Mu2e Solenoid Capture System: Radiation and Heat Shield Optimization using MARS15

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Solenoid Capture Workshop
Brookhaven National Laboratory
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Outline

- Mu2e Experiment at Fermilab
- Production Solenoid Shield Constraints
  - SC in radiation field: quench stability & heat loads
  - Aluminum resistance and lifetime at cryo temperatures
  - Cost
- Shielding Material/Cost Optimization
- Tungsten Mass/Geometry Optimization
- Conclusions

What is μe Conversion?

muon converts to electron in the presence of a nucleus, coherent conversion:
1) neutrinos are not emitted 2) nucleus remains intact 3) signature – 105 MeV monoenergetic electron

$$\mu^- N \rightarrow e^- N$$

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

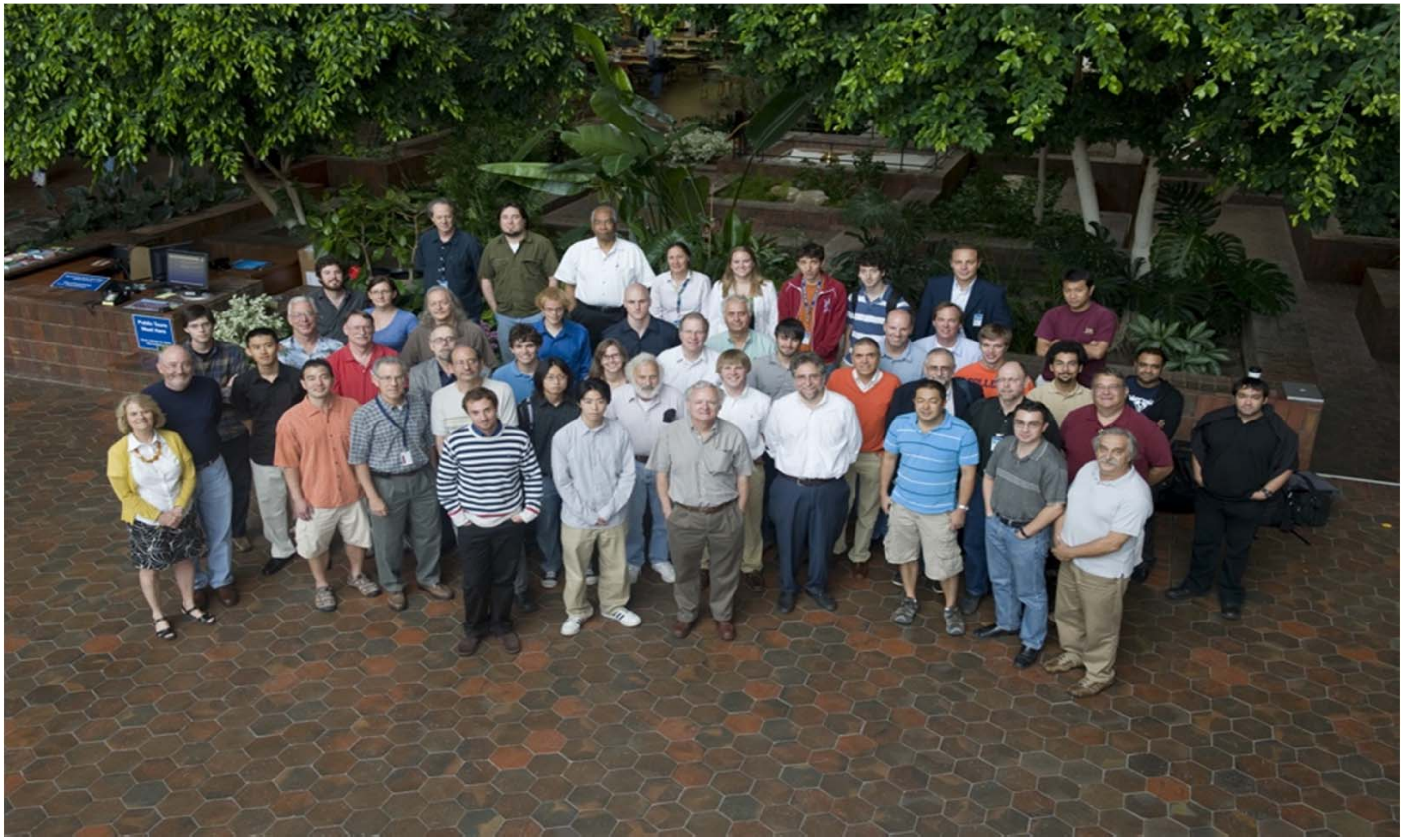
$$R_{\mu e} < 6 \times 10^{-17} \,@\, 90\%\text{CL}$$

Best limit : 6×10^{-13} (90% C.L.) from SINDRUM II

Search for Charged Lepton Flavor Violation, rate in SM $< 10^{-51}$

Explanation: SUSY, extra dimensions, leptoquarks, second Higgs doublet etc.

Mu2e Collaboration



Boston University
Brookhaven National Laboratory
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City University of New York
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University of Illinois, Urbana-Champaign
Institute for Nuclear Research, Moscow, Russia
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Lawrence Berkeley National Laboratory
Los Alamos National Laboratory
Northwestern University
INFN Frascati
INFN Pisa, Università di Pisa, Pisa, Italy
INFN Lecce, Università del Salento, Italy
Rice University
Syracuse University
University of Virginia
College of William and Mary

120 collaborators

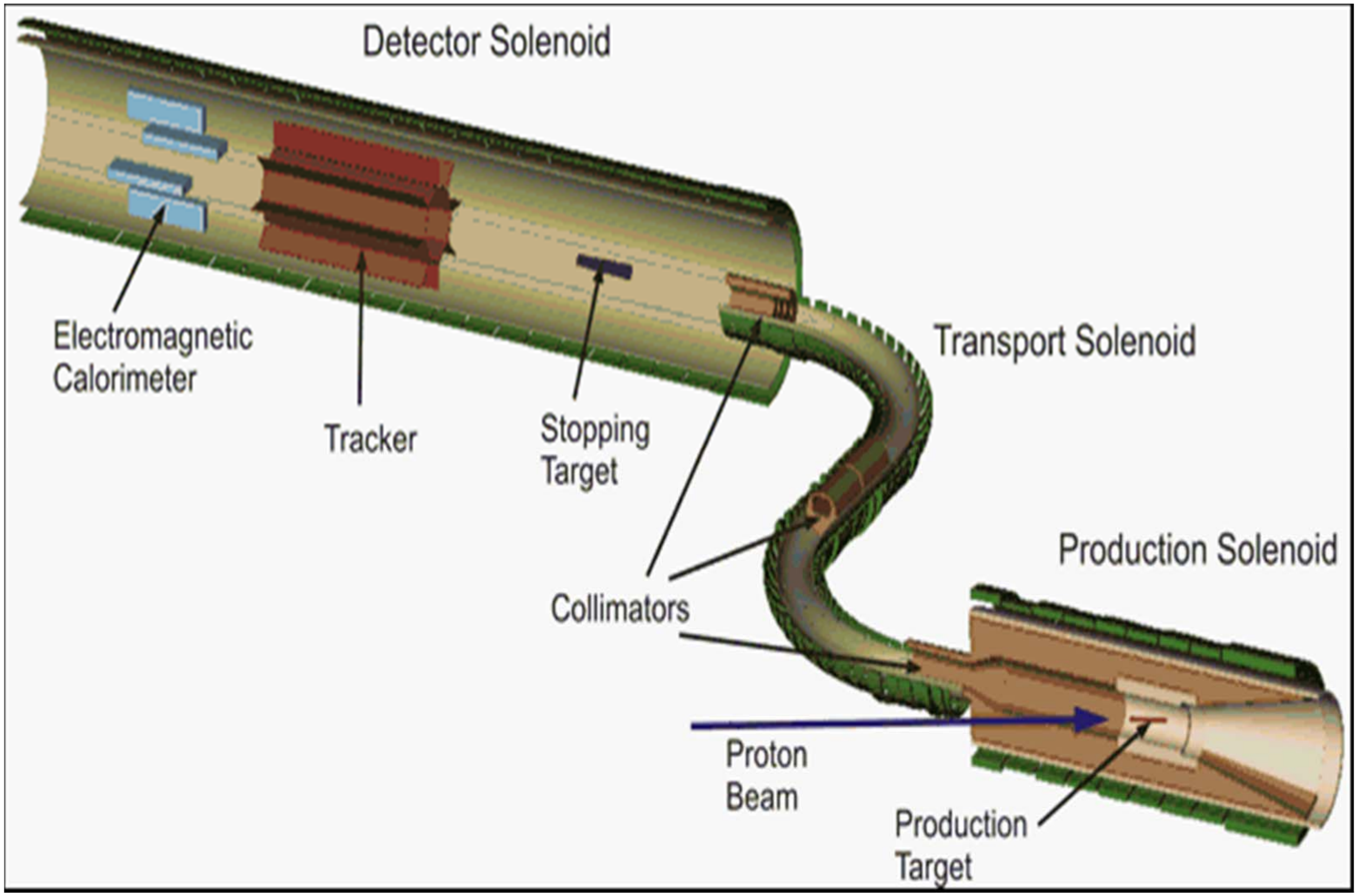
Mu2e experimental setup

Proton beam:

- 8 GeV on Au target
- 25 kW (2E13 p/s)
- $\sigma_x = \sigma_y = 1$ mm

Production solenoid SC coils:

- 5 Tesla
- D= 167 cm

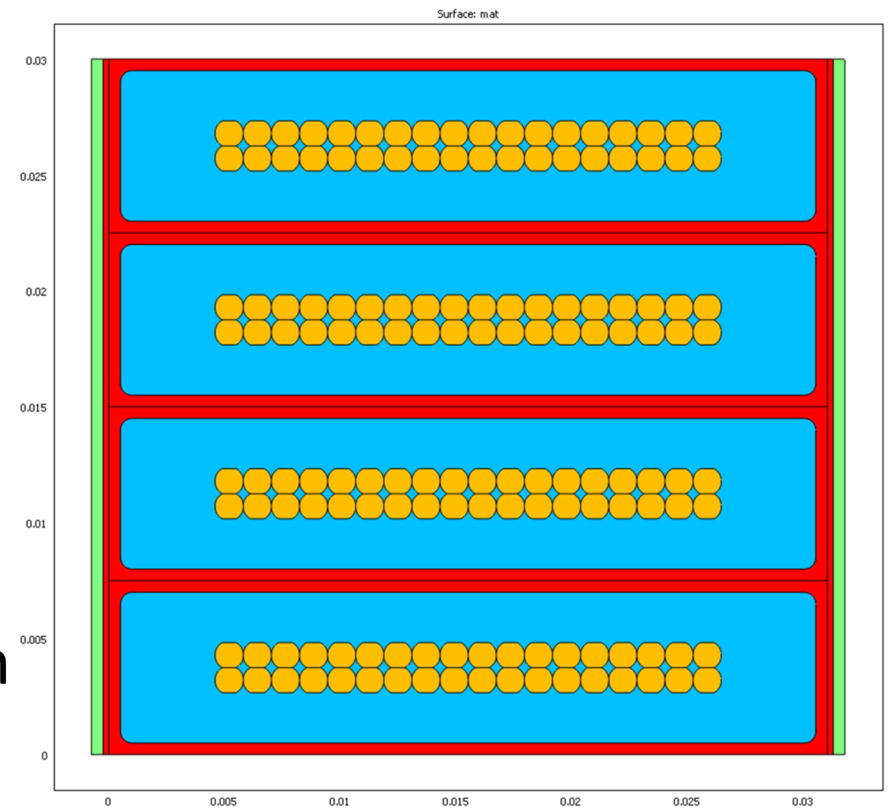


Simulations

- MARS is a Monte Carlo code for inclusive and exclusive simulation of three-dimensional hadronic and electromagnetic cascades, muon, heavy-ion and low-energy neutron transport in accelerator, detector, spacecraft and shielding components in the energy range from a fraction of an electronvolt up to 100 TeV.
- MARS15 (2010) code version was used
- Thresholds: neutrons (from thermal energies), other particles from 0.2 MeV
- Linux cluster, up to 24 processors were used
- Were simulated: DPA, power densities, neutron fluxes, dynamic head loads

Optimization parameters

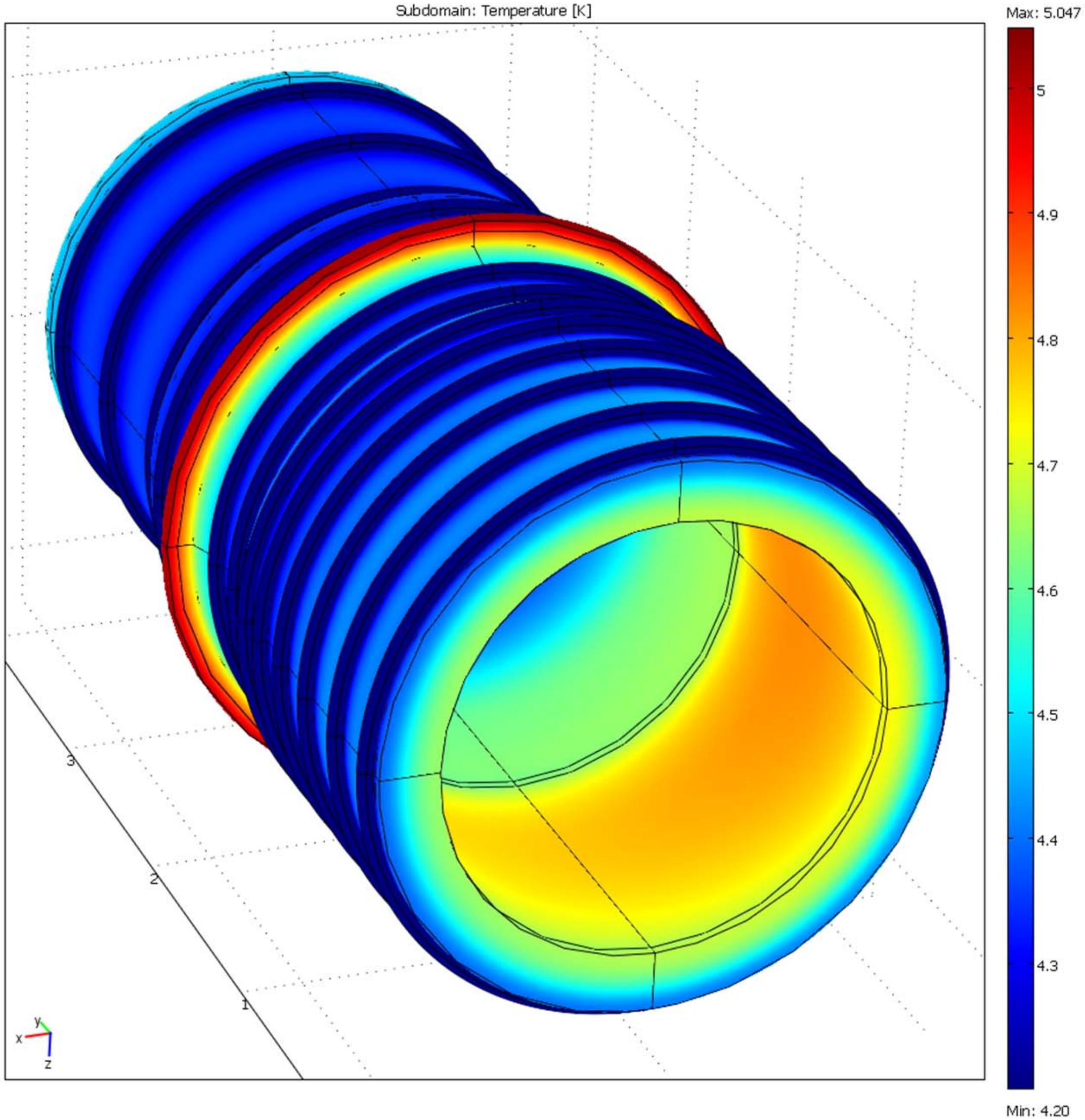
- Absorber (heat and radiation shield) is intended to prevent radiation damage to the magnet coil material and ensure quench protection and acceptable heat loads for the lifetime of the experiment
  - Total dynamic heat load on the coils
  - Peak power density in the coils
  - Peak radiation dose to the insulation and epoxy
  - DPA to describe how radiation affects the electrical conductivity of metals in the superconducting cable

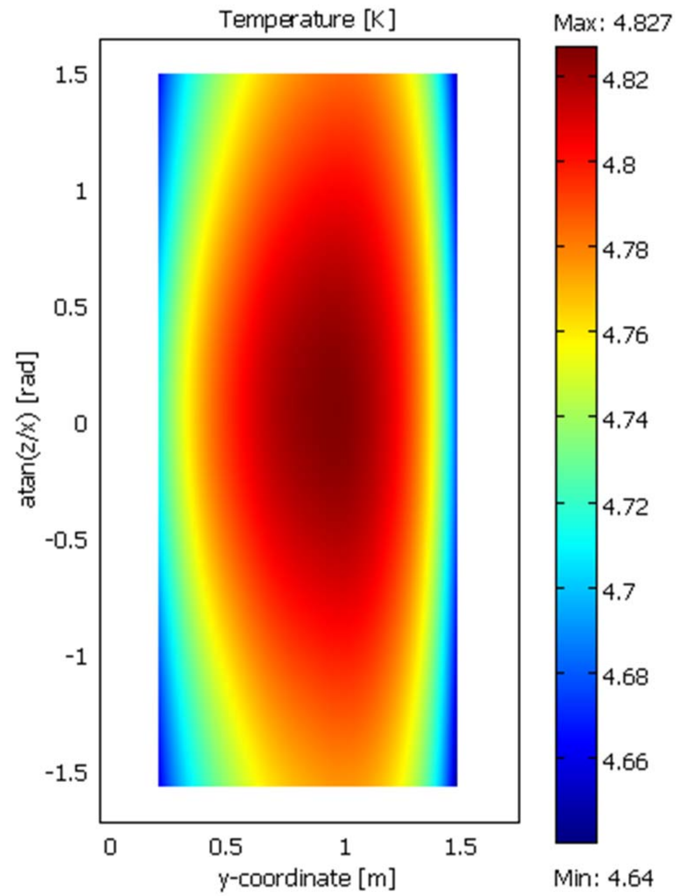


superconducting cable
V.Kashikhin

Materials:
8.35% NbTi
8.35% Cu
17.33% G10
65.97% Al

Optimization parameters. Peak power density





Power density (peak) = 11 μW/g

ΔT = 4.827K - 4.2K = 0.627K

Tcr = 4.6 K

T0 should be ~4.0K

Absorbed dose 300kGy/yr (0.015 mW/g)

V.Kashikhin

Proposed limit = 15 μW/g

Optimization parameters.DPA-1

- DPA (displacement per atom). Radiation damage in metals, displacement of atoms from their equilibrium positions in a crystalline lattice due to radiation with formation of interstitial atoms and vacancies in the lattice.
  – A (PKA) primary knock-on atom is formed in elastic particle-nucleus collisions, generates a cascade of atomic displacements (damage function, ν(T)).
  – A PKA displaces neighboring atoms, this results in an atomic displacement cascade. Point defects are formed as well as defect clusters of vacancies and interstitial atoms (time scale=ps).
- DPA model in MARS15 includes all products of elastic and inelastic nuclear interactions and Coulomb elastic scattering of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV.

Optimization parameters. DPA -2

- Irradiation-induced changes of material properties are measured as a function of DPA (the radiation damage cannot be fully characterized by a single parameter)
- Radiation-induced microstructural changes in materials:
  - Dimensional instability
  - Radiation hardening and embrittlement
  - Irradiation creep
  - Reduction in fatigue performance
  - Degradation of physical properties

    Residual Resistivity Ratio degradation (RRR, ratio of the electric resistance of a conductor at room temperature to that at the liquid He one), the loss of superconducting properties due to change of conditions of electron transport in metals.

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

Optimization parameters. DPA -3

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

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ISOCHRONAL RECOVERY OF FAST NEUTRON IRRADIATED METALS*

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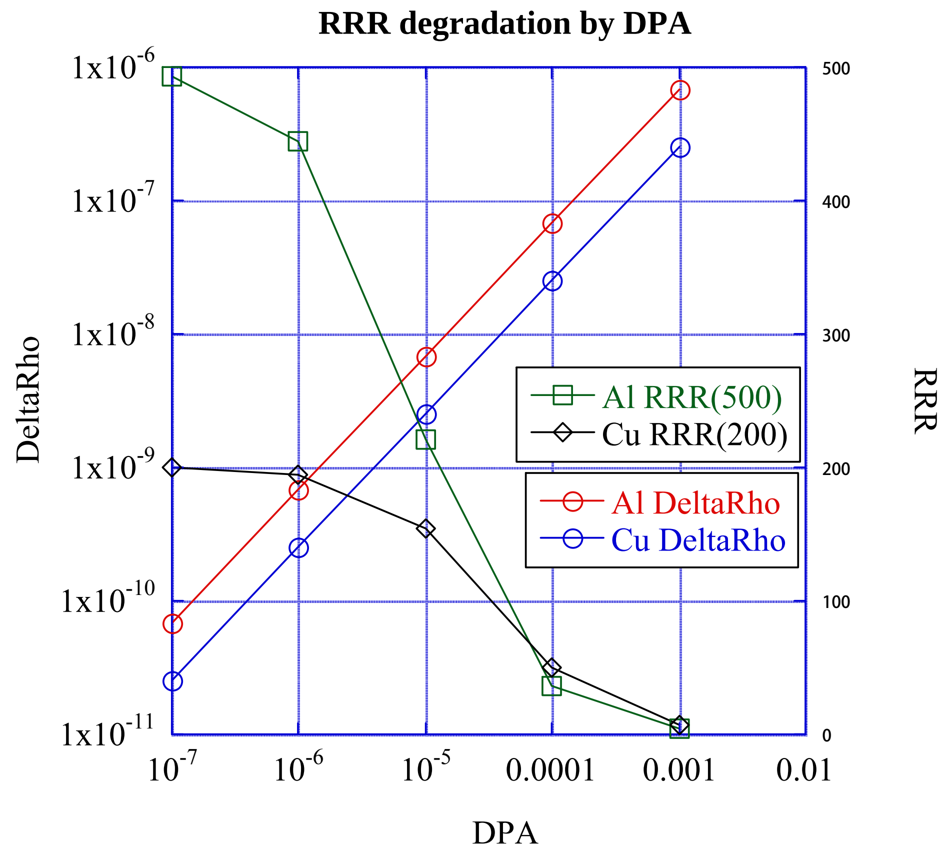
Received 22 May 1973
Revised manuscript received 27 August 1973

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.

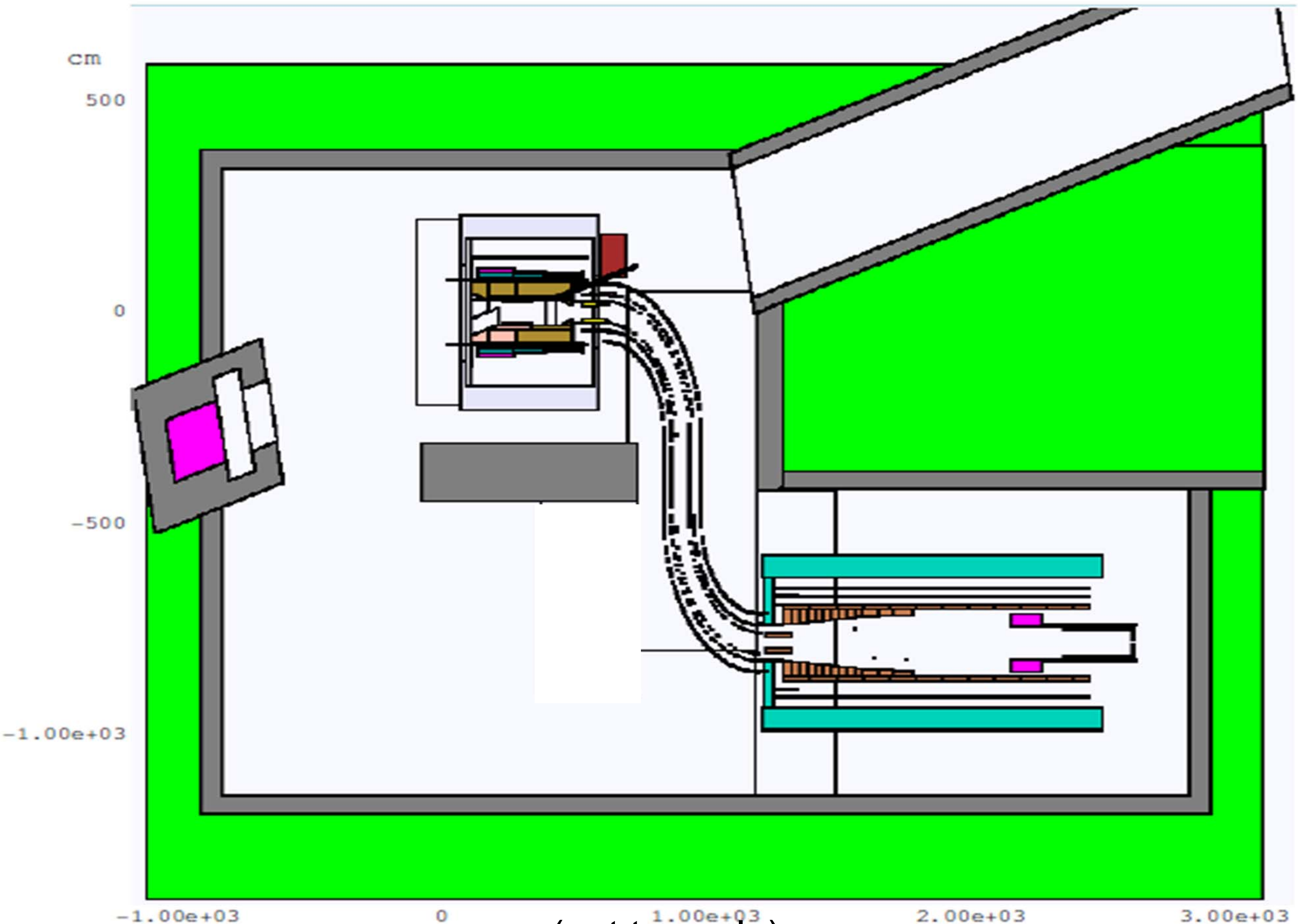
T. Ogitsu's (COMET, Japan) talk at FNAL:



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

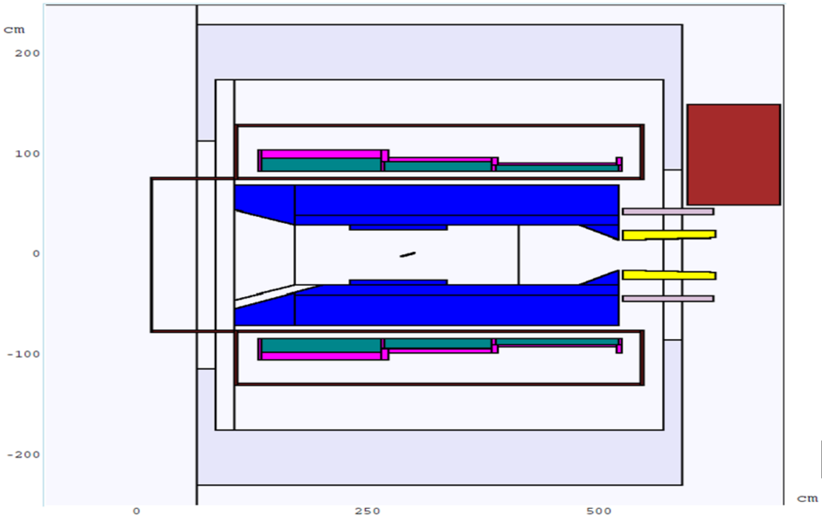
DPA: 2E-5 per 1E21 protons

MARS15 model of the Mu2e hall



(not to scale)

Absorber versions (first optimization)



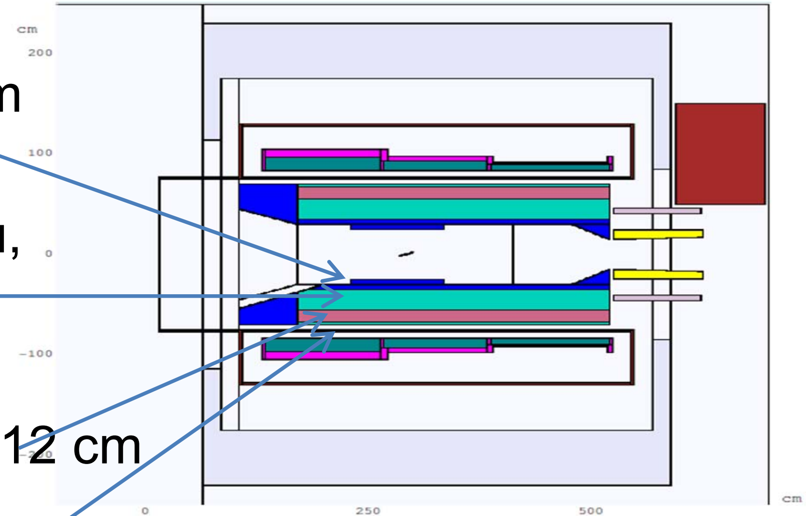
Tungsten, WC, U-238

W, 5cm

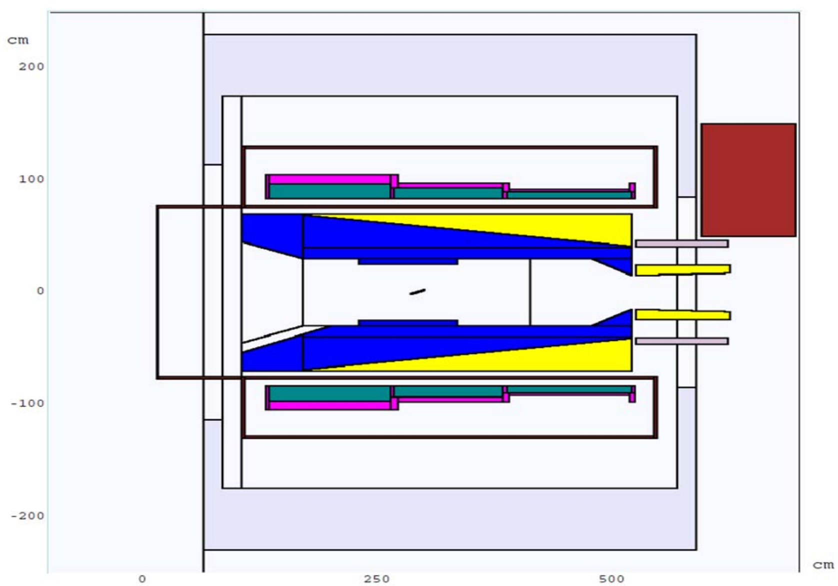
Fe (Cu, WC), 20cm

BCH2, 12 cm

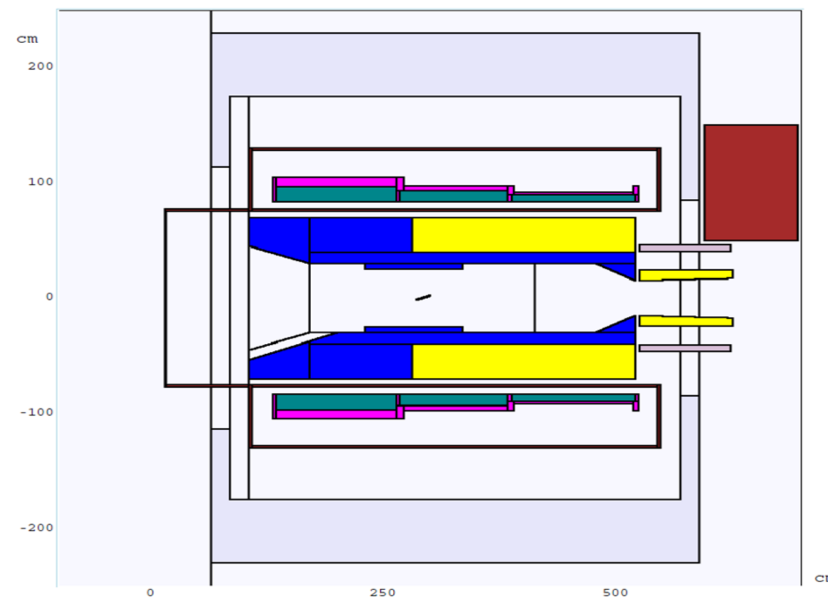
Fe (Cu, Cd), 3cm



multilayer



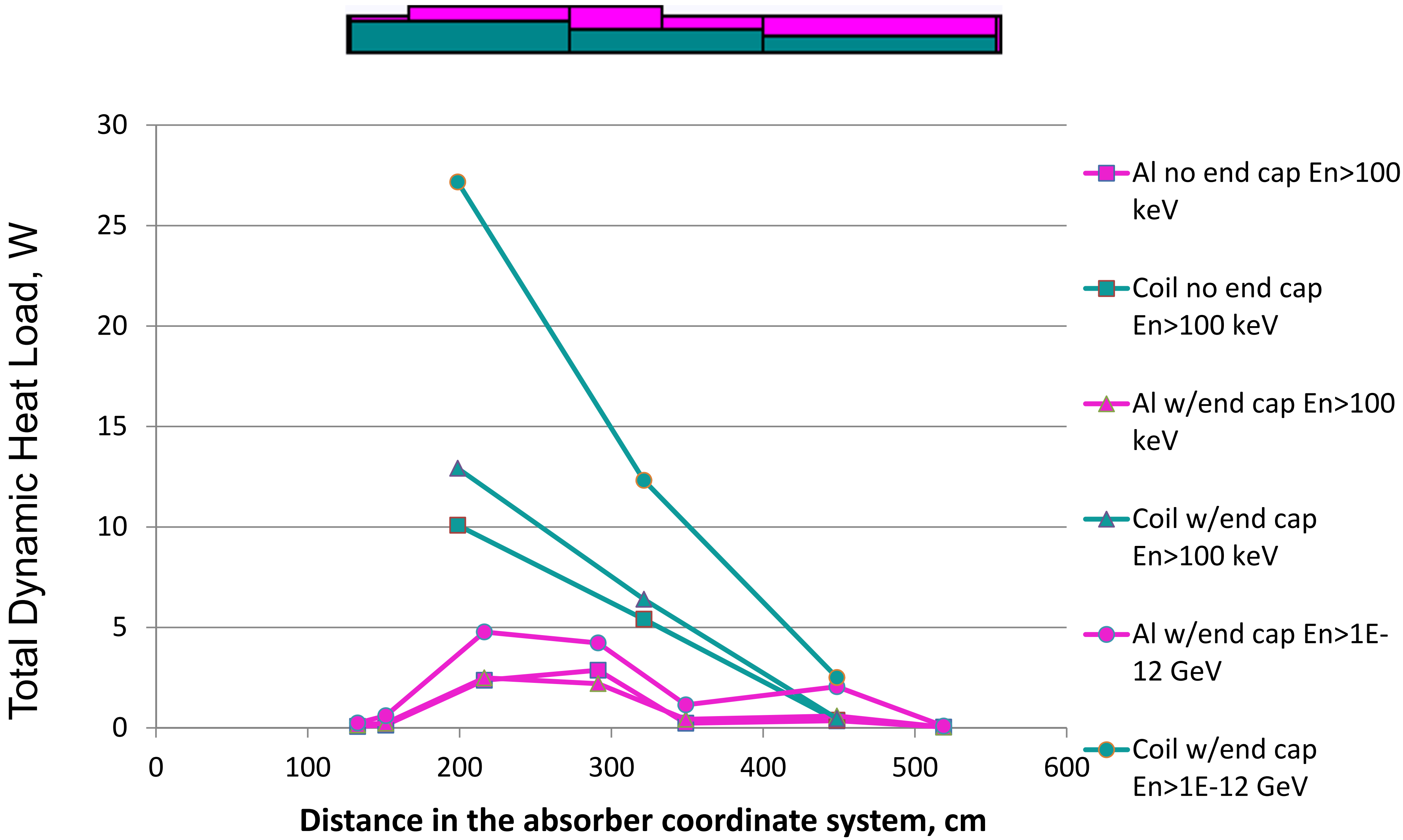
Tungsten/copper



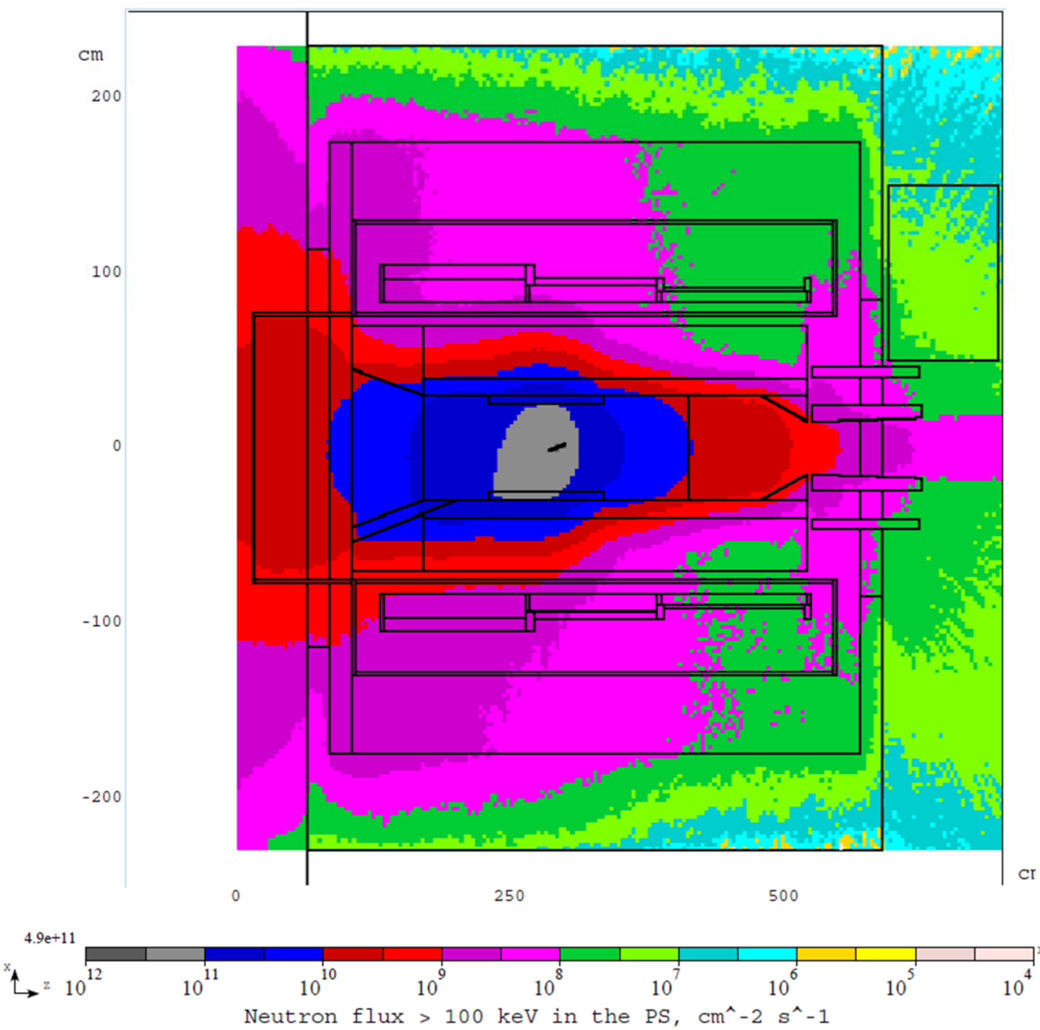
Tungsten/copper

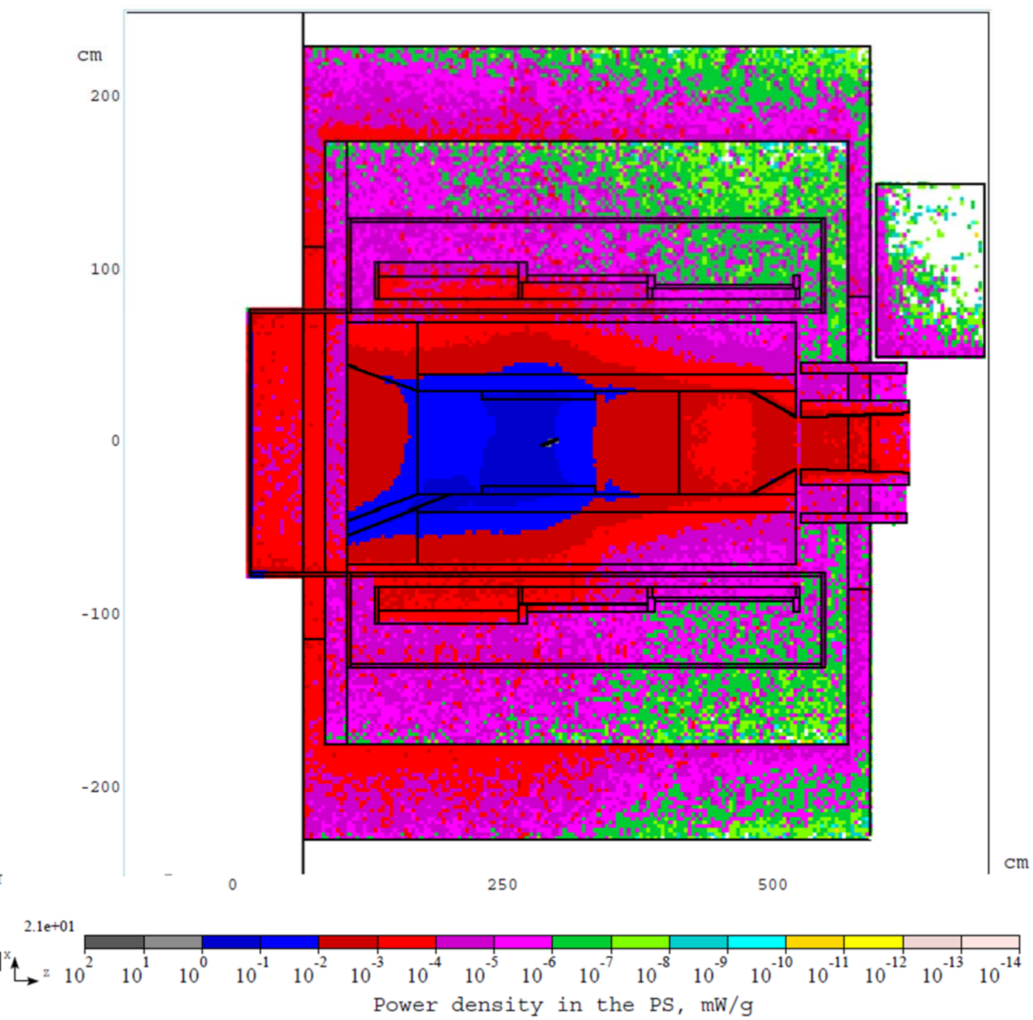
Cases #1-#10

Dynamic HeatLoad (first design, role of the end caps and neutrons)



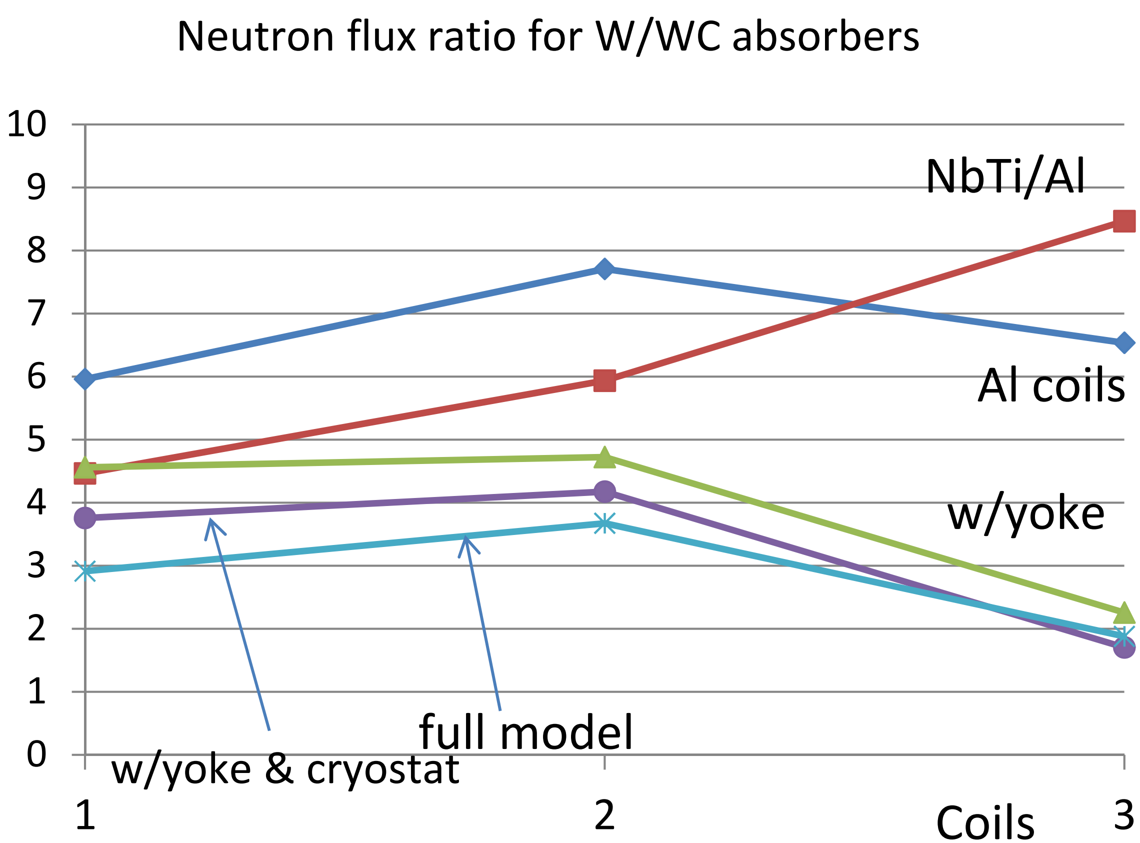
Neutron flux >100 keV and power density

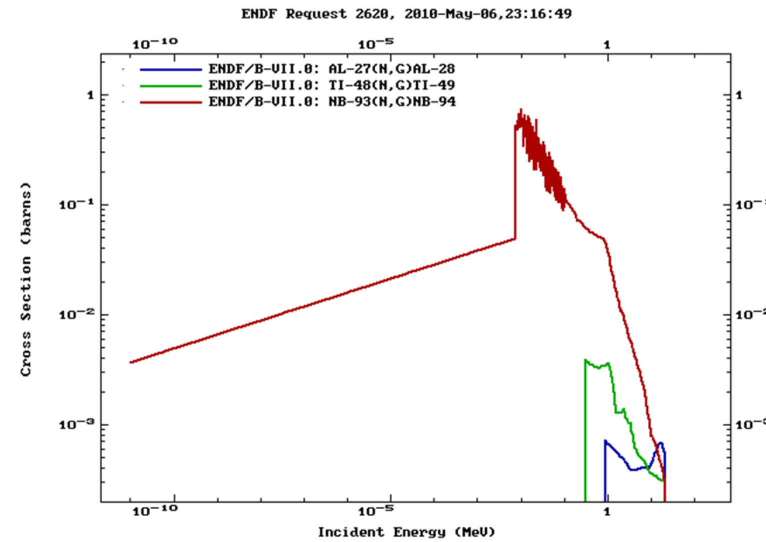


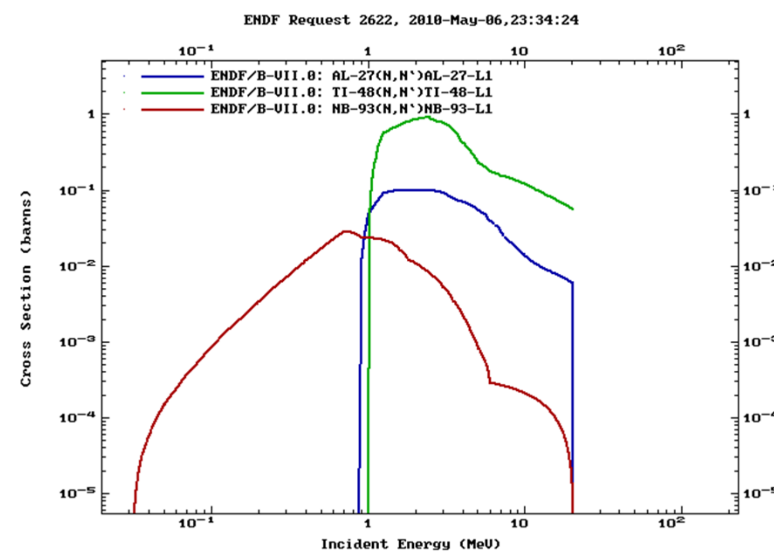


Absorbed dose (Gy/s) = Power density (mW/g), i.e., peak in the coils ~ 40 kGy/yr

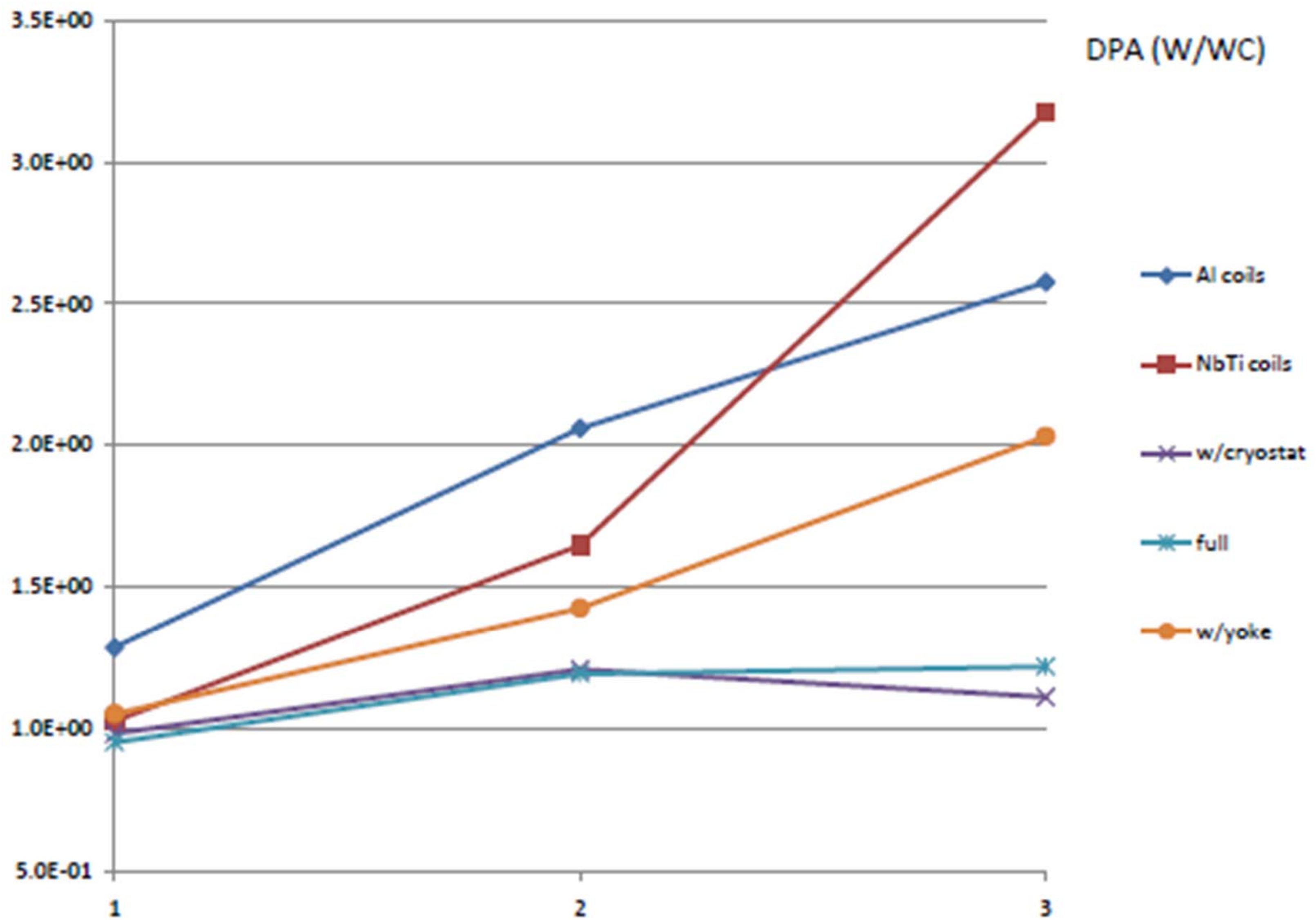
Neutron flux ratio for W/WC absorbers



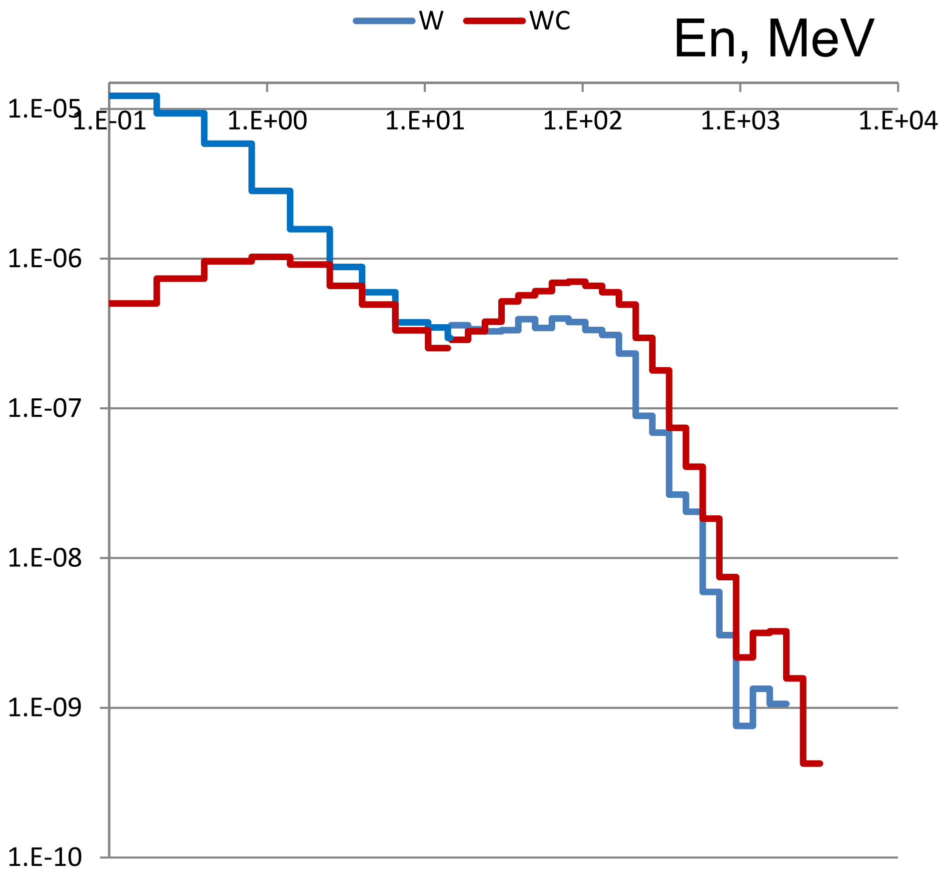




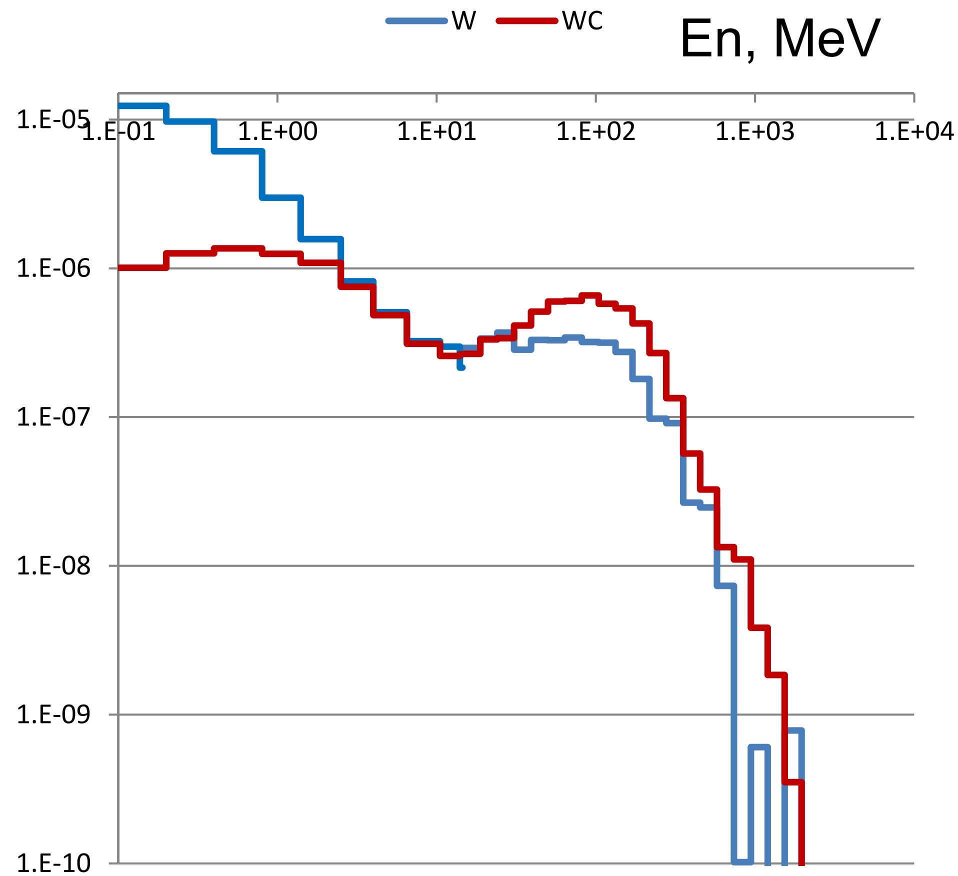
DPA ratios for W/WC absorbers



Neutron lethargies at 1-st coil



Lethargy at 1-st coil simple model



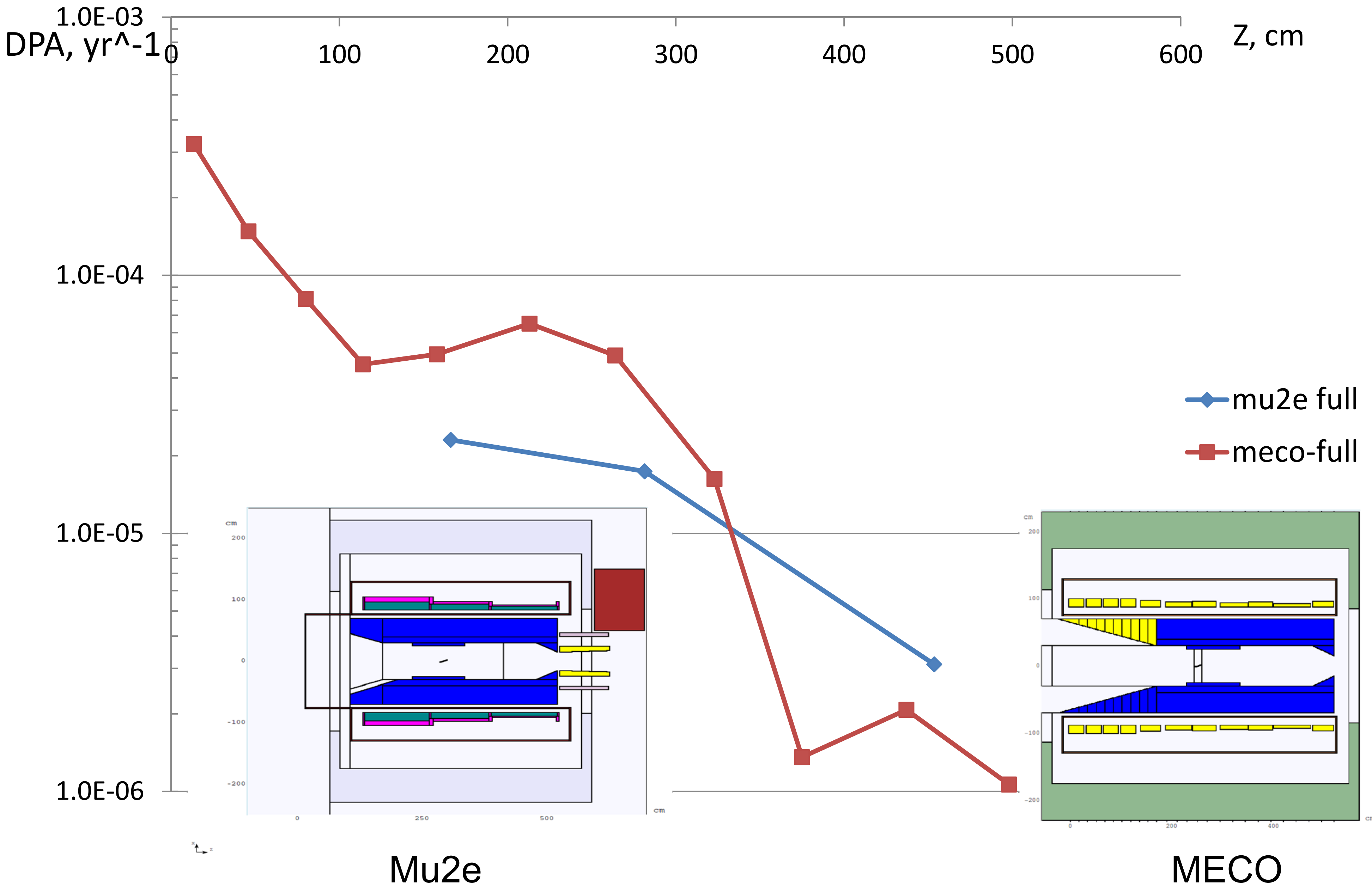
Lethargy at 1-st coil full model

Lethargy = dFlux/d(ln E) = E·dFlux/dE

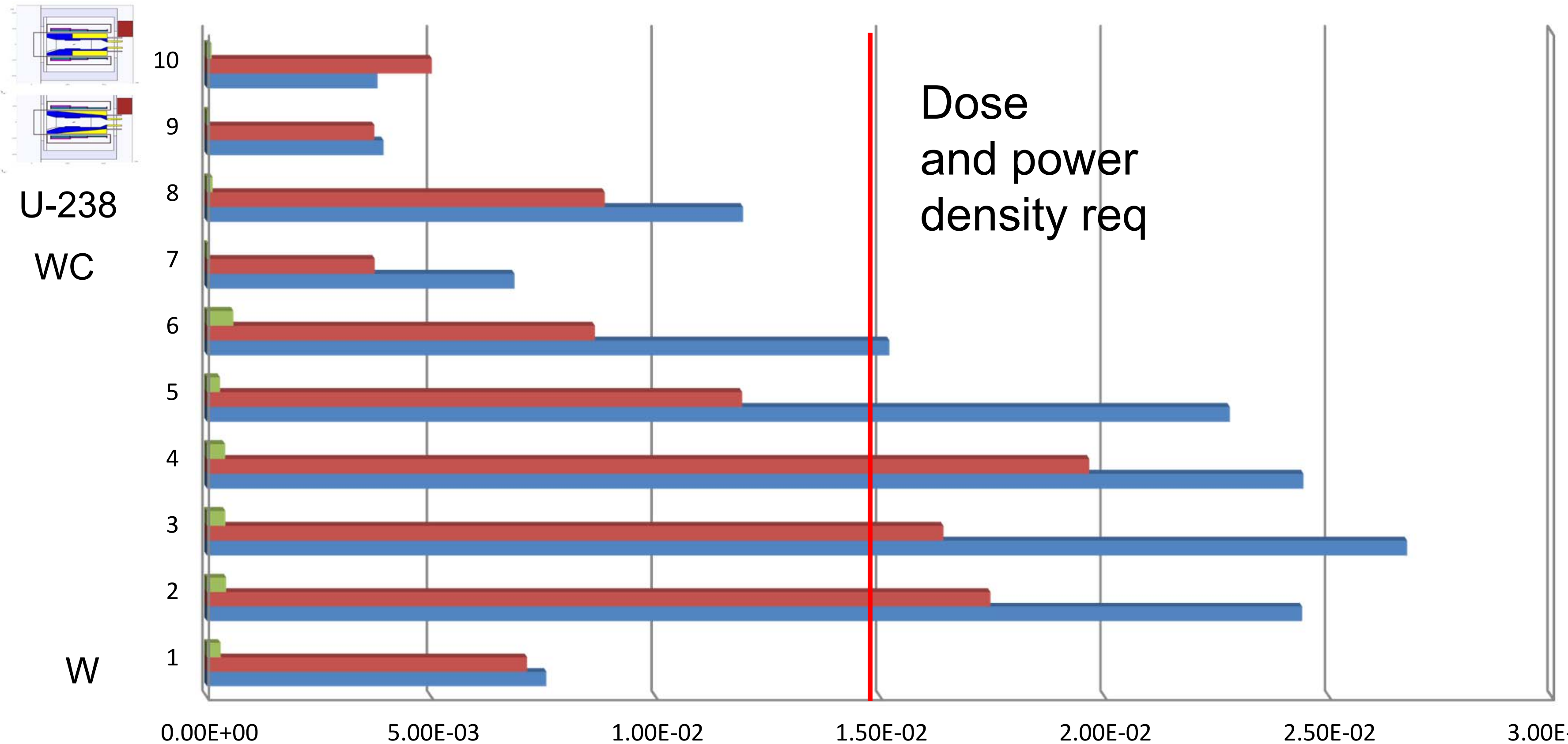
“Simple” model includes only the absorber and the coils

“Full” model includes also cryostat, end cap, yoke, beam shield and 1-st TS coil

Mu2e vs MECO DPA comparison



Peak Power Density in Coils, mW/g

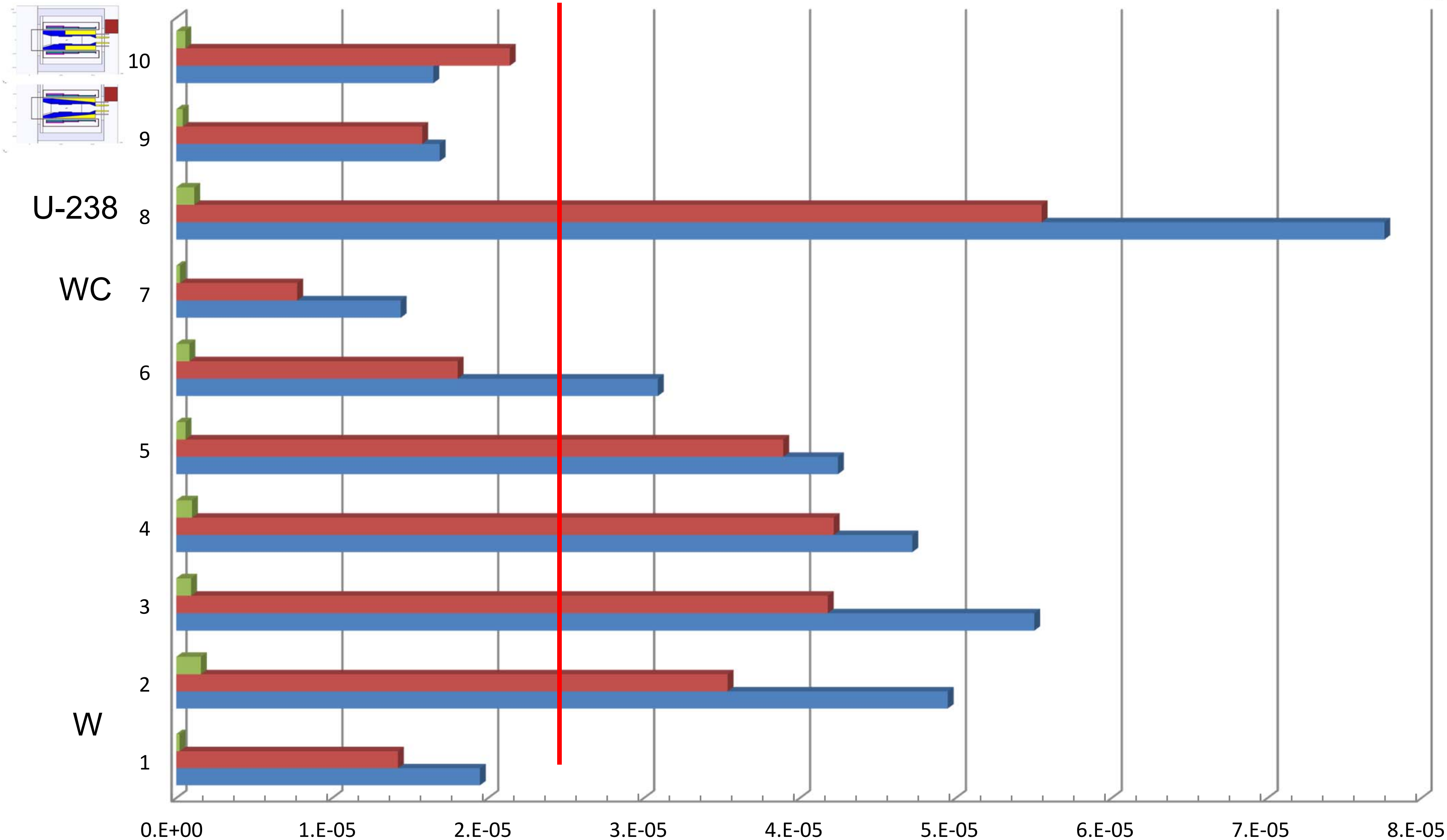


	1	2	3	4	5	6	7	8	9	10
3a	3.04E-04	4.30E-04	4.10E-04	4.05E-04	2.89E-04	5.90E-04	4.86E-05	1.28E-04	7.00E-05	1.03E-04
2a	7.13E-03	1.75E-02	1.64E-02	1.97E-02	1.19E-02	8.64E-03	3.74E-03	8.86E-03	3.73E-03	5.01E-03
1a	7.56E-03	2.44E-02	2.67E-02	2.44E-02	2.28E-02	1.52E-02	6.85E-03	1.19E-02	3.93E-03	3.80E-03

Absorbed dose (Gy/s) = Power density (mW/g)

0.025 mW/g = 500kGy/yr (300kGy/yr (0.015 mW/g)requirement)

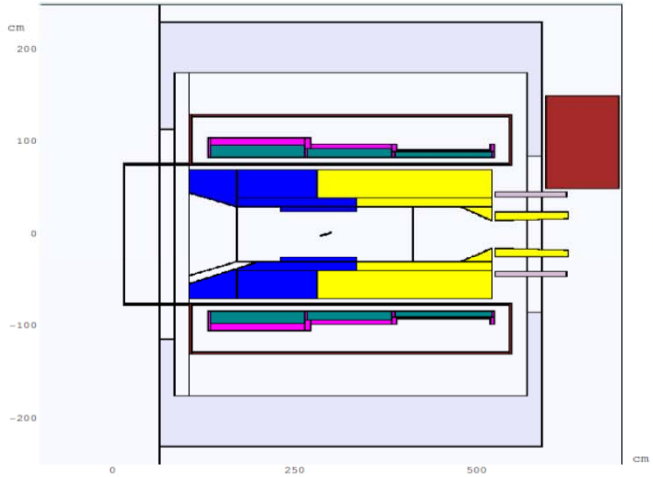
Peak DPA in Coils, yr^-1



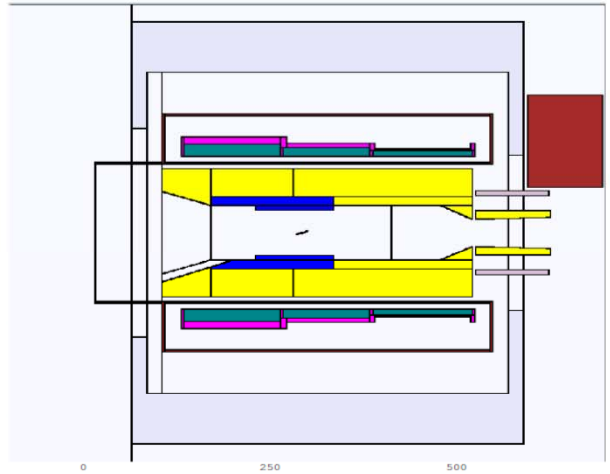
	1	2	3	4	5	6	7	8	9	10
3a	2.23E-07	1.59E-06	9.62E-07	1.02E-06	5.94E-07	8.54E-07	2.42E-07	1.16E-06	4.18E-07	5.93E-07
2a	1.42E-05	3.54E-05	4.18E-05	4.22E-05	3.89E-05	1.81E-05	7.77E-06	5.55E-05	1.58E-05	2.14E-05
1a	1.95E-05	4.95E-05	5.50E-05	4.72E-05	4.25E-05	3.09E-05	1.44E-05	7.76E-05	1.69E-05	1.65E-05

Amount of tungsten: optimization-1

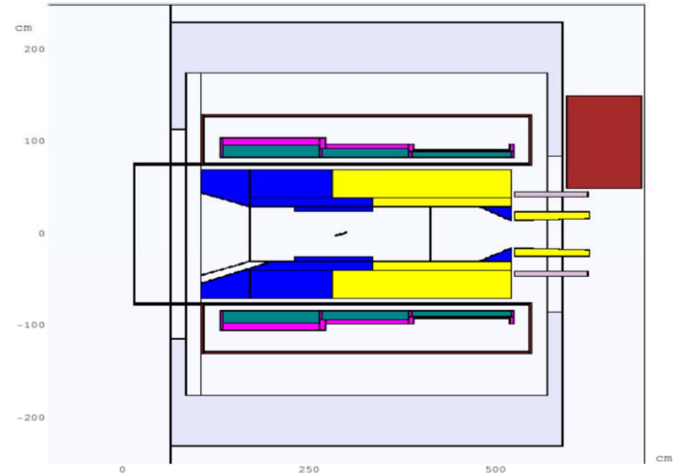
OPT1



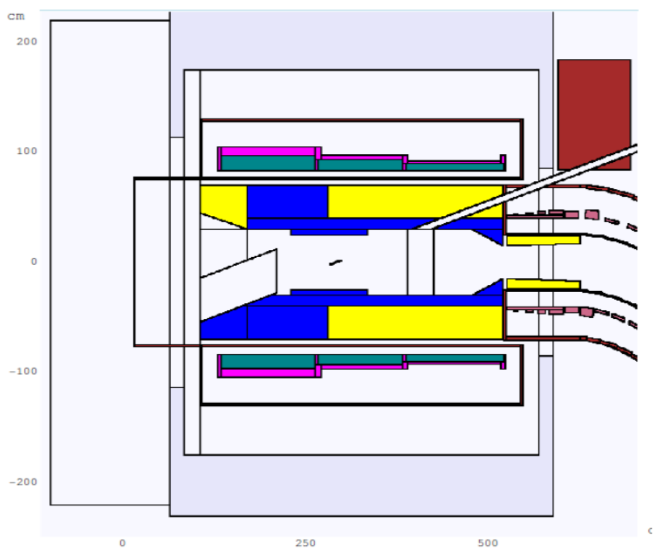
OPT2



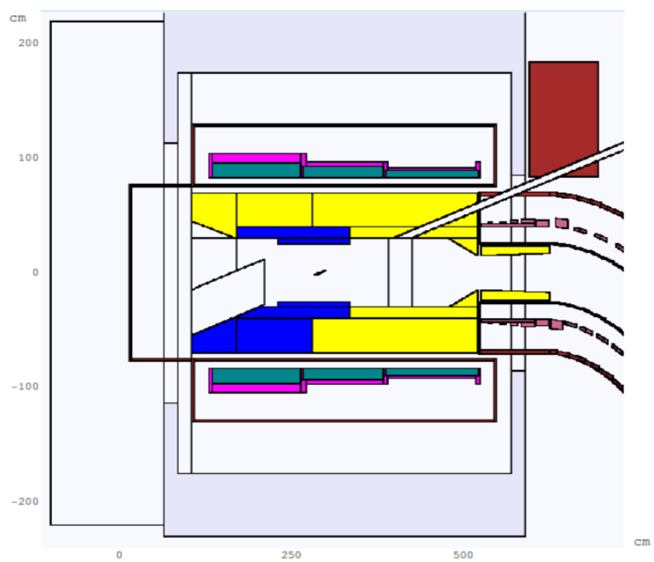
OPT3



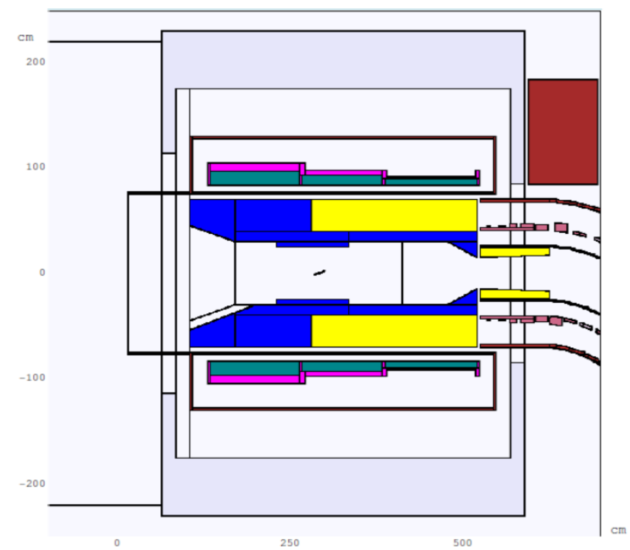
OPT4



OPT5

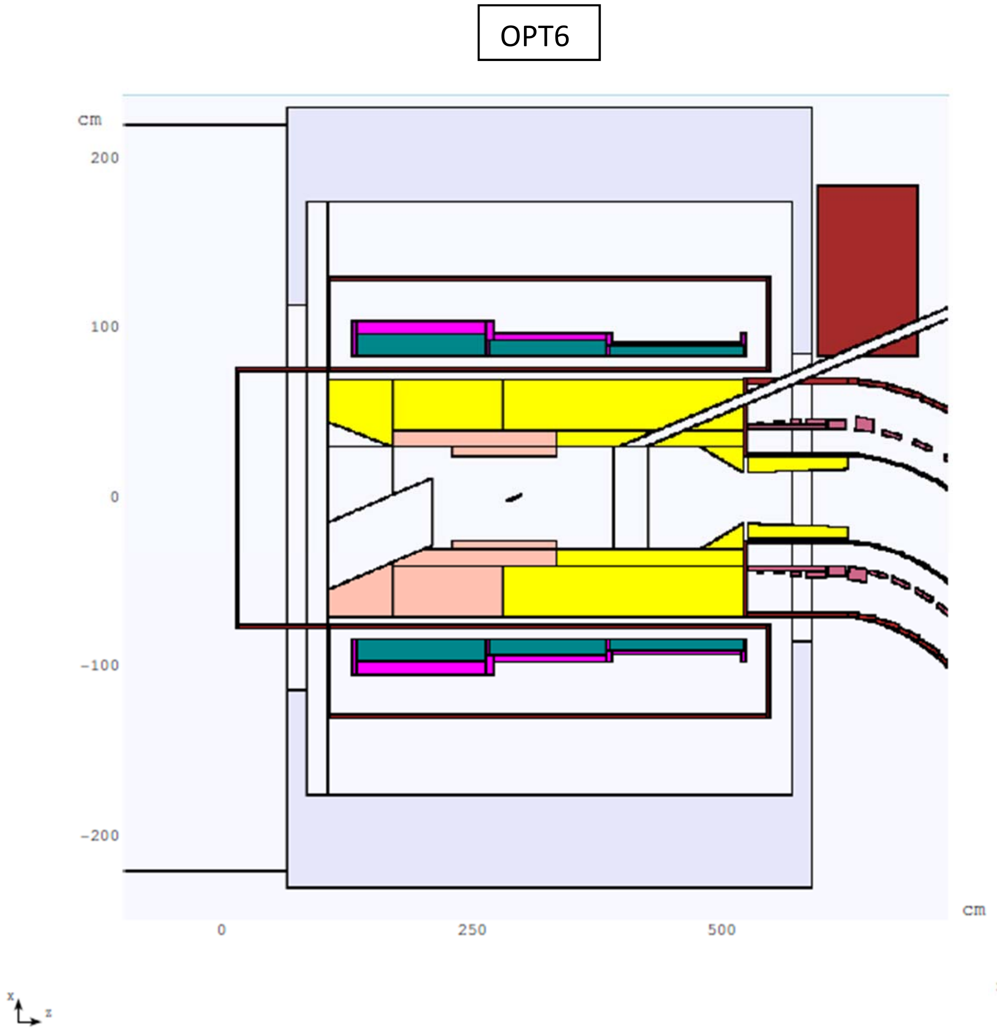


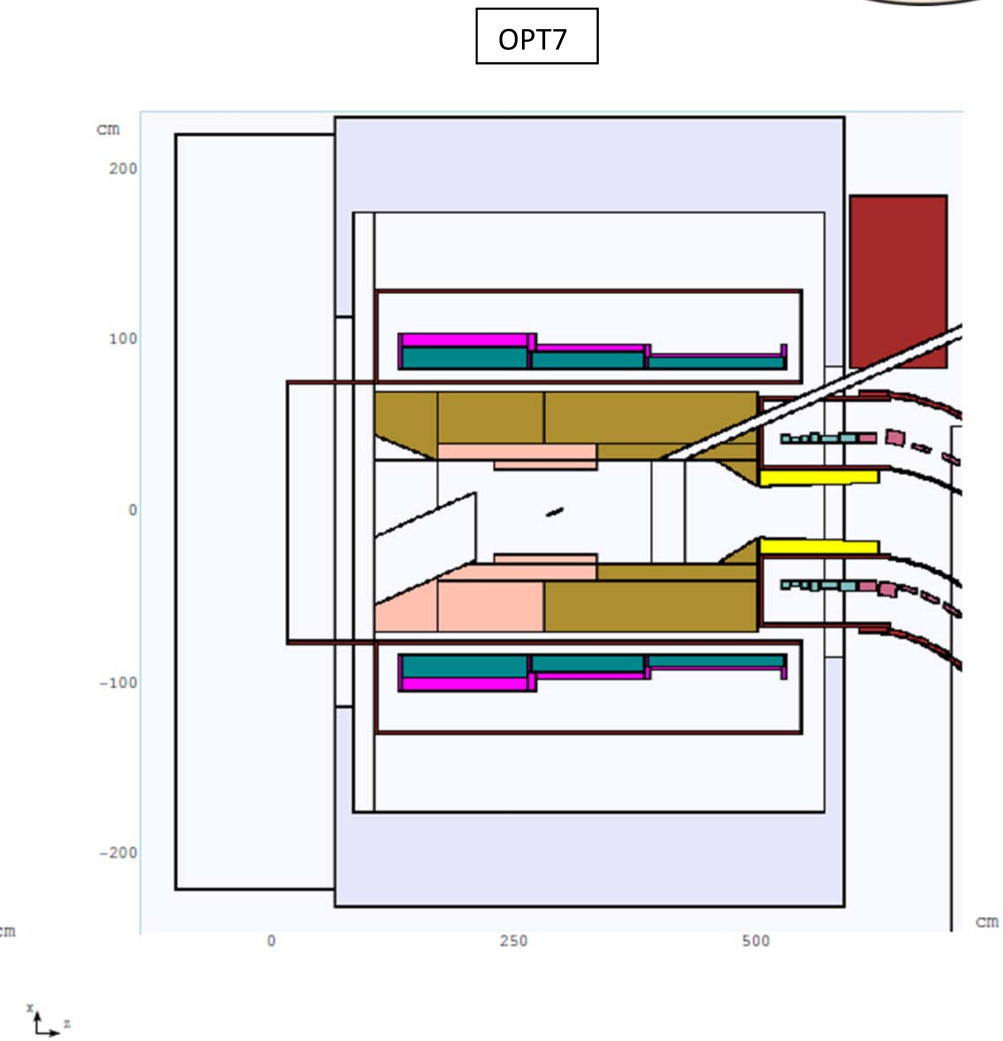
baseline



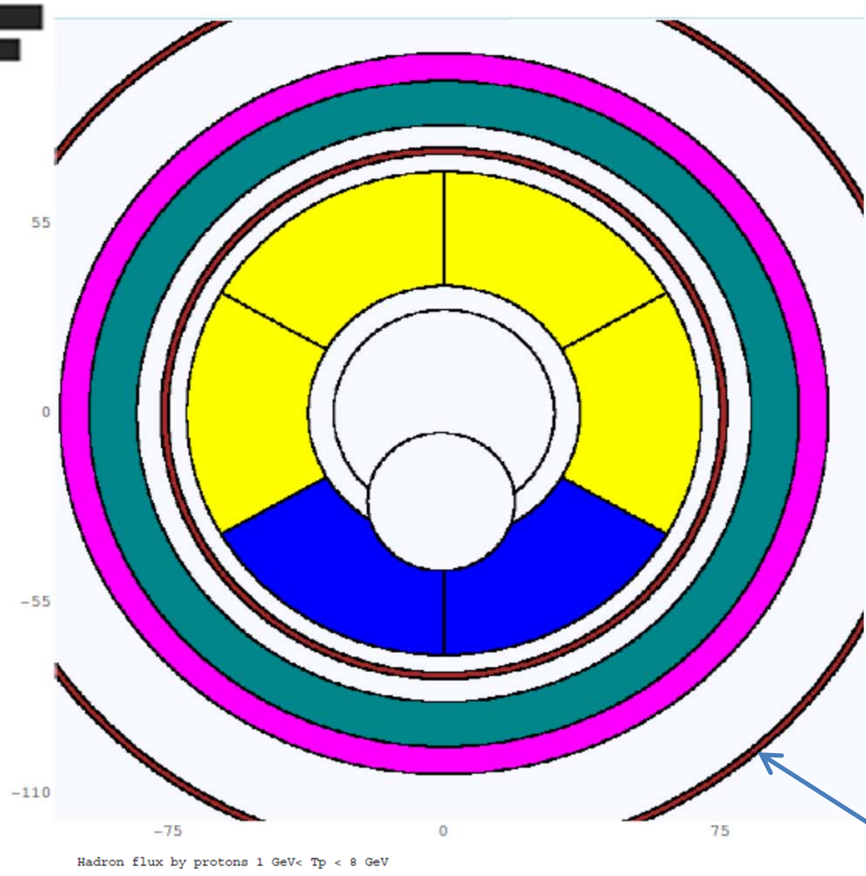
Blue – tungsten, yellow - copper

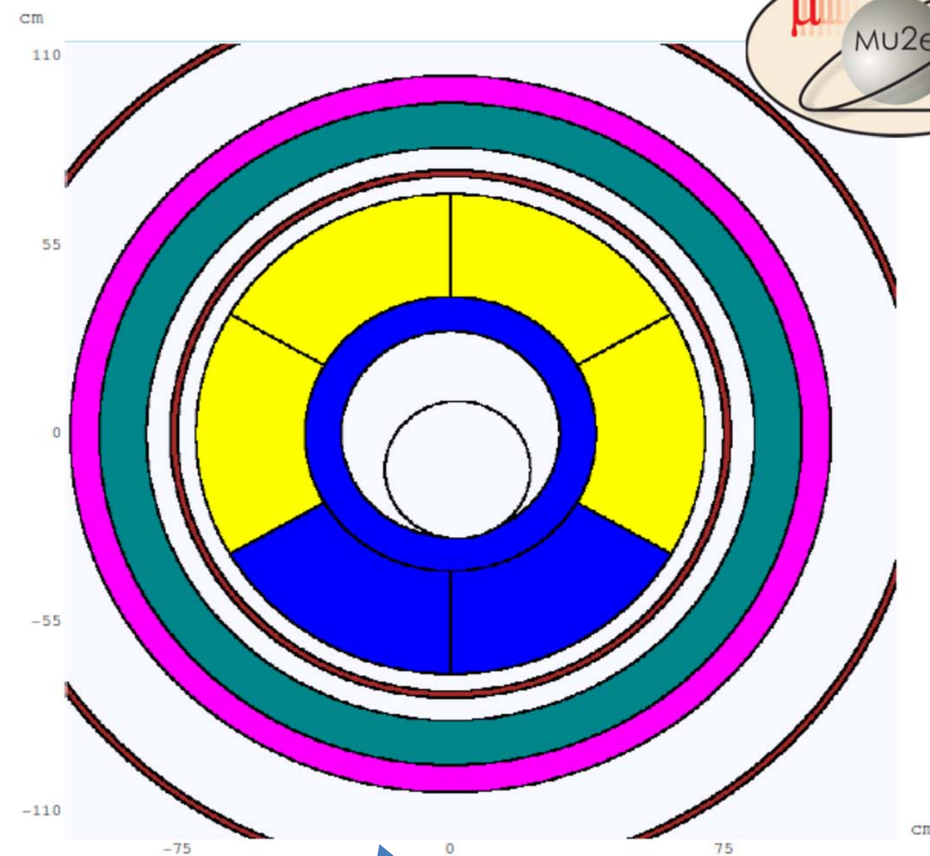
Amount of tungsten: optimization-2

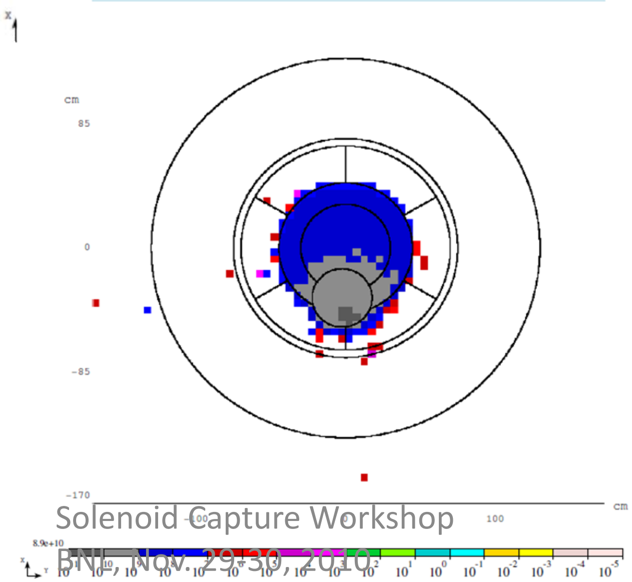


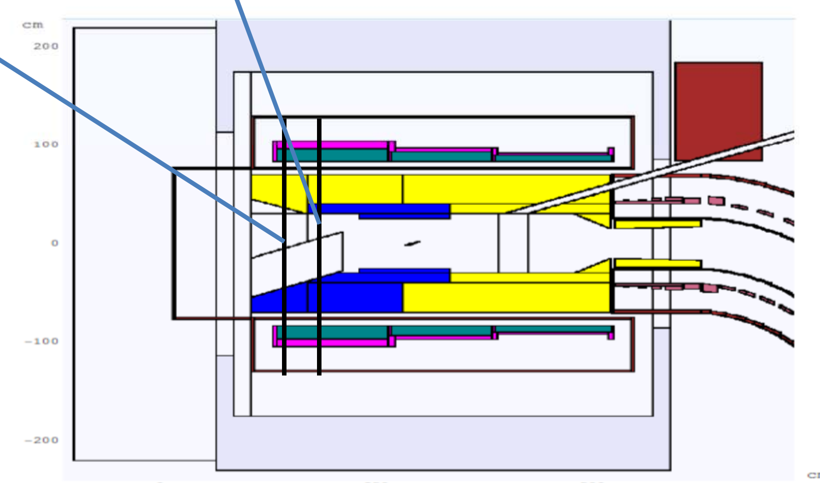


Pink – HEVIMET (90% W, 6% Ni, 4% Cu),
yellow – copper,
brown – high silicon bronze (97% Cu, 3% Si)



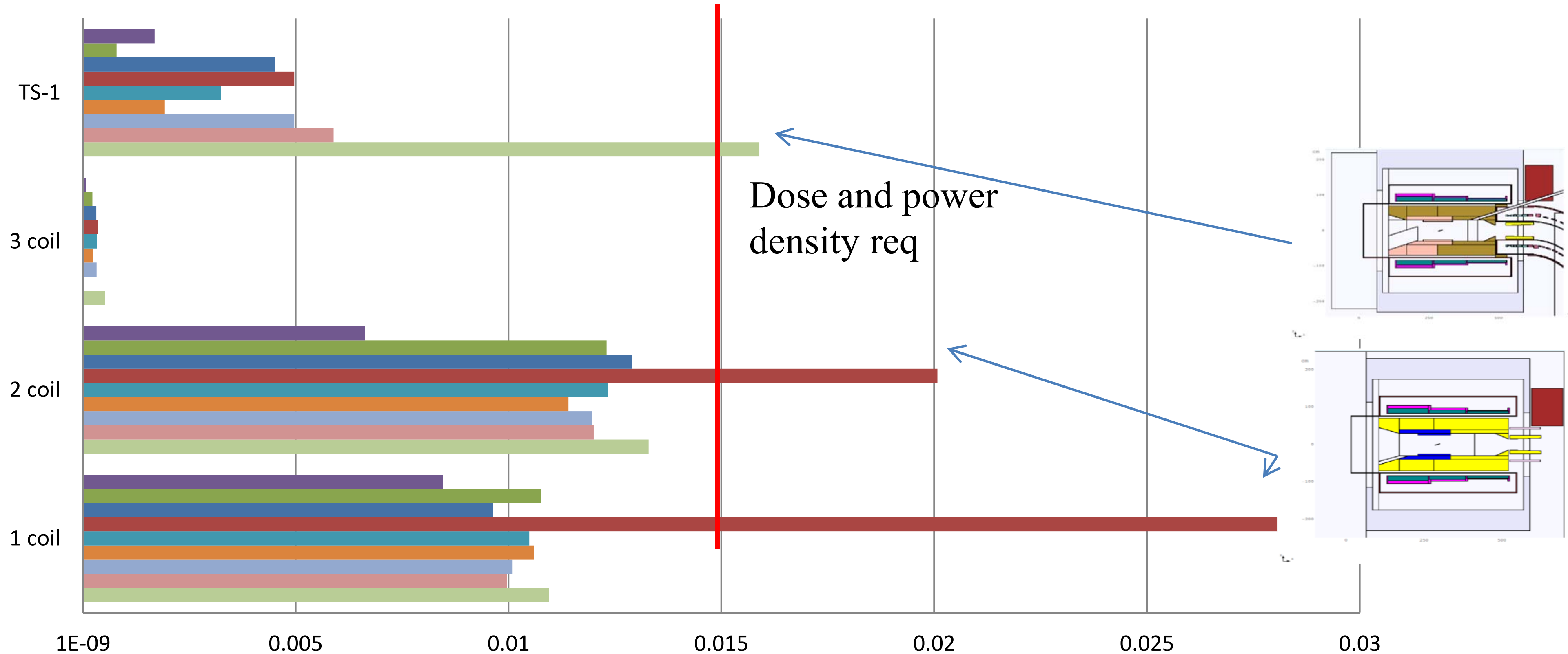






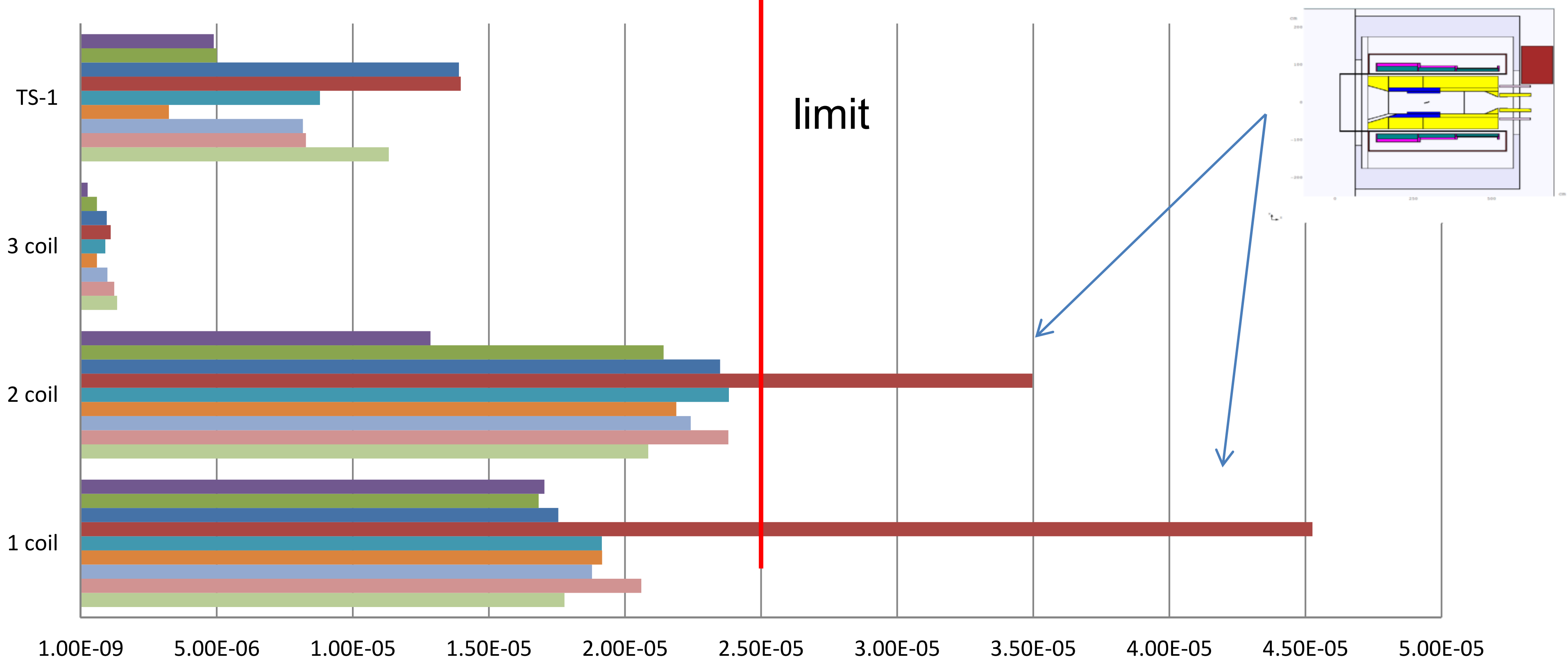
M (W)=20.3 tons
M(Cu)=37.5 tons

Power density, mW/g



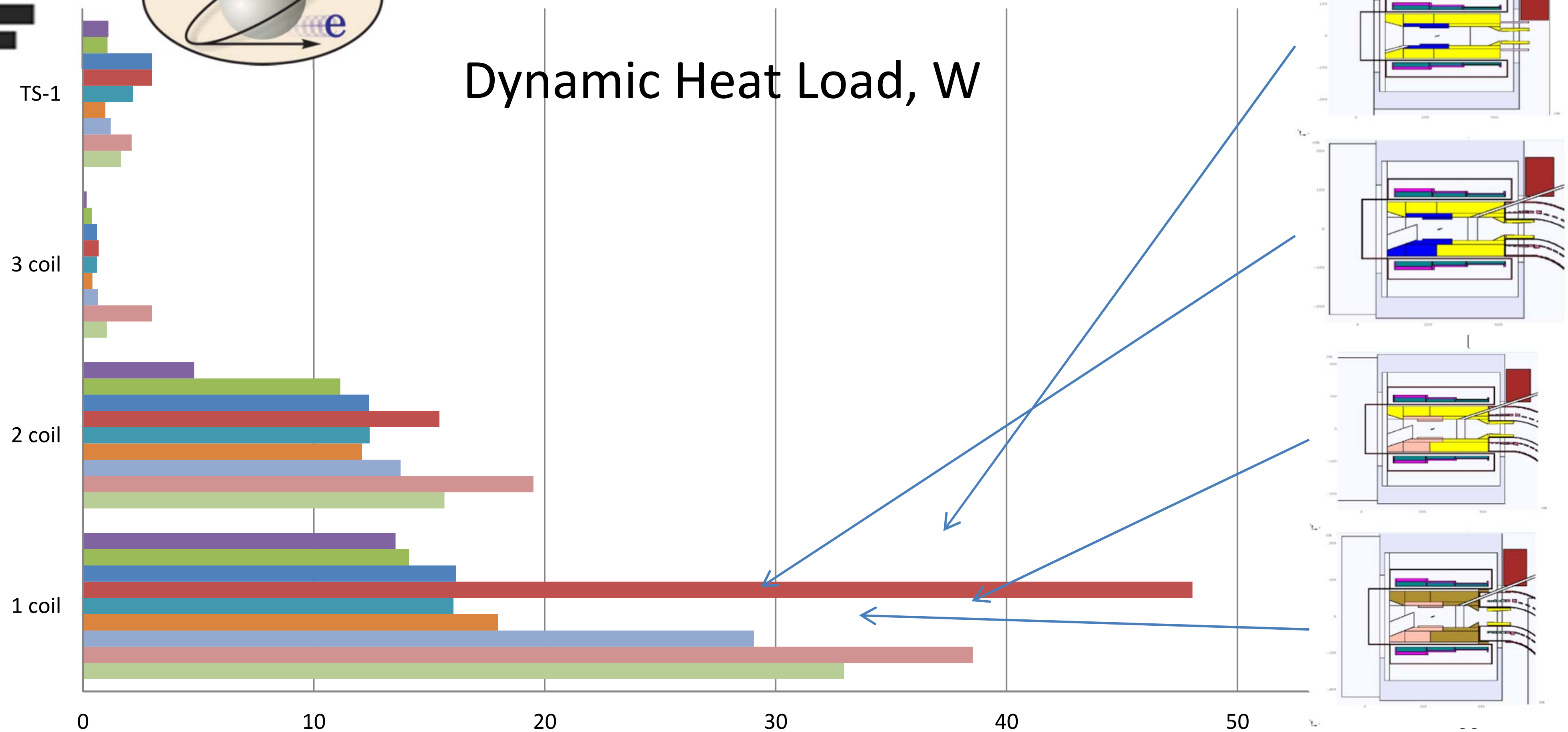
	1 coil	2 coil	3 coil	TS-1
Pure W	8.46E-03	6.62E-03	7.16E-05	1.69E-03
Baseline	1.08E-02	1.23E-02	2.26E-04	7.93E-04
OPT1	9.64E-03	1.29E-02	3.18E-04	4.51E-03
OPT2	2.84E-02	2.01E-02	3.49E-04	4.97E-03
OPT3	1.05E-02	1.23E-02	3.25E-04	3.24E-03
OPT4	1.06E-02	1.14E-02	2.35E-04	1.93E-03
OPT5	1.01E-02	1.20E-02	3.23E-04	4.97E-03
OPT6	0.00996	0.012		0.00589
OPT7	0.010948	0.013294	0.000527252	0.015893

DPA, yr^-1



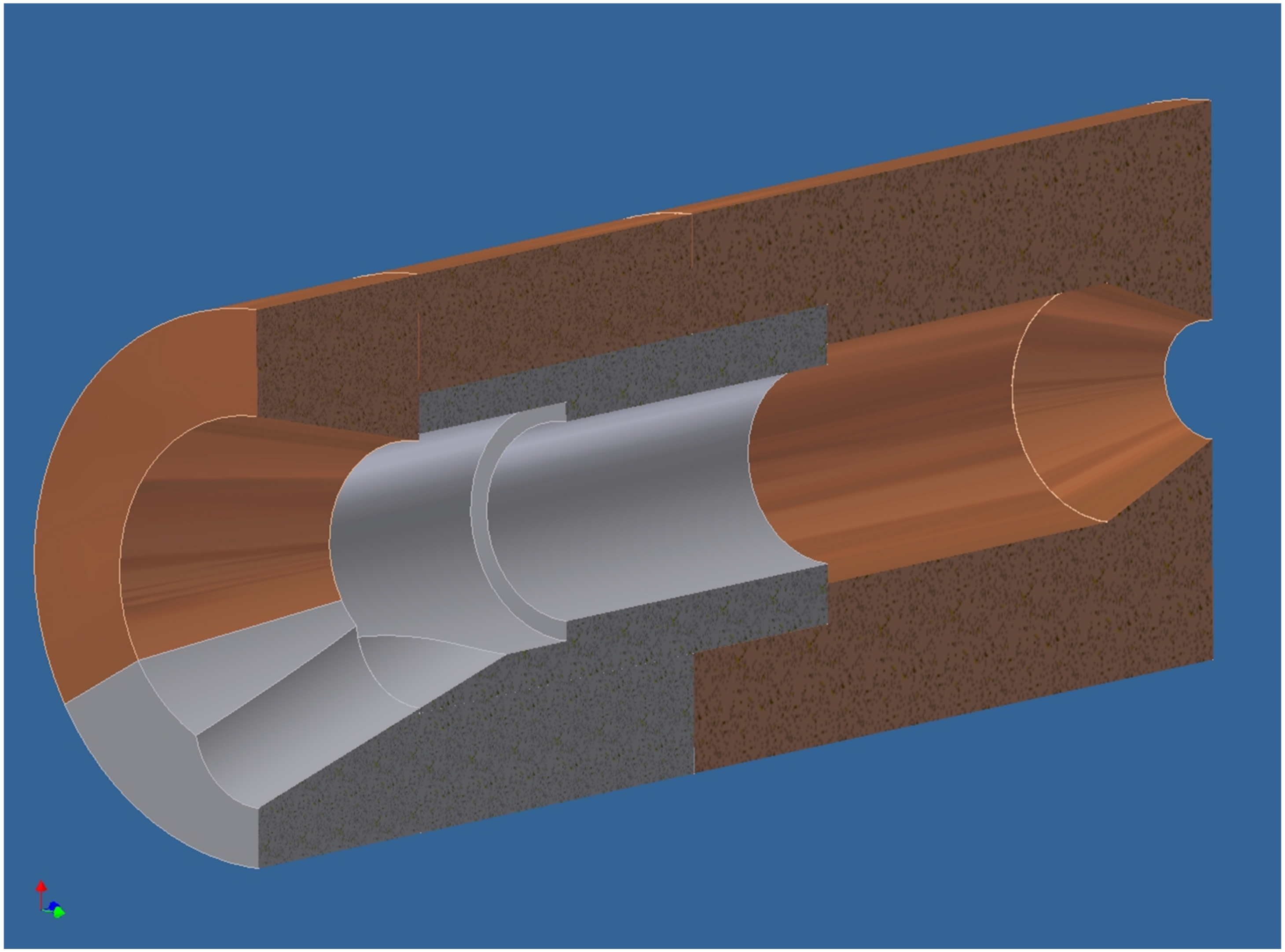
	1 coil	2 coil	3 coil	TS-1
Pure W	1.70E-05	1.29E-05	2.58E-07	4.89E-06
Baseline	1.68E-05	2.14E-05	6.00E-07	5.00E-06
OPT1	1.76E-05	2.35E-05	9.63E-07	1.39E-05
OPT2	4.53E-05	3.50E-05	1.10E-06	1.40E-05
OPT3	1.92E-05	2.38E-05	9.10E-07	8.79E-06
OPT4	1.92E-05	2.19E-05	6.02E-07	3.25E-06
OPT5	1.88E-05	2.24E-05	9.84E-07	8.17E-06
OPT6	2.06E-05	2.38E-05	1.23E-06	8.28E-06
OPT7	1.78E-05	2.09E-05	1.34E-06	1.13E-05

Capital cost vs operational cost are trade off



	1 coil	2 coil	3 coil	TS-1
Pure W	13.53826	4.8221639	0.16466505	1.12585
Baseline	14.13258	11.1458069	0.393369	1.09112
OPT1	16.15911	12.39033	0.6126027	3.0153
OPT2	48.05551	15.437393	0.6848526	3.0038
OPT3	16.0517	12.422668	0.6022366	2.16982
OPT4	17.9745	12.0898212	0.4153386	0.9710945
OPT5	29.06418	13.760463	0.6564683	1.201957
OPT6	38.550	19.516	3.002	2.117
OPT7	32.97004	15.660309	1.0301861	1.650549

Towards Engineering Design

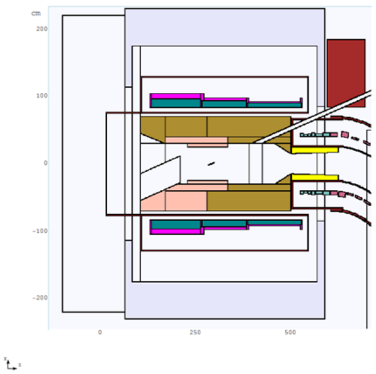


Gray – HEVIMET, brown – bronze

by L.Bartoszek based on MARS15 model

Conclusions-1

- Compact (Mu2e) shielding has advantages (DPA etc.) compared to the MECO one
- As a result of optimization, a combination of tungsten-based and copper-based alloys was selected as the materials for the absorber



- Analysis of $WC+H_20$ for the absorber showed that its advantages are not so big in the case when the influence of other Production Solenoid surrounding structures is considered. While the neutrons below 1 MeV are better suppressed by the $WC+H_20$ absorber, tungsten performs better at high energies (100s MeV) which dominate DPA and power density.

Conclusions-2

- While tungsten carbide with water better slows down neutrons compared to pure tungsten (with neutron flux after WC absorber being significantly lower), WC as having smaller than W its effective Z, stops charged particles worse. As a result, more abundant in the WC absorber charged particles make the effect of decrease in DPA not so evident, while give more rise to the peak power density than neutrons.
- Proposed optimized absorber satisfies the DPA, power density and absorbed dose requirements (although close to the limits), whereas the simple W/Cu version seems to be more safe, especially from the point of view of thermal analysis