Design A Local Beam Dump And Shielding Using FLUKA

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Outline

1) Principal of shielding

2) Principal of dump design

3) Fluka simulation result

4) Summary

Size of The Dump Core

1)The energy loss of highly relativistic electrons due to ionization is approximately constant, while the radiation process scales linear with energy. The energy, at which both mechanisms contribute equally to the energy loss of the particle, is called the critical energy E_c:

$$\text{solids and liquids: } E_c = \frac{610\text{ MeV}}{Z+1.24} \quad ; \quad \text{gases: } E_c = \frac{710\text{ MeV}}{Z+0.92}$$

2)Radial extension of an electromagnetic shower (Moliere Radius):

$$R_M \approx \frac{21.2\text{MeV}}{E_c} \cdot X_0 \qquad\qquad R_{99\%} \approx 5 \cdot R_M$$

3) Longitudinal length that 99% of the particle energy is absorbed:

$$L_{99\%} = \left(1.52 \cdot \ln\left(\frac{E_0}{\text{MeV}}\right) - 4.1 \cdot \ln\left(\frac{E_c}{\text{MeV}}\right) + 17.6\right) \cdot X_0$$

For E_e=8.8GeV (11.0GeV) :
Aluminum: R_M = 4.4 cm, $R_{99\%}$ = 22.0 cm, $L_{99\%}$ = 142.3 cm (145.3 cm)
Copper: R_M = 1.5 cm, $R_{99\%}$ = 7.6 cm, $L_{99\%}$ = 28.8 cm (29.3 cm)

Discussion of Shielding Material

1) Iron: effective shield photons. The lowest inelastic energy level of 56Fe is 847 keV, which greatly limits the effectiveness of iron shielding for low energy neutrons. Additionally, the 27.7 keV resonance and 73.9 keV resonance can result in large fluxes of soft neutrons outside iron shields.

2) Polyethylene: effective shield material for both photons and neutrons. Thermal neutron capture in polyethylene can lead to a build up of 2.2 MeV photons which can be mitigated by addition of a boron compound.

3) Soil(SiO_2): effective shield material for both photons and neutrons.

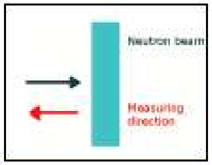
4) Concrete: effective shield material for both photons and neutrons.

Basic Shielding Principal @ JLab

1) Photons and giant resonance neutrons (GRN, <20 MeV) dominate the radiation field.
2) High-energy neutrons (HEN, > 100 MeV, resulting from hadronic cascade initiated by high-energy photons above the photo-pion production threshold) generated in the target, and associated evaporation neutrons and photons generated in the shield, are the determining factor for design the thickness of shielding.
3) MID (Mid Energy Neutrons): neutrons with energies between those for GRN and HEN, including those generated by means of the pseudo-deuteron production mechanism.

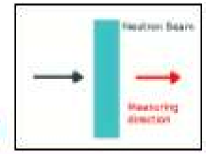
Solution:
To attenuate neutrons with energies above 20 MeV, the best shielding configuration consists of a layer of high-Z material, such as lead or steel, followed by a low-Z shield with high hydrogen content – most often concrete, and polyethylene.
High-Z materials reduces the neutron energy effectively, also efficient for shielding photons of all energies. The lower energy neutrons are then best further attenuated and absorption down to thermal energies in hydrogenous material. Boron element is also very efficient in absorb thermal neutrons.

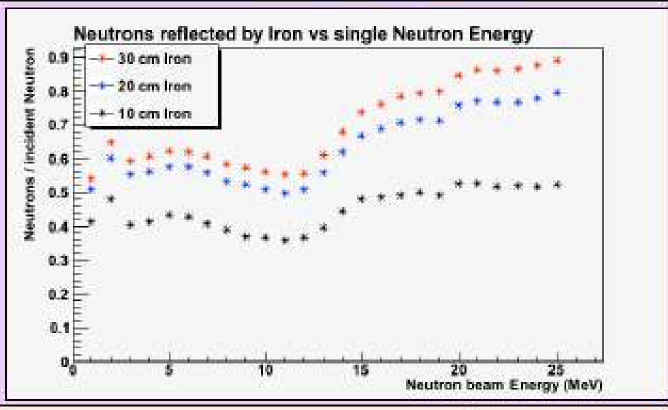
How Neutrons Behave



Reflection

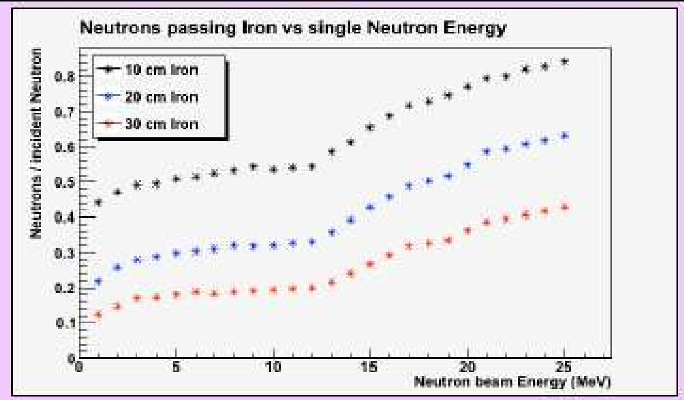
Transmission

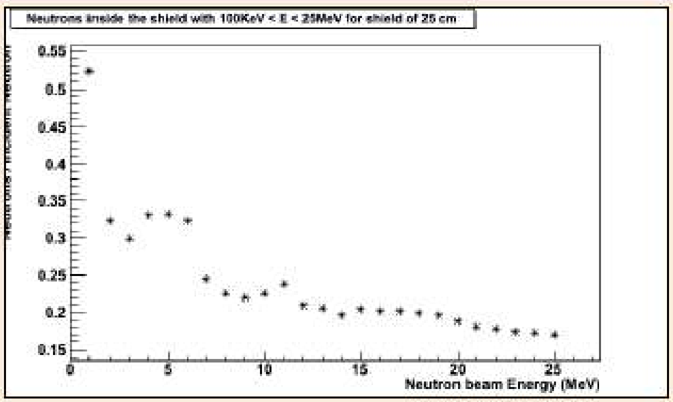




Iron

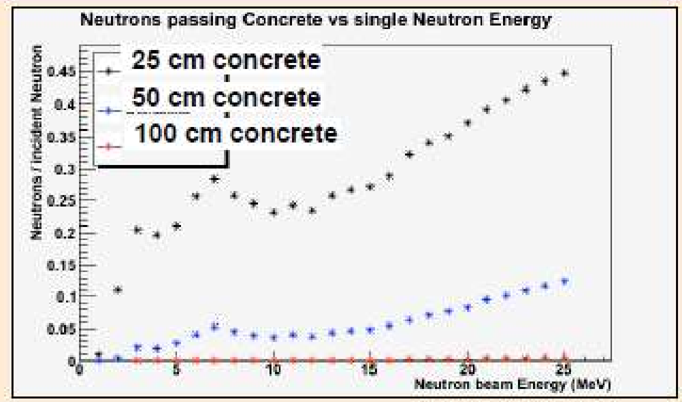
high reflection, not efficient at stopping

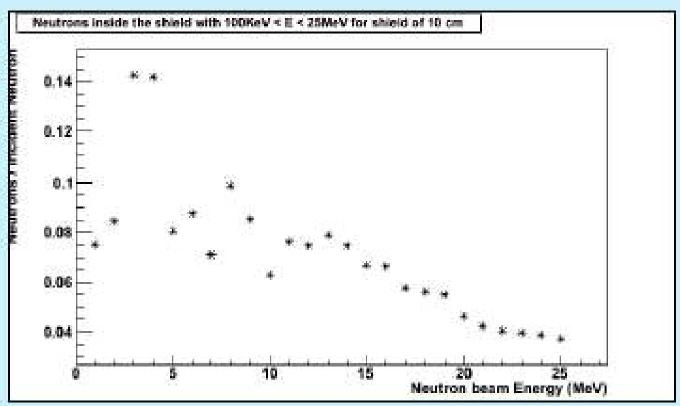




Concrete

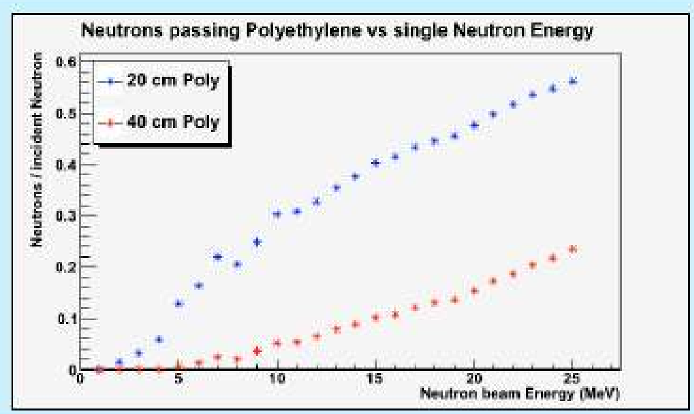
30% reflection, 0.5m to block





HD Polyethylene

low reflection, 30cm blocks well



MAIN RADIATION EFFECTS ON ELECTRONICS

			relevant physical quantity the effect is scaling with
Single Event effects (Random in time)	***Single Event Upset (SEU)***	Memory bit flip (soft error) Temporary functional failure	High energy hadron fluence [cm^{-2}] (but also thermal neutrons!)
	Single Event Latchup (SEL)	Abnormal high current state Permanent/destructive if not protected	High energy hadron fluence [cm^{-2}]
Cumulative effects (Long term)	***Total Ionizing Dose (TID)***	Charge build-up in oxide Threshold shift & increased leakage current Ultimately destructive	Ionizing dose [Gy]
	Displacement damage	Atomic displacements Degradation over time Ultimately destructive	Silicon 1 MeV-equivalent neutron fluence [cm^{-2}] {NIEL -> DPA}

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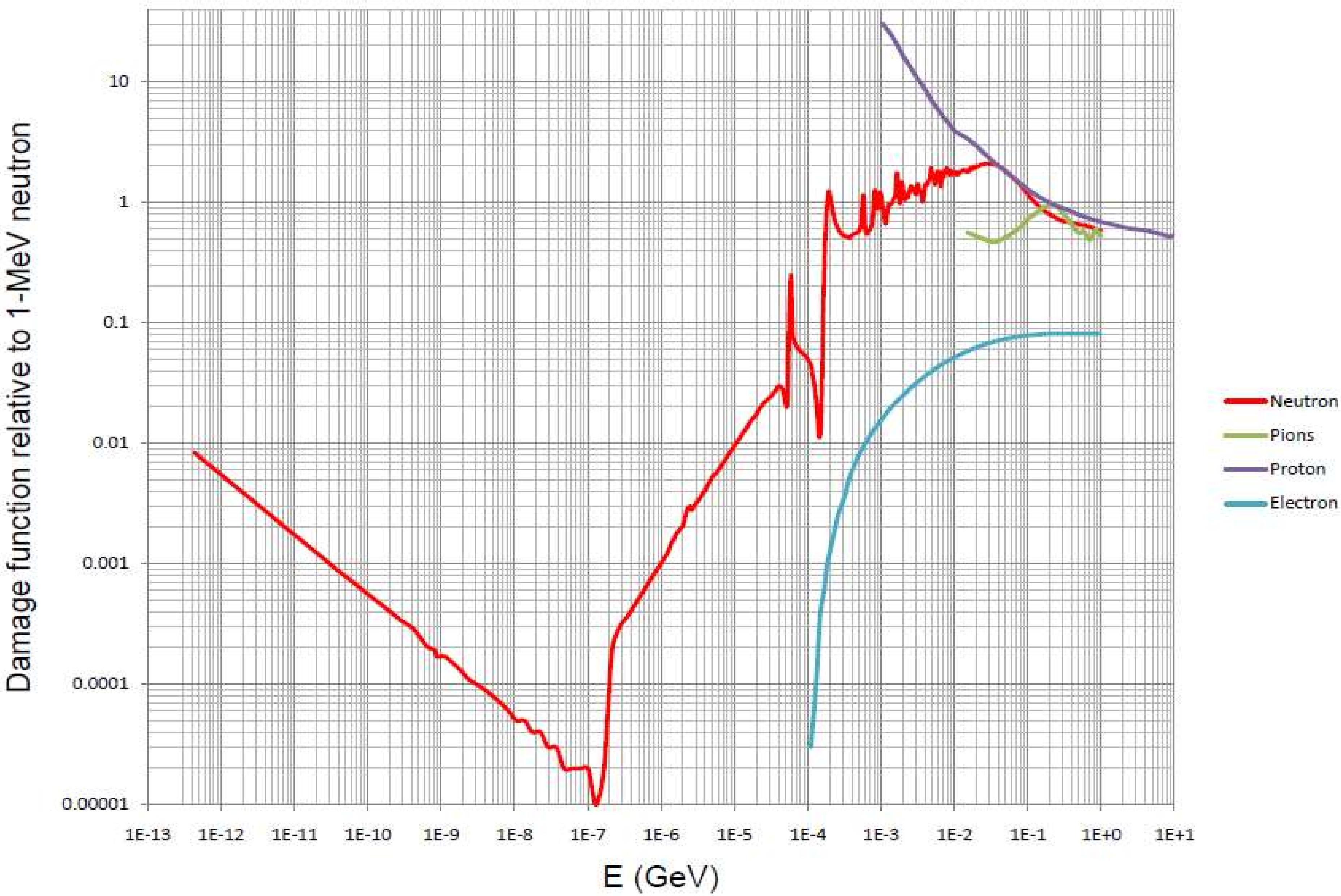
Radiation Damage Conversion Chart

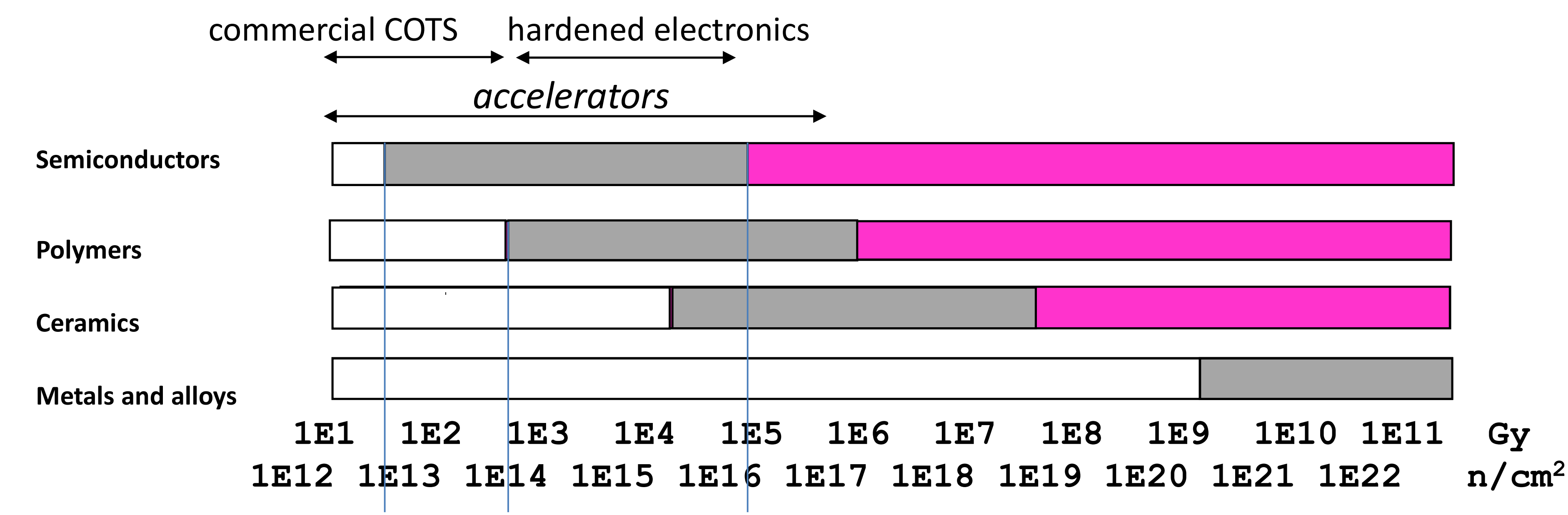


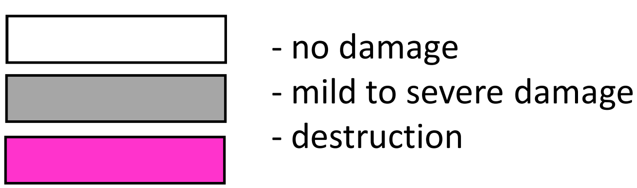
Radiation Damage Chart (Approximate)

Dose & Displacement Damage

Radiation Damage to Materials/Electronics

!!! A Rough Overview Only !!!





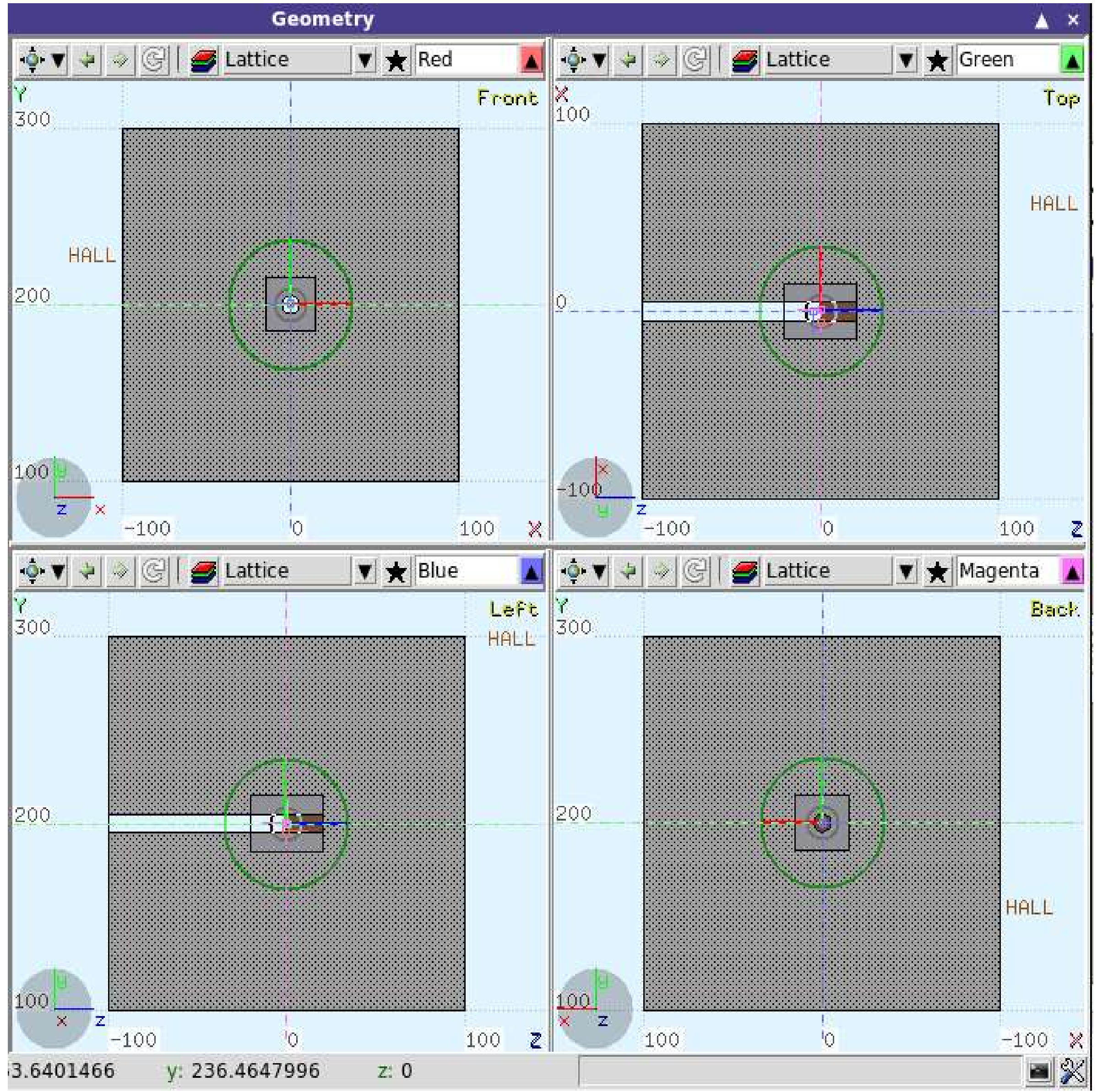
!!! Assumption !!!
(depends on particle energy spectra)
1 neutron (1MeV) /cm^2 ~ 3.3E-11 Gy

First trial: simple dump + 100cm Shielding

Cylinder core:
R=5cm, L=20cm
(HD17)

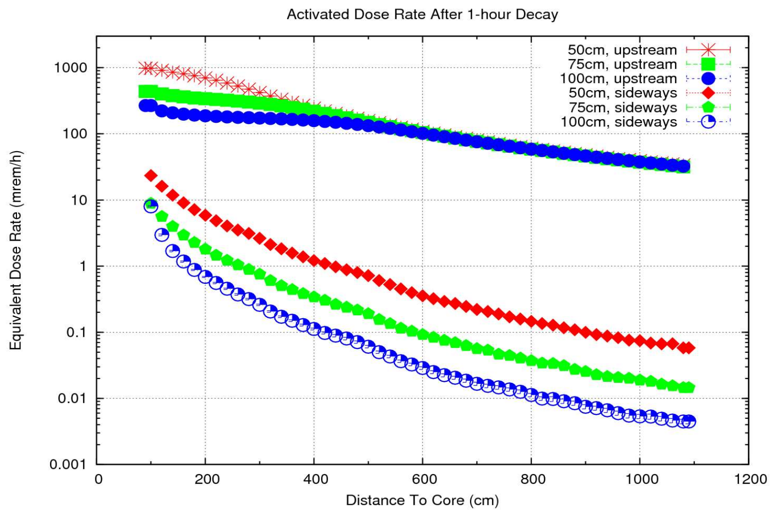
Dump box:
30cm x 30cm x 40cm
(Lead)

The core is aligned to the back face of the dump, therefore there is 20 cm space as entrance window

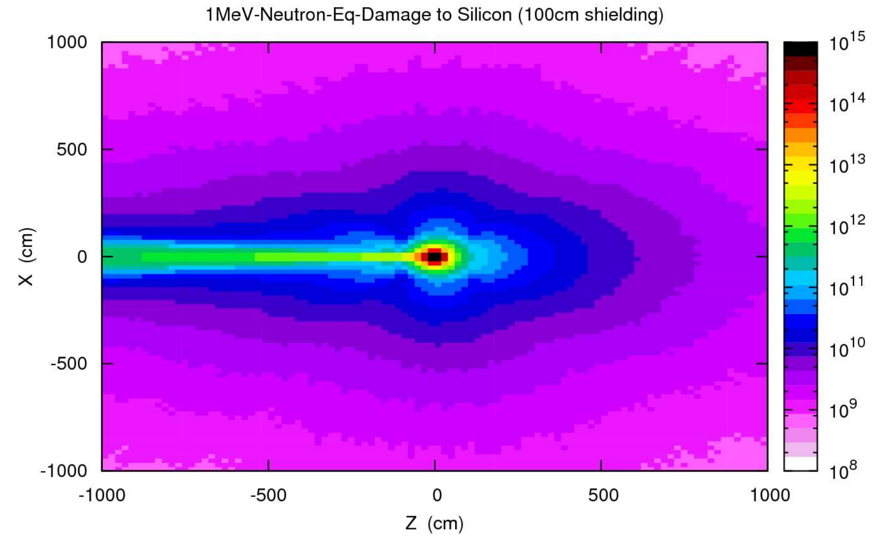


Concrete shielding box: 2m x 2m x 2m, with entrance tunnel

Dose And Residual Dose Rate For the Simple Dump



100cm concrete

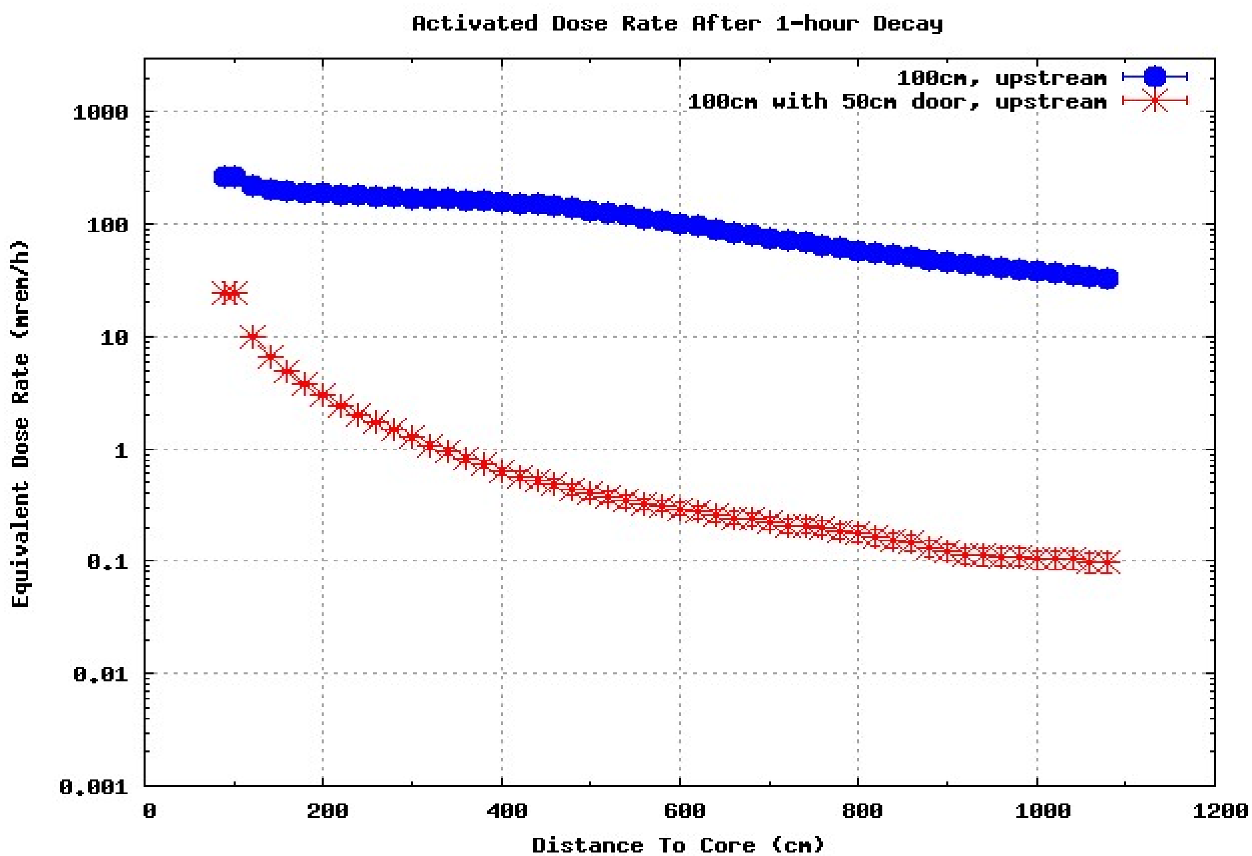


100cm concrete

Upstream means -30 <x<30, it is hot!!!

4 weeks of 3uA beam @ 8.8 GeV

How to Reduce Upstream Activated Radiation Dose Rate?



Upstream means -30 < x < 30, include the beam pipe
Dump only, 4 weeks of 3uA beam @ 8.8 GeV

Adding a 50cm concrete sliding door can efficiently reduce the upstream dose rate.

Edge Cooled Dump Example

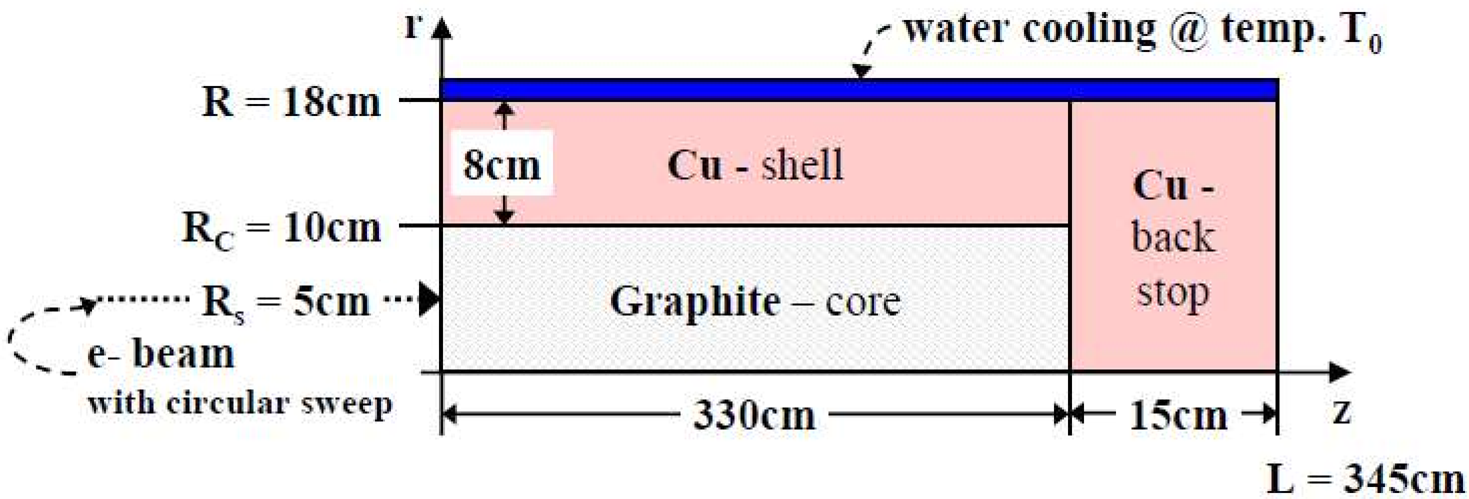


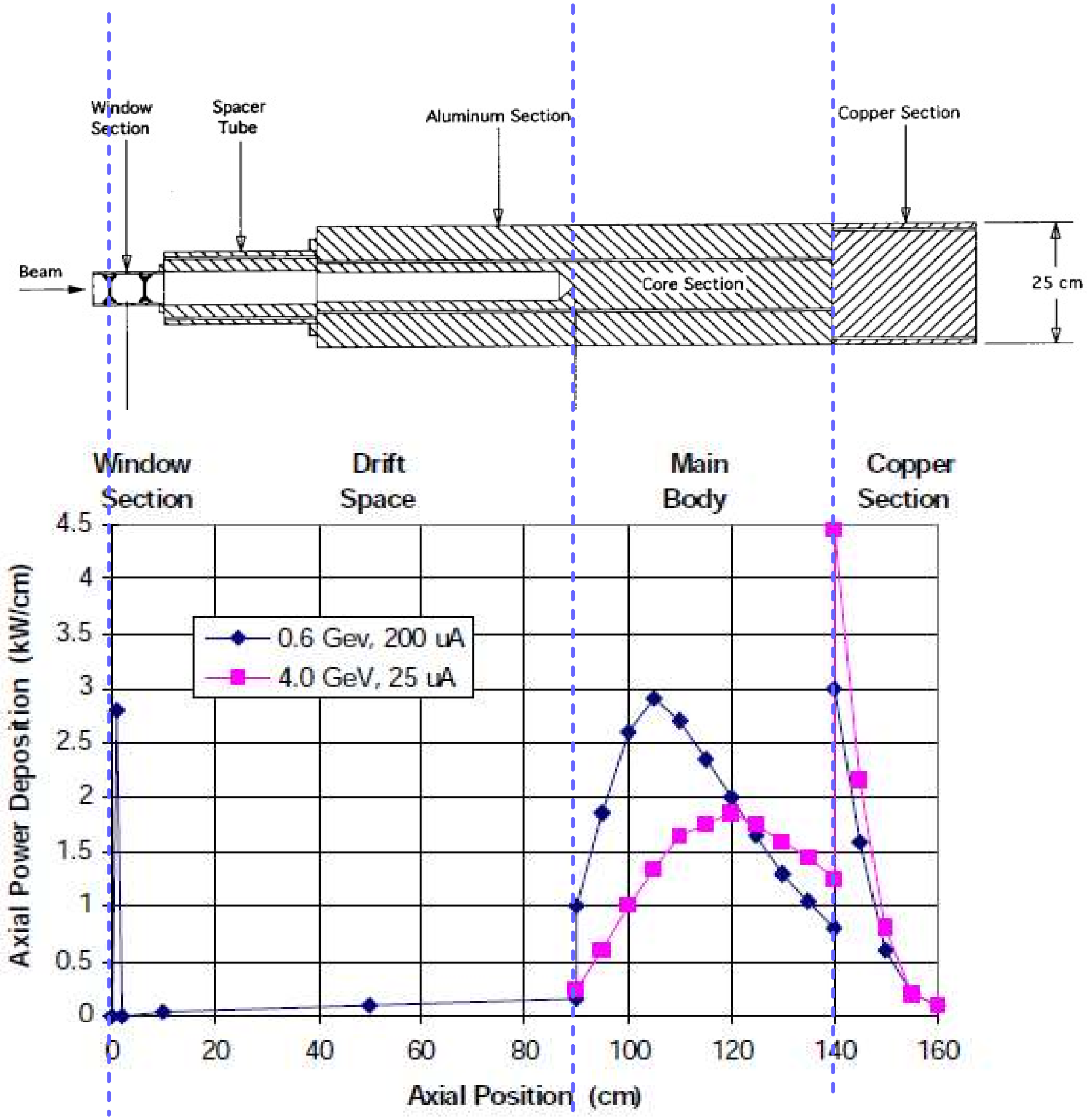
Figure 16: Baseline design of the 25GeV / 300kW main dump for the XFEL with slow (not intra train) beam sweep of $R_s = 5$cm and $\sigma_{beam} \geq 2$mm.

	C-core	Cu-shell	Cu-backstop	cooling water	total leakage
7.5 GeV	275kW / 91.7%	20.8kW / 6.9%	4kW / 1.3%	20W / 67ppm	400W / 0.13%
25 GeV	280kW / 93.3%	19.2kW / 6.4%	10kW / 3.3%	25W / 83ppm	1000W / 0.33%

Table 5: Absolute and relative value of power, which is deposited by a 300kW beam in the various sections of the baseline dump geometry as shown in Figure 16.

The European X-Ray Free Electron Laser (XFEL) beam dump, 300kW.

CEBAF Tune-up Dump: 120 kW



120 kW cooling power

Aluminum core is used in order to distribute the heat deeper alone z direction such that the peak heat flux is less than 100w/cm^2

Copper section is 29 cm thick, will absorb 27% of the power @ 4 GeV beam.

Upgraded Tune up Dump, Side View

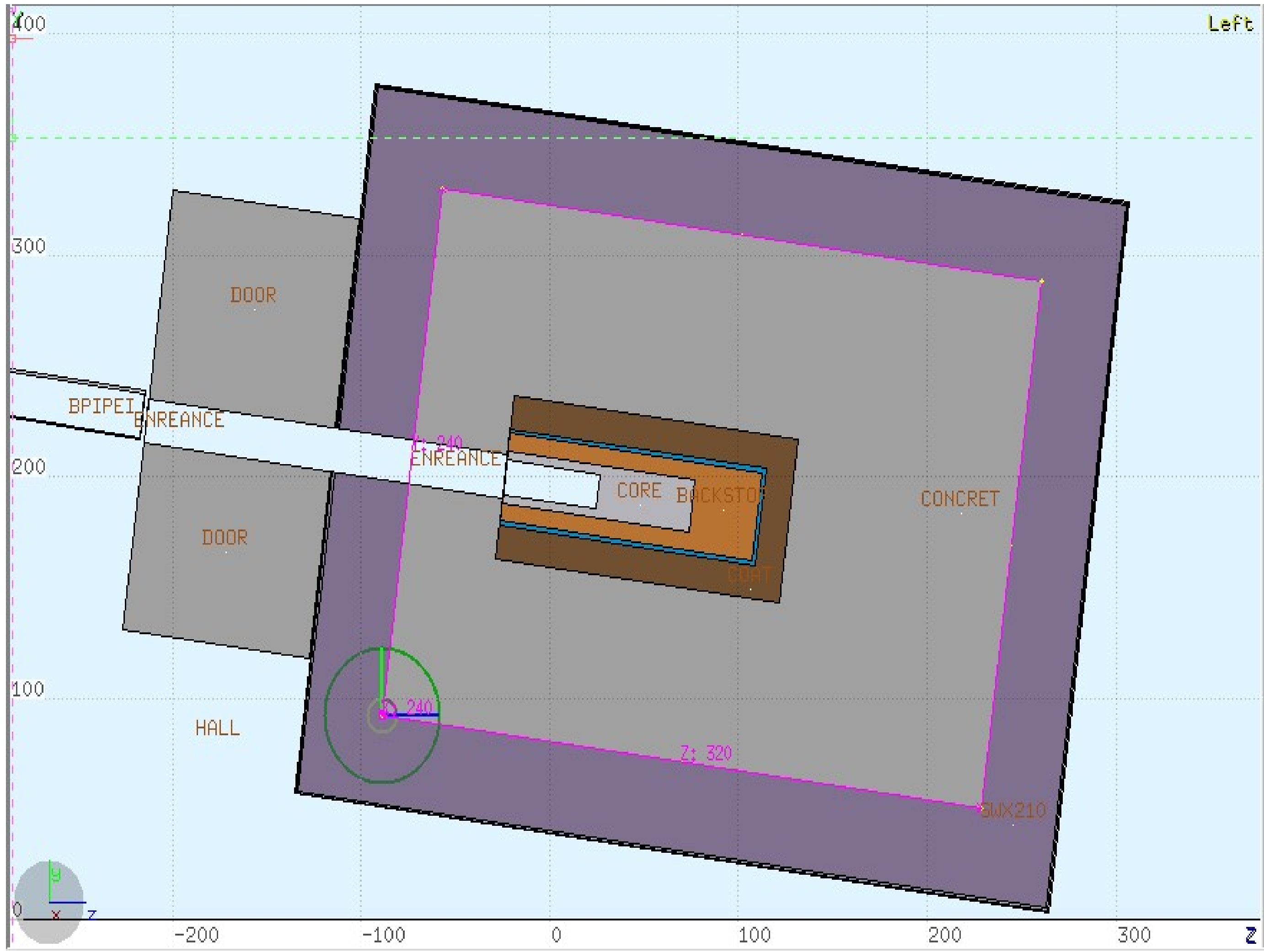
Aluminum cylinder core: R=12cm, L=100cm, drilled by 50cm deep as entrance, entrance radius=8cm

Copper shell and back stop: 8cm thick
in side and 35cm thick in back

Tungsten coat: 15cm thick in sides and 15 cm in back

Shielding: 2.4mx2.4mx3.2m concrete box then 40 cm thick borated plastic wall

Sliding door: 2mx2mx1m concrete



Upgraded Tune up Dump, Top View

Aluminum cylinder core: R=12cm, L=100cm, drilled by 50cm deep as entrance, entrance radius=8cm

Copper shell and back stop: 8cm thick in side and 35cm thick in back

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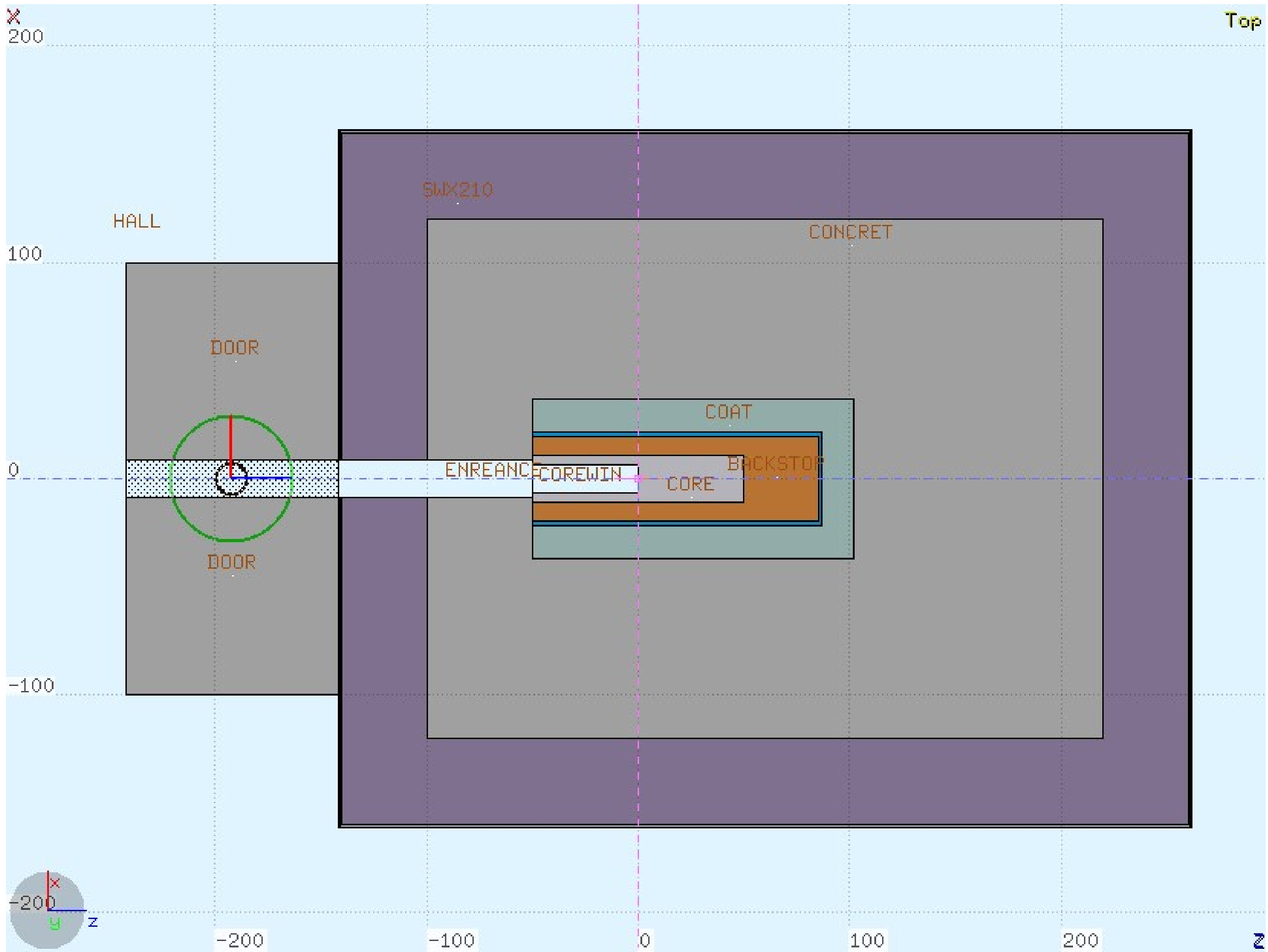

Shift the door to its horizontally right by 20cm when the beam is off to block the dump entrance

Upgraded Tune up Dump, Top View

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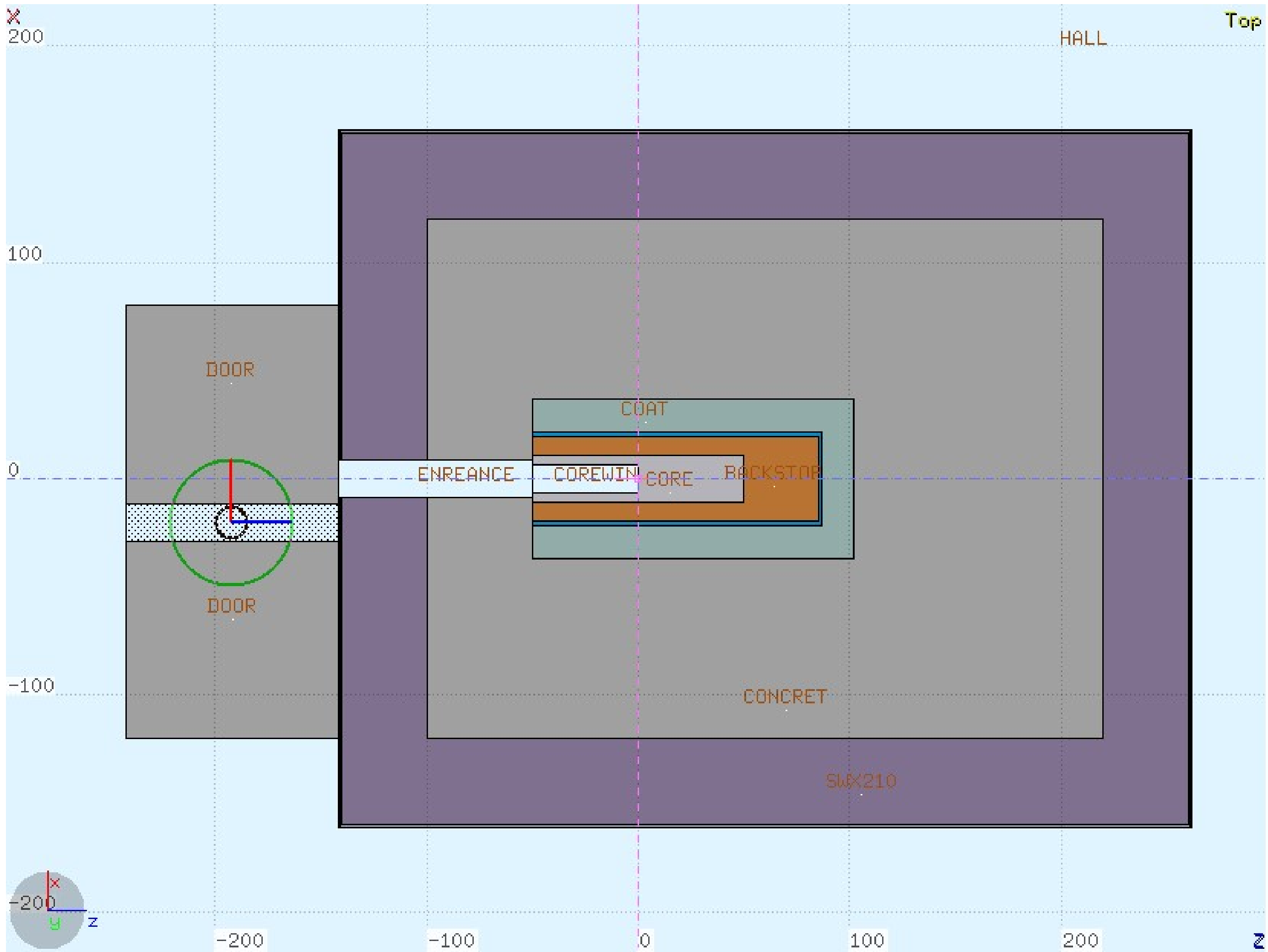


Shift the door to its horizontally right by 20cm when the beam is off to block the dump entrance

Heat Power at Tune-up Dump

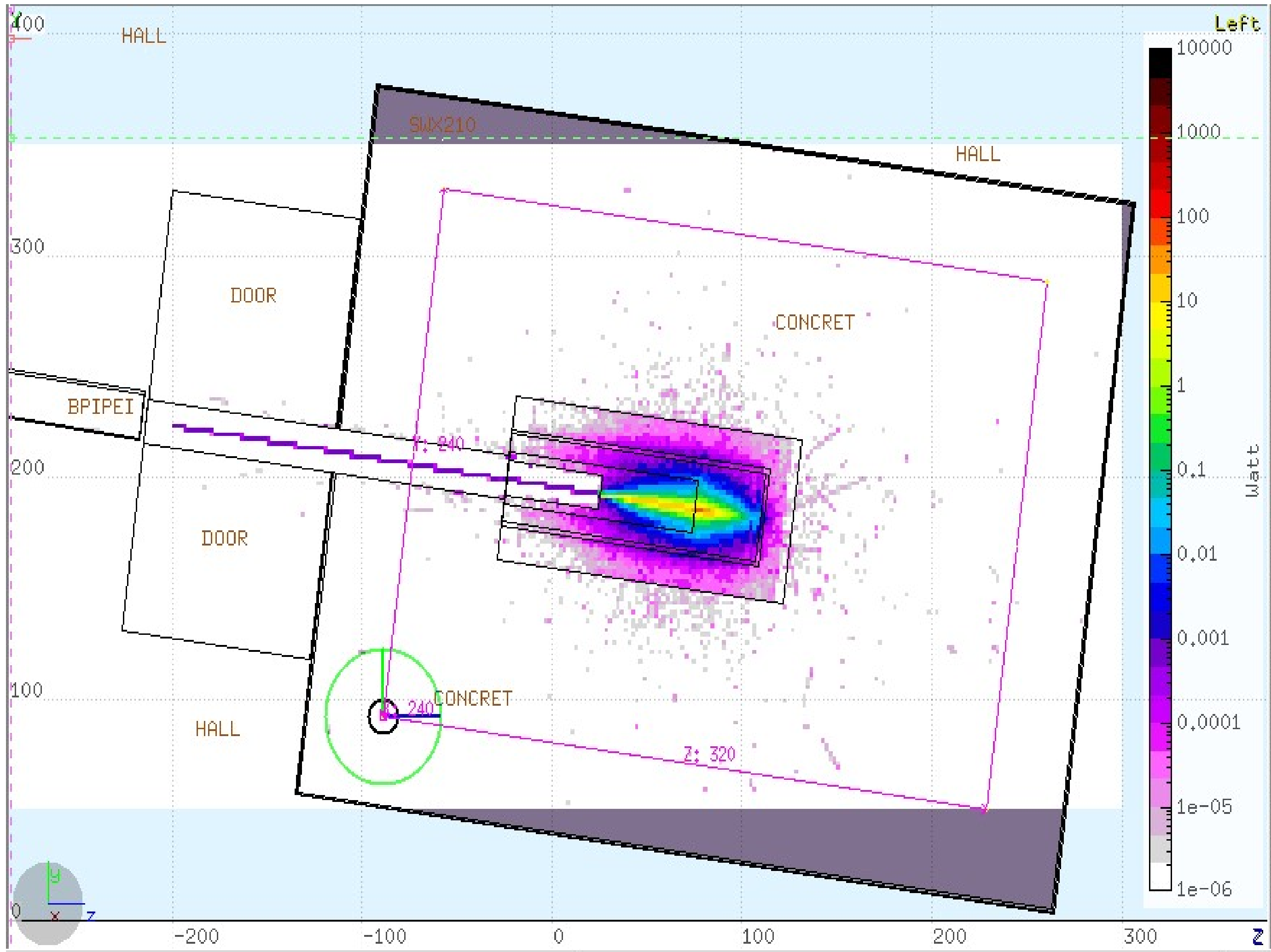
Aluminum cylinder core: R=12cm, L=100cm, drilled by 50cm deep as entrance, entrance radius=8cm

Copper shell and back stop: 8cm thick in side and 35cm thick in back

Tungsten coat: 15cm thick in sides and 15 cm in back

Shielding: 2.4mx2.4mx3.2m concrete box then 40 cm thick borated plastic wall

Sliding door: 2mx2mx1m concrete



Dipole + Collimator

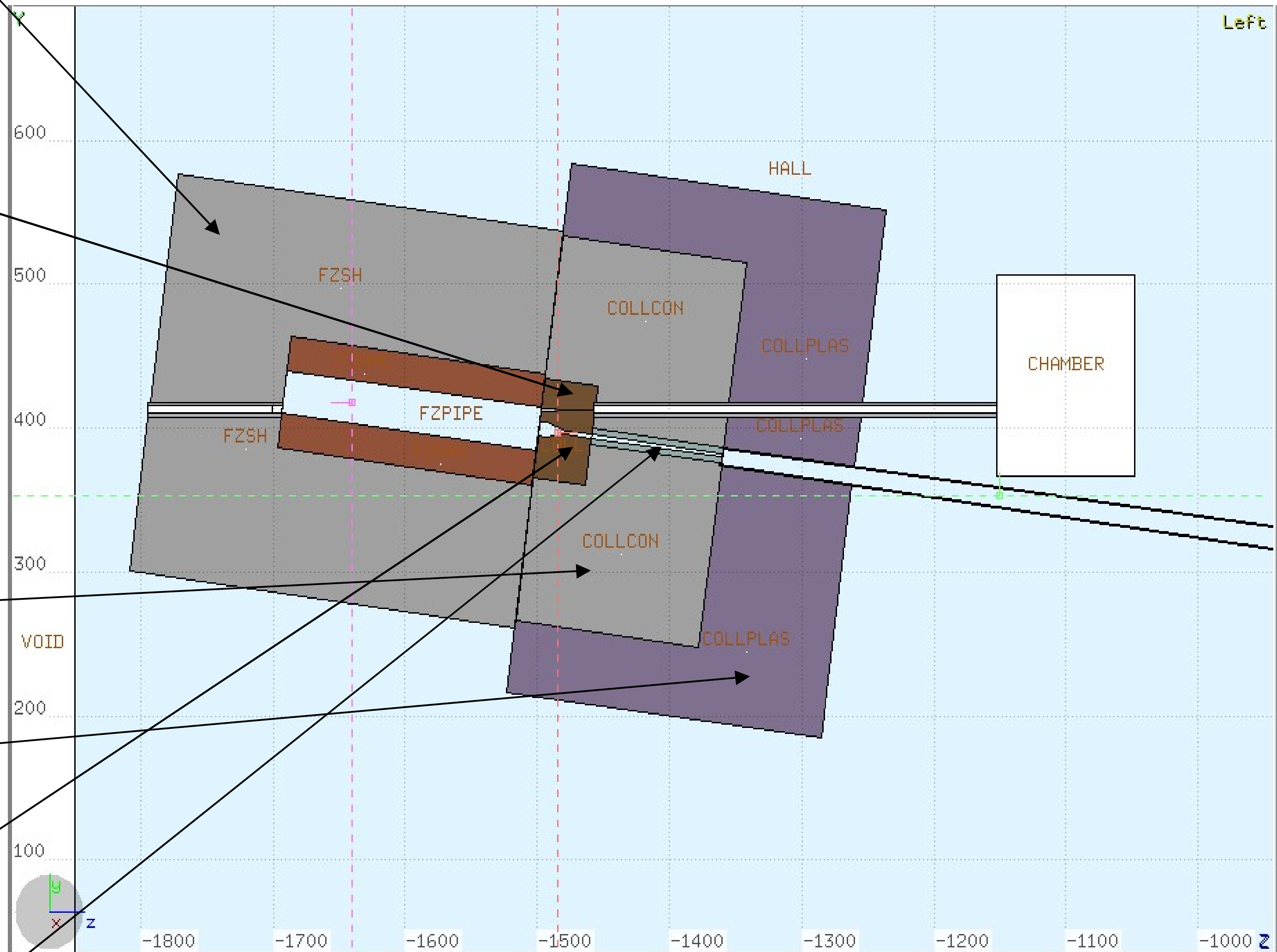
FZ Dipole shielding box:
2.45m x 2.74m x 3.0m
(1m thick in all directions)

Collimator box (Tungsten):
0.45m x 0.60m x 0.40m

Tungsten pipe:
inner_R=1.5cm, 4cm thick wall, 100cm long

Collimator shielding:
2.45m x 2.6m x 1.4m concrete box then 100 cm thick borated plastic wall

Photon collimator:
R=0.1cm, L=20cm
Electron Collimator:
R=1.5cm, L=20cm+100cm

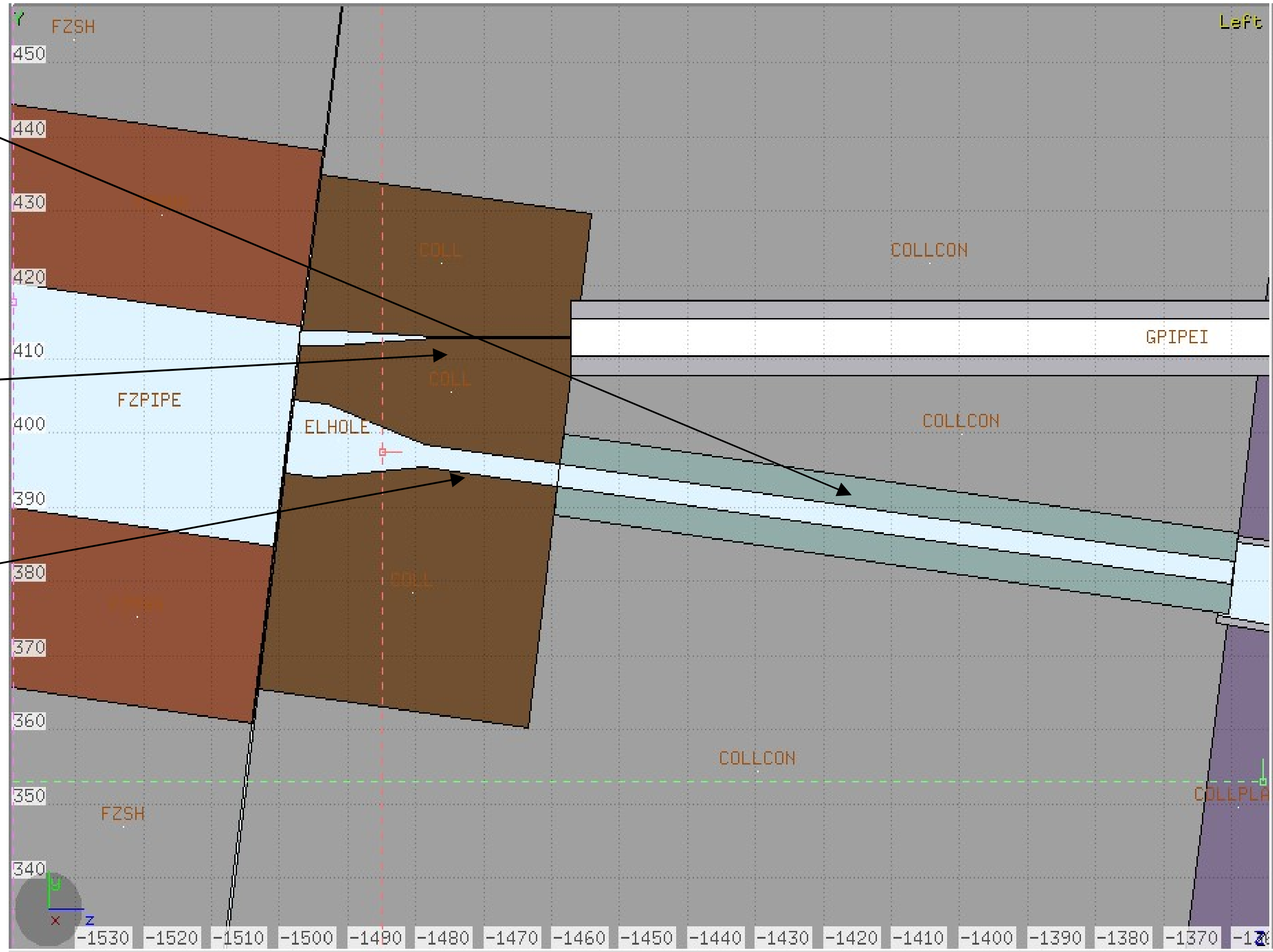


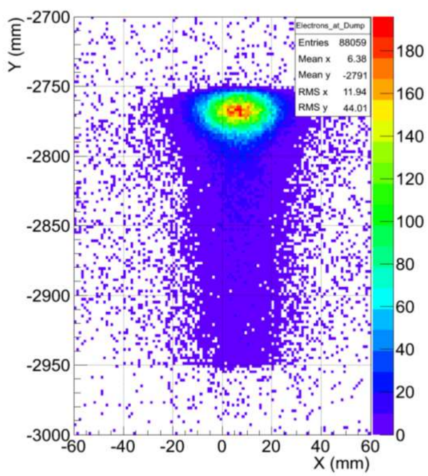
Collimator

Tungsten pipe:
inner_R=1.5cm, 4cm thick wall, 100cm long

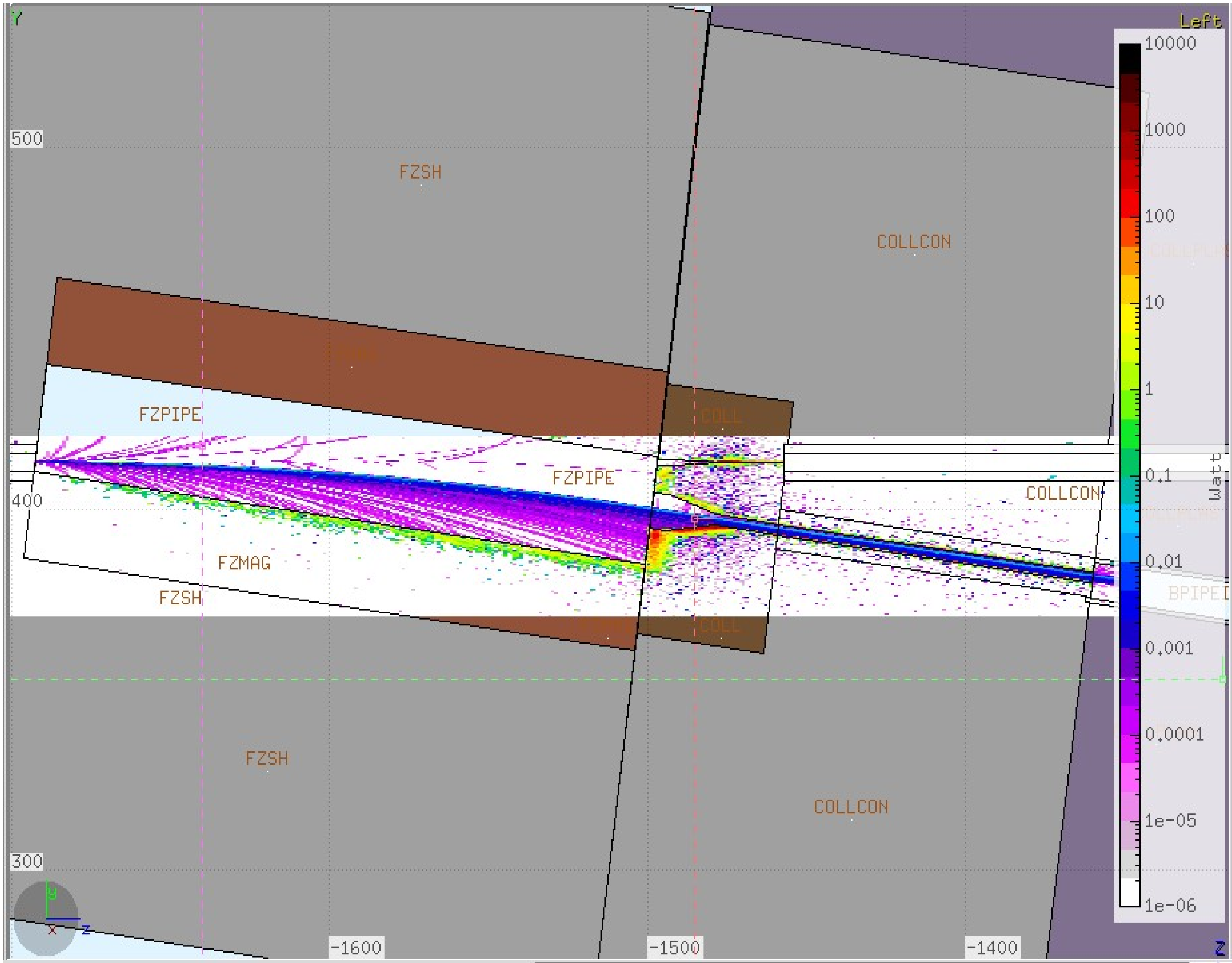
Photon Collimator:
R=0.1cm, L=20cm

Electron Collimator:
R=1.5cm, L=20cm+100cm



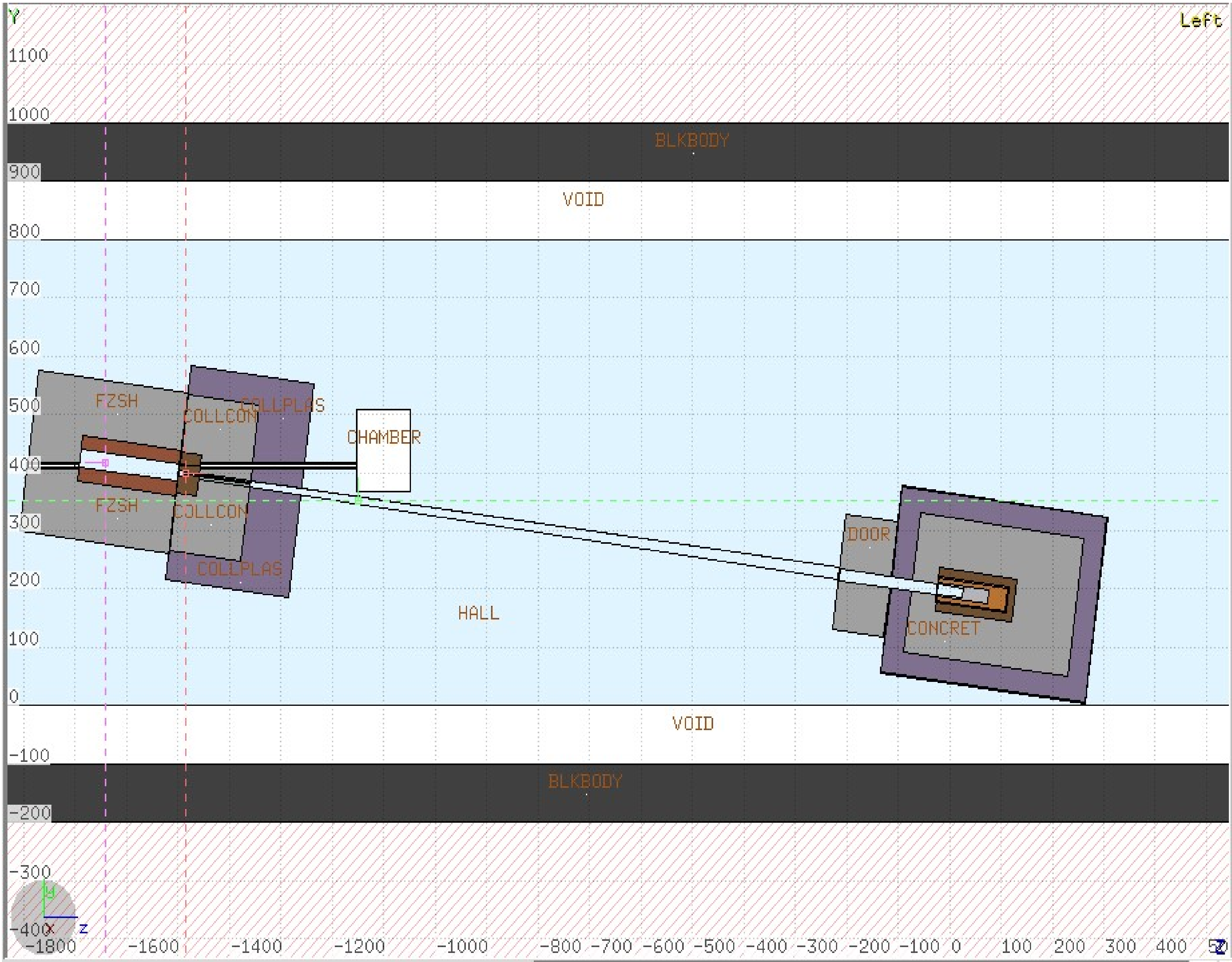


Dipole + Collimator: Heat Power



Peak Heat Power: ~100w/cm^2

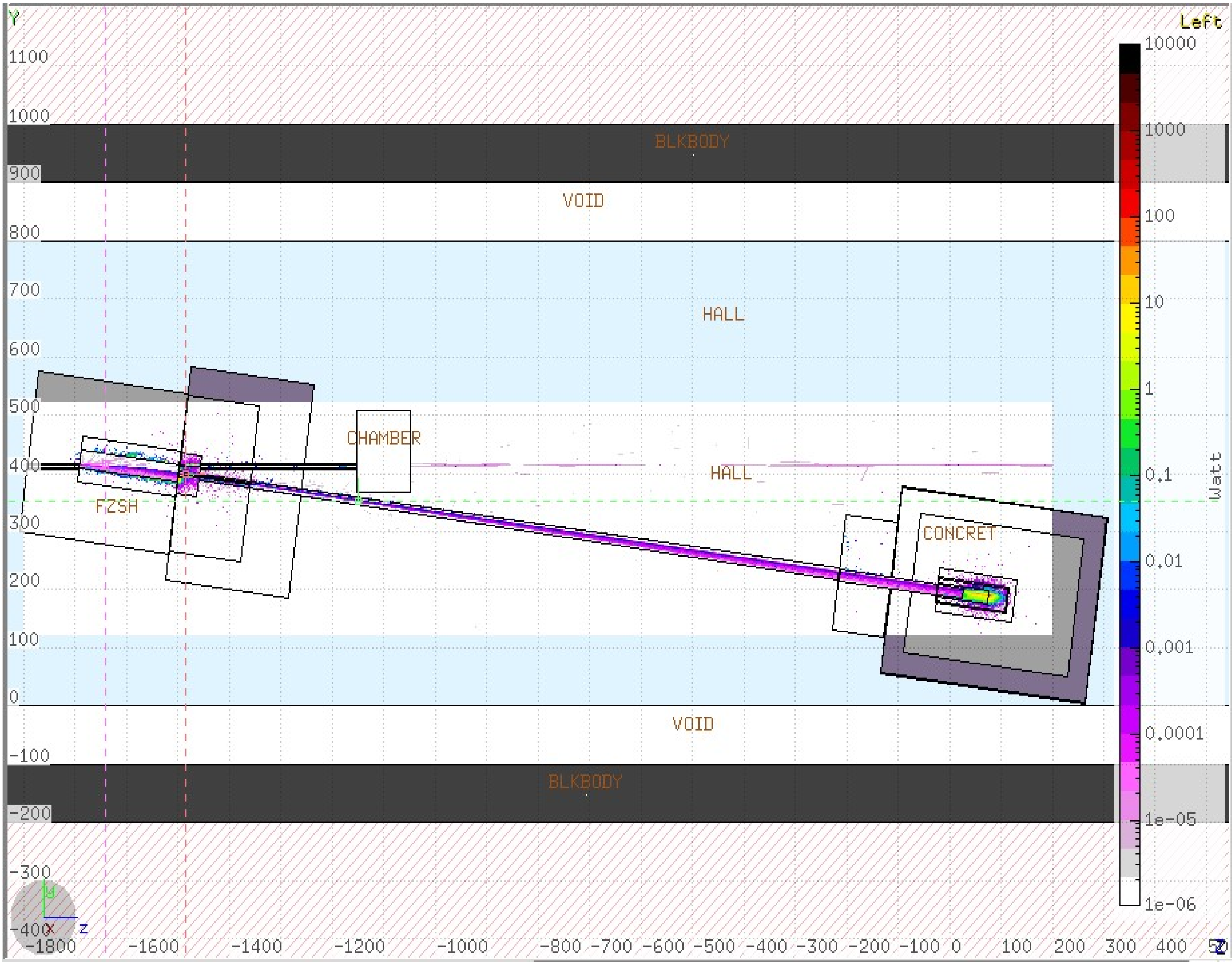
Dipole + Collimator + Dump



40 cm collimator box + 100cm tungsten pipe

Collimator shielding: 100cm concrete + 100 cm borated plastic

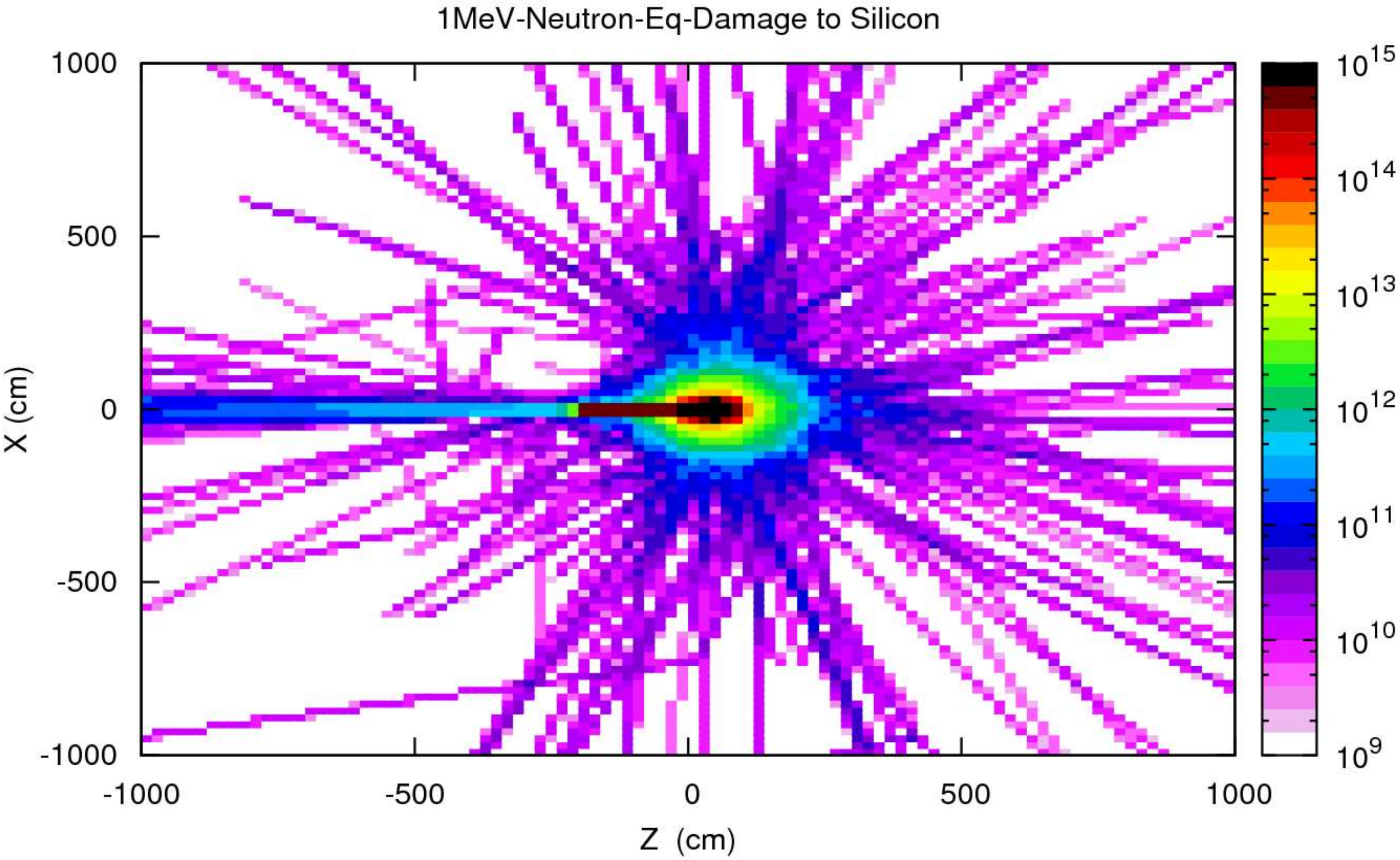
Dipole + Collimator + Dump



40 cm collimator box + 100cm tungsten pipe

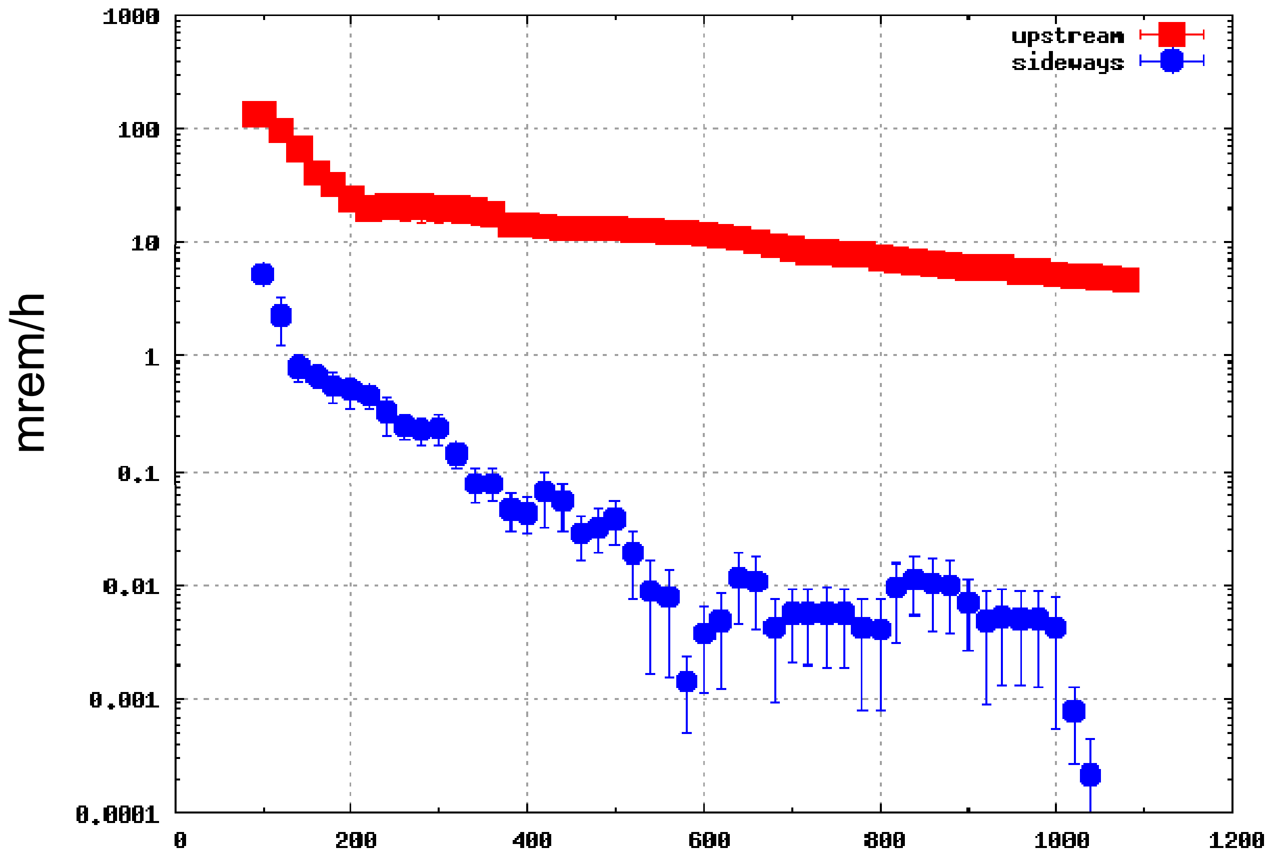
Collimator shielding: 100cm concrete + 100 cm borated plastic

Radiation Damage from Dump 1 MeV Neutron Equivalent



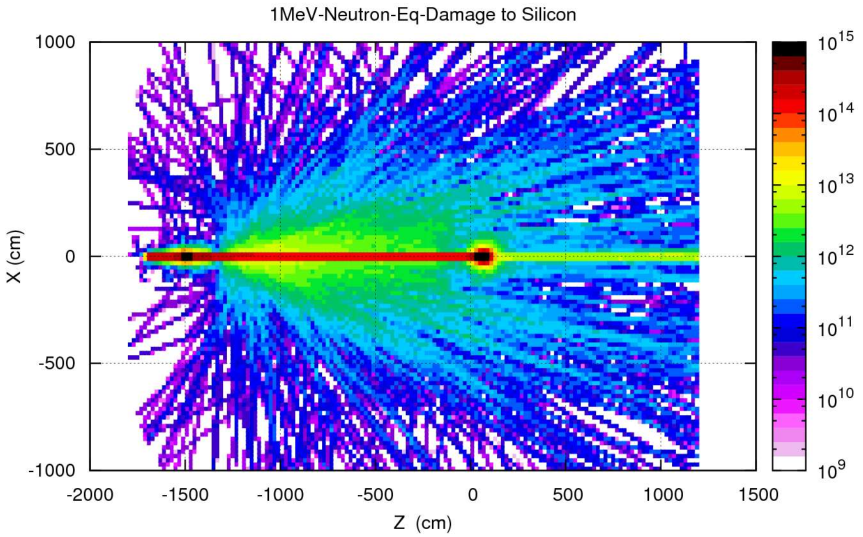
Dump only, 4 weeks of 3uA beam @ 8.8 GeV

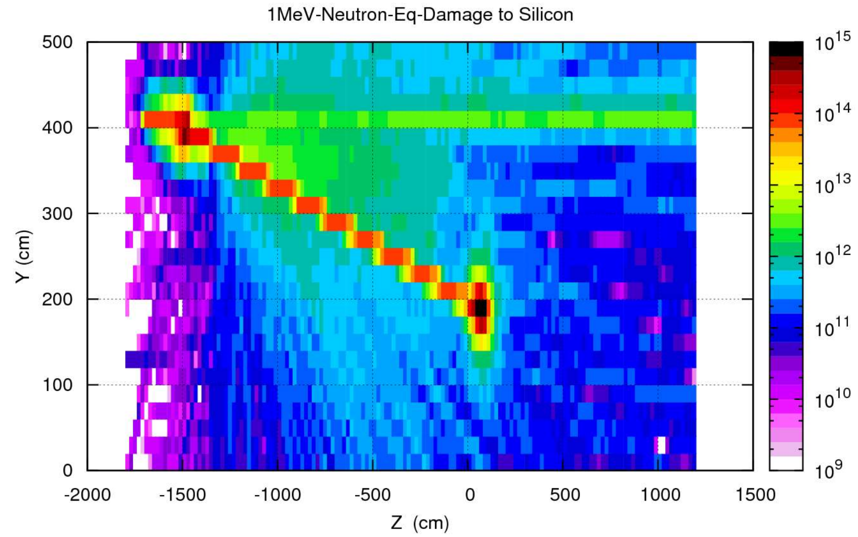
Activated Radiation Dose Rate



Upstream means -30 < x < 30, **include** the beam pipe
Dump only, 4 weeks of 3uA beam @ 8.8 GeV

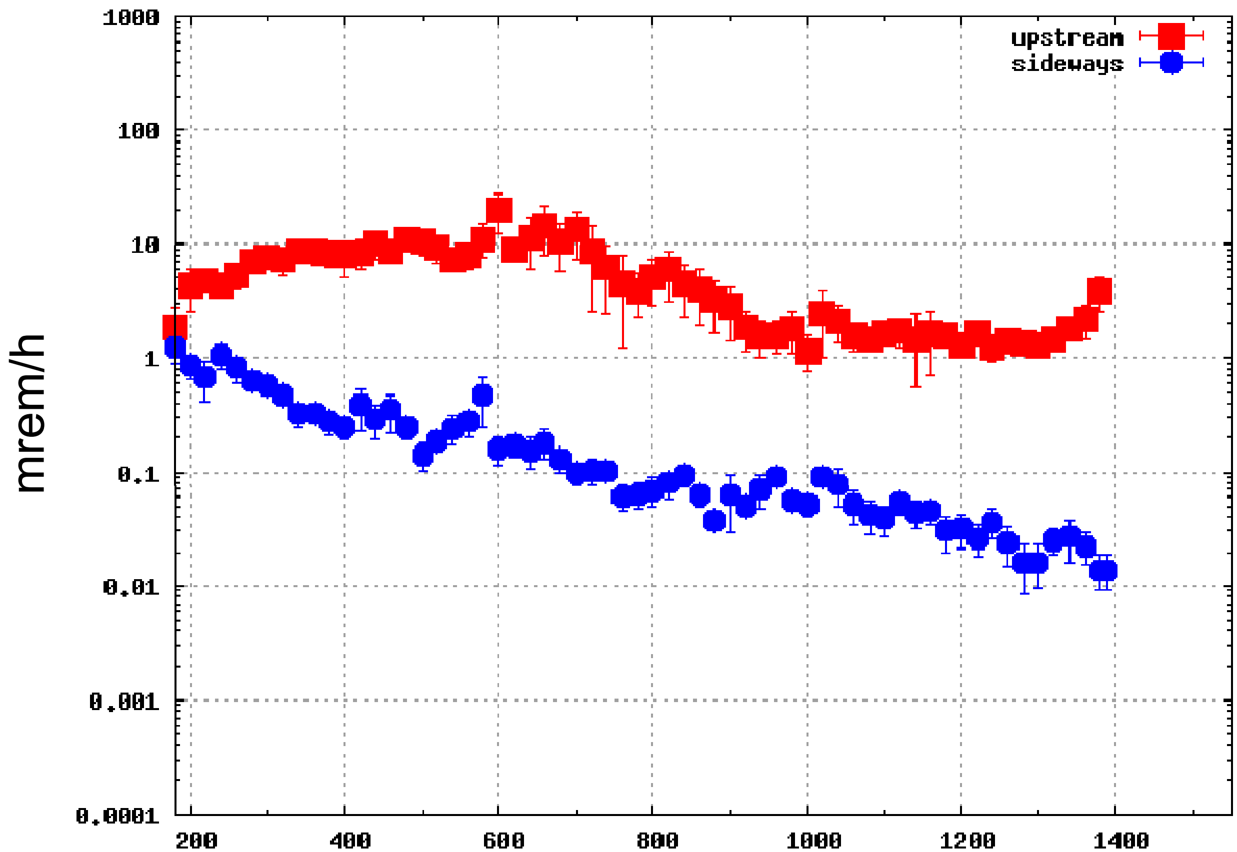
Dipole+Collimator+Dump
1 MeV Neutron Equivalent





4 weeks of 3uA beam @ 8.8 GeV

Dipole+Collimator+Dump Activated Radiation Dose Rate @ 1 h



Upstream means 20 < R < 50, NOT include the beam pipe, sliding door not shift to park mode yet!
4 weeks of 3uA beam @ 8.8 GeV

Summary

1) FLUKA simulation has been performed for a simple dump and its shielding.

2) A dump that similar to the CEBAF tune-up dump, together with the FZ dipole and collimator has been simulated in FLUKA. The same setup has also been studied by Geant4 for cross checking.

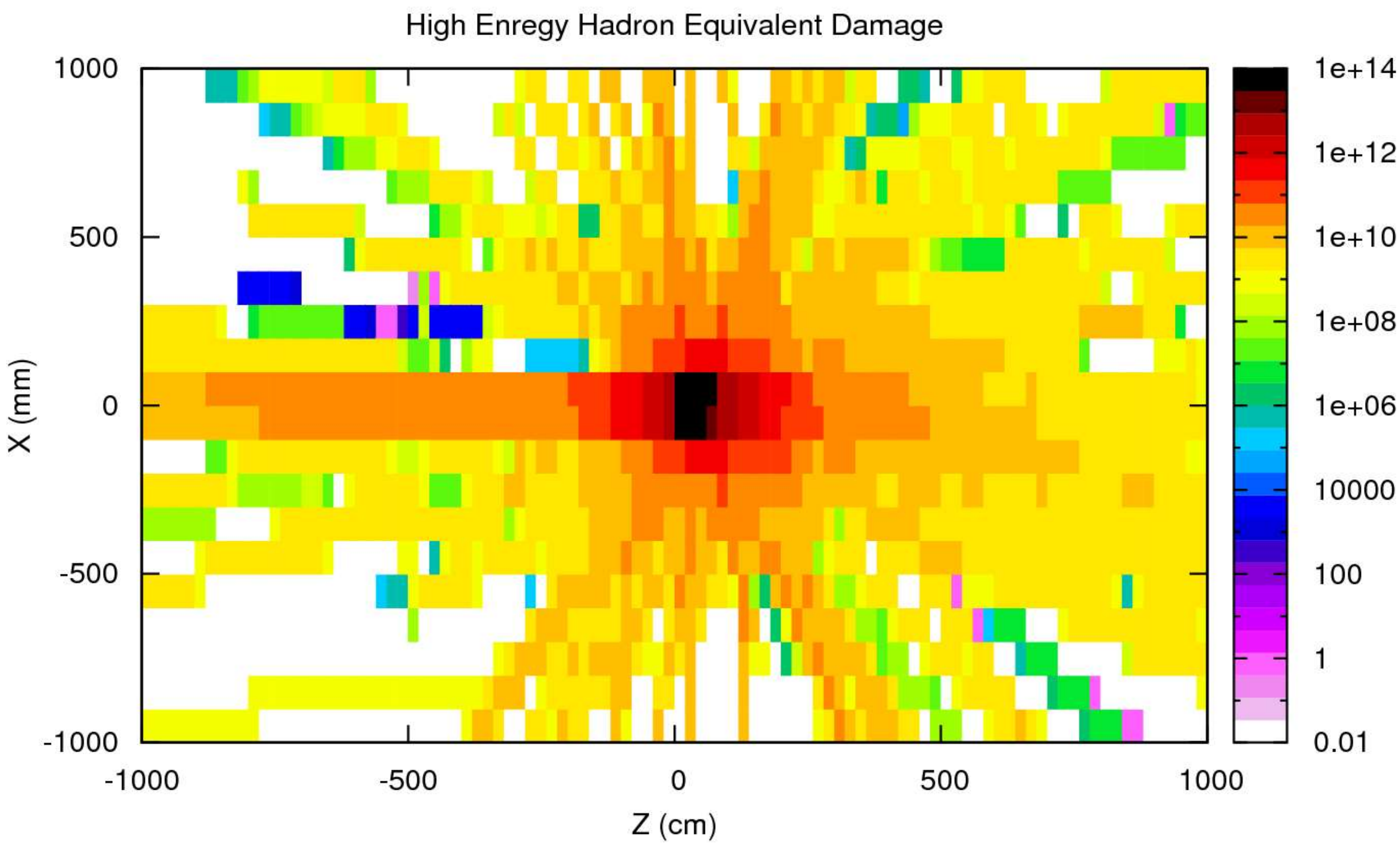
3) Place sliding door to block the dump entrance can effectively reduce residual radiation in the upstream of the dump. The 1 MeV neutron equivalent damage in our current design is below 10^13.

4) There is enough space for us to shield the dump and collimator.

5) We are now working on optimizing the thickness combination of tungsten (lead), concrete and borated plastic.

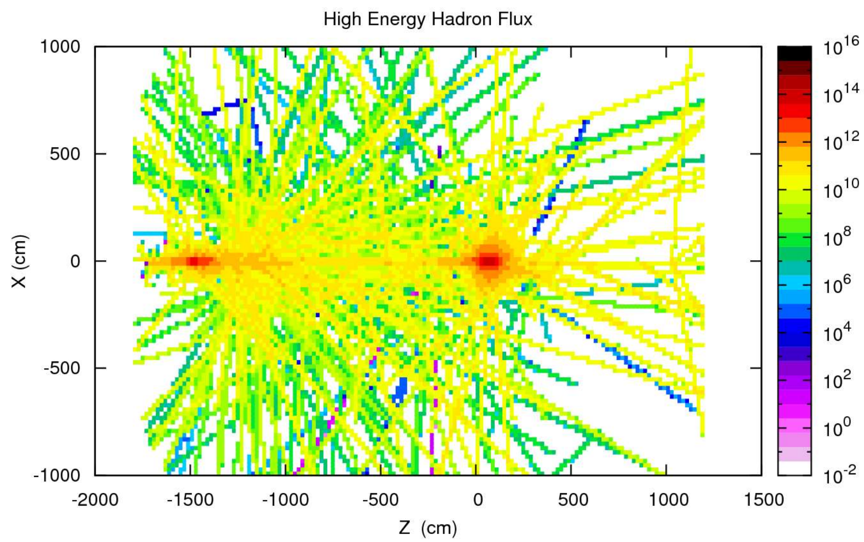
Back up

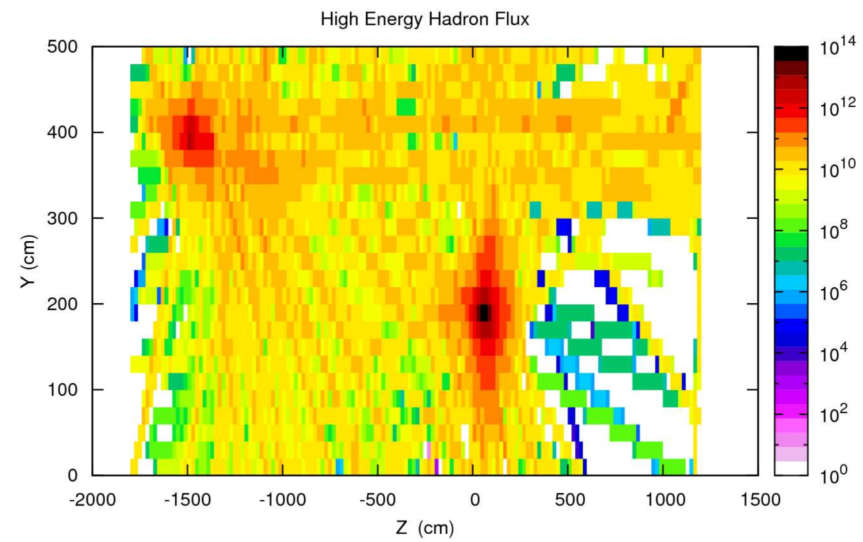
Radiation Damage from Dump
High Energy Hadron Fluence



Dump only, 4 weeks of 3uA beam @ 8.8 GeV

Dipole+Collimator+Dump
High Energy Hadron Fluence





4 weeks of 3uA beam @ 8.8 GeV