Beam-Induced Effects in Targets and Uncertainties in their Modeling

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Outline

- Materials Under Radiation
- Thermal Shock and Hydrodynamics
- Dose to Insulation
- DPA
- Hydrogen and Helium Production
- Uncertainties in Simulations
- Data Needs and Simulation Challenges

Introduction

The consequences of controlled and uncontrolled impacts of high-power high-intensity beams on components of targets, accelerators, beamlines, collimators/absorbers, detectors, shielding and environment can range from minor to catastrophic.

Capabilities and uncertainties of modern simulation codes used to study these impacts are discussed in this talk.

Materials Under Irradiation

Depending on material, level of energy deposition density and its time structure, one can face a variety of effects in materials under irradiation.

This talk is a brief overview of the following ones:

- Thermal shocks and quasi-instantaneous damage
- Insulation property deterioration due to dose buildup
- Radiation damage to inorganic materials due to atomic displacements and helium production.

MARS Code for Intensity Frontier

Particle yields:
p,n,π,K,μ,Σ,HI

Nuclide inventory

Radiation damage:
DPA, dose, H/He,
soft errors (SEE)

MARS

Background
suppression

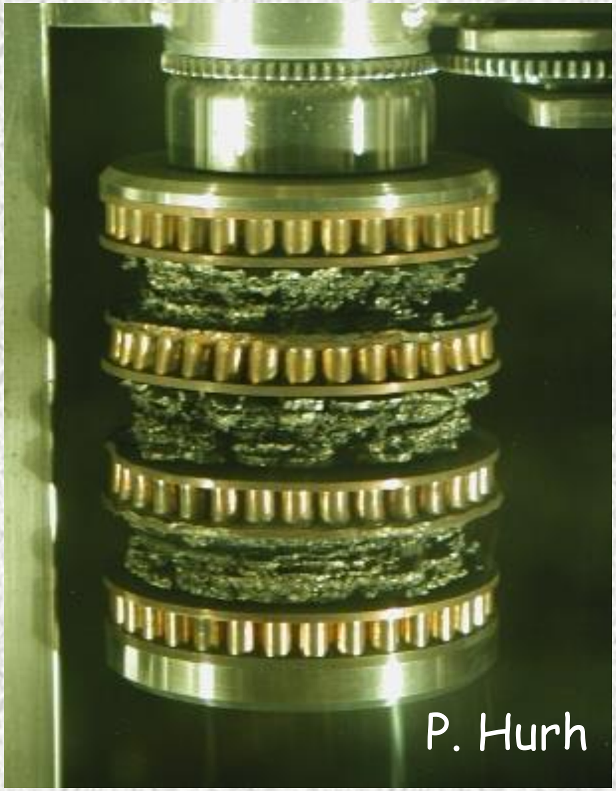
Beamline optimization,
beam loss, particle
capture and collimation,
SC magnet quench

Prompt and residual
radiation, shielding,
impact on environment

Targetry: power dissipation,
integrity (shock & buildup),
magnetohydrodynamics

Thermal Shock

Short pulses with energy deposition density EDD in the range from 200 J/g (W), 600 J/g (Cu), ~1 kJ/g (Ni, Inconel) to ~15 kJ/g: thermal shocks resulting in fast ablation and slower structural changes.

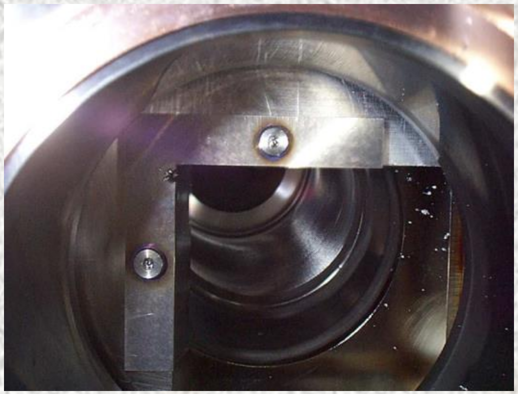


FNAL pbar production target under 120-GeV p-beam (3e12 ppp, σ ~ 0.2 mm)

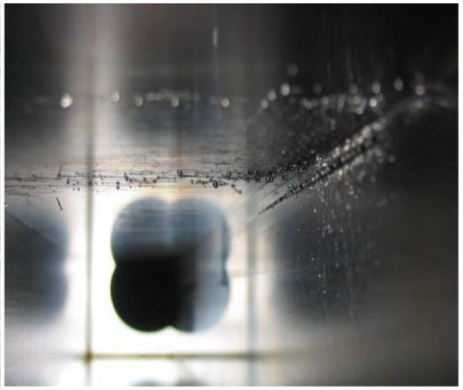
MARS simulations explained target damage, reduction of pbar yield and justified better target materials

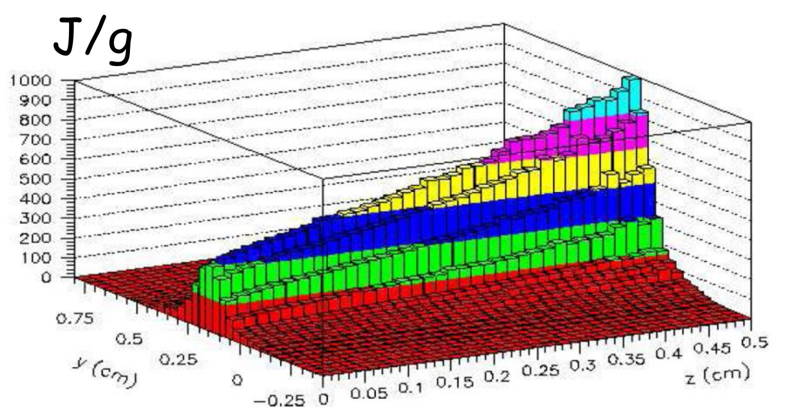
Tevatron Collimator Damage in 2003

Hole in 5-mm W



25-cm groove in SS





Detailed modeling of dynamics of beam loss (STRUCT), energy deposition (MARS) and time evolution over 1.6 ms of the tungsten collimator ablation, fully explained what happened.

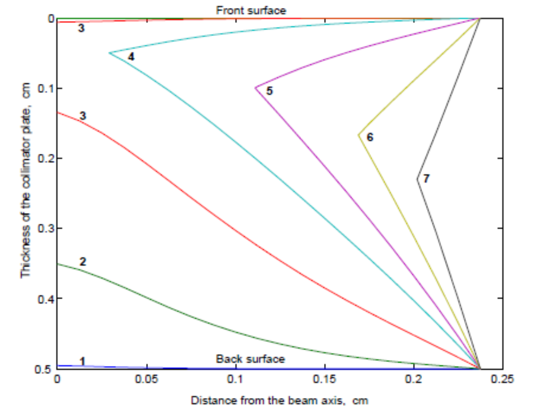
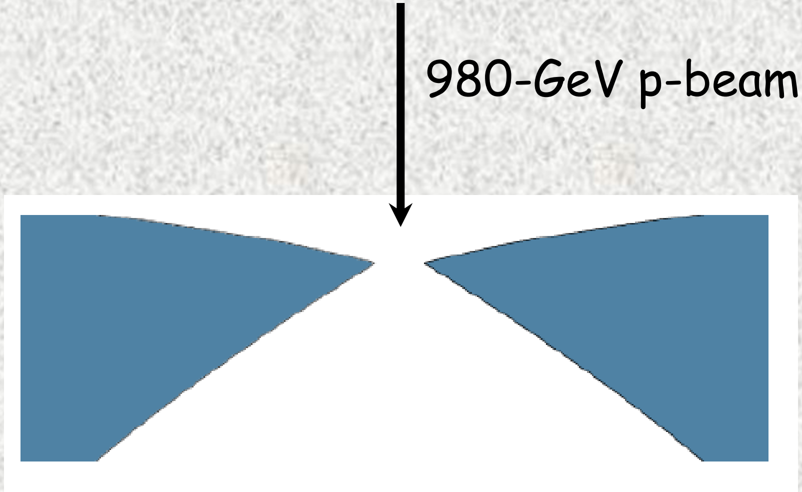


Figure 7: Evolution of the front and back surfaces of the collimator plate at $t = 0.4_{[1]} - 1.6_{[7]}$ ms with Δt=0.2 ms.

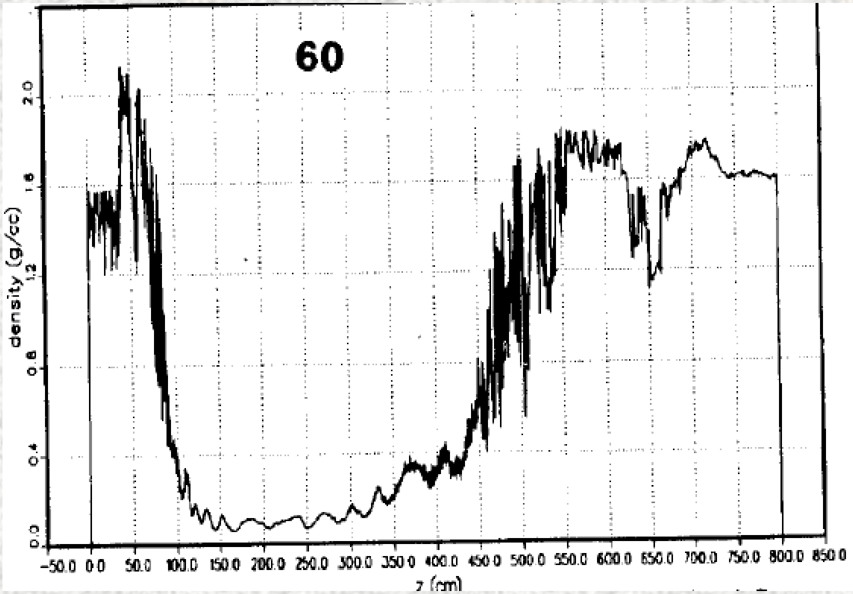


980-GeV p-beam

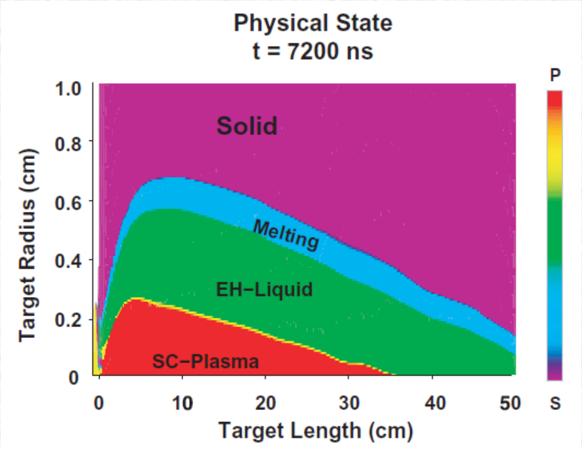
Hydrodynamics in Solid Materials

Pulses with EDD >15 kJ/g: hydrodynamic regime.

First done for the 300-μs, 400-MJ, 20-TeV proton beams for the SSC graphite beam dump, steel collimators and tunnel-surrounding Austin Chalk by SSC-LANL Collaboration (D. Wilson, …, N. Mokhov, PAC93, p. 3090). Combining MARS ED calculations at each time step for a fresh material state and MESA/SPHINX hydrodynamics codes.



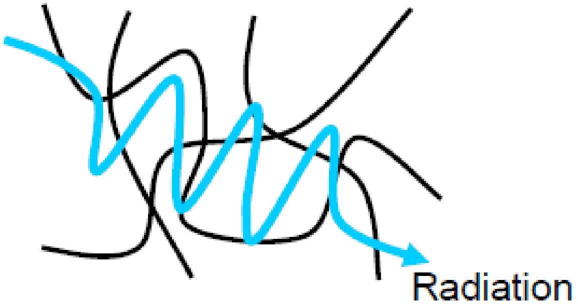
The hole was drilled at the 7 cm/μs penetration rate. Axial density of graphite beam dump in 60 μs after the spill start.



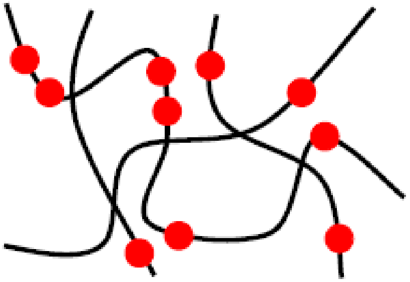
Later, studies by N. Tahir et al with FLUKA+BIG2 codes for SPS & LHC

These days we use MARS+FRONTIER. ← Tools are in hands ↗

Interaction of Radiation with Organic Materials

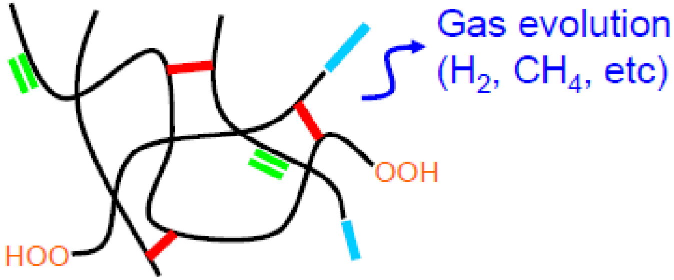


Production of free radicals



Reaction of free radicals

A. Idesaki



Crosslinking

Chain scission

Formation of unsaturated bonds (C=C, etc.)

Oxidation (under presence of oxygen)

Gas evolution

Change of molecular structure

Modification

Degradation

- Irradiation temperature
- Irradiation atmosphere (presence of oxygen)
- Additives

For given insulator and irradiation conditions radiation damage is proportional to energy deposition (dose)

Dose Limits in Insulators

Epoxy, CE/epoxy resins and G11

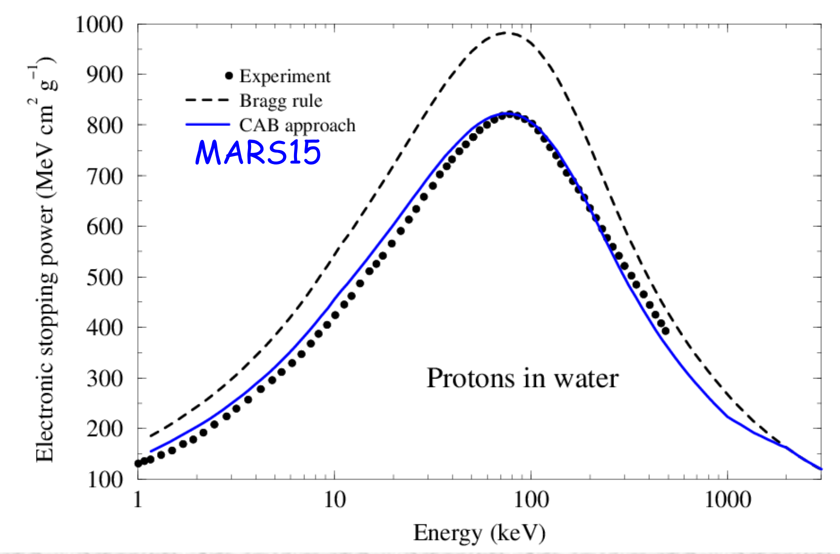
10% degradation of ultimate tensile strength;
Electrical resistivity

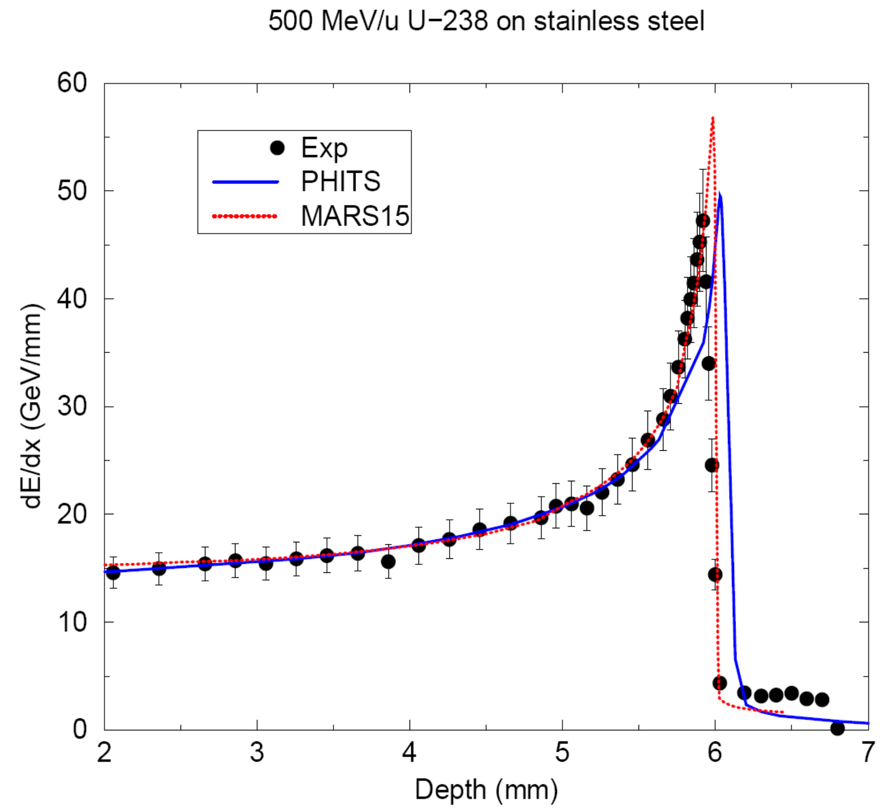
Common limit is 25 to 40 MGy

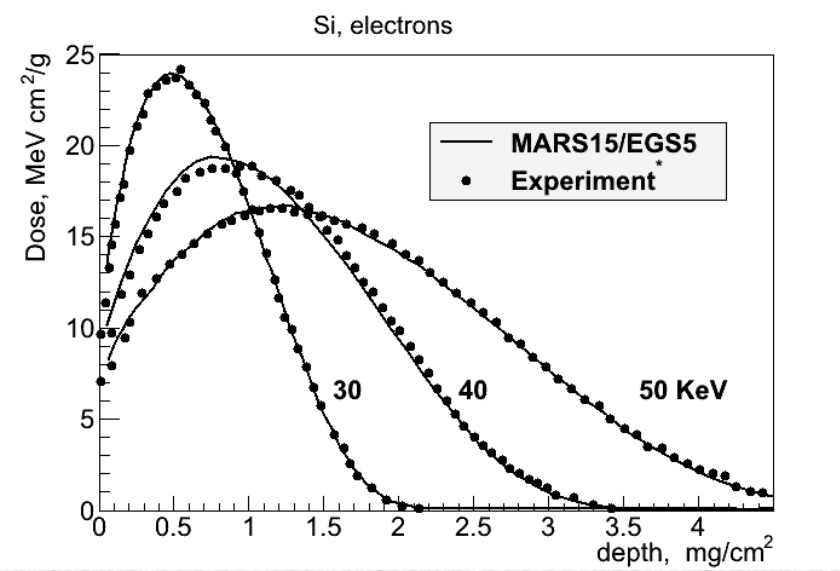
Some projects aim at allowable dose of 10 MGy
Mu2e: 7 MGy

Related: peak power density over SC cable width for quench stability

Energy Deposition Modeling: Highly Accurate

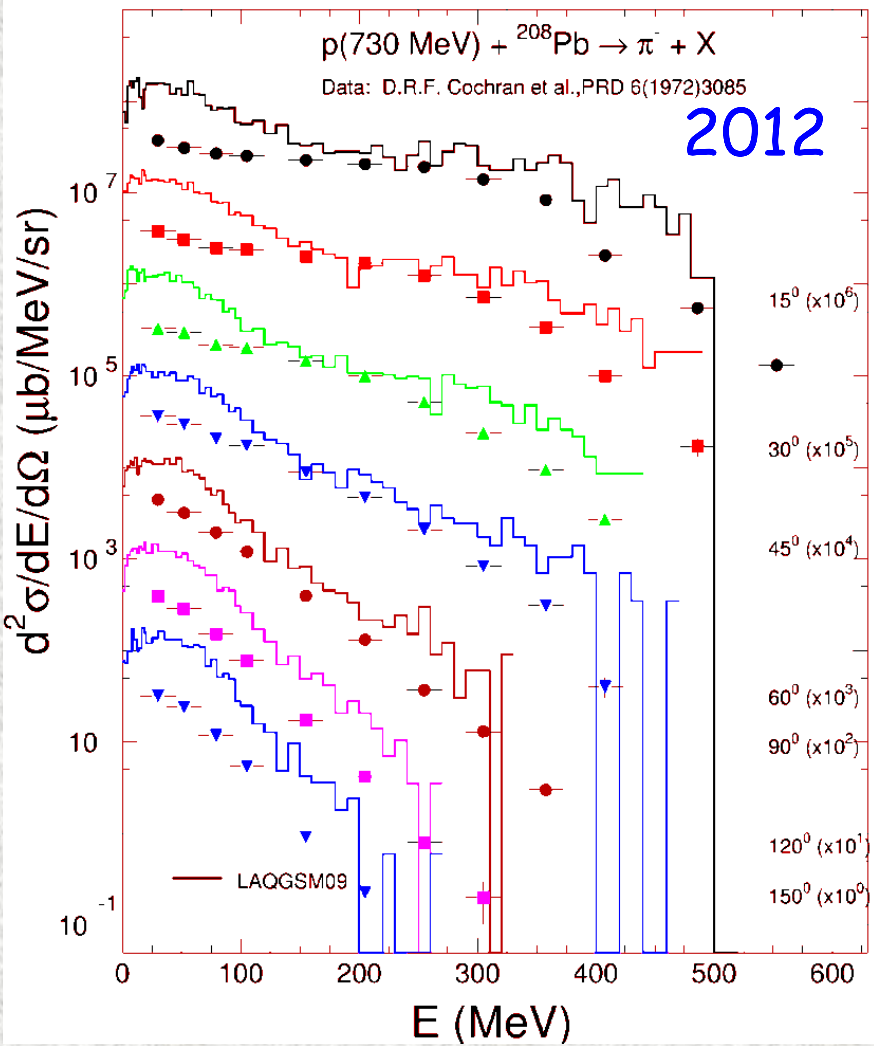


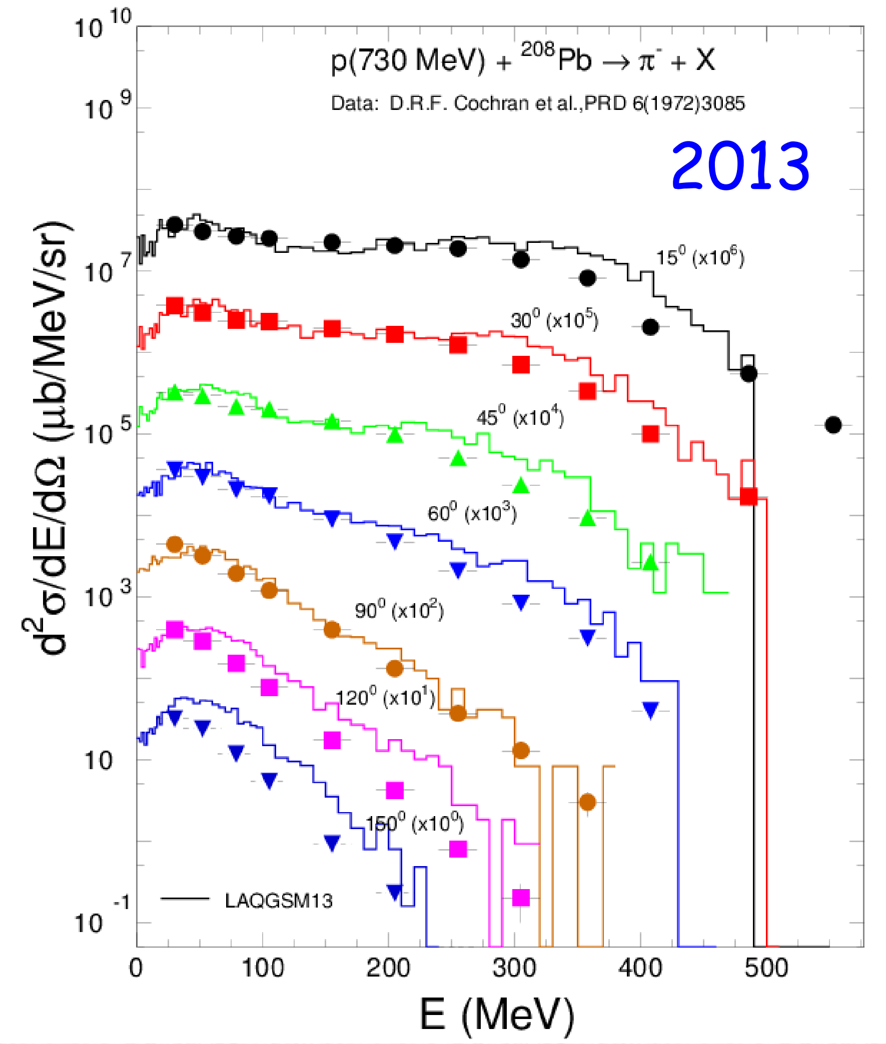




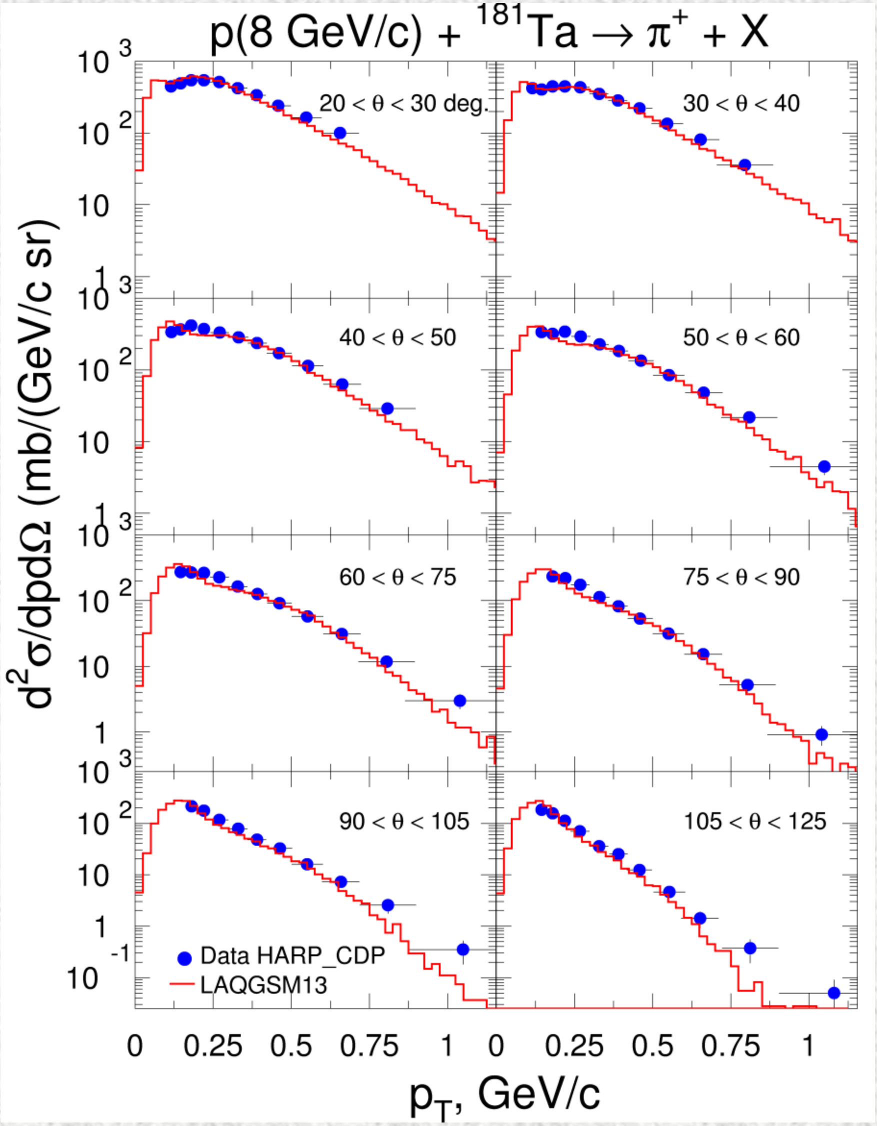
In majority of real-life complex applications, FLUKA and MARS15 energy deposition results coincide within 10% and agree with data.

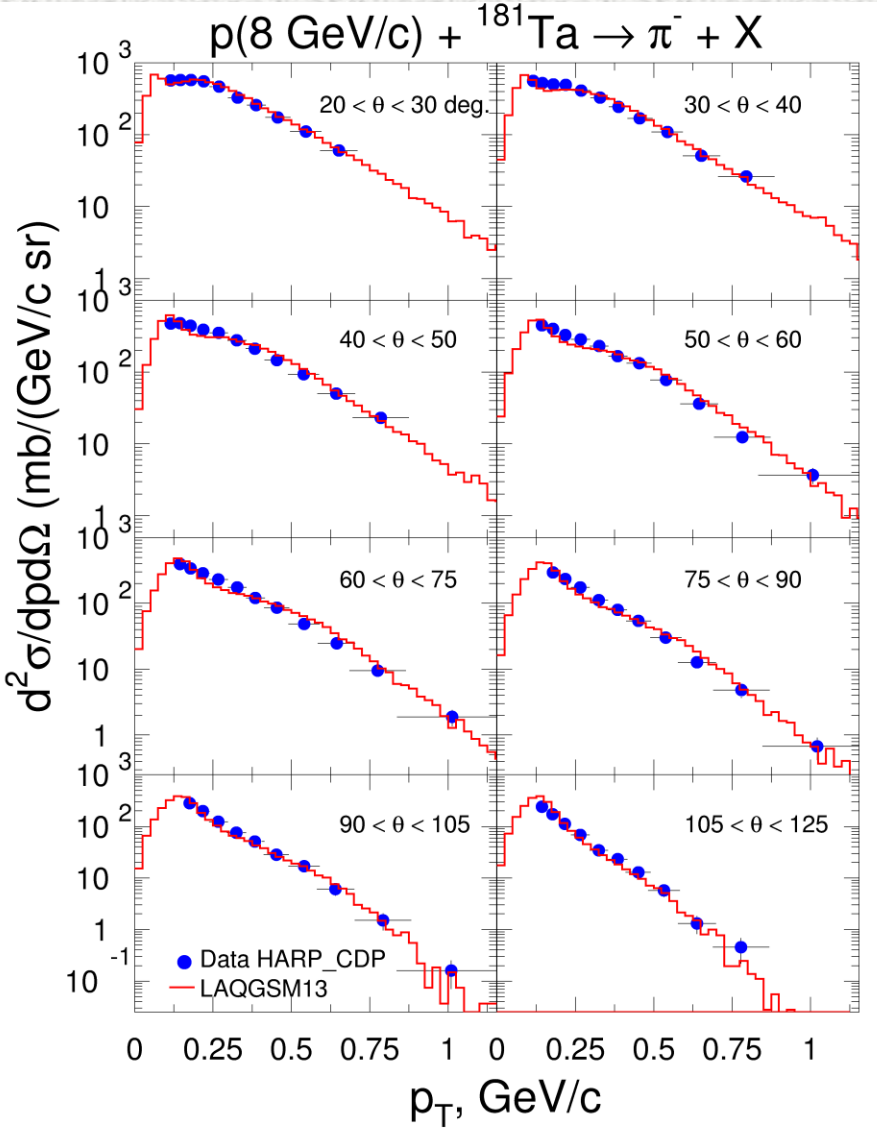
Effects of $N+N \rightarrow \pi+d$ and $\pi+(NN) \rightarrow N+N$N+N
$\sigma(abs)=P(A)\sigma(\pi+d)$



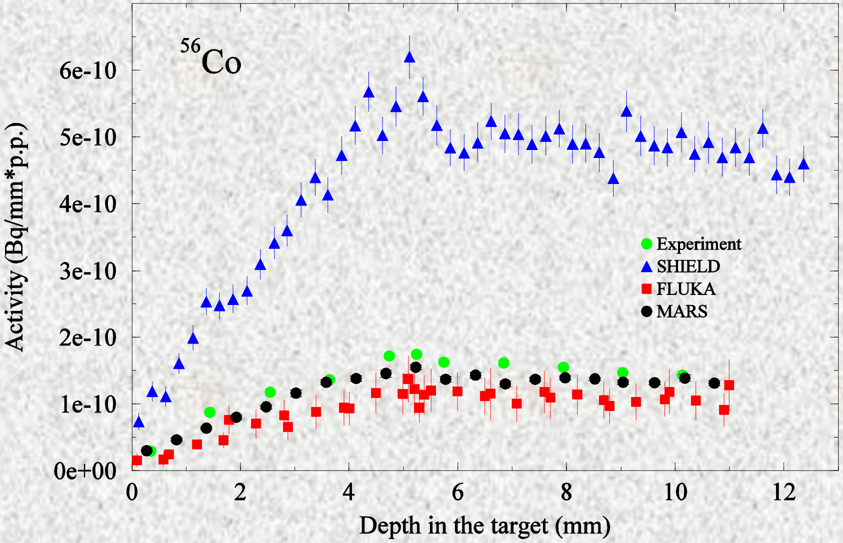


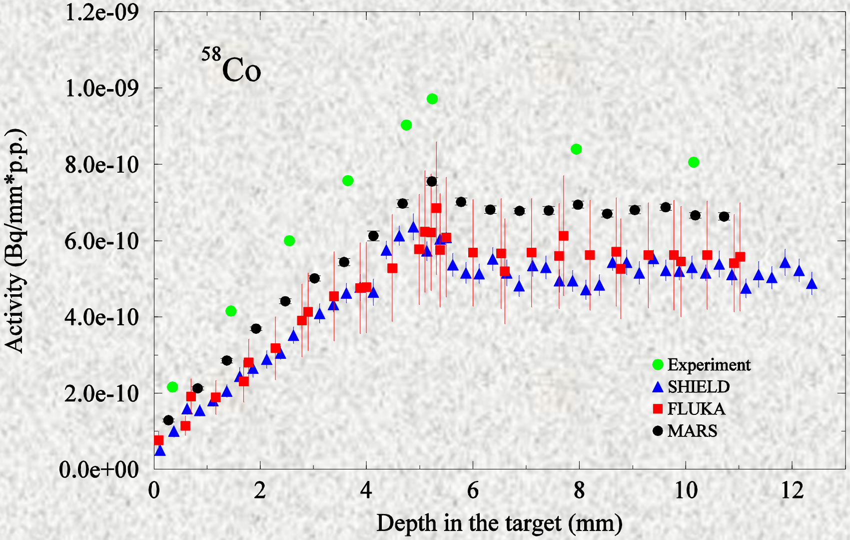
LAQGSM2013 vs HARP-CDP DATA

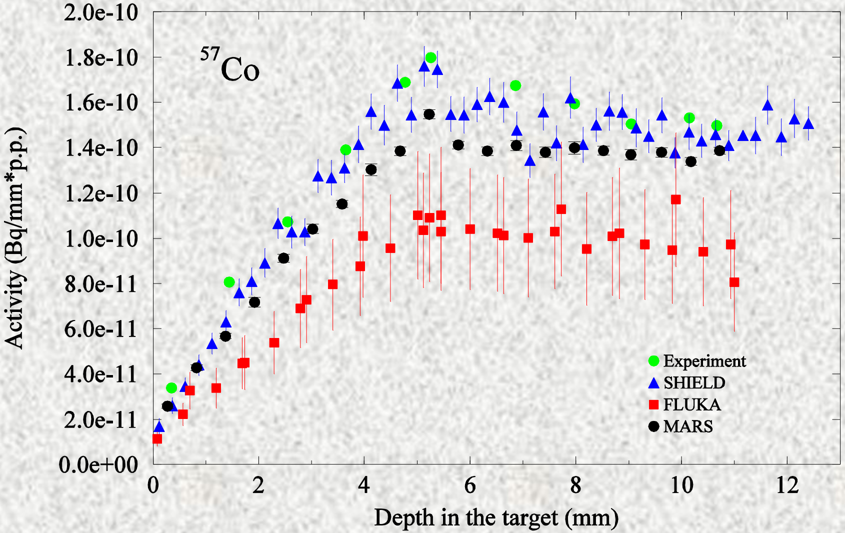




Nuclide Production







Measured at GSI and calculated with FLUKA, MARS15 and SHIELD codes activities in a copper target irradiated with a 500 MeV/A uranium beam

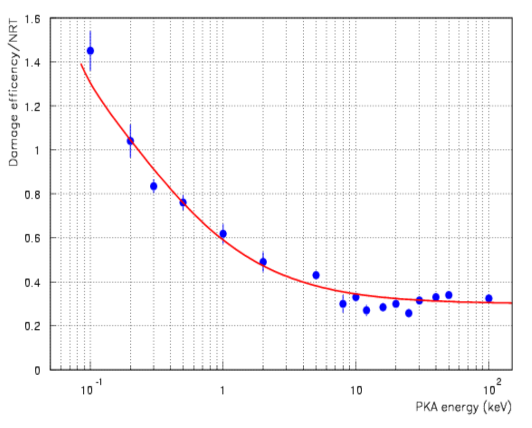
DPA Model in MARS15

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

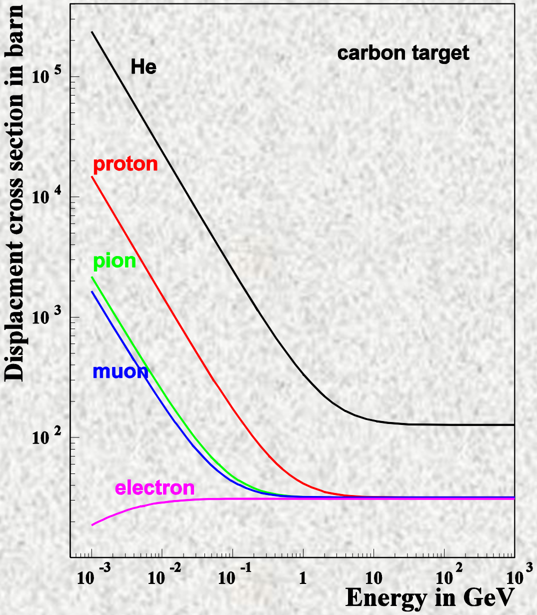
NRT damage function:

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

T_d is displacement energy (~40 eV)
E_d is damage energy (~keV)
Energy-dependent displacement efficiency k(T) by Stoller/Smirnov:

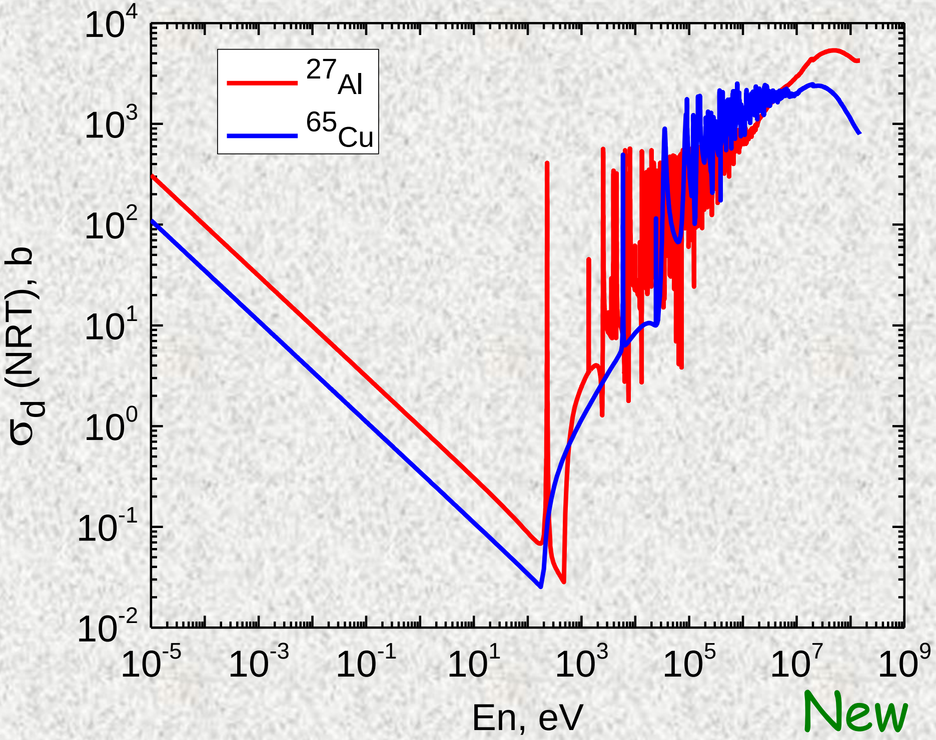


All products of elastic and inelastic nuclear interactions as well as Coulomb elastic scattering (NIEL) of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV contribute to DPA in this model. For electromagnetic elastic (Coulomb) scattering, Rutherford cross section with Mott corrections and nuclear form factors are used.



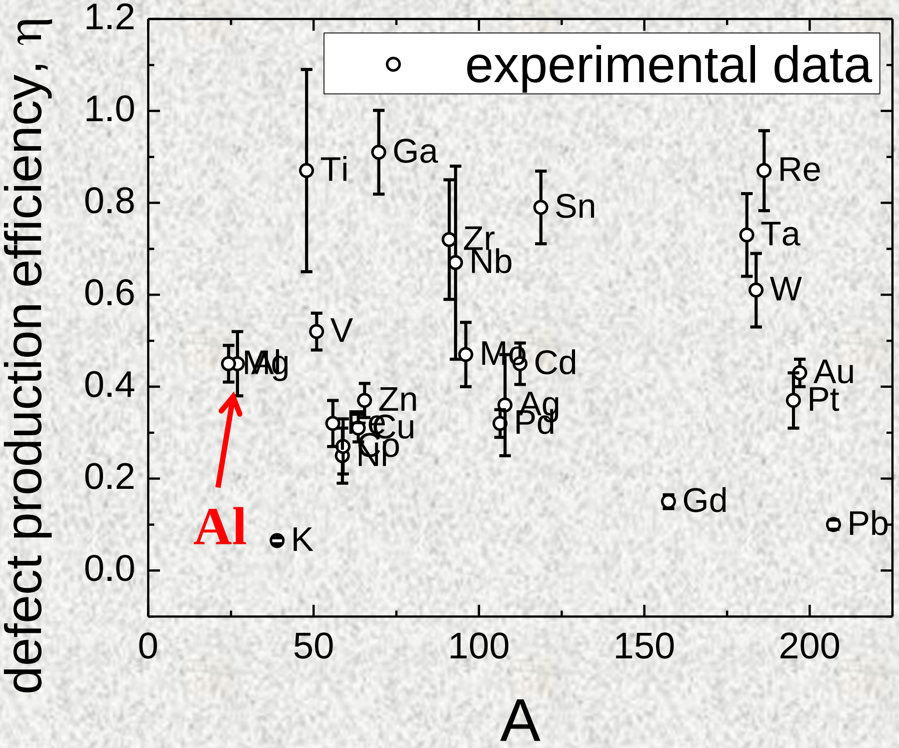
DPA is the most universal way to characterize the impact of irradiation on inorganic materials

Medium- and Low-E Neutron DPA Model in MARS15 and Optional Correction at Cryo Temperatures



New

T = 4-6 K

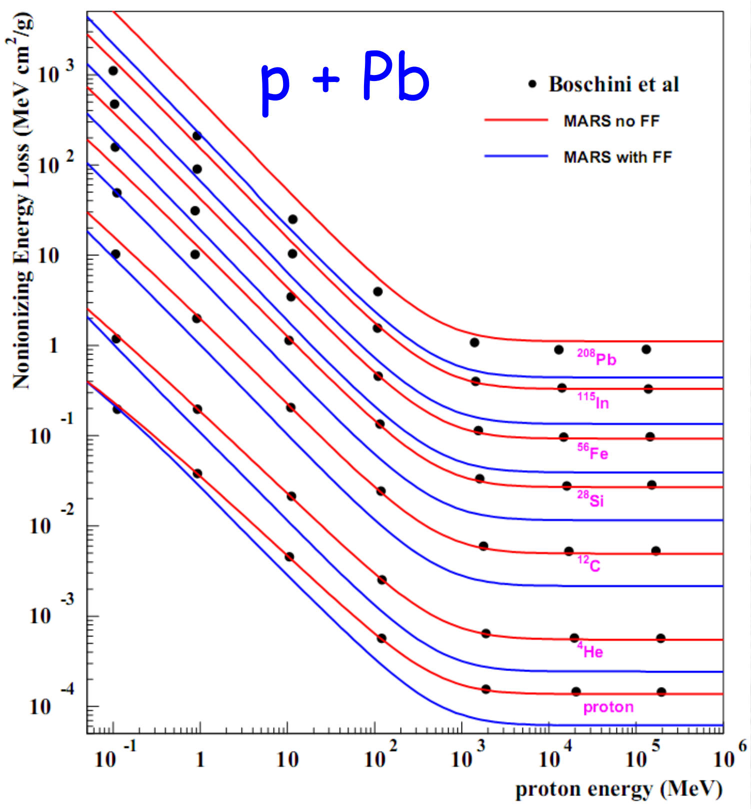


For neutrons from 10^{-5} eV to 150 MeV: NJOY99+ENDF-VII database, for 393 nuclides. At T=4-6K, optional correction for experimental defect production efficiency η (Broeders, Konobeev, 2004), where η is a ratio of a number of single interstitial atom vacancy pairs (Frenkel pairs) produced in a material to the number of defects calculated using NRT model

Code Capabilities in DPA Modeling

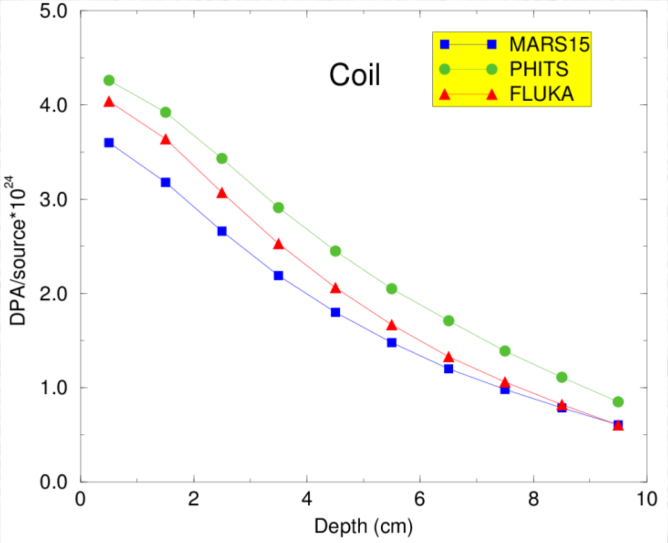
1. **Electron and heavy-ion beams:** in most cases, DPA is dominated by electronic energy loss of a primary beam; FLUKA/MARS/PHITS/SRIM are doing quite well here.
2. **Neutrons at E < 150 MeV:** Point defects; ENDF/NJOY damage x-section libraries & processing – OK.
3. **Protons:** low and medium energies: (1) and (2) – OK.
4. **High-energy hadrons and heavy ions:** nuclear interaction model dependent; most difficult, certainly in targets; mixed (1) and (2) regimes; FLUKA/MARS can be OK even at very high energies.

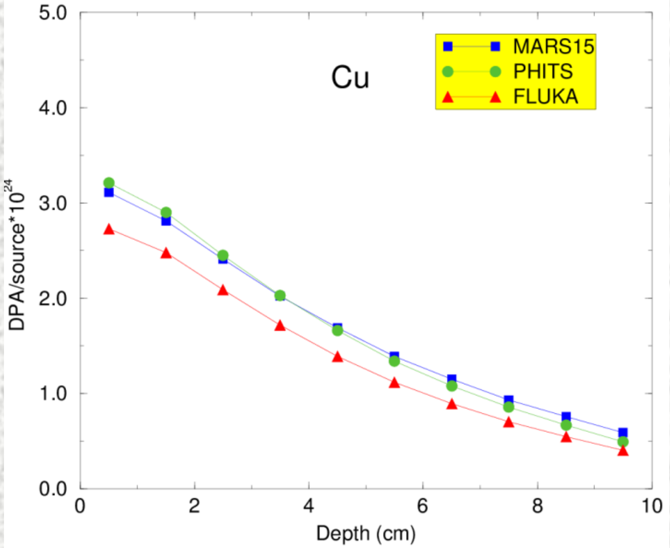
DPA Code Intercomparision

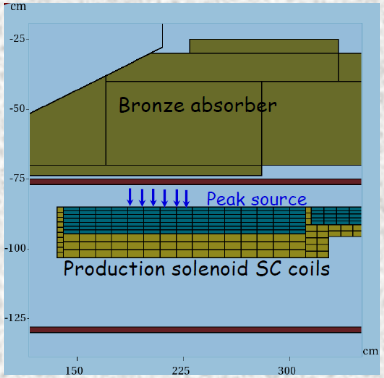


Proton NIEL for lead due the Coulomb scattering

M.J. Boschini et al., "Nuclear and Non-Ionizing Energy-Loss for Coulomb Scattered Particles from Low Energy up to Relativistic Regime in Space Radiation Environment", arXiv:1011.4822v6 [physics.space-ph] 10 Jan 2011



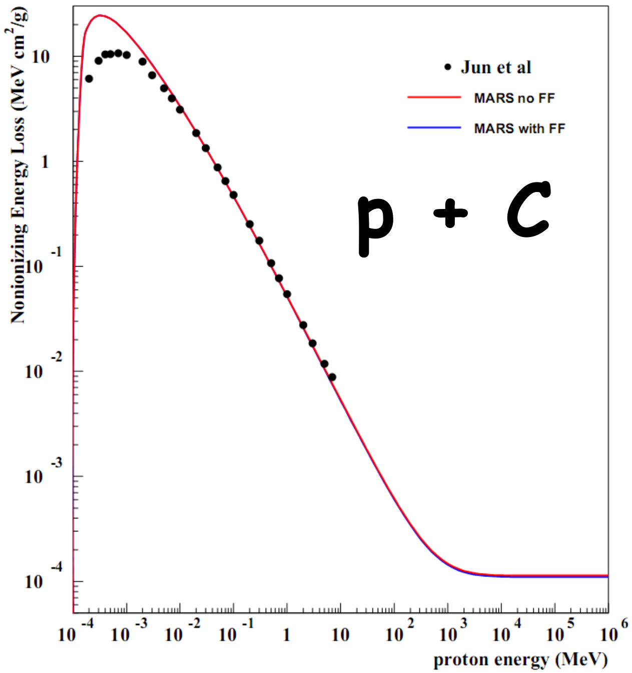




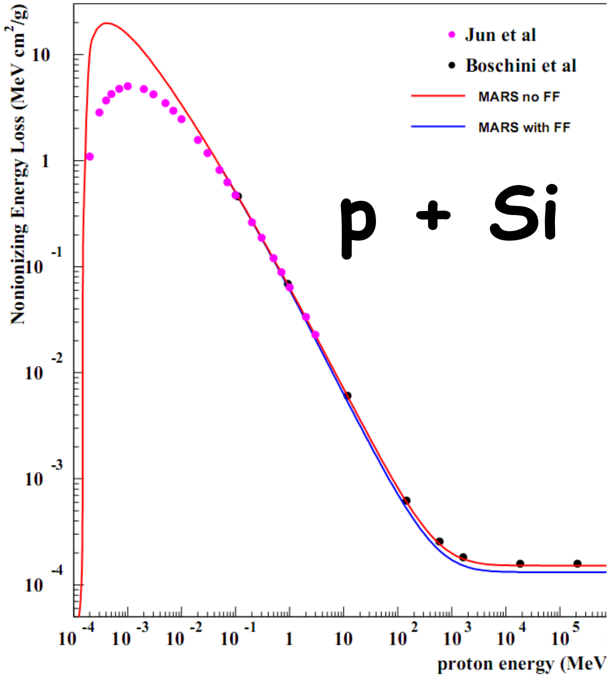
2013 FLUKA, MARS15 and PHITS intercomparison for Mu2e SC coil hottest spot: 15% agreement

MARS15 *vs* Jun Modeling

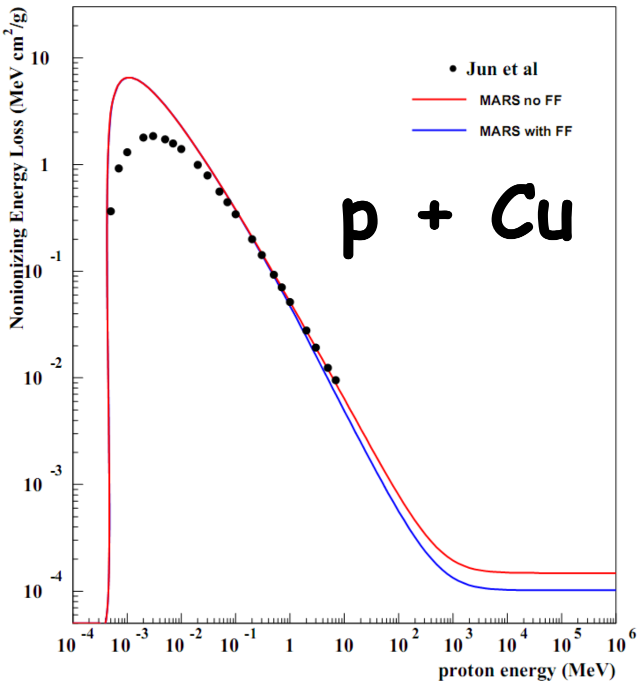
I. Jun, “Electron Nonionizing Energy Loss for Device Applications”,
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 6, DECEMBER 2009



Proton NIEL for carbon due the Coulomb scattering



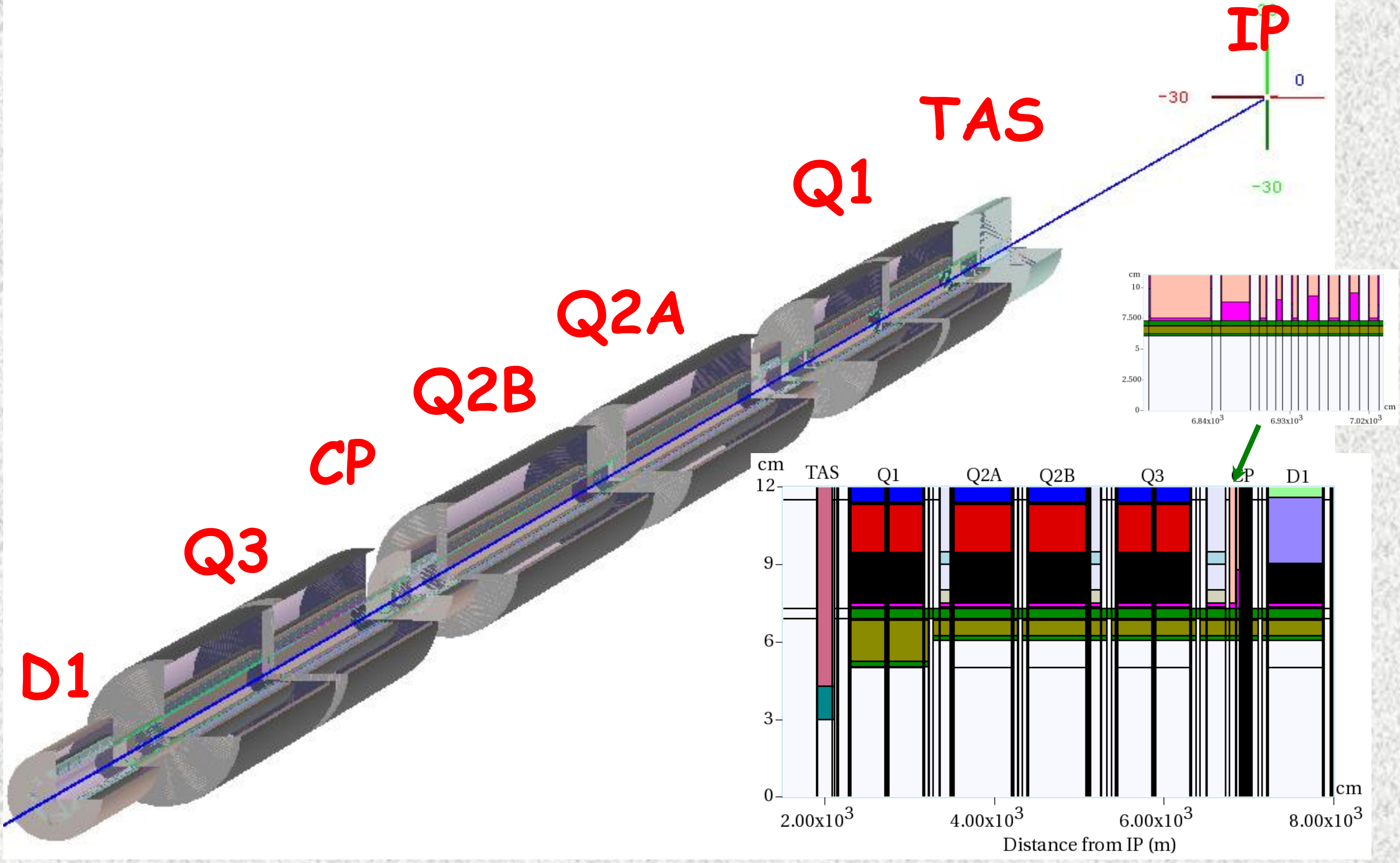
Proton NIEL for silicon due the Coulomb scattering



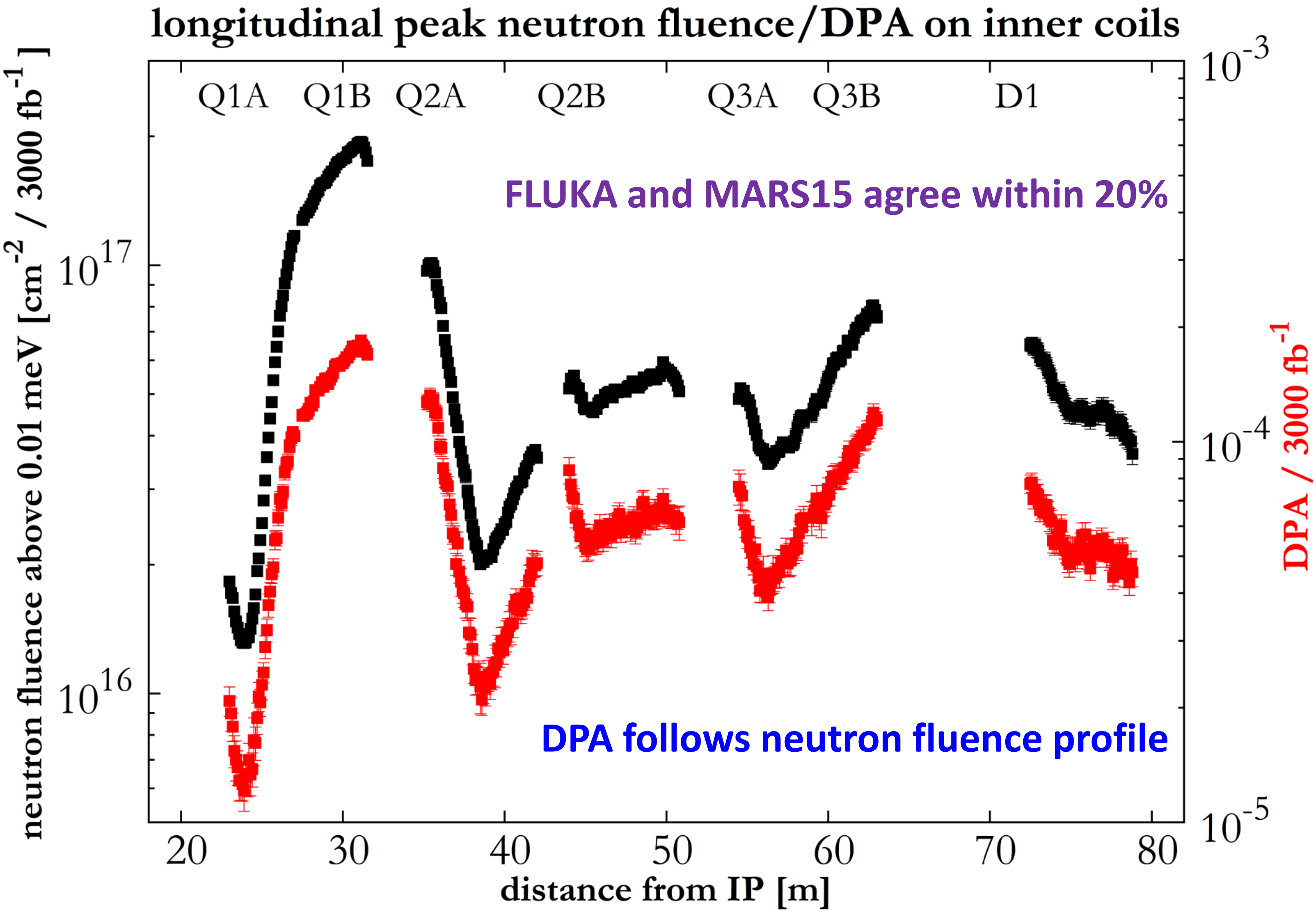
Proton NIEL for copper due the Coulomb scattering

- Minimal proton transport cutoff energy in MARS is 1 keV

150-mm HLumi LHC IT-CP-D1



7×7 TeV pp-collisions



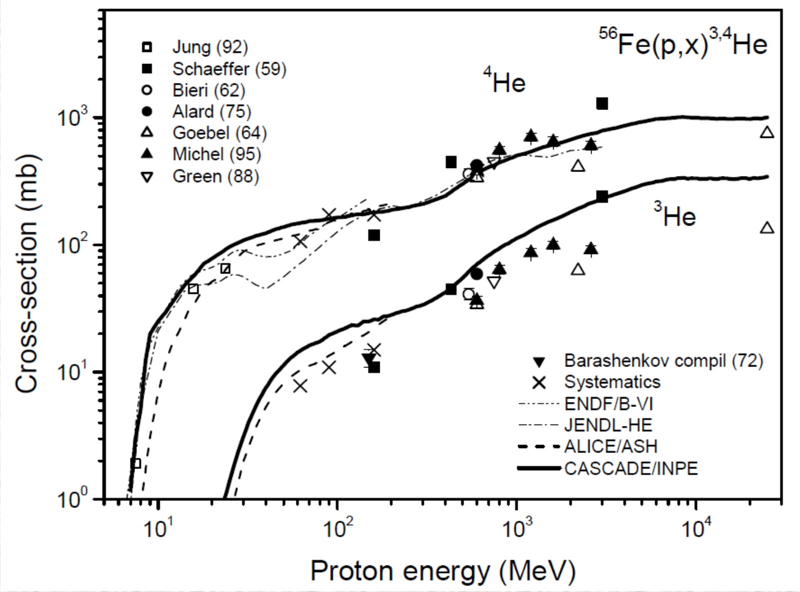
FLUKA and MARS15 agree within 20%

DPA follows neutron fluence profile

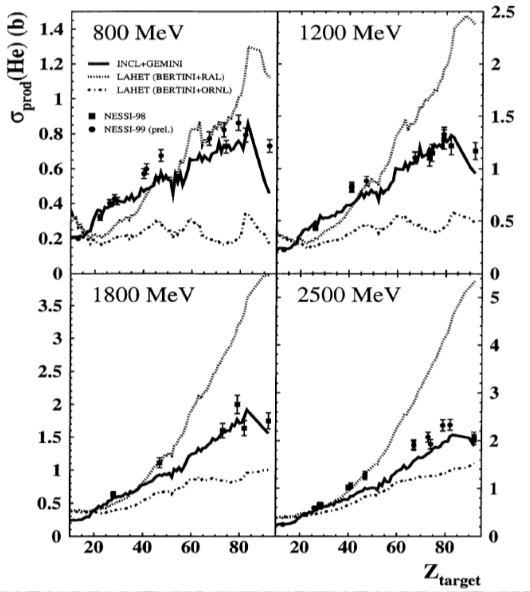
Hydrogen and Helium Gas Production

At accelerators, radiation damage to structural materials is amplified by increased hydrogen and helium gas production for high-energy beams. In SNS-type beam windows, the ratio of He/atom to DPA is about 500 of that in fission reactors. These gases can lead to grain boundary embrittlement and accelerated swelling.

In modern codes at intermediate energies, uncertainties on production of hydrogen are ~20%. For helium these could be up to 50%.



C. Broeders, A. Konobeyev, FZKA 7197 (2006)



D. Hilscher et al., J.Nucl.Mat, 296(2001)83

Uncertainties in Simulations

- Particle production in high-energy nuclear interactions: ~20% in most cases.

- Nuclide production: 30-50% typically; Hydrogen gas production <20%; Helium gas production <50%.

- Energy deposition effects (instantaneous and accumulated): 10-15%.

- DPA calculations by the latest versions of FLUKA, MARS15 and PHITS codes coincide within 15-20%.

- Beam loss generation and collimation: quite good in FLUKA and MARS15 (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.

Simulation Challenges

- DPA industry standard NRT and state-of-the-art BCA-MD differ by a factor of 2 to 3 in some cases. Corrections applied to NRT can fix this. Should we all use these corrections coherently? Meanwhile, MARS will provide two sets of DPA: pure NRT and MD or/and experiment corrected values.
- For neutrons below 150 MeV, MARS15 optionally uses defect production efficiency measured for 24 elements at 4-6K. DPA in SC coils calculated with it at 4.2K is 80% lower than that without this correction. Should we use it in Mu2e, COMET and HiLumi LHC superconducting magnet designs?
- Move from occasional comparisons of calculated radiation-damage related quantities to a comprehensive code intercomparison with “standardized” DPA models and well defined irradiation conditions including temperature, dose rate, H_2/He gas production, etc.
- Link of calculated quantities (DPA, dose, fluence etc.) to observable changes in critical properties of materials remains on the top of the wish-list. **Mission impossible?**

Data Needs & Further Simulation Challenges

- Well-thought experiments – covering various regions of the parameter space - are extremely desirable, including measurements with charged particle beams, their relation to neutron data and degradation measurements at cryogenic temperatures.
- Annealed versus non-annealed defects.
- Low-energy neutron DPA in compounds.
- Standardized approach to modeling of soft errors (e.g., SEU) in electronics, certainly at high-energy accelerators and spacecrafts.