Radiation shielding for the HED science instrument at the European XFEL

RadSynch Conference 2015

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[1]European XFEL, [2]HZDR

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Content

- Introduction to HED at European XFEL
- Radiation sources
- Shielding simulation and design
- Construction and status

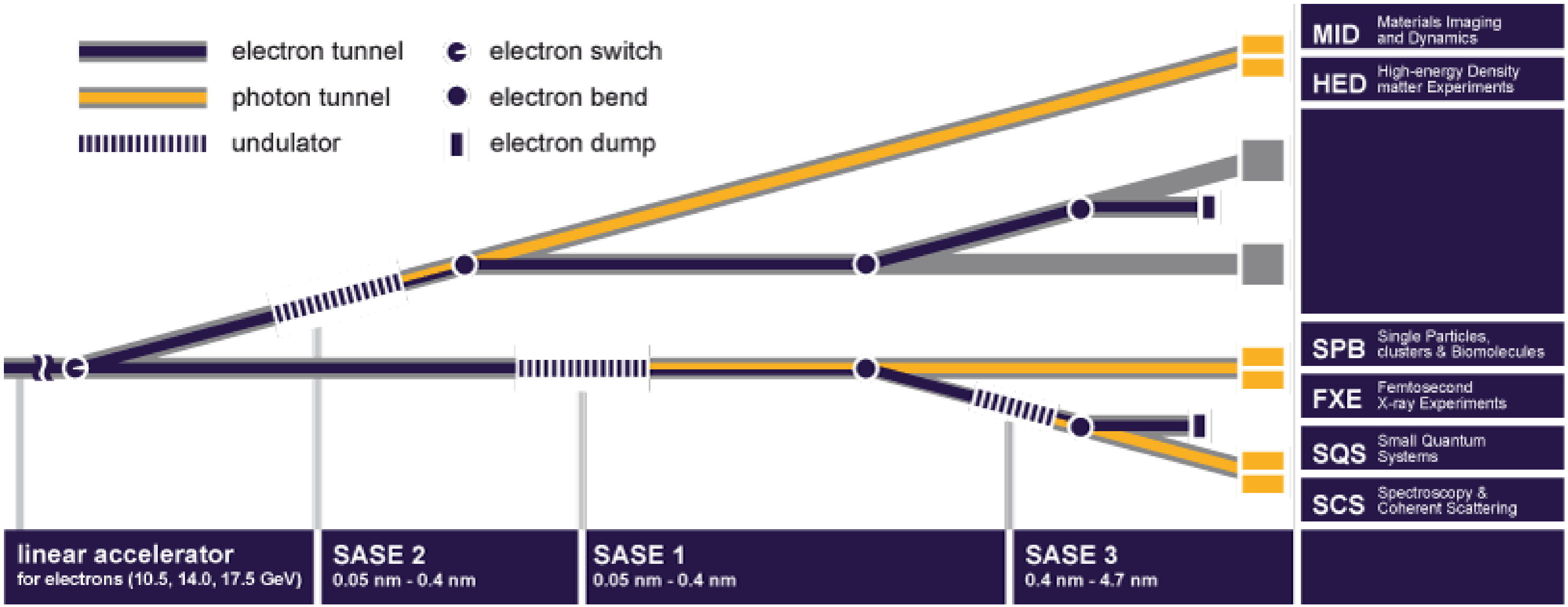
European XFEL

International user facility for FEL research by a multi-disciplinary science community using soft & hard X-ray FEL radiation.

Parameter	Value
Electron Energy	8.5 – 17.5 GeV
Photon energy	0.26 - >20 keV
# of pulses	27000 /s
# of FELs	3 (5)
# of instruments	6 (10-14)
Start of operation	2017
Total cost	1150 M€ (2005)

- **Multidisciplinary: physics, chemistry, biology, materials sciences, geo-sciences, ...**
- **Users propose experiments: peer-review, invitation, support**
- **Basic science: establish the foundations for future high tech applications**

The science instruments



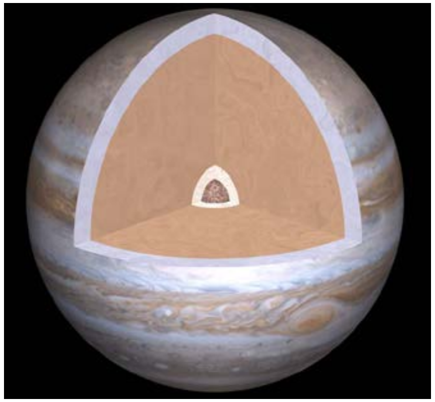
Hard x-rays (SASE1 & SASE2; 3 – 25 keV)

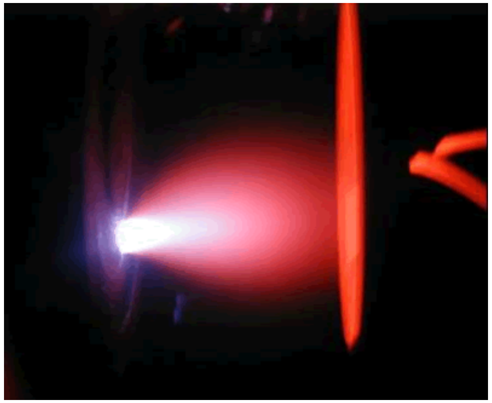
- MID – HED – SPB – FXE
- (Coherent) diffraction – (Coherent) imaging – X-ray spectroscopy

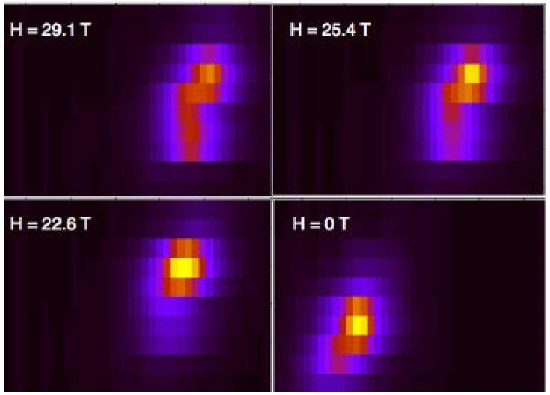
Soft x-rays (SASE3; 0.26 – 3 keV)

- SQS – SCS
- Coherent imaging – Particle & X-ray spectroscopy

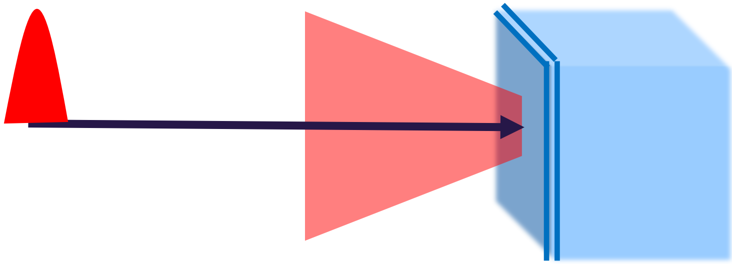
HED instrument: study matter at extreme states







In general: **Matter under extreme conditions of temperature, pressure, electric and/or magnetic field strength**



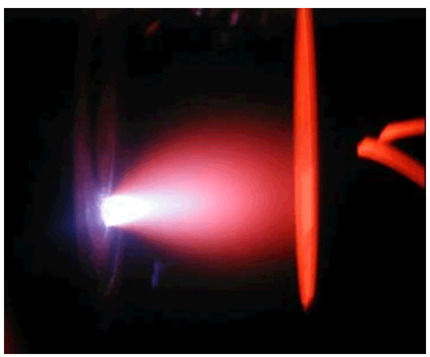
Dynamic, often irreversible processes:

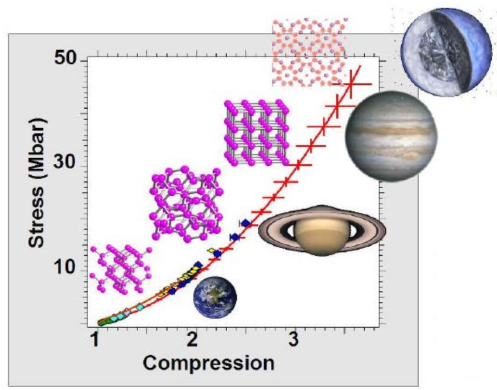
1. **Condensed-matter at extremes**
2. **(Near) solid-density plasmas**
3. **Quantum states of matter**

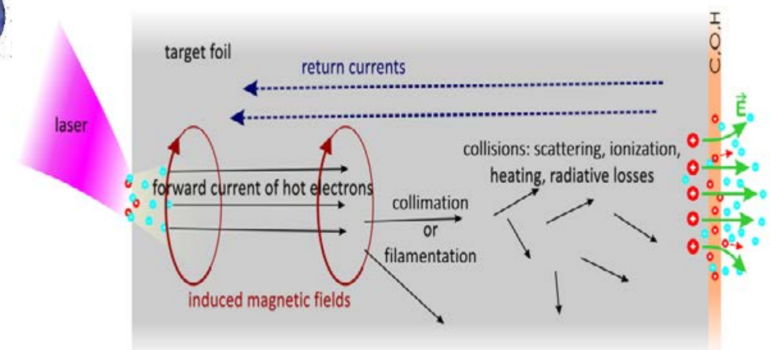
High Energy Density Science – HED

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







Samples generated by pulsed excitation

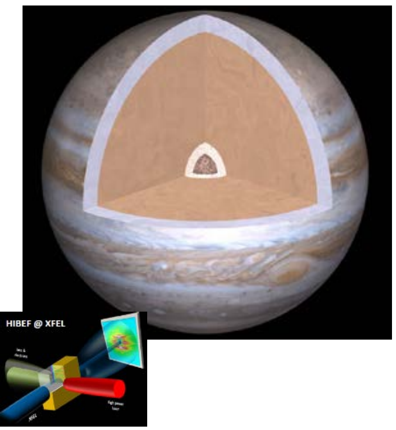
- Highly dynamic and often non-equilibrium
- Irreversible processes → sample refreshment required

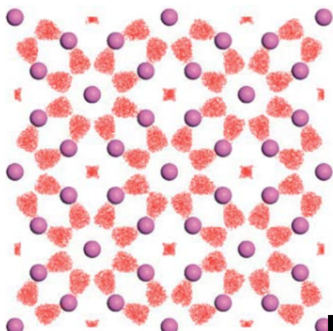
Combination of high excitation with various x-ray techniques

- Use of various pump sources to excite samples (OL, XFEL, ext. fields)

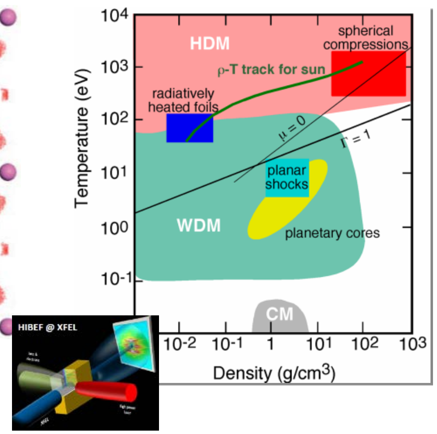
HED science relevant to x-ray FELs (a selection)

Condensed matter at very high T, P, ρ

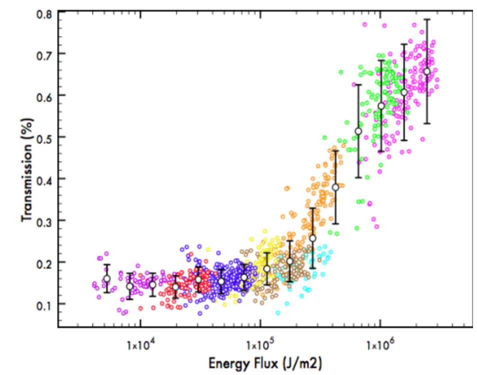




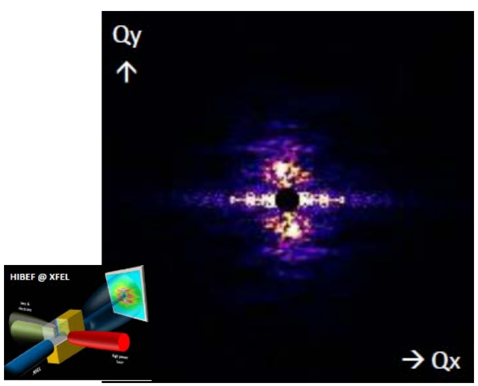
Beyond condensed matter



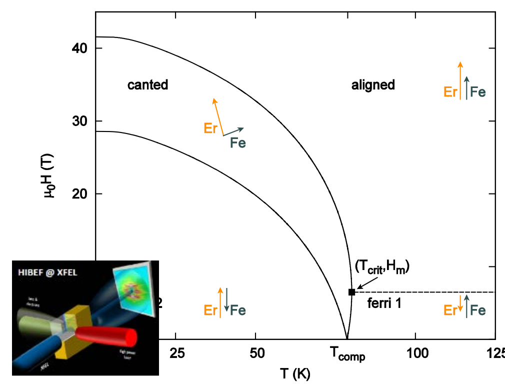
Intense x-ray matter interaction



Relativistic laser-matter interaction



Complex solids in high fields



The ‘drivers’

High energy optical laser (HE-OL)

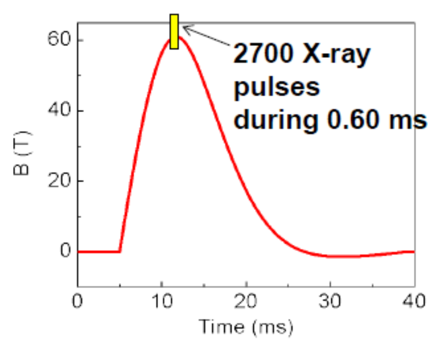
- Long (2-20 ns) duration pulses
- High pulse energy (>100 J@500 nm)
- Selectable temporal shaping

Ultra-high intensity optical laser (UHI-OL)

- Ultrashort (30-50 fs) duration pulses
- Medium high pulse energy (3-5 J@800 nm)
- Very high pre-pulse contrast (>10^{-8})

Pulse magnet

- 50 – 60 T peak field strength
- Few ms pulse duration

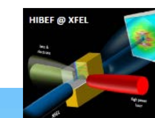


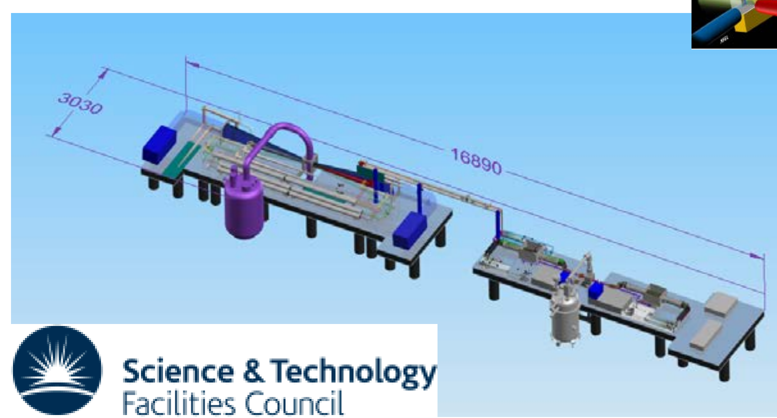
„Laser plan“ for the HED instrument

Start of operation

- PP laser system (mJ; MHz; 15–100 fs & 10 mJ, 100 KHz, ~1 ps)
- 100 TW ultrashort pulse laser (few J; 10 Hz; 40 fs) [contributed by HIBEF UC]
- 100 J nanosecond laser (100 J; 1–10 Hz; 1–20 ns) [contributed by HIBEF UC]
- Small systems (VISAR, etc.)

→ high excitation





→ shocks, dynamic compression

→ rel. laser-plasma IA

HIBEF: Helmholtz International Beamline for Extreme Fields

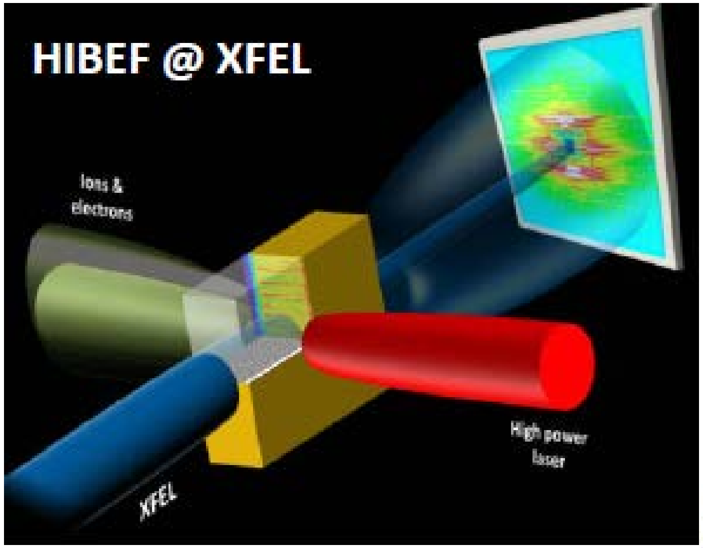
Spokesman: *T.E. Cowan (HZDR)*
Co-PI's: *U. Schramm (HZDR), E. Weckert (DESY), T. Stoehlker (HIJ)*

HIBEF User Consortium: HZDR, DESY, HIJ, CFEL, DLR, FZJ, GFZ, GSI, HZB, MBI, MPIC, MPIK, MPI-S, MPQ, MPSD, U Bayreuth, HU Berlin, TU Darmstadt, TU Dresden, U Duisburg, U Frankfurt, U Freiburg, U Hamburg, FSU-Jena, LMU-Munich, TU Munchen, U Rostock, U Siegen, U Graz, TU Wien, PSI, EP-Lausanne, IOP-ASCR, CTU-Prague, CLPU-Salamanca, UPM-Madrid, IRAMIS-CEA, CEA-Arpajon, CELIA-Bordeaux, ESRF, Jussieu, LULI, UPMC, LNCMI, U Toulouse, U Pecs, U Szeged, Weizmann, U Roma, MUT-Warsaw, NCBJ-Swierk, U Wroclaw, IST-Lisbon, JIHT-RAS, Stockholm, Umea, Uppsala, Cambridge, Edinburgh, Imperial, QUB, UCL, Oxford, Plymouth, STFC-RAL, SUPA, Strathclyde, Warwick, York, Eu-XFEL, ELI-DC, EMFL, IOP-CAS, Peking Univ, SIOM, SJTU, Tata IFR, RRCAT, GSE-Osaka, ILE-Osaka, KPSI-JAEA, U Kyoto, Alberta, BNL, UC Berkeley, Carnegie Inst. Wash., General Atomics, LANL, LBL, LLNL, U. Michigan, ORNL, OSU, U. Penn, Rockefeller U, SLAC, UCSD, UNR, U Texas, WSU

High energy lasers
- **initially 100 TW/10 Hz & 100 J/10 Hz**
- **Future upgrades**

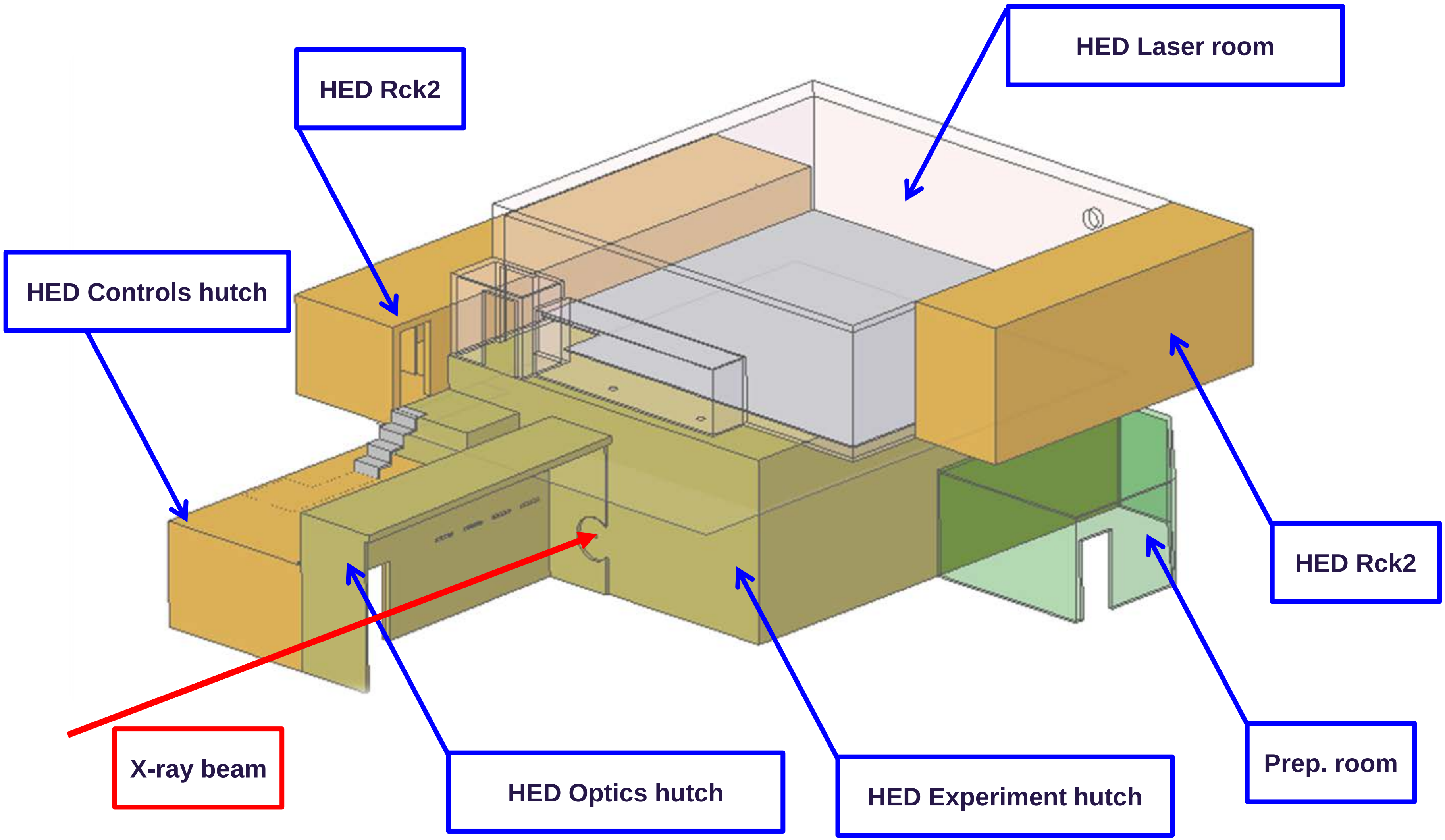
Pulsed magnetic field setup
Diagnostics, spectrometer, etc.
Man-power
Operation

UK:	8 M€
HGF-FIS:	20.5 M€
Others:	12 M€



HELMHOLTZ | ASSOCIATION

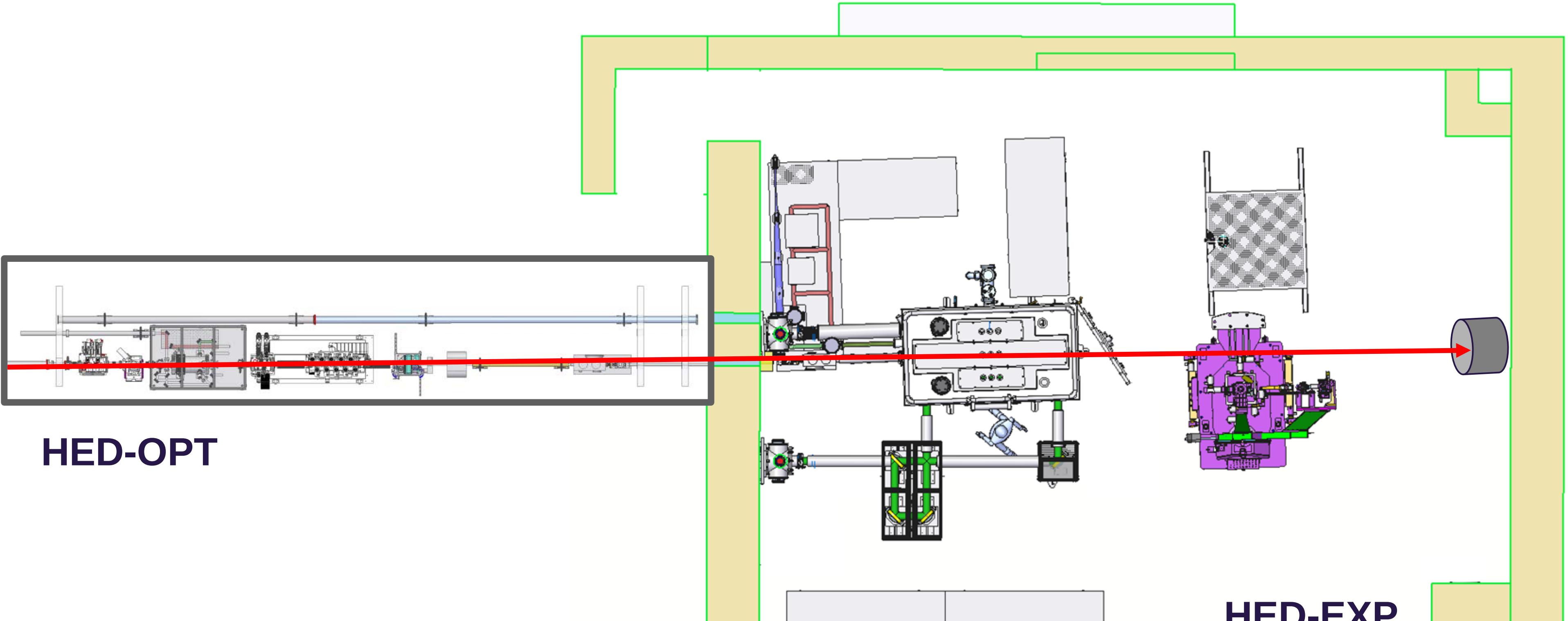
The HED instrument layout

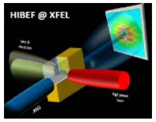


X-ray room layout

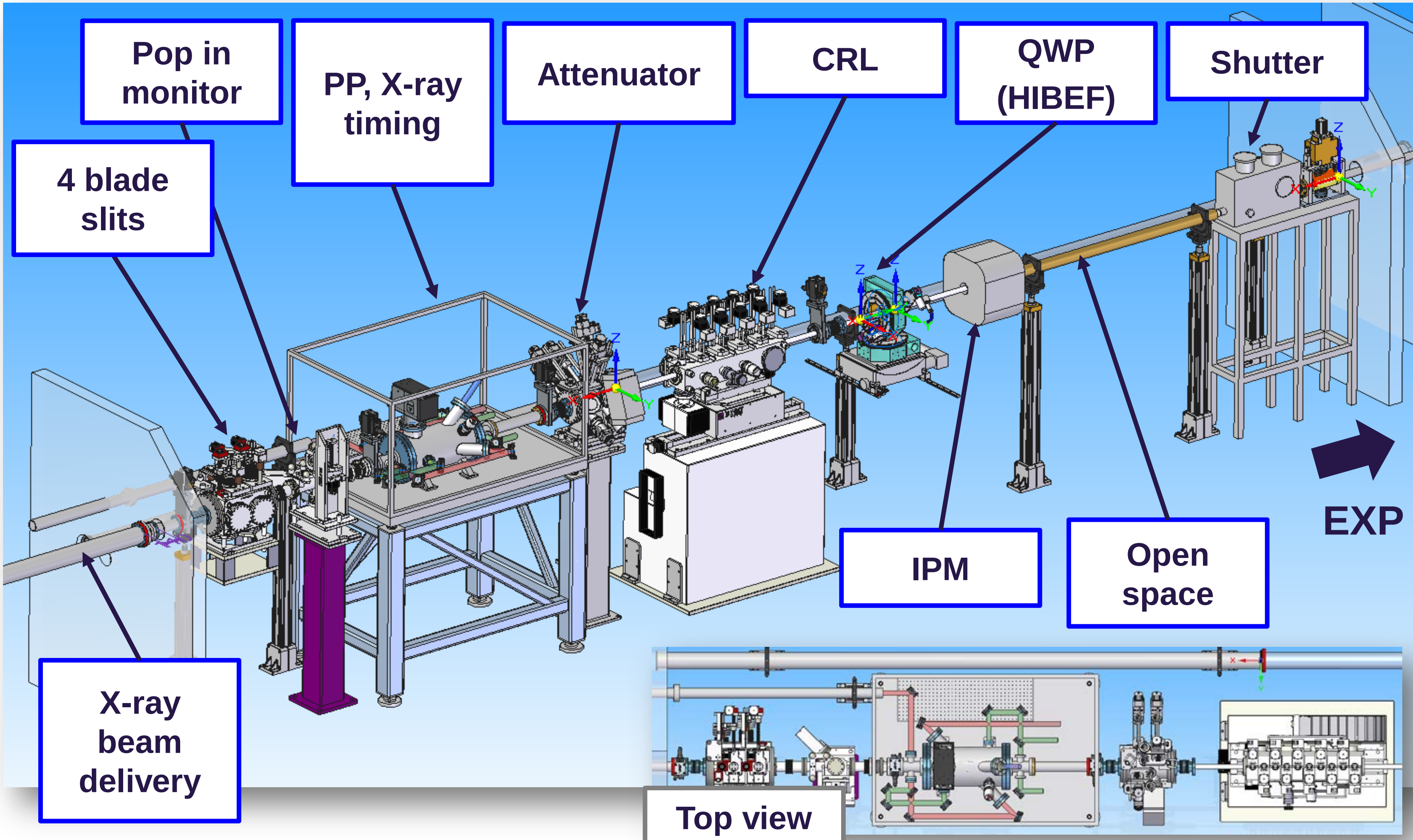
HED-OPT: X-ray optics hutch → preparation of x-ray FEL beam; diagnostics

HED-EXP: Experiment room → User experiments; beam stop

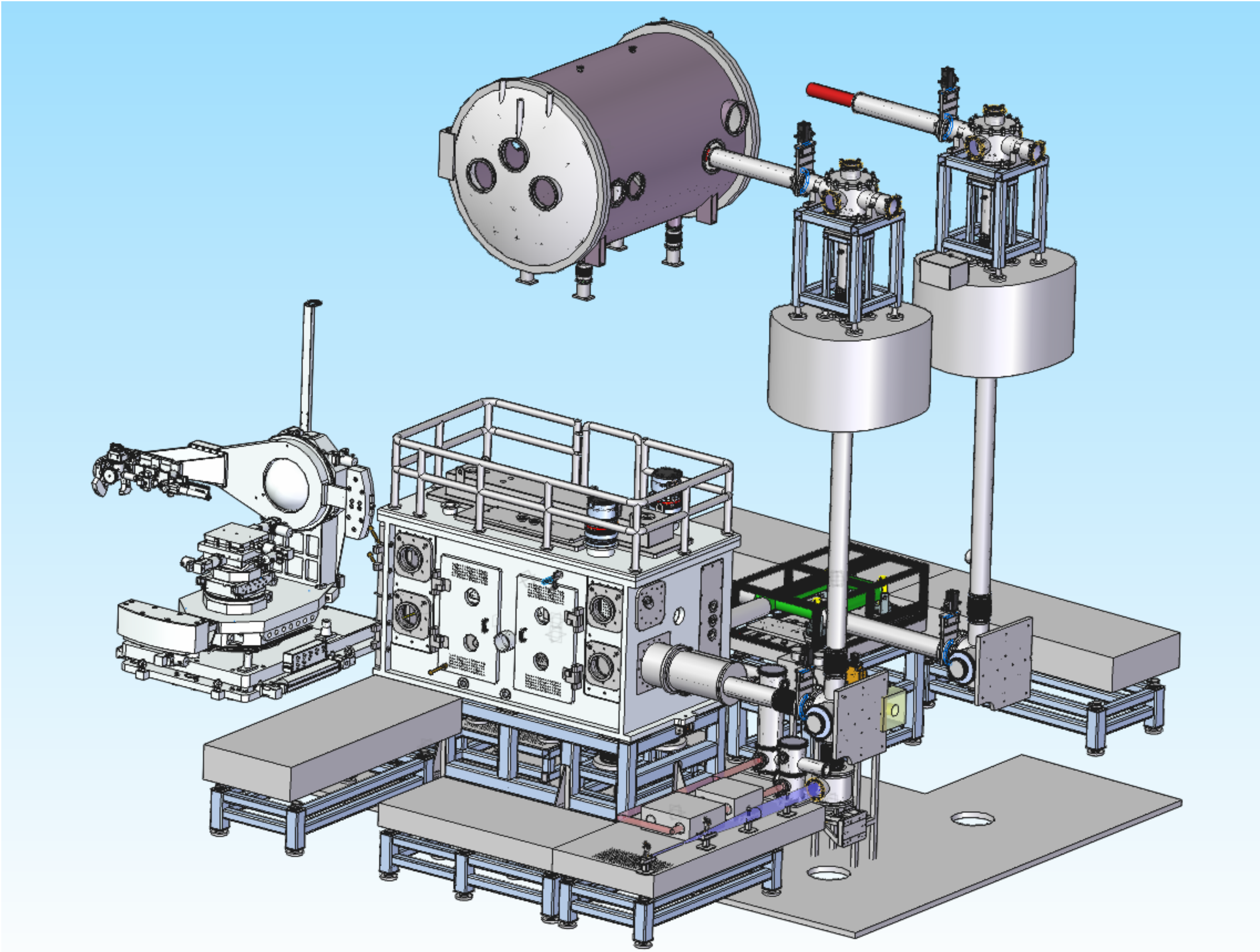


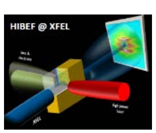


X-ray optics hutch (HED-OPT)

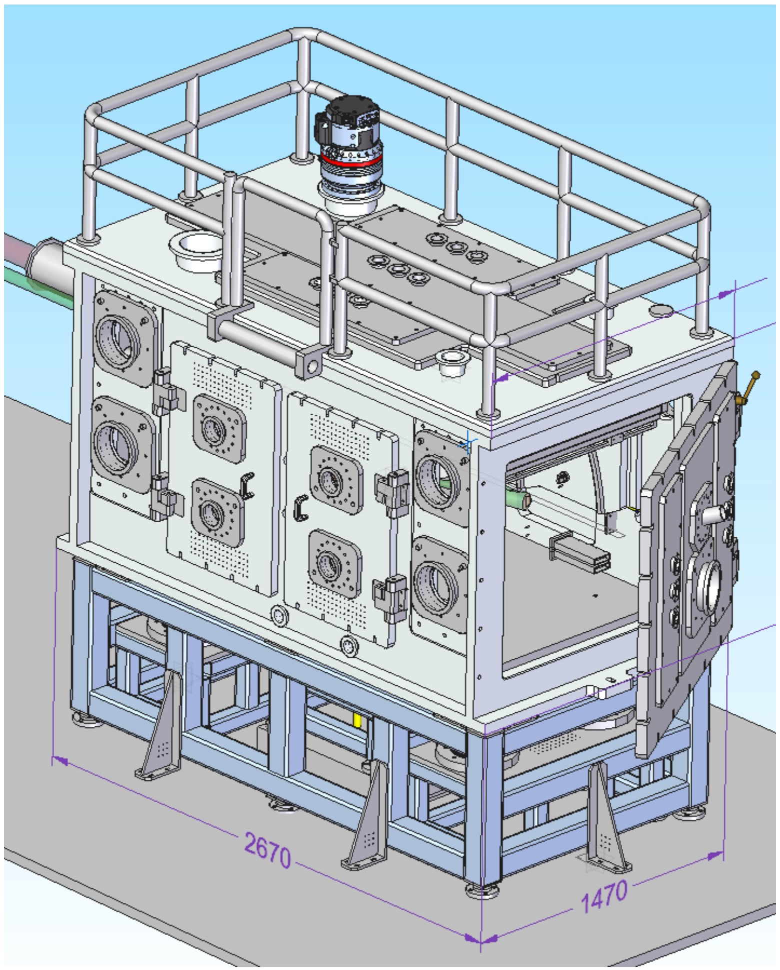


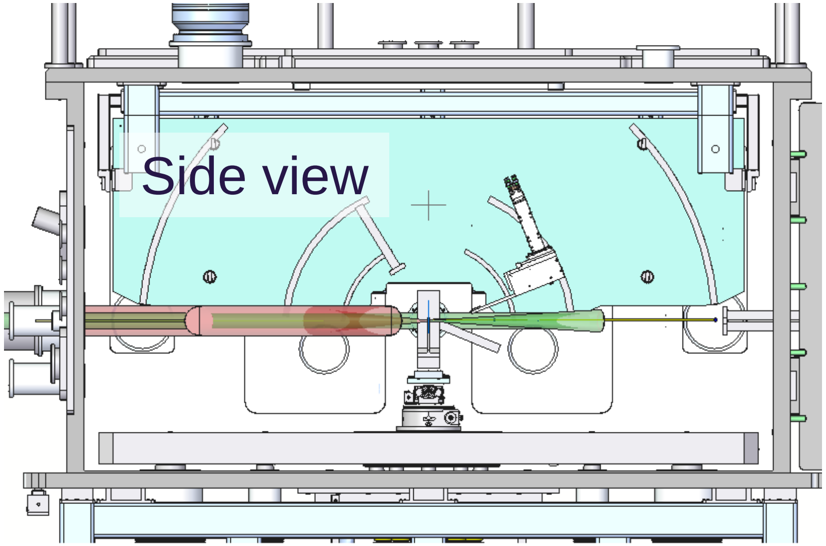
Integrated model

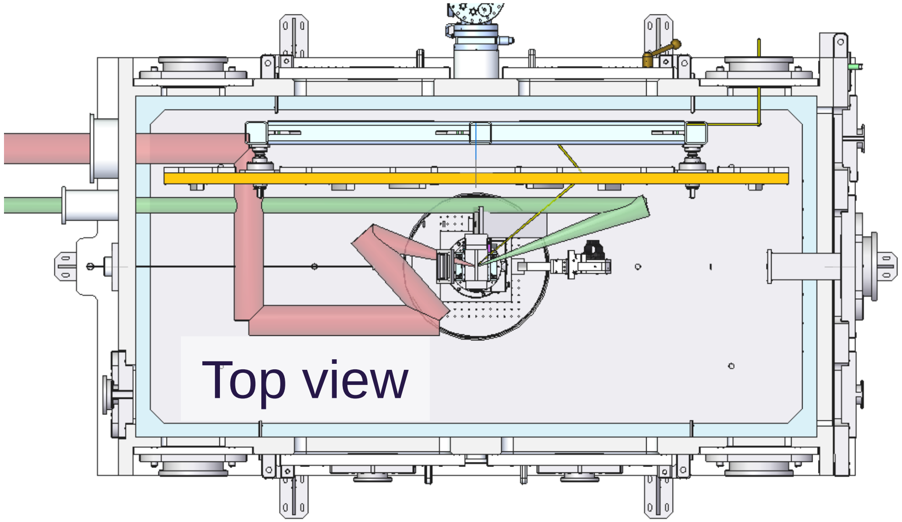




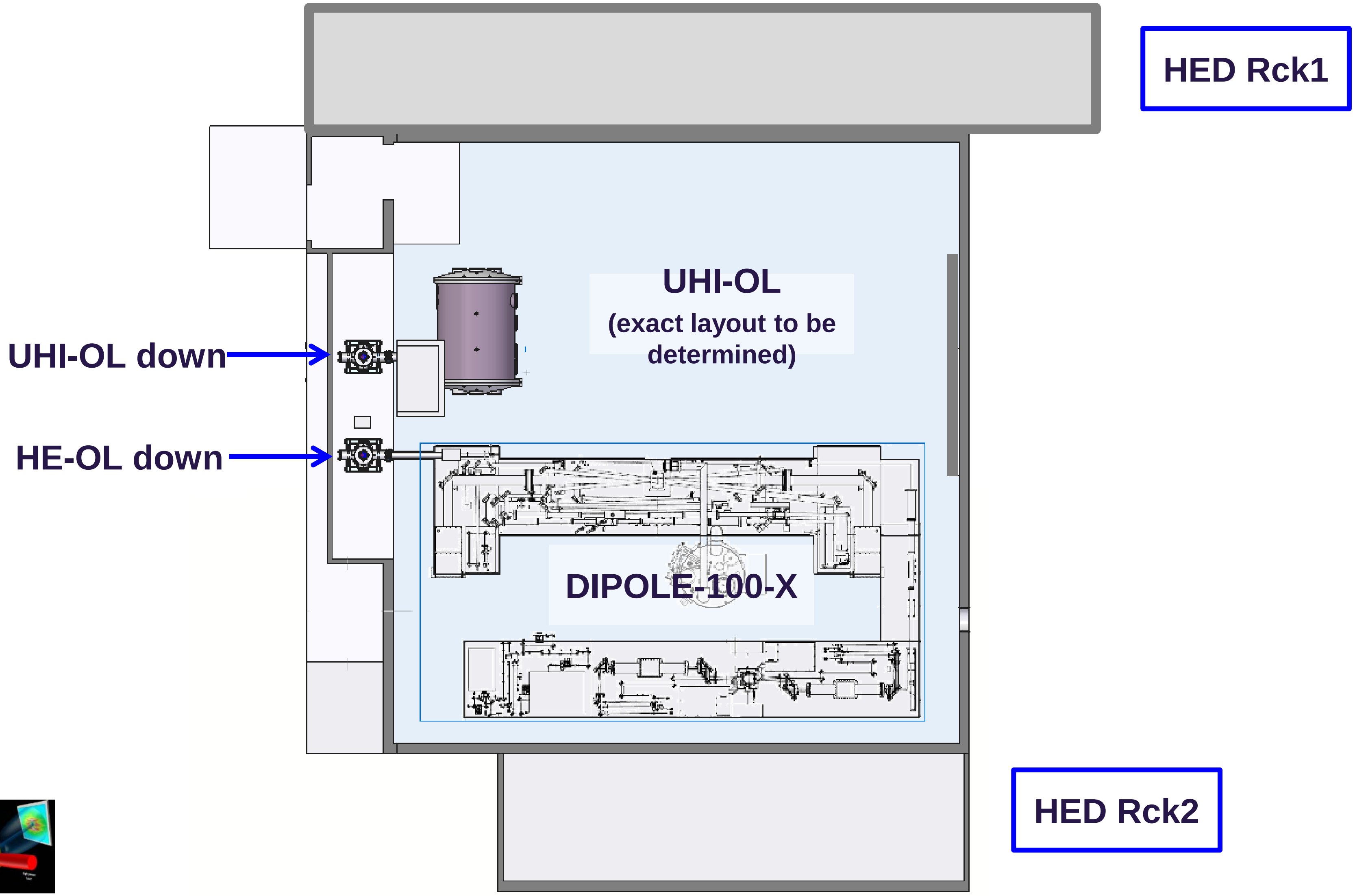
Interaction chamber 1 (IA1)







HED-Laserroom (DIPOLE-100-X & UHI model)



Radiation sources

Radiation sources

1. **X-ray FEL radiation**
   - This can be shielded by few mm of Pb (similar to synchrotrons)
   - See talk by E. Boyd on Friday, 9:25
2. **Secondary radiation released from the interaction of the UHI-OL laser pulses with solid matter**
   - This is the main source of high energy x-rays.
   - Special shielding schemes are required.
3. **Secondary radiation released from the interaction of the HE-OL laser pulses with solid matter**
   - Due to the longer pulse duration (resp. much smaller intensities) the interaction with matter is (largely) non-relativistic (no hot electrons)
   - Does not require further consideration
4. **Pulsed magnet**
   - No generation of x-rays

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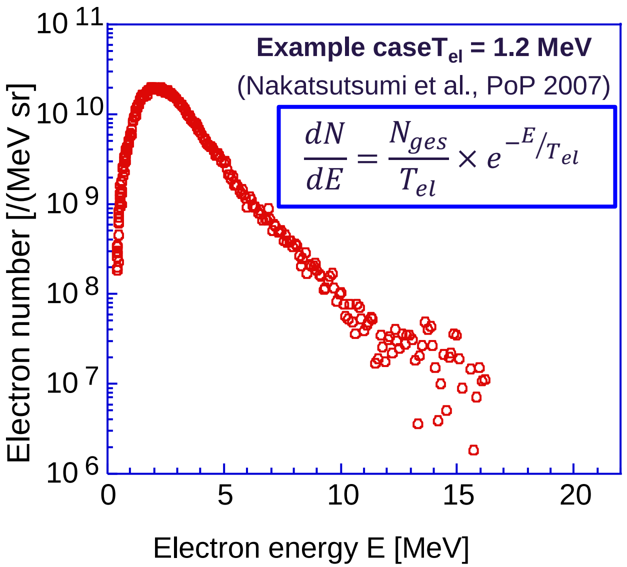
Generation of Bremsstrahlung

High intensity Laser radiation when irradiated on solids creates

- Free electrons (from ionisation of atoms)
- Extreme fields (E, B)
- Thin plasma layer (ions & electrons) on a dense, solid body
- Energetic electrons propagate into solid
- Energy spectral distribution [T. Kluge et al., Phys. Rev. Lett. **107**, 205003 (2011)]

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

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

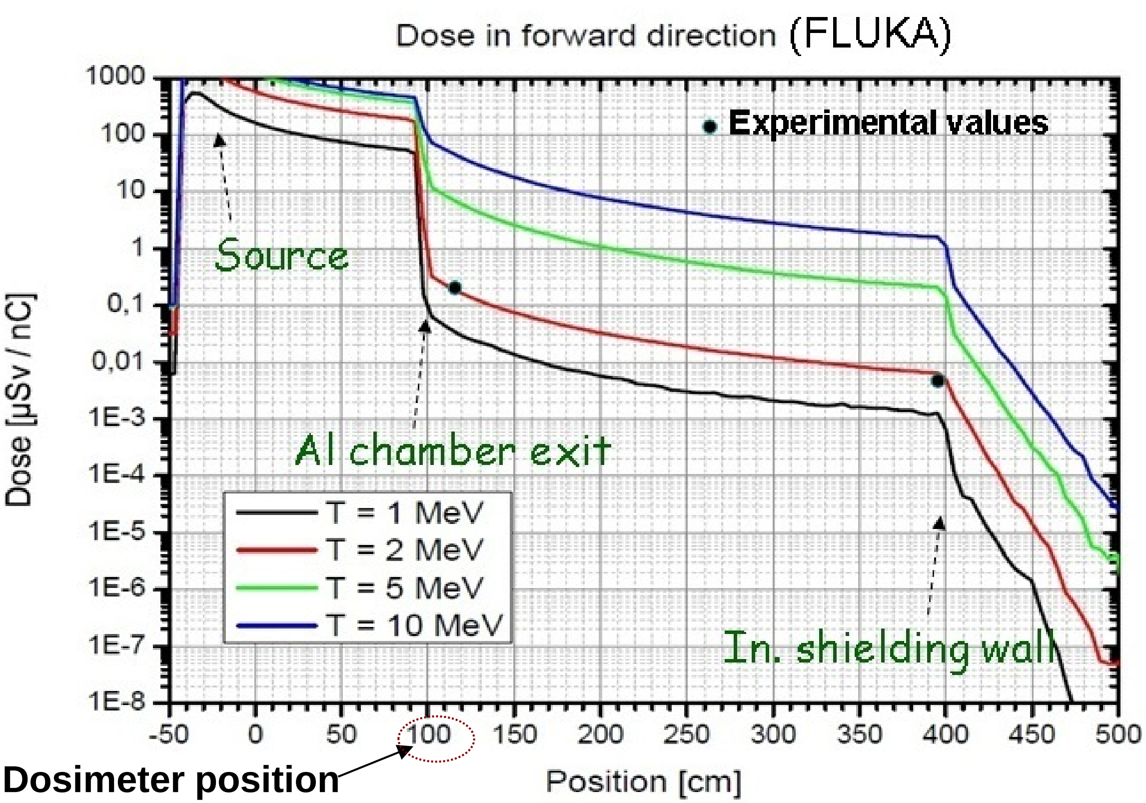


- T_{el} characterises spectral distribution
- T_{el} skales with Laser intensity
- Slowing down of electrons → Bremsstrahlung

Source term characterization: DRACO benchmark   *slide courtesy A. Ferrari (HZDR)*

➢ Electron temperature has been benchmarked for the 100 TW-class case by comparing FLUKA simulations to dose measurements at the DRACO laser facility (HZDR)

DRACO (DResden laser ACceleration sOurce)
operates since 2008 with a **150 TW** Ti:Sapphire laser



Dosimeter position (outside the chamber)

- 2 separate experimental areas, it is used either alone or in combination with the electron pulses of the ELBE radiation source
- Parameters: **5 J, 30 fs**

Experimental points in forward direction are reproduced with kT = 2 MeV and a conversion efficiency in Bremsstrahlung e^- of 16%

@HED Instrument:

- **kT = 2 MeV**
- **e^- charge = 160 nC**

for **100 TW** operation

In addition, the dose measurements indicate an opening angle in forward direction of about 45°

Simulation of radiation fields

Simulations have been using FLUKA code

All simulations have been performed by A. Ferrari (HZDR)

- HZDR operates 100-200 TW systems & currently erects a 1000 TW system

3D model of HED geometry was included

Source terms:

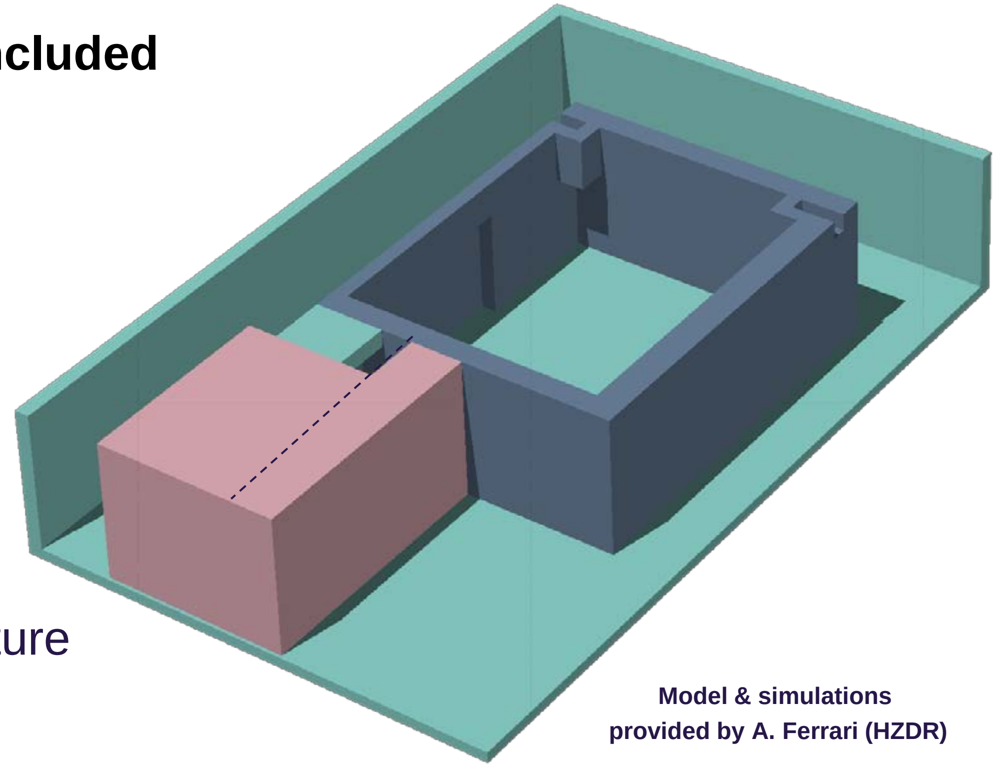
- Bremsstrahlungs electrons
- Maxwellian energy distribution
- Opening angle 45°
- Few µm metal foils

Laser parameter:

- 100 TW, 5 µm focus

⇒ 2 MeV mean electron temperature

⇒ 0.16 µC electron charge



Model & simulations provided by A. Ferrari (HZDR)

Parameters for the UHI-OL simulations

Parameter	**Value**
Pulse energy at IA point	3J
Pulse duration	30 fs
Peak power at IA point	100 TW
Focus size at IA point (80%)	5 µm
Peak intensity	5×10^{20} W/cm^2
Repetition rate (max.)	10 Hz
Electron temperature	2 MeV
Charge per pulse	0.16 µC
Mean power of electrons	3.2 W

Geometry and shielding material

Iteratively it was found that heavy Fe-based concrete for the walls and normal concrete for the ceiling are appropraiate shielding materials.

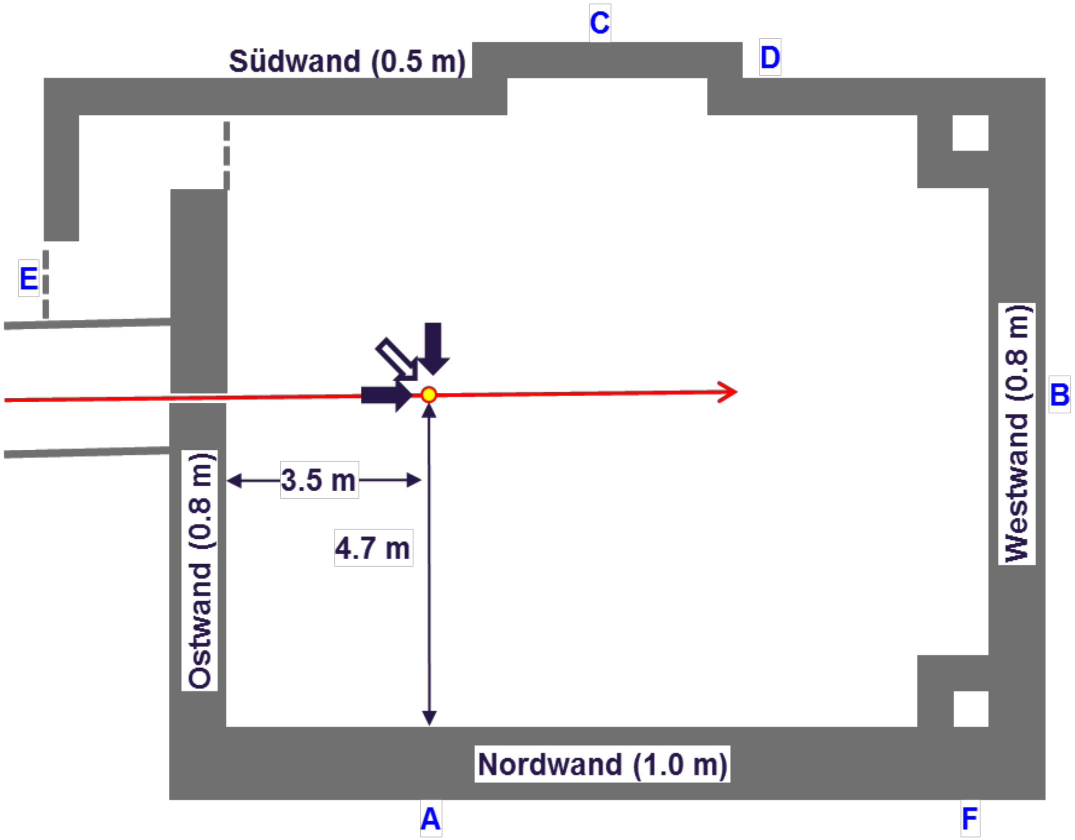
Pointed electron emission leads to restriction for laser in-coupling.

Conditions:

- Heavy concrete walls
  - → **3.6 t/m³**
  - → **Iron as heavy material**
- Normal concrete for ceiling
  - → **2.6 t/m³**

Fixed geometries:

- 90° rel. to x-ray FEL
- 0° (collinear)
- Anything in-between as interpolation



Simulation results

European XFEL

Radiation protection goals

X-ray rooms will be an exclusion area ("Sperrbereich") during operation with x-ray FEL & UHI-OL

- No access
- Unique interlock system (X-ray and OL-induced radiation)

Outside x-ray rooms we'll have regions of supervised area, meaning that no elevated radiation levels are allowed

- 1 mSv per year
- for 2000 working hours this relates to 0.5 µSv per hour
- due to operational considerations (on-off-varying conditions) we are integrating over intervals of 4 hrs → 2 µSv per 4 hrs interval

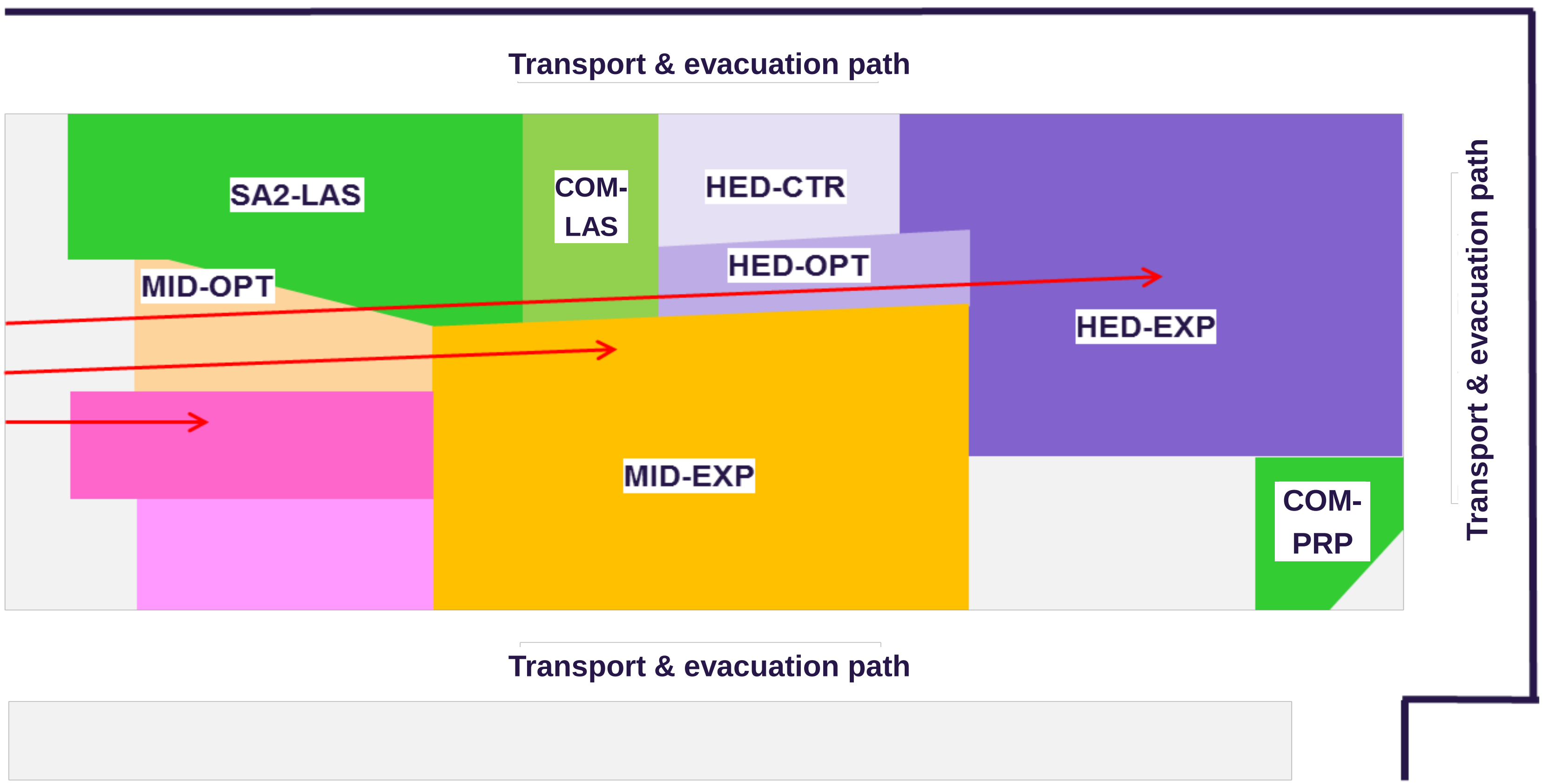
Impact to operation

- separation of HED-OPT & HED-EXP to disentangle operation
  - → **shutters for x-ray FEL and OL-induced x-rays**

SASE2 area

HED has 2 radiation interlocked rooms

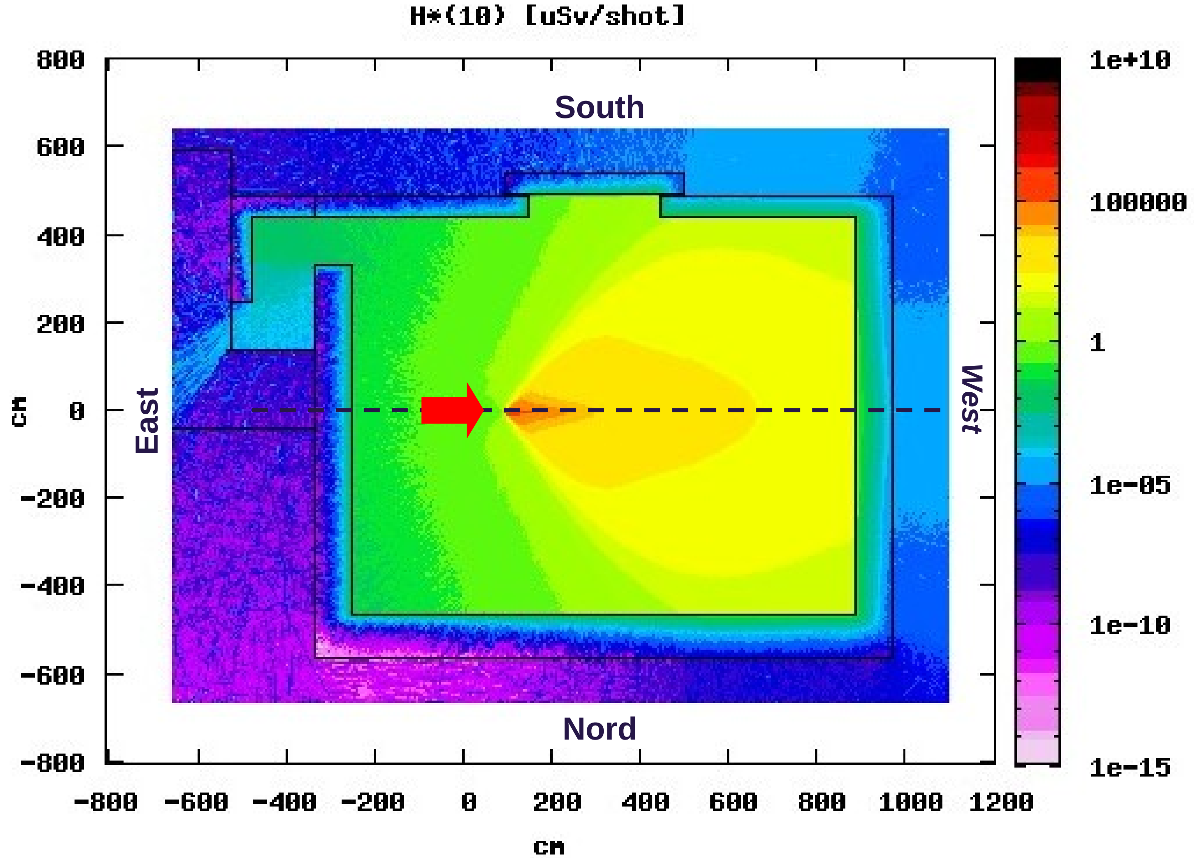
- HED-OPT – x-ray FEL radiation only
- HED-EXP – both x-ray FEL and OL-induced radiation

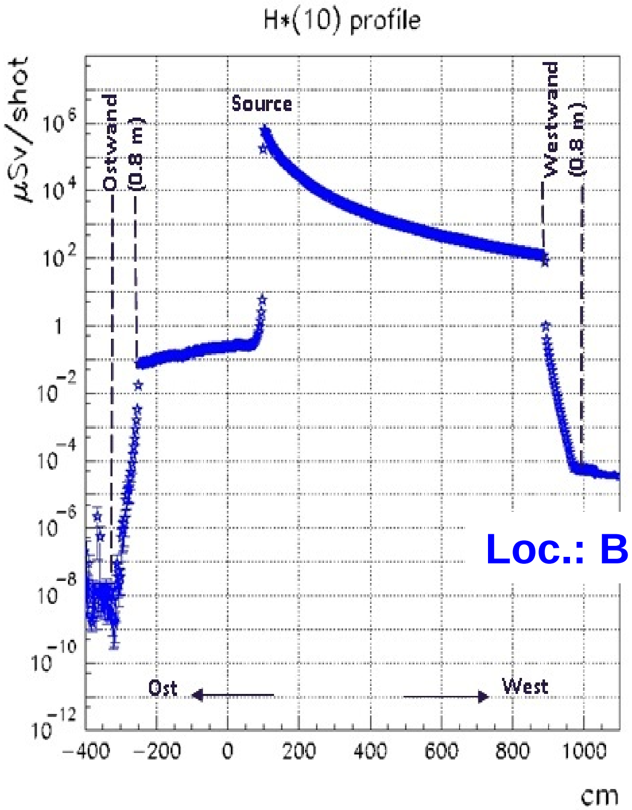


Parallel geometry

100 TW peak power, 5 µm focus

- T_{el}=2 MeV, Q=0.16 µC





All simulations provided by A. Ferrari (HZDR)

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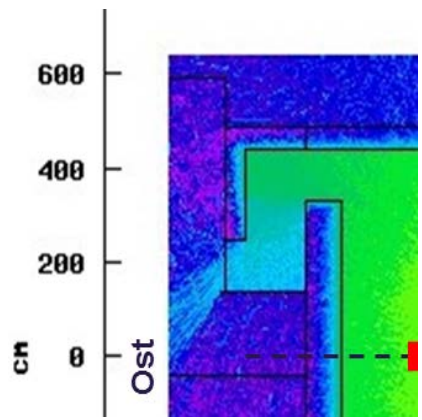

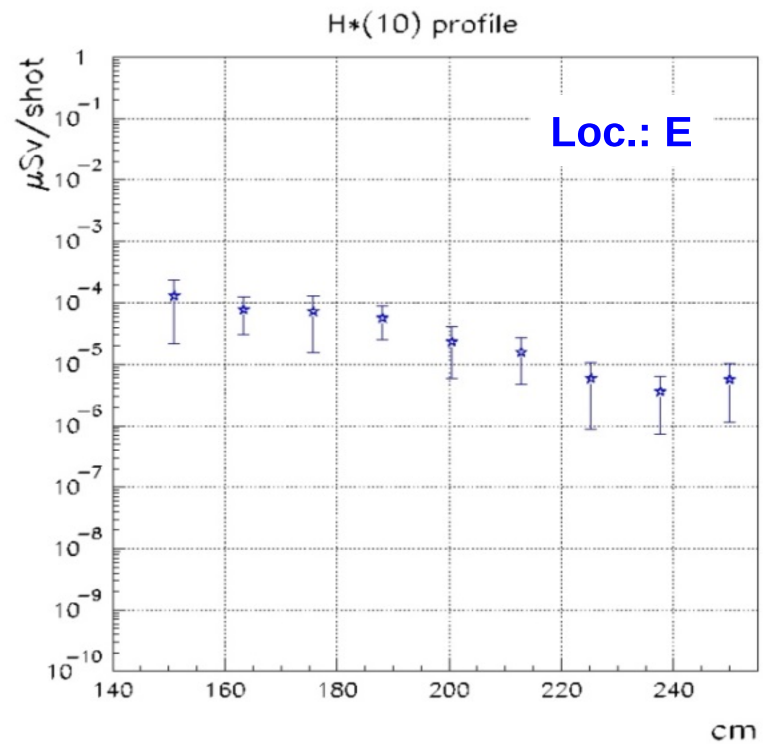

- To high dose increment
- Require add. shielding (door) (low energetic BS)

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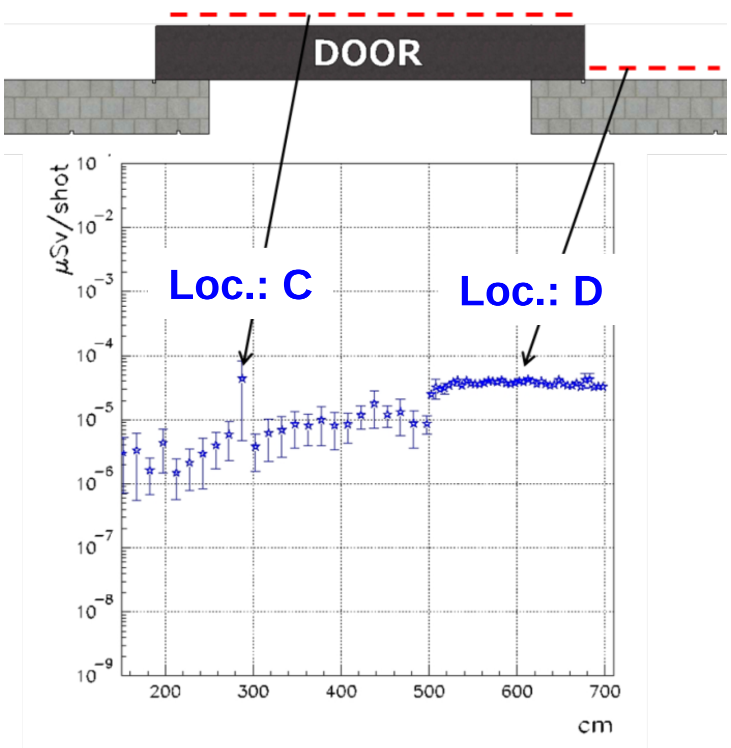

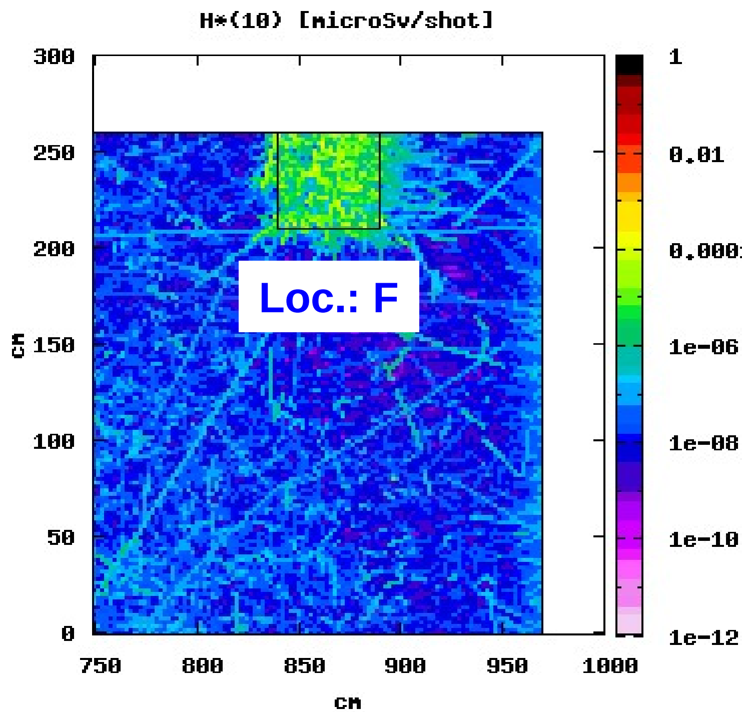

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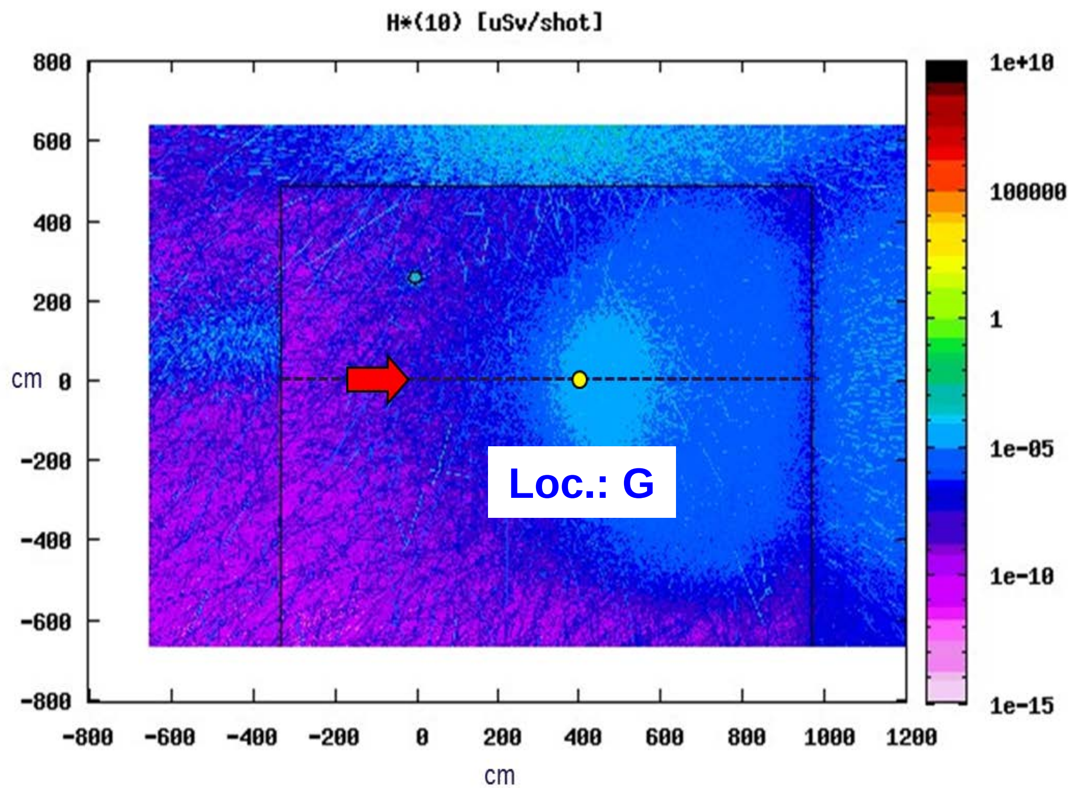

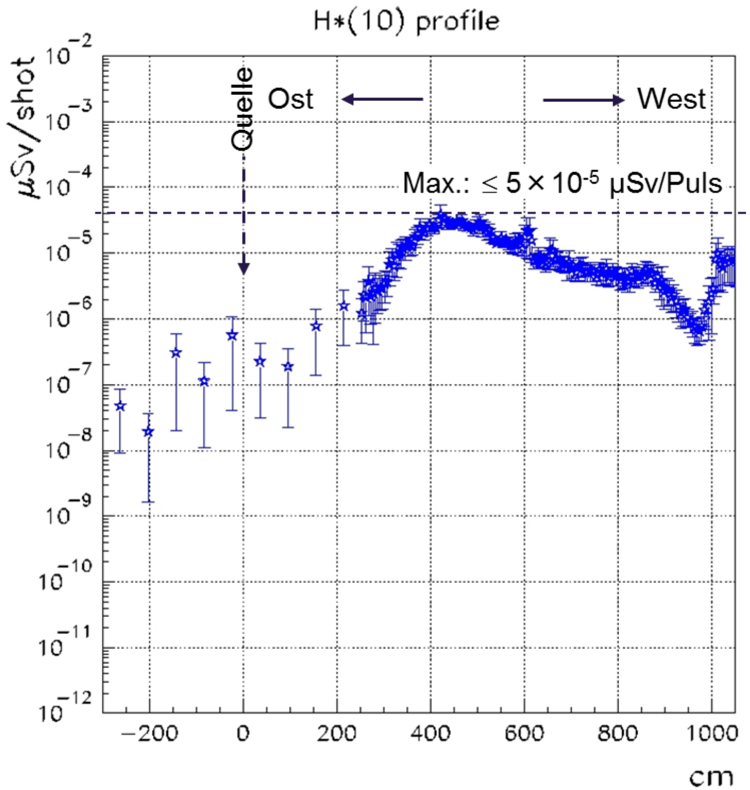

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90° geometry

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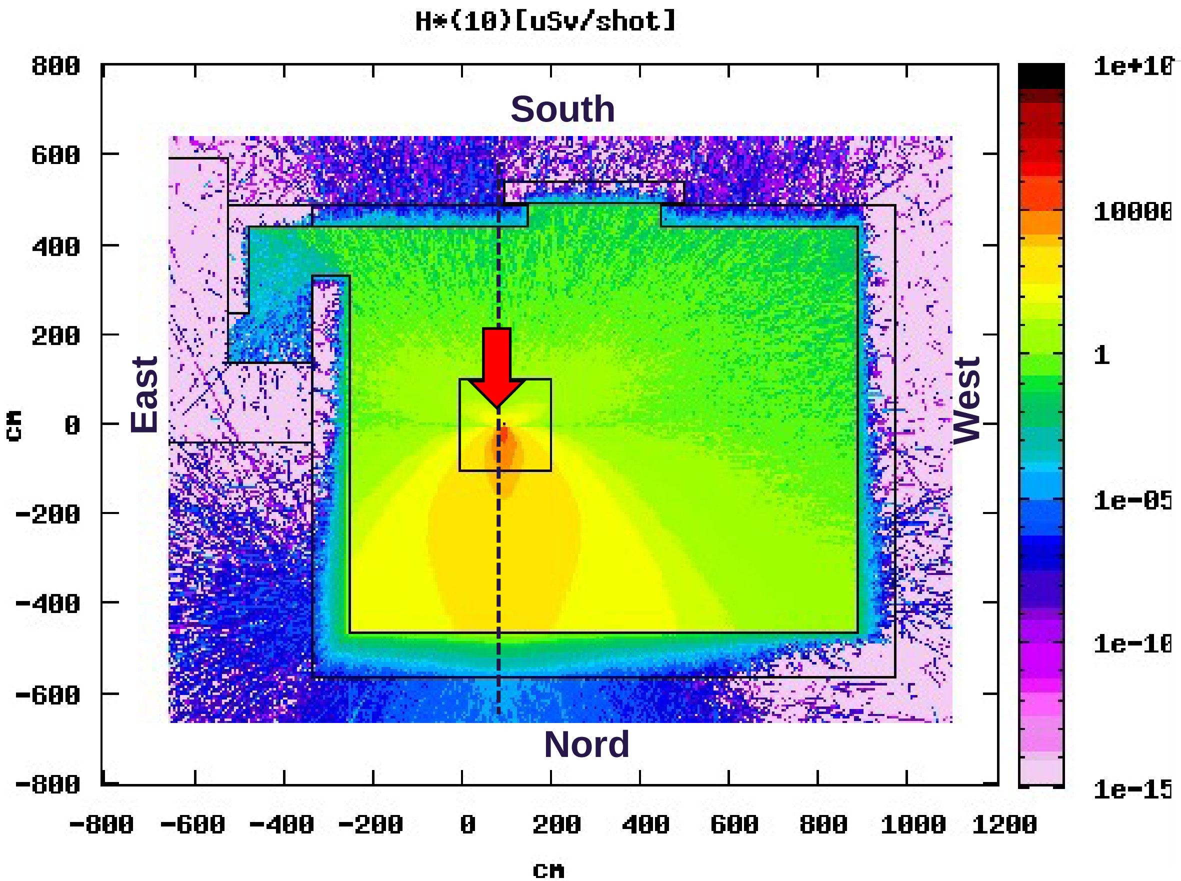

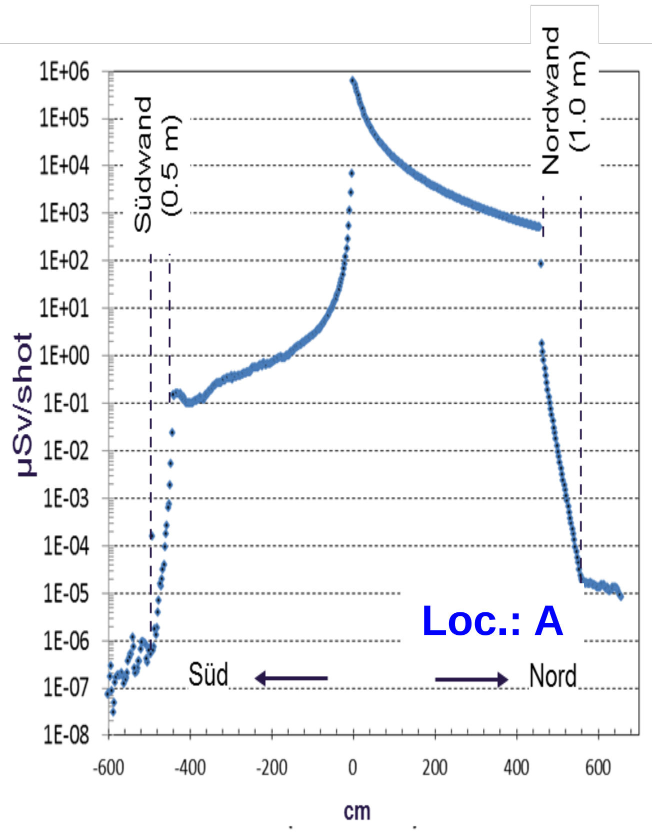

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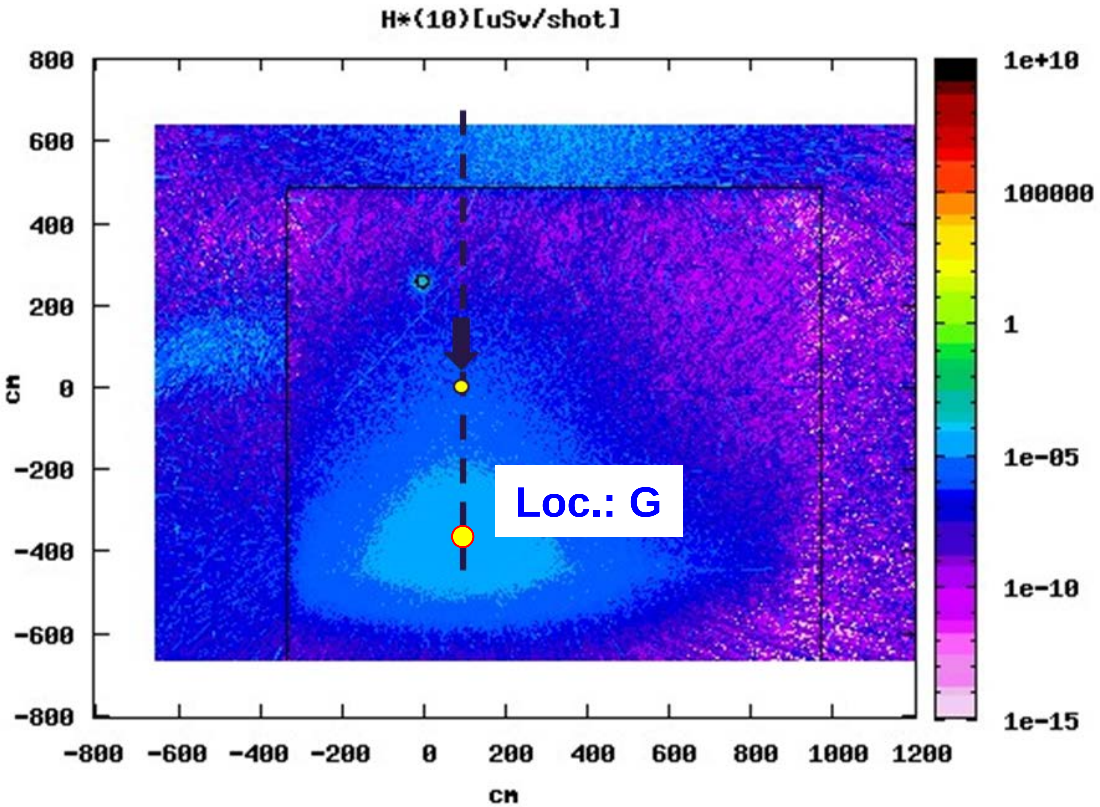
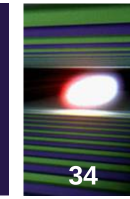


All simulations provided by A. Ferrari (HZDR)

Summary of simulations



100 TW peak power, 5 μm focus

- T_{el}=2 MeV, Q=0.16 μC

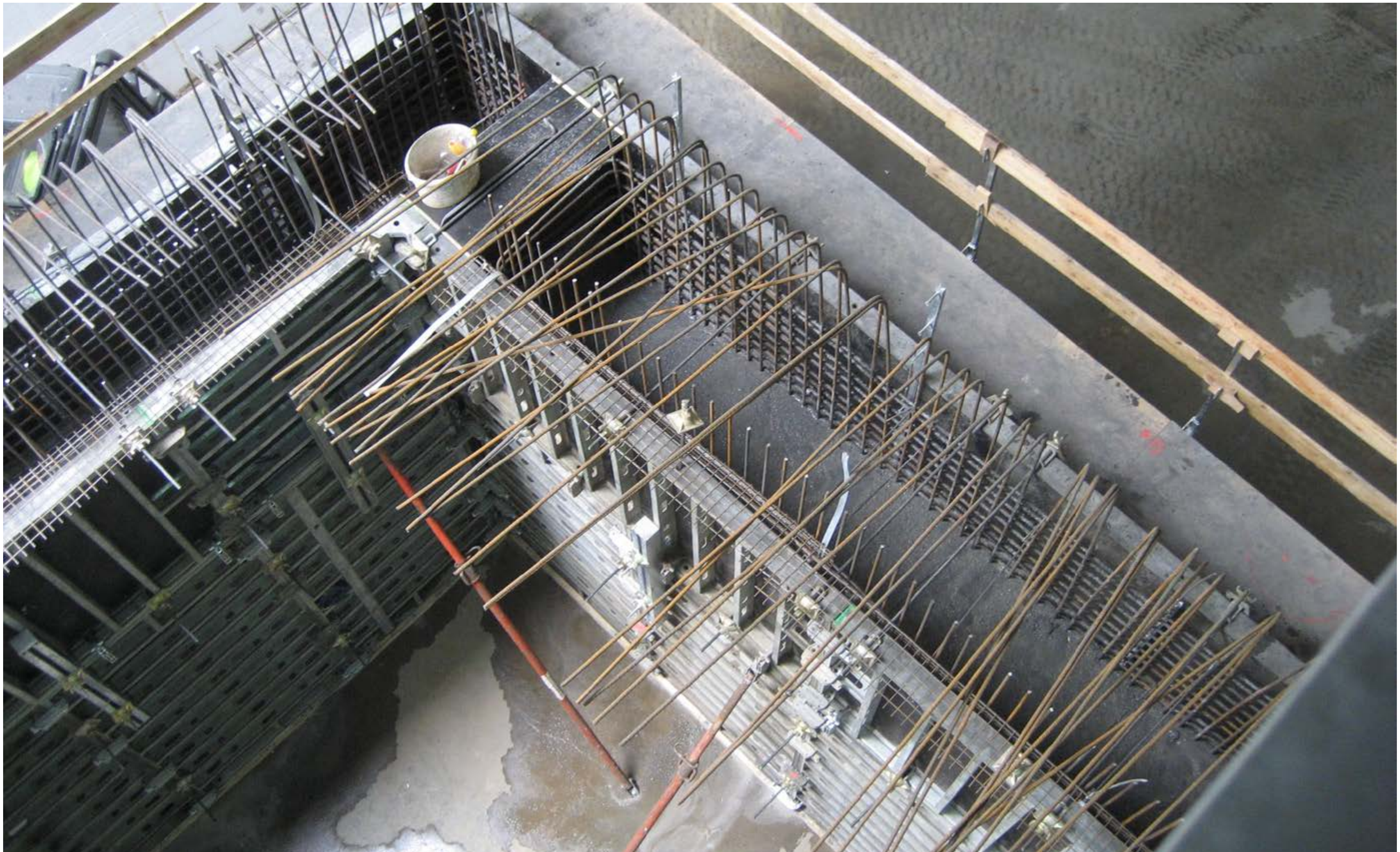
Ort	Probability of person presence	Dose/pulse (0° geometry) [pSv]	Dose/pulse (90° geometry) [pSv]	'4h – Dose' (Max. (p,s)) [μSv]
A	0.1	<1	20	0.29
B	0.1	50	<1	0.72
C	0.1	10	<1	0.15
D	0.1	50	<1	0.72
E	1.0	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$
F	0.1	12	<12	0.18
G	0.1	50	<50	0.72
H	1.0	1.25	<1.25	0.18
Target				2.0

Construction and status

HED enclosure 13.6.2014

HED enclosure casting method 1.7.2014

HED enclosure casting method 1.7.2014



HED enclosure - reinforcement of wall 8.7.2014

inside mesh: 5 cm

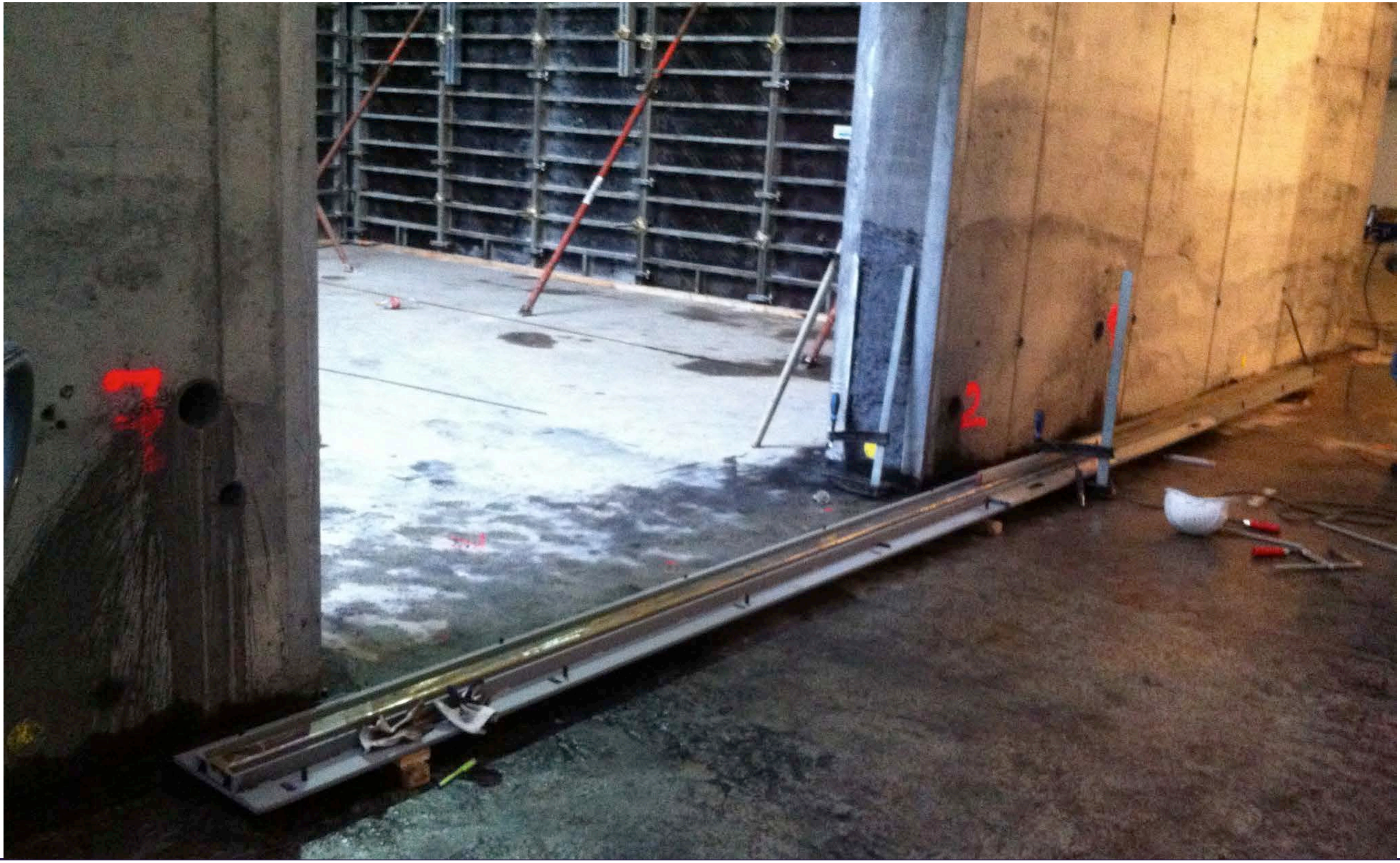
outside mesh: 10 cm

HED enclosure sliding door

6.6.2014

10.7.2014

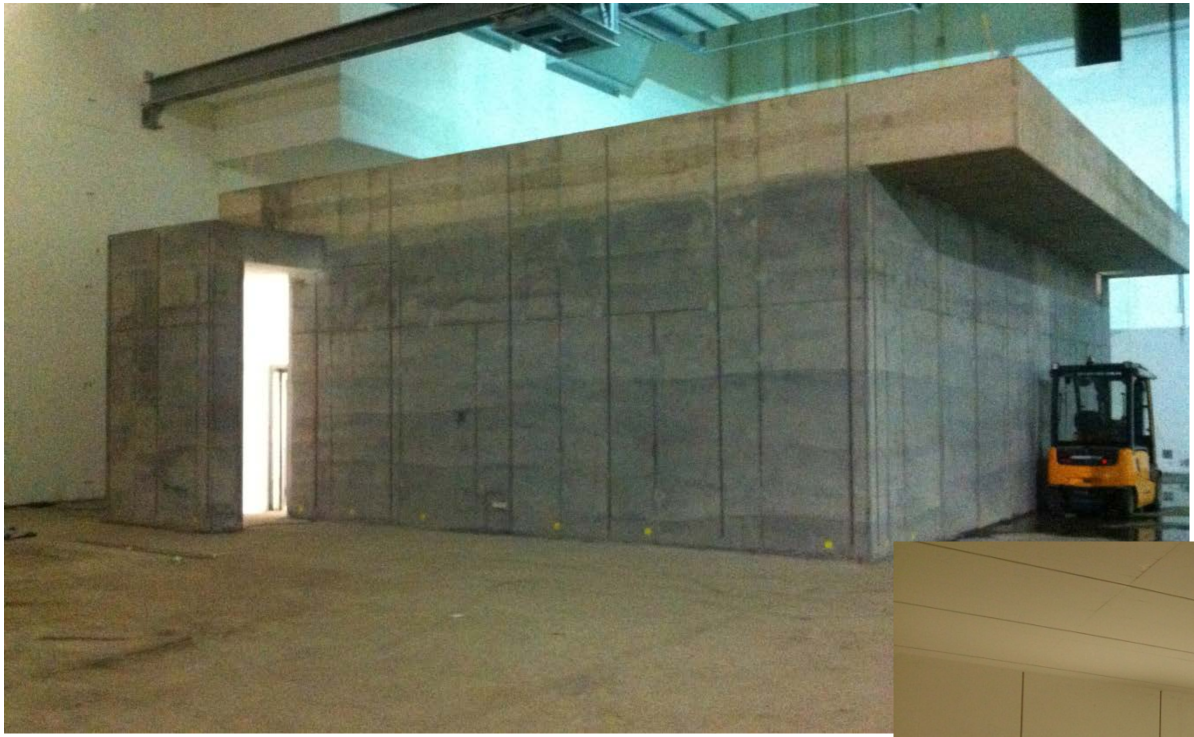
HED enclosure: rail 8.7.2014

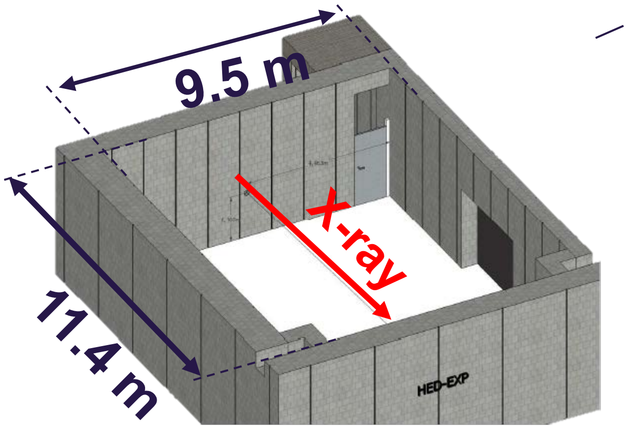


HED enclosure: concrete 8.7.2014

Presently

HED experiments enclosure 95% completed





To come:

- crane
- chicanes

European XFEL

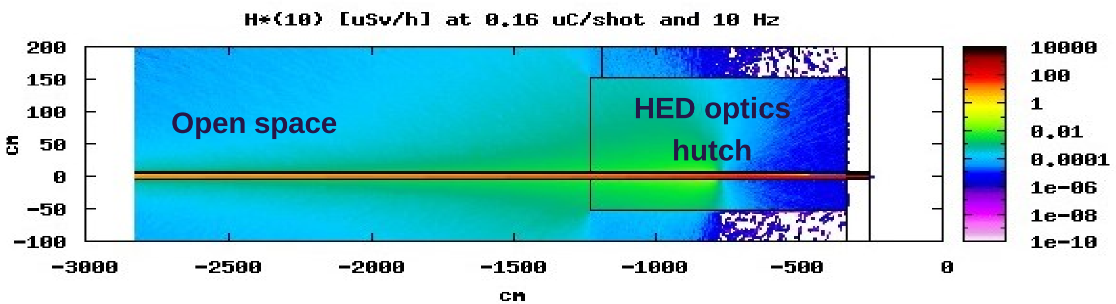
Additional configurations

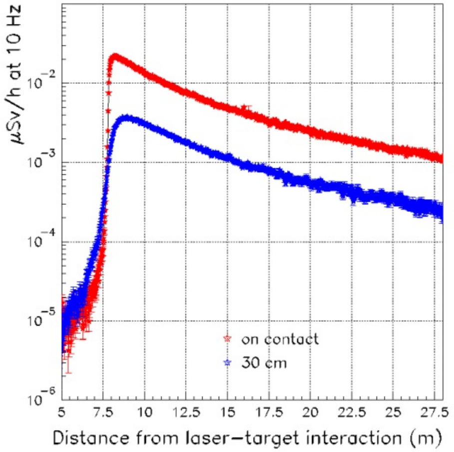
Laser beam transport into HED-EXP

- 3 transport lines: PP-OL (15 cm), HE-OL (25 cm), UHI-OL (25 cm)
- All in geometry not pointing to IA point
- Pb-shielding, resp. chicanes to avoid leakage of radiation

X-ray FEL beam transport

- Beam axis points to IA point
- Protect against leakage from HED-EXP to HED-OPT and upstream area
- Very small solid angle (∅=40 mm, 3.9 m from IA point: 8×10^{-5} Sterad)





All simulations provided by A. Ferrari (HZDR)

Conclusion

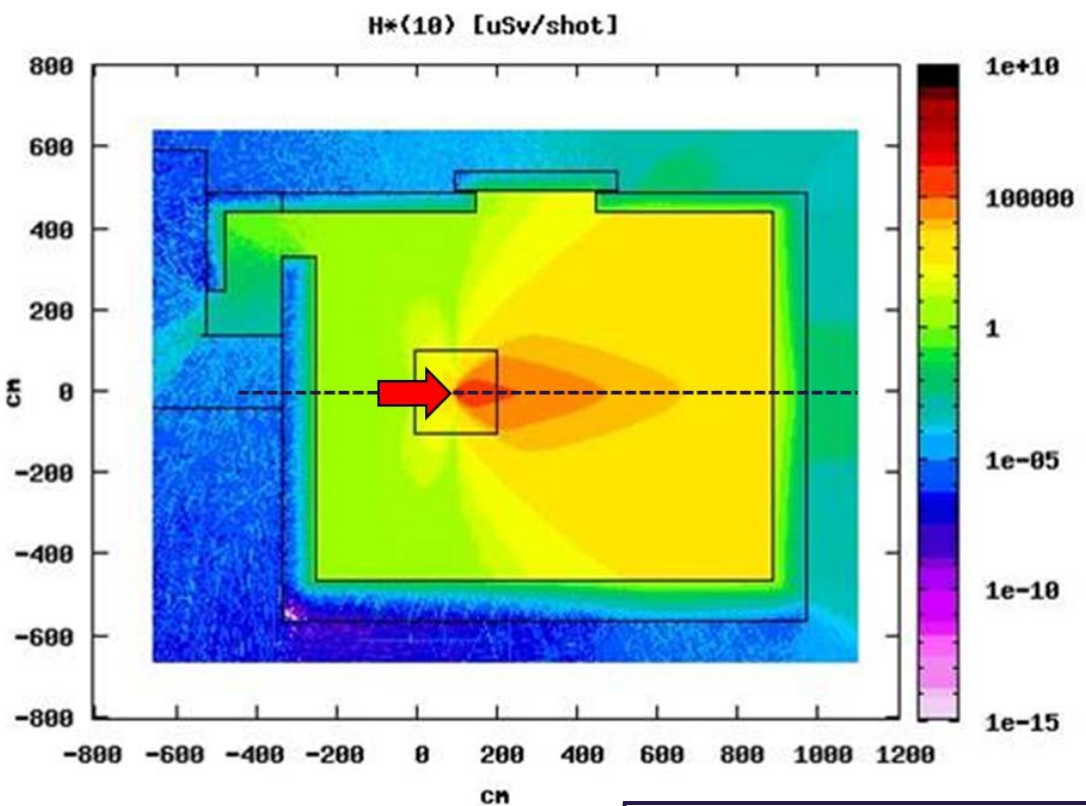
- Ultra-high intensity laser at HED requires specific consideration of shielding
- 100 TW laser with 10 Hz rep rate
- Simulations have been performed by/at HZDR using FLUKA code
- Shielding realized using heavy concrete and an optimization of the room and wall geometry
- Laser installation in 2017
- First experiments in ~2018

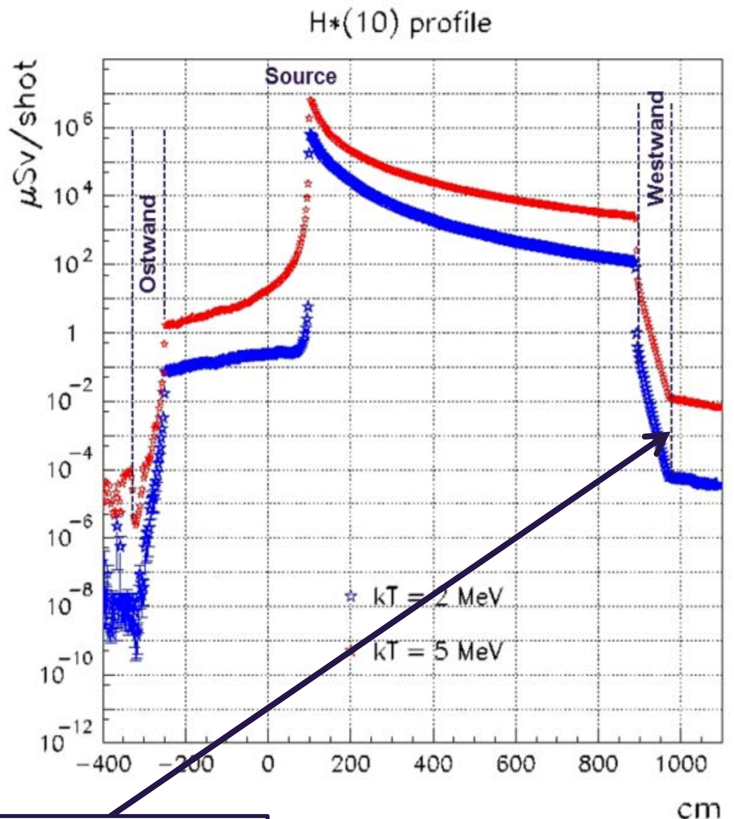
Thank you for your attention

Simulations for 1000 TW Laser upgrade

1000 TW peak power, 5 µm focus

- T_{el}=5 MeV, Q=1.0 µC





Dose increment increased by ~200

- → **Reduce repetition rate**
- → **Local shielding**

Laser-Parametersatz

Parameter	Grundausstattung	Erweiterung*
Pulsenergie an Probe	3J	30 J
Pulsdauer	30 fs	30 fs
Spitzenleistung an Probe	100 TW	1000 TW
Fokusgröße an Probe (80%)	5 µm	5 µm
Spitzenintensität	5×10^{20} W/cm^2	5×10^{21} W/cm^2
Repetitionsrate (max.)	10 Hz	0.1 - 1 Hz
Elektronentemperatur	2 MeV	5 MeV
Ladung pro Puls	0.16 µC	0.8 µC
Mittlere Leistung im Elektronenstrahl	3.2 W	4 W

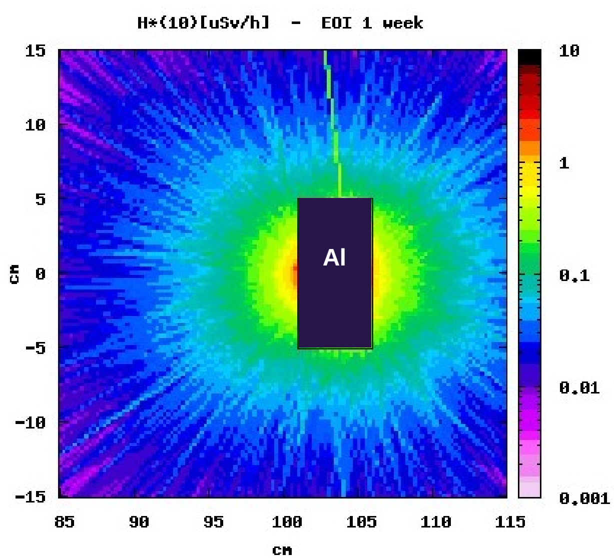
***vorläufig**

Activation analysis

For high primary intensity and high repetition an activation of the vac-cuum chamber or of components inside the vaccuum chamber can occur.

Simulation to estimate such activations

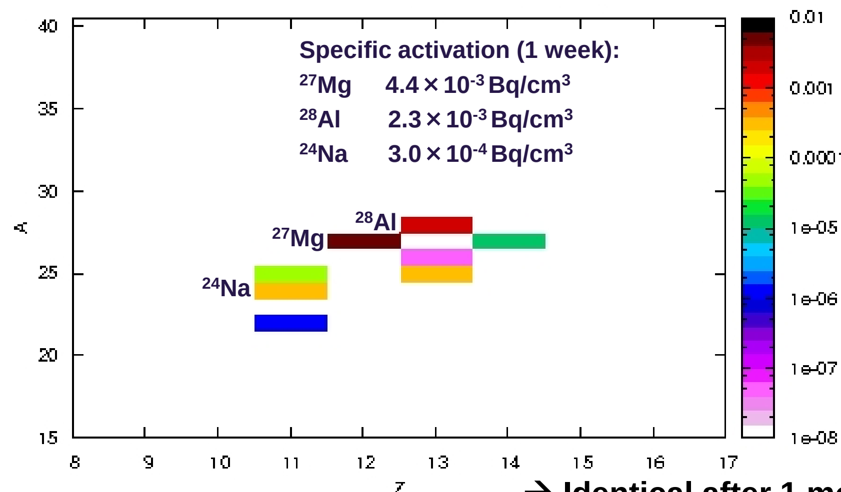
- 1 week of irradiation (10 Hz, 12 hrs/day, 5 days)
- 1 month of irradiation



→ @10 cm <100 nSv/h

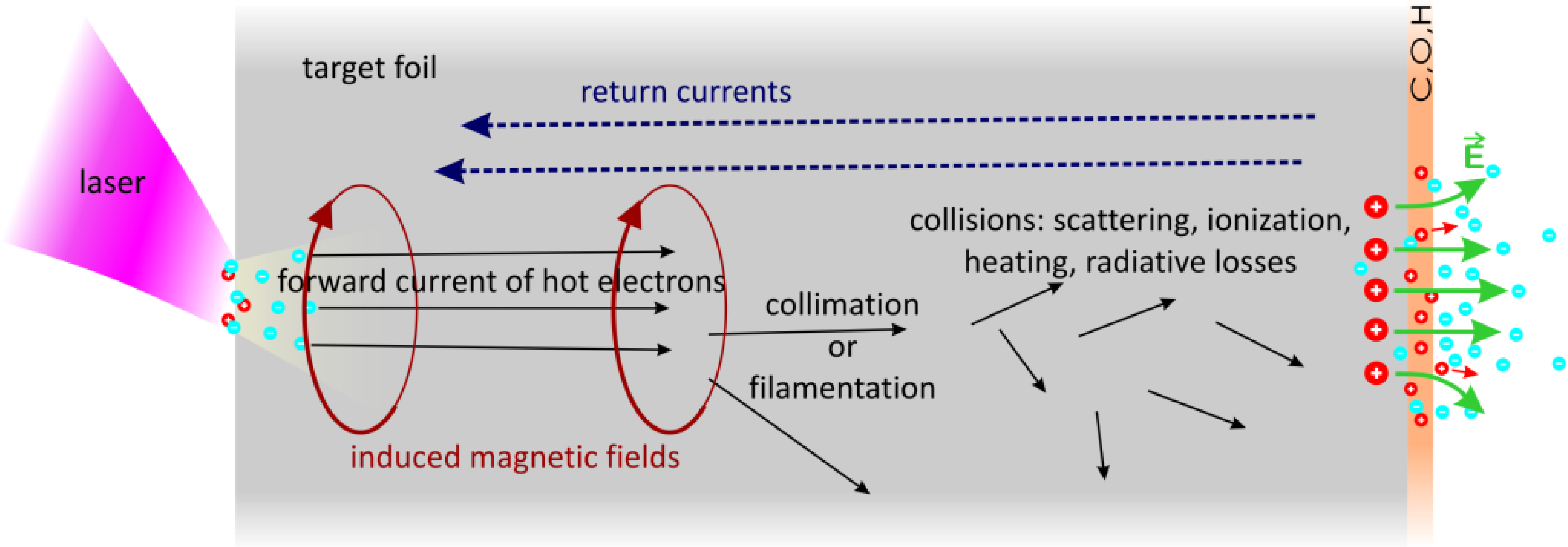
Total activation (1 week):	**7×10^{-3} Bq/cm³**
Total activation (1 week, 1h):	**4×10^{-4} Bq/cm³**

Contributions to activation [Bq/cm³] – EOI 1 week



→ **Identical after 1 month**

Relativistic laser matter interaction



Study microscopic processes during laser-matter IA

⇒ **Density fluctuations**

⇒ **Dynamic & ultrafast processes (electronic, nuclear structure)**

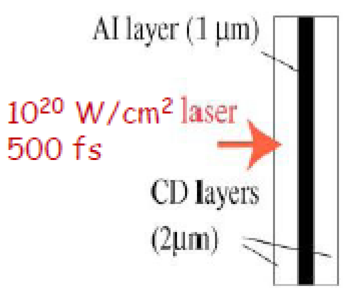
How to study density fluctuations

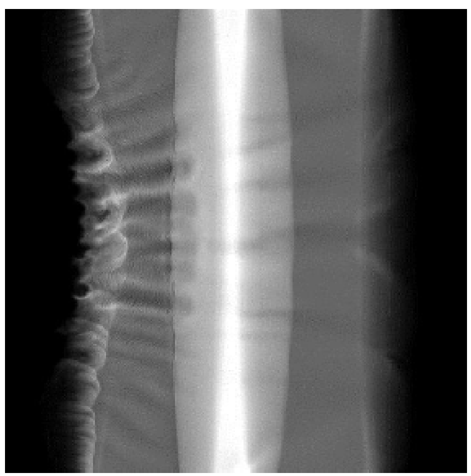
Use coherent x-ray imaging, diffraction, speckle spectroscopy

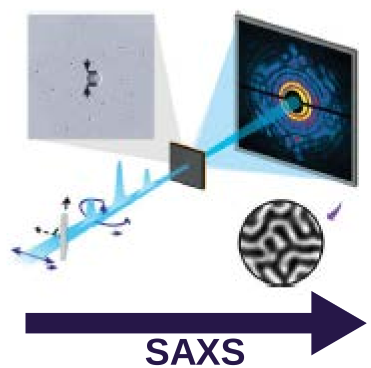
- Use ultrafast probing by x-rays
  - → **space-resolved**
  - → **time-resolved**
  - → **Element selectivity**
- Obtain information about density fluctuations (static & dynamics)

Buried layers

(Courtesy: T. Cowan, T. Kluge)

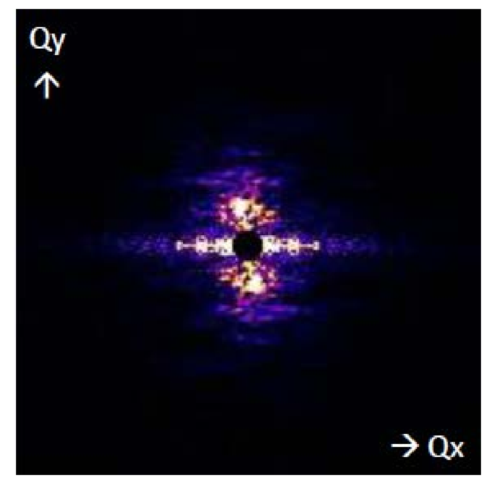






SAXS

(Simulation: C. Gutt)



Repräsentative Orte

A: Nordwand, auf Strahlhöhe; Aufenhaltswahrscheinlichkeit 0.1

B: Westwand, auf Strahlhöhe; Aufenhaltswahrscheinlichkeit 0.1

C: Südwand/Tor, auf Strahlhöhe; Aufenhaltswahrscheinlichkeit 0.1

D: Südwand/westl. Tor, auf Strahlhöhe; Aufenhaltsw.keit 0.1

E: HED-CTR, vor Tür, auf Strahlhöhe; Aufenhaltsw.keit 1.0

F: Nordwand, vor Schikane, 3.5-4m ü. Boden; Aufenhaltsw.keit 0.1

G: HED-HPLAS, im Max.; Aufenhaltswahrscheinlichkeit 0.1

H: XHQ, über G; Aufenhaltswahrscheinlichkeit 1.0