Recent Improvements in Modeling and Radiation Effects in Superconducting Magnets for Mu2e and High-Luminosity LHC

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Workshop on Radiation Effects in Superconducting Magnet Materials

(RESMM'14)

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Outline

- Recent Improvements in MARS15
- Radiation Effects in Mu2e SC Coils
- Radiation Effects in HiLumi LHC IR SC Coils
- Issues
- Summary

Modeling Radiation Loads in LHC IR

MARS simulations in 1996 to 2003 helped design the optimal high-luminosity Interaction Regions IR1 and IR5 of LHC, including their TAS, TASB and TAN absorbers, and predict superconducting magnet short-term (quench stability) and long-term (lifetime) performances.

"MARS predictions of 16 years ago of energy deposition in the low-beta quads agree within 20% with recent measurements in the real LHC machine. No beam-induced quench has been observed at LHC". Lucio Rossi, talk at Fermilab, February 2014.

Note that one and a half decades ago there was no experimental data above 1 TeV to verify the code's physics models. These days – working on the HiLumi LHC upgrade - we have a luxury of coherent studies with the FLUKA and MARS codes benchmarked in the TeV energy region.

LAQGSM Developments at E < 10 GeV

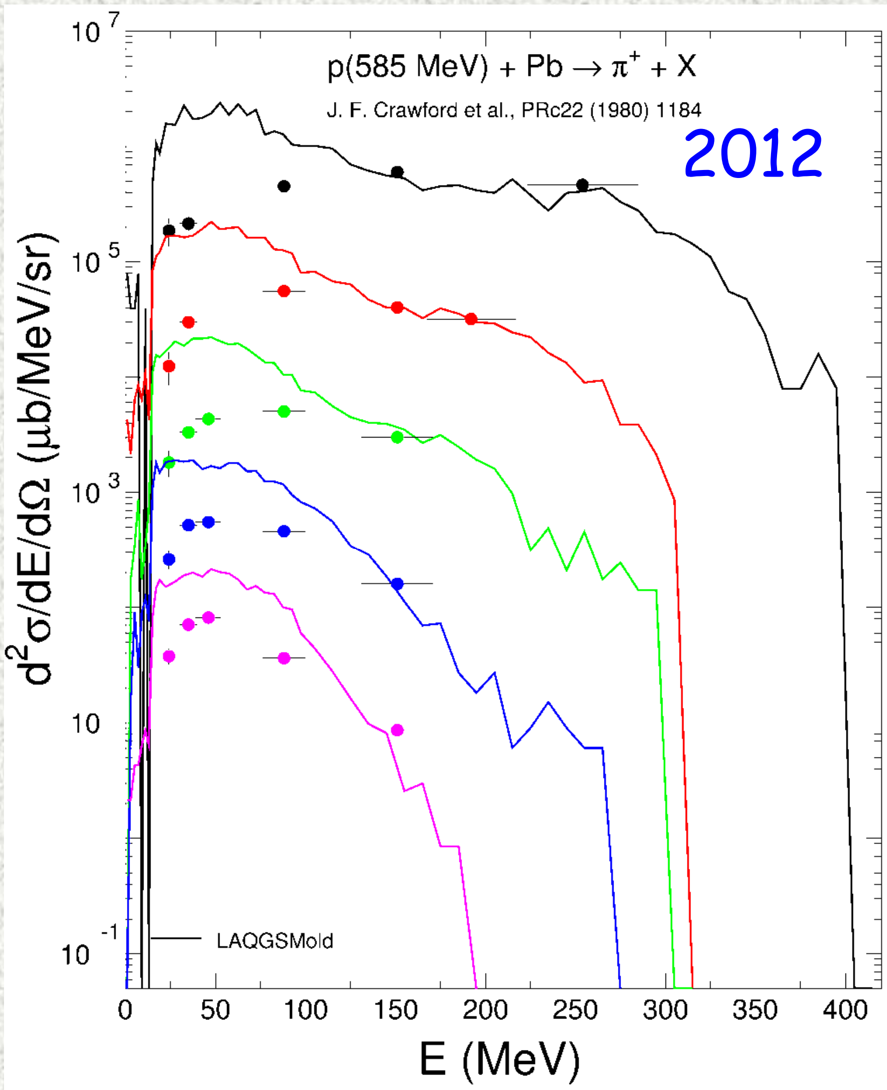
- Improved description of πN elastic scattering.
- Phenomenological parameterization of cross section of pion absorption on NN pair in nuclear medium was constructed based on π+d cross section $\sigma(A,T) = P(A) \times\sigma(\pi+d)$ with $P(A)=\alpha A^{\beta}$. Absorption probability is proportional to nucleon density squared $\rho^2(r)$.
- Improved description of pion absorption in nuclei in

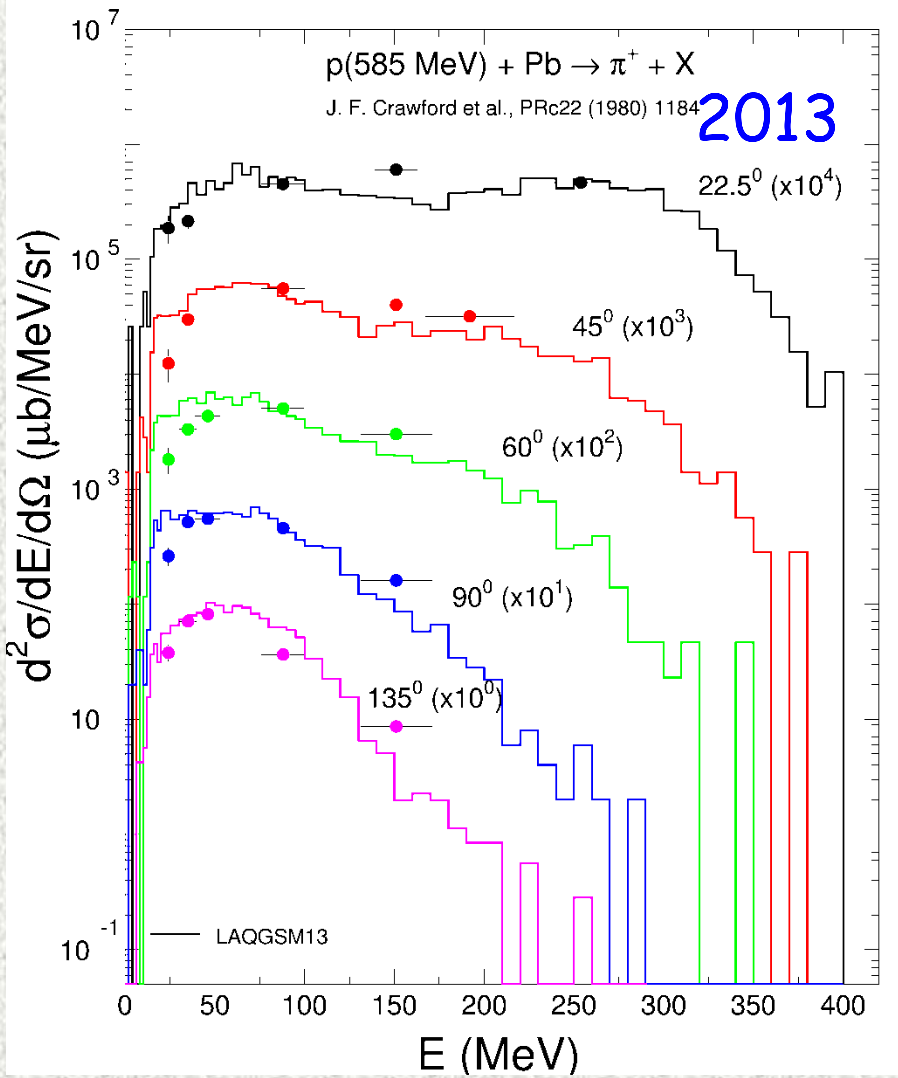
$\Delta+N \rightarrow NN$.

- New channel for pion production near threshold in

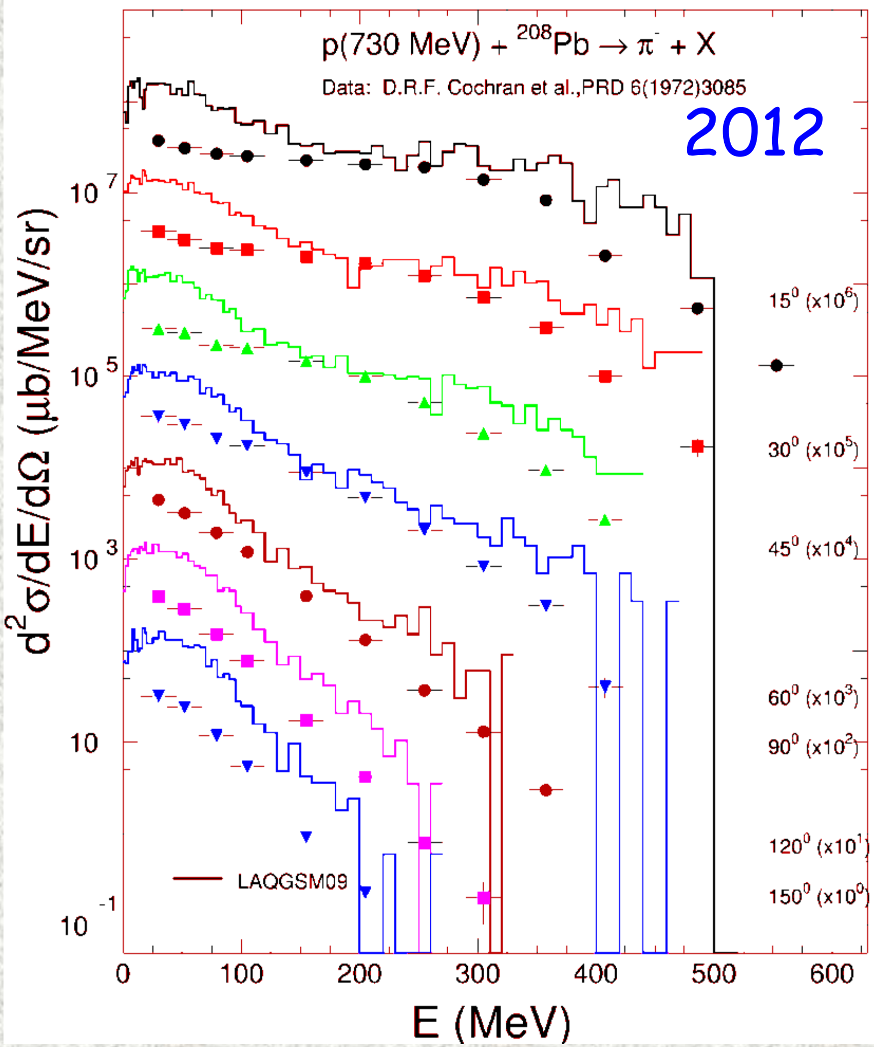
$N+N\rightarrow\pi+d$.

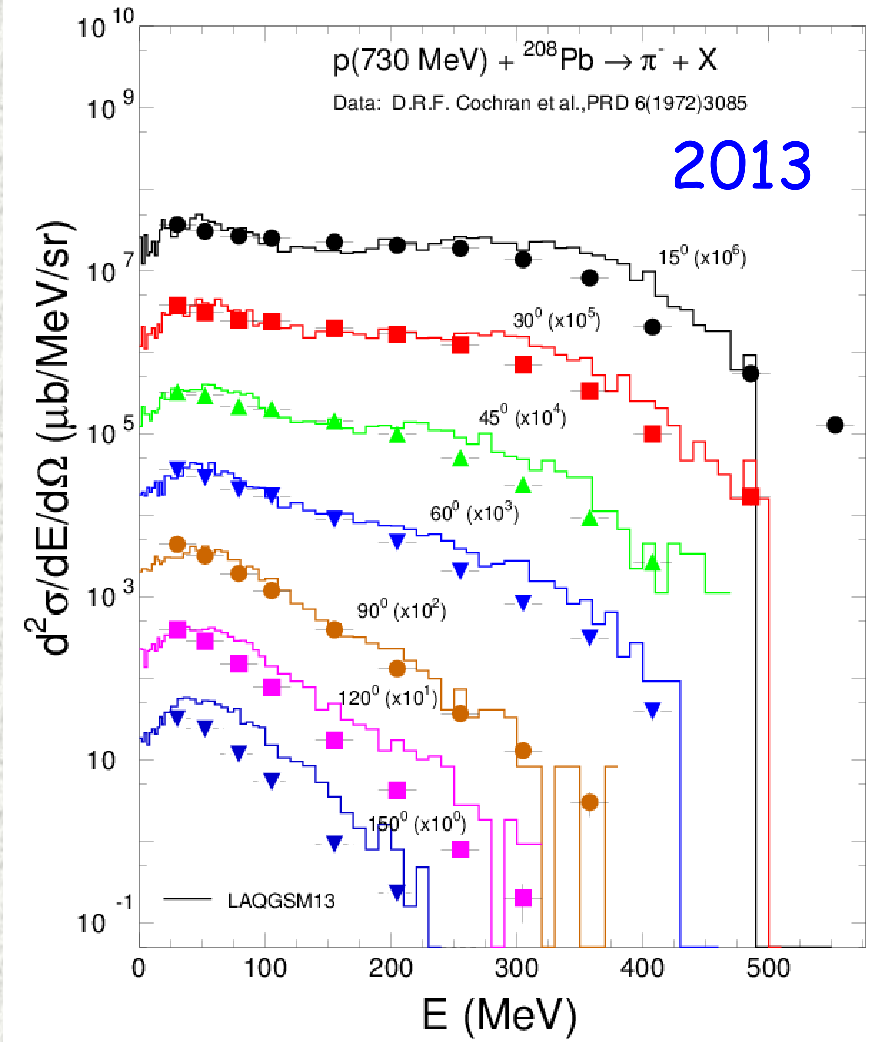
Effects of N+N → π+d and π+(NN) → N+N



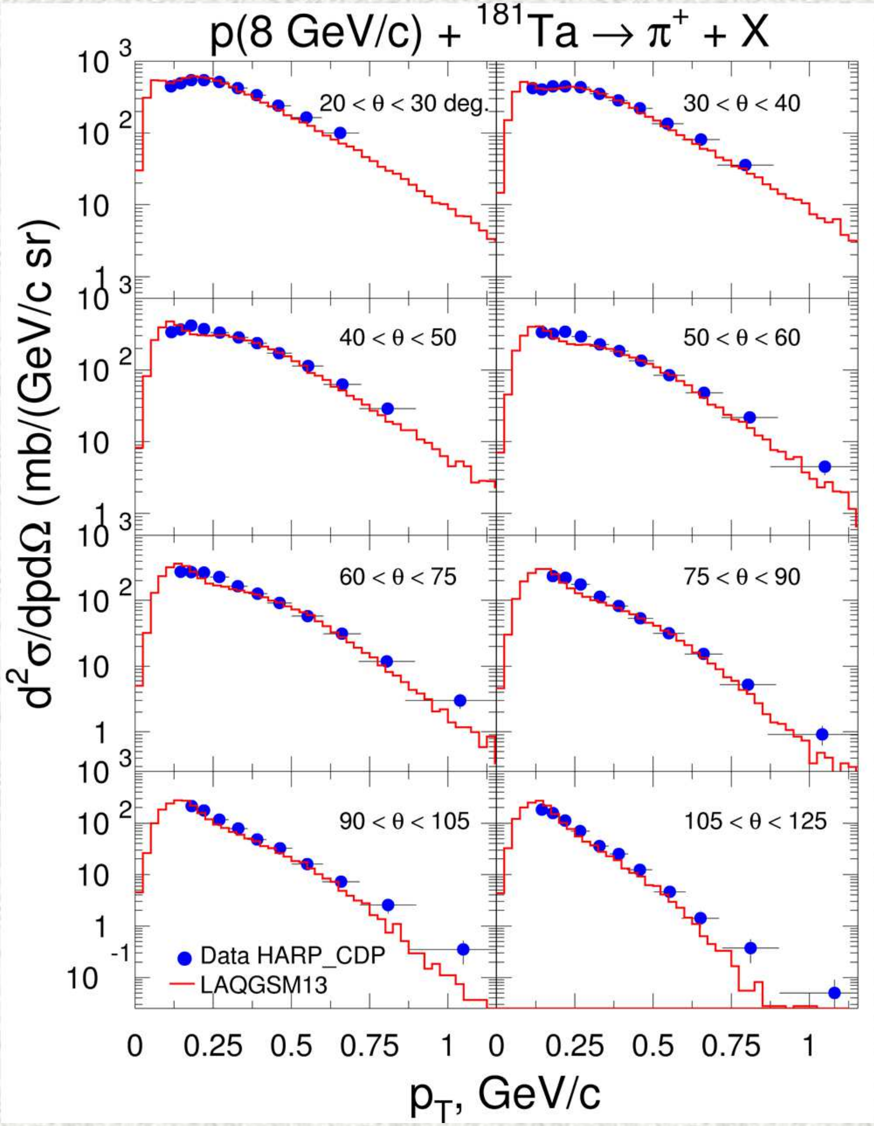


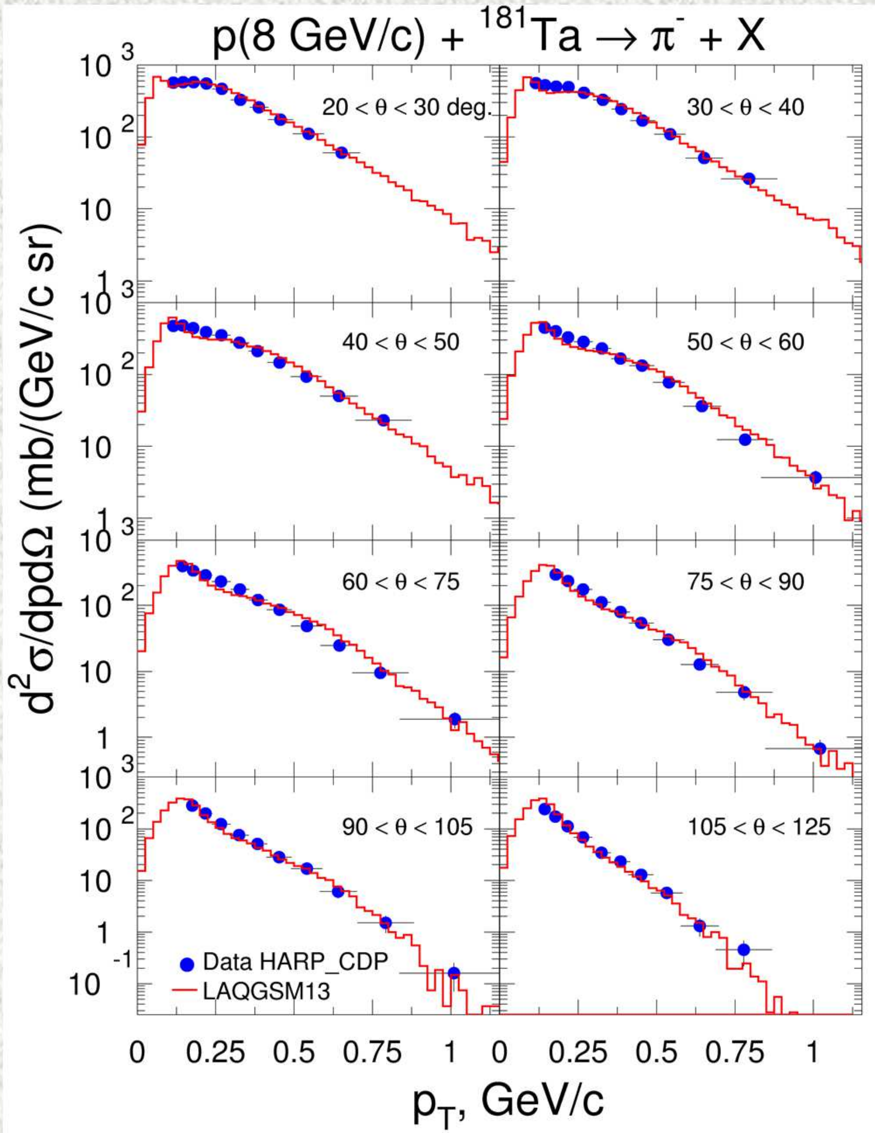
Effects of N+N → π+d and π+(NN) → N+N
σ(abs)=P(A)σ(π+d)





LAQGSM2013 vs HARP-CDP DATA





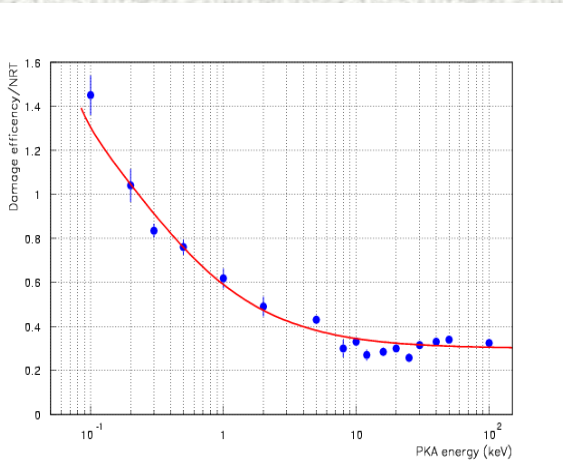
DPA Model in MARS15

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

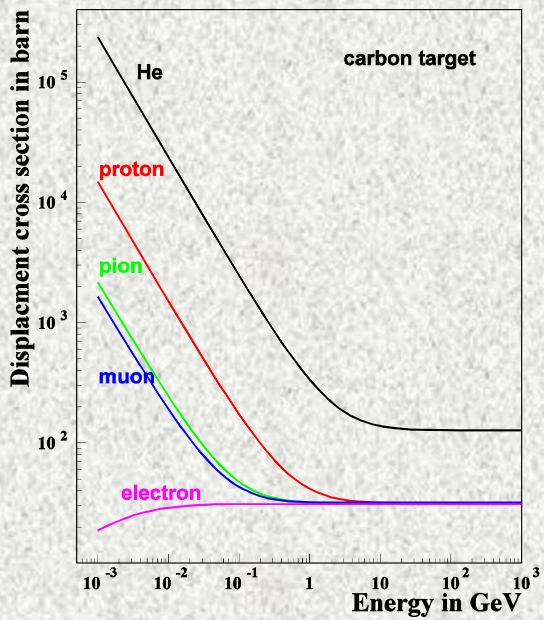
NRT damage function:

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

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

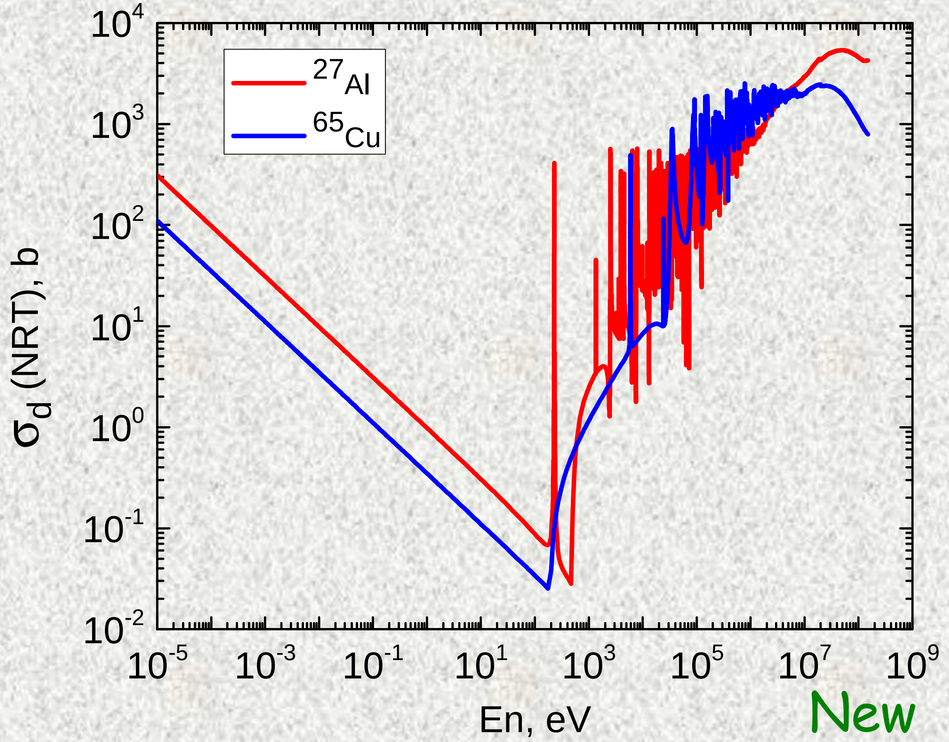


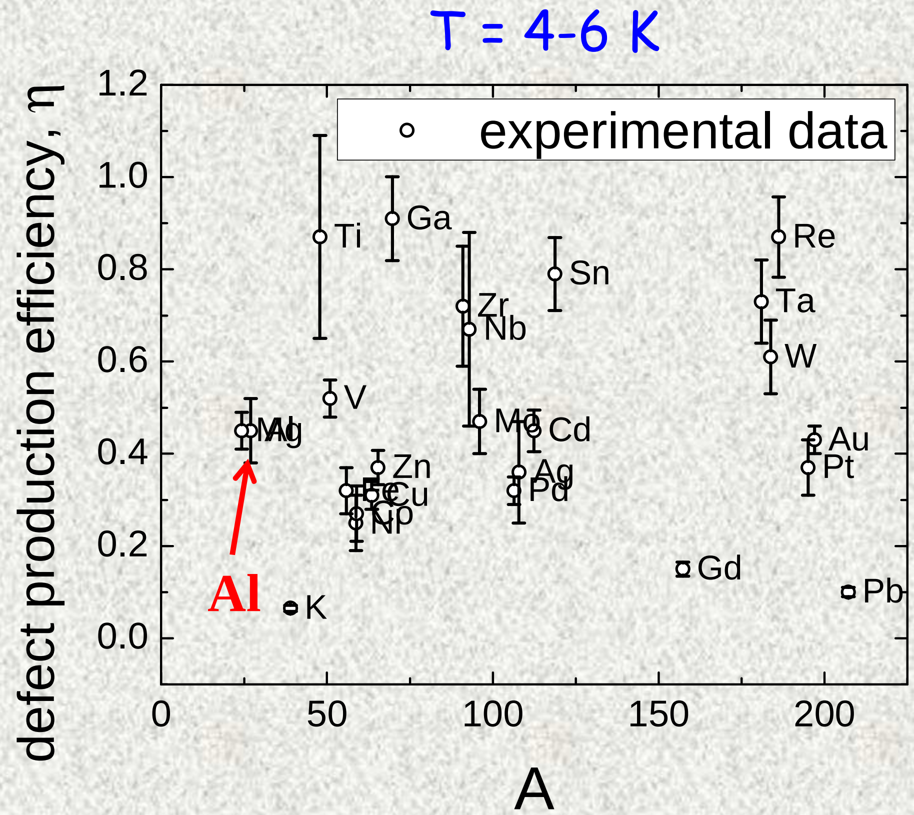
All products of elastic and inelastic nuclear interactions as well as Coulomb elastic scattering (NIEL) of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV contribute to DPA in this model. For electromagnetic elastic (Coulomb) scattering, Rutherford cross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



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

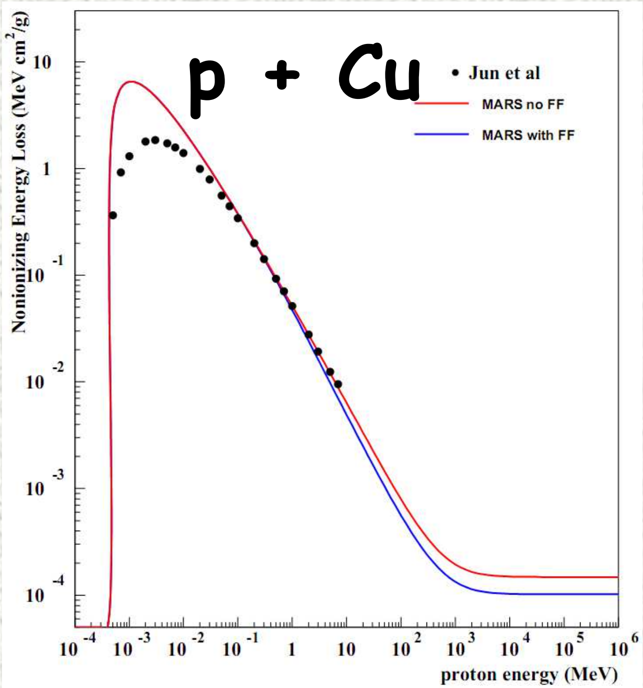
T = 4-6 K





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

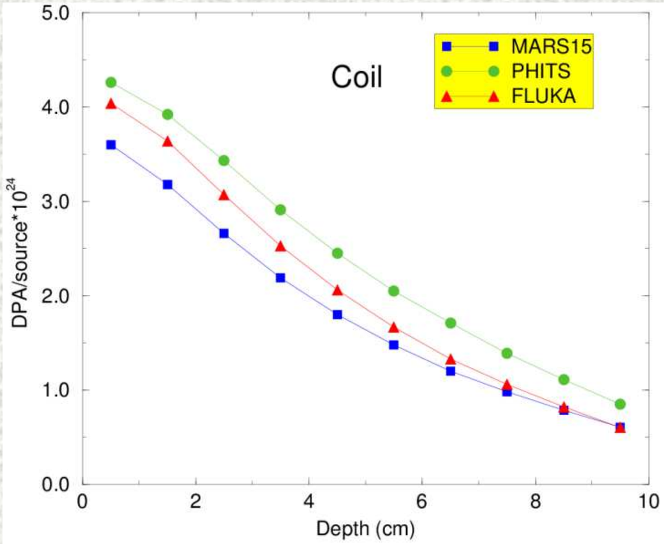
DPA Code Intercomparision

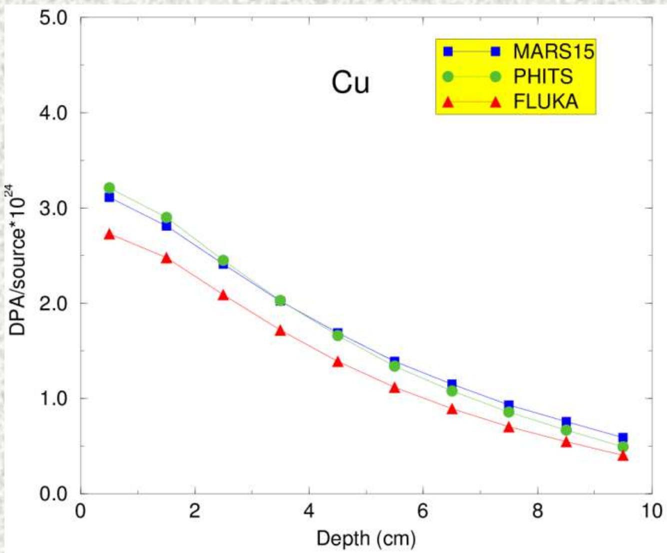


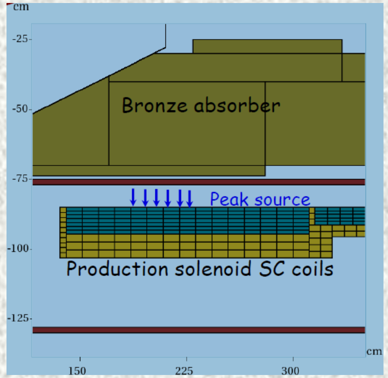
Proton NIEL for copper due the Coulomb scattering

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

E_{th} = 1 keV in MARS15





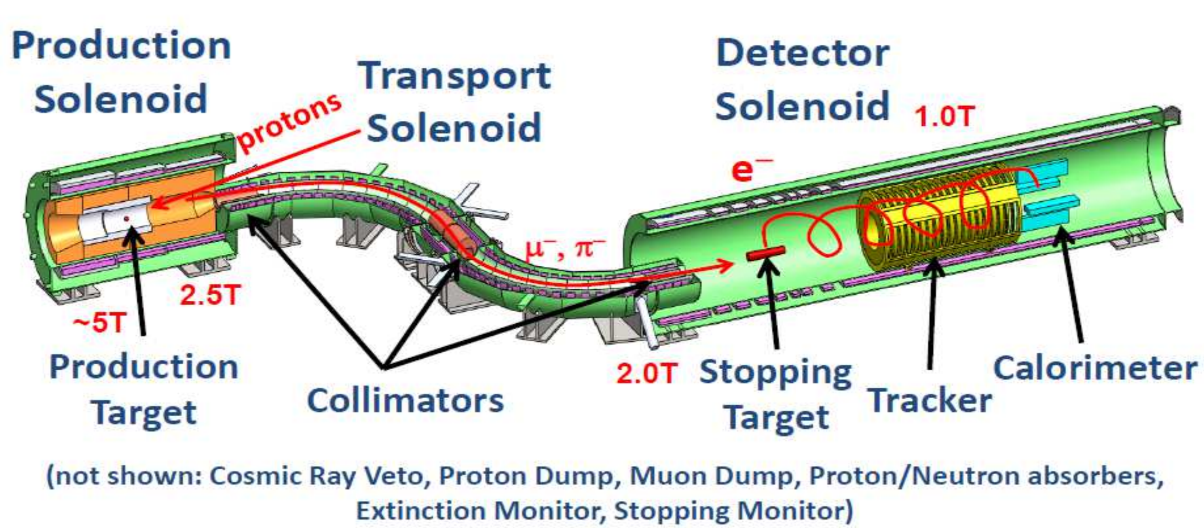


2013 FLUKA, MARS15 and PHITS intercomparison for Mu2e SC coil hottest spot: 15% agreement

Other Improvements and Extensions in MARS15(2014)

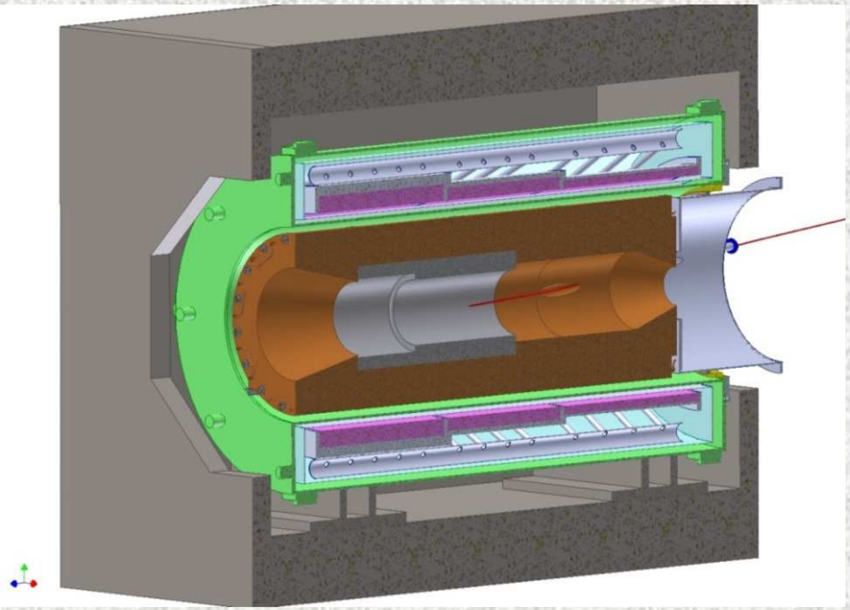
- Robust electromagnetic shower modelling down to 1 keV
- Refined highly-accurate tracking algorithms for arbitrary geometry and magnetic fields
- ROOT geometry as a basis: tracking, variety of shapes, 3D visualization, illegal overlap checking, ROOT-based MAD-MARS Beamline Builder, geometry import/export: MARS to/from GDML (HEP detectors) and MARS to/from STEP (CAD).
- Coming: Extended-to-ROOT geometry converter, ROOT-based histograming and TENDL-based event generator at E < 30-200 MeV

Mu2e Production Solenoid

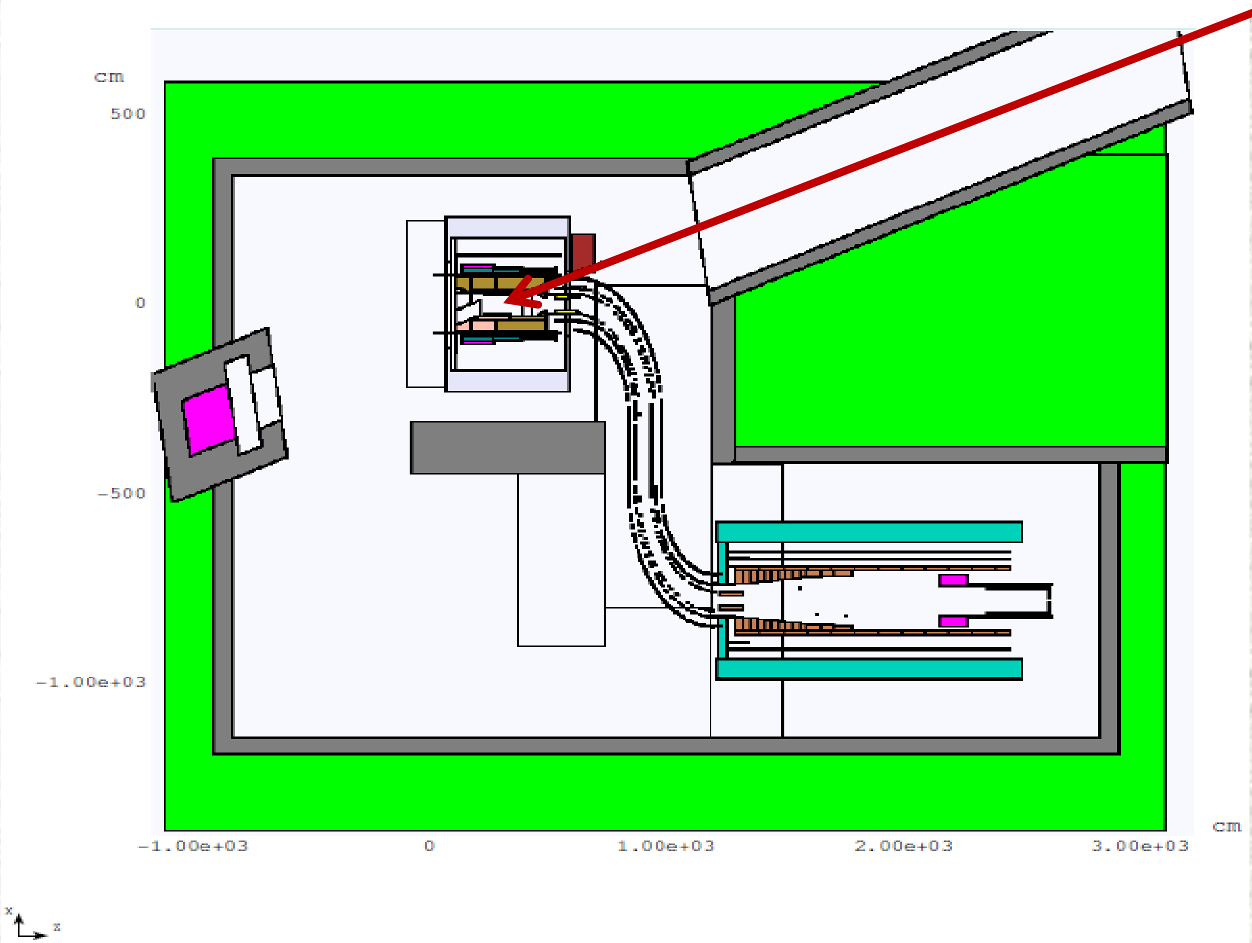


Mu2e: Measurement of conversion of μ^- to e^- in the field of a nucleus without emission of neutrinos.

One of the main parts of Mu2e is its SC production solenoid (PS), in which negative pions are generated in interactions of the primary proton beam with high-Z target. Pions then decay into muons which are delivered by transport solenoid to the detectors. The off-axis 8-GeV proton of $6 \cdot 10^{12}$ p/s on the target.



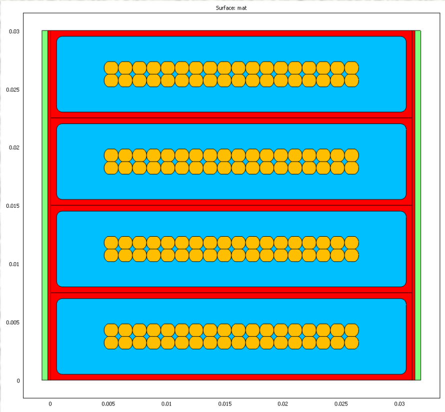
RRR Degradation: DPA limit for SC coils ~5×10^{-5} /yr



8-GeV p, 8 kW

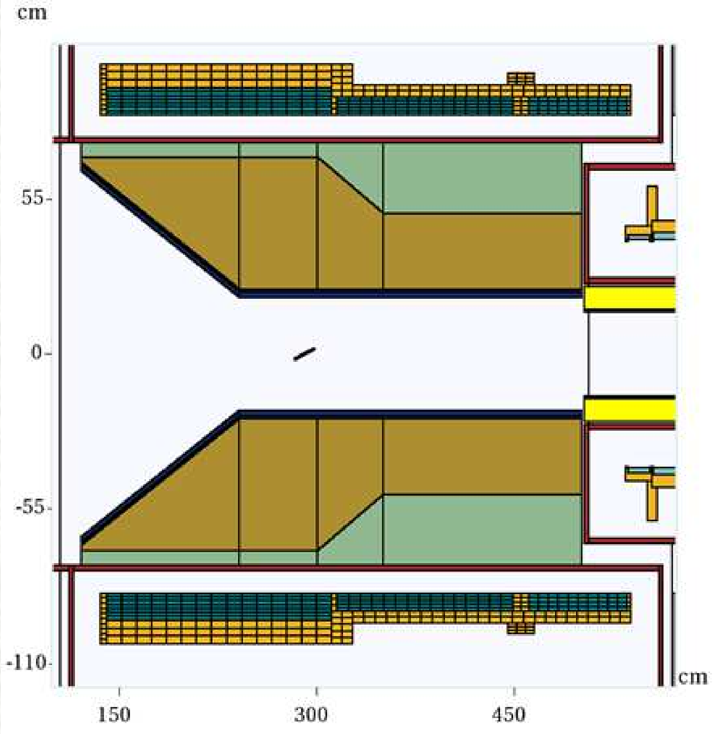
Mu2e and COMET

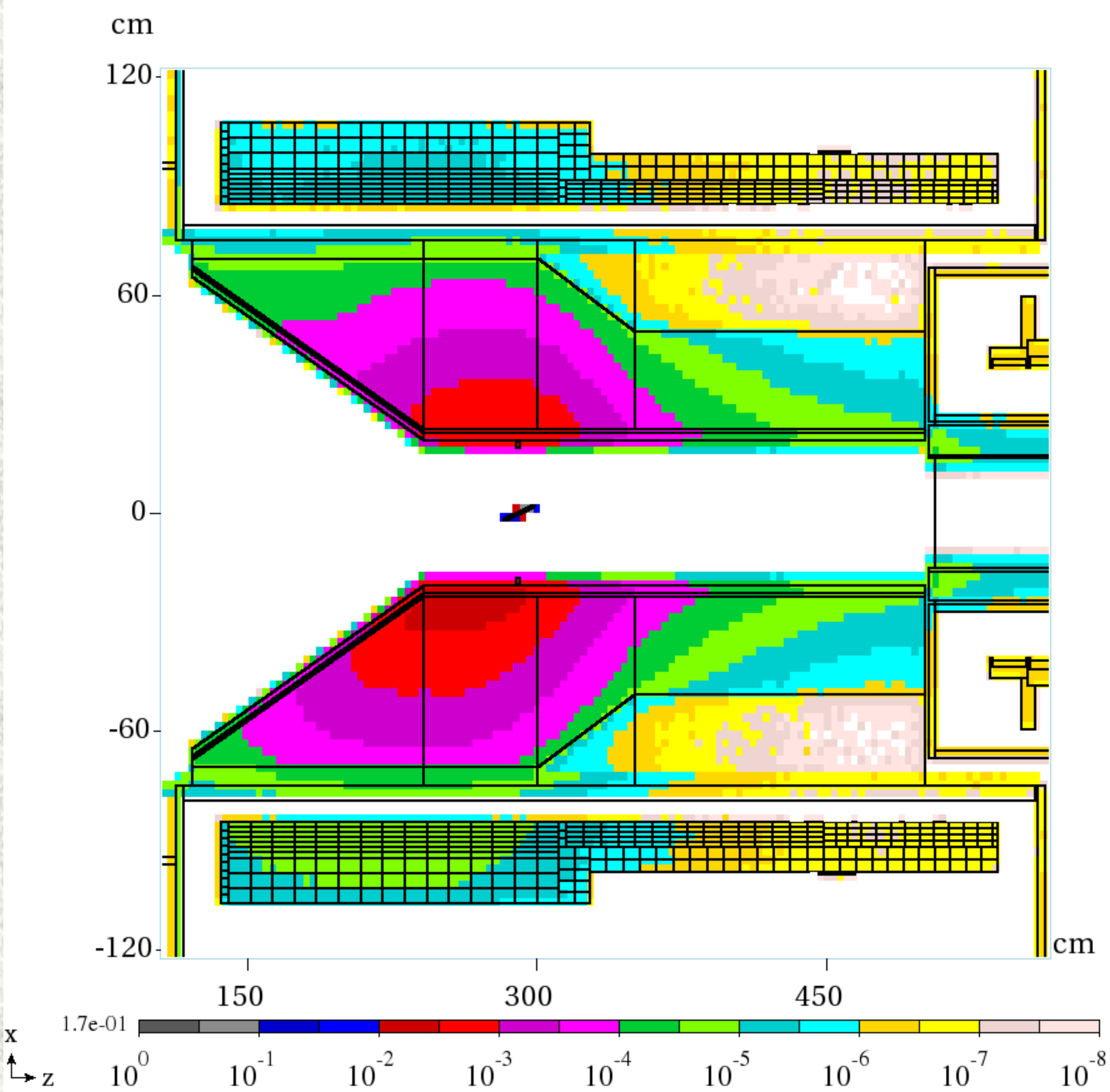
SC coil



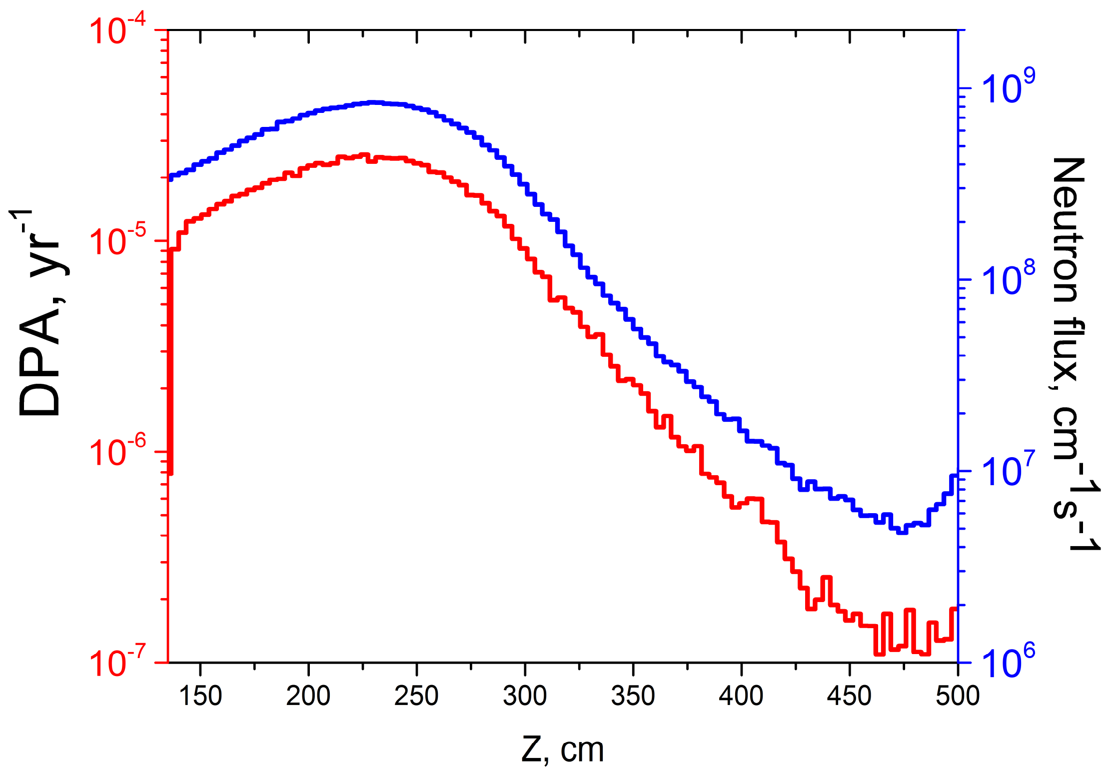
Bottleneck: degradation of Residual Resistivity Ratio (RRR) of **stabilizer** (ratio of electric resistivity of a conductor at room temperature to that at the liquid He one).

MARS15 Model and DPA/yr for 8-kW Beam



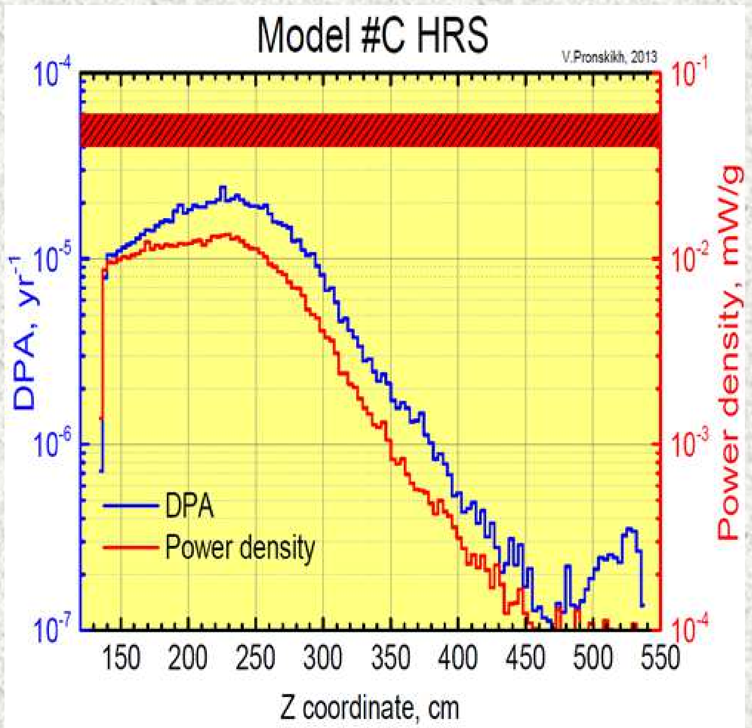


Mu2e PS: Peak Quantities Along Inner SC Coil

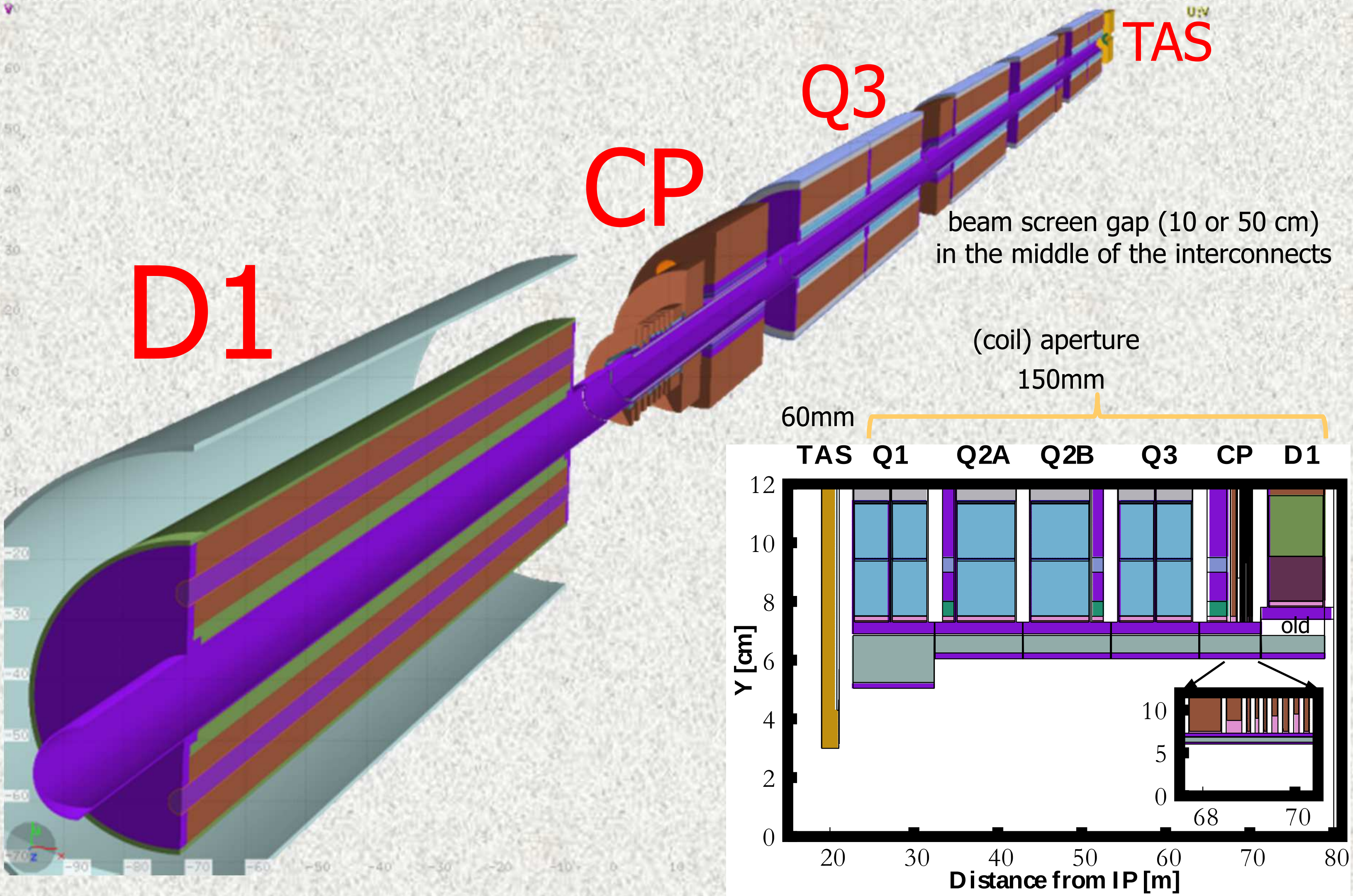


DPA and neutron flux: good correlation

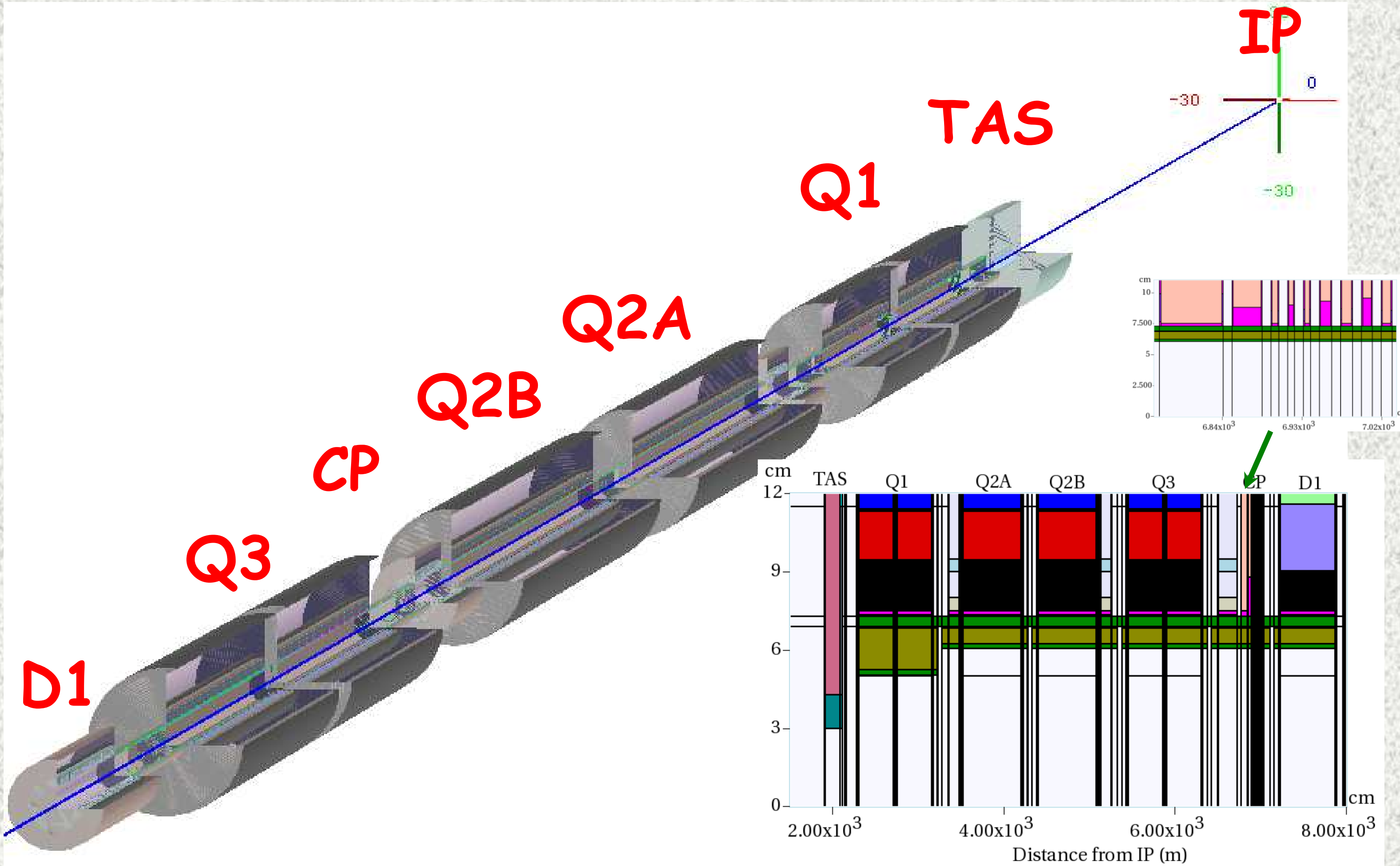
DPA and power density



150-mm HLumi LHC IT-CP-D1: FLUKA



150-mm HLumi LHC IT-CP-D1: MARS15



Parameters in MARS15 and FLUKA Runs

295 μrad half-angle in the IP1 vertical crossing plane

85 mb proton-proton cross-section at $\sqrt{S}$ = 14 TeV

Normalization: **power** density at 5×10^{34} cm^{-2}s^{-1}; **dose** at 3000 fb^{-1}

DPMJET III as event generator, 10^5 pp collisions *minimum*

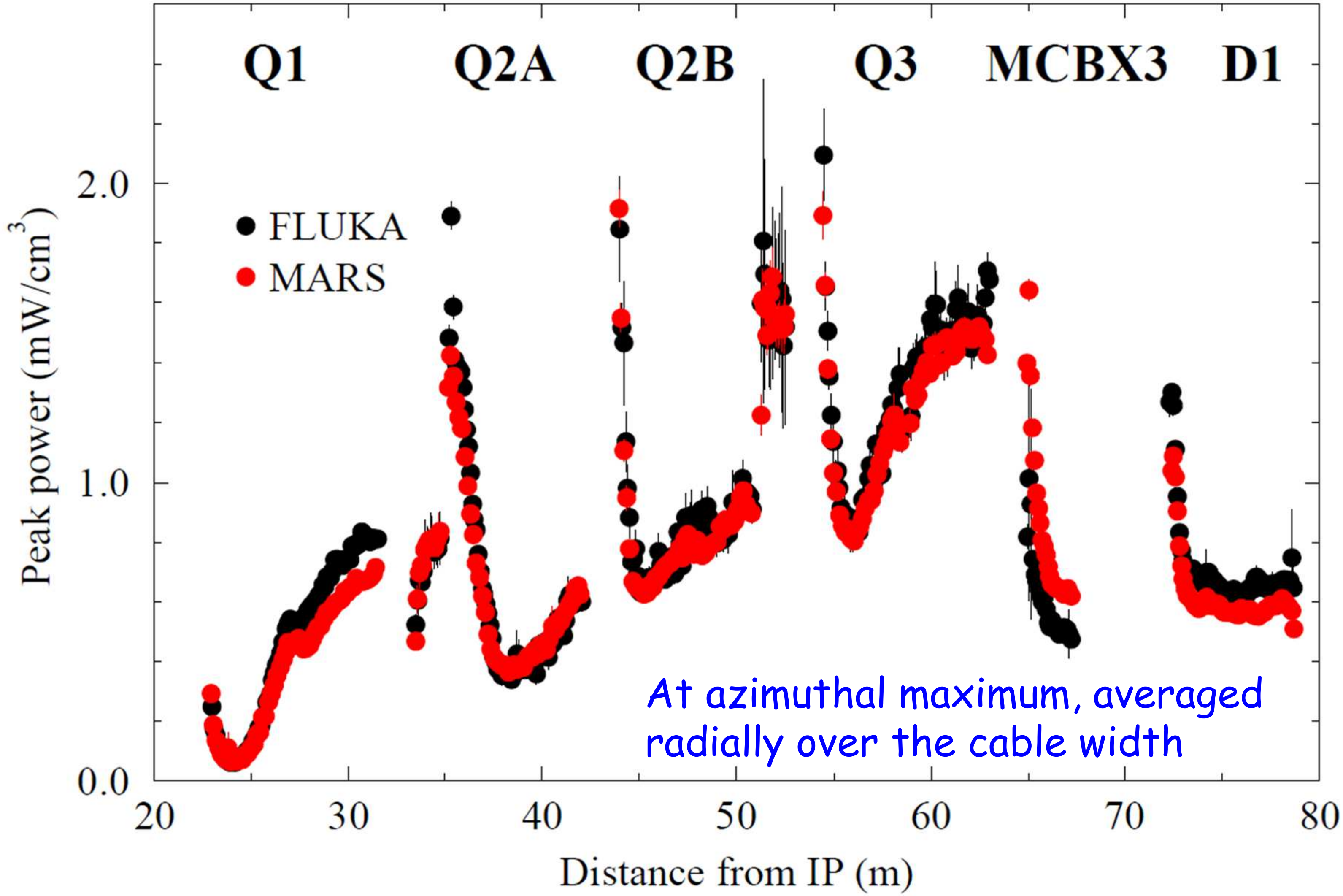
Default cutoff energies

Scoring bins: $\Delta z \simeq 10$ cm, $\Delta\varphi = 2^0$

Δr = cable width for power density

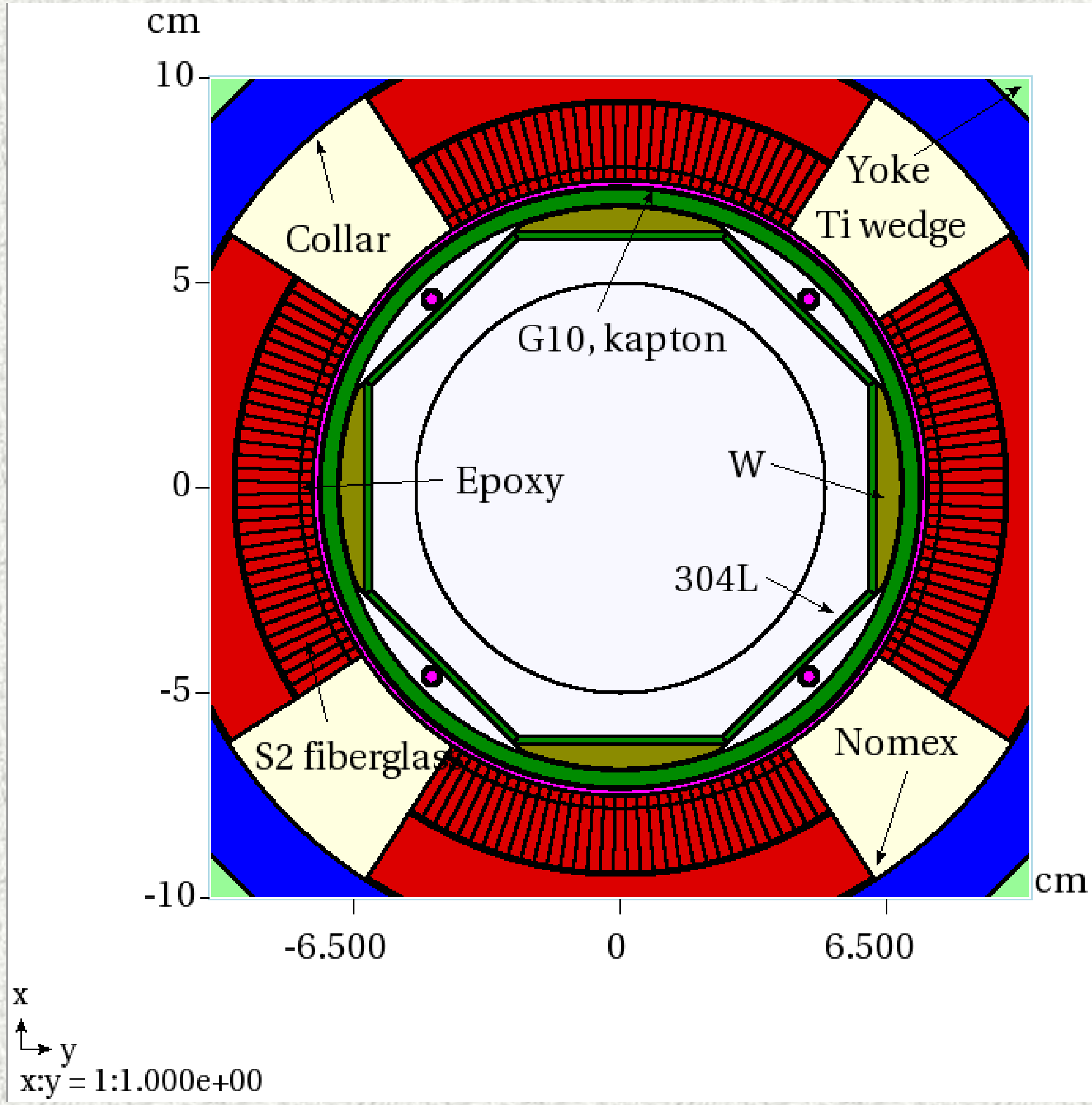
= *min*{3mm, thickness} for dose and DPA

Longitudinal peak power profile on inner coils @ $L=5\times10^{34}\ cm^{-2}s^{-1}$

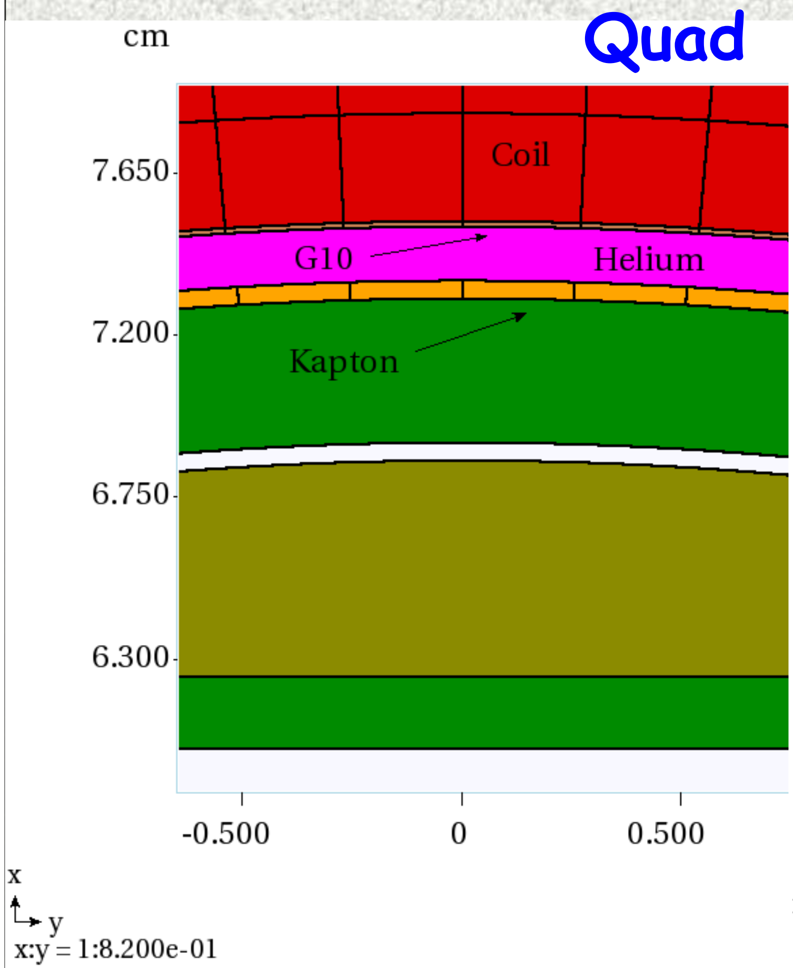


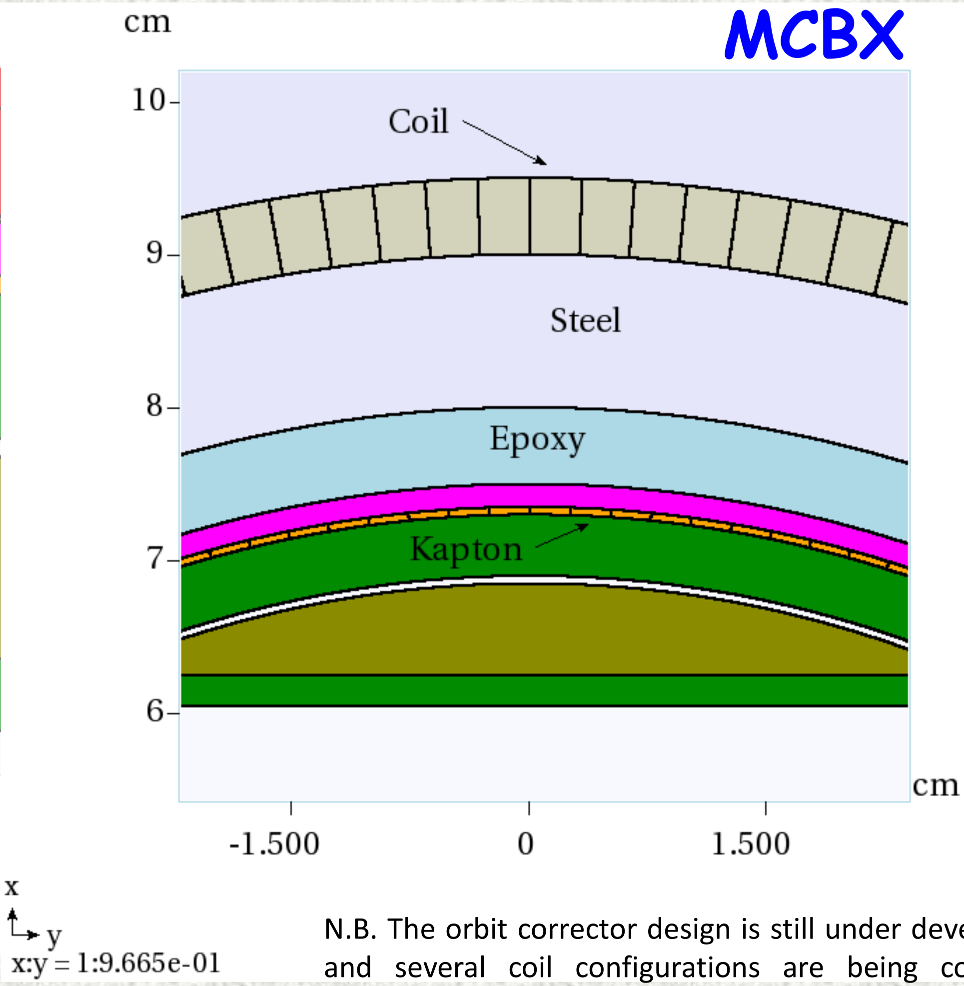
Good margin wrt assumed quench limits of 40 (Nb_3Sn) and 13 (NbTi) mW/cm^3

Inner Part of Q2 Quadrupole



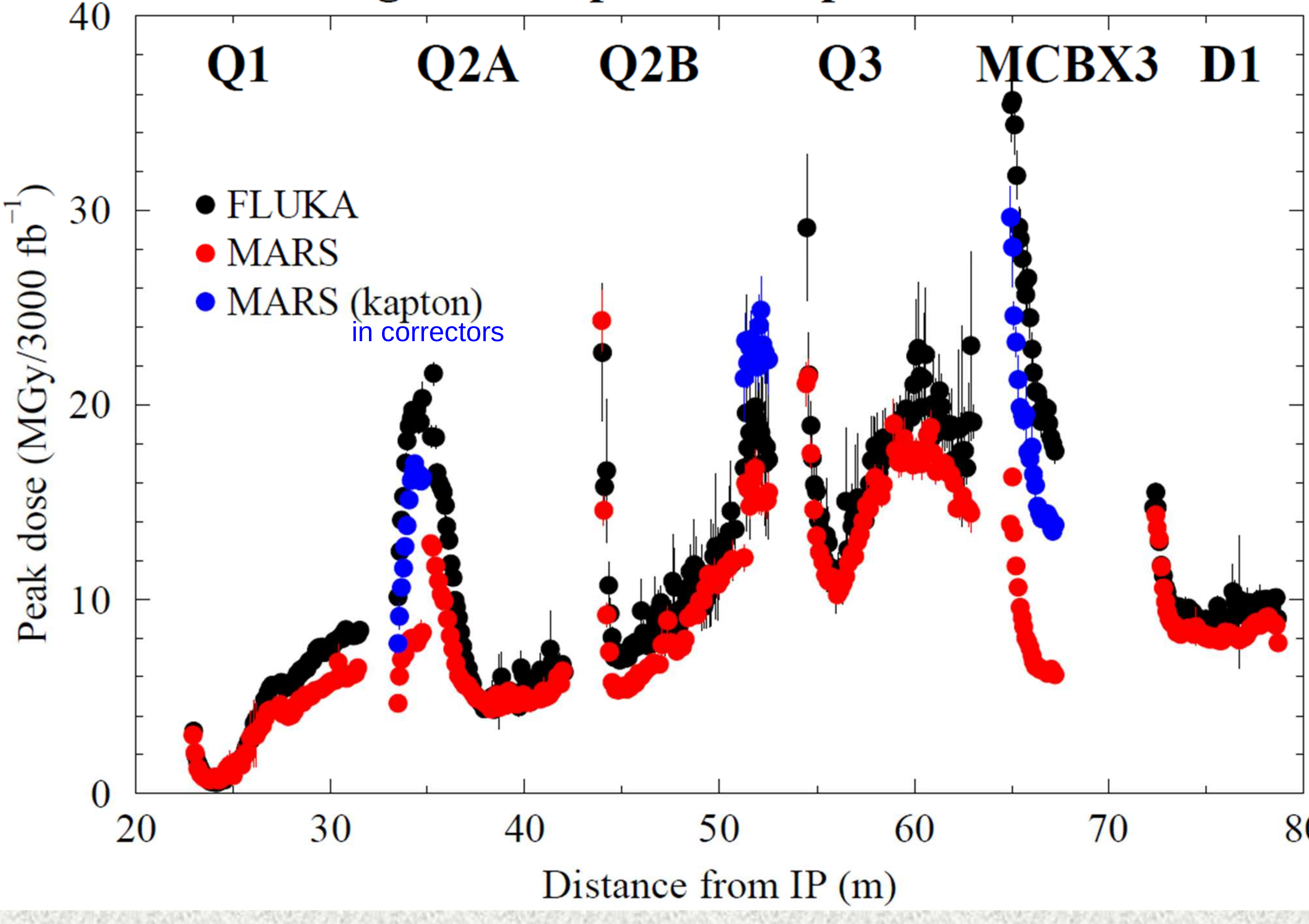
Hot Spot Details in Quads and Correctors



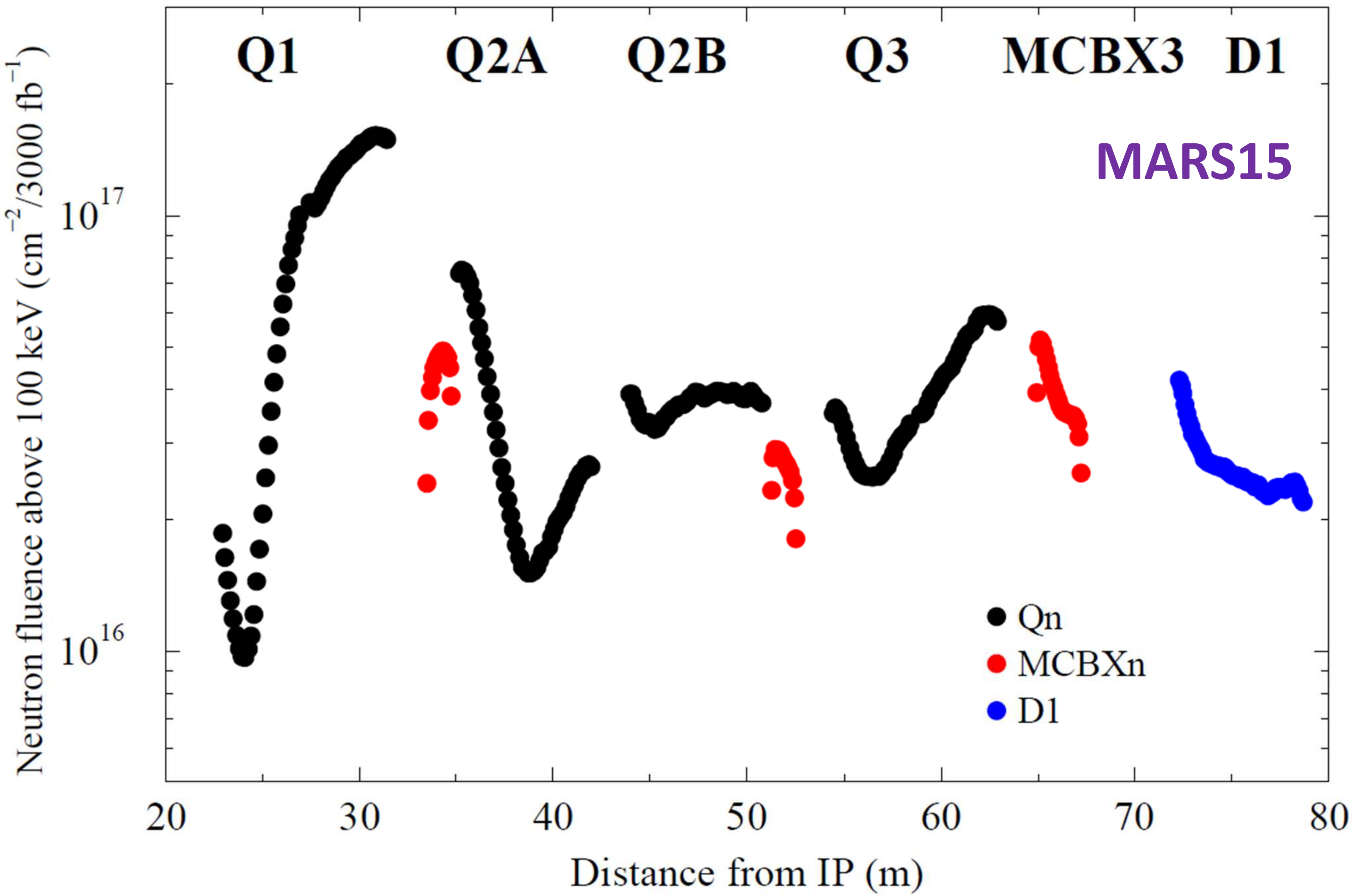


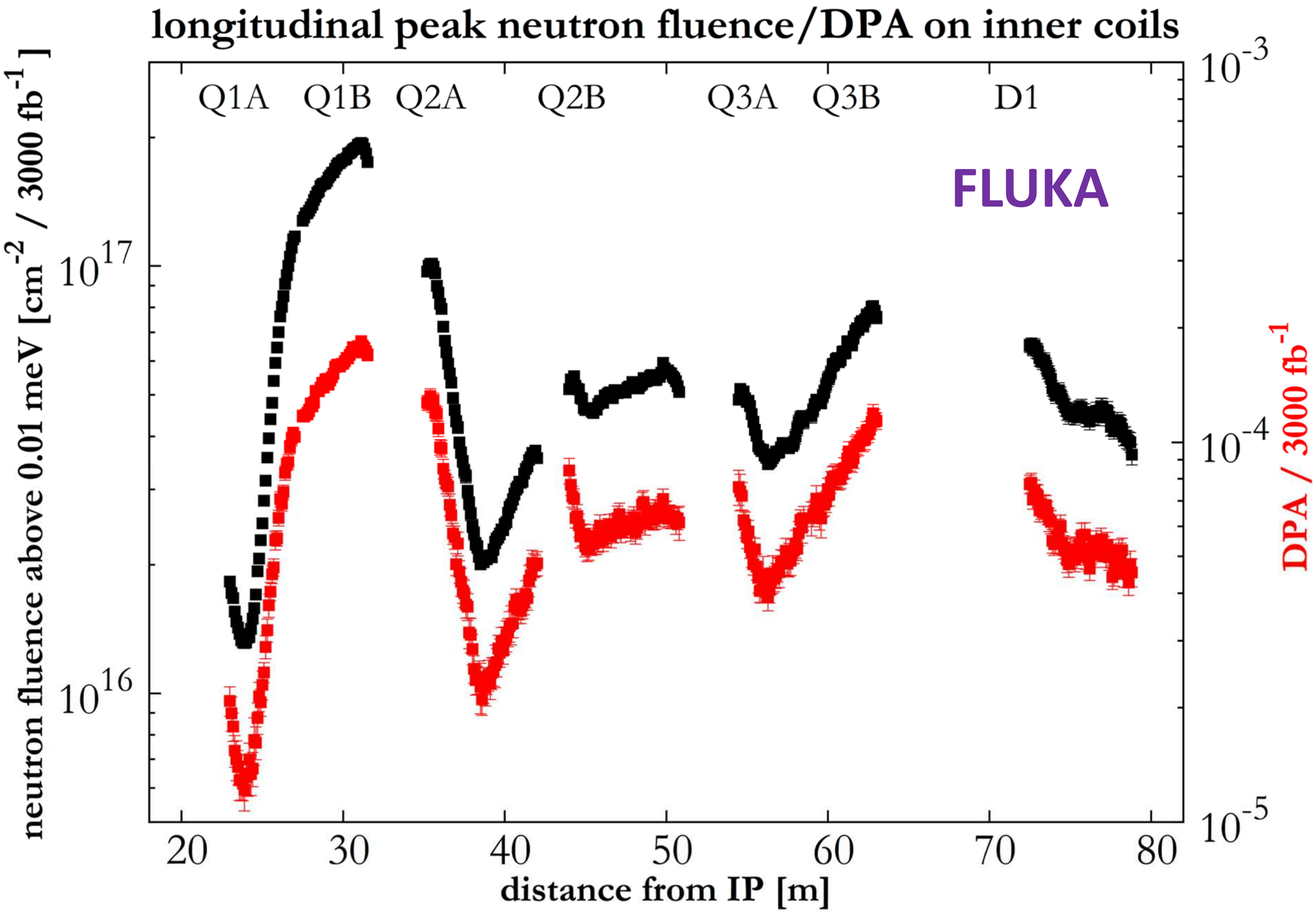
N.B. The orbit corrector design is still under development and several coil configurations are being considered (*Paolo Fessia and CIEMAT colleagues*). The coil layer in FLUKA and MARS models has to be revised according to future specs.

Longitudinal peak dose profile on inner coils



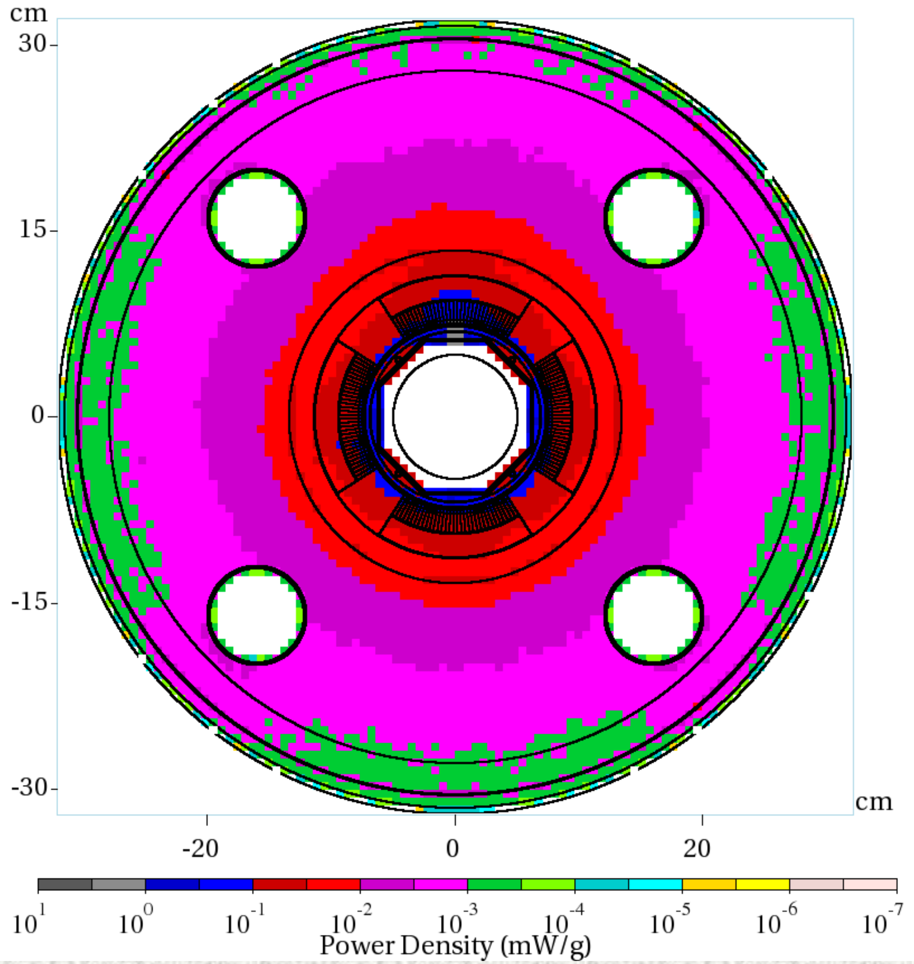
Longitudinal peak neutron fluence on inner coils

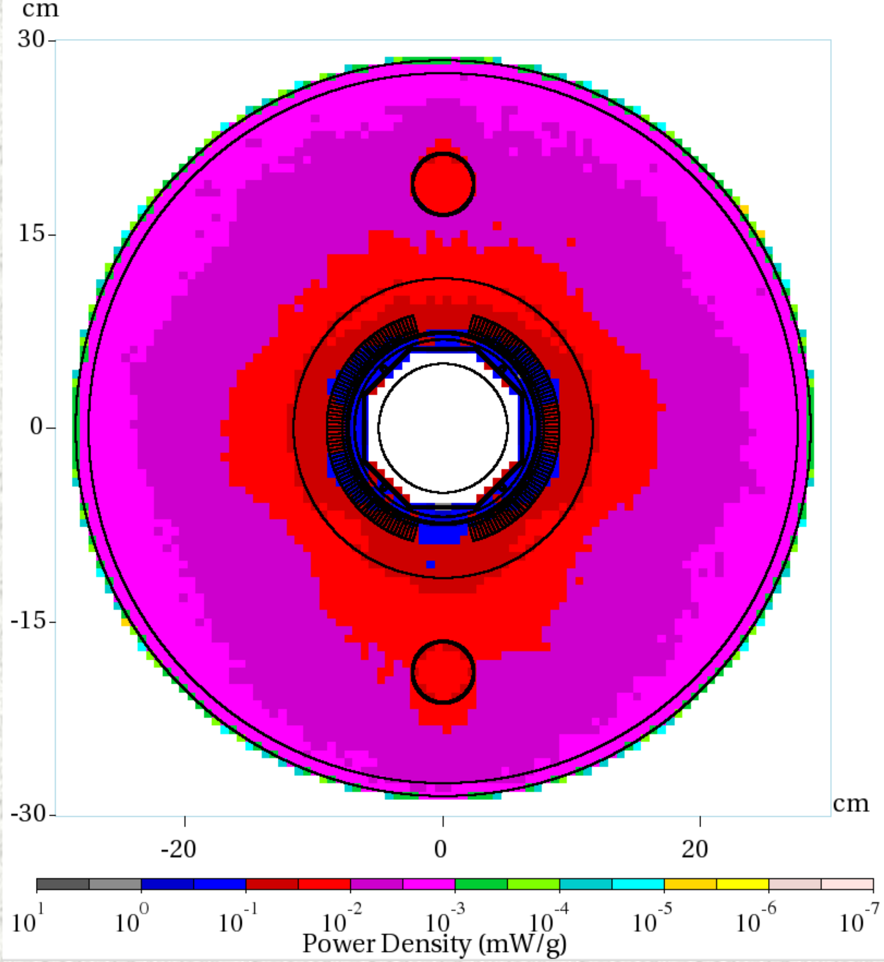



longitudinal peak neutron fluence/DPA on inner coils
Q1A
Q1B
Q2A
Q2B
Q3A
Q3B
D1
FLUKA
neutron fluence above 0.01 meV [cm^{-2} / 3000 fb^{-1}]
10^{17}
10^{16}
DPA / 3000 fb^{-1}
10^{-3}
10^{-4}
10^{-5}
20
30
40
50
60
70
80
distance from IP [m]

Power Density (mW/g) in Q2A & D1

At IP end





Radiation Loads to <u>Organic</u> Materials in Q2B

Name	Material	Maximum calculated value per I_0=3000 fb^{-1}	Limit
		Absorbed Dose (MGy)	
Insulation	Kapton	30	25-35
Insulation	G10	28	20
Glue/insulation	Epoxy CTD-101K	24	25
Insulation	S2 fiberglass	24	15 (?)
Insulation	G11	24	25-40
Support material	Nomex	6.7	15 (?)
Insulation	Polyimide	6.7	25

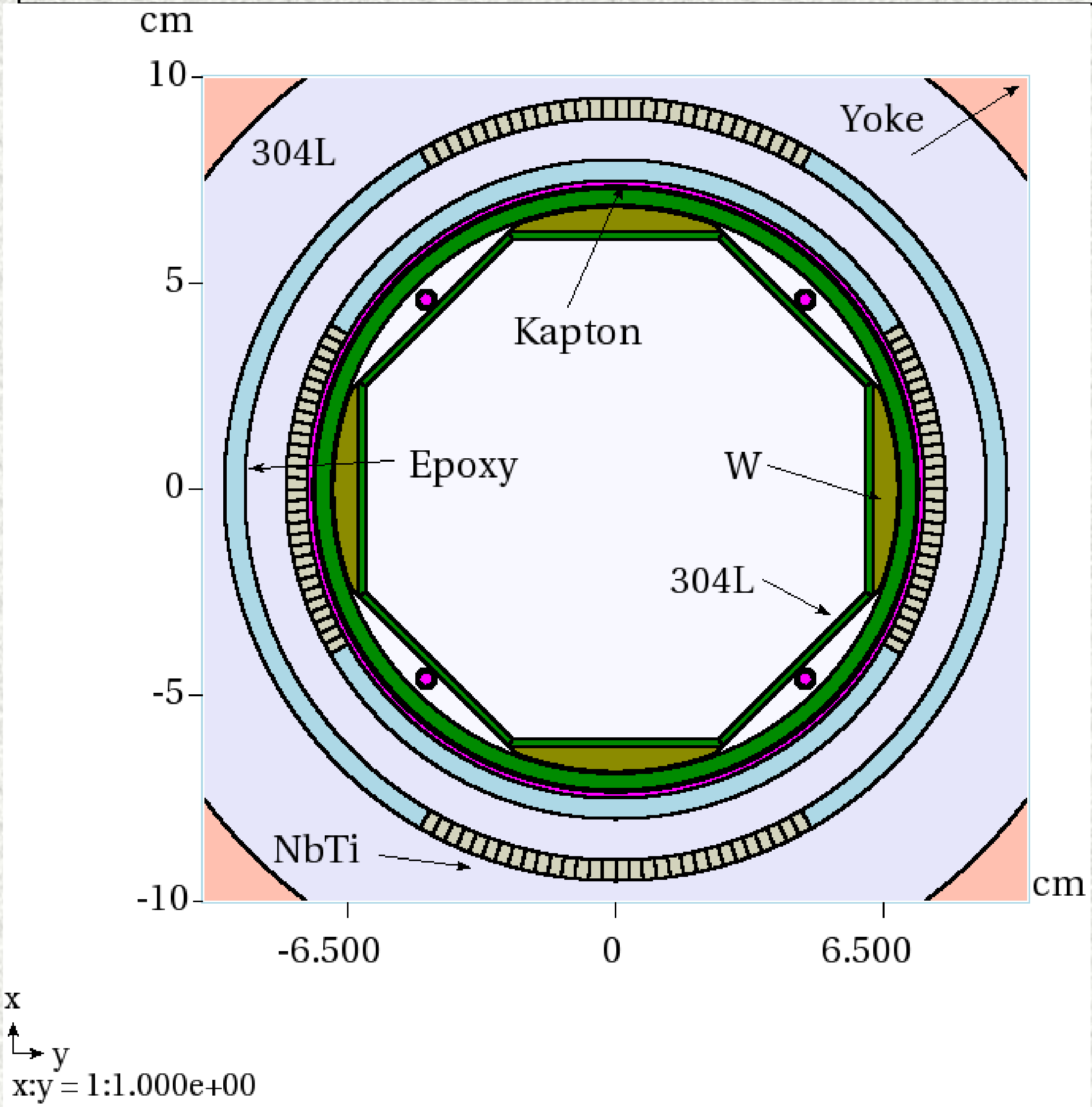
Radiation Loads to Inorganic Materials in Q1B

Name	Material	Maximum calculated value per I_0=3000 fb^{-1}		Limit	
		DPA	Φ_n (cm^{-2})	DPA	Φ_n (cm^{-2})
Coil	Nb_3Sn	3.4×10^{-4}	1.4×10^{17}		3×10^{18}
Coil	Cu	3.4×10^{-4}	1.4×10^{17}	6×10^{-5} **	
Pole	Ti6Al4V		9×10^{16}		
Wedge	Phosphorous Bronze 5% Sn		1×10^{17}		
Solder	60/40 Pb/Sn		1×10^{17}		
Collar*	Alu EN AW-6082	1×10^{-4}	6×10^{16}	10	5×10^{21}
Yoke*	ARMCO 99.99% Fe		5×10^{16}		7×10^{22}
Rod, washer, nut*	Steel 1.3964; Steel A4		3×10^{16}		7×10^{22}
Shell*	Low carbon steel		3×10^{16}		7×10^{22}
Cooling channel	Cu		3×10^{16}		
Steel*	304L		2×10^{17}		7×10^{22}
Liner	W	0.003	3×10^{17}	9.5	10^{21}

*) Mechanical properties start changing at DPA > 0.1 and mostly getting better with irradiation

**) RRR, 80% annealed

Inner Part of MCBX3 Corrector



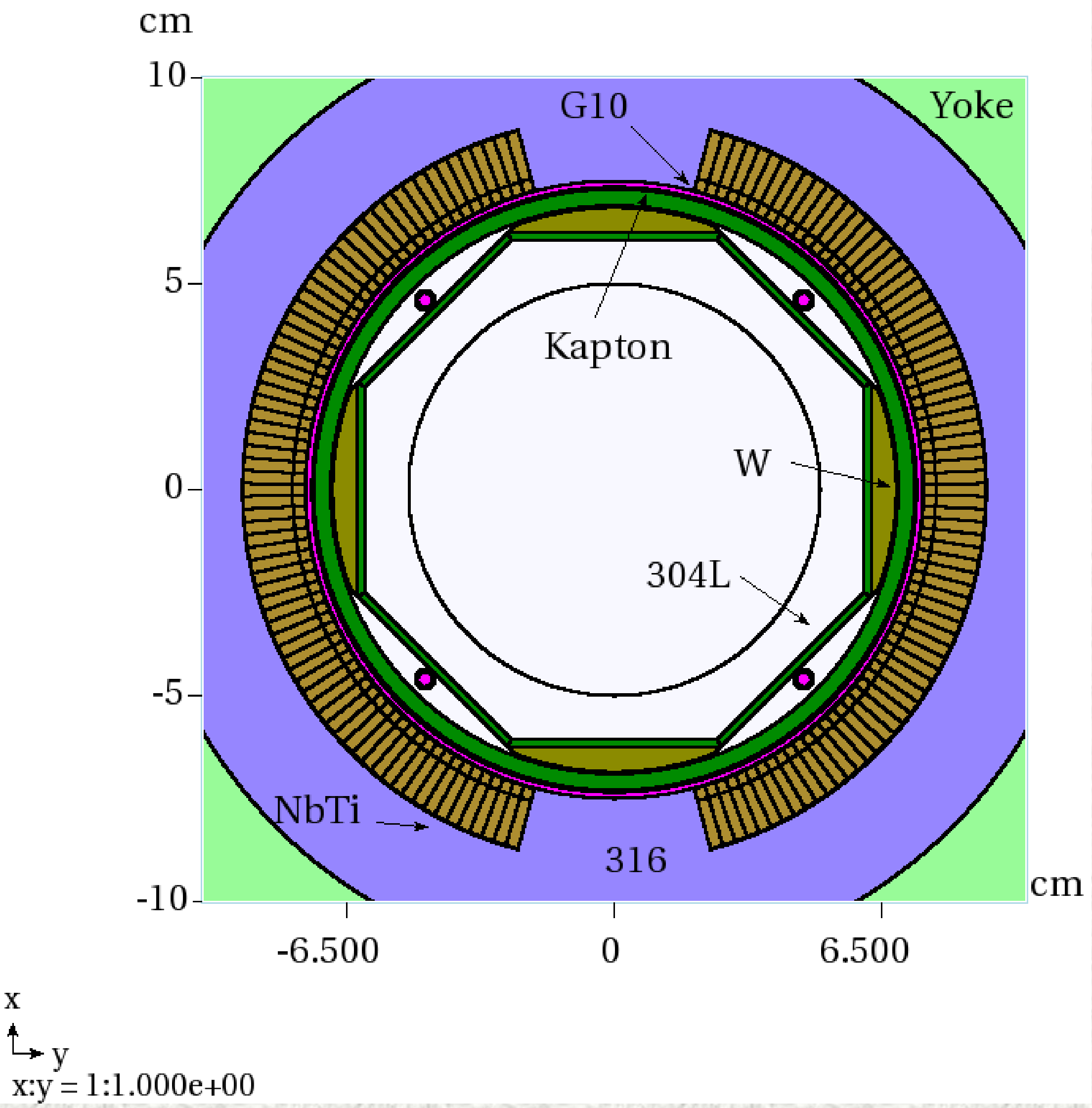
N.B. The orbit corrector design is still under development and several coil configurations are being considered (*Paolo Fessia and CIEMAT colleagues*). The coil layer in FLUKA and MARS models has to be revised according to future specs.

Radiation Loads to Materials of MCBX3

Common name	Material	Maximum calculated value per I_0=3000 fb^{-1}			Limit		
		D (MGy)	DPA	Φ_n (cm^{-2})	D (MGy)	DPA	Φ_n (cm^{-2})
Insulation	Kapton	30			25-35		
Epoxy	CTD-101K	27			25		
Coil	NbTi		1.7×10^{-4}	5×10^{16}			10^{18}
Coil	Cu		1.7×10^{-4}	5×10^{16}		6×10^{-5} **	
Steel*	304L	360	3.6×10^{-3}	8×10^{16}	> 10^4		7×10^{22}
Cooling channels	Cu	2.0	1.0×10^{-4}	1×10^{16}	> 10^4		
Yoke*	ARMCO 99.99% Fe	7.5	4.6×10^{-4}	3×10^{16}	> 10^4		
Liner	W	240	8.3×10^{-3}	1×10^{17}		9.5	10^{21}

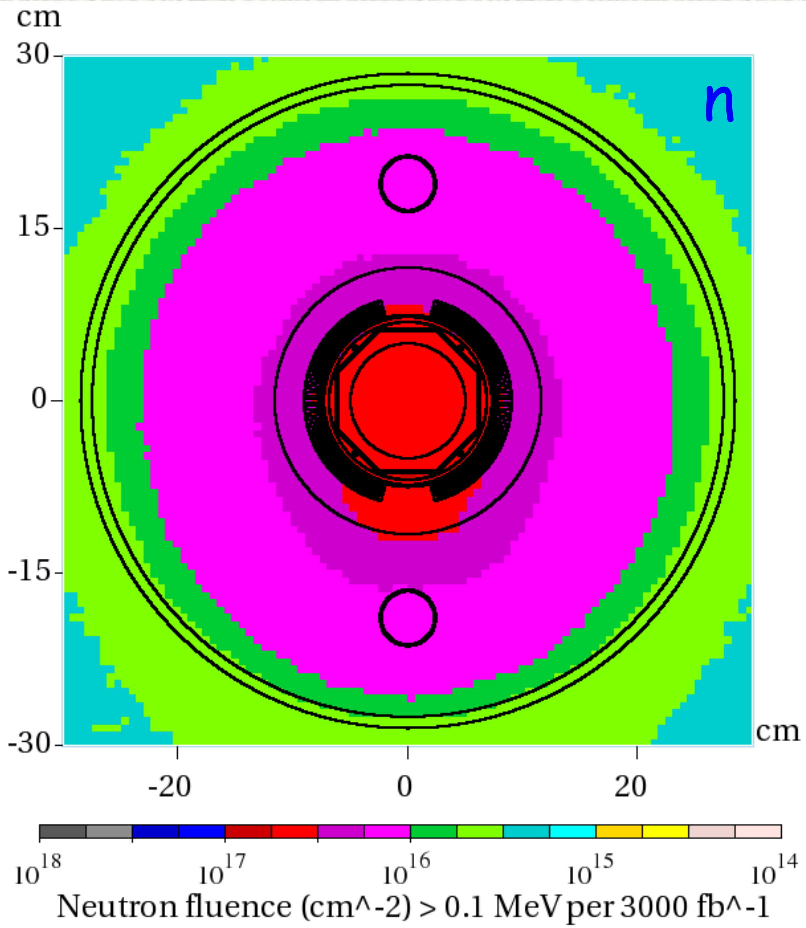
*) Mechanical properties start changing at DPA > 0.1 and mostly getting better with irradiation
**) RRR, 80% annealed

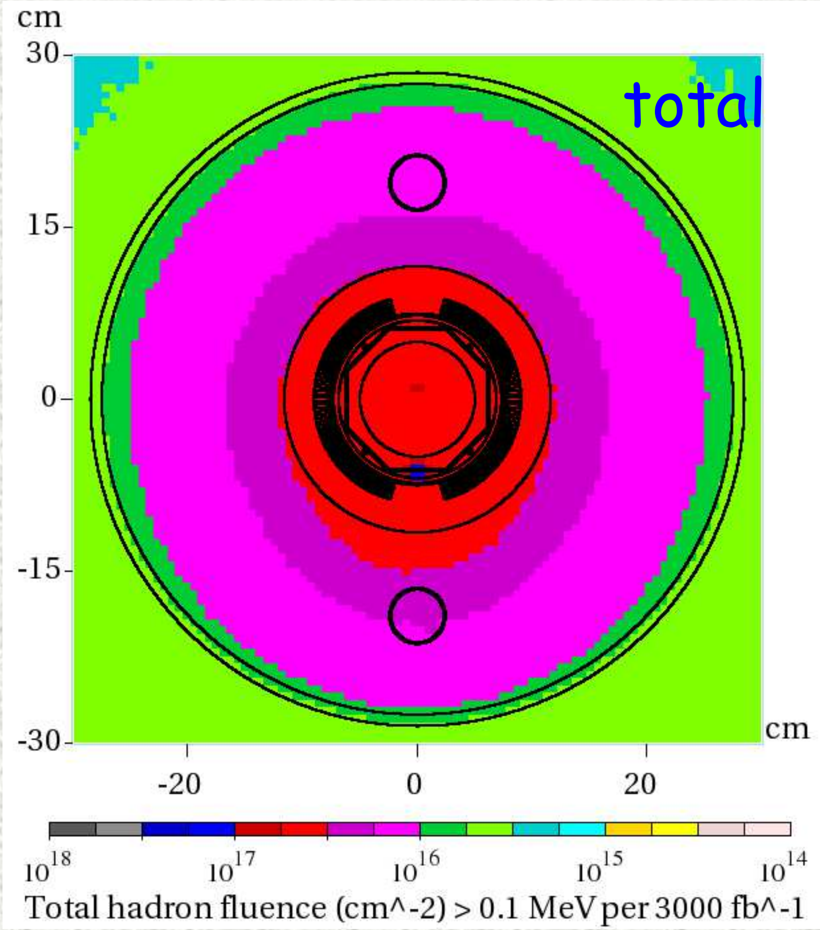
Inner Part of D1 Dipole



Hadron Fluence at D1 IP End

E > 0.1 MeV





SC Peak: 3.4e16 cm^{-2}/3000 fb^{-1}

SC Peak: 5.5e16 cm^{-2}/3000 fb^{-1}

SC: 5% change in J_c at ~5e17 cm^{-2}

Radiation Loads to Materials of D1

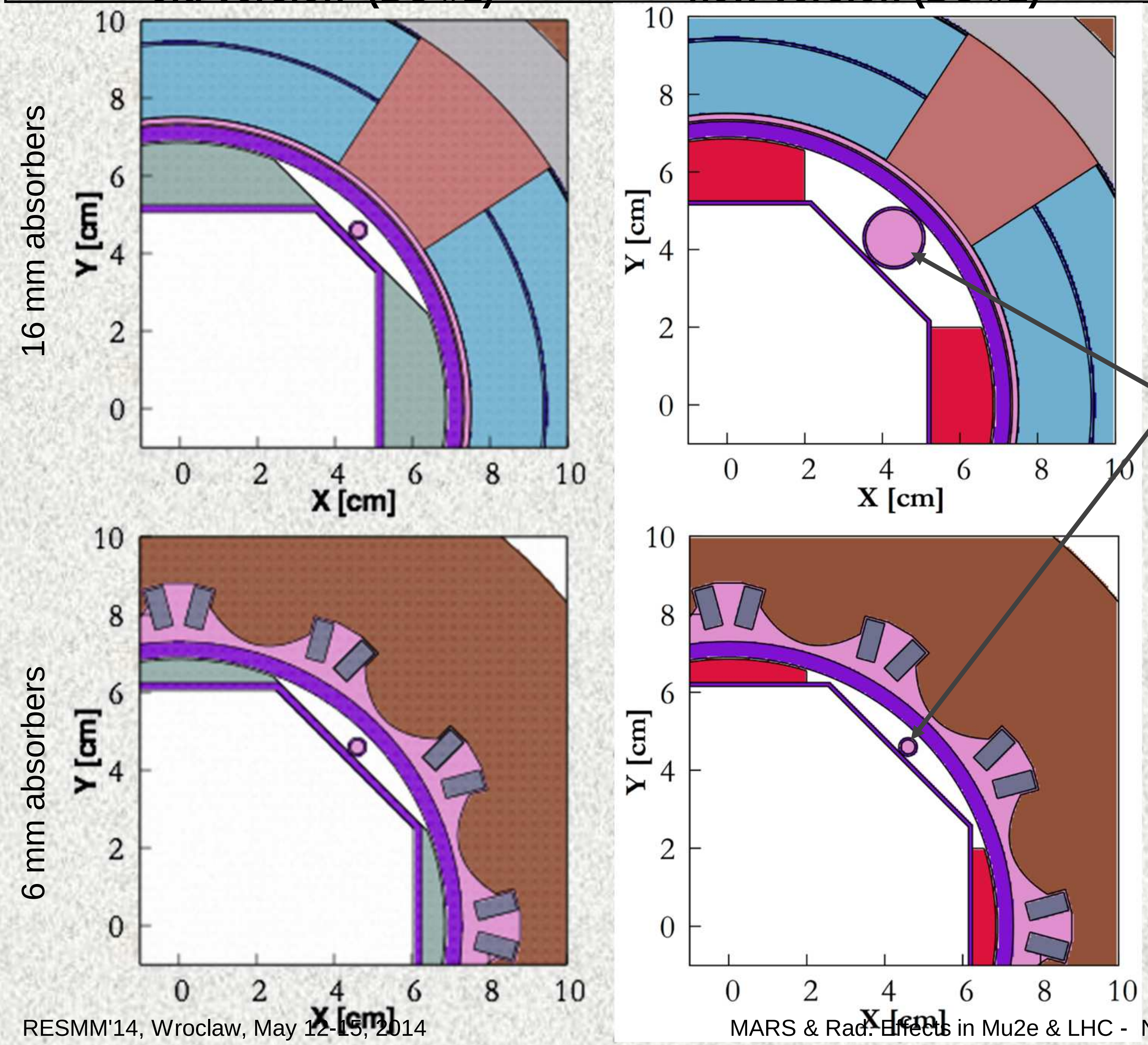
Common name	Material	Maximum calculated value per I_0=3000 fb^{-1}			Limit		
		Dose (MGy)	DPA	Φ_n (cm^{-2})	Dose(MGy)	DPA	Φ_n (cm^{-2})
Insulation	Kapton	22			25-35		
Insulation	G10	20			20		
Coil	NbTi		9.0×10^{-5}	4.2×10^{16}			10^{18}
Coil	Cu		9.0×10^{-5}	4.2×10^{16}		6×10^{-5} **	
Steel*	304L		4.6×10^{-3}	9×10^{16}			7×10^{22}
Steel*	316		3.8×10^{-4}	5×10^{16}			7×10^{22}
Cooling channels	Cu		7.0×10^{-5}	2×10^{16}			
Yoke*	ARMCO 99.99% Fe		1.0×10^{-4}	3×10^{16}			7×10^{22}
Steel Shell*	Mild STL		5.0×10^{-5}	1×10^{16}			7×10^{22}
Liner	W		0.01	1×10^{17}		9.5	10^{21}

*) Mechanical properties start changing at DPA > 0.1 and mostly getting better with irradiation

**) RRR, 80% annealed

Towards New Beam Screen and Absorber Designs

old version (BS #1) **new version (BS #2)**



Note:
- BS #1 is the version used in FLUKA/MARS simulations so far
- BS #2 is the design presented in the previous slide
The differences are reported below

1. cooling capillary (tube) size

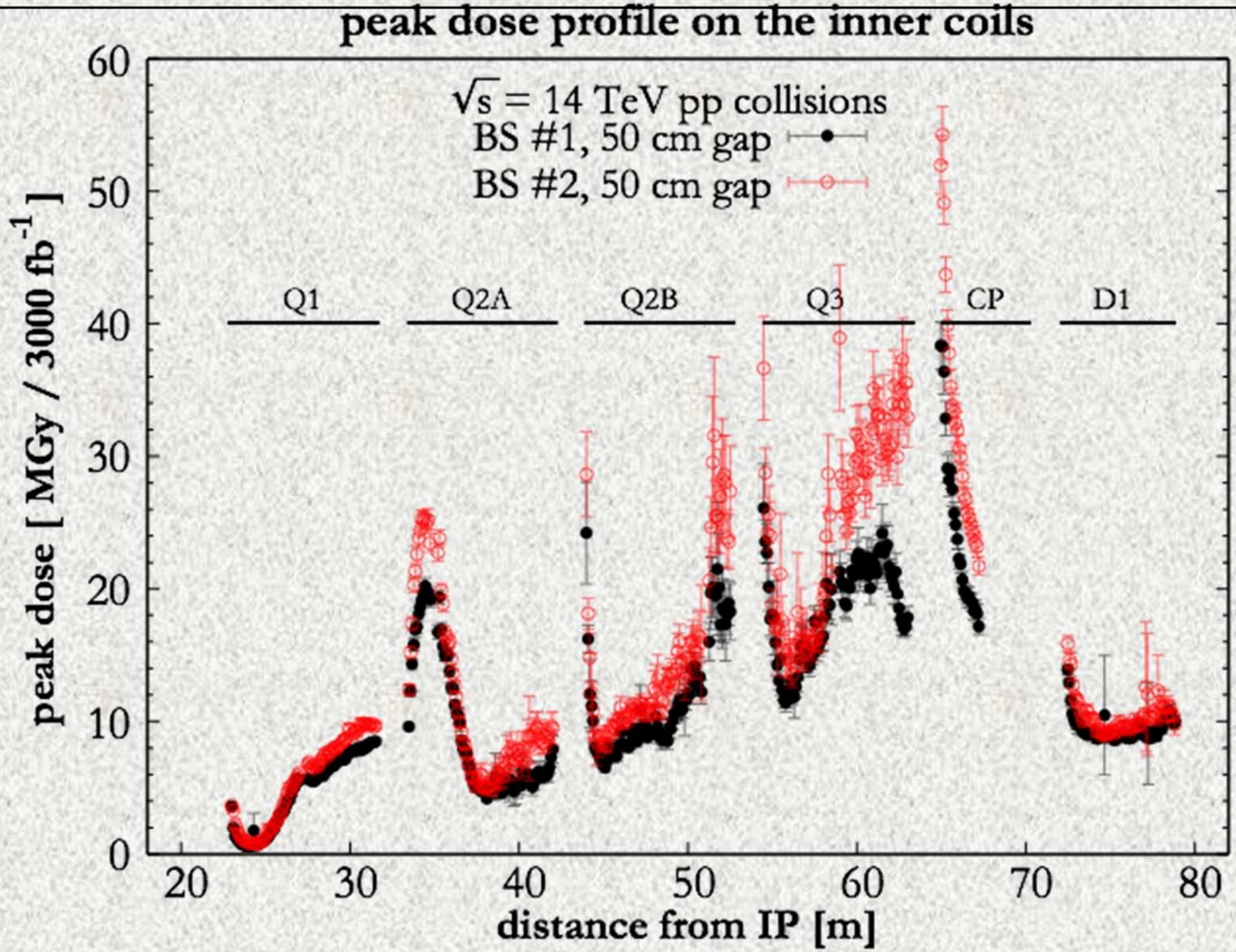
[still to be modified]

2. **absorber shape**

3. **INERMET 180 (W-Ni-Cu, ρ = 18gcc)**

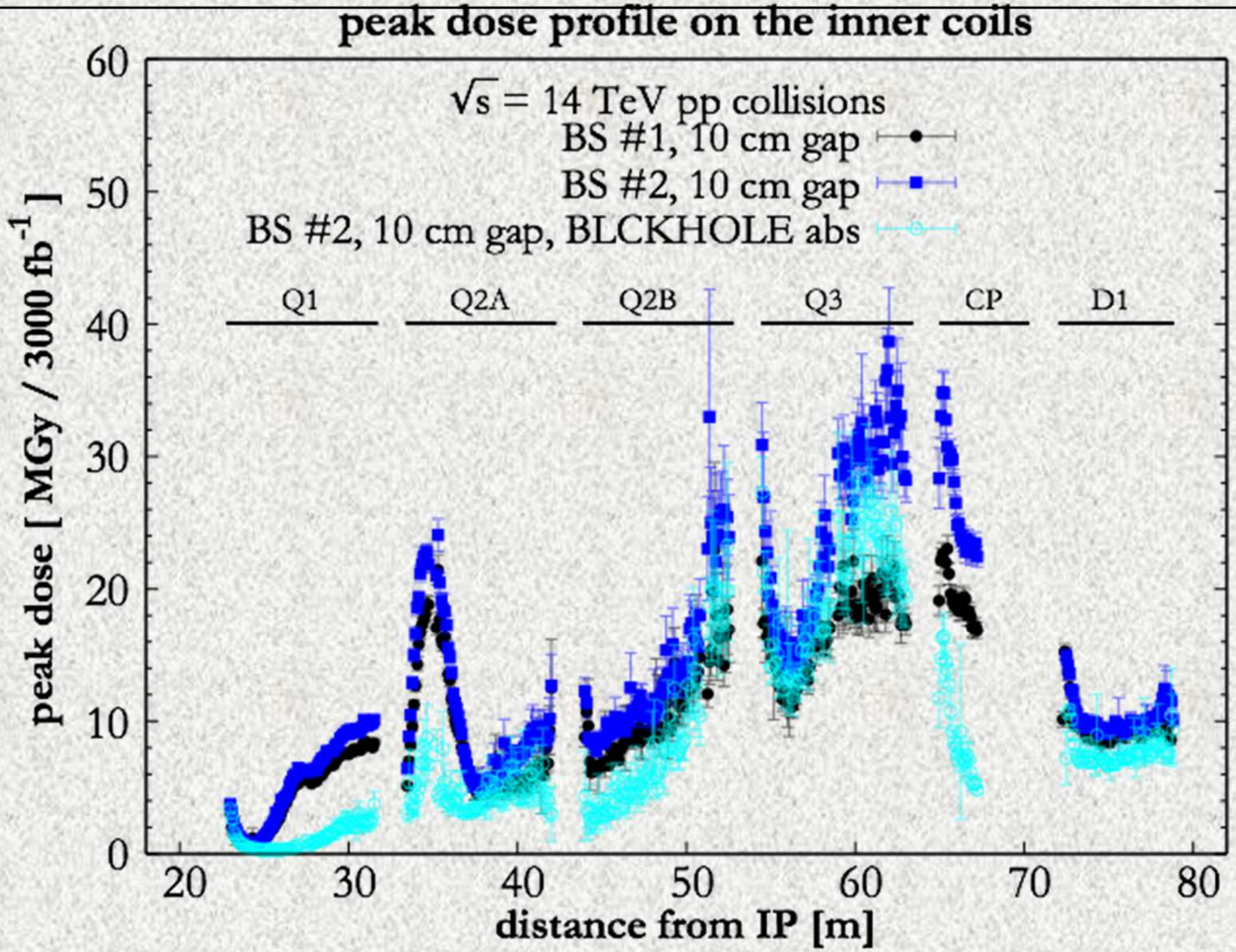
4. beam screen thickness (**2⇒1 mm**) thus bringing Q1 aperture to 113 mm elsewhere to 123 mm

Effect on Peak Dose due to Design Changes



Peak dose on beam screen ranges from 100 to 700 MGy/3000 fb^{-1}.
Relevant for carbon coating used to mitigate electron cloud heating.

Criticality of BS Geometry (rather than material)

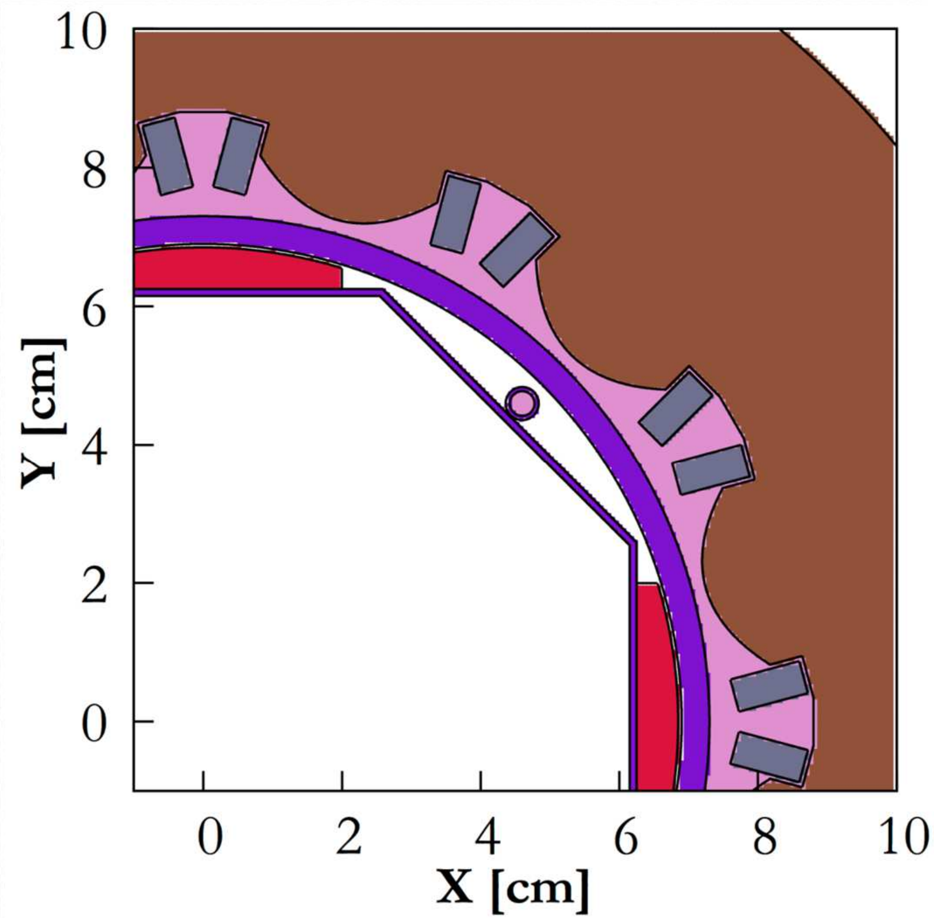


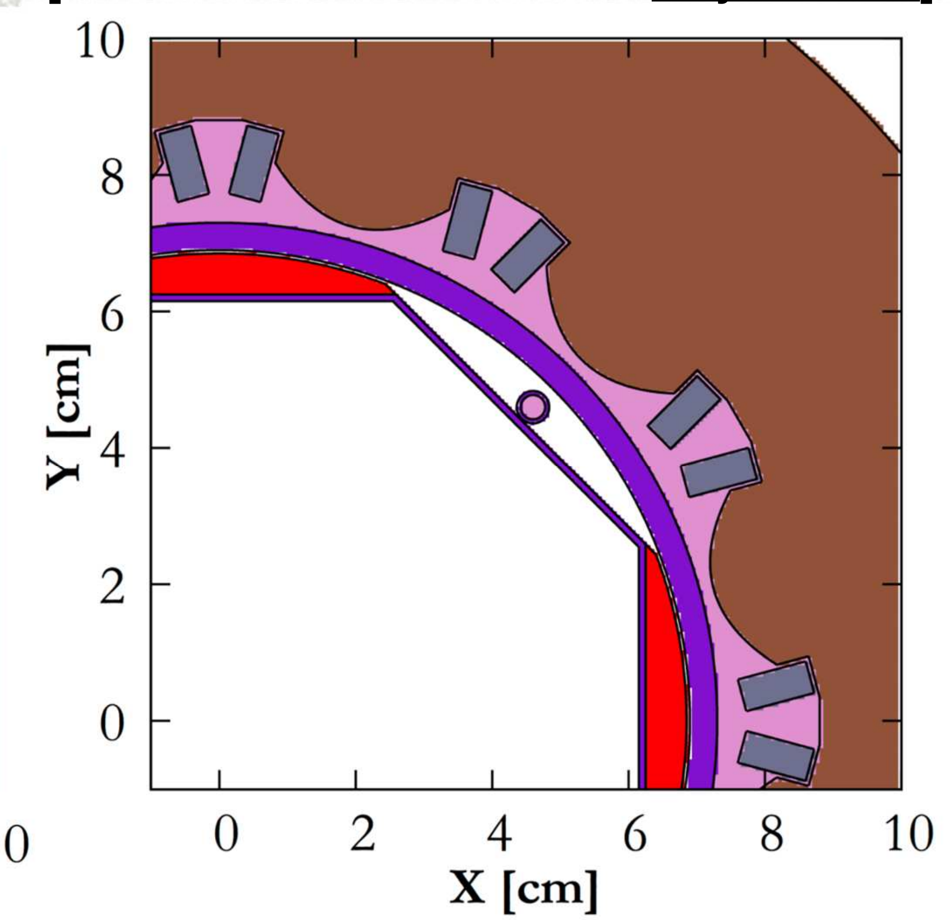
Even taking ideal absorbers totally opaque, the Q3 peak dose remains high due to the revised shape

Back to (almost) the Original BS Geometry

BS #2

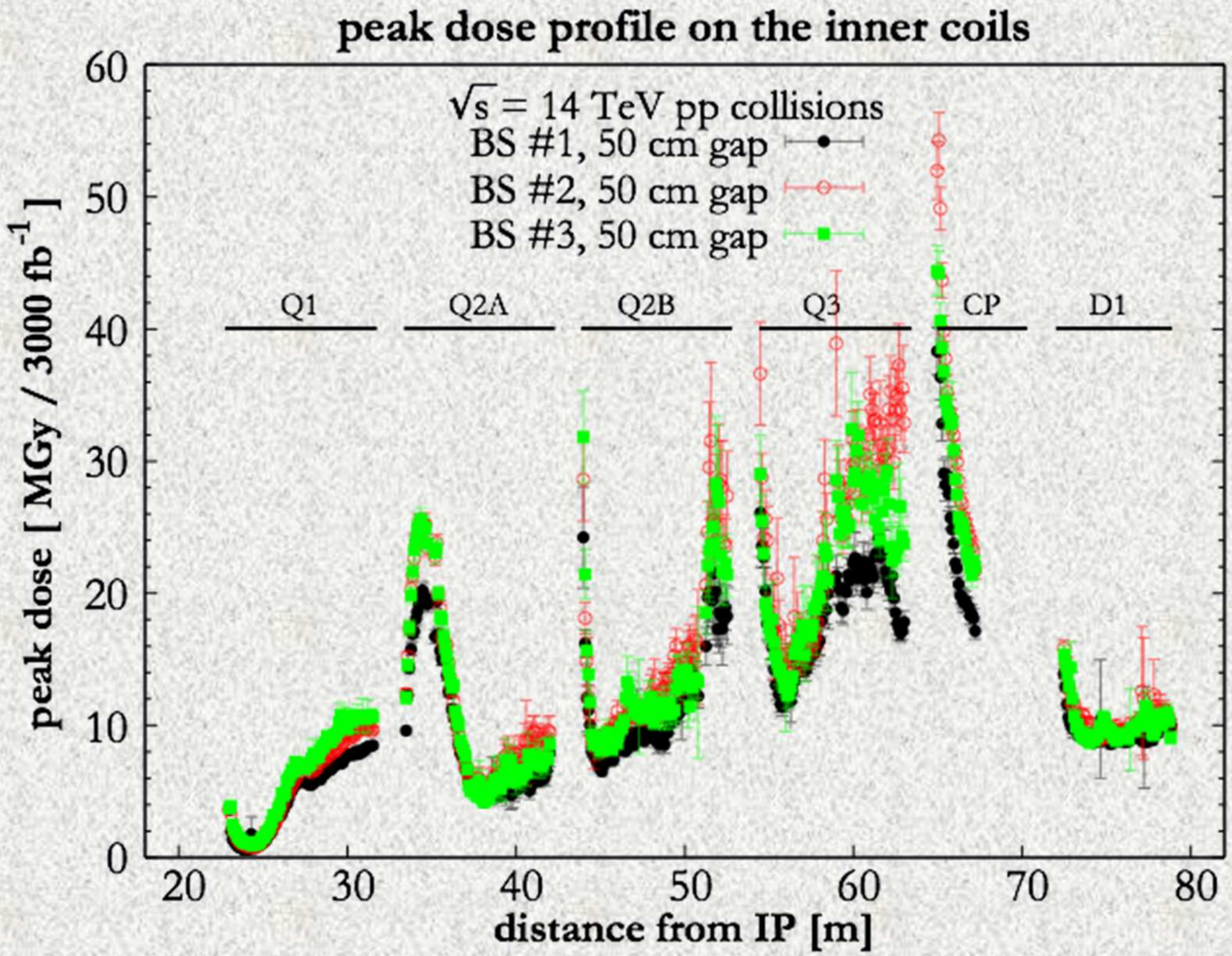
BS #3
[i.e. BS #1 with INERMET and only 1mm SS]





(For Q1 stay with BS #2 as on slide 32)

Improvements with BS #3



Issues

1. 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?

2. 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?

3. Move from occasional comparisons of calculated radiation-damage related quantities to a comprehensive code intercomparison with "standardized" DPA models, well defined irradiation conditions including temperature, dose rate, H_2/He gas production, etc.

4. Link of calculated quantities (DPA, dose, fluence etc.) to observable changes in critical properties of materials remains on the top of the wish-list. Well-thought experiments – covering various regions of the parameter space - are extremely desirable.

Summary (1)

- Recent improvements and extensions in MARS15 further increase its predictive power, reliability and flexibility.
- Design of the Mu2e systems to protect superconducting coils and mitigate backgrounds is based on detailed MARS15 simulations – we are OK here.
- Detailed radiation load maps are obtained in coherent FLUKA and MARS15 simulations for the HL-LHC IT-CP-D1 magnets.
- FLUKA and MARS results on power density, dose and neutron flux agree within 15%; on DPA these agree within 50%.

Summary (2)

- There is a good correlation of DPA and neutron flux profiles; neutrons above 100 keV contribute most to the neutron flux in LHC magnets.
- There is a factor of 5 to 10 margin on power density wrt the quench limits for both Nb_3Sn and NbTi coils.
- In most cases, the calculated peak quantities related to radiation damage are within the limits for 3000 fb^{-1}. Very low limits on DPA for copper and aluminum stabilizing materials in the coils at cryo temperatures need further attention.
- Several issues still need to be resolved.