Radiation Damage: Accelerator Surprises

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Fermilab

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OUTLINE

1. Radiation Damage at High Energies
2. DPA at Cryo Temperatures
3. Neutrino Yield Degradation

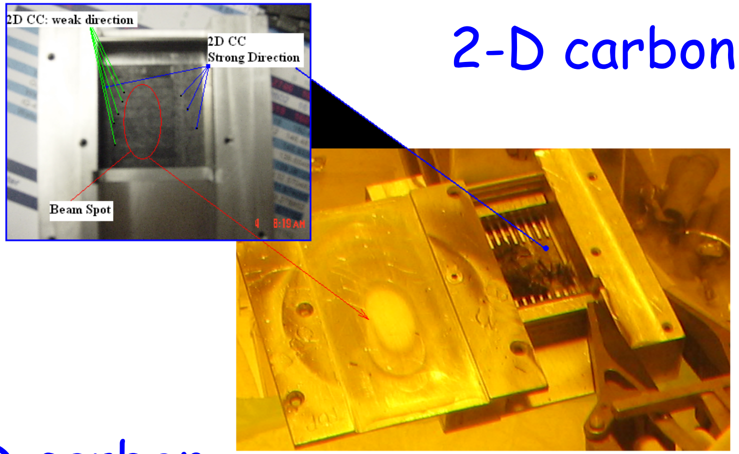
Introduction

Deterioration of critical properties of crystalline materials under irradiation is usually analyzed as a function of displacements per atom (DPA). The latter is a strong function of projectile type, energy and charge as well as material properties including its temperature.

These dependencies – amplified by increased helium gas production for high-energy beams - are responsible for "surprises/unknowns" learned recently at accelerators.

Nick Simos' Rad.Damage Studies at BLIP with 100-200 MeV protons

2-D carbon



Graphite

3-D carbon

Glidcop in both axial and transverse directions sees 40% reduction at ~1 dpa.
3-D CC (~ 0.2 dpa) conductivity reduces by 3.2.
2-D CC (~0.2 dpa) measured under irradiated conditions (to be compared with company data).
Graphite (~0.2 dpa) conductivity reduces by 6.

DPA for Proton/Ion Beams

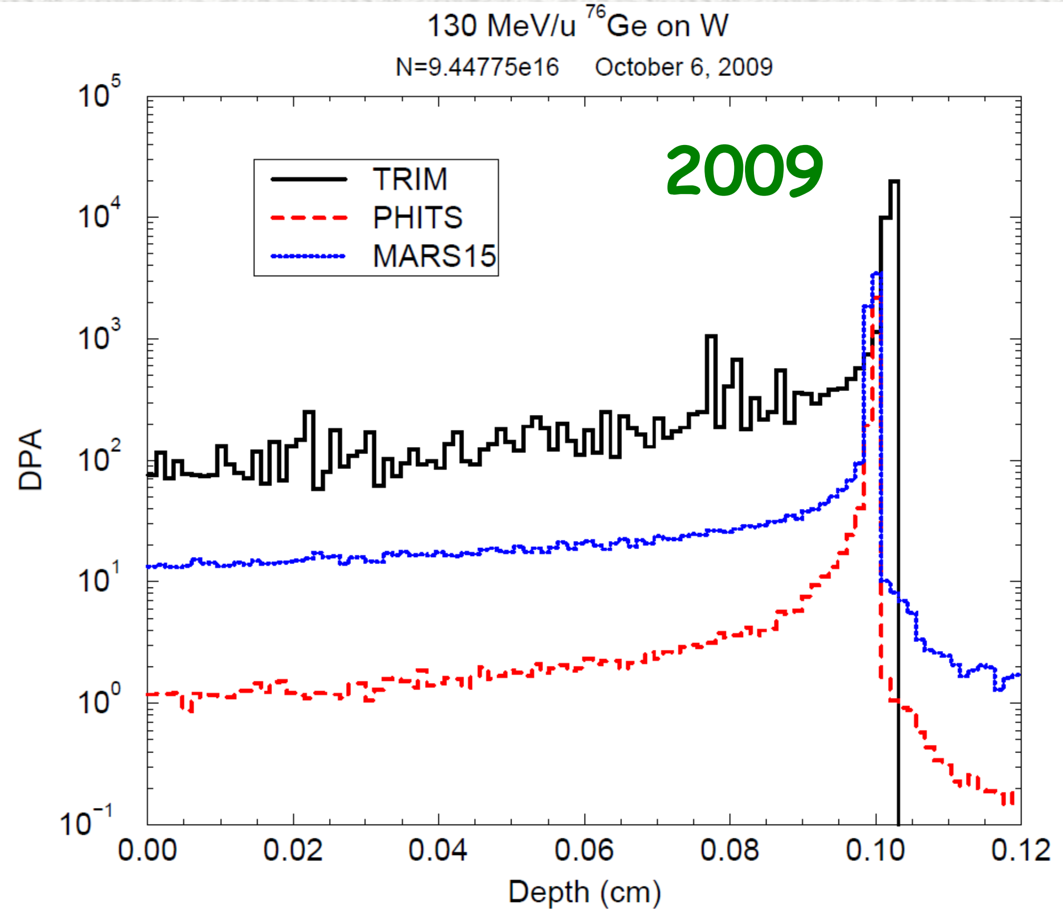
Observation:

In proton irradiation, a threshold exists on carbon composites and graphite at ~0.2 DPA, lower than expected from reactor data (although there were indications of such a level for CTE in reactor data).

Possible explanations:

- Contribution of Coulomb elastic scattering $\sim Z_p^2$, becomes important (dominant in some instances) for charged particle irradiation.
- DPA in BLIP tests was estimated with earlier versions of MCNPX known to underestimate (neglect) contribution of this process.
- Helium gas production adds, becoming increasingly important at high energies.
- Graphite is indeed less radiation-resistant than expected.

Shocking Disagreement in Model Predictions for High-Z projectiles (2009)



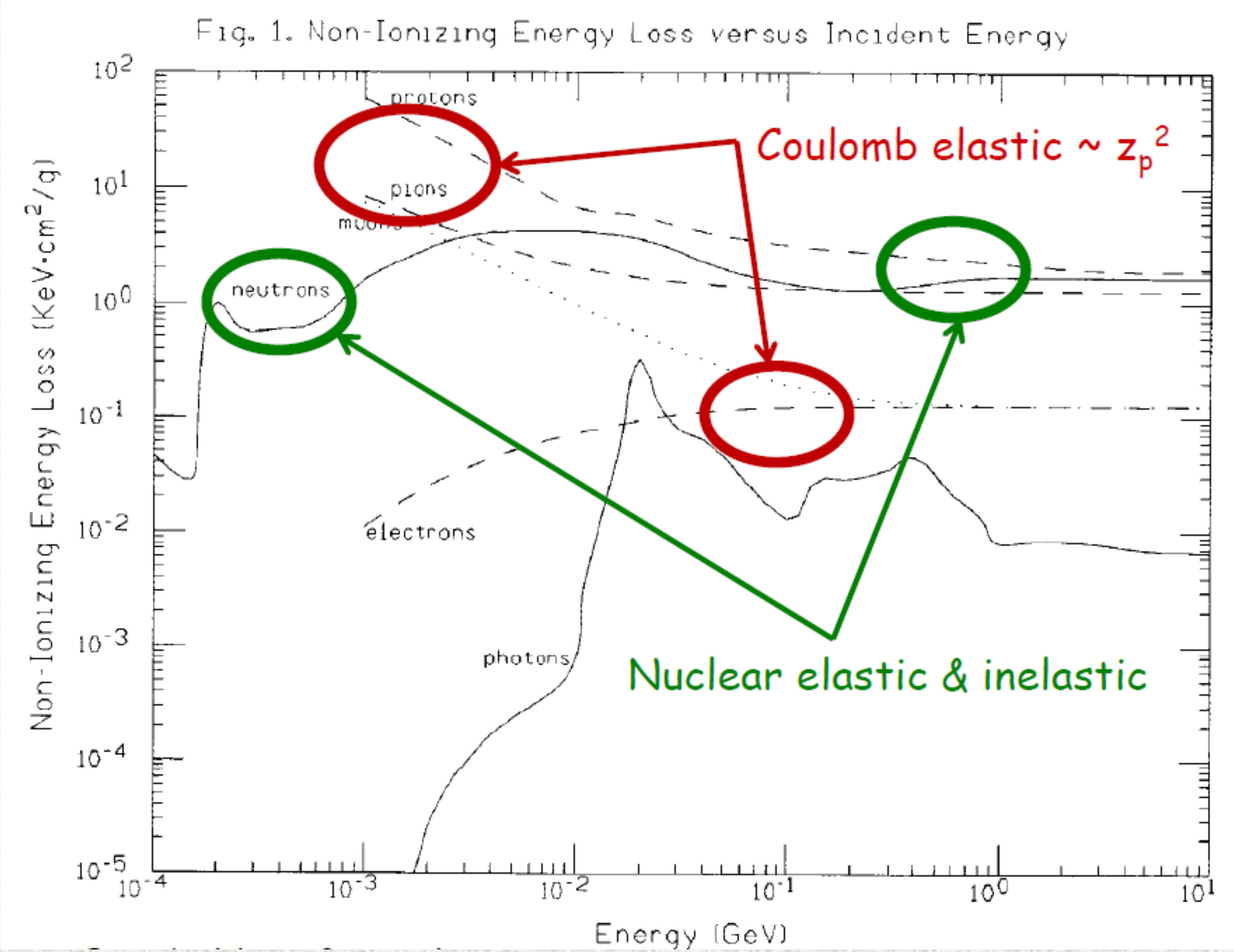
Pencil beam,
uniform in R=0.03568 cm disc.
Target W_{nat}, cylinder with
R=0.03568 cm, L=0.12 cm.

TRIM and PHITS by
Yosuke Iwamoto.

0.32-GeV/u ^{238}U on 1-mm Be, 9 cm^2 beam

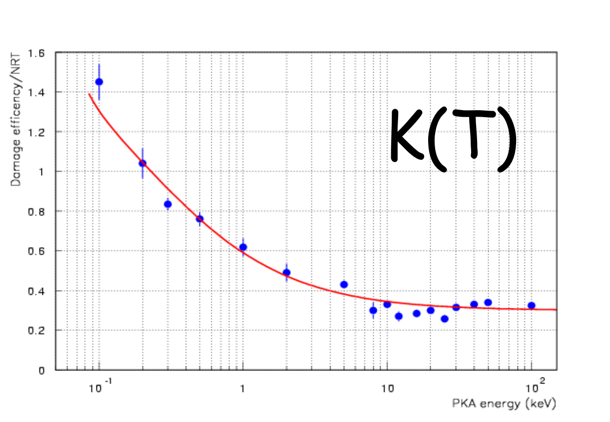
Code	SRIM	PHITS	MARS15
DPA/pot	2.97e-20	5.02e-22	2.13e-20

DPA/NIEL vs Particle Type & Energy in Si

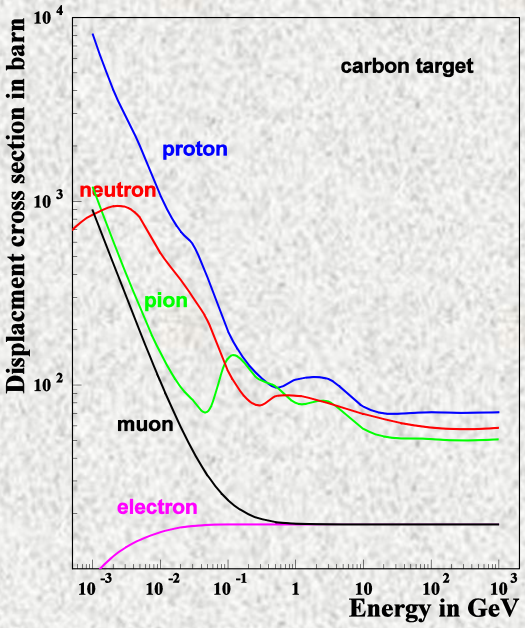


DPA Model in MARS15 in One Slide

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), displacement energy T_d (irregular function of atomic number) and displacement efficiency K(T).

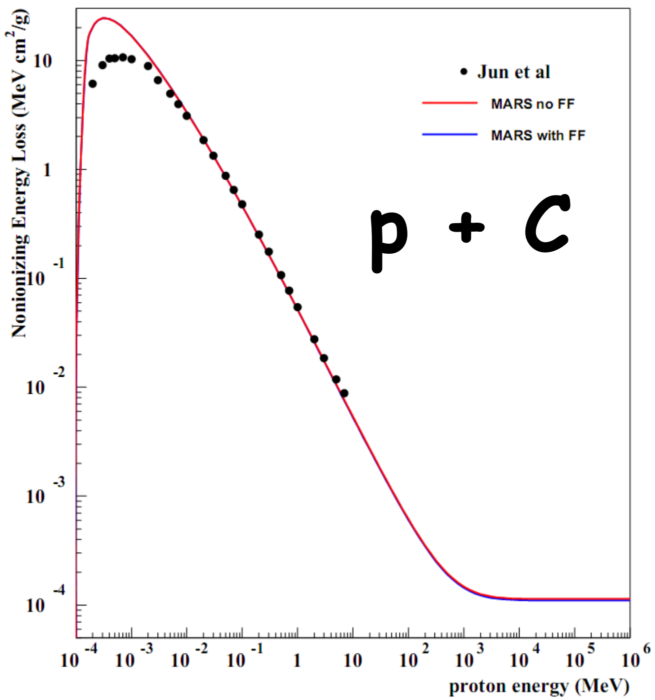


All products of elastic and inelastic nuclear interactions as well as Coulomb elastic scattering (NIEL) of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV. Coulomb scattering: Rutherford x-section with Mott corrections and nuclear form factors for projectile and target.

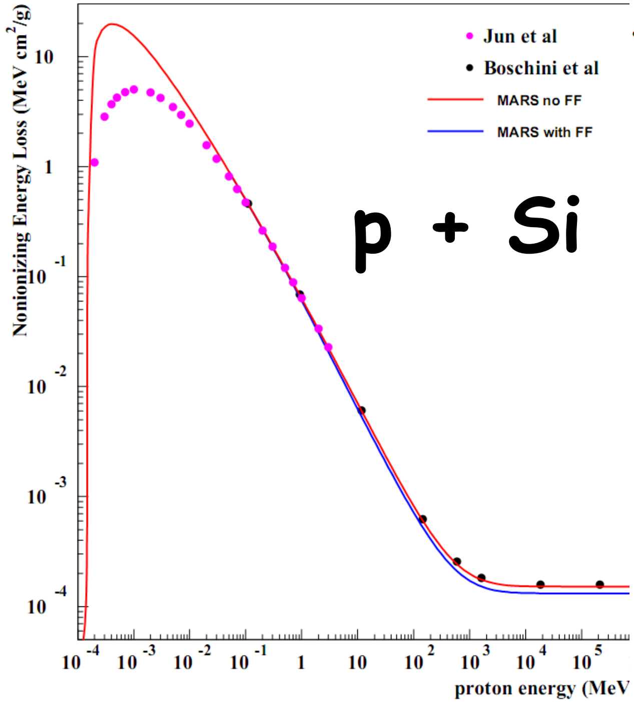


Comparing MARS15 with Most Recent Models

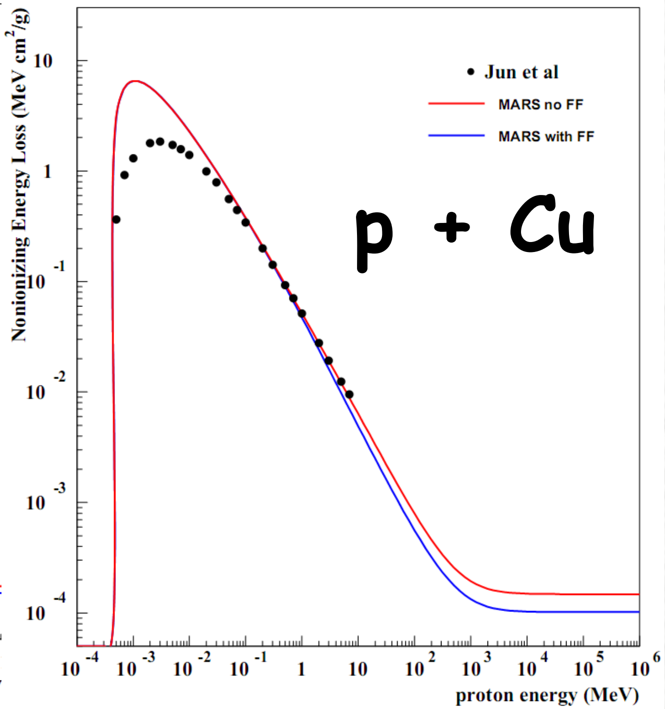
I.Jun, "Electron Nonionizing Energy Loss for Device Applications",
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 6, DECEMBER 2009



Proton NIEL for carbon due the Coulomb scattering



Proton NIEL for silicon due the Coulomb scattering

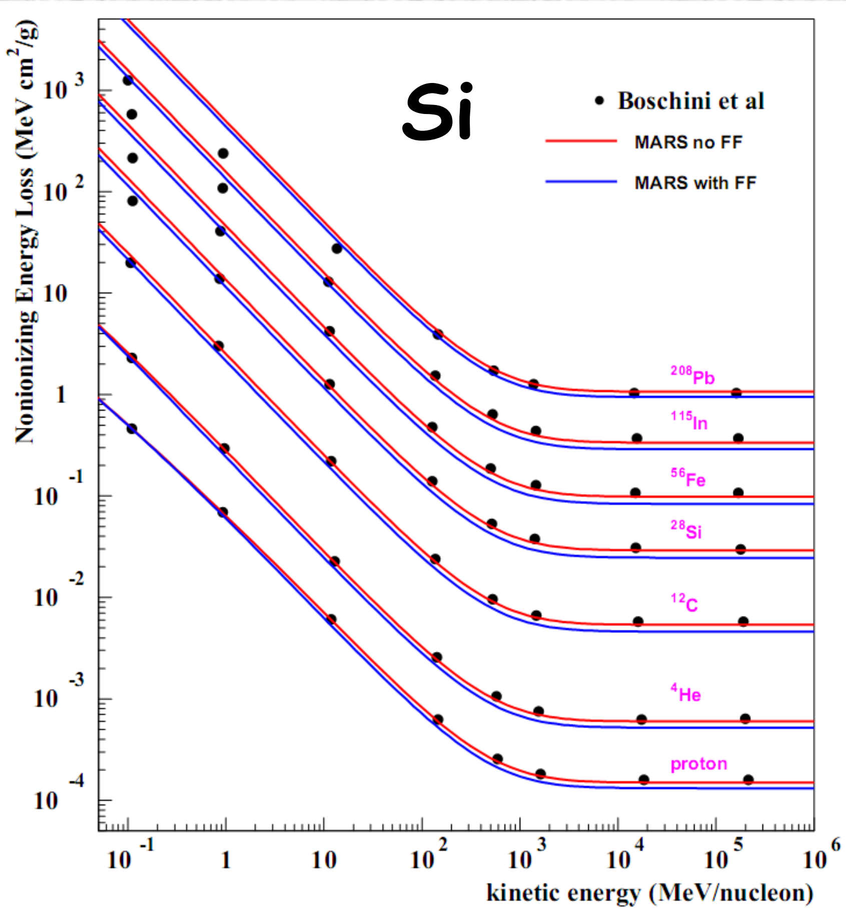


Proton NIEL for copper due the Coulomb scattering

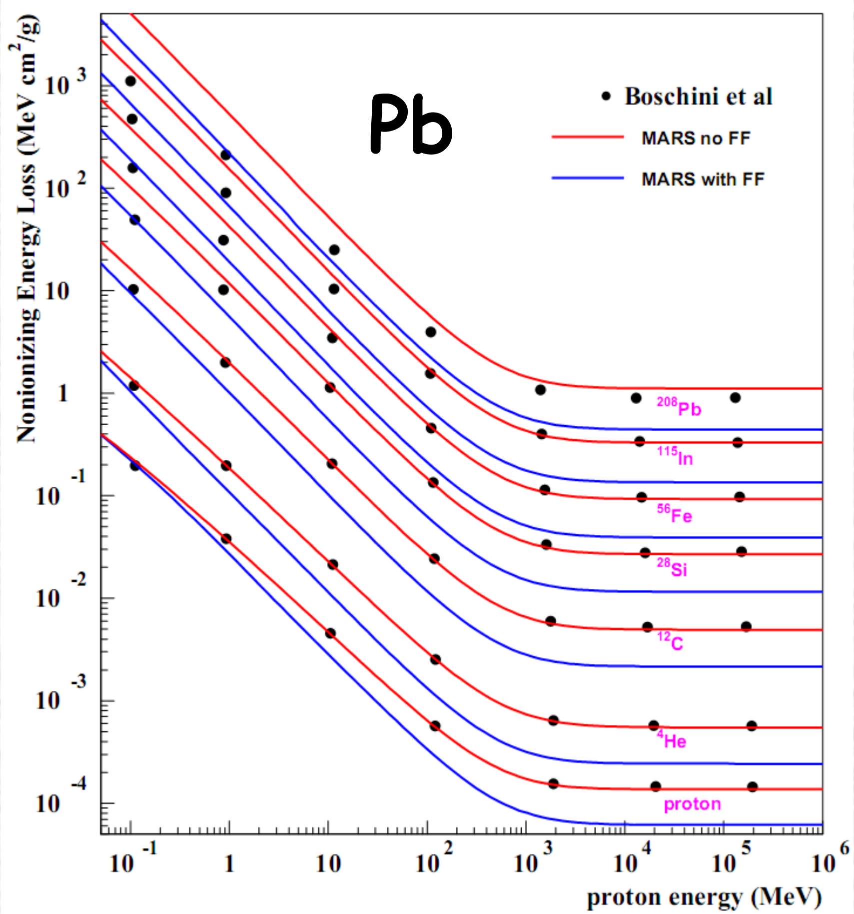
- Minimal proton transport cutoff energy in MARS is 1 keV

Comparing MARS15 with Most Recent Models

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



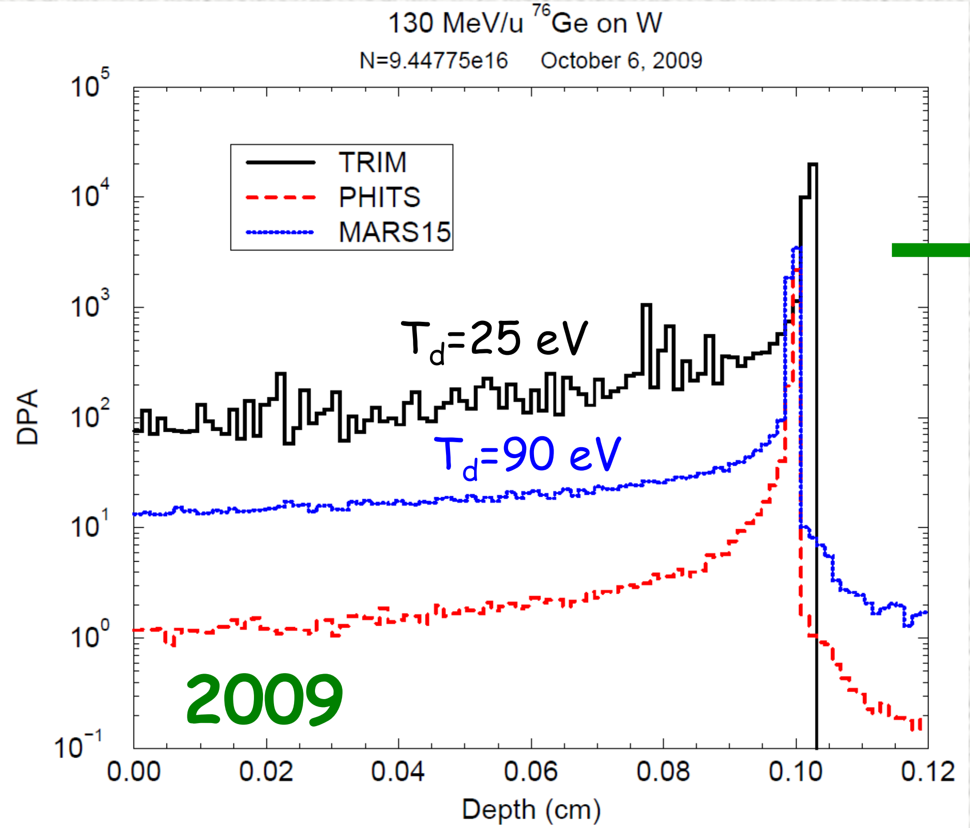
NIEL for silicon due the Coulomb scattering

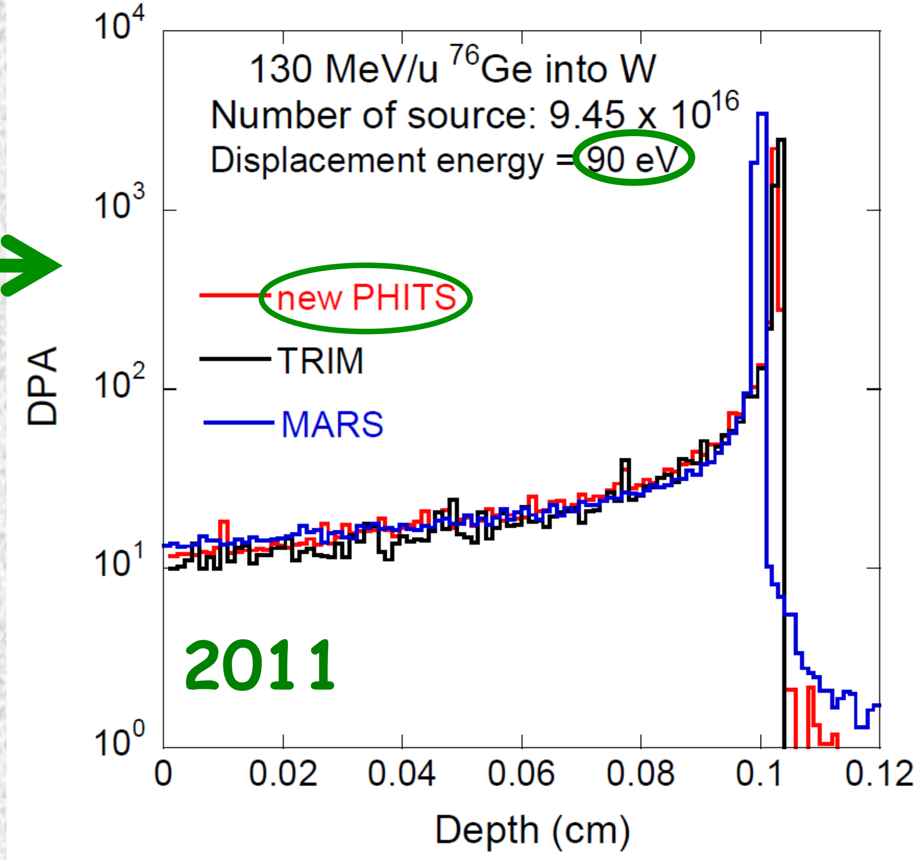


Proton NIEL for lead due the Coulomb scattering

MJB et al. do not include form factors of target and projectile (default in MARS15), which are substantial for high Z

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

TRIM and PHITS results: Courtesy Yosuke Iwamoto

DPA Calculation Comparisons (1)

0.32-GeV/u ^{238}U on 1-mm Be, 9 cm^2 beam

* Courtesy Susana Reyes (2009)

Code	SRIM*	PHITS*	MARS15
DPA/pot	2.97e-20	5.02e-22	2.13e-20

6.50e-20, new PHITS by Yosuke Iwamoto (2011)

MARS15: Physics process (%)

Nucl. Inel.	EM elastic	L.E. neutron	$e^{\pm}$
0.3	99.06	0.02	0.62

DPA Calculation Comparisons (2)

1-GeV p on 3-mm Fe, 1 cm^2 beam

* Courtesy Susana Reyes (2009)

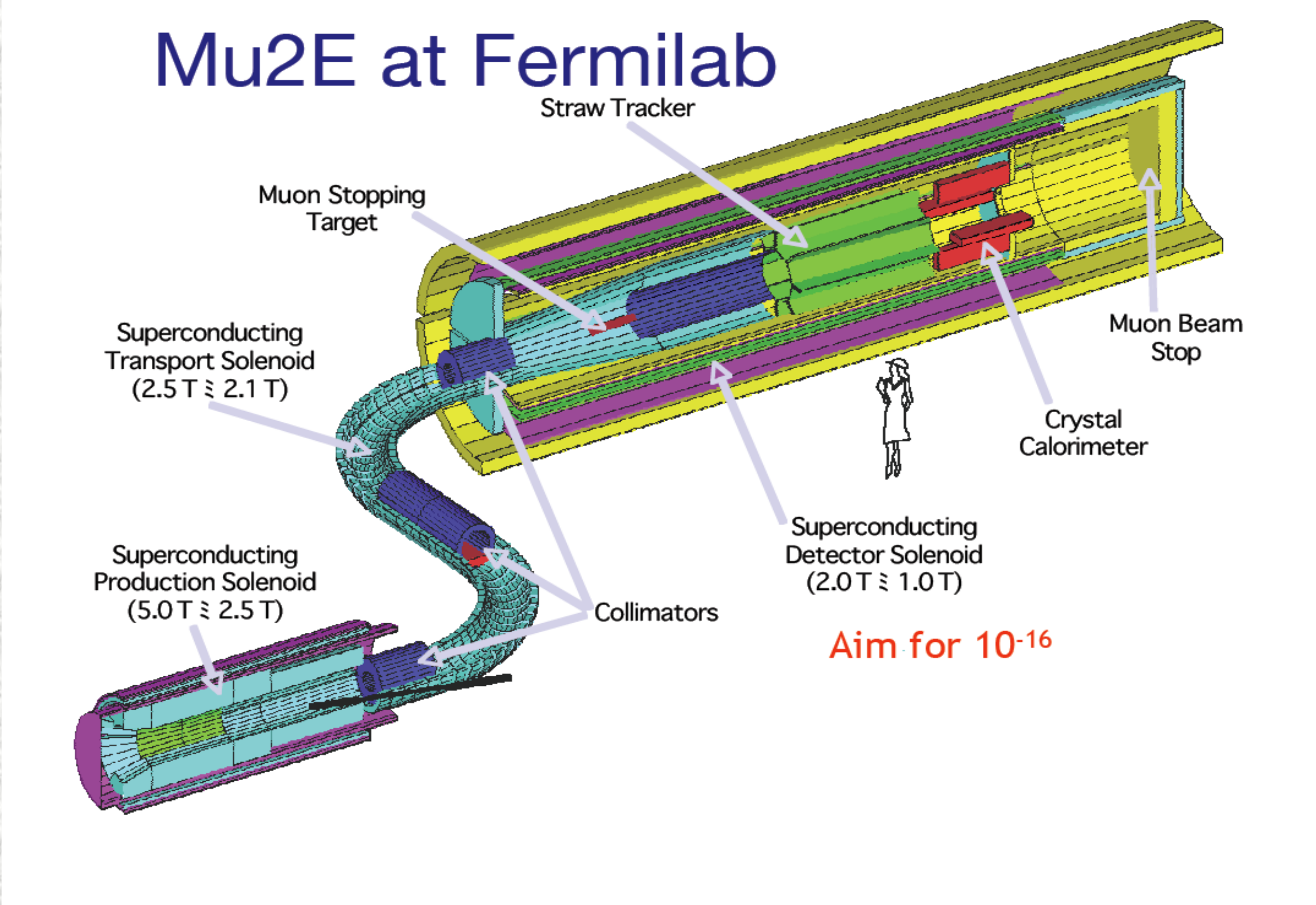
Code	SRIM*	PHITS*	MCNPX*	MARS15
DPA/pot	1.18e-22	2.96e-21	3.35e-21	8.73e-21

7.79e-21, new PHITS by Yosuke Iwamoto (2011)

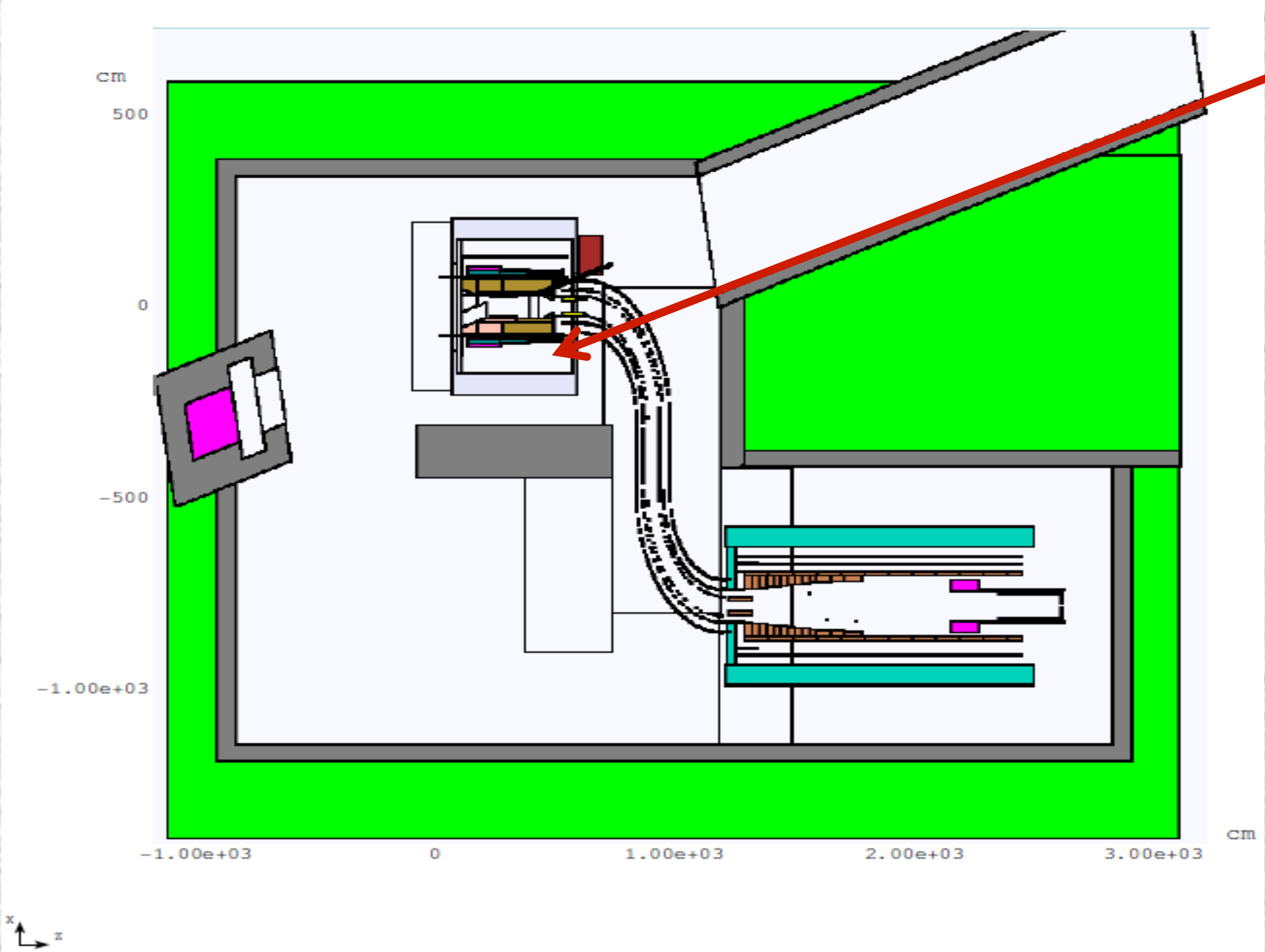
MARS15: Physics process (%)

Nucl. Inel.	Nucl. Elastic	EM elastic	L.E. neutron	$e^{\pm}$
75.5	16	2.75	5.5	0.25

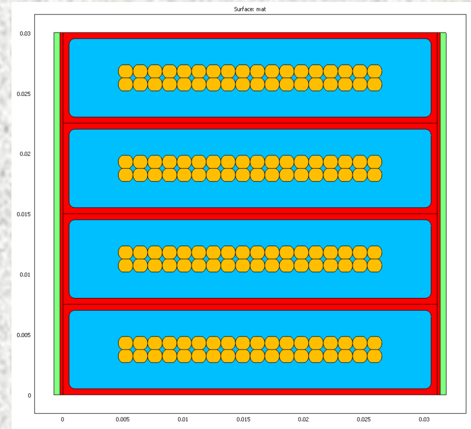
DPA at Cryo Temperatures: Mu2e



RRR Degradation: DPA limit for SC coils = 2.5E-5 /yr



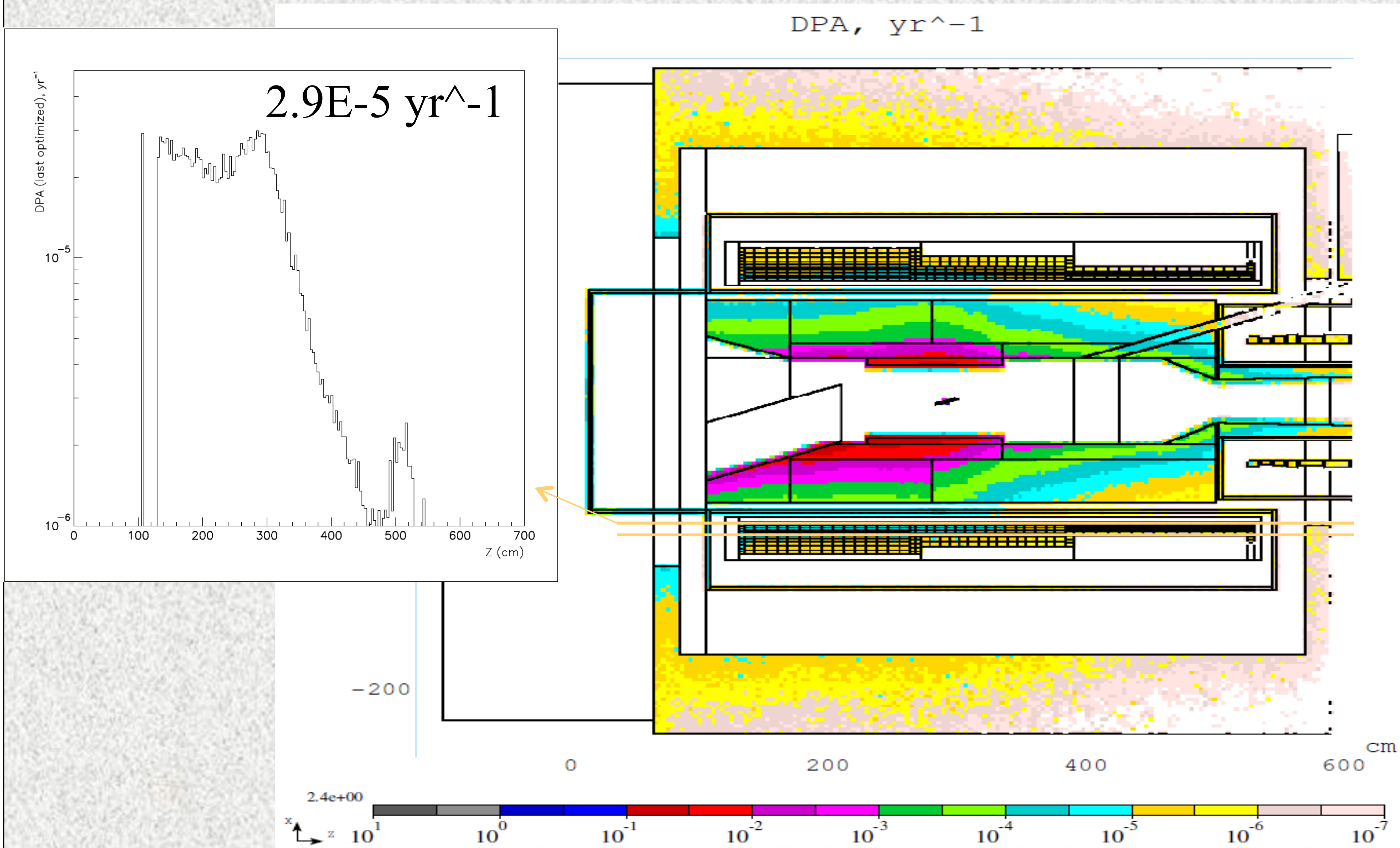
8-GeV p, 25 kW
2.e13 p/s
$\sigma_x = \sigma_y$ = 1mm
Gold water-cooled target (r=3mm, L=160mm)



Coil materials:
8.35% NbTi
8.35% Cu
17.33% G10
65.97% Al

Bottleneck: degradation of Residual Resistivity Ratio (RRR) of **stabilizer** (ratio of electric resistivity of a conductor at room temperature to that at the liquid He one).

MARS15: DPA, yr^-1



RRR vs DPA

Journal of Nuclear Materials 133&134 (1985) 357–360

DEFECT PRODUCTION AND RECOVERY IN FCC METALS IRRADIATED AT 4.2 K *

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Lawrence Livermore National Laboratory, Livermore, California, USA

ISOCHRONAL RECOVERY OF FAST NEUTRON IRRADIATED METALS*

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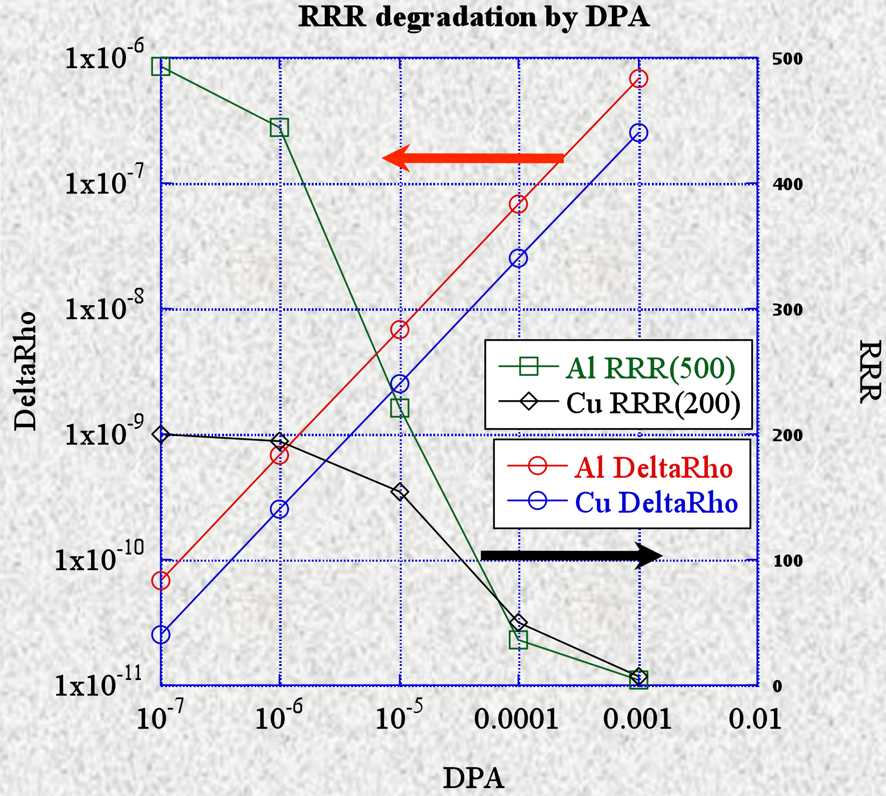
Received 22 May 1973
Revised manuscript received 27 August 1973

a) The values used for the resistivity per Frenkel pair are:

Element	Resistivity per Frenkel pair, $\rho_{F.P.}$ (10^{-4} $\Omega \cdot$cm/atom fraction)	Ref.
Aluminum	6.8	[4]
Nickel	6.4	[4]
Copper	2.5	[4]
Silver	2.5	[4]
Gold	2.5	[4]
Platinum	7.5	[5]
Iron	12.5	[6]
Molybdenum	10.0	estimated
Cobalt	10.0	estimated

[4] P.G. Lucasson and R.M. Walker, Phys. Rev. 127 (1962) 1130.

T. Ogitsu's (COMET, Japan):



- Resistivity will degrade by Frenkel Pairs induced by neutron
- Number of Frenkel Pairs = DPA

DPA: 2E-5 per 1E21 protons

Consequences of Higher DPA

1. Higher electrical resistivity at 4.5K/lower RRR:
    - Higher peak temperature during quench
    - Higher resistive voltage across the coil during quench
    - Reduced stability against heat pulses

2. Lower thermal conductivity at 4.5K:
    - Increased temperature increment across the coil
    - Reduced thermal margin
    - Reduced stability against heat pulses

RRR change by a factor of 2 leads to the temperature change by ~50 mK

NuMI 2nd target depletion (ZXF-5Q amorphous graphite)

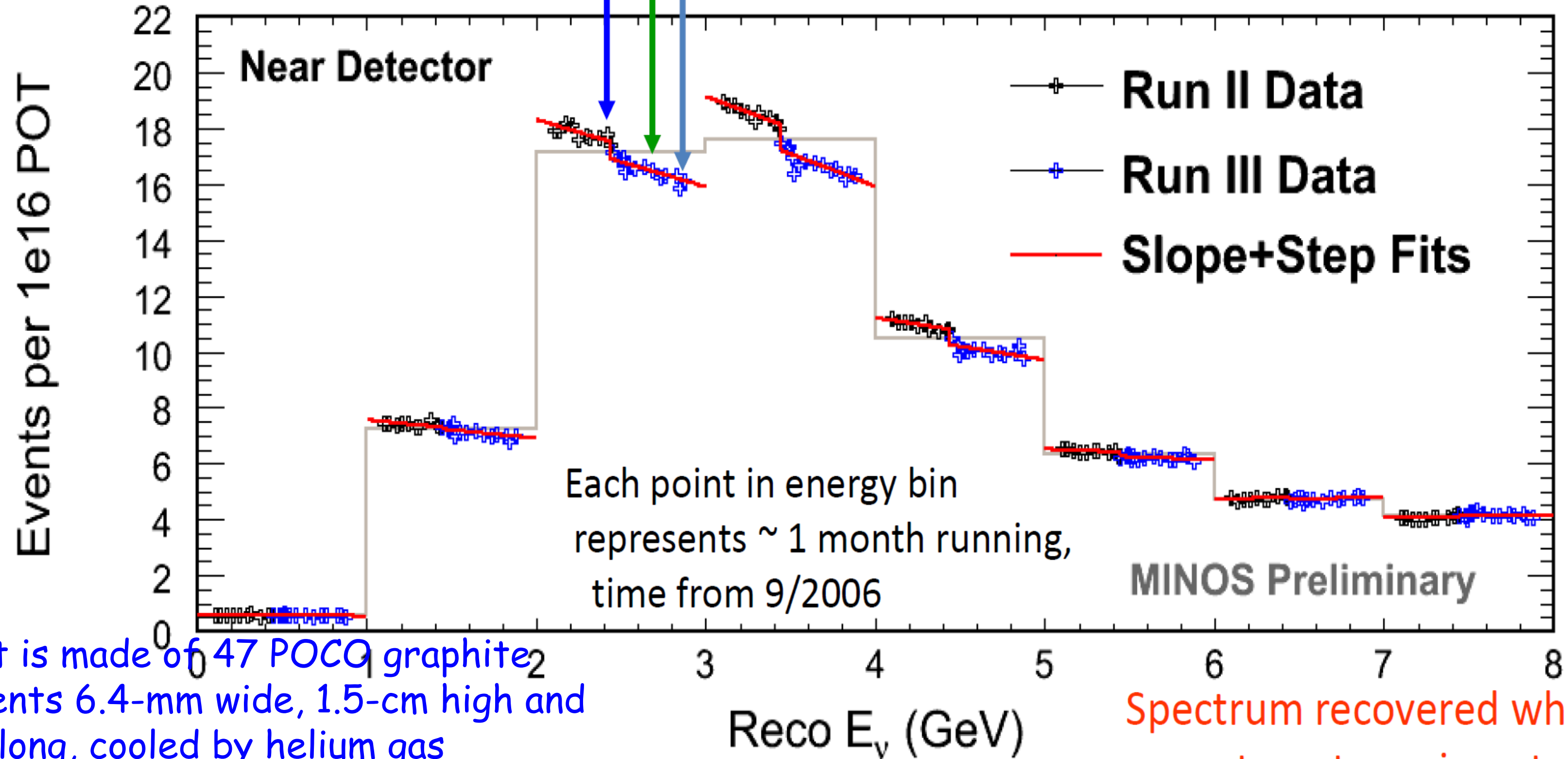
NT-02 replaced when spectrum shift became too large.

Gradual decrease in neutrino rate attributed to target radiation damage

Decrease as expected when decay pipe changed from vacuum to helium fill

No change when horn 1 was replaced

No change when horn 2 was replaced



Target is made of 47 POCO graphite segments 6.4-mm wide, 1.5-cm high and 2-cm long, cooled by helium gas

Spectrum recovered when new target was inserted

Courtesy: J.Hylen

Neutrino Yield and Target Degradation

Observation:

Neutrino yield has degraded by up to 10% after exposure of the target with 6e20 protons.

Explanation: Radiation damage of the target material in the shower maximum region (z ~ 10-15 cm, r < 1-2 mm).

Possible mechanisms:

1. Void creation due to DPA (a simple model tried by two groups).
2. Helium bubble production, quite substantial at 120 GeV. Trapped bubbles and helium pressure would reduce target density in the above region.
3. Graphite amorphization: ρ = 1.8 gcc → porous carbon ρ ~ 1.5 gcc (according to M. Tomut).
4. Transmutation of carbon nuclei.

DPA and Helium Distributions

Maximum of DPA distribution produced by 120 GeV/c proton beam with $\sigma_x = \sigma_x = 1.1$ mm during Run II (2 10^{20} POT) is 0.25 DPA

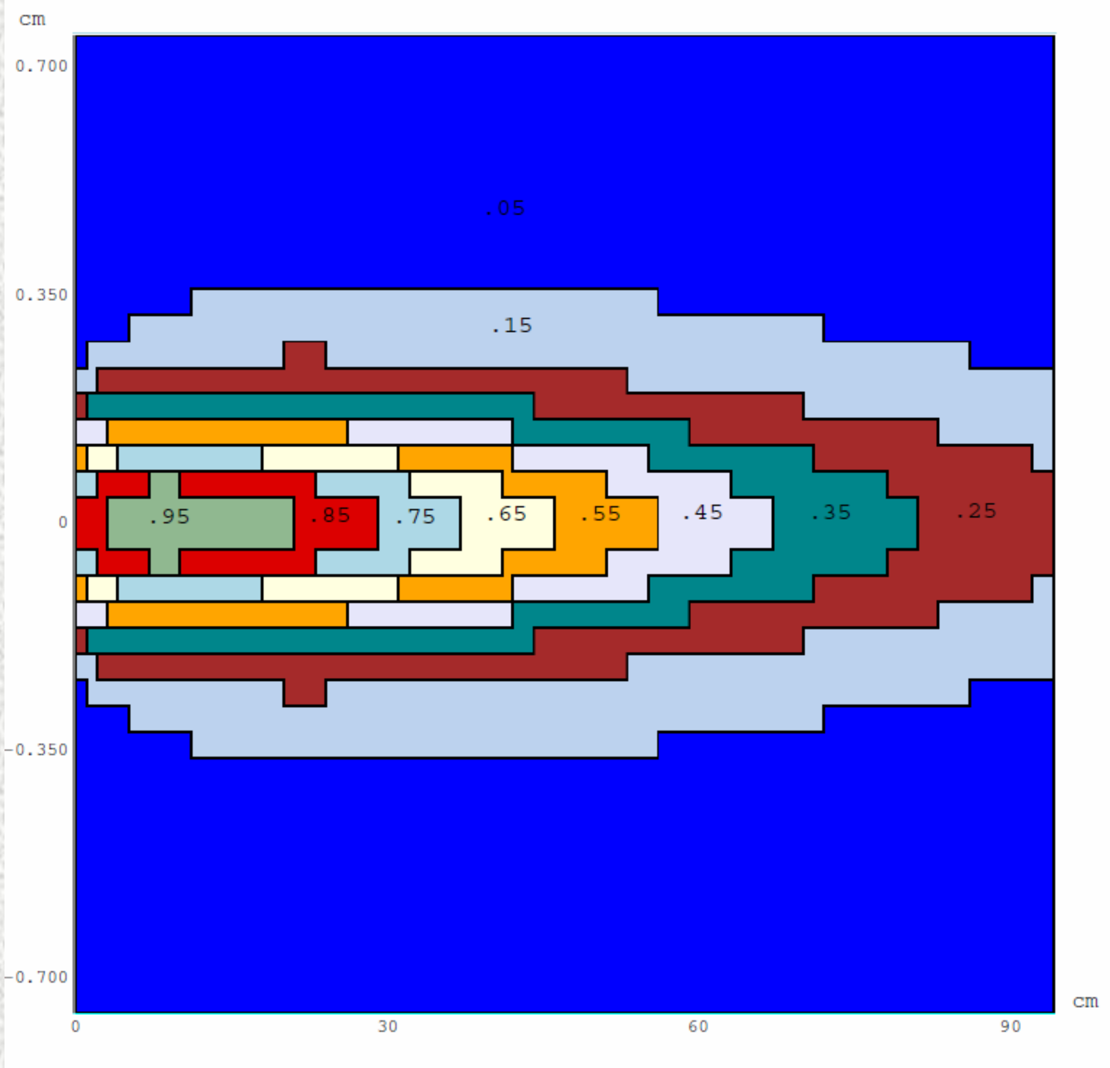
After Run III (4 10^{20} POT) maximum of DPA distribution reaches 0.75 DPA

Distribution of produced helium atoms is very similar to DPA distribution

After Run II (2 10^{20} POT) maximum of helium concentration is 1.6 10^{19} atom/cm^3

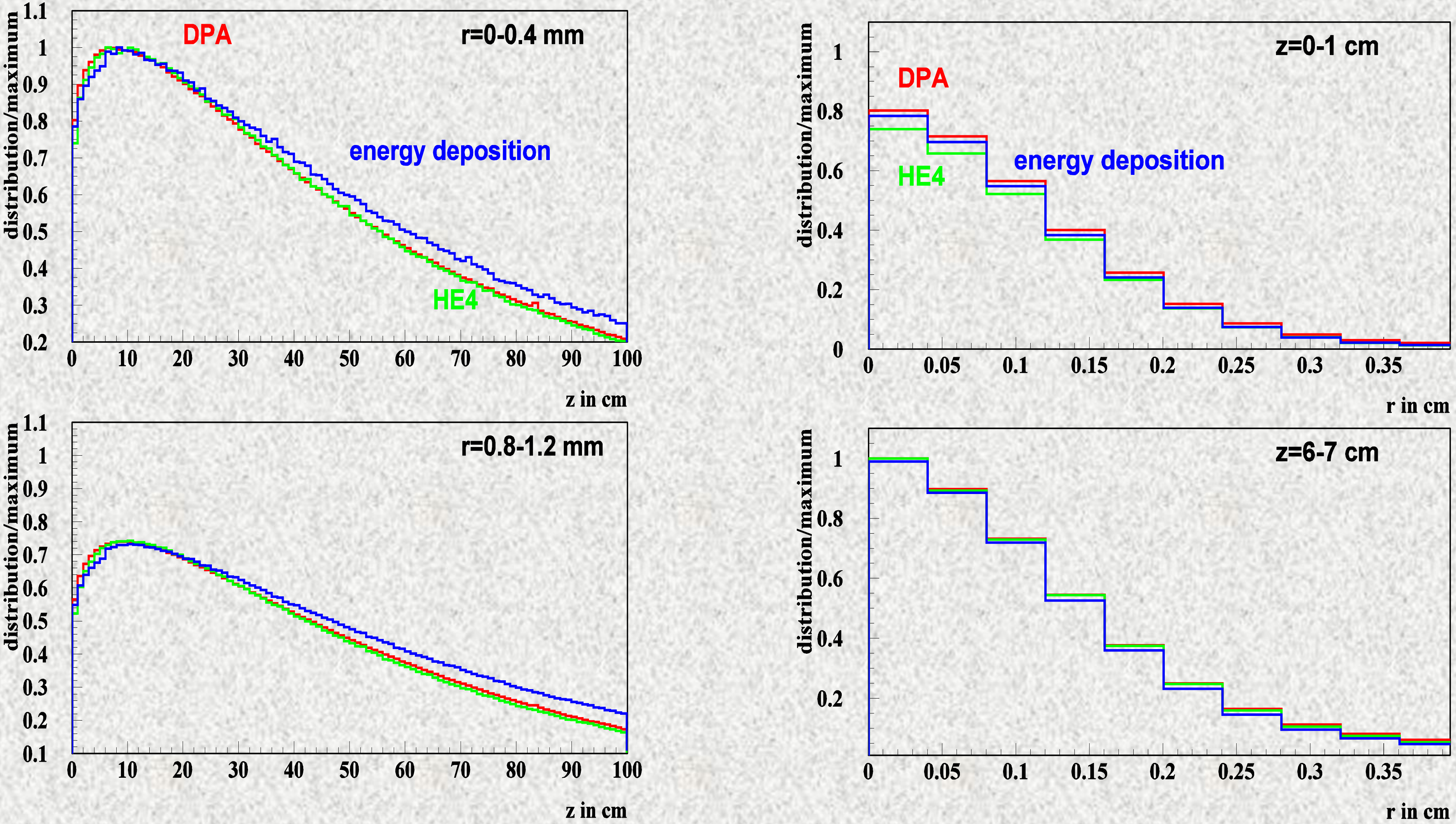
After Run III (4 10^{20} POT) concentration run up to 4.8 10^{19} atom/cm^3

DPA/DPA$_{max}$ as function of r and z



DPA, Helium and Energy Deposition Distributions

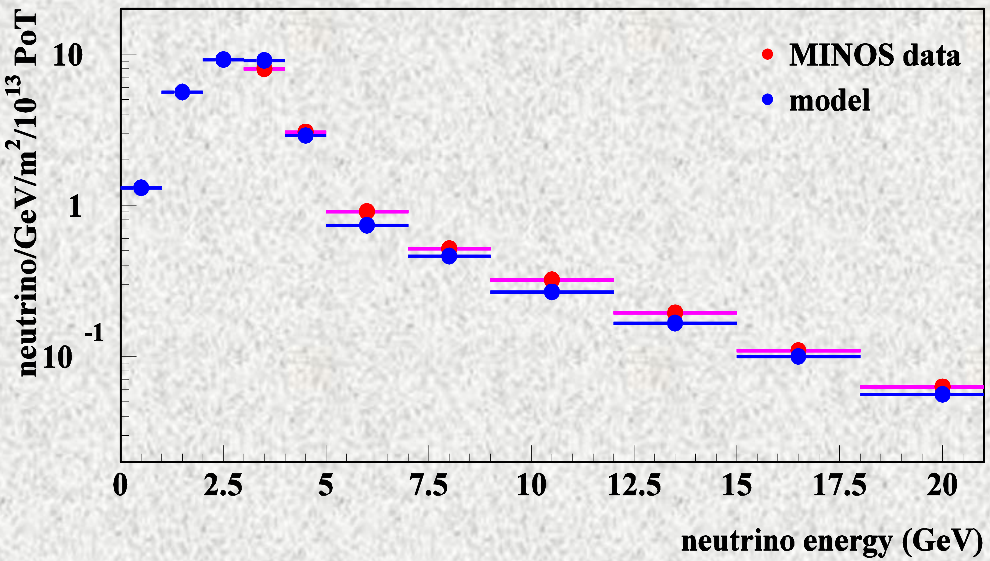
Similar in this particular case (high energy, low-Z, small r), not in general

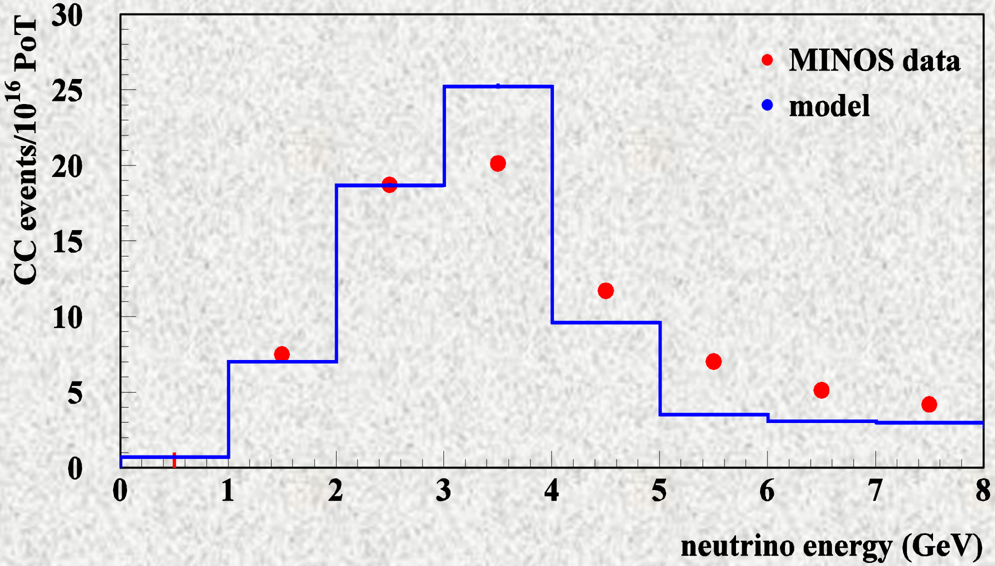


Modeling Neutrino Spectra

A simplified model of the channel: target, 2 horns, decay pipe, absorber

This model does not take into account production of secondary particles in interactions with horns, walls of decay tube and scattering in horns. It describes well measurements of neutrino spectra and reasonably – without including the detector response – rate of CC events.

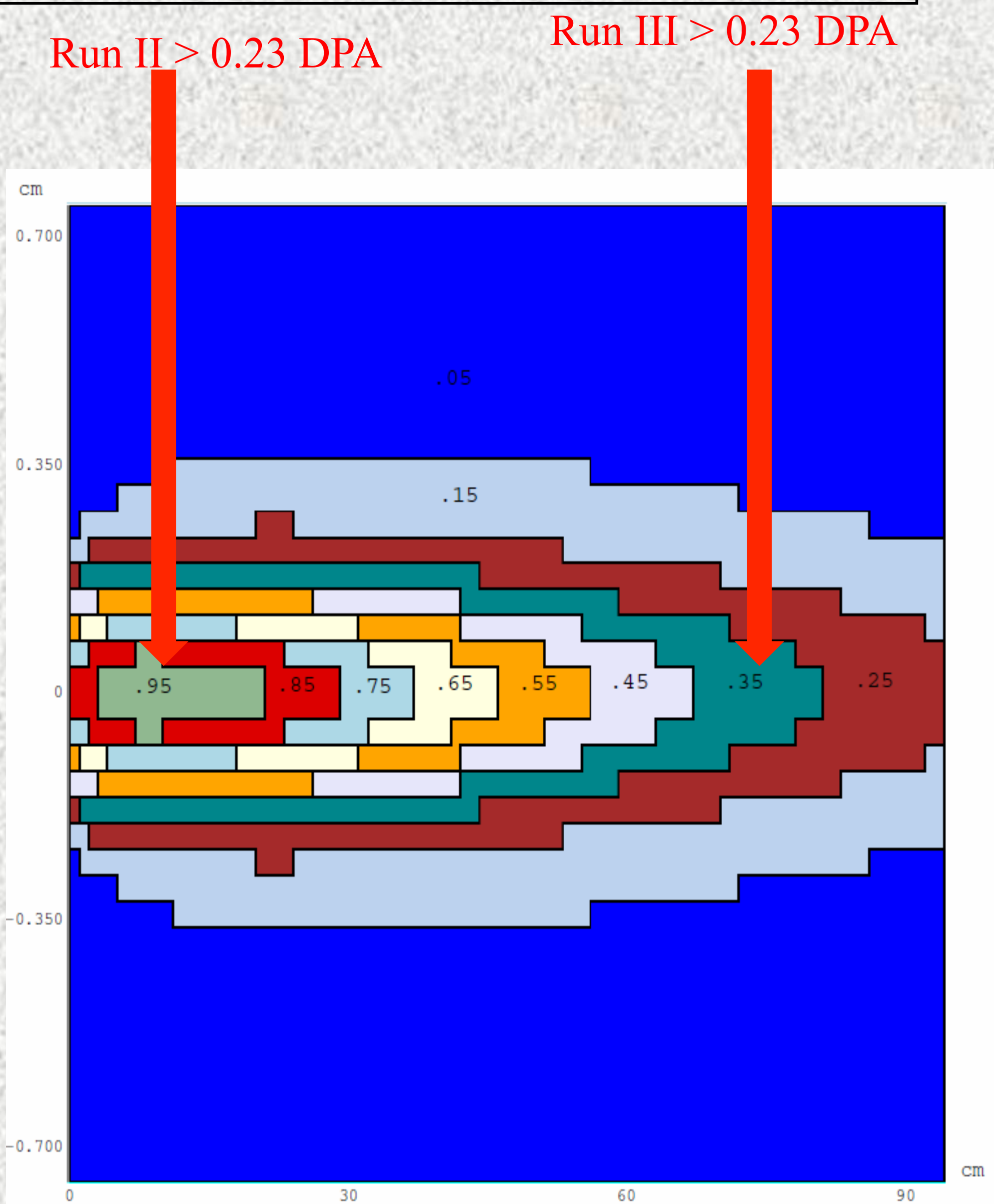




DPA-Driven Void in the Target

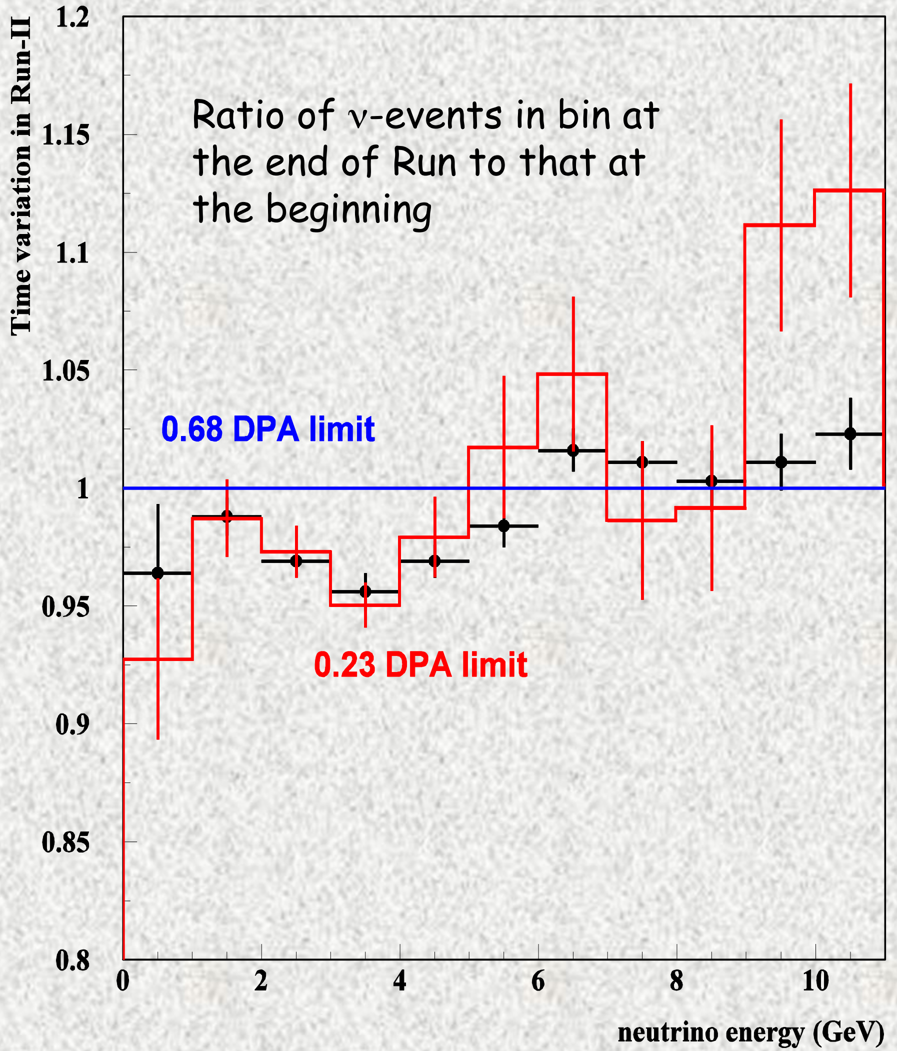
A void model of target destruction: graphite is replaced by hole in the region where DPA level exceeds the threshold, taken here as 0.23 DPA.

DPA_{max}=0.25 after Run II:
0.95-grey hole
DPA_{max}=0.75 after Run III:
0.35-green hole

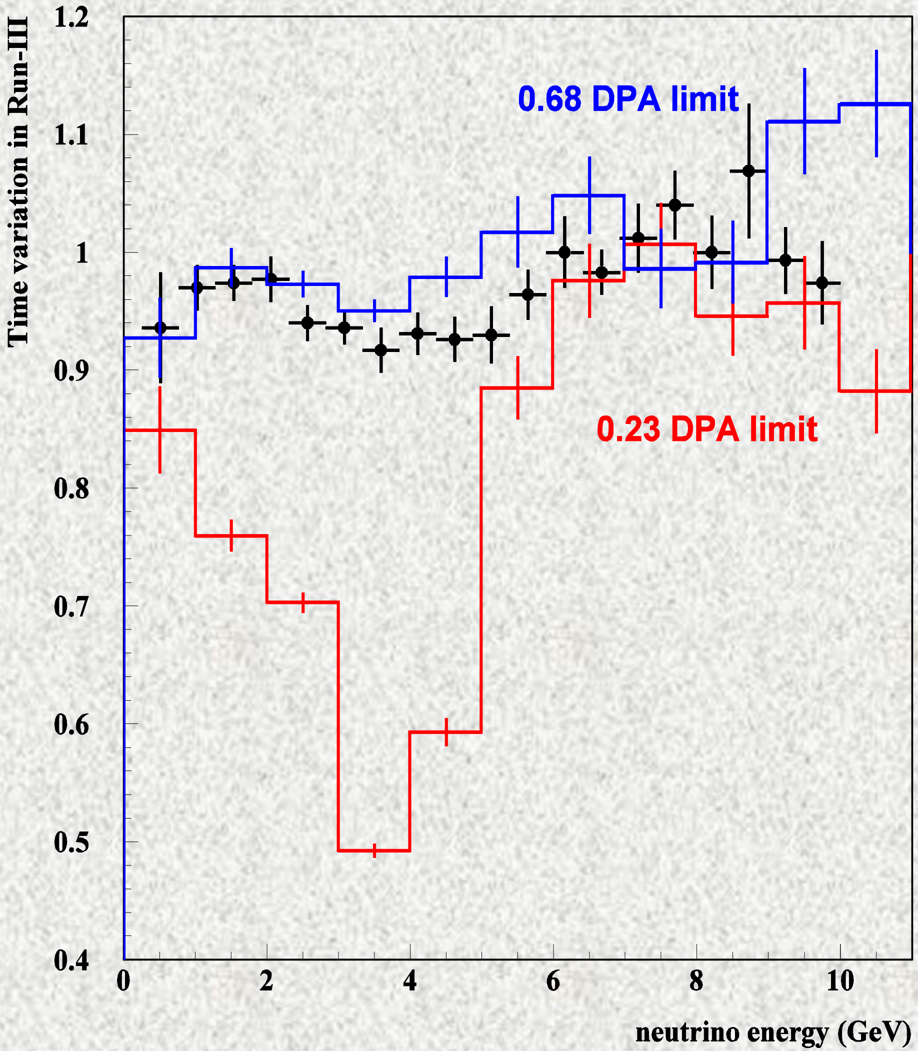


Void Model: a Limited Success

After Run II, 2 10^{20} POT



After Run III, 6 10^{20} POT

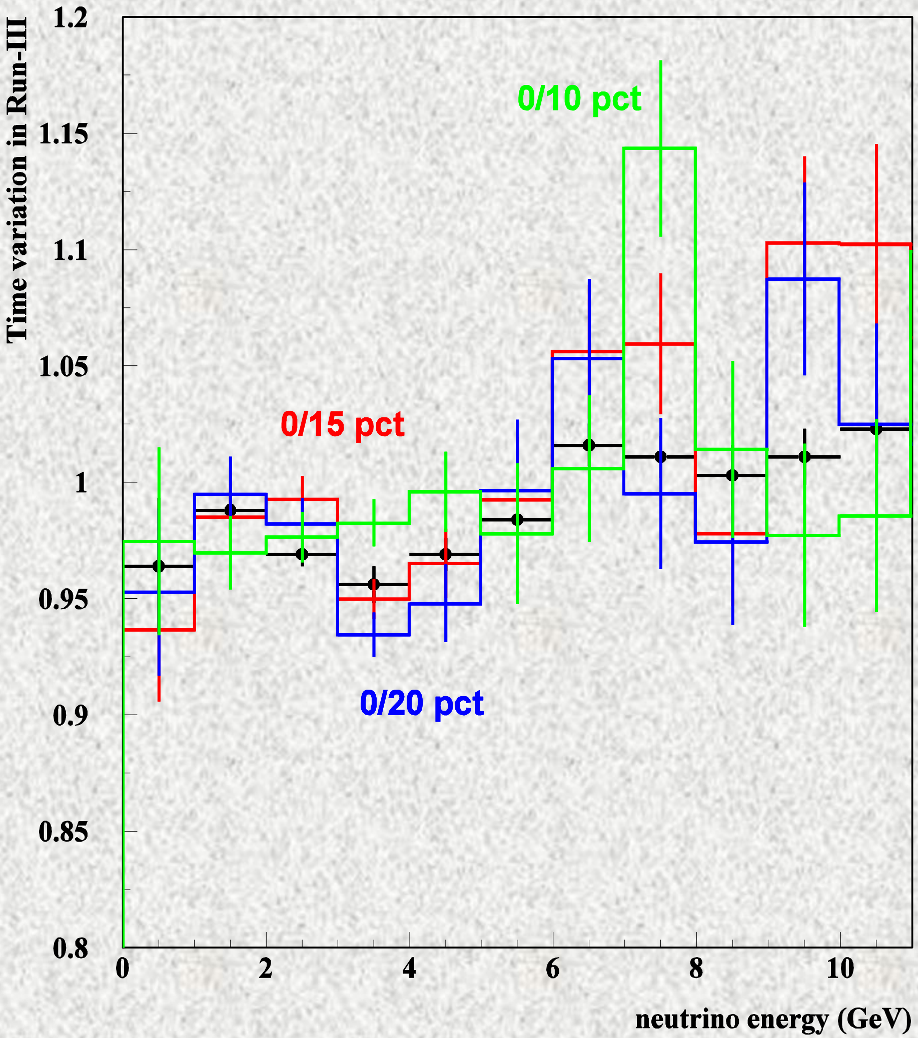


Density Reduction due to Helium or Amorphization

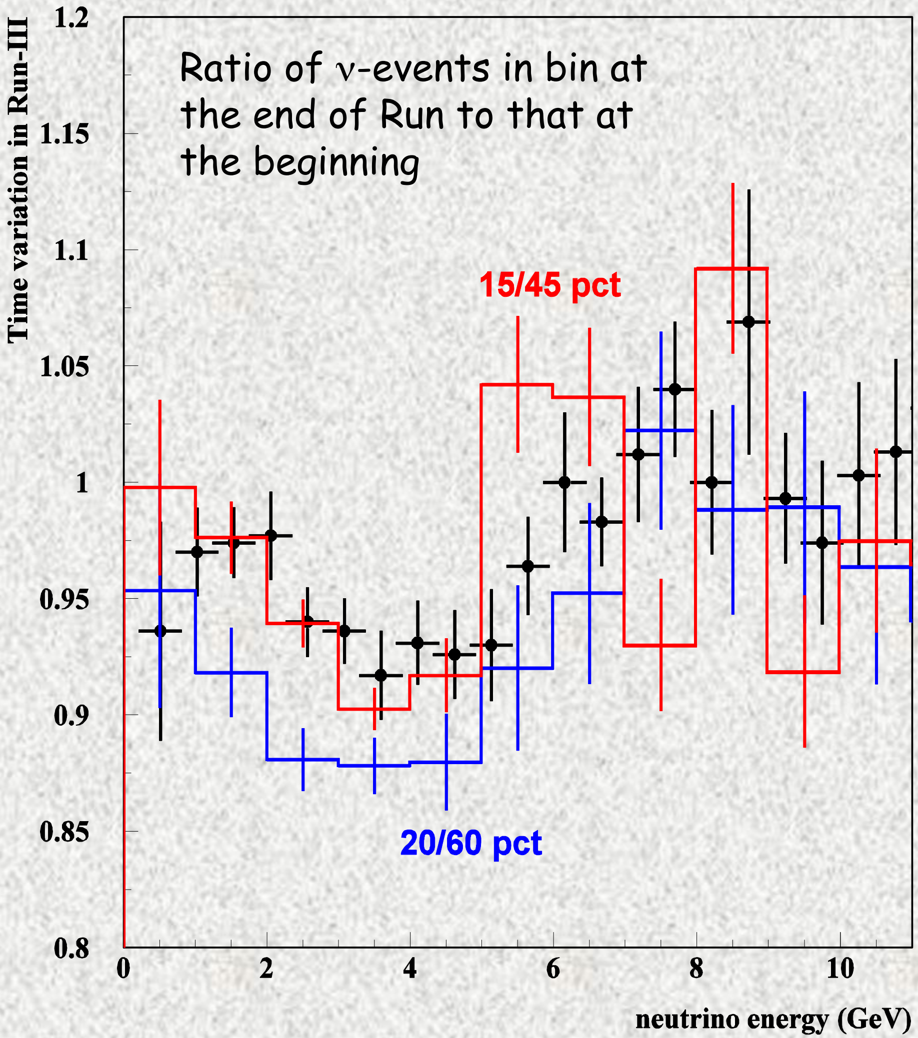
- Target density in each point is proportional to radiation-induced porosity (~DPA) and inversely proportional to the helium concentration in that point.
- Target mass is not change.
- There is only one unknown parameter in this model. There are two sets of data from NuMI, therefore the model can be checked against measurements.

Density Reduction Model: Seems Reasonable

Run II, 2 10^{20} POT



Run III, 4 10^{20} POT



Summary

• Radiation damage by high-energy beams is more intense (for the same fluence) due to Coulomb elastic scattering $\sim Z_p^2$; codes which include this process, nuclear interactions, and same DPA model parameters agree quite well; radiation damage at high energies is amplified by intense helium gas production.

• The bottleneck in design of large superconducting magnet systems is extremely low level of the allowable DPA ($\sim 10^{-5}$) in stabilizing materials (Al and Cu).

• Observed neutrino yield degradation is attributed to reduction of graphite density in shower maximum region due to helium gas production or/and amorphization of graphite.