Proposal for experiment at European XFEL – Experiment description
User
User community assisted commissioning of the UHI Laser at HED, impact of relativistic plasma environment on x-ray diagnostics

1) Scientific background of this proposal

The UHI laser system at the HED station at EuXFEL, a high-intensity laser system delivering up to 300 TW contributed by the HIBEF User consortium is currently the most impulsive laser driver at a XFEL worldwide. Recently this HED driver has been successfully commissioned at 100 TW level as standalone device and the synchronization scheme was demonstrated in a dedicated beamtime "PAM 2552" at lower laser power. This community assisted commissioning proposal is dedicated to study for the first time the effect of a heavy noise environment (EMP, bremsstrahlung background, salt and pepper noise by direct hot electron hits) as generated by a highly relativistic laser-plasma interaction on XFEL x-ray diagnostics. In particularly the community will contribute to this run targets, that will cover various scientific fields mirroring general interest of the community. Each target considered, is expected to generate different backgrounds levels and will introduce different levels of complexity to signal/noise ratio mitigation scenarios. It is paramount to study and identify possible issues before full scientific proposals are considered. Previous knowledge will allow us to further develop if needed the shielding of detectors, or the detection schemes themselves, therefore maximizing the scientific output at later times. First attempts to discriminate scattering signals in Small Angle Scattering detection scheme have been successfully implemented, by introducing an analyzing crystal in the direct line of sight for the laser interaction point in the beamtime "SAX mirror tests 2554". Complementary, phase contrast imaging, diffraction and absorption spectroscopy are also foreseen as analyzing methods, and the feasibility will be tested. From past experience in various laser facilities we know that the above-mentioned issues are not only dependent from the target used, but will also be highly dependent in the specific experimental environment at the facility (e.g. target frame, galvanic insulation concept, vacuum chamber itself), thus have to be investigated at HED.

2) Motivation for this proposal: expected results and their impact in relevant scientific area(s)

This section provides a panoramic view over the general scientific interests of the community and touch the underlaying science.

i. **Measuring the laser hole boring or ablation velocity, duration, and strength as well as the plasma expansion into vacuum before, during and after laser irradiation (*thin wires, mini stripes*):** Relativistic intensity lasers generate plasma pressures at a solid density target front surface exceeding giga-bar pressures. This can push the surface forward with high velocity, an acceleration mechanism being actively studied for the development of compact laser-plasma ion sources [1-3] and for laboratory astrophysics [4]. So far, hole boring on the few fs level was only possible to be measured by optical techniques, which are however limited to a density of few times the critical density [5] while theories predict a hole boring density of tens to hundred times the critical density [6]. Of particular interest is the transition to ablation during and after the optical pump laser irradiation. It is expected from theory and simulation that the steep and hot density plasma at the front will release energy by plasma ablation into the vacuum, decreasing the front surface sharpness. This has been measure using SAXS before, but only with a time resolution exceeding 100 fs [7].

ii. **Relativistic surface instability and its transition to streaming and resistive instabilities (*wires/mini stripes & flat foils*):** Structure formation at the surfaces of laser irradiated solids is a very important and widespread feature. It is of particular interest due to its connection with the relativistic electron motion and harmonic production, ion mobility and ionization, and therefore plasma resistivity and heating. While the changes of the surface optical properties are important e.g. for plasma mirrors at sub-relativistic laser intensities, at relativistic intensities self-generated structure can directly influence the ionization and laser energy absorption into relativistic electrons, Subsequently, instability-induced quasi-static magnetic and electric fields can influence the electron transport properties and hence all subsequent dynamics such as e.g. isochoric heating and ion acceleration. The growth rates of the involved instabilities are typically exceeding a tenth of an inverse fs during the optical high-intensity laser pump, and spatial scales range from the plasma wavelength (few 10s of nm) in the case of the parametric 2-photon plasma wave decay [1] up to the laser wavelength for the relativistic two-stream instability [2].

iii. **Isochoric heating in buried layers targets (*sandwich targets, buried layer gratings, copper gratings*):** Achieving the extreme conditions of solid density plasmas at ~ keV thermal temperature is of particular interest in astrophysics, nuclear physics and inertial confinement fusion. Here we propose to realize the plasma conditions by ultrafast isochoric heating of buried layer solid targets with high intensity laser generated hot electrons. The particle-in-cell simulations show that the expansion/compression waves are launched at layer interfaces due to Gigabar electron pressure gradients caused by return current heating. The ionic hydro-motion pushed by the expansion/compression waves is rapidly converted into thermal motion mainly due to the efficient ion-ion collisional coupling, leading to near keV ion temperatures at about solid density [1]. Meanwhile, strong filaments are triggered in the front surface and inside of the buried layer target due to the different instability mechanisms, which reflects the transport dynamics of hot electron [2].

iv. **Proton energy enhancement with *mass-limited targets* irradiated by high intensity short pulse laser:** Proton acceleration in laser-plasma interactions is considered to be a solution to develop table-top accelerators for medical applications. One of the main challenges of this approach is to achieve clinical relevant energies where the proton beam could be used for tumor therapy. Mass-limited targets have shown an enhancement in maximum proton energy compared to planar foils [1]. The effect is attributed to the limitation of the electron lateral circulation due to the geometry of the target resulting in a larger accelerating field for the ions, as previously shown by Particle-in-a-Cell simulations [2]. The combination of the high-power laser and XFEL beam at the HED station will enable the study of such effects with the help of X-Ray scattering techniques. We intend to use PCI and SAXS to study the plasma distribution for different target geometries and laser intensities. Correlating these measurements with particle diagnostics (electron, proton and bremsstrahlung spectrometers) will provide an insight into the enhancement of proton energies and potentially lead to the optimization of these targets for future applications.

v. **Exploring structural dynamics of keV ion distributions in laser-irradiated foams for nuclear reactions at near solid-density (*tamped foams*)**: We propose using Small Angle X-ray Scattering (SAXS) and Phase Contrast Imaging (PCI) to investigate the temporal expansion of the nano-filaments that make up a near solid density foam (CH or CD) that is heated by an ultra-intense laser pulse. Laser-irradiation of tamped foams create small volumes, ~ 10 x 100 x 100 µm3, of dense (near solid), hot (~20 keV) plasma [Kemp et al., Nature Comm 2019] suitable for astrophysically-relevant nuclear reaction (S-factor) rates. This system allows for the study of nuclear cross sections that would be inaccessible in accelerator studies as the reactant density is ten orders of magnitude higher.

vi. **Opacity experiments at Astro, ICF & HED conditions to validated atomic kinetic and radiative transport models (buried layer low and mid-Z in CH):** We propose to measure the opacity of materials at HED and ICF relevant conditions by creating a highly ionized plasma with the short pulse beam and probing the ground state of a given ion with the XFEL. The experimental setup for this measurement involves relatively low risk by using flat crystal spectrometers and scanning XFEL energies over a narrow band from the standard configuration. The target is a buried layer with an co-mixed sample, 50 nm thick and 50 µm diameter, embedded in a thick plastic tamper. Relativistic electrons from the short pulse isochorically heat the material to 100s of eV via return current heating and the plastic acts as an inertial tamper to keep the target near solid density.

vii. **X-ray imaging of relativistically transparent filaments (Cu dopped µg/cc CH foams)**: A remarkable feature of laser pulses with relativistic intensities is that they can change fundamental optical properties of the material they irradiate by heating the bulk of the electrons to relativistic energies. The focus of this part of the proposal is on the so-called relativistically induced transparency that enables laser propagation through high density plasmas and, as a result, opens to exploration novel regimes of light-matter interactions. Even though the relativistic transparency is widely considered to be an integral part of laser-plasma interactions at extreme intensities, it has never been directly observed. The main difficulty is that the plasma becomes transparent inside an optically opaque material. We propose to use x-ray imaging to directly observe for the first time laser pulse propagation enabled by the relativistic transparency. This experiment will pave the way for developing experimental techniques needed for experimental studies of light-matter interactions at extreme intensities.

viii. **Isochorically heated warm dense matter (thin foils, Al, CH, diamond):** The combination of a high intensity laser and an XFEL source enables unprecedented opportunities for the study of condensed matter isochorically heated to warm dense matter states. Hot electrons generated by the intense laser-matter interaction deeply penetrate solid materials and heat the ion the lattice via various energy exchange mechanisms. Corresponding relaxation rates have been debated for several decades and precise measurements are required to benchmark state-of-the art models. At XFEL, spectrally resolved X-ray scattering in combination with X-ray diffraction will allow for highly precise measurements accessing electron temperature and density of free electrons as well as simultaneously monitoring the evolution of ion correlations.

ix. **Phase contrast imaging of laser generated shocks (ablator layer on CH foams):** We propose using the UHI laser to heat a thin aluminium ablator coupled to a solid plastic or plastic foam disc, creating a >10's Mbar high-pressure differential which results in a shock being transmitted into the cylinder. PCI would be used to diagnose the predicted rapid decay of the shock (shock velocity and density), expansion of the Al ablator (particle velocity), and expansion of the plastic due to preheat. As part of a longer-term objective, these measurements will help inform whether it is feasible to carry out absolute EoS measurements on this type of platform, by combining data from multiple shots with varying delay.

x. **Ultrafast dynamics of plasma optics (Si-foils, Si etched ns structured targets, wire forest):** Plasma optics have huge potential for future high power systems as they enable operation at laser fluences far beyond conventional optics. The effectiveness of these optics is strongly dependent on plasma scale length, yet the underpinning plasma hydrodynamics are poorly understood on fine spatial (sub-micron) and temporal time scales (< few ps). The HED end station on EU-XFEL provides cutting-edge techniques to clearly probe ultrafast dynamics beyond that possible with optical sources or 1-3rd generation x-ray sources. We intend to use SAXS and PCI techniques to resolve plasma dynamics beyond the optically opaque regime on ultrashort timescales.

This data will lead the way towards optimising the performance of plasma optics on high-power laser facilities enabling access to novel fundamental physics at ultra-high intensities.

xi. **Conductivity impact on return current filamentation in relativistic laser-matter interaction (graphite, diamond like carbon, Al foils):** Conductivity in the warm-dense matter regime has a strong impact on return current filamentation in relativistic laser-matter interaction. Quantum-molecular dynamic calculations have shown that a crystalline lattice can significantly increase the conductivity. In experiments a strong influence of the target crystallinity on the spatial uniformity of laser-accelerated proton beams has been found, suggesting that the crystalline order is maintained throughout the acceleration process.

References: 1. **DOI:10.1103/PhysRevLett.69.1383** *Absorption of ultra-intense laser pulses;* 2. **DOI: doi:10.1088/1367-2630/10/1/013021** *Radiation pressure acceleration of thin foils with circularly polarized laser pulse*; 3. **DOI:10.1103/PhysRevLett.103.245003** *Radiation-Pressure Acceleration of Ion Beams Driven by Circularly Polarized Laser Pulses;* 4. **DOI:10.1103/PhysRevLett.108.235004** *Weibel-Instability-Mediated Collisionless Shocks in the Laboratory with Ultraintense Lasers;* 5. **DOI:10.1103/PhysRevLett.84.2405** *Laser-Hole Boring into Overdense Plasmas Measured with Soft X-Ray Laser Probing*; 7. **DOI: 10.1103/PhysRevX.8.031068** *Observation of Ultrafast Solid-Density Plasma Dynamics Using Femtosecond X-Ray Pulses from a Free-Electron Laser;*

3) Experimental plan

The targets provided by the community will be mounted together with synchronization samples (YAG) and alignment fiducials in the EuCall frame and deployed in the Fast Sample Scanner provided at Interaction Chamber 1 of the HED station. For each target frame a single vacuum pumping cycle is envisioned, allowing the execution of up to 100 shots (provisional to target fragility and spacing). We have identified two different possible target orientations with target surface normal axis perpendicular or parallel to the x-ray propagation direction. We will use the nano-focusing setup provided by HiBEF UC (CRLs) to HED as final focusing optic, capable of fast switching between short (10 cm) or long (30 cm) focal length geometries, as required by the individual magnification factors. FOV from 10x10μm^2 to 100x100μm^2 will be used. We will employ a SAX analyzer setup utilizing two HOPG bent crystals (bound to a XFEL energy of 8.15 keV), and shield the direct line of sight between UHI/XFEL interaction point and SAX detector (which one?Jungfrau/TIMEPIX/Pixis?). The primary x-ray beam passing between the SAX analyzer gap will propagate to the detector bench, and be used for PCI (detected by what?). In general, since the SAXS method is limited to spatial correlations up to only a few tens of nm, PCI will complement it, as capable of probing larger scales. Also PCI will help localize the origin of the small scale correlations probed by SAX to specific spatial extents of the probed volume. For each target setup the synchronization between UHI and XFEL will be directly checked in IC1, and will be referenced for any temporal delay scans. We will deploy additional diagnostics such as x-ray spectrometers or cameras, charged particle probes, bremsstrahlung-spectrometer as ride-alongs complementing the main XFEL diagnostics. As significant amount of XFEL pulse energy is required for the online monitoring of the delay UHI-XFEL, a pulse energy in extent of 1 mJ is requested. The UHI laser will be used up to 100 TW power levels, with corresponding pulse duration of 30 fs and up to 3 J energy on target.

a) Justificaton for the use of an X-ray free-electron laser facility and motivation for the selected instrument

Currently the HED instrument at EuropeanXFEL is worldwide uniquely offering a high intensity laser at 100TW power level for user experiments in combination with a XFEL beam.

b) Justification for the number of shifts requested

Due to the plethora of target setups to be tested 10 shifts are requested. 1 shift is needed for setup and optimization of the Photon Arrival Monitor, up to 1 shift will be dedicated each for target setups provided be the 11 science cases. We request scheduling accounting for a 1-week break, allowing to change setup between perpendicular and parallel x-ray probing geometry.