# Inter-comparison of electron Monte Carlo dose calculations for EGSnrc, GEANT, and PENELOPE

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# Overview of Presentation

- What is electron therapy and how is it performed?
- Monte Carlo dose calculation systems/codes that can be used
  - **EGSnrc**
  - GEANT
    - Standard Electro-Magnetic Physics Lists (**STD_EM**)
    - Low Energy Physics Lists (**LowE**)
    - Penelope Physics Lists (**PENELOPE**)
- Review of Physics within each code
- Inter-comparison of Electron MC codes for mono-energetic beams
  - **Dose deposited as a function of depth;**
  - **Angular distribution of electrons at a fixed depth;**
  - **Mean energy spatial distribution at a fixed depth.**

# Electron Simulations

Early work

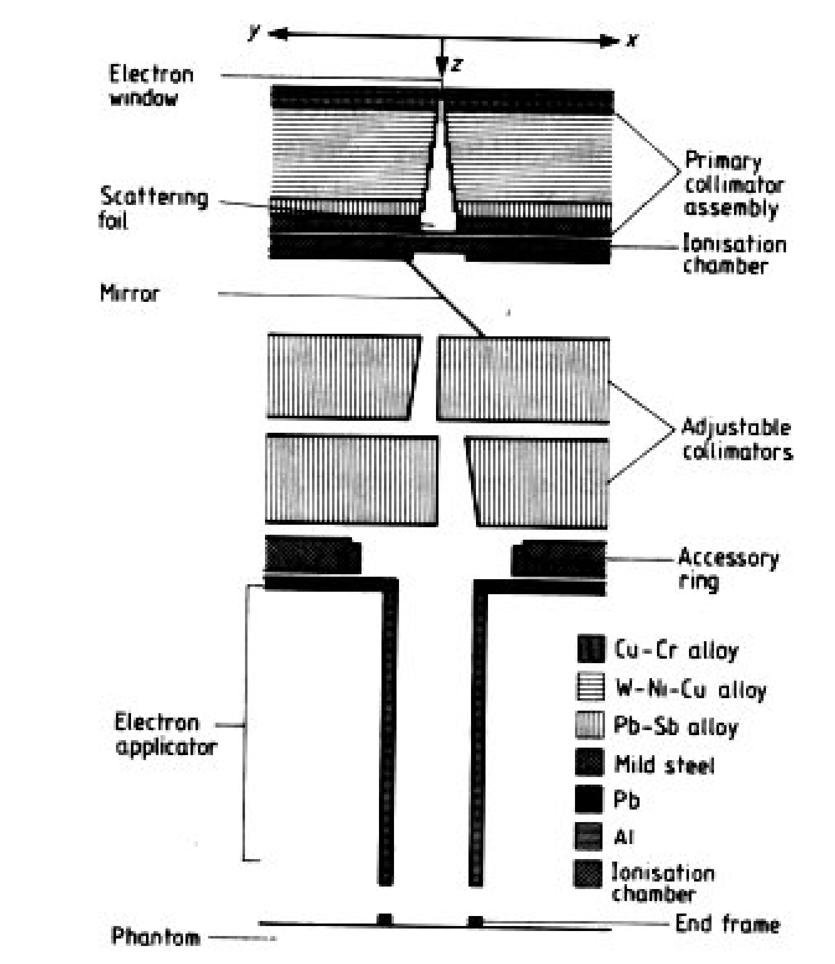
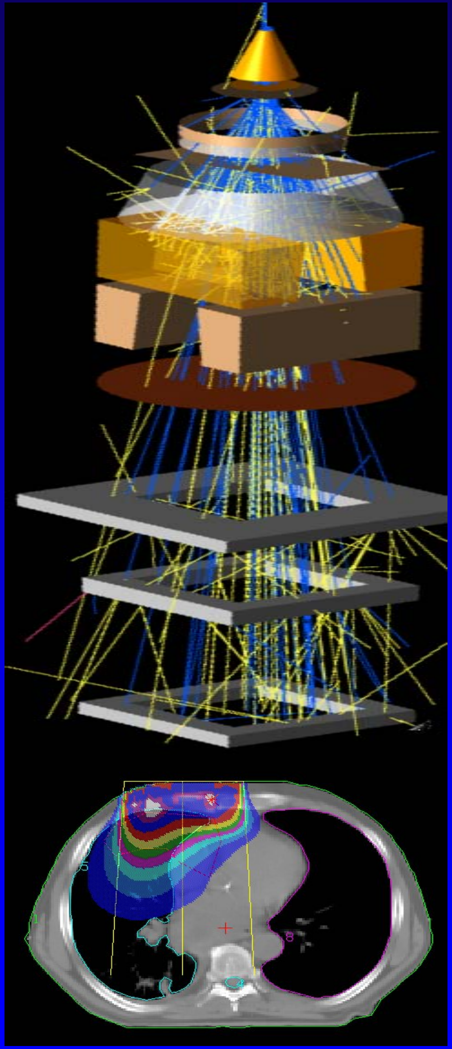



**Figure 1.** Detailed diagram of full simulation geometry.

***Udale 1988, PMB, 33 939-54***

Present



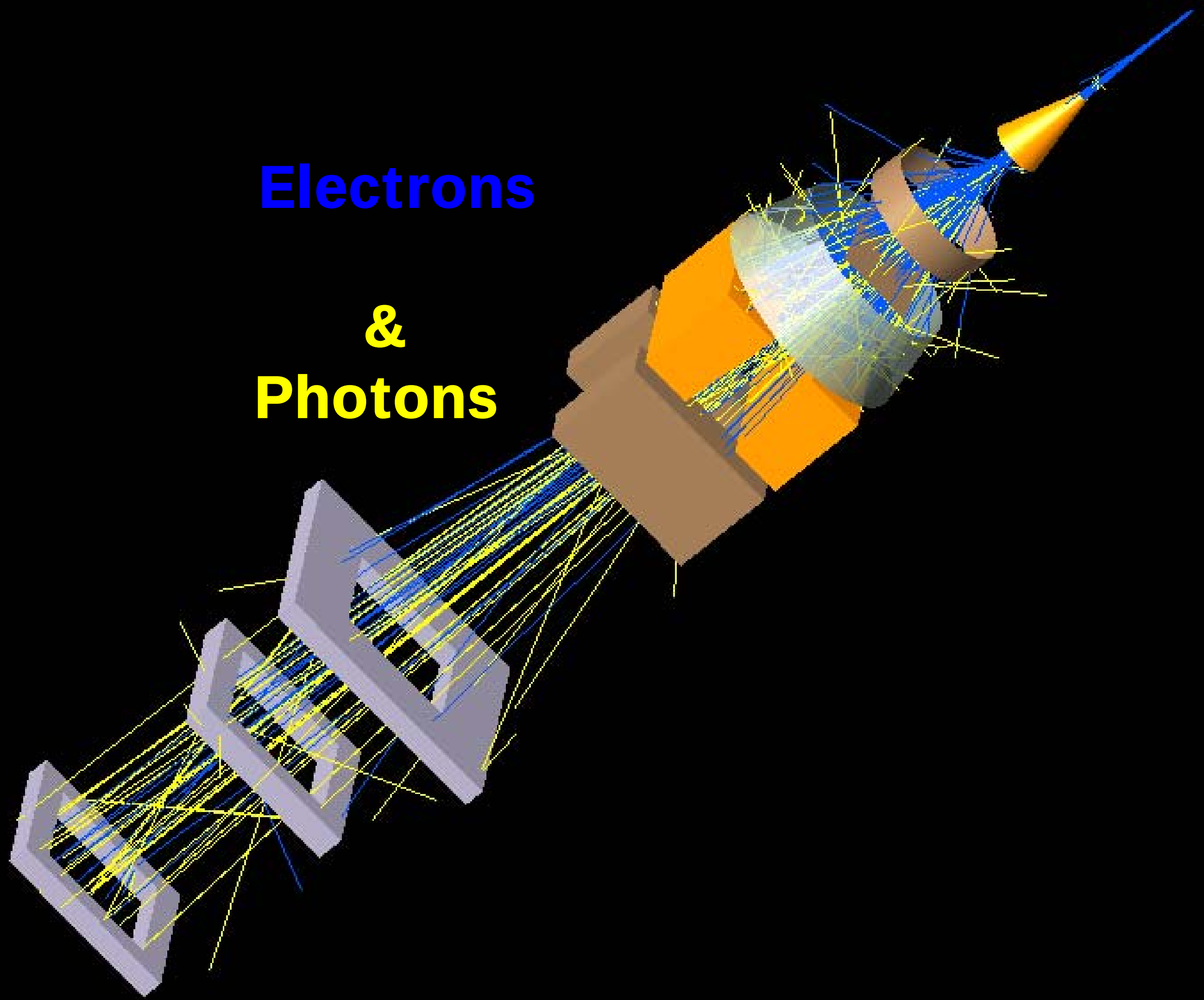
- Udale first to suggest multi-stage simulation to save computing time

# Clinac 2100C

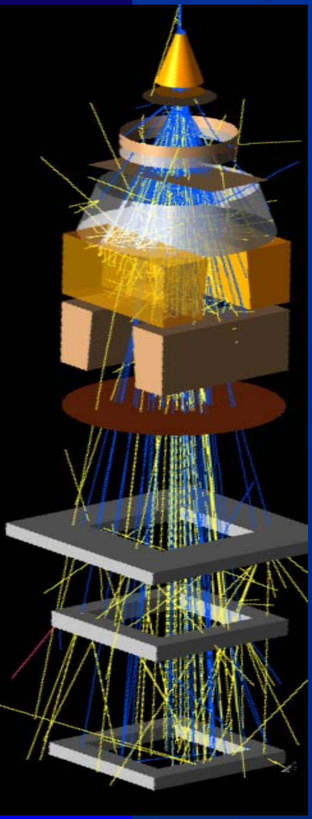
**Electrons**

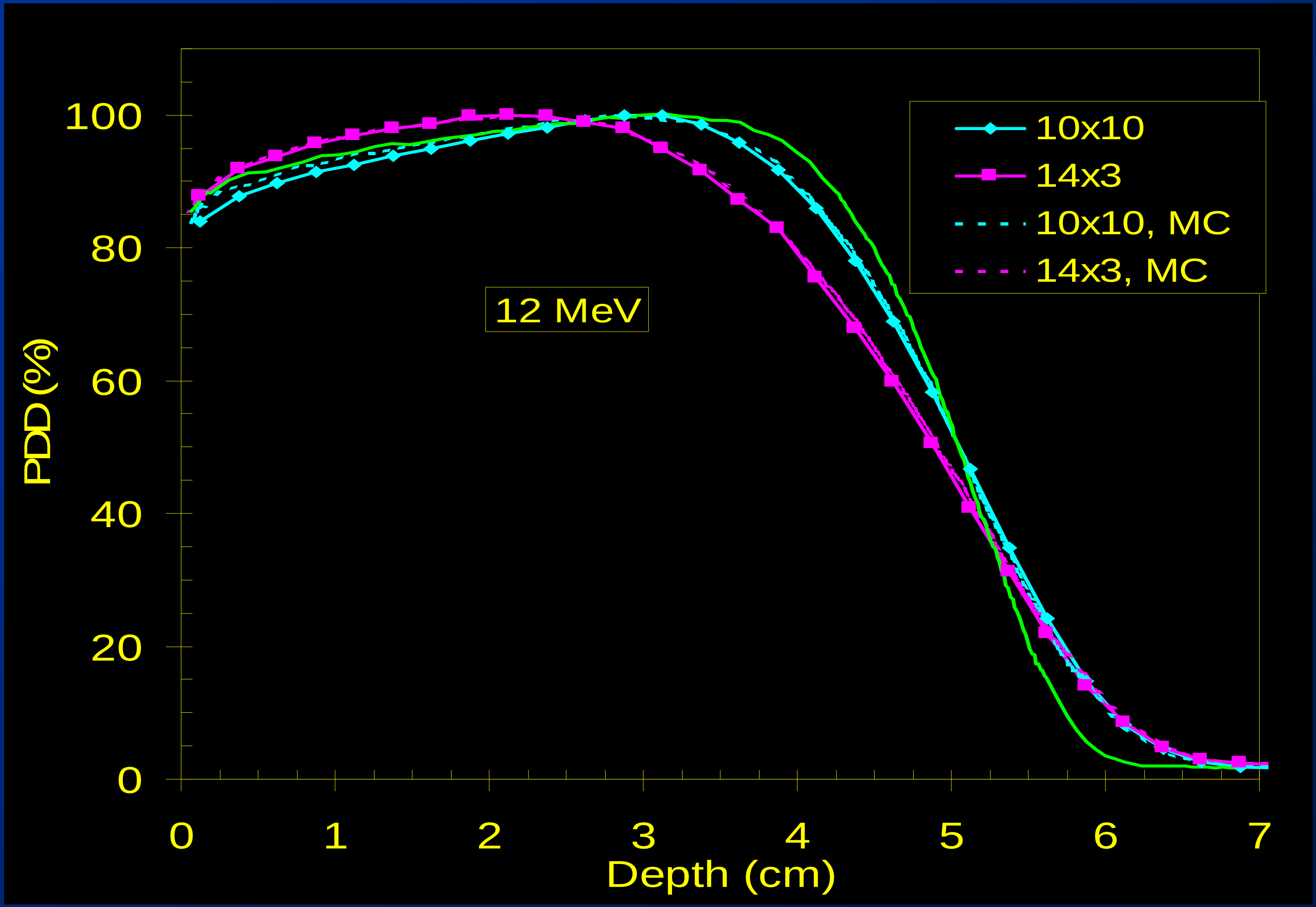
**&**

**Photons**

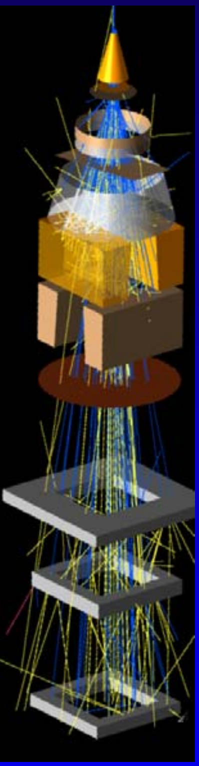


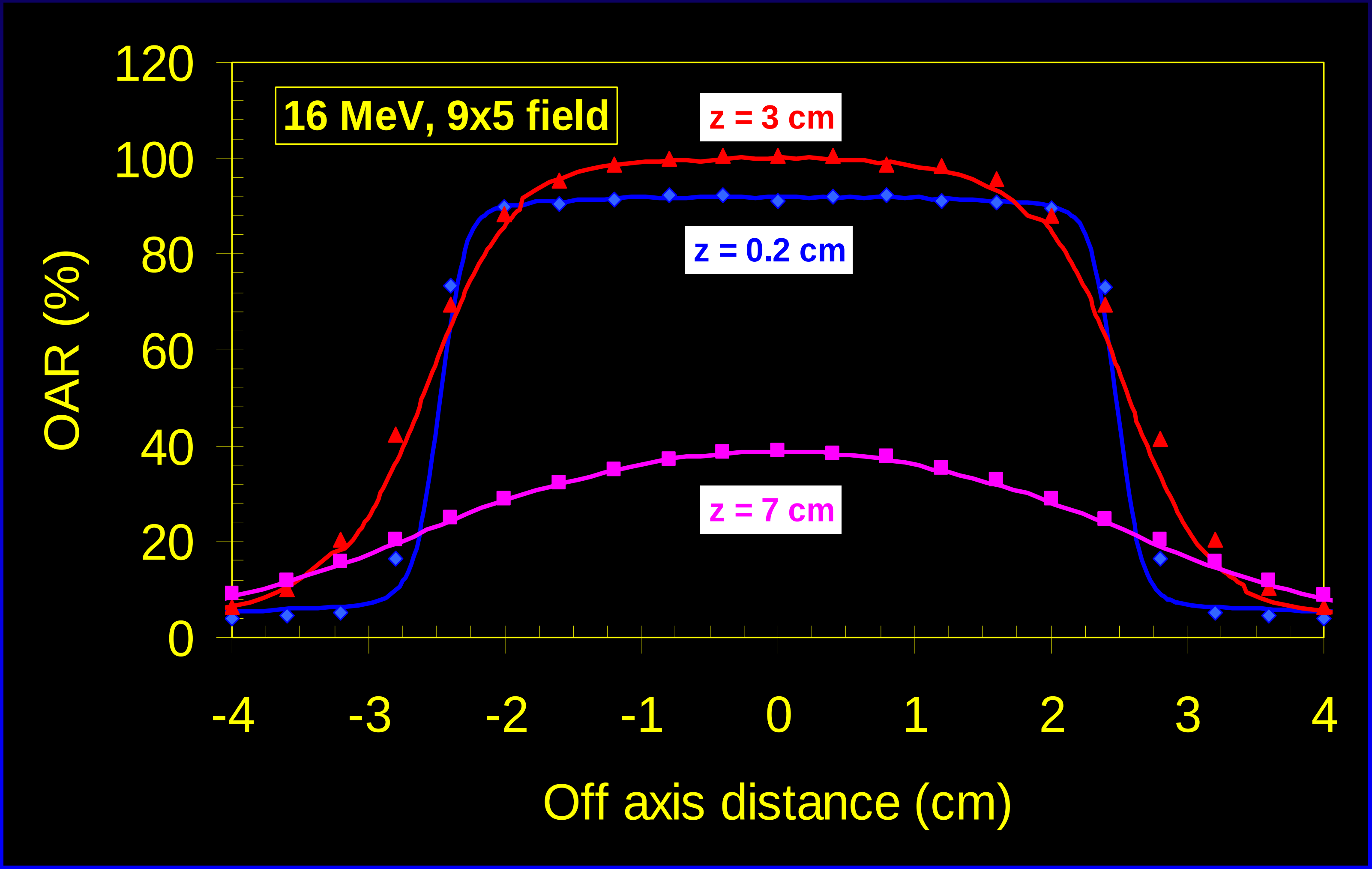
# Verification of MC model





# Verification of MC simulations






**MC: symbols** **Experimental: solid lines**

# Review of Physics within each code

Table 1. (Continued.)

| MC code | $(e^-e^-)$, $(e^-e^+)$ inelastic scattering | Bremsstrahlung | Electron impact ionization | Multiple scatter algorithm | Positron annihilation | Transport algorithm (class) | Cross section data |
|---|---|---|---|---|---|---|---|
| | | | | Charged particles | | | |
| EGS4 (A) | Møller (1932) and Bhabha (1936) scattering | Coulomb corrected extreme relativistic, Bethe–Heitler | No | Molière, switched off for short step sizes | Two photon annihilation in flight and at rest | Class II, PRESTA I electron step algorithm, BCA and lateral correlation algorithm | ICRU 37 (1984) restricted collision and radiative stopping powers |
| EGSnrc (B) | Møller (1932) and Bhabha (1936) scattering | EGS4 or NIST bremsstrahlung cross | No | Elastic scattering with spin or screened Rutherford elastic scattering (user selectable), single elastic scattering for short step sizes | Two photon annihilation in flight and at rest | Class II, PRESTA II electron step algorithm, single scattering BCA, improved energy loss evaluation, corrected fictitious discrete interactions | ICRU 37 (1984) restricted collision and radiative stopping powers |
| ETRAN/ ITS (C)/ MCNP4 (D) | Møller (1932), $e^+$ treated as $e^-$ for scattering | Seltzer (1988), Berger and Seltzer (1970) | Yes | Goudsmit–Saunderson (1940), Landau (1944), Blunck–Leisegang (1950) | Two photon annihilation at rest | Class I down to 1 keV | Seltzer and Berger (1985, 1986). ICRU 37 (1984). Sternheimer *et al* (1982), Sternheimer and Peierls (1971) |
| PENELOPE (E) | Møller (1932) and Bhabha (1936) scattering for hard collisions. Generalized Oscillator Strength approach | Bethe and Heitler (1934) | Yes | Mixed scheme: single and multiple scatter. MS: Goudsmit–Saunderson (1940). Random-hinge method | Two photon annihilation in flight and at rest | Class II, down to 100 eV. Random hinge method | Seltzer and Berger (1985, 1986) |
| GEANT4* (F) | Møller (1932) and Bhabha (1936) scattering | Cerenkov effect simulated | Yes | Lewis theory (1950), Goudsmit and Saunderson (1940) | Two photon annihilation in flight and at rest | Class II, down to 1 keV | Seltzer and Berger (1985) EEDL (Perkins *et al* 1991a) |

† All codes use an independent atom approach to obtain form factors for compounds.
(A) Nelson *et al* (1985).
(B) Kawrakow (2000).
(C) Halbleib (1988).
(D) Briesmeister (2000).
(E) Salvat *et al* (2001).
(F) GEANT4 (2003).
* In GEANT4, the low-energy extension module has to be used to model transport of photons and charged particles correctly for radiotherapy applications.





***Verhaegen and Seuntjens 2003, PMB, 48 R107-R164***

# Reference Monte Carlo code used ...

## The EGSnrc Code System:
### Monte Carlo Simulation of Electron and Photon Transport

I. Kawrakow and D.W.O. Rogers
Ionizing Radiation Standards
National Research Council of Canada
Ottawa, K1A OR6
iwan@irs.phy.nrc.ca
dave@irs.phy.nrc.ca

**Nov 7, 2003**

NRCC Report PIRS-701

# Geant4 Collaboration

*New organization for the production phase, MoU based*

**Distribution, development and User Support**

- Atlas, BaBar, CMS, HARP, LHCB
- CERN, JNL,KEK, SLAC, TRIUMF
- Barcelona Univ., ESA, Frankfurt Univ.,Helsinki Univ. IGD, IN2P3, Karolinska Inst., Lebedev, TERA
- COMMON (Serpukov, Novosibirsk, Pittsburg etc.)

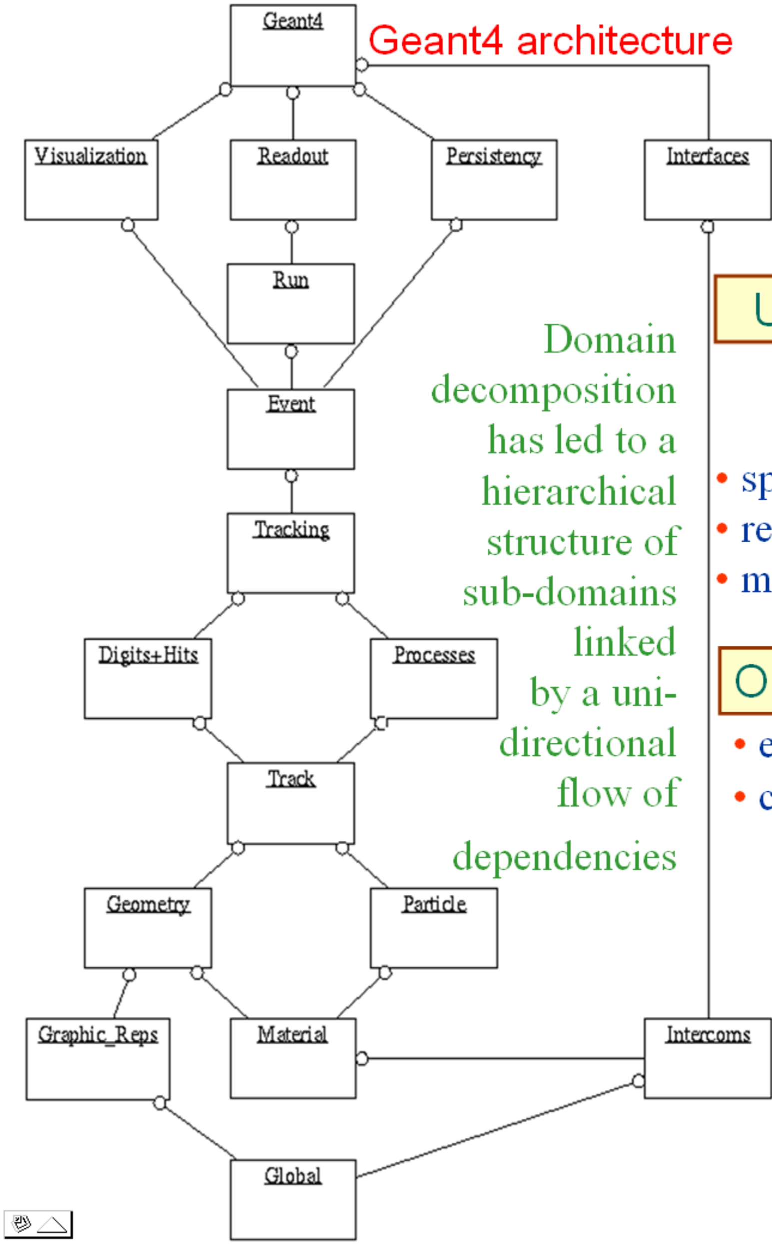
- **Collaboration Board**
  - manages resources and responsibilities
- **Technical Steering Board**
  - manages scientific and technical matters
- **Working Groups**
  - do maintenance, development, QA, etc.

Members of National Institutes, Laboratories and Experiments participating in Geant4 Collaboration acquire the right to the Production Service and User Support

*For others: free code and user support on best effort basis*

Budker Inst. of Physics
IHEP Protvino
MEPHI Moscow
Pittsburg University

Geant4 architecture




Domain decomposition has led to a hierarchical structure of sub-domains linked by a uni-directional flow of dependencies

# *Software Engineering*

plays a fundamental role in Geant4

## User Requirements

- formally collected
- systematically updated
- PSS-05 standard

## Software Process

- spiral iterative approach
- regular assessments and improvements
- monitored following the ISO 15504 model

## Object Oriented methods

- OOAD
- use of CASE tools
- essential for distributed parallel development
- contribute to the transparency of physics

## Quality Assurance

- commercial tools
- code inspections
- automatic checks of coding guidelines
- testing procedures at unit and integration level
- dedicated testing team

## Use of Standards

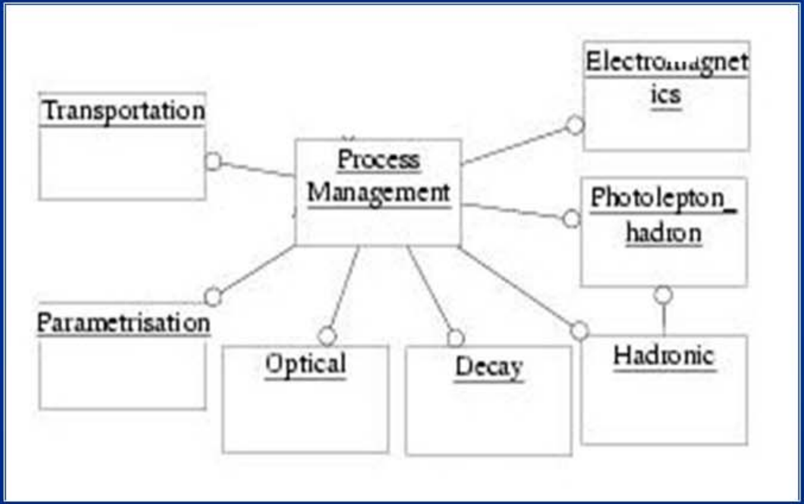
- de jure and de facto

# Processes

**Processes describe how particles interact with material or with a volume itself**

Three basic types

- At rest process
  (e.g. decay at rest)
- Continuous process
  (e.g. ionization)
- Discrete process
  (e.g. decay in flight)




**Transportation** is a process

- interacting with volume boundary

The process which requires the shortest interaction length limits the step

# Electromagnetic physics

It handles

- electrons and positrons
- $\gamma$, X-ray and optical photons
- muons
- charged hadrons
- ions

energy loss {

- multiple scattering
- Bremsstrahlung
- ionisation
- annihilation
- photoelectric effect
- Compton scattering
- Rayleigh effect
- $\gamma$ conversion
- $e^+e^-$ pair production
- synchrotron radiation
- transition radiation
- Cherenkov
- refraction
- reflection
- absorption
- scintillation
- fluorescence
- Auger *(in progress)*

Comparable to Geant3 already in the 1st $\alpha$ release (1997)

- **High energy extensions**
  - fundamental for LHC experiments, cosmic ray experiments etc.
- **Low energy extensions**
  - fundamental for space and medical applications, neutrino experiments, antimatter spectroscopy etc.
- **Alternative models for the same physics process**

# Physics processes relevant for medical applications

- *Low Energy extensions of electromagnetic interactions*
  - 250 eV electrons, photons
  - ~ 1 keV positive hadrons, ions
  - ICRU-compliant and ICRU-consistent
  - Barkas effect taken into account for antiprotons, negative ions
  - further extensions and refinements in progress
- *Radioactive Decay Module*
  - simulation of radioactive sources, including all the secondary emissions
- *Multiple scattering*
  - new improved model, taking into account also lateral displacement
- *Hadronic interactions*
  - ample variety of complementary and alternative models
- *Neutrons*
  - exploiting **all** the evaluated n data libraries worldwide

# Low Energy Electromagnetic Physics

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

Geant4
***Low Energy Electromagnetic***
package extends the coverage
of physics interactions

Needed for space and medical applications, ν physics, antimatter searches

- down to 250 eV for electrons and γ
  - *based on the LLNL data libraries*
  - *shell effects*
- down to ~ 100 eV in the near future
  - *based on Penelope Electron Photon Transport*

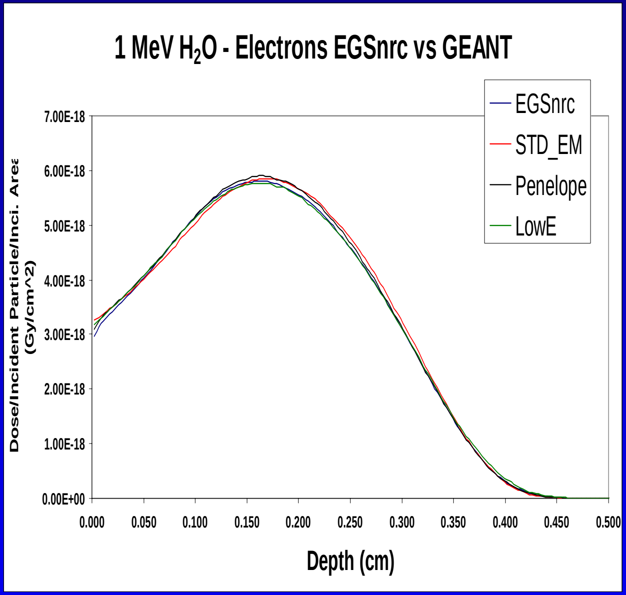
down to ~ 1 keV for hadrons and ions

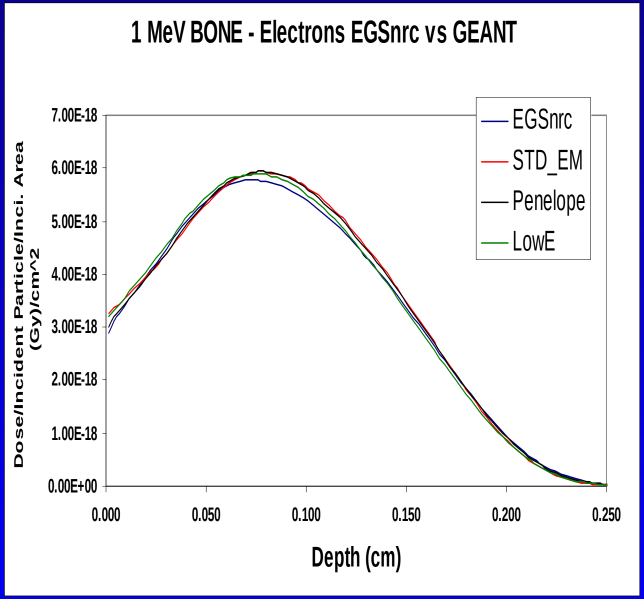
- *Bethe-Bloch above 2 MeV*
- *Ziegler and ICRU parameterisations* (with material dependence)
- *free electron gas model*
- *quantal harmonic oscillator model*
- *charge dependence (Barkas effect)*

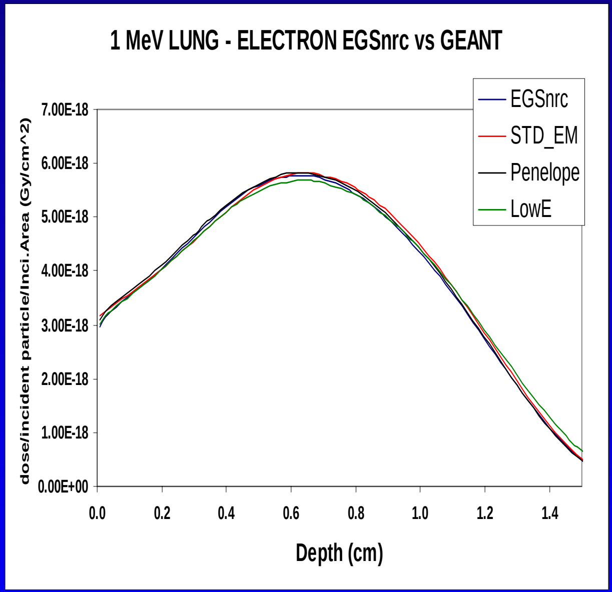
# Our Preliminary results with

# EGSnrc, STD_EM, LowE and PENELOPE .....

## 1 MeV incident electrons on homogeneous material



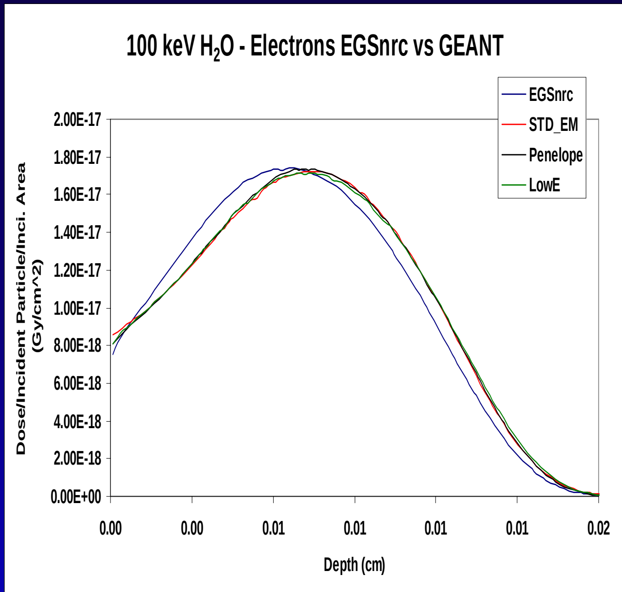



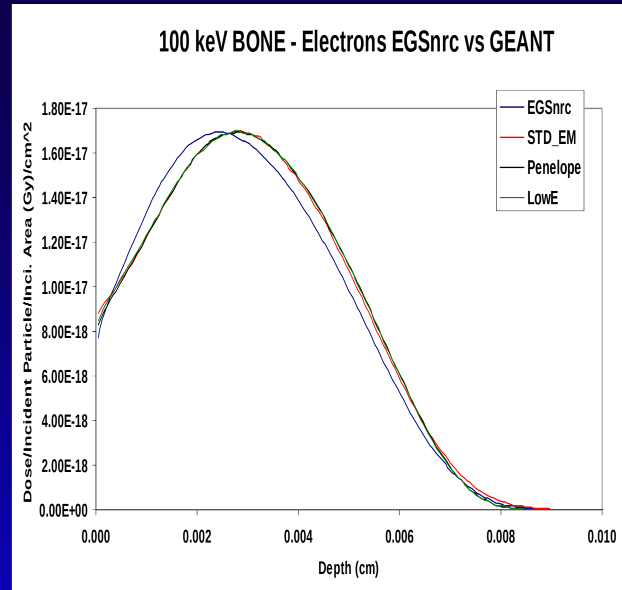

$$\textbf{SLAB\_THICKNESS} = \frac{\textbf{CSDA}}{\textbf{100}*\rho}$$

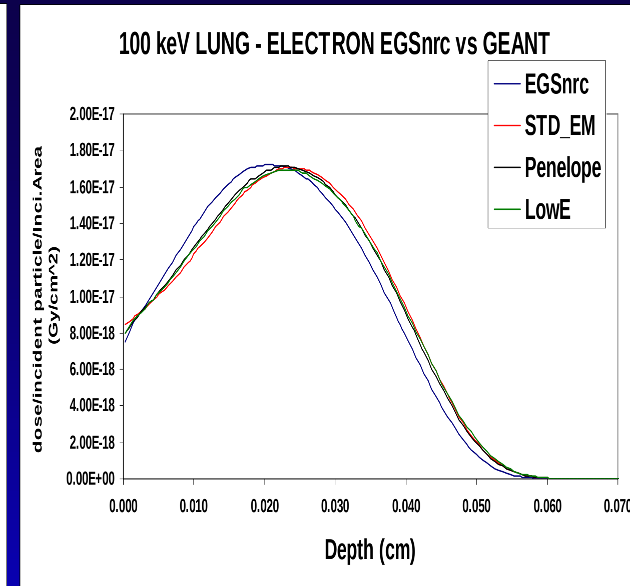
CSDA - continuos slowing down approximation in $g/cm^2$

$\rho$ – material density in $g/cm^3$

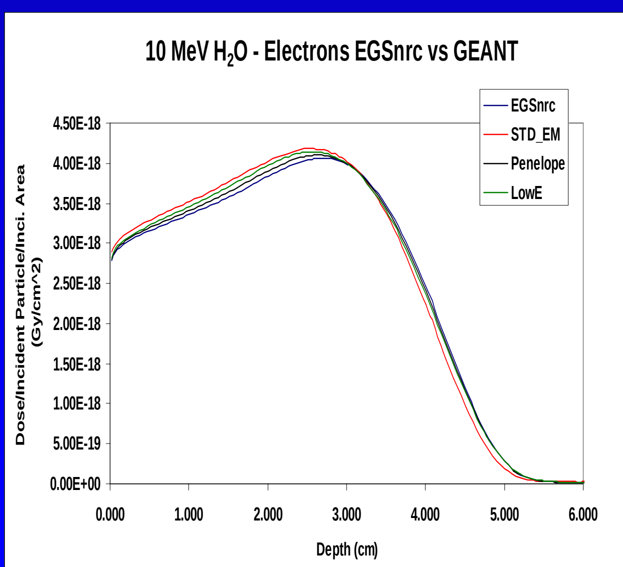
# 100 keV incident electrons on homogeneous material

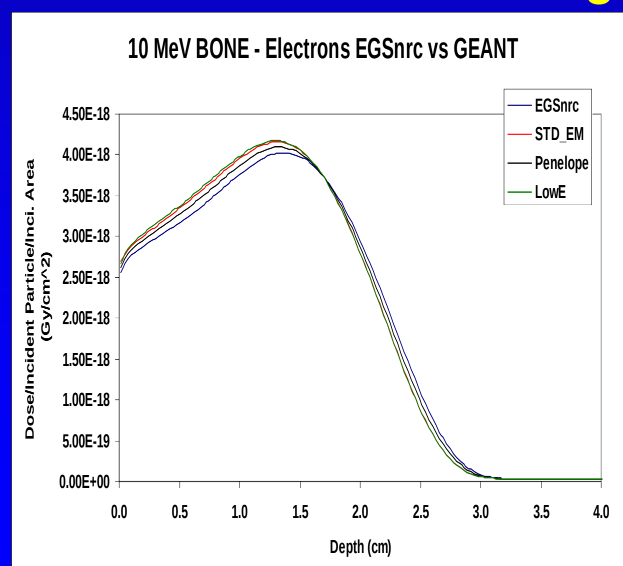


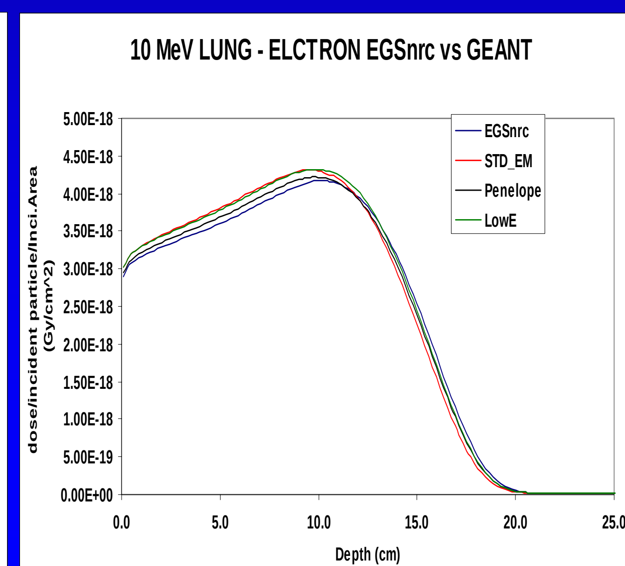




# 10 MeV incident electrons on homogeneous material

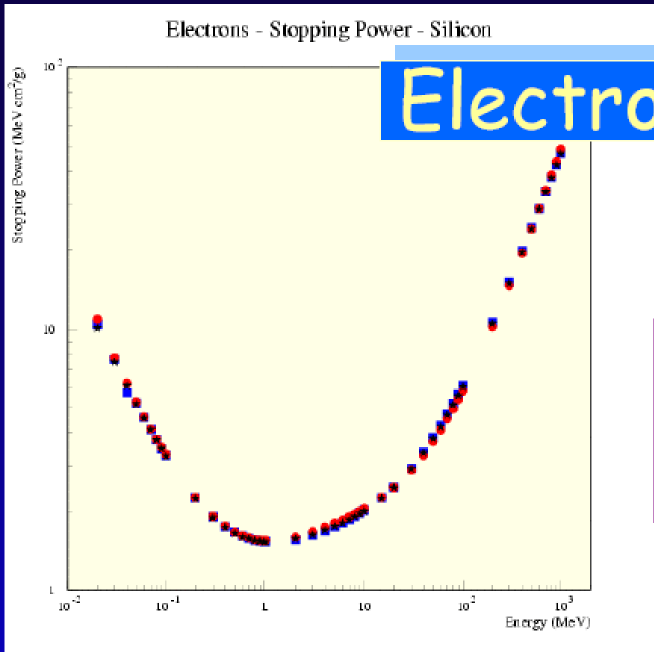


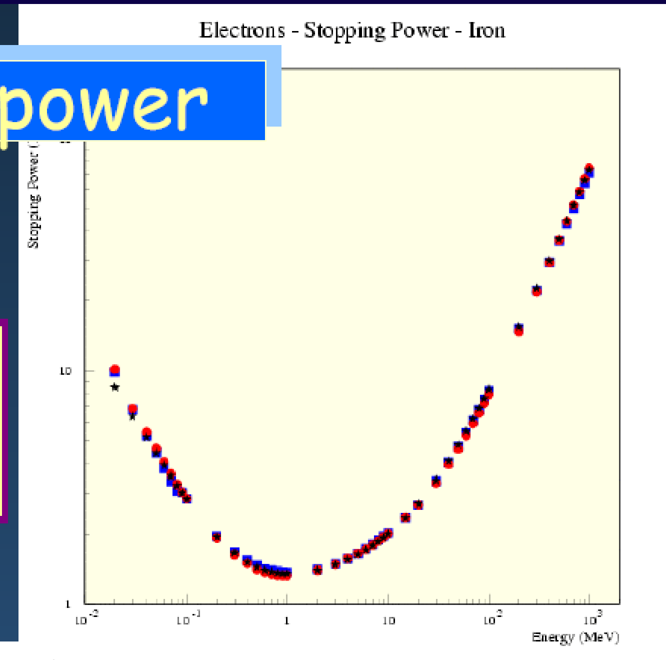



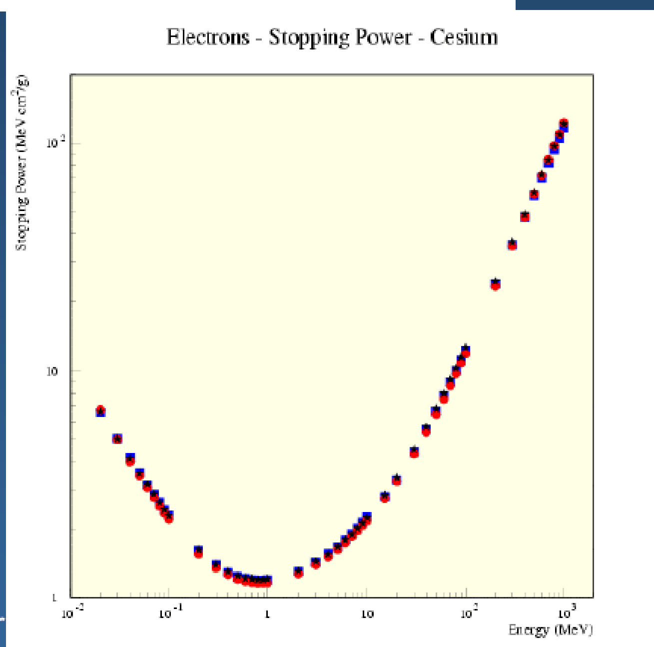



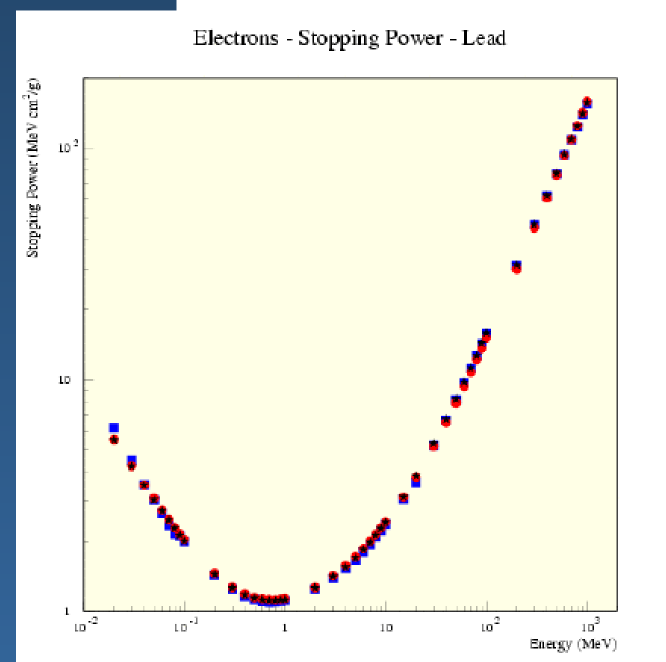
# Electron stopping power

**G4 Standard**
**G4 LowE-EEDL**
**NIST**

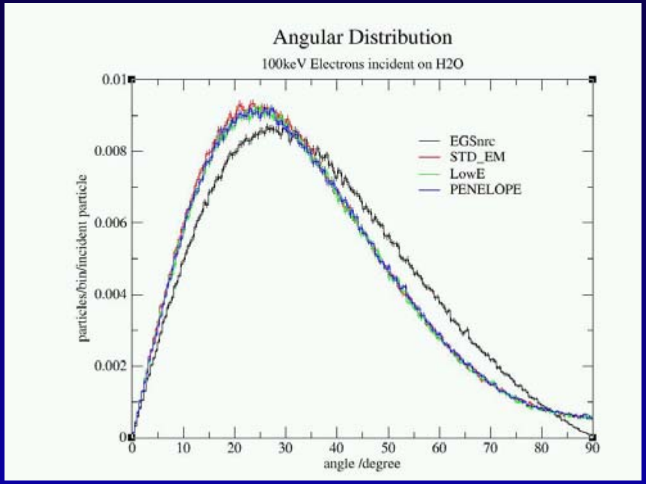


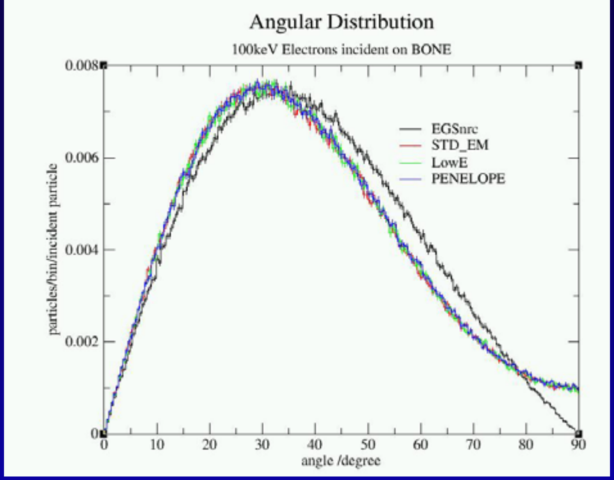



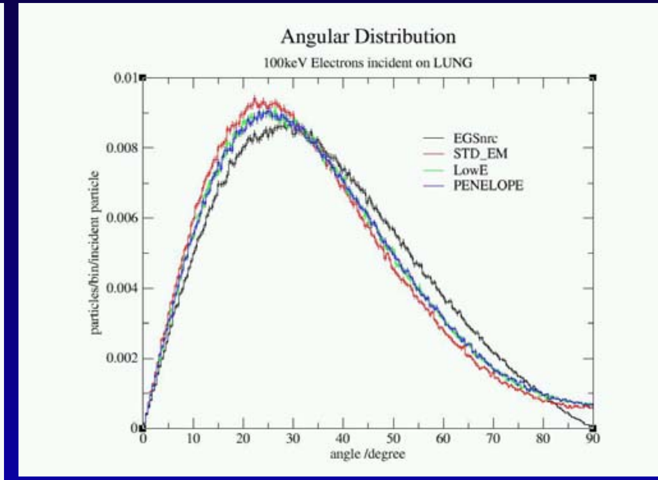



## 100 keV incident electrons on homogeneous material

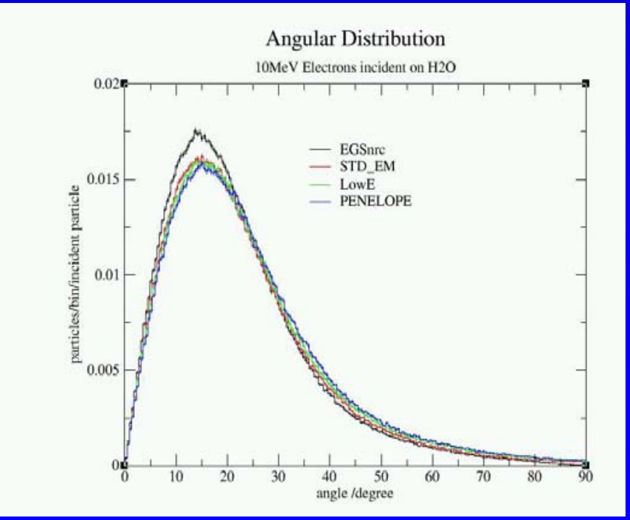


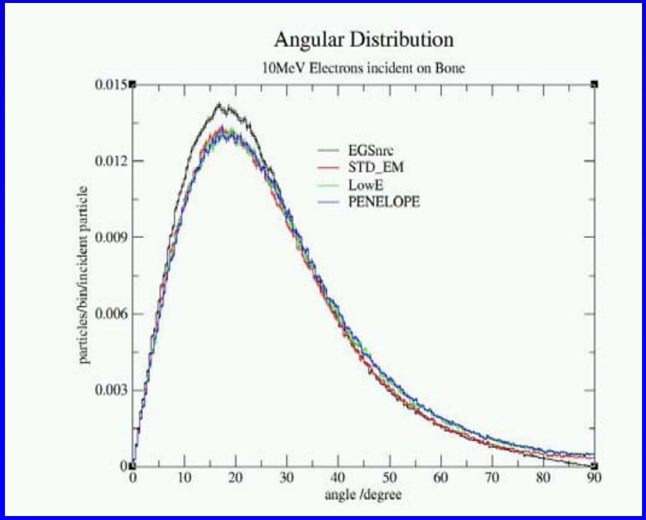



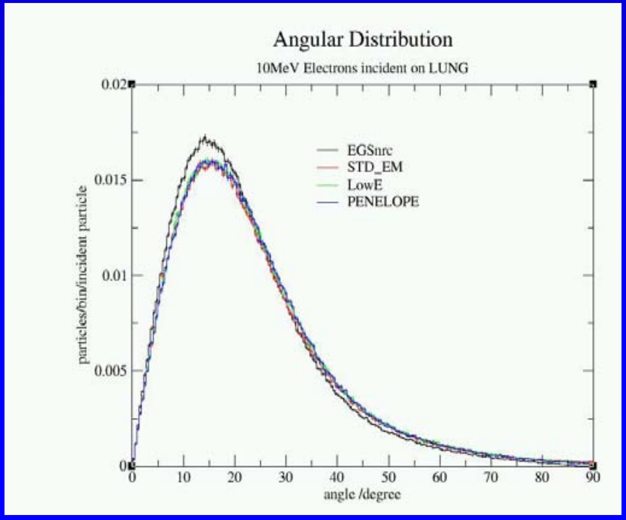




# POSSIBLE PROBLEM IN THE ELASTIC MULTIPLE SCATTERING ALGORITHM....

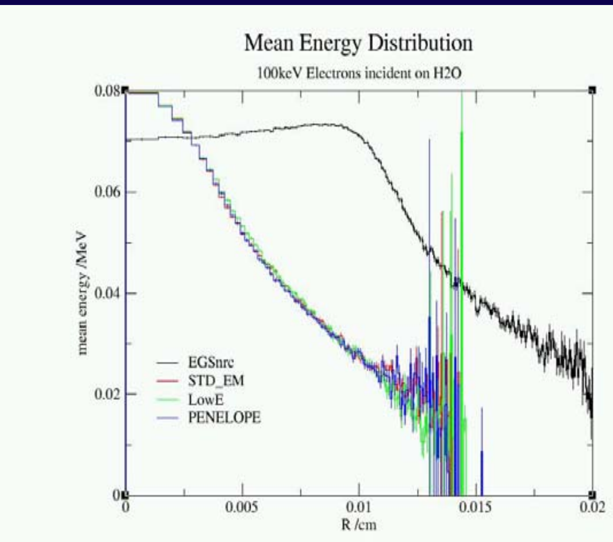
## 10 MeV incident electrons on homogeneous material

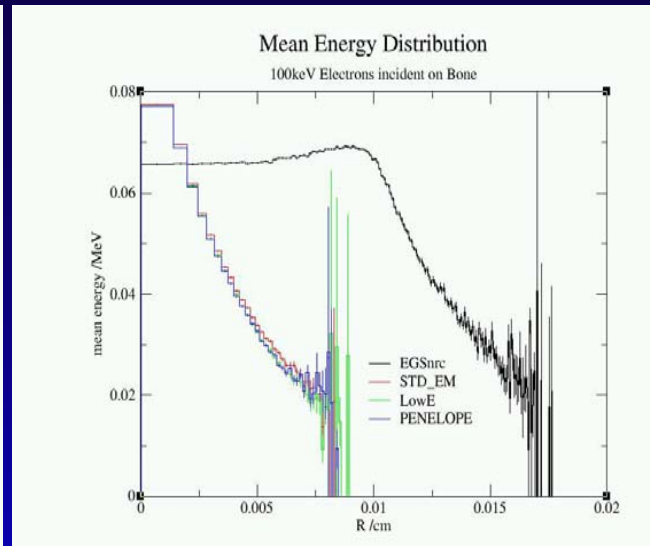


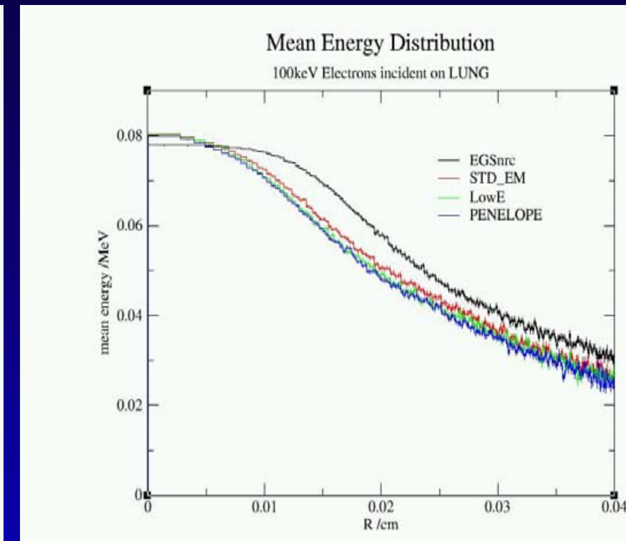



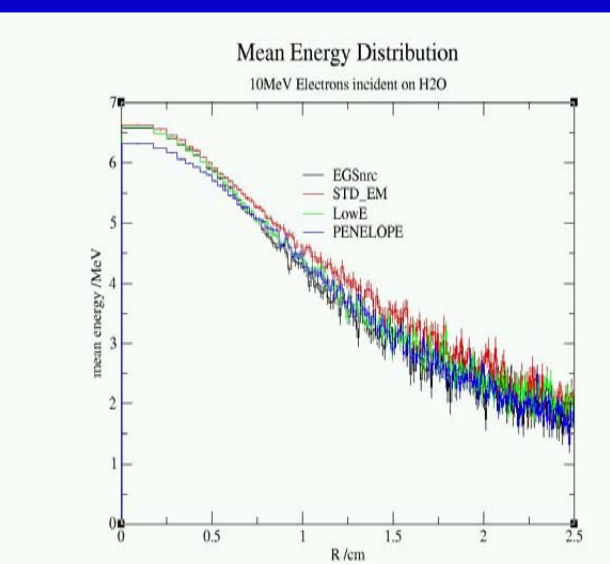
# 100 keV incident electrons on homogeneous material

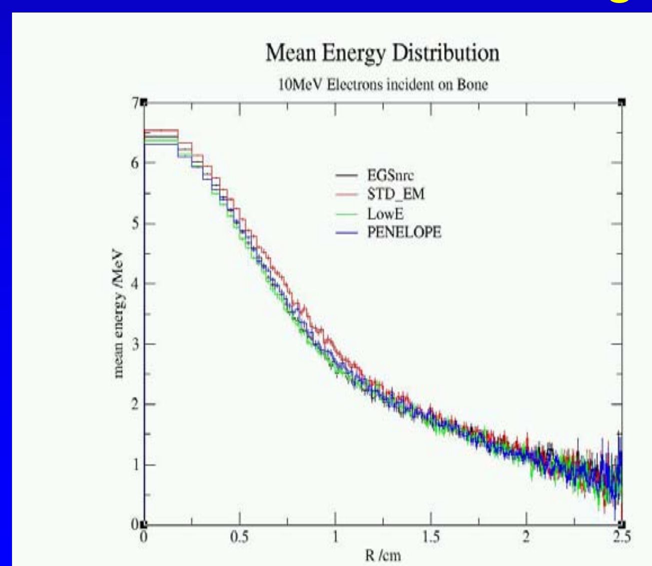


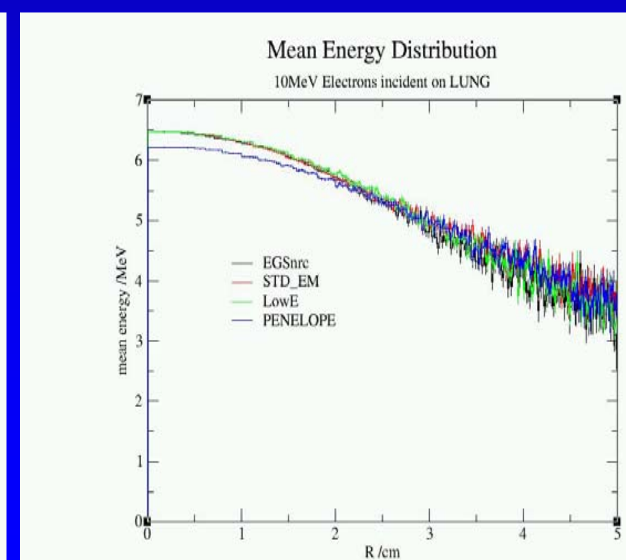




# 10 MeV incident electrons on homogeneous material



# Preliminary Conclusions

**EGSnrc vs GEANT (STD_EM, LowE, PENELOPE models)**

Preliminary results indicate that the elastic multiple scattering algorithm used in GEANT to model electron elastic scattering and diffusion is not adequately implemented...

# Acknowledgements

Cephas Mubata, Iwan Kawrakow, Hugo Palmans, David Shipley,...