significantly exceeds them in collecting power. The ICA geometry-efficiency factor of ≥ 2 m^2-sr (within the 2700kgs mass constraint) is the largest of any studied, except for a cubic (five sided) design. Studies of back-scattered particles from the ACCESS calorimeter are not yet complete, but calculations so far indicate potential problems any primary charge detector with pixel dimensions exceeding ~1 cm. The ICA fine-sampling that allows accurate reconstruction of primary trajectories from the calorimeter cascades (2mm σ at top of target for 10 TeV protons) may prove an essential performance feature for ACCESS. Further information about ICA study results can be found at the ACCESS Data Management Web-Site.

5 References

ACCESS-NRA, NASA Research Announcement, NRA 97-OSS-13
Biermann, P.L., 23rd ICRC Rapportuer Paper (1994)
Brun et al, "Geant User's Guide", CERN, DD/EE/84-1, Geneva (1984)
Burnett T.H. et al., NIM, **A251**, 583 (1986)
Christl M.J. et al., Proc. of SPIE, V**2806**, 155 (1996)
Christl, M.J. et al., 26th ICRC Proc. (Salt Lake City), Vol. **5**, pg. 5 (1999)
Lagage, et al., Astronomy & Astrophysics, V**118**, p223 (1983)
Tamura, T et al., 26th ICRC Proc. (Salt Lake City), Vol. **5**, pg.21 (1999)
Watts, J.W. et al., 26th ICRC Proc. (Salt Lake City), Vol. **5**, pg. 457 (1999)
Watts J. W., et al, "Simulations of Performance for the Imaging Calorimeter for ACCESS," 26th ICRC Proc. (Salt Lake City), Vol. **5**, pg. 457 (1999)
Parnell, T., et al, "The Imaging Calorimeter for ACCCESS (ICA)", 26th ICRC Proc. (Salt Lake City), Vol. **5**, pg. 171 (1999)
Howell, L., "Estimation of Cosmic Ray Spectral Parameters From Simulated Detector Responses With Detector Design Implications," NASA TP, In Press (2001)
Howell, L., "Maximum Likelihood Estimation of the Broken Power Law
Spectral Parameters with Detector Design Applications," NIM A(submitted 3/2001)
Howell, L., "A Recommended Procedure for Estimating the Cosmic-Ray Spectral Parameter of a Simple Power Law," NIM, In Press (2001)
Parnell, T., et al, "A Thin Sampling Calorimeter for Measurement of Cosmic Ray Spectra from 0.1 to 1,000 TeV," Proc. 8th International Conference on Calorimetry in High Energy Physics, World Scientific Publishing Company, pg. 795 (2000)
Lee, J. , Watts, J. W. , Howell, L. W. , " Simulations of a Thin Sampling Calorimeter With GEANT/FLUKA", NIM A, In Press (2000)
ICA Home Page:
http://science.msfc.nasa.gov/cosmicray/ica
ACCESS Data Management Site:
http://access.phys.psu.edu/frames/dbase-login.shtml

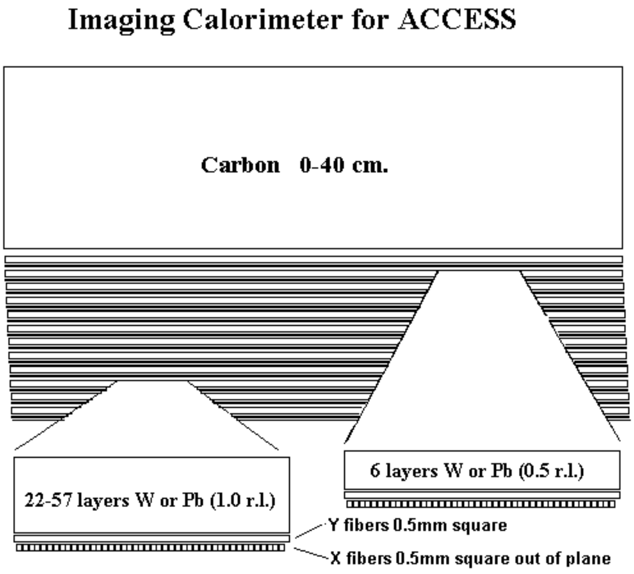

Figure 1. Schematic of the ICA configuration