Mu2e Production Solenoid MARS15 Studies: Update

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June 3, 2010
Fermilab

Outline

- Issues in the Mu2e production solenoid:
  - SC in radiation field, Power Density, Cryo $
  - Al resistance and lifetime vs flux at cryo temperatures
  - Cost of W ($7.5 M)
- DPA modeling in MARS15
- W absorber study
- Comparative study of W and WC absorbers (Dependence on presence of other structures):
  - Neutron flux ratio
  - DPA ratio, Power Density ratio
  - Neutron lethargy
- Multilayer absorbers: W + SS(Cu, C) + BCH2 + SS(Cd, Cu) + WC
  - Total Power Dissipation in cryo
  - Peak power density in the coils,
  - Peak neutron flux in the coils,
  - Peak DPA in the coils
- Conclusion

Residual resistivity ratio degradation

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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ISOCHRONAL RECOVERY OF FAST NEUTRON IRRADIATED METALS*

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Received 22 May 1973
Revised manuscript received 27 August 1973

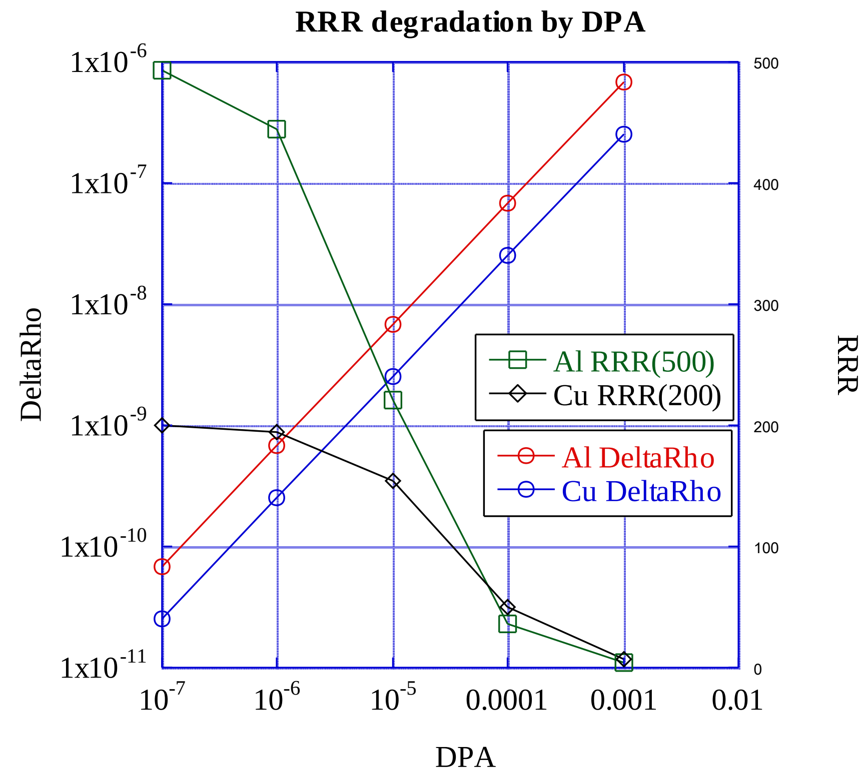
a) The values used for the resistivity per Frenkel pair are:

Element	Resistivity per Frenkel pair, $\rho_{F.P.}$ (10^{-4} Ω · 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.

Experiment on Al (and Cu) is planned for October January at Osaka reactor in Japan, Φ≈1E21 at 10-20 K

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

Resistivity degradation (contd)

PHILLIP ALBERT SANGER

A STUDY OF RESISTIVITY INDUCED BY 400 GeV PROTONS IN COPPER AND ALUMINUM

TABLE VIII

SUMMARY OF 400 GeV PROTON INDUCED RESISTIVITY CHANGES

Run	Sample Diameter (cm)	$\Delta\rho_{measured}$ (10^{-9} $\Omega\cdot$cm)	Dose ϕt (10^{16} p/cm^2)	$d\rho/d\phi t$ (Ωcm/p/cm^2)	$\sigma_d\phi$ 10^{-8} Displacements per atom per sec
	Copper				
5	.0254	8.95	2.50	3.58	2.4
6,7,8,9	.0254	44.6	13.4	3.33	~13
11,12	.0254	10.43	3.15	3.31	~13
10	.064	8.09	2.43	3.33	~13
	Aluminum				
14	.0254	5.21	3.50	1.49	~ 3

The close similarities between 400 GeV proton damage with fission neutron damage open up many possibilities of simulating the high damage rates of fusion reactors.

1. The resistivity increase due to 400 GeV protons in copper has been found to be $3.6\pm.2\times10^{-25}$ $\Omega\cdot$cm per proton per cm^2. For aluminum this value is $1.5\pm.1\times10^{-25}$ $\Omega\cdot$cm per proton per cm^2. These values allow for a ten year operation of a superconducting accelerator with loss levels comparable to present Fermilab synchrotron.(54)

Sanger:
Ip(max)=4E13 p/cm2/sec
7.5E-22 DPA/cm2/p

We:
Peak DPA=1.95E-5 yr^-1
In=5E16 n/cm2 yr^-1
3.9E-22 DPA/cm2/n

19 year operation? Al?

IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

RADIATION DAMAGE LIMITATIONS FOR THE FERMILAB ENERGY DOUBLER/SAVER

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DPA modeling in MARS15

Damage cross section:

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

E – projectile kinetic energy,
T – kinetic energy transferred to the recoil,
Td – displacement energy,
Tmax – highest (kinematic) energy,
Damage function:

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

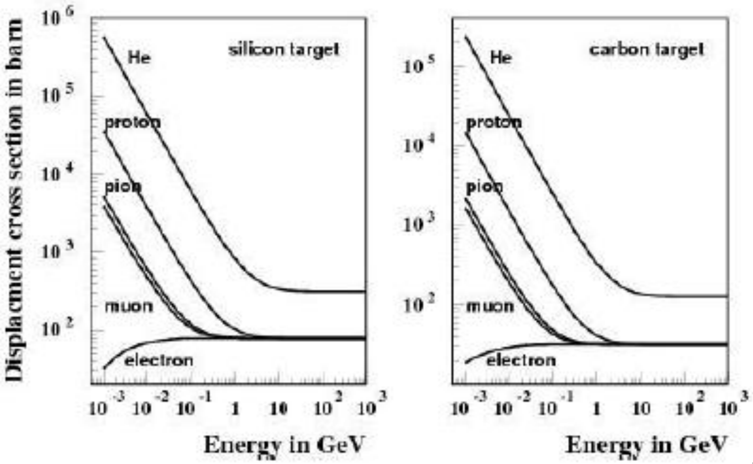
Ed – “damage” energy in elastic collision
Td – function of atomic number
k(T) – displacement efficiency (R.E.Stoller)

Kinchin-Pease model:

G.H. Kinchin, R.S. Pease, Rep. Prog. Phys., 18, 1 (1955).

Projectile energy 1 keV to 10 TeV

Primary knock-on atom (PKA) created in nuclear collisions can generate a cascade of atomic displacements.



DPA modeling (contd)

$$\frac{N_d}{N_0 t} = \int \sigma_d(E)\varphi(E)dE = \text{ DPA rate}$$

from MARS

particle flux

damage cross section

N_d - defects per unit volume, cm^{-3}

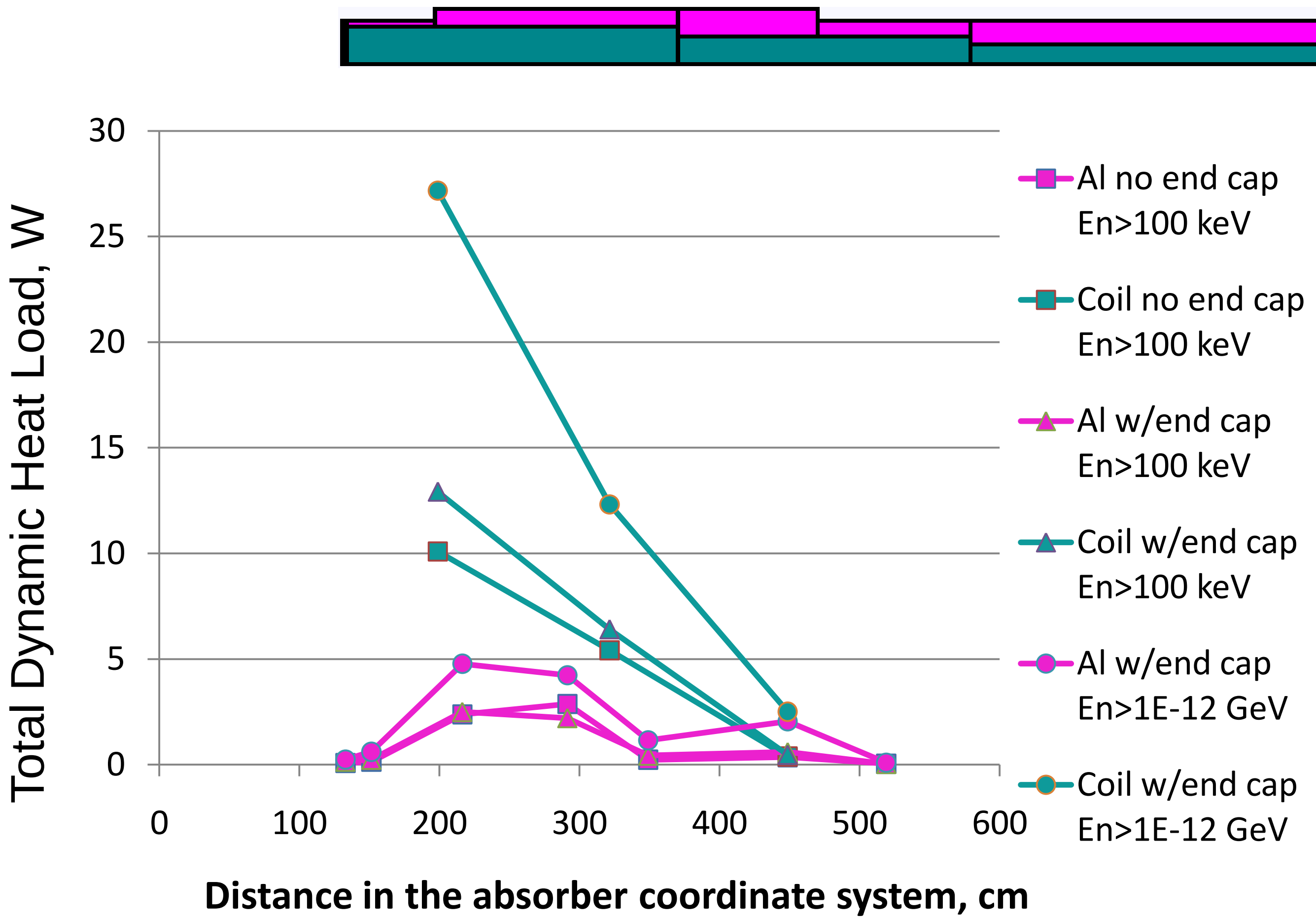
N_0 - atomic density, cm^{-3}

Example:

DPA rate on Al = 2.5E-5 yr^{-1} $\rho(Al) = 2.7 g / cm^3, A = 27 amu, N_0 = \frac{\rho}{A} N_A = 6E22\ at / cm^3$

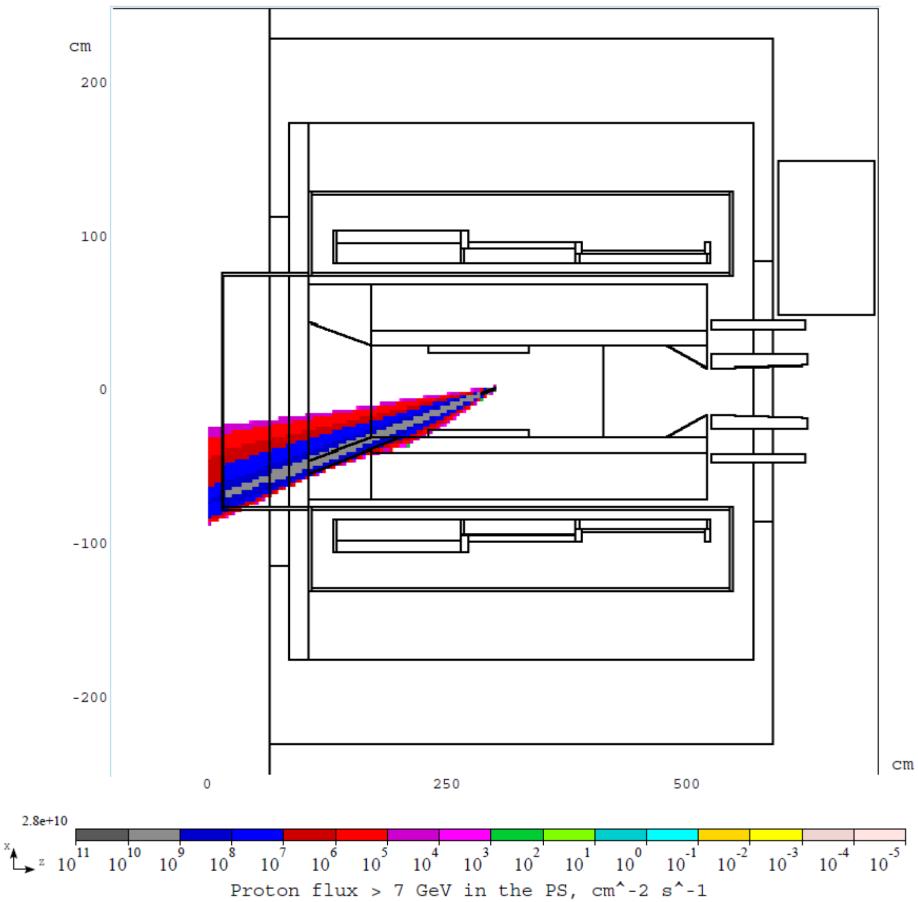
$N_d = 1.2E18$ displacements per cm^3 per year

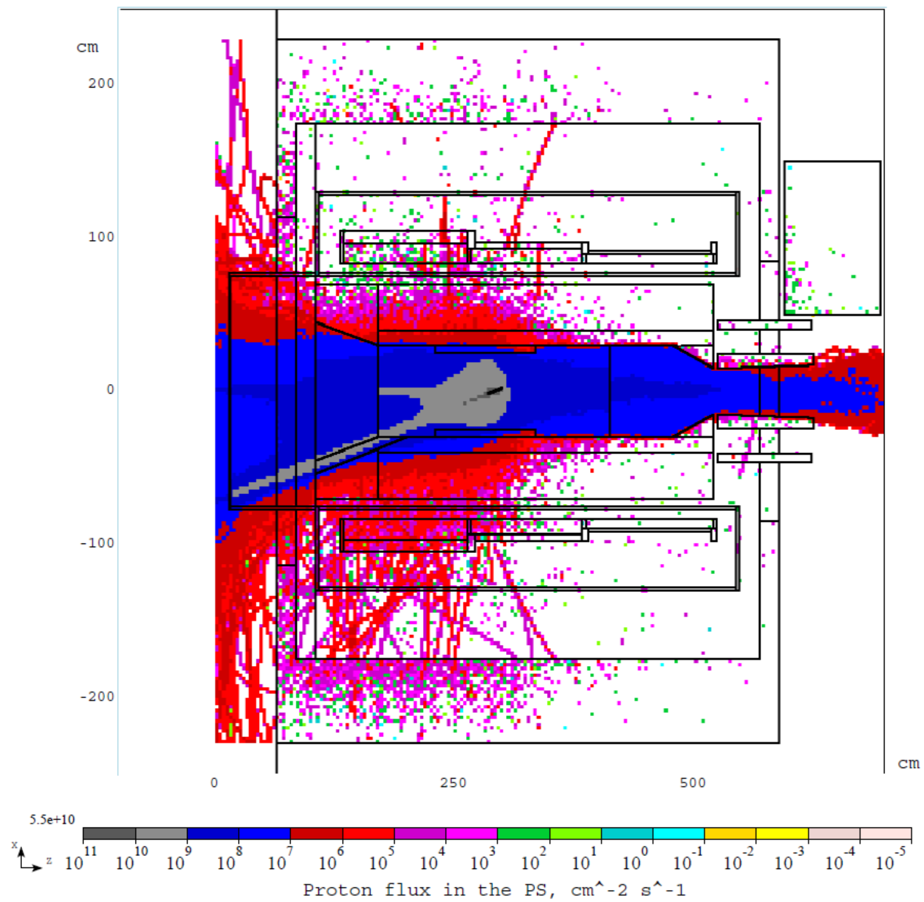
Dynamic HeatLoad (first design, role of the end caps and neutrons)



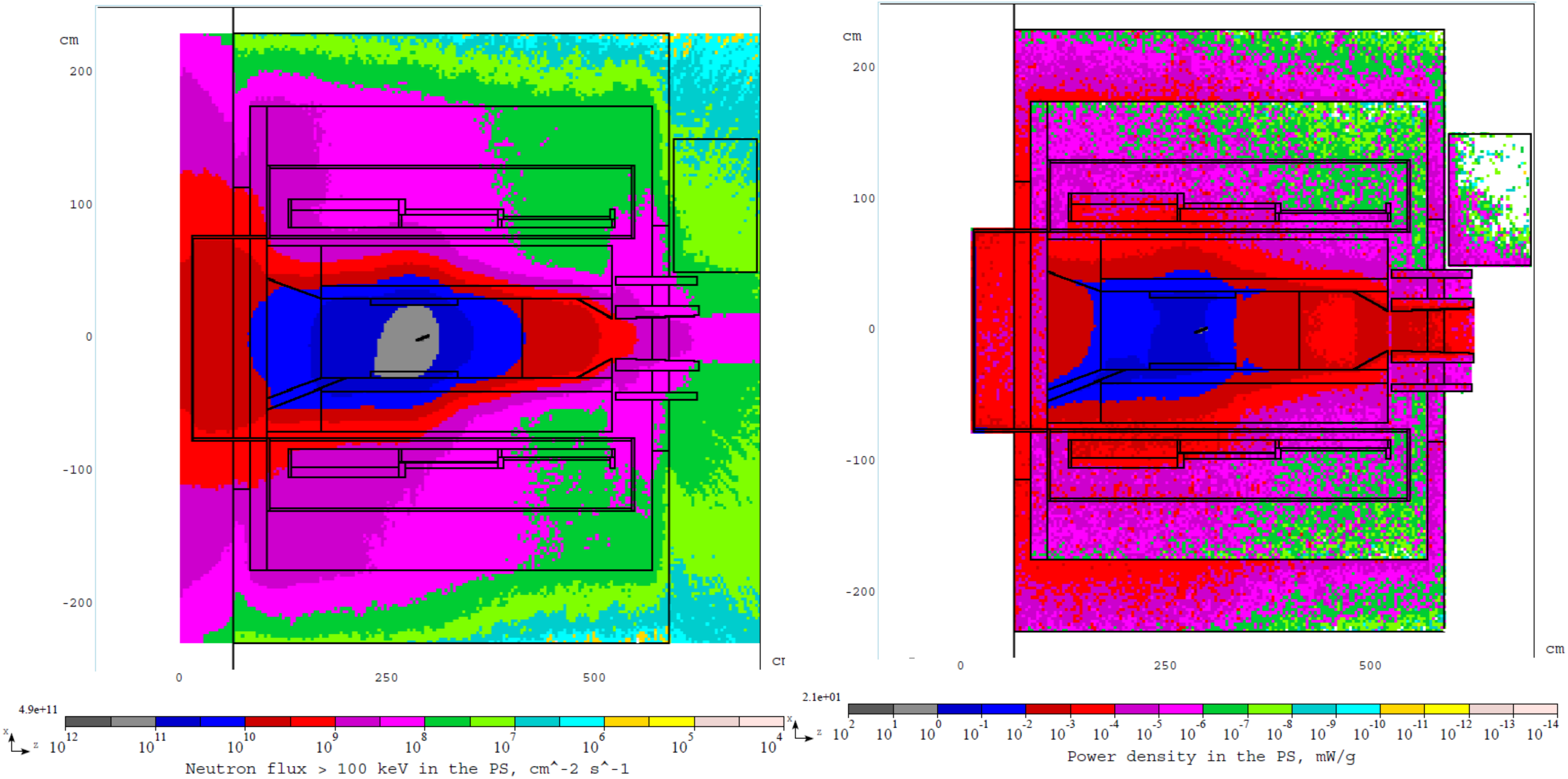
Results in the rest of the talk are with and En > 100 keV

Proton flux in PS



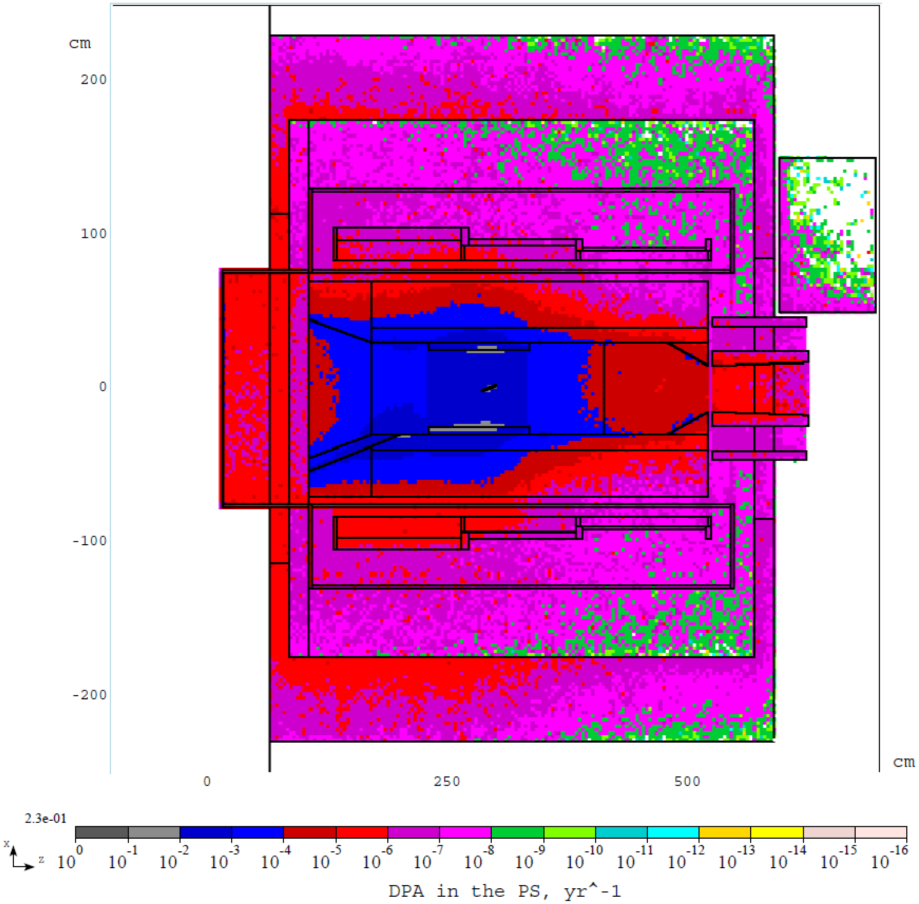


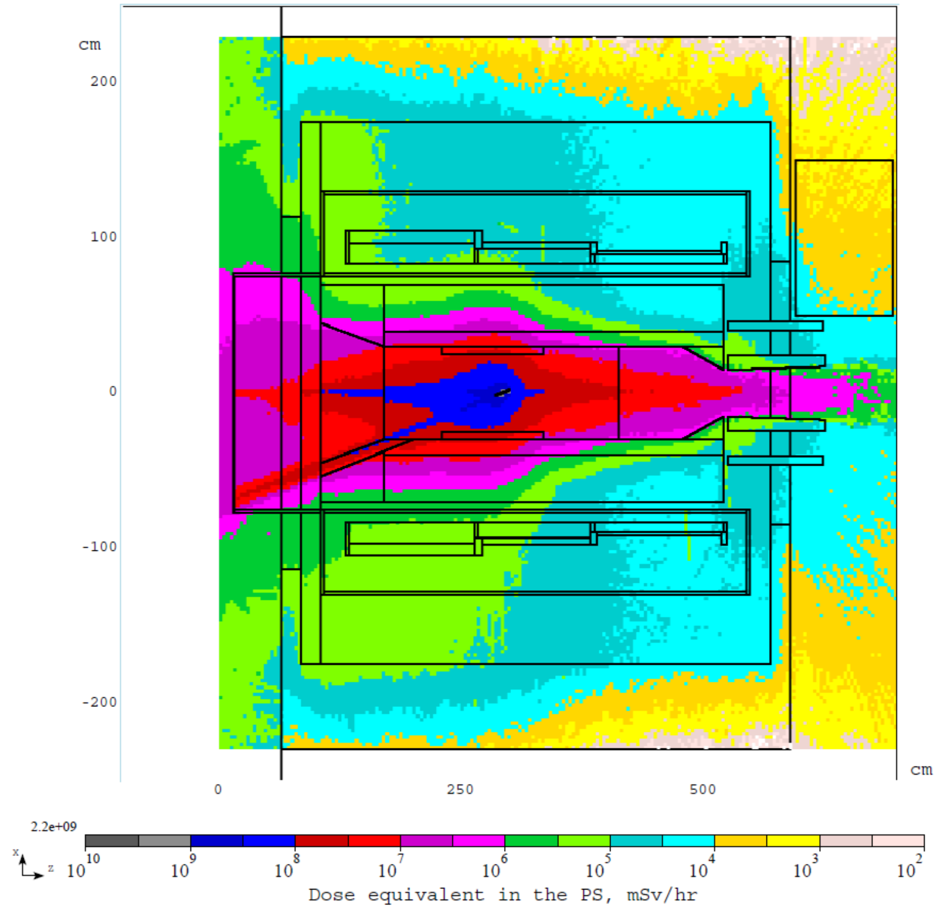
Neutron flux >100 keV and power deposition



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

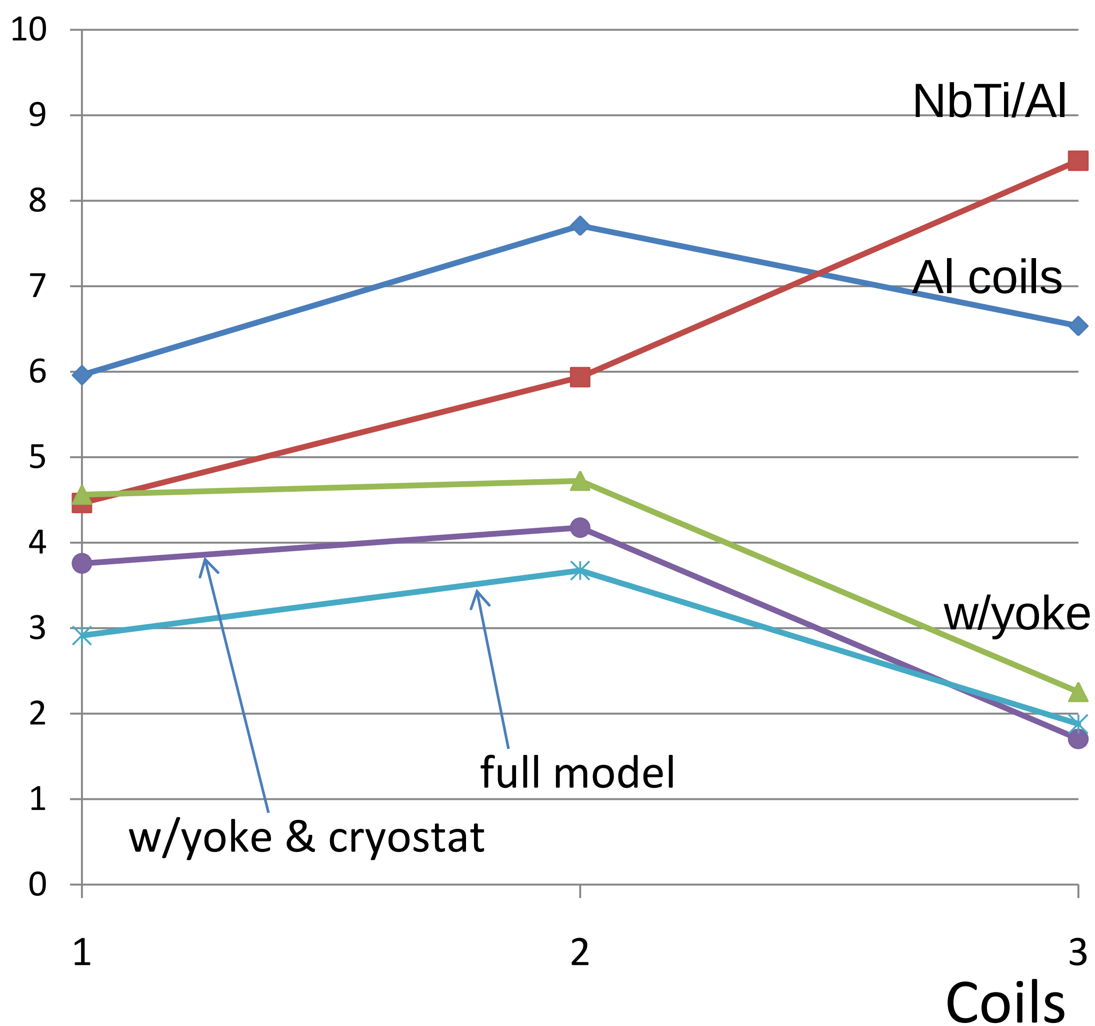
DPA and Prompt Dose

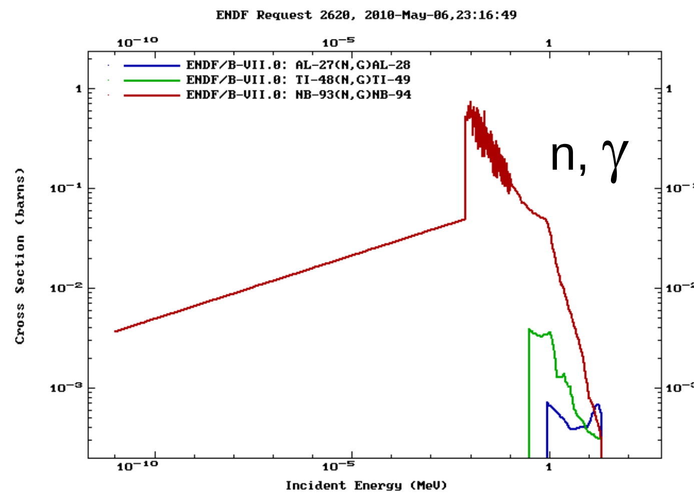


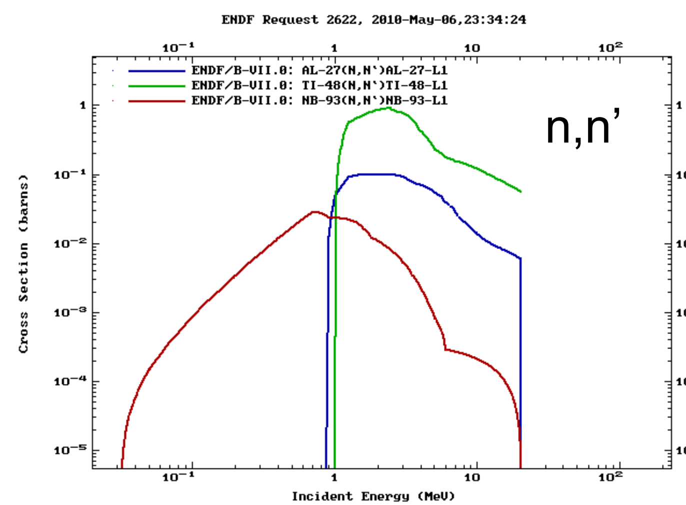


Need radiation shielding!!!

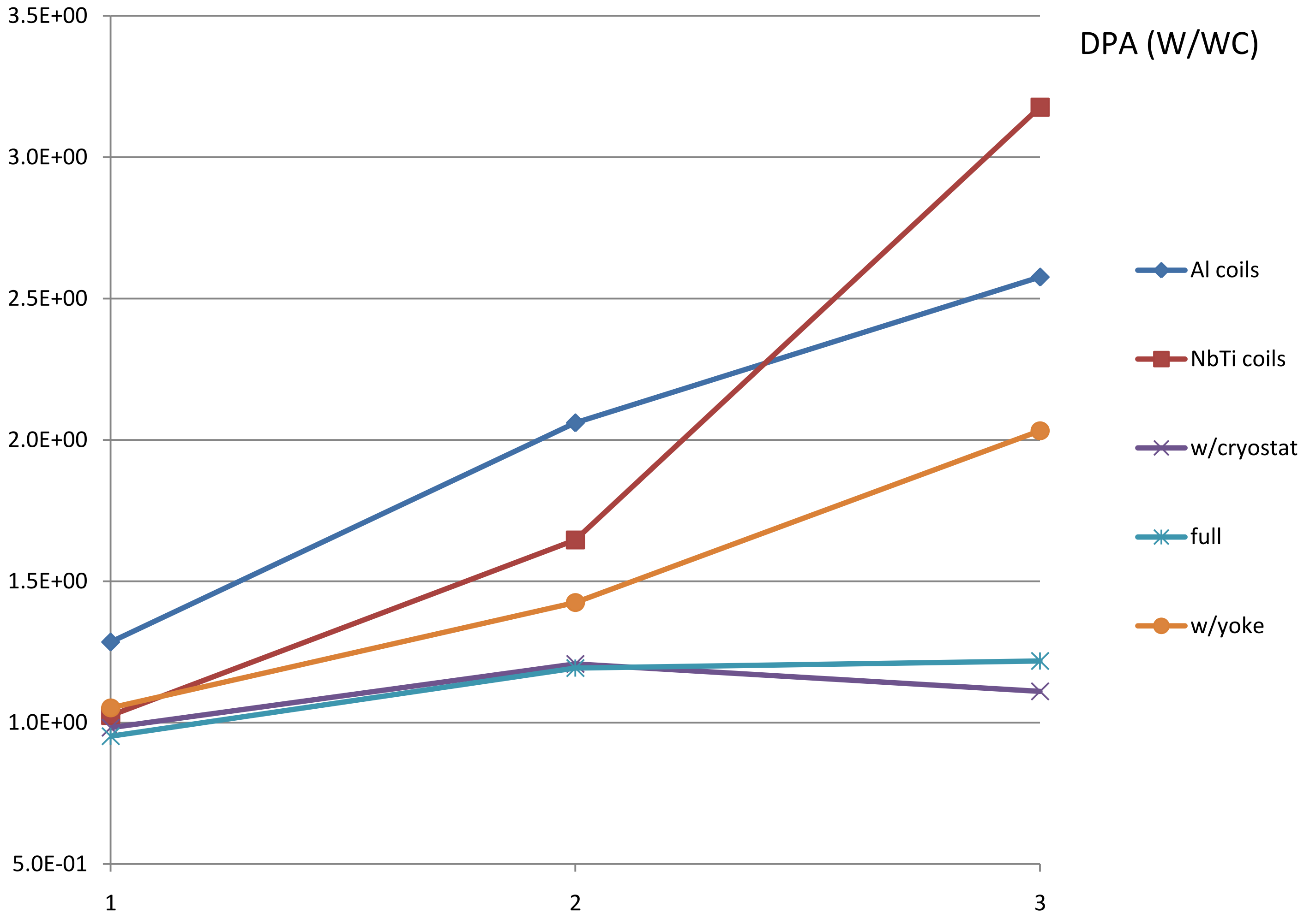
Neutron flux ratio for W/WC absorbers



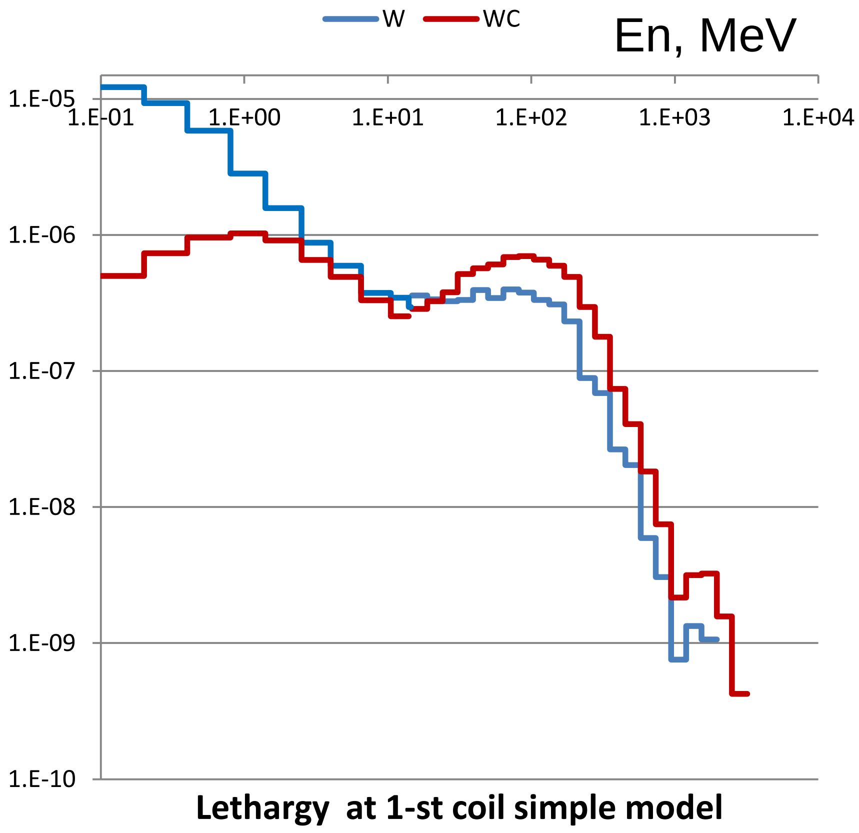


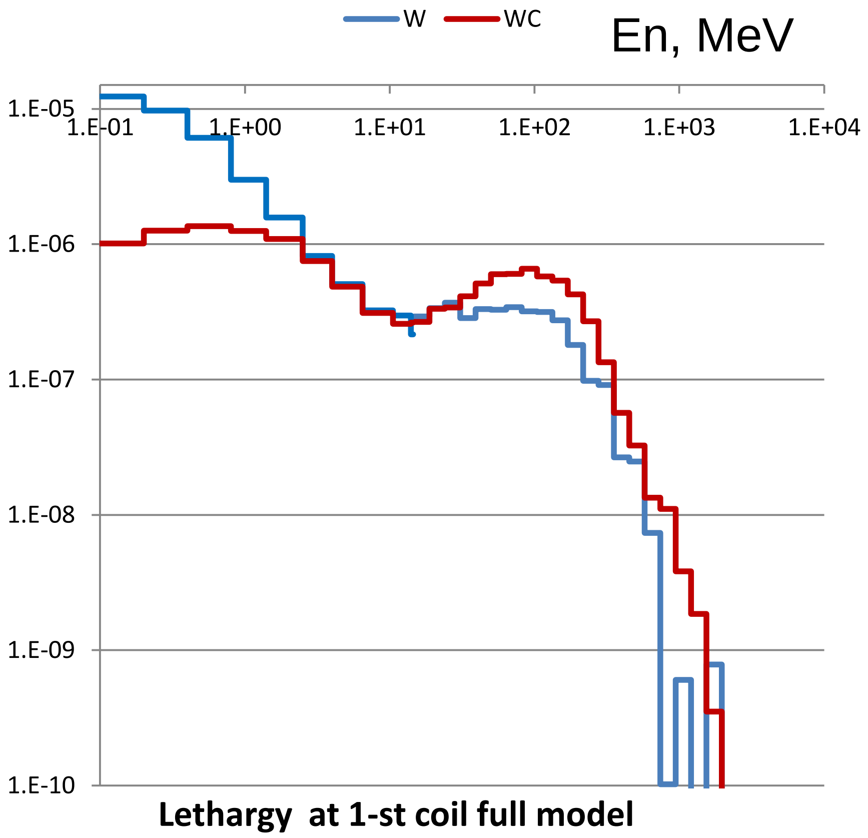


DPA ratio for W/WC absorbers



Neutron lethargies at 1-st coil



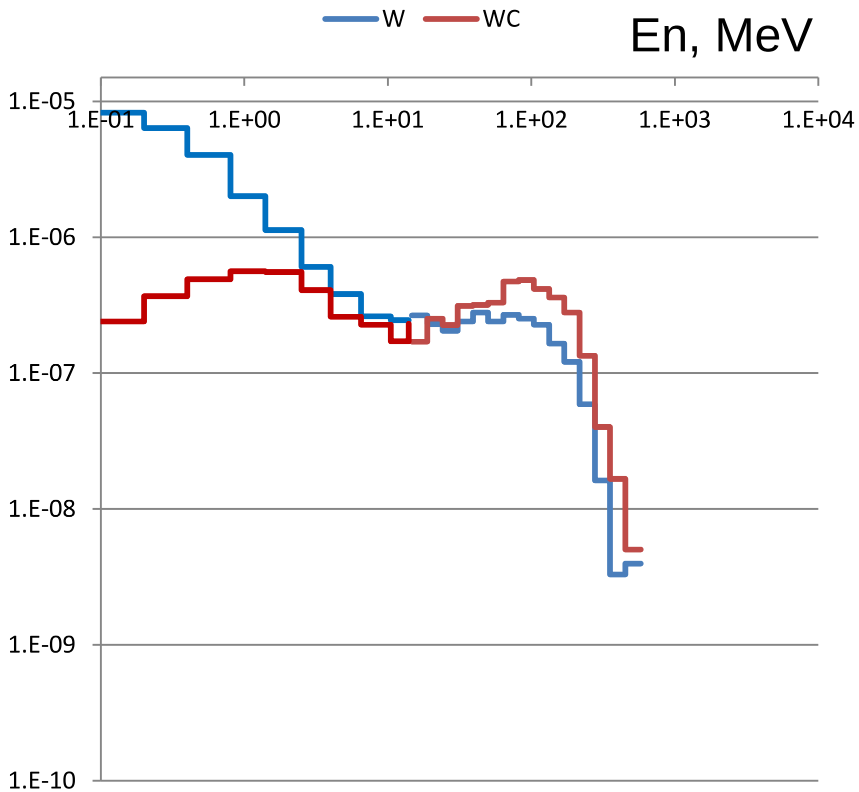


dF/d(ln E)

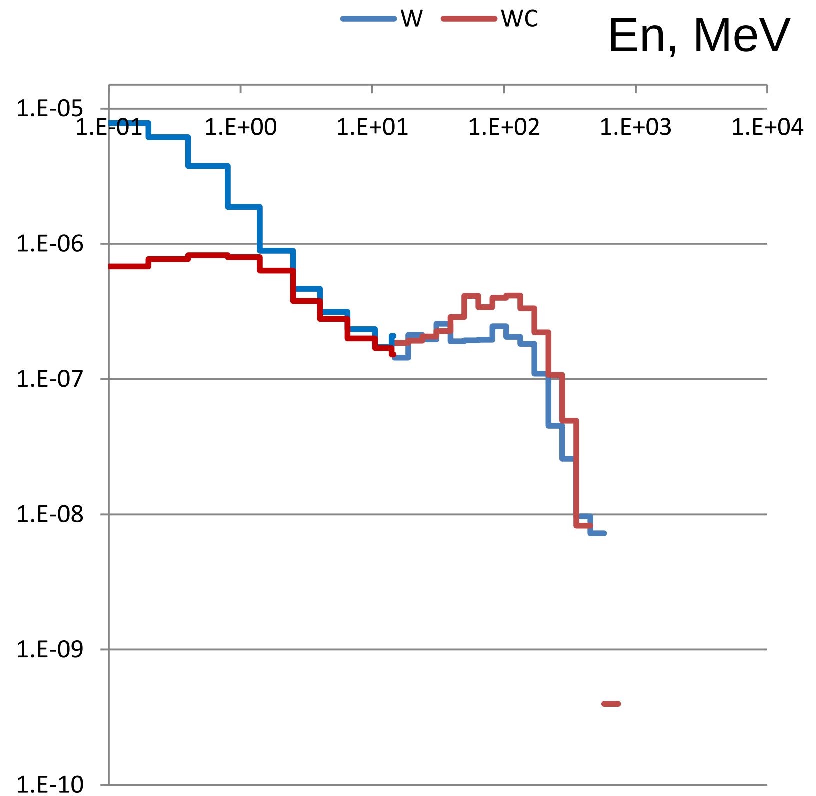
“Simple” model includes only the absorber and the coils

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

Neutron lethargies at 2-nd coil



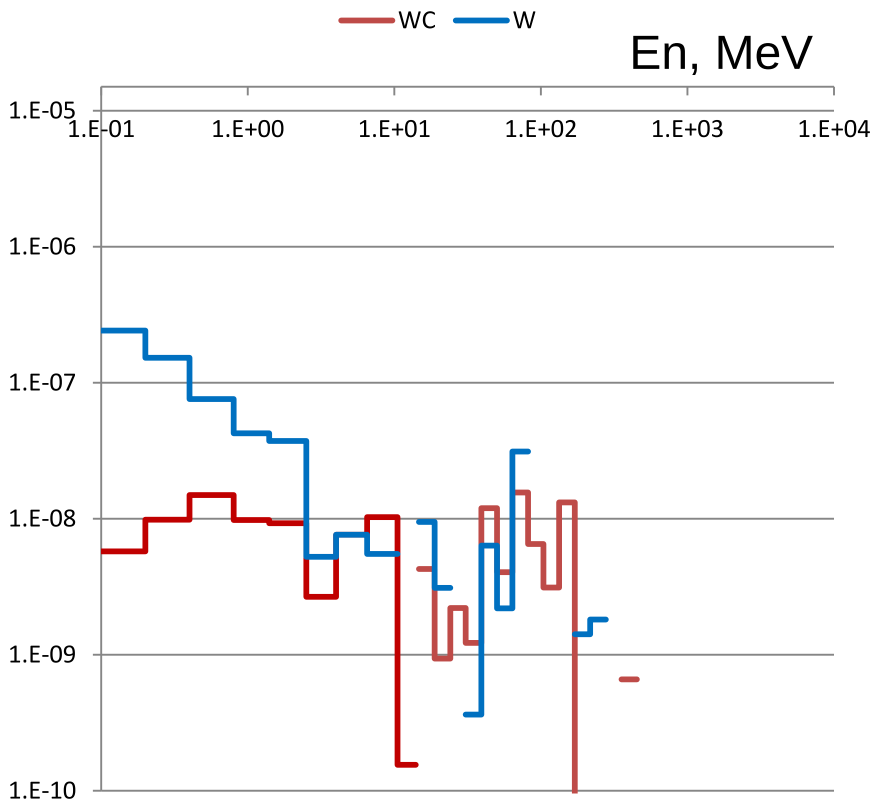
Lethargy at 2-nd coil simple model



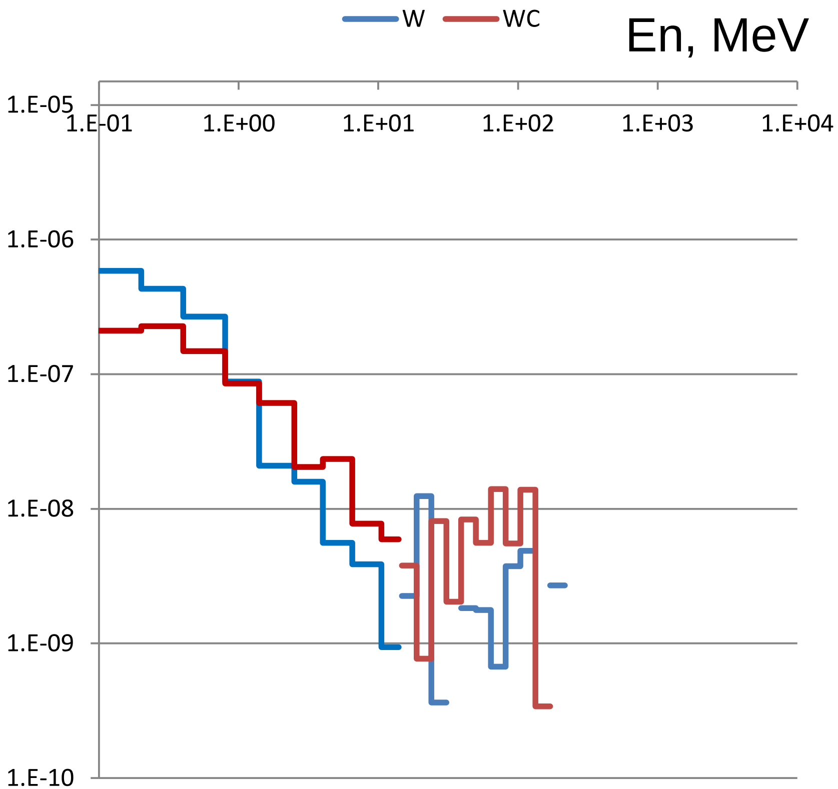
Lethargy at 2-nd coil full model

dF/d(ln E)

Neutron lethargies at 3-rd coil



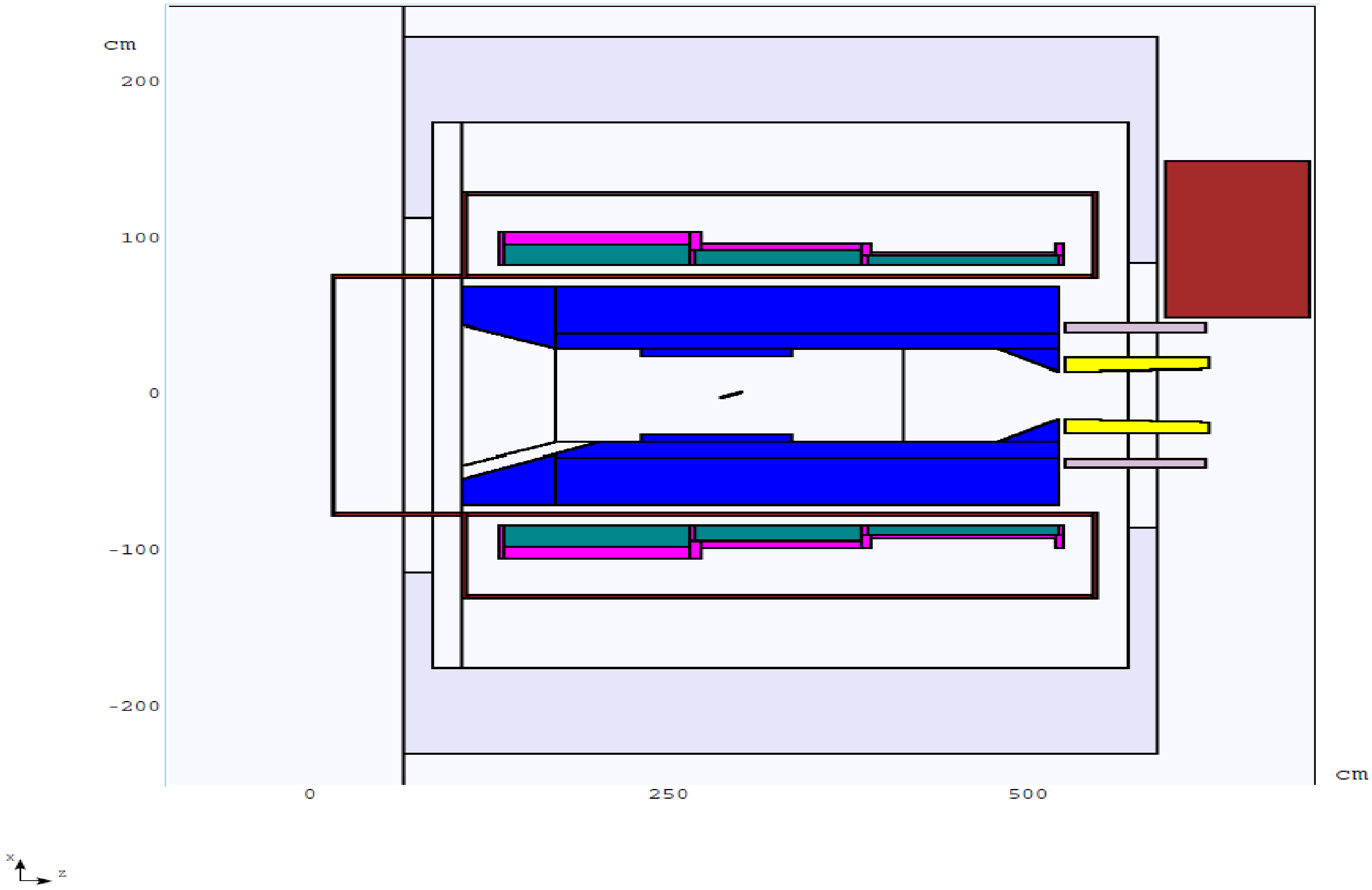
Lethargy at 3-rd coil simple model



Lethargy at 3-rd coil full model

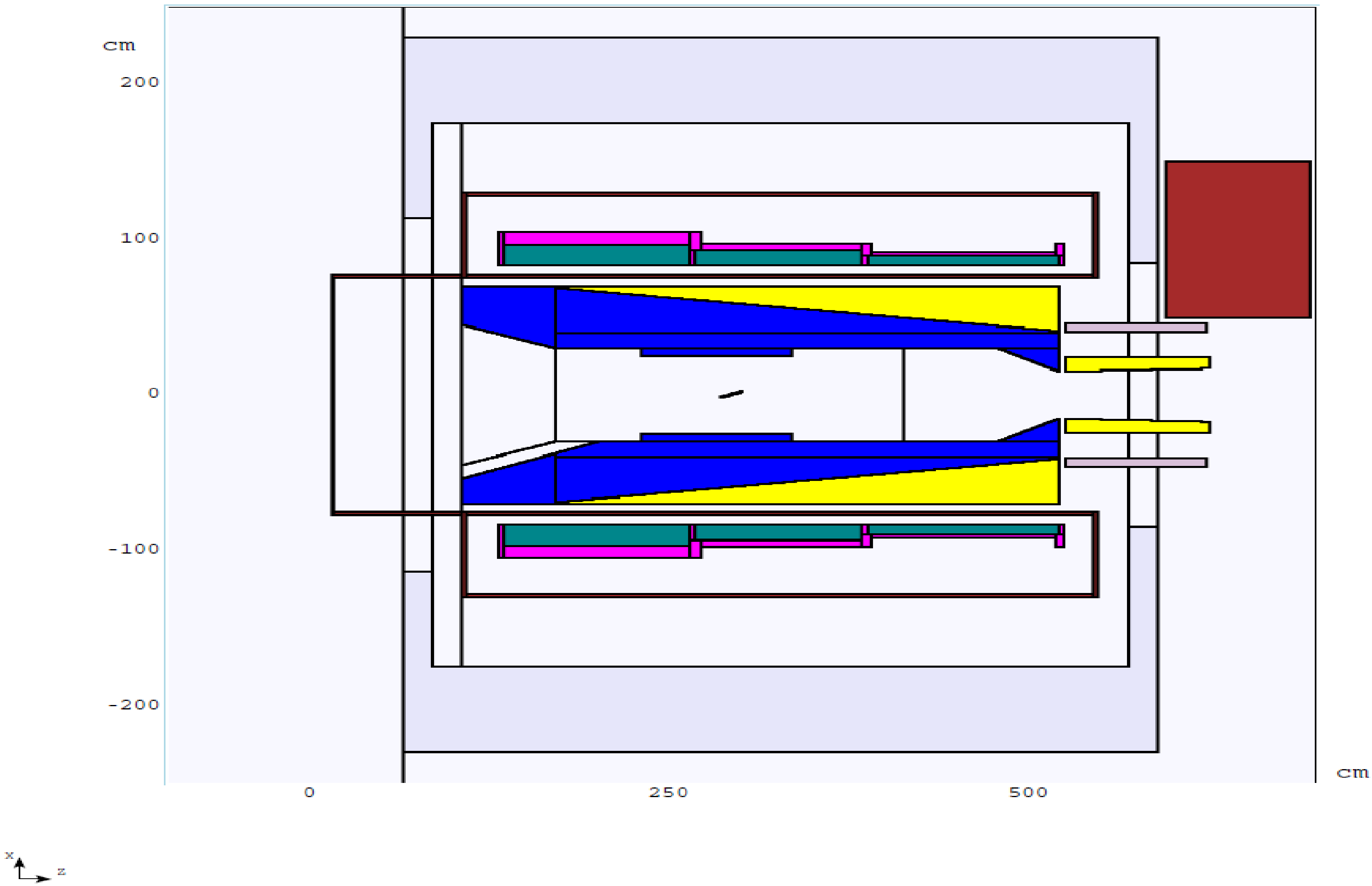
dF/d(ln E)

Mu2e PS: Tungsten Absorber (Case 1)



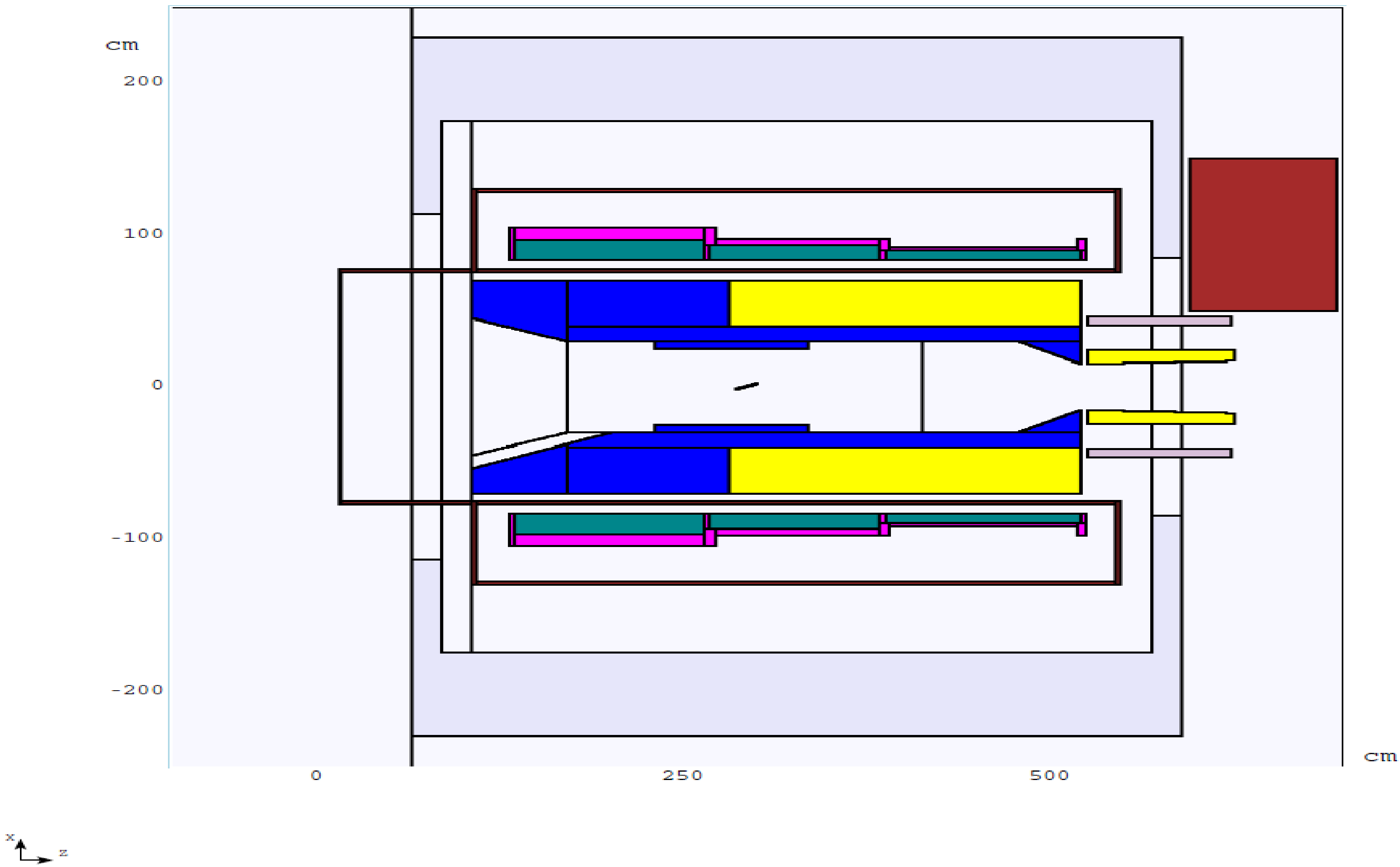
8 GeV proton beam, Au target (r=0.3 cm, H_20, Ti), 25 kW, I=2E13, $\sigma_x = \sigma_y$ = 1 mm

Mu2e PS: Tungsten/Copper Absorber (Case 2)



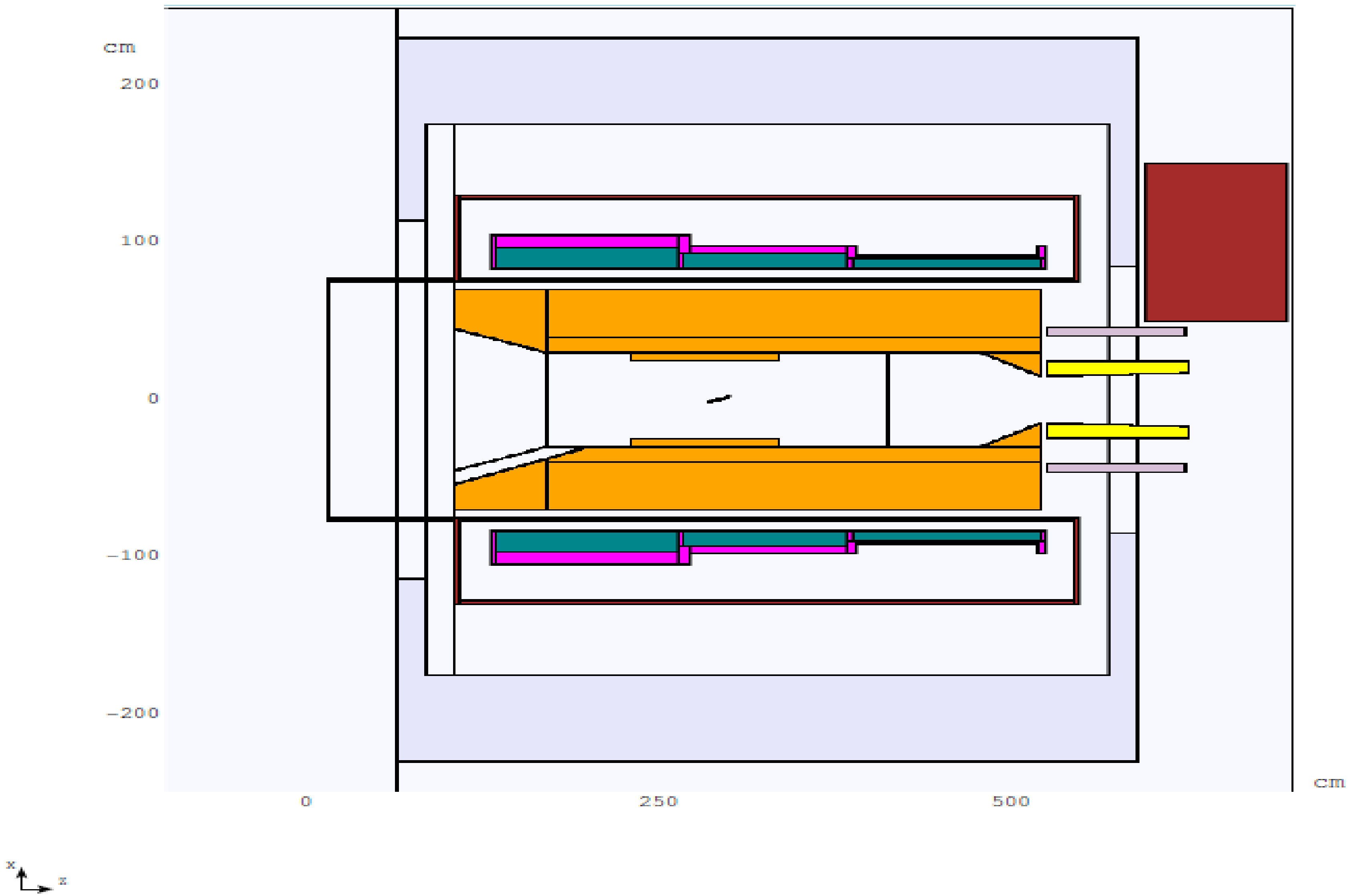
8 GeV proton beam, Au target (r=0.3 cm, H_20, Ti), 25 kW, I=2E13, $\sigma_x = \sigma_y = 1$ mm

Mu2e PS: Tungsten/Copper Absorber (Case 3)



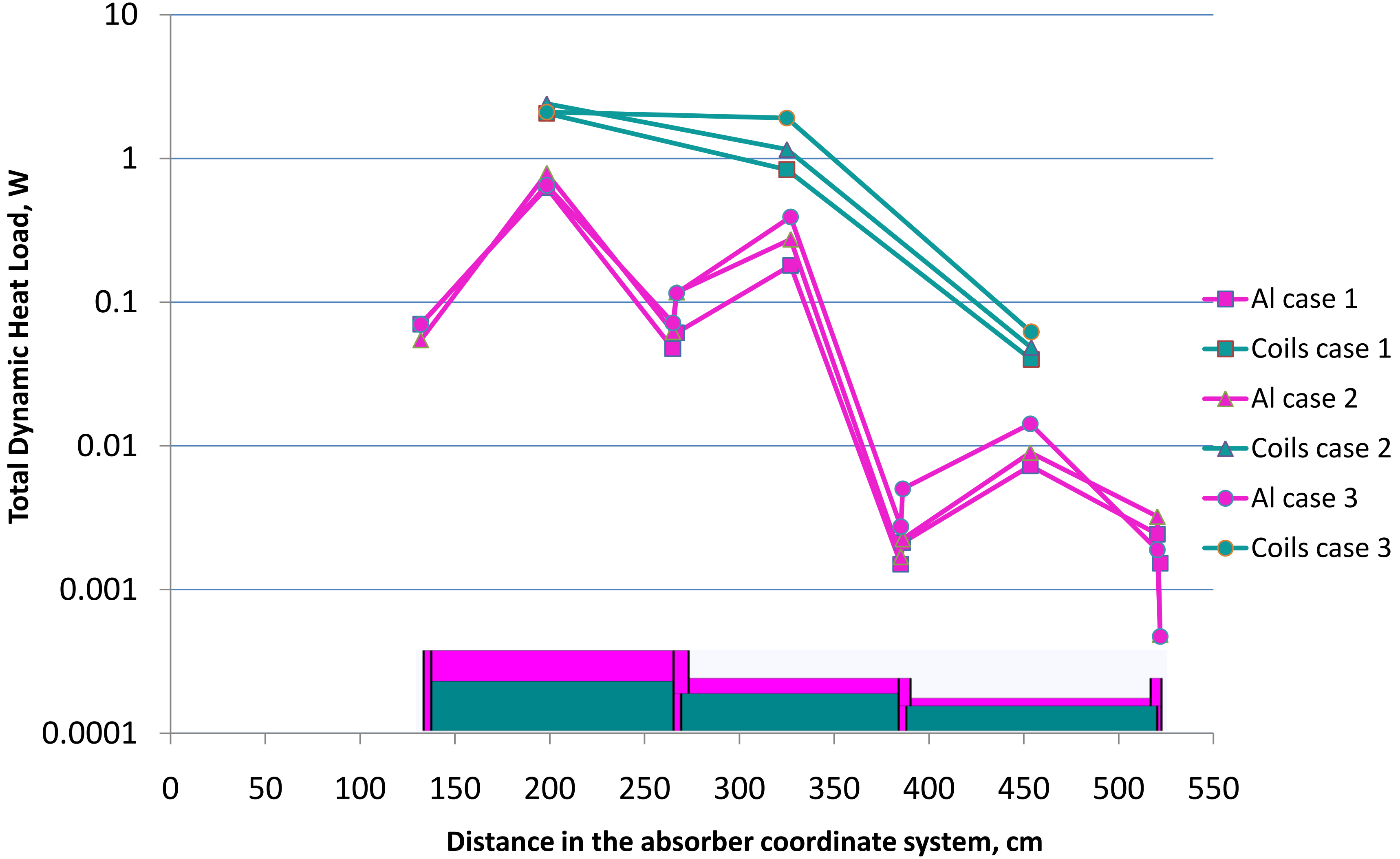
8 GeV proton beam, Au target (r=0.3 cm, $H_2 0$, Ti), 25 kW, I=2E13, $\sigma_x = \sigma_y$ = 1 mm

Mu2e PS: Tungsten Carbide + H_2O Absorber (Case 4)

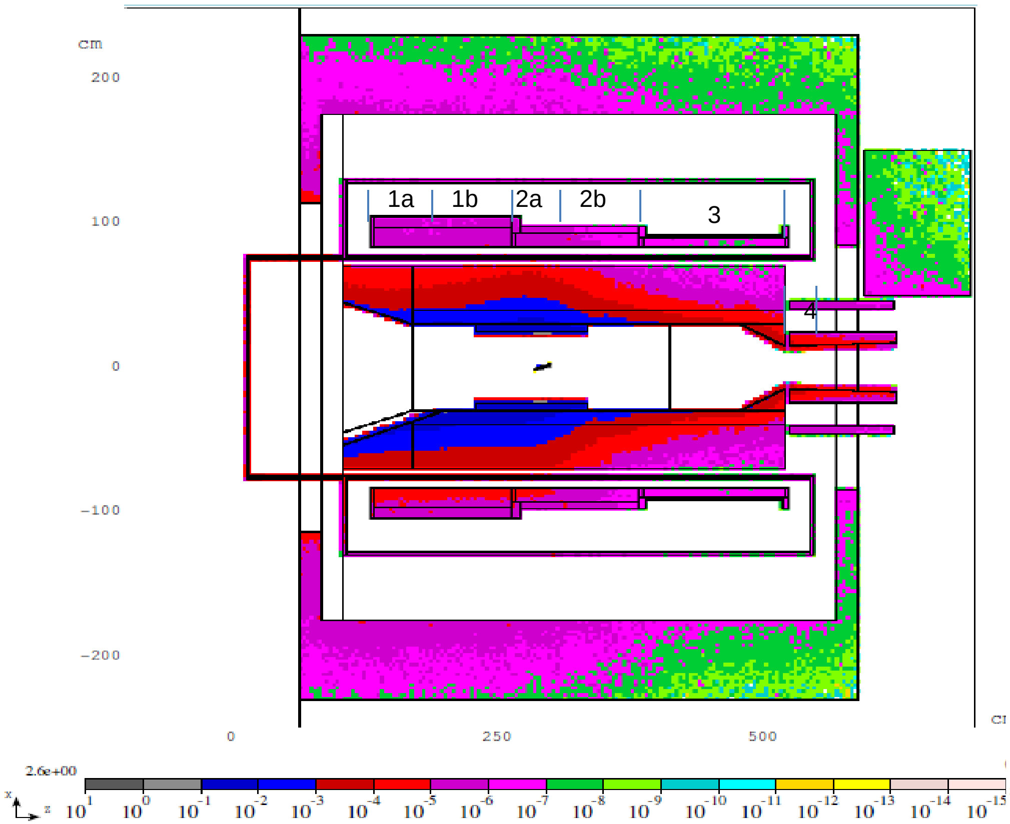


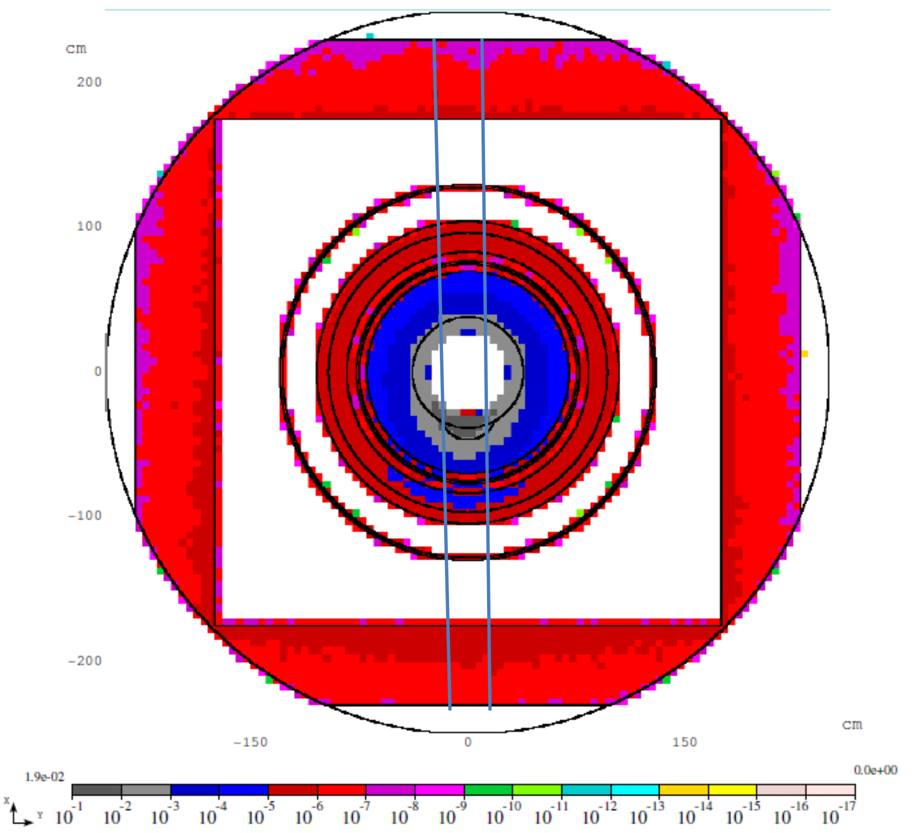
8 GeV proton beam, Au target (r=0.3 cm, H_20, Ti), 25 kW, I=2E13, $\sigma_x = \sigma_y$ = 1 mm

Dynamic Heat Load (W)



PS DPA histograms (case 1)





Peak neutron flux, cm^-2 yr^-1

Case/coil	1	2	3	4
1a	4.90E+16	4.98E+16	4.93E+16	8.18E+15
3	7.58E+14	1.33E+15	2.21E+15	8.18E+14

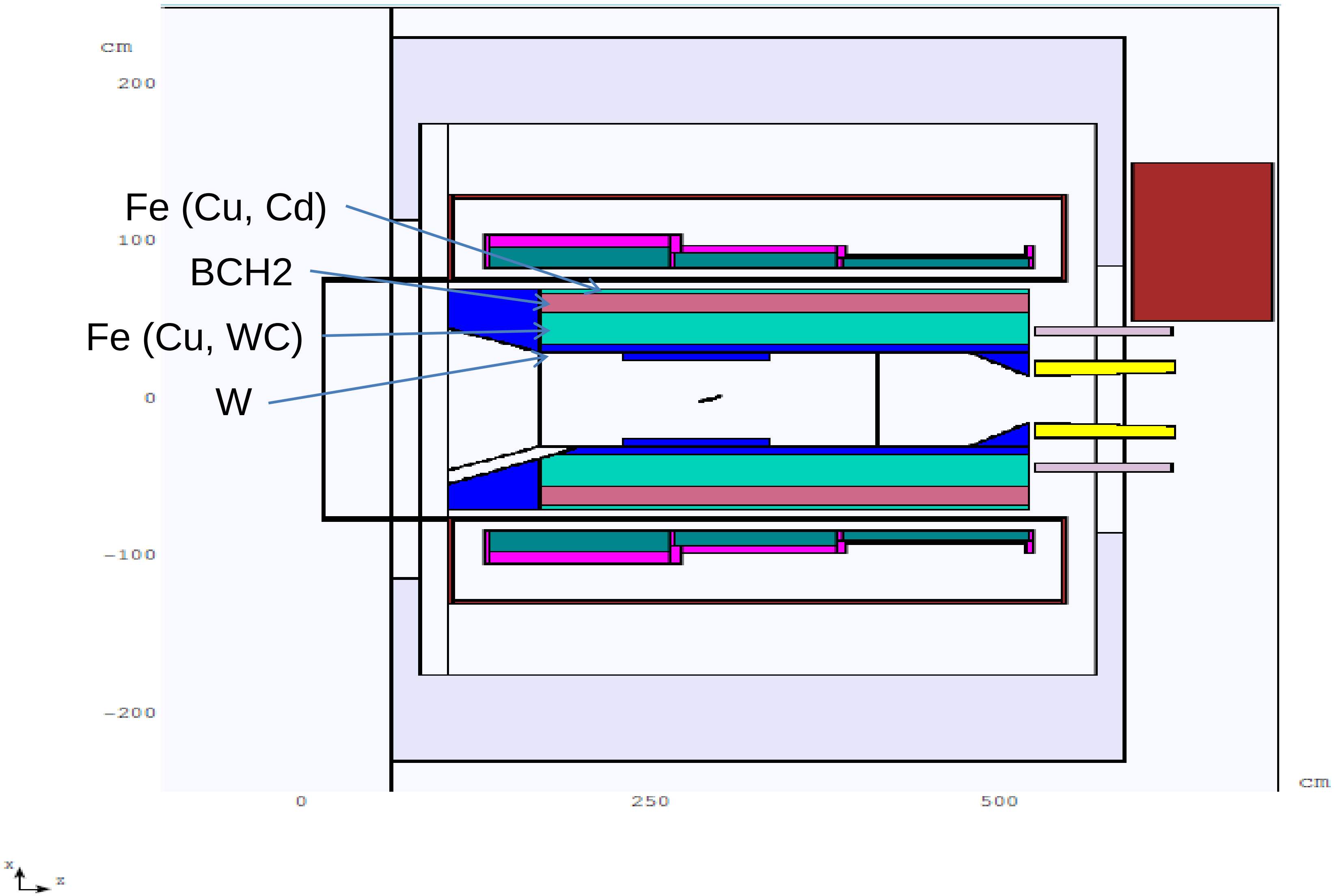
Peak power density, mW/g

Case/coil	1	2	3	4
1a	3.68E-03	3.93E-03	3.8E-03	6.85E-03
3	3.15E-05	7.00E-05	1.03E-04	1.95E-04

Peak DPA, yr^-1

Case/coil	1	2	3	4
1a	1.71E-05	1.69E-05	1.65E-05	1.44E-05
3	2.58E-07	4.18E-07	5.93E-07	2.42E-07

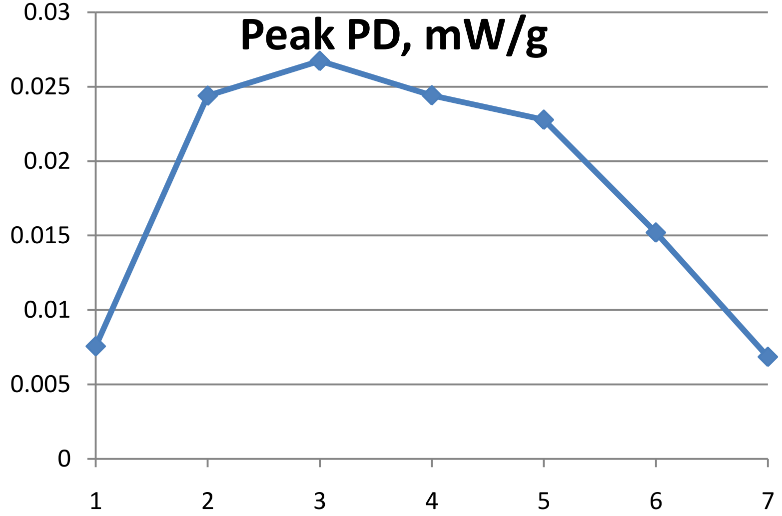
Multilayer absorber versions

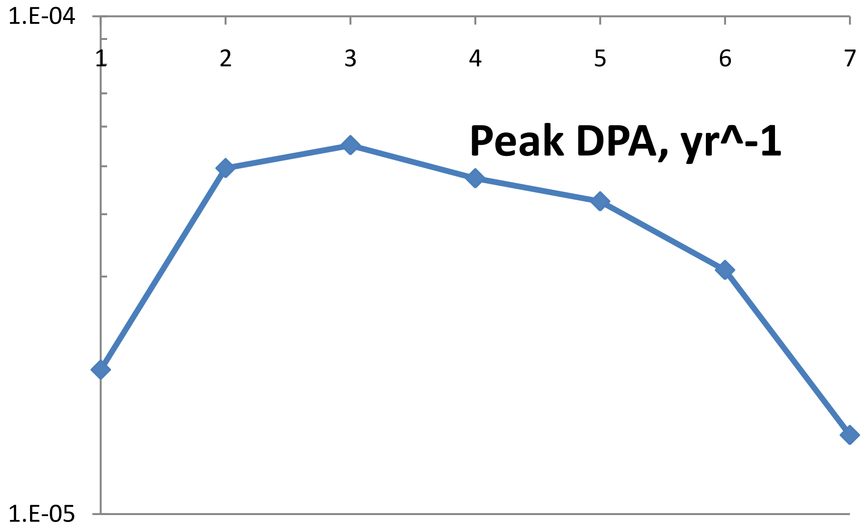


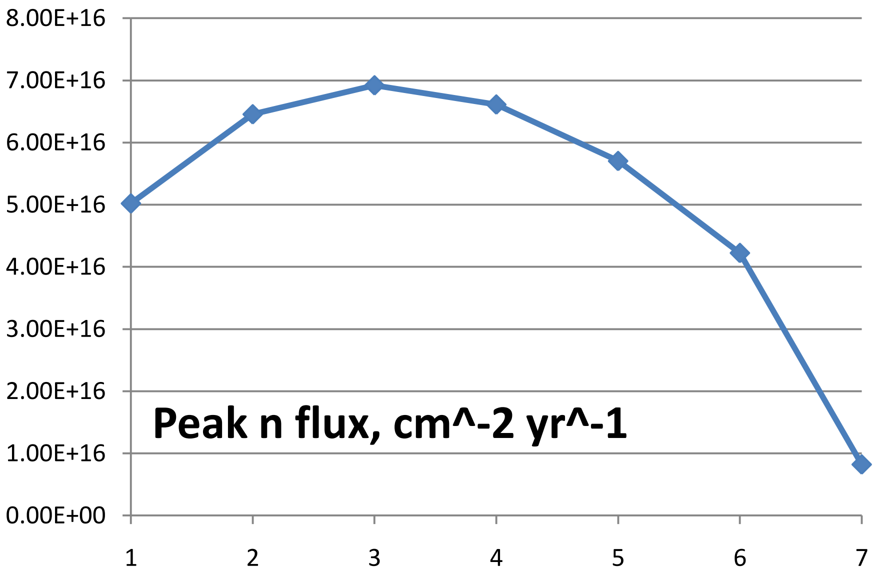
Layer versions to compare:

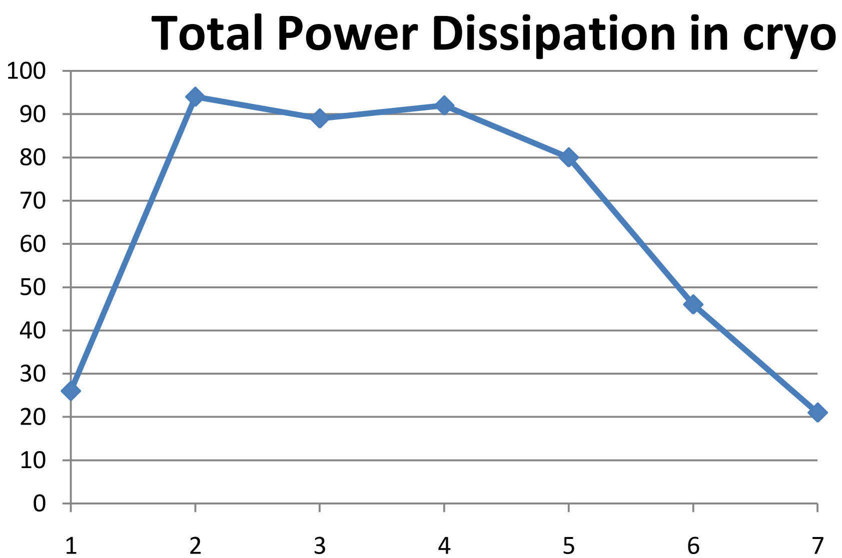
- 1 – entire absorber W
- 2 – 5cm W + 20cm Fe + 12cm BCH2 + 3cm Fe
- 3 – 5cm W + 20cm Fe + 12cm BCH2 + 3cm Cd
- 4 – 5cm W + 20cm Fe + 12cm BCH2 + 3cm Cu
- 5 – 5cm W + 20cm Cu + 12cm BCH2 + 3cm Fe
- 6 – 5cm W + 20cm WC + 12cm BCH2 + 3cm Fe
- 7 – entire absorber WC + H2O (80% WC+20% H2O)

Power density, DPA and neutron flux for 1-st coil, Total Power Dissipation in cryo

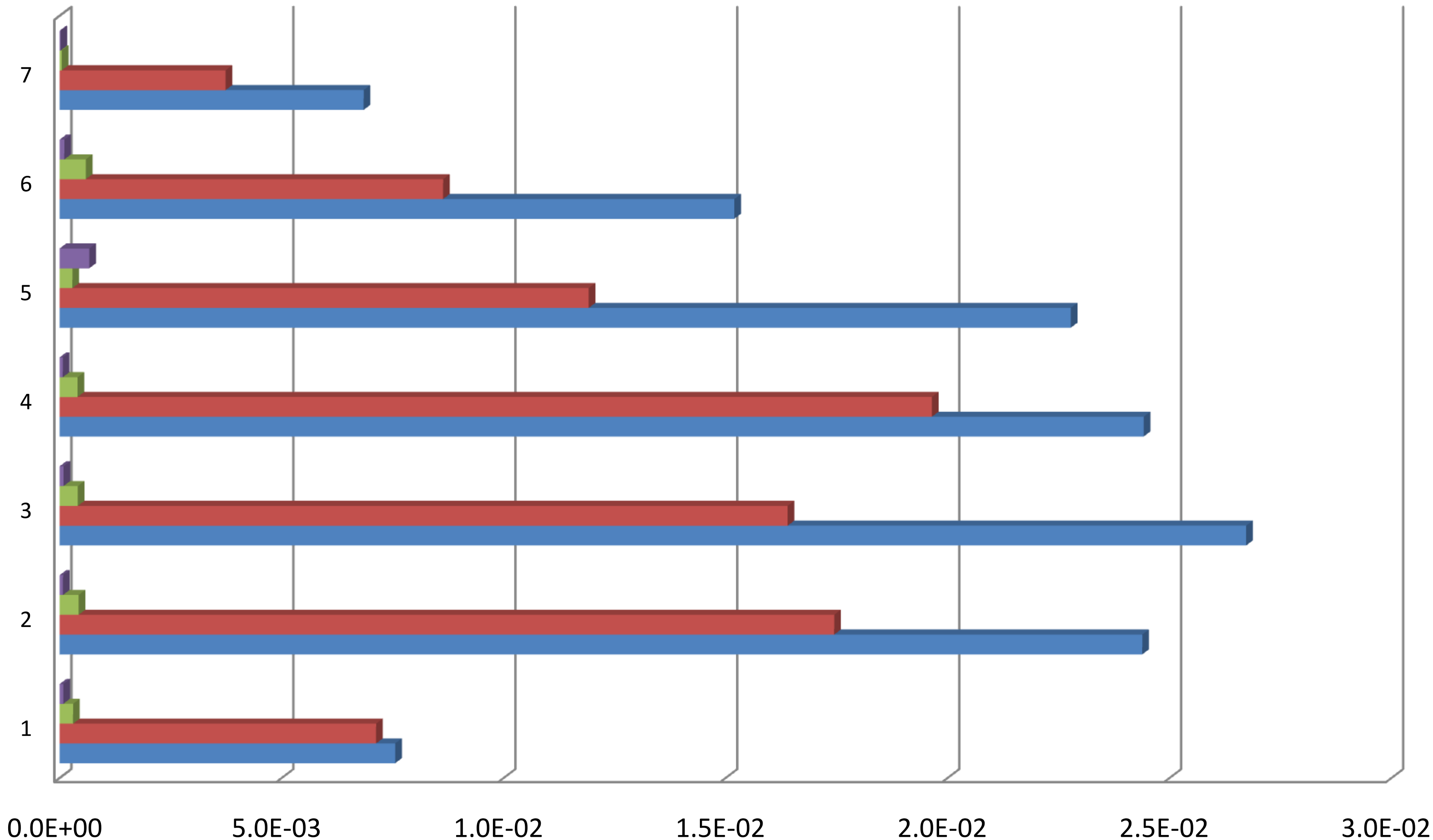






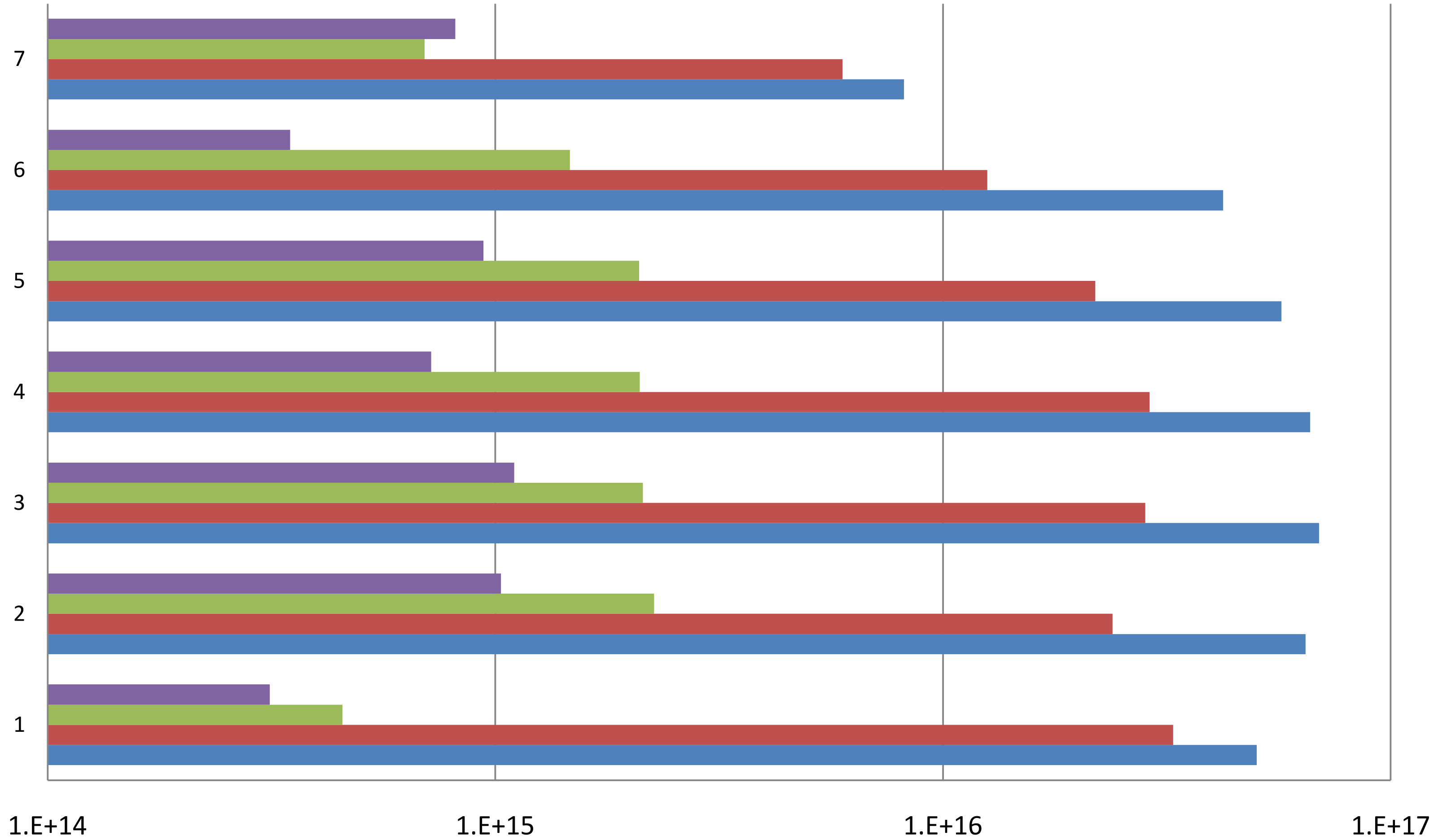


Peak Power Density in Coils, mW/g



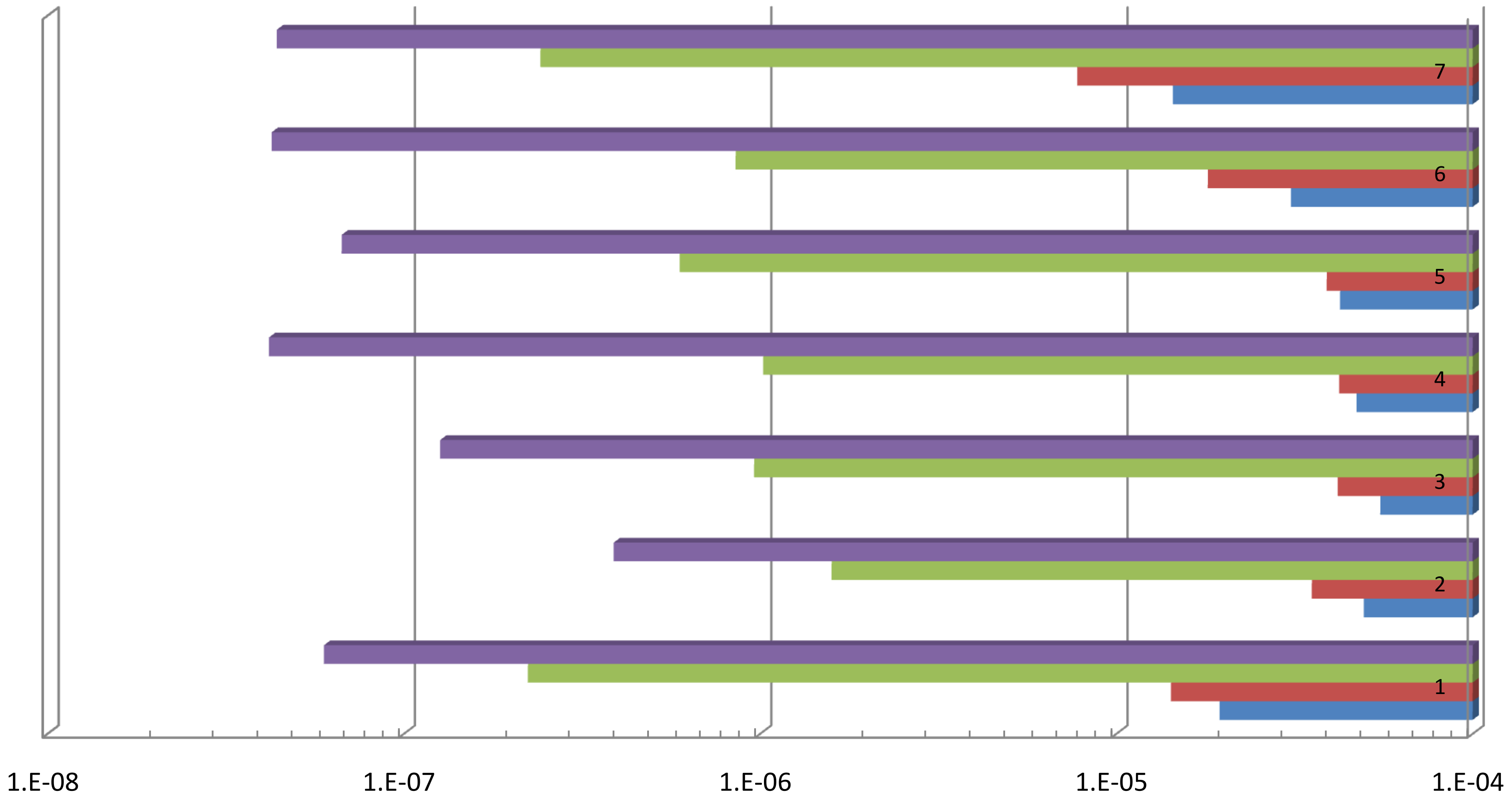
	1	2	3	4	5	6	7
TS	8.30E-05	7.67E-05	8.90E-05	7.26E-05	6.69E-04	1.07E-04	2.09E-05
3	3.04E-04	4.30E-04	4.10E-04	4.05E-04	2.89E-04	5.90E-04	4.86E-05
2a	7.13E-03	1.75E-02	1.64E-02	1.97E-02	1.19E-02	8.64E-03	3.74E-03
1a	7.56E-03	2.44E-02	2.67E-02	2.44E-02	2.28E-02	1.52E-02	6.85E-03

Peak neutron flux, cm^-2 yr^-1



	1	2	3	4	5	6	7
TS	3.14E+14	1.03E+15	1.10E+15	7.20E+14	9.42E+14	3.48E+14	8.14E+14
3	4.55E+14	2.26E+15	2.14E+15	2.10E+15	2.10E+15	1.47E+15	6.95E+14
2a	3.27E+16	2.39E+16	2.83E+16	2.90E+16	2.19E+16	1.26E+16	5.96E+15
1a	5.02E+16	6.46E+16	6.92E+16	6.61E+16	5.70E+16	4.22E+16	8.18E+15

Peak DPA in Coils, yr^-1



	1	2	3	4	5	6	7
TS	5.97E-08	3.88E-07	1.26E-07	4.18E-08	6.69E-08	4.25E-08	4.40E-08
3	2.23E-07	1.59E-06	9.62E-07	1.02E-06	5.94E-07	8.54E-07	2.42E-07
2a	1.42E-05	3.54E-05	4.18E-05	4.22E-05	3.89E-05	1.81E-05	7.77E-06
1a	1.95E-05	4.95E-05	5.50E-05	4.72E-05	4.25E-05	3.09E-05	1.44E-05

Conclusions

- Advantages of WC absorber become not so big when influence of other PS elements is considered
- While the neutrons below 1 MeV are better suppressed by WC absorber, in the region around 100 MeV W works better
- Both W/Cu versions of absorber exhibit peak values of PD, neutron flux and DPA very close to that of pure W one. In the WC case the neutron flux is much smaller, DPA are not significantly smaller, while PD is higher. For all the cases these quantities seem to be within allowable values
- In the set of six absorbers including multilayer ones those of pure W and with a WC layer have the smallest values of PD and DPA (difference with worst cases by coefficient of 2), while the neutron fluxes are quite similar