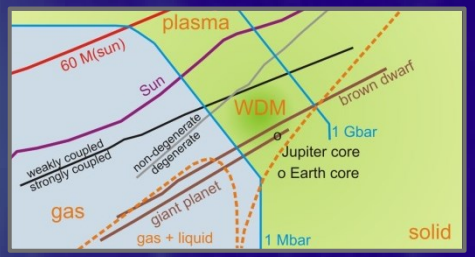
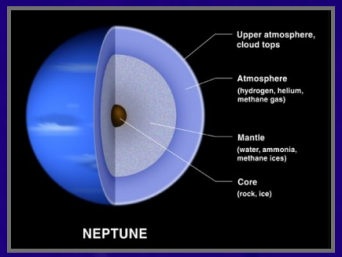
Science at High Energy-Density

The HED instrument at the European XFEL



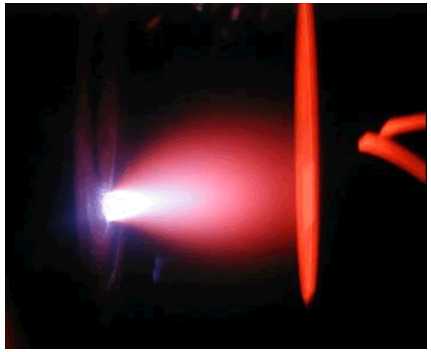


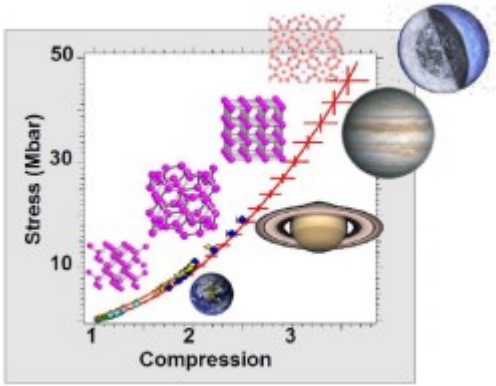
Ulf Zastrau *et al.*

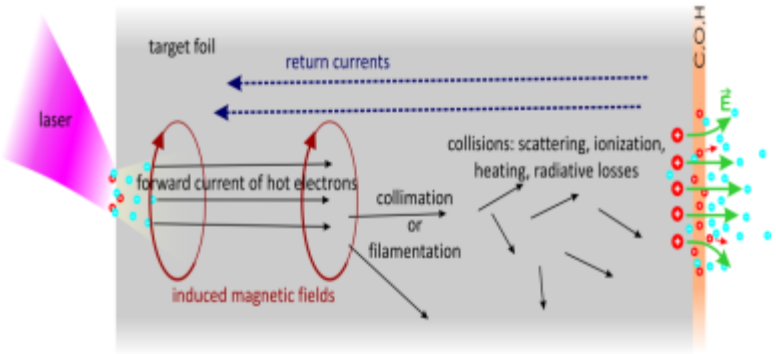
HED science group, European XFEL, Hamburg - Germany

High-Energy Density instrument

- 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 (future upgrade)







- Combination of high excitation with various X-ray techniques
  - Use of **various pump sources**: optical laser, XFEL, B-fields
  - **Various X-ray probe techniques**: XRD, SAXS, XRTS, hrIXS, XI, XAS….

HIBEF: Helmholtz International Beamline for Extreme Fields

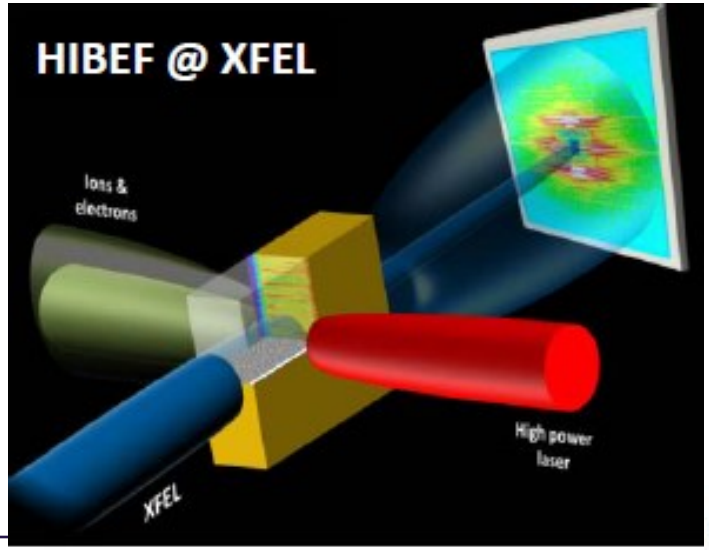
Spokesman: *T.E. Cowan (HZDR)* . Management Board: *J. Wark (U Oxford), E. Weckert , C. Schroer (DESY), R. Redmer (U Rostock).* Coordinator: *C. Baehtz (HZDR)*

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 200 TW/10 Hz & 100 J/10 Hz
- Future upgrades

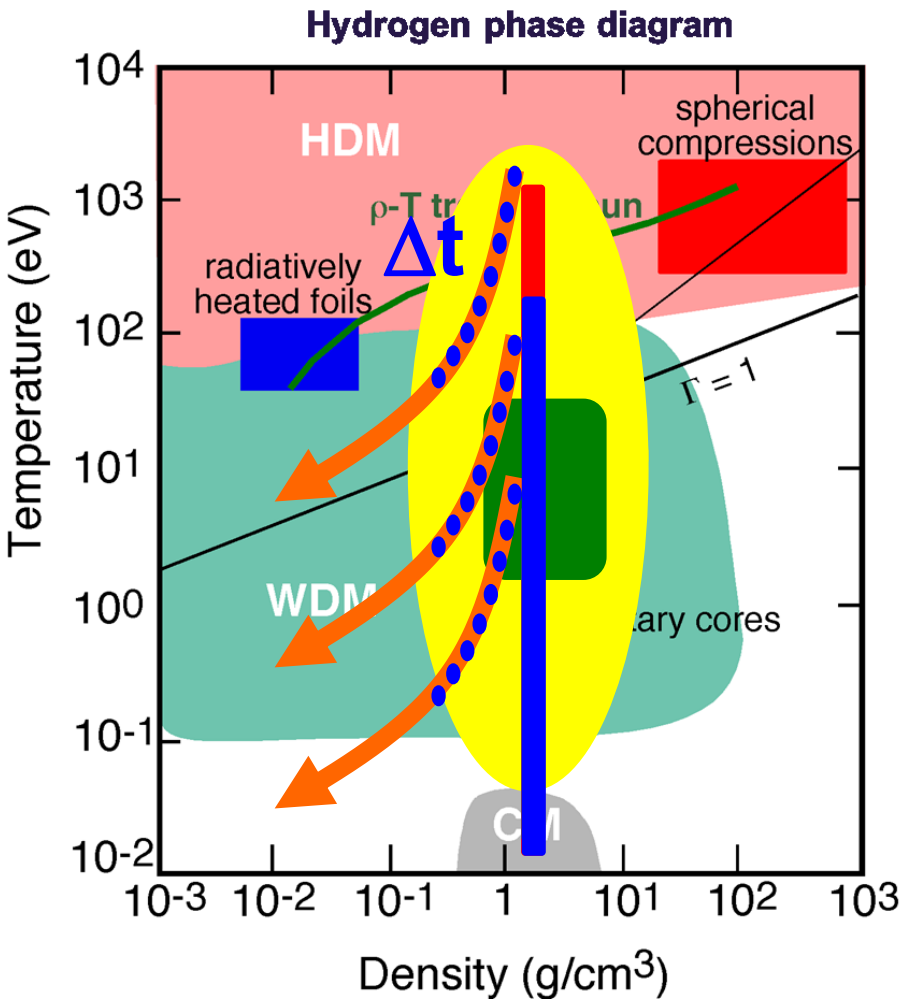
Pulsed magnetic field setup
Diagnostics, spectrometer, etc.
Man-power
Operation

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



HELMHOLTZ ASSOCIATION

Drive capabilities at HED



Three optical lasers (2x HIBEF)

- Pump-Probe (PP) >10^{17} W/cm^2
  - 2 mJ/0.1MHz, 0.08mJ/4.5MHz 15 fs
  - 45mJ/0.1MHz, 1mJ/4.5MHz, 900 fs
- High-Intensity (HI) >10^{20} W/cm^2
  - ~5 J, ~25 fs, 10 Hz on sample
- High-Energy (HE)
  - ~100 J, 2–15 ns, 1-10 Hz
  - ~3x compression, ~10 Mbar

DAC set-up (HIBEF):

- dynamic and double-stage DACs

Pulsed magnet (HIBEF)

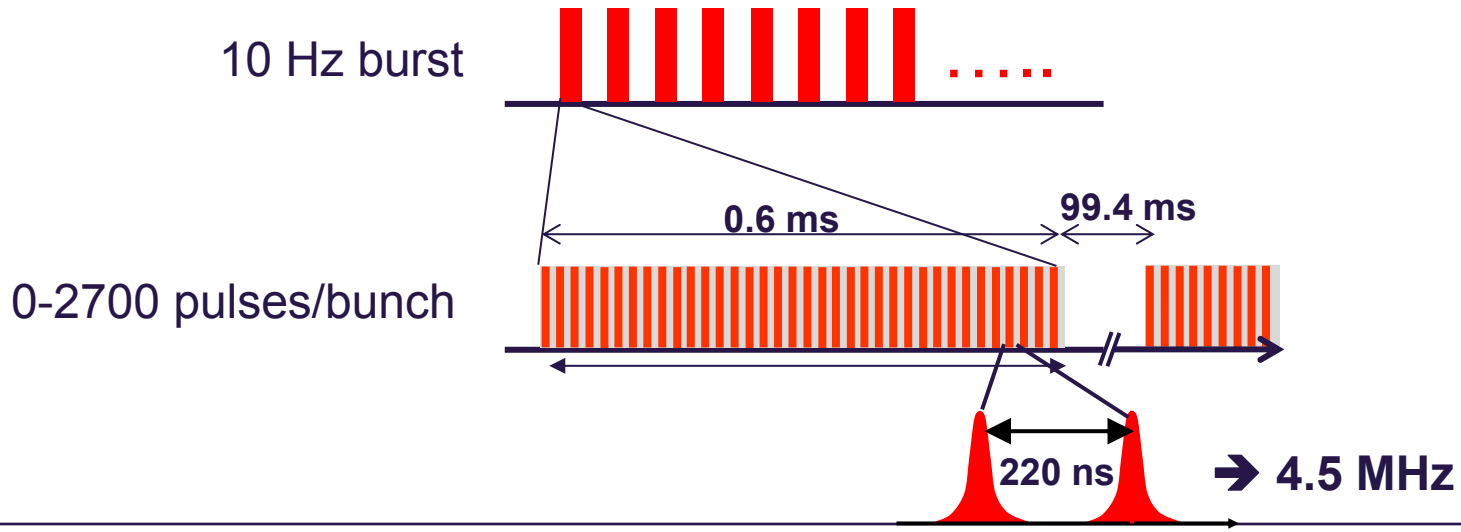
- ~60 Tesla (10 kbar, 1GPa)

XFEL

- >10^{11} phot, <μm, > 10^{19} W/cm^2

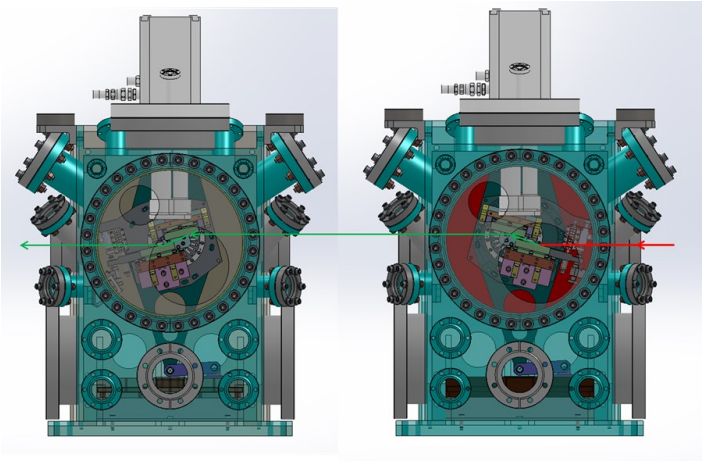
Final X-ray properties at the HED instrument

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, in-chamber focusing), few μm, 20 – 30 μm, 200 – 300 μm, few mm
Seeded beam	In preparation; installation after initial commissioning
Repetition rate	shot on demand, 10 Hz – 27000 pulses/sec



X-ray Monochromator – Split & Delay Line

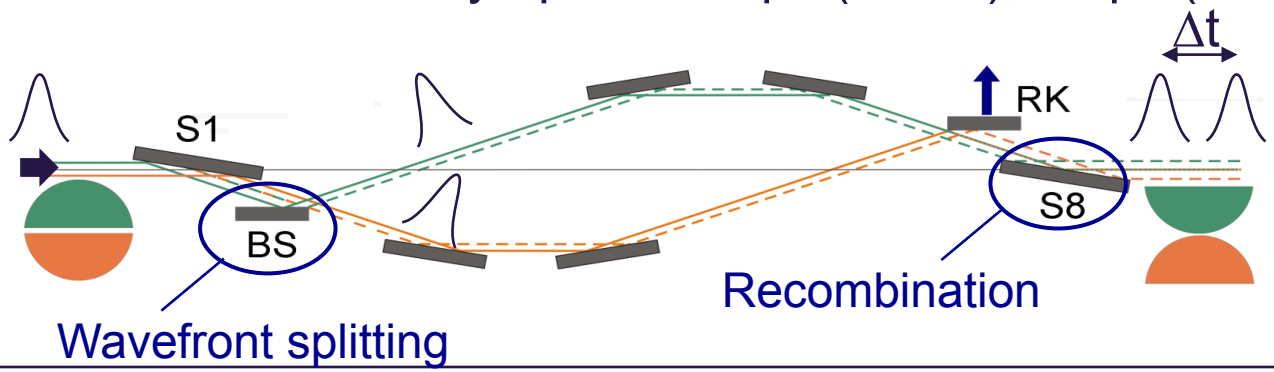
- Five different bandwidth levels:
  - $\Delta E/E = 10^{-3}$: SASE
  - $\Delta E/E = 10^{-4}$: Si_{111} monochromator
  - $\Delta E/E = 10^{-4} - 10^{-5}$: seeded
  - $\Delta E/E = 10^{-6}$: at selected x-ray energies



H. Sinn et al., *TDR X-Ray Optics and Beam Transport* - XFEL TR-2012-006, 73ff.

Split & Delay Line (SDL)

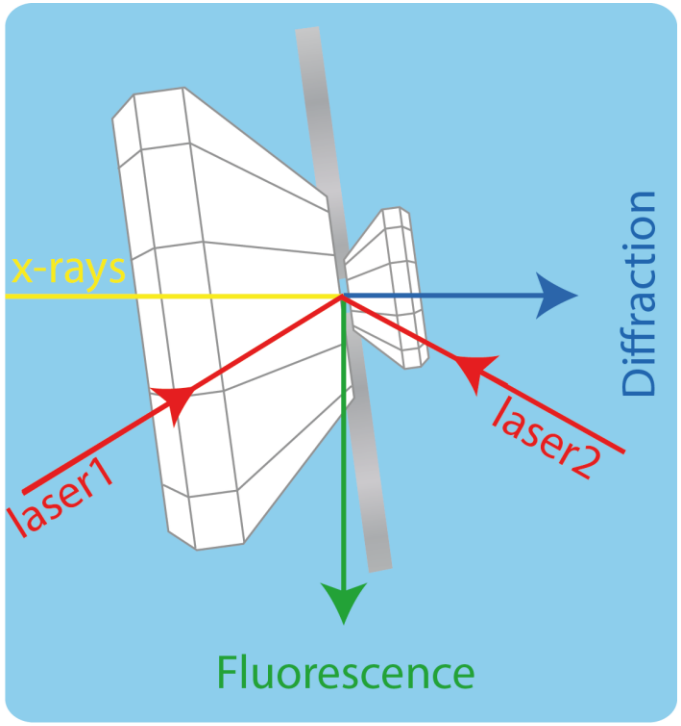
- Multi-layer mirrors
- Variable delay up to ~23 ps (5 keV), ~4 ps (15 keV), 2 ps (20 keV)

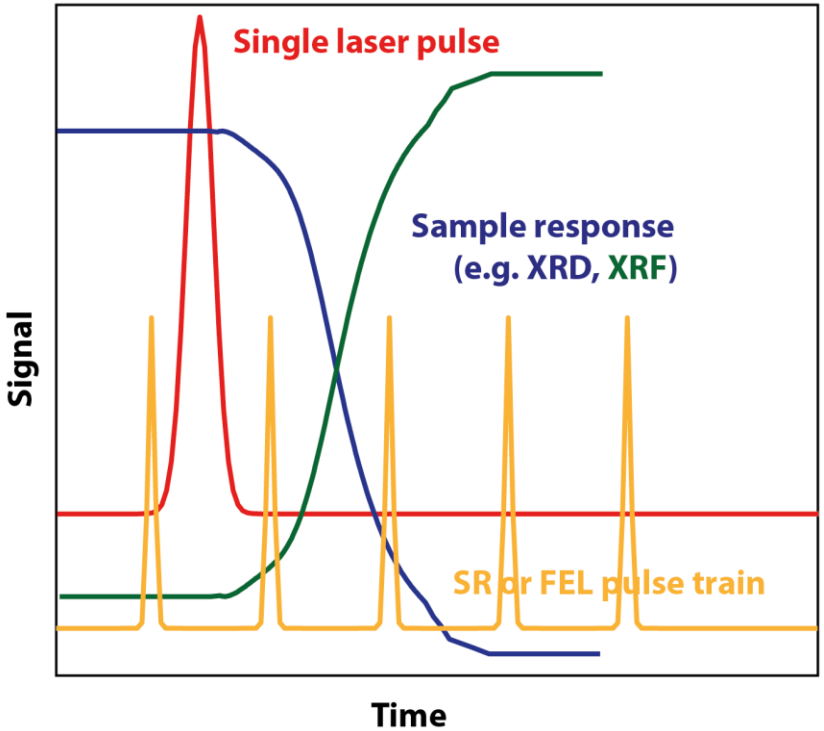


S. Roling, H. Zacharias, et al., SPIE conf 8504, 850407 (2012)
BMBF project 05K10PM2
University of Münster

Tools: laser-heated mDAC & SR or FEL source

The HED group is involved in the implementation of laser-heated mDAC at the HED instrument





Pressure Range:
mDAC (limit 1.5 Mbar)
3-4 Mbar up to strain rate 10^3
Temperature Range:
up to 5000 K – 0.5 eV (with laser heating)

XRD: Detectors for different repetition rates
- Perkin Elmer (25 Hz)
- Jungfrau (2 kHz)
- AGIPD (4.5 MHz)

XRF: Fluorescence detector

The pump-probe (PP) laser concept

Currently being developed by the optical laser group, European XFEL

Accurately aligned with the temporal structure of XFEL,
up to 4.5 MHz intraburst

Start operation for users: first half of 2018

Energy and repetition: 4 working points, 2 lasers

λ ~0.8 µm / 15 fs (NOPA):

2 mJ / 100 kHz, 1.7 mJ / 188 kHz, 330 µJ / 1.1 MHz, 80 µJ / 4.5 MHz

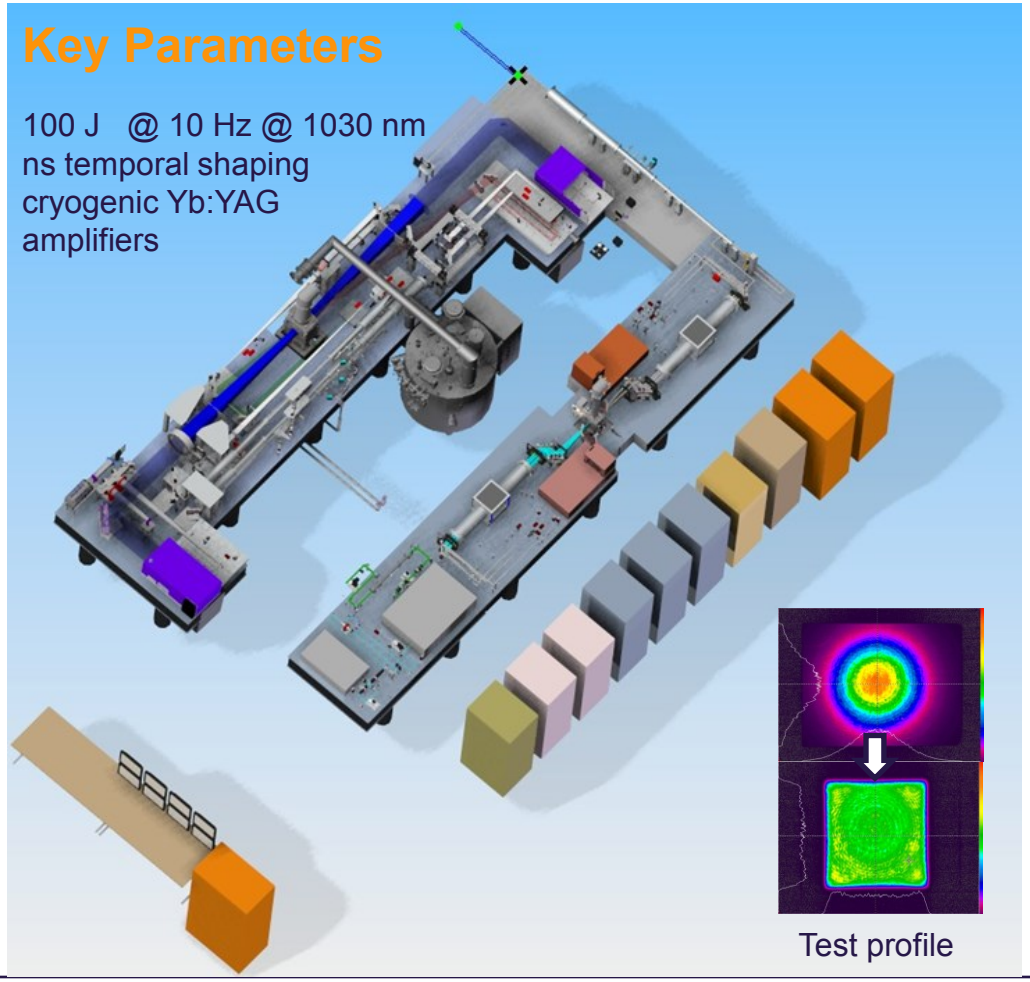
λ ~ 1.03 µm / 900 fs (Yb: YAG):

45 mJ / 100 kHz, 25 mJ / 188 kHz, 4 mJ / 1.1 MHz, 1 mJ / 4.5 MHz

High-Energy-Laser Integration

Science & Technology Facilities Council

DiPOLE laser design for XFEL
(100 J, 2ω, 10 Hz, ramped)



Front-end:

- Temporally-shaped 1030 nm fibre seed
- Active spatial shaping (SLM)
  - Pre-compensation, Masking

10 J Amplifier:

4 x square gain slabs
7-pass extraction architecture
  - Relay imaging, 22mm x 22mm beam size

Pump diodes
  - Up to 2 x 400W average power

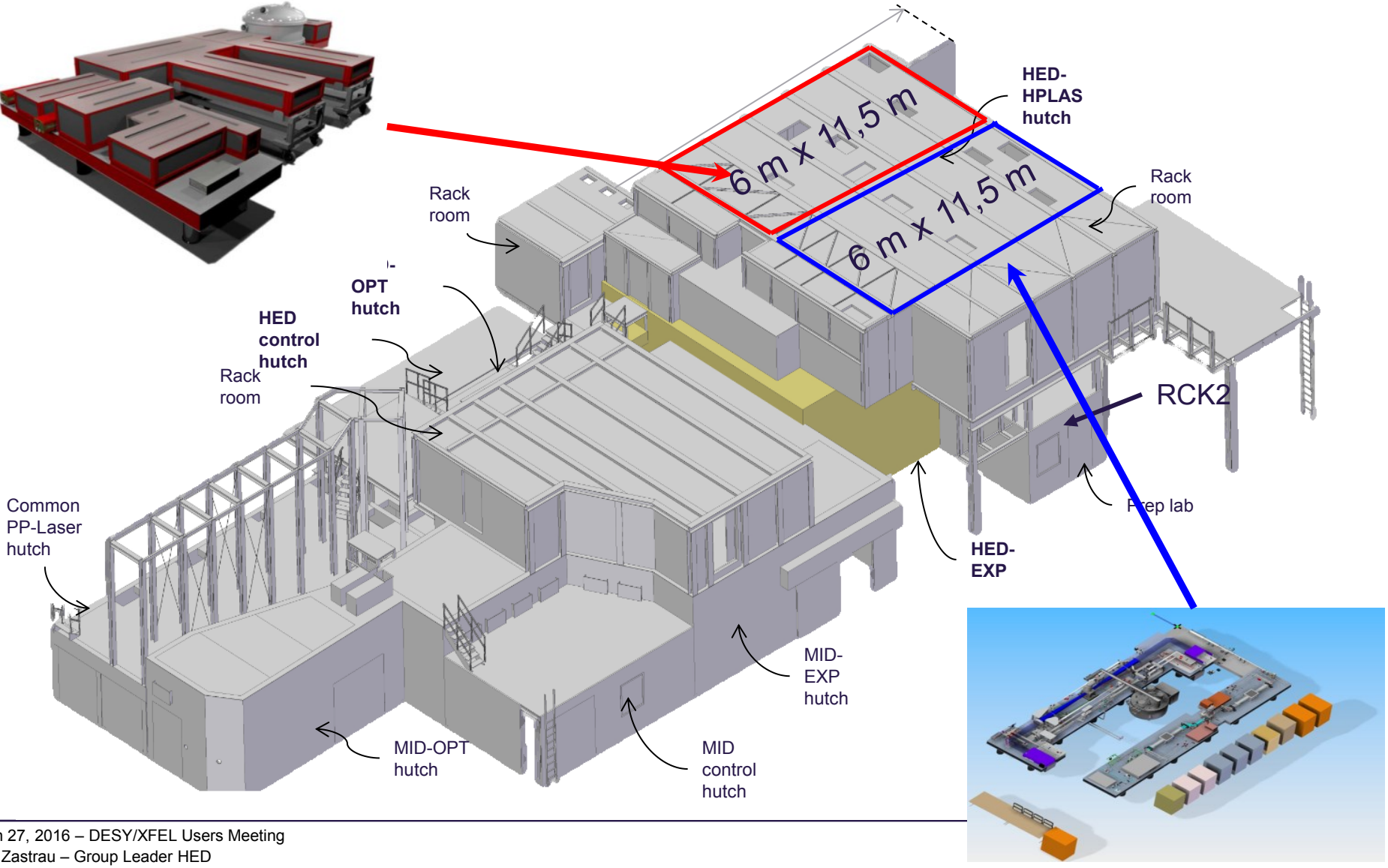
LN_2 based helium cryo-cooler
  - Low risk, low cost technology

100 J Amplifier:

Input: 9J @ 10Hz
Spatially & temporally-shaped
Feedback isolation, Polarisation controlled
Position stabilised

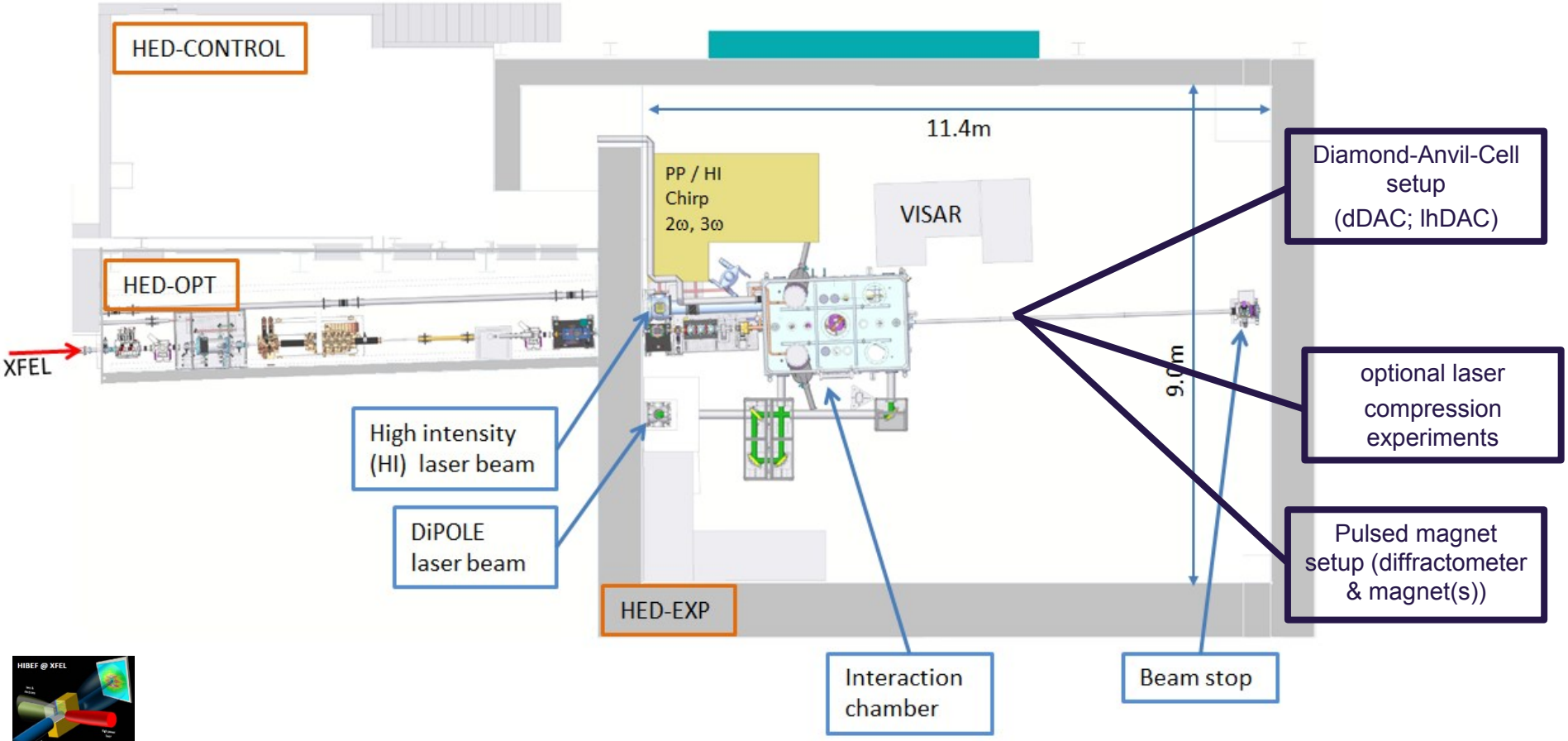
Output: 100J @ 10Hz
Wavefront corrected, Position stabilised

High-Energy and High-Intensity Lasers (HIBEF)

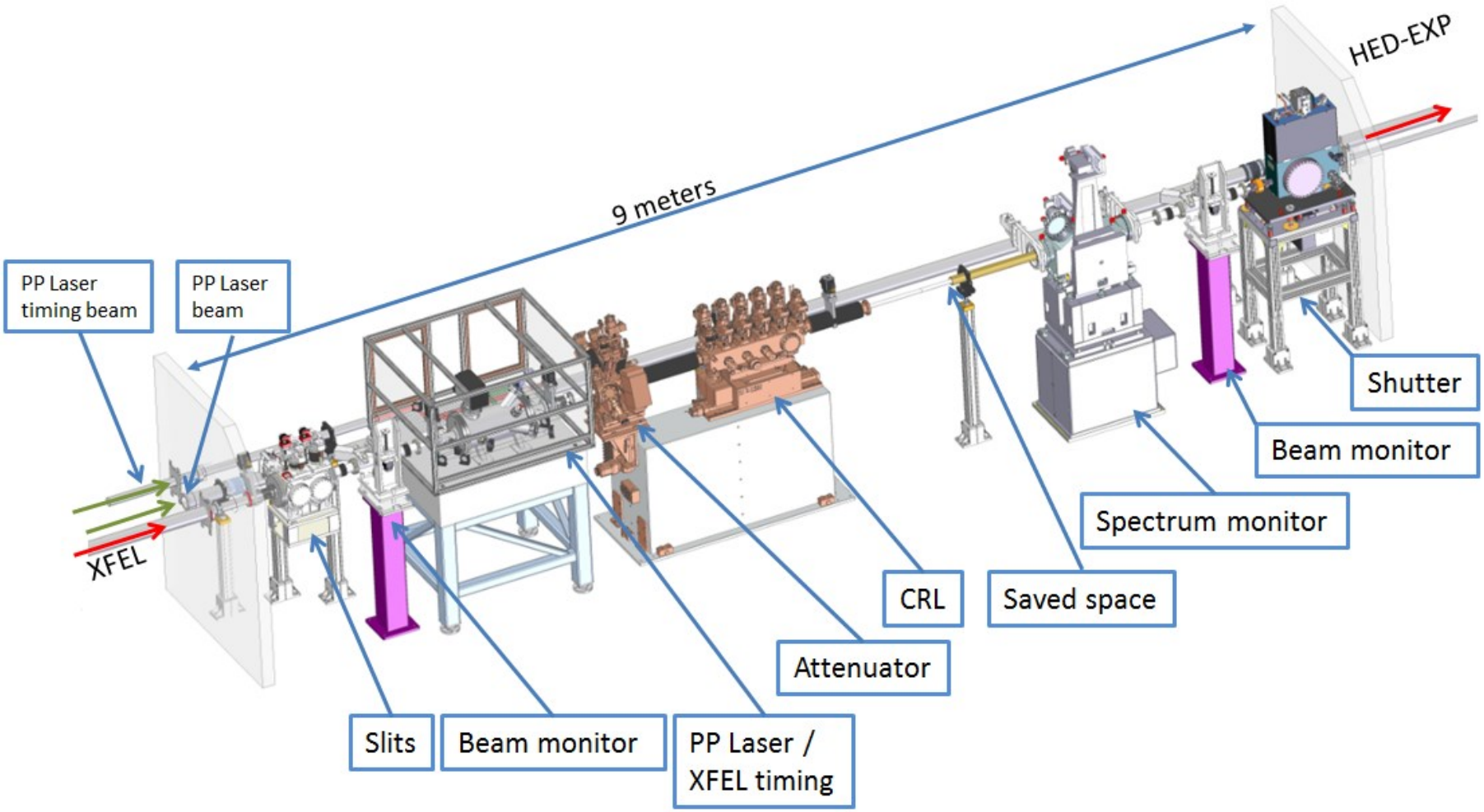


X-ray room layout

- HED-OPT: X-ray optics hutch → preparation of x-ray FEL beam; diagnostics
- HED-EXP: Experiment room → User experiments; beam stop

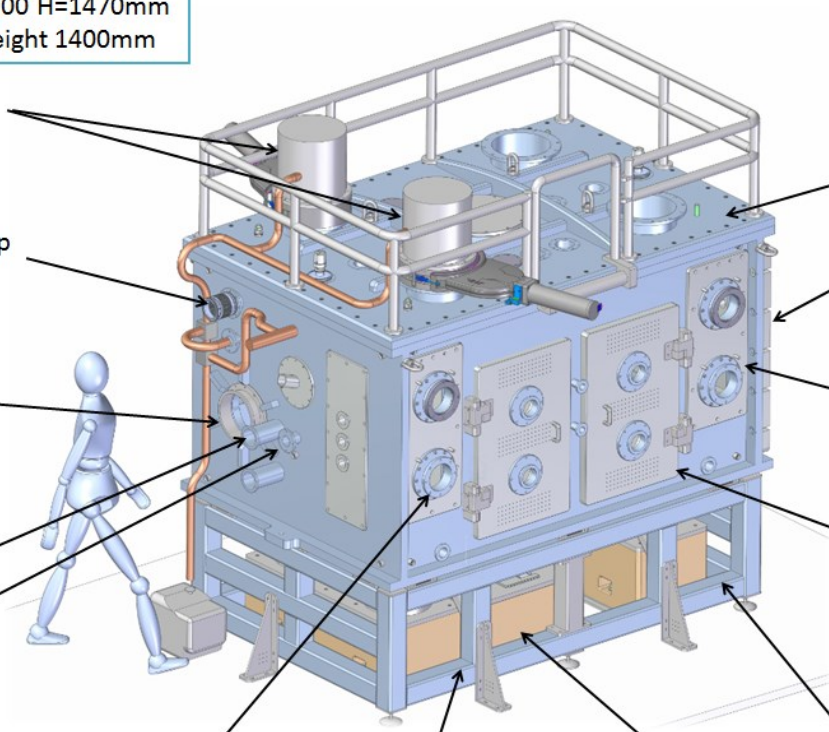


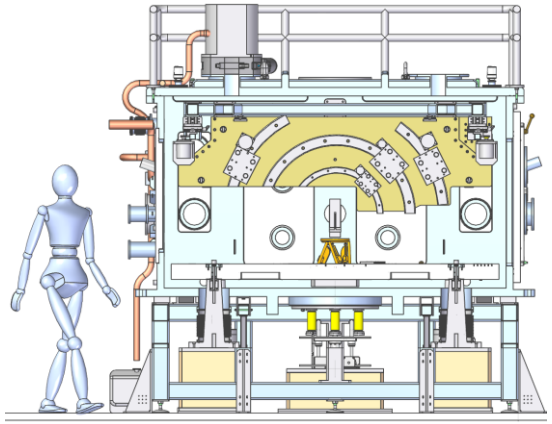
X-ray transport optics hutch



Interaction Chamber 1

L=2670 W=1700 H=1470mm
XFEL beam height 1400mm





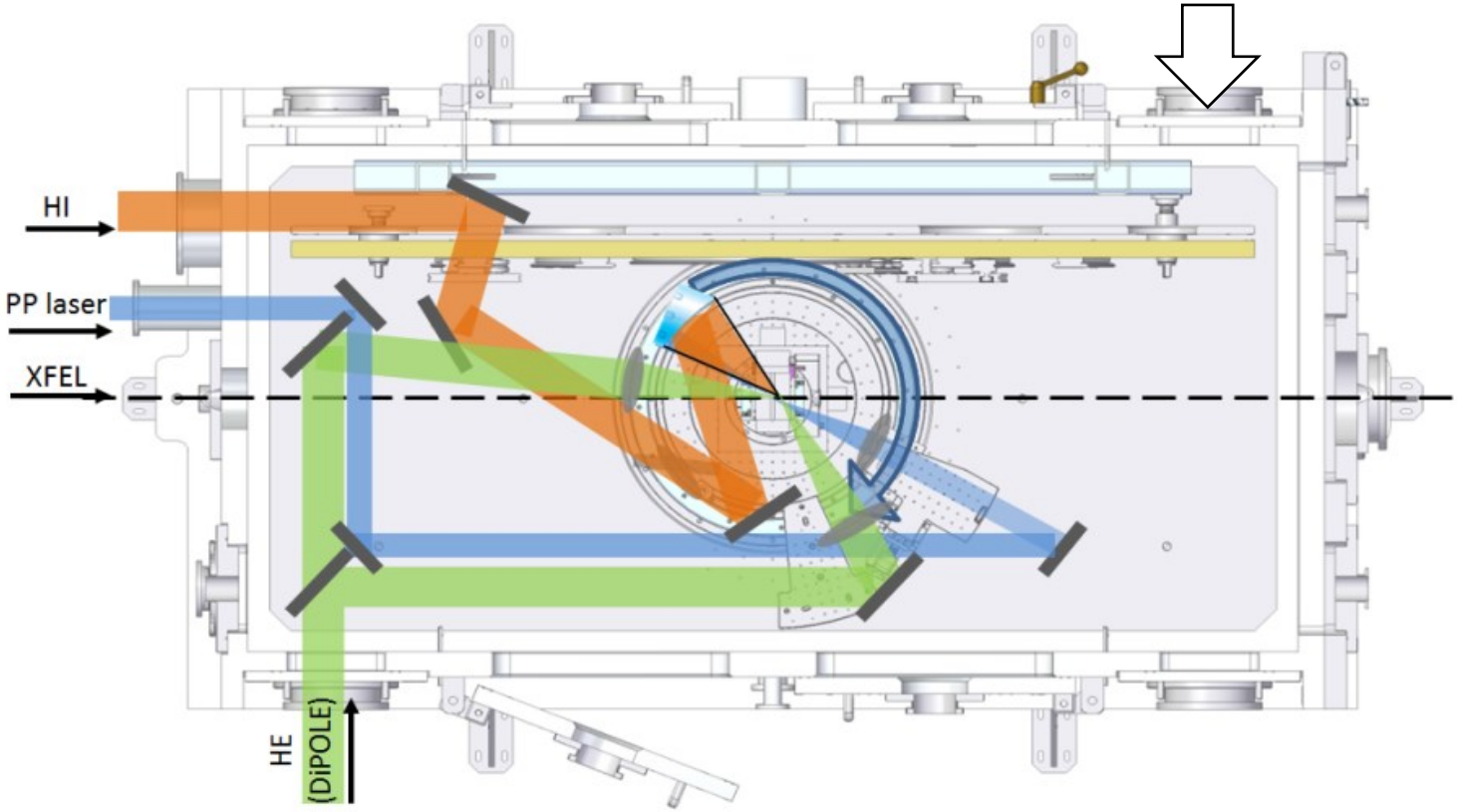
Side cut

- Huge chamber for flexible scattering setups in vertical plane, high pump power, many ports.
- Spectrometers, focusing parabola on rail systems, fast sample scanner
- Pre-defined laser schemes for HI and HE laser.

Fixed optical lasers entrance ports

VISAR in/out

Optical probe out

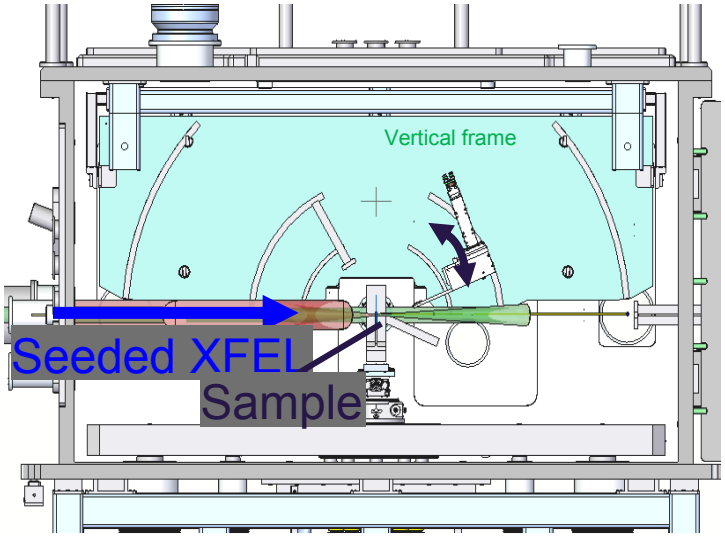


XFEL beam: fixed

Optical beams: highly flexible

X-ray diagnostics

- Inside vacuum chamber:



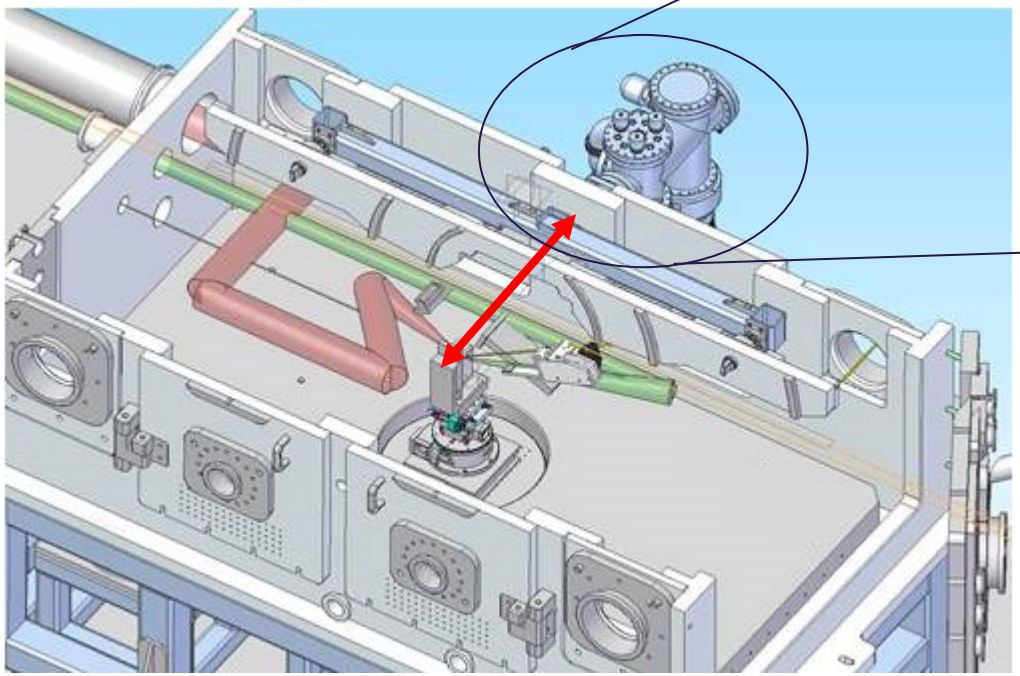
- HAPG X-ray spectrometer (ΔE = 10 eV)
- High-resolution X-ray scattering
- set-up (down to 40 meV) (BMBF?)
- X-ray diffraction area detectors

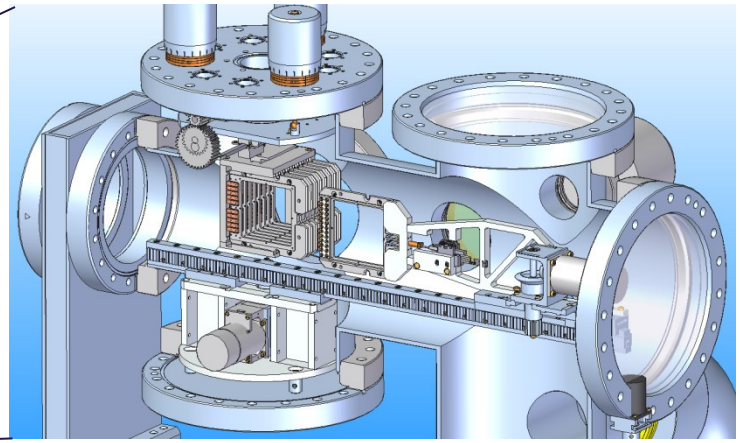
- Outside vacuum chamber (Detector Bench), HIBEF:

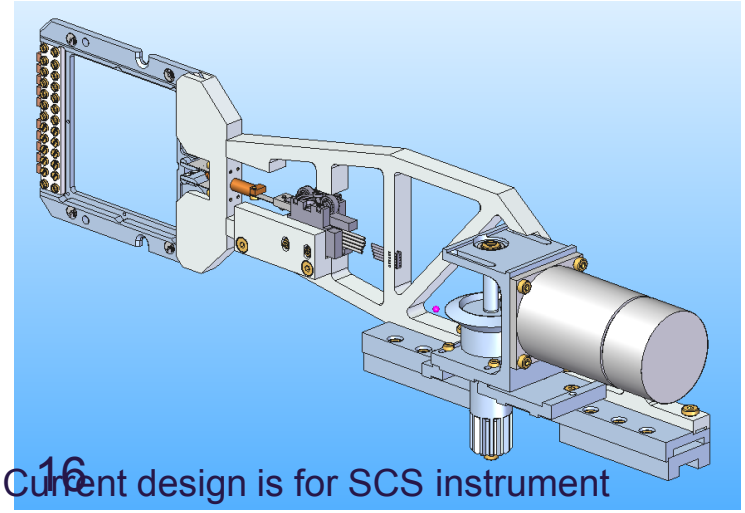
- X-ray spectrometer for XANES (upstream and downstream)
- SAXS detector at 2.5 – 6.5 m downstream from sample (HIBEF)
- Ptychography X-ray detector at 4 m downstream of the sample (HIBEF)
- Phase contrast imaging detector at 4 m downstream of sample (HIBEF)
- X-ray diffraction area detector (HIBEF)

10 Hz sample changer

- Separated mini-chamber for sample frame reservoir
  - ➔ Keep the main chamber in vacuum



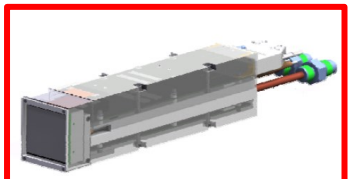
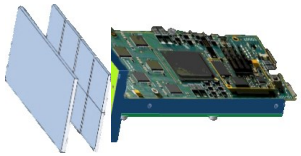
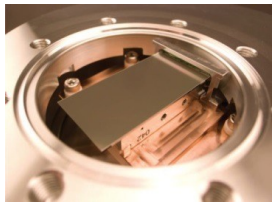
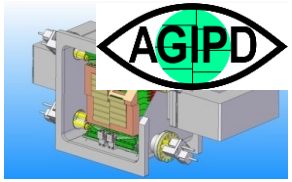




Design ongoing by C. Deiter,
Sample environment group

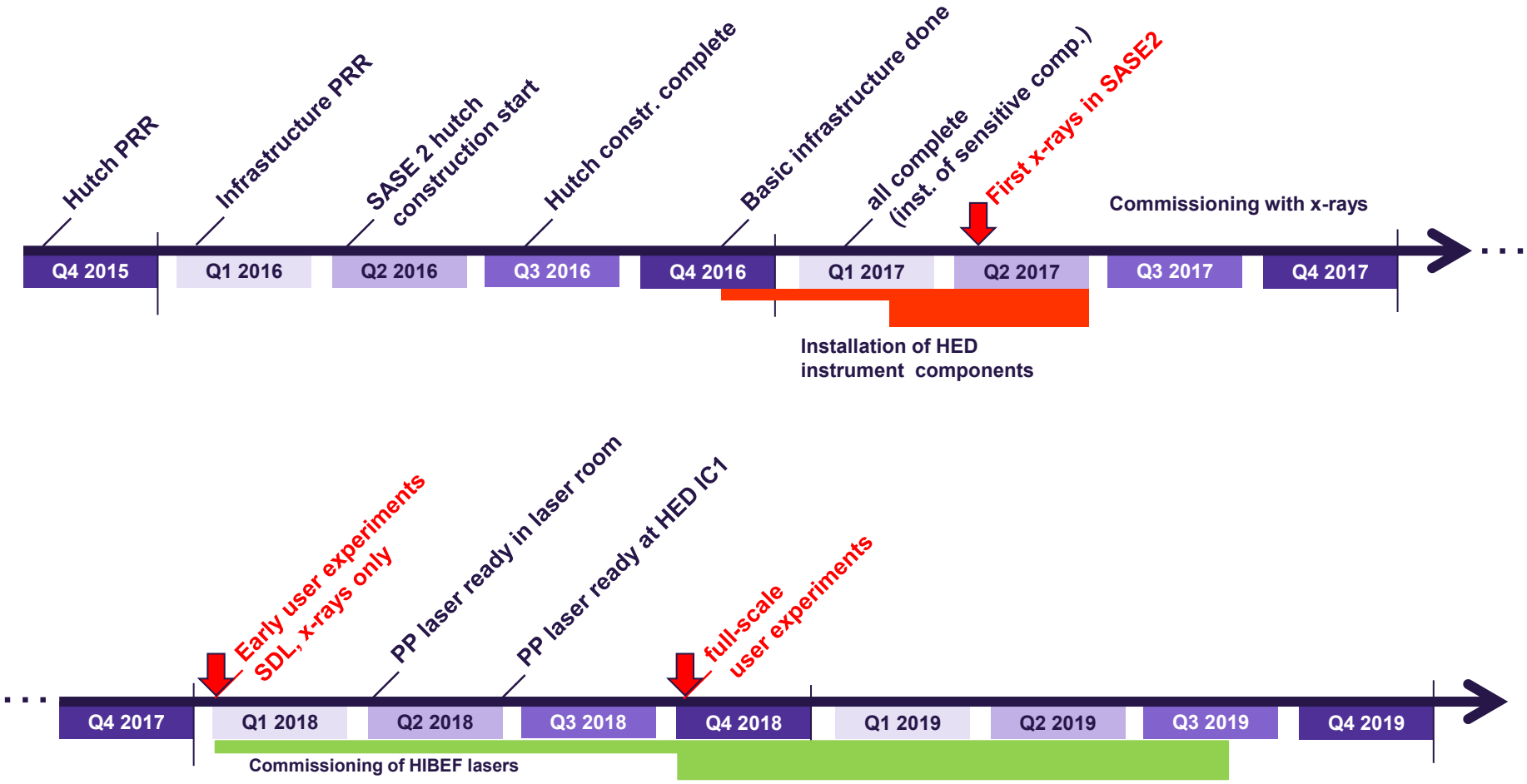
Current design is for SCS instrument

X-ray detector choices

Parameter	ePix100 / 10k	Jungfrau	MPCCD	AGIPD
	LCLS	PSI	SACLA	PSI
Sensor	500 µm Si	450 µm Si	300 µm Si	500 µm Si or GaAs
Repetition	120 Hz	2000 Hz	60Hz	4.5 MHz
Pixel size	50/100 µm	75 µm	50 µm	200µm
Dyn. range at 12keV	$10^2/10^3$	10^4	10^3	10^4
Vacuum?	Yes	Maybe	Yes	Yes
EMP resistance	*HED group initiated interational EMP work group*			
Noise	~0.4 keV	~0.4 keV	~ 1.2 keV	~1.5 keV
Size	Small	Small	Medium	(very) Big

Key Milestones and Time Plan



Possible day one experiment

Parameters for first commissioning and early experiments:

Electron energy	**17.5 GeV**
Photon energy	8.4 keV
Repetition rate	100 kHz (=1/45 of full power)
Max. number pulses per train	60
Undulator K-value	3.9
Undulator Gap	10 mm
Pulse energy	2 mJ (slightly oversaturated)
Divergence	2.2 urad
Pulse duration	43 fs
Saturation length	58 m

First lasing SASE2 in 2017

PP laser with x-ray-laser timing tool
X-ray methods: IXS with HAPG, XRD,
x-ray pump probe with SDL
DAC experiments: dynamic DAC and double stage at 8.4 keV
Note: DAC will benefit from higher photon energies ~25 keV or 3rd harmonic

The current HED group at XFEL

Thomas Tschentscher

responsible
scientific director

Ulf Zastrau

HED science
group leader

(since 4/2015)

Affiliated:

Emma McBride
(PostDoc)

Nicole Biedermann
(Ph.D.)

HED Instrument Scientists

Motoaki
Nakatsutsumi

Karen
Appel

Sebastian
Göde

Zuzana
Konôpková (2/2016)

+ …

HED Instrument Engineers

Ian
Thorpe

Andreas
Schmidt

Konstantin
Sukharnikov (3/2016)

+ …

Others:

Carsten Bähtz
(HIBEF
coordinator)

Alexander Pelka
(HIBEF
scientist)

Gerd Priebe
(optical laser
scientist)

Bolun Chen
(CAEP guest
scientist)

+ …

Acknowledgements

- Other European XFEL coworkers
  - L. Batchelor, H. Sinn, M. Dommach, G. Palmer, C. Deiter, A. Madsen, T. Roth, T. Haas, G. Wellenreuther, S. Kozielski, E. Boyd, W. Tscheu, V. Lamayaev, J. Schulz, M. Lederer, and many more …
- HIBEF User Consortium
  - Work package leaders for HIBEF sub-projecs + C. Baehtz (coordinator)
  - T. Cowan, C. Baehtz, A. Ferrari (HZDR), C. Schroer, J. Wark (Oxford)
  - SAC and TAC members
- plus
  - R. Cauble, F. Dorchies, J. Eggert, J. Hastings, Z. Konopkova, G. Gregori, G. Monaco, P. Audebert, A. Higginbotham, H. J. Lee, D. Neely, P. Neumayer, K. Sokolowski-Tinten, S. Toleikis

Thank you

- HED/HIBEF satellite meeting: Thursday 2pm
- Several posters: Friday afternoon,
  Including:
  - details of the HED instrument
  - details of PP laser at HED
- Open-community workshop for day-1 experiments in late 2016 or 2017 (tbd)
- Visit our updated website:
  http://www.xfel.eu/research/instruments/hed