5-6 April 2017 Workshop: High Intensity Laser Matter Science at the HED Instrument at the European XFEL

INTRODUCTION

The European X-Ray Free-Electron Laser Facility (European XFEL) will provide photons at unprecedentedly high brightness and previously unreached energies up to 25 keV. At the HED instrument station the X-rays will offer unique insights into high energy density states of matter. The HiBEF User Consortium contributes and will operate two high power optical lasers at the HED station. When irradiated onto matter, these lasers will generate transient extreme states of density and temperatures. The HED instrument is currently in the final stage of its technical implementation. X-ray operation will become available to users in summer 2018, while the optical lasers will be commissioned in parallel to first user operation and made available for integrated experiments with the XFEL in a staged process.

The HiBEF user consortium is providing High Intensity (HI) and High Energy (HE) lasers, dynamic diamond anvil cell and pulsed magnetic fields. The goal of this workshop is to cover early user experiments and future plans by exploiting the unique experimental possibilities offered by the combination of the HI laser, a multi 100 TW class laser, the Pump-Probe laser system (PP), a ~0.1 TW class laser, also the HE laser, a 100 J and 10 ns class laser. Technical details of the available HED station experimental infrastructure will be partially covered, too. Scientific applications include studying properties of highly-excited solids, ionization dynamics at high intensities, relativistic laser plasma interaction, high energy density states of matter, energetic particle propagation in matter, investigation of microscopic dynamics details of laser-driven radiations and acceleration of particles (mostly in solid density systems), XFEL probing techniques for high-intensity laser matter Interactions (e.g., X-Ray Thomson Scattering, Small Angle X-ray Scattering, Coherent X-ray Diffraction Imaging, X-ray Faraday Rotation, X-Ray Diffraction, X-ray Absorption Spectroscopies,...) and probing QED effects.

The workshop will take place at the European XFEL campus in Schenefeld, Schleswig-Holstein, Germany on 5–6th April. It is addressing potential users that intend to submit a project to the HED instrument in one of the first calls for proposals. The meeting aims also at enabling lively discussions between the user community and paving the path for future collaborations.

We encourage contributions on the basis of instrument properties as described by the technical paragraphs below. The deadline for submissions is 28 Feb 2017. Due to limited availability the organizing committee reserves the right to preselect contributions.

THE HED INSTRUMENT AND X-RAY PROPERTIES

The HED instrument operates one of the six experimental stations at the European XFEL. HED receives hard X-rays in a tunable range from 3 to 25 keV photon energy. The system is designed for delivering a high number of individual X-ray pulses in macro pulses at a repetition rate of 10 Hz. Each macro pulse is 600 µs in duration, contains up to 2700 X-ray pulses as short as 2 fs. Arbitrary pulse selection, including a 'single-shot' mode is also available. The X-ray properties at the HED instrument are summarized in Table 1. The main experimental vacuum chamber is designed to provide extensive experimental capabilities and diagnostics options. It is located in a radiation shielded area extending 11 m along the X-ray propagation direction and 9 m wide. The chamber design is based on the concept of high versatility and flexibility allowing multiple setups combining optical lasers and the XFEL beam. It is due to be delivered to HED in the spring 2017. The chamber has a horizontal inner footprint of 2.4 x 1.5 m^2, with the optical lasers beam transport arranged in this plane. The horizontal polarization of the XFEL beam leads to the detectors to employ X-ray scattering in the vertical plane accommodated by a vertical breadboard. In addition, an integrated fast sample scanner, capable of replacing samples at the interaction point at a repetition rate of 10 Hz is currently developed. The area downstream the chamber is foreseen for detection of forward and small-angle X-ray scattering and offers room for a second interaction area with several dedicated setups and specific experiments, as indicated in Figure 1.

TABLE 1: X-RAY PROPERTIES AT THE HED INSTRUMENT OF THE EUROPEAN XFEL

Property	Value	Comment
Photon energy	3–25 keV	Fully tunable. 3–5 keV with limited performance.
Pulse duration	2–100 fs	Via changing the electron bunch duration. Peak brilliance is almost constant for any pulse duration (fewer photons for shorter pulse duration).
Number of photons per pulse	~ 10^{12} (5 keV) ~ 10^{11} (25 keV)	
Energy bandwidth ΔE/E	10^{-3}: SASE 10^{-4}: Si_{111} mono 10^{-5}: seeded 10^{-6}: Si_{533} at ~ 7.5 keV	Seeded beam available soon after initial commissioning. 10^{-6} resolution available only at limited photon energy around 7.5 keV.
Repetition rate	4.5 MHz intraburst	600 µs duration electron bunch trains at 10 Hz, with each train containing up to 2700 bunches. Shot on demand possible.
Split and delay (double pulse)	Yes	Variable delay up to ~ 23 ps (5 keV), ~ 4 ps (15 keV), ~ 2 ps (20 keV) in collinear geometry.

TABLE 2: SUMMARIZES BASELINE X-RAY DETECTORS TO BE IMPLEMENTED:

PARAMETERS	ePix100 (SLAC)	ePix10k (SLAC)	Jungfrau (PSI)	Gotthard-I (PSI)
Sensor	300 µm Si	300 µm Si	320 µm Si	320 µm Si
Sensor size (pixel)	704x768 (35x38 mm^2)	352x384 (35x38 mm^2)	512x1024 (40x80 mm^2)	1x1280 (8x64 mm^2)
Pixel size (µm)	50	100	75	50
Dynamic range	10^2 (@ 8 keV)	10^4 (@ 8 keV)	10^4 (@ 12 keV)	10^4 (@ 12 keV)
Noise (eV)	~180	~360	~450	~900
Repetition (Hz)	120	120	2000, 1MHz in burst mode, 16 images on-chip memory	2000,1MHz in burst mode,150 images on-chip memory
# of modules	2	3	4	2

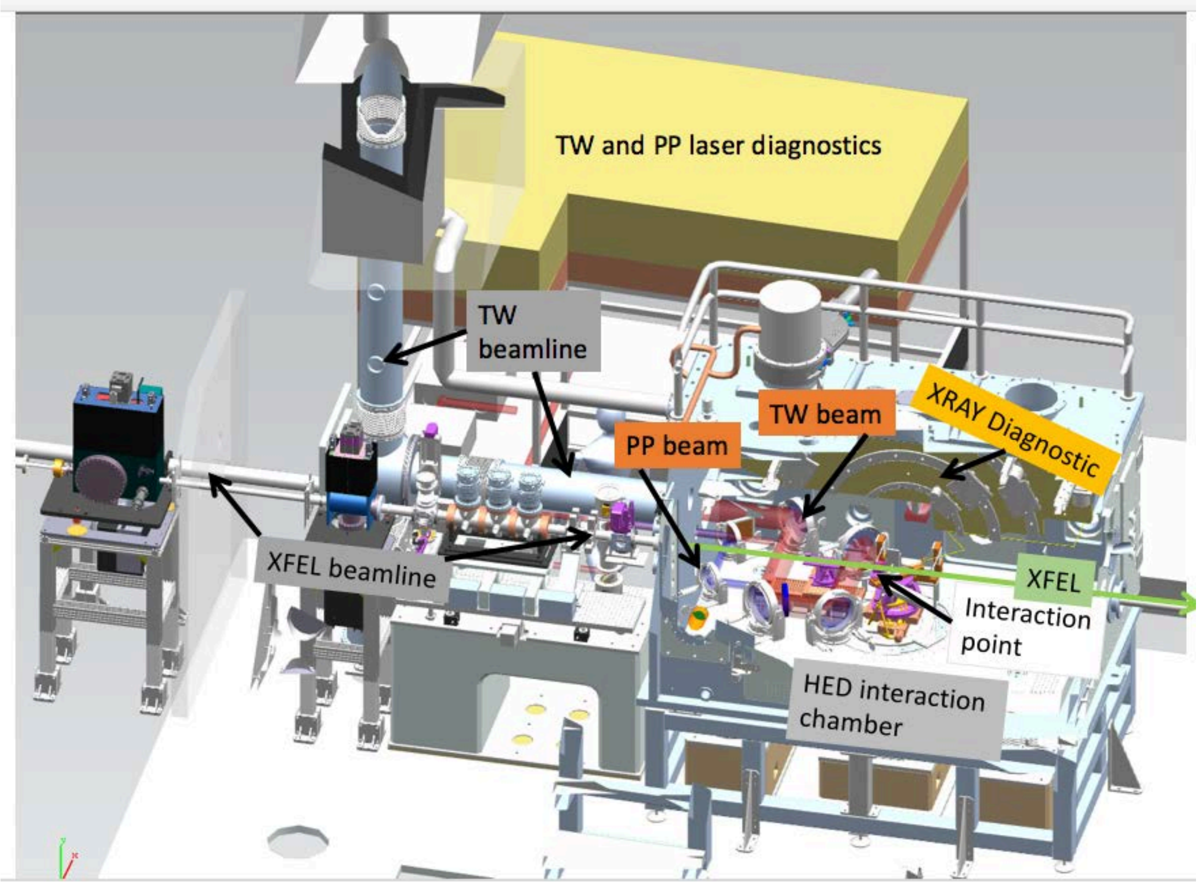


Figure 1: Detailed view inside the HED hutch. The X-ray beam comes from the left side (through the X-ray optics hutch) into the main interaction vacuum chamber together with the HI (denoted as TW in the figure) and PP lasers. A second interaction point downstream of the HED chamber is foreseen for additional experiments.

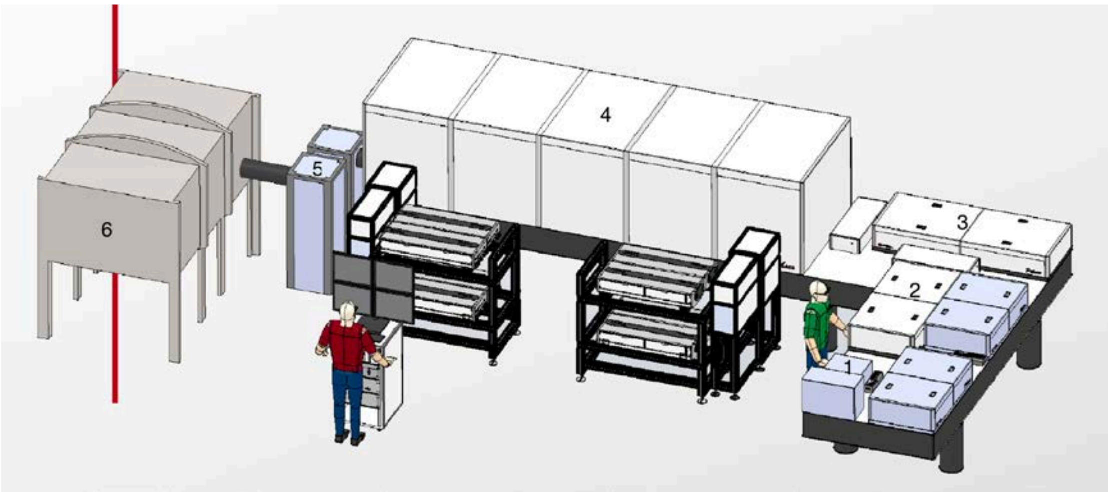
THE HIGH INTENSITY LASER SYSTEM

The HIBEF User Consortium provides for integration at the HED instrument at the European XFEL and will operate by an in-kind contribution of HZDR/HFG a 100 TW/10 Hz class short pulse laser. The laser system is manufactured by AMPLITUDE TECHNOLOGIES in France. This laser system is designed to be operated with large industrial margins allowing a high reliability as required by the user facility operation mode envisioned at European XFEL. In particular, a unique solution was adopted supporting redundancy and multiplicity strategy of pumps in particular for the main amplifiers, stress of high power optical components, flexibility in different modes of user operation, and the high level of surveillance and automatic control in standard operation.

THE HI LASER CAPABILITIES

The High Intensity laser (HI), a Ti:Sa based double CPA laser system will be installed in the HED optical laser hutch. The laser hutch will be shared with the High Energy (HE) DIPOLE 100X system provided by the UK HIBEF consortium. Both lasers are envisioned to be operated simultaneously and will provide a unique experimental platform for the generation of high energy density states of matter. The capabilities of the HE laser have been covered in the 2016 Workshop: Dynamic Laser Compression Experiments at the HED instrument of European XFEL, the basic properties of this laser system are summarized by the next section.

The basic architecture of the HI laser is presented below:



1.) oscillator supporting DESY synchronization with XFEL pulse at jitter < 15 fs.
2.) double CPA front-end up to 25 mJ, 10 Hz (Booster XL, PW stretcher, regenerative amplifier, pre-amplifier with pumps)
3.) first high energy amplifier > 0.9 J @ 800 nm, 10 Hz
4.) TWIN main amplifier 5 - 10 Hz with various energy level and repetition capabilities, pumped by 8x TITAN 6 pump lasers
5.) beam line between TWIN amplifier
6.) 400 TW compatible compressor.

A double CPA architecture was chosen to ensure high-quality temporal laser contrast as required by the irradiation of solid density matter. Additionally, we discriminate between maximal capabilities of the laser system and nominal energy operation levels. The achievable maximal laser pulse energy is set by design to be significantly higher in order to operate within high safety margins in a heavy duty nominal operation mode. The maximal stability of the laser is to be reached at nominal operation values. The stability window at maximal values is 1h that will allow the execution of single-shot/shot on demand style experiments. The laser system can also provide optical synchronized lower energy pulses that can be utilize as probe beams, as to be determined by user requirements. The main laser parameters are summarized in the Table 3.

The design also includes 10% energy backscattering protection of the laser chain, shot on demand capabilities, burst and continuous operation modes at best parameters, attenuation from full laser energy preserving the temporal and spatial properties for user friendly alignment and diagnostics. Also a novelty will be the use of vibration free cryostats for the main amplifier. At the low temperature provided by cryogenic cooling thermal conductivity is enhanced and thermal lensing is reduced in Ti:Sa compared to ambient temperature water cooling techniques. The design of the compressor and beam transport line will allow for easy switching between S and P-polarization irradiation on the target and will also accommodate a full beam aperture adaptive deformable mirror for the optimization of the final laser focus.

TABLE 3 PROPERTIES OF THE HI LASER:

repetition rate	5Hz / 10Hz
duration	> 25 fs
pulse energy (J) (on target)	7.5 J at 5 Hz (nominal) – 250 TW@30fs 10.0 J at 5 Hz (maximum) – 333 TW @30fs 3.0 J at 10 Hz (nominal) – 100 TW@30fs 4.0 J at 10 Hz (maximum) – 133 TW @30fs
energy stability	1.5% rms @5 Hz (1 min)
energy drift	< 5% over 12 hrs (1min averaging)
wavefront quality	Strehl ratio > 0.85 behind the last amplifier (with deformable mirror)
beam profile	round top hat profile/peak fluence < 1.5 times the average fluence of the plateau; beam diameter 145mm $1/e^2$
beam pointing	stability < 3 µrad rms, output drift < 3 µrad
ns temporal contrast	absence of prepulse from the pulse up to -10 ns
ps temporal contrast	$<10^{-11}$ @>100 ps, $<10^{-7}$ @>10 ps, $<10^{-5}$ @ >5 ps, $<10^{-3}$ @ >1 ps

THE HIGH ENERGY LASER SYSTEM

Using funding obtained through EPSRC and STFC grants, the UK's Science and Technology Facilities Council (STFC) and Oxford University are providing the DiPOLE-100X laser system for use in the HED instrument at the European XFEL as part of the HIBEF UK user consortium. The system is similar to the DiPOLE100 system that the CLF has recently delivered to the HiLASE Facility in the Czech Republic. This being the first 100 J diode-pumped solid-state laser (DPSSL) system in the world. A full description can be found in S. Banerjee, et al, Optics Express 23, (2015). It's success is based on cryogenically cooled Yb:YAG amplifier architecture with a central wavelength of 1030 nm. The use of the HE laser includes the generation of high density states of matter and XRAY backlighted sources. A parallel use of both the HI and the HE laser is foreseen and integrated experiments within the scope of the facility.

TABLE 4 PROPERTIES OF THE HE LASER:

repetition rate	1Hz- 10Hz
duration	2-15 ns
pulse energy (J) (on target)	100 J@ 10 ns
temporal shaping	spacing controlled in 125ps intervals
energy drift	< 5% shot to shot
wavefront quality	< λ/2 P-V and <λ/4 RMS
beam profile	square super Gaussian beam 75mmx75mm

PUMP-PROBE LASER

Additionally, to the HiBEF optical lasers, the pump-probe laser (PP), developed at the European XFEL by the optical laser group, offers unique experimental capabilities tailored to the XFEL beam. The PP laser operates as non-collinear optical parametric amplifier (NOPA). The laser is adapted to the XFEL time structure, i.e. deliver synchronized pulses of comparable pulse width within 10 Hz bursts of 600 µs length and an intra-burst repetition rate up to 4.5 MHz. A maximum pulse energy of about 2 mJ will be available at reduced intra-burst repetition rate of 100 kHz. Fourier-limited pulse duration of 15 – 300 fs will be provided by tuning the spectral bandwidth. The NOPA pump laser pulse, with a fundamental wavelength of 1030 nm and ps duration, can also be provided to the experiment providing higher pulse energies up to ~40 mJ. One possible application of the PP laser is femtosecond optical probing of HI-laser induced plasmas.

TABLE 5: SPECIFICATIONS FOR PUMP-PROBE LASERS THAT WILL BE INTEGRATED AT THE HED INSTRUMENT AT THE EUROPEAN XFEL

Laser name	wavelength (nm)	Repetition rate	Pulse duration (FWHM)	Max.pulse energy	Laser type
Pump–probe *mode 1*	800	100 kHz @ > 2 mJ 4.5 MHz @ 0.05 mJ	15 – 300 fs nearly transform limited	> 2 mJ	Non-collinear optical parametric amplification (NOPA)
Pump–probe *mode 2*	1030	100 kHz @ >40 mJ 4.5 MHz @ 1 mJ	~ 0.9ps	> 40 mJ	Amplifier for NOPA

ONLINE TIMING JITTER MEASUREMENT BETWEEN X-RAYS AND OPTICAL LASERS

The operation and synchronization of 3 short pulse laser systems (XFEL, HI and PP) requires high demands on environmental stability and an extensive online diagnostics pool. Monitoring the different arrival times of the optical laser and X-ray pulses with few-fs resolution is one of the most crucial instrument aspects that will allow proper temporal analysis of the acquired single-shot data. The online, X-ray – optical laser relative timing jitter measurement will be provided on a shot-to-shot basis. A photon arrival monitor (PAM) will be permanently installed ~ 10 m upstream from the sample. The PAM at this location before the X-ray attenuator and the last X-ray focusing optics allows measurements quasi-decoupled from the experimental environment. The timing jitter information can be used for time sorting and binning after data acquisition.