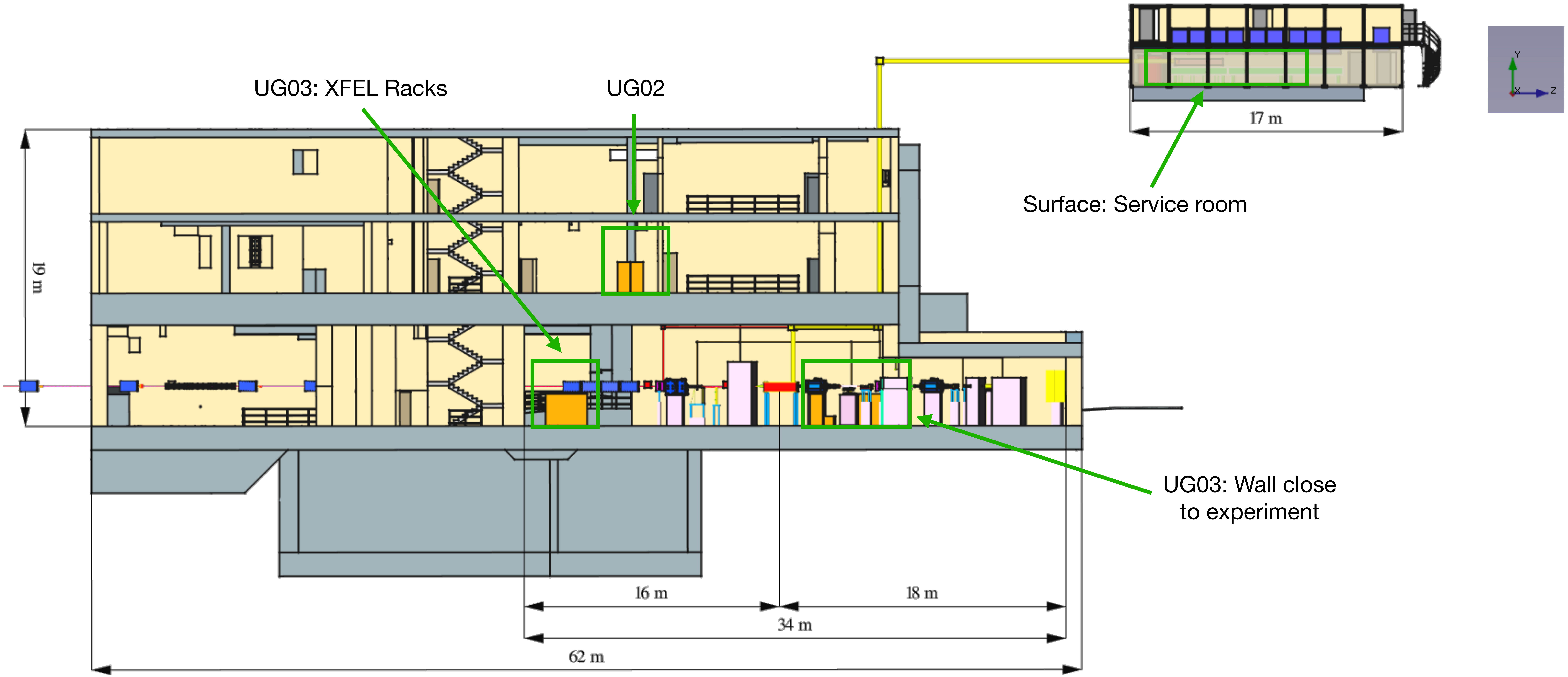
LUXE BEAM DUMPS

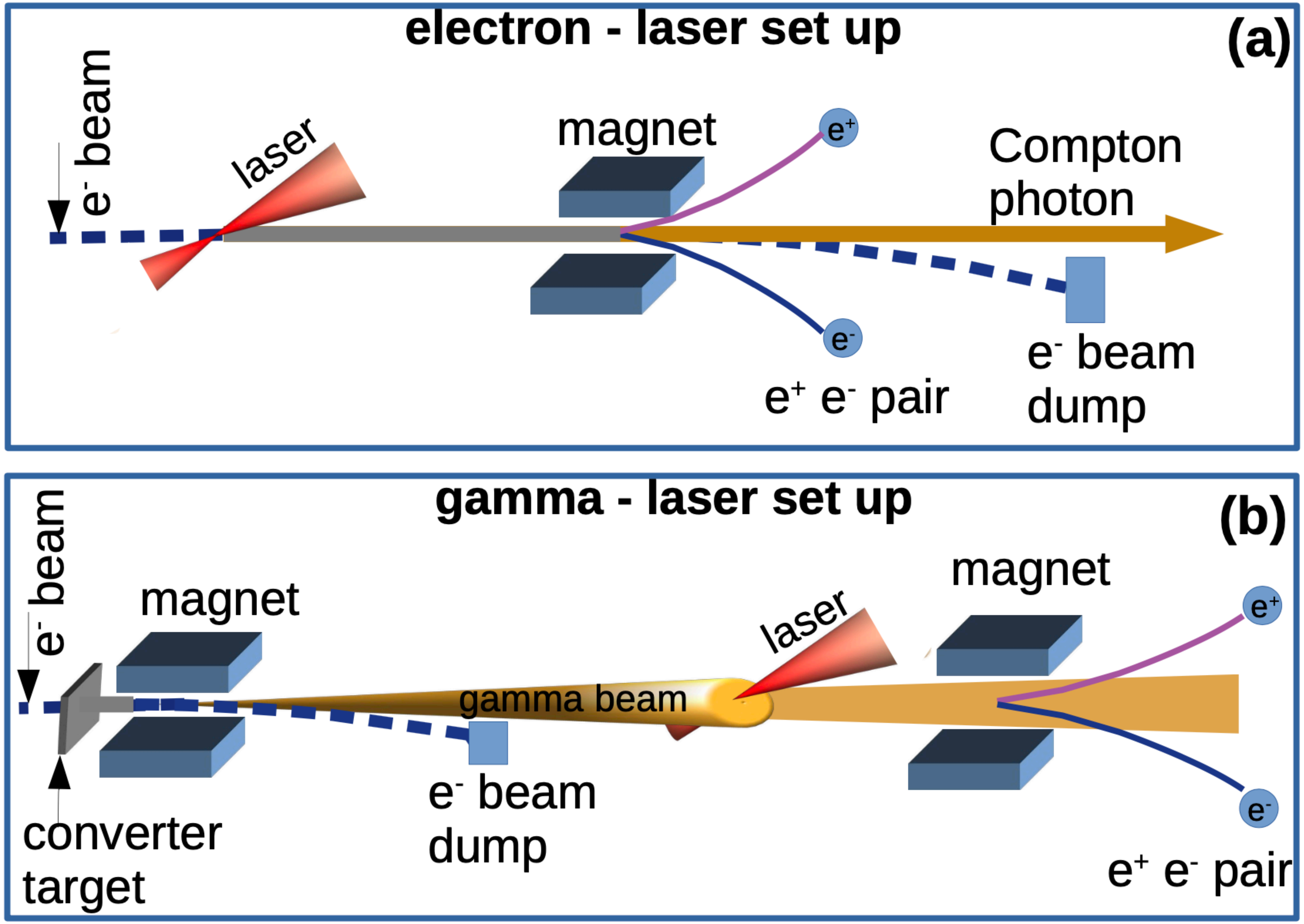
LOUIS HELARY (DESY)

NOVEMBER 29TH 2022

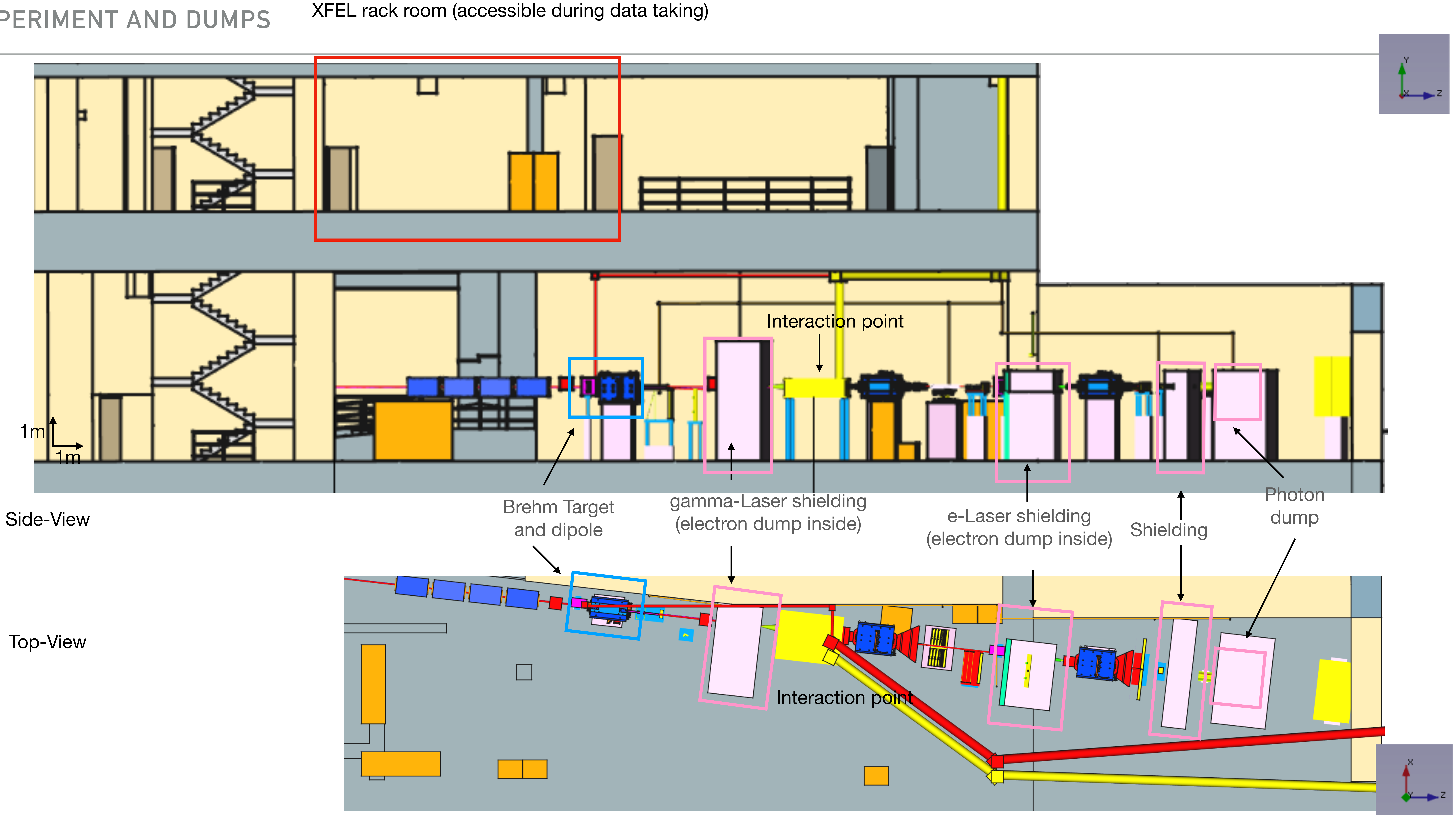
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

LUXE IN XS1


UG03: XFEL Racks
UG02
Surface: Service room
17 m
19 m
UG03: Wall close
to experiment
16 m
18 m
34 m
62 m
Y
Z

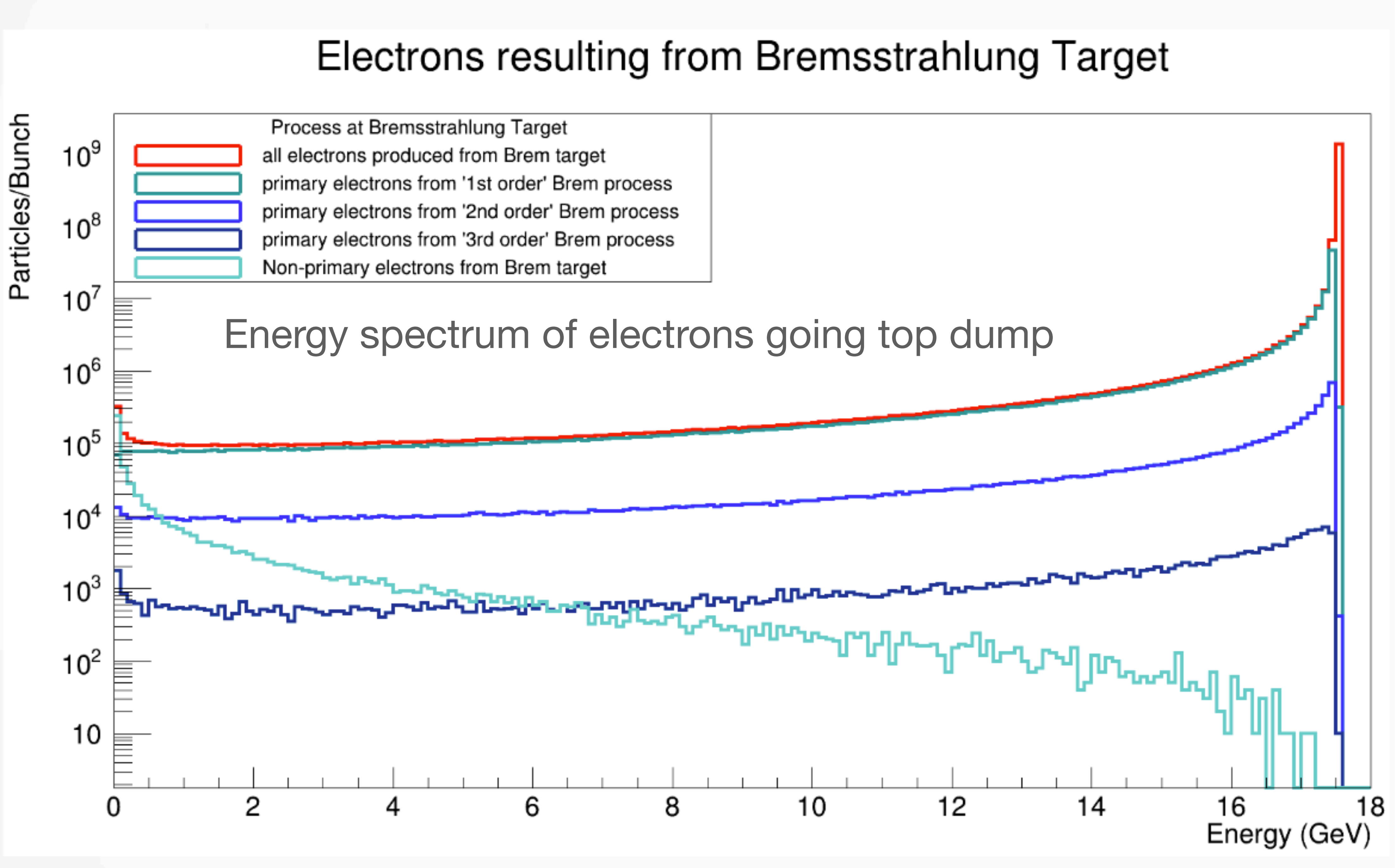

electron - laser set up
(a)
e^- beam
laser
magnet
e^+
Compton photon
e^-
e^+ e^- pair
e^- beam dump
gamma - laser set up
(b)
e^- beam
magnet
gamma beam
laser
magnet
e^+
e^-
converter target
e^- beam dump
e^+ e^- pair

EXPERIMENT AND DUMPS

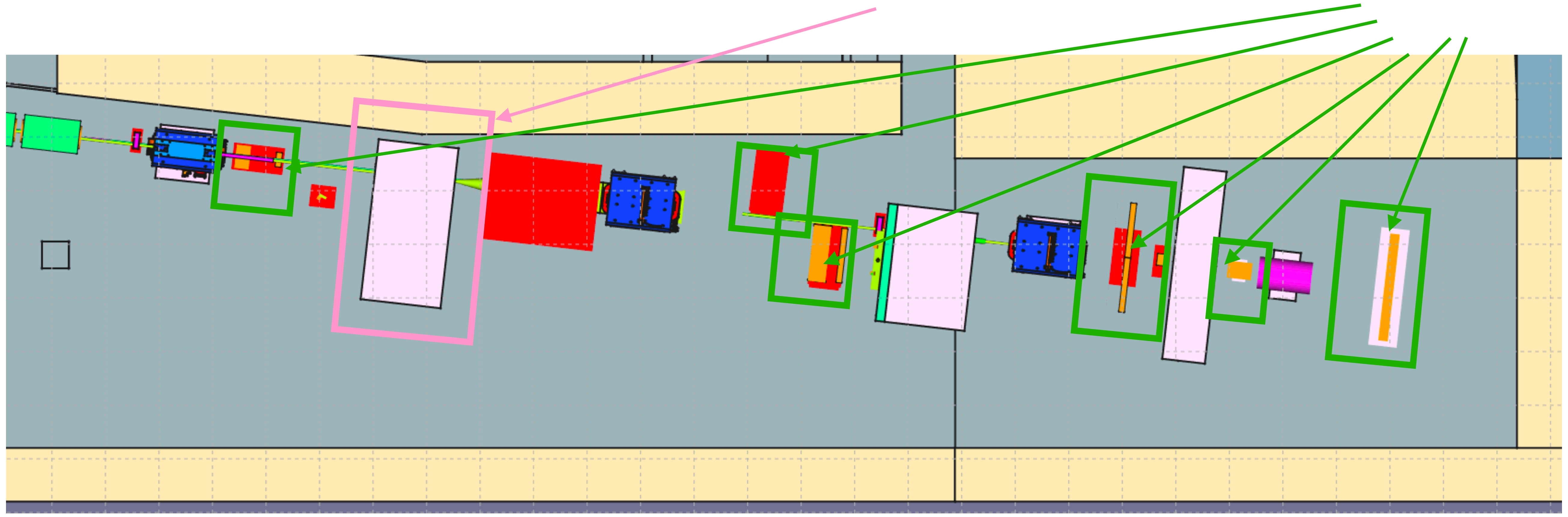


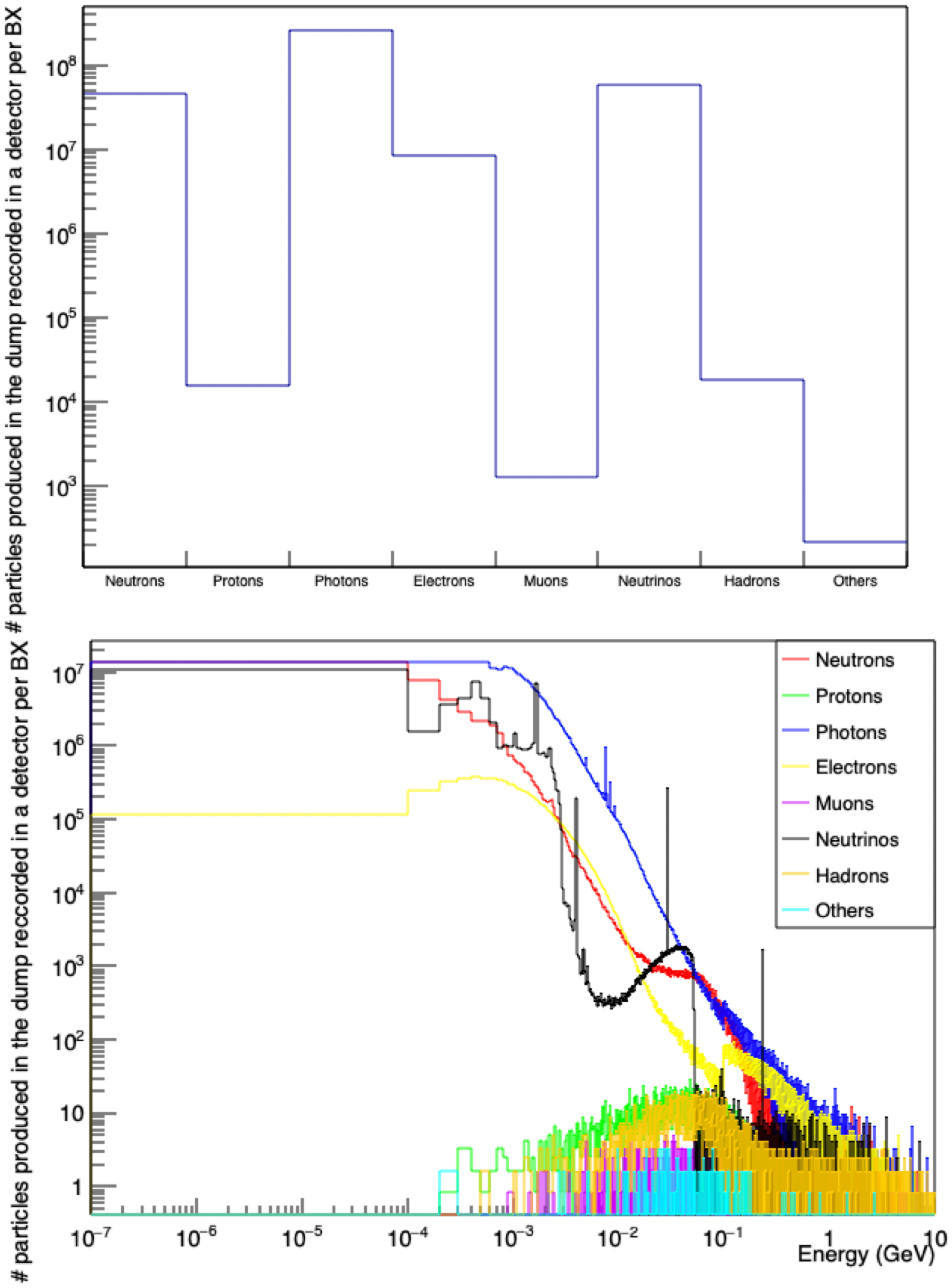
GAMMA-LASER ELECTRON BEAM DUMP

GAMMA-LASER ELECTRON BEAM DUMP ENERGY AND PARTICLE SPECTRUM

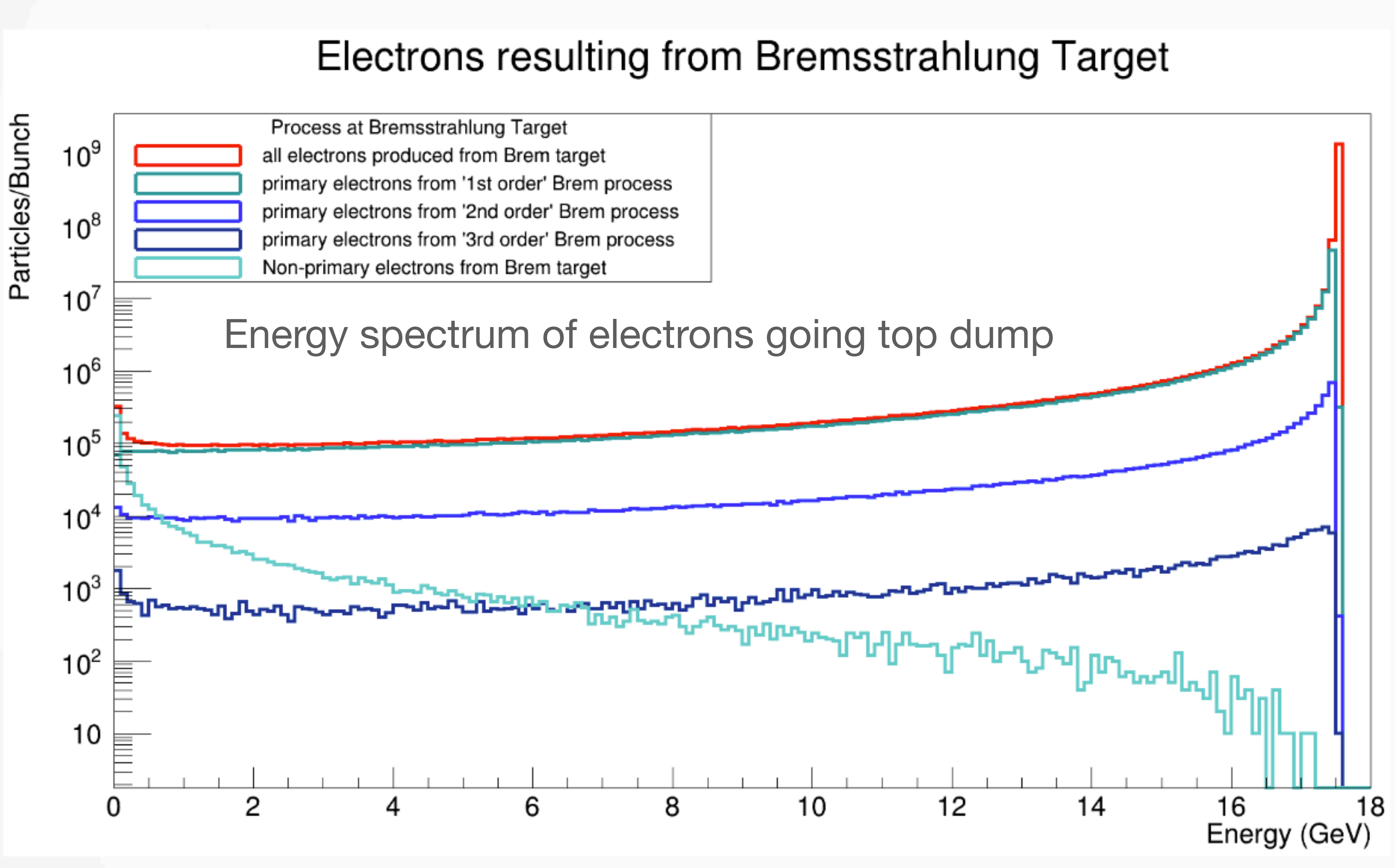


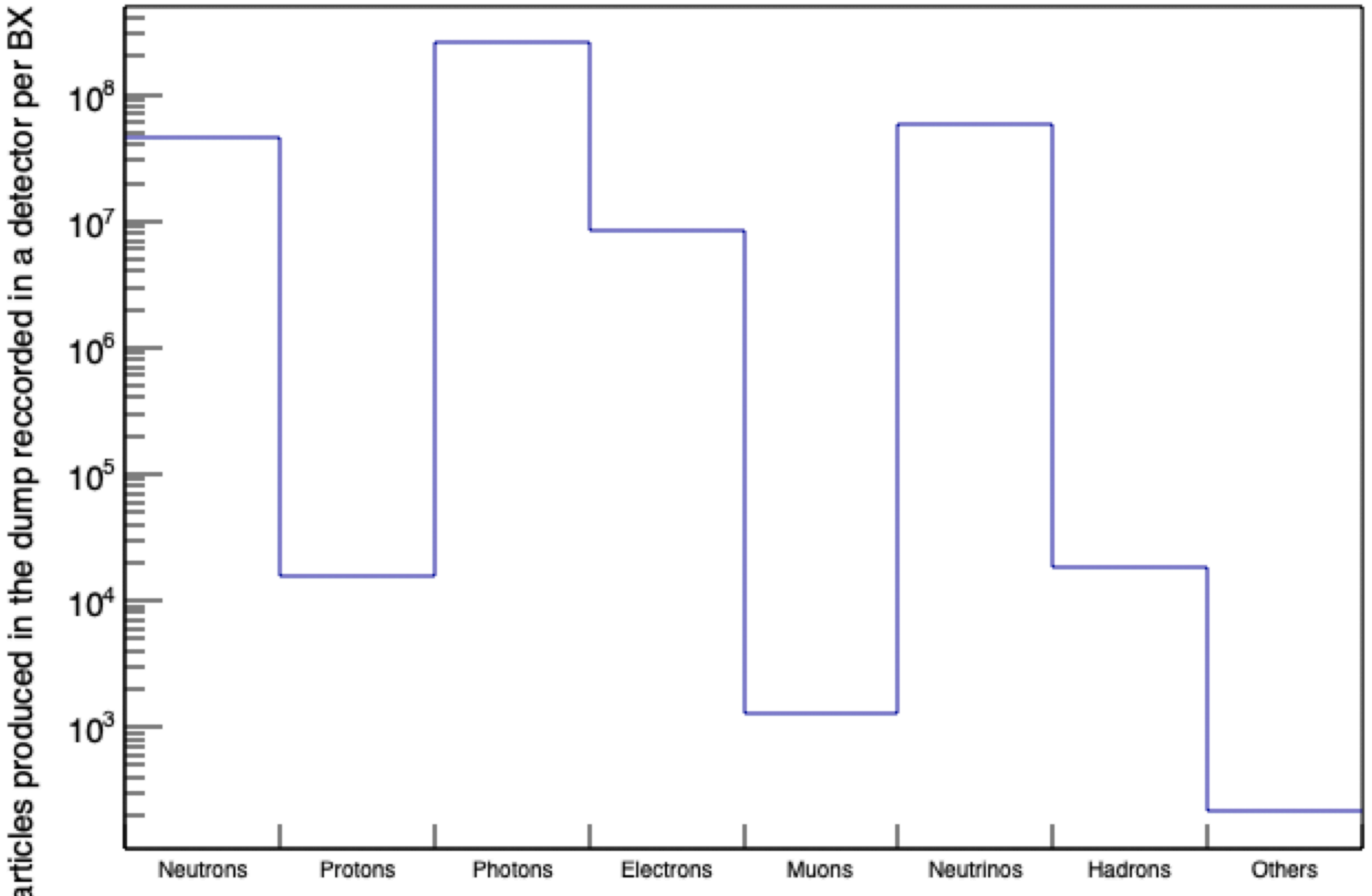
Output spectrum, particles produced in the dump here, but recorded in one of the detectors

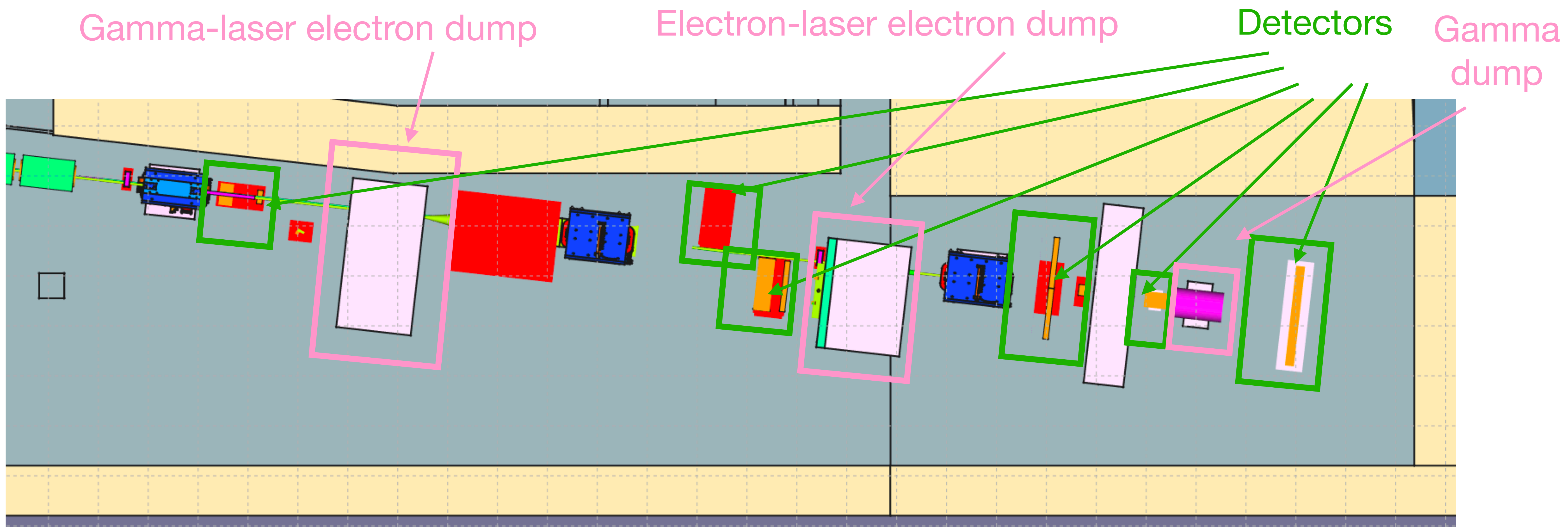


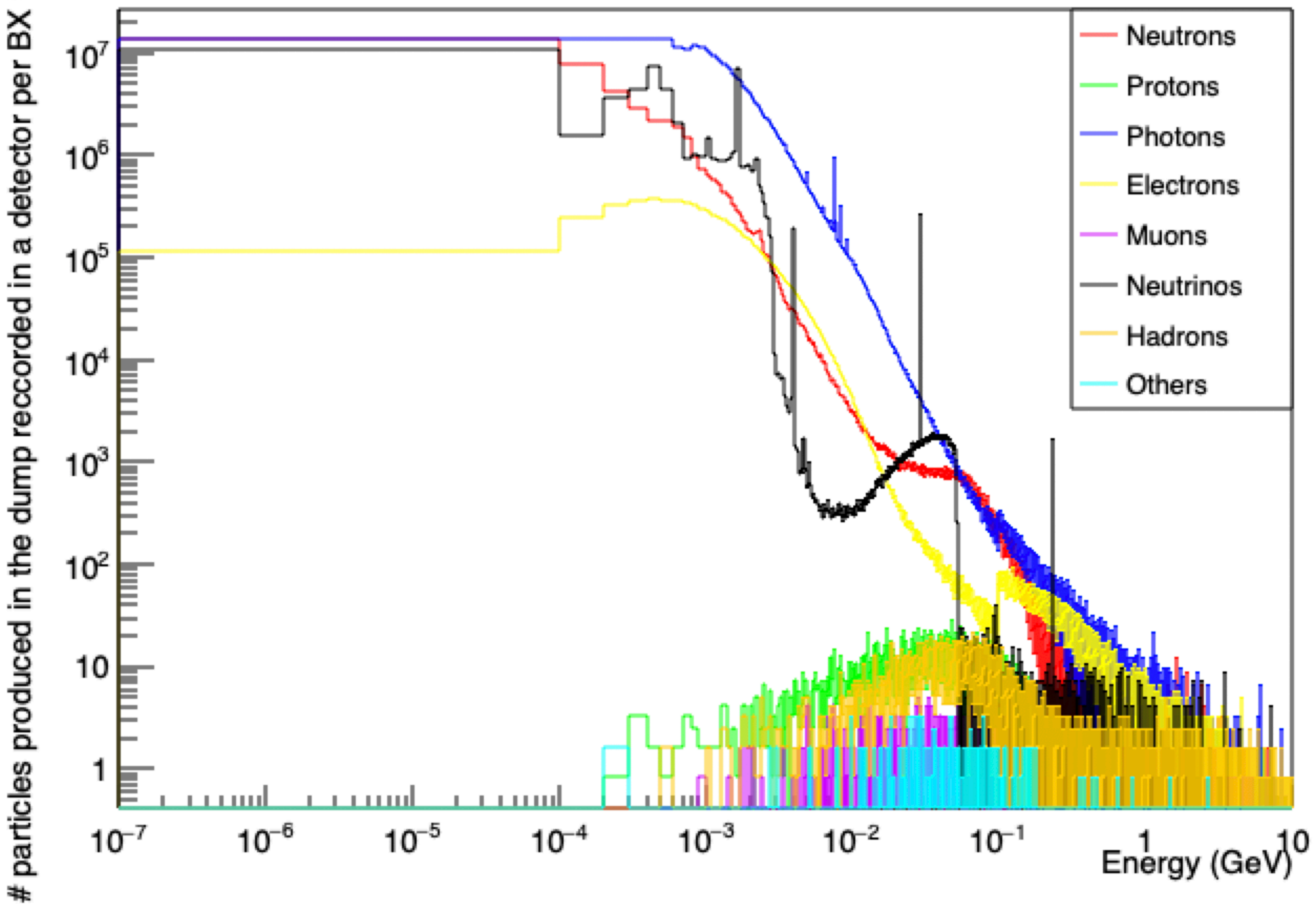


GAMMA-LASER ELECTRON BEAM DUMP ENERGY AND PARTICLE SPECTRUM

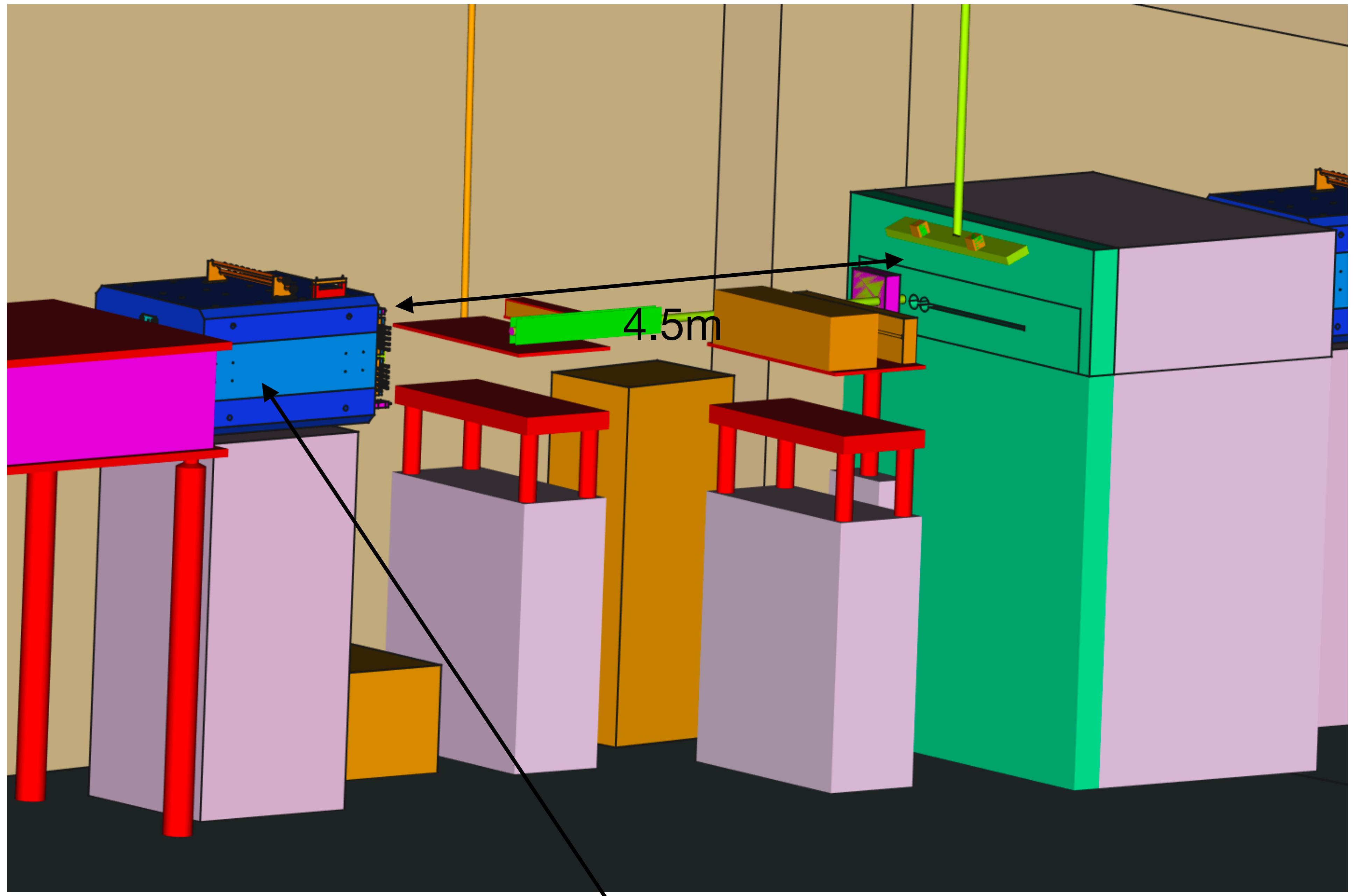




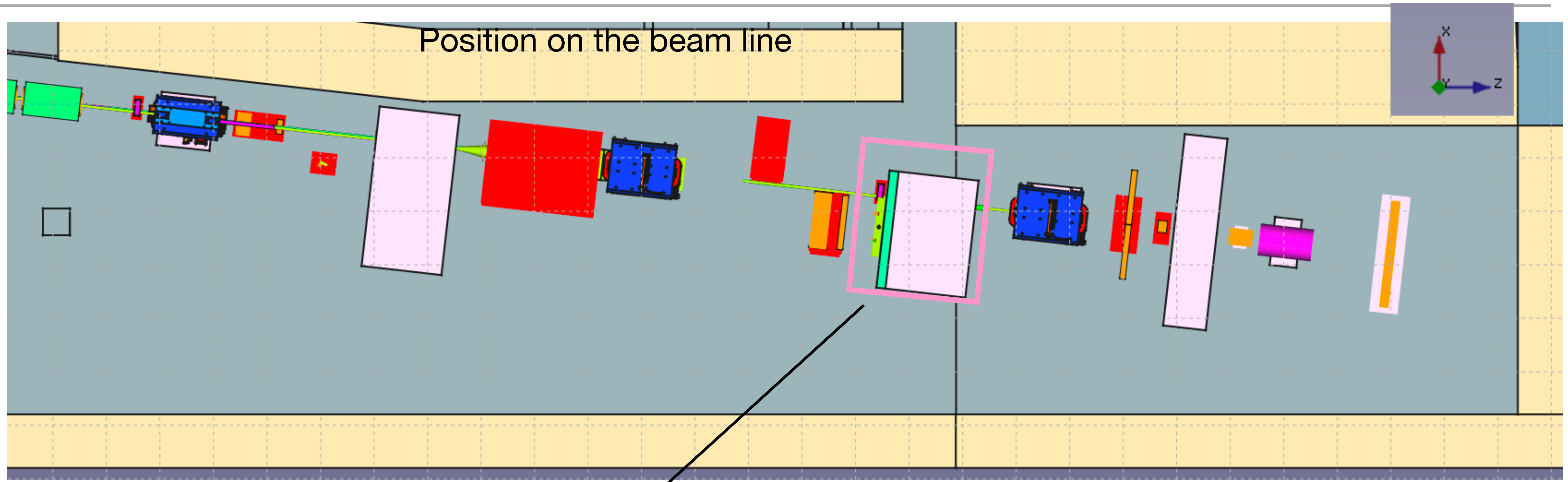




ELECTRON-LASER ELECTRON BEAM DUMP

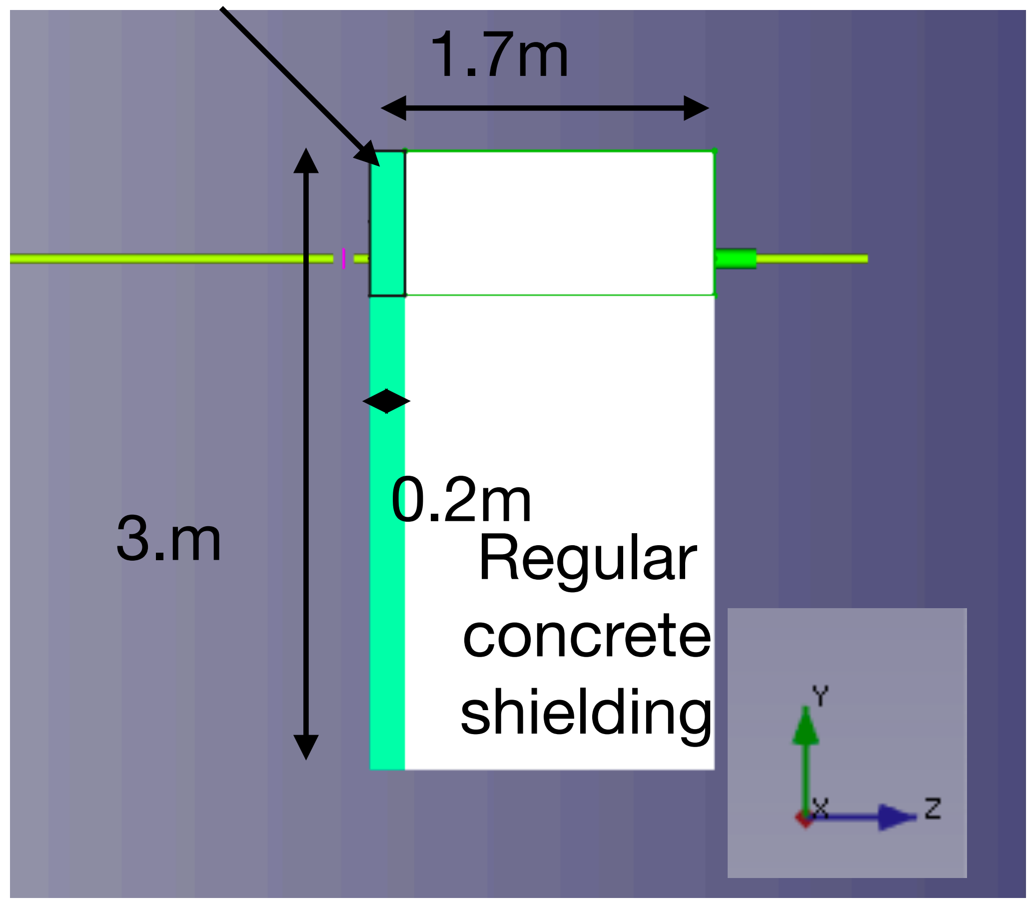


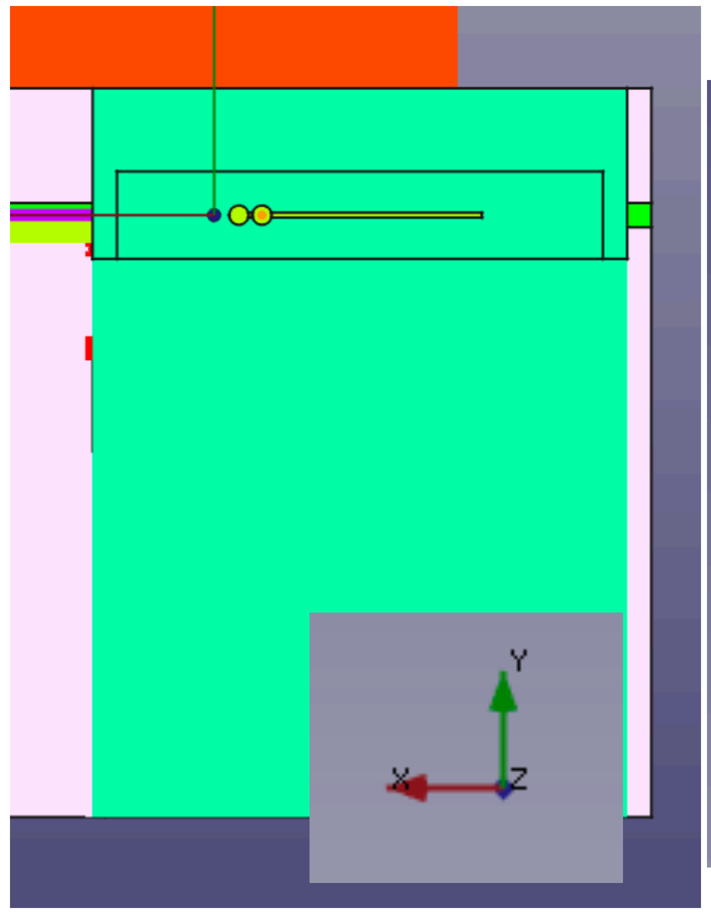
Magnet bend electrons horizontally 1.4 T

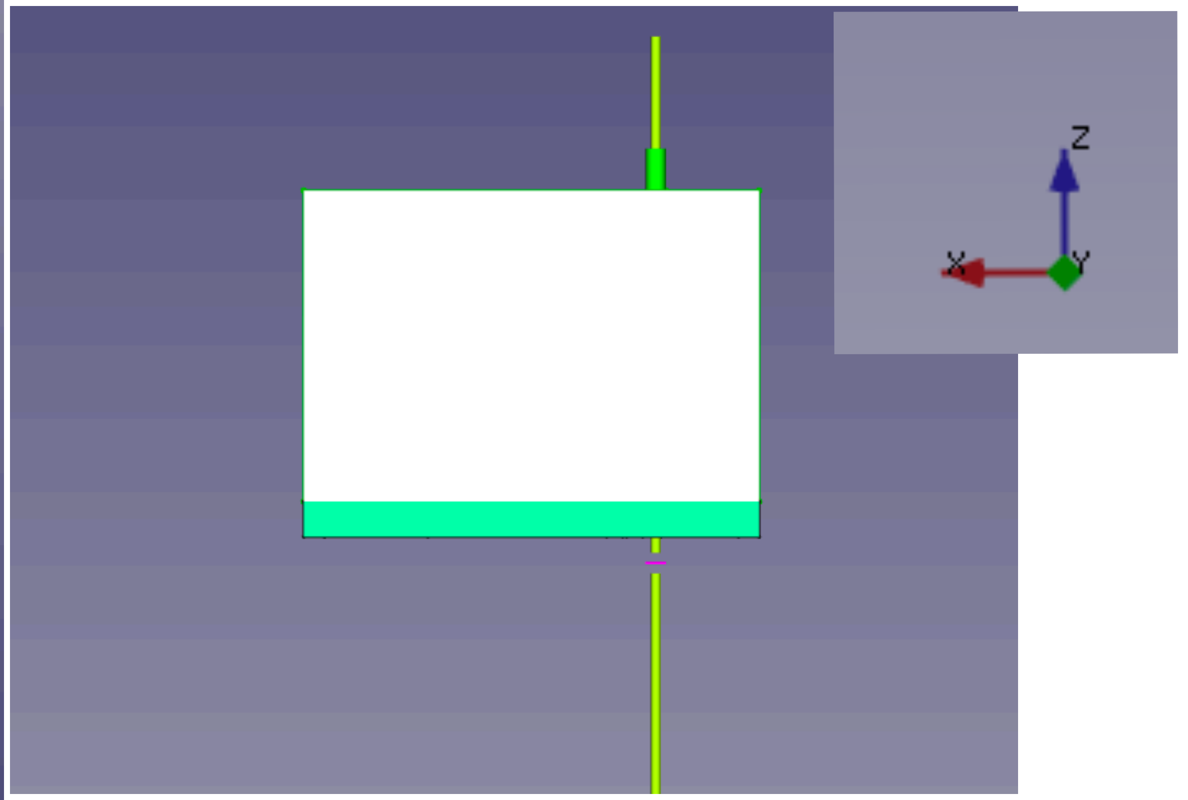


Regular concrete shielding

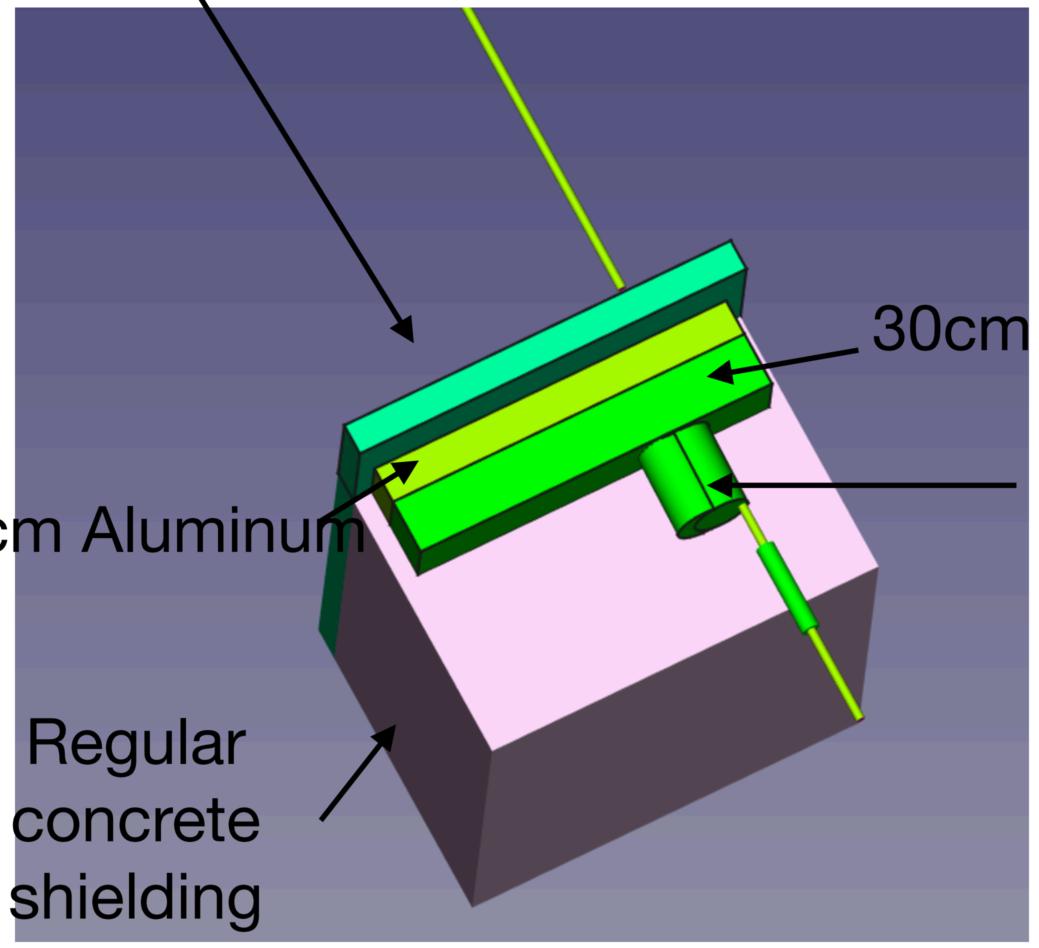
20cm of boron+polyethylene concrete







20cm of boron+polyethylene concrete

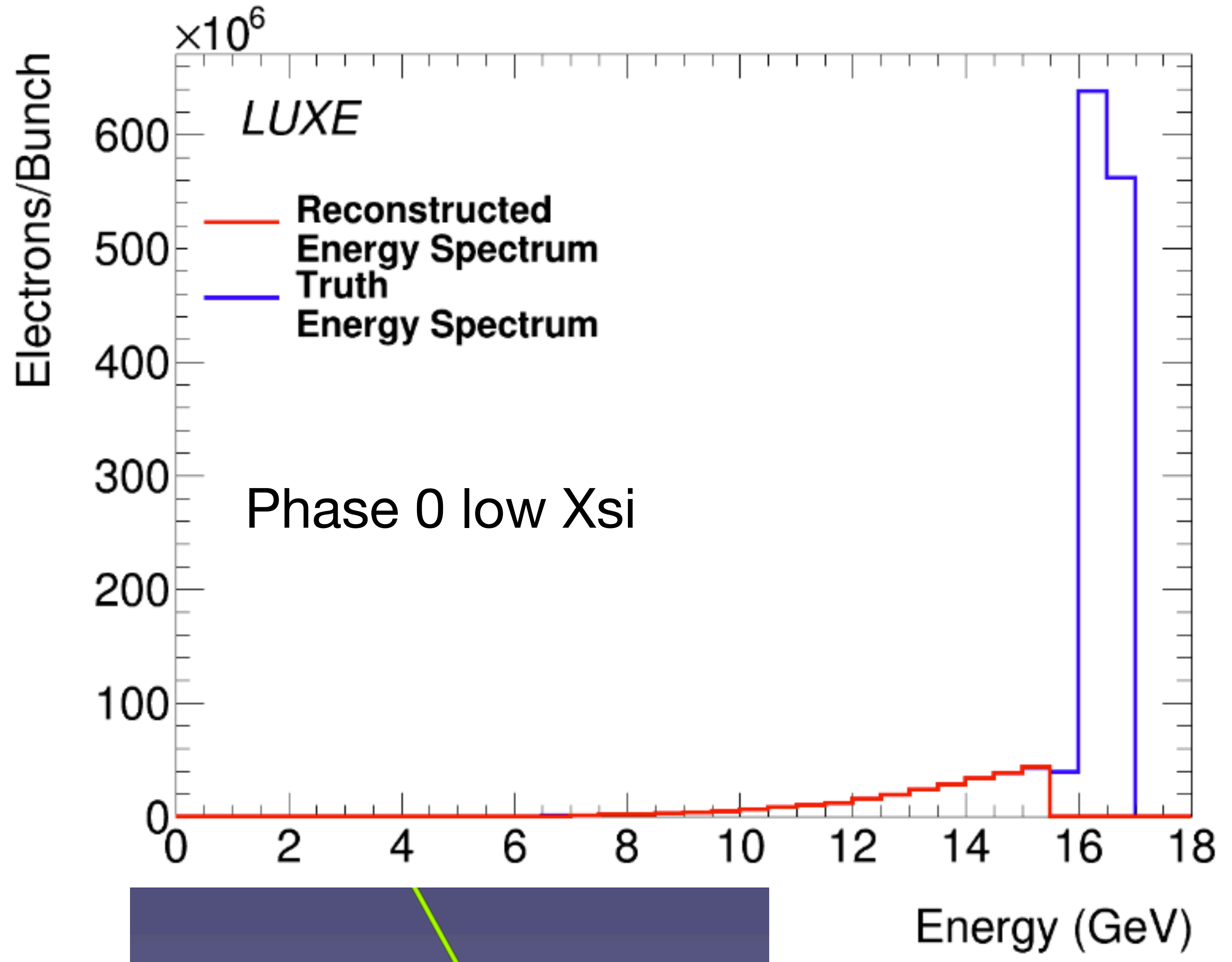


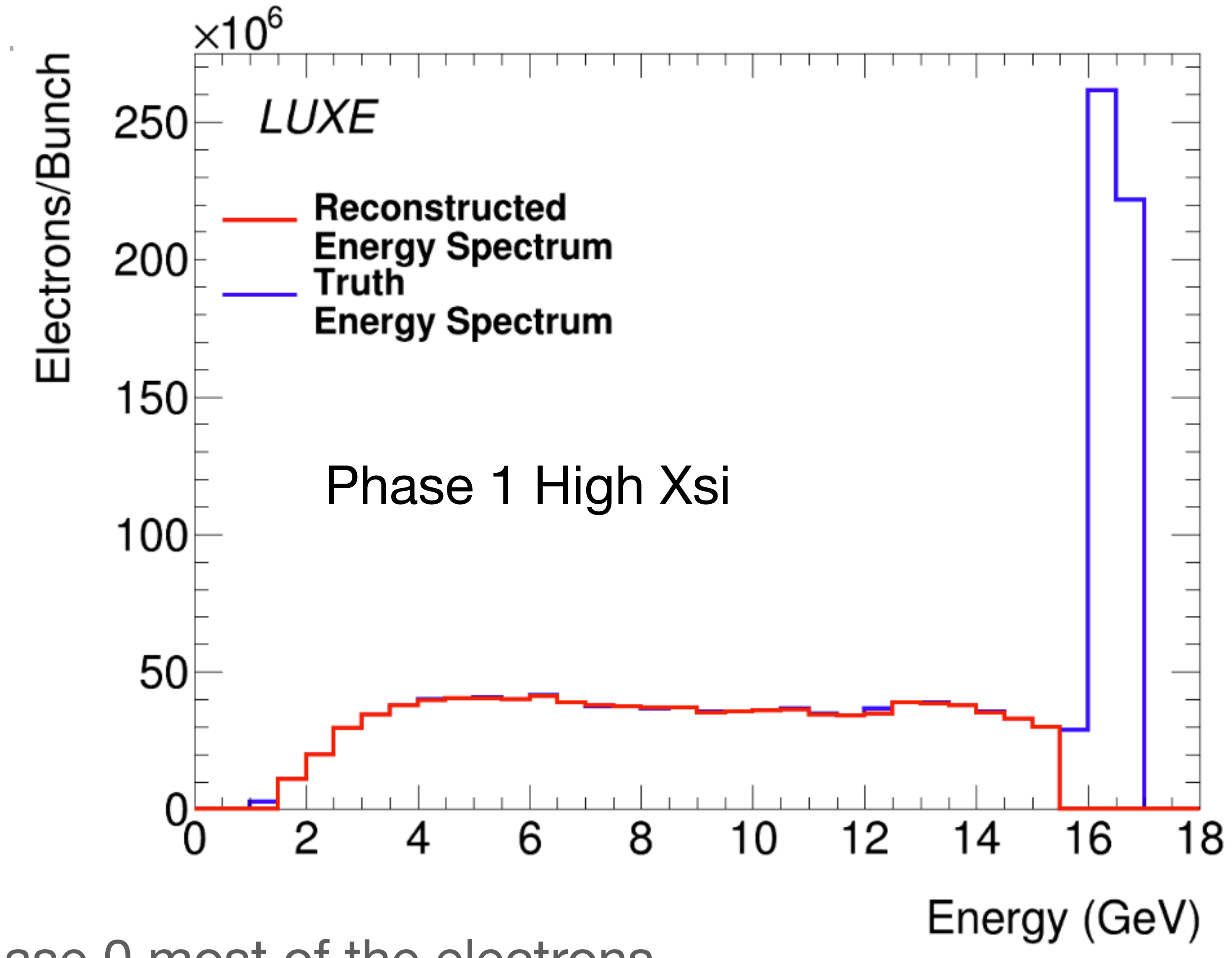
30cm lead

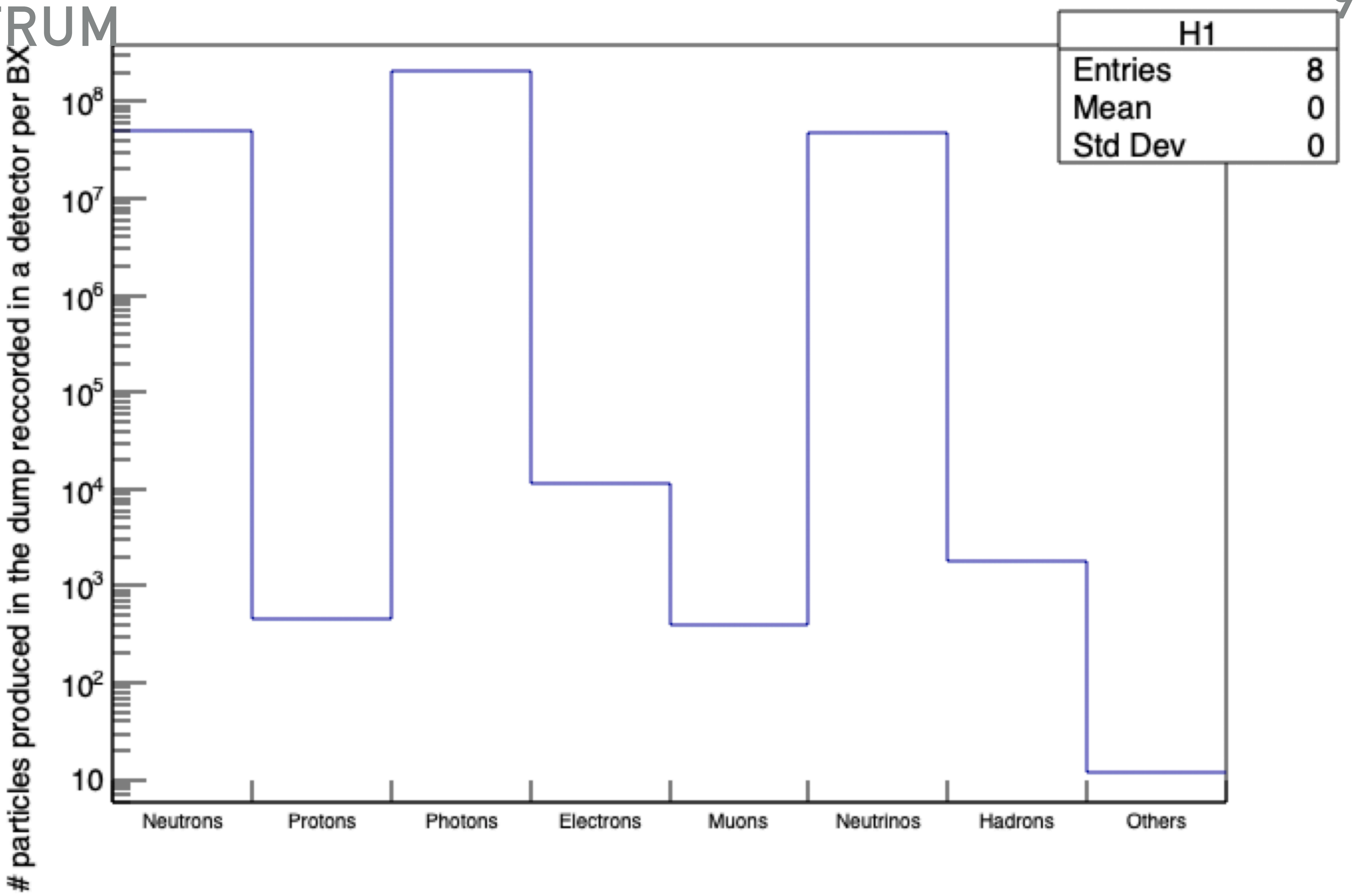
lead+alu insert (45cm) total collect ~15X0 of electrons 16.5 - 12 GeV

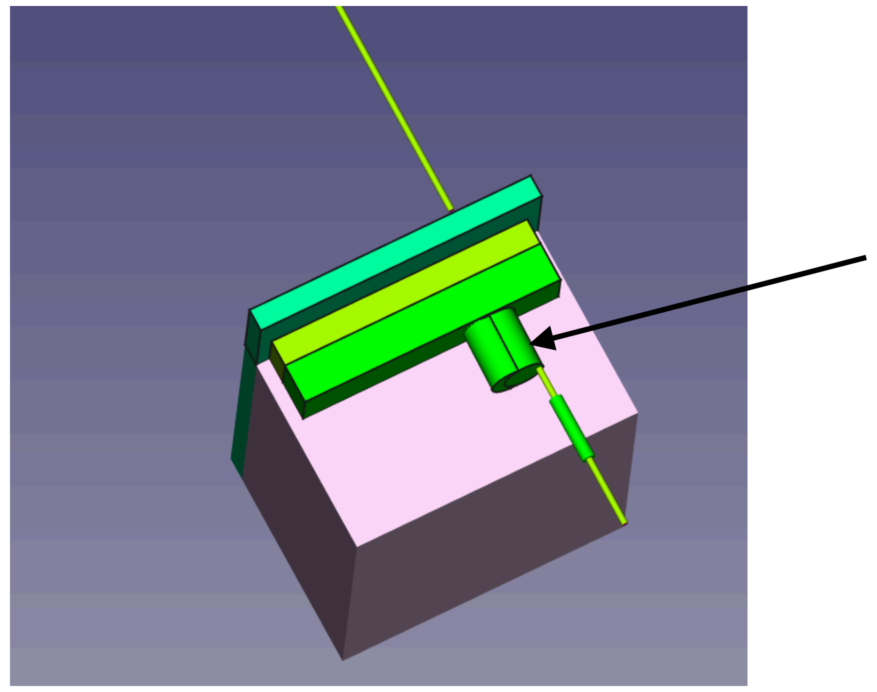
20cm Aluminum

ELECTRON-LASER ELECTRON BEAM DUMP ENERGY AND PARTICLE SPECTRUM







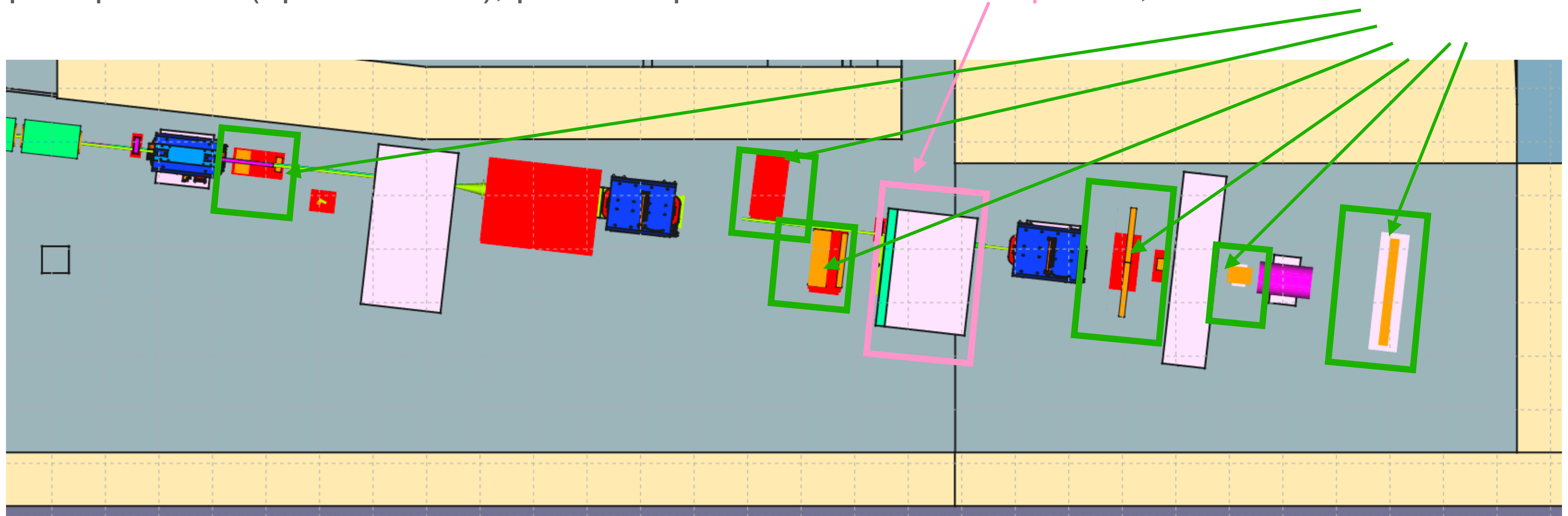


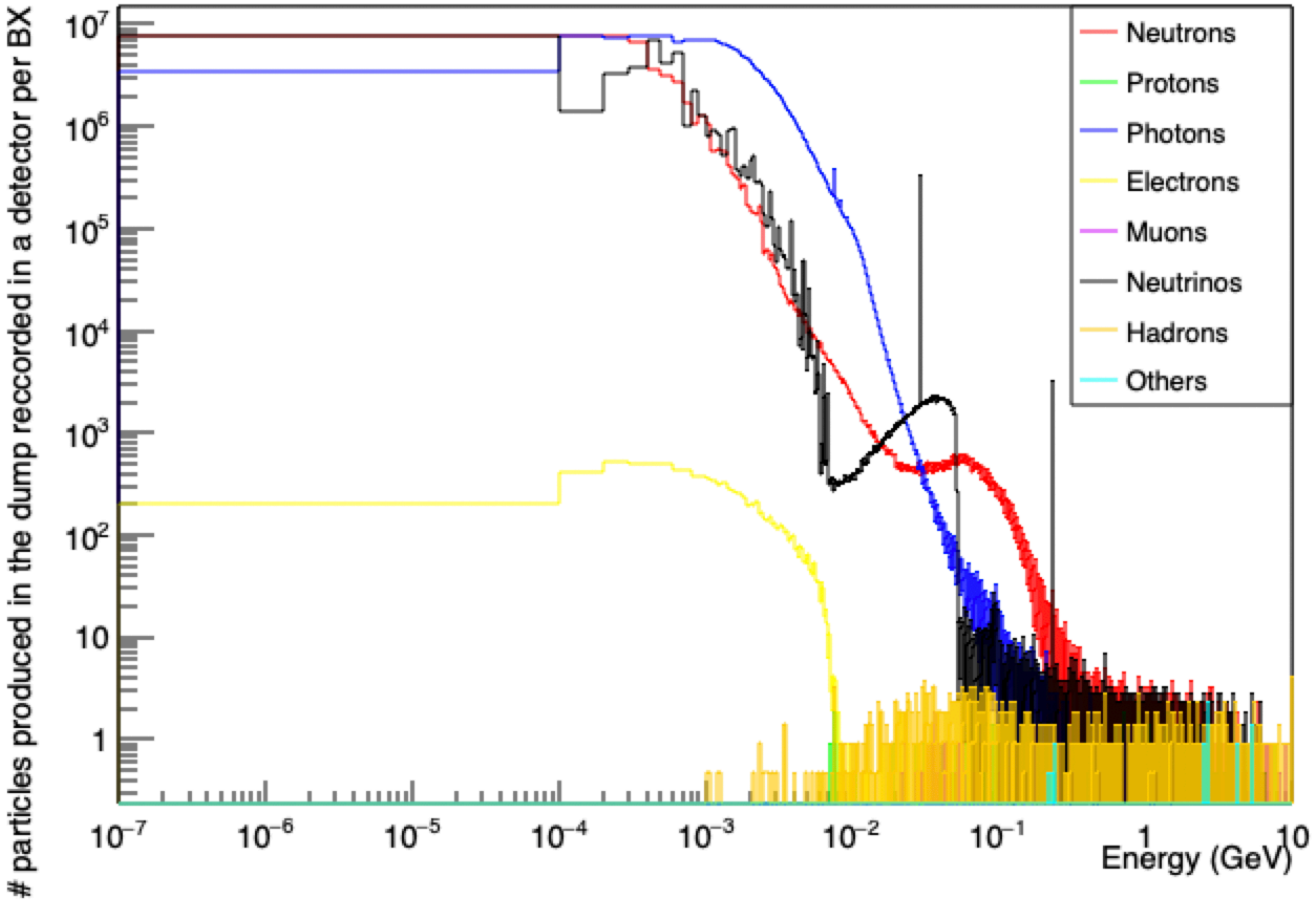
In phase 0 most of the electrons are dumped in the insert, spectrum at 16.5 GeV.

In phase 1, continuum of electrons from 1 GeV to ~15 GeV due to Compton scattering.

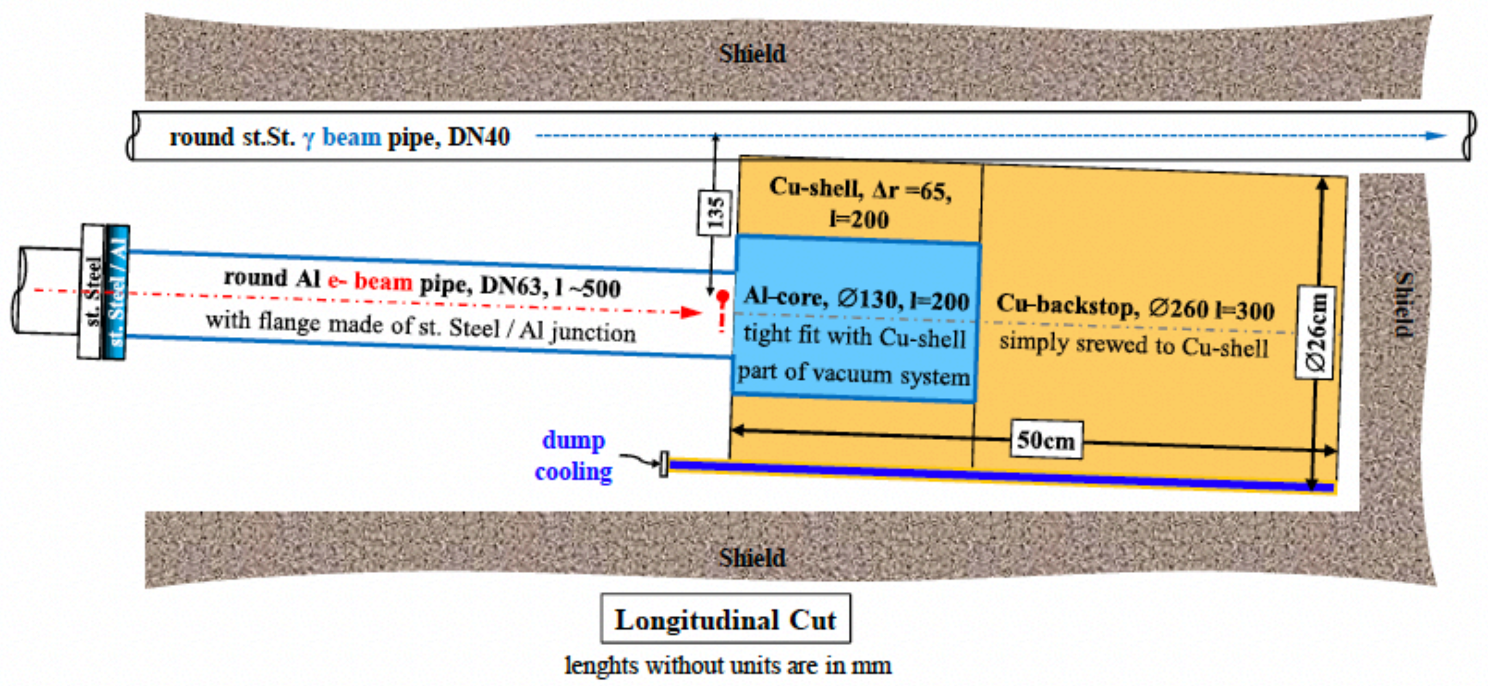
Need special dump to cover the physics!

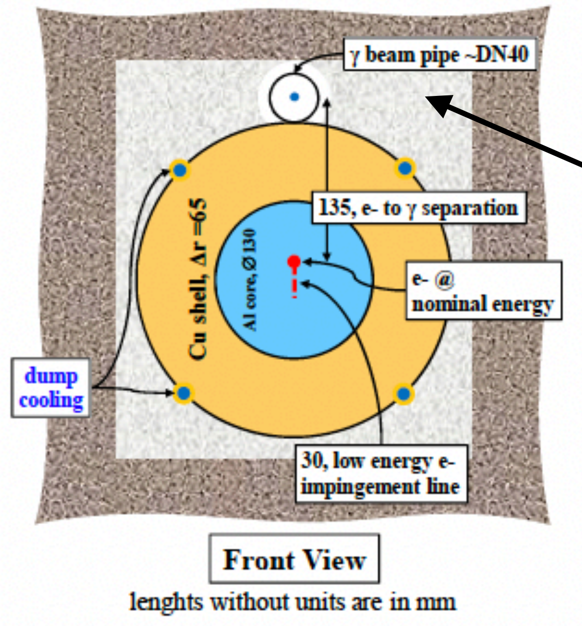
Output spectrum (~phase 0 run), particles produced in the dump here, but recorded in one of the detectors

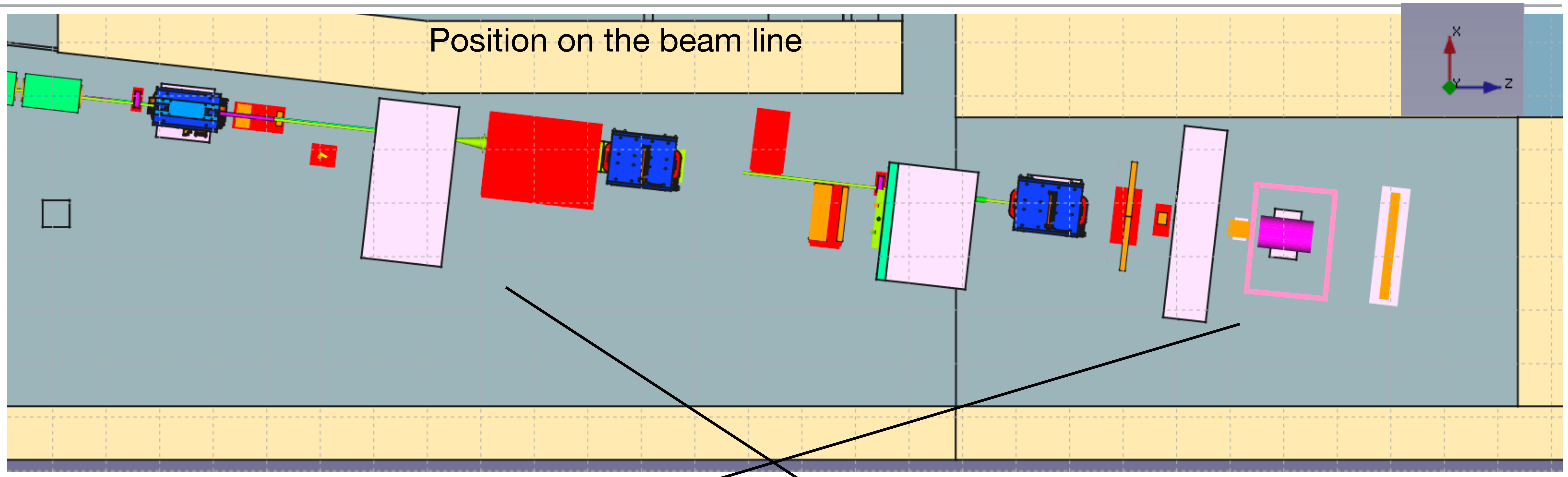




PHOTON BEAM DUMP



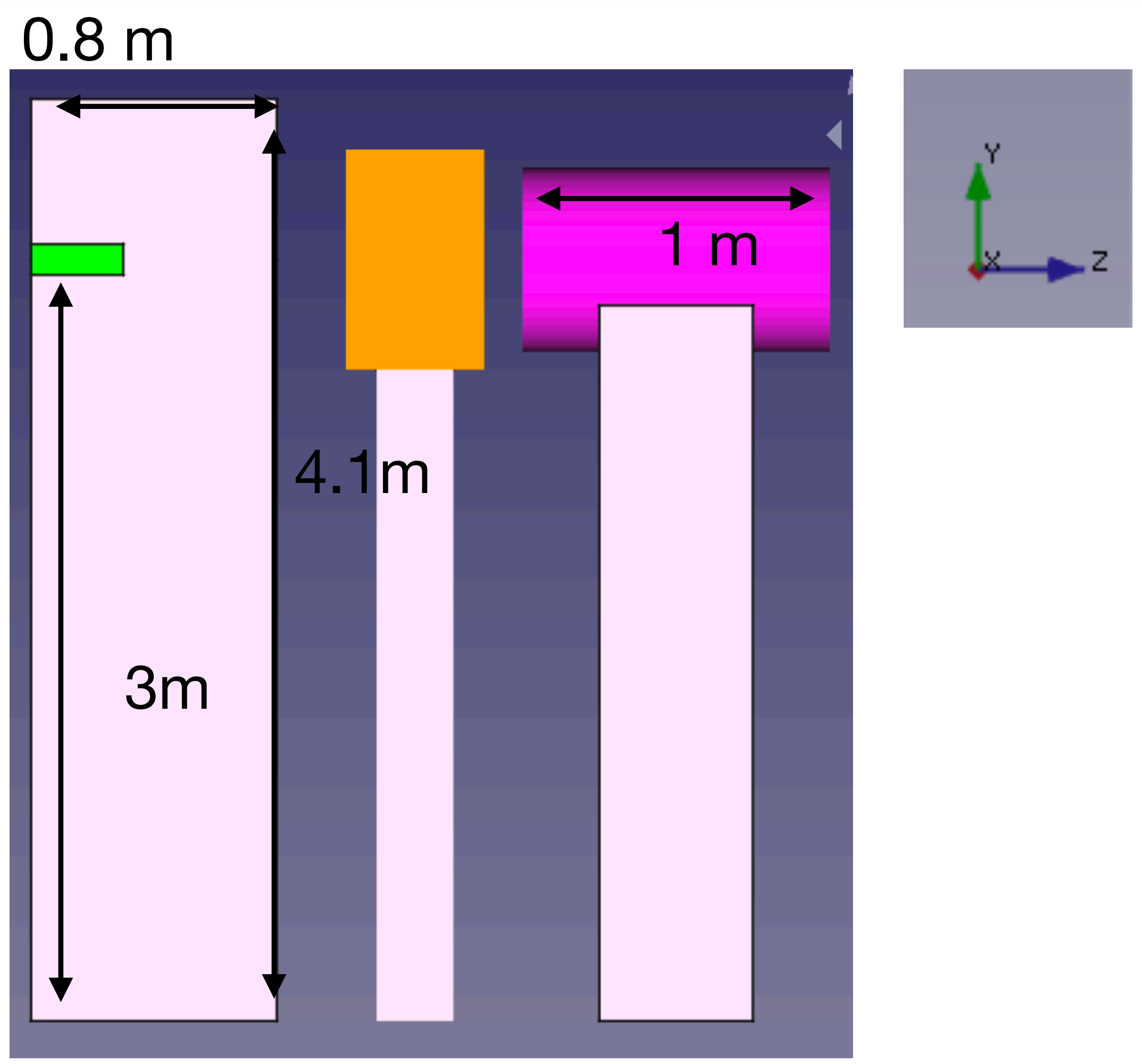


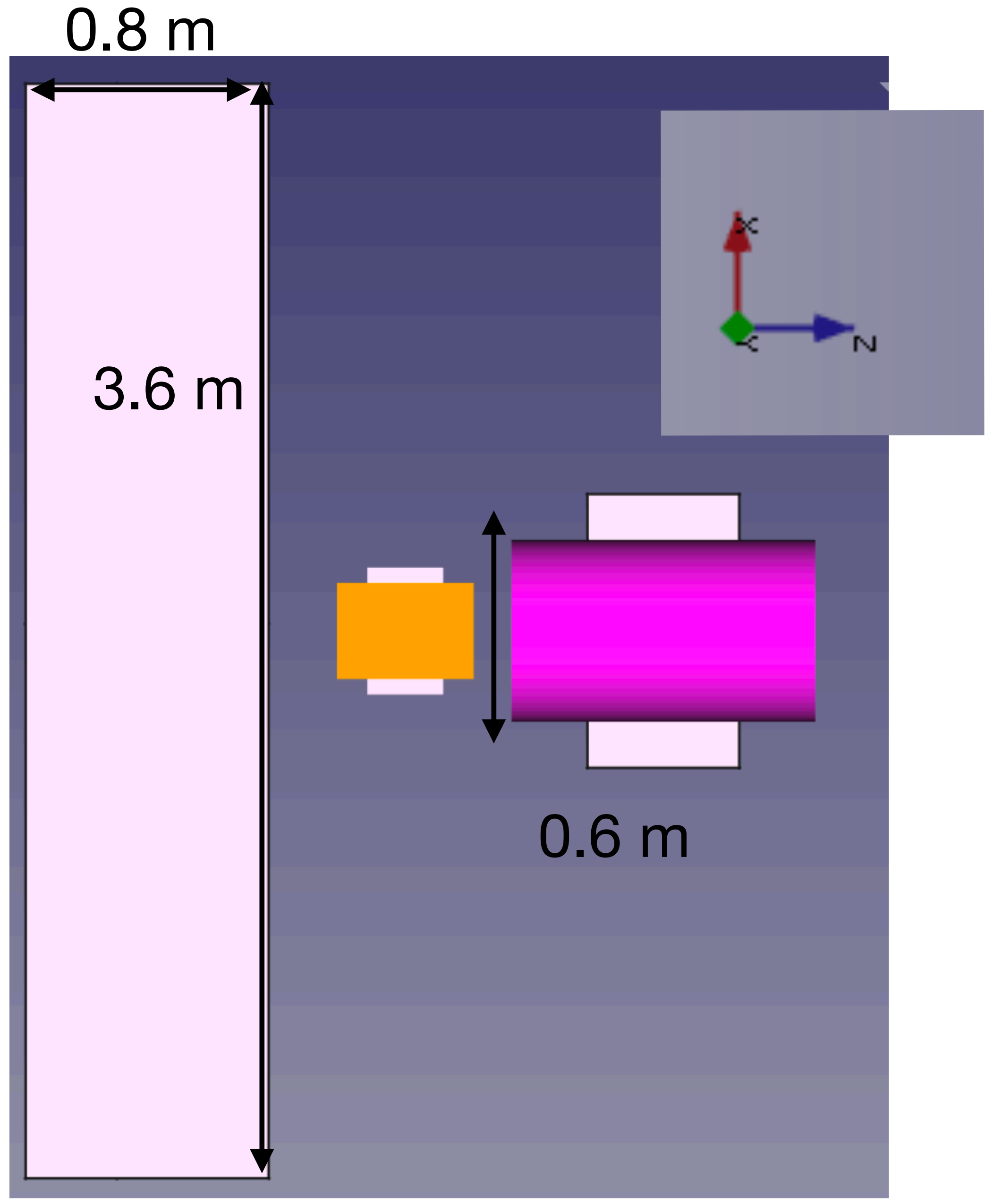


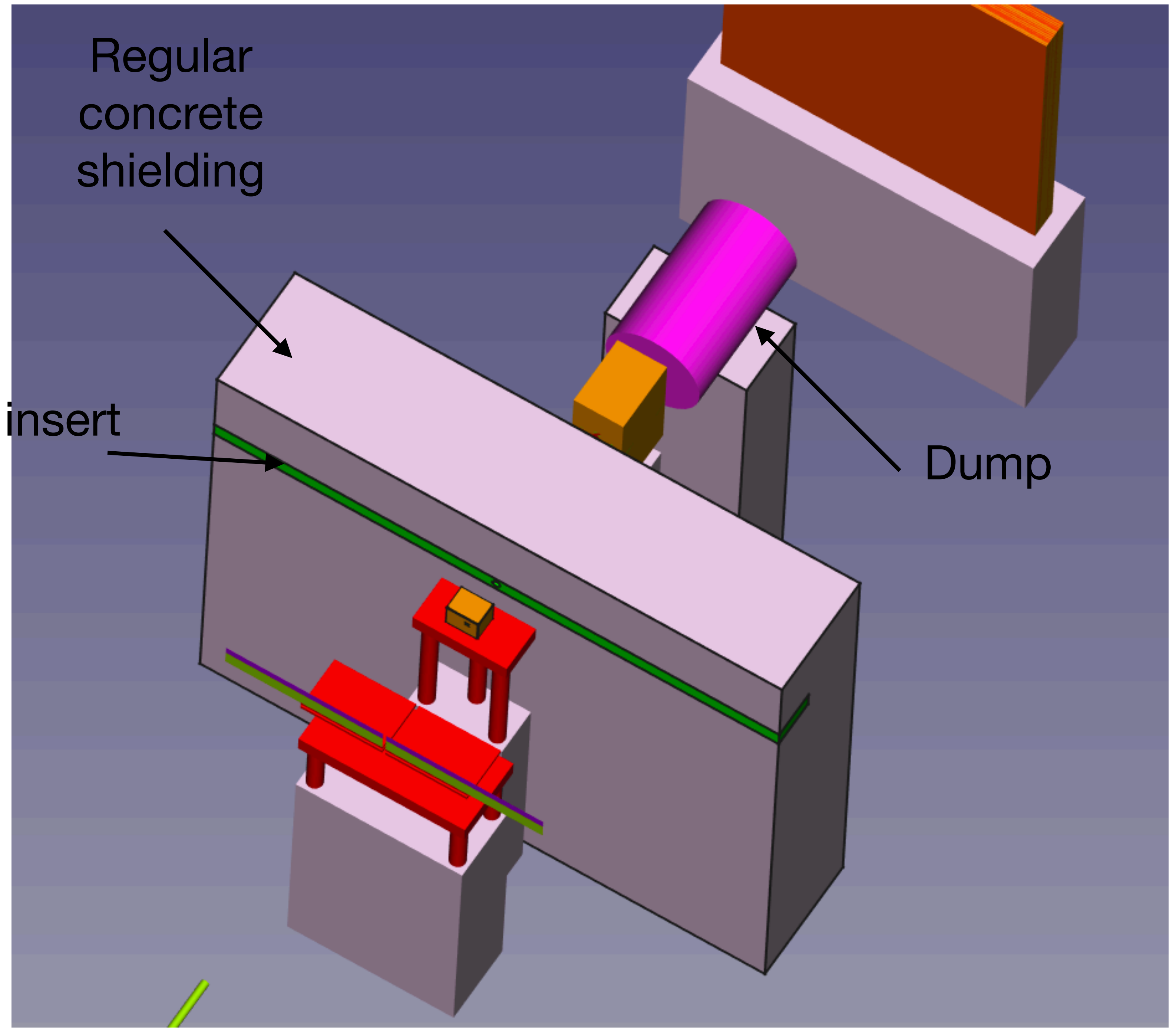
Beam dump designed according to (twice all dimensions)

Regular concrete shielding

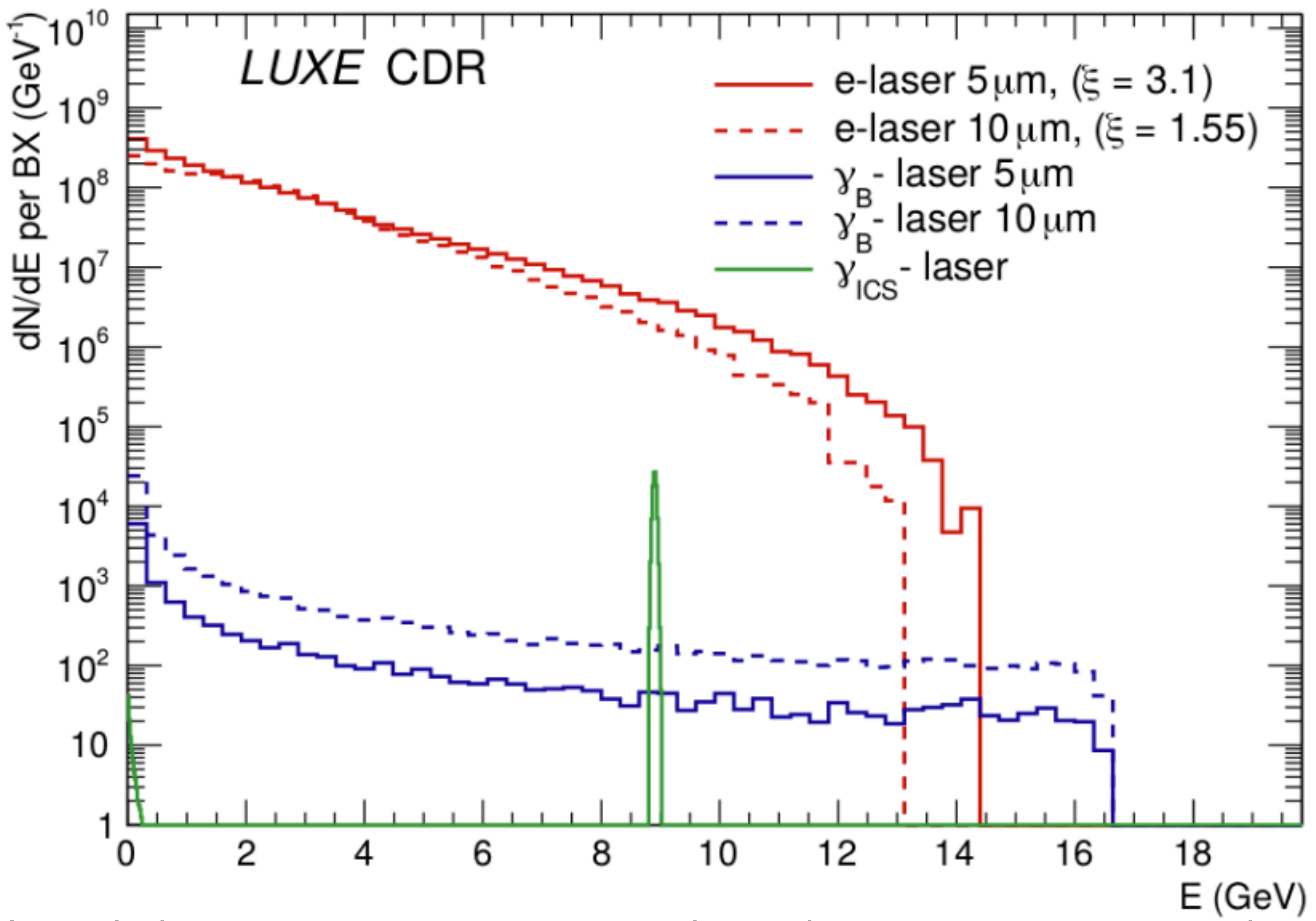
20cm Lead insert



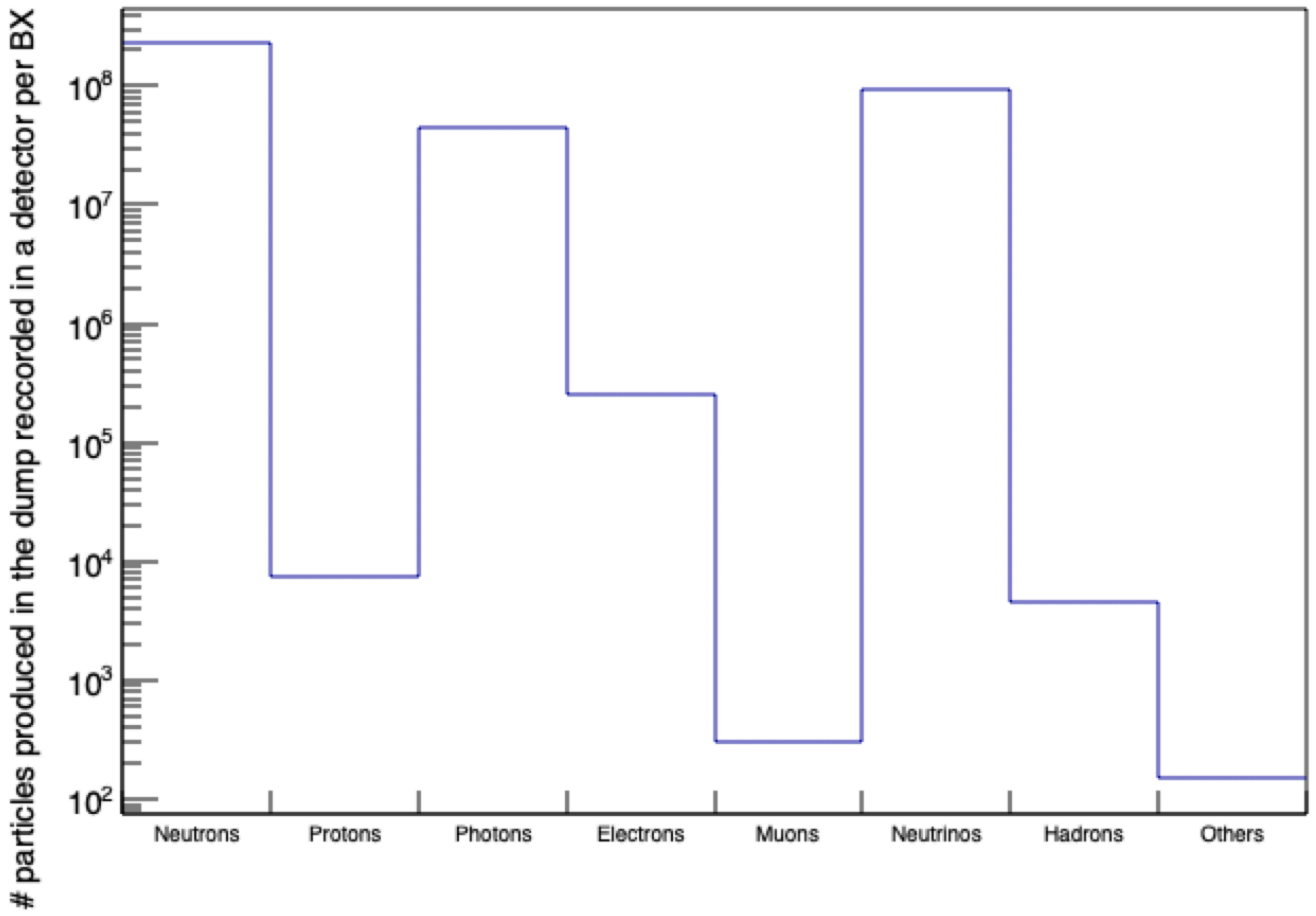




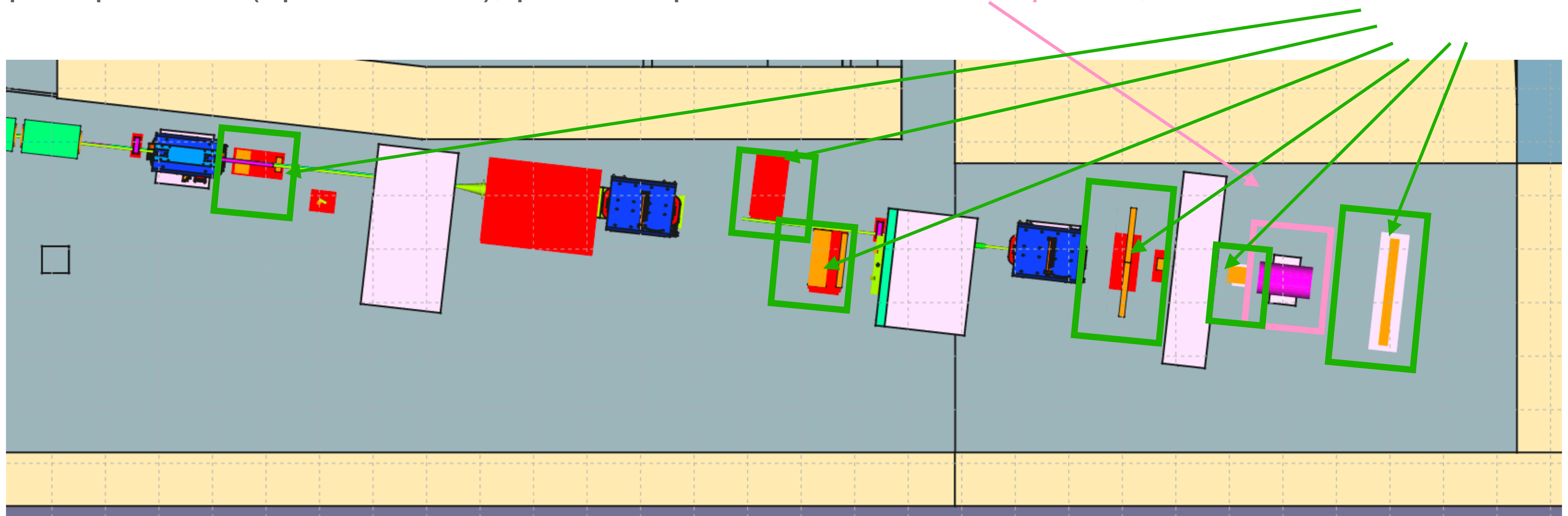
ELECTRON-LASER ELECTRON BEAM DUMP ENERGY AND PARTICLE SPECTRUM

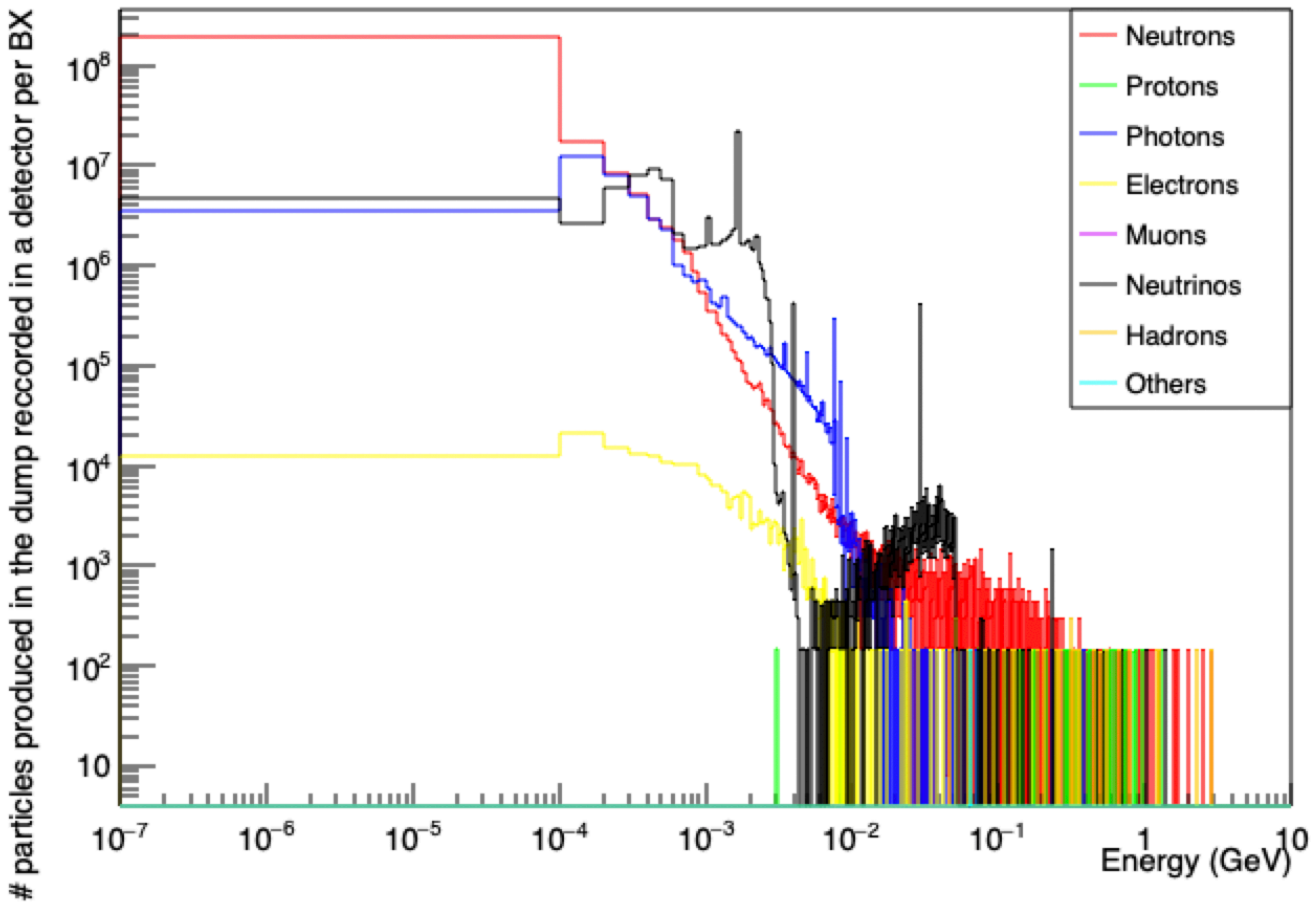


e produced through, brem target, compton scattering or inverse compton scattering

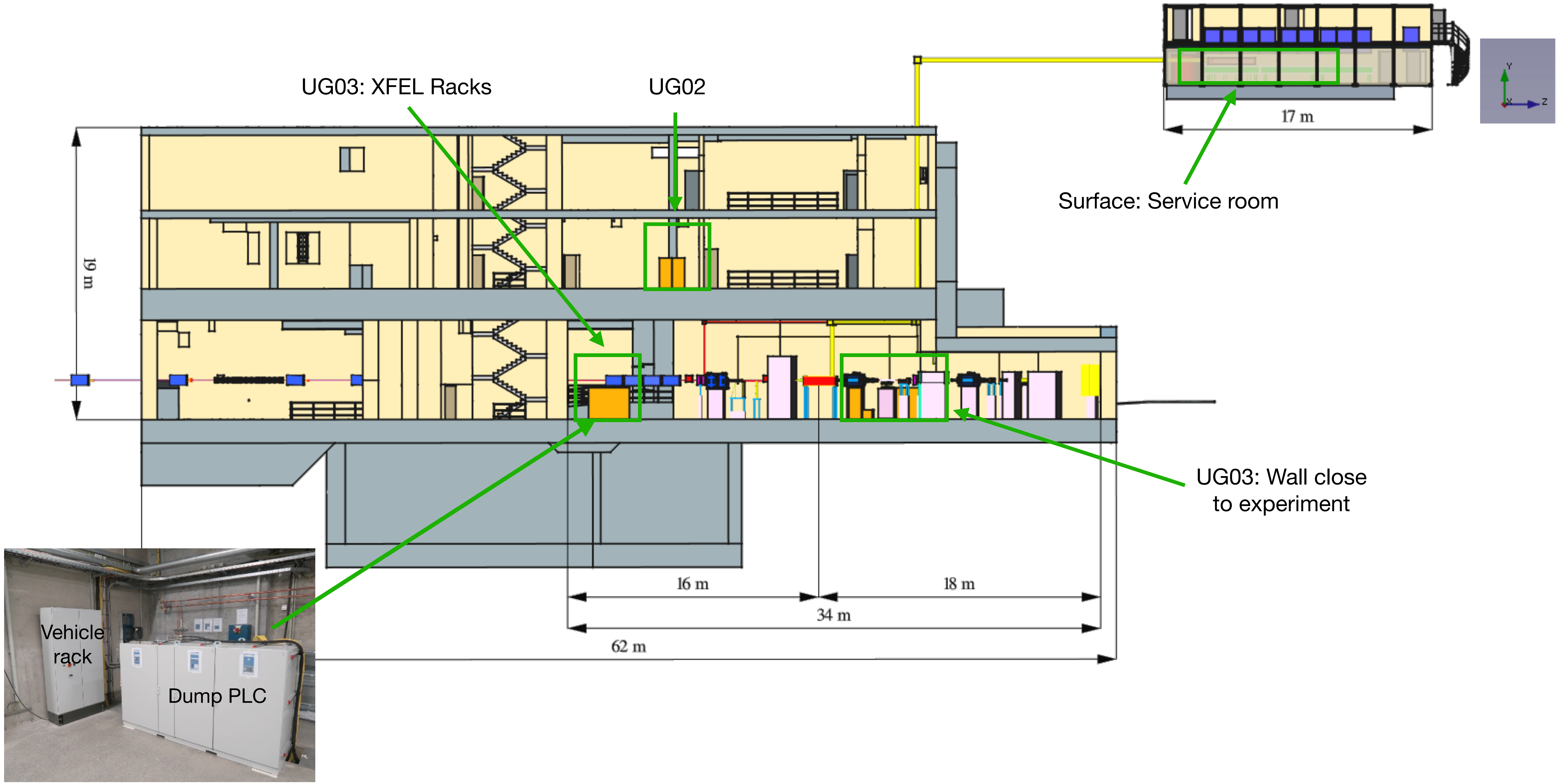


Output spectrum (~phase 0 run), particles produced in the dump here, but recorded in one of the detectors





XFEL DUMP PLC AND VEHICLE RACK



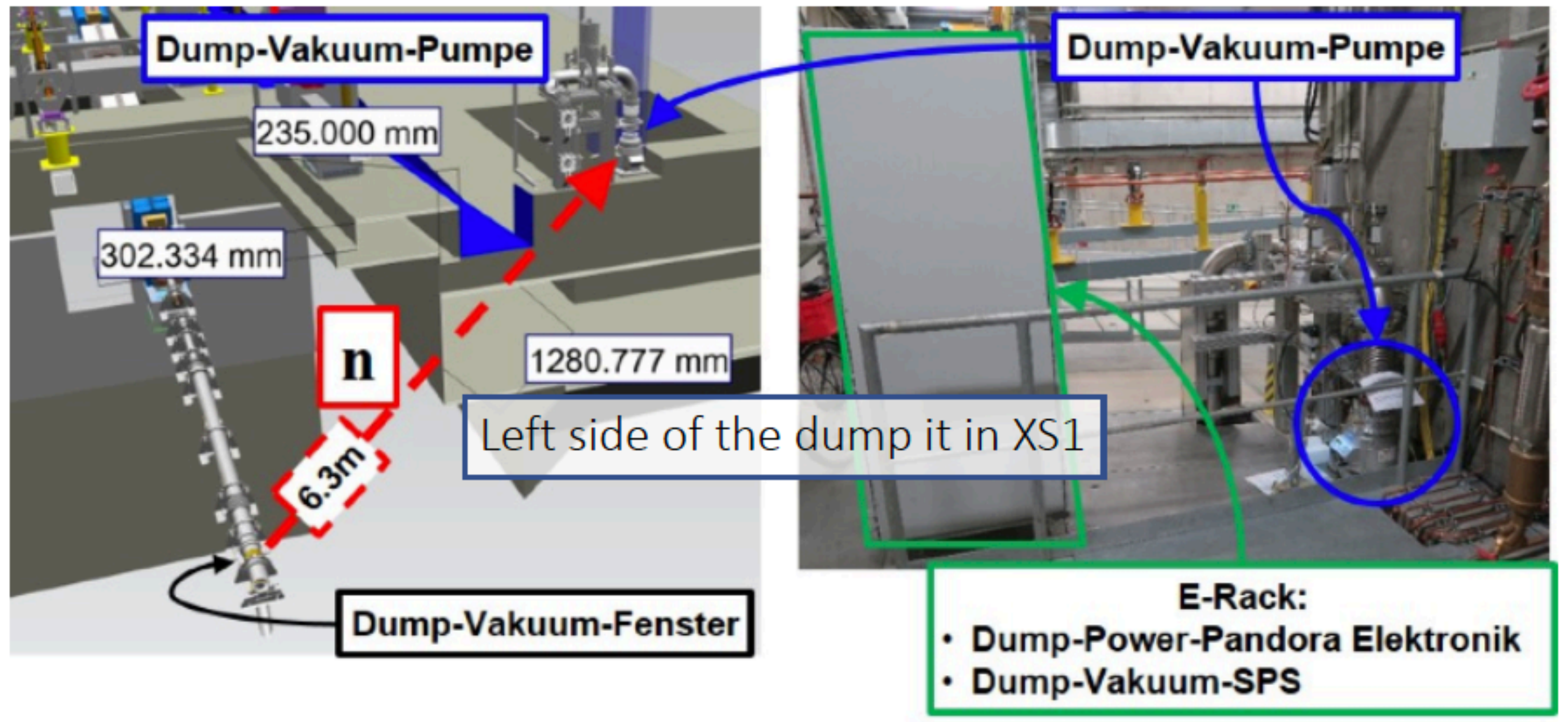
What Level of Neutron Field is aimed for, i.e. „safe“?

Regard the n-fluence as created by a 10kW beam near the (old) pos. of pump and PLC as „safe“ (factor 3-4 below trip probability rises)

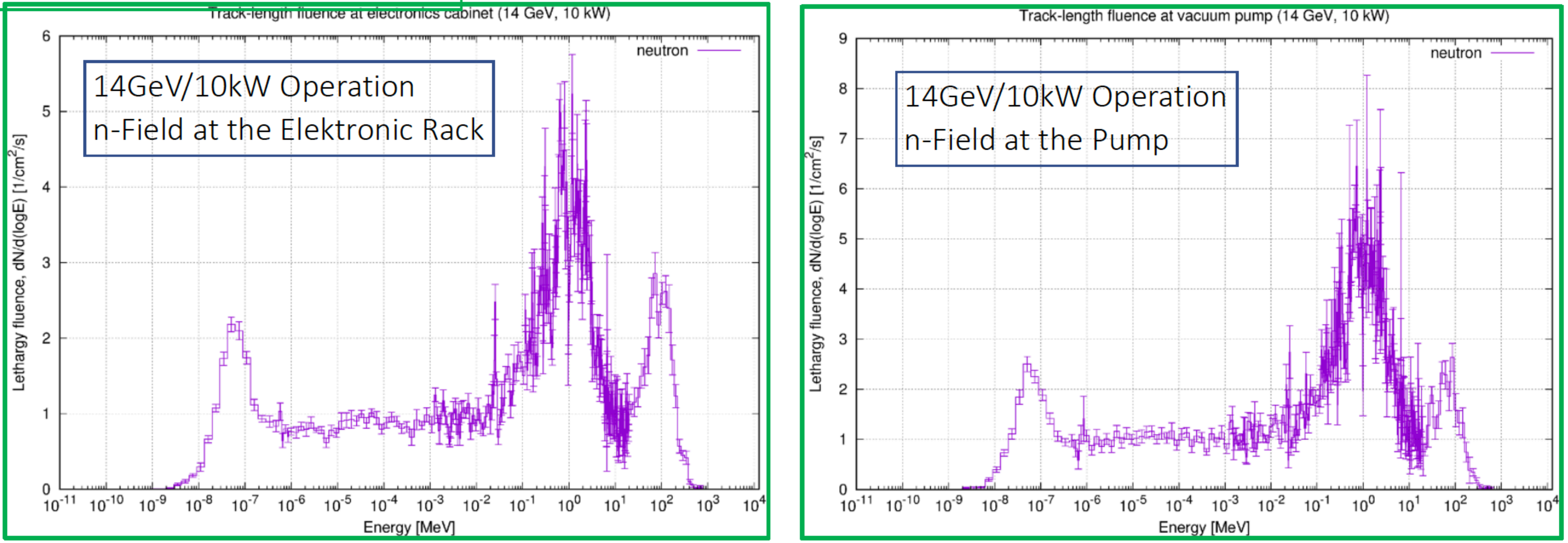
=> dN/d(logE):

~4-5/cm²/s for 1MeV n‘s

~2-3/cm²/s for 100MeV n‘s

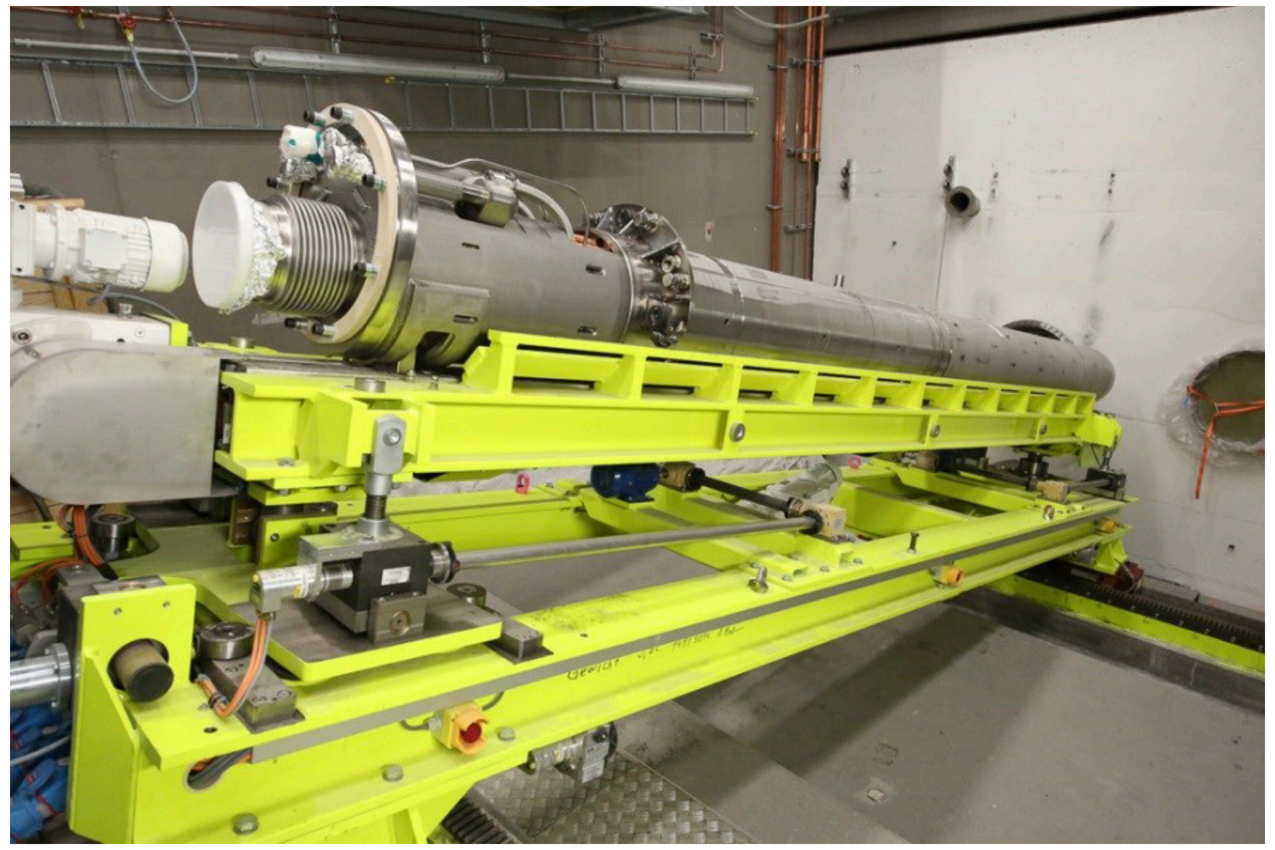


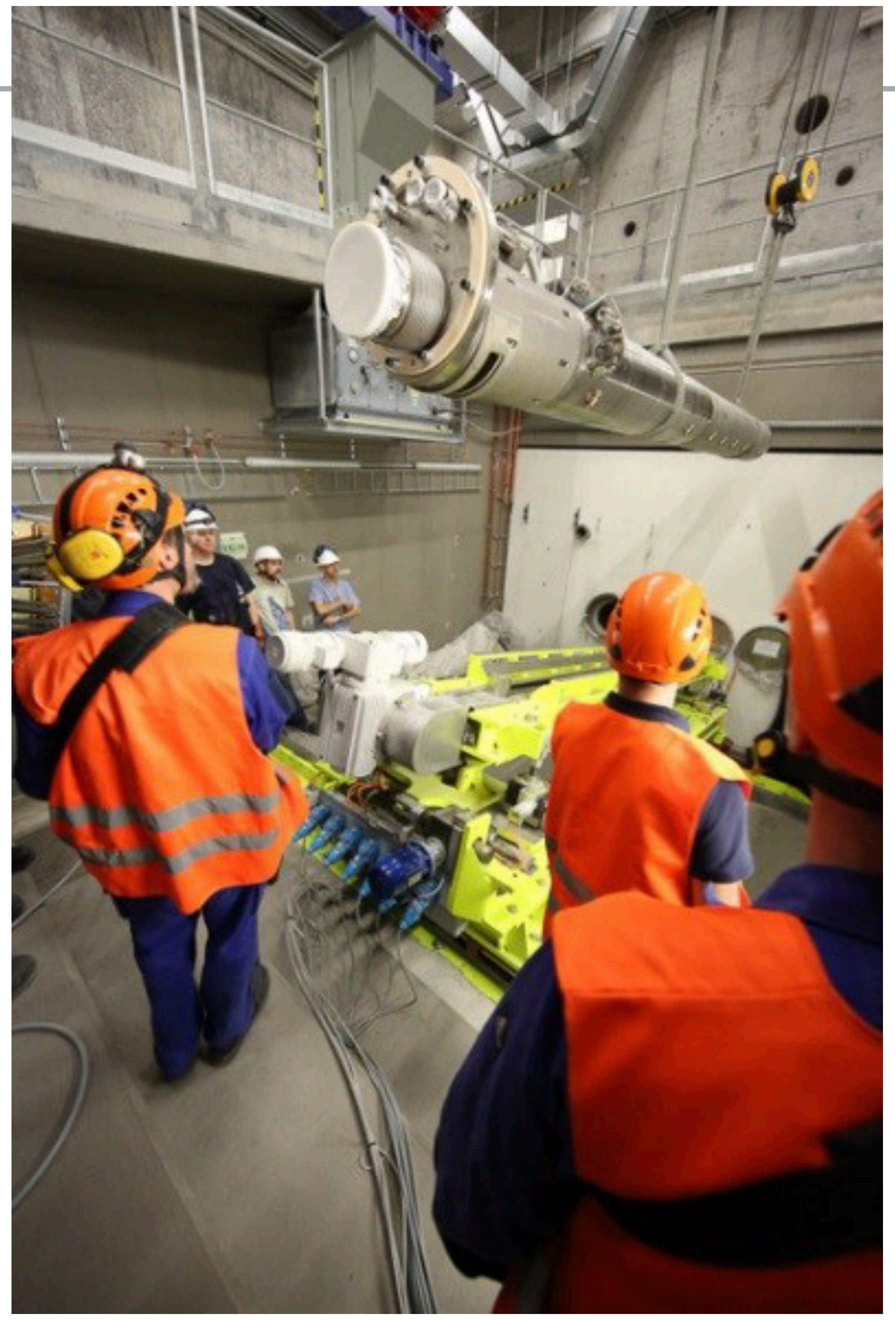
At about 30-40kW beam power, XFEL-operation sufferd from significant number of trips of the vacuum system, either or RELATED PLC of vac. system in the rack. ~47 trips in whole operation year 2020 !!

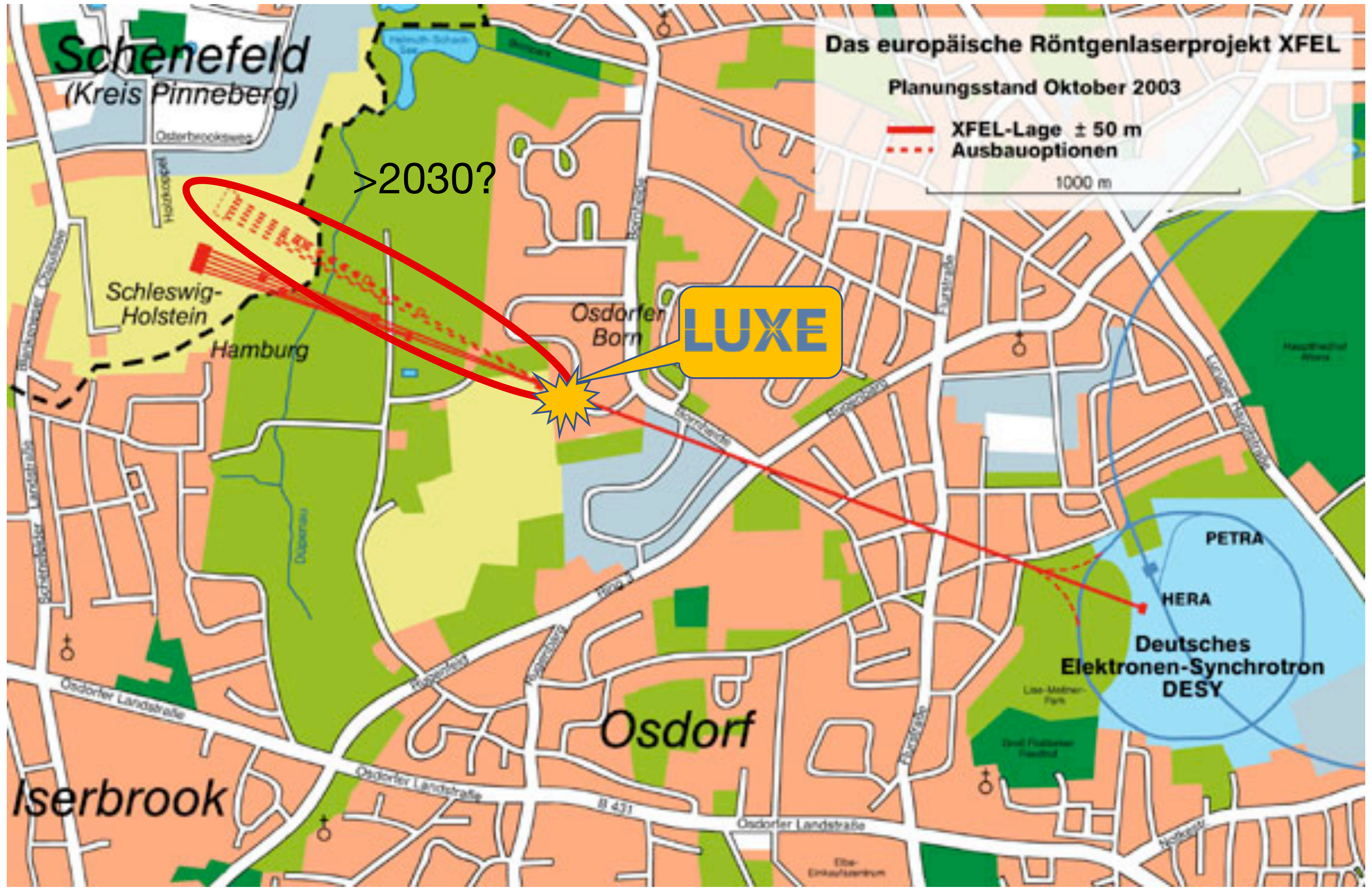


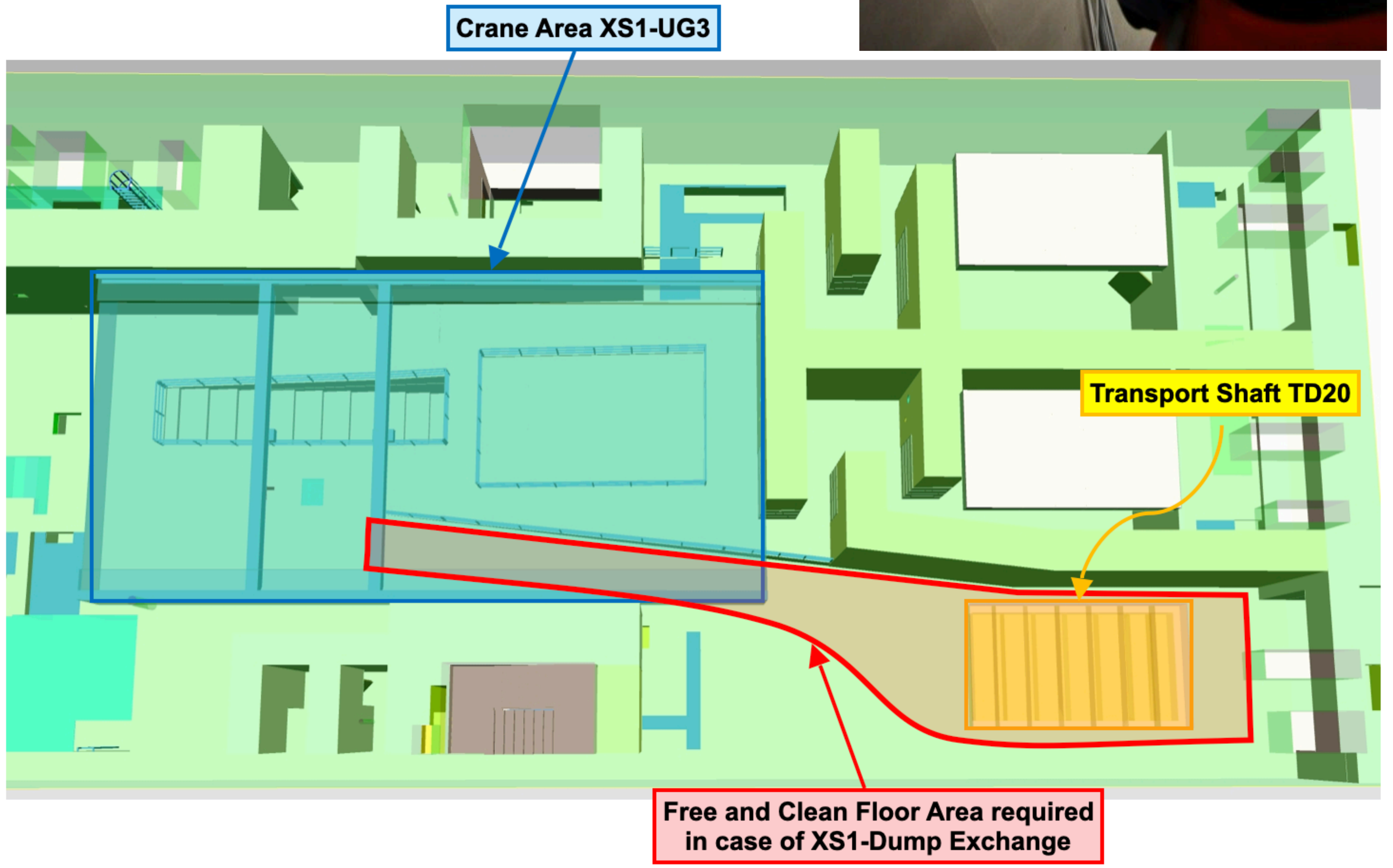
EXPERIMENT REMOVAL

- LUXE will be installed in not-yet used Annex of Osdorfer Born (XS1) building.
  - Experimental area needs to be clean-able on short notice for XFEL dump vehicle in case of dump failure.
  - Experiment decommissioning included in design:
    - Experiment must be entirely removable for second XFEL fan (>2030?).
  - Support structure and shielding made of standard elements which can be easily removed.
  - Low power electrons and photons dumps (1 bunch@10 Hz ≈ 200W).









Chapter 6

Single Bunch Beam Dump and Radiation Protection

The LUXE experiment at the European XFEL (EuXFEL) uses single electron bunches at a maximum energy of E_0 =17.5GeV with a maximum charge of q_t =1nC repeating at a rate of ν_t =10Hz in parallel to the standard FEL operation. Behind the LUXE interaction point (IP) a strong dipole magnet deflects electrons and positrons in opposite directions, each by an angle of 38mrad, while the photons go straight of course. Positrons, electrons and photons are analyzed at the detectors of the experiment. The non-interacting electrons, which carry the bulk part of the primary power have to be dumped safely. According to the numbers given above, the total average power in the electron beam is not more than P_{ave} = 175 W at 17.5 GeV. Although this is not a challenging demand for a beam dump, one has to keep in mind that the proposed location of the LUXE experiment in the XTD20 area of the XS1 shaft was never foreseen and thus not designed (e.g. in terms of concrete thicknesses etc.) to loose some 100W of a 17.5GeV beam there continuously. Thus special attention has to be paid on a high capture efficiency of the dump and a sufficient radiation shielding around it. The latter is important in multiple aspects:

1. The adjacent area of the XTD2 tunnel must stay safe in a sense that persons may work there, while the XTL area including the LUXE experiment is in operation.
2. The radiation protection rules concerning the activation of air, water and soil have to be obeyed. As already known from the layout of the EuXFEL beam dumps behind each of the bunch compressor sections in the XTL tunnel, air activation is an issue for poor shielded beam dumps operating at a few 100W.
3. The XS1 annex houses some racks with electronic for the EuXFEL, which must not suffer by the additional radiation from the LUXE setup.

In principle there is roughly up to 1 m of space around the dump for shielding purposes. In combination with a dump of $\sim$ 99 % primary energy capture a suitable shielding layout for a 200 W dump operated 5000 h/year will be possible.

Although the extraction of single bunches towards the LUXE experiment is done by means of a kicker with a half sine pulse, whose base-width is 2 μs and does not allow to drive more than a few bunches of a long train (4.5 MHz bunch to bunch separation) into the LUXE transfer line. This could be regarded as some intrinsic limit, but the same trajectory can be established by equivalent dc-magnets and thus the radiologically forbidden case where the whole bunch train of the linac is directed into the XTD20 arm is excluded by the MPS system. In addition, fail-safe and robust diagnostics has to give an alarm whenever the beam power into the XTD20 line exceeds the allowed limit of 200 W. At least 2 redundant detection schemes, which are independent of the timing system, like self-triggered toroids or radiation measurement devices like the Pandora may be used for this purpose.

The questions of radiation safety in terms of sufficient shielding layout and a fail-safe alarm diagnostic are fundamental preconditions for the LUXE experiment. Solution approaches have been sketched rudimentary and have to be worked out in detail during the technical design phase. The following section focuses on the layout considerations for the beam dump itself.

Beam Dump Layout

Following the goal as described in the introduction, the dump itself should have a high capture efficiency of $\sim$ 99 %. Since average power and cyclic load are low, materials that are easy to handle in terms of fabrication processes (joining, machining) should be selected. That is why aluminum and copper are suitable candidates for such a dump. For a given absorption materials of high density make a dump more compact. Nevertheless neutron production increases with the atomic number Z of the material and thus aluminum is preferable compared to copper. In addition the long term cyclic strength (endurance limit) of an aluminum alloy is better than that of copper, which will show fatigue effects and might get brittle along the axis where the beam enters. Therefore a cylindrical dump layout is proposed, which consist of an aluminium core, that is radially enclosed by a copper shell and followed by a solid copper backstop with the same diameter as that of the shell. Heat as dissipated around the axis of the absorbed beam is extracted by radial heat flow towards a heat sink at the radial surface of shell and backstop. Such a layout was also used for the beam dump behind the injector and the bunch compressor sections BC1 and BC2 of the EuXFEL facility. Therefore size specifications and manufacturing procedures are adopted from those dumps. The proposed layout for the LUXE-dump is shown in Fig.6.1 and its design principles are motivated in the following paragraphs.

The Al-core has a vacuum tight connection (e-beam or laser weld) to an

MACHINE CDR DUMP DESCRIPTION 2

aluminum beam pipe, that is equipped with a special flange made out of an explosion bonded stainless steel to aluminum transition. By that means the aluminum dump vacuum chamber can be welded to the flange, from where a standard stainless steel based vacuum system with CF-flanges can be connected to. The Al-core of the dump is thus part of the beam line vacuum system and can be regarded as a thick exit window.

A tight fit between Al-core and Cu-shell allows a simple assembly of these parts as well as a good thermal contact during operation when the core gets hotter than the shell and thermal expansion leads to a rising contact pressure at this boundary. The backstop can be joined (e.g. screwed) to the Cu-shell without any specific constraint in terms of heat contact.

Concerning the size of a dump an estimate of the length $L_{99\%}$ and the radius $R_{99\%}$ of a homogeneous cylindrical absorber, which captures about 99 % of the primary beam energy, is given by the radiation length X_0 and the critical energy E_c of the absorber material as:

$$R_{99\%} \approx 5 \cdot R_M \approx 5 \cdot \frac{21.2\,\text{MeV}}{E_c} \cdot X_0$$
$$L_{99\%} \approx \left[1.52 \cdot ln\left(\frac{E_0}{[\text{MeV}]}\right) - 4.1 \cdot ln\left(\frac{E_c}{[\text{MeV}]}\right) + 17.6\right] \cdot X_0 \quad (6.1)$$

Property		Al	Cu
ρ	$[\frac{g}{cm^3}]$	2.7	8.96
X_0	[cm]	8.9	1.44
E_c	[MeV]	40	19
R_M	[cm]	4.67	1.61
$R_{99\%}$ (20GeV)	[cm]	23.4	8.1
$L_{99\%}$ (20GeV)	[cm]	156	30

R_M denotes the so called Molière radius which quantifies the radial shower size and is independent of the beam energy E_0.

Thus a homogeneous cylindrical absorber, with 99 capture efficiency in each dimension, made of aluminum must have a diameter of $D_{Al,99\%}$ ~50cm and a length of $L_{Al,99\%}$ ~1.6m while for copper this will be only $D_{Cu,99\%}$ ~16cm and $L_{Cu,99\%}$ ~30cm, as summarized together with the mass density, the radiation length, the critical energy and the Molière radius in Table 6.

For the desired Al-Cu layout the radius of the Al-core is chosen such that there is a radial layer of at least $1 \cdot R_M$ (Al) ~5cm between the beam impact area and the outer rim of the core. The remaining $4 \cdot R_M$ (Cu) ~6.5cm in radial size determine the thickness of the Cu-shell. In that case the total radius of the dump would be 11.5cm, but the beam enters the dump along a vertical line rather than at a single point. As a consequence of the experiment the interacted electron beam is not mono-energetic anymore, but distributed between its nominal energy E_0 =17.5GeV down to 14GeV. Such an energy spread of $\frac{\Delta E}{E_0}$ =20 translates into a displacement spread of the incoming beam at the dump face. This is indicated with the red dashed line in Fig. 6.2.

The dump should be located in a distance behind the dipole, where the photon/electron beam separation, namely the displacement of the electron beam Δr, is large enough to guide the photon beam line very close but not through the dump. For the radial size of the dump as explained above this can be achieved for Δr =13.5cm and results in a displacement range of $\frac{\Delta E}{E_0} \cdot \Delta r$ ~3cm. As a consequence the Al-core has a radius of R_M (Al) + 3cm/2 ~6.5cm instead of 5cm as it would be for the non-spreaded beam impact.

The length of the Al-core has been defined to fulfil a certain aspect of technical safety. As being part of the vacuum system a destruction of the Al-core by the beam must be avoided in any case. If its transverse size is tiny enough, even a 1 nC beam pulse may create an energy density in the core, which exceeds aluminum's specific melting heat of ~400Jg. The position of the maximum energy density, as created by one beam pulse, is somewhere on the beam- resp. shower-axis and for a pencil-like beam it is located right at the surface, where the beam enters. Due to shower development the energy deposition profile widens and the number of secondary particles increases. These counteracting processes determine the quantity of the deposited energy density. Independent of how small the spot of the impinging beam was, after a certain depth of the material the energy density has fallen down to a tolerable value. A reasonable tolerable limit for aluminum in a pulsed heating application, where fatigue phenomena after a large number of cycles (endurance strength) play a role, is about 15Jg [12]. From existing 20GeV shower simulations [13] with the monte carlo code MARS [14] in the context of the EuXFEL dump layout, we know that a Al-length of 20cm fulfils the explained goal.

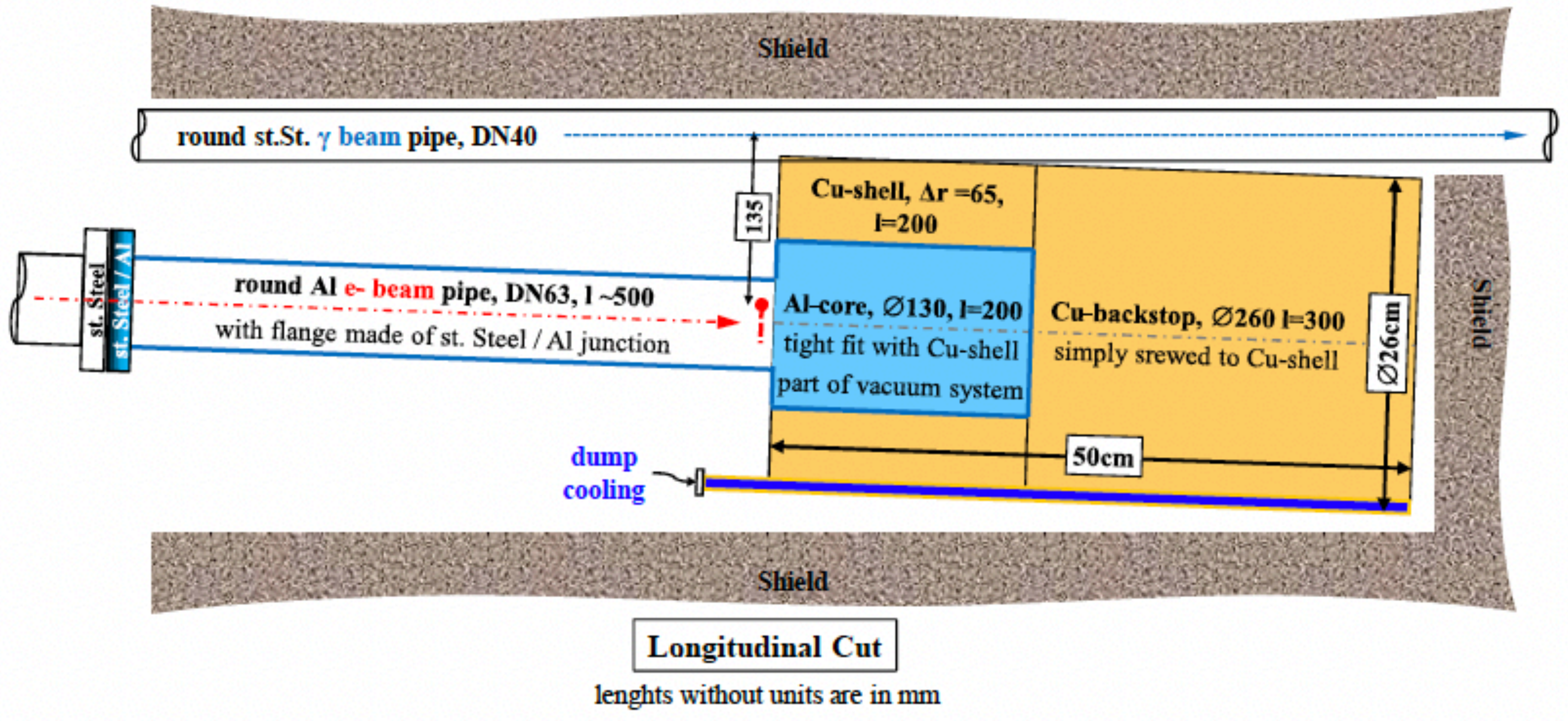
Nevertheless such an intrinsic safety against the risk of a vacuum leak by tiny beams is not a long term protection, because repeating melting / solidification cycles may result in the development of a porous channel along the beam axis after a while. Thus a safe and long term dump operation requires a size of the incoming electron beam of $\sigma_x \cdot \sigma_y \geq (100\mu\text{m})^2$, by which the above mentioned limit is exceeded nowhere in the Al-core.

Finally the size of the Al-core/Cu-shell front part results in a length of 20cm and a radius of 13cm (r_{Al} =6.5cm, Δr_{Cu} =6.5cm). Its capture efficiency for 20GeV electrons is about 4. Thus the subsequent Cu-backstop must do the major part of the absorption. Since the shower is already pre-diluted and the backstop has no critical function, like being part of the vacuum system, the question of energy density is not an issue here. For simplicity its radius is made identical to the one of the front part and with a length of 30cm a 99 longitudinal capture is achieved according to Eqn.6.1. The total weight of the dump is 220kg (Al-core: 7.1kg, Cu-shell: 71kg, Cu-backstop: 142kg).

A sketch of the overall LUXE-dump area starting at the separation dipole and including a 0.5m thick shield around the Al-Cu dump is shown Fig.6.2, drawn to scale. As already mentioned, the dimensions of the shield are a rough first guess and subject to detailed considerations during the technical design phase. Air activation will be one of the issues in radiation safety. Thus the

MACHINE CDR DUMP DESCRIPTION 3

shield must prevent air exchange between dump surface and ambient air outside of the shield. As a consequence dump cooling by (forced) air convection cannot be applied, although it might be realistic if the outer surface of the dump is increased (corrugation etc.) by a factor of 3 to 4. The pure cylindrical surface of shell and backstop has a size of $2\pi \cdot \frac{26\text{cm}}{2} \cdot 50\text{cm} = 0.4$ and is not large enough for air cooling heat transfer purposes. With a thermal heat transfer coefficient for unforced convection at smooth surfaces $\alpha = 5$Watt the temperature drop at 200W heat dissipation is about 100K and intolerable. A simple water cooling at this surface should be used instead. Due to the low power this system can be supplied by the water as used for the standard magnet cooling. No separate water system with a heat exchanger system is necessary.



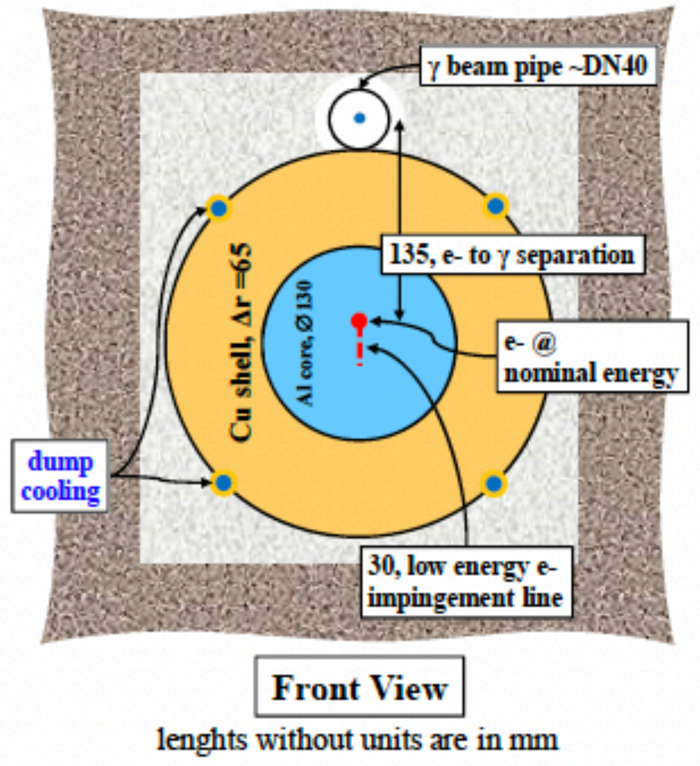
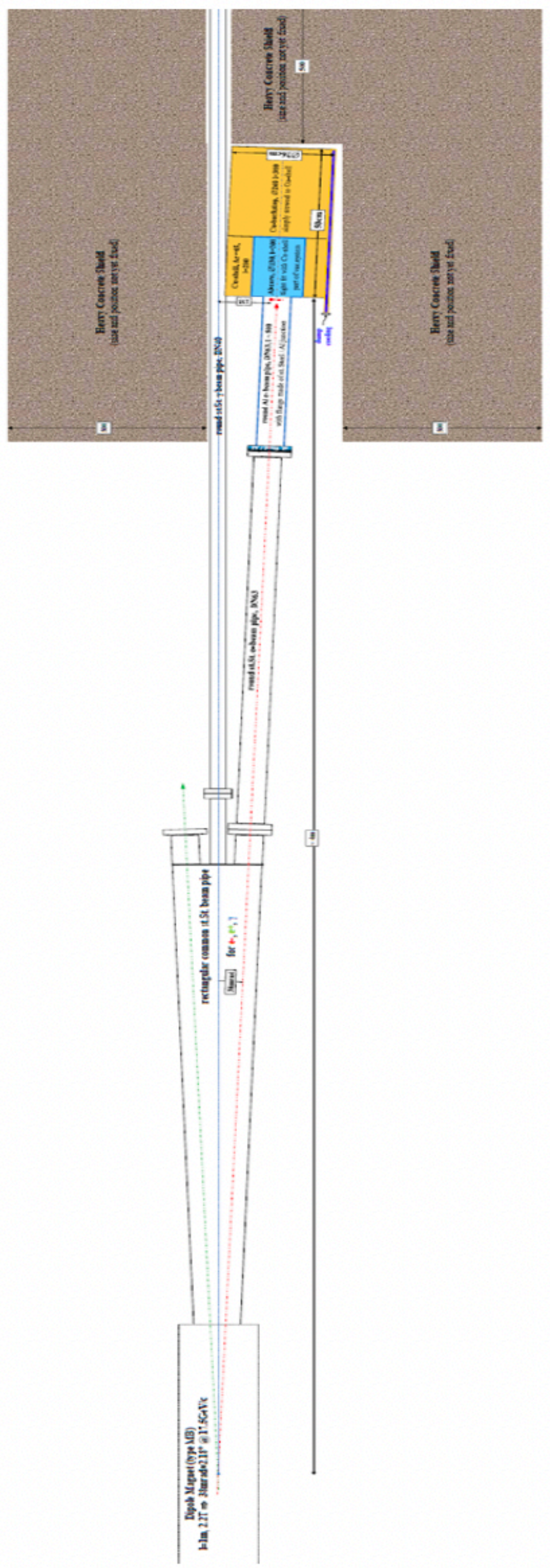


Figure 6.1: *Schematical layout of the LUXE beam dump.*

MACHINE CDR DUMP DESCRIPTION 4



28

Figure 6.2: *Overview of LUXE dump area with separation dipole and radiation shield.*