GEANT4 Applications for Astroparticle Experiments

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Abstract— **The GEANT4 Monte Carlo radiation transport toolkit, developed by the RD44 and GEANT4 Collaborations, aims to become a tool of generalized application in high energy physics, nuclear physics, astrophysics and medical physics research. Due to its Object–Oriented design, GEANT4 is a distinct new approach for the development of flexible simulation applications, while offering a wide energy range coverage both for electromagnetic and hadronic physics processes. GEANT4 provides also an optical physics process category, allowing to describe the production and propagation of scintillation and Cherenkov emitted light. Such capabilities are well tailored for the requirements of the new generation of astrophysics experiments to be installed in the International Space Station, like EUSO and AMS. In this paper, the system architecture of a GEANT4 based simulation framework and its application to EUSO/ULTRA and AMS/RICH performance studies are presented.**

Index Terms— **GEANT4, ISS–Astrophysics Experiments, AMS, EUSO, ULTRA**

I. Introduction

MONTE CARLO techniques are currently recognized as the tool of choice for radiation transport studies. Its use in astroparticle physics experiments is well established and mandatory for the detector design phase, in order to assess the physics performance and background characterization. For a Monte Carlo code to be successfully used in this type of applications it must combine extended physics models, applicable to an energy range from the eV to the TeV, with enhanced geometry modeling capabilities, supported by advanced software programming techniques.

The GEANT4 Monte Carlo radiation transport toolkit is a recently developed simulation code, which had its first public release in 1998 [1], [2]. General capabilities include coupled hadron–lepton–photon transport in 3D geometries of arbitrary complexity. Two sets of electromagnetic physics categories are available: Standard Physics and Low Energy. Standard physics handles the basic process for charged particles and photons from 1 keV to 10 TeV (up to 1000 PeV for muons) while the low energy extensions provide alternative models down to 250 eV, based on the EEDL97/EADL/EPDL97 libraries [3]. An extensive set of hadronic physics models, spanning over 15 orders of magnitude in energy starting from neutron thermal energies, are also included, coupled with a realistic treatment of radioisotope decay, through the Radioactive Decay Module [4]. The same physics process can be treated by alternative implementations, which can have different energy validity ranges, accuracy and computing time. In addition, the user can add new physics processes without the need to modify the underlying framework. GEANT4 provides also an optical physics process category, which models the optics of scintillation and Cherenkov detectors and the tracking through light guides. In GEANT4 the user can interface her/his simulation code with different primary event generators, namely the General Particle Source [5]. This generator fulfils several requirements from the space simulation comunity and is being extensively used in astroparticle experiments simulation [6], [7].

In this paper an overview of a software framework, based on the GEANT4 toolkit, integrating simulation, event reconstruction and data analysis capabilities is presented. This framework is foreseen to be exploited in EUSO [8] and AMS [10] related applications. A description of the first implementation examples, along with preliminary results, is also presented.

II. EUSO – Extreme Universe Space Observatory

The main goal of EUSO (Extreme Universe Space Observatory) is to detect Extreme Energy Cosmic Rays (EECR) and neutrinos, indicative of unknown particle production and acceleration mechanisms in the Universe [8]. When a high energy cosmic particle interacts with the Earth atmosphere it initiates an extensive air shower (EAS) which in turn excites the atmospheric nitrogen molecules. De–excitation produces ultraviolet (UV) fluorescence light. The relativistic charged particles in the shower produce also a beam of UV photons, emitted through the Cherenkov effect, collimated with the shower. The observation of the Cherenkov light, diffusely reflected from the Earth surface, provides additional information. EUSO will be installed in the International Space Station (ISS), looking downwards to the dark Earth atmosphere to detect the faint UV traces produced by EECRs – Figure 1. The EUSO instrument consists of a wide–angle optical system (Fresnel lenses) concentrating the UV light onto a large focal surface made up of thousands of multipixel photomultipliers. On-board electronics takes care of the overall triggering and data taking operations. The EUSO design criteria are based on an orbital altitude of about 400 km, a field of view of 30° around the

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nadir, a pixel size corresponding to an area on ground of about 1 km^2 and an energy threshold of the order of 5×10^{19} eV.

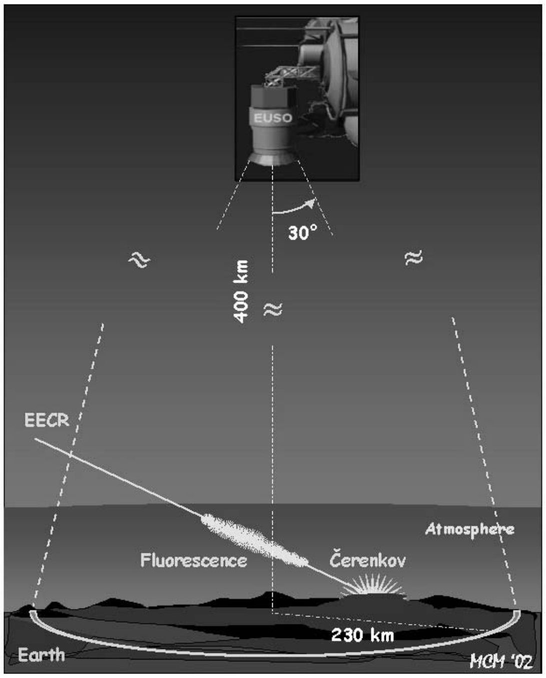

Fig. 1. Schematic representation of the EUSO operational principle.

Within the EUSO experiment there is an on-going program of experimental support activities performing various studies of parameters that are critical for EUSO. The detection of the Cherenkov light associated with EAS, measuring the UV light diffusion coefficients of different types of media at the surface of the Earth, is the main goal of the ULTRA project (ULTRA - UV Light Transmission and Reflection in the Atmosphere) [9]. The ULTRA detector is a hybrid system consisting of an UV detection system, the UVscope, and an array of scintillation detectors, the ETscope. The UVscope is used to detect the diffused Cherenkov light from EAS, in coincidence with the ETscope array. A typical configuration of the ULTRA experiment is schematicaly shown in figure 2.

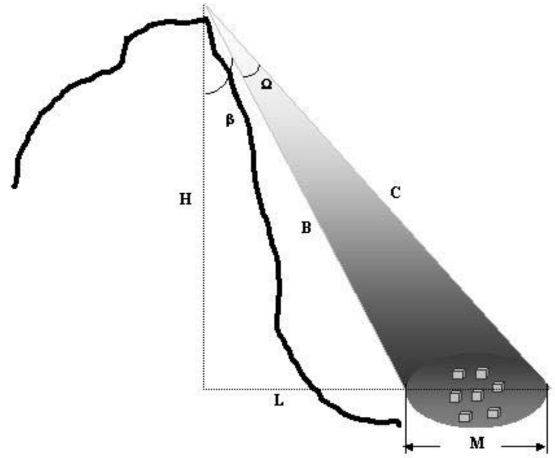

Fig. 2. Typical configuration of the ULTRA experiment. The area covered by the ETscope array, at M, is seen in the UVscope field of view from a height H.

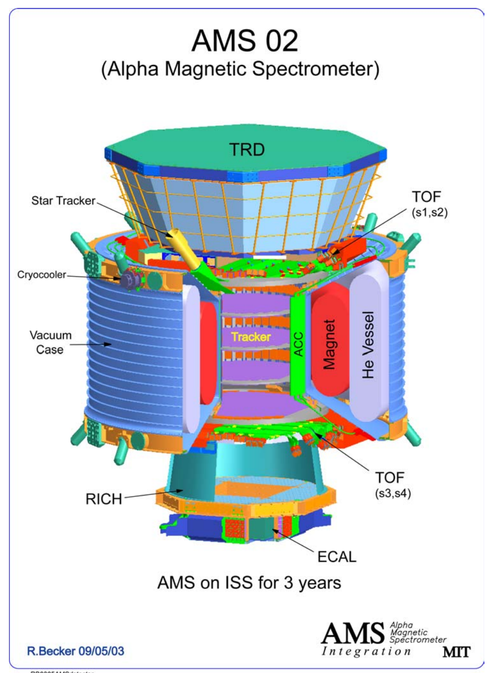

Fig. 3. Schematic representation of the AMS detector layout.

III. AMS – Alpha Magnetic Spectrometer

The main objectives of AMS (Alpha Magnetic Spectrometer) are the search for antimatter and dark matter and the study of the propagation and confinement of cosmic rays in the galaxy [10]. AMS had a precursor flight in June 1998 aboard the Discovery Space Shuttle, with around 100 million events recorded. The capabilities of the AMS spectrometer will be improved and extended through the inclusion of new detectors and a stronger magnetic field. Figure 3 shows schematicaly the integration of the different subdetectors of AMS.

The RICH (Ring Imaging CHerenkov), built with a low refractive index radiator, will provide an independent measurement of the particles velocity with a resolution of the order of 10^{-3}. Such a resolution, together with an improved measurement of the particle momenta (1% up to 10 GeV/c) due to the higher magnetic field ($\approx$0.9T), will allow an electron-proton separation up to 10 GeV/c. Moreover, the presence of the RICH will be essential for isotope separation. The chosen solution is a conical shaped detector with a low refractive index radiator (aerogel, n=1.035) on the top, photodetectors on the bottom and an enveloping outer mirror of very high reflectivity. RICHs are complex detectors which performance assessment depends critically on the correct modeling of the light production, transmission and collection. The possibility of having two radiators of different refractive indices is currently being considered.

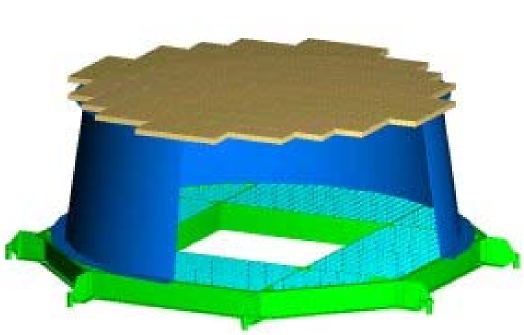

Fig. 4. The AMS RICH detector layout. From top to bottom are shown the Cherenkov radiator, the surrounding mirror and the photomultipliers matrix.

IV. Simulation Framework Description

One of the general requirements that guided the development of the presented GEANT4 based framework is its ability to accommodate different geometry organizations. This was accomplished by introducing an interface class in which the user can plug–in the concrete geometry implementation. For the primary event generation, the General Particle Source was used in order to sample primary particle kinematic characteristics from cosmic-ray distributions (ISS orbit or Earth surface) or from phase–space data describing accelerator beams. Physics lists include the standard electromagnetic physics processes for muons, electrons, positrons, photons and charged hadrons. Since optical transport of scintillation and Cherenkov optical photons was required, the processes of scintillation, Cherenkov production, Rayleigh scattering and light absorption were also included. As an option, and for sensitive detectors where the particle tracking must go down to the 250 eV limit, the physics lists are build with the low energy electromagnetic physics processes. Optical surfaces have been defined according to the specifications required by the GEANT4 UNIFIED optical model [11]. The user specifies reflector coatings and optical glues in terms of their refractive index, absorption length, reflectivity coefficients and polishment characteristics. Full characterization of scintillators includes the emission spectra, nominal light yield, the fast and slow scintillation components and associated time decay constants.

Since an accurate validation of Monte Carlo results against experimental data requires to take into account the influence of different readout electronics arrangements, data acquisition systems and trigger algorithms, a previously developed digitization module (DIGITsim [12]) was adapted to the application. This stand–alone module provides a series of abstract classes which perform the interface with user supplied models for fast optical generation, detector electronic signal, noise and pulse shape buildup, ADC pulse digitization, raw data production and event reconstruction. DIGITsim receives as input information previously stored in GEANT4 hits collections, which provide a convenient solution to store the relevant data required for the digitization stage. Since the GEANT4 hit production step is decoupled from DIGITsim, it is possible to study different electronics arrangements without performing new simulations. At the end of the event, the information stored in this collection of hits is made persistent, by performing a deep–copy to TClonesArray objects and then streamed with ROOT I/O mechanism [13]. Hit collections hold event quantities, like the energy deposited in a sensitive volume or array of sensitive detectors, the number of optical photons that reach the photosensitive surface (like the photomultiplier's photocathodes), optical photon wavelength and time–of–flight.

V. Simulation of EUSO ULTRA detector

The simulation of an ULTRA ETscope station was implemented in the simulation framework described previously. Each detector – Figure 5 – consists of a NUCLEAR NE 102A plastic scintillator, with dimensions 80×80 cm^2 and 4 cm thick, housed in a pyramidal stainless steel box. The inner walls of the box are coated with a white diffusing paint. Light is collected by two photomultipliers at approximately 30 cm from the scintillator surface.

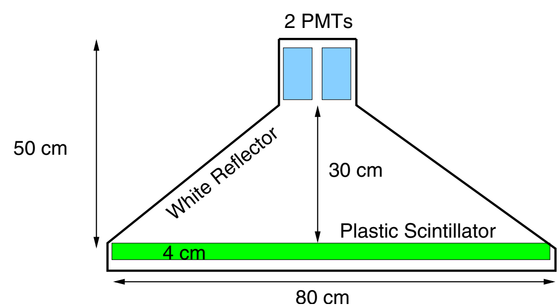

Fig. 5. Schematic drawing of an ULTRA ETscope station.

For the specification of the optical properties of the surface defined by the air and the painted aluminum interface, within the UNIFIED model, a "dielectric-dielectric" TYPE and "groundfrontpainted" FINISH were used. The scintillator emission spectrum, which peaks at 423 nm, and its light yield, about 10000 photons per MeV of deposited energy, were included in the optic material properties.

The scintillation photons produced by a particle crossing the detector are tracked through the various materials until reaching the surface of the photocathode. Propagation inside the scintillator, passage across the interface between the scintillator and the air, reflection or absorption in the painted walls, are taken into account in the photon tracking. Figure 6 shows the trajectories of a small fraction of the photons emitted when one 80 MeV electron enters the detector, using the VRML visualization driver of GEANT4. The spectrum of energy deposited in the scintillator by 80 MeV electrons is shown in figure 7, together with the curve obtained from a fit with a Landau function.

A preliminary digitization module, based on the DIGITsim framework, was also implemented in the simulation of the ULTRA detector stations. In this preliminary implementation, the energy deposited in the scintillator is directly used to

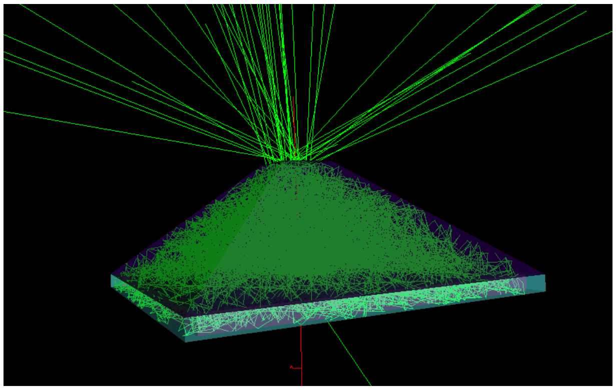

Fig. 6. Image of an ETscope station (without the photomultipliers on the top) produced with the GEANT4 VRML driver. The tracks represent optical photons generated by a 80 MeV electron.

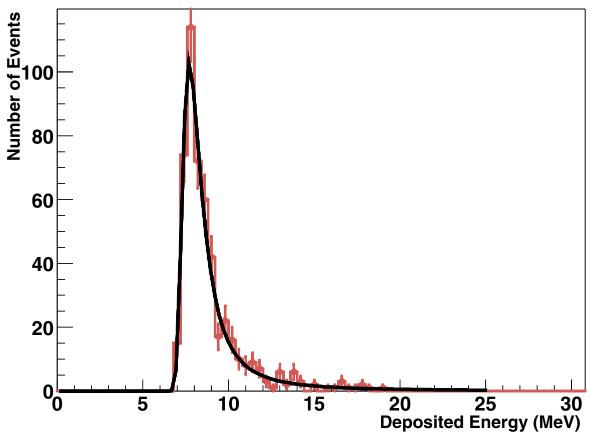

Fig. 7. Distribution of deposited energy by 80 MeV electron events in the ETscope plastic scintillator.

compute the total collected charge and thus obtain the pulse shape buildup. An average light collection efficiency, previously computed with the simulation, is used. Figure 8 shows a preliminary example of the output from the digitization module, using a 100 MHz sampling frequency, together with the analog pulse obtained at the amplifier output stage. Further developments of the digitization module will be implemented, including the explicit simulation of the optical photons conversion at the photomultiplier's photocathode.

VI. Simulation of AMS RICH sub–detector

A simplified design of the AMS RICH radiator setup, consisting of aerogel tiles supported by a plexiglass foil, was implemented in the GEANT4 based simulation framework. The procedure consisted on implementing a variable number of aerogel tiles of $11.3 \times 11.3 \times 3.0$ cm^3, separated by a 0.1 cm gap, placed in a vacuum tank, of corresponding variable dimension, on top of a 0.1 cm thick plexiglass foil. The gaps between the aerogel tiles can be alternatively left in vacuum, filled with plexiglass or with

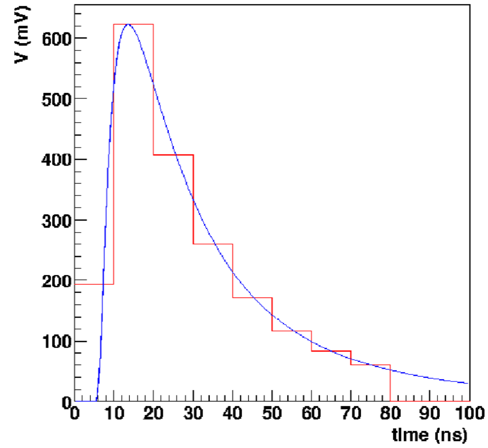

Fig. 8. An example of the output from the digitization module. The superimposed smooth curve represents the pulse shape at the amplifier stage.

a material opaque to the Cherenkov photons. The implemented aerogel (SiO_2 + vacuum) and plexiglass ($C_5H_8O_2$) properties - refractive index, absorption length, and clarity in the case of aerogel - correspond to the AMS RICH radiator setup description. A simulation of a Cherenkov counter, to be used in RICH prototype beam tests in order to obtain an independent measure of the charge of the incident beam particles, is also being implemented in the simulation framework. The Cherenkov counter, made of PMMA (Polymethilmethacrylate), 1.1 cm thick and 8.5 cm^2 area, is wrapped in aluminium foil and coupled to a photomultipler through a light guide. Optimization studies of the Cherenkov counter, namely its geometry and the wrapping material, are being performed using the implemented simulation.

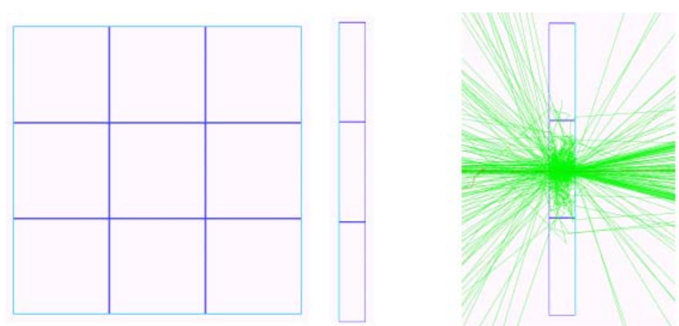

Fig. 9. View of the aerogel tiles arrangement in the simulation (left) and Cherenkov photons radiated by a 80 MeV electron (right).

VII. Summary and Future Developments

An overview of a software framework, based on the GEANT4 toolkit, integrating simulation, event reconstruction and data analysis capabilities was presented. The framework includes a standalone digitization module for simulation of readout electronics. As first implementation examples, the simulation of one ULTRA ground array station and of a simple design of the AMS RICH radiator setup were described.

This framework can be exploited in a wide range of applications in the scope of the EUSO and AMS experiments. In particular, the simulation of the ULTRA UVscope detector performance is foreseen and detailed studies of the light collection in the AMS RICH radiator will be carried on. The simulation of an experimental setup for fluorescence measurements, an important parameter in EUSO, is also under investigation. An upgrade to the persistency mechanism provided by the LCG/POOL persistency framework is foressen, enhancing the framework code modularity.

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