Radiation Effect Modeling at Intensity Frontier: Status and Uncertainties

Nikolai Mokhov

Fermilab

HB2012 - 52nd ICFA Workshop on High-Intensity and High-Brightness Hadron Beams

Beijing, China

September 17-21, 2012

Outline

- Introduction
- Addressing Issues via MC Modeling
- LBNE and Mu2e as an Example
- Particle and Nuclide Production
- Electromagnetic Interactions
- Energy Deposition
- DPA and Radiation Damage
- Radiation Shielding
- Conclusions

Introduction

The next generation of accelerators and experiments for MegaWatt proton, electron and heavy-ion beams moves us into a completely new domain of extreme specific energies of ~0.1 MJ/g and specific power up to 1 TW/g in beam interactions with matter.

The consequences of controlled and uncontrolled impacts of such high-intensity beams on components of accelerators, beamlines, target stations, beam absorbers, shielding and environment can range from minor to catastrophic.

Related Issues in Machine and Experiments

- Accidental and operational beam losses and their destructive impact on machine and detector components, performance and environment
- Maximum useful particle & minimal background particle yields
- Quench, integrity & lifetime: power density, integrated dose, DPA, gas production in critical components, e.g., SC coils and organic materials as well as soft errors (SEU) in electronics
- Radiological aspects: shielding, nuclide production, residual dose, impact on environment.

All of the above are attacked via thorough simulations. How reliable are they?

MARS Code for Intensity Frontier

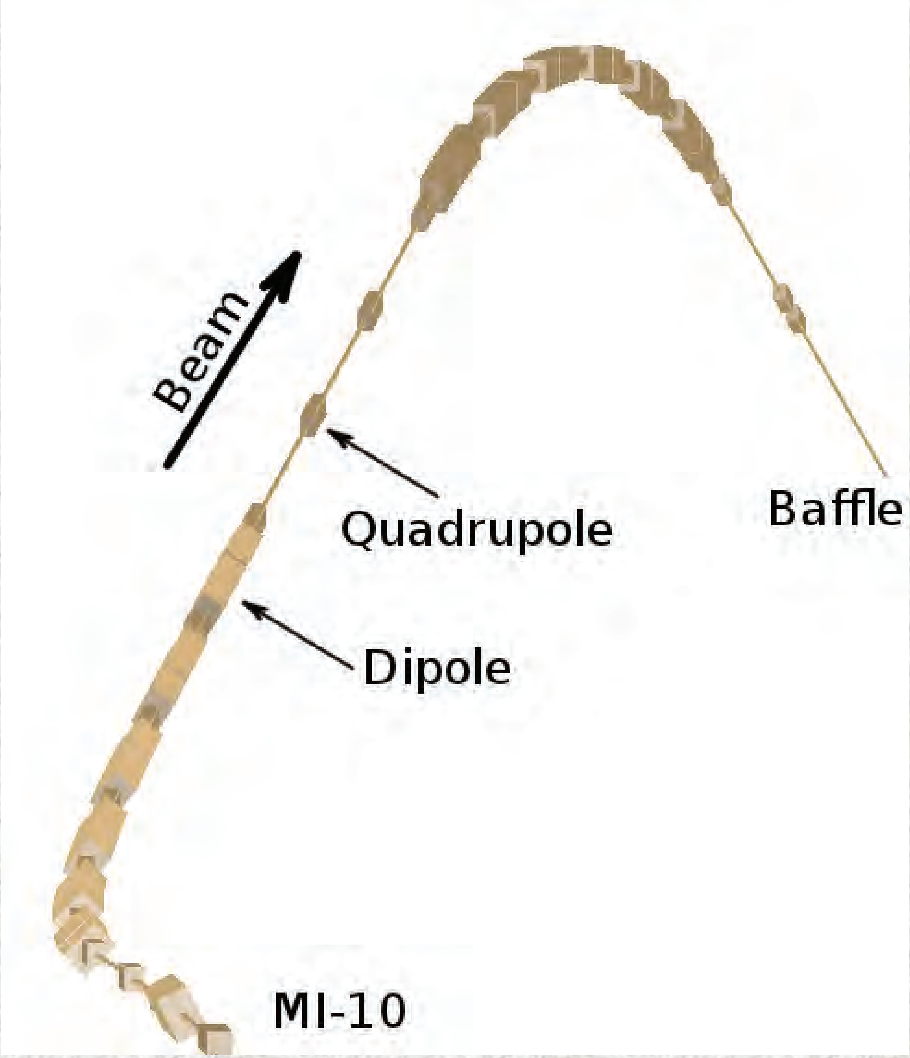
MARS

- Particle yields: p,n,π,K,μ,Σ,HI
- Nuclide inventory
- Radiation damage: DPA, dose, H/He, soft errors (SEE)
- Background suppression
- Beamline optimization, beam loss, particle capture and collimation, SC magnet quench
- Prompt and residual radiation, shielding, impact on environment
- Targetry: power dissipation, integrity (shock & buildup), magnetohydrodynamics

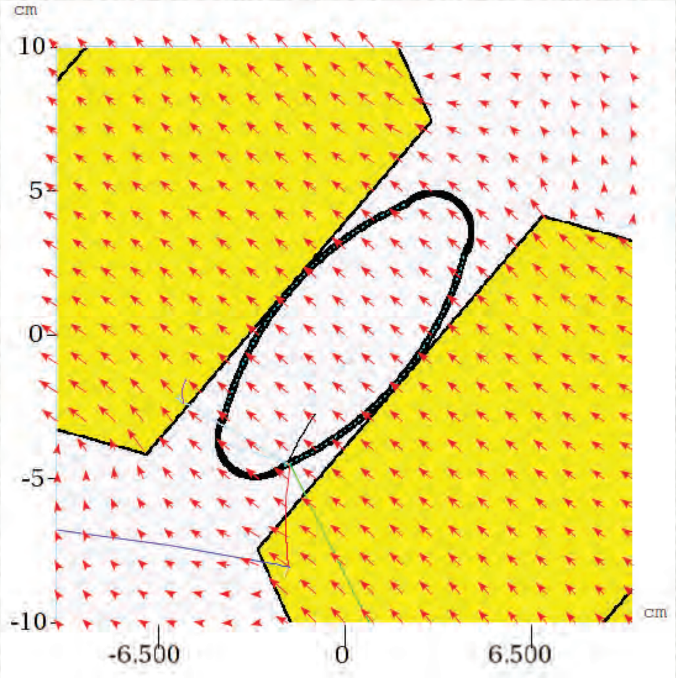
LBNE Primary Beamline

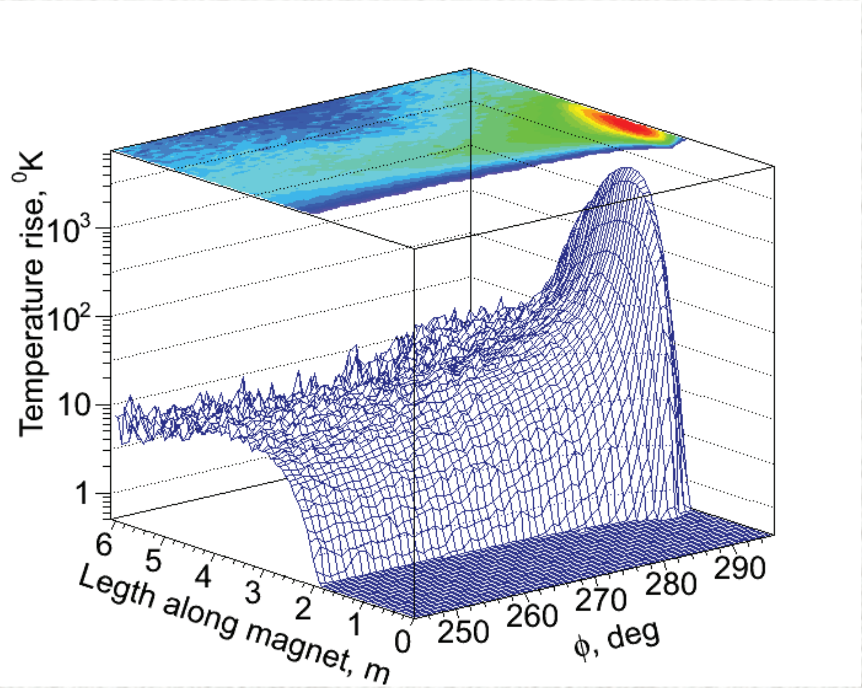
Detailed simulations to evaluate the impact of beam loss ranging from a single pulse full loss to sustained small fractional loss.

Radiation requirements are quite stringent and vary from region to region. Accidental beam losses can cause beam line component damage. Prompt radiation may be one of the main issue in the above-grade target option.



Localized Full Beam Loss at Any Location Along the Beamline





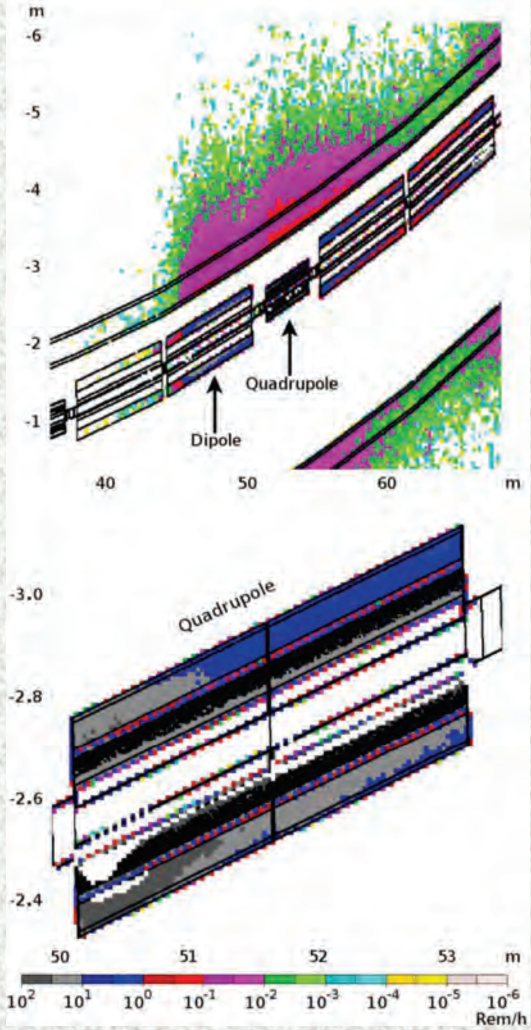
Peak beam pipe temperature of **<u>twice the melting point for stainless steel</u>** is reached with a **<u>single lost full beam pulse</u>** of 1.6e14 ppp. **Large beam loss for even a single pulse needs to be robustly prevented.**

Residual Activation at Sustained Fractional Beam Loss

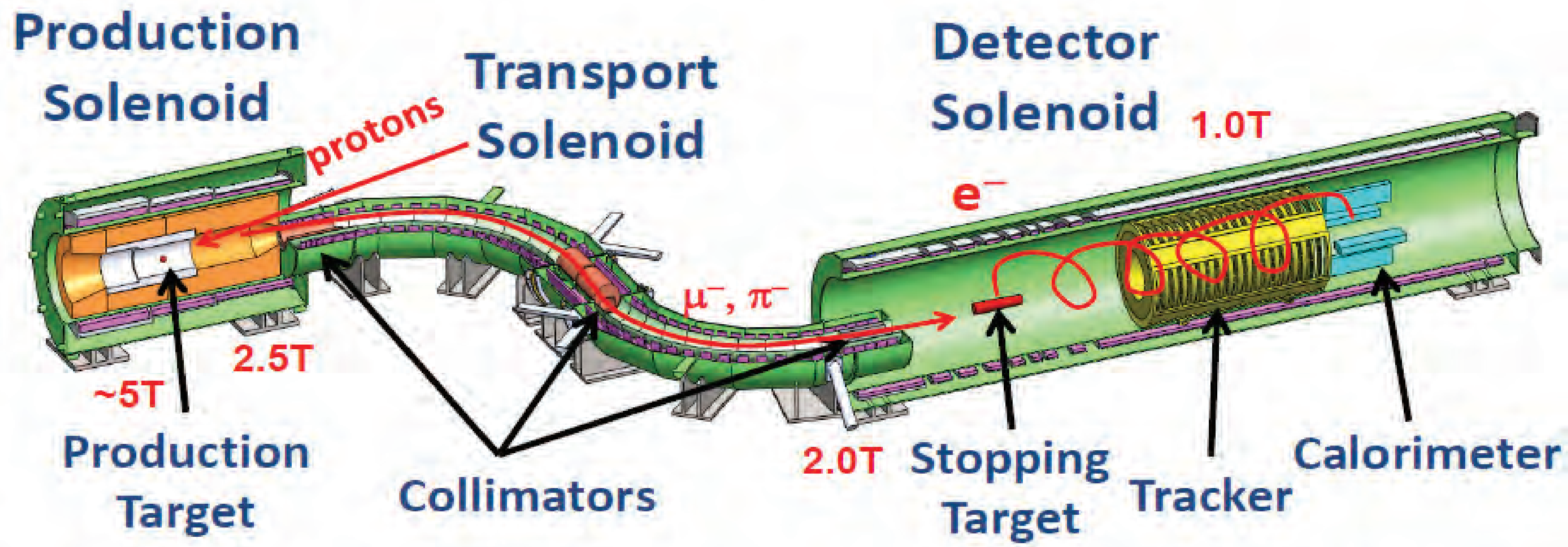
For a scenario where there is **accidental beam loss at 0.3% of the beam** for 30 continuous days, calculated with MARS15 the peak contact dose after 24 hours of cool-down is:

- For tunnel walls, **5 mSv/hr** over a 20-ft region of the tunnel, and > 1 mSv/hr over a 50-ft tunnel region.
- For the hottest magnet, **500 mSv/hr** over several feet of magnet steel, and > 100 mSv/hr over most of a 10-ft magnet.

Even after waiting 6 months with no beam, a magnet would still be at > 30 mSv/hr in the hottest region. Fermilab limit of 0.5 mSv/hr on contact to "safely permit all necessary maintenance" dictates sustained localized beam loss to be a **factor of one thousand** less than considered above, in a good agreement with NuMI req. Hence, **Integrated Beam Permit System**.



Mu2e Experiment



(not shown: Cosmic Ray Veto, Proton Dump, Muon Dump, Proton/Neutron absorbers, Extinction Monitor, Stopping Monitor)

MARS Optimized-Design Values vs Limits

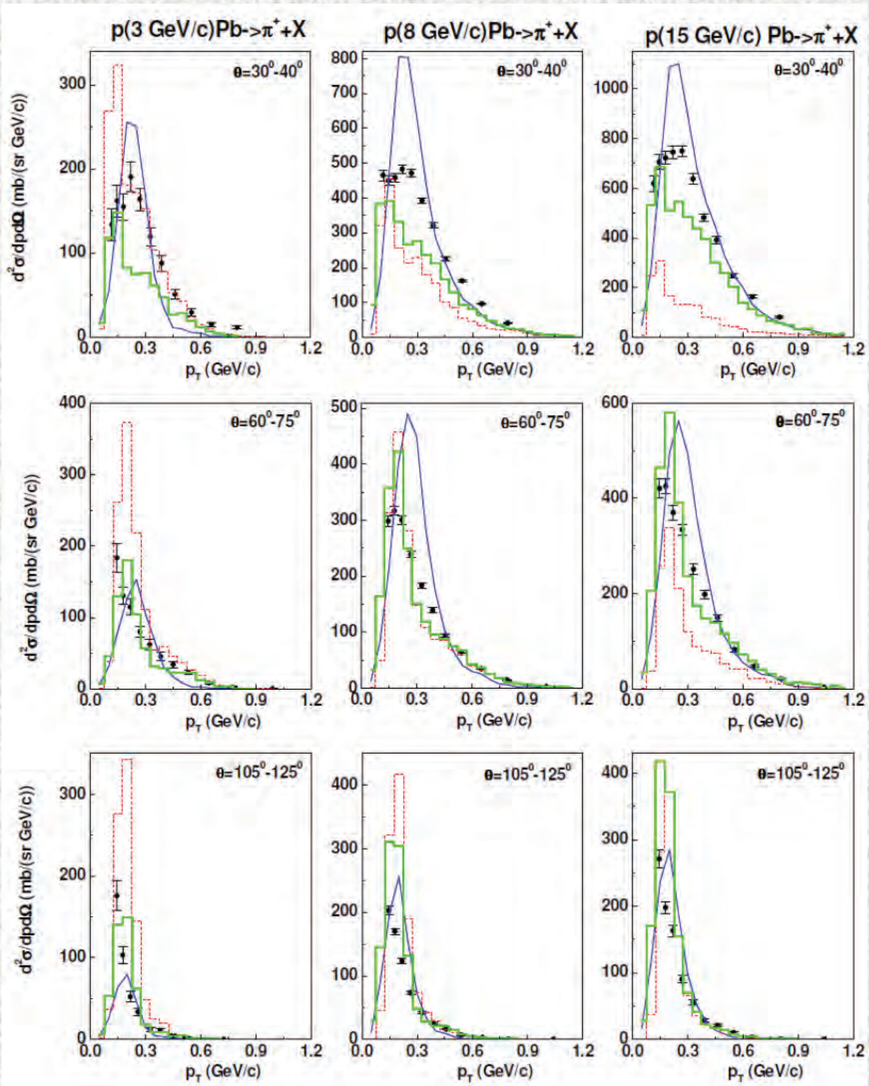
Quantity	MARS15	Limits
Peak Total Neutron flux in coils, n/cm2/s	$8.3*10^9$	
Peak Neutron flux > 100 keV in coils, n/cm2/s	$3.1*10^9$	
Peak Power density, μW/g	18	30
Peak DPA	$3.2*10^{-5}$/yr	$4\text{-}6*10^{-5}$
Peak absorbed dose over the lifetime, MGy	1.65	7
Dynamic heat load, W	20	100

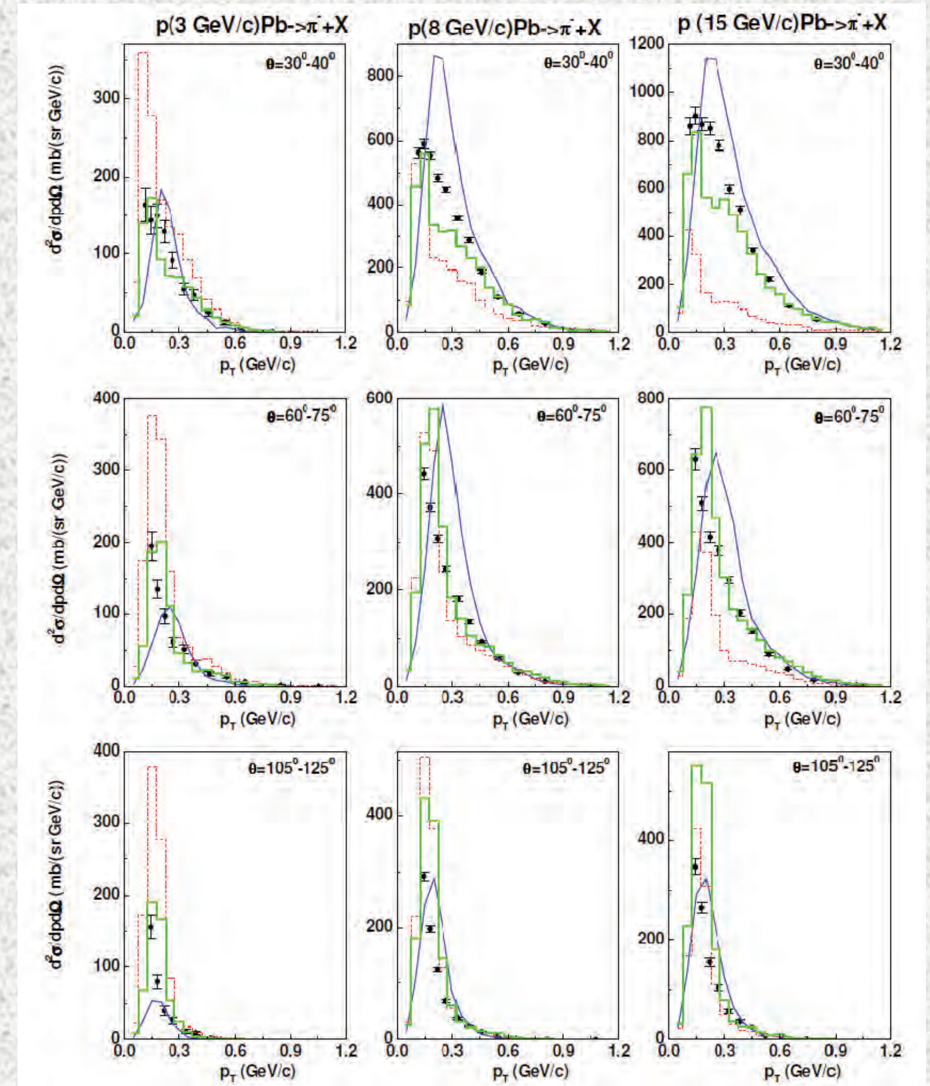
- Radiation damage is a key issue for experiments at the Intensity Frontier
- Models are developed and experiments are proposed to understand and address the issue
- Current Mu2e design solutions are safe during the lifetime of the experiment but more work is needed for fine tuning, value engineering and upgrade (Project X)

Particle Production in Nuclear Interactions

- The key for fixed target and collider experiment planning.
- The origin of the majority of beam-induced deleterious effects in machine/detector components and environment.
- OK at E_p < 1 GeV and E_p > 10 GeV.
- At intermediate energies, most interesting for the Intensity Frontier: substantial theoretical difficulties; experimental data contradict each other; the main problem with low-energy pion production that is crucial, e.g., for all Project X experiments.

Geant4 Models vs HARP-CDP for p+Pb -> $\pi^{\pm}$ X at 3, 8 and 15 GeV/c

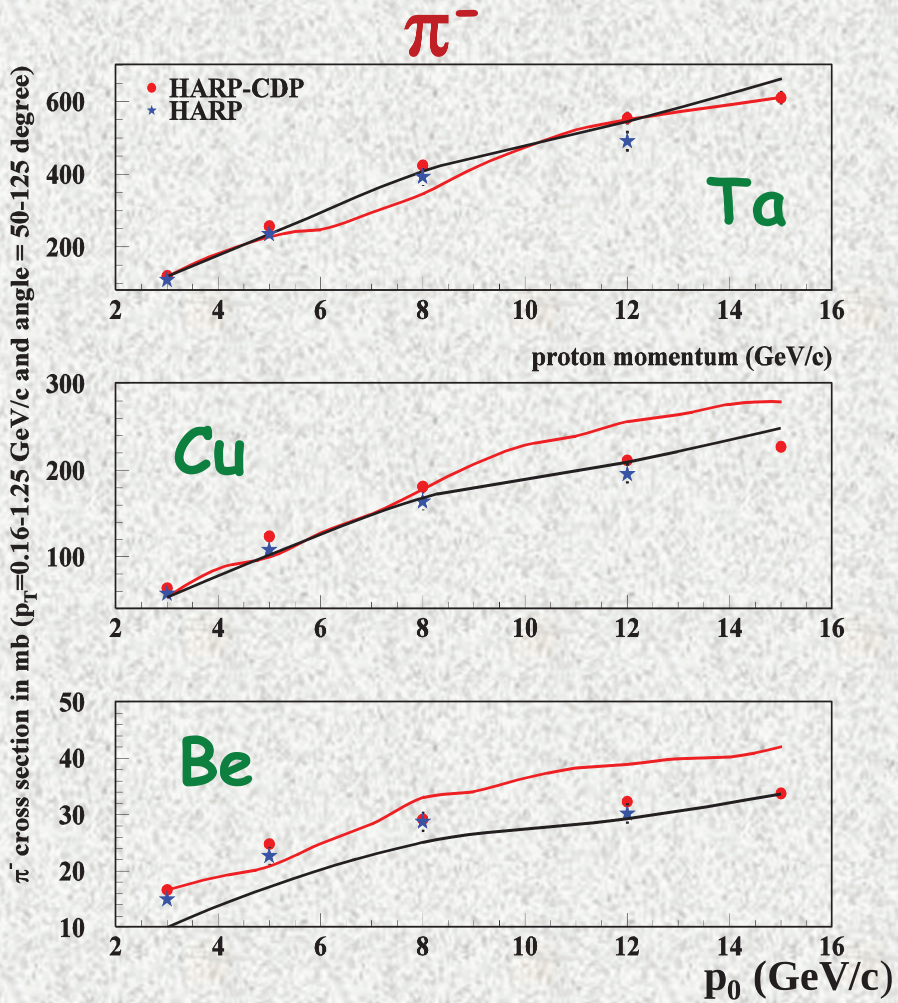




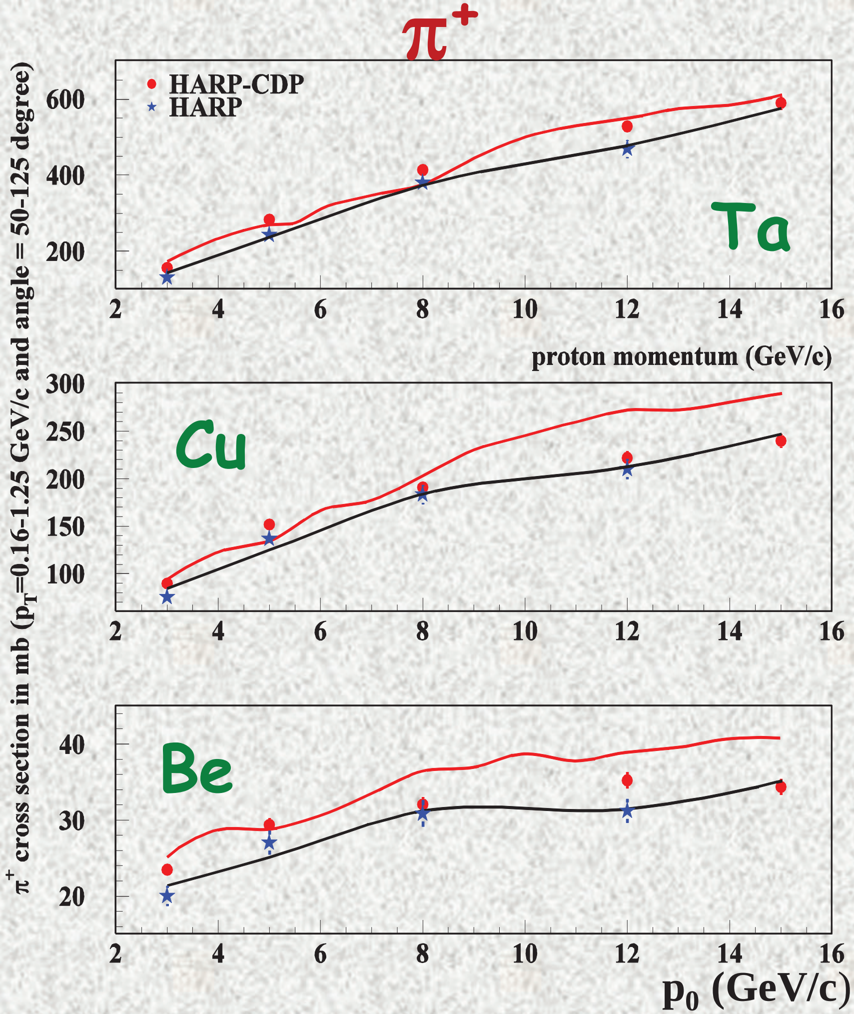
Green – UrQMD, red – Binary, blue – Fritiof

Pion Production Cross-Sections at 3-15 GeV/c

Protons on Be, Cu and Ta: FLUKA and MARS15/LAQGSM vs HARP



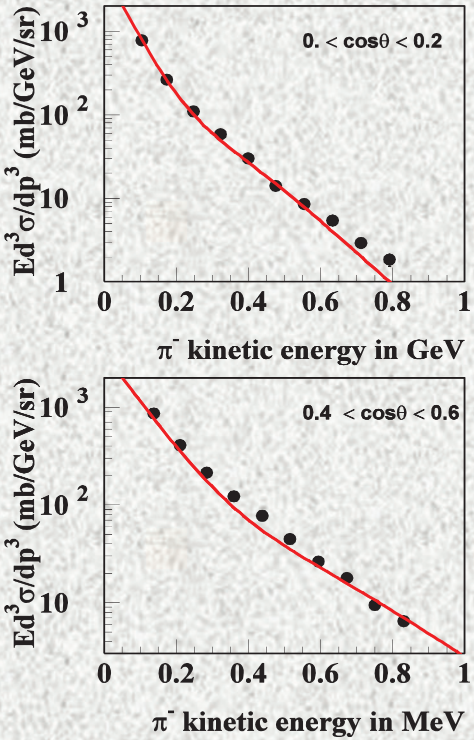
Red lines - FLUKA, black lines - LAQGSM



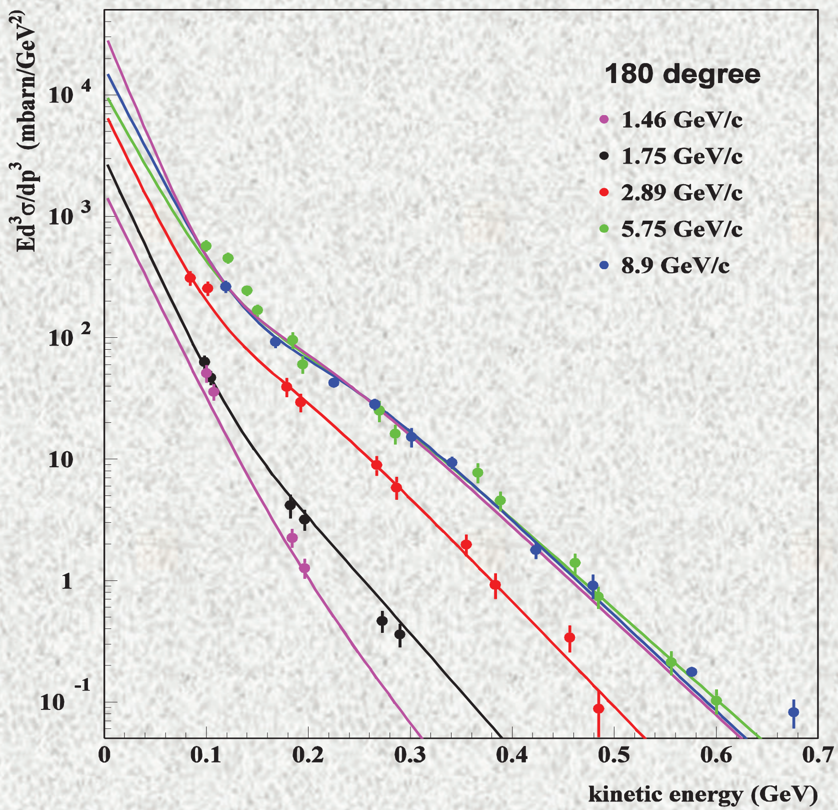
Red lines - FLUKA, black lines - LAQGSM

MARS15 Inclusive Model: π^- Production on Lead

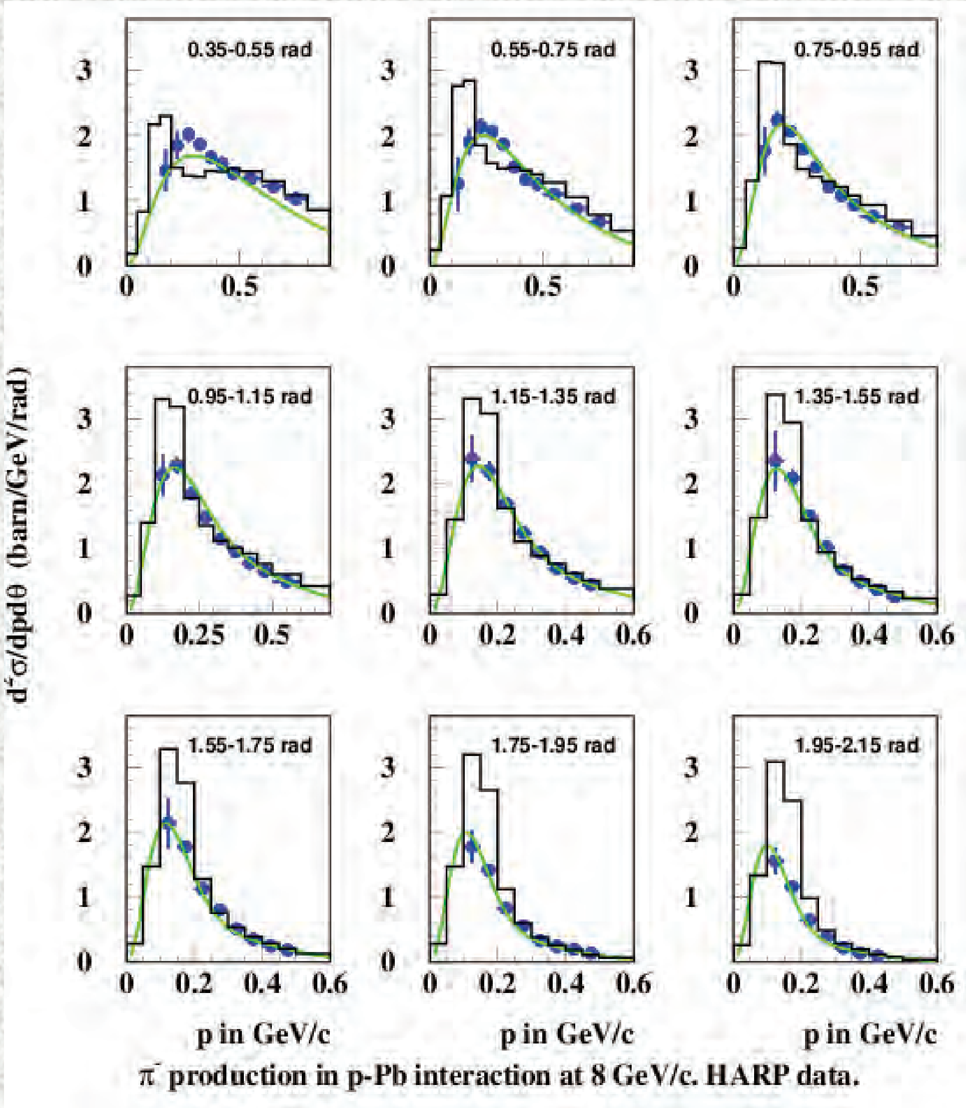
Versus KEK data at 4 GeV/c



Versus 1.46-8.9 GeV/c data



Problem Still Remains…



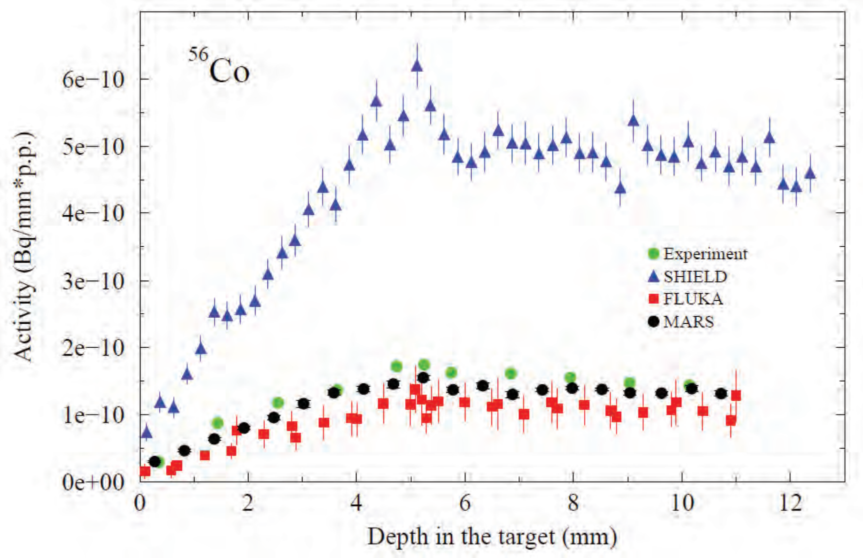
π^- production in p-Pb interaction at 8 GeV/c. HARP data.

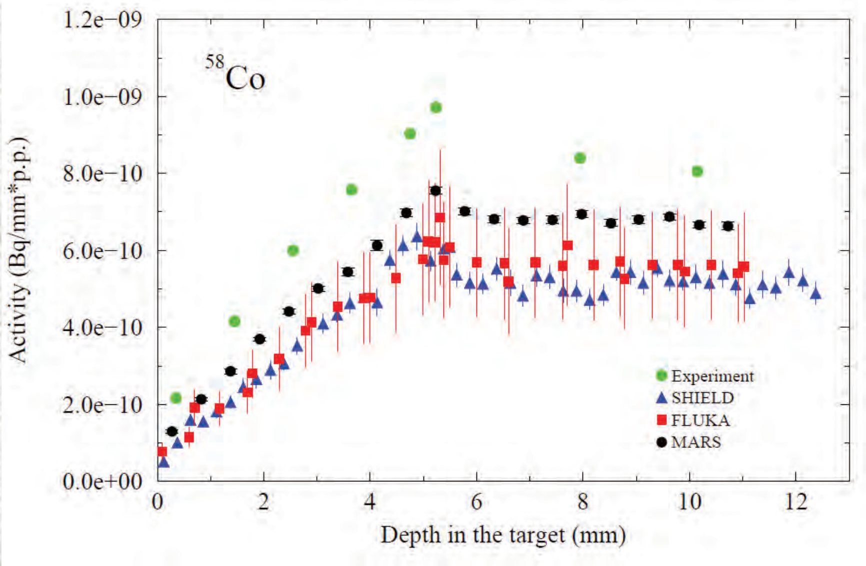
Despite of substantial improvements in LAQGSM2012, it still overestimates HARP pion data at p<200 MeV/c at large angles on heavy targets, being at the same time in a good agreement with HARP-CDP data for this region (data contradict each other!)

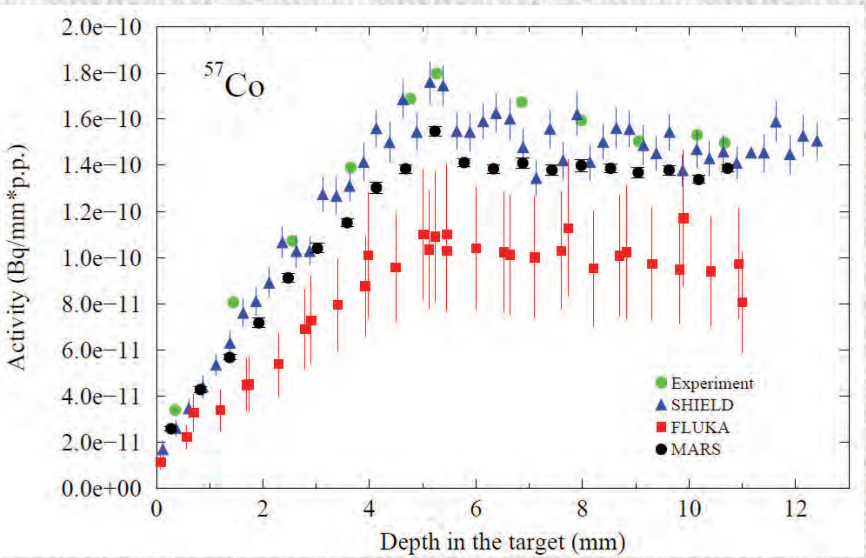
Trivial attempts to fix the problem by increasing the pion absorption x-section do not help much damaging the whole picture.

Work is underway to resolve this issue.

Benchmarking Calculated Activity: 500 MeV/A U + Cu







GSI data: E. Mustafin et al. Proc. of EPAC 2006, TUPLS141.

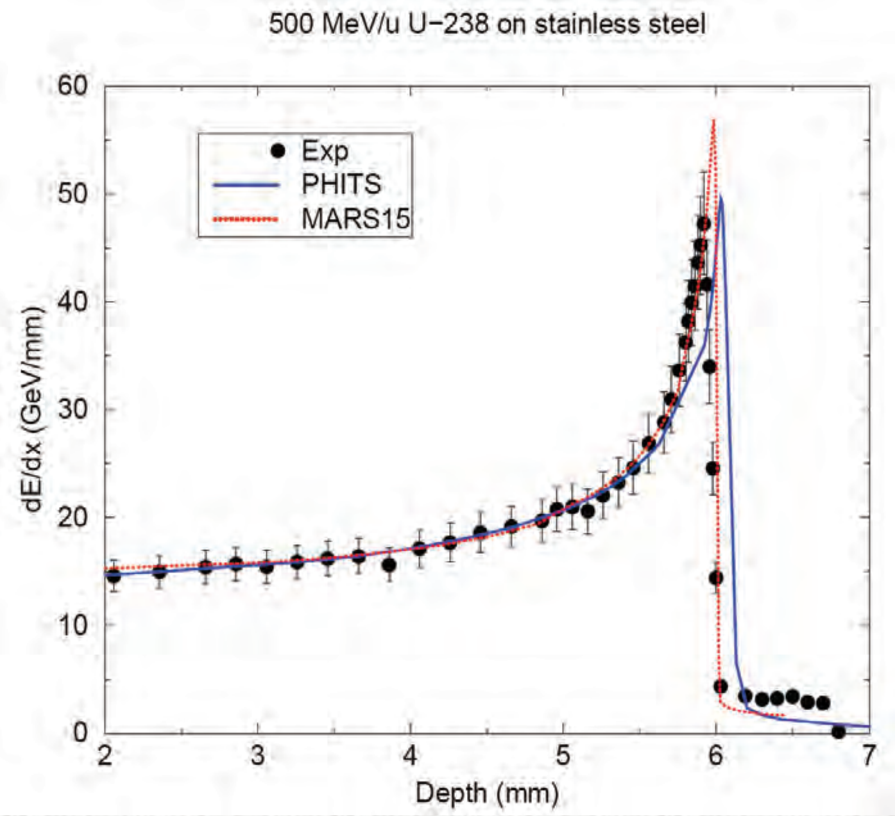
Particle and Nuclide Production at 1-10 GeV: Status and Needs

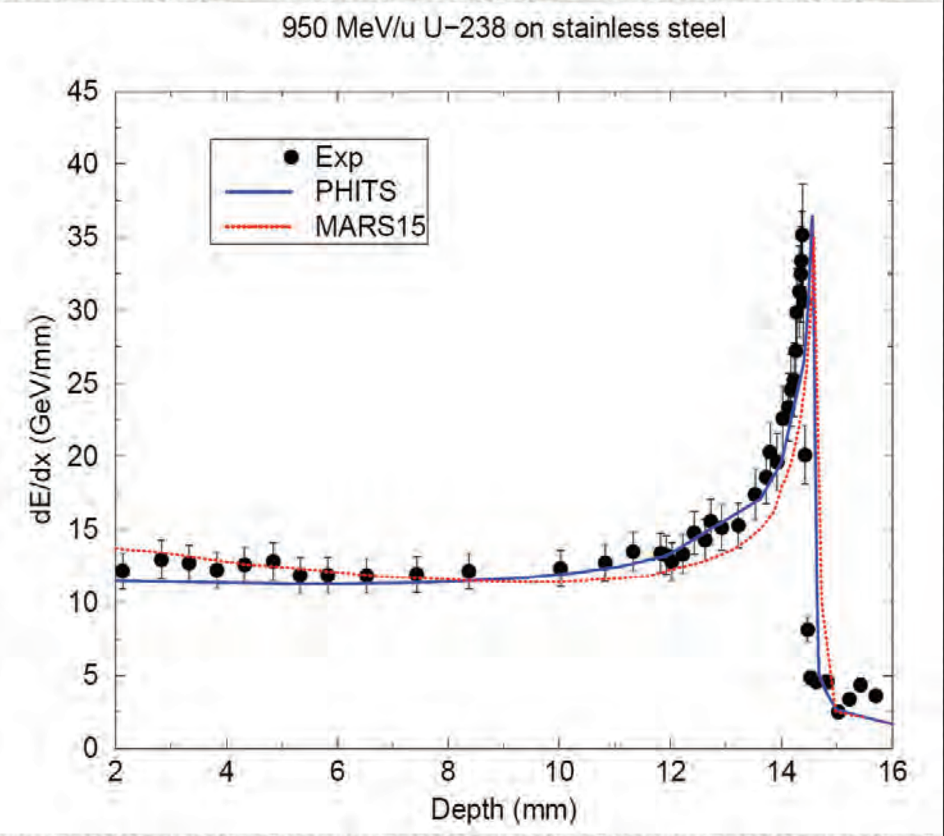
- Production x-sections (total particle yields) modeled with the current versions of MARS15, FLUKA and INCL-HE agree within 10% with data. These code's event generators (for MARS15: CEM, LAQGSM and inclusive) predict general features of double differential x-sections, but can disagree with data up to a factor of 2 to 3 in some phase space regions.

- Nuclide production is described quite reliably by the event generators of the above three codes, although there are issues with some channels.

- <u>**Data needs:**</u> low-energy pion/kaon/pbar spectra at E_p=2-8 GeV; neutrons in fragmentation region; light fragment yields; nuclide yields for difficult cases; more ion and photon induced reactions.

500 and 950 MeV/u U-238 on Stainless Steel





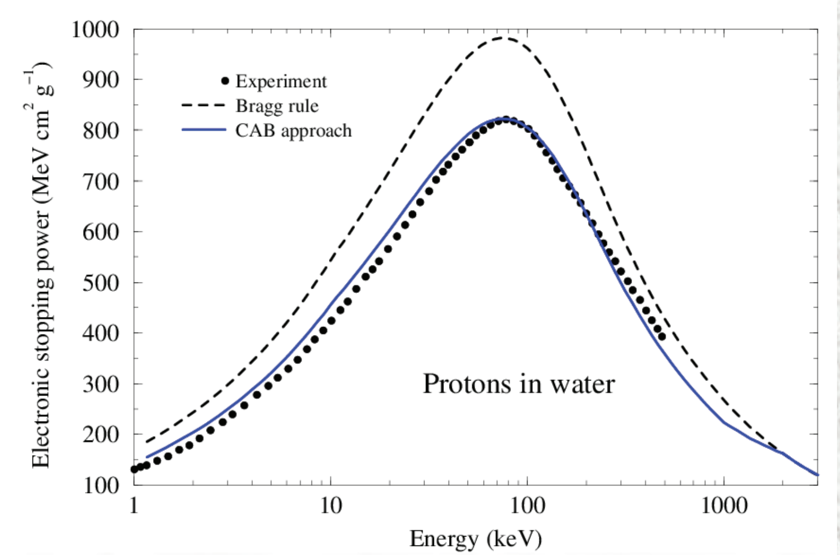
MARS15 and PHITS vs GSI data

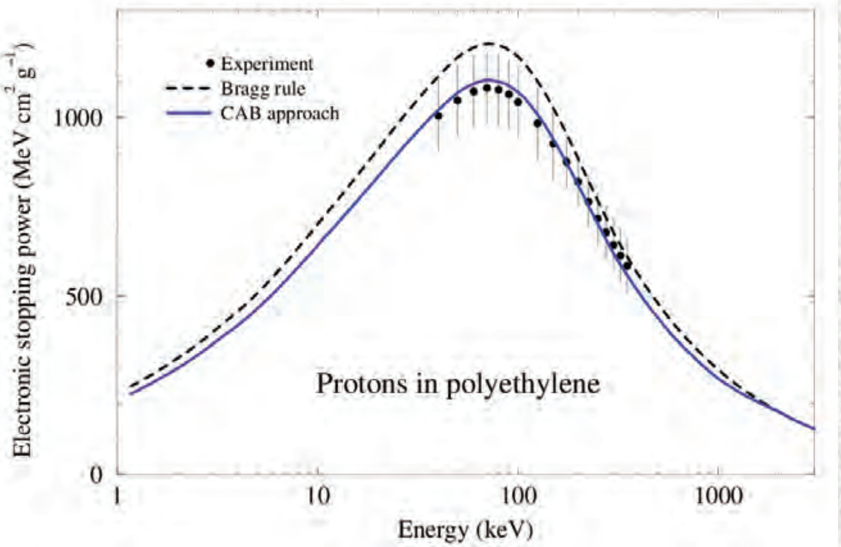
Mean Stopping Power in Compounds: CAB (2012)

Stopping power of ions in compounds usually is described according to Bragg's rule. At low energies and for low-Z materials the difference between measured and predicted dE/dx can be as large as 20%.

The "cores-and-bonds" (CAB) method developed by G. Both et al. was implemented in MARS15(2012) taking into account chemical bonds fitted to experiment for various compounds at 1 keV to 3 MeV.

At higher energies, the Sternheimer and Peierls density correction algorithm for compounds is employed.



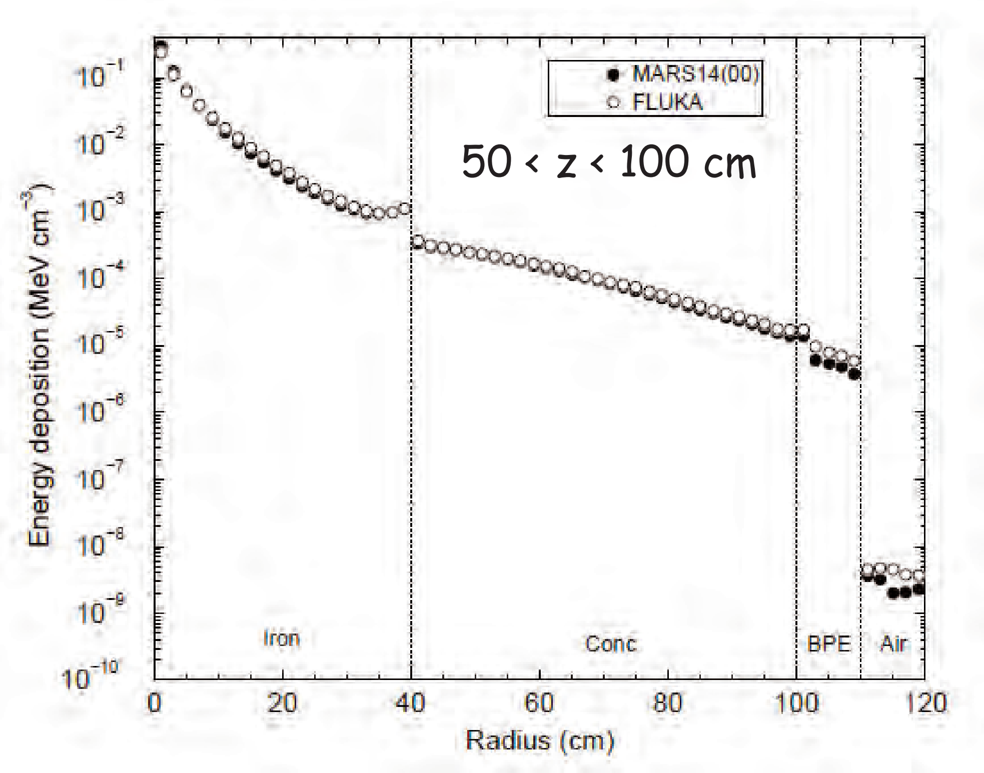


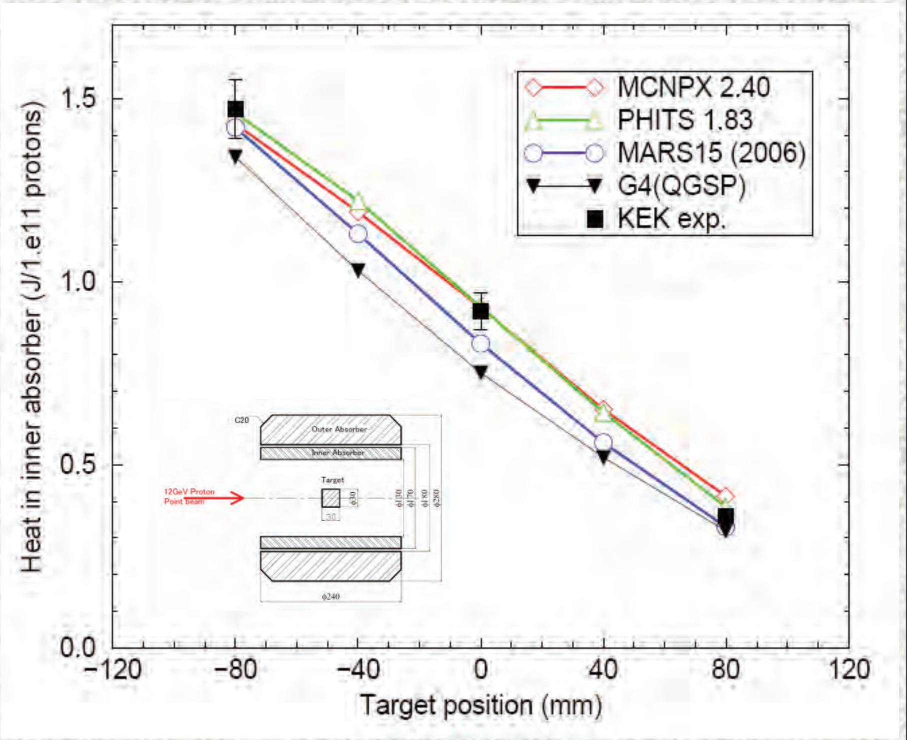
Electromagnetic Interactions: Status and Needs

- Coulomb scattering and ionization and radiative energy losses are described with a percent level accuracy in the considered codes at both CSDA and (in many cases) differential levels.
- **Models/codes:** Accurate description of particle and heavy-ion dE/dx down to ~1 keV in mixtures is mandatory; precise algorithms for Coulomb scattering especially for heavy ions.
- **Data needs:** Whatever possible to help with the previous bullet.

Energy Deposition

10 GeV/c p on 2-m long radial sandwich cylinder





12 GeV p on KEK Copper target

FLUKA-MARS15 Intercomparison

7×7 TeV LHC IR Q1

Total heat loads in the insertion region elements (W) for upgrade luminosity L=10*L0

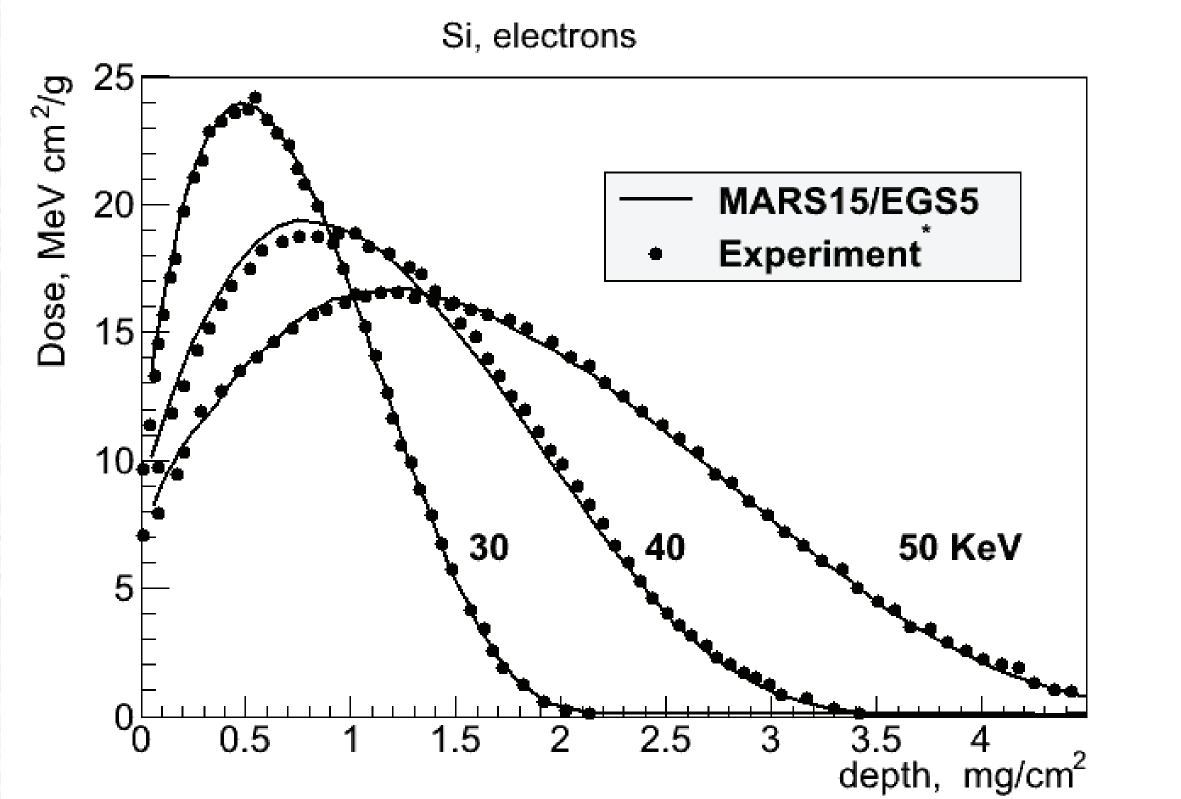
	FLUKA	+/- (%)	MARS	+/- (%)	Ratio FLUKA/MARS
TAS	1853.7	0.5	1827.3	0.1	1.01
Beam pipe	89.1	1.0	97.9	0.4	0.91
Q1 cable	158.0	0.6	159.1	0.2	0.99
yoke	96.3	0.9	78.5	0.4	1.23
aluminium layer	2.3	0.6	2.4	0.5	0.98
mylar insulation	19.5	0.8	20.4	0.3	0.96
stainless steel vessel	16.8	0.8	17.3	0.3	0.97

60-GeV protons ($\sigma_x=\sigma_y=0.35$ cm)
on Be target (R=1.05 cm, L=100 cm)

	MARS15	FLUKA
Peak (GeV/cc)	0.0066	0.0076
Total (GeV)	0.685	0.662

EGS5 Mode in MARS15

The EGS5 code has been implemented in MARS15 for precise modeling of electromagnetic showers in the 1 keV to 20 MeV energy range globally or in specified materials: crucial, for example, for accurate description of transition effects in fine accelerator and detector structures, background studies and medical applications.



Energy Deposition: Status and Needs

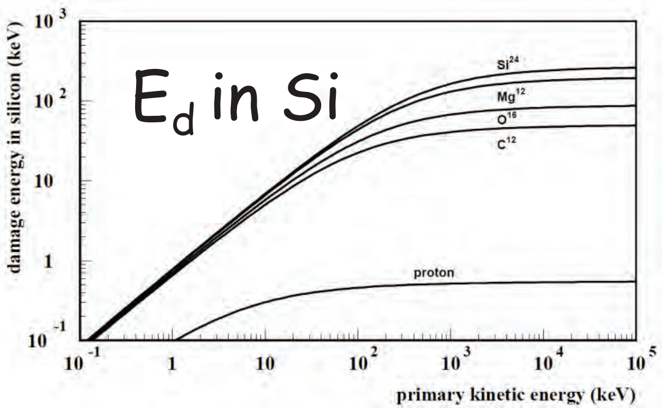
- Comparison to data and FLUKA/MARS (and recently PHITS) intercomparison reveal ~10% (or better) accuracy in majority of cases.
- **Models/codes:** The key is precise description of material properties, geometries, magnetic fields and source terms.
- **Data needs:** Longitudinal and lateral energy deposition profiles in fine-segmented setups with combination of low-Z and high-Z composite materials for primary beam (heavy ions), hadron, electron and low-energy neutron dominated cases.

DPA Model in MARS15 (in one slide)

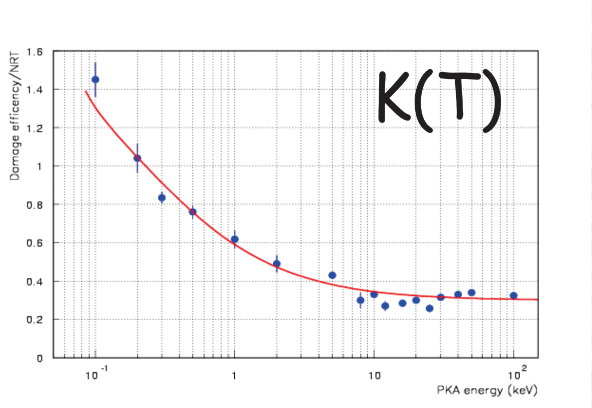
Norgett, Robinson, Torrens (NRT) model for atomic displacements per target atom (DPA) caused by primary knock-on atoms (PKA), created in elastic particle-nucleus collisions, with sequent cascades of atomic displacements (via modified Kinchin-Pease damage function ν**(T)**), displacement energy T_d (irregular function of atomic number) and displacement efficiency **K(T)**.

$$\sigma_d(E) = \int_{T_d}^{T_{\max}} \frac{d\sigma(E,T)}{dT} \nu(T) dT$$

$$\nu(T) = \begin{cases} 0 & T < T_d \\ 1 & T_d \le T < 2.5T_d \\ k(T)E_d / 2T_d & 2.5T_d \le T \end{cases}$$



M. Robinson (1970)

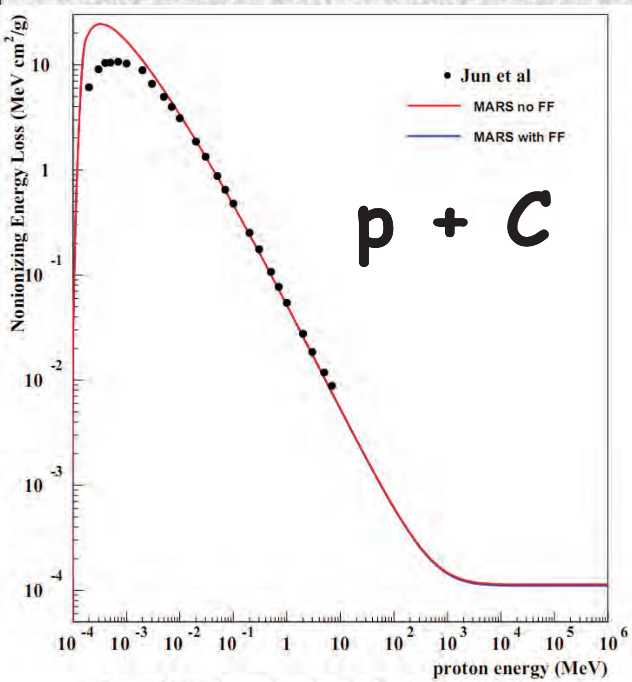


R. Stoller (2000), G. Smirnov

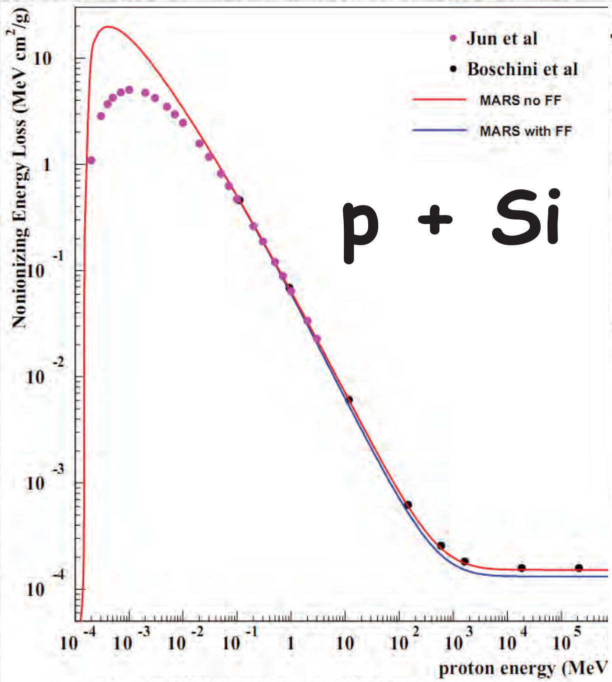
All products of elastic and inelastic nuclear interactions as well as Coulomb elastic scattering of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV. Coulomb scattering: Rutherford cross-section with Mott corrections and **nuclear form factors for projectile and target** (important for high-Z projectiles and targets, see next two slides).

Comparing MARS15 with Most Recent Models

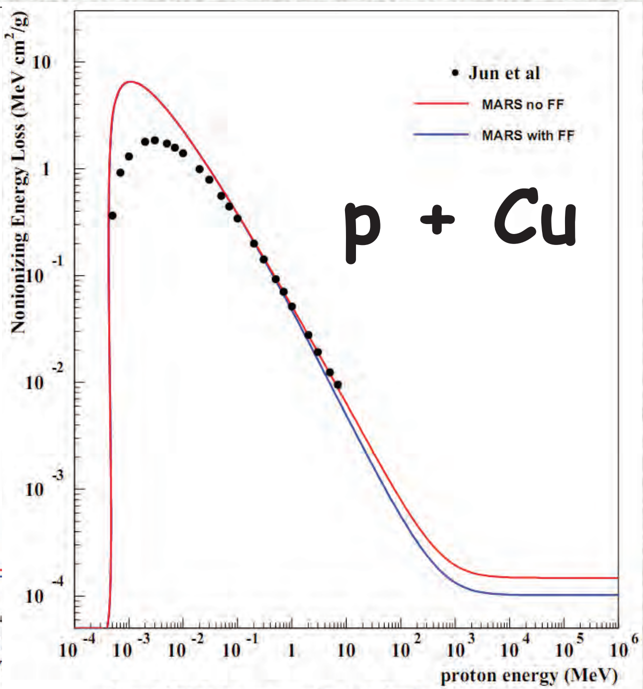
I.Jun, "Electron Nonionizing Energy Loss for Device Applications",
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 6, DECEMBER 2009



Proton NIEL for carbon due the Coulomb scattering



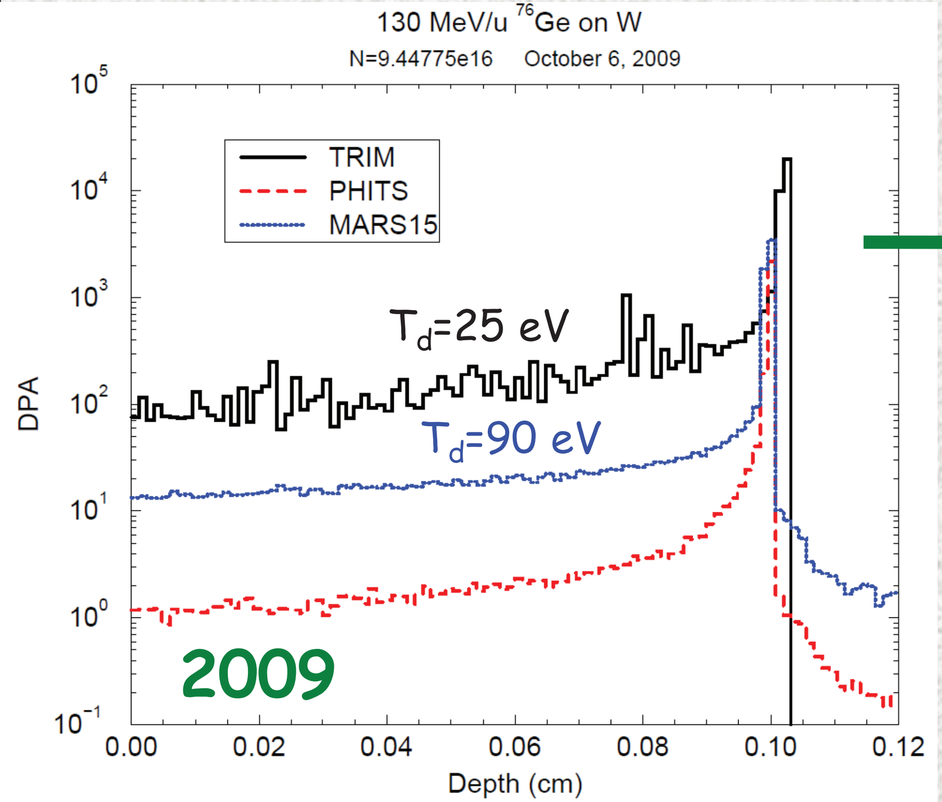
Proton NIEL for silicon due the Coulomb scattering

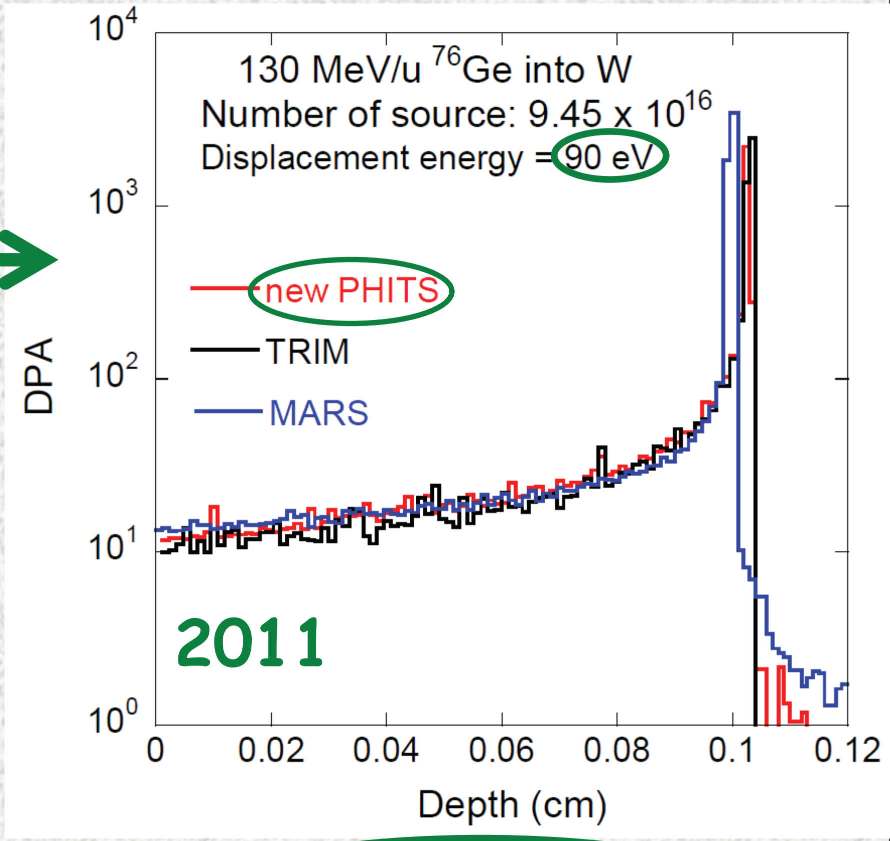


Proton NIEL for copper due the Coulomb scattering

- Minimal proton transport cutoff energy in MARS is 1 keV

DPA Comparison: 130 MeV/u ^{76}Ge on W





Pencil beam, uniform in R=0.03568 cm disc.
Target W_{nat}, cylinder with R=0.03568 cm, L=0.12 cm
Old PHITS: T_d=90 eV, no Coulomb elastic

Include all processes, use correct parameters

TRIM and PHITS results: Courtesy Yosuke Iwamoto

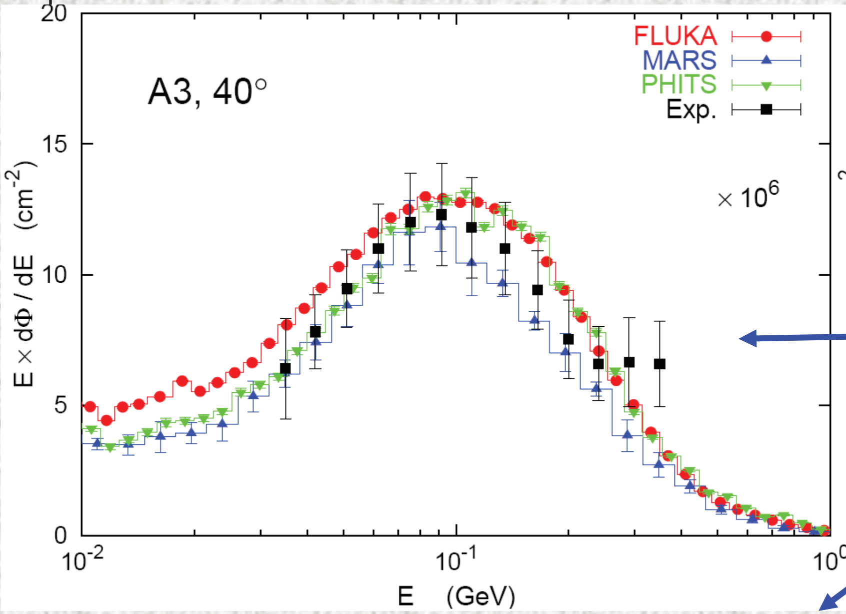
DPA and Radiation Damage: Status and Needs

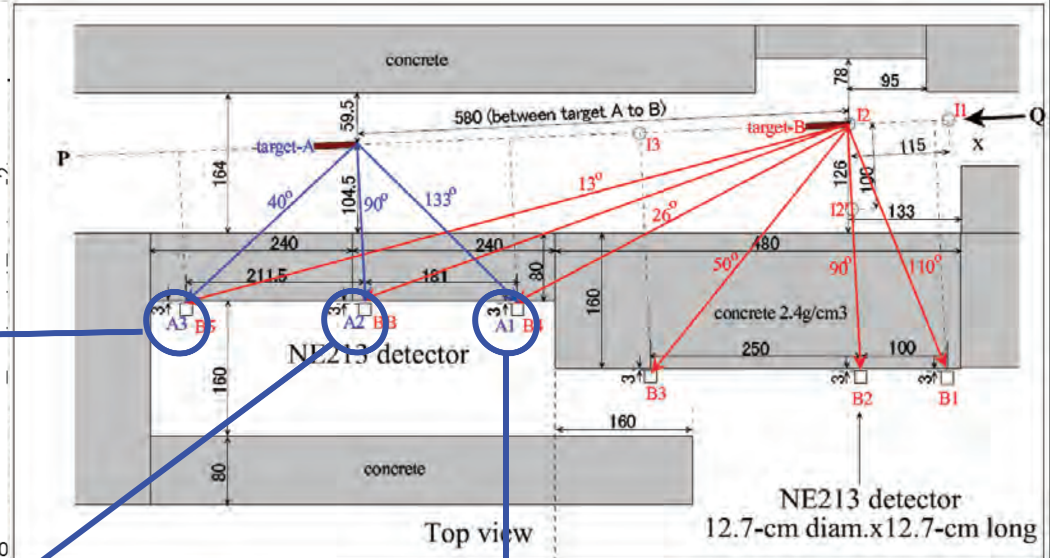
- Modern models/codes which include Coulomb elastic scattering (crucial for high-Z projectiles), nuclear interactions, and same DPA model parameters agree quite well between each other and with (indirect) data. At the same time, industry standard NRT and state-of-the-art BCA-MD can differ by a factor of 2 to 3 in some cases

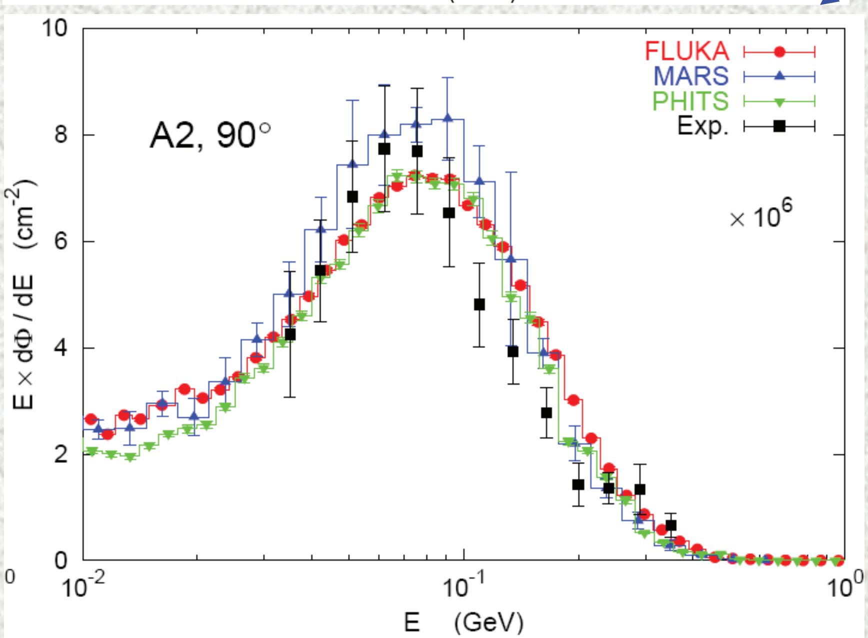
- **Models/codes:** Strong dependencies on projectile type and energy (1 keV to a few GeV), projectile/target charge and nuclear form-factor and material properties to be further studied; work in progress in MARS on better low-energy neutron model; link DPA to changes in material properties

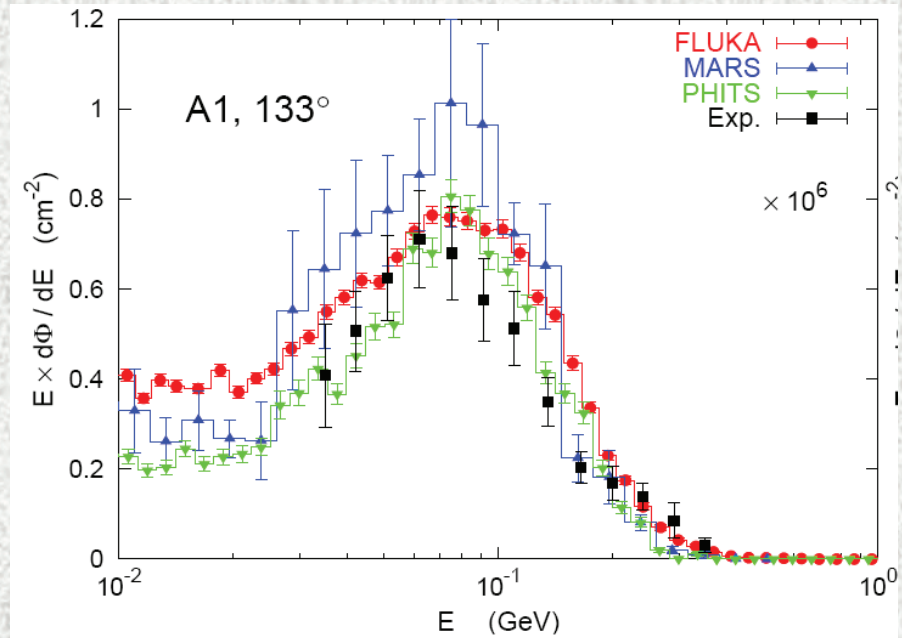
- **Data needs:** Annealed vs non-annealed defects; cryo temperatures!

120-GeV p/π on CERF Cu-Target: Concrete, 80cm

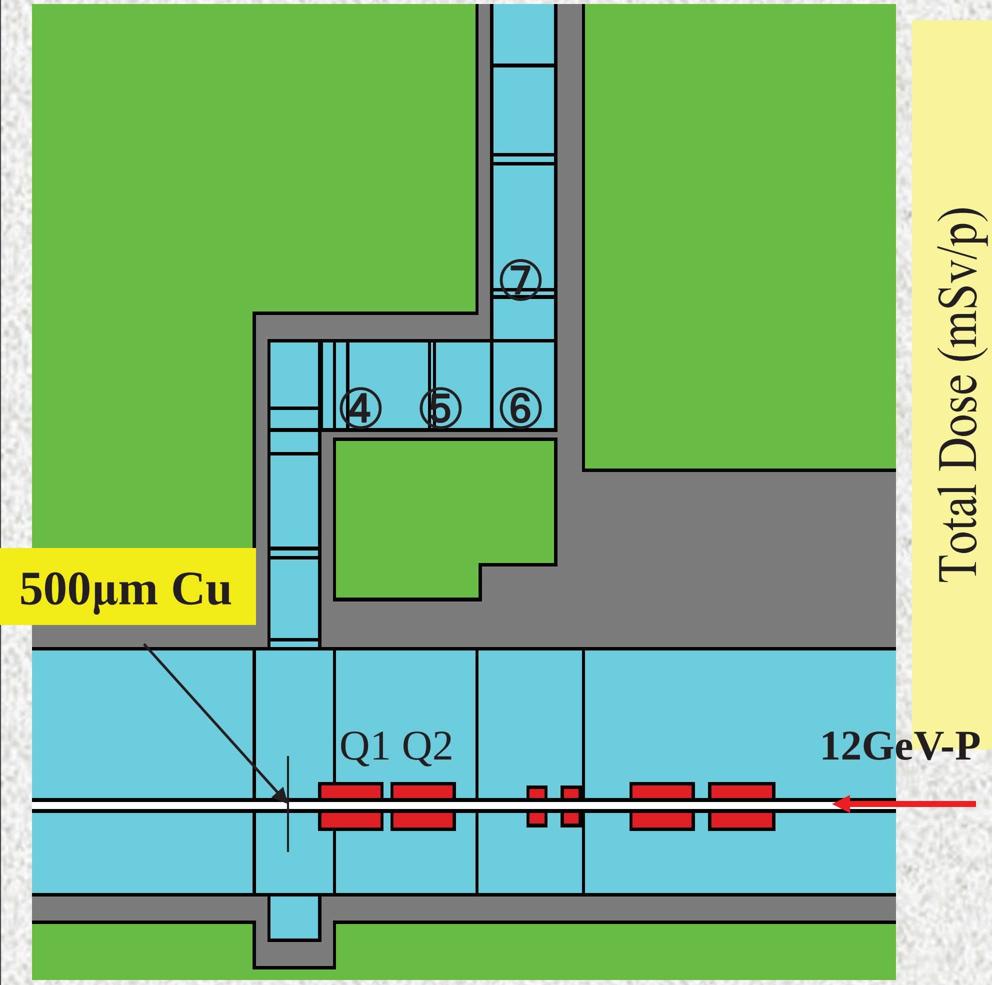


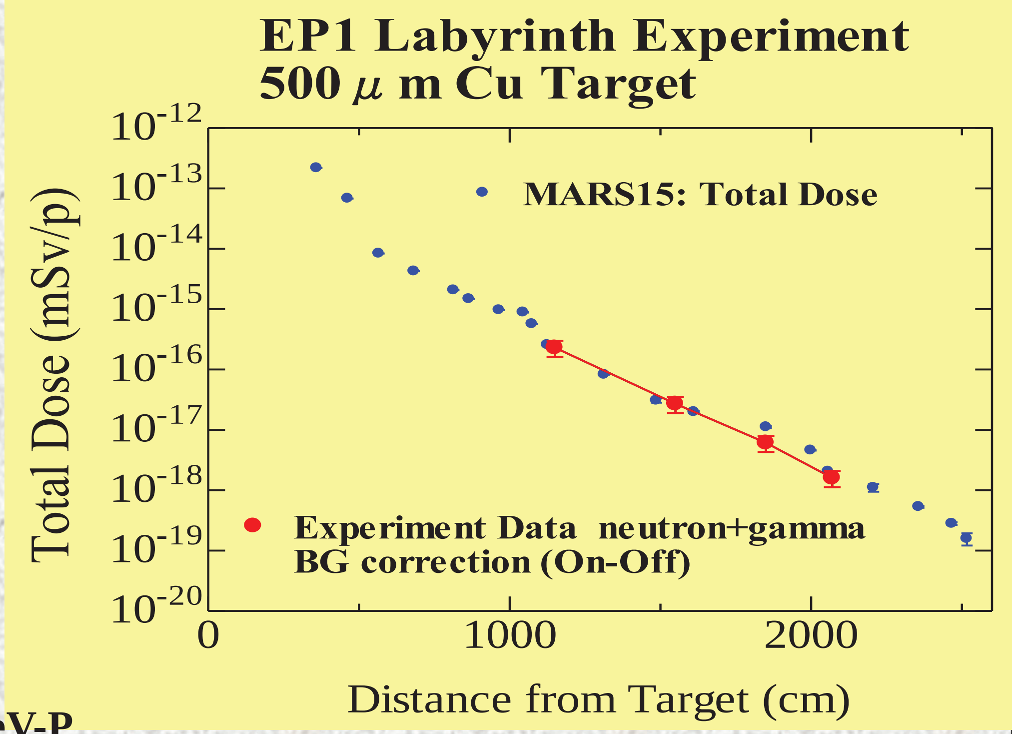






KEK: EP1 Labyrinth





Courtesy: Takenori Suzuki

Radiation Shielding: Status and Needs

- Current FLUKA, MARS and PHITS agree with each other and data within a factor of 2 for most radiation values, **IF** all details of geometry, materials composition and source term are taken into account.
- **Models/codes:** Further intensification of variance reduction technique use, especially for thick shielding ("deep penetration problem"), growing computation power is not a panacea.

Data needs: JASMIN is on the right track (Japan-FNAL Collaboration on Shielding and Radiation Effect Experiments)

Conclusions

- Predictive power, capabilities and reliability of major particle-matter interaction codes used in accelerator applications are quite high.
- On particle yields, accuracy of predictions is at a 20% level in most cases, although the issues (up to a factor of 2) remain in some phase space regions. EM interactions are described at a few % level.
- Accuracy of beam-induced macroscopic effect predictions today:
  - Energy deposition effects (instantaneous and accumulated) < 15%
  - Hydrogen/Helium gas production and DPA: ~20% (with similar DPA models) to a factor of 2; still need better link of DPA to changes in material properties
  - Beam loss generation and collimation: quite good (Tevatron, J-PARC, LHC)
  - Radiological issues (prompt and residual): a factor of 2 for most radiation values, if all details of geometry, materials composition and source term are taken into account.