Geant4 studies for radiation exposure in interplanetary manned missions

S. Guatelli[1], B. Mascialino[1], P. Nieminen[2], M. G. Pia[1]

[1]INFN Genova , [2]ESA-ESTEC

http://www.ge.infn.it/geant4/space/remsim

http://www.ge.inf.it/geant4/dna

Geant4 REMSIM Simulation - Netscape

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Radiation Exposure and Mission Strategies for Interplanetary Manned Missions

Geant4 REMSIM SIMULATION Simulation and Analysis of Vehicle Concepts and Surface Habitat Designs

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- Architecture
- Design
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- Iteration Plan
- Artifacts in detail
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- ESA Aurora
- Geant4
- Geant4-INFN

AURORA, the European programme for the **exploration of the Solar System**, is part of Europe's strategy for space. The primary objective of Aurora is to create, and then implement, a European long-term plan for the robotic and human exploration of the solar system, with Mars, the Moon and the asteroids as the most likely targets.

Artist's impression on a base on Mars, courtesy of ESA

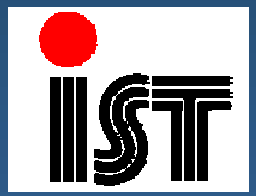
The **radiation hazard to crew** is critical to the feasibility of interplanetary manned missions. To protect crew, **shielding** must be designed, the **environment** must be anticipated and monitored, and a **warning system** must be put in place. Because of the strong influence on the mission design and the vehicle/habitat designs, early study must be made.

The ESA **REMSIM** Project addresses these issues, including the development of a Geant4 **simulation** for a preliminary quantitative study of existing vehicle concepts and habitat designs, and the radiation exposure of crews therein. The vision underlying the REMSIM Simulation is described in a dedicated document.

Last update 26 February 2004- Susanna Guatelli, Maria Grazia Pia

Dosimetry with Geant4 for radiotherapy

- Activity initiated at IST Genova, Natl. Inst. for Cancer Research (F. Foppiano et al.)
  - hosted at San Martino Hospital in Genova (the largest hospital in Europe)
- Collaboration with San Paolo Hospital, Savona (G. Ghiso et al.)
  - a small hospital in a small town



Major work by **Susanna Guatelli** (Univ. and INFN Genova)

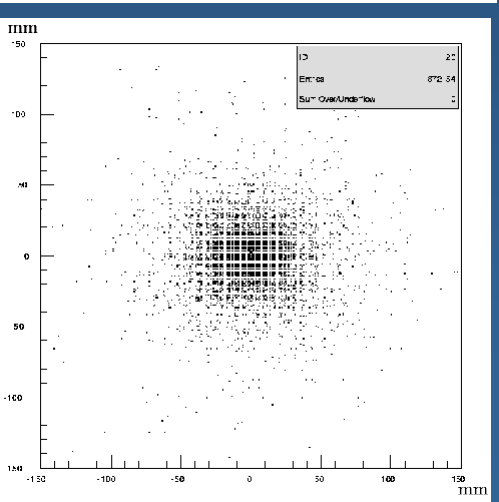
MSc. Thesis, Physics Dept., University of Genova, 2002
http://www.ge.infn.it/geant4/tesi/

Dosimetry

Simulation of energy deposit through
Geant4 Low Energy Electromagnetic package
to obtain accurate dose distribution

Production threshold: 100 μm

2-D histogram
with energy deposit
in the plane containing
the source



Analysis of the energy deposit in the phantom resulting from the simulation

Dose distribution

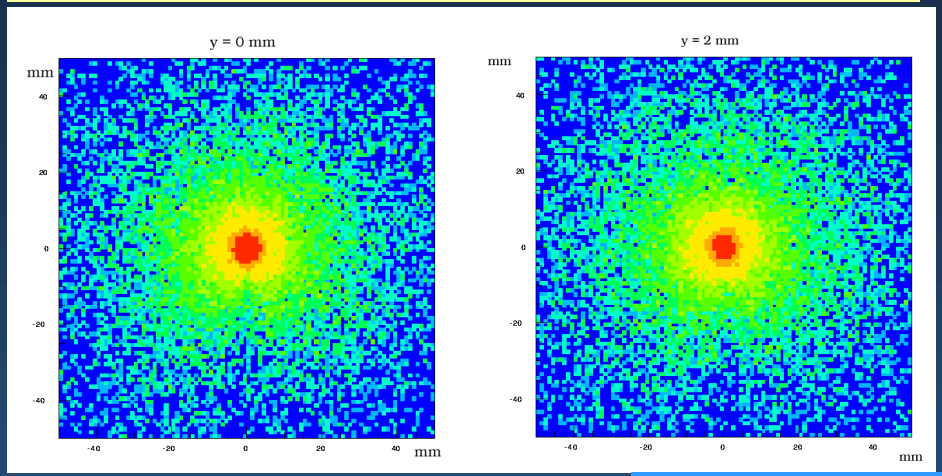
Isodose curves

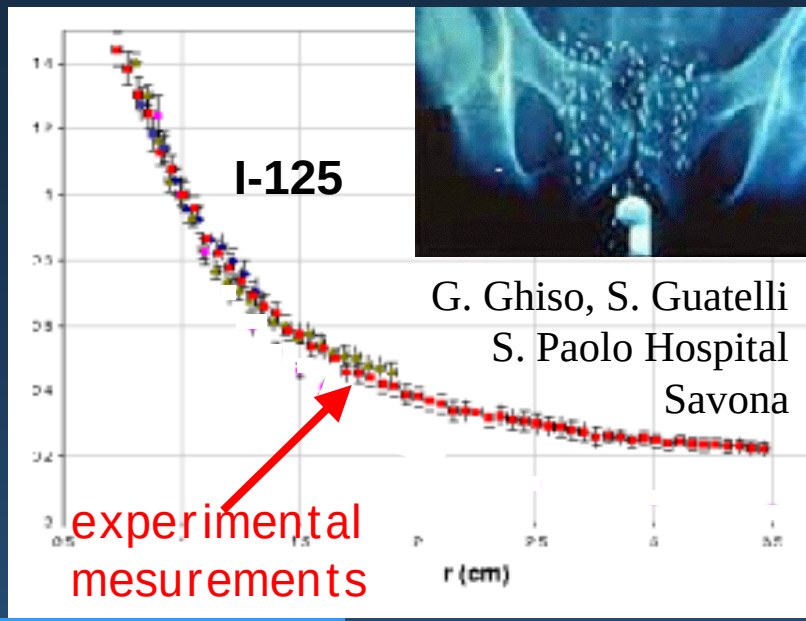
AIDA + Anaphe
for analysis

Python
for interactivity

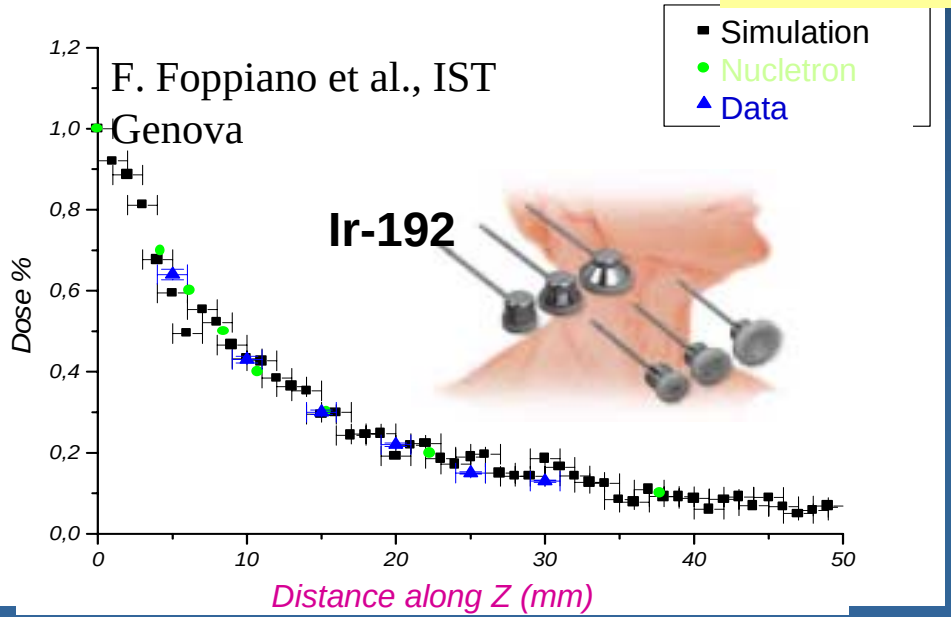
may be any other AIDA-compliant analysis system

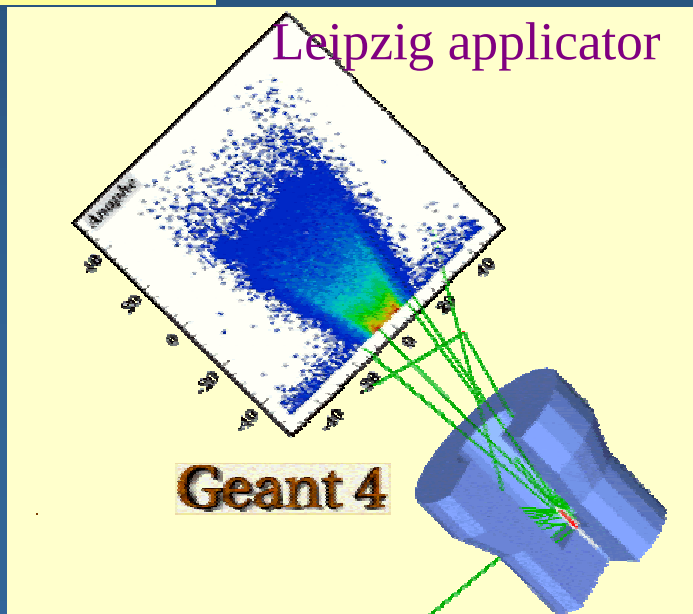
Dosimetry
Endocavitary brachytherapy



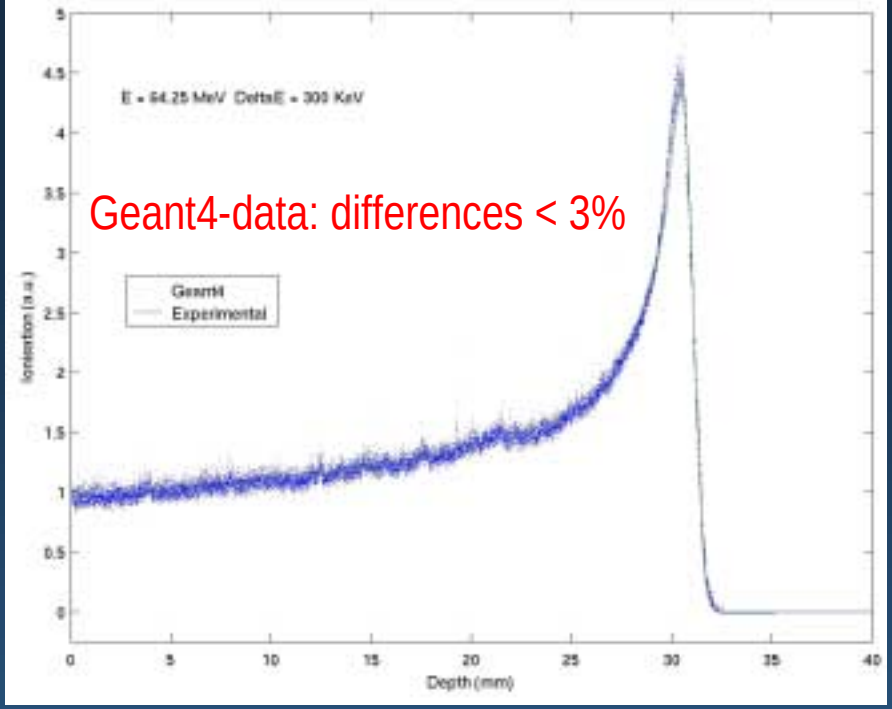


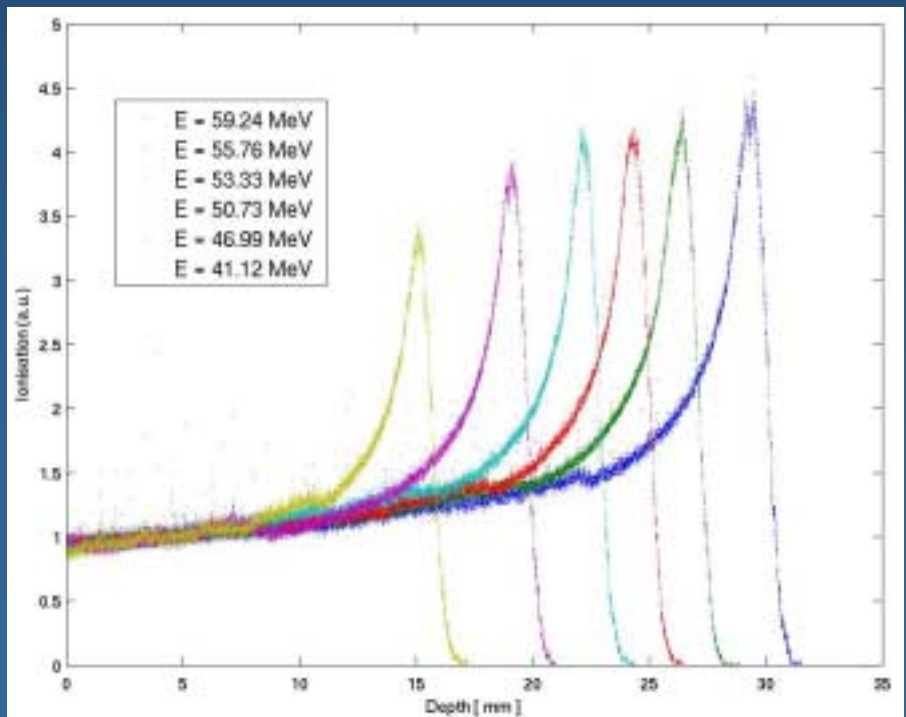
Dosimetry
Superficial brachytherapy





CATANA, INFN-LNS





Vision

- Especially important in the context of REMSIM
  - wide scope of the project
  - complex scientific and technical environment
  - limited time frame

REMSIM Simulation Vision

- A critical analysis of the Geant4 tools currently available for this type of studies, highlighting necessary extensions and improvements to the existing tools, as well as the need of further validation tests
- A first quantitative analysis of proposed shielding solutions, contributing to an evaluation of feasibility of existing shielding hypotheses

Strategy

- The process consisted of a series of iterations

Each iteration adds:

- a refinement in the experimental model
- the usage of further Geant4 functionality

- Simplified geometrical configurations

  keeping the essential characteristics for dosimetric studies

  - Vehicle concepts
  - Moon surface habitats

- Physics processes

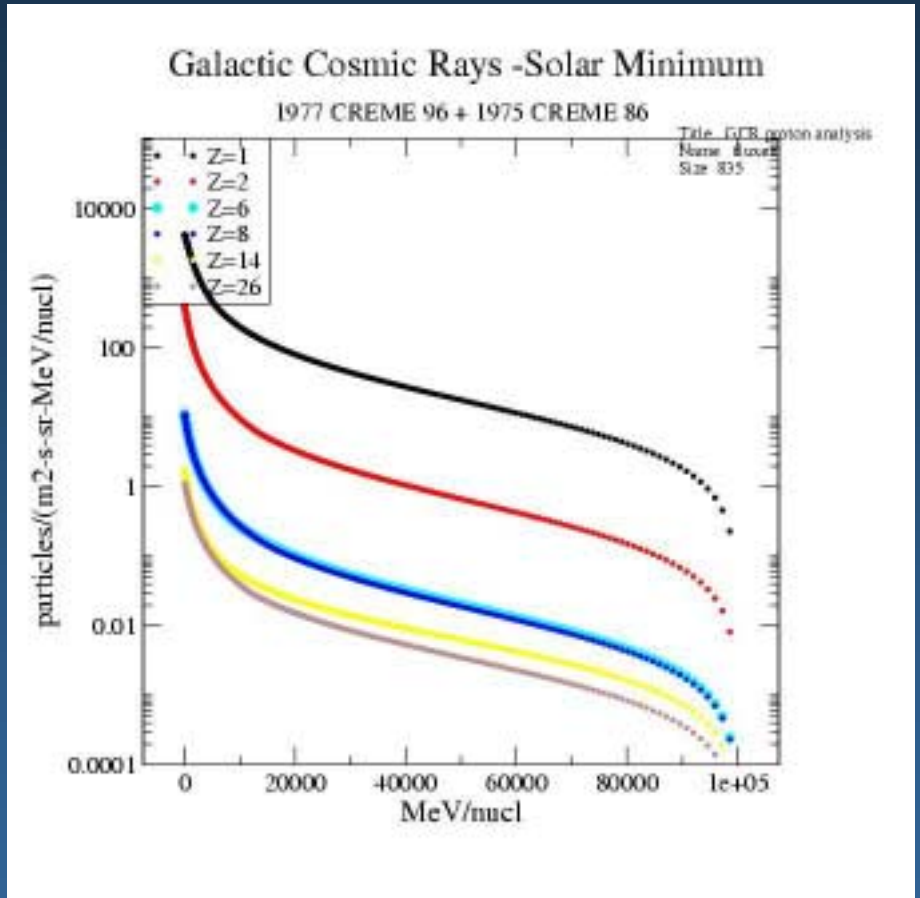
  - Electromagnetic physics
  - + hadronic physics

Outline

- Model of the radiation environment
- Model of vehicle concepts
  - Simulation with Geant4 electromagnetic processes
  - Evaluation of GCR and SPE shielding options
  - Same simulation with Geant4 hadronic physics on top
- Model of moon surface habitat concepts
  - Simulation with Geant4 electromagnetic processes
  - Evaluation of GCR and SPE shielding options
  - Same simulation with Geant4 hadronic physics on top
- Parallelisation of the REMSIM Geant4 application
- Conclusions

GCR spectra

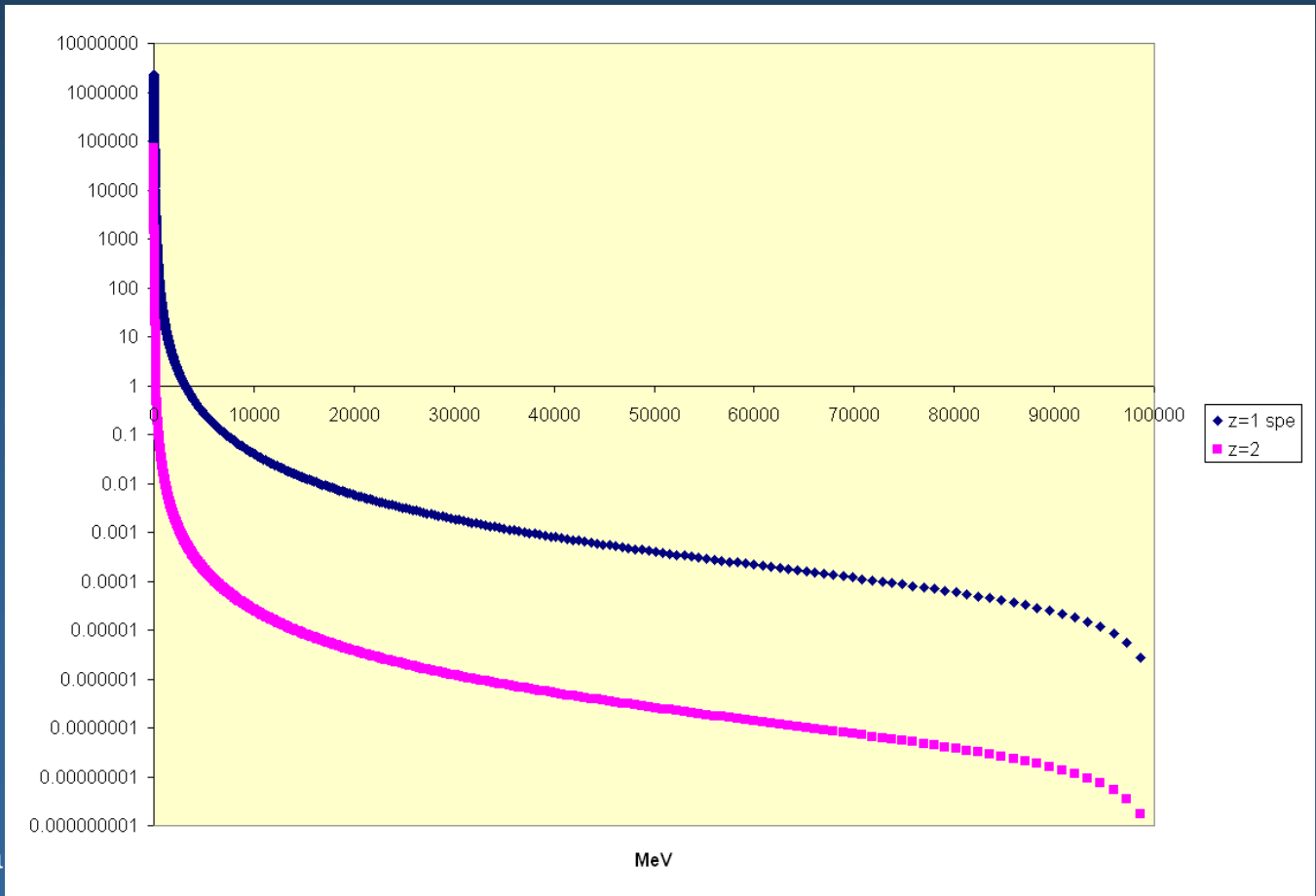
- The energy spectra are predicted for 1 AU
- The spectra correspond to solar minimum activity
- Ions considered for Geant4 simulation: C-12, 0-16, Si-28, Fe-52



Envelope of CREME96 1977 and CRÈME86 1975 solar minimum spectra

Solar Particle Events

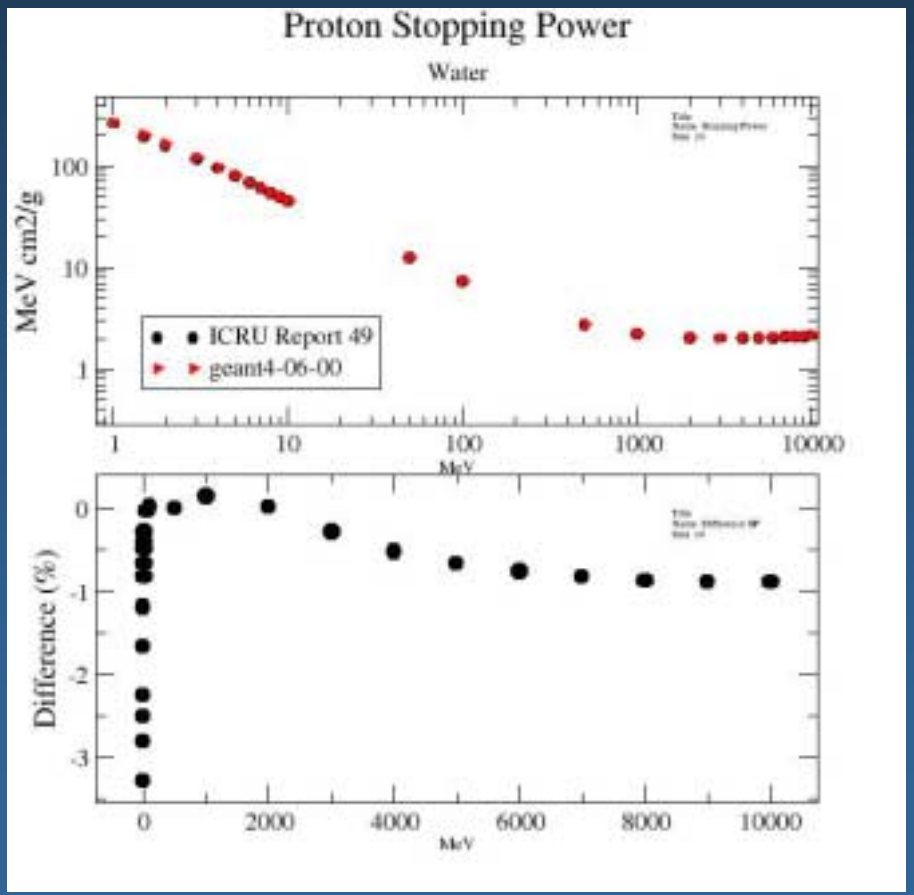
- Protons and α spectra considered
- Envelope of CREME96 October 1989 and August 1972 spectra

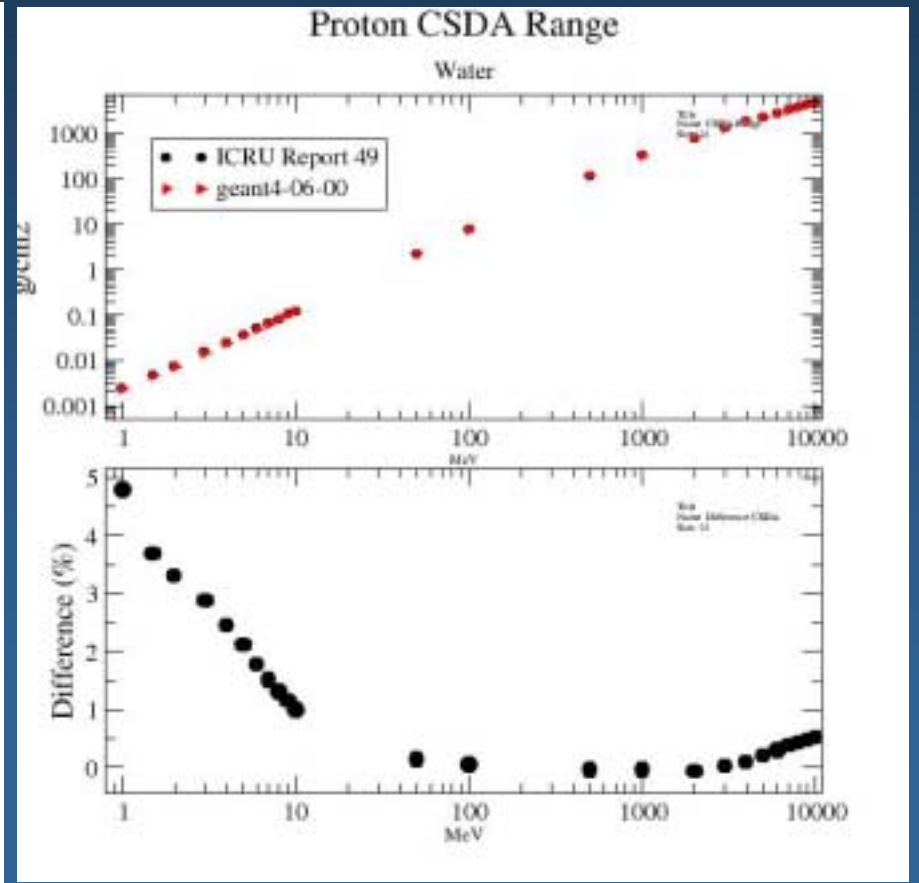


Verification of REMSIM Physics List

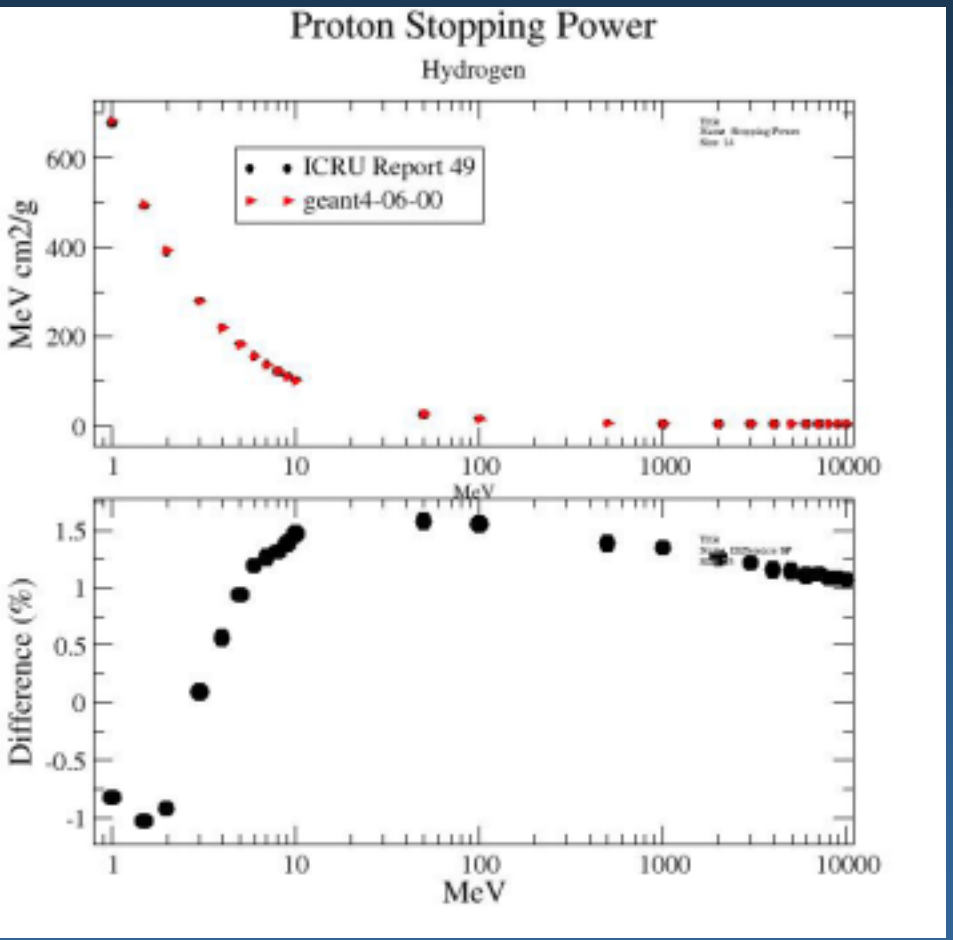
- First iteration: Geant4 electromagnetic physics only
- Proton and alpha Stopping Power and CSDA Range are calculated for materials of interest
- Energy range of test: from 1 MeV to 10 GeV
- Comparison of the test results to ICRU Report 49 (protocol for dosimetry in oncological radiotherapy)

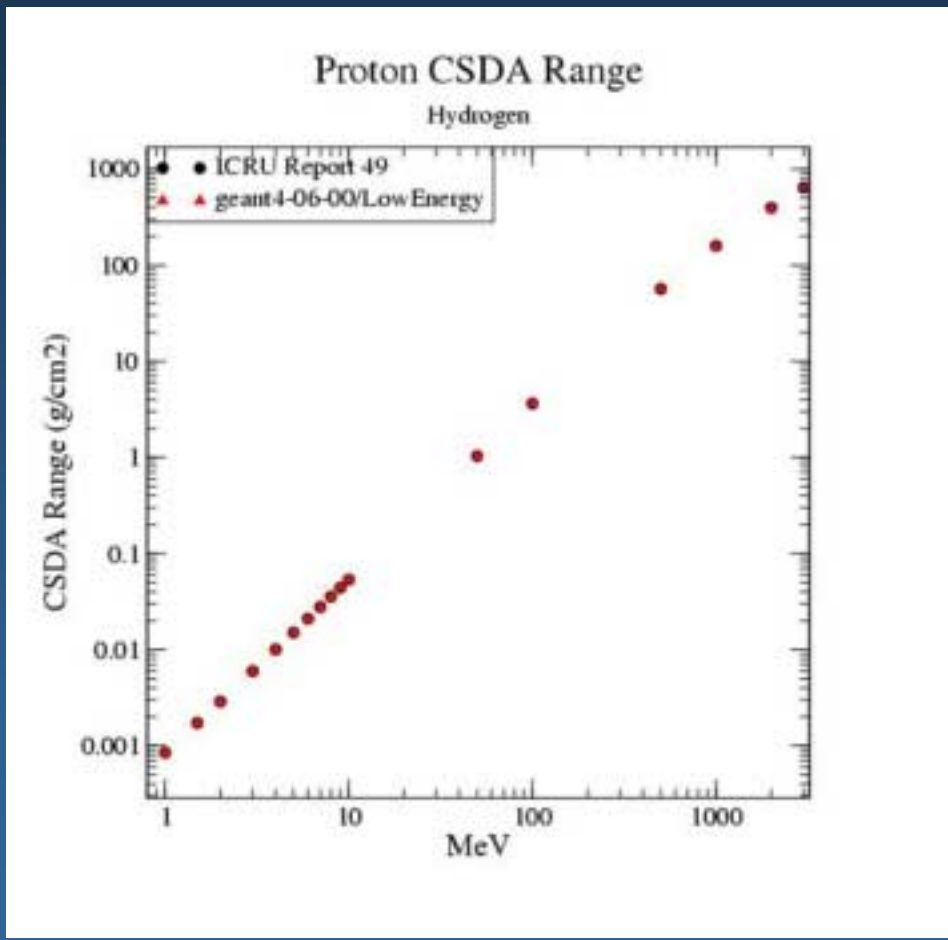
Results: water, protons



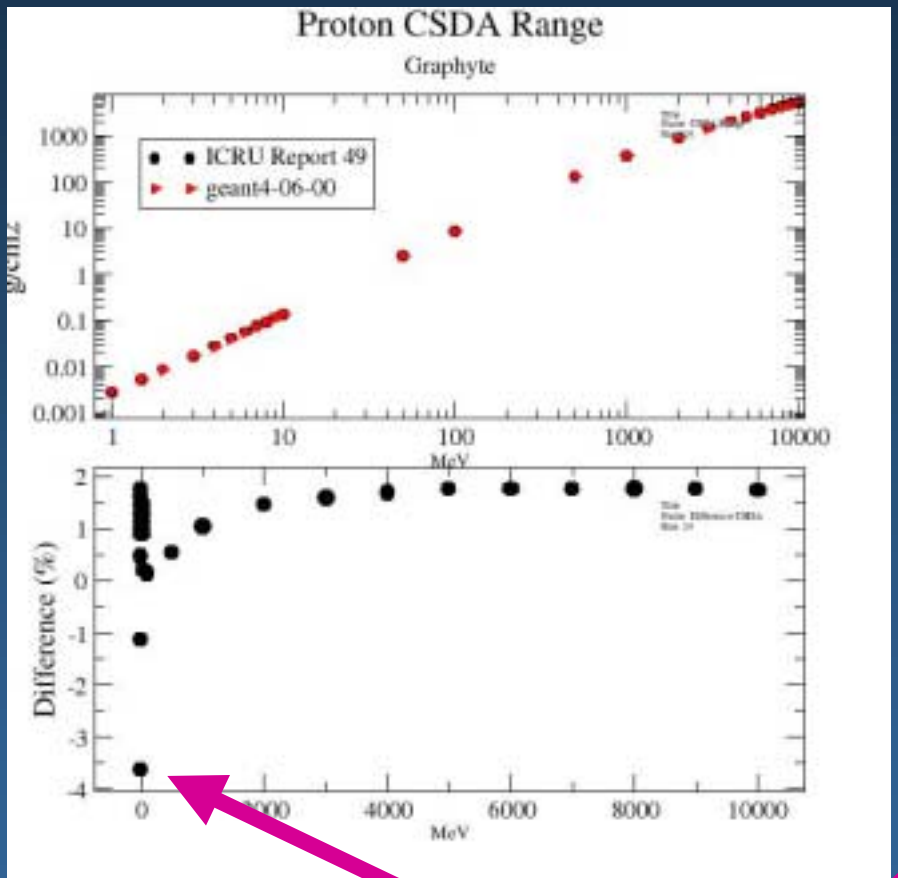


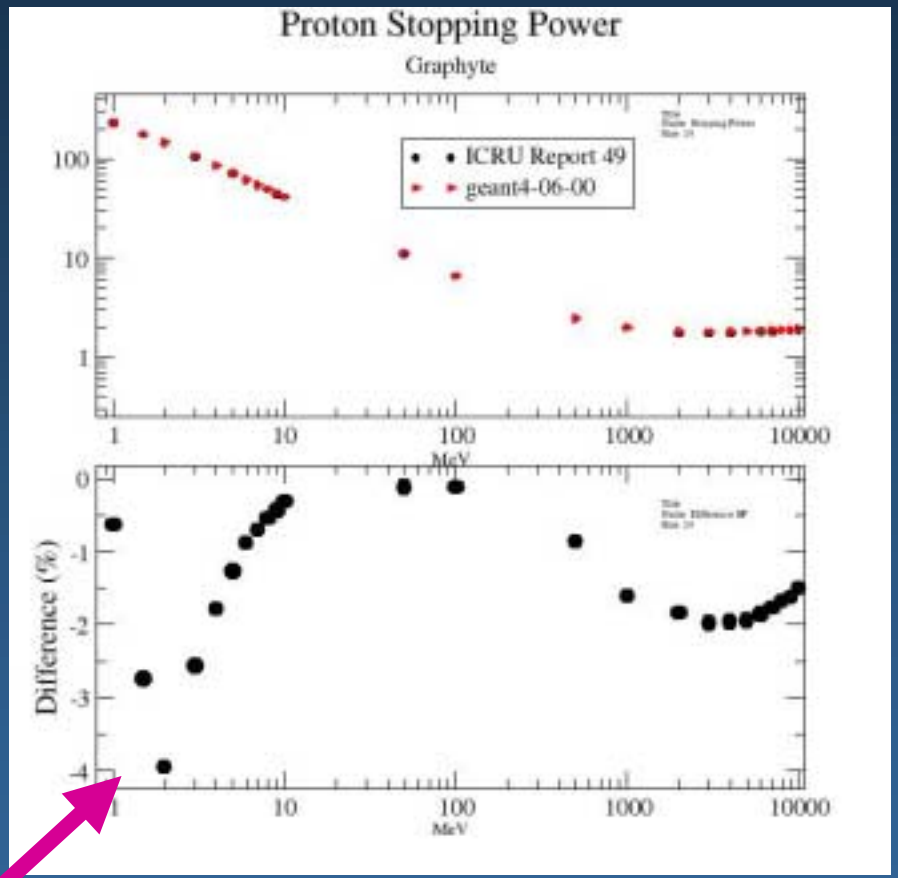
Results: hydrogen, protons





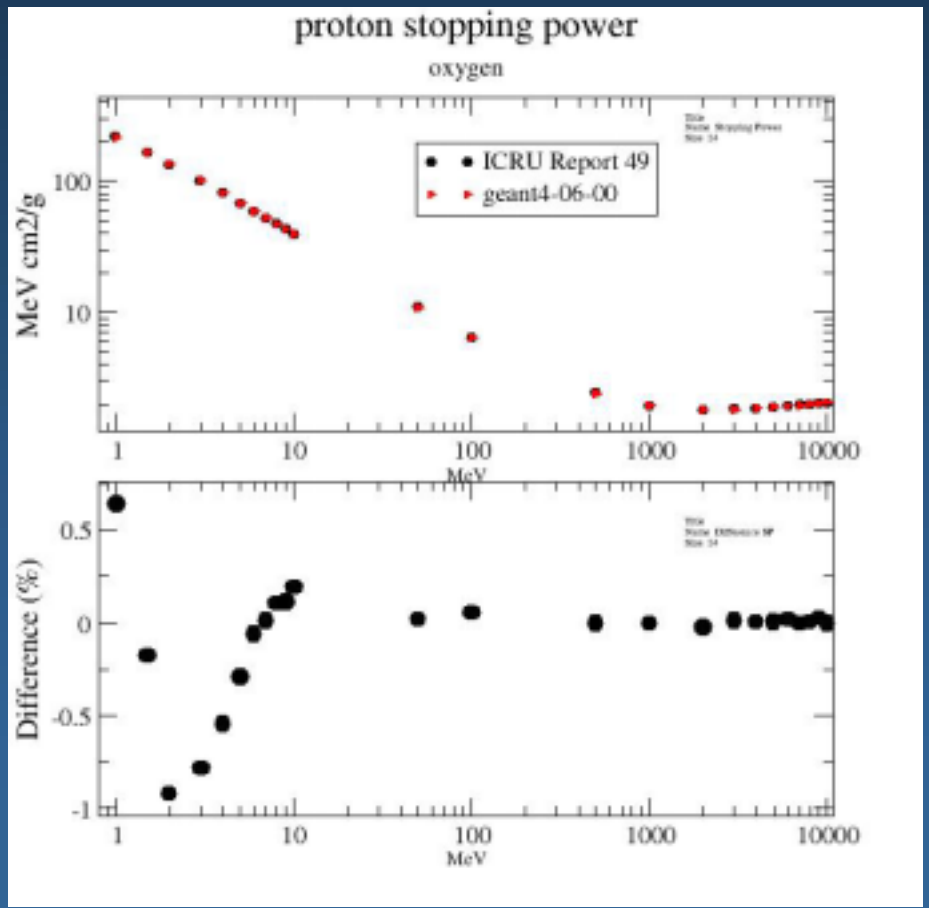
Results: graphite, protons

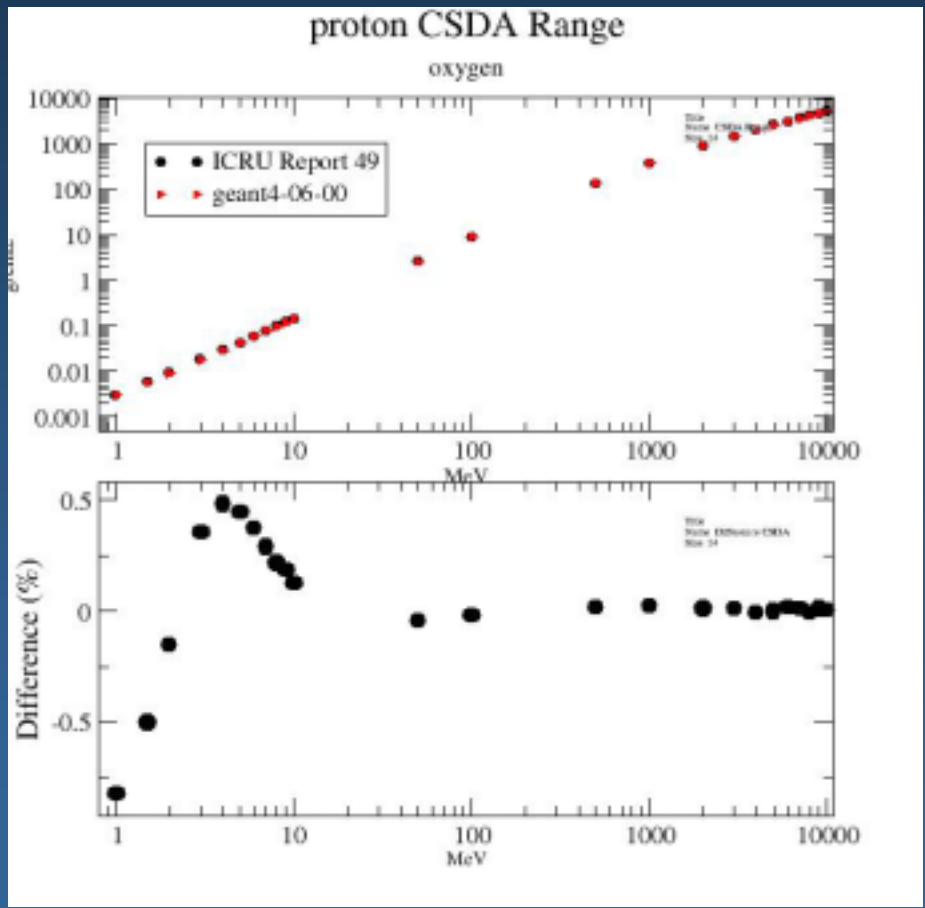




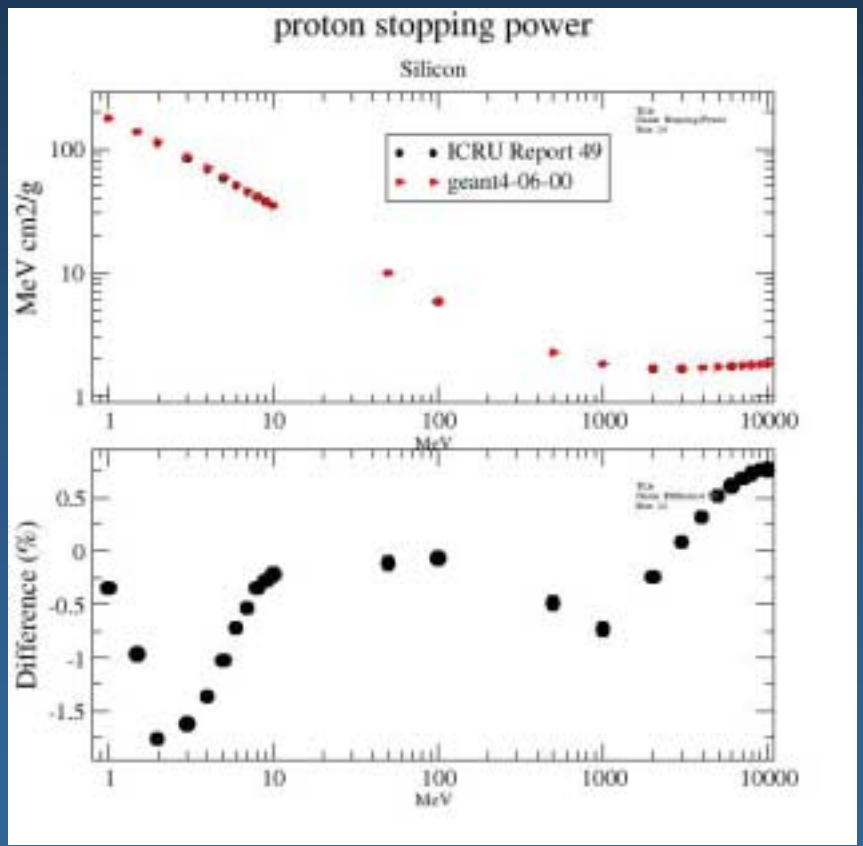
Problem identified: improved parameterised model
to be released in LowE Ionisation in Geant4 6.2

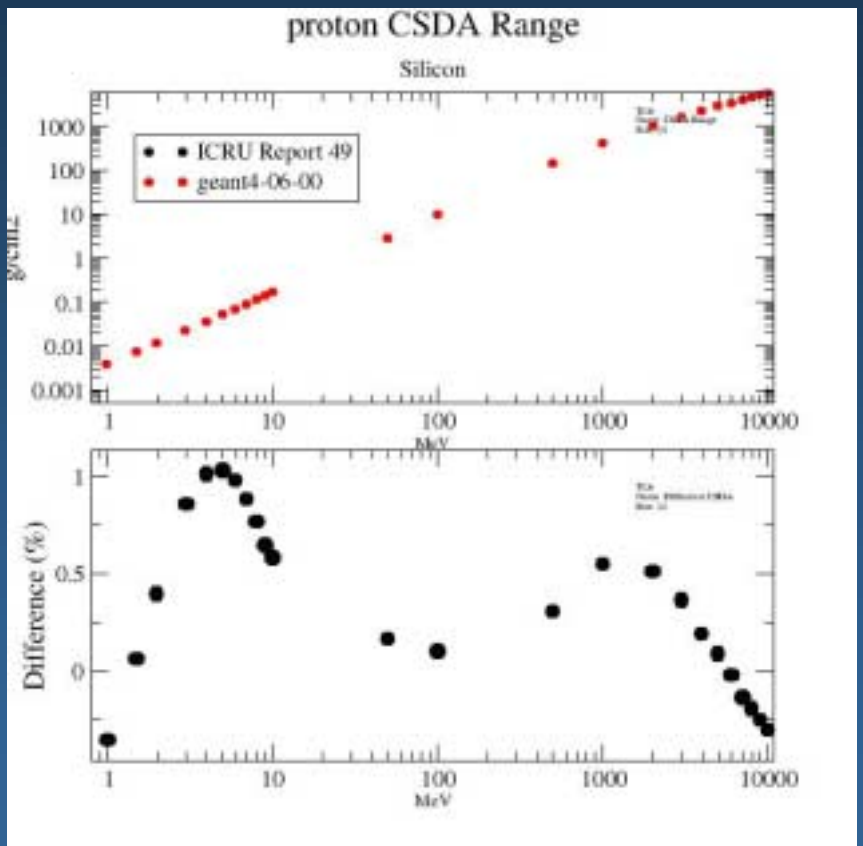
Results: oxygen, protons



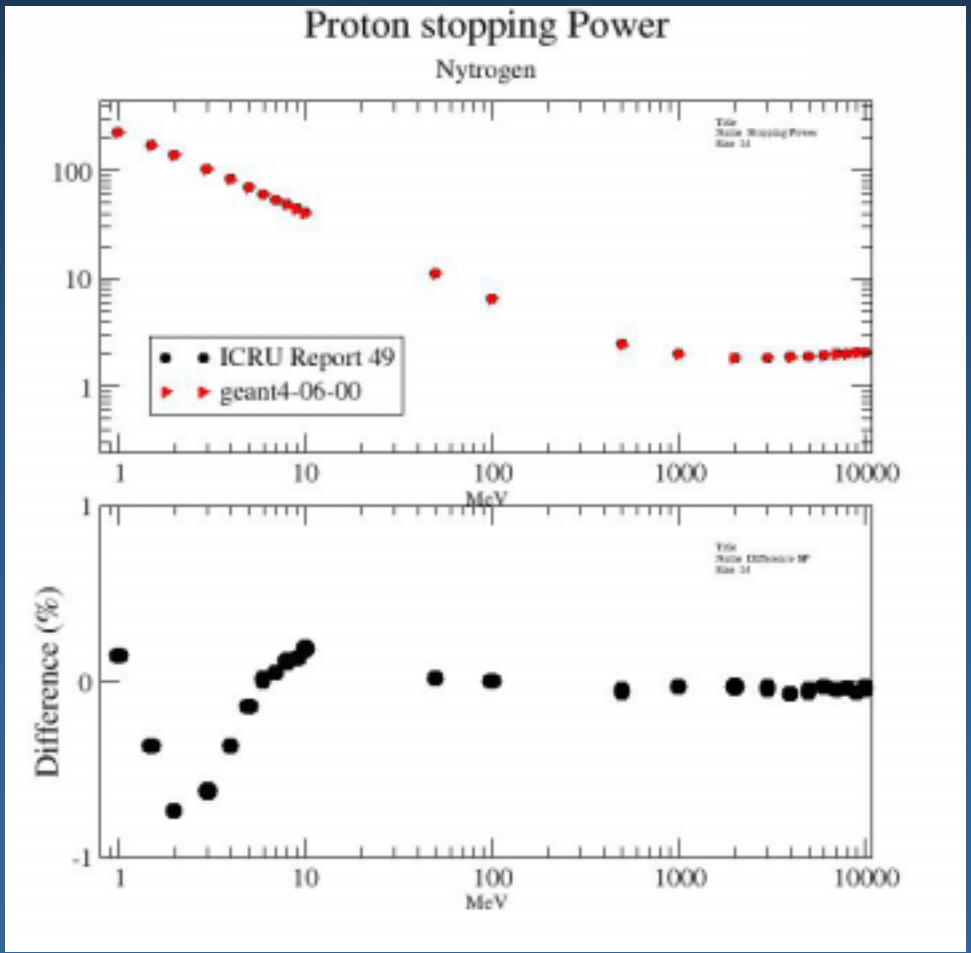


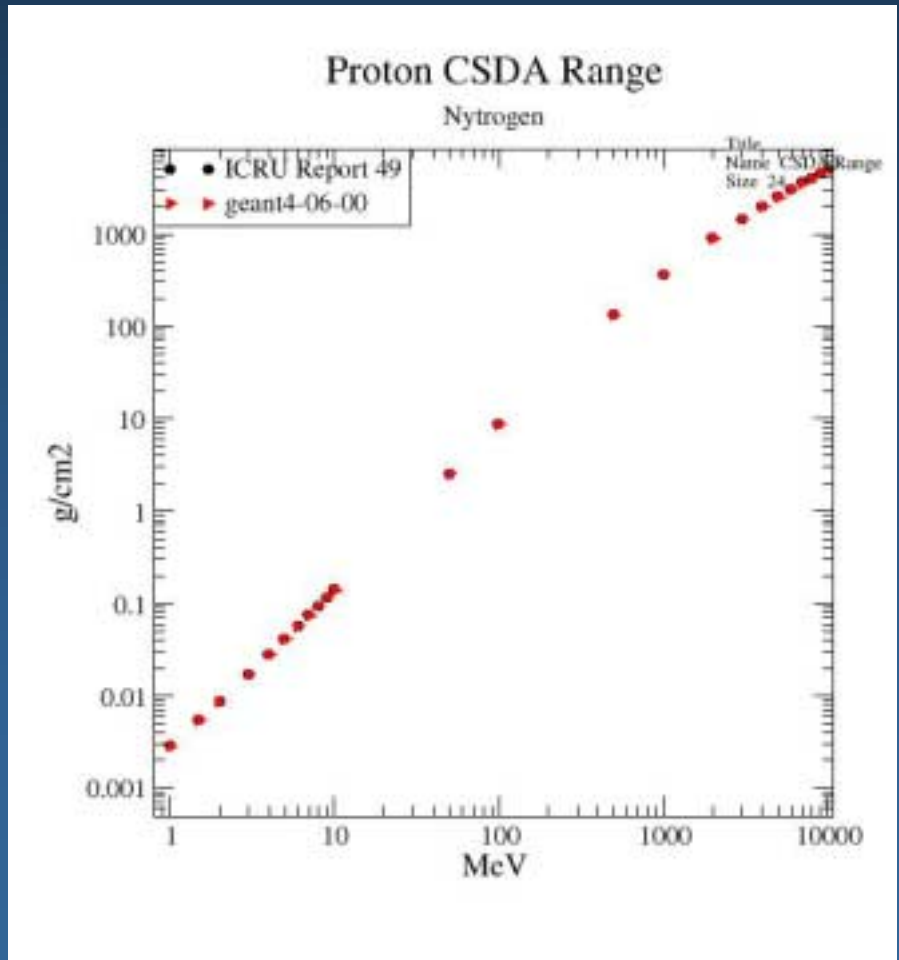
Results: silicon, protons



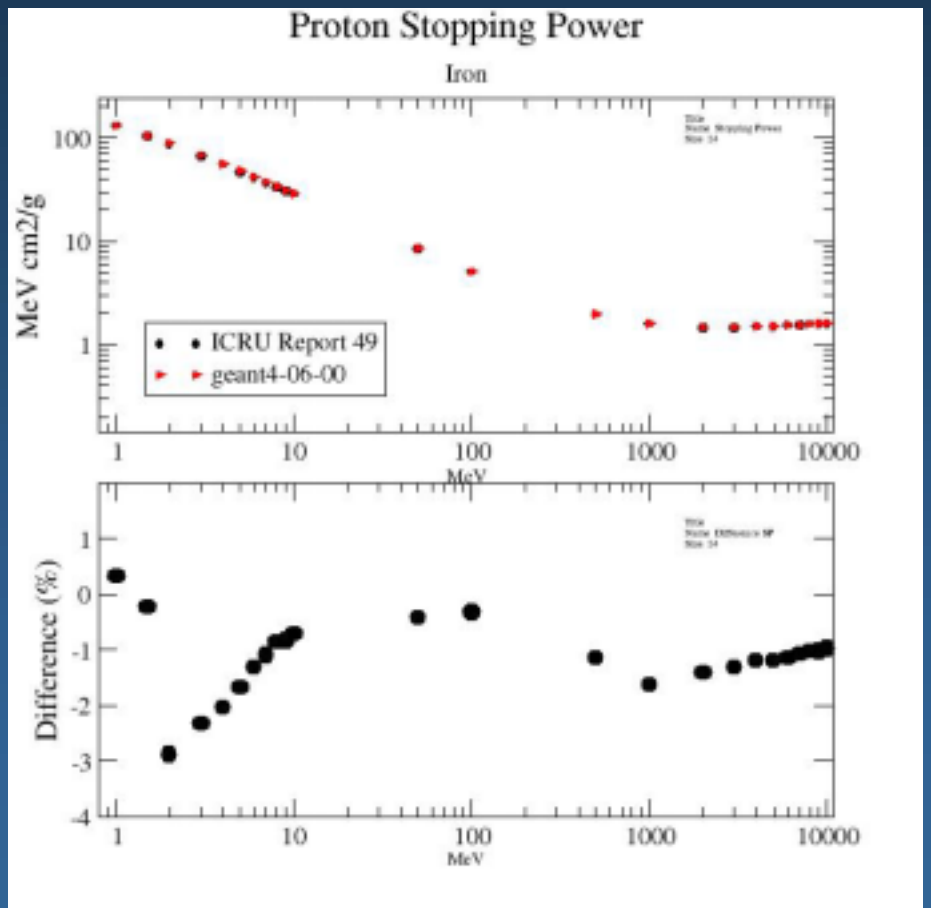


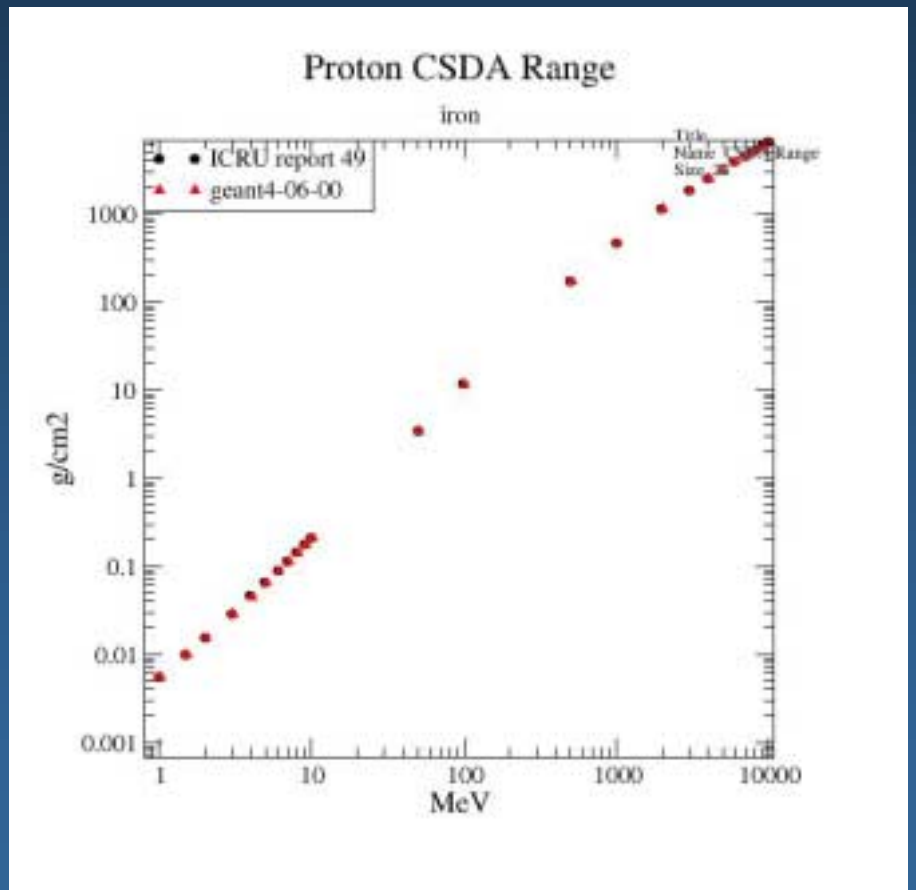
Results: nitrogen, protons



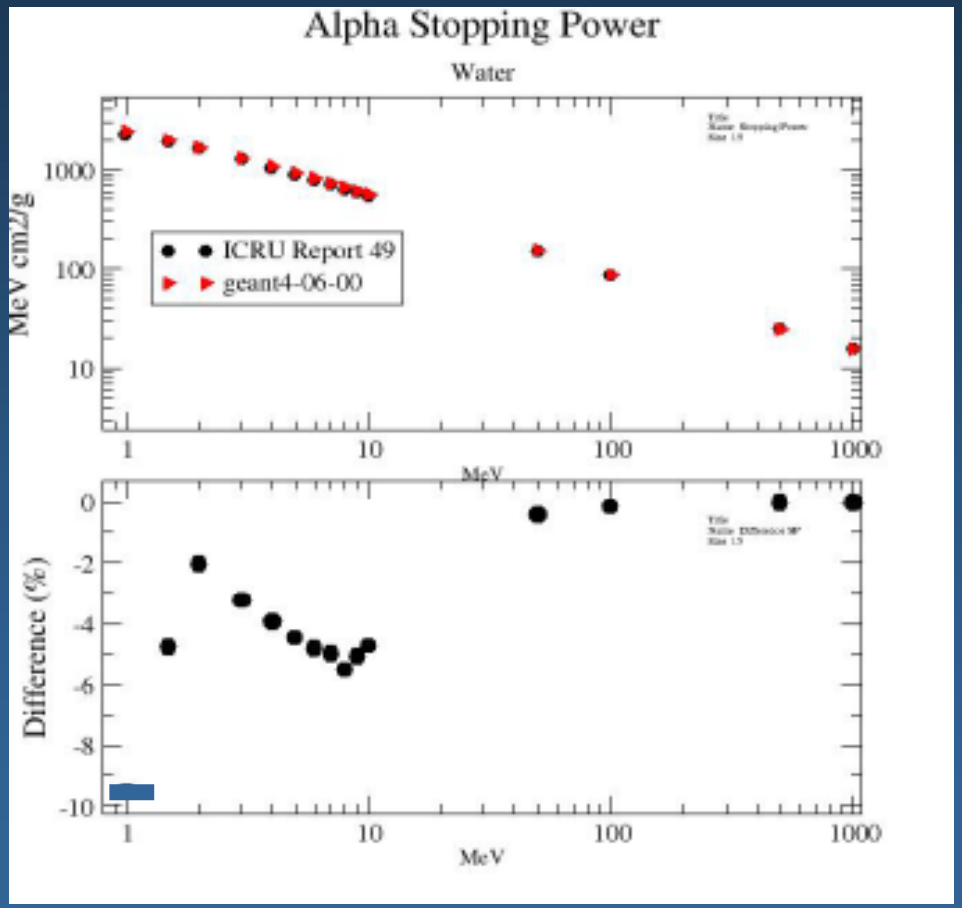


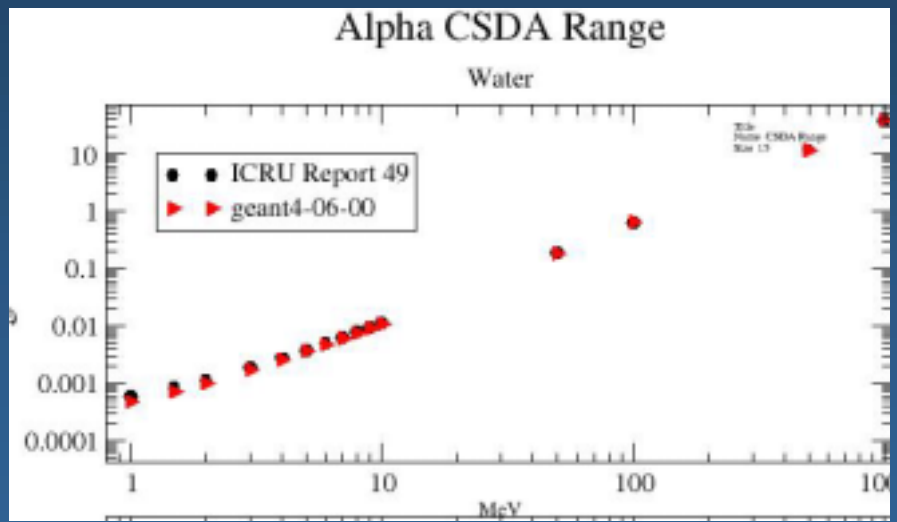
Results: iron, protons



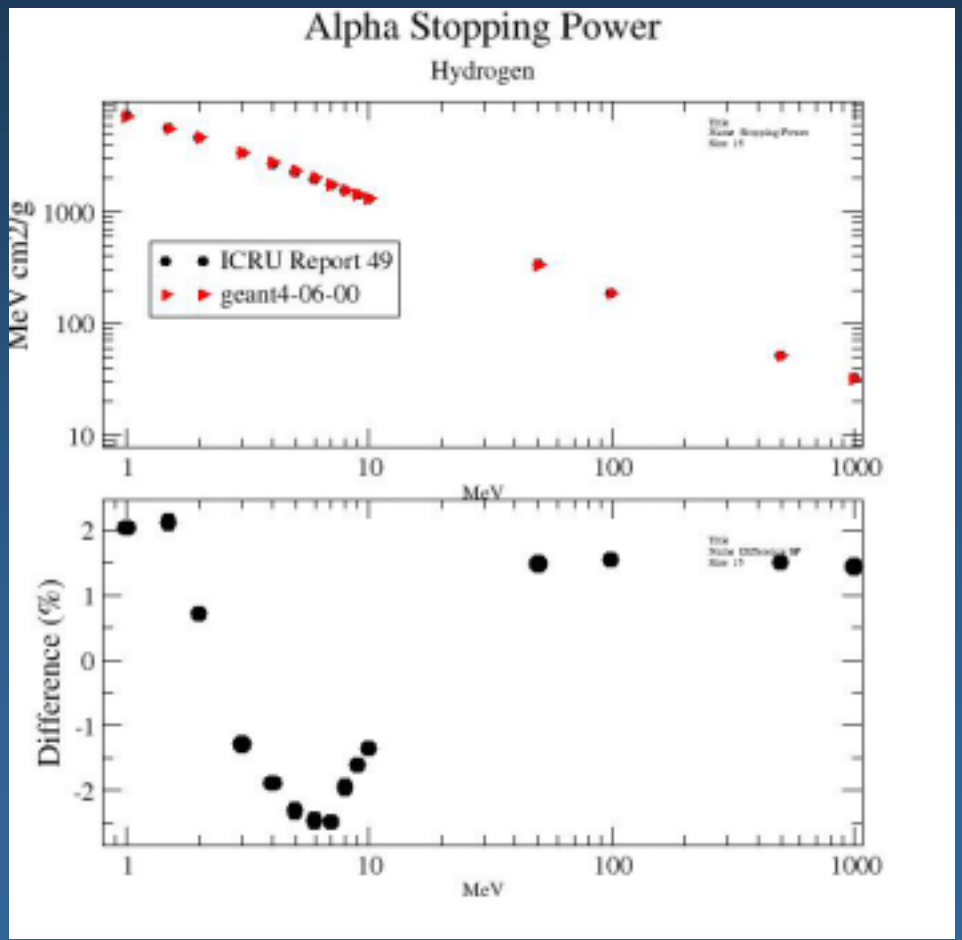


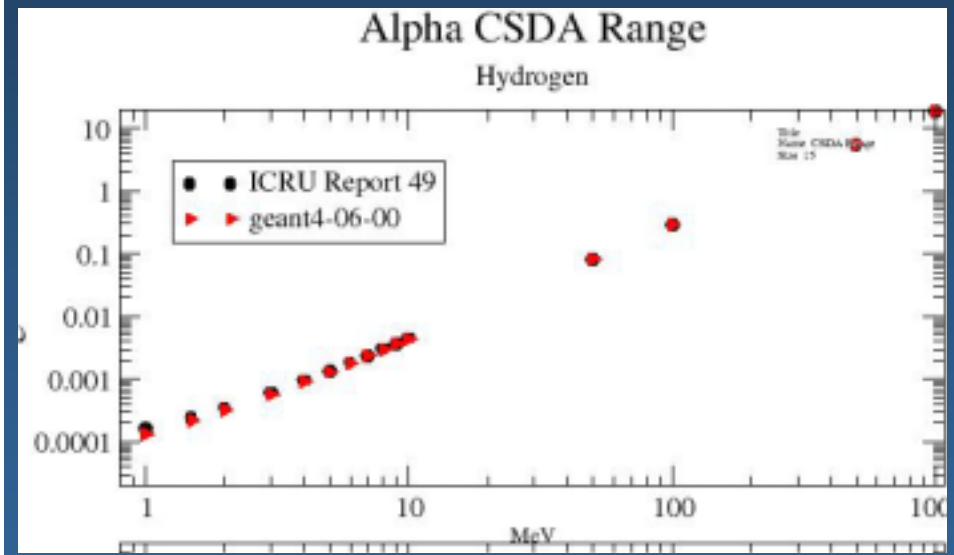
Results: water, α



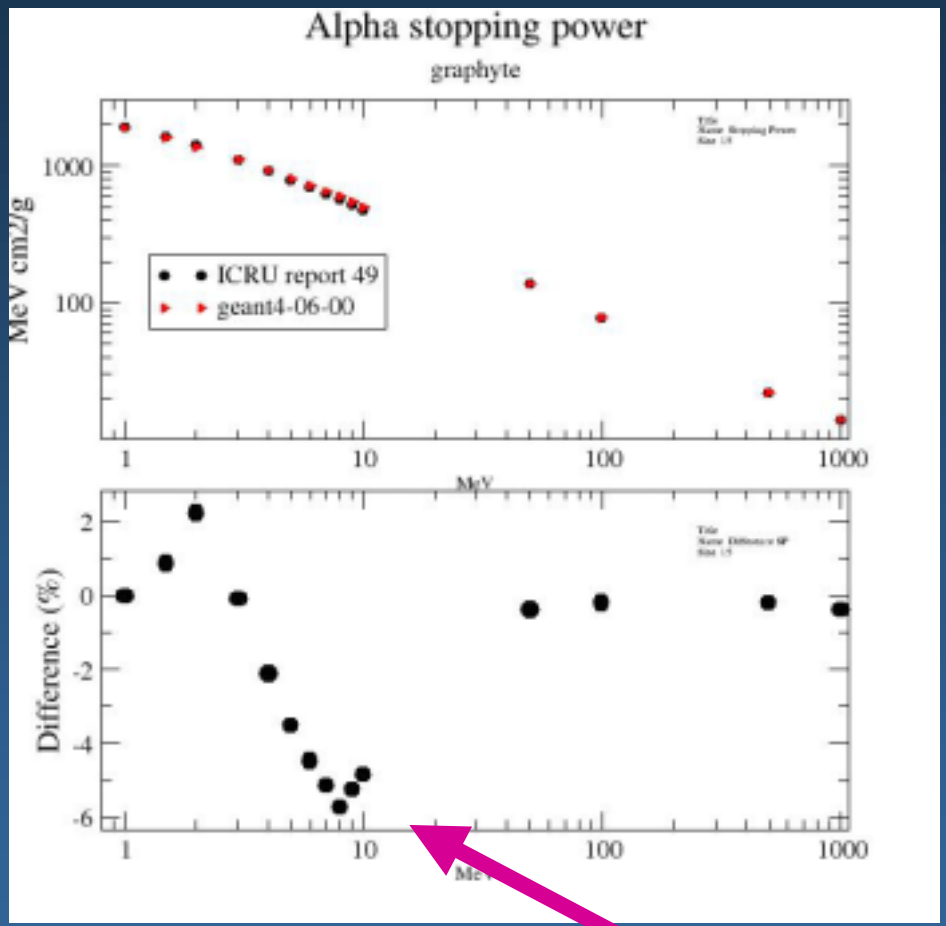


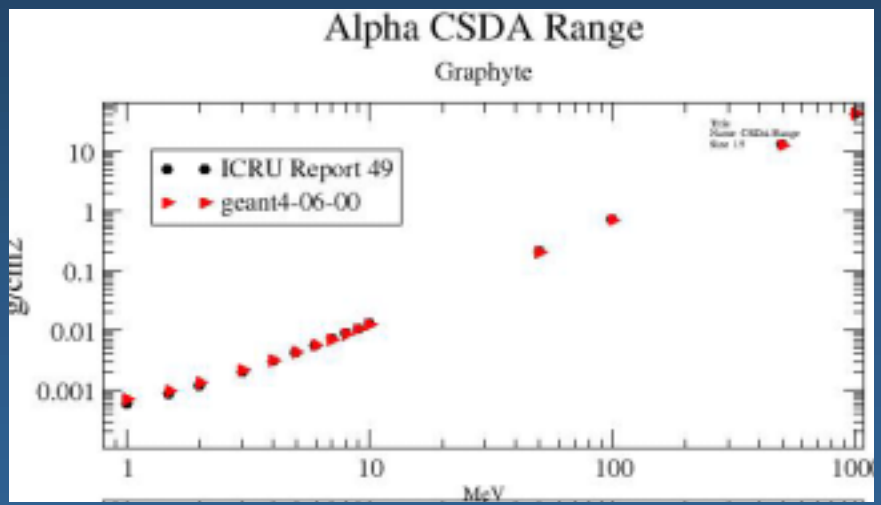
Results: hydrogen, α





Results: graphite, α





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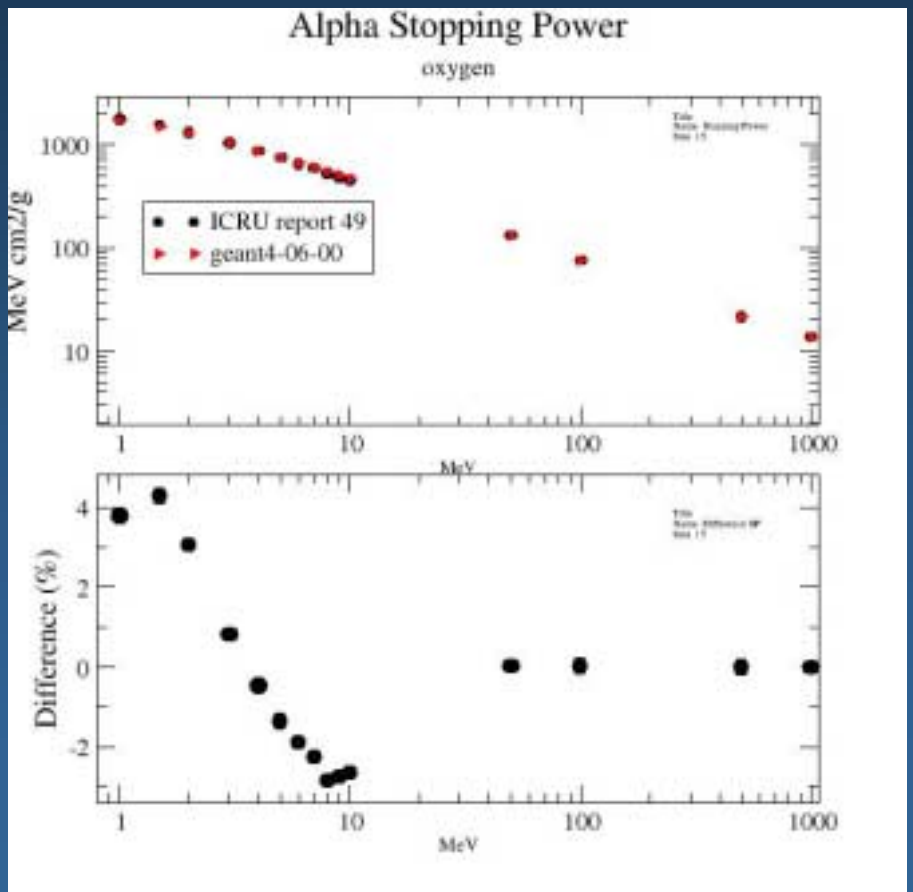
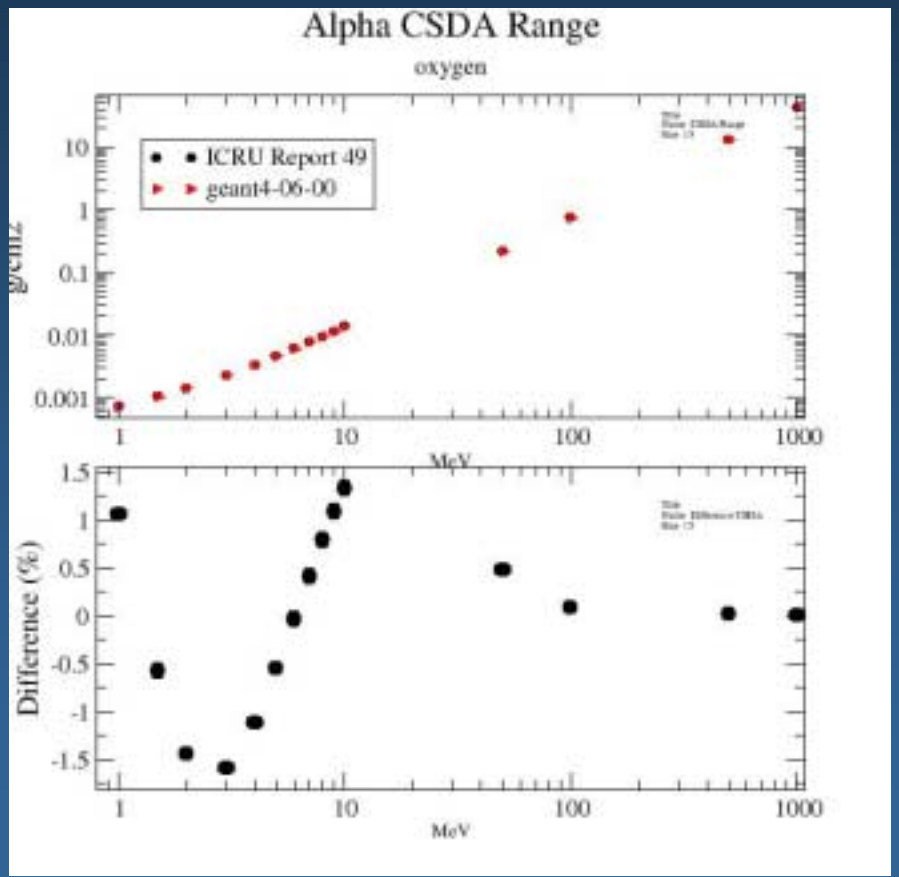
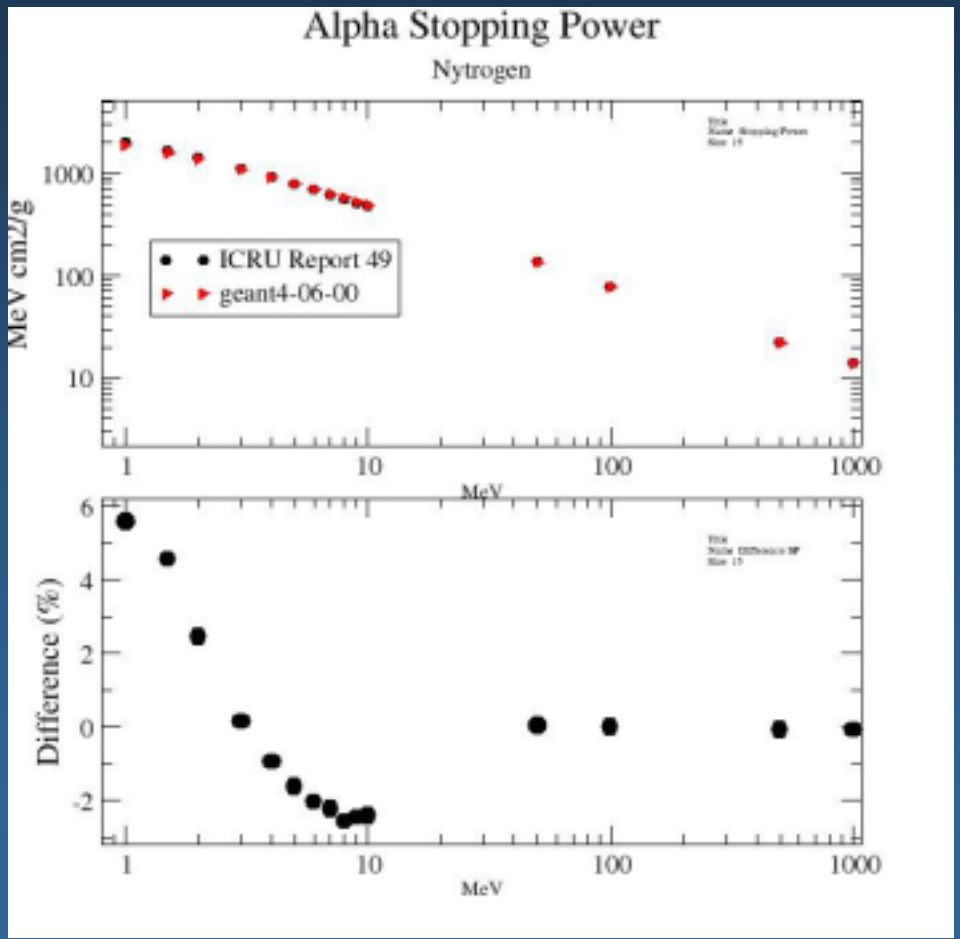
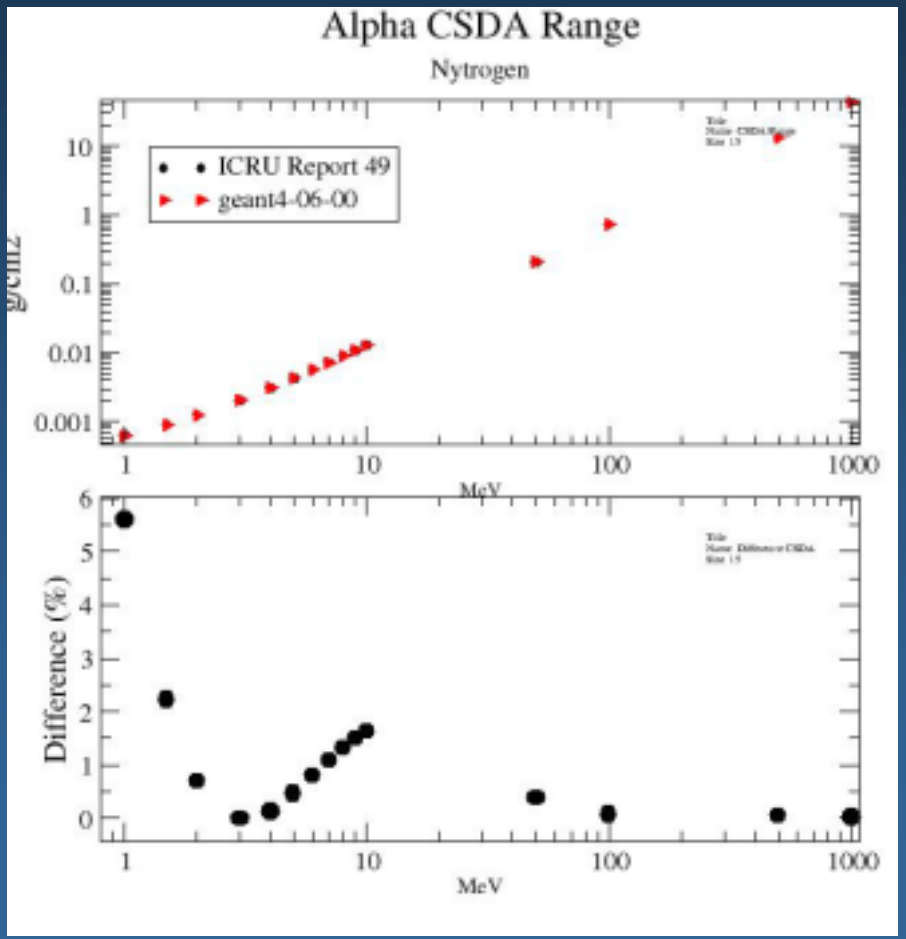
Results: oxygen, α



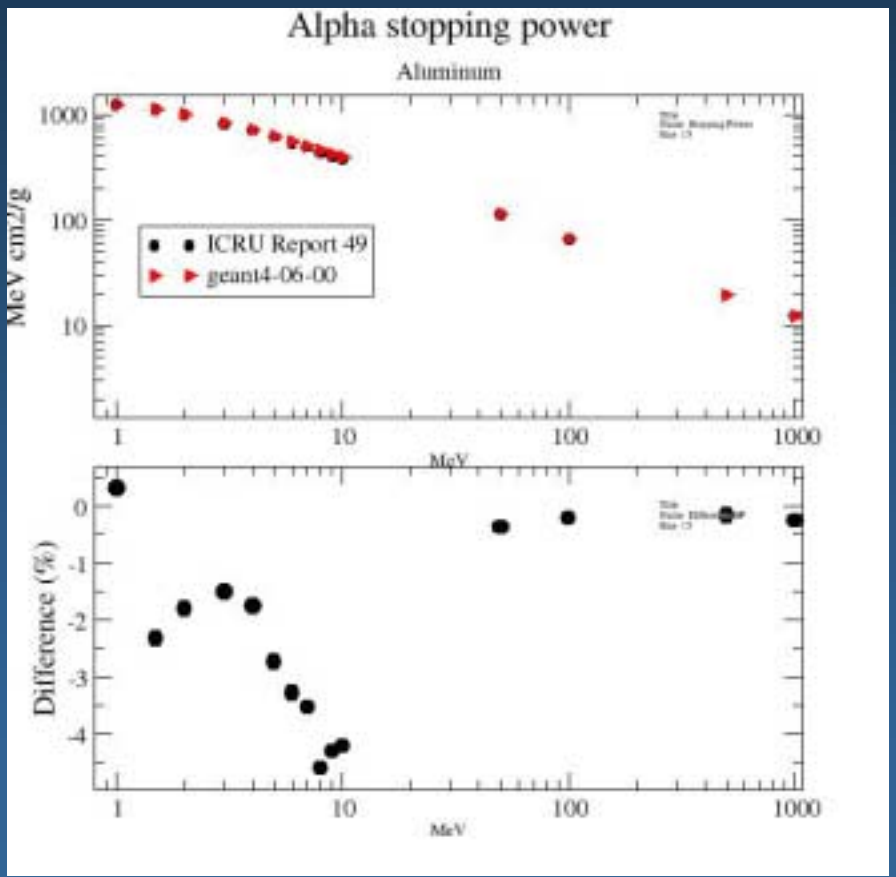


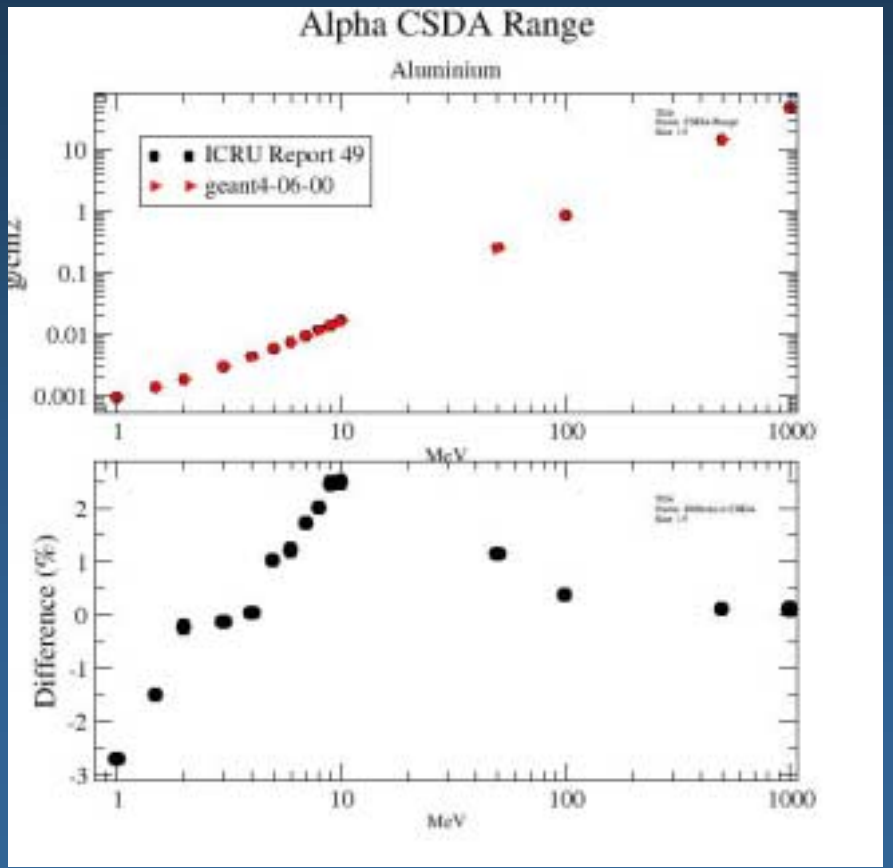
Results: nitrogen, α



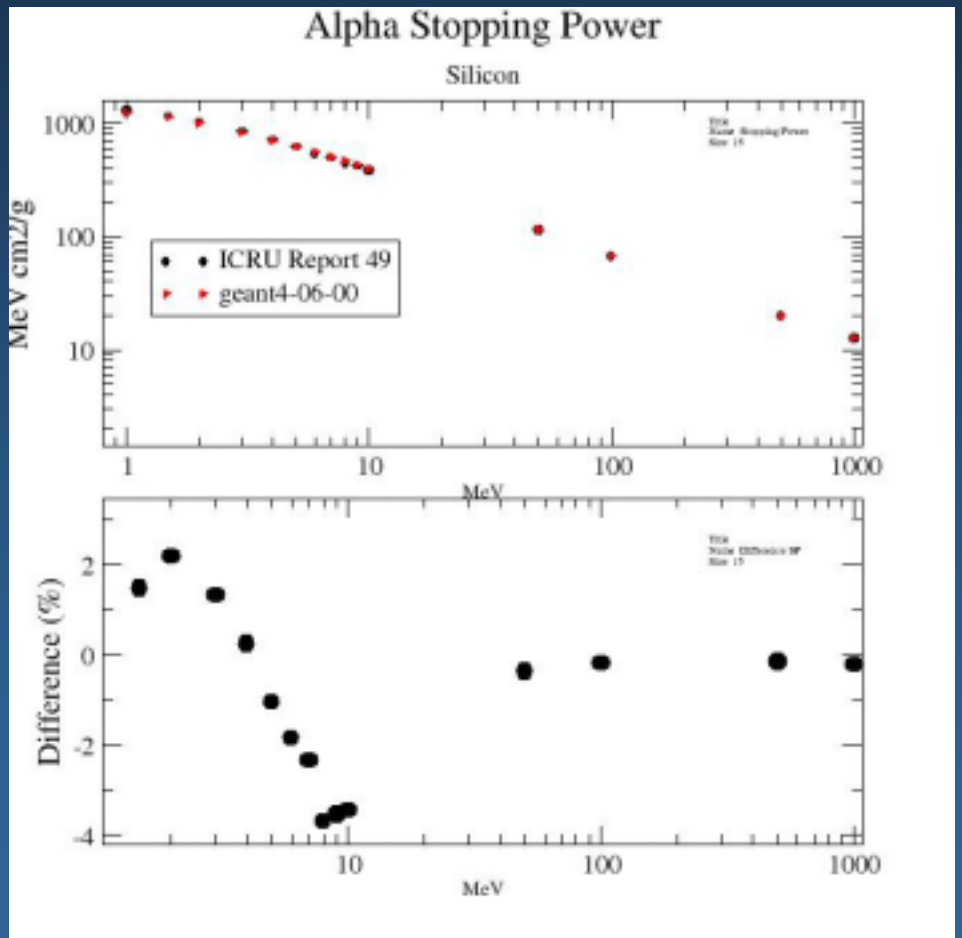


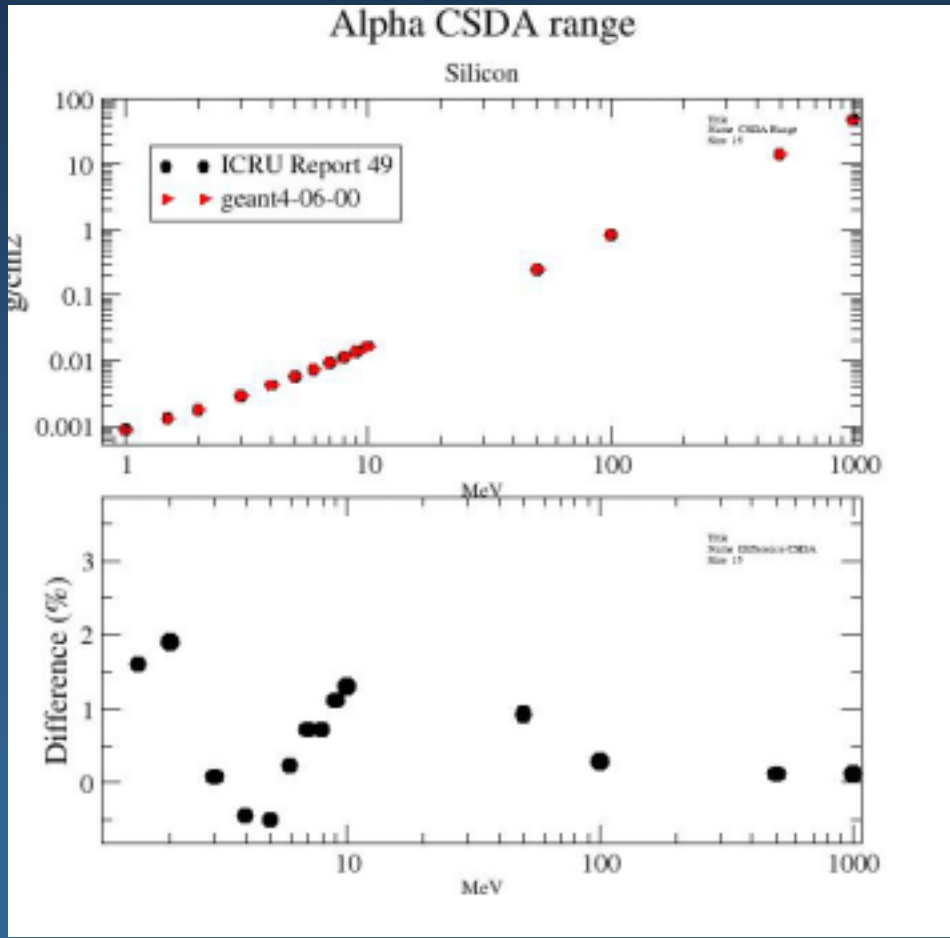
Results: aluminum, α



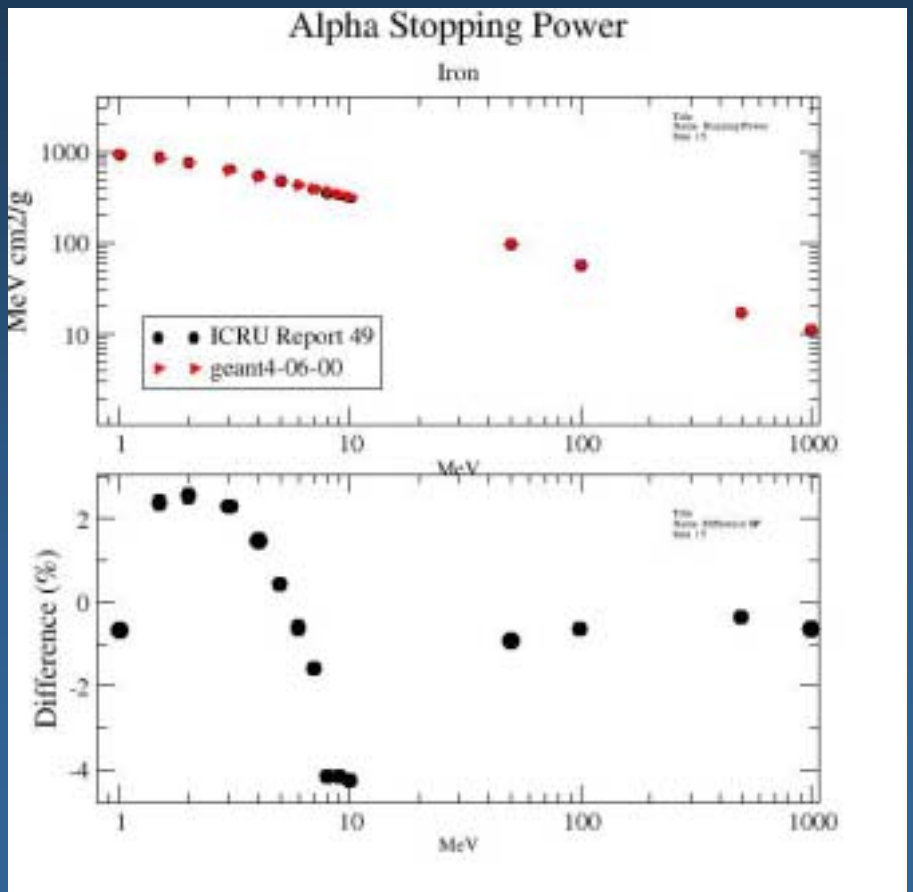


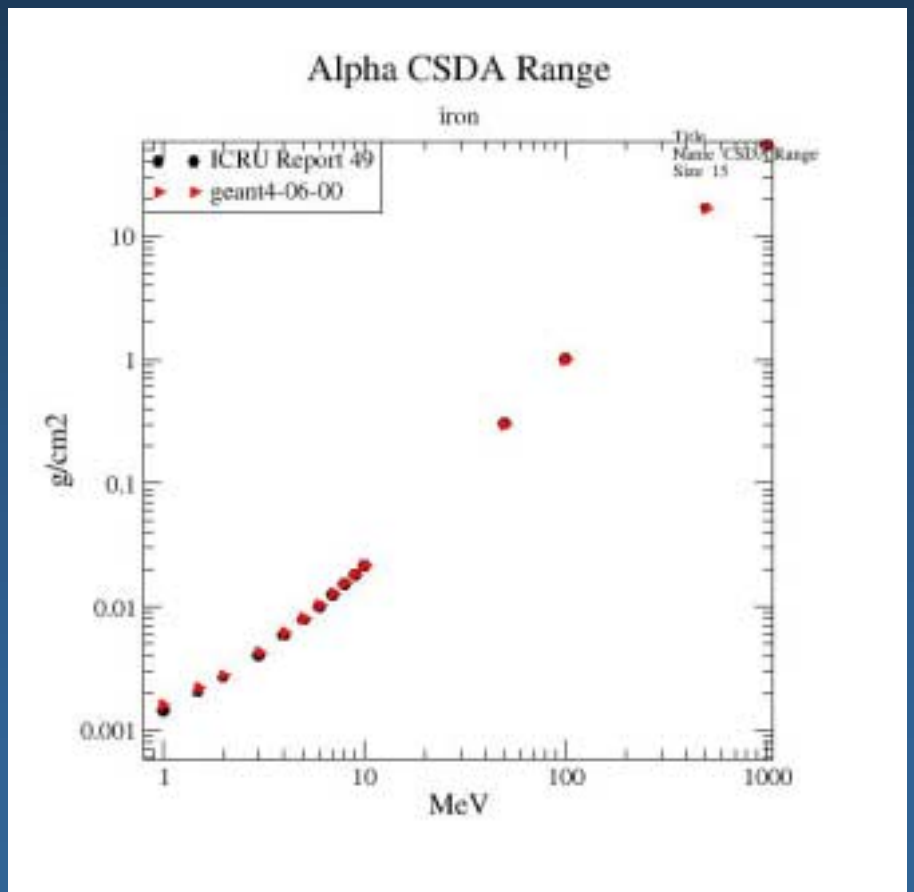
Results: silicon, α





Results: iron, α



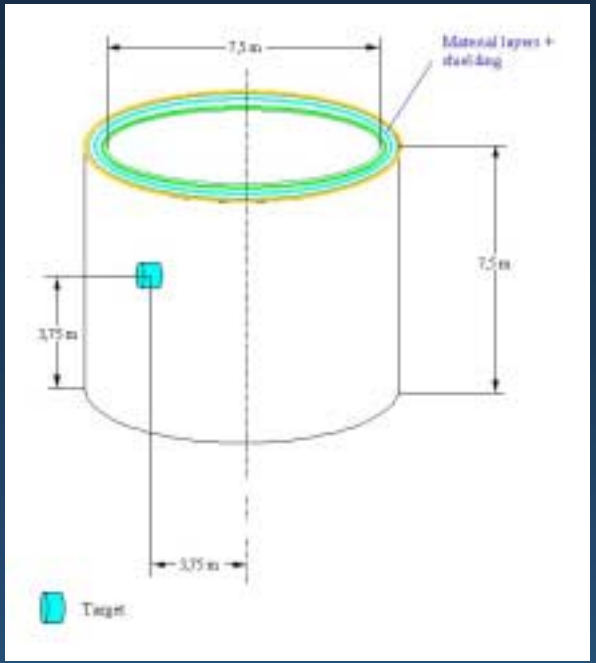


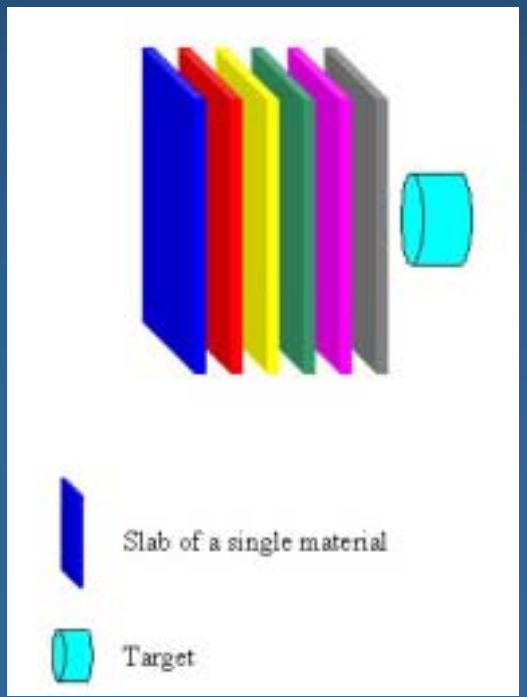
Analysis of tests

- Uncertainties for Stopping Power given by ICRU Report 49:
  - Elements
    - E < 1 MeV: ~ 5 %
    - E > 1 MeV: ~ 2 %
  - Compounds
    - E < 1 MeV: ~ 5 %
    - E > 1 MeV: ~ 4 %
- The electromagnetic physics models chosen are accurate: the differences between test results and ICRU Report 49 are compatible with ICRU errors
- In graphite for E =2 MeV the difference between Geant4 test and ICRU Report 49 is about ~4%
  - understood, improvement of LowE model planned

Vehicle habitat concepts

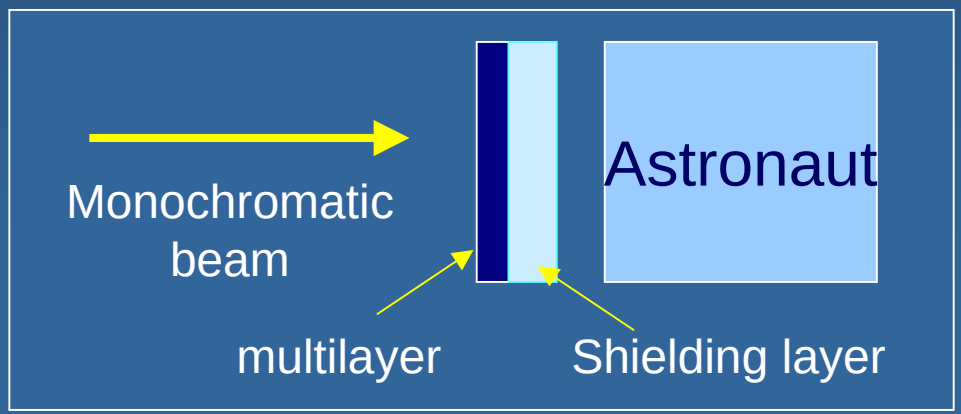
- Conceptual designs of vehicle habitats have been proposed in various studies
- Simplified Inflatable Habitat concept (SIH) consisting of:
  - Meteoroid and debris protection
  - Structure
  - Rebundant bladder
  - *No shielding*
- The **multilayer** is a simplified model of the SIH for preliminary shielding studies
  - keeping the essential characteristics of the SIH relevant for a dosimetric study at this stage of the project





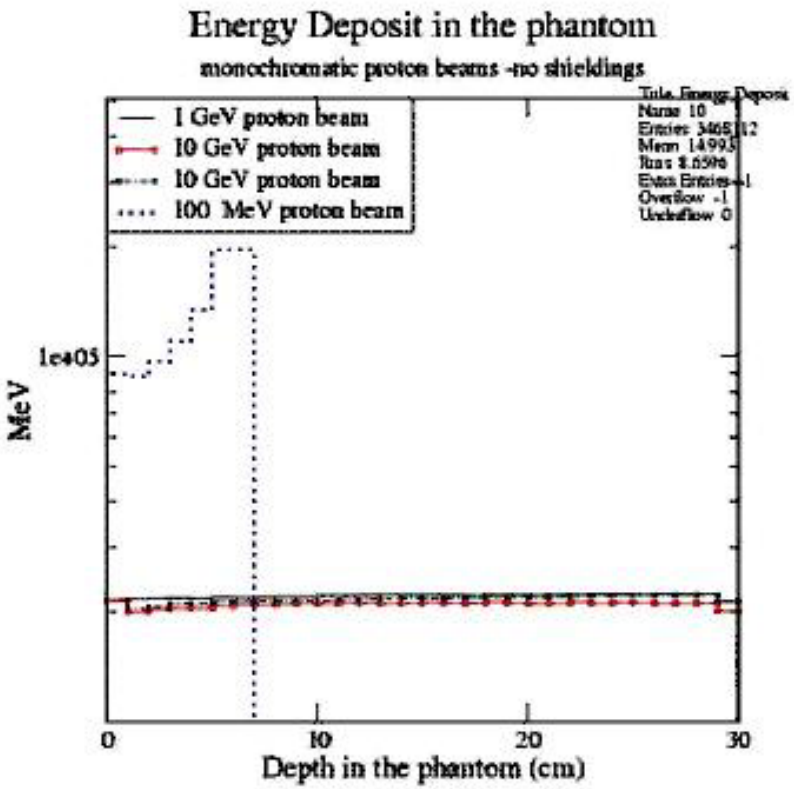
Dosimetry with EM physics

- Preliminary study with particle beams incident on multilayer + shielding
  - 5/10 cm water, 10 cm polyethylene
- Geant4 LowE electromagnetic processes + multiple scattering

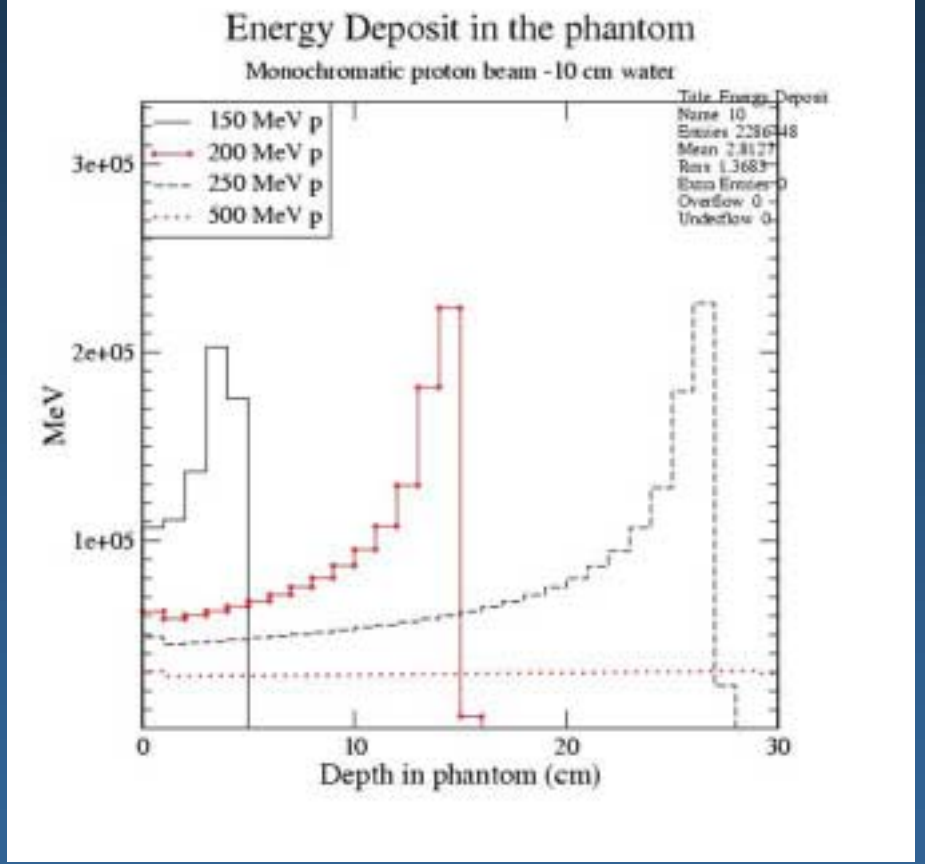


Proton energy deposit in the Astronaut

No shielding



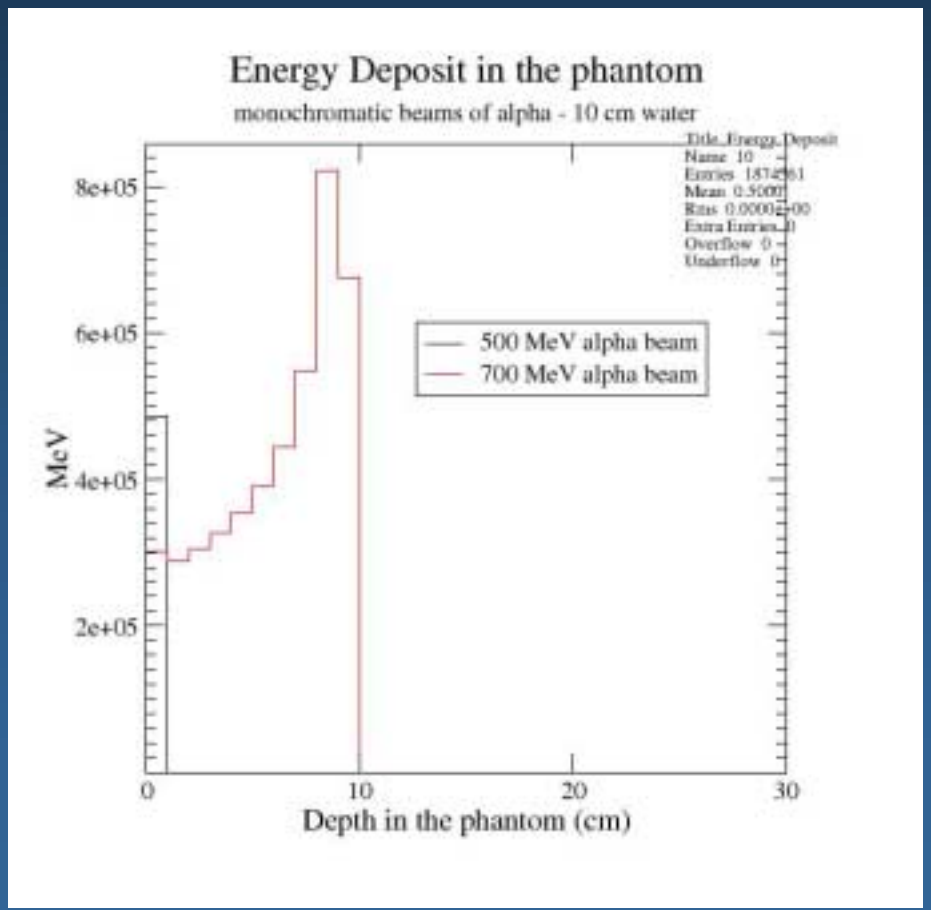
10 cm water shielding

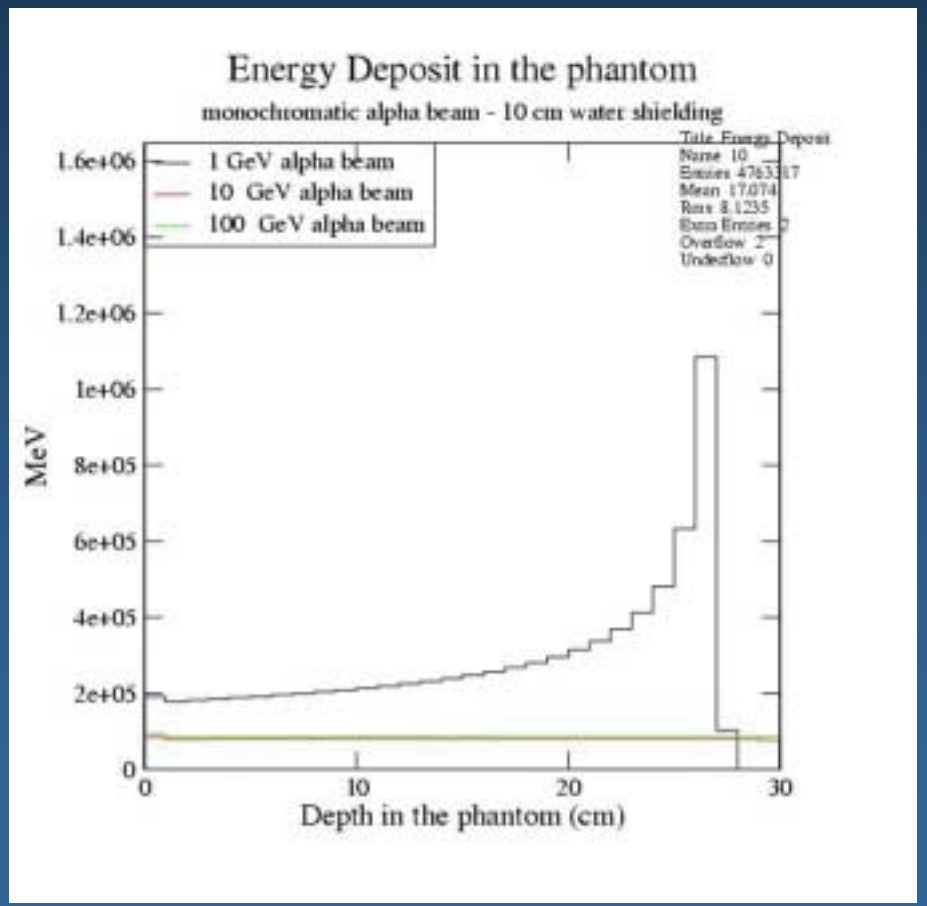


Effect of the shielding layer:

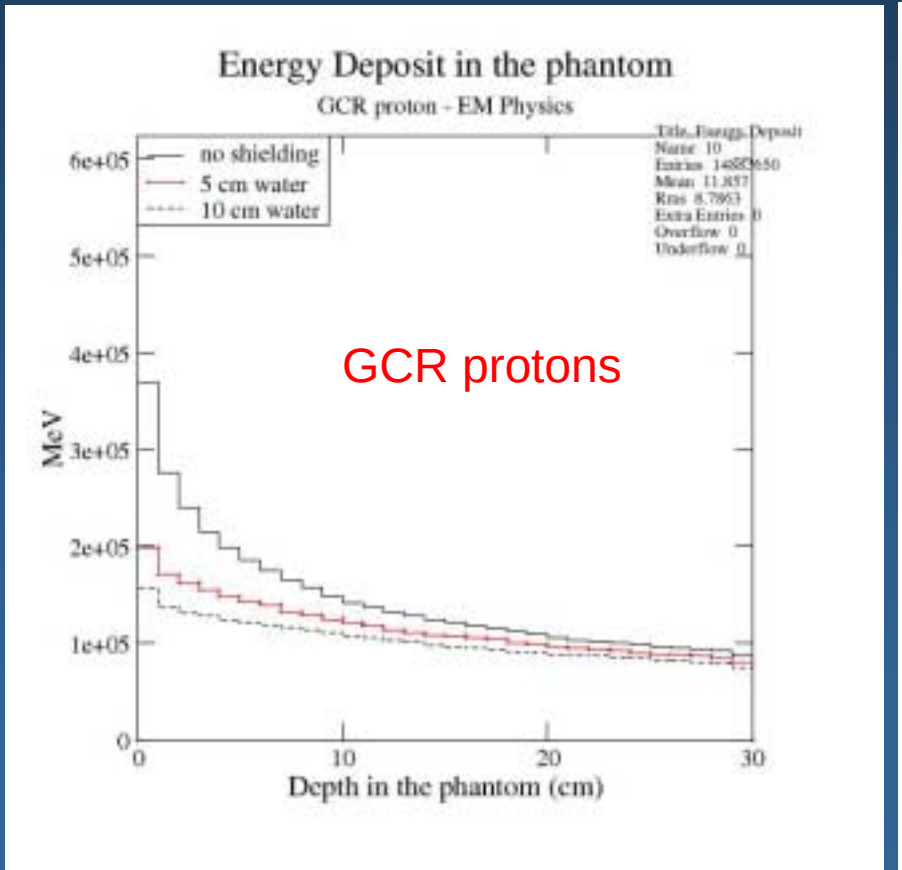
the Bragg peaks inside the phantom are shifted to higher energies

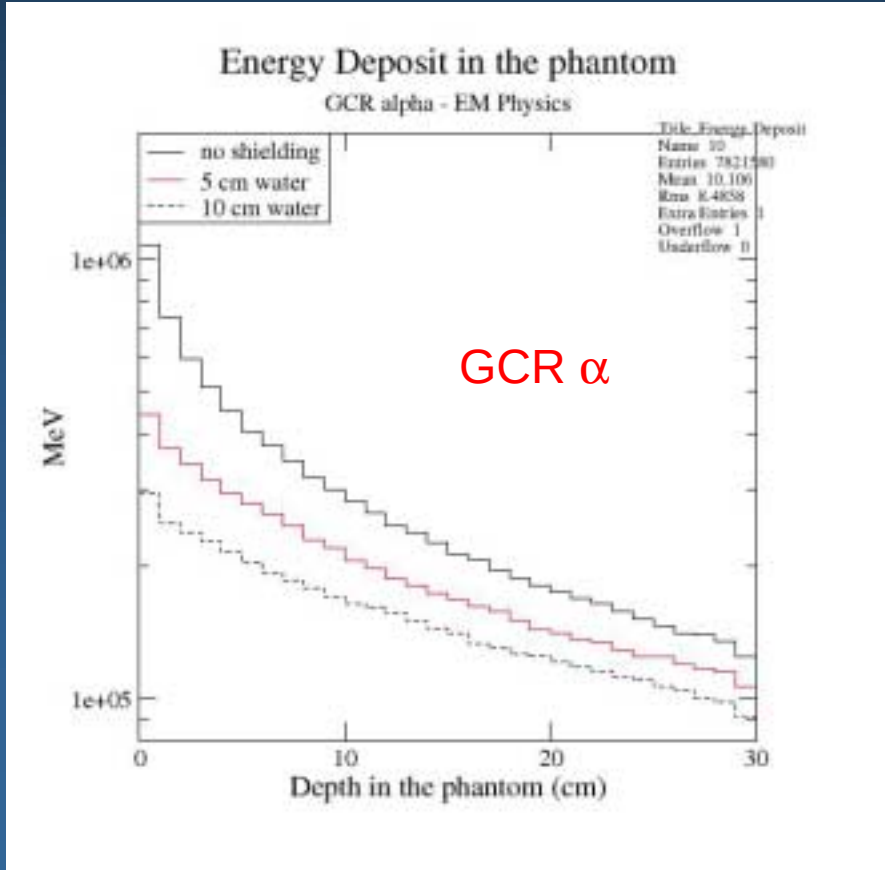
Alpha energy deposit



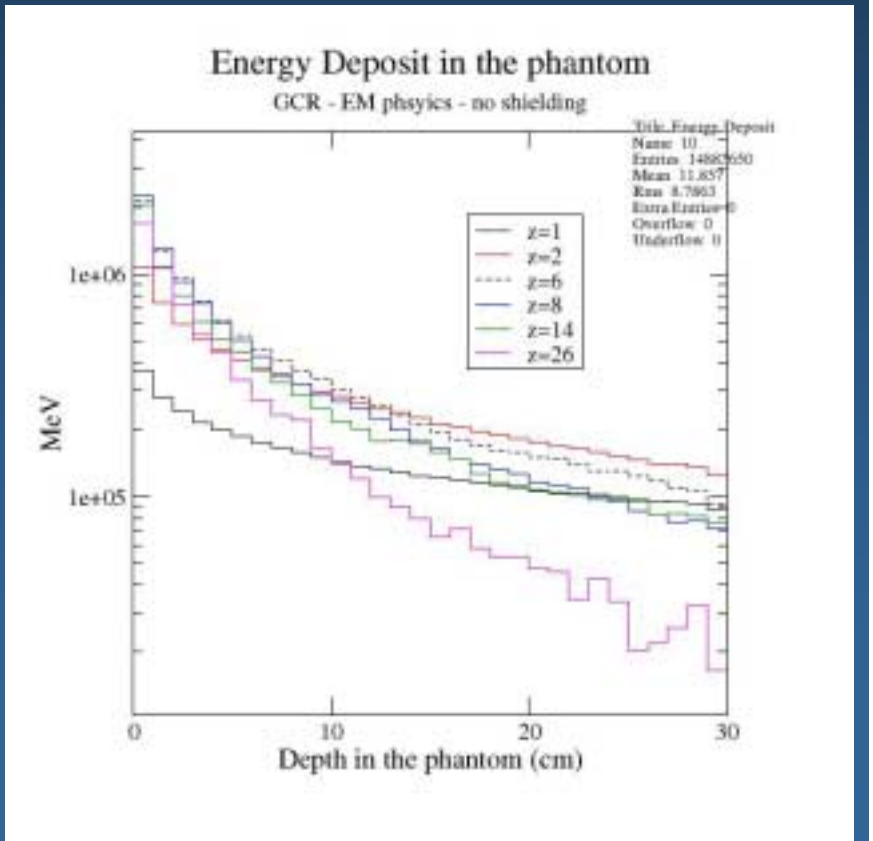


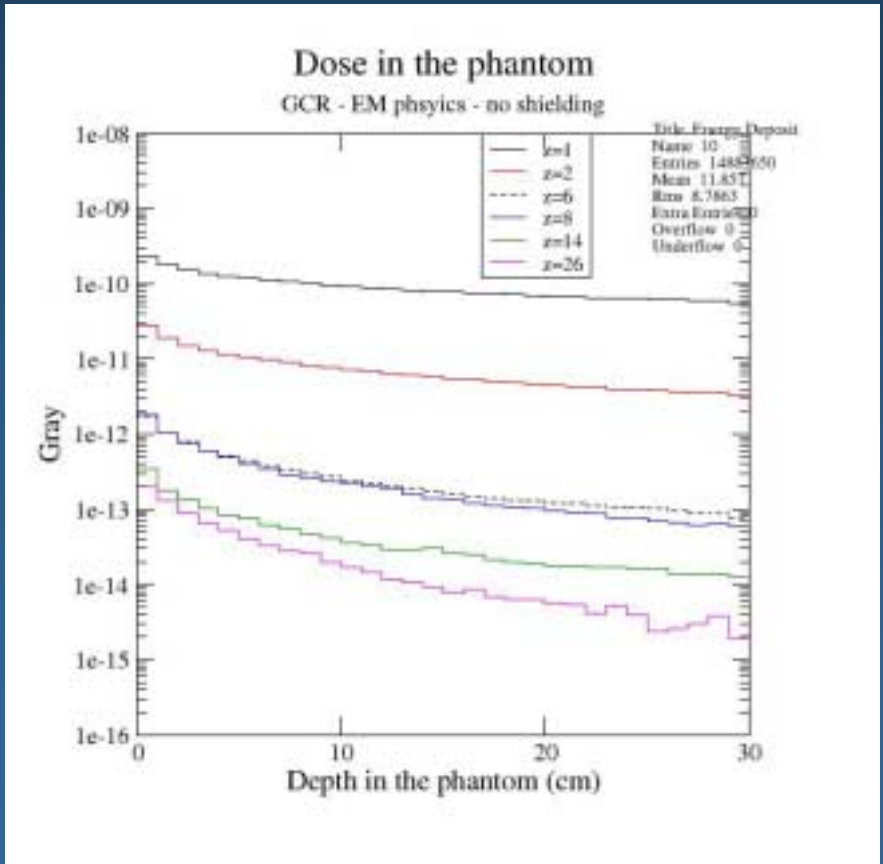
Comparison 0, 5 cm, 10 cm water shielding



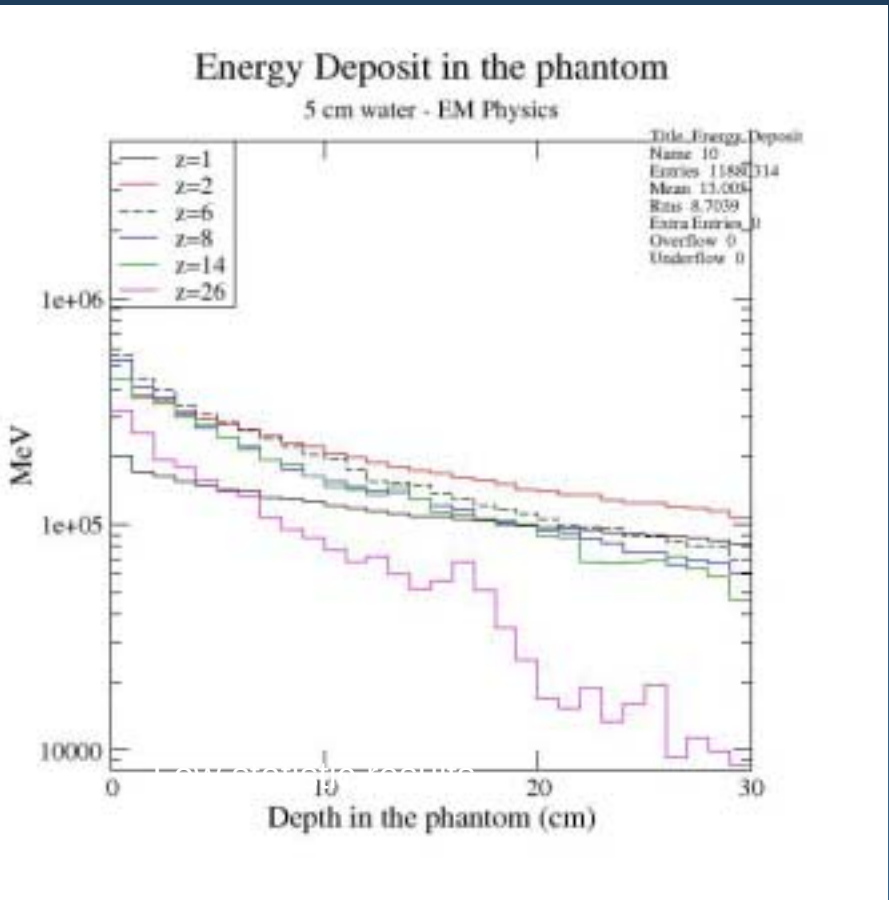


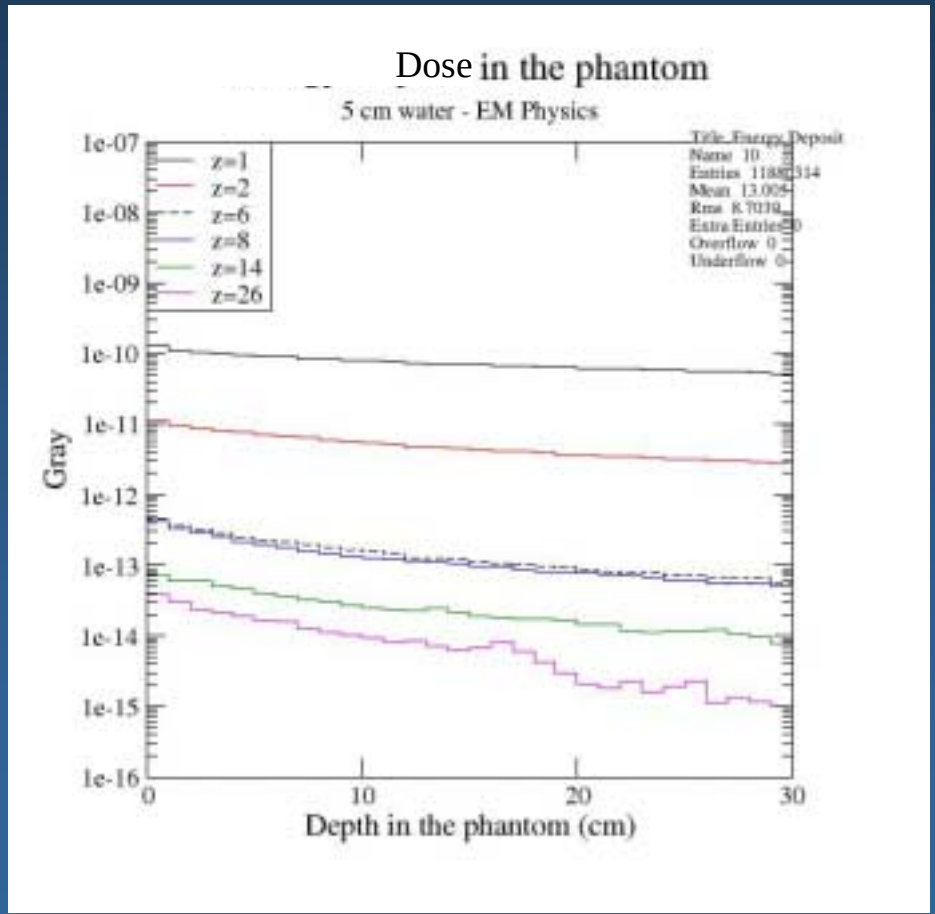
GCR, no shielding



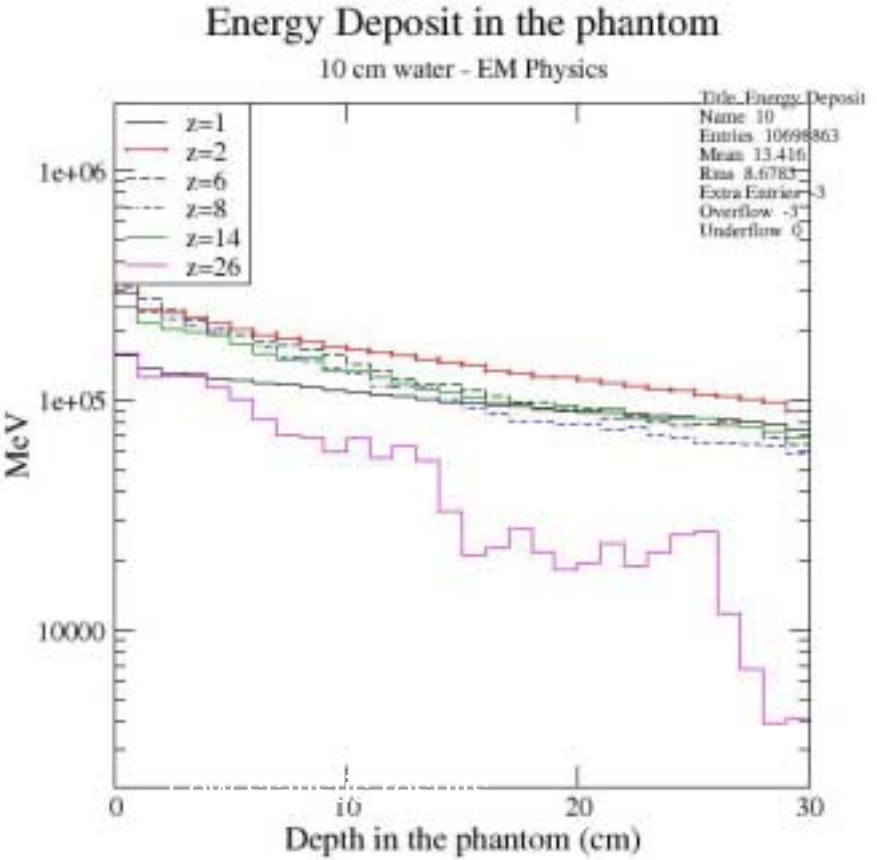


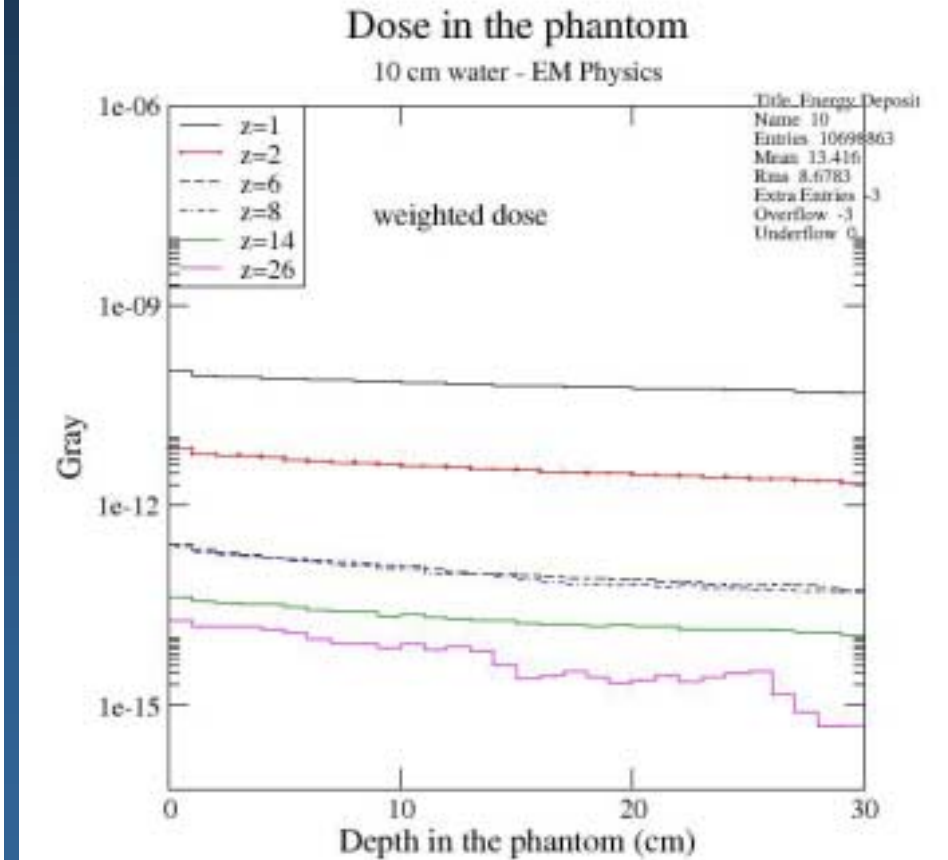
GCR, 5 cm water shielding



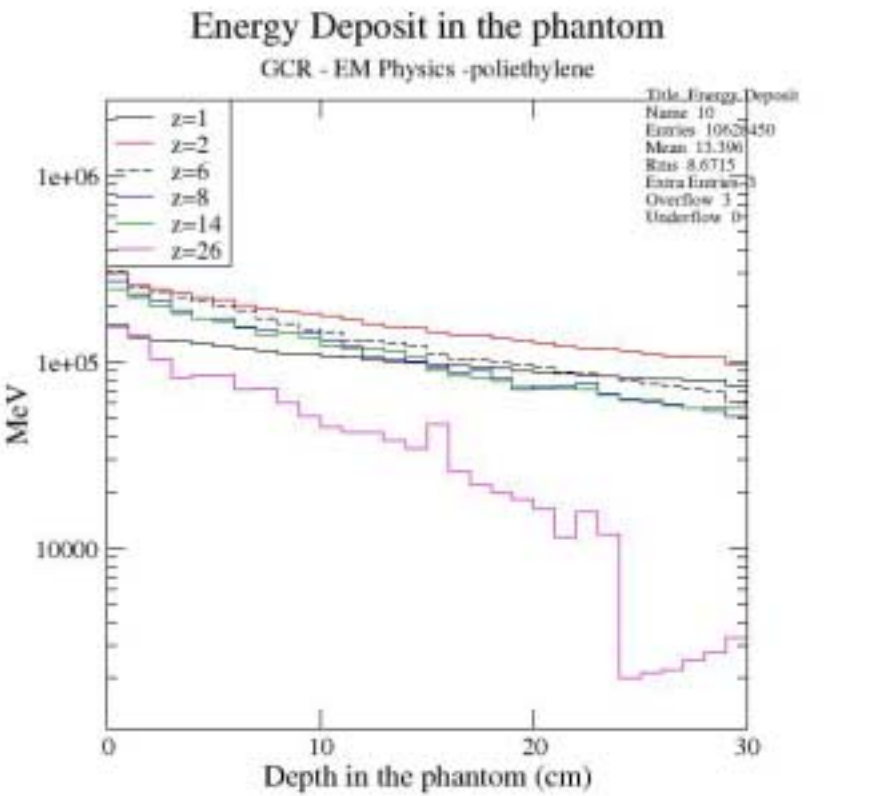


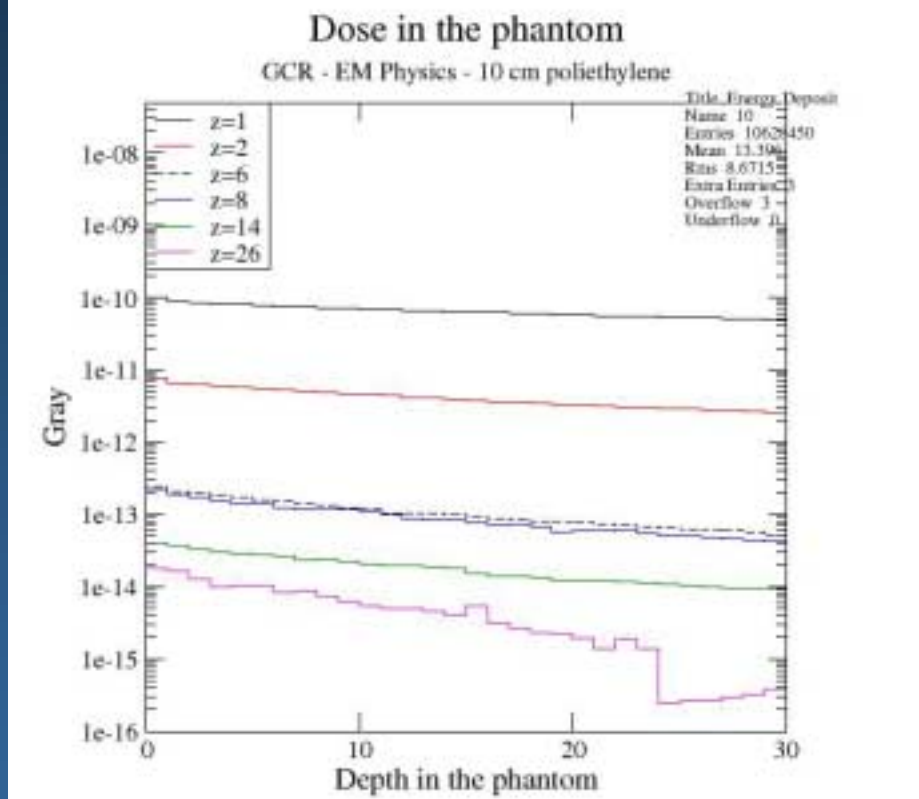
GCR, 10 cm water shielding





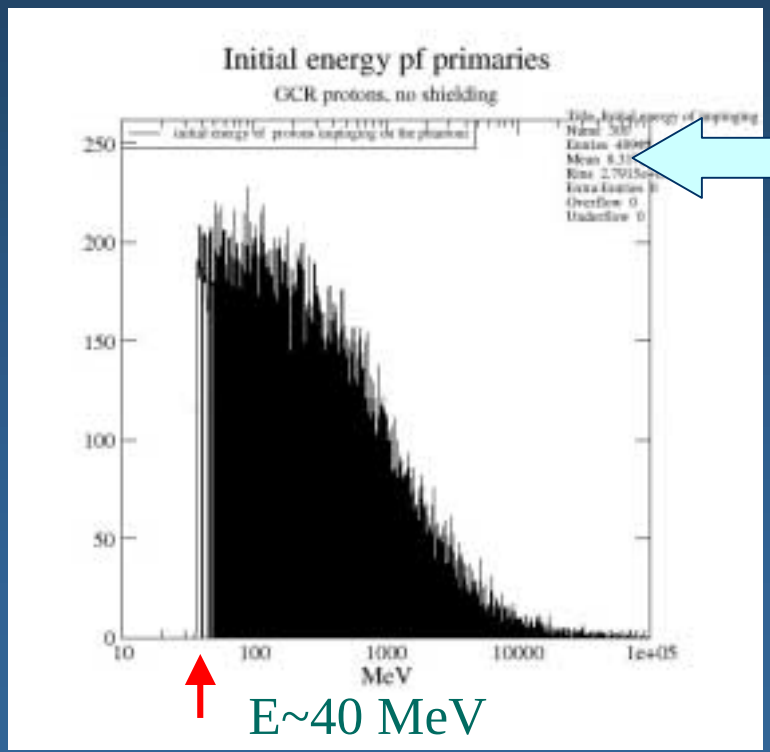
GCR, 10 cm polyethylene shielding





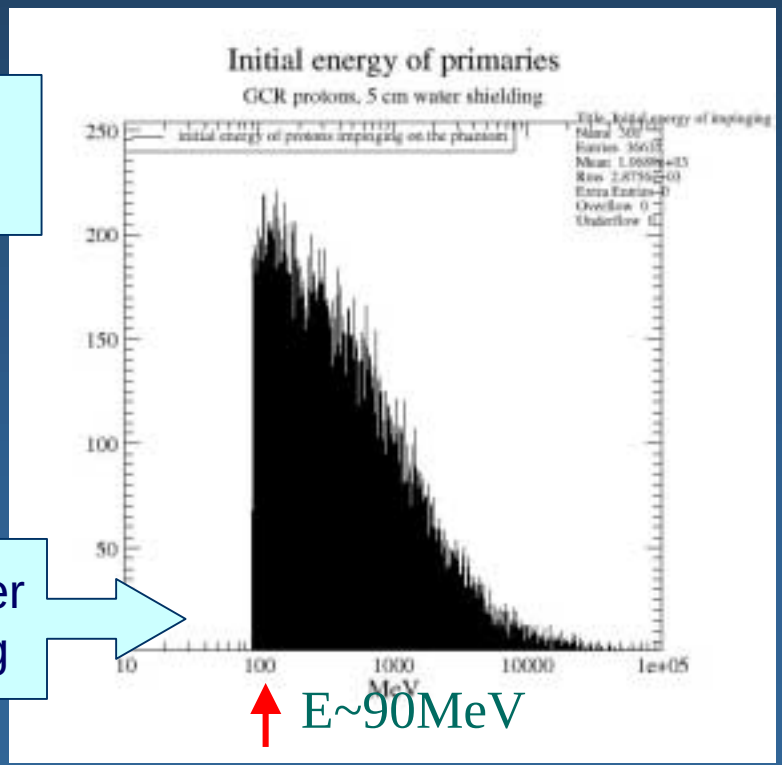
GCR proton analysis

Initial energy of primary p reaching the Astronaut



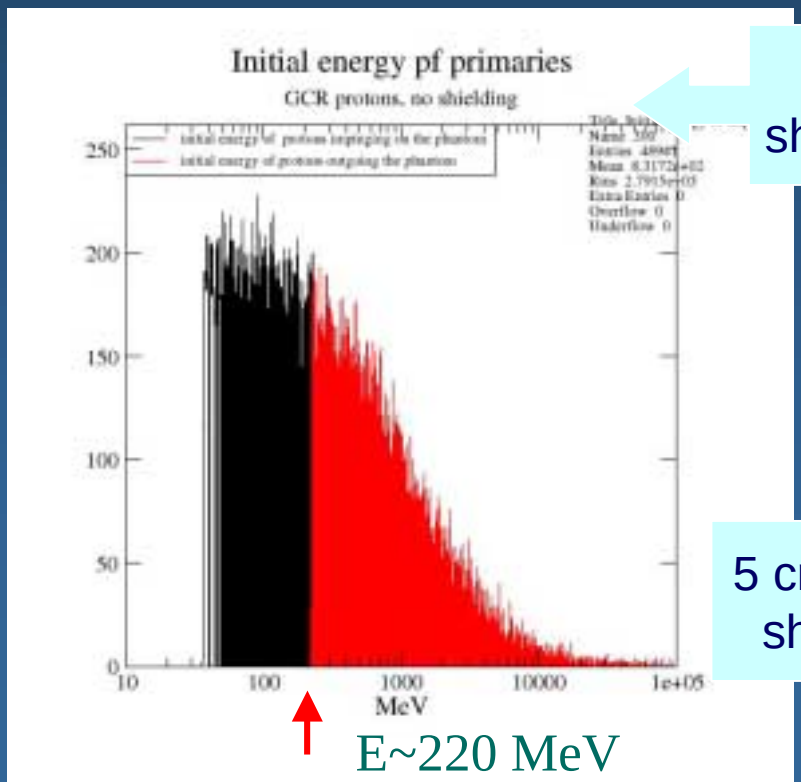
no shielding

5 cm water shielding



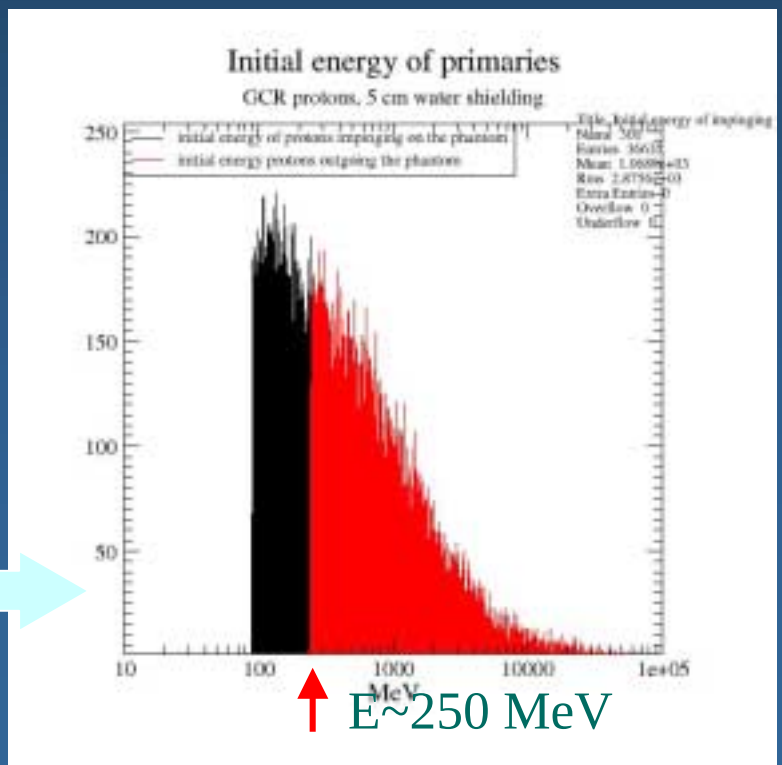
GCR p

- Initial energy of p reaching the Astronaut
- Initial energy of p traversing the Astronaut



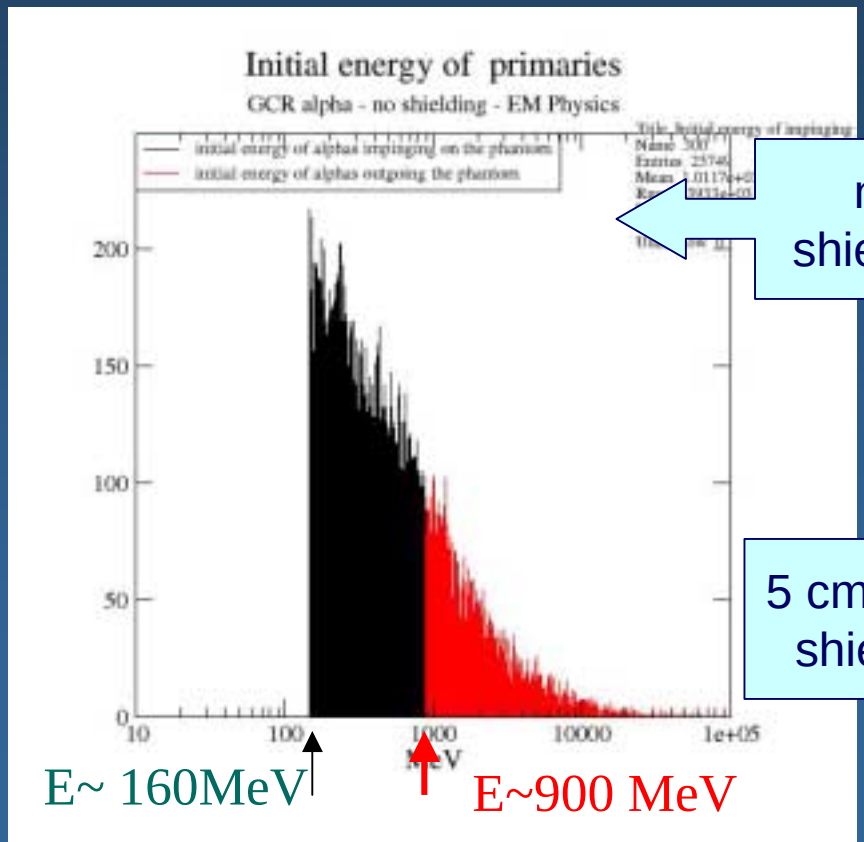
no shielding

5 cm water shielding



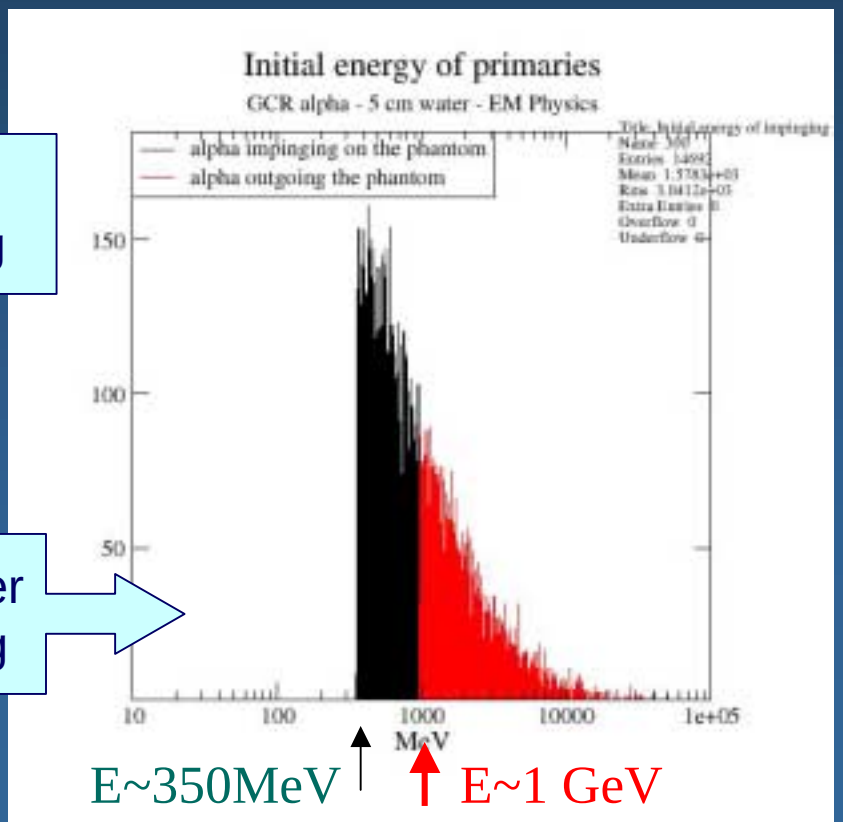
GCR alpha

- Initial energy of alpha particles reaching the Astronaut
- Initial energy of alpha particles traversing the Astronaut



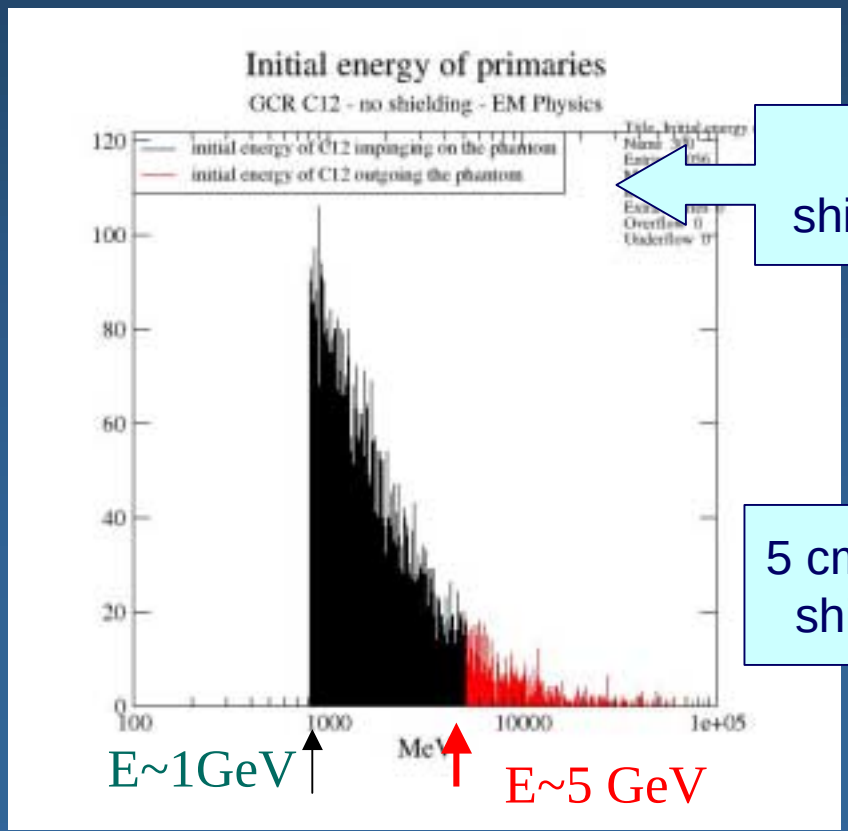
no shielding

5 cm water shielding



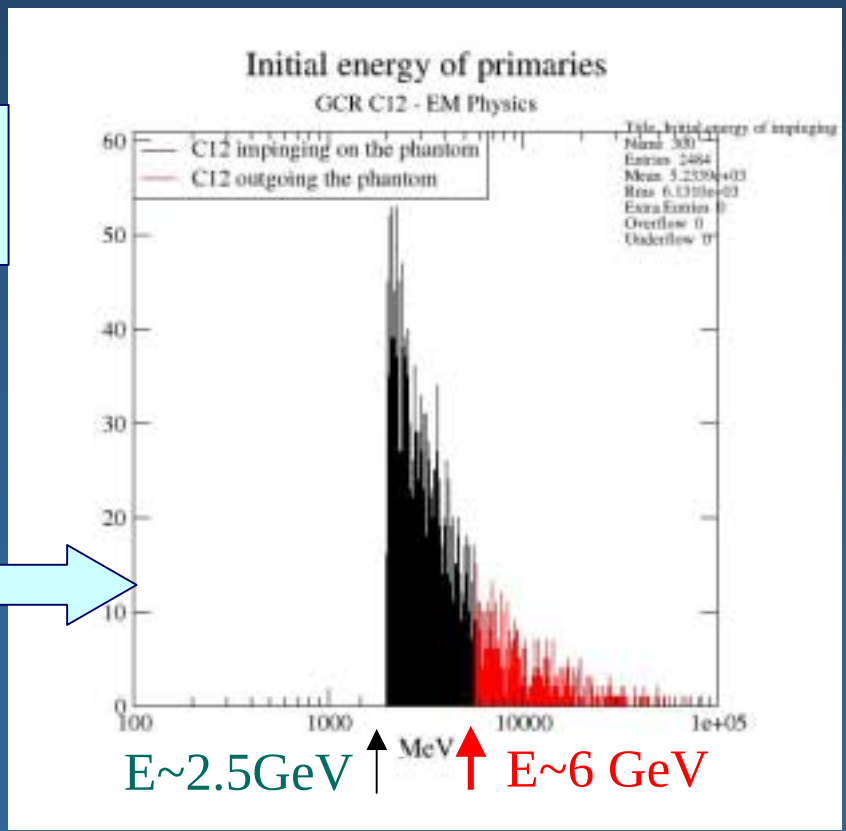
GCR C-12

- Initial energy of C-12 reaching the Astronaut
- Initial energy of C-12 traversing the Astronaut



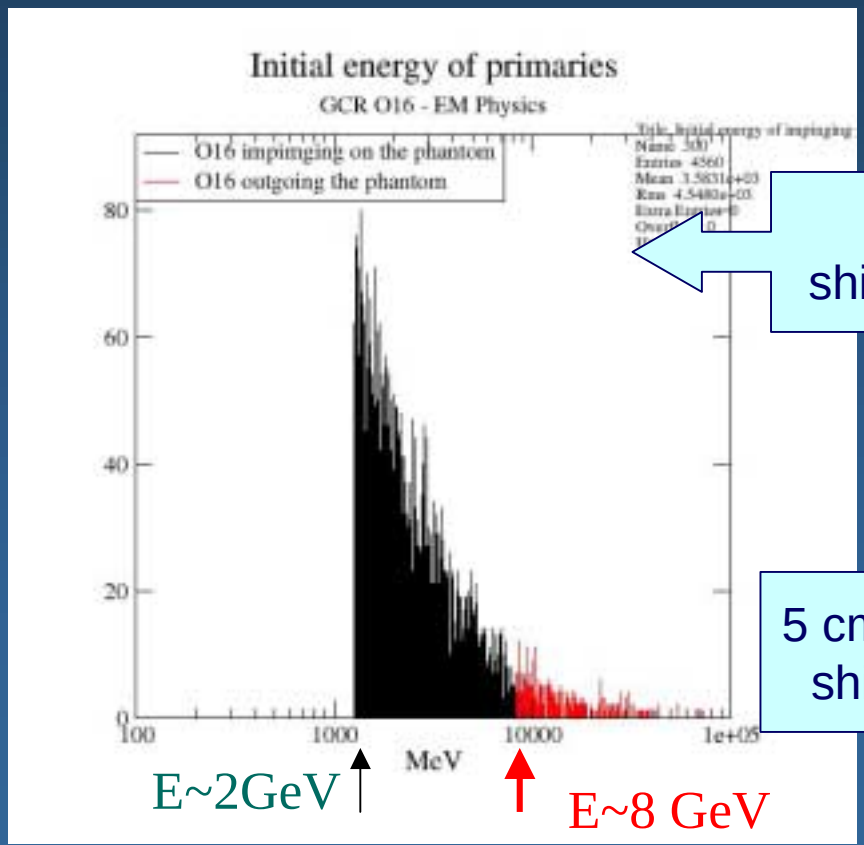
no shielding

5 cm water shielding



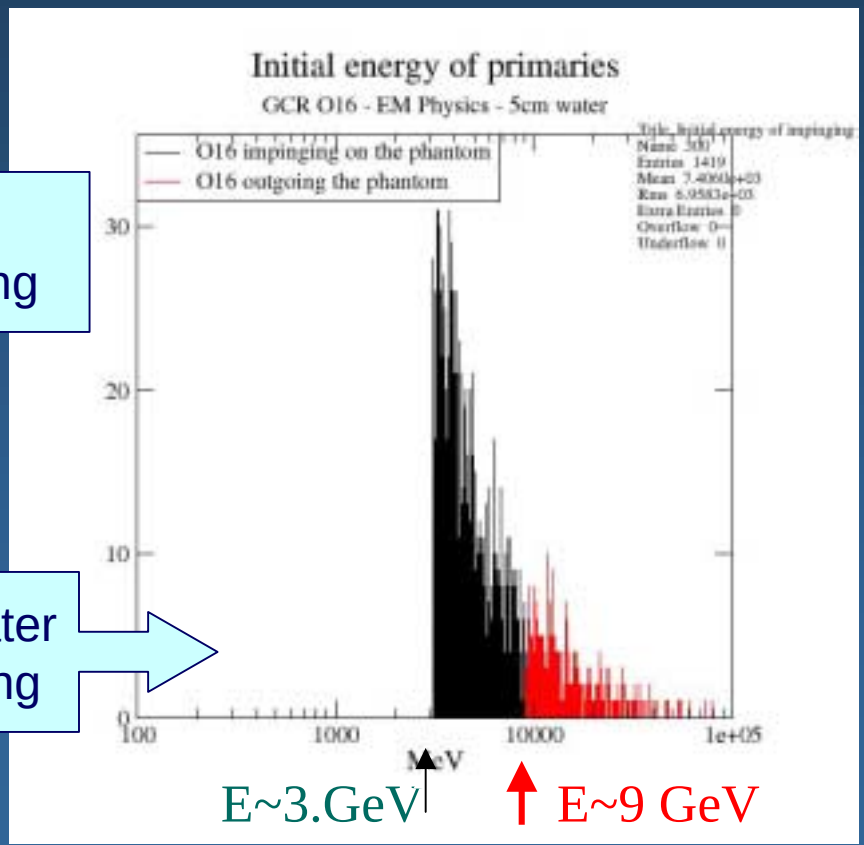
GCR O-16

- Initial energy of O-16 reaching the Astronaut
- Initial energy of O-16 traversing the Astronaut



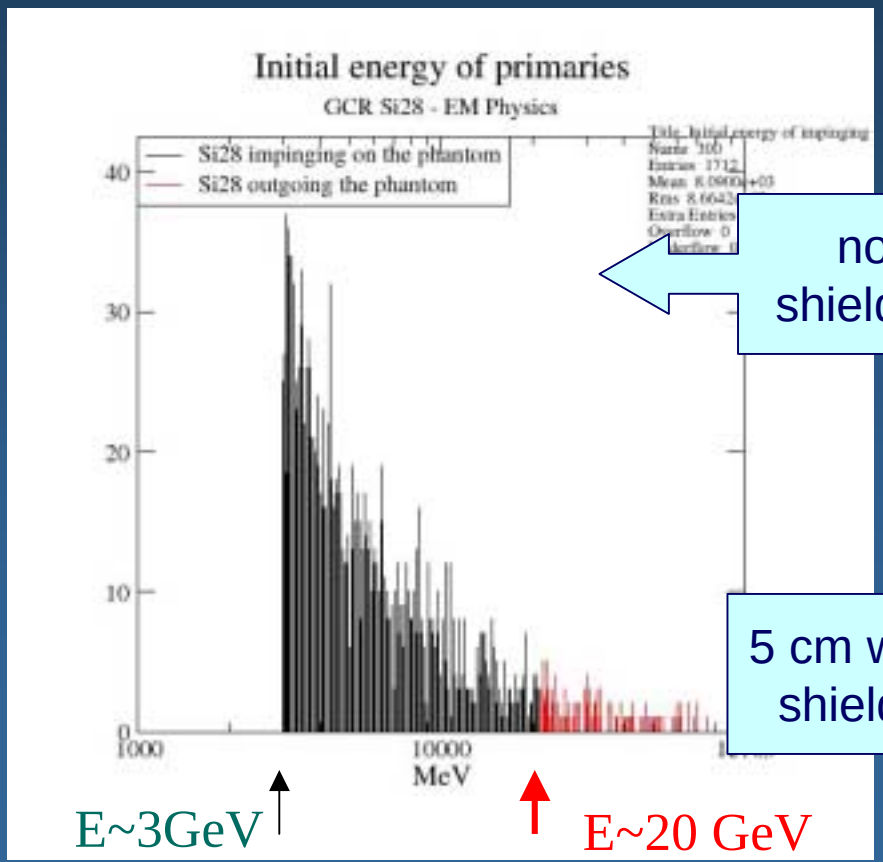
no shielding

5 cm water shielding



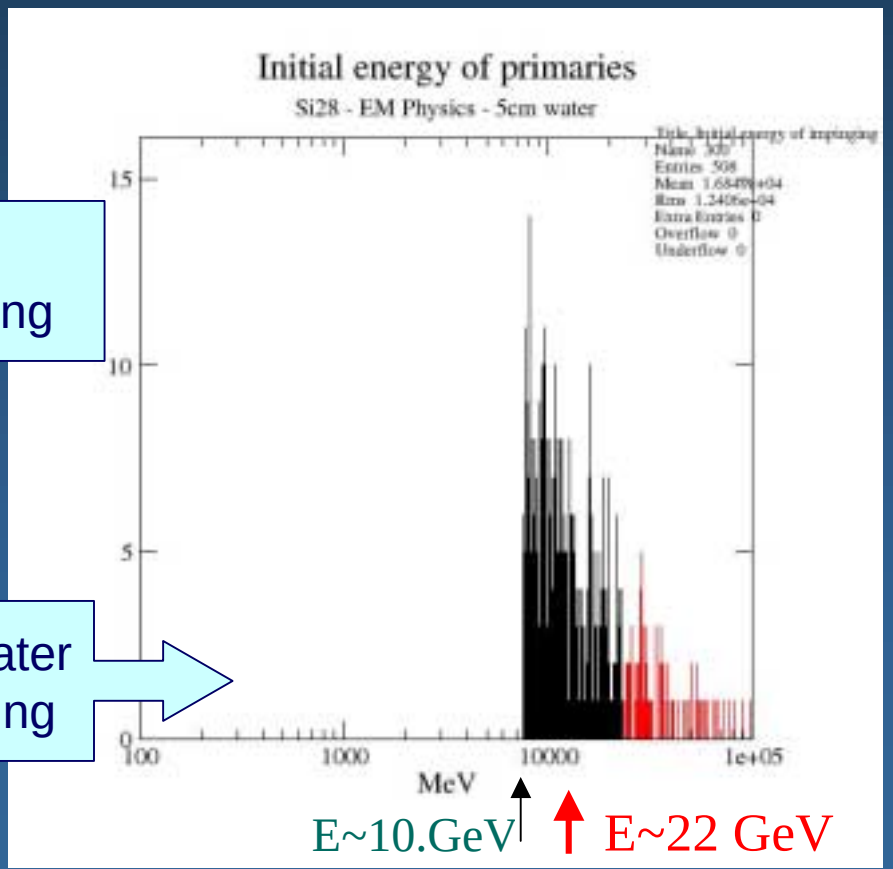
GCR Si-28

- Initial energy of Si-28 reaching the Astronaut
- Initial energy of Si-28 traversing the Astronaut



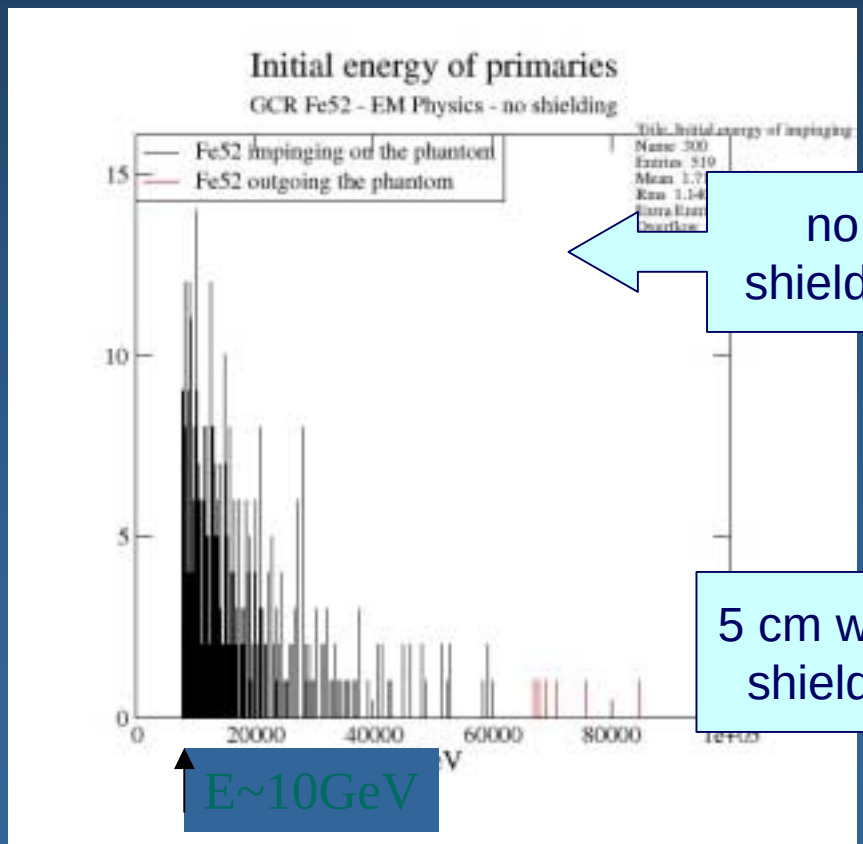
no shielding

5 cm water shielding



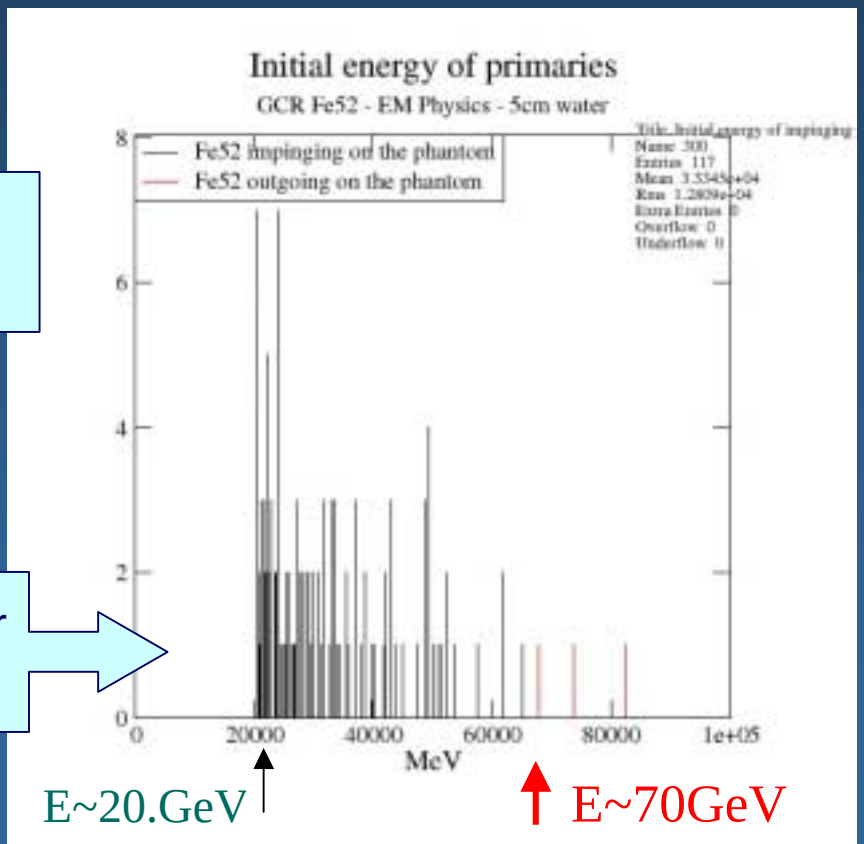
GCR Fe-52

- Initial energy of Fe-52 reaching the Astronaut
- Initial energy of Fe-52 traversing the Astronaut



no shielding

5 cm water shielding



Selection of hadronic models

For p, n, π:

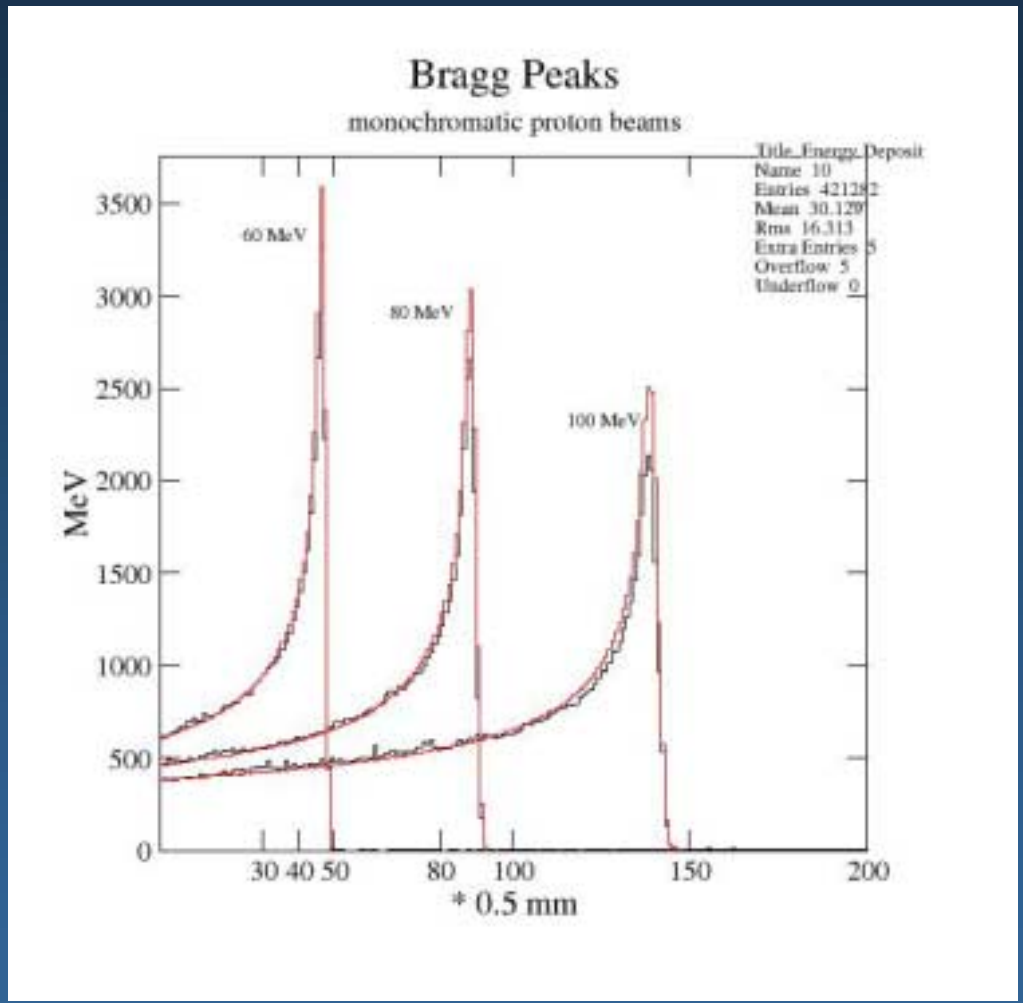
- Inelastic scattering
  - 0 - 3.2 GeV: Bertini Cascade
  - 2.8 - 25 GeV: Low Energy Parameterised (LEP) model
  - 15 GeV –100 TeV: Quark Gluon String (QGS) model
- Elastic scattering

For α:

- Inelastic scattering
  - 0 – 100 MeV: LowEnergy Parameterised (LEP)
  - 80 MeV – 100 GeV: Binary Ion Model
  - Alpha-nuclear cross sections: Tripathi, Shen
- Elastic scattering

Educated guess, no systematic validation yet:
results are to be considered as preliminary indications, rather than quantitative estimates

Results

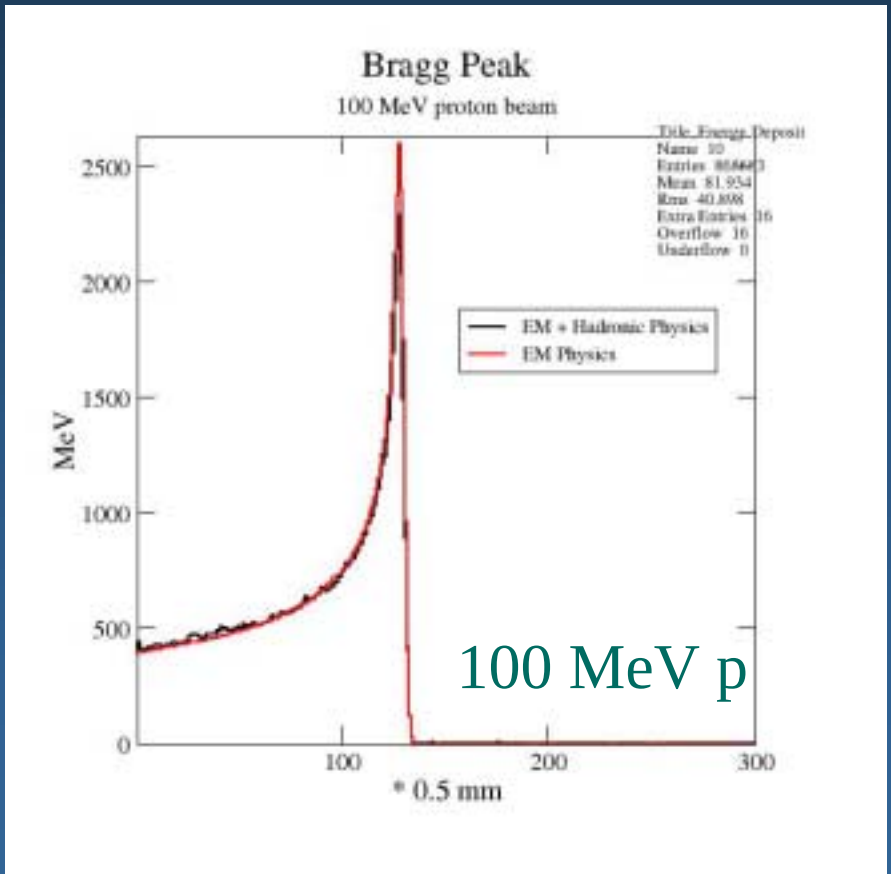


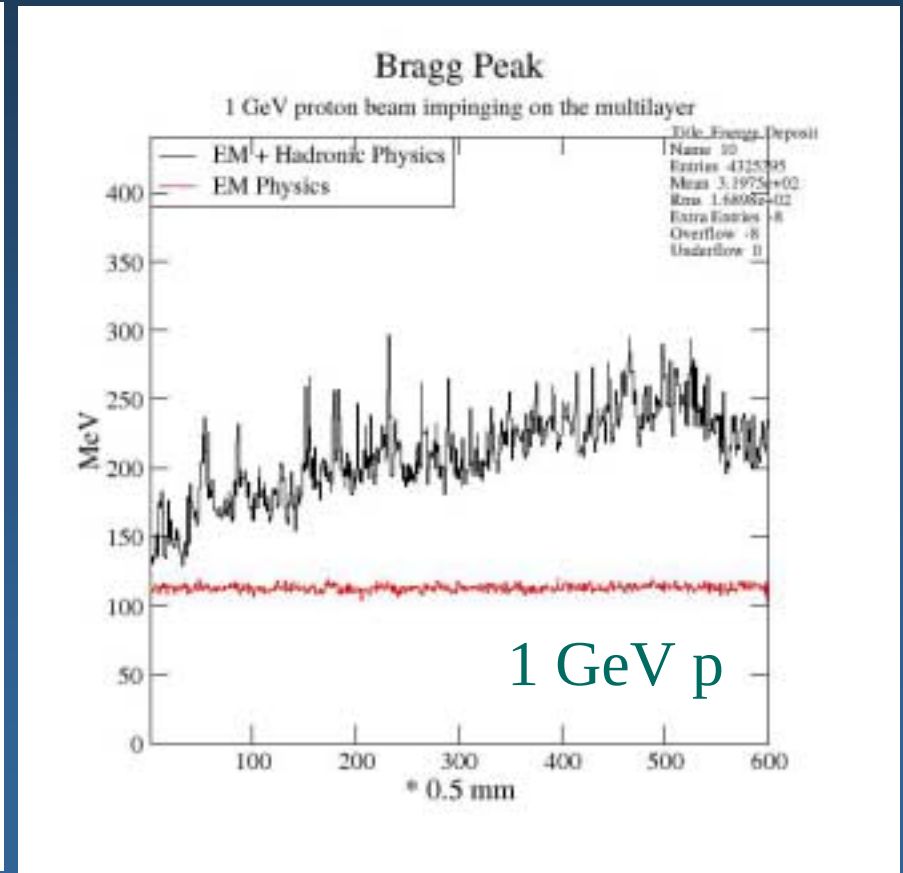
60 MeV proton beam Bragg peak:

- depth ~ 25. mm
- FWHM ~ 2.8 mm

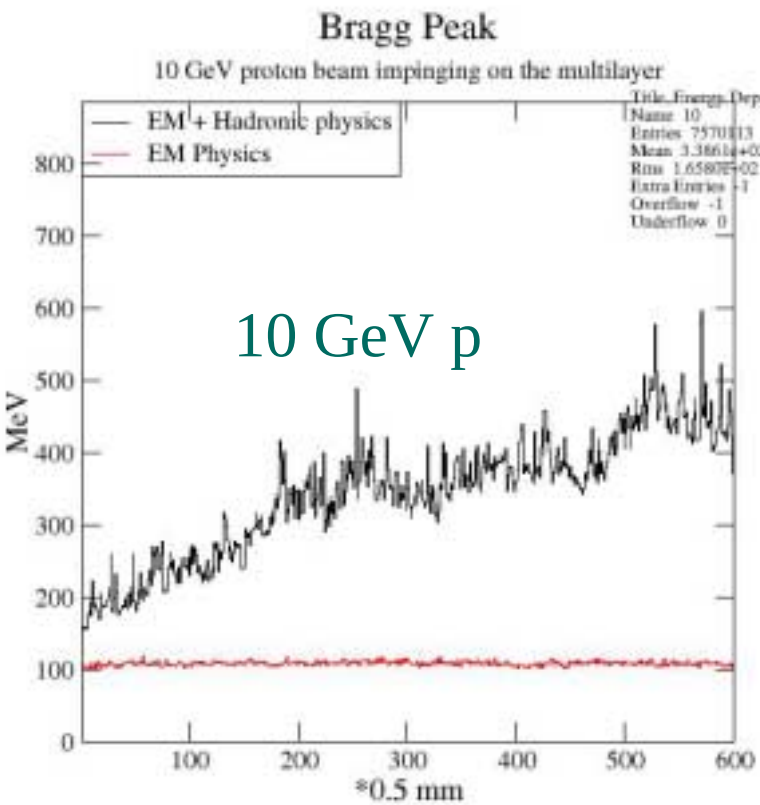
Results compatible with CATANA experimental data

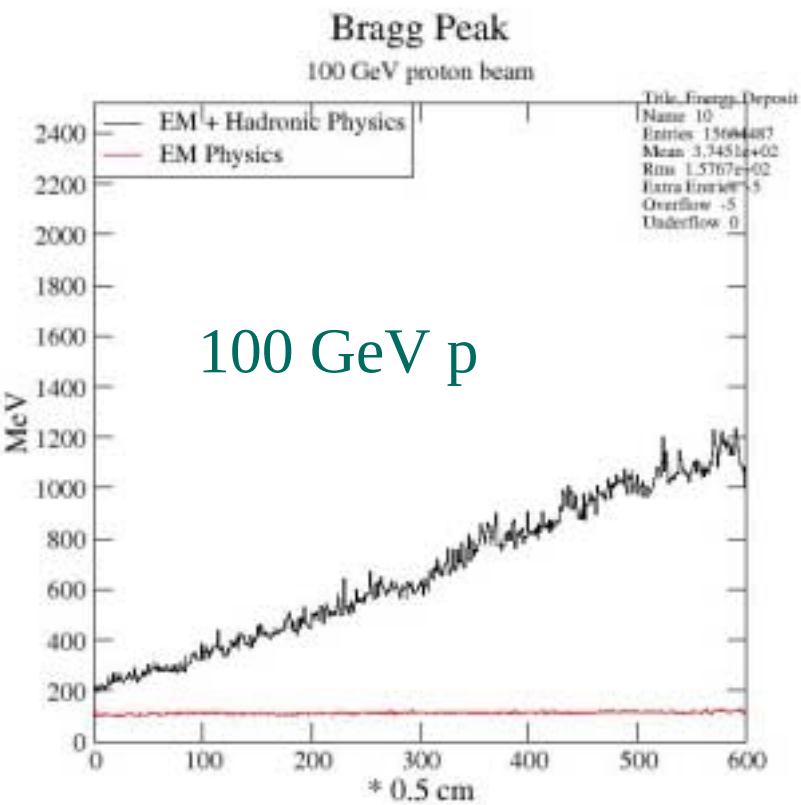
Results: no shielding





Protons: no shielding



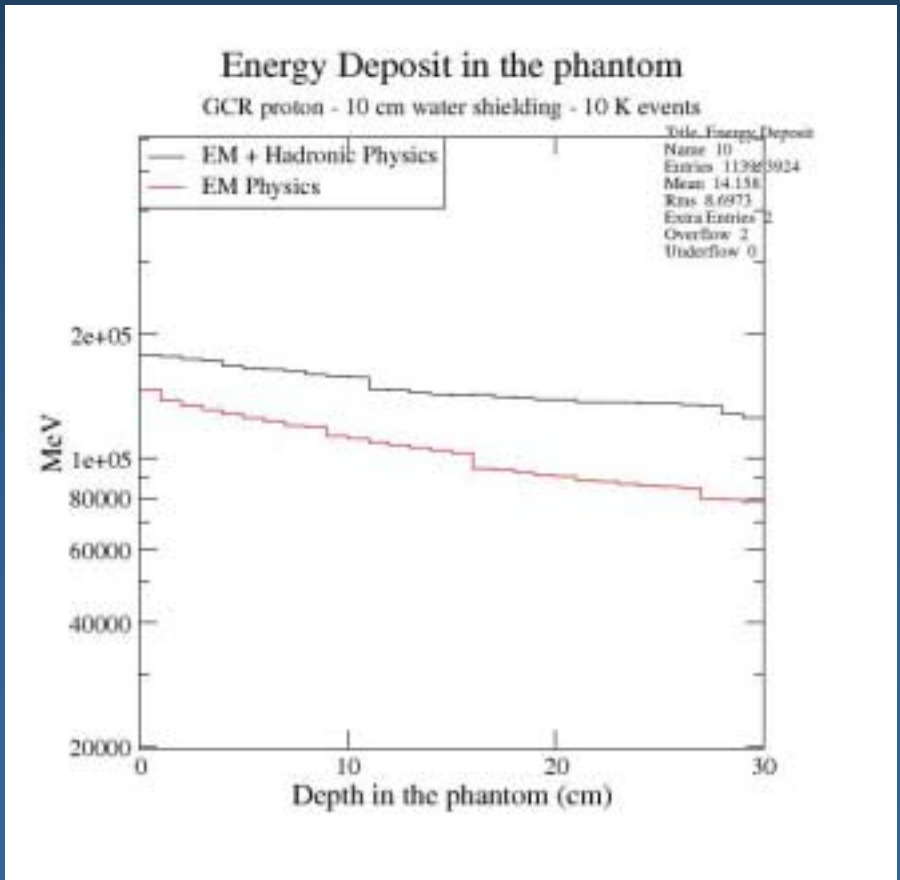


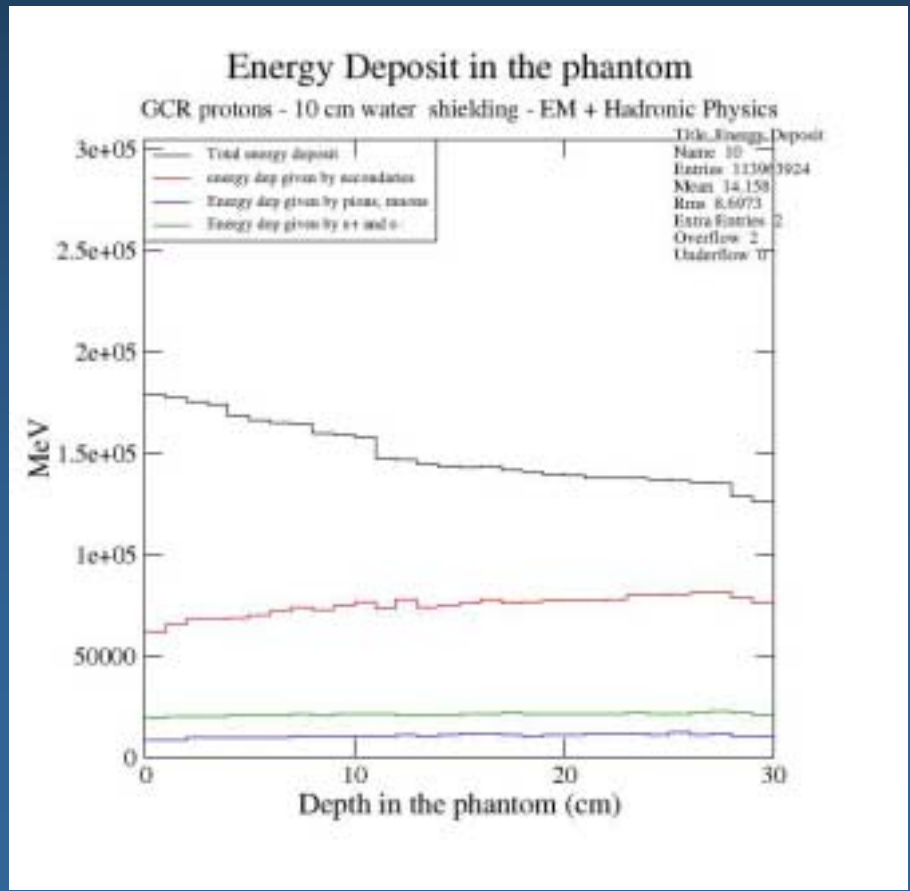
Multilayer + 10 cm water shielding

Comparison
EM physics
EM + hadronic physics

GCR protons

Contribution to energy deposit from secondary particles



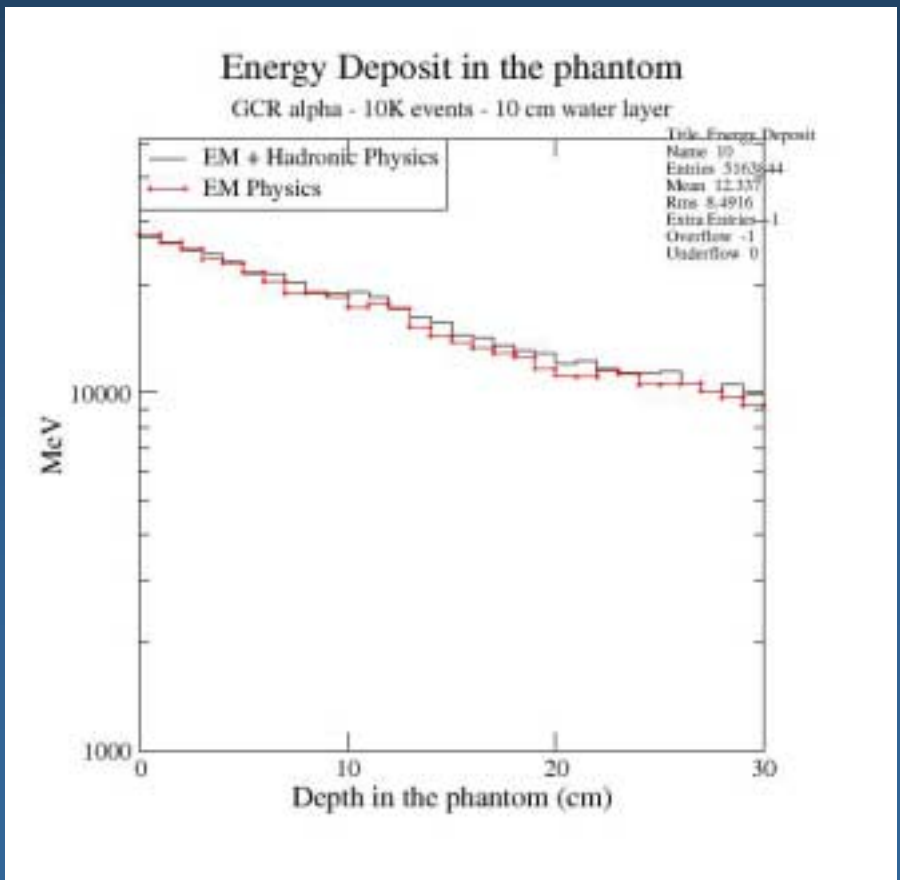


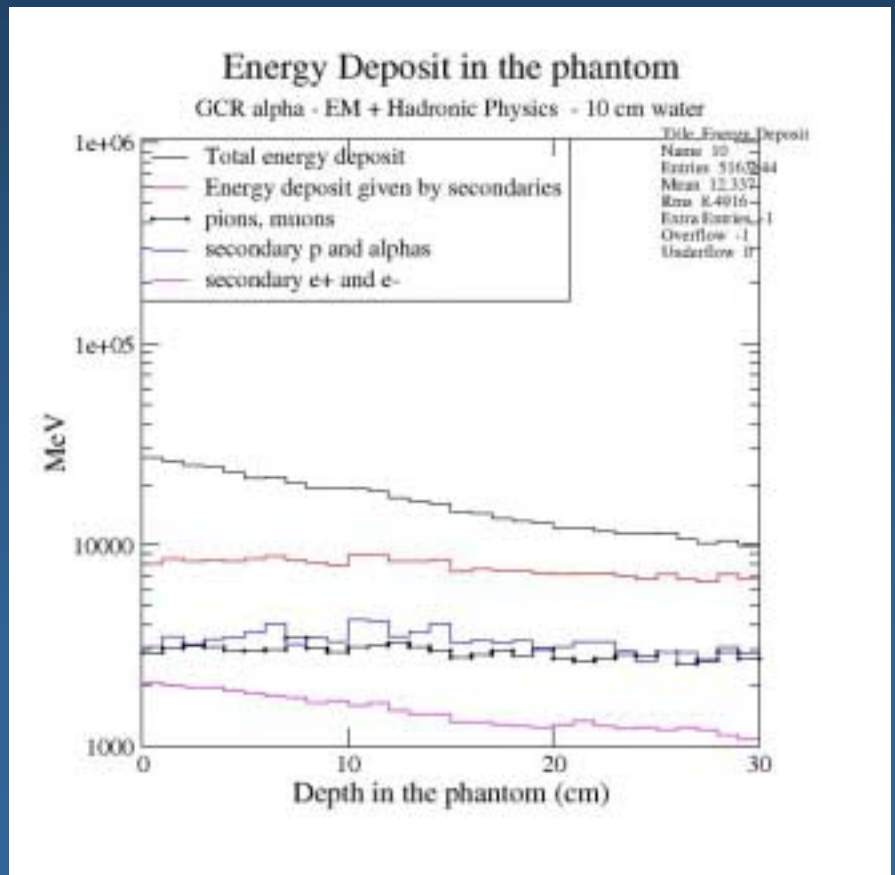
Multilayer + 10 cm water shielding

Comparison
EM physics
EM + hadronic physics

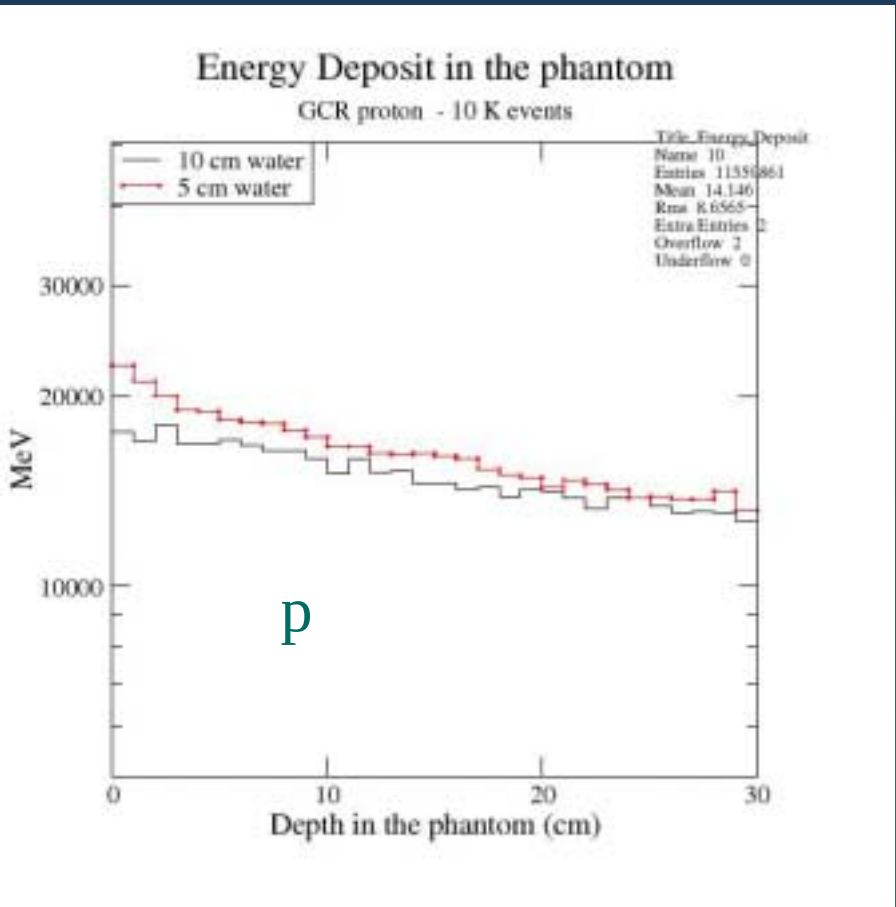
GCR alpha

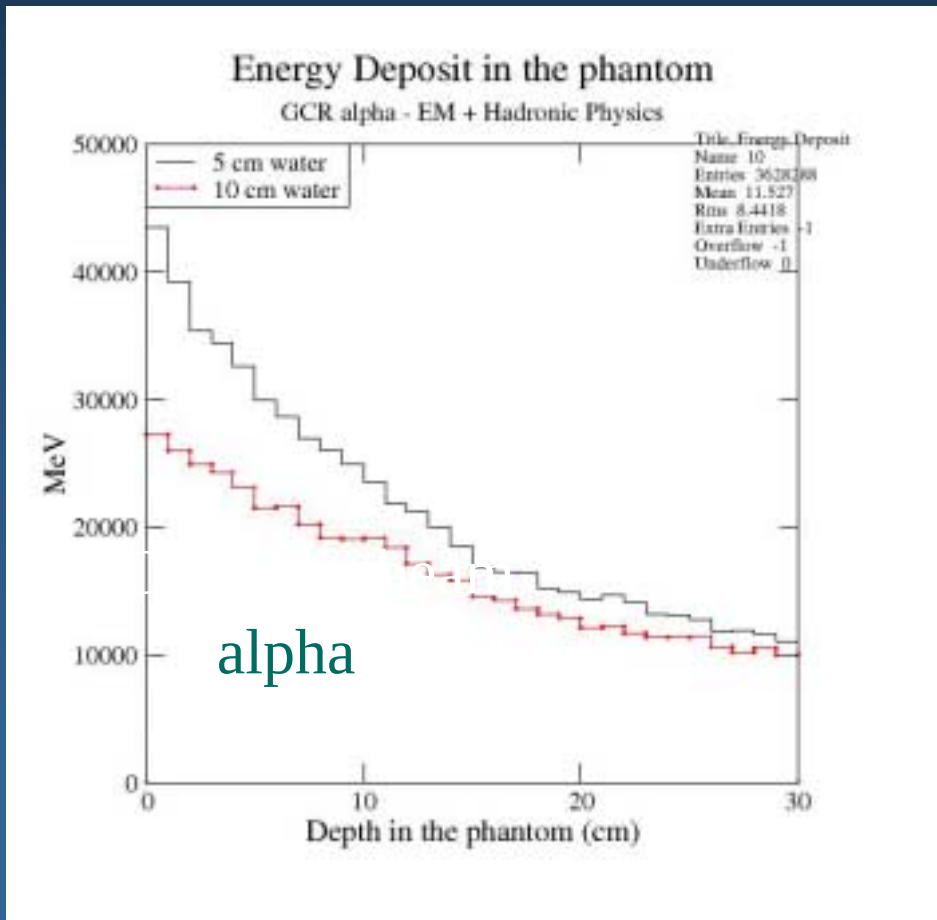
Contribution to energy deposit from secondary particles



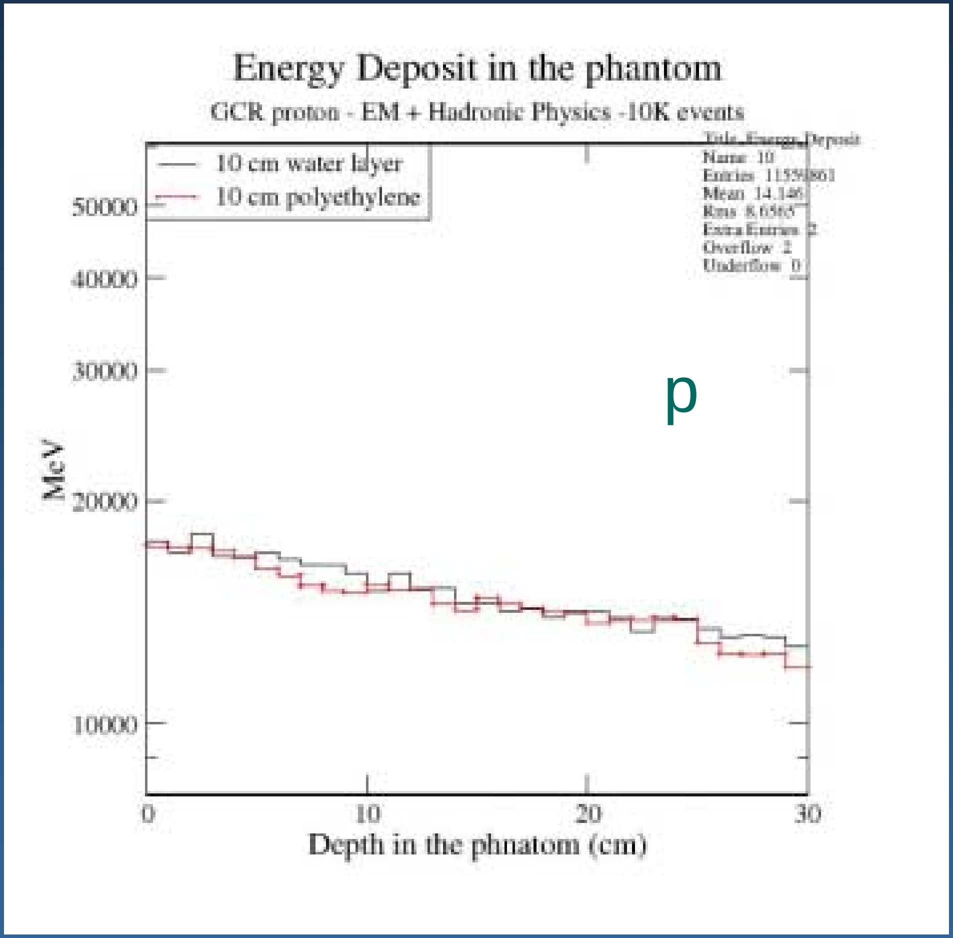


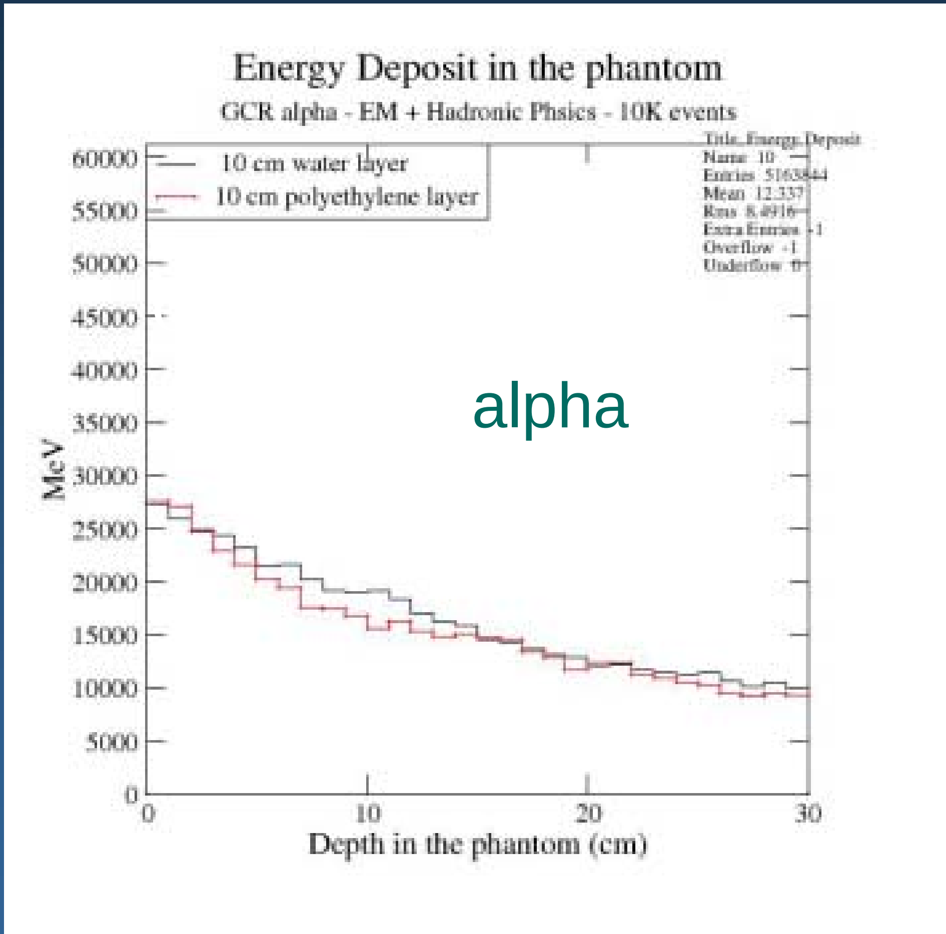
Comparison: 5-10 cm water shielding





Water/polyethylene shielding

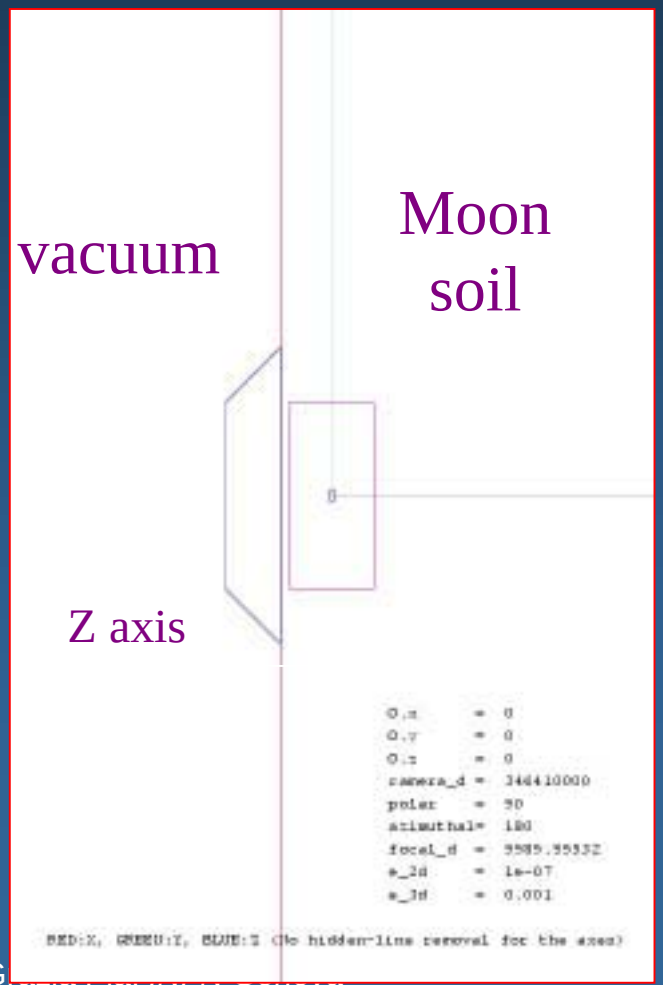


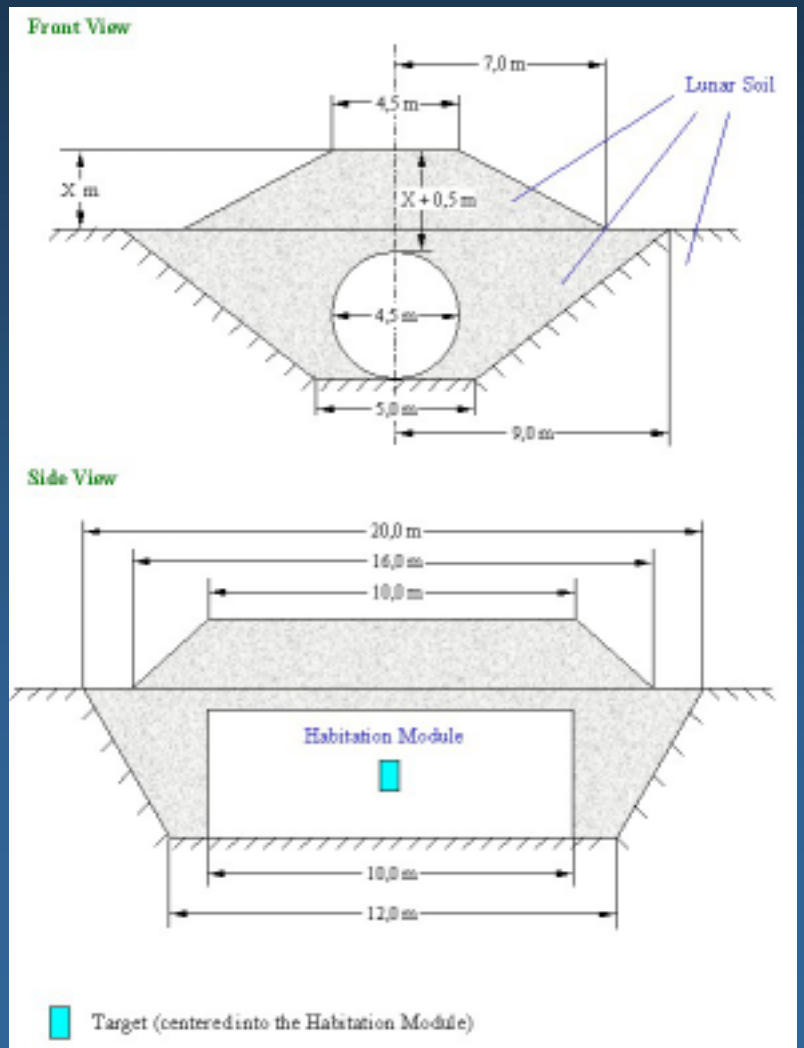


- There are no significant differences in the energy deposit in the Astronaut
- Water and polyethylene have the same radioprotective impact

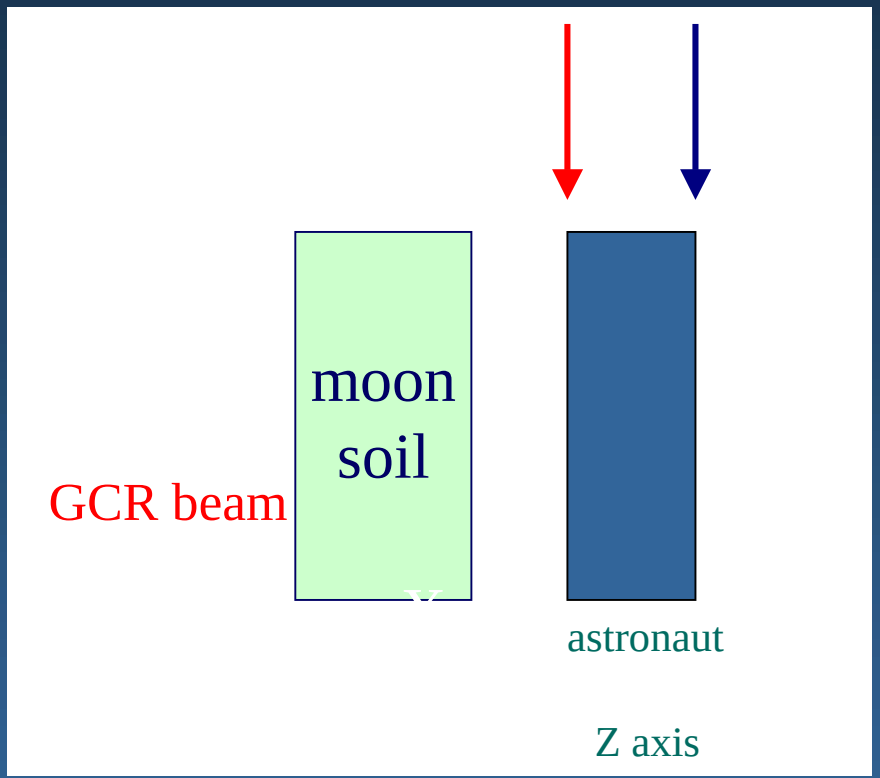
Moon habitats

X = 0, 3 m
Material of the shelter = moon soil





Experimental set-up of preliminary study

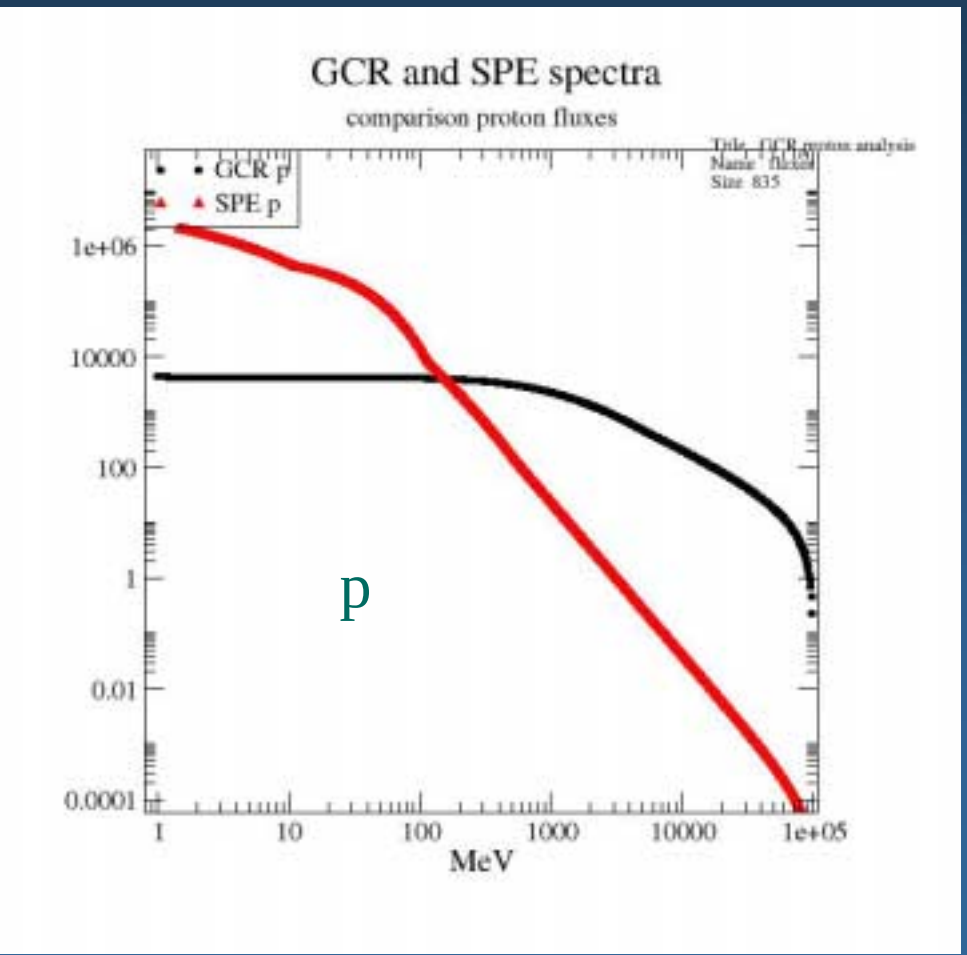


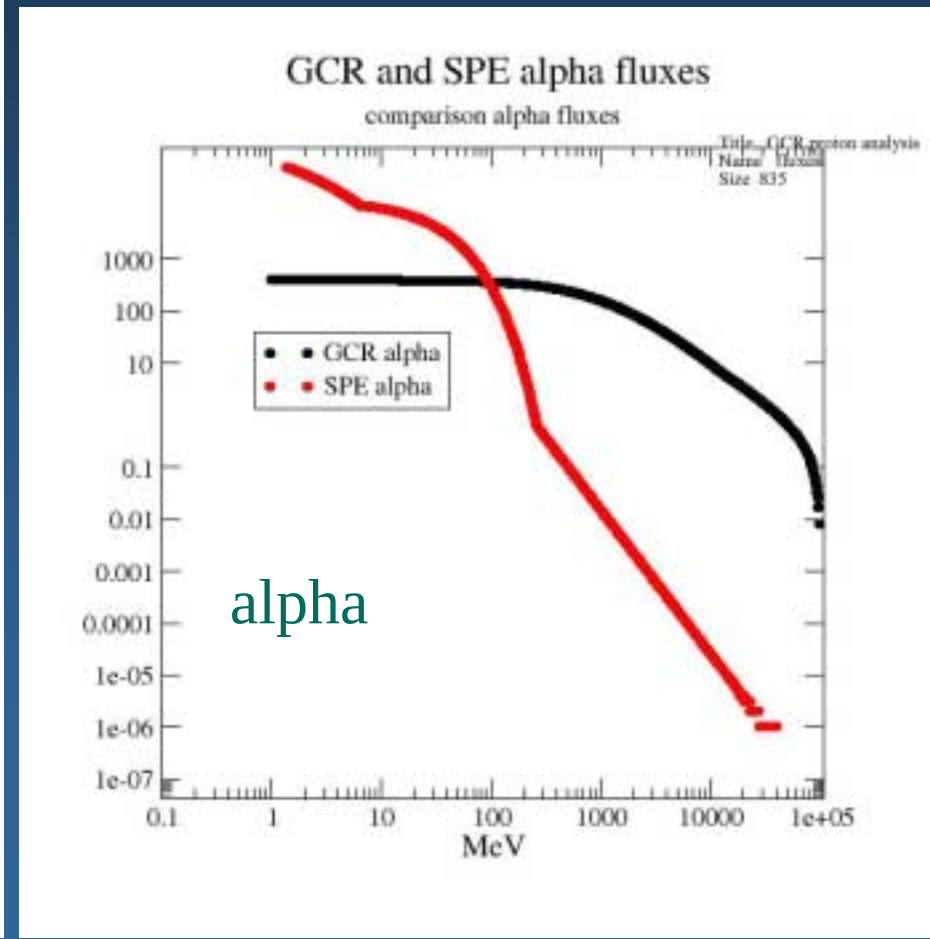
- GCR as primary particles
- EM Physics active
- Thickness X of moon soil:
  - 0.5 m
  - 3.5 m

Analysis of GCR primary particles reaching the Astronaut

Analysis of GCR primary particles traversing the Astronaut

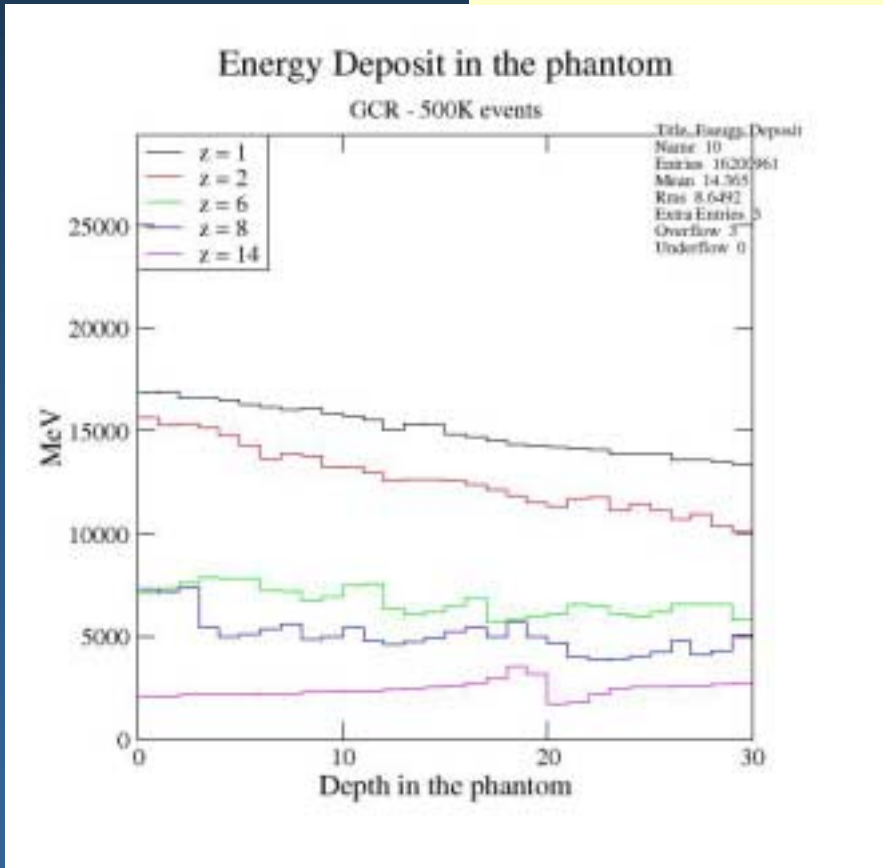
GCR-SPE spectra

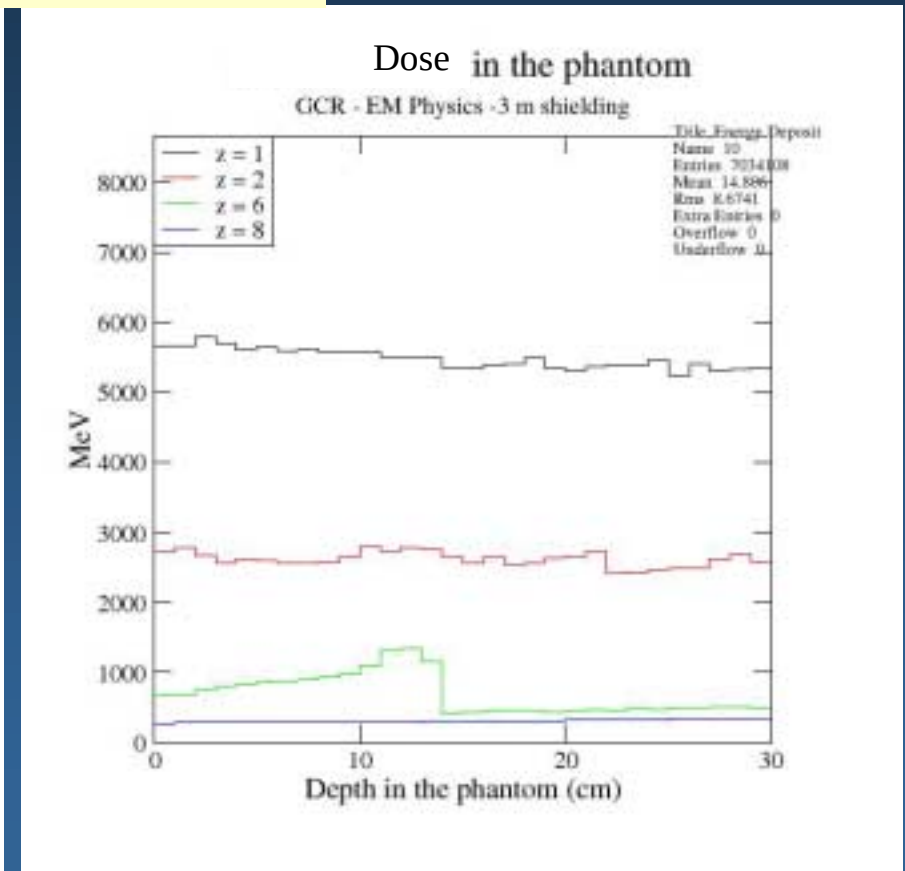




Galactic Cosmic Rays, moon habitat

EM Physics



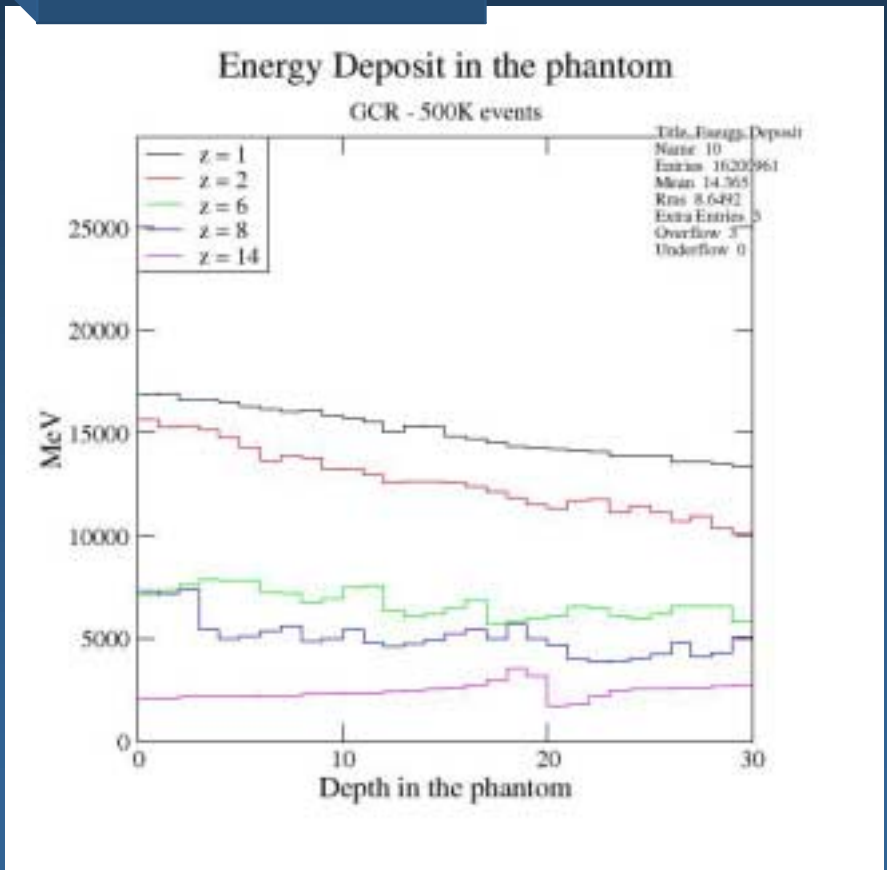


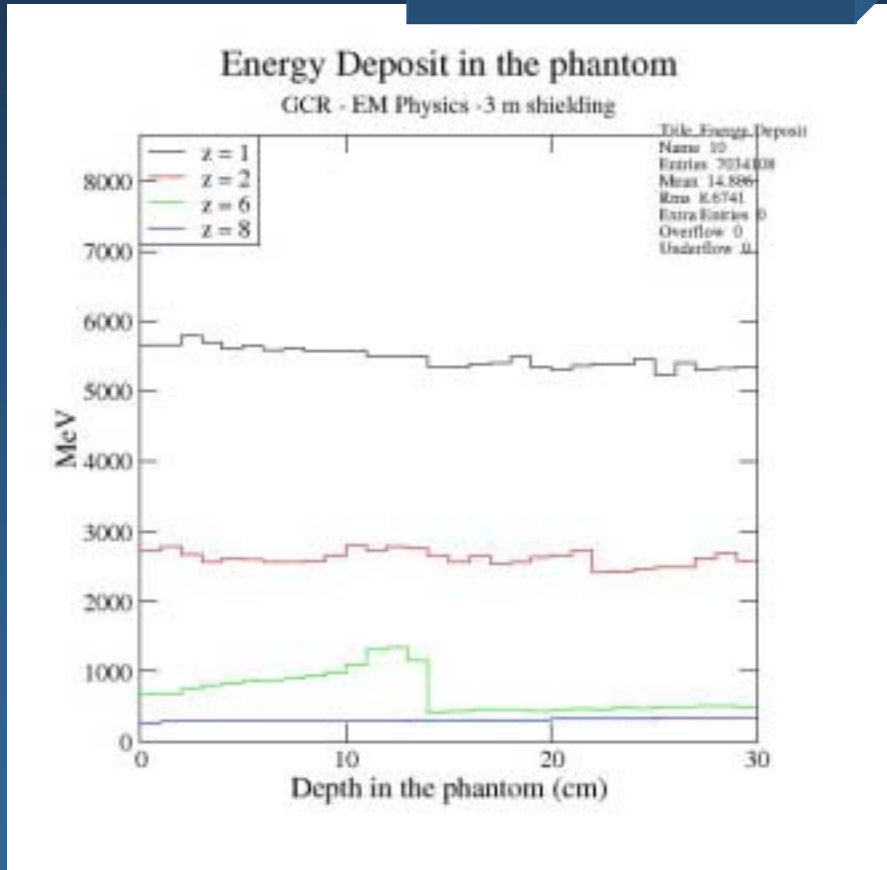
Galactic Cosmic Rays, moon habitat

X = 0. m

EM Physics

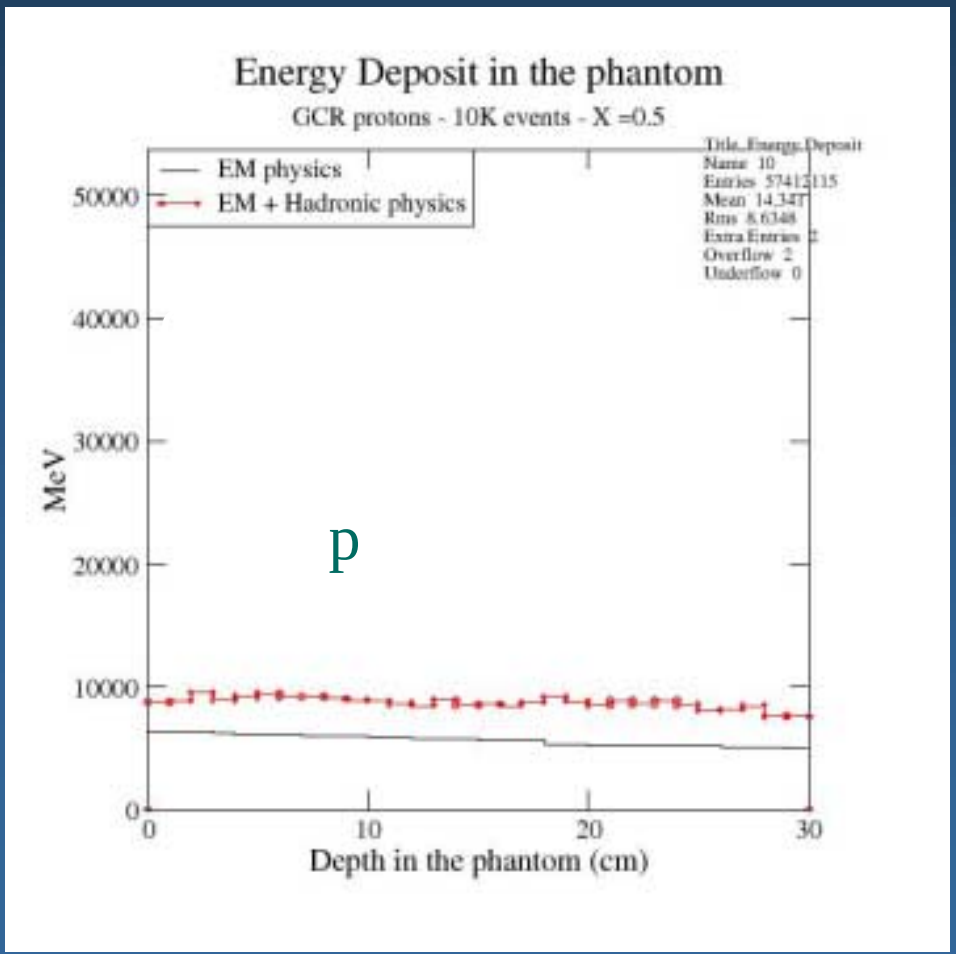
X = 3. m

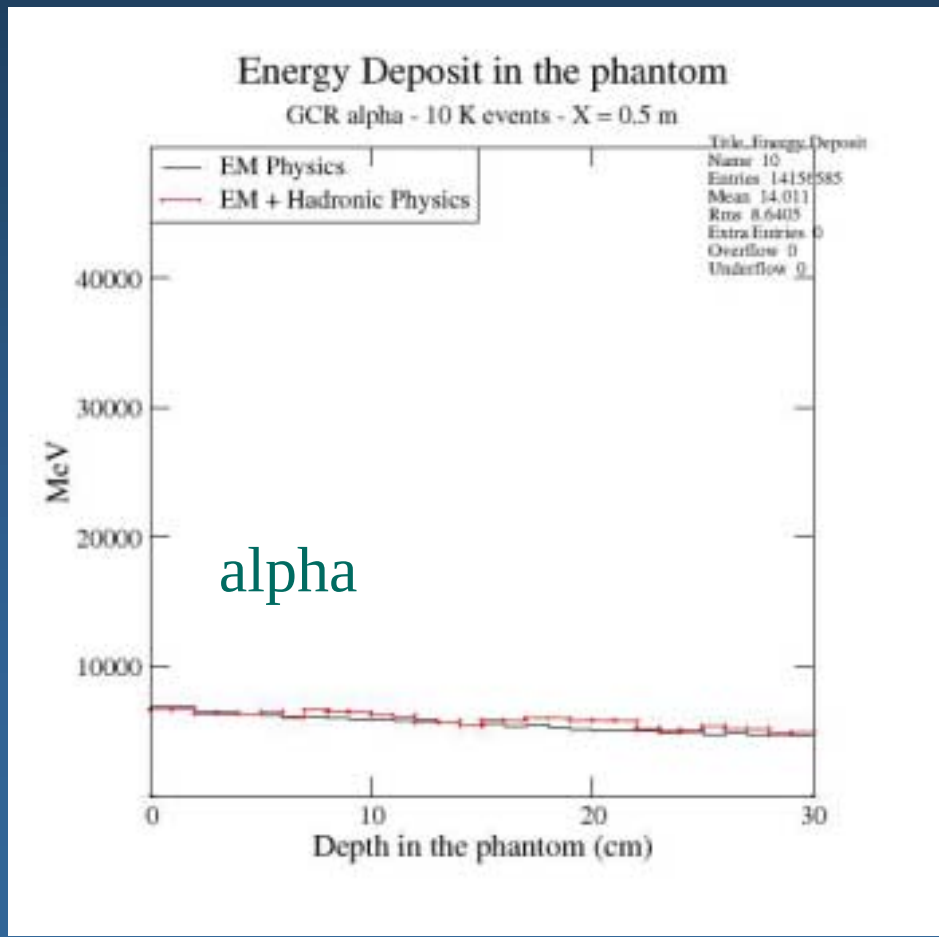




Hadronic physics effect

EM Physics
EM + H physics

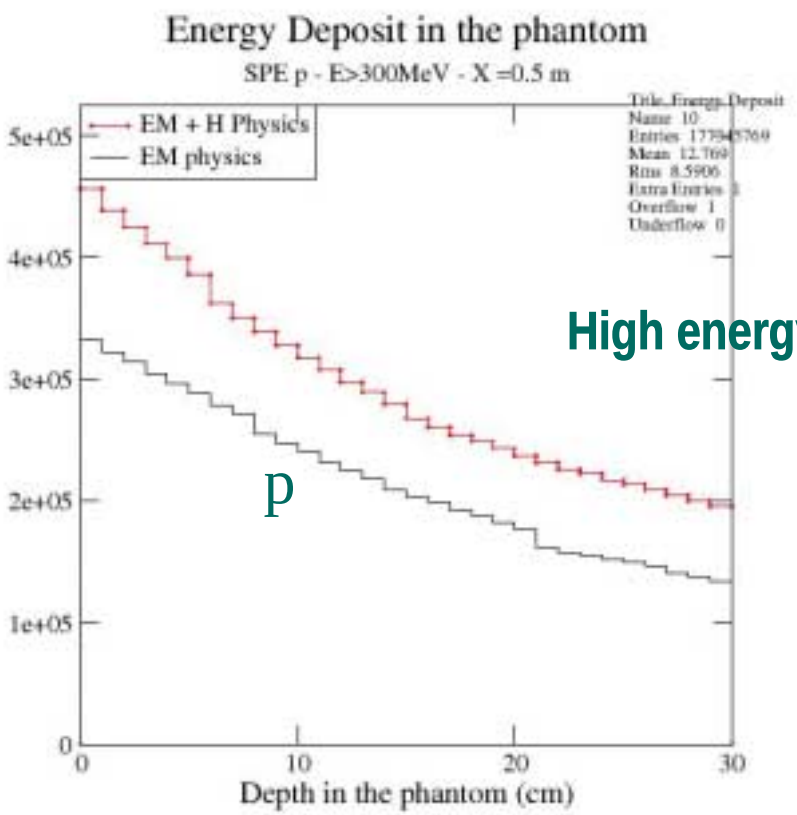




Hadronic physics effect, X=0

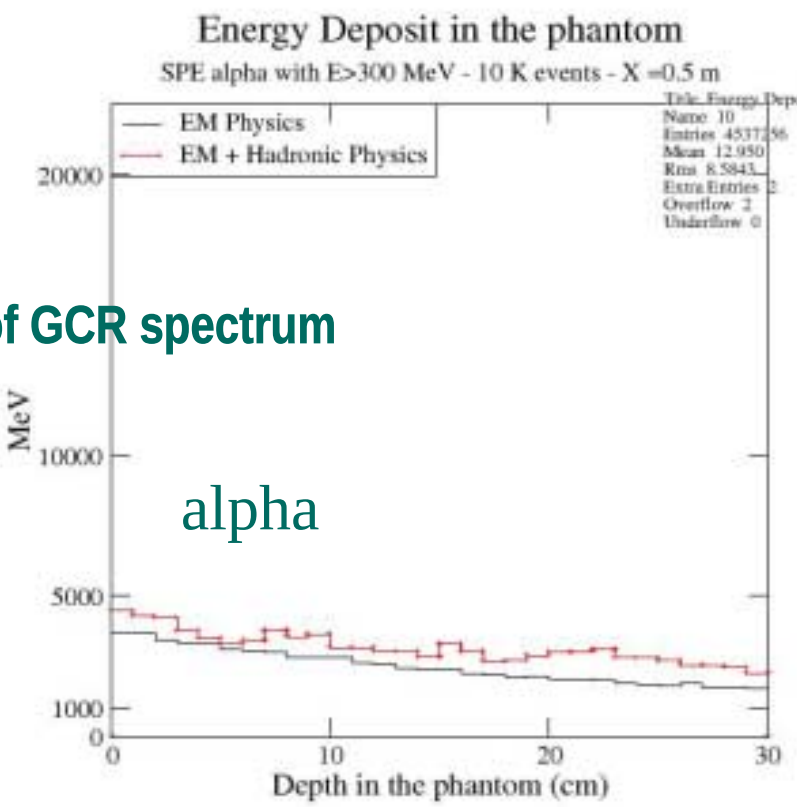
EM Physics

EM + H physics



p

High energy tail of GCR spectrum

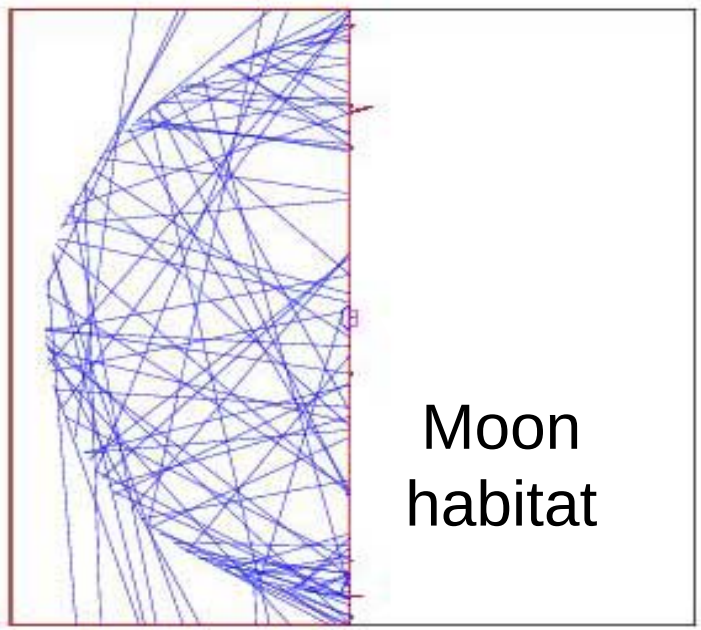


alpha

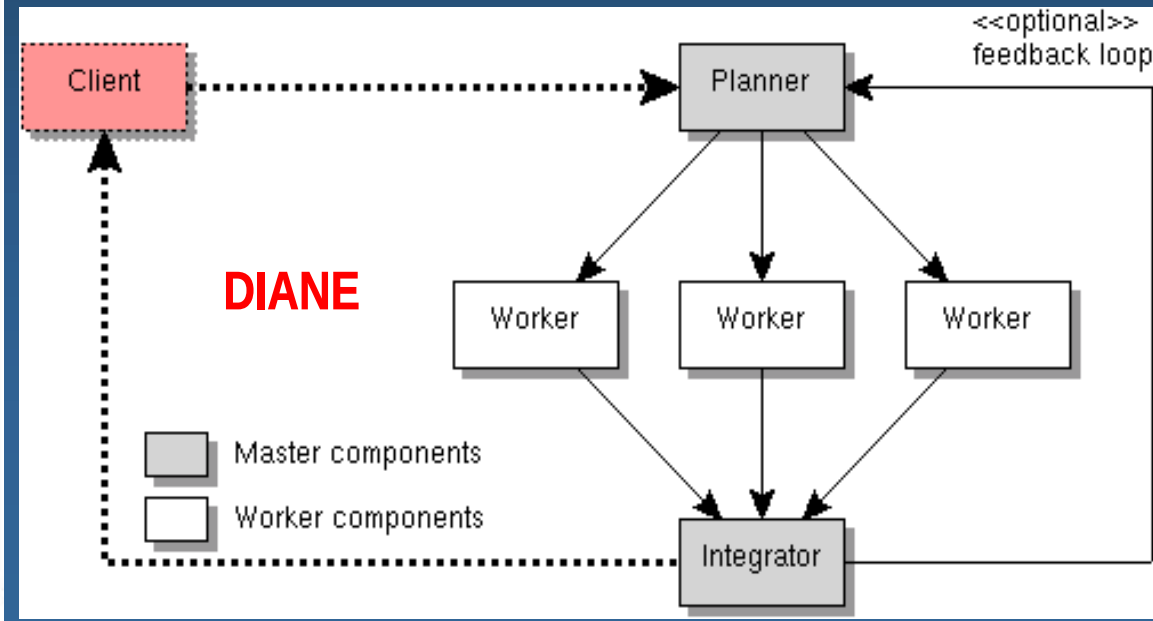
CPU resources

Estimate:

- ~100 K events
- Total CPU (runs for GCR and SPE) ~ 24 days on a PIII
- Solution: parallelisation of the application



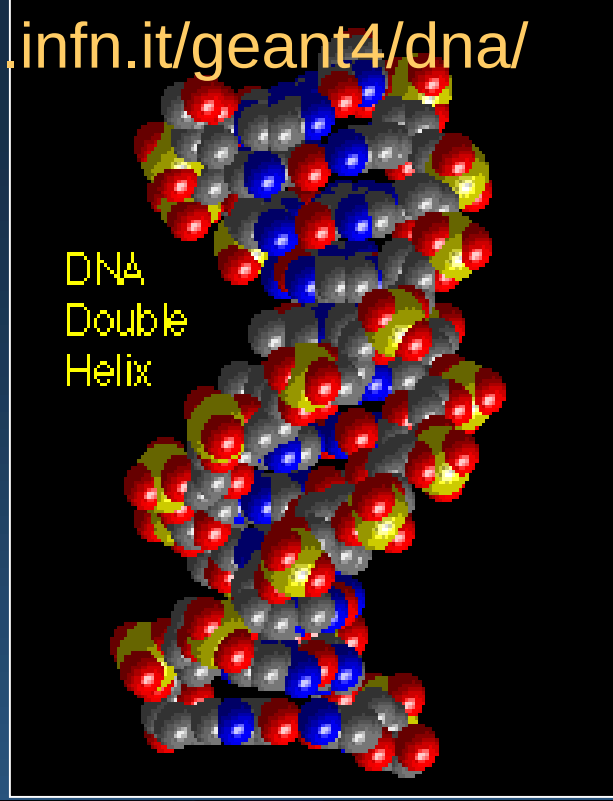
Moon habitat



Geant 4 DNA

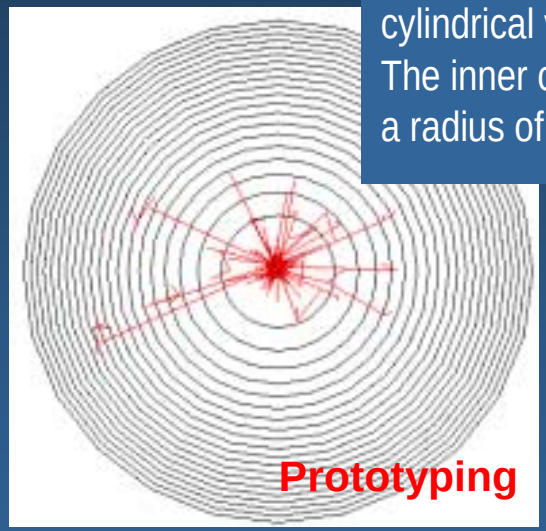
http://www.ge.infn.it/geant4/dna/

Study of radiation damage at the cellular and DNA level in the space radiation environment *(and other applications…)*



Multi-disciplinary Collaboration of

- astrophysicists/space scientists
- particle physicists
- medical physicists
- computer scientists
- biologists
- physicians



5.3 MeV α particle in a cylindrical volume
The inner cylinder has a radius of 50 nm

- Relevance for space: astronaut and airline pilot radiation hazards, biological experiments
- Also in radiotherapy, radiobiology...

Maria Grazia Pia, *INFN Genova*

Conclusions

- Geant4 LowE electromagnetic physics provides accurate models for dosimetry (hadrons, ions) in interplanetary environment
  - precision of the physics compatible with protocols used in oncological radiotherapy
  - quantitative results for shielding studies
- Geant4 offers a rich set of hadronic physics models for protons
  - systematic validation in progress
  - preliminary results are indicative, not quantitative estimates yet
- Geant4 coverage of hadronic interactions of ions should be improved
- Synergy with the medical physics community is productive
- New approaches to study radiation damage to biological structures are in progress