Radiological Safety Considerations of a 40 kW 35 MeV Electron Linear Accelerator at the Canadian Light Source

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7th International Workshop on Radiation Safety at Synchrotron Radiation Sources

Brookhaven National Laboratory, New York, USA

Scope of Presentation

- Highlights of Medical Isotope Project
- Radiation Shielding Design
- Hazard perceptions and their Mitigations
- Calculated radiation shielding using IAEA Technical document # 188
- Fluka simulated MC dose and fluence

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MIP – Objective & Safety

- Class-II Nuclear Facility – Independent Licence
- Production of Mo-99 - Medical Diagnostics Use
- High Power Linear Accelerator – High Mo Yield
- Commissioning Licence just obtained from CNSC and commission is in progress
- Operating Licence Expected – Q3, 2013
  - Radiation Commissioning report, MIP Safety Procedures & ACIS Training
- First shipment of Product – Q4, 2013

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Medical Diagnostics Use

- The moly-99 will be shipped off site to a medical lab
- It has a half life of 66 hours
- It decays to Technetium-99m (^{99m}Tc)
- half life = 6 hours
- The tech-99m is used for medical diagnostic procedures

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How it Works?

- The accelerator is an electron linear accelerator (linac)
  - 35 MeV
  - 40 kW
- The electrons hit a “converter” target to produce Bremsstrahlung
- The Bremsstrahlung photons hit ^{100}Mo target (a stable isotope) to produce ^{99}Mo from the Nuclear Reaction $^{100}Mo(\gamma,n)^{99}Mo$

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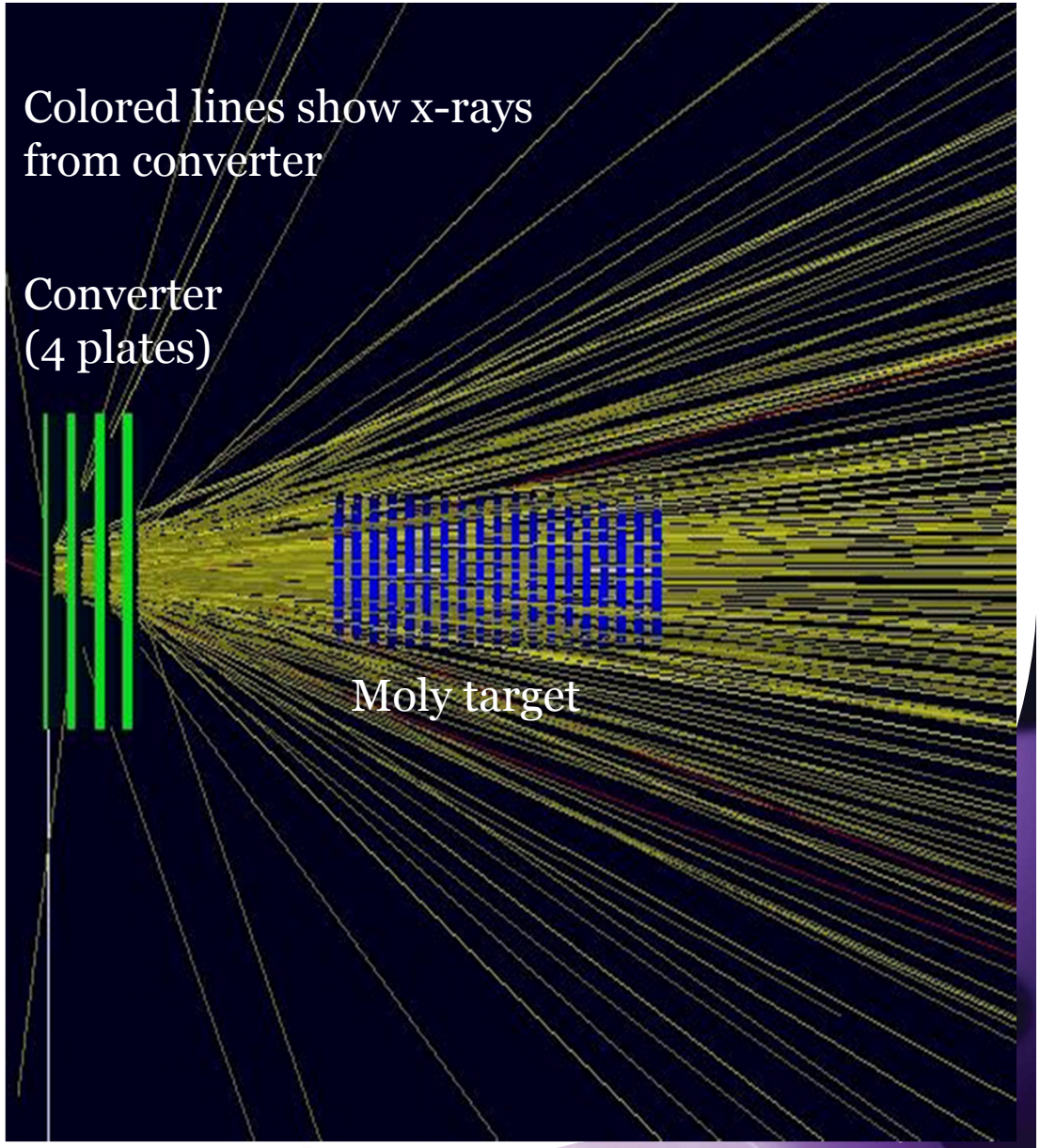
Pictorial Overview of MIP

Electron beam



Converter – 4 Tantalum plates
Moly target – 18 plates

MIP Safety Requirements

- Shielding Radiation Level to ALARA
- ACIS – Prohibit Entry to Radiation Zone
- Radiation Hazards from Water, Air & accelerator components
- Non-Radiation Hazards –Ozone, H2 & O2 deficiency (SF6)
- Remote handling of the desired product Mo
- Shipping with Class-A Container

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MIP Shielding

There are two types of shielding:

- Local Shielding close to the accelerator & target
  - Lead
  - Steel
  - Polyethylene (for neutrons)
- Room Bulk shielding
  - concrete and earth

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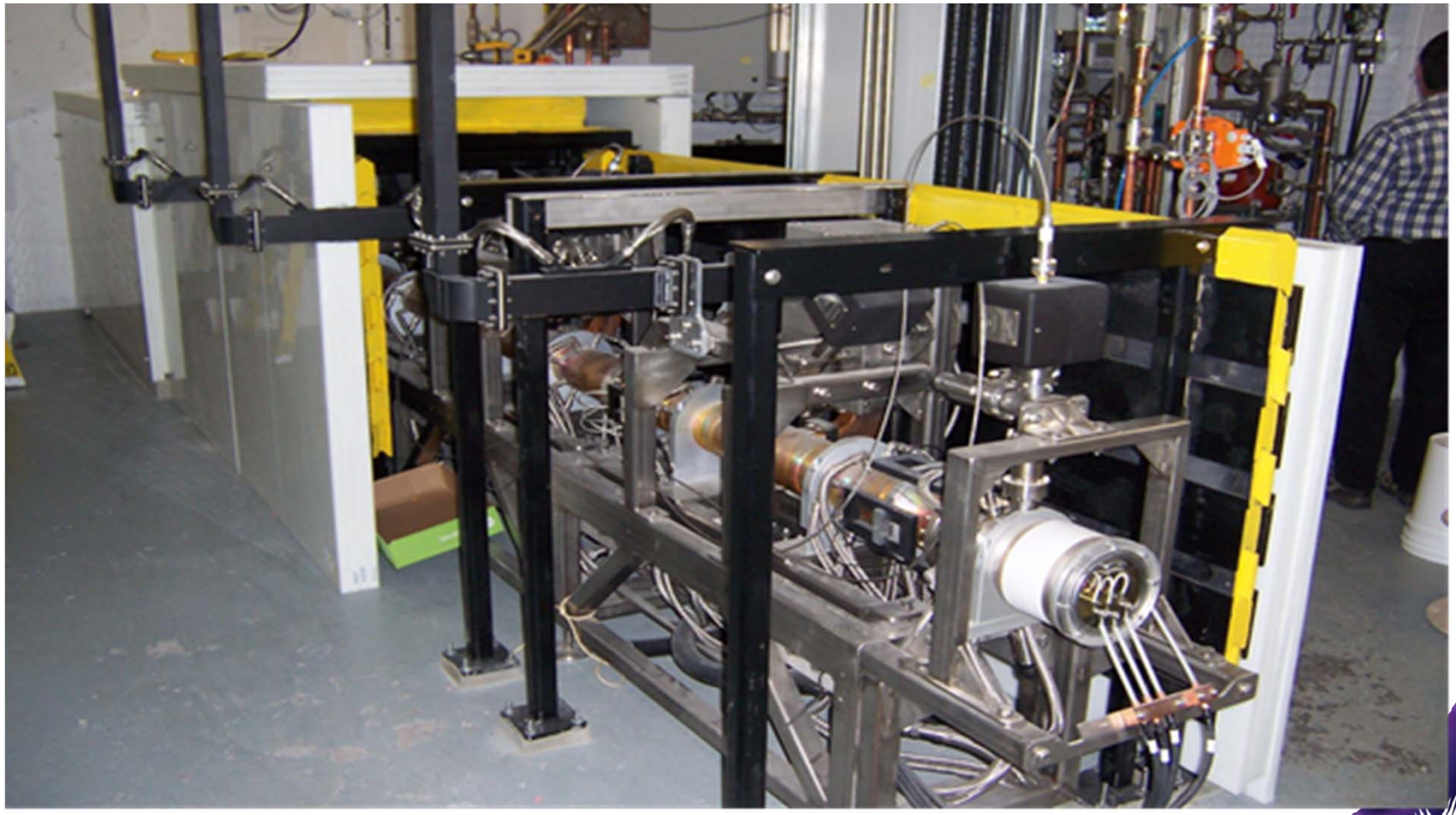
Linac and target shielding



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Bremsstrahlung Radiation

- For electron energies above a few MeV, the bremsstrahlung is produced mainly in the forward direction. The conversion of electron energy to bremsstrahlung is described in detail in Section 2.4 of the IAEA document "Technical Report Series – 188" equation (17), the 0° radiation dose rate at one metre produced by a 35 MeV electron beam incident upon a thick tantalum target is given by:

  R_0 (Sv/h) = 300 × 35 MeV × 40 kW

  = 4×10^5 Sv/h at 1 m

- Similarly, using equation (18), the approximate 90° radiation dose rate one meter from the target is given by:

  R_{90} (Sv/h) ≈ 50 × 40 kW

  = 2×10^3 Sv/h at 1 m

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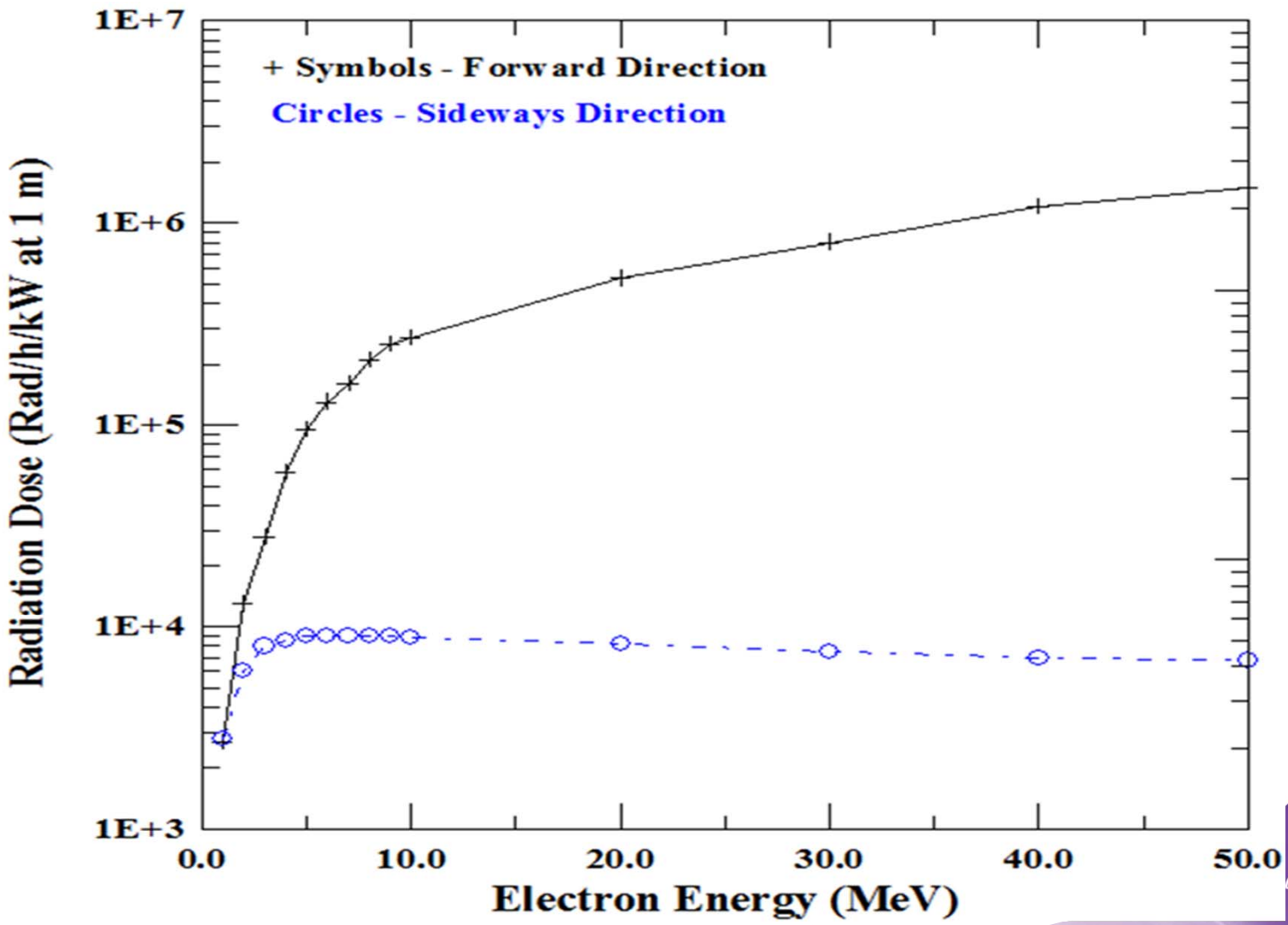
Thick-target bremsstrahlung yield from a high-Z target

The y-axis is the radiation dose at one meter from the thick target in units of rads/h/kW, Ref. [Technical Report Series – 188].



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Neutron Radiation

- The total neutron yield has been estimated by using a conservative assumption that the 35 MeV, 40 kW electron beam is stopped entirely in a thick heavy target such as tantalum or lead.

- From Table XV in reference [IAEA – 188], the thick target neutron yield of a tantalum target is 1.2×10^{12} n/s/kW at ~ 35 MeV. This is multiplied by 40 kW to produce a neutron yield of:

$$Y_{neutron} \sim 5 \times 10^{13} \text{ n/s}$$

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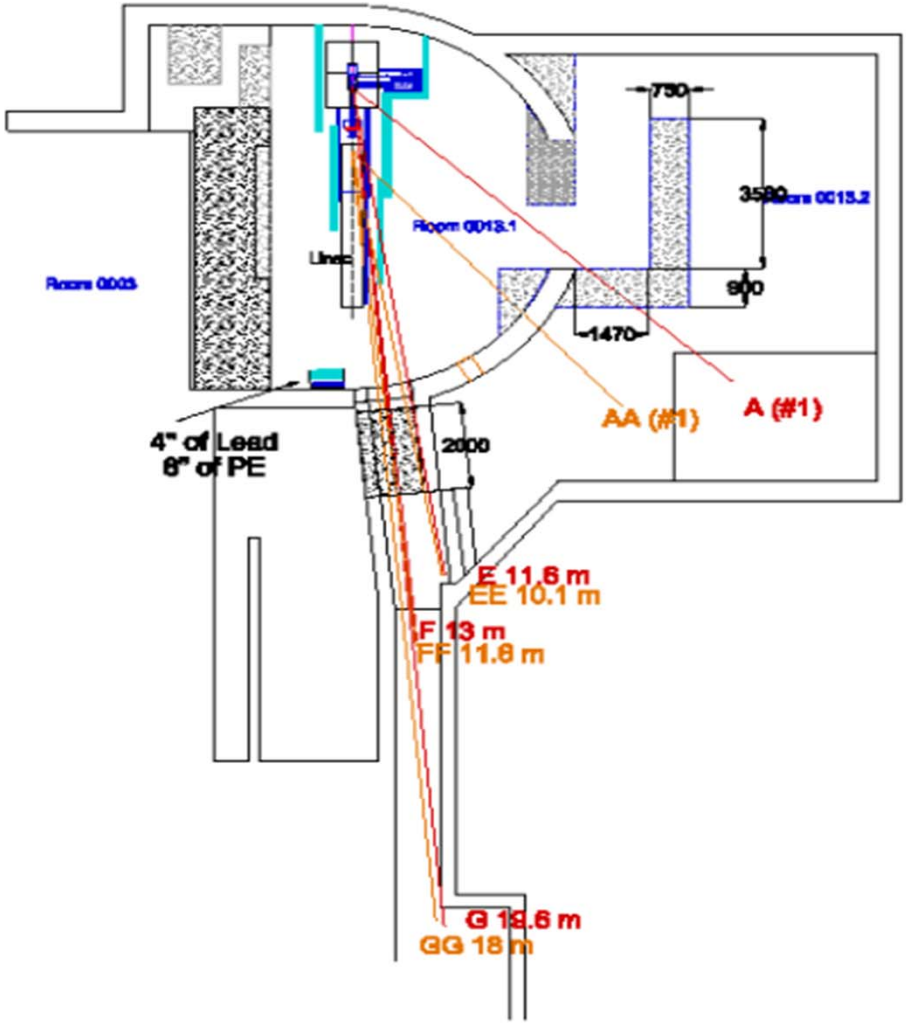
Source and Dose Points for the MIP shielding Design



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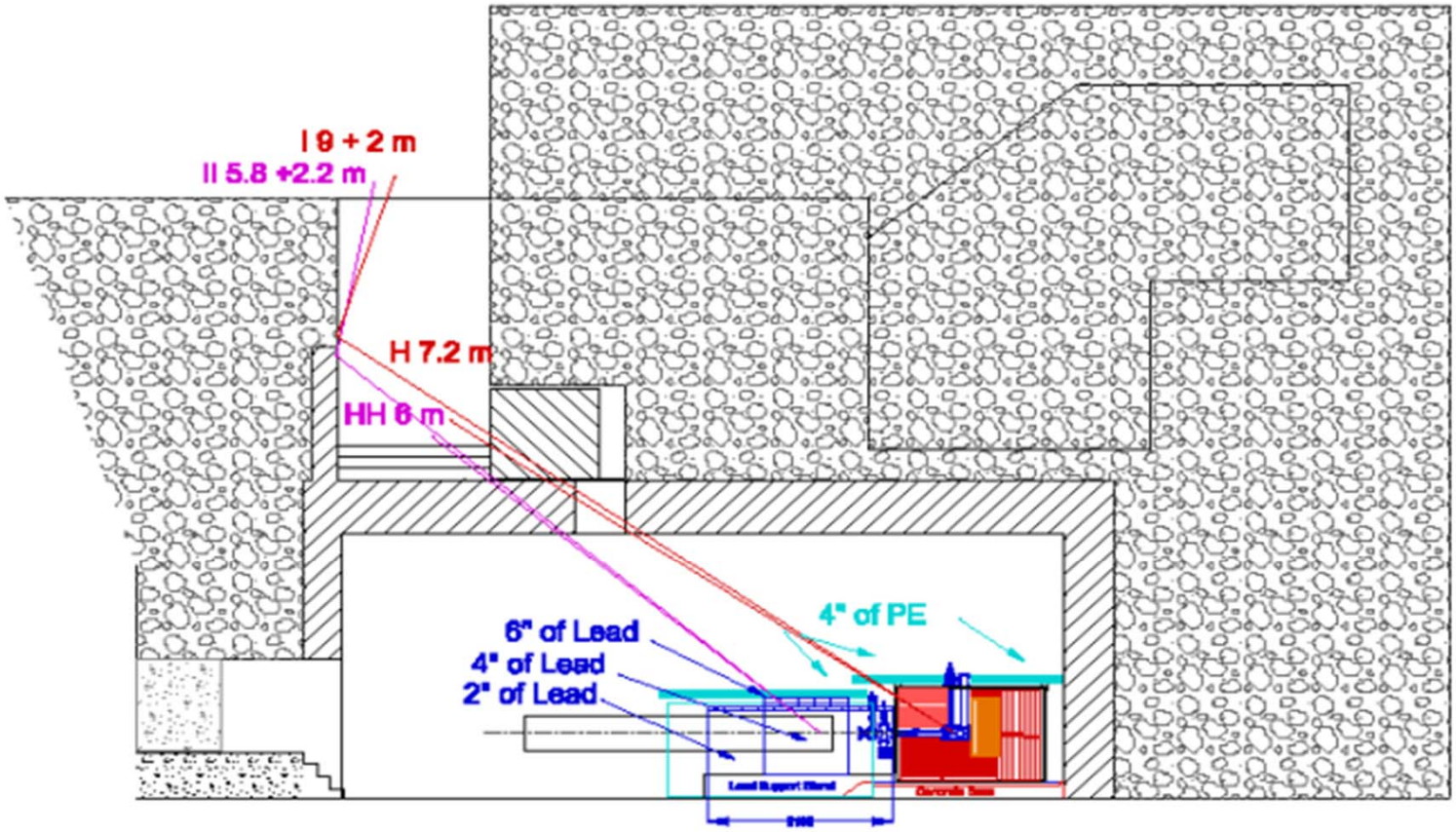
Source and Dose Points for the MIP shielding Design

Shielding for Positions H and I (HH and II)



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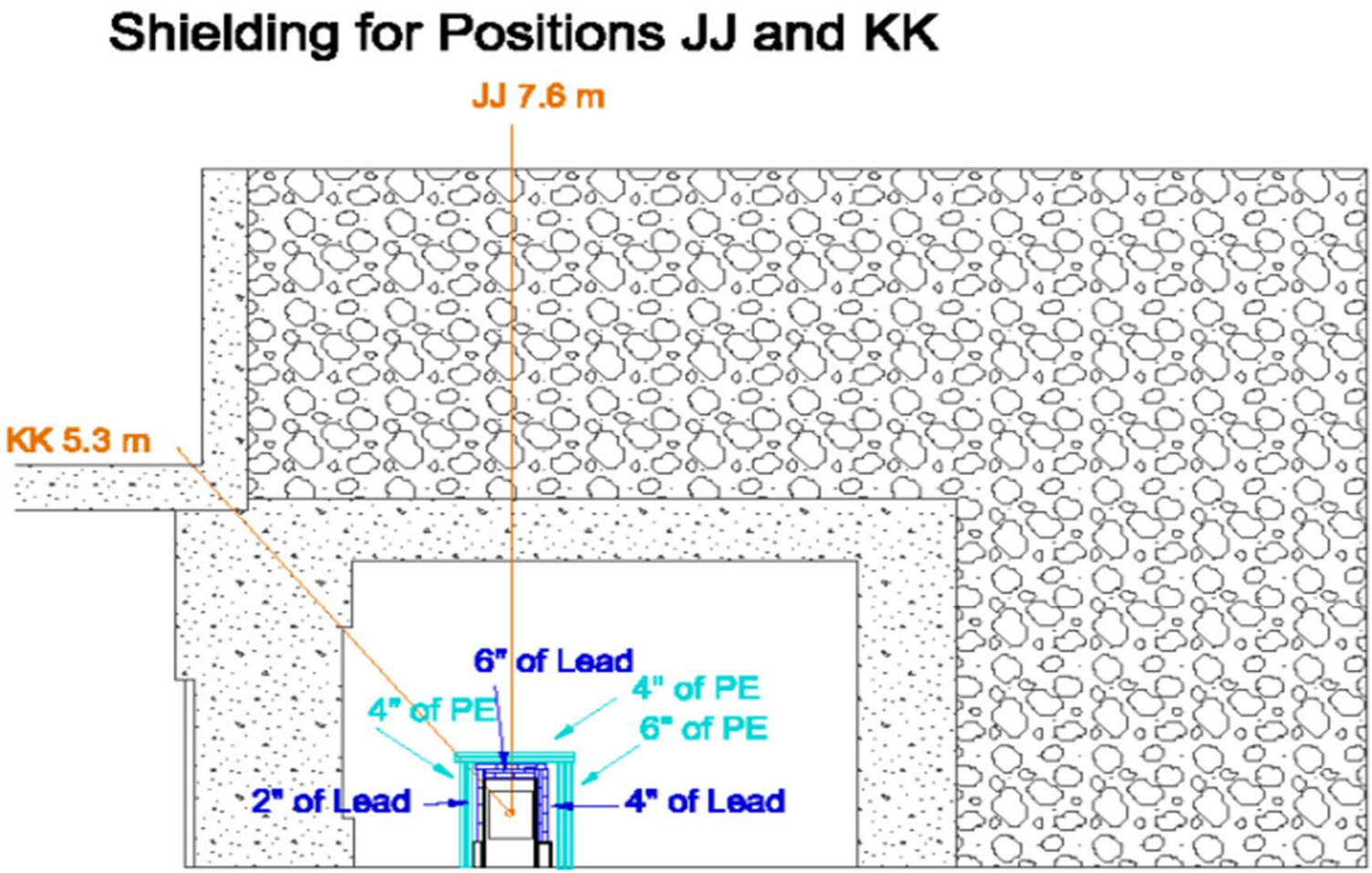
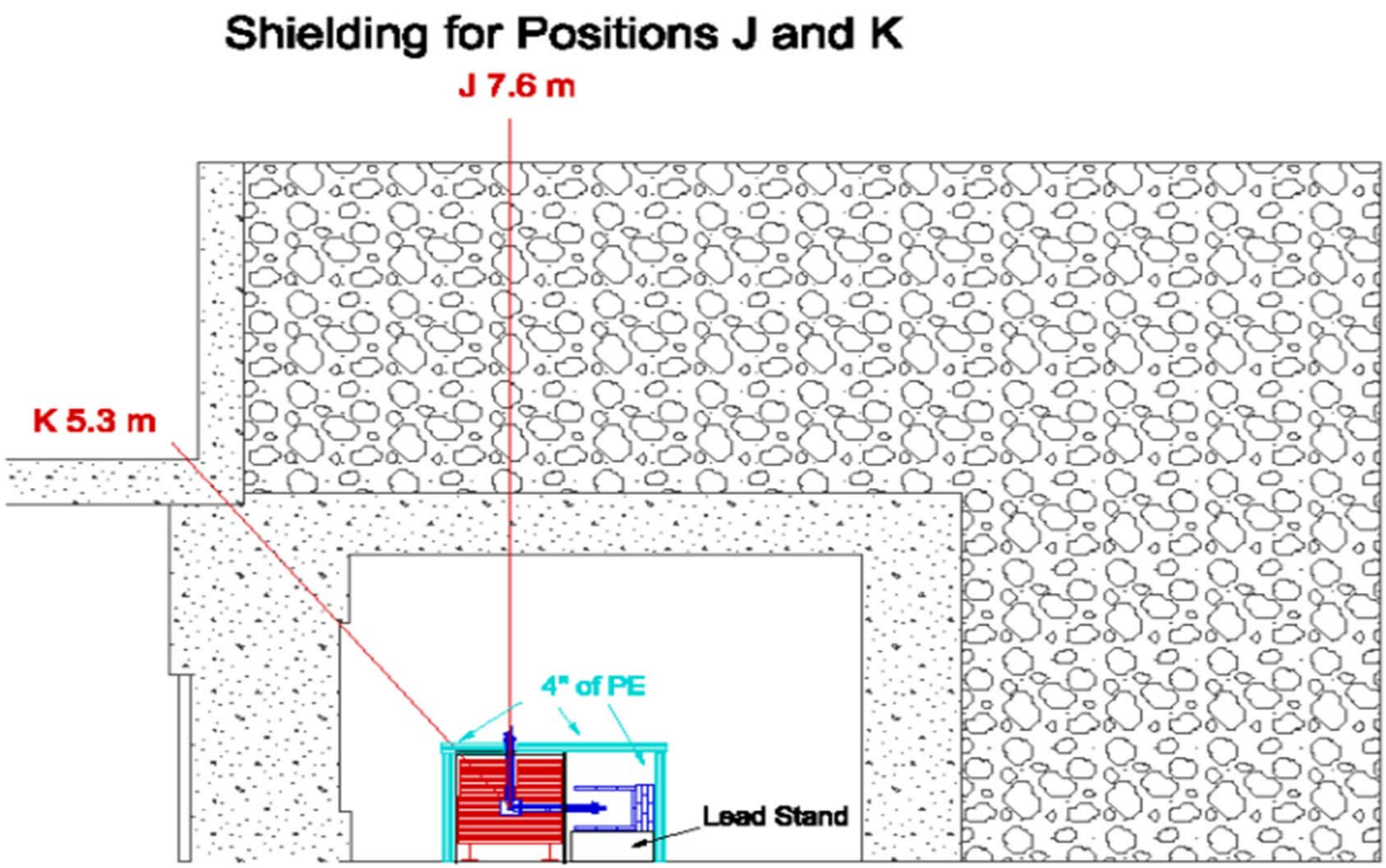
Source and Dose Points for the MIP shielding Design



Source and Dose Points for the MIP shielding Design



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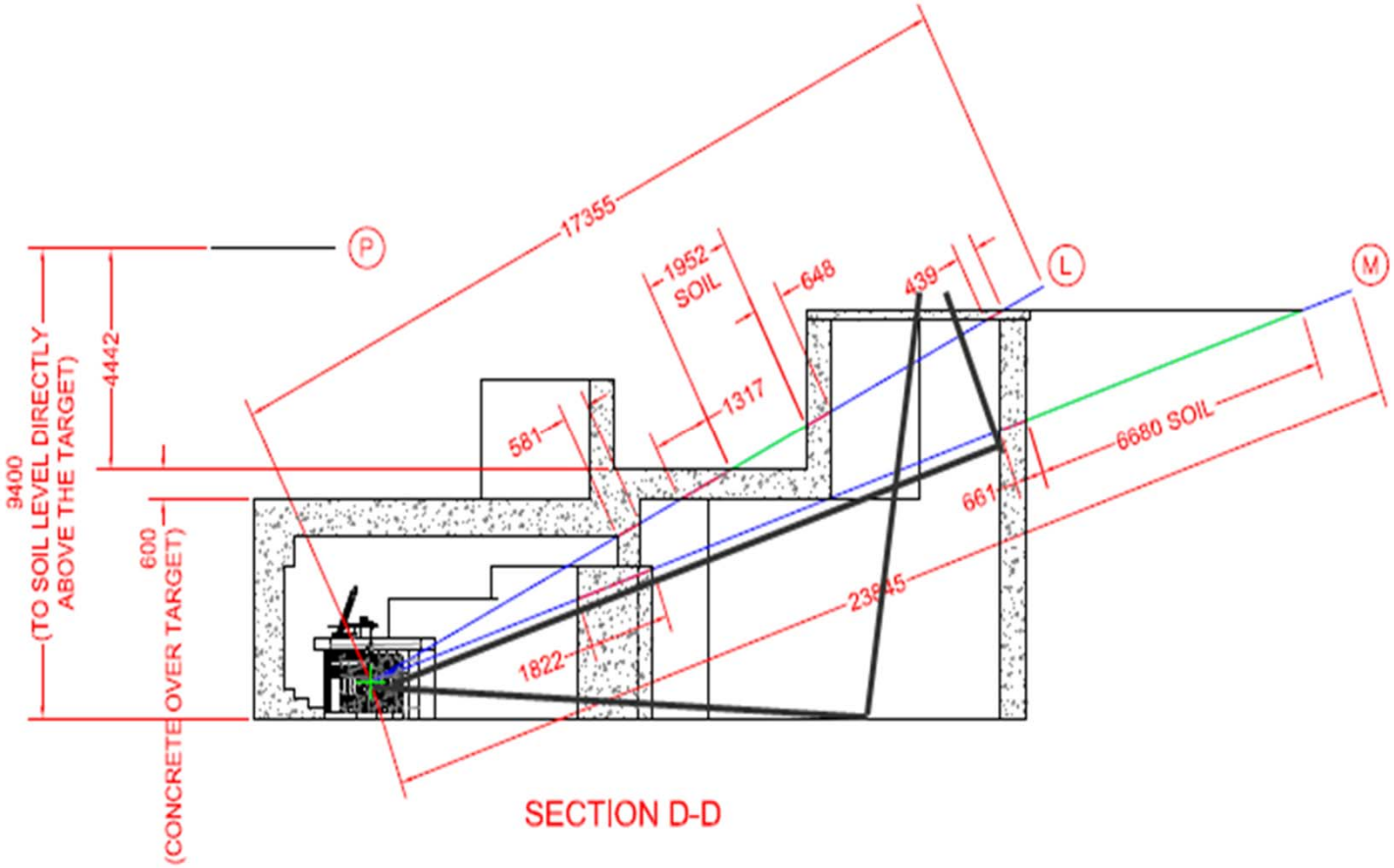
Source and Dose Points for the MIP shielding Design

- **Rays for Positions A-1 and A-2 and Path Lengths for Positions L and M.**



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Bremsstrahlung Shielding

- For bremsstrahlung, the primary barrier transmission factor is determined using equation 2.1 in NCRP-151:

$$B_{pri} = P(d_{pri})^2/WUT$$

- Where: P is the shielding goal (expressed as dose equivalent) beyond the barrier
- d_{pri} = distance from the source to the dose point
- W = photon dose at one m from the source
- U = fraction of the workload that the beam is directed at the barrier in question
- and T = occupancy factor at the dose point

- Number of 1/10th-values of shielding required: $n = -\log(B_{pri})$
- Shielding barrier thicknesses have been evaluated based on ALARA:

  Individual occupational doses are unlikely to exceed 1 mSv per year

  Dose to individual members of the public is unlikely to exceed 50 µSv per year
- Using these recommendations as the shielding goal (P) and a yearly operation of 2000 hours (U) leads to exposure rates of:

  Controlled areas 0.5 µSv/h

  Non-controlled areas 0.025 µSv/h

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Calculated dose equivalent for bremsstrahlung photons at select positions.

Position	P/UT µSv/h	n - # of 1/10th-value layers required	n - # of 1/10th-value layers Installed (Plus scattering)	Calculated Photon Field µSv/h
AA or A (#1) PO	0.25	5.0	8.3	0.001
AA or A (#2) PO	0.25	5.4	8.2	0.001
HH or H NEW	5.0	6.5	8.5	0.37
II or I PO	0.25	5.4	9.5	0.03
JJ PO	0.25			0.02
J PO	0.25	8.3	9.5	0.02
KK NEW	2.5			0.4
K NEW	2.5	7.6	10.8	0.002
LL and L PO	0.25	7.3	12.2	3×10^{-4}
MM and M PO	0.25	7.7	15	1×10^{-8}
EE and E NEW	5.0	6.6	21.5	3×10^{-5}
FF and F NEW	25	5.9	13.3	1.2×10^{-6}
GG and G NEW	5.0	6.2	13.7	2×10^{-7}

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Calculated dose equivalent for neutrons at select positions.

Position	P/UT µSv/h	n - # of 1/10th-value layers required	n - # of 1/10th-value layers Installed (Plus scattering)	Calculated Neutron Field µSv/h
AA or A (#1) PO	0.25	4.7	10.1	0.008
AA or A (#2) PO	0.25	5.6	11.2	3×10^{-4}
HH or H NEW	5.0	5.2	6.8 + (2.0) = 8.8	0.26
II or I PO	0.25	5.8	8.6 + (1.0) = 9.6	0.01
JJ PO	0.25			1×10^{-5}
J PO	0.25	6.0	8.6	6×10^{-4}
KK NEW	2.5			0.002
K NEW	2.5	5.5	11.4	3×10^{-7}
LL and L PO	0.25	5.5	11.0	1.8×10^{-6}
MM and M PO	0.25	5.3	18.9	-
EE and E NEW	5.0	4.6	11.2	2×10^{-4}
FF and F NEW	25	4.1	5.6	0.83
GG and G NEW	5.0	4.3	5.6	0.26

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Air and Water Hazards

4.2 HAZARDS ASSOCIATED WITH INDIVIDUAL SUBSTANCES

The medical Isotopes Project (MIP) has several potential hazards due to radioisotopes, ozone, or hydrogen gas produced in the cooling water or room air. We need to demonstrate that these products cause a negligible hazard or that adequate precautions are taken to mitigate the hazard.

In the air, the main products of interest are ^{15}O, ^{13}N, ^{41}A and ozone (O_3). In the water they are ^{11}C, ^{15}O, ^{7}Be, ^{3}H (tritium) and hydrogen (H_2). ^{11}C, ^{15}O, ^{13}N, ^{7}Be, and ^{41}Ar are gamma emitters; tritium is a weak beta emitter only hazardous if ingested; ozone is a gaseous poison.

An additional hazard is the possibility of a sulfur hexafluoride (SF_6) leak from the waveguides. Sulfur hexafluoride is an asphyxiant, heavier than air.

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Cooling Water Hazards

The following table showed the activities for the Moly-99 production target water 2.1 cm path length system:

Nuclide	$t_{1/2}$	Saturation Activity (GBq)	Activity after 2000 h of operation (GBq)	Dose at 100 cm (if contained in a 42 USG tank) (mSv/h)
O-15	123 s	264	264	22.9
O-14	70.9 s	3.0	3.0	*0.26*
N-13	9.96 m	3.0	3.0	0.26
C-11	20.34 m	12.0	12.0	1.04
C-10	19.5 s	3.0	3.0	*0.26*
Be-7	53.6 d	1.2	0.8	0.0034
H-3 (tritium)	12.26 y	6.0	0.08	-
Total at EOB				24.6

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Ventilation to Reduce Hazard

- The linac room will be ventilated with a fan with a rate of 700 ft^3 min^{-1}.
- ^{13}N is the dominant gaseous radioisotope produced by the (γ,n) reaction. The concentration of the ^{13}N will be 1.1 x 10^{-3} Bq/cm^3, which is below the MPC (maximum permissible concentration) of 0.074 Bq/cm^3.
- Argon activation from neutrons streaming out the shielding void in place for the converter target support is estimated to give a concentration of 0.014 Bq/cm^3 for ventilation of 700 ft^3 min^{-1}, where the MPC is 0.2 Bq/cm^3.
- The total ozone production in the room including the shielding void spaces inside is conservatively estimated to be 1.4 x 10^{-8}. This is well below the allowable concentration (threshold limit value) of 10^{-7}.

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Monte Carlo Fluka Simulation of

- Statistics Obtained for 15 Million Particles
- 35 MeV Electrons at 40 kW power
- Dose Calculated for Converter, Target, Beam Dump and Shielding structures
- Independent dose profiles from electron, gamma and neutron are exhibited
- Fluence map of the electron beam entrance at Diamond window & converter exit done

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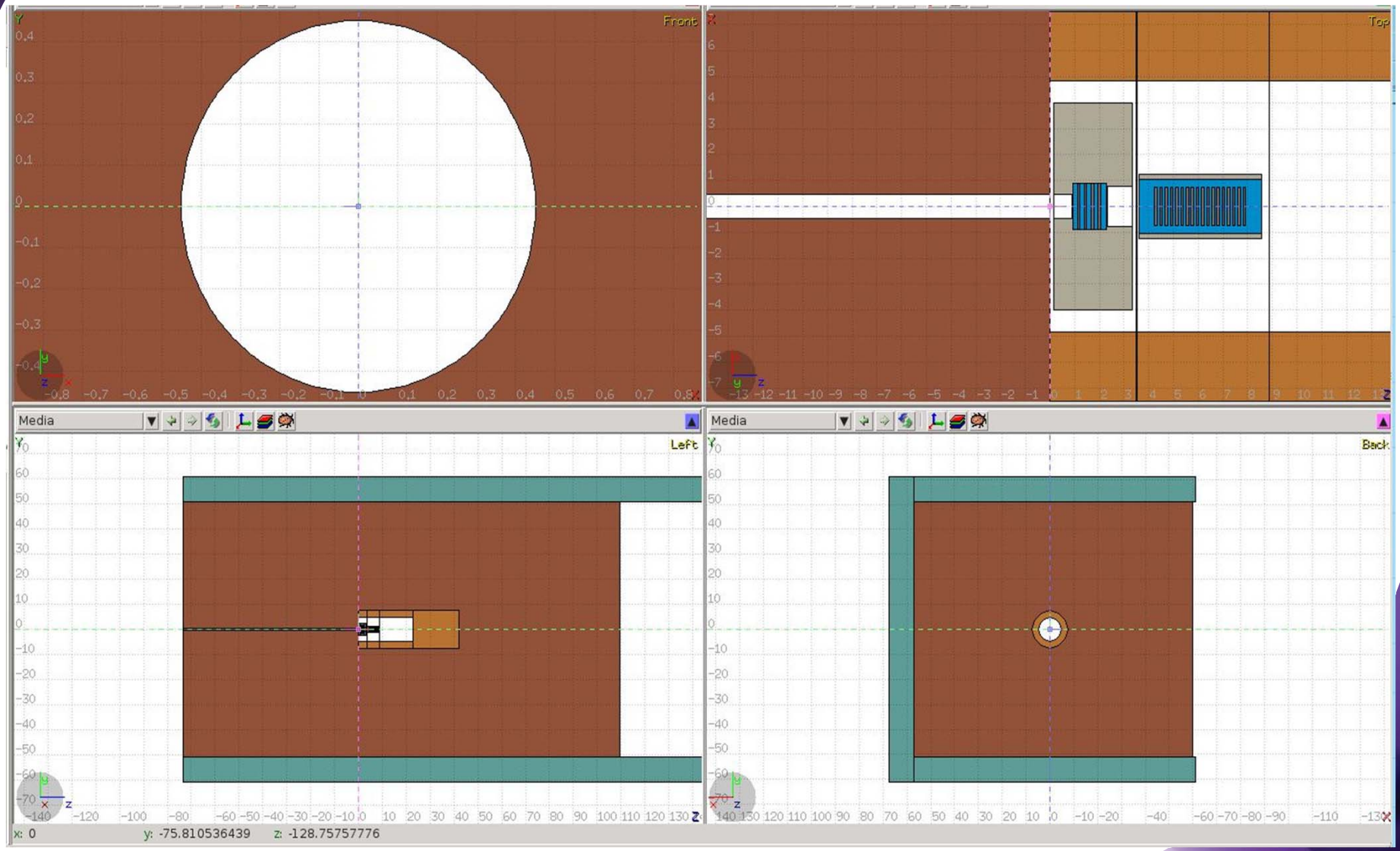
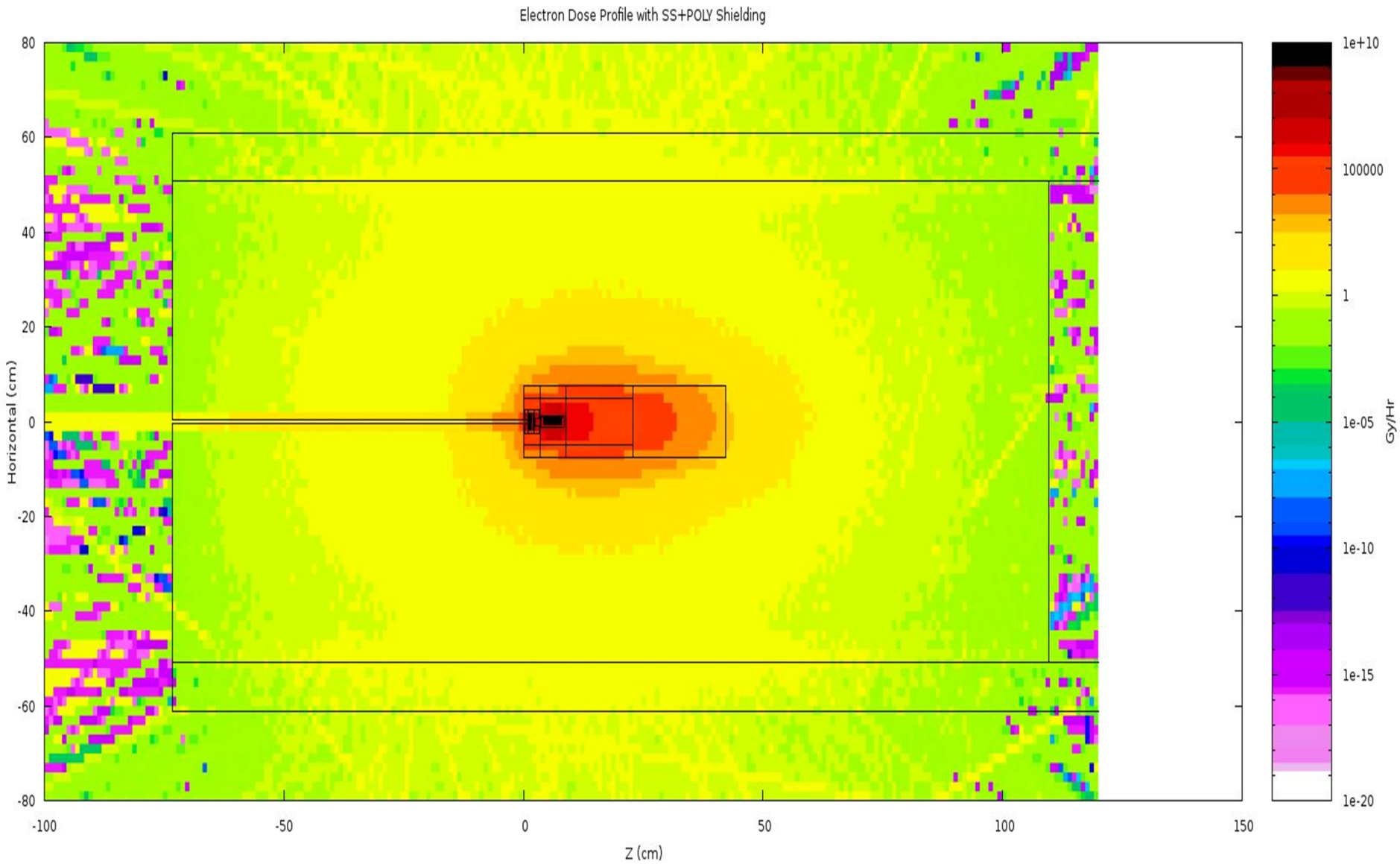
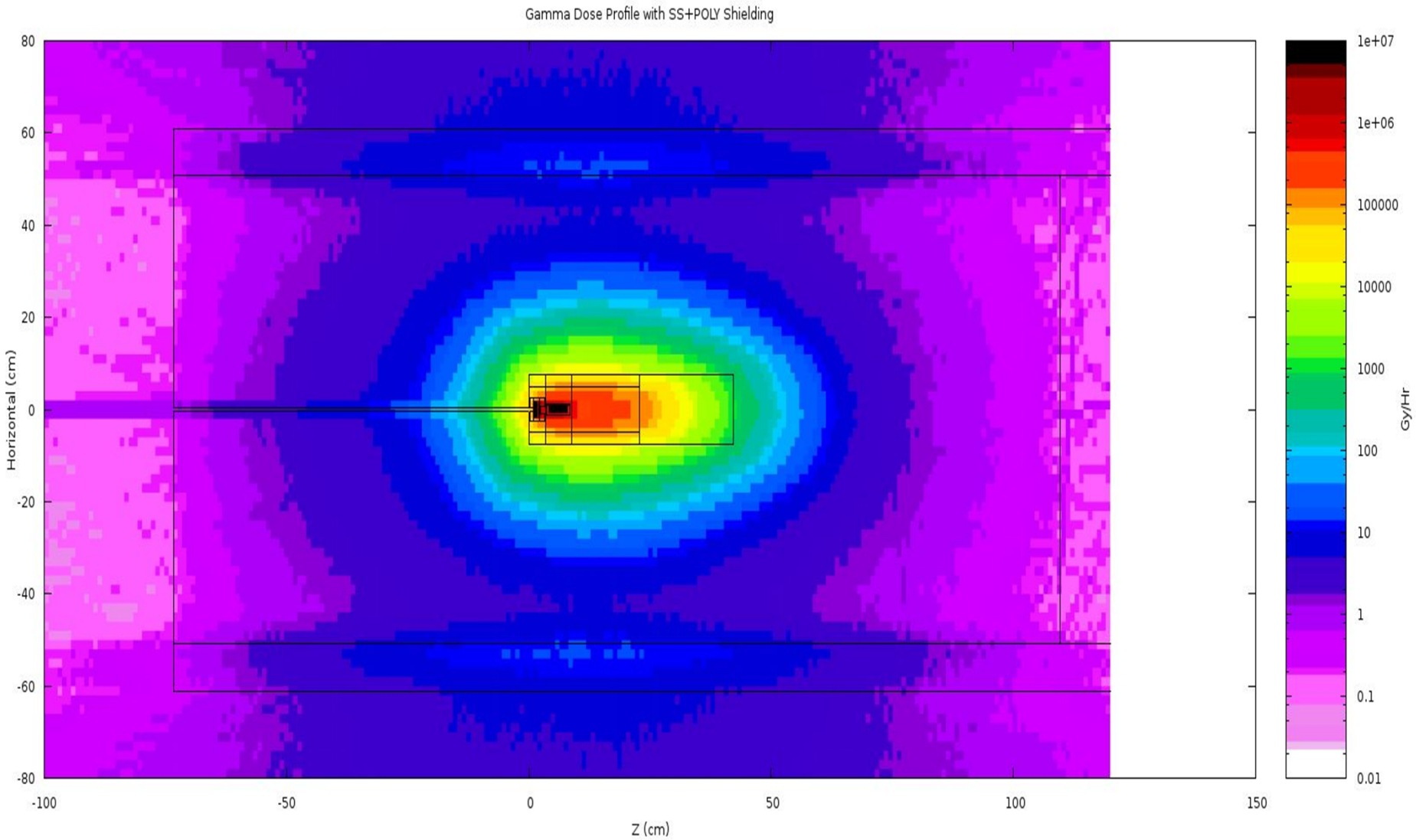
Four views of the geometries of materials used for Fluka simulation



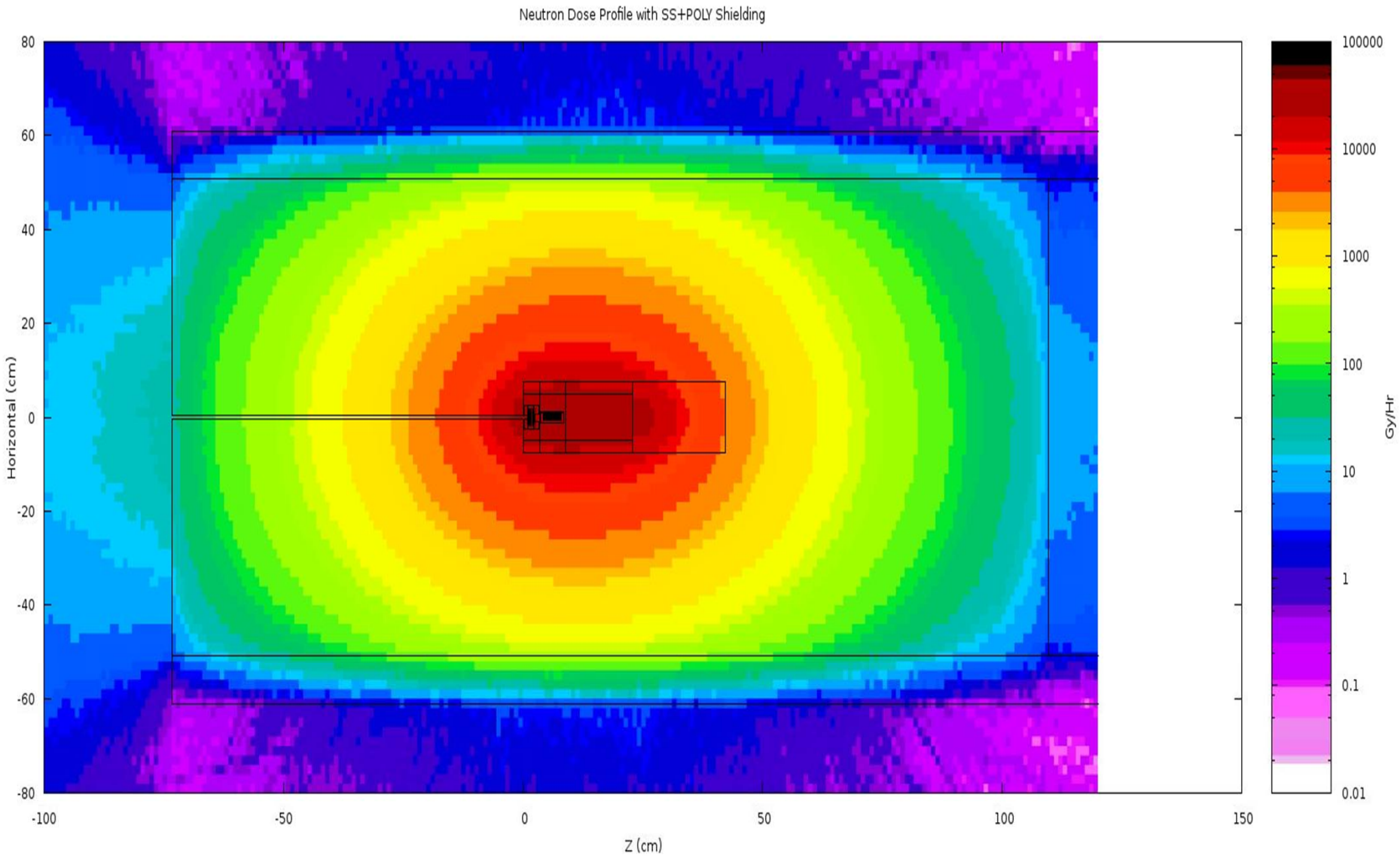
Electron Dose Profile / SS+Poly



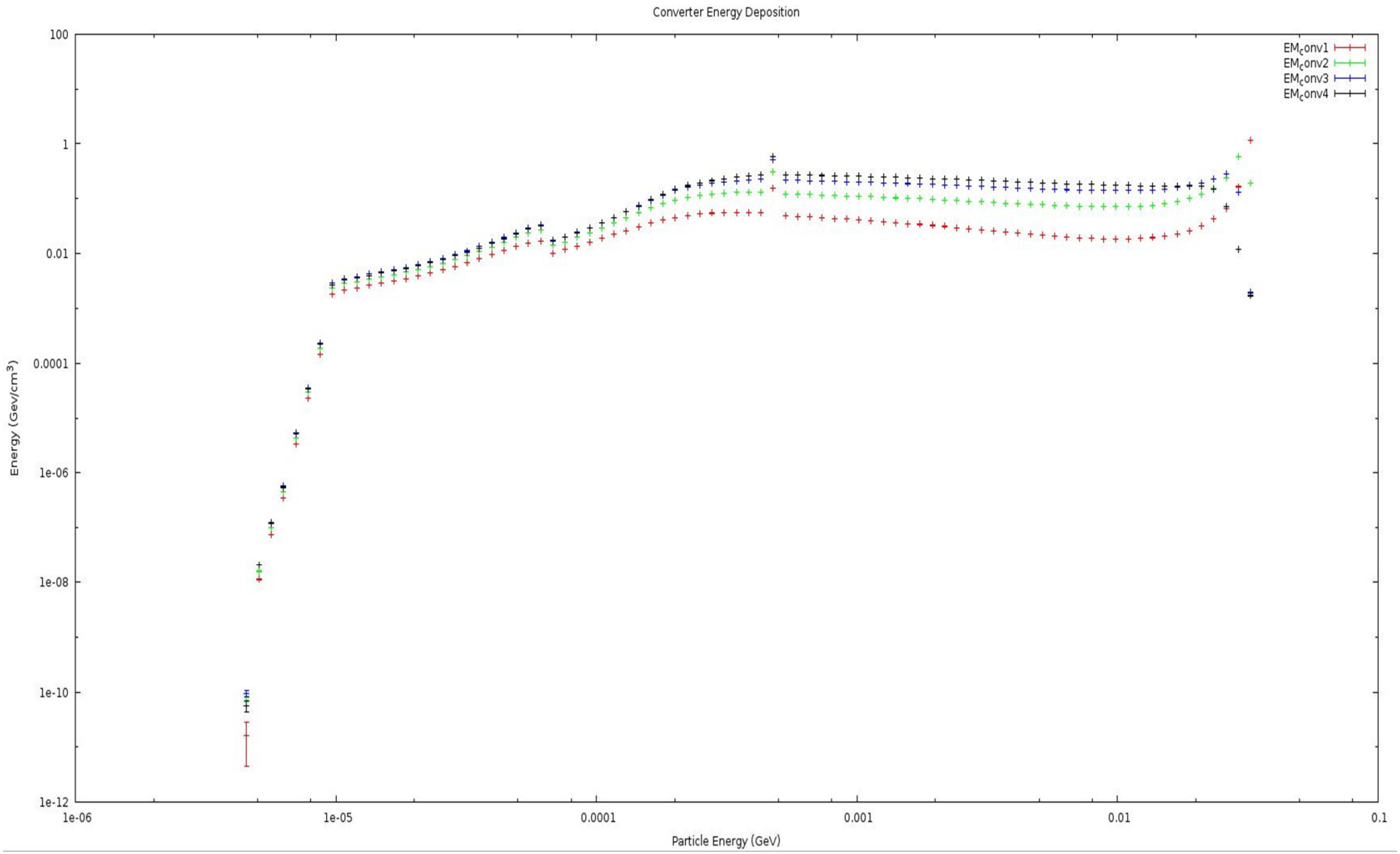
Gamma Dose Profile / SS+Poly



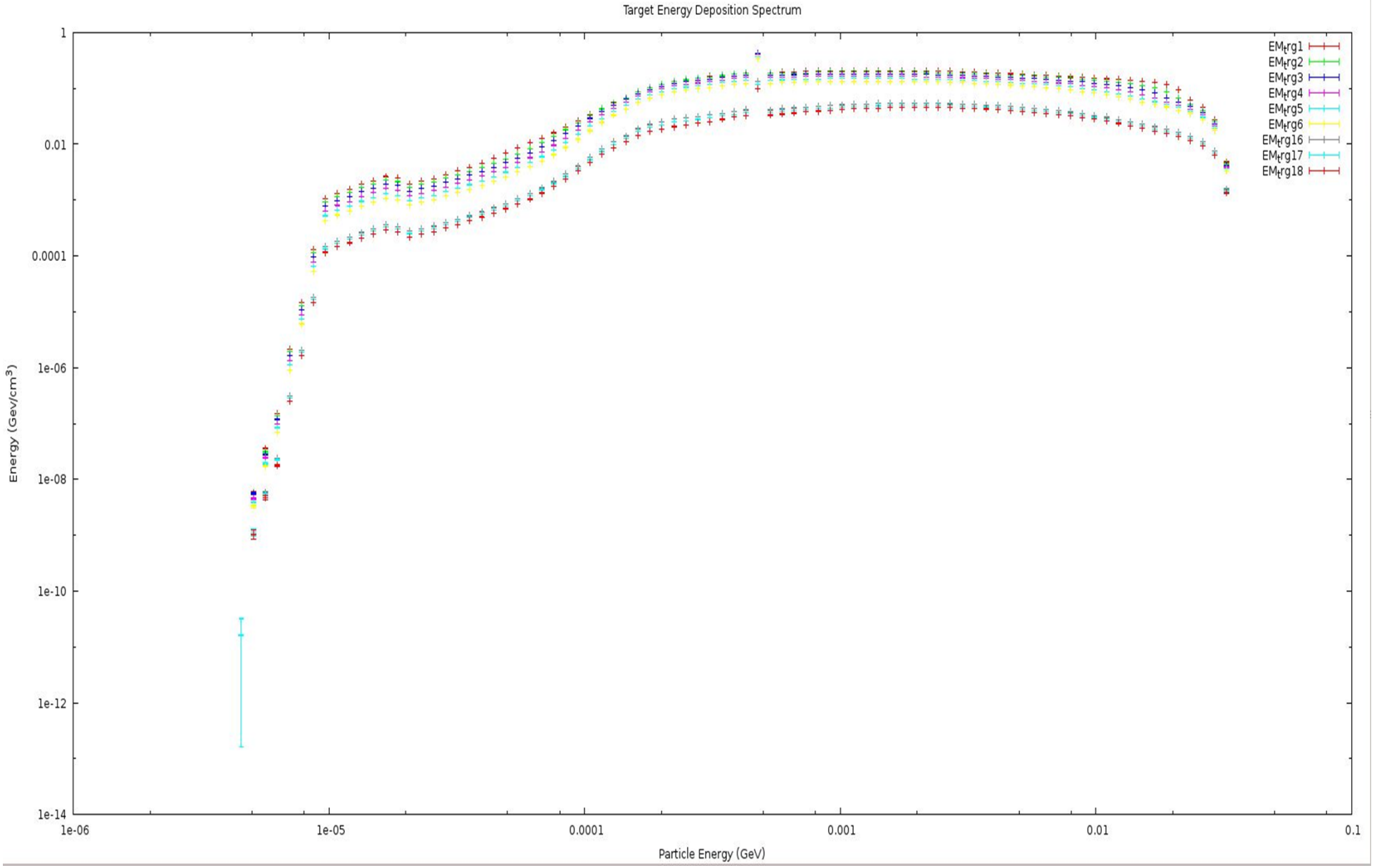
Neutron Dose Profile / SS+Poly



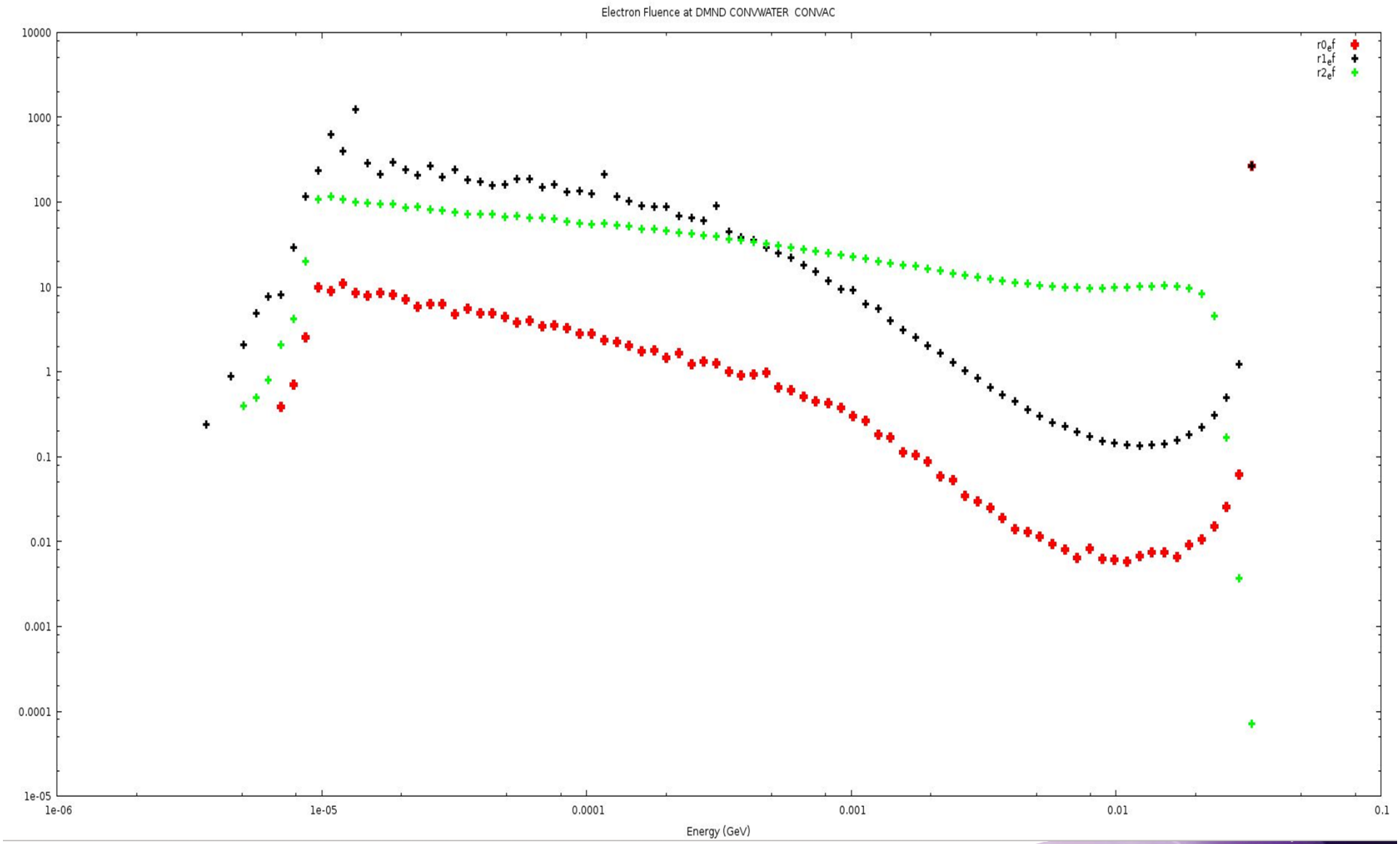
Converter Energy Deposition Spectrum



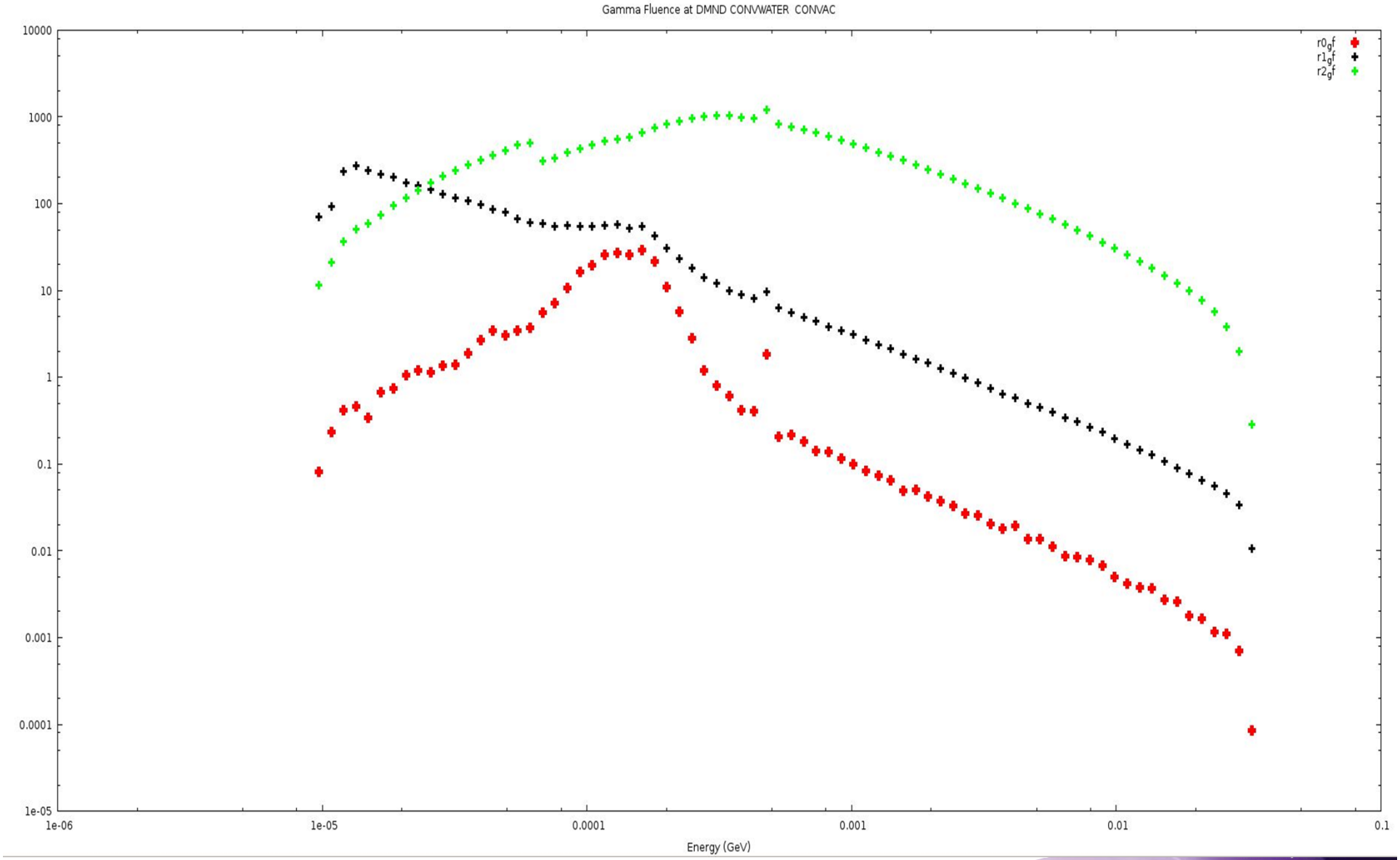
Moly Target Energy Deposition Spectrum



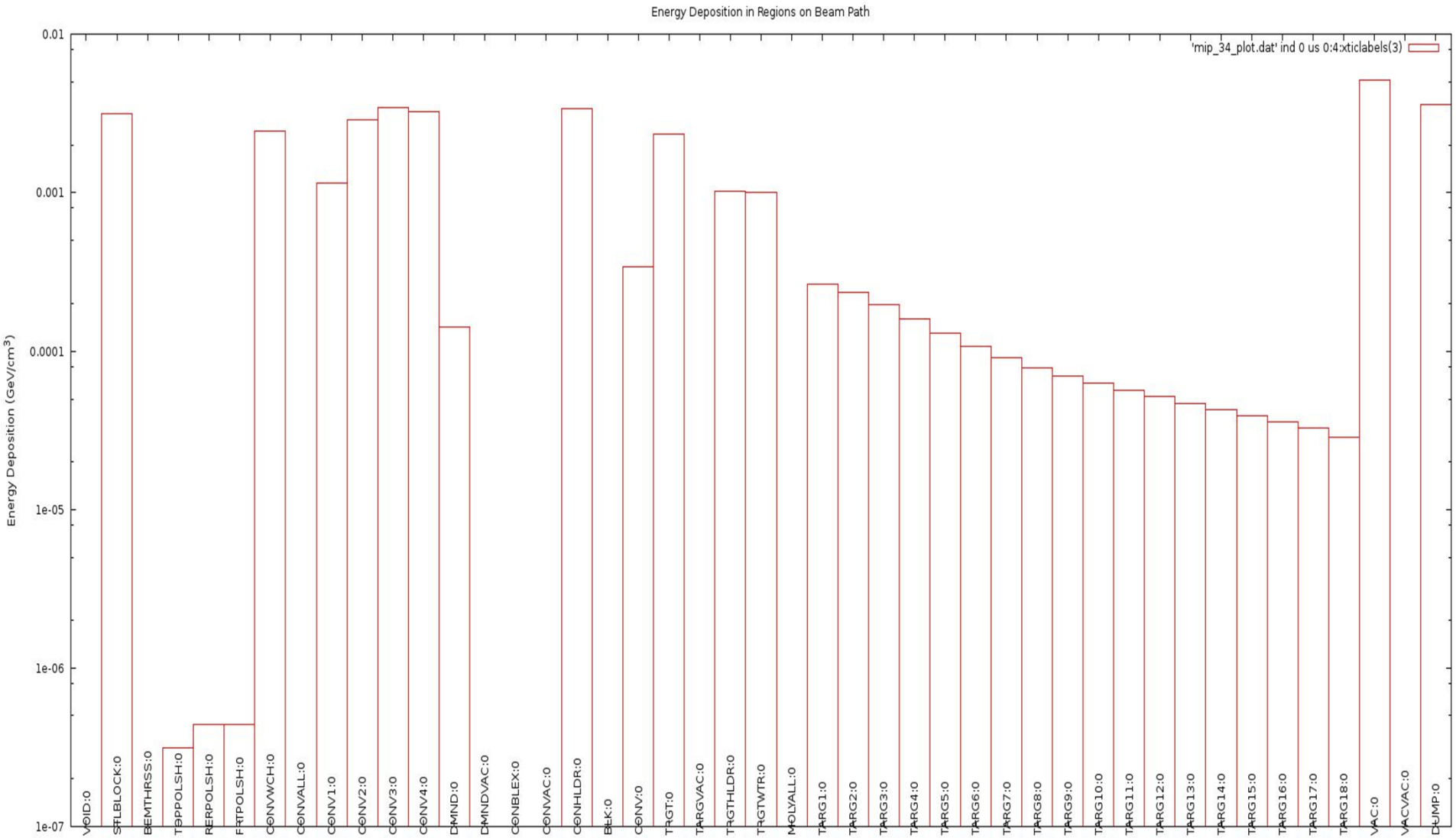
Electron Fluence at Diamond Window, Converter Water & Converter Exit



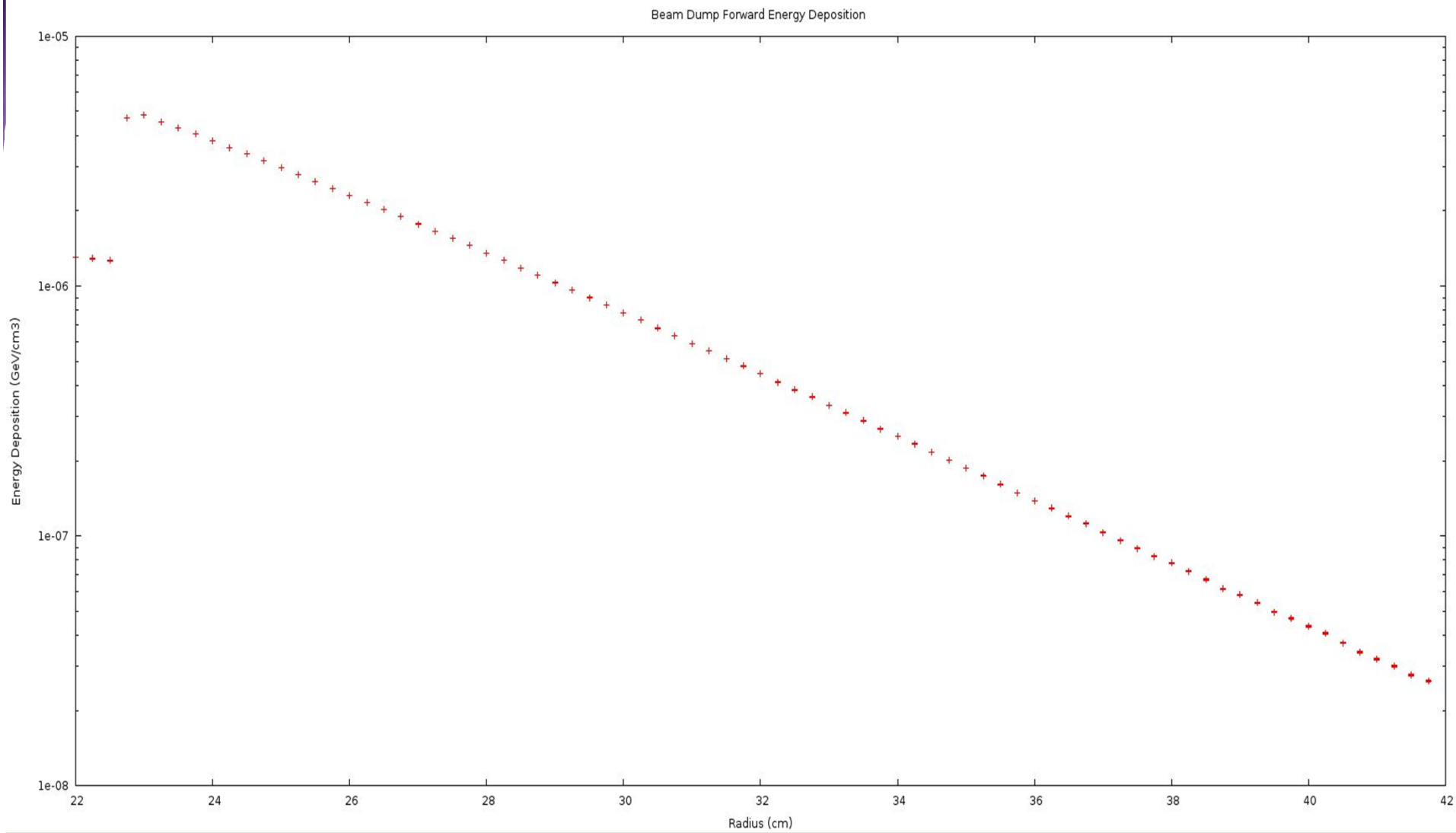
Gamma Fluence at Diamond Window, Converter Water & Converter Exit



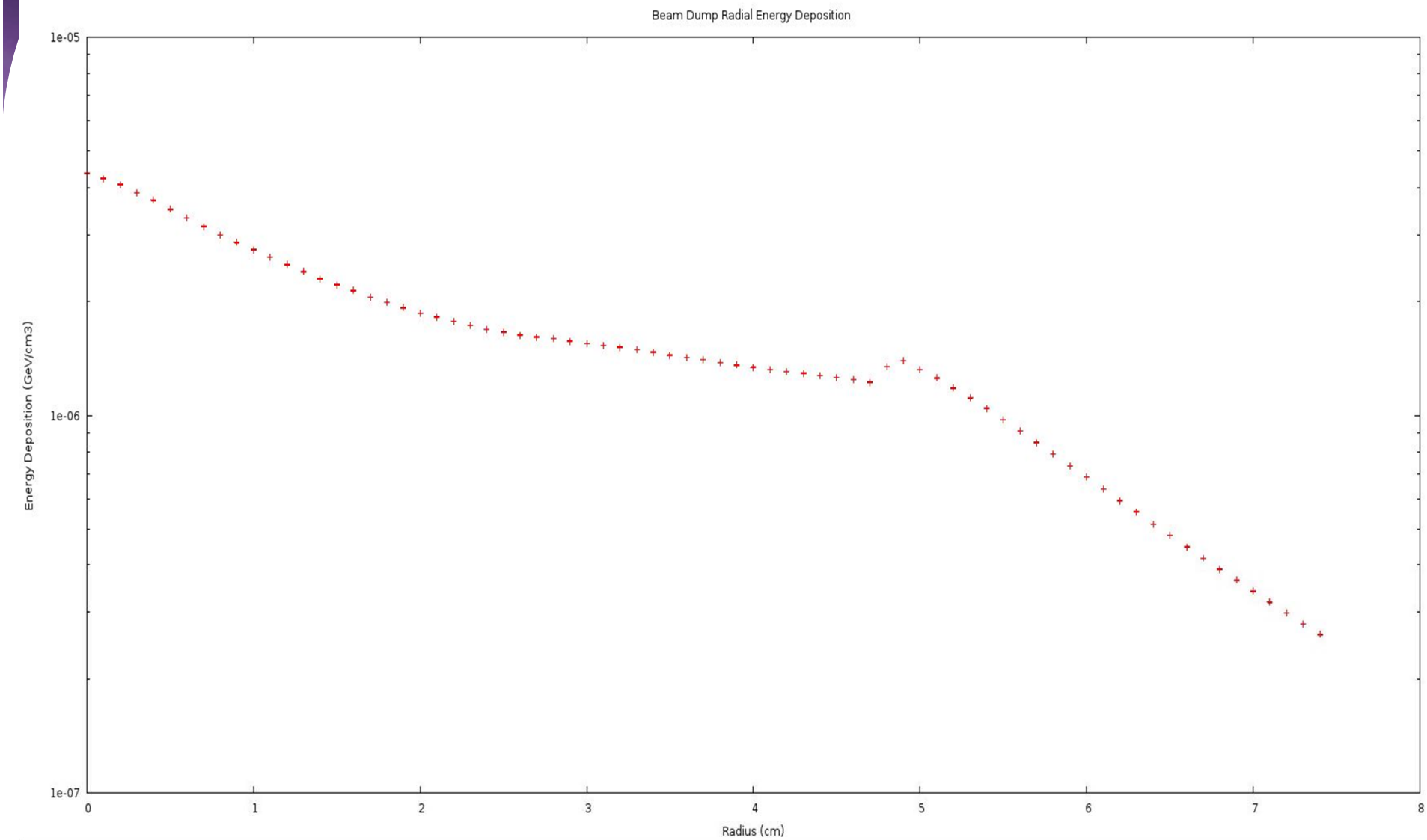
Regional Energy Deposition



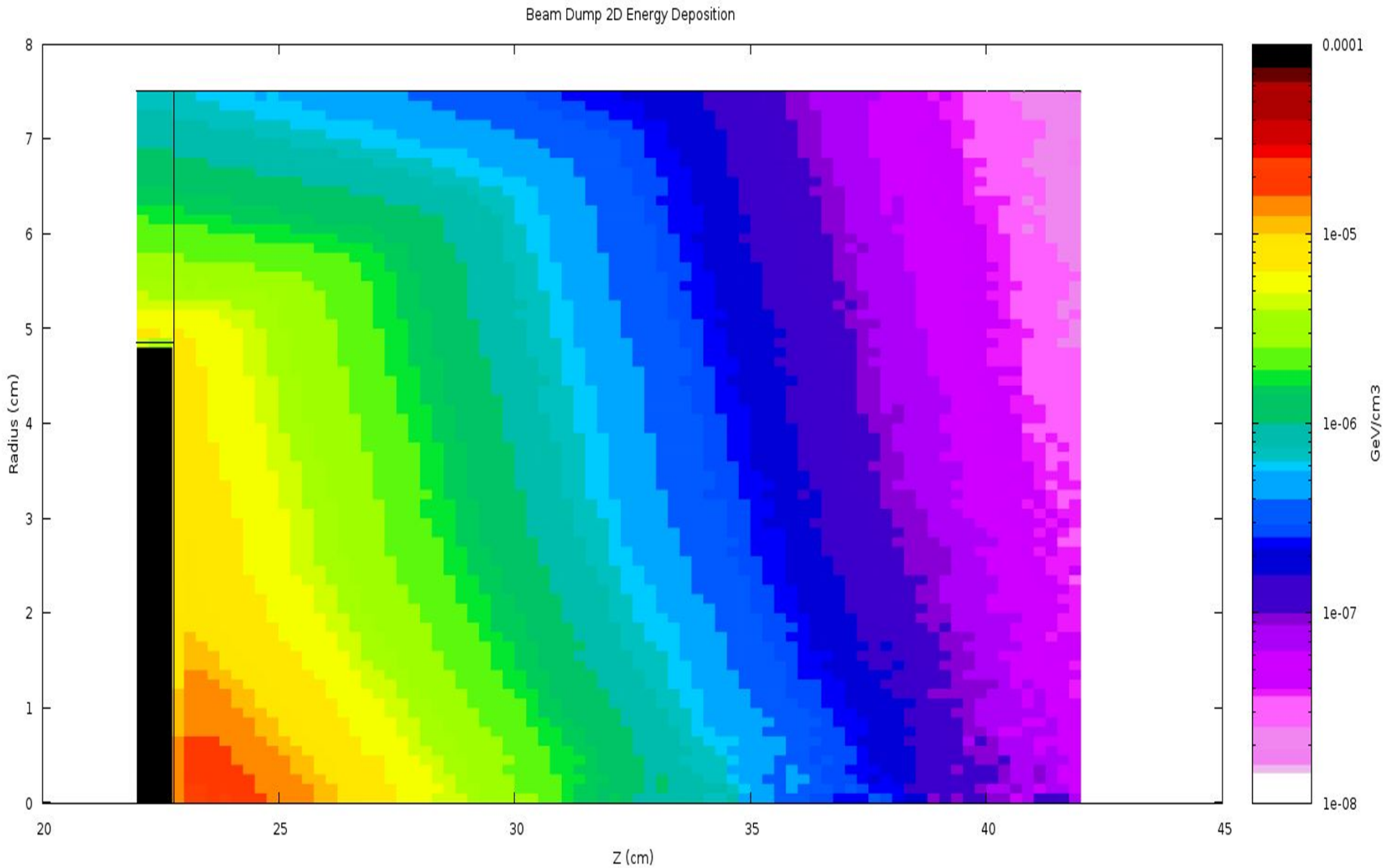
Beam Dump Forward Energy Deposition



Beam Dump Radial Energy Deposition



Beam Dump 2D Energy Deposition



Power Deposited Comparison

Dose Material	MCNP	FLUKA
Converters	32%	30.7%
Targets	5%	5%
Vacuum container	39%	14.6%
Beam Dump	17%	10.3%
Diamond Window		0.4%
Iron Shielding		9%
Poly Shielding		0.004%
Black-hole		0.006%
Converter Block		0.9%
Converter Holder		9.7%
Converter water		7%
Target Block		6.7%
Target Holder		2.9%
Target water		2.9%

Future Directions

- During commissioning, the dose rates will be measured at various points.
- Will verify if the shielding design is adequate and the Linac safety modes and ACIS are working properly.
- The dose rates will be compared with Fluka simulated doses.
- The Radgas, Ozone and Water contaminants will be assessed.
- The role of ventilation in reducing the airborne hazards will be assessed.

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