Geant4 Simulations for Hadronic Interactions in Space Radiation Environment

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Outline

- Physics Motivation
- Space Radiation Environment
- Genat4 Simulations
- Process steps to model Space Radiation Environment in Geant4
- Detector Geometry in Geant4
- Energy loss through Bethe Bloch
- Results
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Physics Motivation

- The space radiation environment is a significant challenge to future manned and unmanned space travels.
- Future missions will rely more on accurate simulations of radiation transport in space to predict the radiation dose within spacecraft electronics.
- The existing radiation models are not be able to explain the experimental data precisely.
- It is required to develop precise radiation model for deep space missions through fast simulations.

⇨ **Aim is to simulate and model the hadronic interactions of high energy particles in space radiation environment and measure the radiation dose.**

Space Radiation Environment

- The space radiation consists of charged particles and heavy ions, which come from the burst of solar wind created at the surface of the sun.

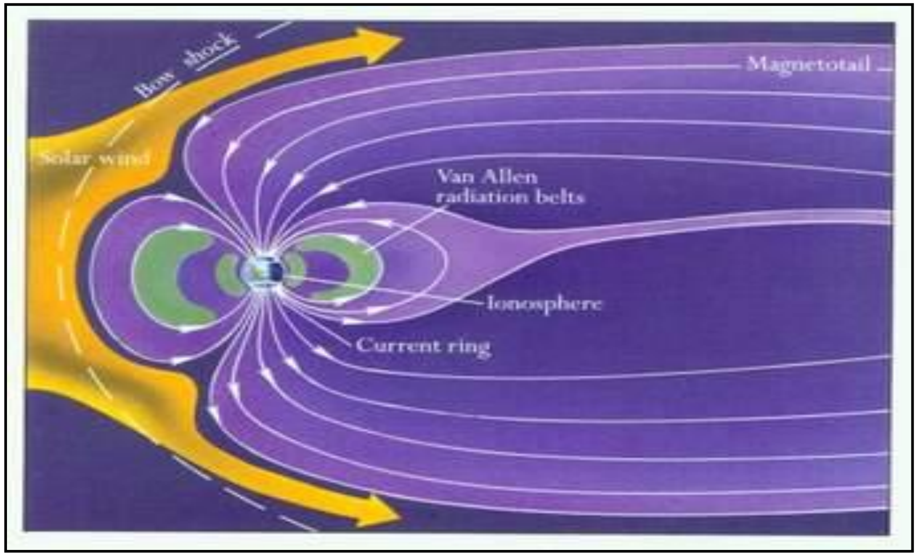
- The interaction of the particles and the magnetic field of earth occur and particles get deflected.

- Still some particles manage to enter the magnetosphere and become trapped.

- These trapped particles are contained in two doughnut-shaped magnetic rings around earth called the Van Allen radiation belts.

- Three main components of space radiations:
  - Trapped particles
  - **Galactic Cosmic Rays (GCRs)**
  - **Solar Particle Events (SPEs)**

The energies of space radiation lies in the range of eV to the order of few TeV.



To understand the interactions of protons and heavy ions during space travel, fast Monte Carlo Simulations are required.

→ **Geant4 (Geometry and Tracking Software) Simulations**

GEANT4 is *a toolkit for the simulation of the passage of particles through matter.*

- Used in nuclear physics, high energy physics, accelerator physics, medical as well as space applications.
- Using GEANT4 tool, user can build a simulation program for specific application.
- GEANT4 is written in C++.

http://www.cern.ch/geant4 (Open Source)

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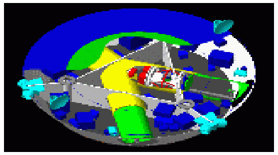
Overview

Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. The three main reference papers for Geant4 are published in Nuclear Instruments and Methods in Physics Research A 506 (2003) 250-303, IEEE Transactions on Nuclear Science 53 No. 1 (2006) 270-278 and Nuclear Instruments and Methods in Physics Research A 835 (2016) 186-225.

Applications

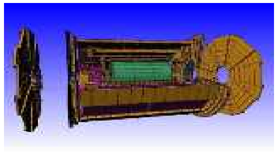
A sampling of applications, technology transfer and other uses of Geant4

User Support



Getting started, guides and information for users and developers

Publications



Validation of Geant4, results from experiments and publications

Collaboration

Who we are: collaborating institutions, members, organization and legal information

printer friendly version

News

- *12 Feb 2019*
  Patch-03 to **release 10.4** is available from the source archive area.
- *7 Dec 2018*
  Release 10.5 is available from the Download area.
- *20 Oct 2017*
  Patch-03 to release 10.3 is available from the source archive area.

- Our group at MNIT Jaipur is actively working on Geant4 simulations for medical and space applications.
- Had delivered hands-on sessions and training programs on Geant4 in workshops/ Summer schools.

- **For Geant4 Training/ for any query: please contact us @ kavita.phy@mnit.ac.in**

Important Features of Geant4

- Open Source
- Long term support
- Object Oriented design
- Supports multithreading
- Geometry of the system
- Definition of Material
- Generation of particles and events
- Tracking through matter and EM fields
- Response of detector components
- Storage of events and tracks
- Visualization
- Analysis of data using ROOT software developed by CERN

Flow chart to Model Space Radiation Environment in Geant4

Material Definition and Geometry Creation

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Model Space Radiation Environment Spectrum

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Generate Particles

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Transport Particles through Physics Processes

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Simulated Results : Edep, Radiation Dose, Track length

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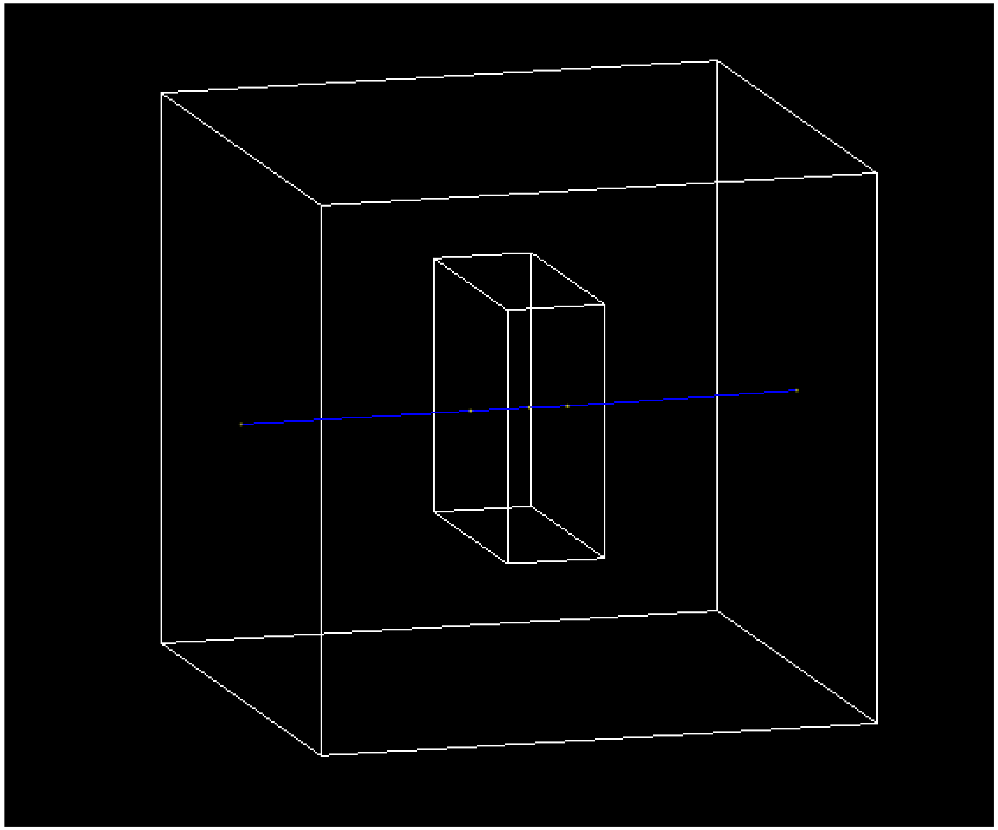
Analysis through ROOT software

Visualization of Detector Geometry

Geometry: Slab



- The Geometry is constructed using Detector Construction class.
- The detector geometry: Slab

  Material: Water
  Size: 922× 922 × 350 (in μm)
- Incoming Beam: Proton (blue colour)
  Ekin: 50 MeV

Radiation Model for Hadronic Interactions

- In Geant4, hadronic interactions are simulated and model through FTFP_BERT_HP (Fritiof + Pre-compound Bertini Cascade).

- This model explains the interactions of charged particles (hadrons) and heavy ions, which are the main components of space radiation environment.

- This radiation model works for kinetic energy of protons and heavy ions from eV range to order of few TeV.

Energy Deposited

- When beam of charged particles enter the detector material, they loss their energy via coulomb interactions with electrons and nucleus of the atom.

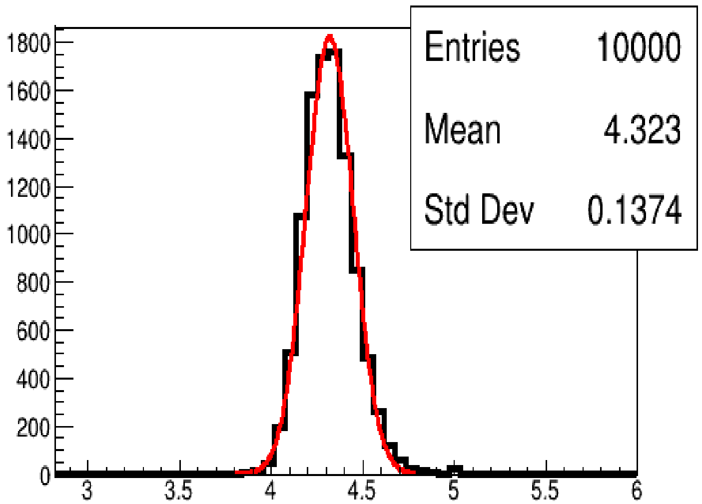
- The energy loss by charged particles in the detector material is measured through energy deposited, which is given by Bethe-Bloch formula:

$$\frac{S}{\rho} = -\frac{dE}{\rho dx} = 4\pi N_A r_e^2 m_e c^2 \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right]$$

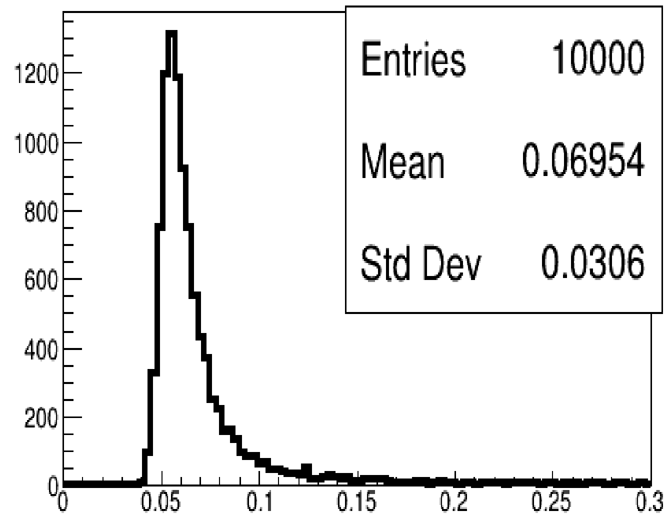
➡ dE/dx is proportional to the inverse square of the incoming particle's velocity, and the square of its ion charge z.

Energy Deposited

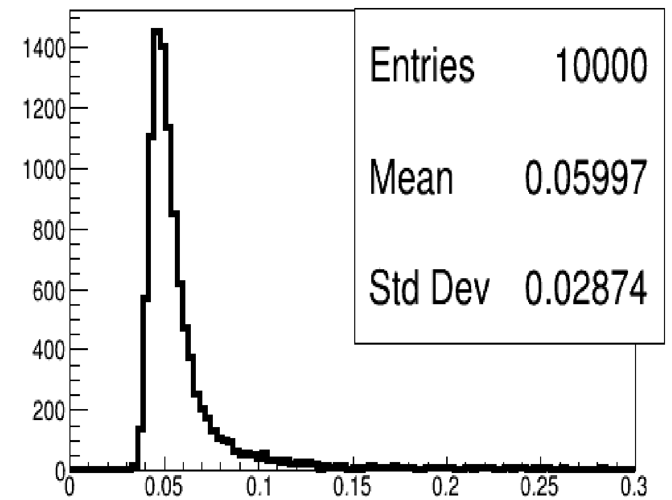
@ E_{kin}: 5MeV



@ E_{kin}: 1GeV

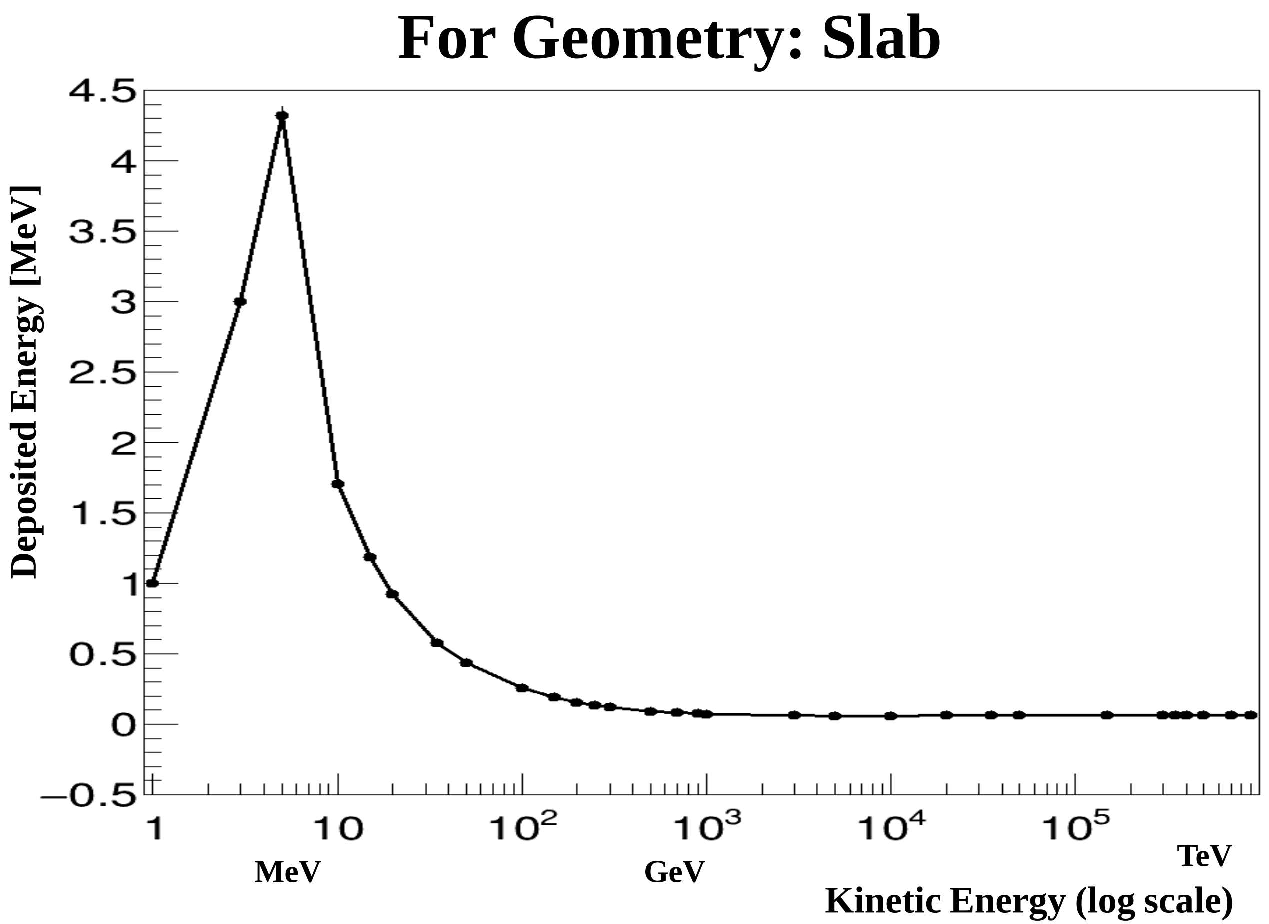


@ E_{kin}: 900GeV



- At low kinetic energy, energy deposited is quite large due to more interactions of proton beam with water phantom.
- At high kinetic energy (order of GeV &TeV), the energy deposited is very small, because of less interaction of proton beam with water phantom.

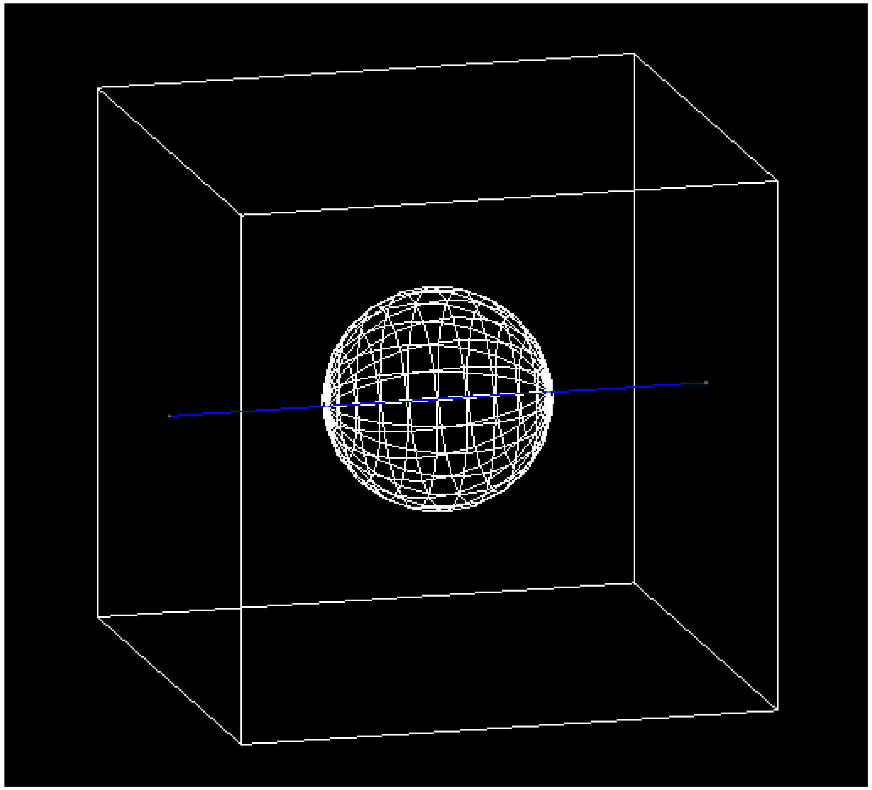
Energy Deposited vs Kinetic Energy



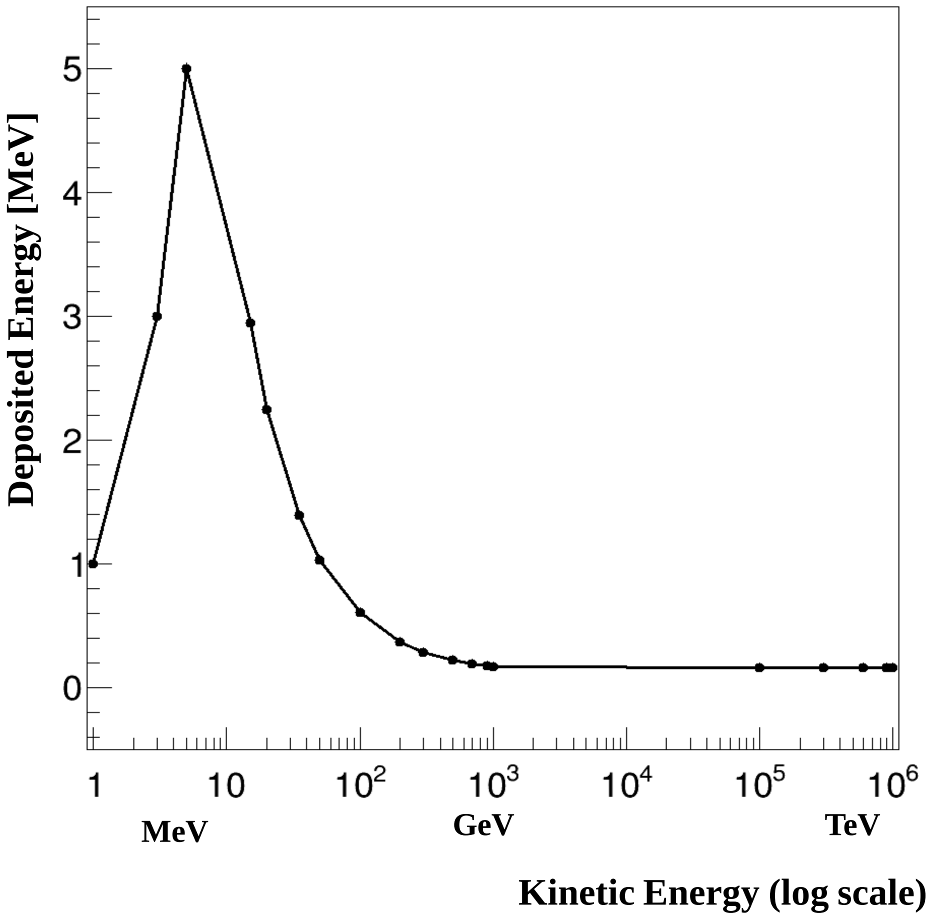
- At low energy, almost complete energy is deposited due to more interactions with material, therefore behaviour is almost linear in nature.
- As the incoming energy increases, the energy deposited inside the geometry decreases rapidly, due to less interaction of proton beam with material.
- At higher energies (GeV to order of few TeV) the deposited energy is almost constant as the beam passes the geometry without undergoing much interactions.

Visualization of Detector Geometry

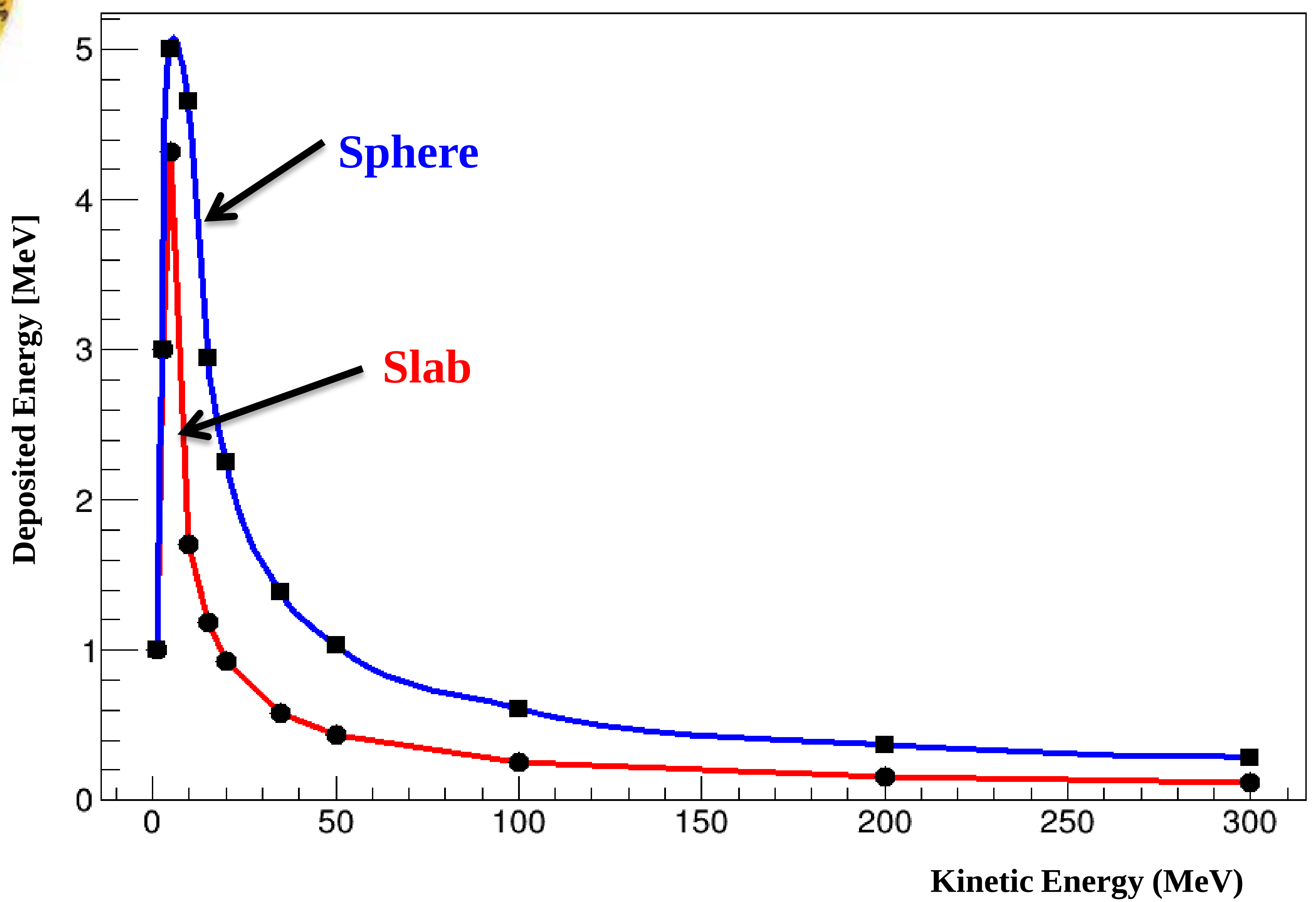
Geometry: Sphere
Size: Radius = 414 μm
Material: Water
Incoming Beam: Proton



Energy Deposited in Sphere

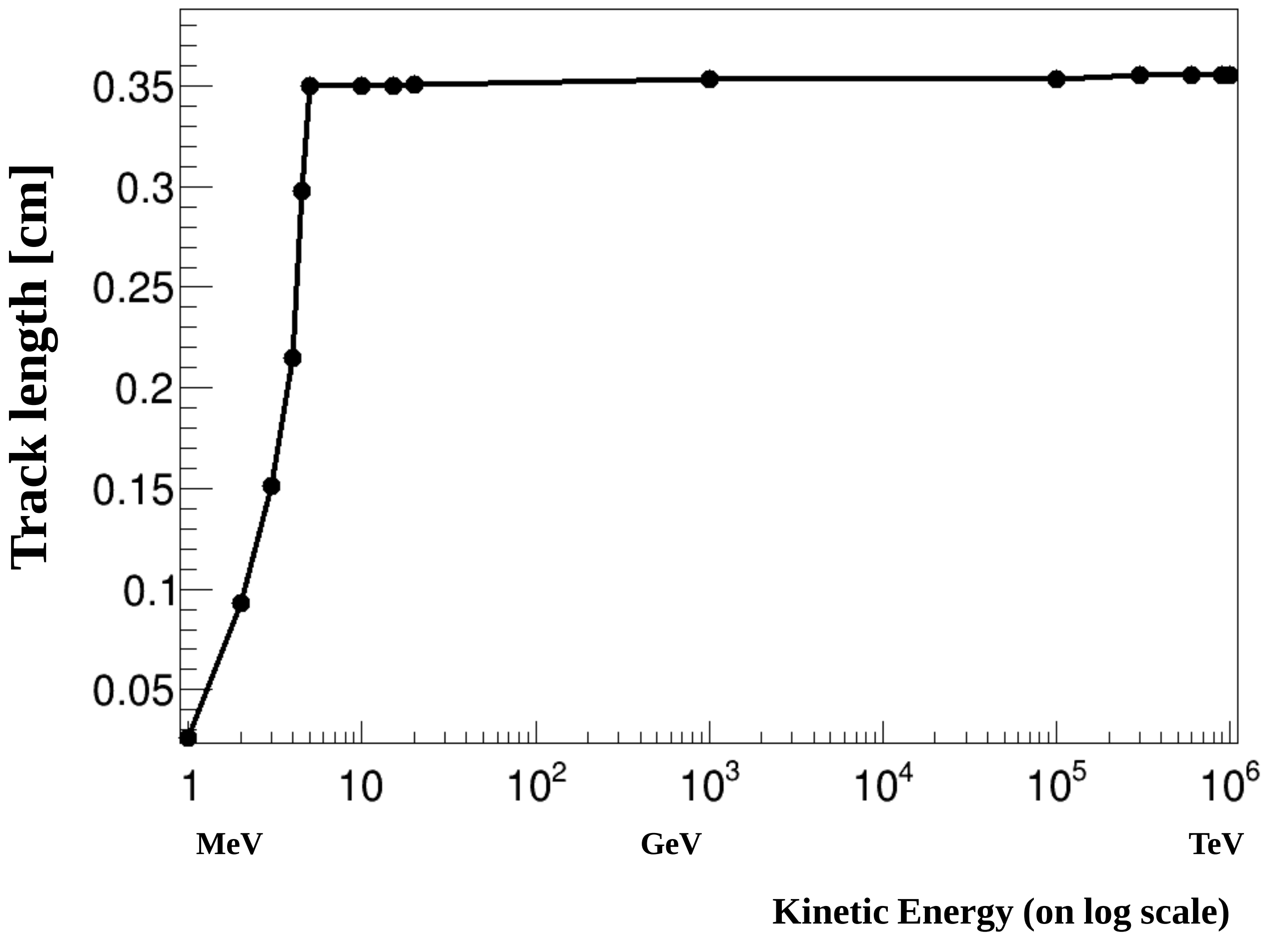


Effect of Shapes on Deposited Energy



Energy deposited in spherical geometry is higher than rectangular shape due to the less boundary effects in sphere as compared to slab.

Track length vs Kinetic Energy



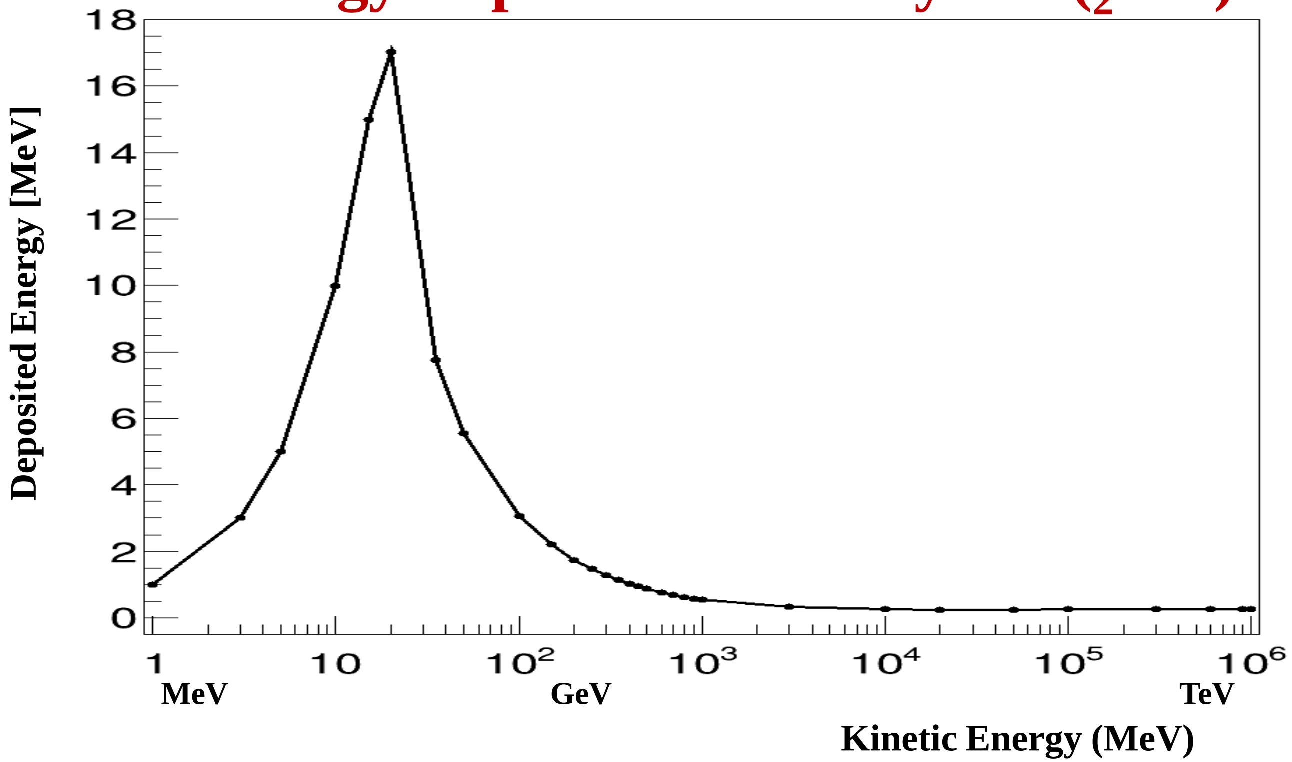
- At low energy, due to large interaction of proton beam with detector material, it penetrates a small portion of geometry, thus traces a small track length.
- As the energy increases, the track length increases and becomes almost constant for higher energies.

Interaction of Heavy Ions with Detector Material

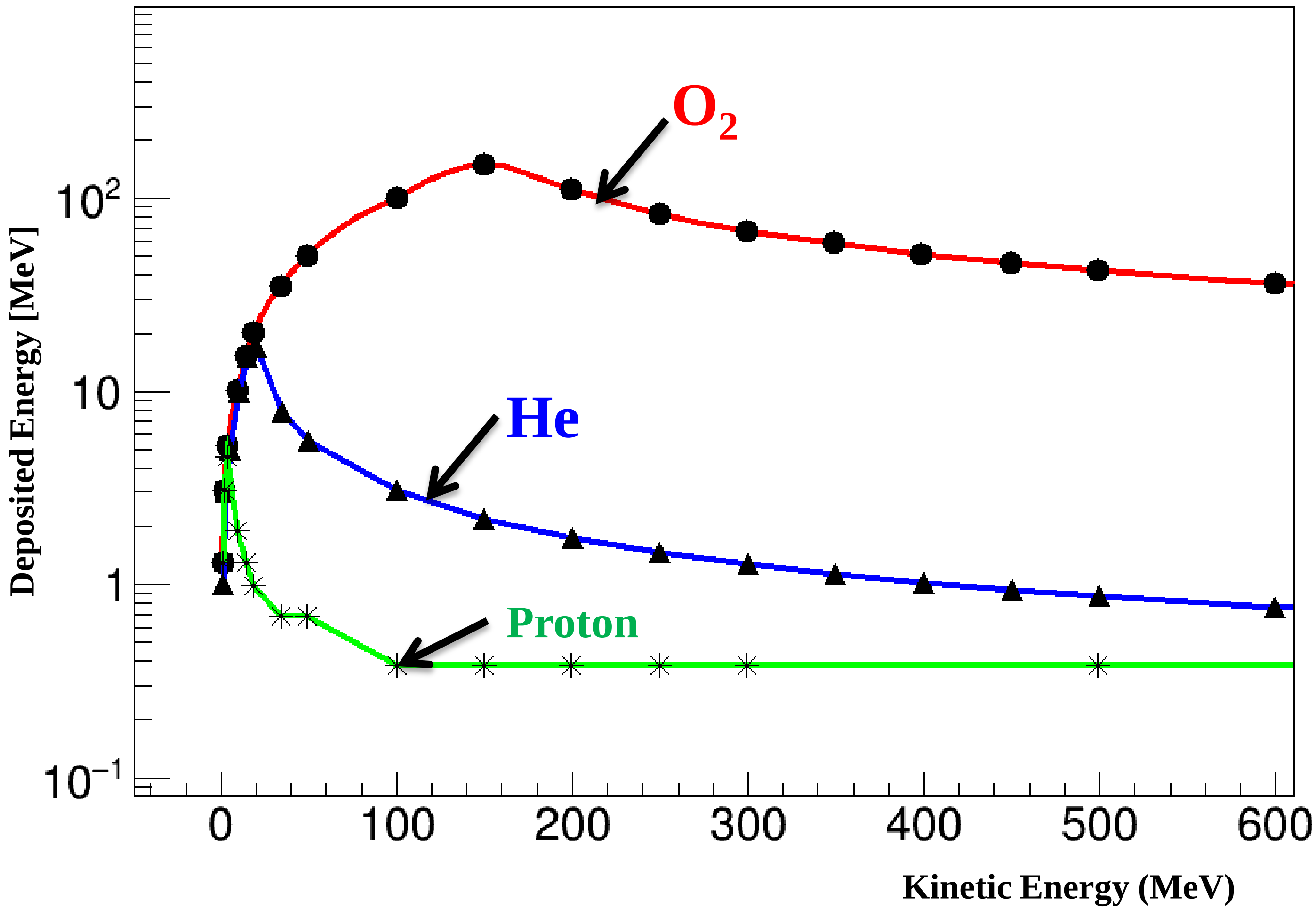
- To simulate the interaction of heavy ion (He and O_2) in detector material, Physics Model (FTFP_BERT_HP) implemented in Geant4.

- The heavy ions deposited higher energy in the detector material as compared to proton beam due to higher charge (atomic no) as compared to proton.

Energy Deposited in Heavy Ion ($_2He^4$)

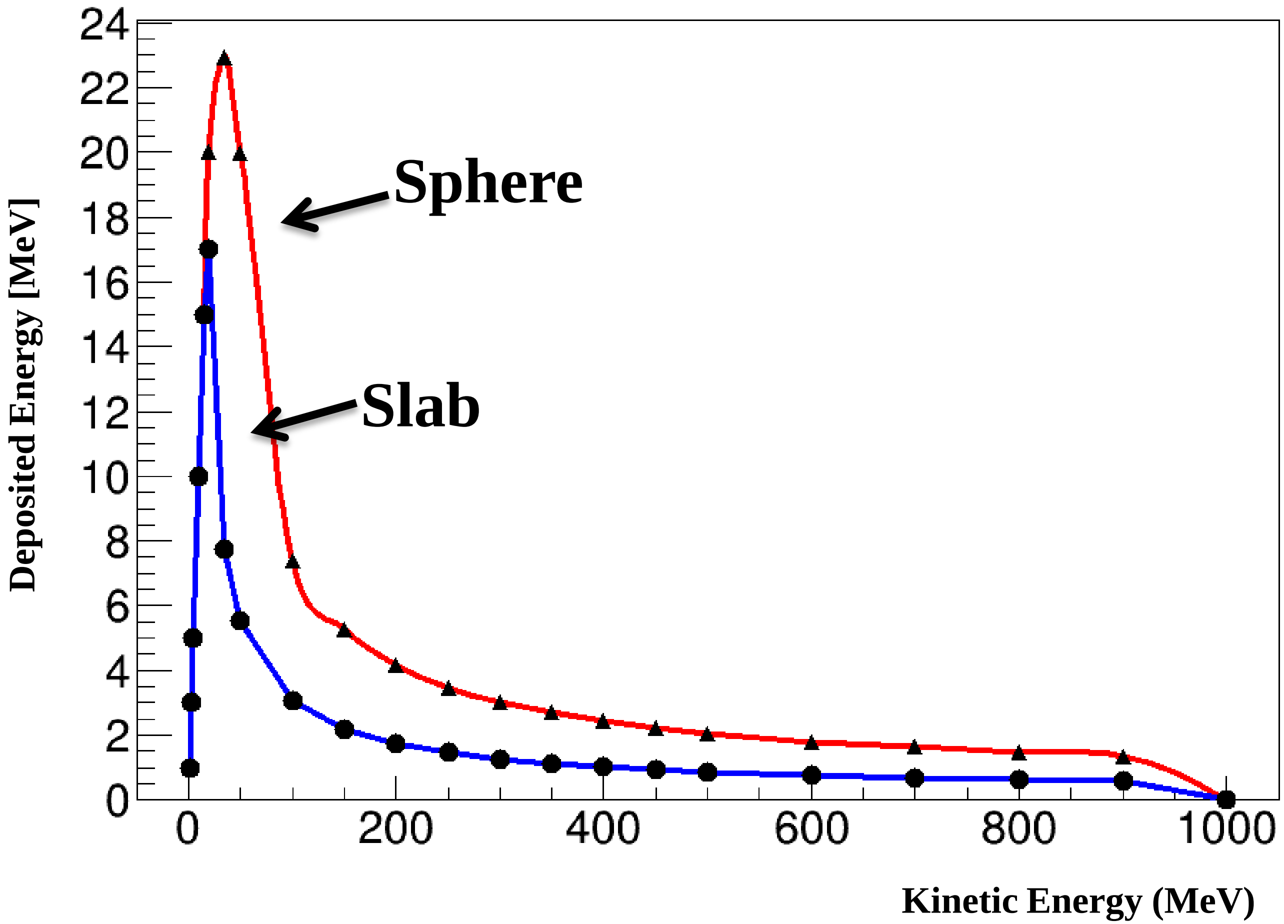


Effect of Charge on Energy Deposited



Heavy ions passing through detector material cause much more damage due to high energy deposited as compared to proton, because energy deposited by charged radiation depends on the square of charge (slide 11: Bethe Bloch Formula).

Effect of Shapes on Energy Deposited by Heavy Ions



Higher energy is deposited in spherical geometry due to absence of boundary effects.

Summary

- Implemented physics model FTFP_BERT_HP to understand the interaction of proton and heavy ions with water phantom for two detector shapes:
  a) Slab b) Sphere

- Energy Deposited by proton and heavy ions are measured and compared for both shapes for beam kinetic energy in the range of eV to the order of TeV.

- Track length is also measured for both detector shapes.

Future Plan

- Study the interactions of space radiations with shielding materials in Geant4.
- Participate in the following systematic simulation studies:
  (a) Radiation Dose calculation with shielding material during the space flight.
  (b) Effect of shielding depth and charged particle flux on radiation dose measured in human tissue.