Integrating High-Power Lasers into a Free Electron Laser Environment: Insights from the ReLaX Laser at European XFEL

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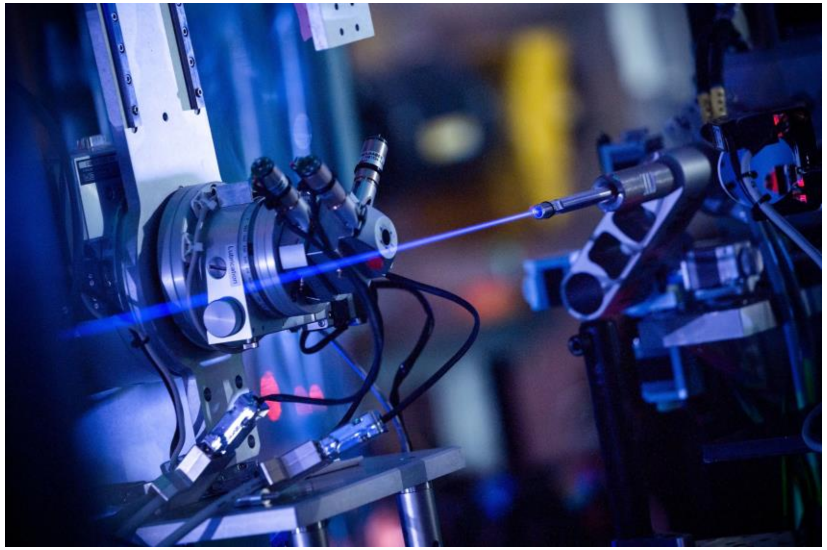
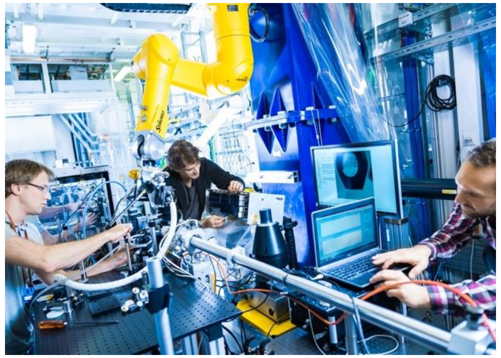


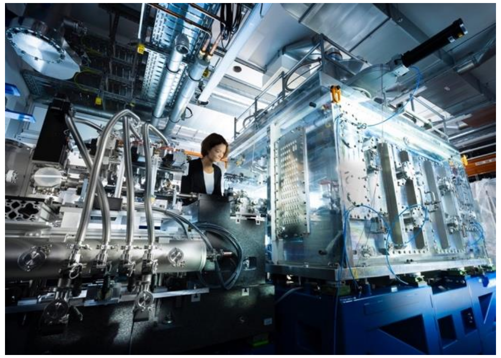
What is the European XFEL

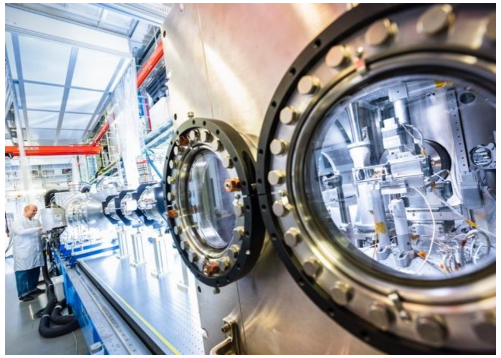
- World’s brightest X-ray free-electron laser
- Produces ultra-short, ultra-intense X-ray flashes at up to 27,000 pulses per second
- Enables atomic-resolution imaging of matter in motion
- Supports diverse fields: physics, chemistry, biology, materials science, and more
- Hosts seven experimental stations (instruments) for user-driven research

- Each experimental station is optimized for a distinct class of experiments — ranging from femtosecond-resolution imaging of biomolecules, to studies of quantum materials, ultrafast chemical reactions, dense plasmas, and extreme states of matter

- **HED (High Energy Density)** is unique: it also operates with an independent ultra-intense laser, the ReLaX system

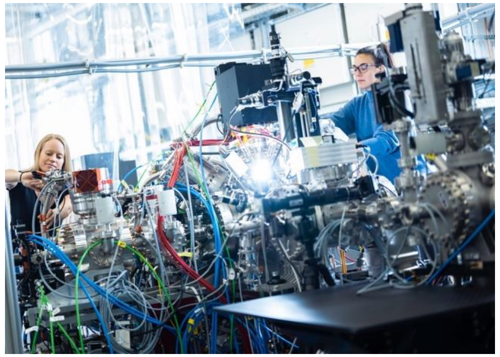

Femtosecond X-ray Experiments


High energy density science

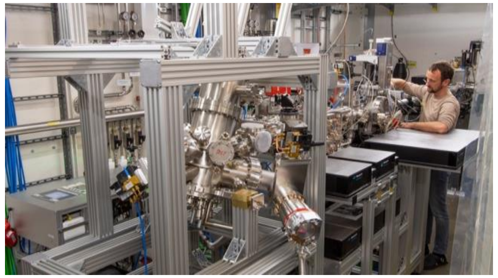

Ultrafast coherent diffraction imaging of single particles, clusters and biomolecules


Materials imaging & dynamics


Spectroscopy & coherent scattering


Small quantum systems

Soft X-ray Port

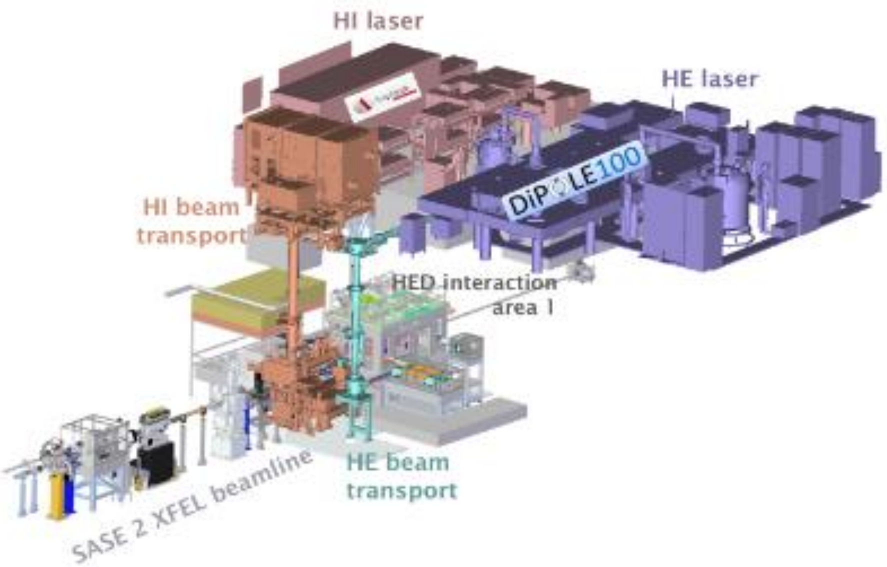


What is the ReLaX Laser?

- **ReLaX** stands for *Relativistic Laser at XFEL* — a high-power, ultrafast laser system.
- It is a **Ti:Sapphire laser** capable of delivering:

  Up to 400 TW peak power
  Pulse durations as short as **25 femtoseconds**
  Focused intensities exceeding **10^{22} W/cm²**

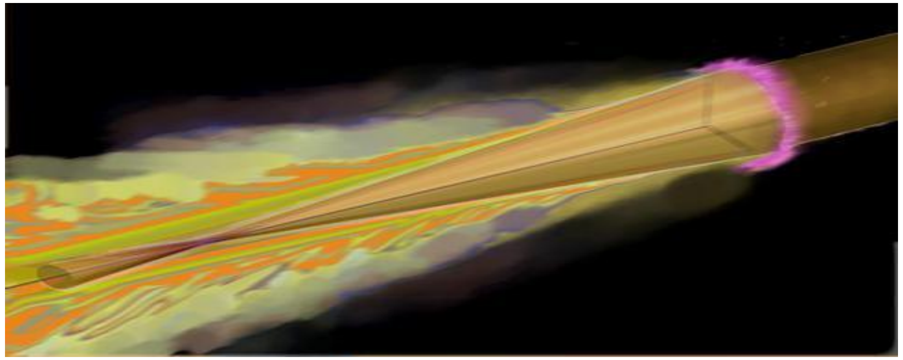
- Developed and continually supported in close collaboration with **HZDR** (Helmholtz-Zentrum Dresden-Rossendorf), a leading center for high-intensity laser physics.
- **HZDR** provides expertise in laser-plasma interactions, simulation, and system optimization — playing a key role in the scientific and technical success of ReLaX.



HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

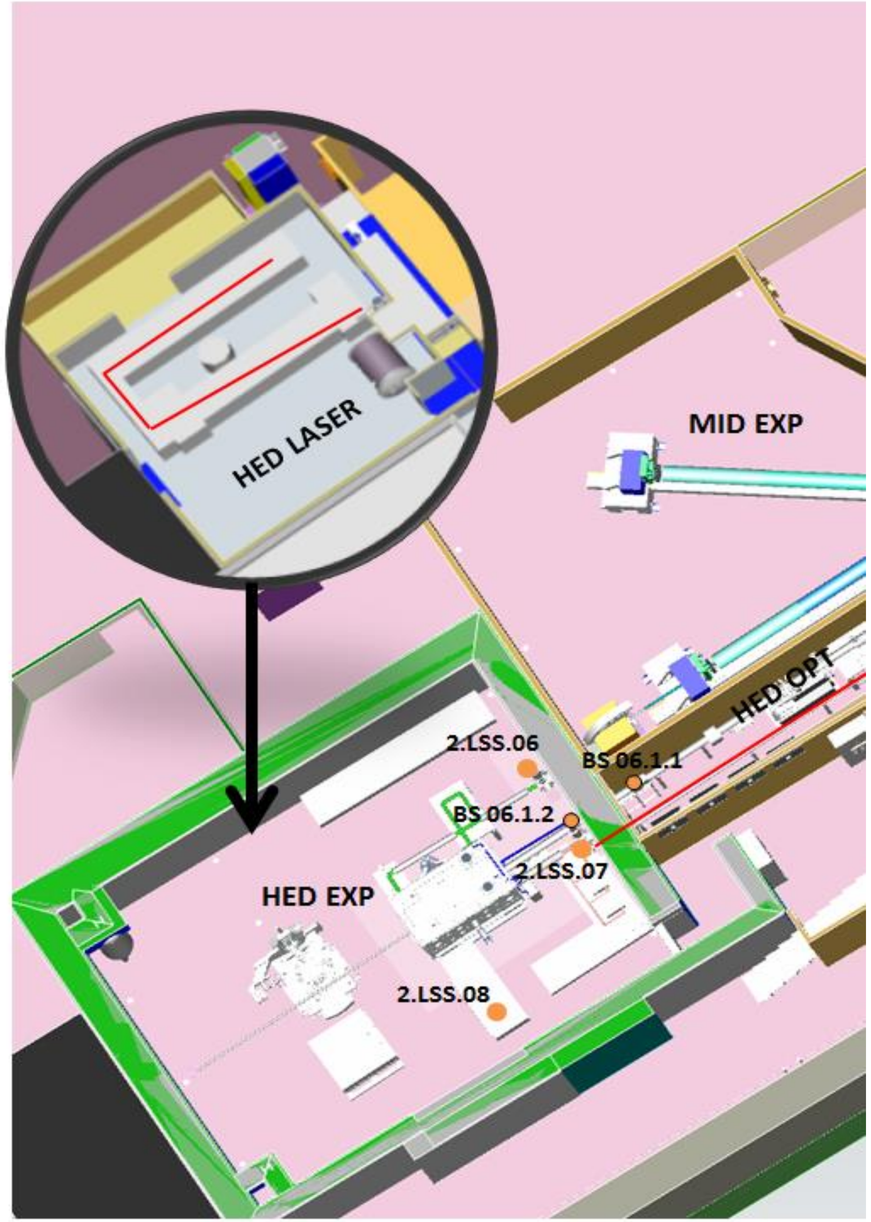
Why The ReLaX Laser at XFEL

- Enables the creation of **extreme plasma conditions** similar to those in planetary interiors or star formation
- Combined with **XFEL X-ray pulses** to probe these plasmas with ultra-high precision
- Provides **valuable data for astrophysics**, helping test theories about:
  - The Earth's formation and current structure
  - The internal conditions of heavier planets
  - The formation and evolution of the solar system



Mixed Radiation Field:
What Gets Produced During Laser Shots

- **Electrons**
  - High-energy electrons are generated at the target
  - Most are contained within the vacuum chamber's thick metal walls
- **Photons**
  - Produced when fast electrons strike the target and surrounding materials
  - Additional photons may result from neutron or proton interactions with matter
- **Neutrons**
  - Created through nuclear reactions involving aluminum and other chamber components
  - Can also result from high-energy photons interacting with atomic nuclei
- **Protons**
  - Accelerated from the target surface by strong electric fields in the plasma
  - Typically lower in number but still part of the radiation mix



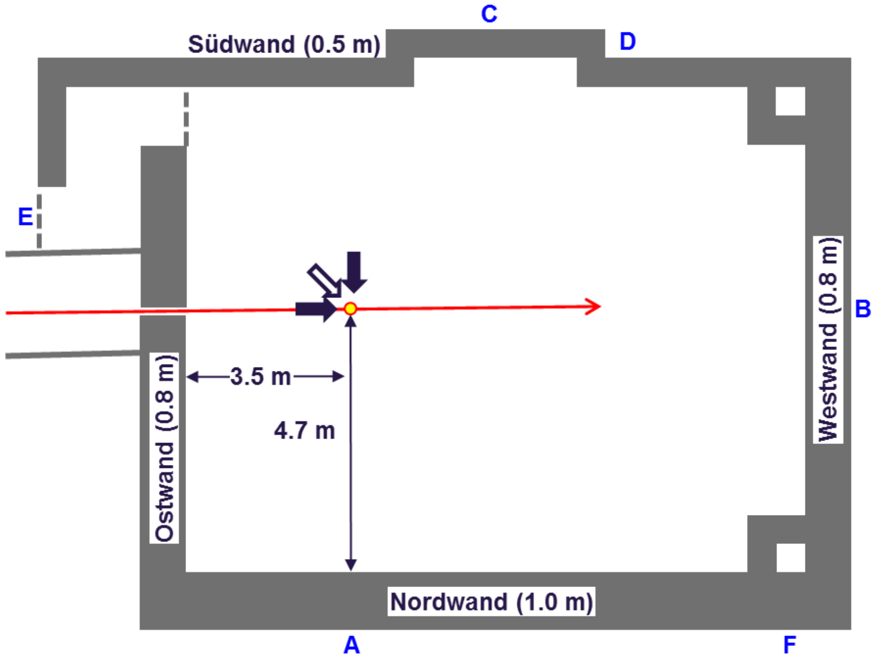
Legal Notification of the ReLaX Laser Plasma Source

- In **2014**, we submitted a **technical report** to **MELUND** (Ministry of Energy Transition, Environment, and Nature in Schleswig-Holstein), detailing:
  - Expected radiation levels
  - Laser operation parameters
  - Shielding design and interlock strategy
  - Target material (solids metals only)
  - Irradiation geometry
- MELUND reviewed the report and confirmed that **no additional approval** would be required for operation within the specified limits.
- This documentation forms the legal and technical basis for ReLaX operation at HED.

Laser parameter	Maximum achievable laser parameters	Laser parameters – basic configuration
Pulse energy at sample	Up to 10J	3J
Pulse duration	25 femtoseconds	30 femtoseconds
Peak power at sample	400 TW (Terawatt)	100 TW (Terawatt)
Focal spot size at sample (80%)	5 Micrometers	5 Micrometers
Peak Intensity	10^{21} W/cm^2	10^{20} W/cm^2
Repetition rate (max.)	5Hz for 10J	10Hz

Shielding of the HED Experiment Hutch

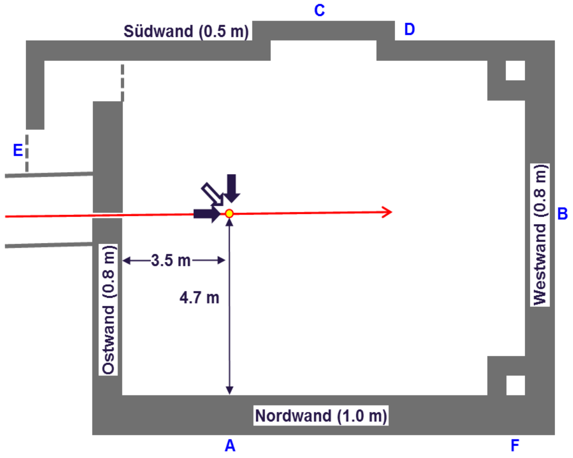
- Designed for **UHI laser operation at up to 10 Hz**, assuming up to 1000 hours/year
- Meets radiation protection goal of <2 µSv per 4 hour period (<0.5 µSv/h)
- Heavy concrete walls (>3.6 t/m³) 0.5m – 1.0m thick
- Normal concrete roof (2.35 t/m³) 0.88m thick
- HED shielding is **>5 tenth-value layers thicker** than what is required for XFEL radiation
- The radiation field calculations were carried out by Dr. Anna Ferrari at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) and are based on the FLUKA Monte Carlo method

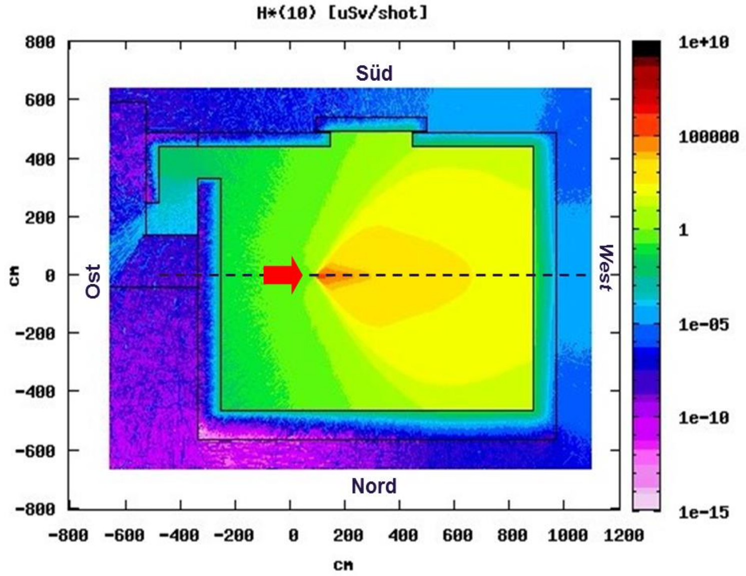


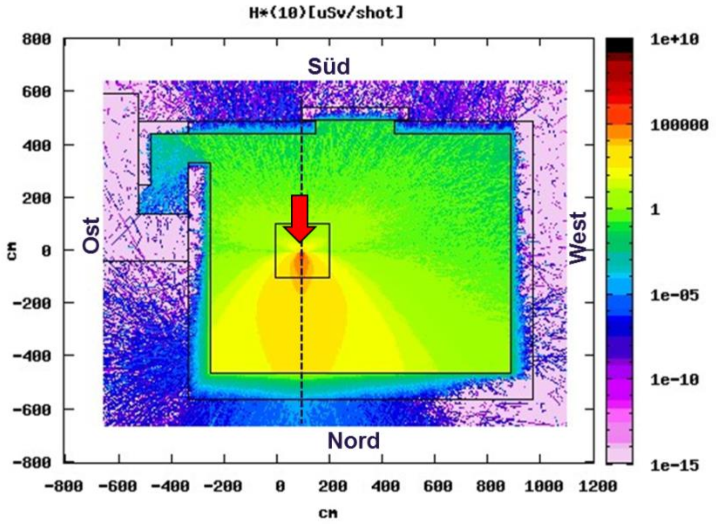
Shielding of the HED Experiment Hutch

- 20 µm Gold solid target
- 100 TW @ 10 Hz

Ort	Occupancy Probability	Dose/Pulse parallel [pSv]	Dose/Pulse perpendicular [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
Protection Goal				2.0







Interlocks

Radiation Interlocks

- Same Interlock system as the XFEL
- ReLaX can not be in shot mode until hutch is searched.
- After search HED is a prohibited area
- The following conditions will trip the interlock and shutdown the ReLaX oscillator.
    1. Pressing an emergency off or emergency access button.
    2. Opening a door to HED exp.
    3. Loss of door locked signal
    4. Triggering of Pandora detector
    5. Interlock cable disconnect or failure
    6. System communication fault

Laser Interlocks

- Laser interlock must be set from inside the hutch to operate relax in alignment mode (no oscillator)
- Hutch is restricted to class IV laser operators (DACHS)
- The following conditions will trip the interlock and shut all laser shutters
    1. Pressing an emergency off or emergency access button.
    2. Opening side door
    3. Both labyrinth doors open
    4. Interlock cable disconnect or failure
    5. System communication fault

Commissioning of ReLax

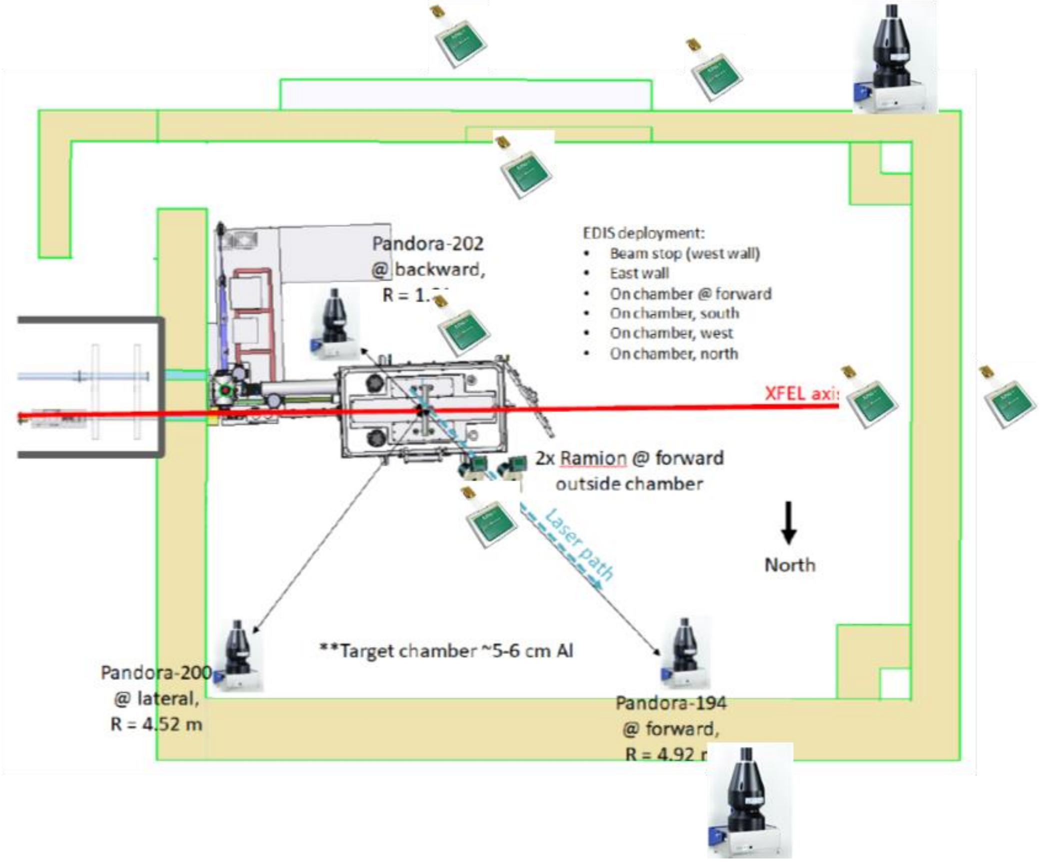
- Commissioning period: **19 Nov – 6 Dec 2019.**
- Electrons, Photons, Neutrons, Protons Generated from high intensity shots on metal foils (Al, Ti, Au).

Laser Parameter	Value
Pulse Energy	3 Joules (only 30–50% of this in the focused beam)
Pulse Duration	100 femtoseconds
Power	30 terawatts
Focused Beam Size	5 micrometers × 15 micrometers
Intensity	10^{18} – 10^{19} watts/cm²
Repetition Rate	32 shots total over 2 weeks

Commissioning of ReLaX

Radiation Measurement Setup

1. 20 EDIS-1 detectors + TLDs (inside and outside HED)
2. 5 PANDORA detectors (3 inside, 2 outside)
3. RAM-ION ion chamber
4. Thomson parabola for proton energy measurement



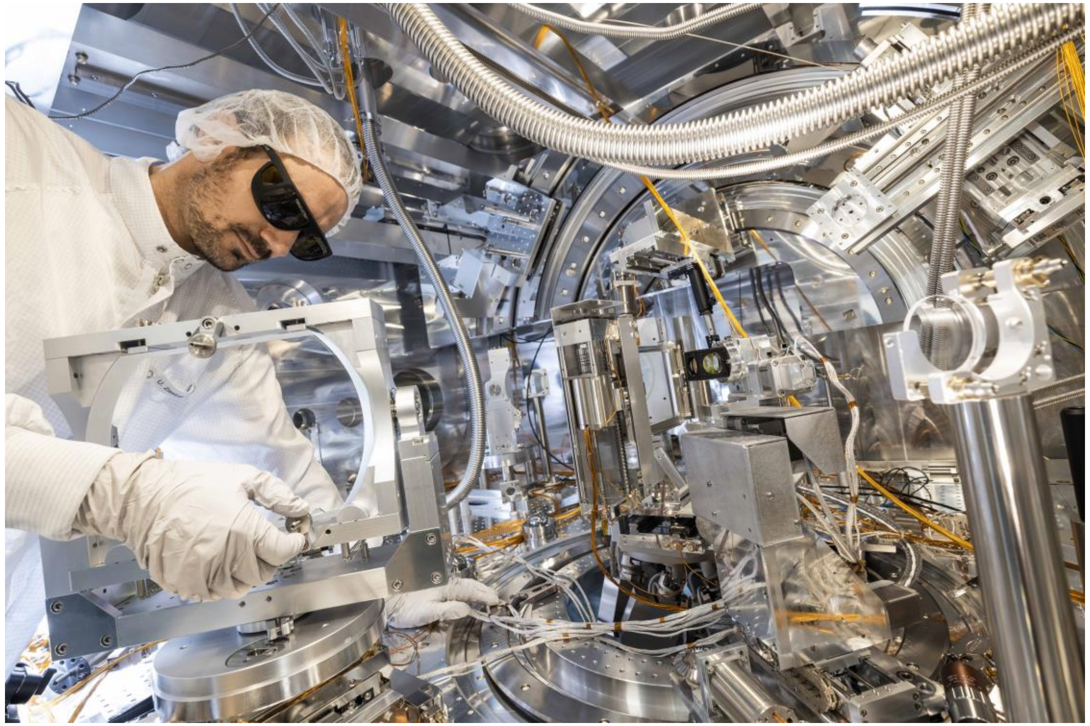
Commissioning of ReLaX

Radiation Type	Detector	Max Measured Value	Outside A12
Photons	PANDORA	0.7–2.3 nSv/pulse	None
	EDIS-1	13 μSv total	None
	RAMION	~0.26–3 μSv/pulse	None
Neutrons	PANDORA	~500 pSv/pulse	None
Protons	Thomson	13 MeV	Not Measured
Electrons	Simulated	0.4–2 MeV	0.4–2 MeV

- Commissioning successfully validated radiation safety

Operational Experience Since Commissioning (2019)

- **Usage:** ~4 weeks of experimental operation per year
- **Pulse Rate:**
  - 10 Hz used only rarely and briefly
  - **Max observed:** 500 pulses/day
  - **< 0.4%** of originally assumed 144,000 pulses/4h at 10 Hz
- Radiation Dose Findings:
  - **Integrated dose** remains far below 2014 conservative estimates
  - **No measurable dose** above background outside the prohibited area
  - **No evidence of material activation** in the sample chamber



Accompanying Radiation Protection Measures

Since the commissioning of the RELAX laser, we have implemented several measures to closely monitor operation:

- Experiments are individually evaluated by the radiation protection officer for potential risks and approved with appropriate conditions if necessary.
- The prompt dose near the radiation source is continuously monitored with an ionization chamber.
- The integral dose of each experiment is measured and recorded at several points within the HED Experiment Hutch.
- After opening the controlled area, checks are carried out for possible activation; the readings are recorded.
- Radiation monitors are installed in the monitored area, which shut down the laser in the event of elevated dose rates.

Expansion of Operating Conditions

- Why Expand?

  Proven technical reliability
  Evolving scientific questions
  Advances in laser system capabilities

- Key Parameter Changes:

  Laser Peak Power:
  Increase from **100 TW → 400 TW**
  Intensity up to 10^{22} W/cm² (with extreme focusing)
  Average power: from 30 W → 50 W

- Target Materials:

  Now includes:
  Liquids
  Low-density materials (foams)
  Gases (potentially)

- Irradiation Geometries:

  Addition of **counter-propagating geometry**
  Required for a **key quantum physics experiment**
  High international scientific relevance

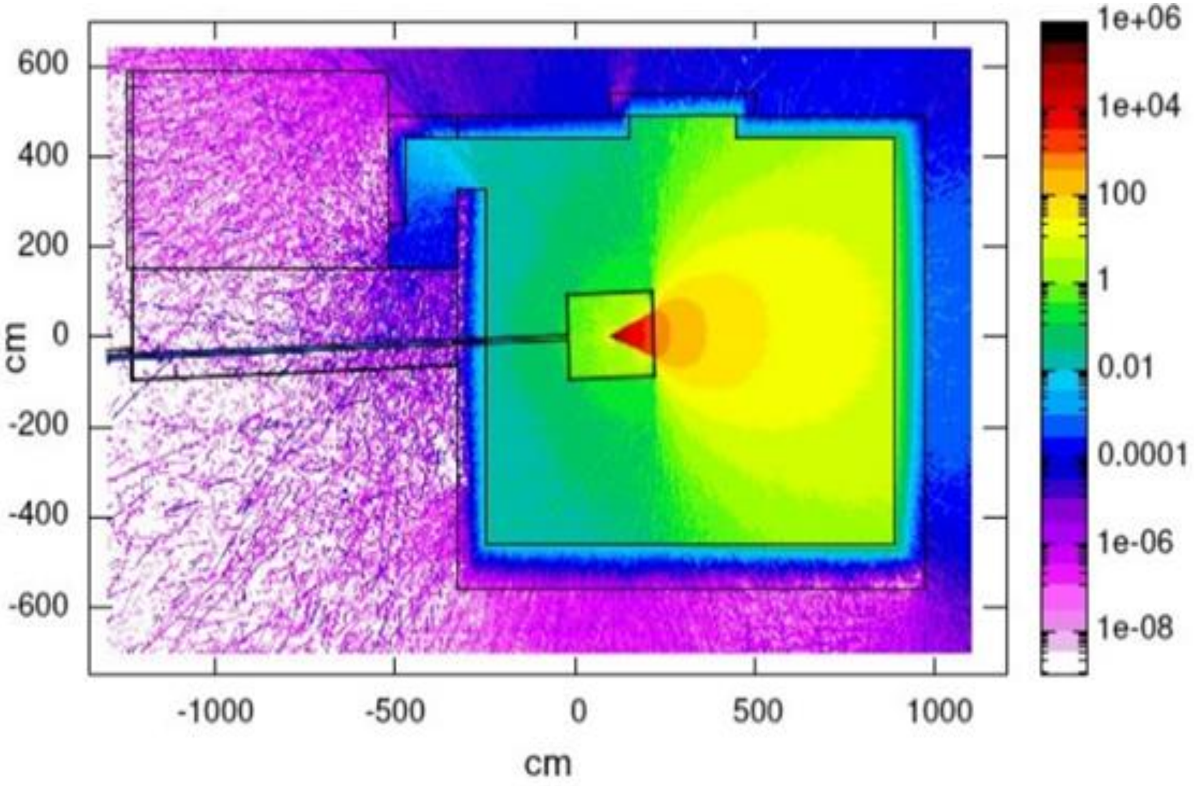
Radiation Protection Consequences from the new operating conditions:

Higher Laser Power & Lower-Density Samples

- Lead to higher-energy electrons.
- **15 MeV** (vs. 2 MeV previously)
- More intense bremsstrahlung radiation

Updated Dose Simulations

- At shielding wall: **~1 nSv/pulse → ~0.5 µSv/h** at 500 shots/hour.
- Remains within **2 µSv/4h** radiation protection goal.
- Validated by previous experimental data.



Regulatory Proposal: A Pragmatic Safety Strategy for RELAX

Operational Experience Confirms Safety

- Radiation measurements inside and outside shielding match simulation predictions.
- Radiological conditions are now well understood.
- Real-world use has shown that actual shot rates are **much lower** than originally assumed in 2014.

Proposed Change

- **Remove hard limits** on laser parameters (e.g., 100 TW, solid targets only).
- Replace them with a **dose-based operational target**: **< 2 μSv per 4 hours** outside the shielding
- This is **well below** the legal threshold of **10 μSv/h**, meaning regulatory reclassification is not needed.

Regulatory Proposal: A Pragmatic Safety Strategy for RELAX

Safety strategy going forward

- Every laser use must be **authorized by the Radiation Protection Officer (RPO)**.
- Parameters considered: power, repetition rate, geometry, target type, simulation results.
- Max number of shots/hour clearly defined.

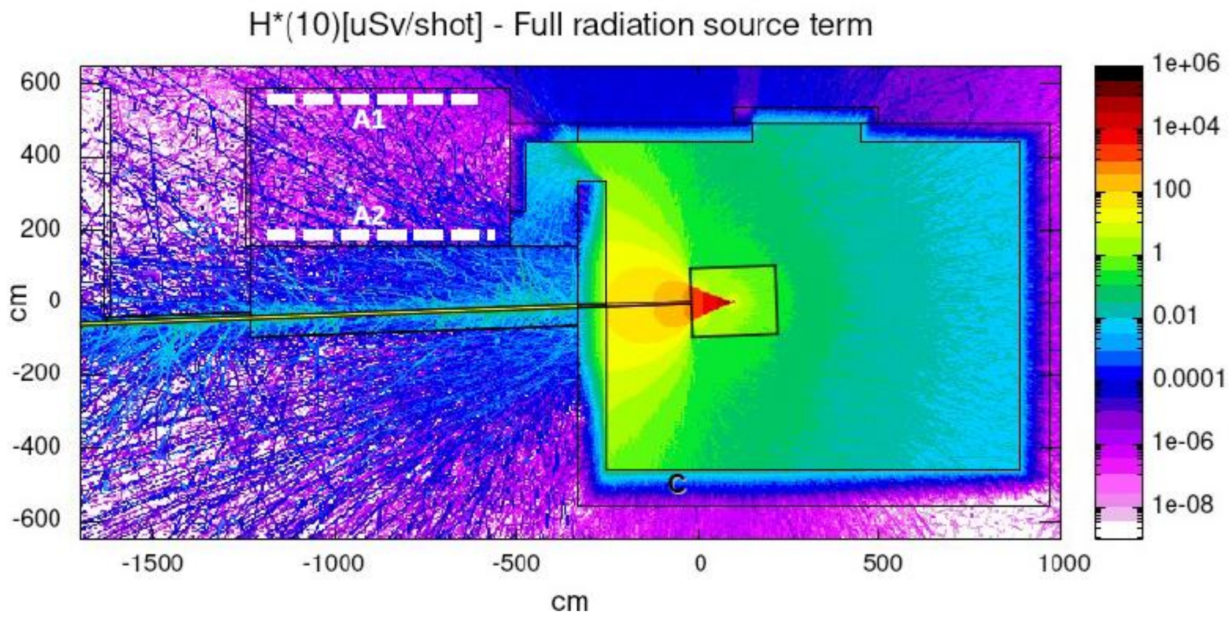
Additional dose monitoring

- Measurements inside the Experiment Hutch
- Background monitoring outside shielding.
- **PANDORA system** provides an **independent safety layer**, tracking cumulative dose to ensure compliance.

Review mechanism

- After ~1 year, all authorizations and results will be reviewed.
- Summary report to evaluate effectiveness and identify improvements.

Counter-Propagation Experiment: Probing the Quantum Vacuum



Counter-Propagation Experiment: Probing the Quantum Vacuum

- What's being done?

  We are combining the **ReLaX high-intensity laser** with the **XFEL beam** in a **counter-propagating geometry** — meaning the laser and X-rays collide head-on at the interaction point.

- Goal of the experiment:

  To search for **quantum vacuum birefringence** — a predicted phenomenon in which empty space behaves like a transparent crystal under extreme fields, slightly altering the polarization of X-rays.

- Why it matters:
  - This is a rare opportunity to test predictions of quantum electrodynamics (QED) in extreme conditions.
  - Success would be a first-ever laboratory detection of this exotic quantum effect.
  - It helps improve our understanding of the quantum vacuum — relevant to astrophysics, particle physics, and fundamental theory.

Counter-Propagation Experiment: Probing the Quantum Vacuum

- This unique experimental setup introduces new beam geometries and radiation paths, which must be assessed for safety — especially since the laser beam enters the XFEL vacuum system.

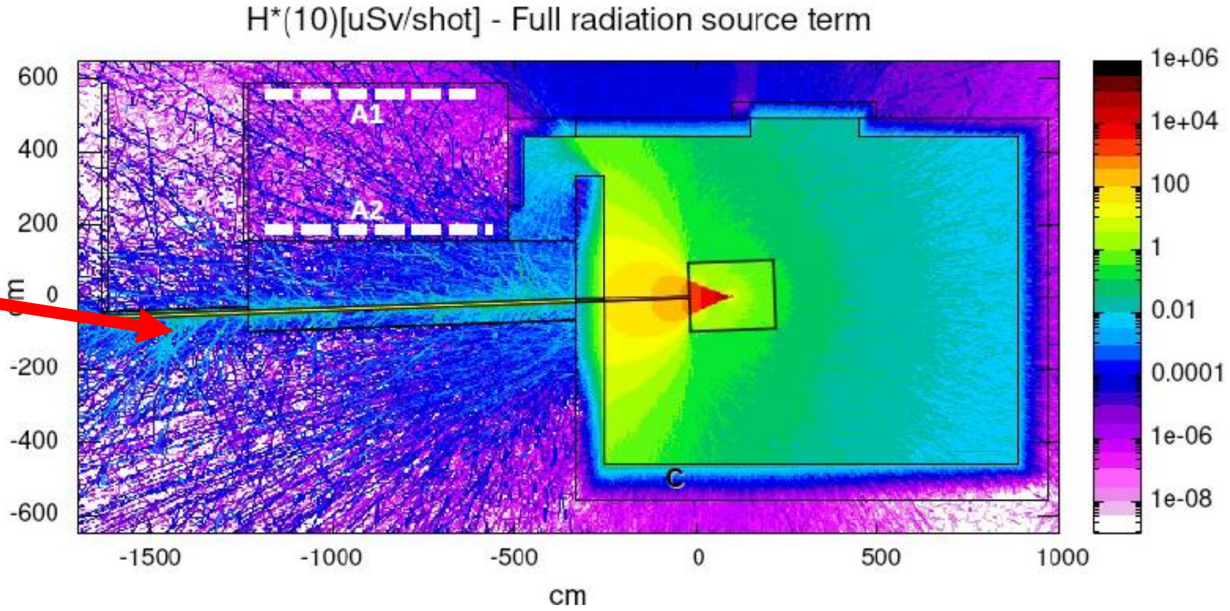
- **No physical target** is placed at the interaction point — we're studying how the laser interacts with **vacuum only**.

- Why this matters:

  - With **no target**, **no electrons** are generated → **no bremsstrahlung**, no radiation source.
  - The **laser beam rapidly diverges** after the focus → intensity drops sharply → no further interactions downstream.

Counter-Propagation Experiment: Probing the Quantum Vacuum

- What if something goes wrong?
  - In a **worst-case scenario** (a sample accidentally left in the beam), the laser would **destroy it immediately**.
  - Even then, simulations show **doses remain well below the 2 µSv / 4 h target**, especially since only **individual pulses** could contribute.



Summary and Outlook

- ReLaX introduces a new regime of high-intensity laser–matter interaction to European XFEL — and with it, new radiation protection challenges
- Through shielding, interlocks, simulation, and monitoring, we've demonstrated safe operation even as parameters and experiments evolve.
- Our move toward dose-based controls provides flexibility while ensuring compliance.
- And our experience so far — including real-world measurements and safe commissioning — confirms that our models are reliable.
- As we prepare for increasingly ambitious experiments — including quantum vacuum birefringence — we remain committed to maintaining world-class safety standards alongside world-class science.

Thank you and Questions?