GEANT3/4 Simulations for Radiation Budget and Background Calculations

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Pre-Conclusions

- There's a reasonable degree of confidence in the methods implemented at JLab for the radiation background calculations and modeling
- The administrative Radiation Budgeting system works for the goals of radiation protection and for the goal of minimizing experimental backgrounds
- However, the development of the Monte Carlo simulation software should be sustained and supported:
  - JLab-specific Physics models developed and tested
  - Results of the calculations experimentally verified and benchmarked
  - Geant4 Toolkit: (the only?) suitable future package

Continuous Electron Beam Accelerator Facility

- Powerful beam
  - Up to 800 kW to a hall
- Fixed target experiments
  - Large halls / thin roofs
  - Radiation inside and outside
- Environmental radiation
  - Skyshine from neutrons exiting through the roofs, close to the site boundary (~90 m)
  - Ground water activation: negligible by design
  - Air activation: measured to be small and contained

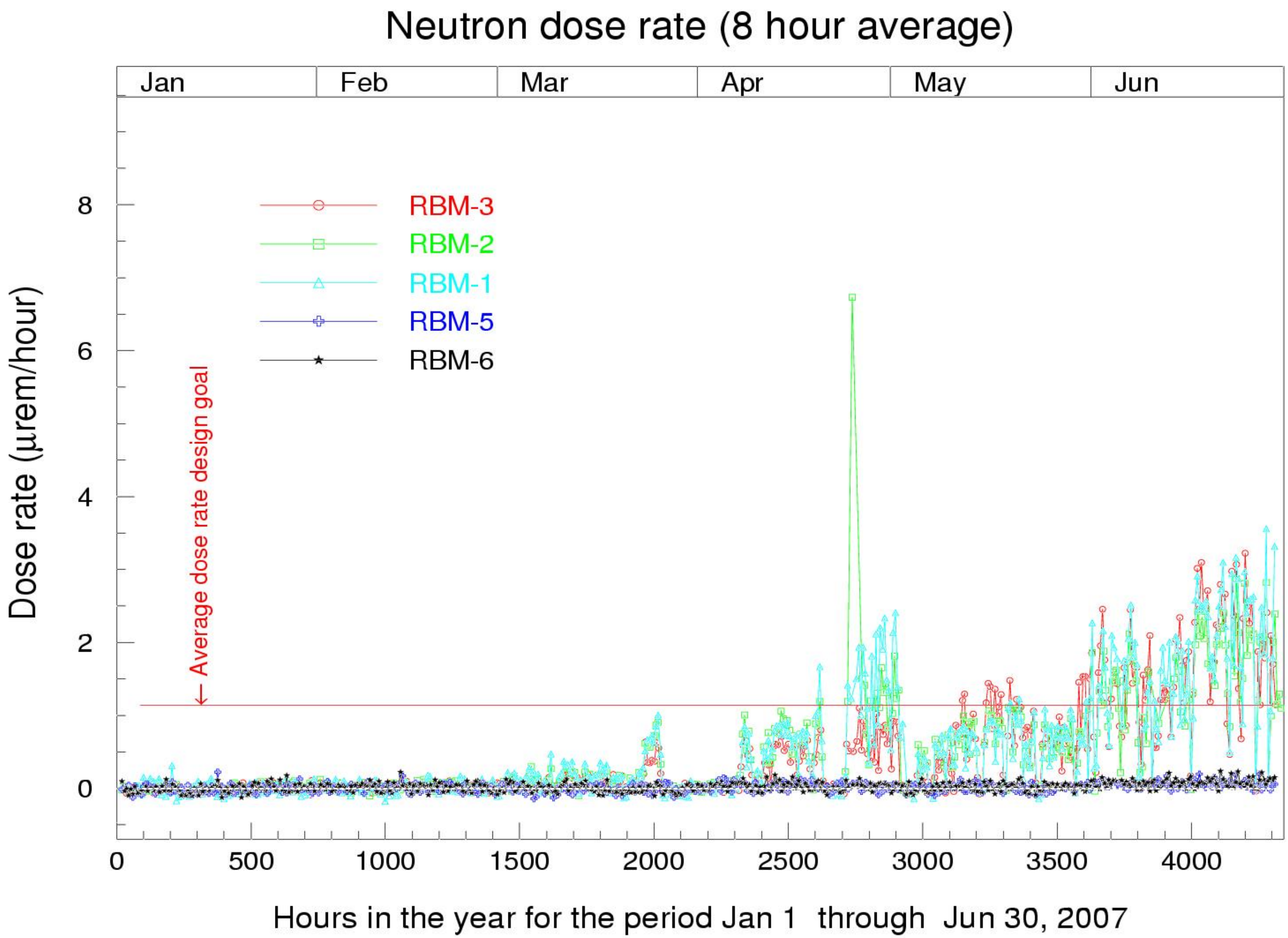
Risk Mitigation Factors

- The general classification of risk mitigation factors in Radiation Protection at JLab:
  - Passive protection systems
    - Engineered / Fixed / Temporary shielding
  - Active protection systems
    - Failsafe radiation detectors wired for trips if conditions are unsafe
  - Continuous monitoring, logging and on-line analysis of data from the area radiation monitors
  - Administrative measures
    - Safety assessments for experiments (RSADs)
    - Environmental Radiation Budgeting

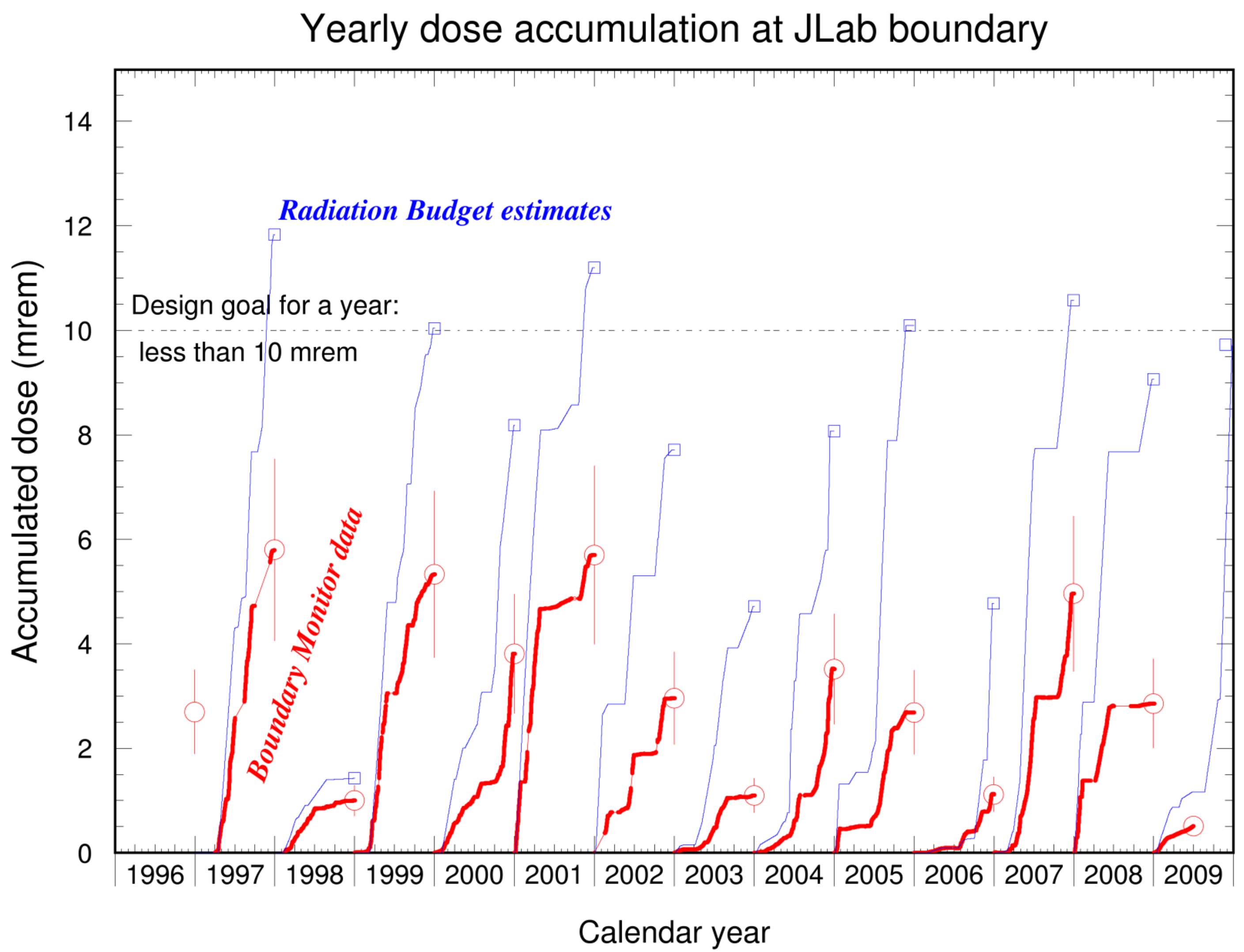
Radiation Budgeting at JLab

- Design Goal: less than 10 mrem at the boundary per calendar year (10% of the DOE allowance of the additional yearly dose for general population).
- Prior to beam time approval for an experiment, the Rad. Budget Form is completed with the estimate of average boundary dose rate and total accumulated dose
  - ELEC5b calculation tool is used for standard setups
  - DINREG/GEANT modeling is used for non-standard setups and for the local shielding design
- Physics Division EH&S Officer manages the budget:
  - time out/ modify "costly" experiments, review schedule,...
- "Actual expenditure": regular comparisons with measurements, reports

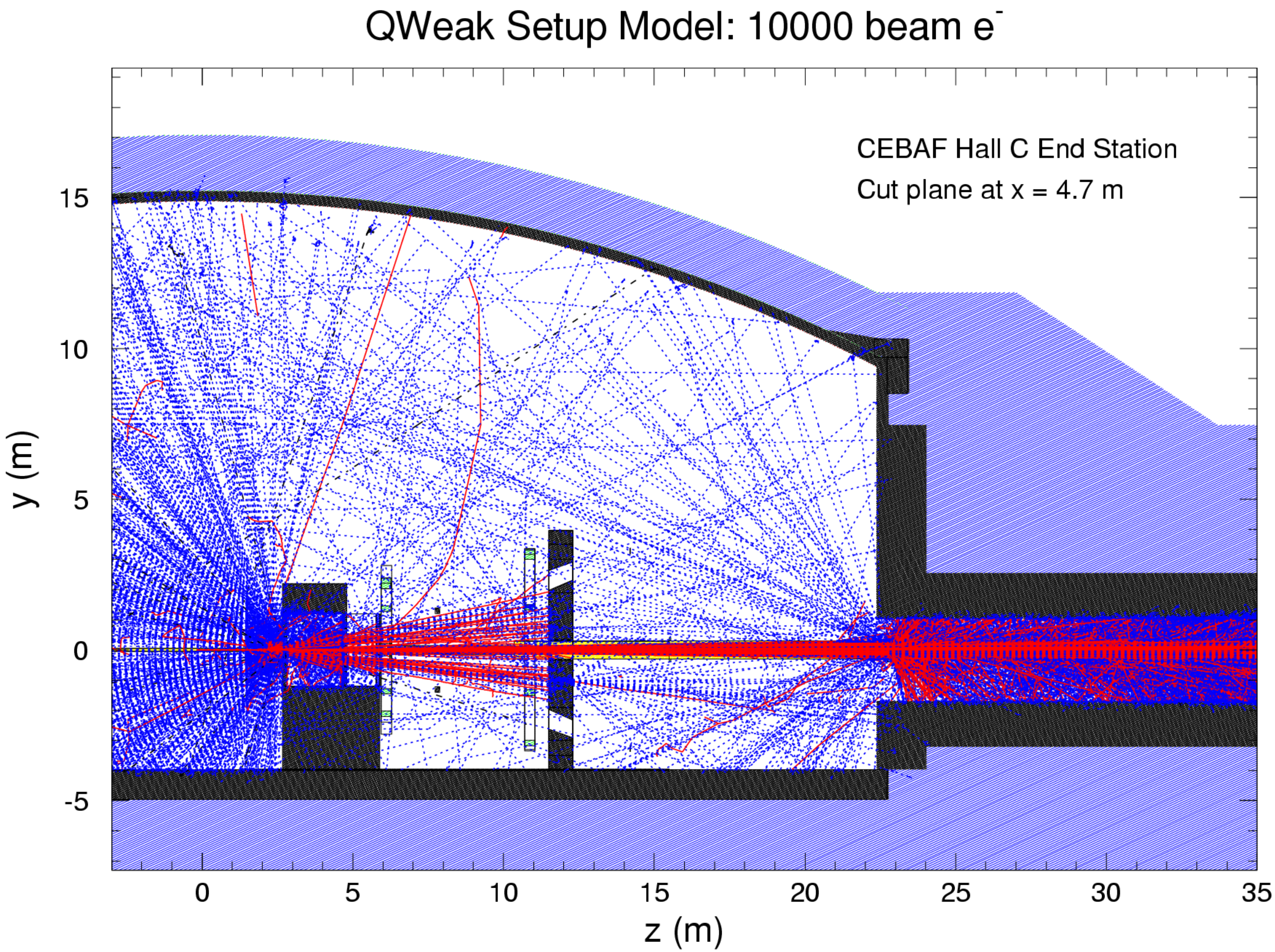
Neutron Boundary Dose Rates



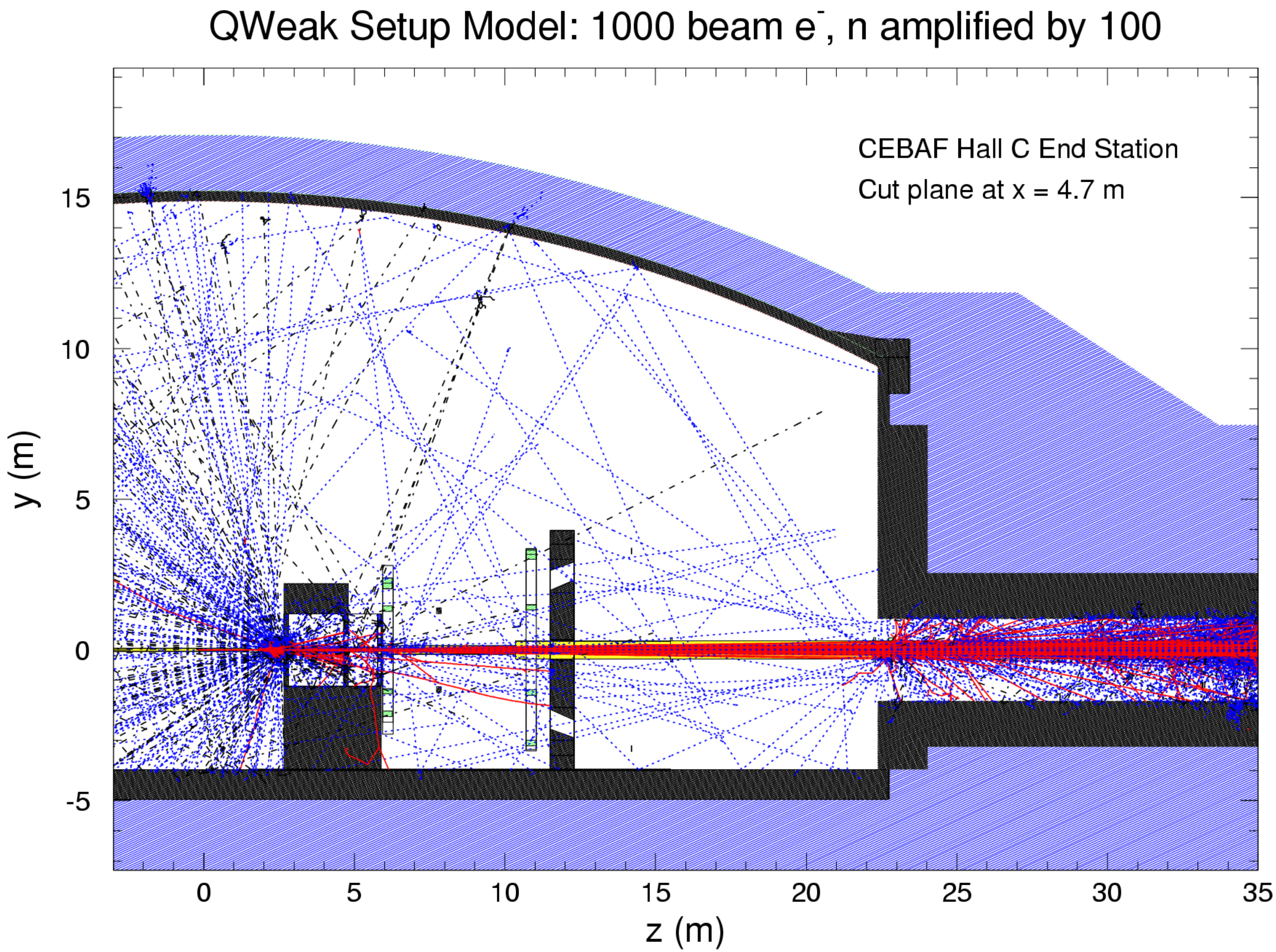
Radiation Budgeting Reports



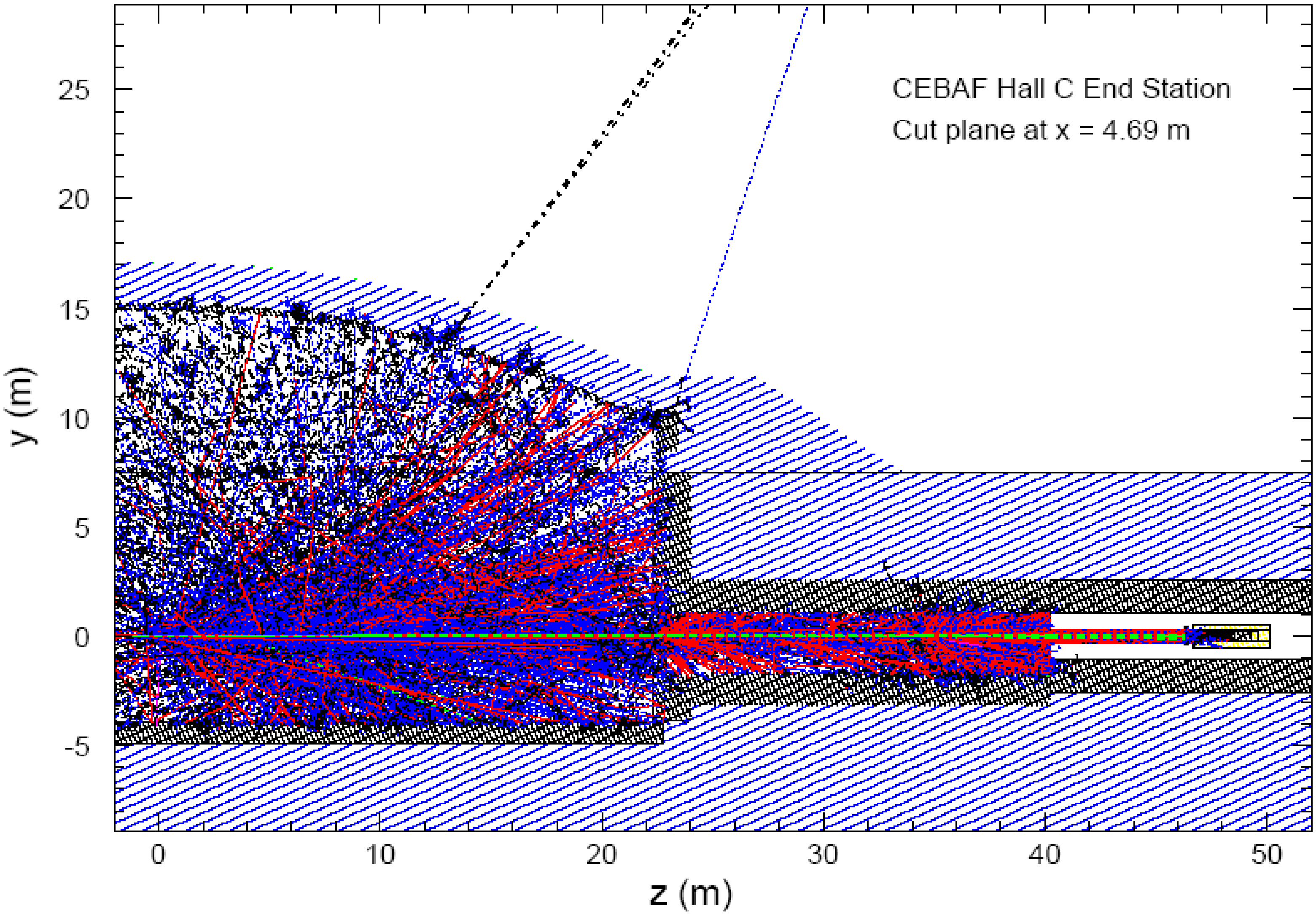
Qweak Model Calculations



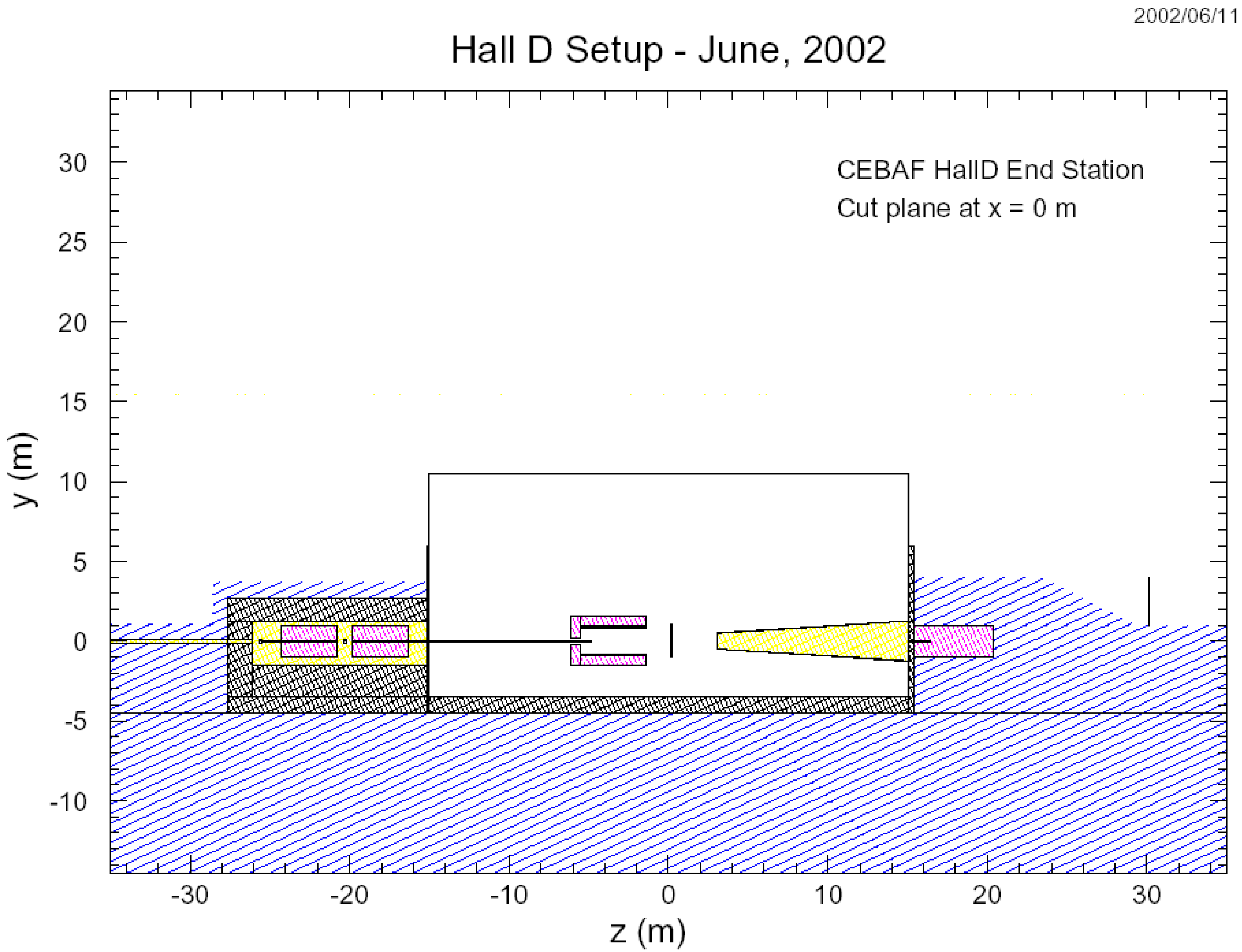
Qweak Model Calculations



Neutrons Outside the Hall

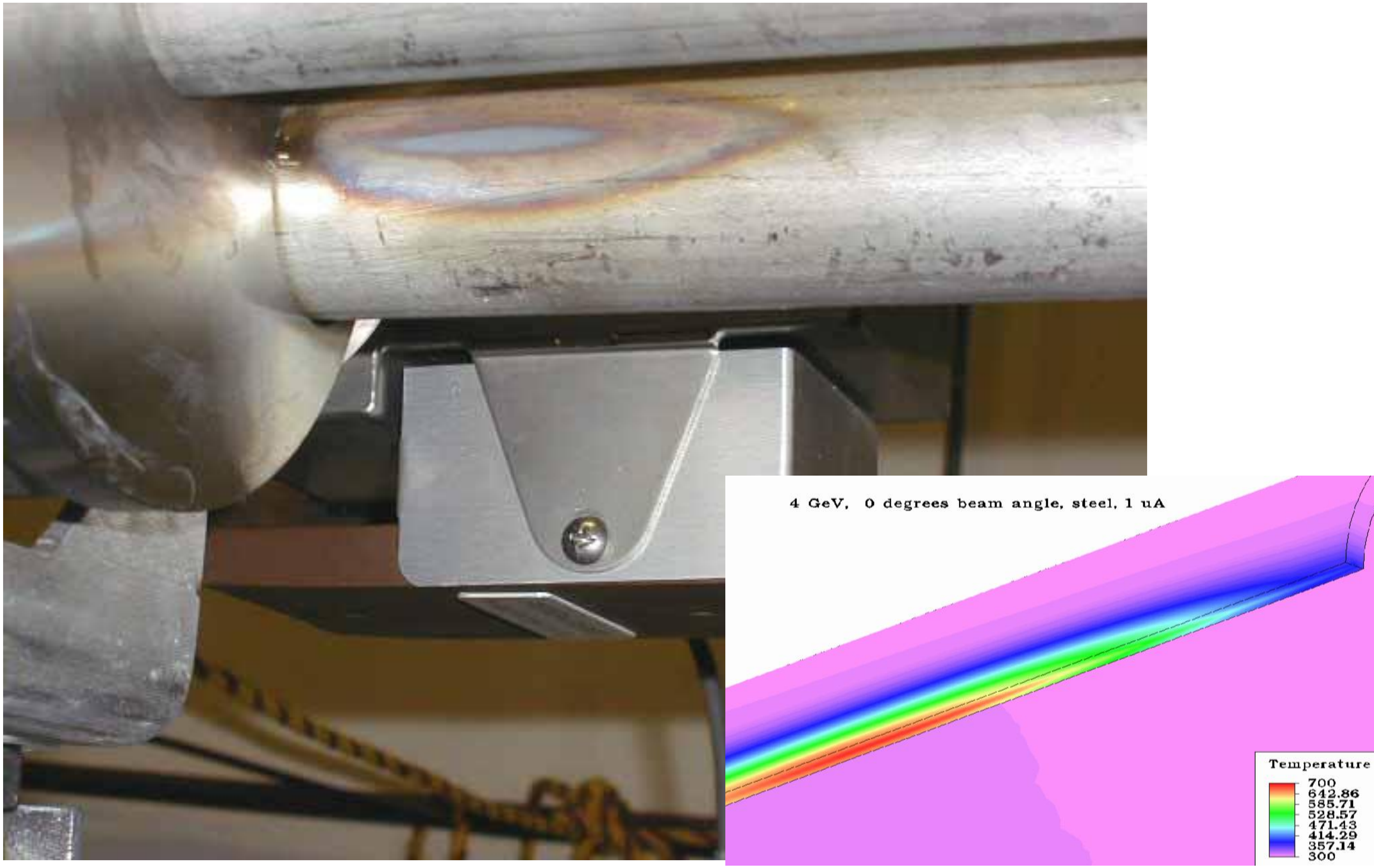


Hall D Model



2002/06/11
Hall D Setup - June, 2002
CEBAF HallD End Station
Cut plane at x = 0 m
y (m)
30
25
20
15
10
5
0
-5
-10
-30
-20
-10
0
10
20
30
z (m)

Typical Pattern of a Beam Line Hot Spot



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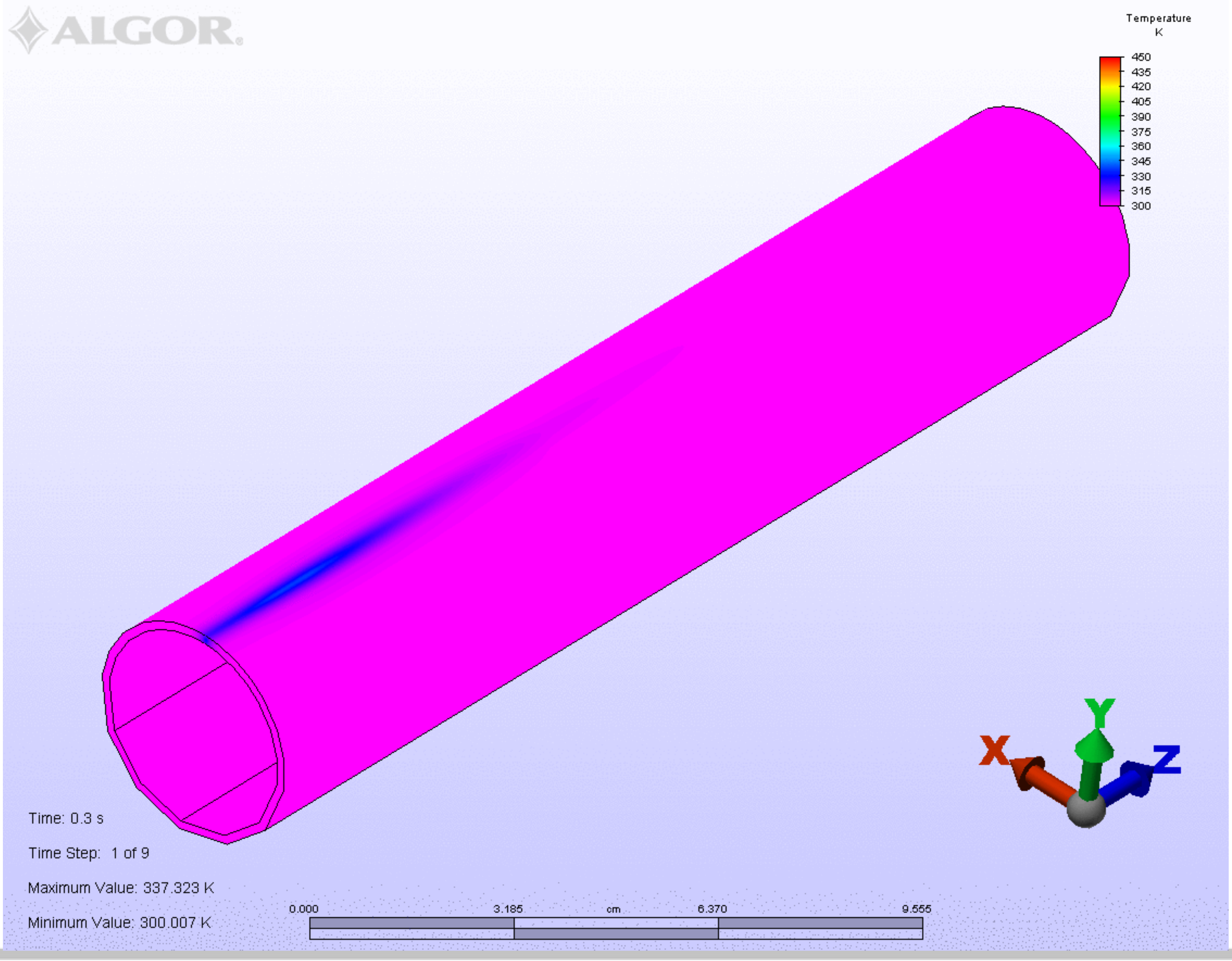
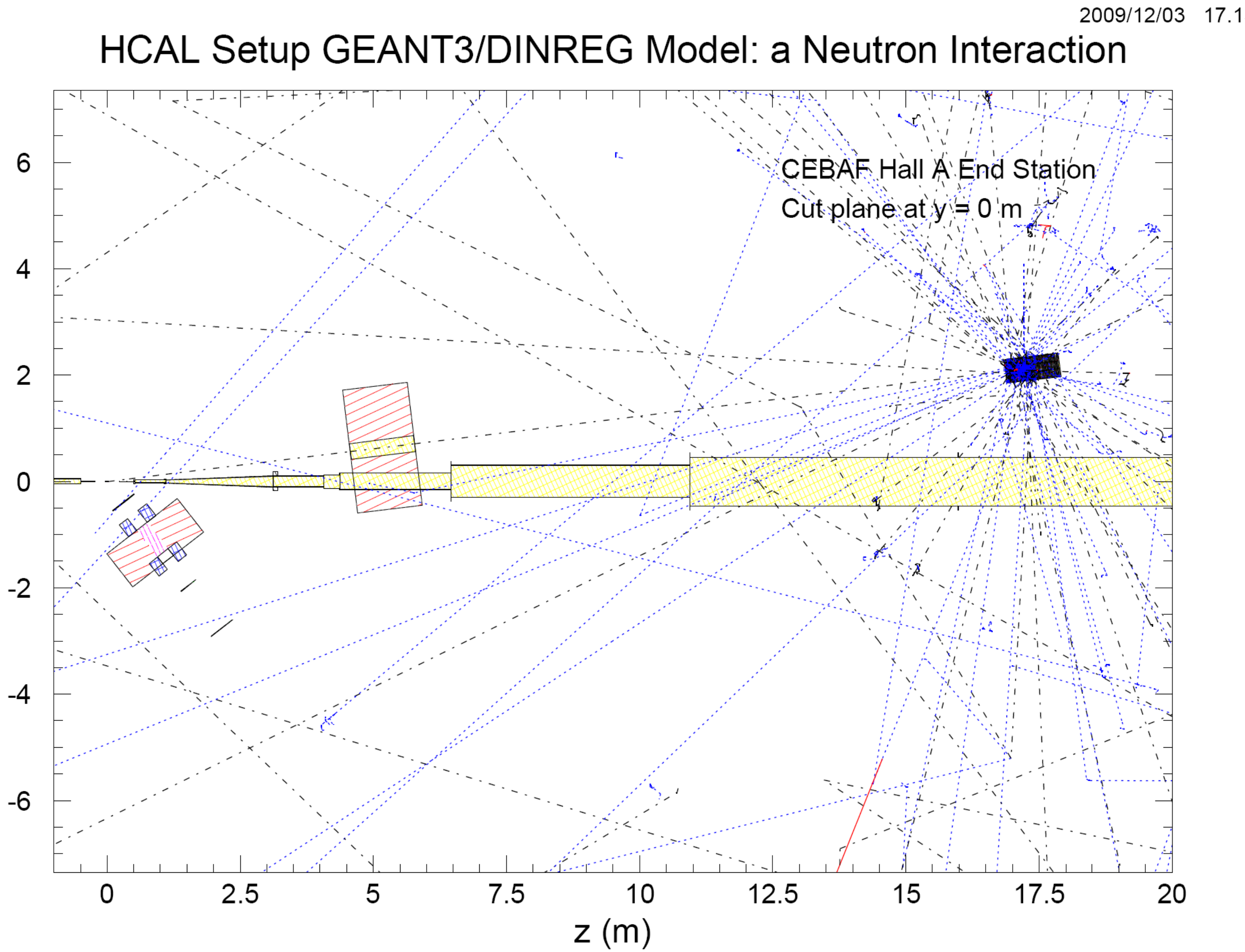
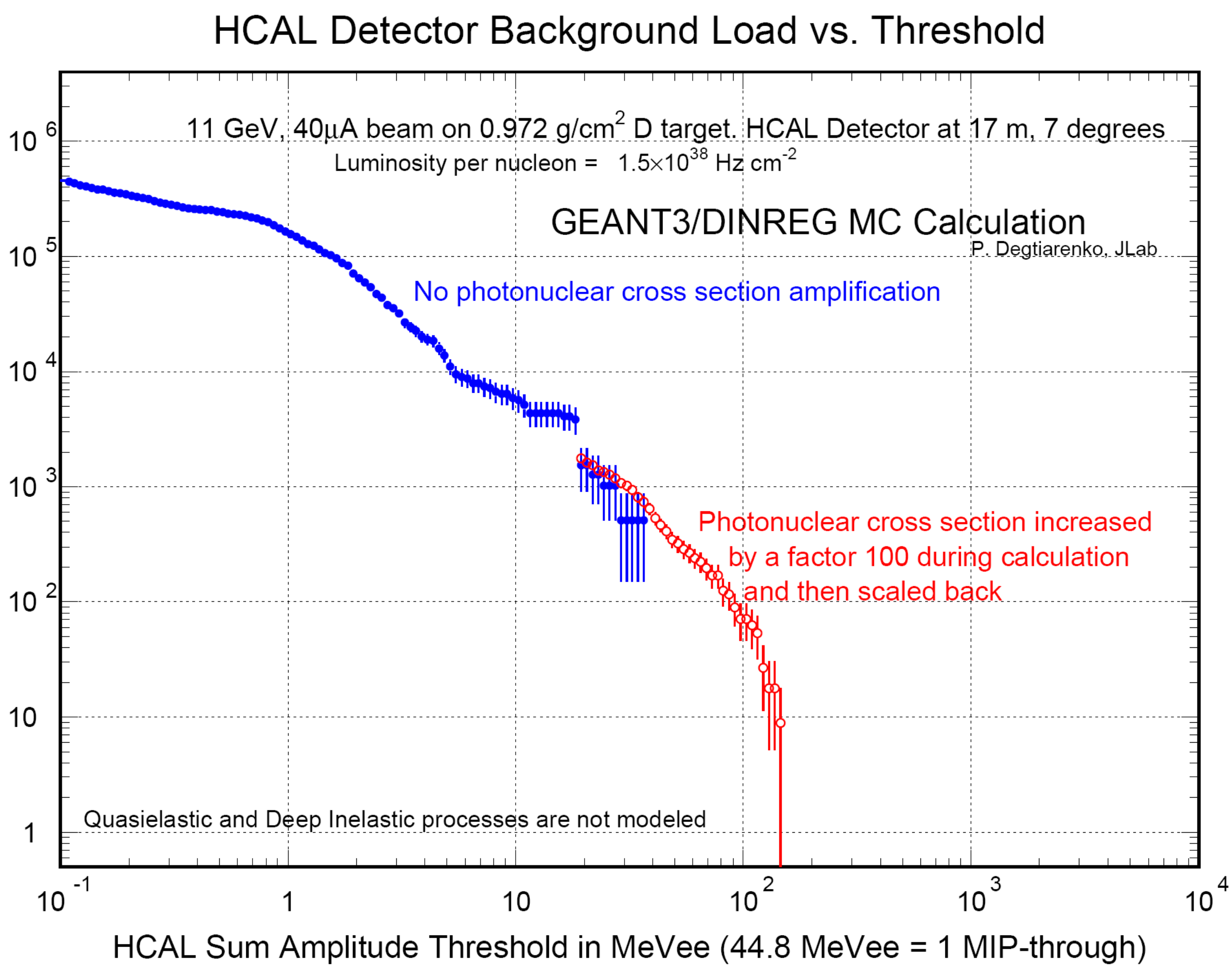


Hadron Calorimeter in Hall A



Hadron Calorimeter in Hall A



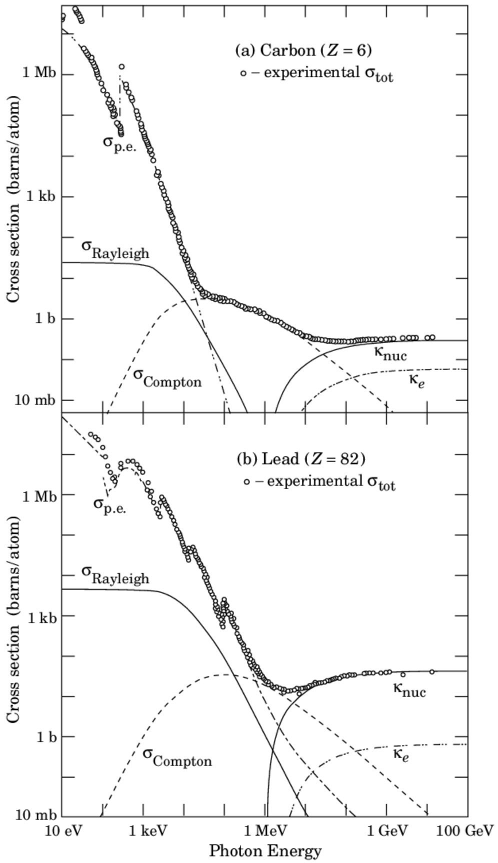
Monte Carlo Simulations

- Often, an MC simulation is the only method that could provide realistic estimates for the radiation fields, experimental backgrounds and count rate evaluations
- MC results can only be as good as the Physics Models implemented, and quality and reliability of the software, and skills and experience of the user
- The set of Physics models in a MC code is determined by the interests of the contributing Institutions
  - There was no γA in the standard GEANT3
- JLab supported setup of the DINREG code in GEANT3 and original development of the CHIPS code in Geant4 to include photo- and electro-nuclear processes

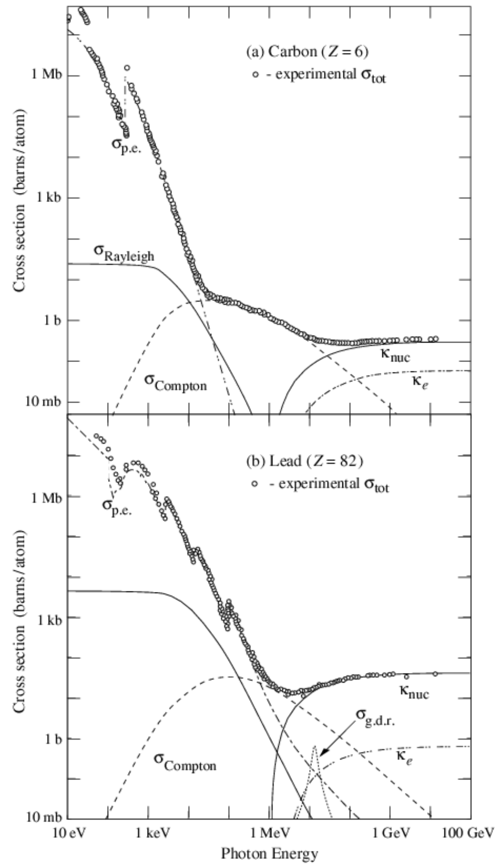
Physics Processes Important at JLab

- Electromagnetic processes:
  - Atomic photo-effect, Compton scattering, pair production (photons)
  - Ionization, bremsstrahlung, scattering, annihilation (electrons/positrons)
- Photonuclear and electronuclear reactions:
  - (γ,n), (γ,2n), (γ,p) … , or, in general,
    (electron or photon) + A $\rightarrow$ (hadron) + (anything)
- Both can't be neglected in shielding and radiation protection calculations
  - E-M processes determine the major portion of the bulk radiation dose and background at the vicinity of the target in an experimental hall
  - Energetic neutrons (E_{kin} > 50 MeV) from targets and beam lines in the halls give major contribution to the dose at CEBAF boundary

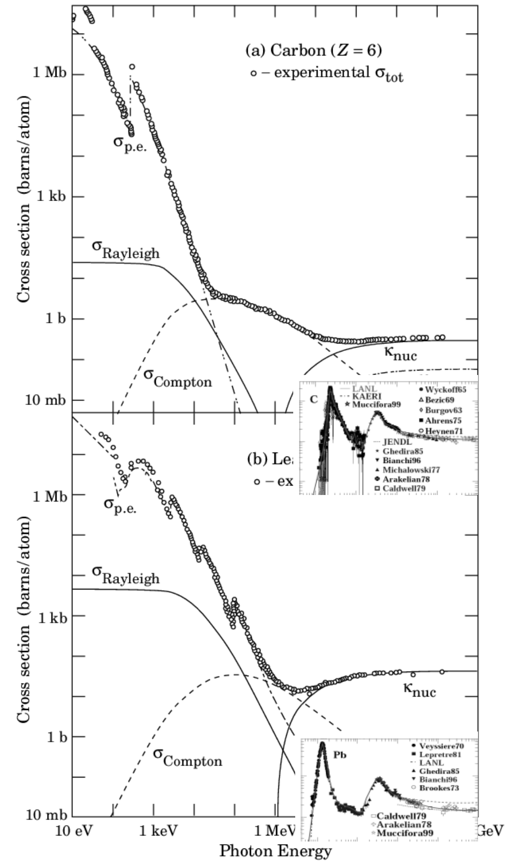
Physics Processes: Photonuclear



PDG'2002



PDG'2006



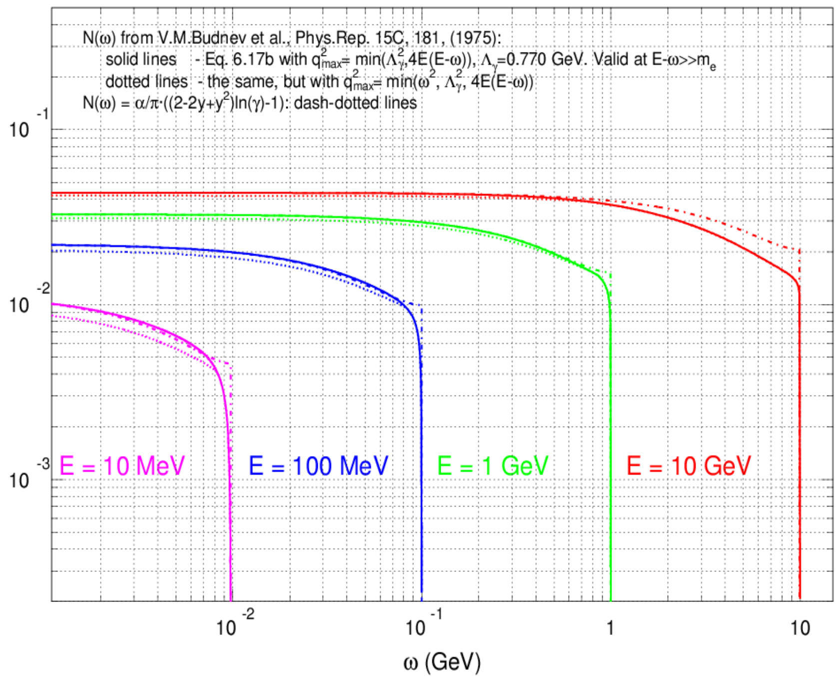
PDG'2010 (should be)

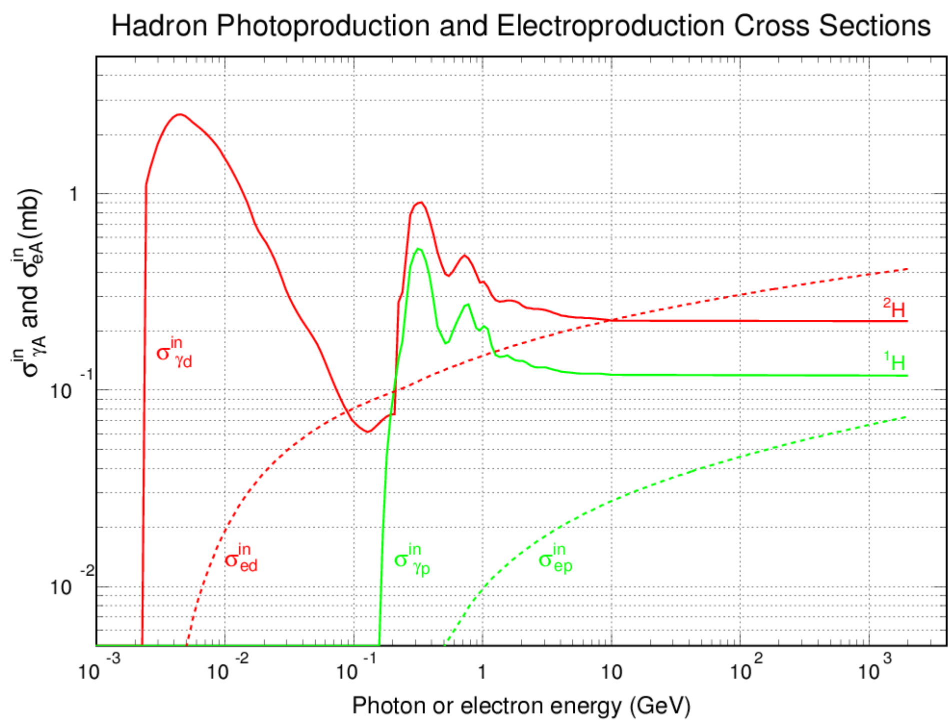
Photonuclear hadron production: missing in Particle Data Group listings until 2004!

Physics Processes: Electronuclear

Electronuclear processes: electron scattering that leads to a nuclear breakup: major contribution to backgrounds around thin experimental targets and their heat loads

Use Equivalent Photon Approximation (EPA) method: an electron interacts as a flux of photons with energy distribution $dN_\gamma / d\omega = N(\omega)/\omega$



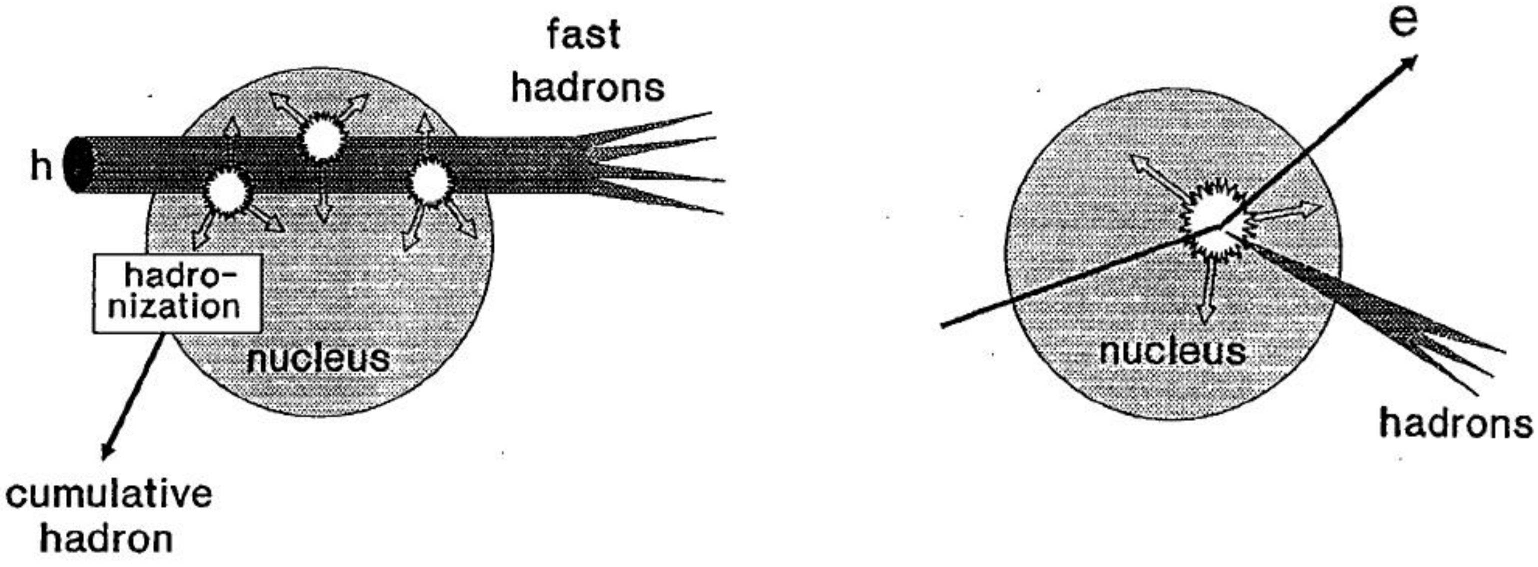


Source Terms at the Interaction Level

- Electromagnetic processes
  - Very well known
  - Can be described analytically, or using Monte Carlo event generators in EGS4, GEANT, MARS, or FLUKA simulation program packages, all of which give similar results. We use different approaches depending on the problem.
- Electro- and photoproduction of protons, neutrons, and pions from nuclei
  - Little known experimentally in the energy range from 1 to 12 GeV
  - Analytical description not known: would be complex function of beam energy, target nucleus, and energy, emission angle and type of the secondary hadron
  - Monte Carlo event generator DINREG/GEANT3 is used:
    - To derive source terms at the interaction level for subsequent use in analytical calculations
    - To model hadron production in the realistic models of experimental setups, thus allowing calculations of flux and dose distributions.

Physics of Nuclear Multifragmentation

- Model for the nuclear breakup: DINREG/CHIPS (M. Kossov, P. Degtyarenko)
  Based on experimental observations of hadron production at high energies, Deep Inelastic Nuclear Reactions (DINR)
- Universality of spectra and multiplicities of secondary hadrons and fragments
- Two-stage model of the process: (1) – excitation by incident particle, and (2) – energy dissipation by means of emitting hadrons and nuclear fragments
- Quark exchange mechanism of hadron and fragment production



DINREG Monte Carlo code

M. Kossov (ITEP, Moscow), and P. Degtiarenko (ITEP/JLab)

- Exclusive Monte Carlo event generator
- Use of experimental values of total cross sections
- Charge, energy, and momentum conservation
- Reproduces multiplicities and spectra in reactions with multihadron production at nuclear excitations 0.2 GeV and above
- Empirically found possible to be extended to the region of lower nuclear excitations: Giant Dipole Resonance and nuclear evaporation process
- DINREG code stays formally unpublished, but used extensively at JLab
- The new version of the code, CHIPS, has been developed for use in the Geant4 physics detector simulation package. A series of papers in the European Physics Journal published.

Need to Switch to Geant4 and Support It

- GEANT3: outdated, not supported, limited
- GEANT3/DINREG: barely publishable due to the use of old FLUKA for hadron transport…
- Geant4 has the latest physics, but:
  - Needs detailed benchmarking and comparison with experimental data for JLab environment
  - Needs re-analysis of available, and getting new experimental data on photonuclear and electronuclear reactions, and other physics processes of interest
- JLab should join Geant4 collaboration in providing benchmarking data and developing relevant models (Quasielastc, Deep Inelastic, eA elastic, high Q2, etc.)

Conclusions

- There's a reasonable degree of confidence in the methods implemented at JLab for the radiation background calculations and modeling
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- However, the development of the Monte Carlo simulation software should be sustained and supported:
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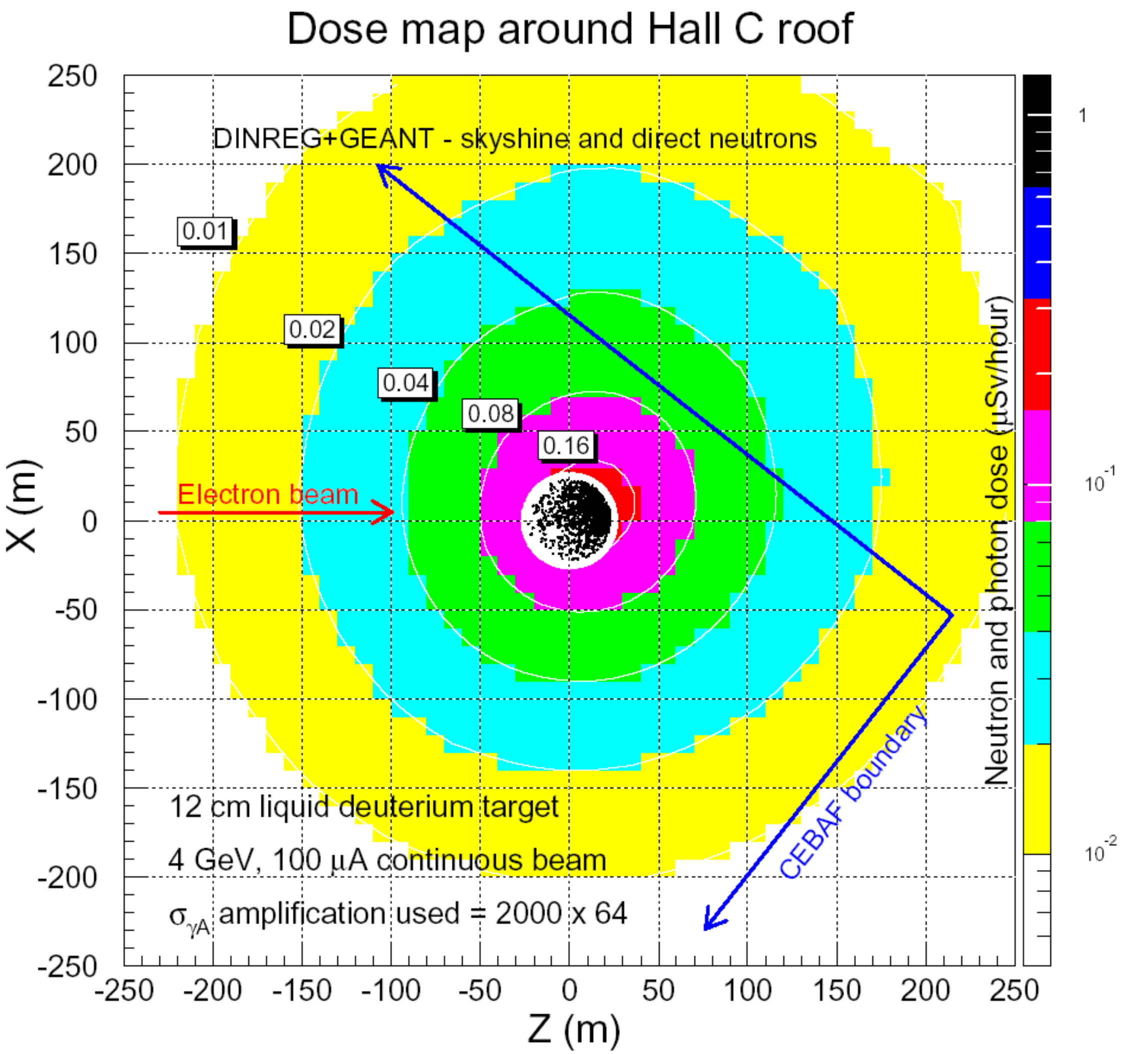
DINREG in GEANT3

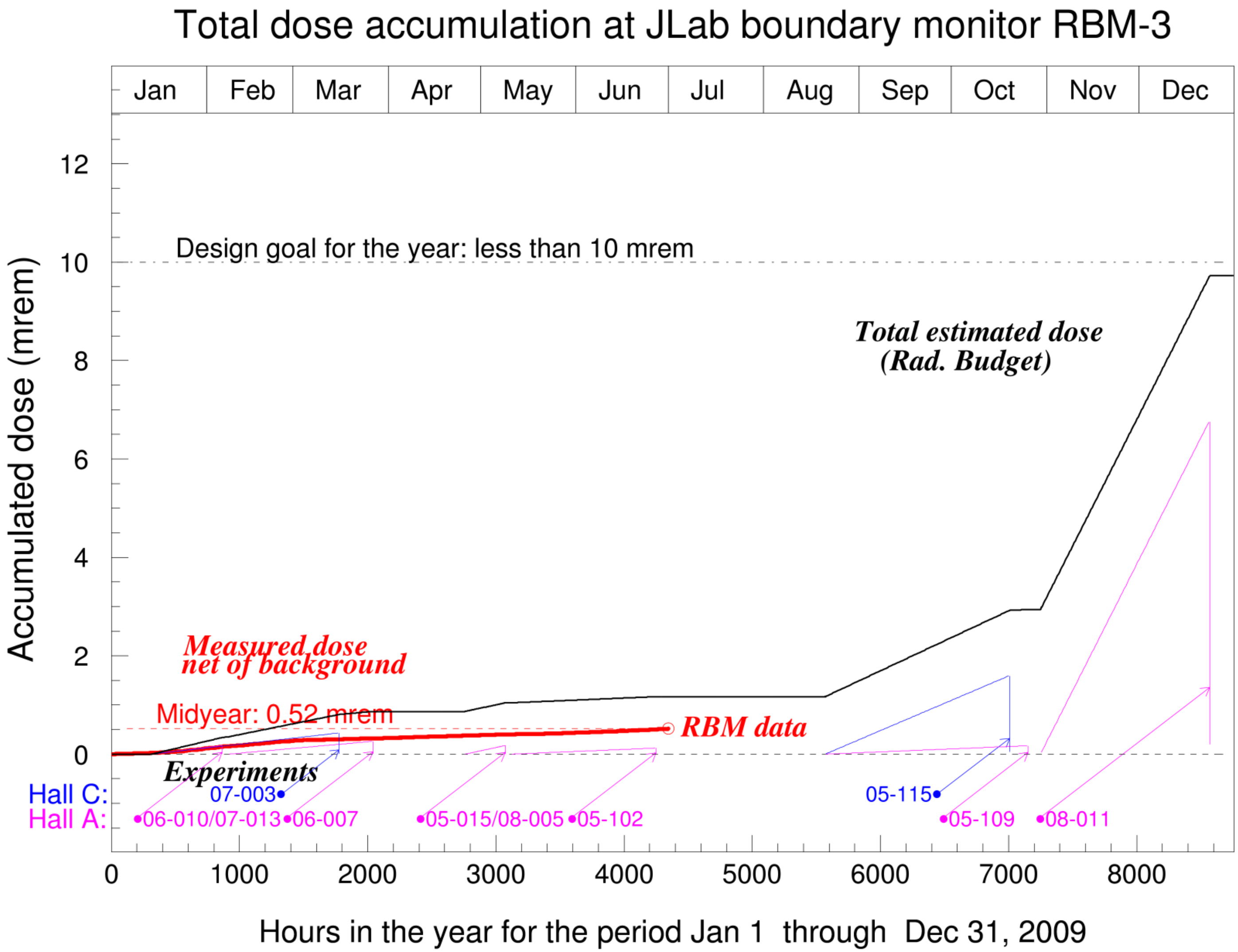
- GEANT3: detector simulation package from CERN
  - Detailed MC-simulation of all major physics processes
    - electromagnetic interactions
    - hadron interactions
  - Flexible geometry package with powerful graphics
  - Bundle with data analysis package PAW
  - User-open
- Add DINREG
  - New γA interaction mechanism: use experimental cross sections
  - New eA interaction mechanism: electron/positron representation in the form of spectrum of equivalent photons
  - Tools for cross section amplification
- DINREG/GEANT results agree well with sparse data available

Dose Map Calculation Example

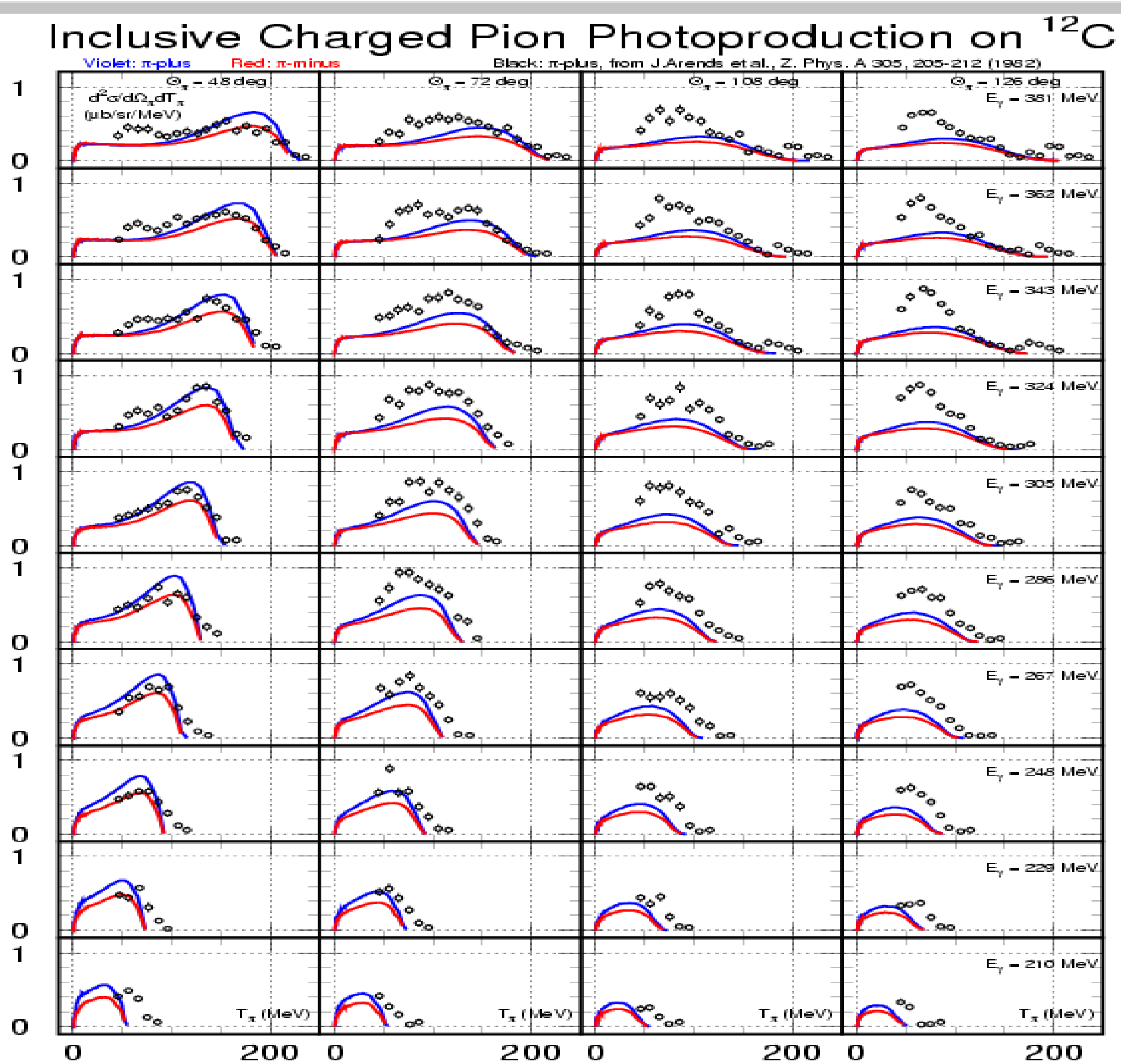


- Example shows the standard setup in the Hall C with Liq.D target, run at 4 GeV, 100 μA beam
- Neutrons exit the roof (shown by black dots), scatter and cascade in the air, producing dose rate at the boundary.
- Dose rate expected is about 6-7 μrem/h

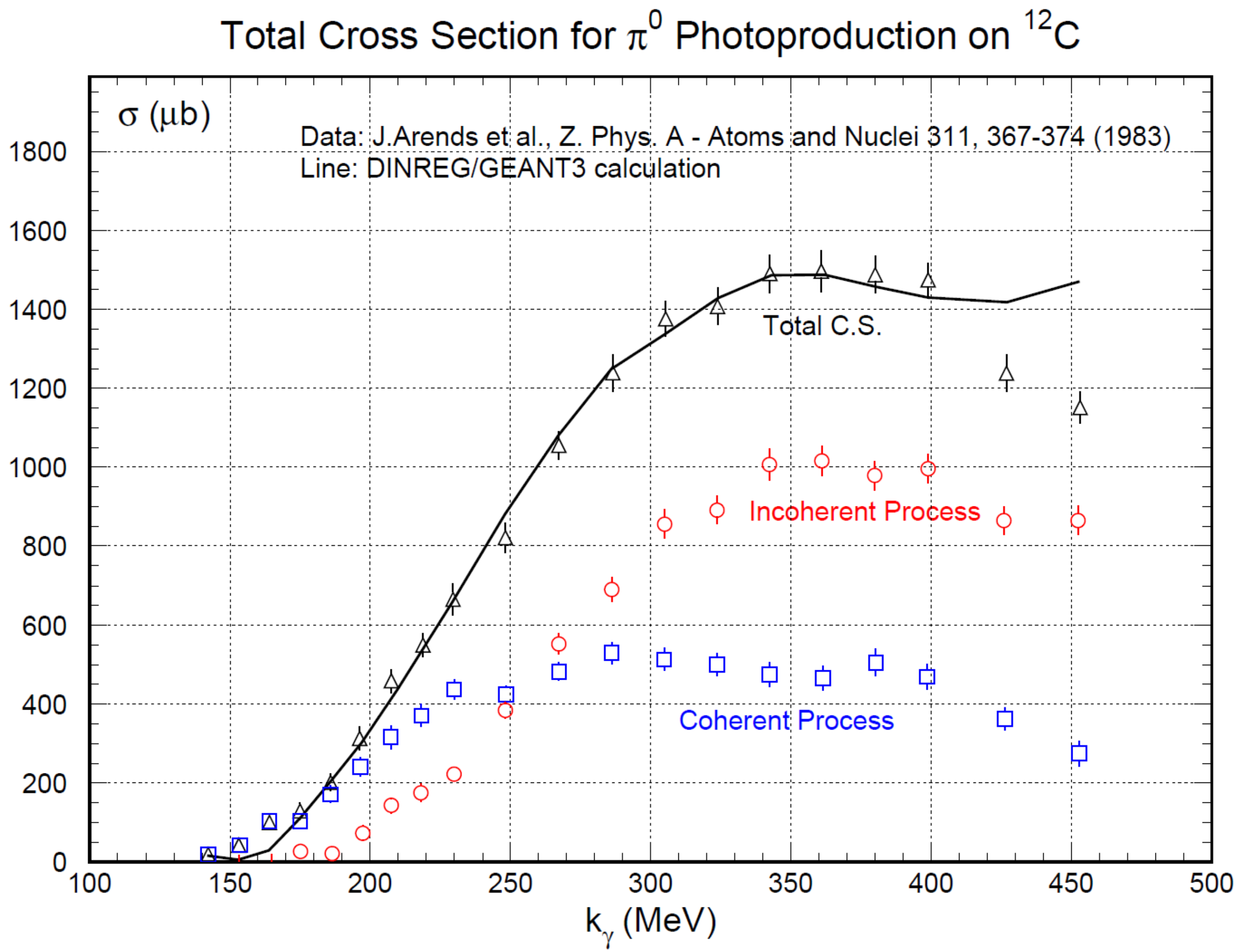
Radiation Budgeting Reports



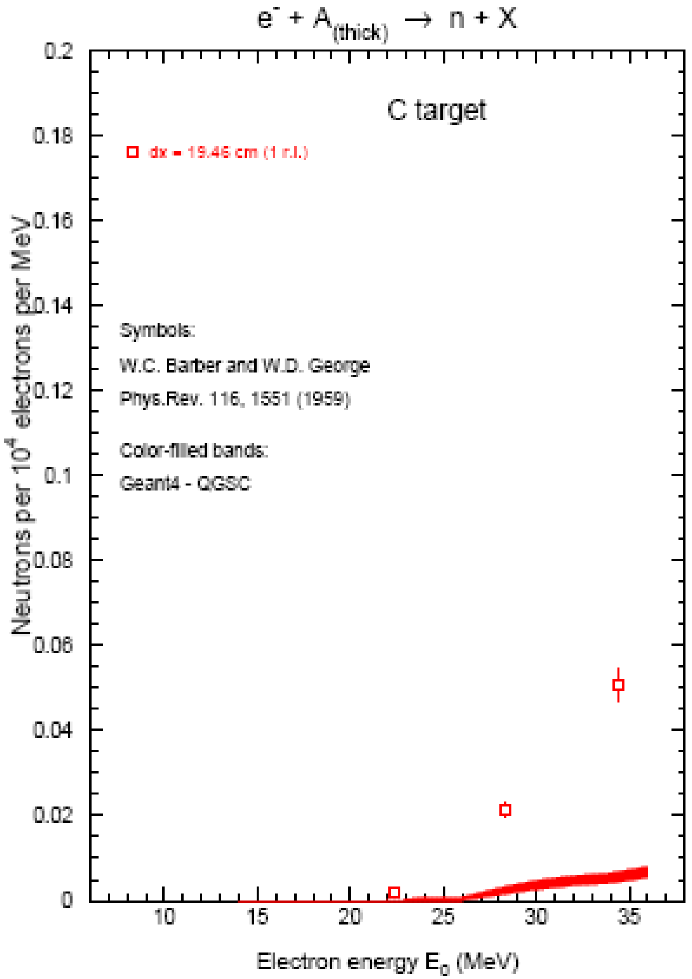
Benchmarking: charged pions

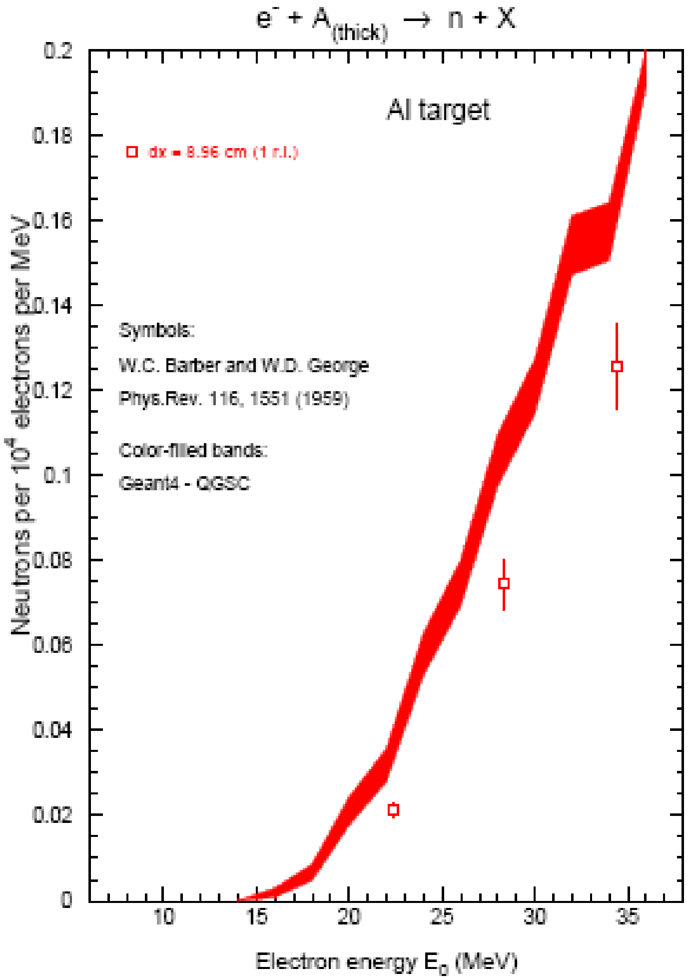


Benchmarking: neutral pions

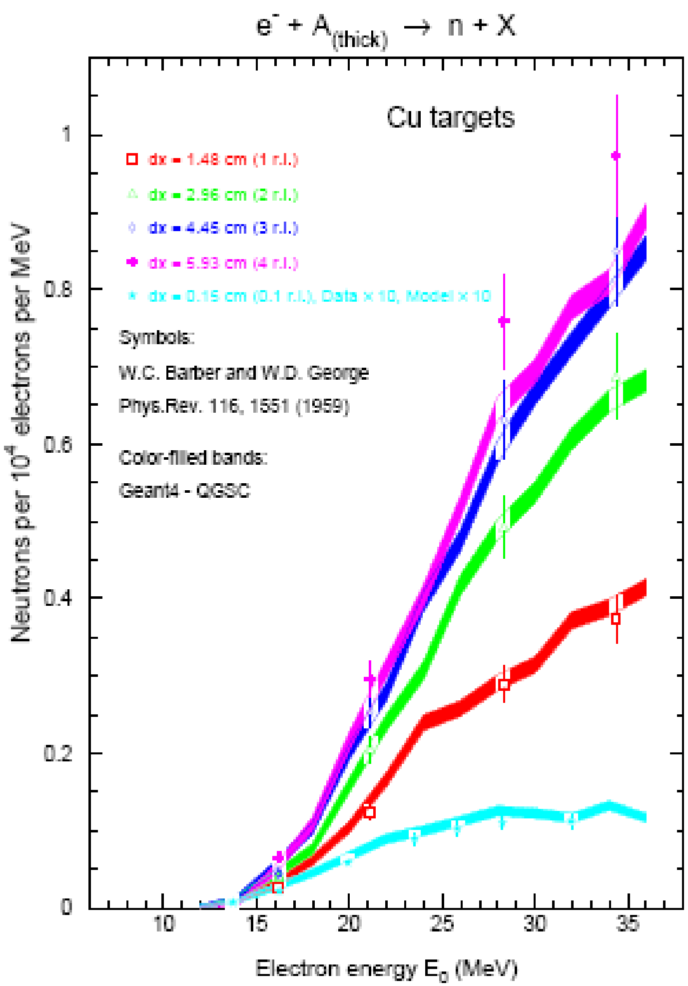


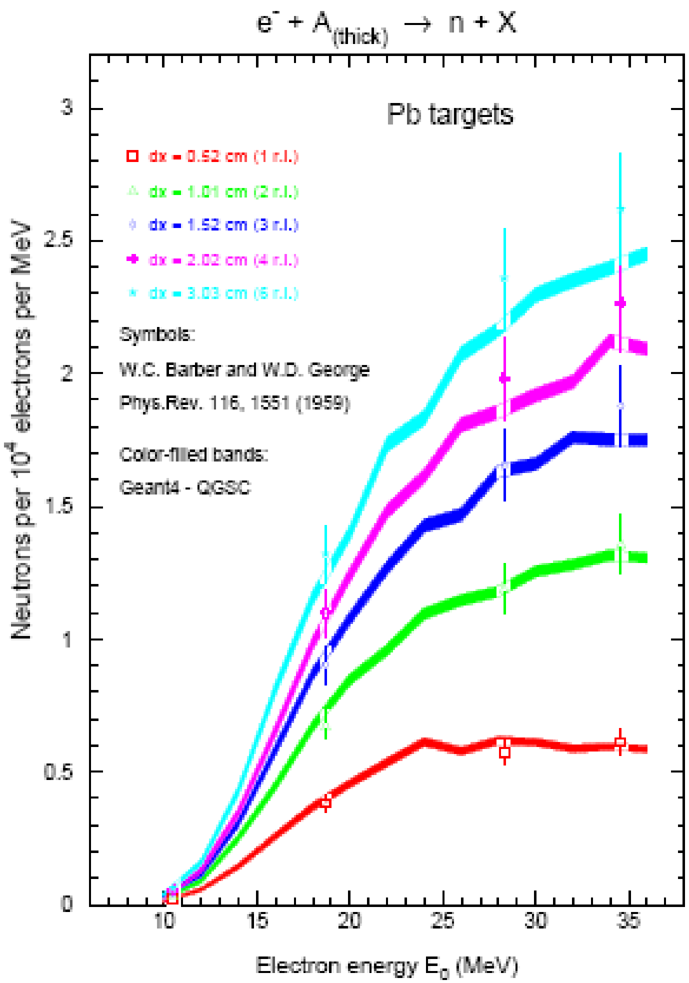
Benchmarking: Geant4, neutrons from C, Al





Benchmarking: Geant4, neutrons from Cu, Pb





Benchmarking: Geant4, neutrons from U tgts