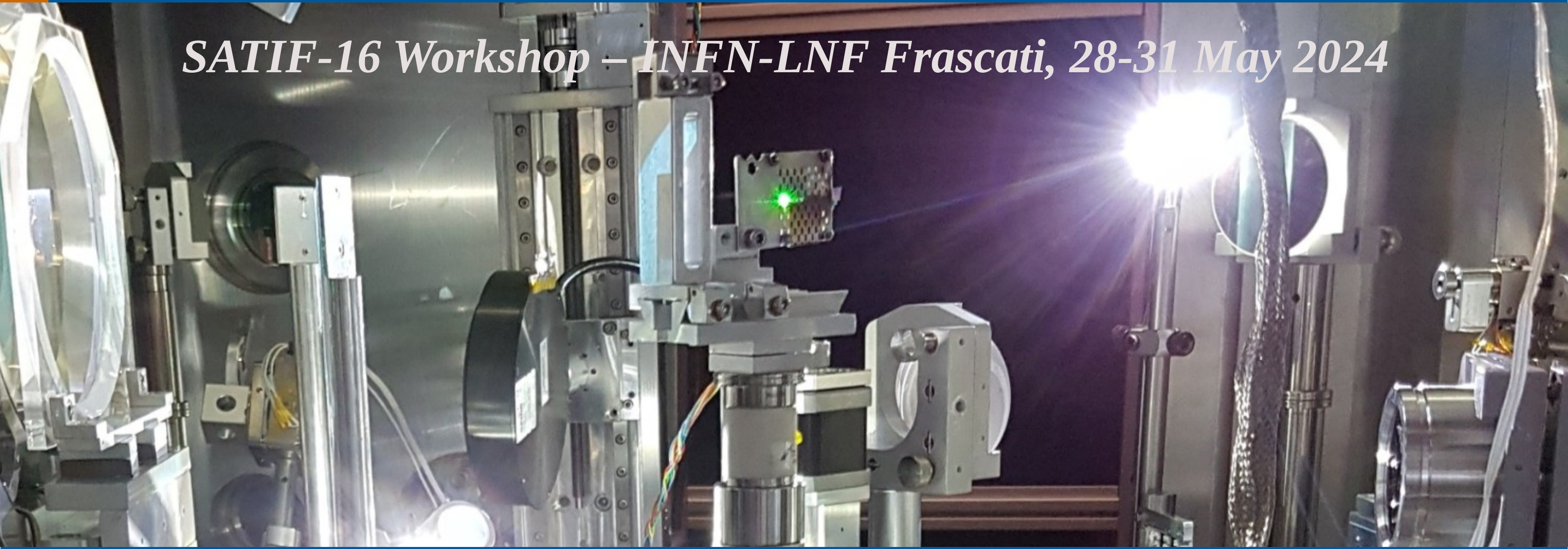


Source terms for the HED science in short-pulse experiments with solid target, and further perspectives

A. Ferrari, T. Cowan *Helmholtz-Zentrum Dresden-Rossendorf*
E. Brambrink *European XFEL*

….with contributions from the HED group at HZDR
L. Huang, M.Molodtsova

DRESDEN concept SCIENCE AND INNOVATION CAMPUS

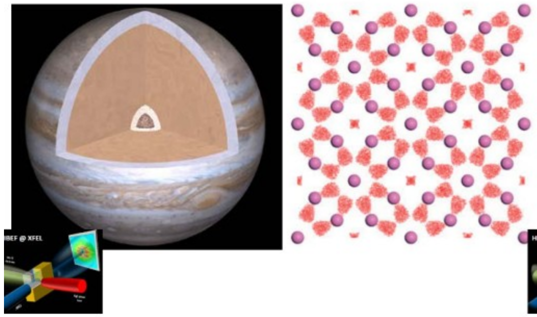
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Introduction

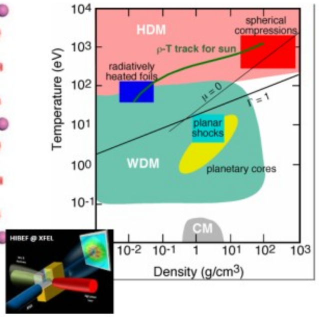
Ultrafast dynamics and structural properties of matter at extreme states

- Highly excited solids → laser processing, dynamic compression, high B-field
- Near-solid density plasmas → WDM, HDM, rel. laser-matter interaction
- Quantum states of matter → high field QED

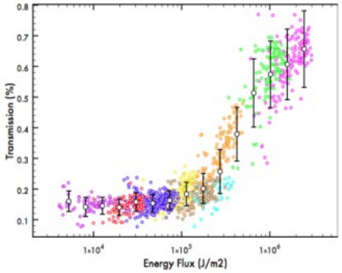
Condensed matter at very high T, P, ρ



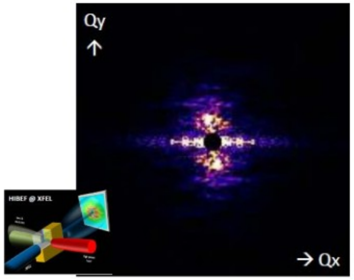
Beyond condensed matter



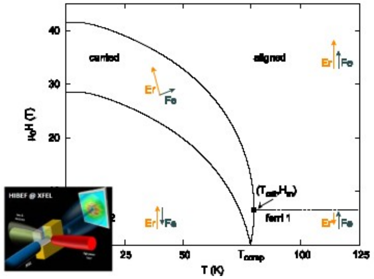
Intense x-ray matter interaction



Relativistic laser-matter interaction



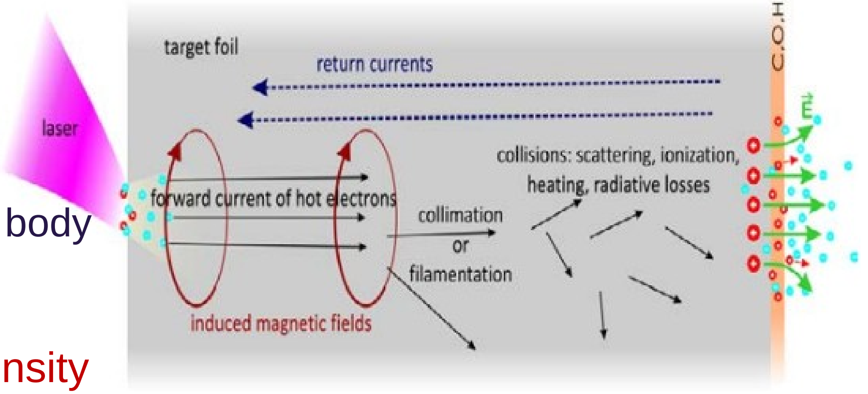
Complex solids in high fields



The dominant radiation source term

High intensity Lasers when hits solid targets creates:

- free electrons (from ionization of atoms)
- extreme electric and magnetic fields
- thin plasma layer (ions & electrons) on a dense, solid body
- energetic electrons propagate into solid



- 'Hot electron temperature' is related to the laser intensity

  and relativistic effects must be taken into account

$$T_e^{hot} = 2\pi\left[\int_0^{2\pi}\left(1 + a_0^2 \sin^2 t\right)^{-1/2} dt\right]^{-1} - 1$$

$$a_0 = \sqrt{2I / n_C m_e c^3}$$

T. Kluge et al.,
Phys. Rev. Lett. 107, 205003 (2011)

n_C= critical density of the dense plasma

- T_{el} scales with the laser intensity

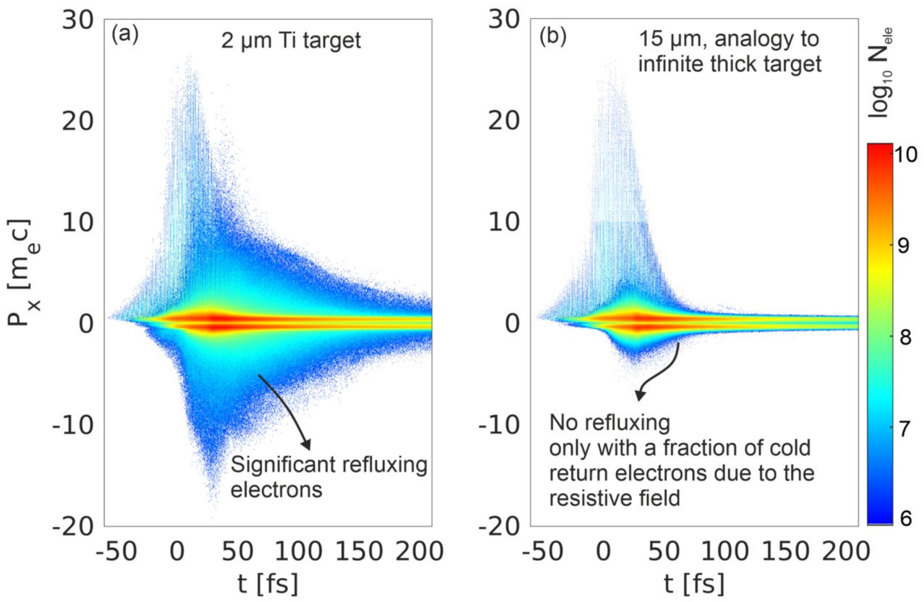
Electrons are originated in the target with a Boltzmann-like distribution
and generate bremsstrahlung radiation

Escaping electrons + bremsstrahlung radiation

are the dominant radiation source term for the facilities in HED science

Investigating the hot electron dynamics via PIC simulations - *(Satif-15)*

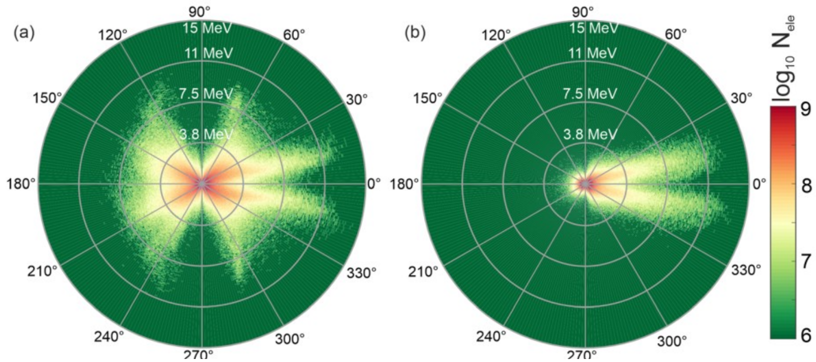
In PIC simulations:
- similar laser and target parameters as in experiments
- study of the temporal evolution of the sheath field, to take into account the hot e^- refluxing mechanism



Thin target case

2 µm Ti foil target

'Thick' target case



L.G. Huang, M. Molodtsova, A. Ferrari et al.,

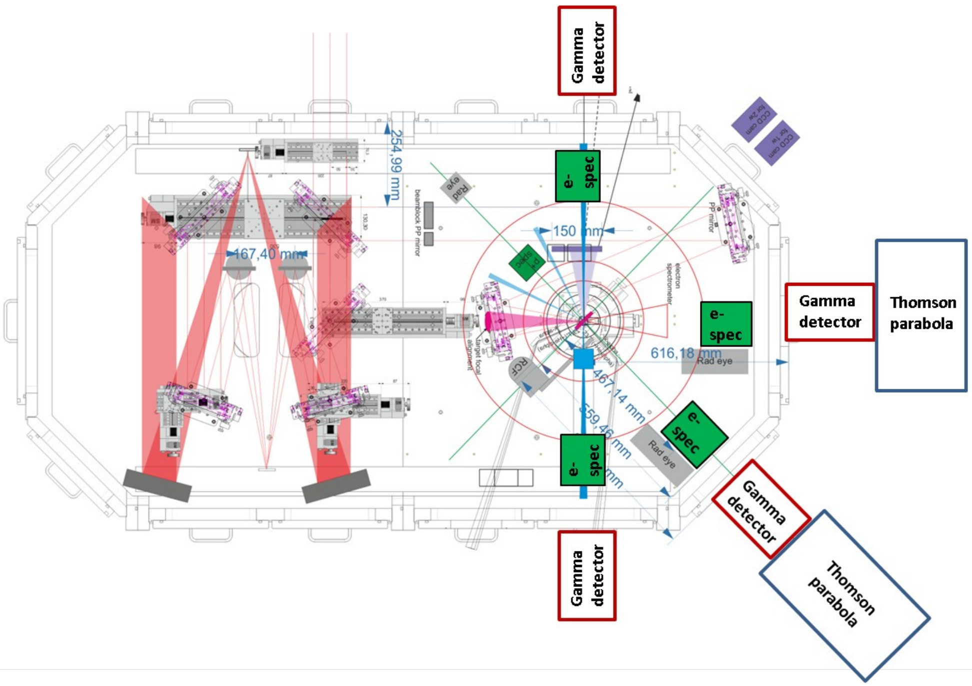
Phys. Plasmas 29, 023102 (2022)

- The energy spectra of forward and backward hot electrons are integrated on 4 probing boundaries
- The optimal integration time (132 fs) is calculated from the study of the temporal evolution of the sheath field

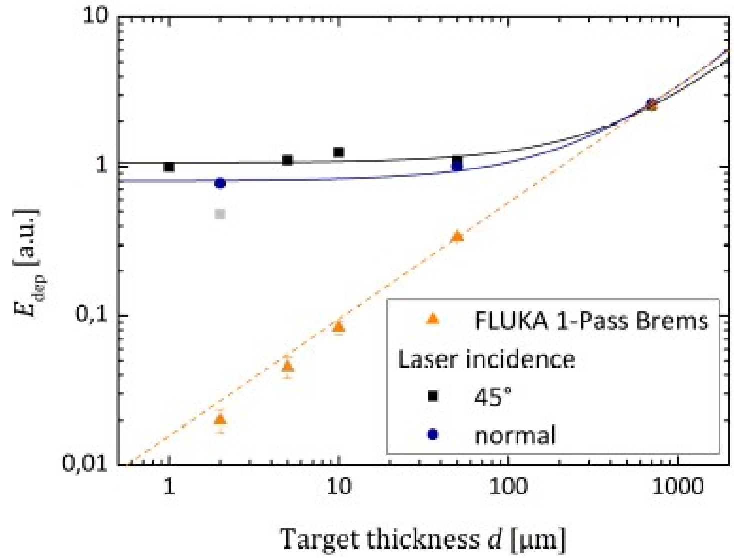
Experimental signature of hot electrons refluxing in thin targets

Large experimental campaign to study the **bremsstrahlung properties** associated to the proton acceleration (**DRACO facility**, Ti:Saffire laser, **8J**, **150 TW**)

- Foils of different materials (**Ti, Al, W**)
- Thickness scan of Ti (1/2/10/50/700 µm)
- Alternative shapes (cones, wires)

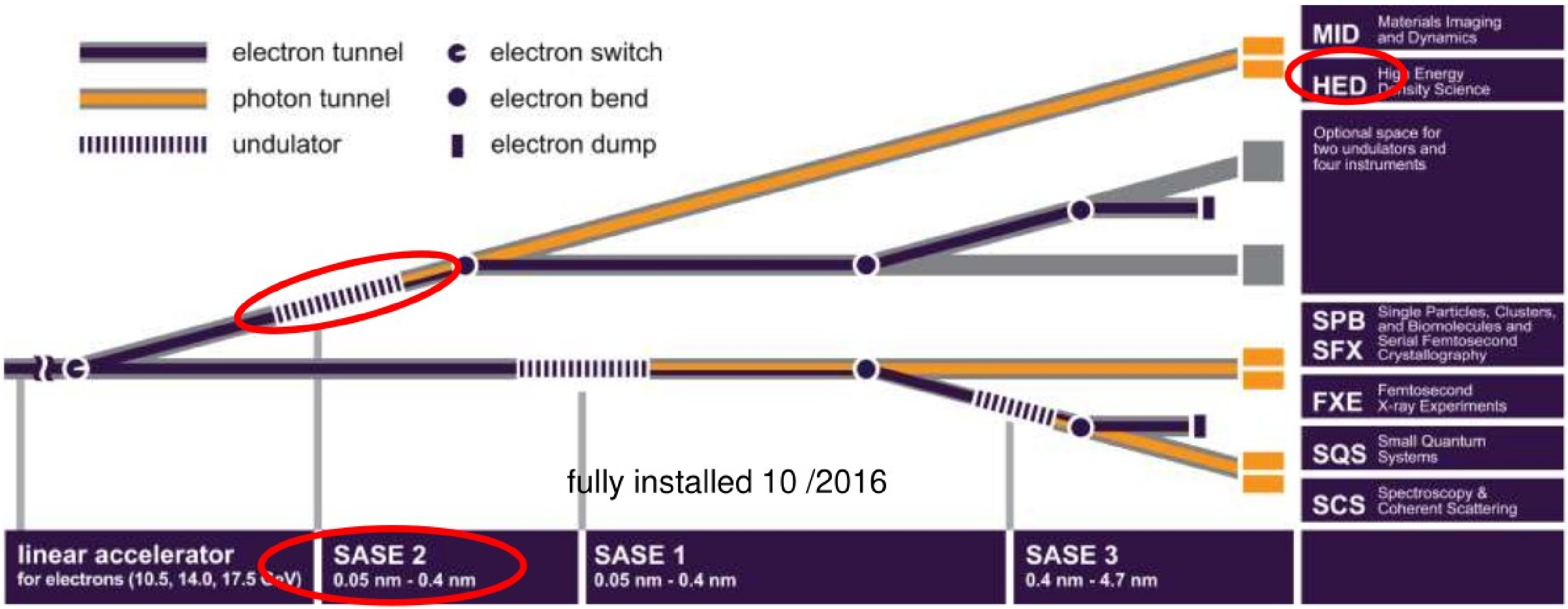


Scaling of the deposited energy



Measured energy
(a.u., normalized to the first data point)
deposited by the bremsstrahlung
*in our **photon detectors***
as a function of the target tickness,
compared with FLUKA simulations
without electron refluxing description

European XFEL: beamlines and instruments



HED – some numbers

- Beamline commissioning 2019, first user experiments spring 2019
- Typically 20 experiments/year
- Photon energies: 5-25+ keV
- Pulse energies: > 3 mJ @ 8 keV

- HED is a versatile platform for High Energy Density Physics and dynamic compression experiment

Hibef user consortium

Helmholtz international beamline for extreme fields

HiBEF

- Installation and operation of lasers and part of the HED instrument
- 80 institutions, 20 countries
- > 40 M€ budget

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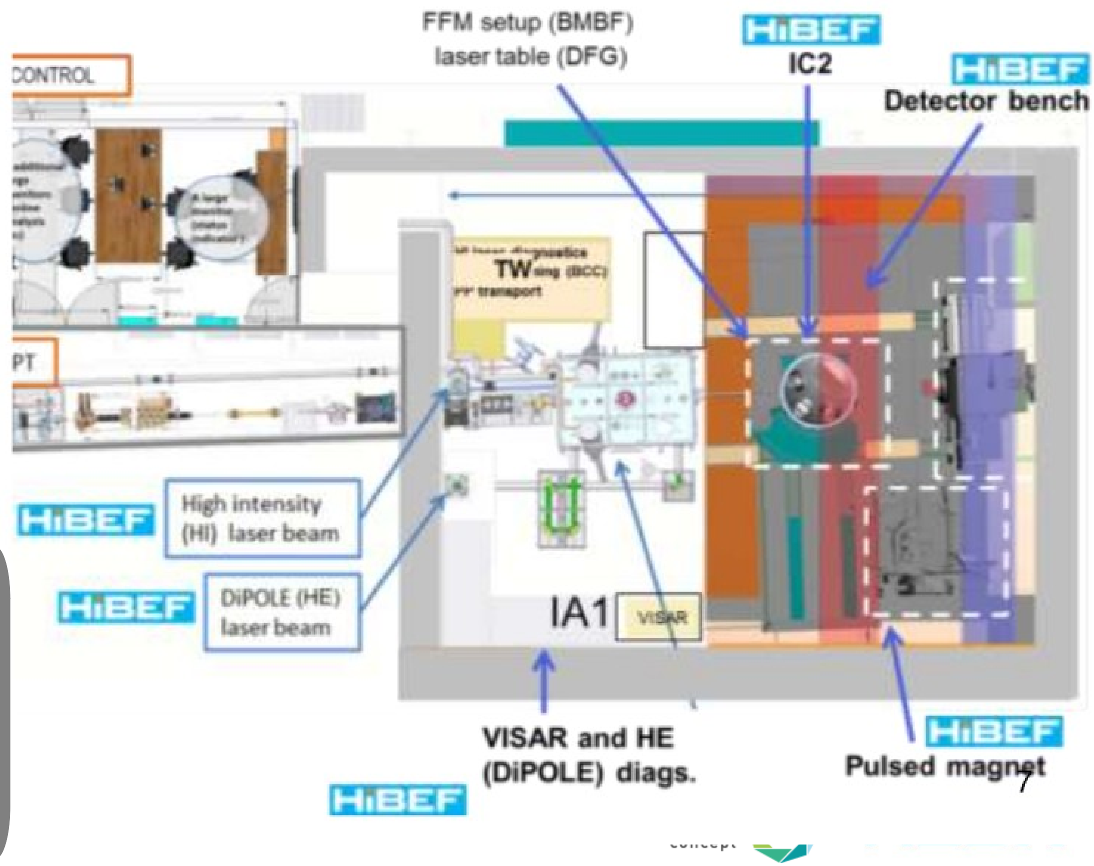
DESY.

cnrs

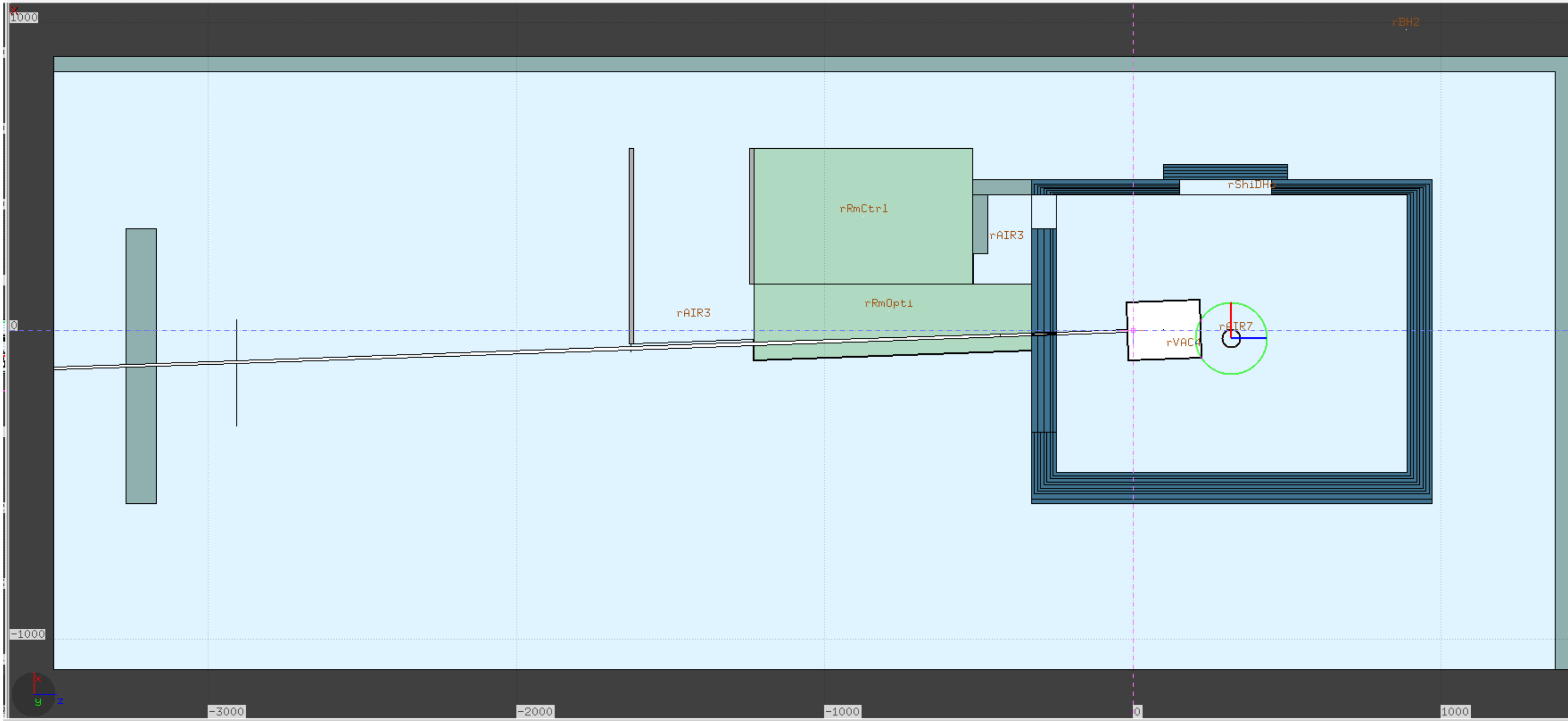
Los Alamos NATIONAL LABORATORY EST. 1943

Shielding optimized
for **150 TW** operation

Now: ***up to 400 TW***



Geometry: HED + upstream region



The present simulation includes the elements above

The lead/steel/lead local shielding has been described in the first 16.5 m from the HED

Source terms for solid target experiment up to 400 TW: General strategy for shielding assessment

1. To be sure to cover the full possible electron temperature range for the **400 TW** case, including expected improvements in the beam conditions, we extend the calculations from the typical electron energy **kT_{el} = 5 MeV** to the "upper limit" case **kT_{el} = 15 MeV**

Anna Ferrari I Institute of Radiation Physics / Helmholtz-Zentrum Dresden-Rossendorf I www.hzdr.de

Source terms for solid target experiment @400 TW: General strategy for shielding assessment

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2. In every geometry configuration (collinear with the XFEL, 90°, 45° forward and counter-propagating as accident scenario) we have always 2 contributions:

   - the escaping electrons source term, described with a **10 nC** charge emitted in a **45°** semi-opening cone

   - the "pure bremsstrahlung" source term, due to the electron recirculation in the sheat field in the solid target. Since this radiation source term is approximately isotropic, it is important to stress that its contribution to the counter-propagating radiation is always present, in every geometry configuration. This means that it must be evaluated not only for an accident scenario (where we will see that it is negligible respect to the escaping e- source term), but also for normal operation. From the calculation we will conclude that it is negligible for RP purposes

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3. We evaluate the Bremsstrahlung source term due to the recirculating electrons. To describe this we calculate the electron current in the sheath field in the target assuming 20% conversion efficiency from a laser pulse of 10 J.

Depending o the kT_{el}, we obtain (the case with kT=2 MeV, characteristic of operation up to 150 TW, is for comparison):

	kT_{e-} = 15 MeV	kT_{e-} = 5 MeV	kT_{e-} = 2 MeV
Charge (10 J/kT_{e-}) x 20%	0.133 μC	0.4 μC	1 μC

4. We calculate for every geometry the contribution of escaping electrons. We will demonstrate that this is always the dominant part for RP purposes

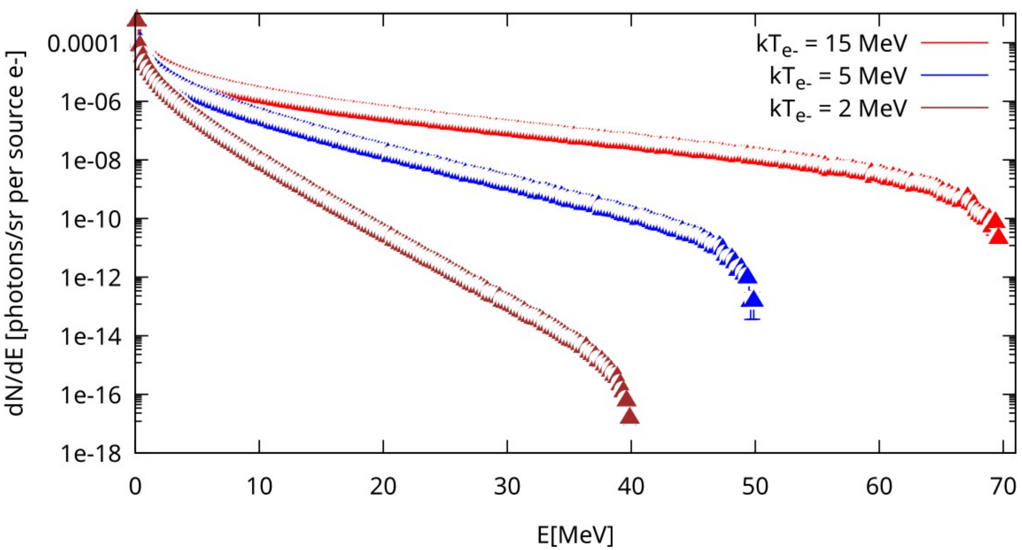
The Bremsstrahlung Source Term

To evaluate the Bremsstrahlung source term we do a **two-step simulation**:

(1) We simulate first an isotropic electron source with the proper kT_{el}, at the center of a copper sphere (material representative of a typical target), 30 μm thick. This thickness has been evaluated identifying the effective recirculation time with the the life window of the sheath field, evaluated in ~ 100 fs from PIC calculations **[ref: Huang et al., PoP 29, 023102 (2022)]**.
Considering v_e ~ c we obtain a 30 μm path length.
We save then the photon spectrum exiting the sphere, to be used in the next simulation step, and we calculate the photon yield (N_{ph} per source electron)

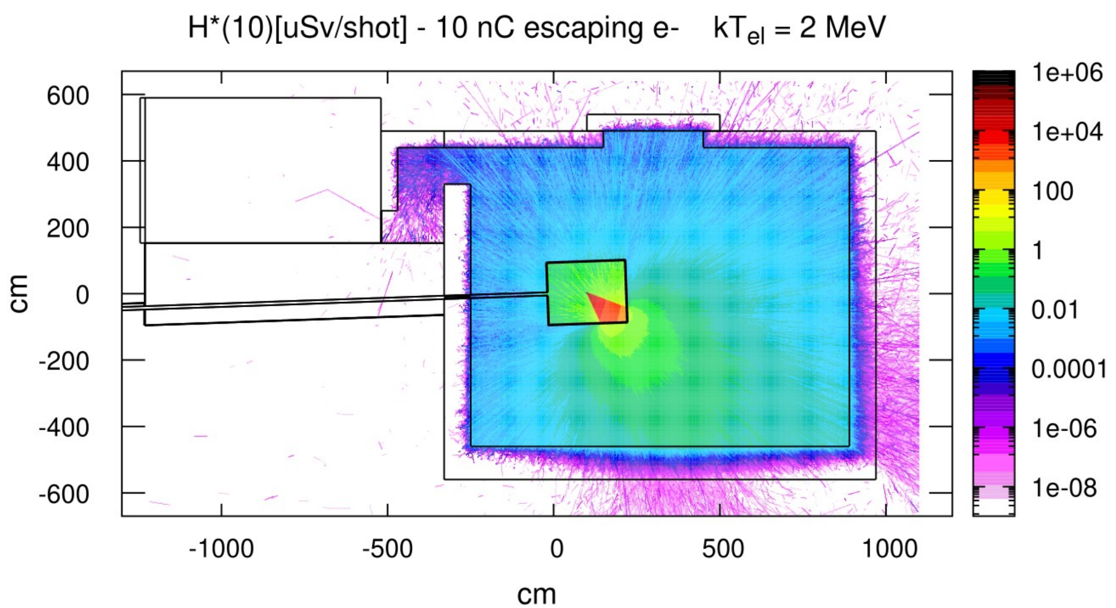
(2) As second step we use the calculated photon spectrum, properly weighted, as Bremsstrahlung source term.

(This two-step method is more accurate and much faster- once the photon spectra are computed- respect to the previous killing of electrons out of the sphere and filtering the photon dose)

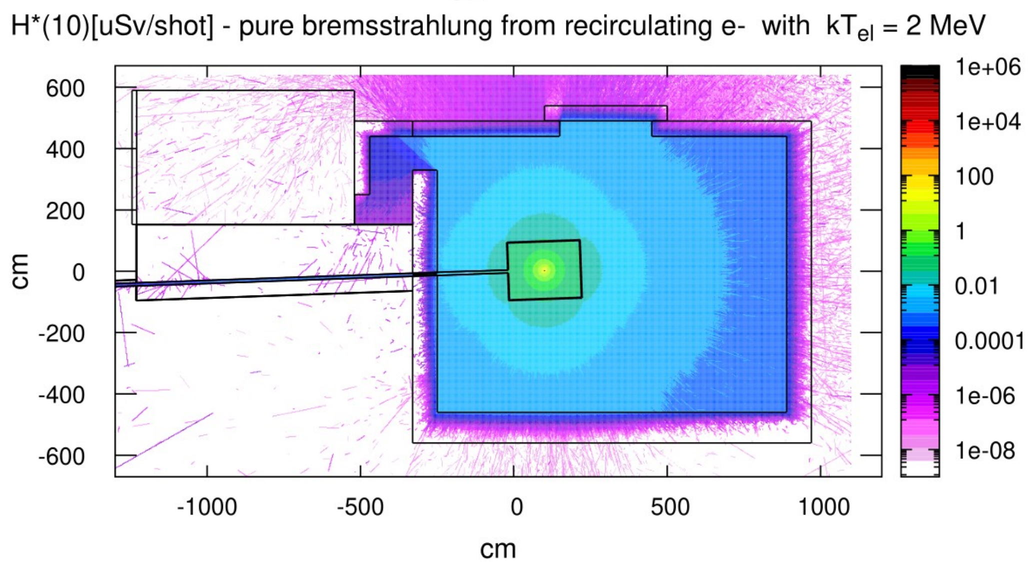


	kT_{e-} = 15 MeV	kT_{e-} = 5 MeV	kT_{e-} = 2 MeV
Yield *(e^- ⟶ photons)*	3.87 E-3	3.06 E-3	2.50 E-3

The two components of the source term with kT_{el} = 2 MeV in 45° forward geometry

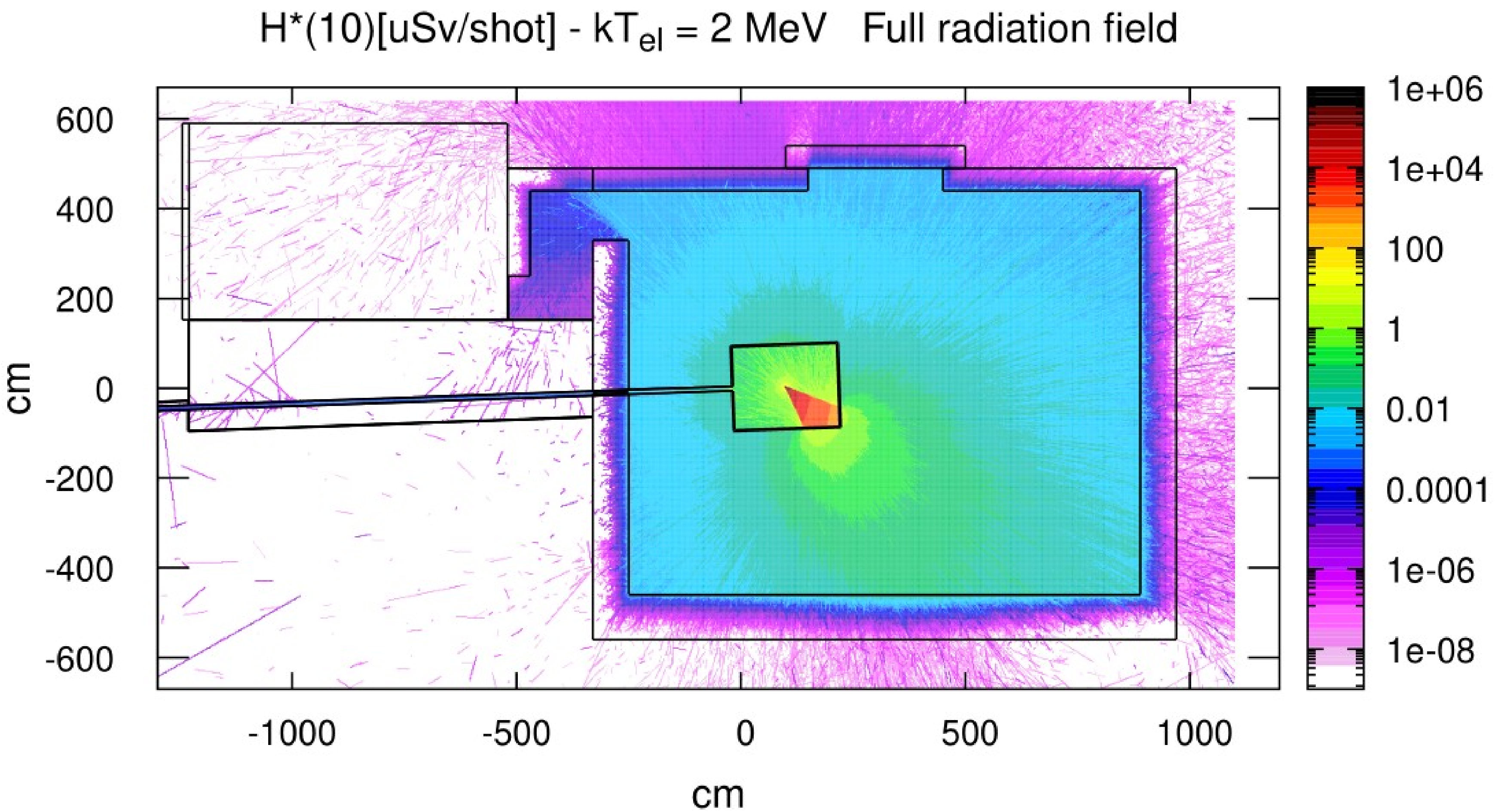


- kT_{el} = 2 MeV
<u>escaping electrons source term</u>, described with a **10 nC** charge emitted in a **45°** opening cone



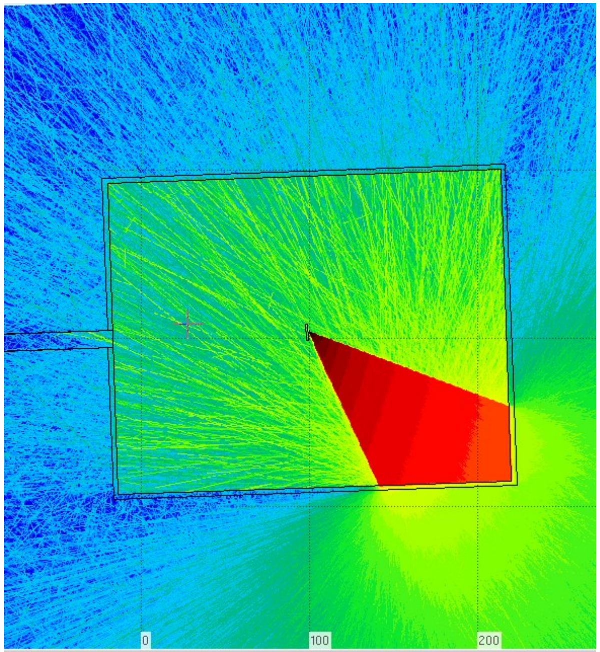
- kT_{el} = 2 MeV
Bremsstrahlung source term

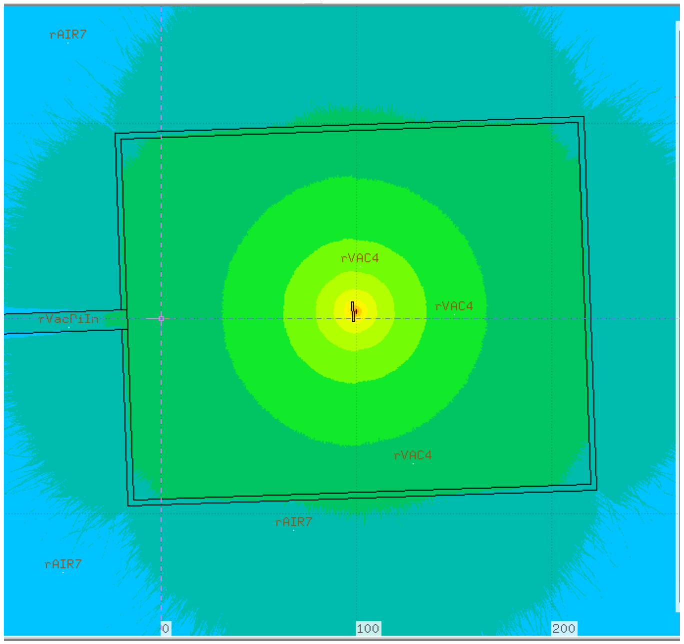
The full radiation field

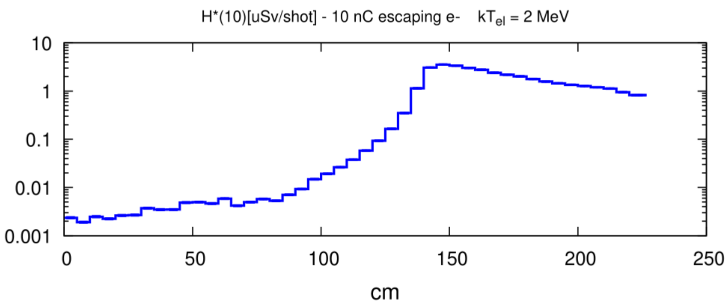


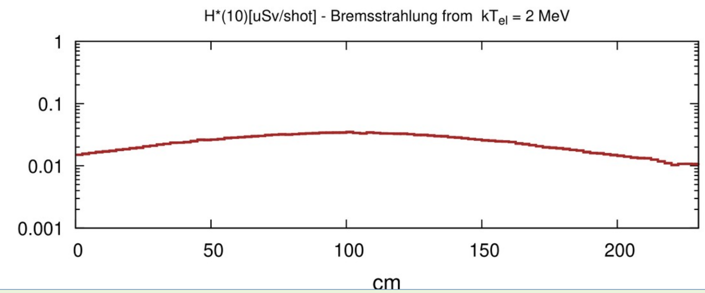
H*(10) outside the shielding walls remains ≤ 10^{-6} μSv/shot

Benchmark: dose distribution around the chamber









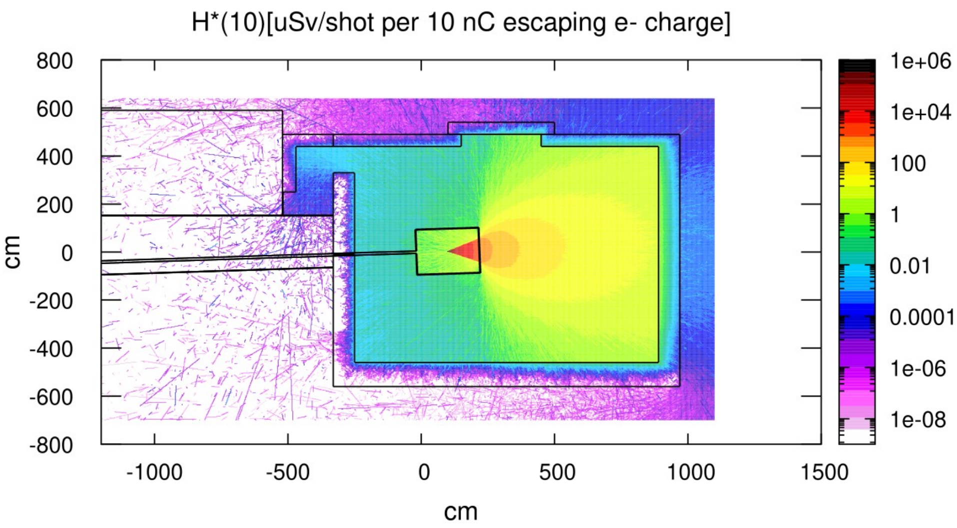
MC Dose at the dosimeter position:

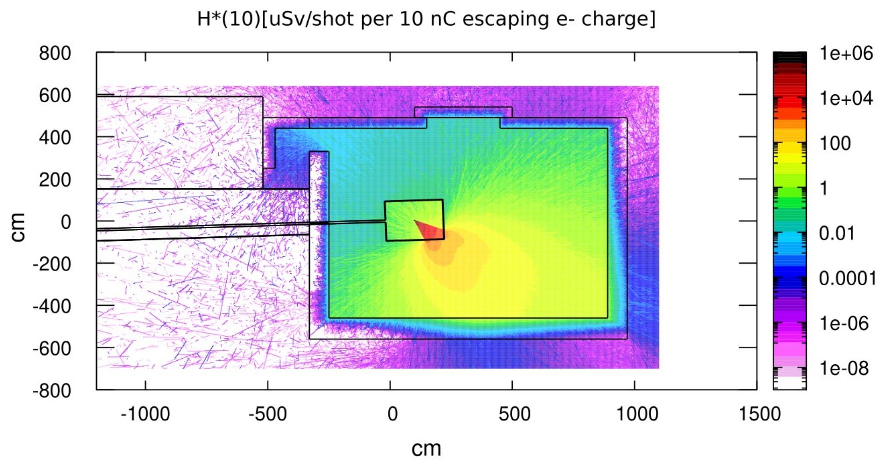
3.5 μSv/shot

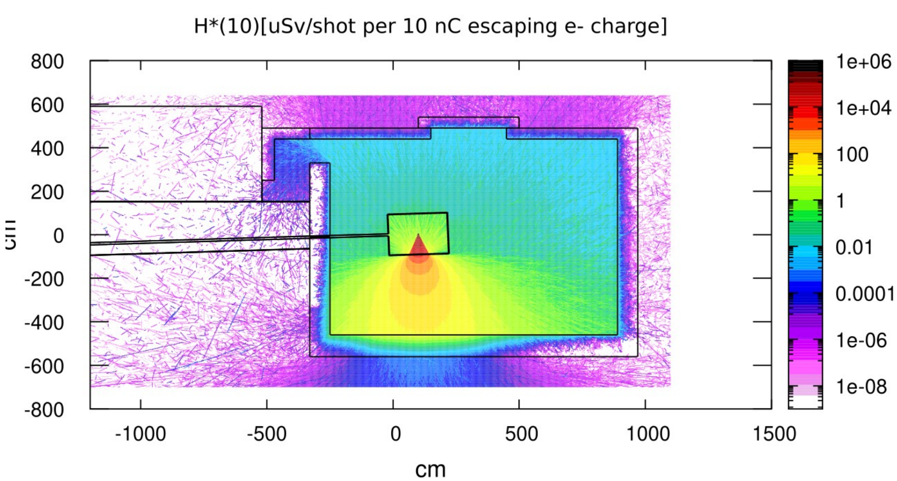
Measured dose:

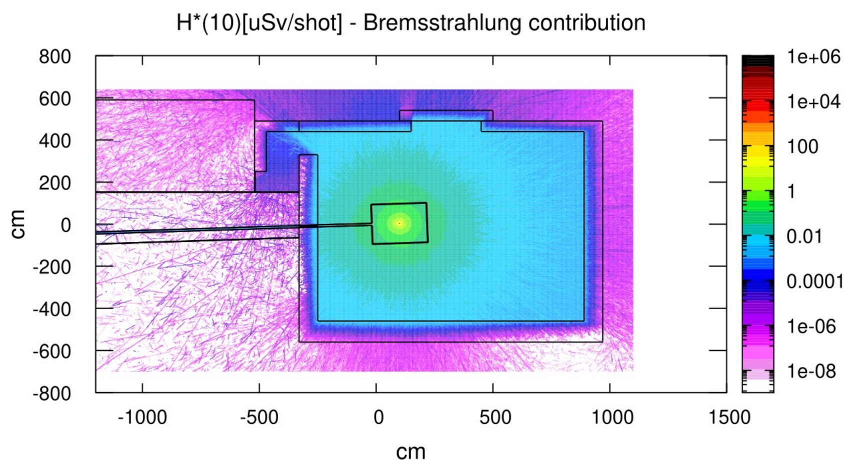
~ 1 μSv/shot for most of the thin foil targets
Few shots up to 5 μSv/shot for advanced targets

The two components of the source term with kT_{el} = 15 MeV









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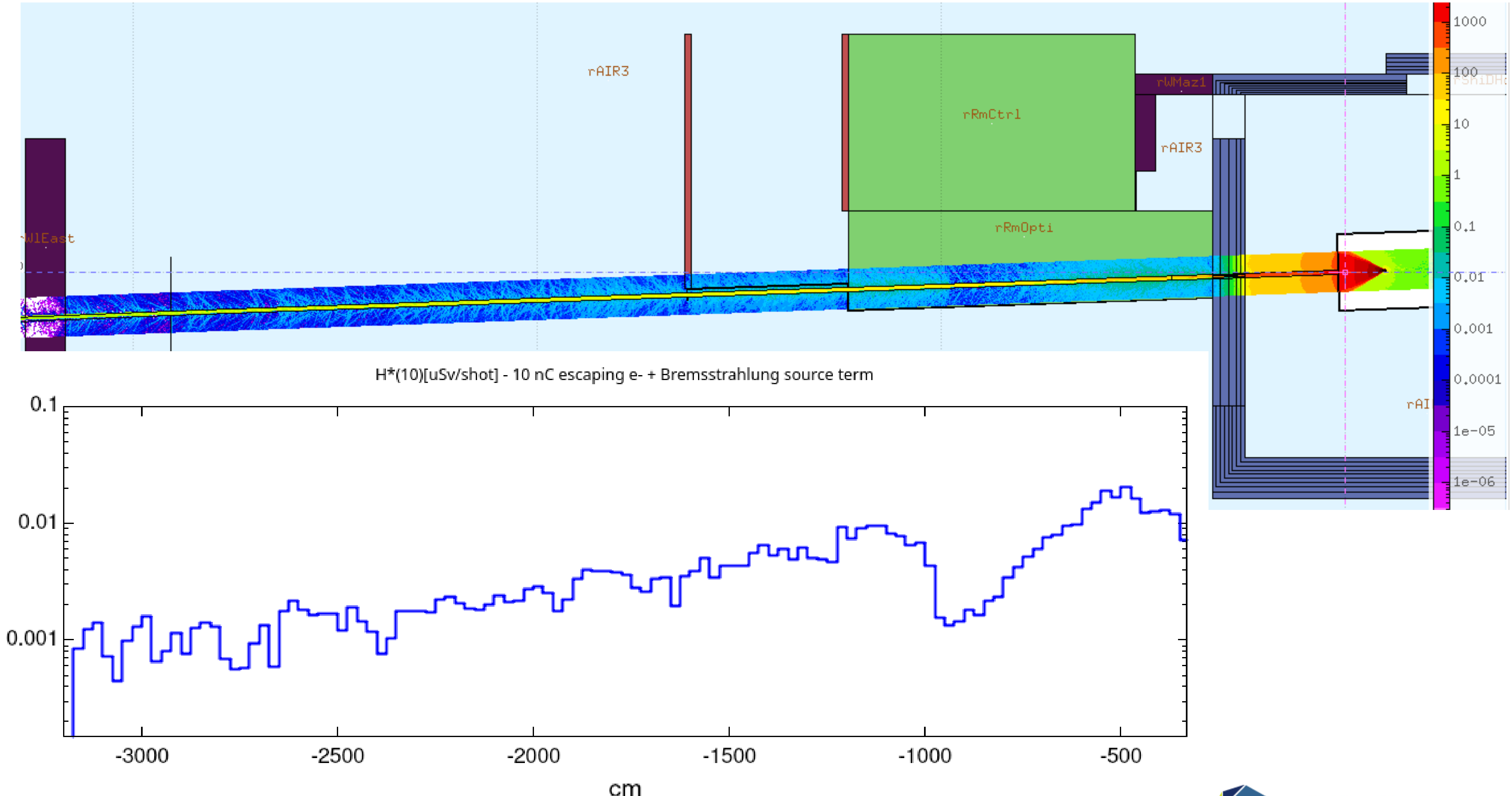
Accident scenario:
Full counter-propagating source term in the case kT = 15 MeV
Escaping electrons + Bremsstrahlung




Thank you for your attention !