Integrating high-repetition rate high-energy/high-intensity laser to FEL experiments

Motoaki Nakatsutsumi

on behalf of
HED instrument at the European XFEL and
HIBEF user consortium to the HED instrument

NWP-2: Lasers with High Peak and High Average Power
26th July 2017

The current HED/HIBEF group at European XFEL

Group Leader HED Scientists Laser Group


Ulf Zastrau


Motoaki Nakatsutsumi


Karen Appel


Sebastian Göde


Zuzana Konôpková


Mikako Makita


Thomas Preston (7/'17)

N.N.

N.N.


Gerd Priebe

Engineers Technicians/Mech's


Ian Thorpe


Andreas Schmidt


Konstantin Sukharnikov


Thomas Feldmann


Eike Martens

Externally funded PostDocs / Ph.D.s / Guest Scientists


Emma McBride


Wolfgang Morgenroth


Nicole Biedermann


Markus Schölmerich

Volkswagen Foundation BMBF DFG DFG

Coordinator HIBEF UC staff at European XFEL


Carsten Bähtz


Alexander Pelka

N.N.

N.N.


Toma Toncian (HIBEF lasers)


Monika Toncian


Hauke Höppner (5/17)

HIBEF at HZDR:
Klaus Knöfel
Wolfgang Seidel
Jörn Dreyer, …

European XFEL

HED High-Energy Density science

HIBEF USER CONSORTIUM

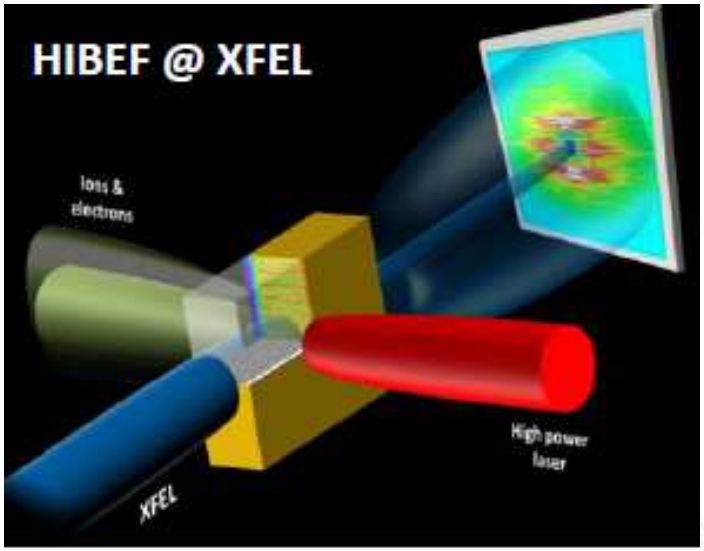
HIBEF: Helmholtz International Beamline for Extreme Fields

Management Board: *T.E. Cowan (HZDR, spokesperson)*
Justin Wark (Oxford), Edger Weckert (DESY), Ronald Redmer (Rostock)
Coordinator*: Carsten Baehtz (HZDR),*
HIBEF-Asia: Hideaki Takabe (HZDR), HIBEF-US: Robert Cauble (LLNL)

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 power/energy lasers
- initially >100 TW/10 Hz & 100 J/10 Hz
- Future upgrades

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



UK:	10.3 M€
HGF-FIS:	20.5 M€
Others:	12 M€

European XFEL

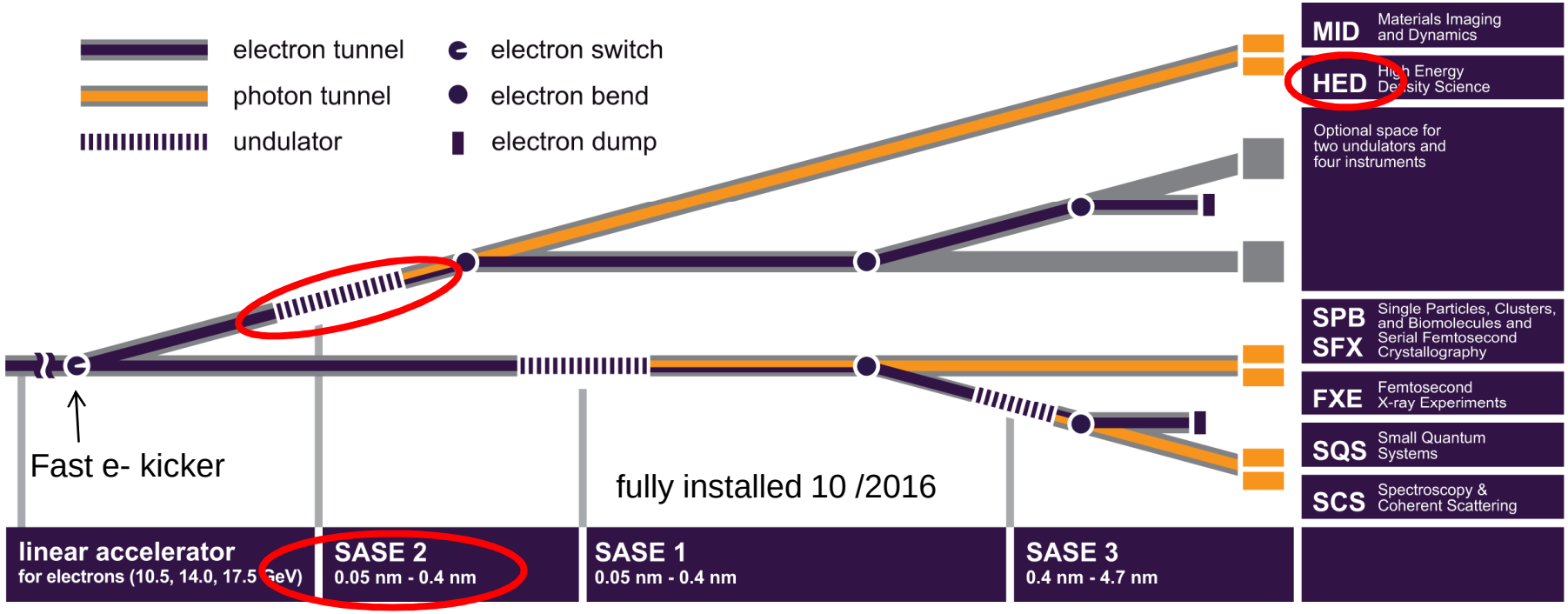
High-Energy Density science

HELMHOLTZ ASSOCIATION

Outline

- Brief overview of the European XFEL
- X-ray properties and optical lasers at the HED instrument
- X-ray techniques and science applications

European XFEL: beamlines and instruments



- Cool down of accelerator modules to 2 K — Dec. 2016
- 6 keV lasing in SASE1 with up to 0.9 mJ — May 2017

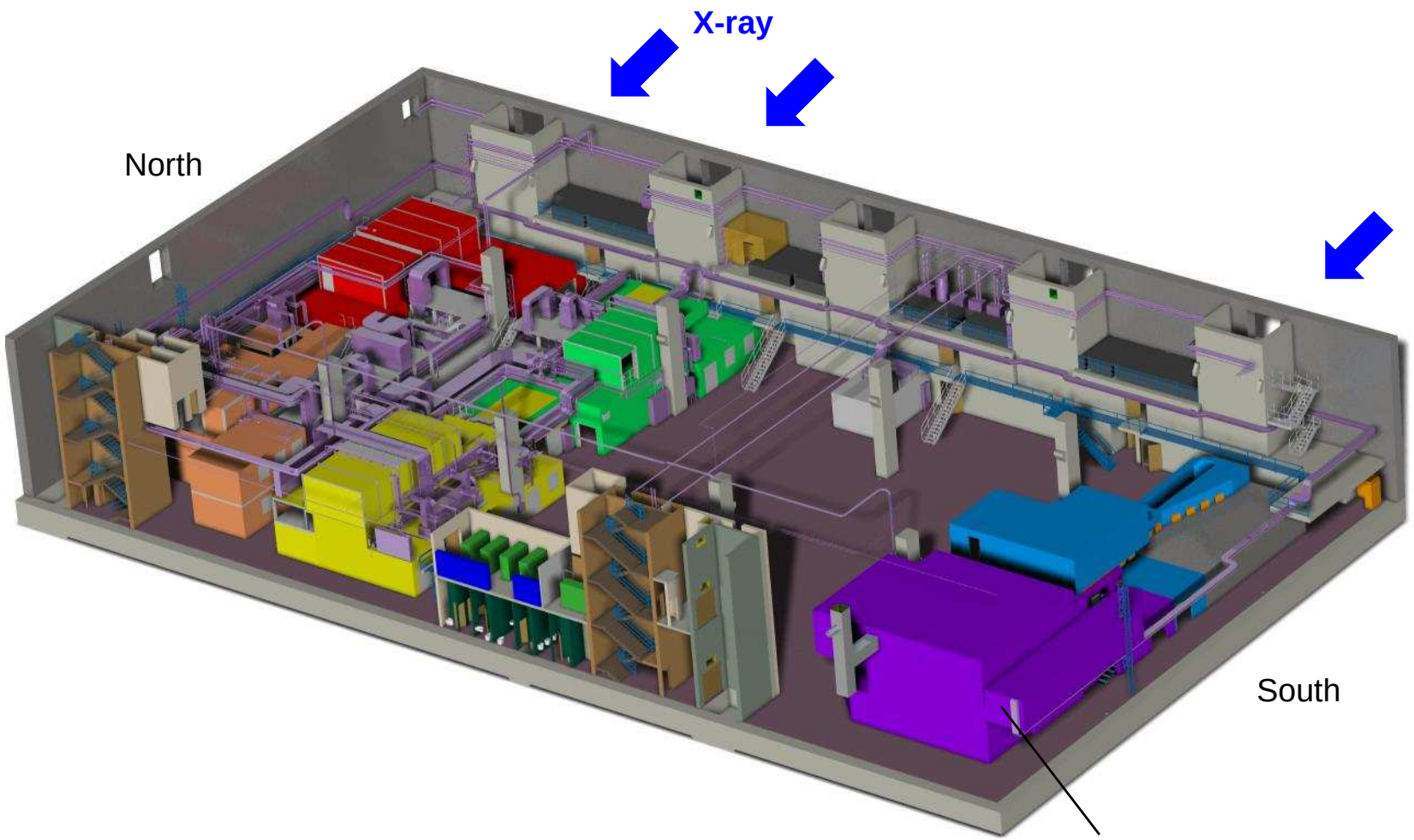
Achieved

- Commissioning SASE1 FXE/SPB — July 2017
- First experiments at SASE1 — Sept. 2017

About European XFEL

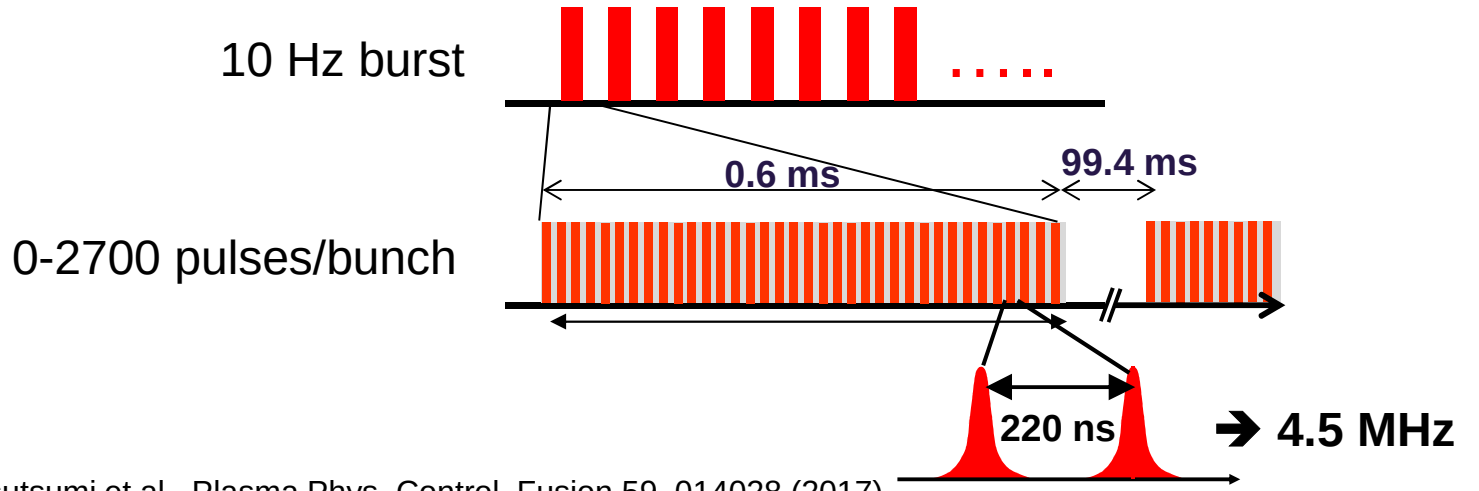
- Organized as a non-profit corporation in 2009 with the mission of design, construction, operation, and development of the free-electron laser
- Supported by 11 partner countries
- Germany (federal government, city-state of Hamburg, and state of Schleswig-Holstein) covers 58% of the costs; Russia contributes 27%; each of the other international shareholders 1–3%
- Total budget for construction (including commissioning)
  - 1.22 billion € at 2005 prices (div by 6: 200 M€ per scientific instrument)
  - 600 M€ contributed in cash, over 550 M€ as in-kind contributions (mainly manufacture of parts for the facility)

Experiment hall: SASE2 (HED, MID)



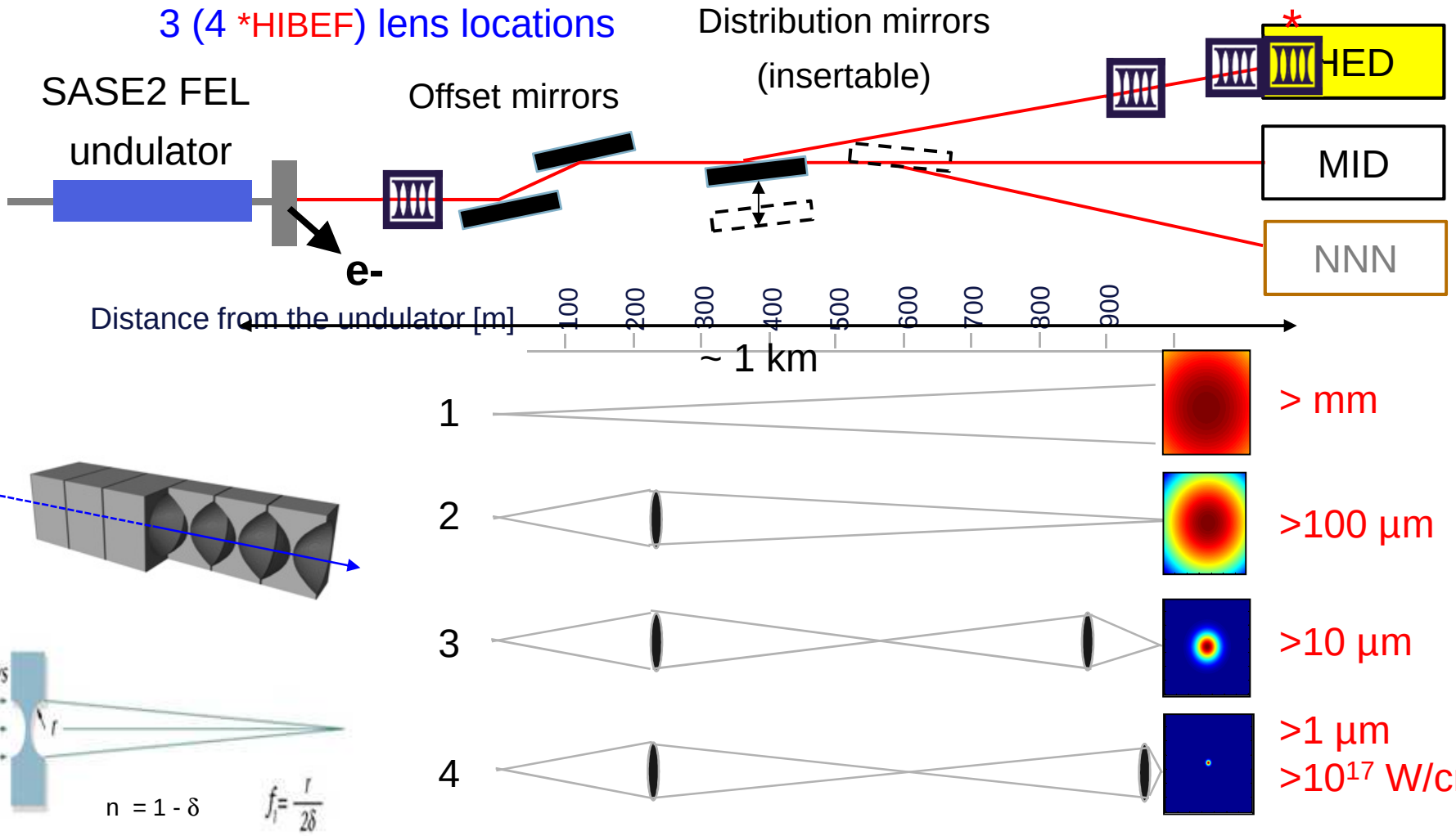
XFEL properties at the HED instrument (SASE2)

Fully tunable between	3 – 25 keV (3 – 5 keV with limited performance)
Pulse duration	2 – 100 fs
Number of photons per pulse	~10^{10} (25 keV), ~10^{12} (5 keV)
Spot size on sample	sub-μm (HIBEF), few μm, 20 – 30 μm, 200 – 300 μm, few mm
Spectral bandwidth ($\Delta E/E$)	10^{-3} (nominal), 10^{-4} (Si 111 mono), 10^{-5} (high res. mono) Seeded beam (no shot-to-shot spectral fluctuation) at 10^{-4} bw
Repetition rate	shot on demand (pulse picker), 10 Hz – 27000 pulses/sec



M. Nakatsutsumi et al., Plasma Phys. Control. Fusion 59, 014028 (2017)

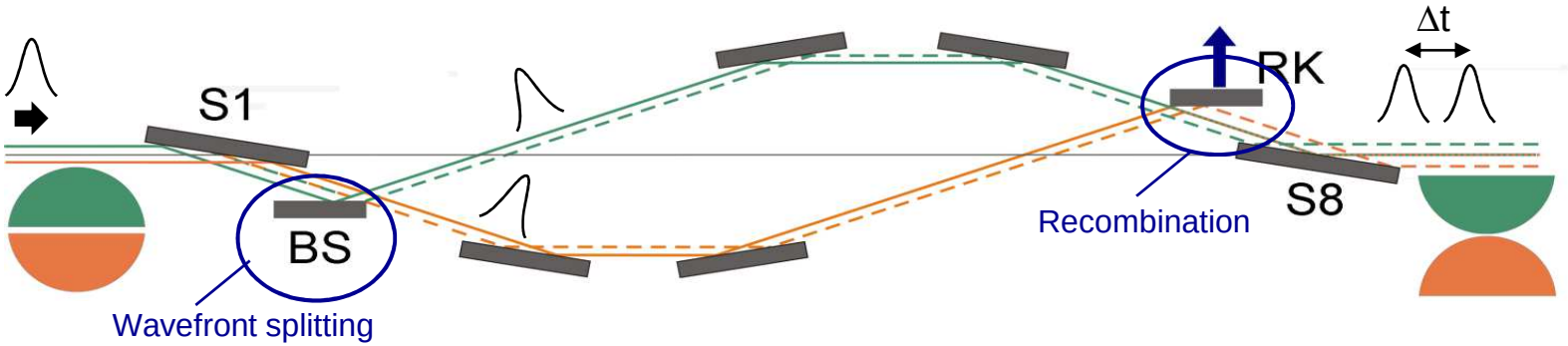
Beryllium lens for x-ray focusing



X-ray beam split & delay:

Multi-layer mirrors --- Variable delay up to ~23 ps (5 keV), ~4 ps (15 keV), ~2 ps (20 keV)

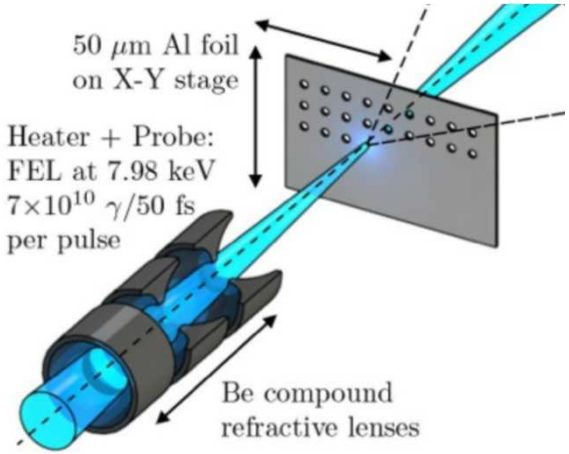
➔ With 2 subsequent fs x-ray pulses launched into sample



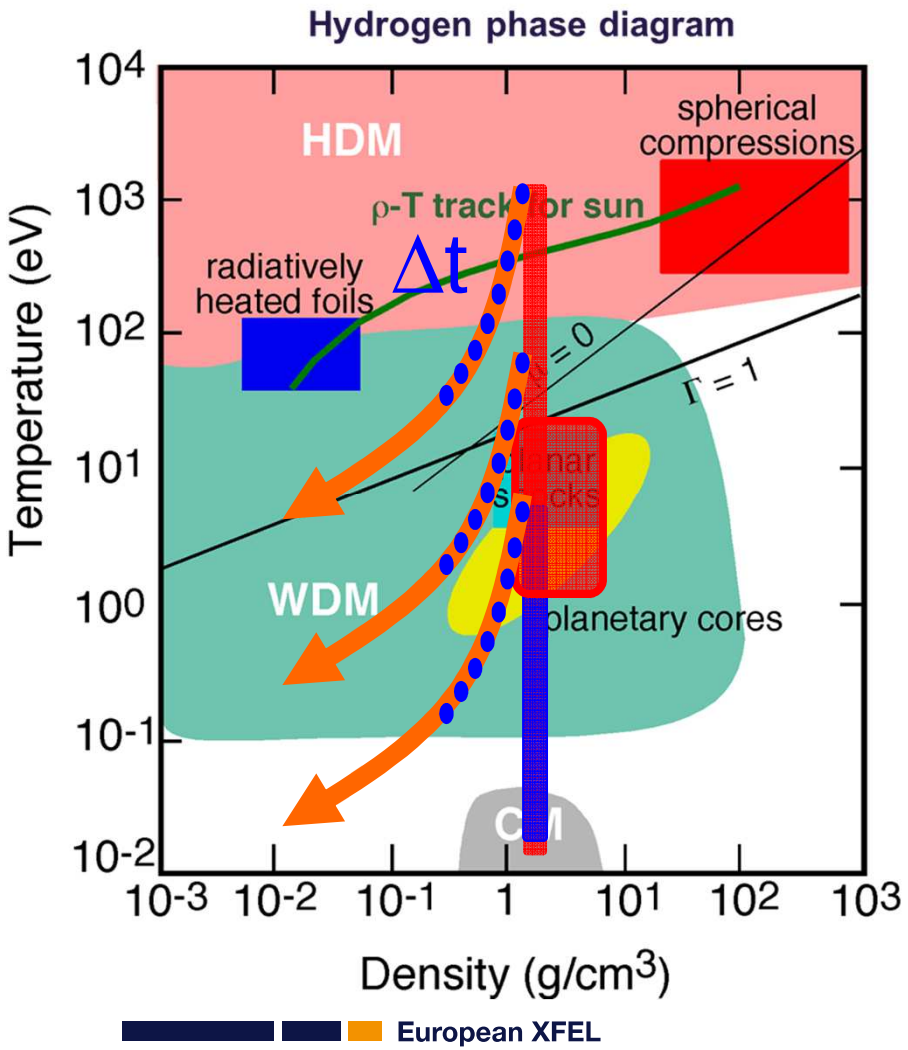
S. Roling, H. Zacharias, et al.,
SPIE conf 8504, 850407 (2012)
BMBF project 05K10PM2
University of Münster

Measure ultrafast dynamic response

- electron-electron, electron-ion equilibration



3 optical lasers at the HED instrument



In-house R & D by OL group

- Pump-Probe (PP) >10^{17} W/cm^2
  - 0.2–2 mJ, 0.1–4.5 MHz, ~15 fs
  - 1–40 mJ, 0.1–4.5 MHz, ~1 ps
- ≥100 TW high-intensity (HI)
  - >10^{20} W/cm^2
  - > 3 J, 30 fs, 10 Hz on sample
- High energy (HE)
  - 100J, 2–15ns, 1-10Hz
  - ~3 x compression, ~10Mbar

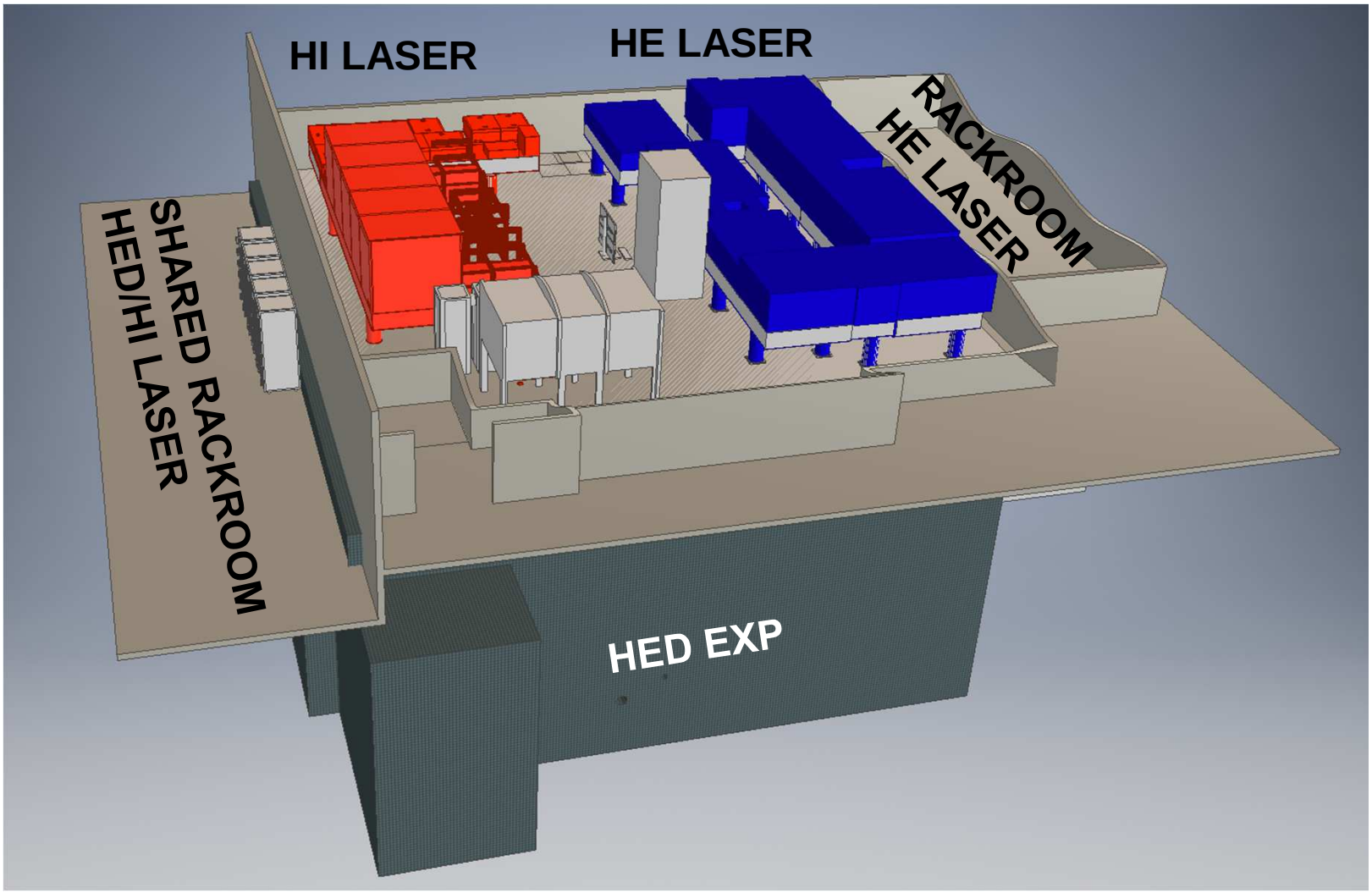
HiBEF USER CONSORTIUM

European XFEL

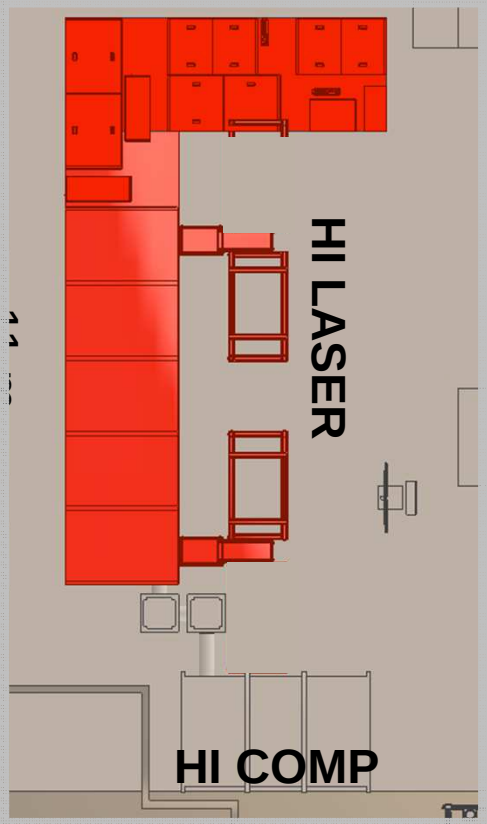
HED High-Energy Density science

HiBEF USER CONSORTIUM

HI/HE laser locactions – on the roof of 1m thick concrete enclosure!



300 TW laser system - key properties -

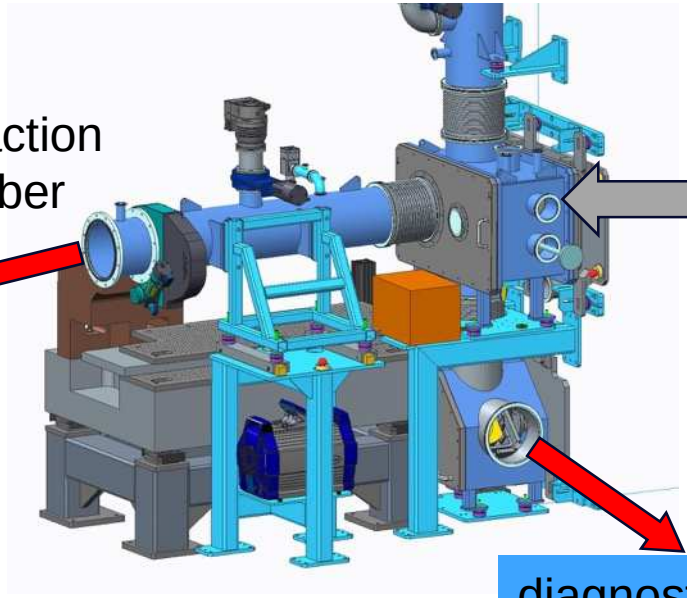


Amplitude TECHNOLOGIES

- >100TW @ 10 Hz
- >300 TW @ 5 Hz
- shot on demand
- double CPA Ti:Sa
- high redundancy
- Valuable attenuation (up to OD~2)
- Fixed attenuation (OD = 2.5 / 5)

- Commissioning in 2018

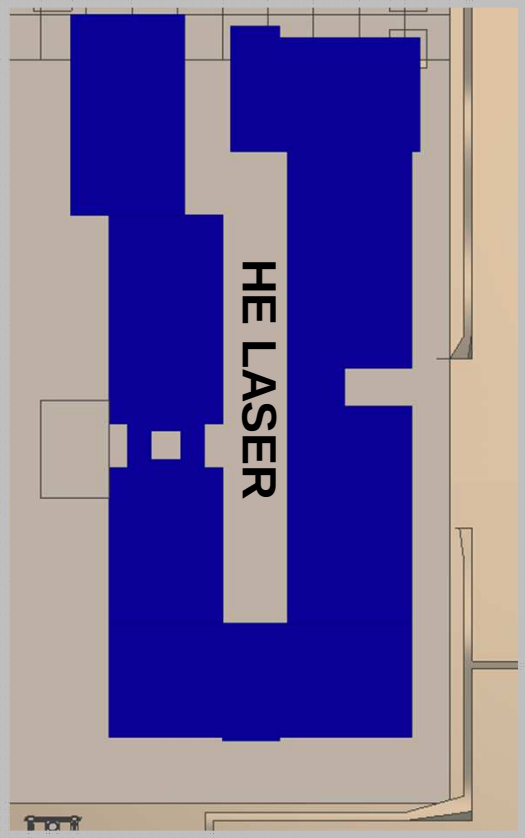
Beam transport status- diagnostics port-



- On shot
  - 2nd order AC
  - wavefront
  - NF/FF
- On demand
  - scanning midfield
  - 3rd order AC
  - spectral phase

The High-E Laser System - key properties -

DiPOLE100

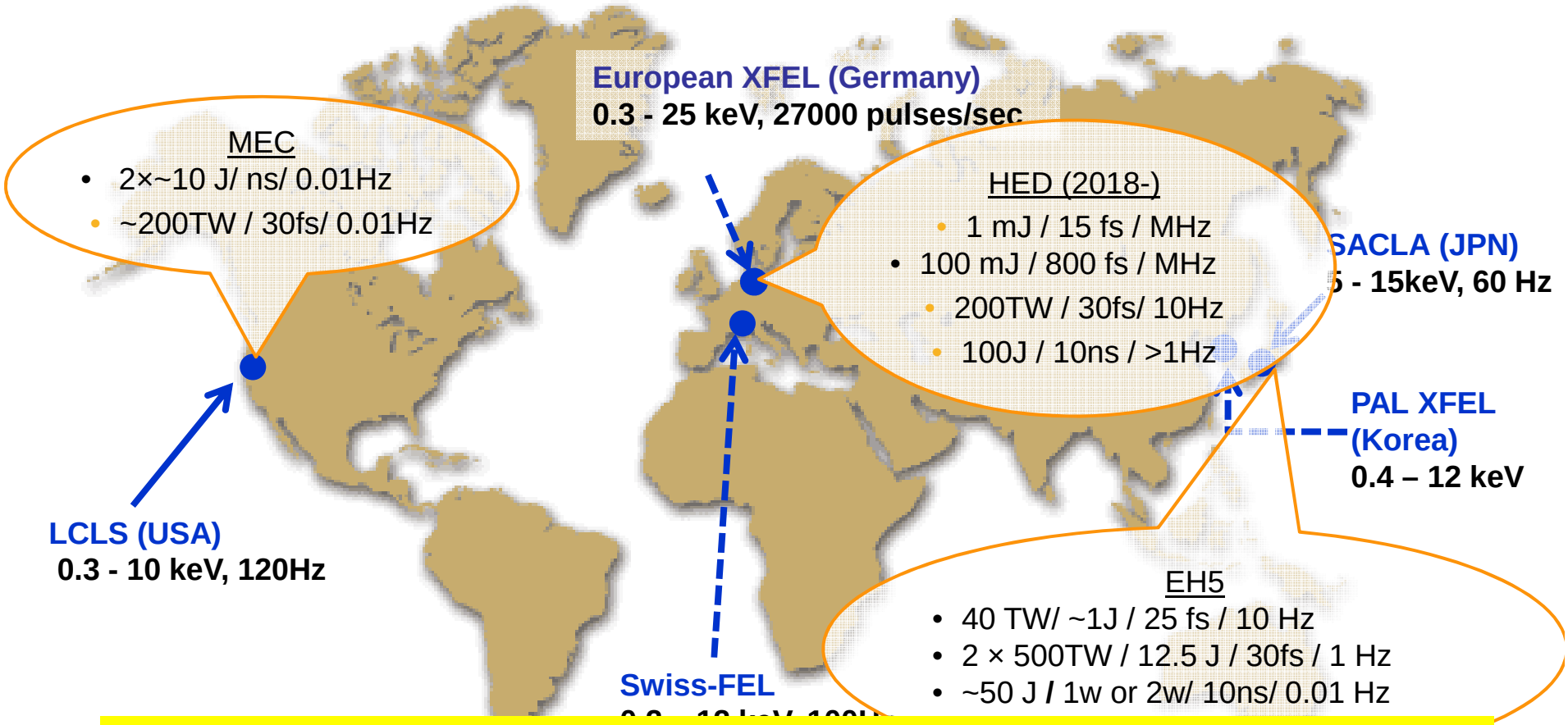


- UK contribution in kind
- EPSRC – Oxford University
- STFC – Central Laser Facility

- Diode-pumped
- >100 J @ 10 Hz
- 2-15 ns pulse
- Temporal pulse shaping
- 2ω conversion
- delivery mid 2018
  - Designed, built and commissioned at CLF, UK

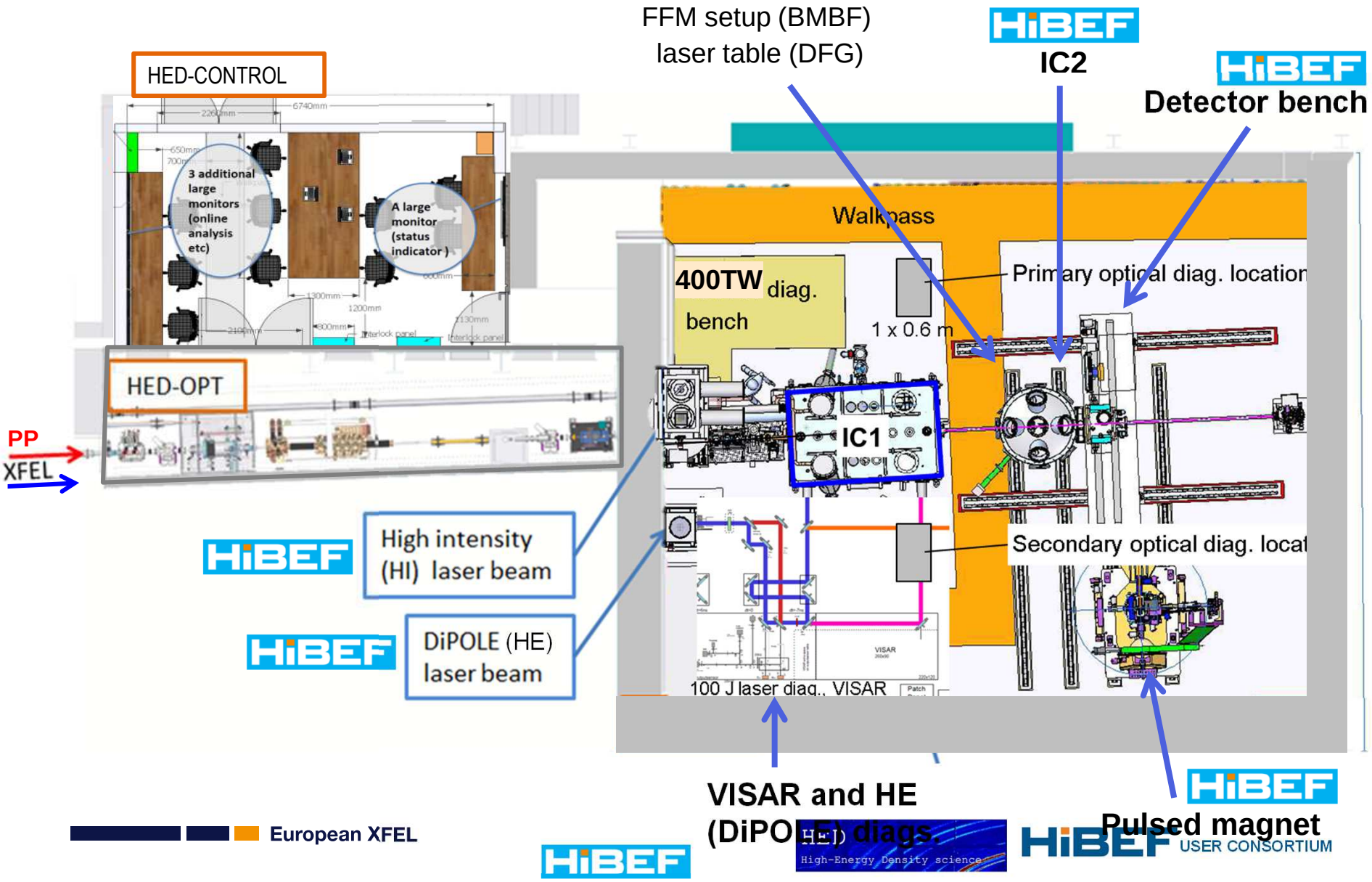
Commissioned at **hilase** in 2016

Hard X-ray FELs worldwide with big OLs



High photon energy, high repetition, much more # of beamtimes for users will be provided thanks to in-parallel operations for 3 beamlines

HED control room, optics hutch, and enclosure



IC1 in the factory at TOYAMA, Japan.

- 2.4 x 1.5 m^2 (inner)
- Installed in May 2017

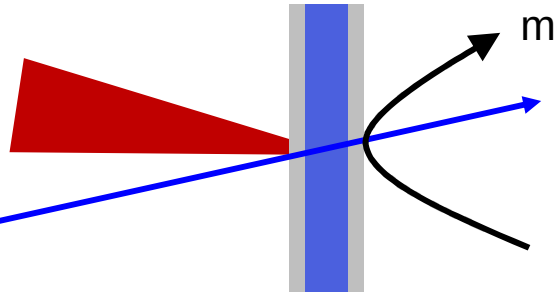
X-ray techniques and science applications

Isochoric heating of solid via XFEL or laser-induced ballistic electrons. Study equilibration process, EOS, opacity.

Femtosecond excitation produce hot electrons with cold lattice ($T_e \neq T_i$).
Reaching $T_e = T_i$ before significant hydrodynamic expansion is a challenge.

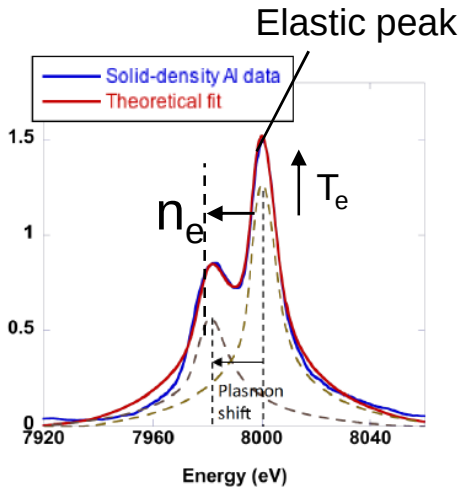
fs pump
- XFEL
- fs optical laser

fs XFEL probe



Optical probe (Reflectivity, surface motion)

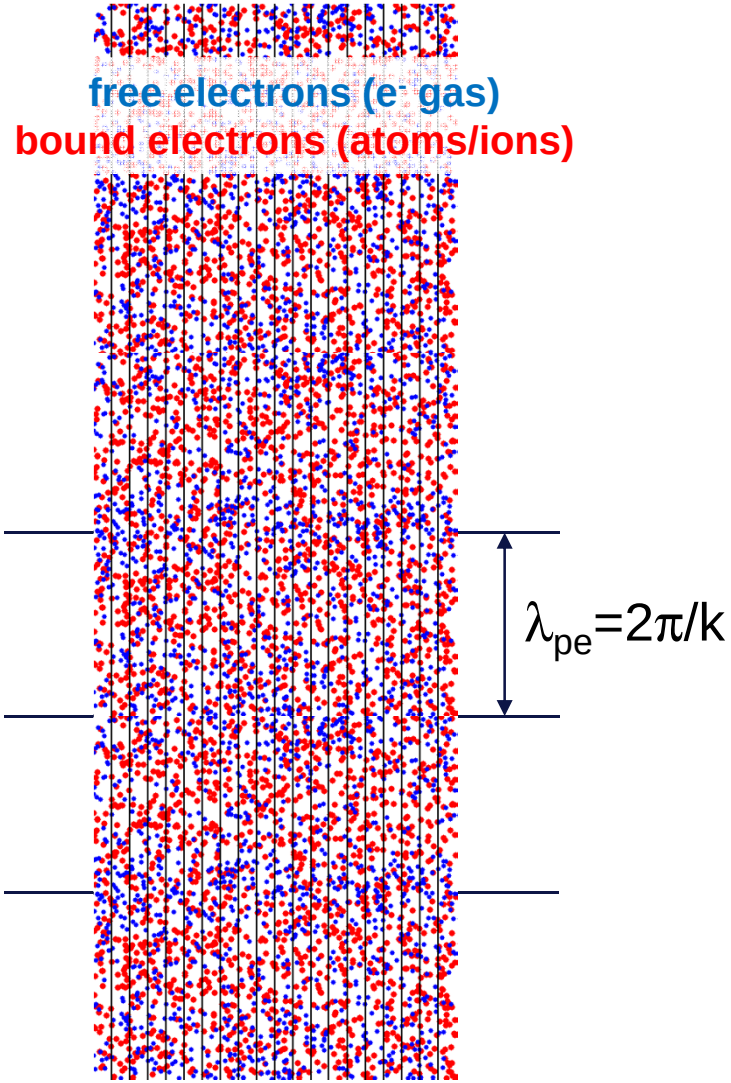
- X-ray techniques
  - (inelastic) scattering spectroscopy[*1] –n_e, T_e, Z and possibly T_i
    - ▶Photon hungry !
  - Absorption spectroscopy[*2] – short-range order structure
  - X-ray emission, transmission[*4], … – T_e, Z, …

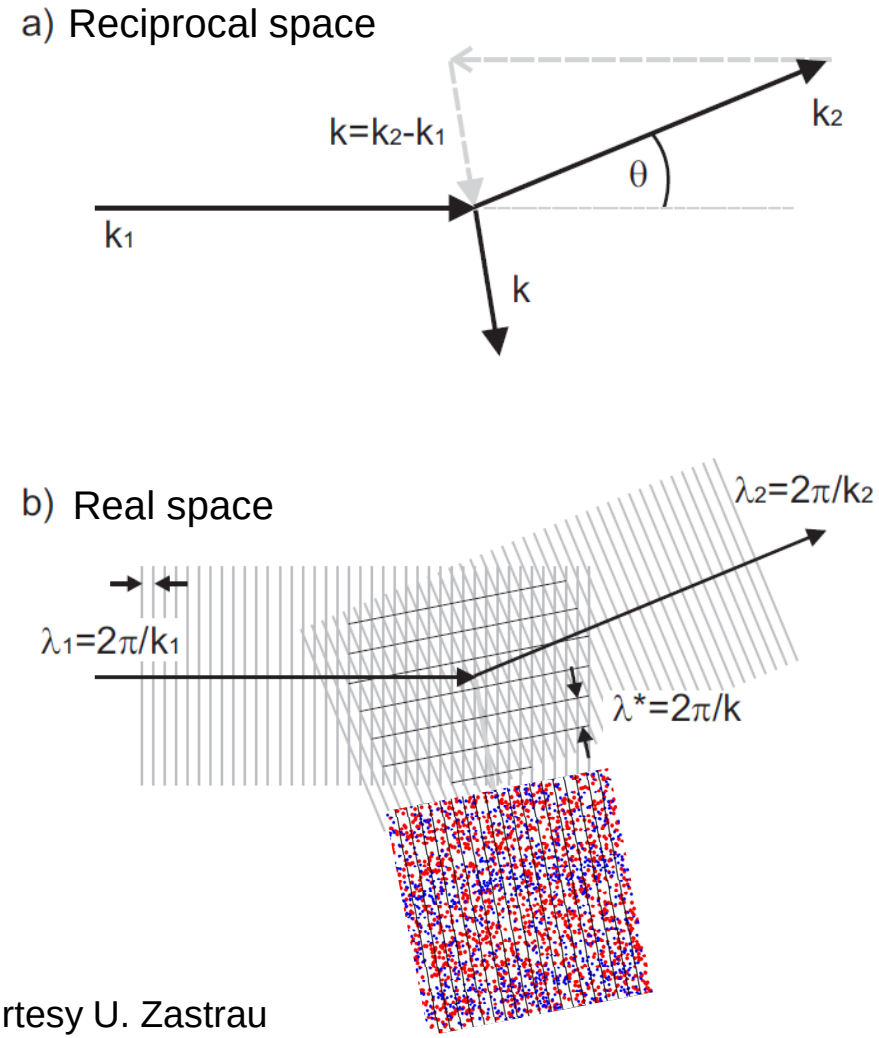


L.B. Fletcher et al. JINST (2013)

[*1] S. Glenzer, U. Zastrau, G. Monaco, G. Gregori, Ph. Sperling, L. Fletcher…. [*2] F. Dorchies et al., PRB (2015), [[*4] S. Vinko et al, nature (2012), U. Zastrau et al PRE (2008).
…

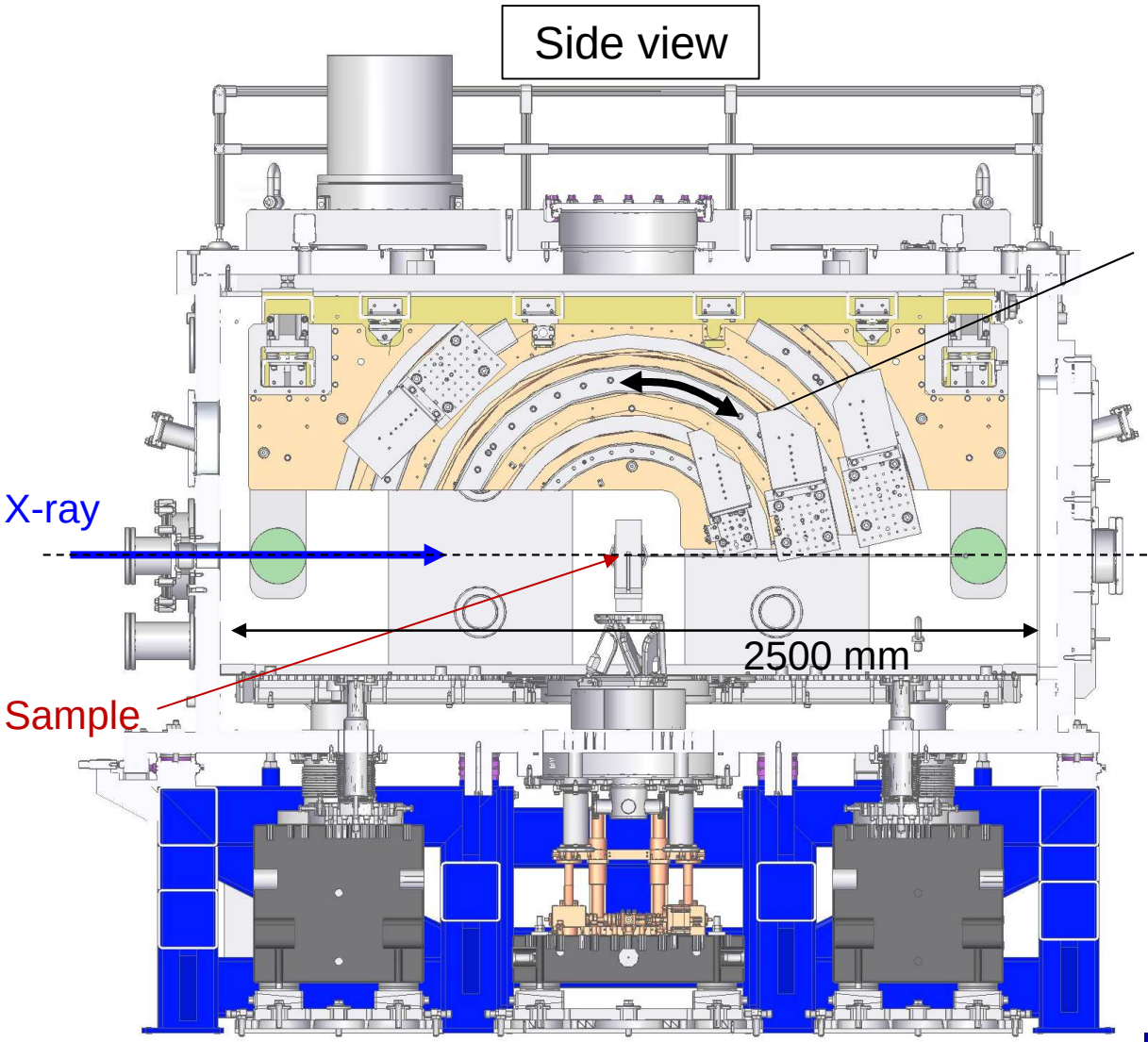
probing electronic plasmon oscillations





Courtesy U. Zastrau

IC1 – side view inside



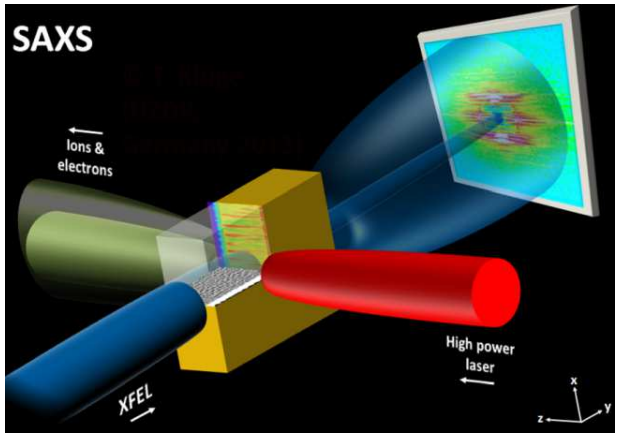
Circular rails on the 'Vertical' breadboard

- Spectrometers, analyzer crystals, area detectors
- Scan ***k***

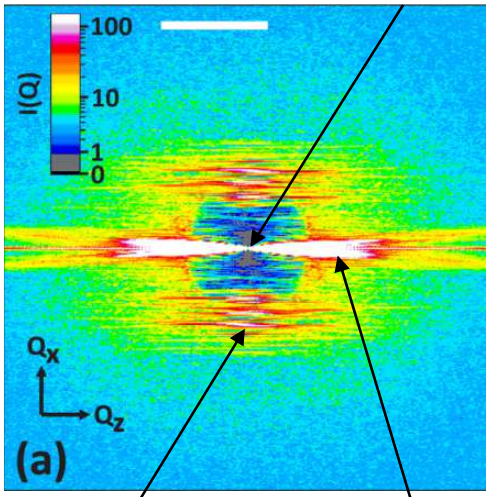
(XFEL: hor. polarized)

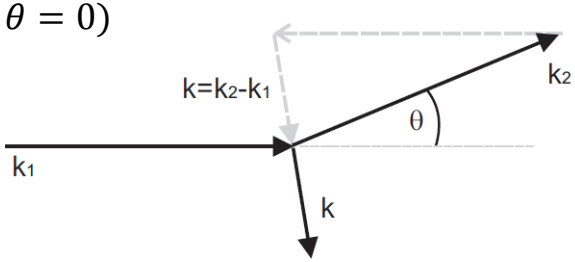
Small angle x-ray scattering to visualize ~10 nm periodic modulation

Weibel instability, surface ripples, hole boring under relativistic laser-solid interaction



X-ray axis ($Q = \theta = 0$)





$$Q = 2k_1 sin\left(\frac{\theta}{2}\right) = \frac{4\pi}{\lambda_{XFEL}} \sin\left(\frac{\theta}{2}\right) \; [nm^{-1}]$$

8 keV, θ ~ 2 mrad →
Q ~ 0.1 nm^{-1} ➔ d = 10 nm ~ c/ω_{pe}

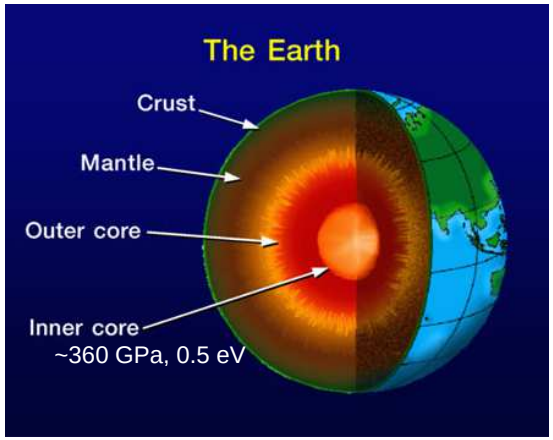
Surface ripples
Filamentation

Hole boring

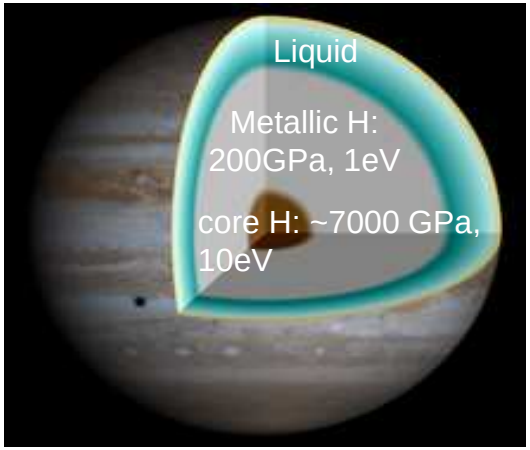
T. Kluge et al., Phys Plasmas **21** 033110 (2014)
T. Kluge et al., Phys Plasmas **23** 033103 (2016)

Planetary science

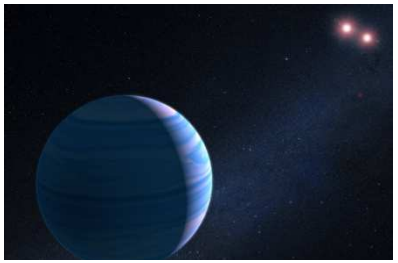
- Create matters exist in the core of solar planets and exoplanets at laboratory. Goal is to exploit thermodynamic properties; equation of state, melting temperature, thermal conductivity, structural phase transition under high pressure etc…



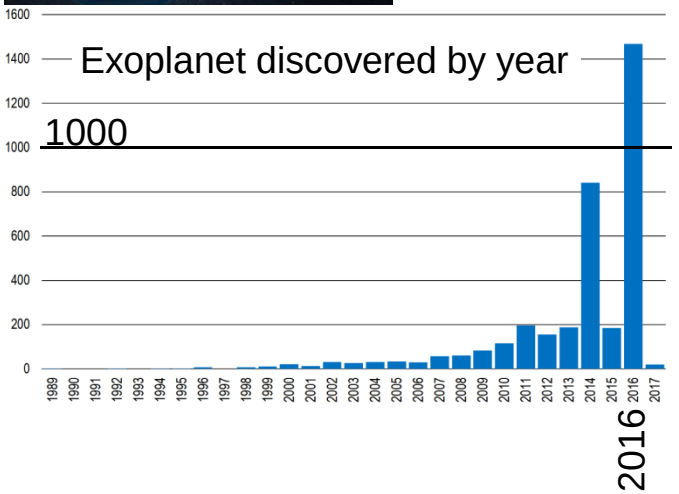
Earth inner core
~360 Gpa



Jupiter core
~7000 Gpa

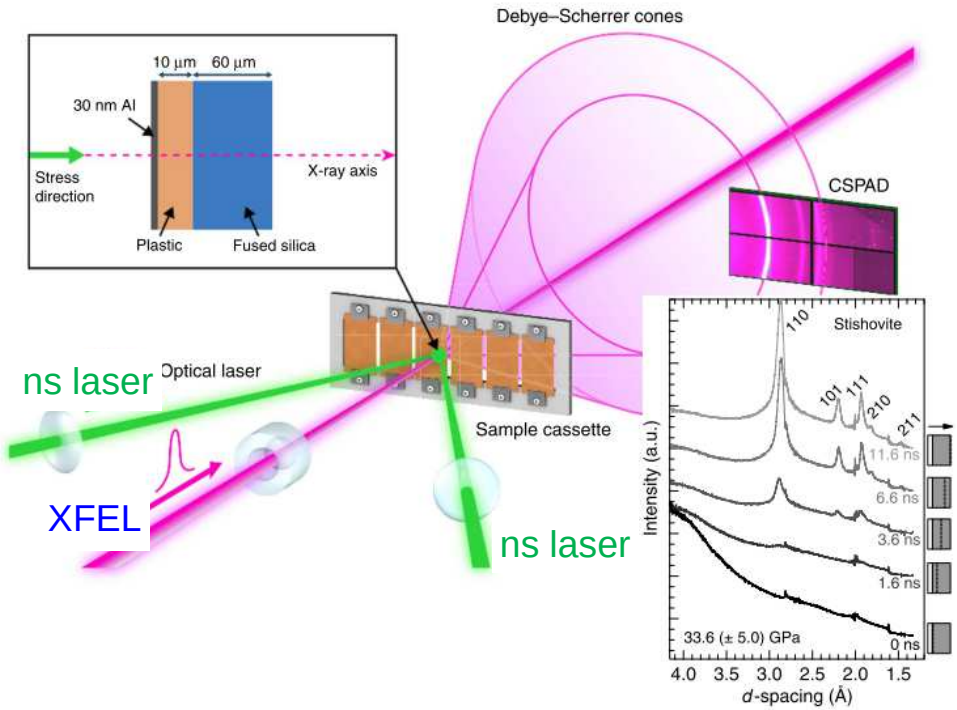


Exoplanet



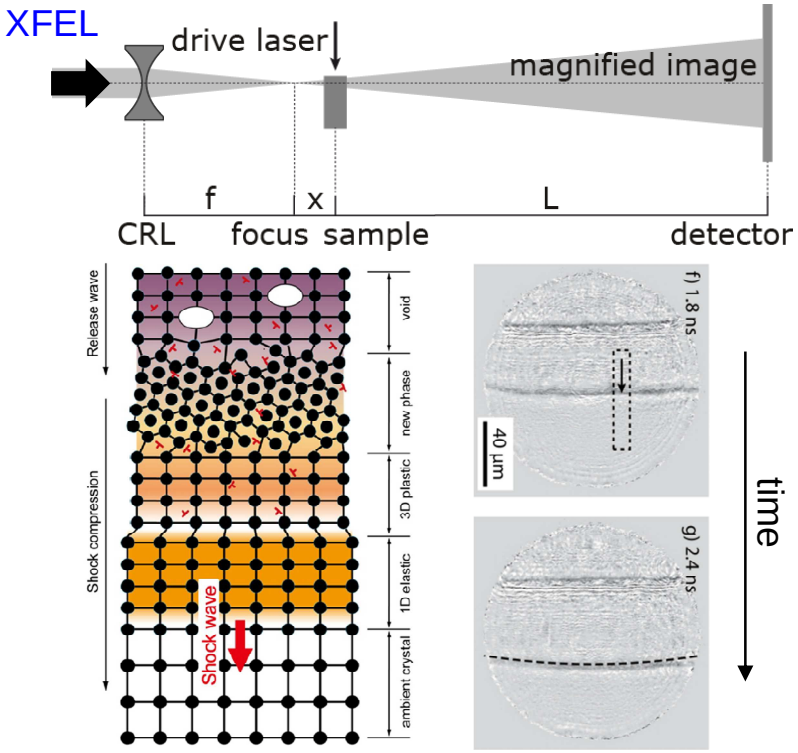
Hard X-ray up to 25 keV ➔ atomic resolution
Short pulse < 100 fs ➔ movement of the compression wave ~ 10 nm (no blurring)
High # of photons (10^{10} - 10^{13}) per pulse: ➔ single-shot capability
Coherent ➔ imaging

X-ray diffraction (large Q)



A. E. Gleason et al., Nat. comm. **6** 8191 (2015)
D. Milathianaki et al., Science **342**, 220 (2013)

Magnified x-ray phase contrast imaging



A. Schropp et al., Sci. Rep **5** 11089 (2015)

HED instrument milestones

- **Spring - Summer 2018**
  - **Commission of components without beam**
    - ► Optics hutch ready to take beam
  - Installation of delicate optical mirrors in experimental area
  - Tentative plan: first call for proposals for HED and MID

- **Summer- autumn 2018** **X-ray commissioning, HiBEF laser delivery & installation**
  - delivery of Amplitude laser and DiPOLE laser to HED laser bay

- **Autumn – Winter 2018** **Start of early user operation**
  - X-ray only (plus split-and-delay unit).
  - End-2018: pump-probe (PP) laser becomes available

- **Summer – Autumn 2019** **HED instrument fully operational including large HiBEF lasers**

Summary

- **HED instrument at European XFEL is one of the 6 experimental stations.**

- **3 laser systems.**
  - PP laser (2.5 mJ / 15 fs and 40 mJ / ps)
  - High-intensity (HI) laser (> 100 TW @ 10 Hz, 300 TW @ 5 Hz)
  - High-energy (HE) laser (100 J, 2 – 15 ns @ 10 Hz)

- **Science motivation**
  - EOS, melting, phase transition under dynamically compressed matter. Nano-second laser temporal shaping crucial.
  - Isochoric heating of solids (WDM). Equilibration dynamics.
  - Relativistic electron beam dynamics, nonlinear plasma optics
  - And more…

- European XFEL is a user facility. About 20-30 experiments will be allocated to the HED per year (1wk/exp). Everyone can apply. All proposals will be peer-reviewed and beam time is allocated according sorely to the quality (except HIBEF priority access beamtime max ~ 30% of total beamtime).