Status and Science at HED instrument and of the HIBEF UC

28 January 2016, DESY campus, Building 90, Seminar Room ZOQ

Organizers: Carsten Bähtz, Ulf Zastrau

The workshop on the HED instrument and the HIBEF UC is organized as a satellite of the 2016 European XFEL Users' Meeting. We will present the current status of the HED instrument with emphasis on the expected setups and early user experiments. Further the status of the HIBEF project in general are presented and linked to the schedule of the HED installation. The recent activities in the US and at DESY are presented. Talks will give an overview of planned instrumentation and science at HED as well as recent achievements at the LCLS.

Programme

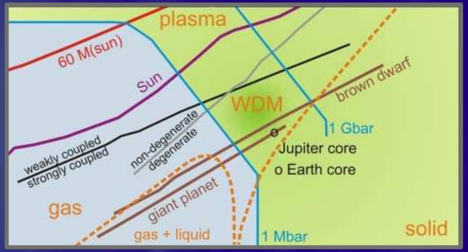
Thursday, 28 January 2016

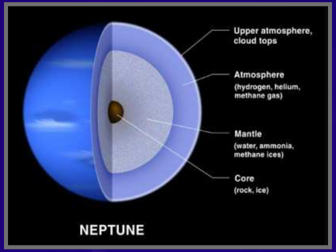
14:00	**HED instrument - Early parameters**	**Ulf Zastrau**	***European XFEL***
14:20	**Status of HIBEF**	**Carsten Bähtz**	***HIBEF, HZDR***
14:40	The US HIBEF Consortium	Bob Cauble	*LLNL*
15:00	Conceptual design of the DAC-setup at HIBEF	Hans-Peter Liermann	*ECB, DESY*
15:20	**Coffee Break**		
15:50	The single-shot incident spectrometer at HED	Bolun Chen	*Chinese Acad. of Sciences*
16:10	Ion dynamics using highest-resolution inelastic x-ray scattering	Ingo Uschmann	*Universität Jena*
16:30	Transverse Diffraction Setup at LCLS: Shock Compressed Silicon	Emma McBride	*European XFEL/SLAC*
16:50	Dynamic warm dense matter research using XFELs	Dominik Kraus	*UC Berkeley*
17:10	Recent results from the HED group at MEC, LCLS	Siegfried Glenzer	*SLAC/Stanford University*
17:30	**Adjourn / Informal discussions**		

Registration at www.xfel.eu/2015-users-meeting

Science at High Energy-Density

The HED instrument at the European XFEL



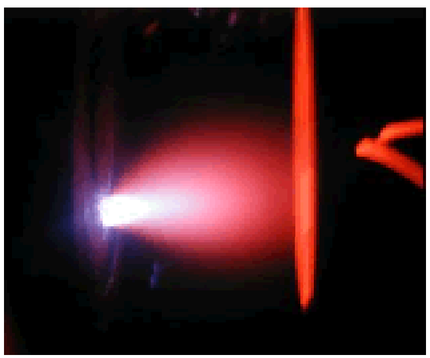


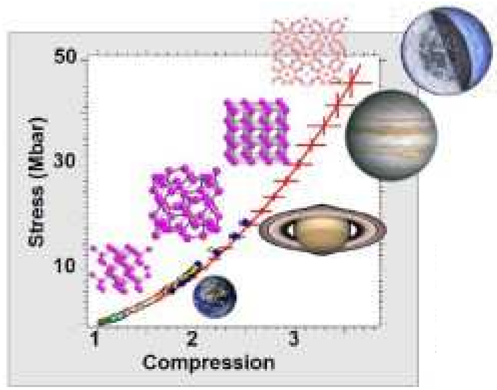
Ulf Zastrau *et al.*

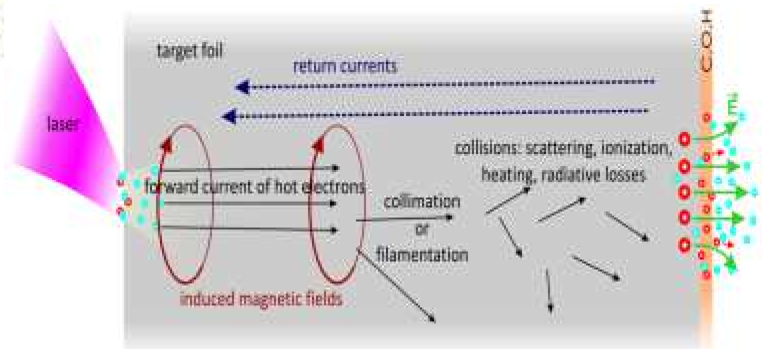
HED science group, European XFEL, Hamburg - Germany

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.

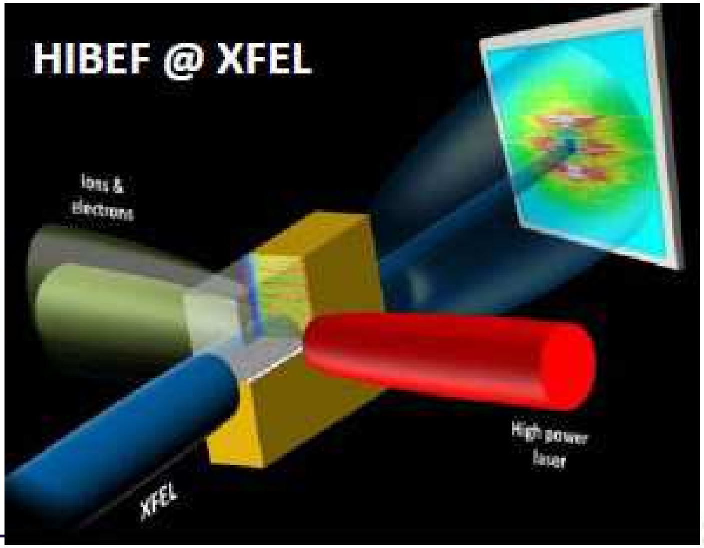
Man-power

Operation

UK: 10.3 M€

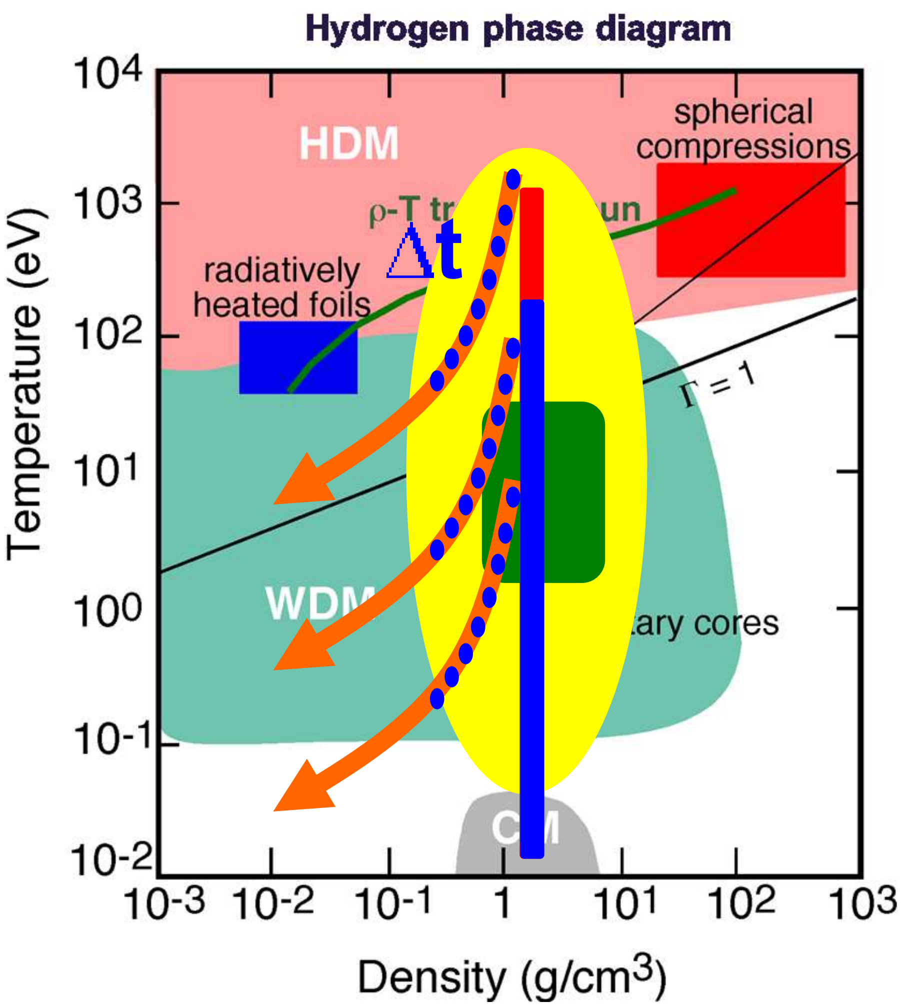
HGF-HIBEF: 20.5 M€

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)

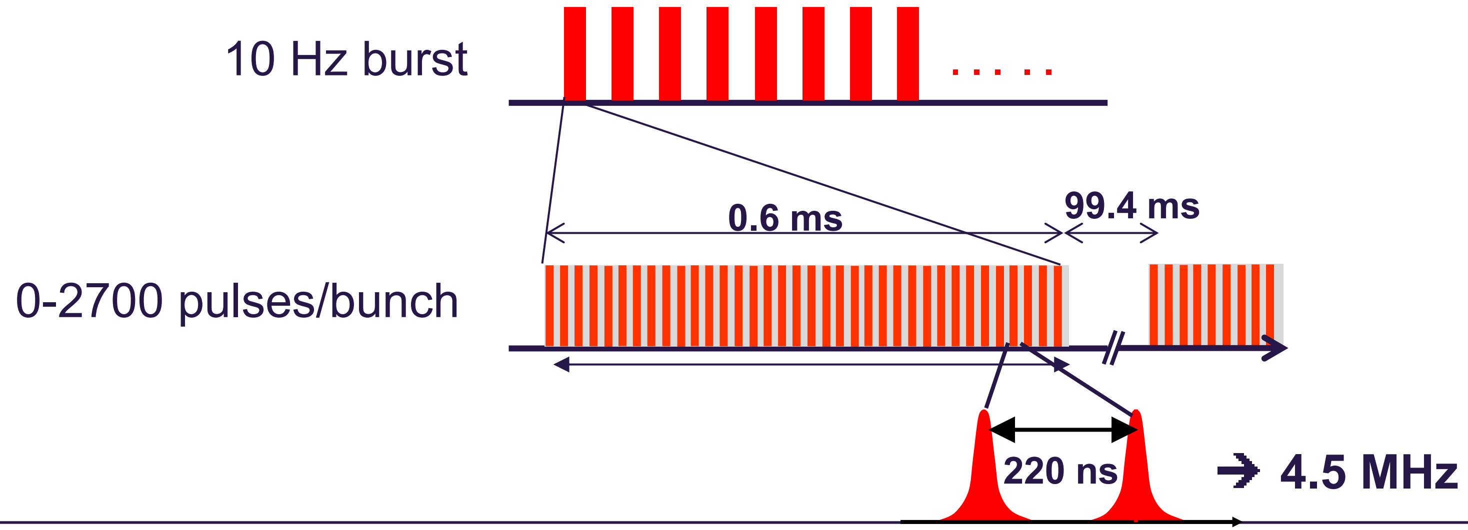
- ~60 Tesla (10 kbar, 1GPa)

XFEL

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

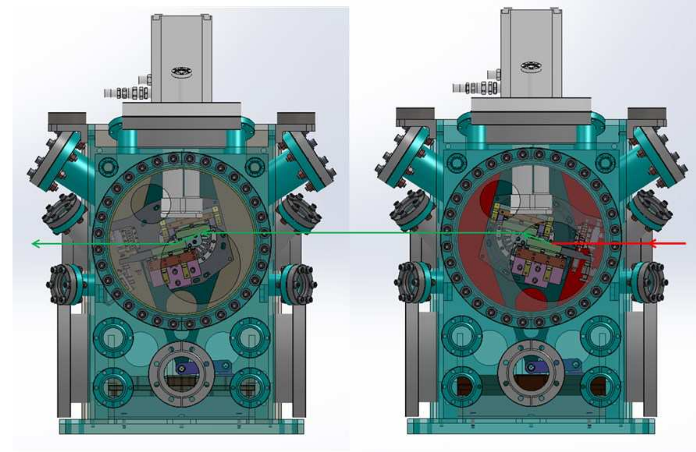
Final X-ray properties at the HED instrument

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

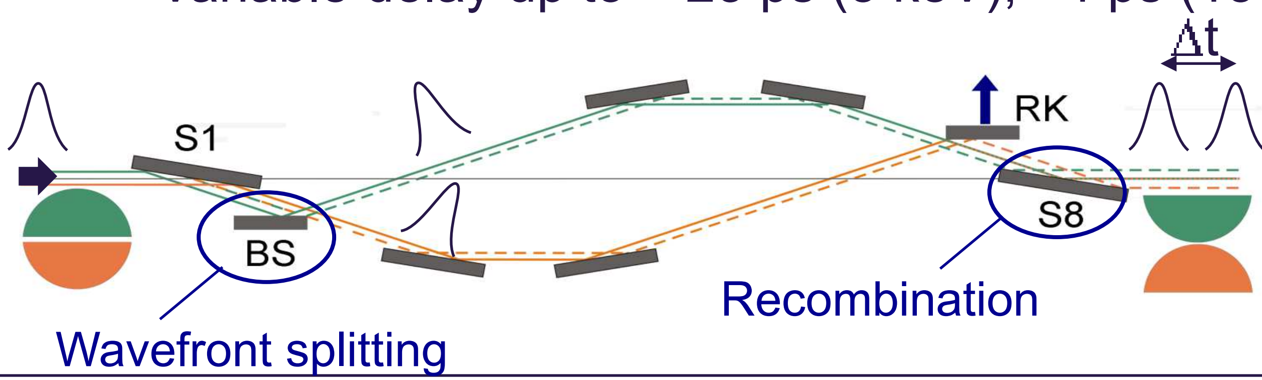
- Five different bandwidth levels:
  - $\Delta E/E = 10^{-3}$: SASE
  - $\Delta E/E = 10^{-4}$: Si_{111} monochromator
  - $\Delta E/E = 10^{-4} - 10^{-5}$: seeded
  - $\Delta E/E = 10^{-6}$: at selected x-ray energies



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

Split & Delay Line (SDL)

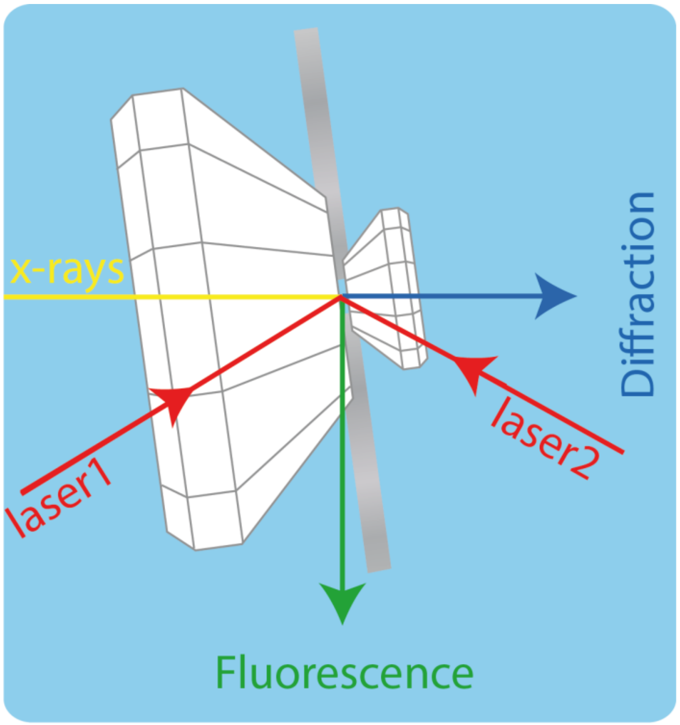
- Multi-layer mirrors
- Variable delay up to ~23 ps (5 keV), ~4 ps (15 keV), 2 ps (20 keV)

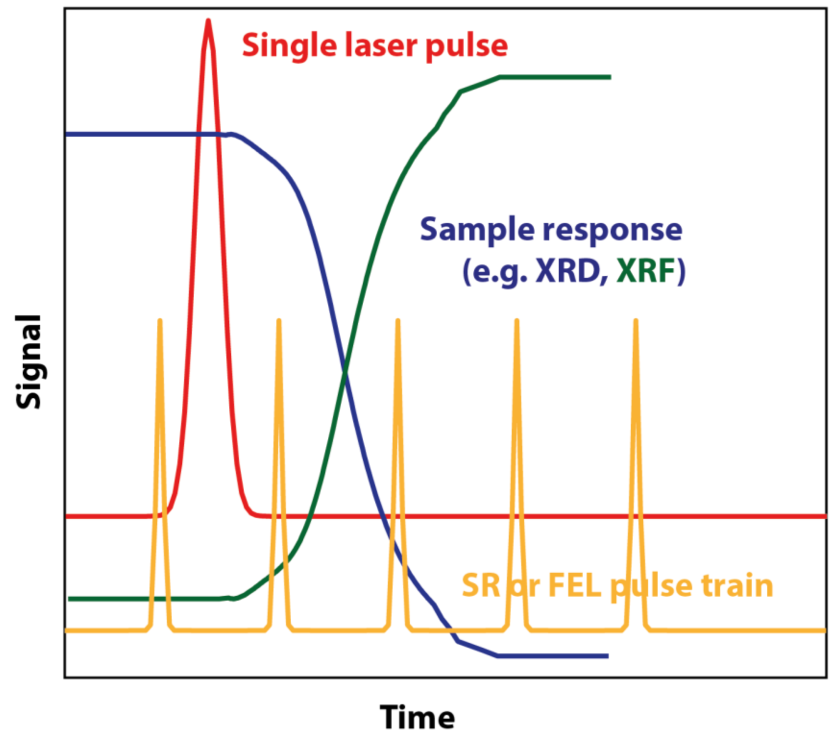


S. Roling, H. Zacharias, et al., SPIE conf 8504, 850407 (2012)
BMBF project 05K10PM2
University of Münster

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 intrabunch

Start operation for users: first half of 2018

Energy and repetition: 4 working points, 2 lasers

$\lambda \sim$ 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

$\lambda \sim$ 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

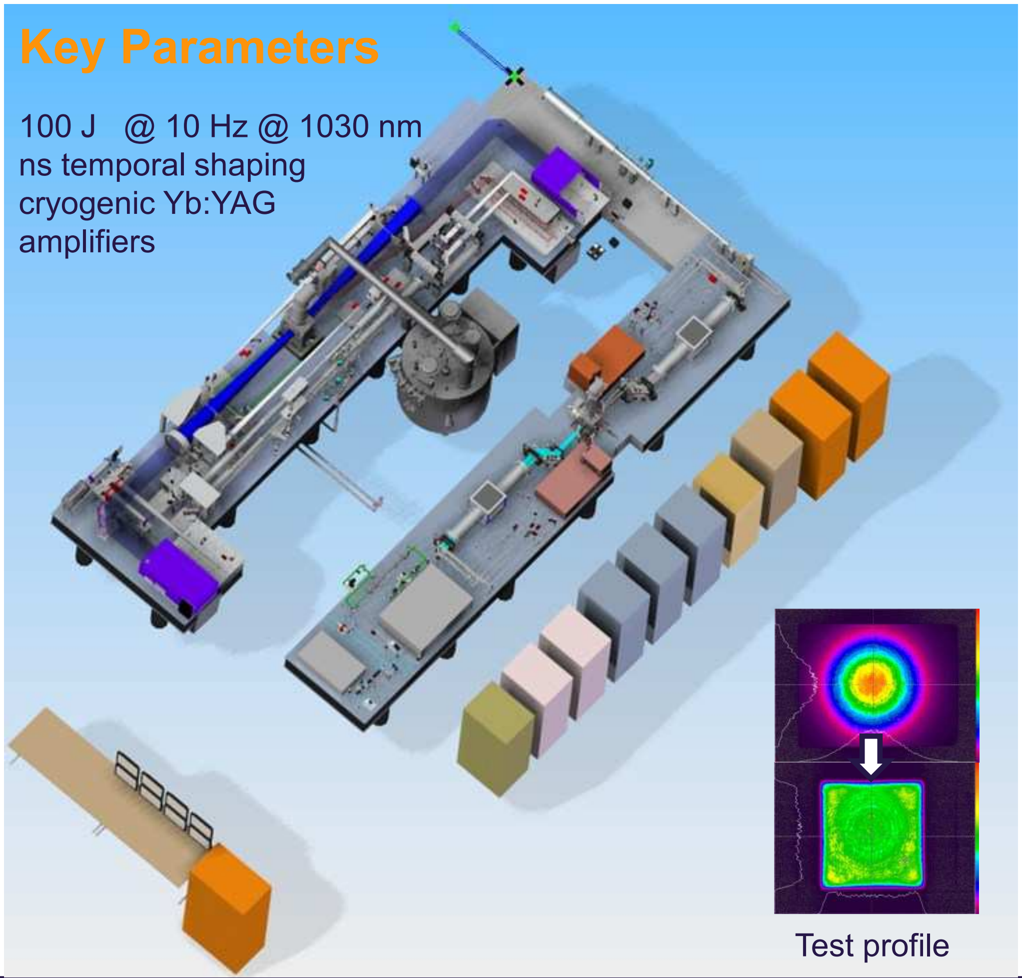
High-Energy-Laser Integration

Science & Technology Facilities Council

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

Key Parameters

100 J @ 10 Hz @ 1030 nm
ns temporal shaping
cryogenic Yb:YAG
amplifiers



Test profile

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

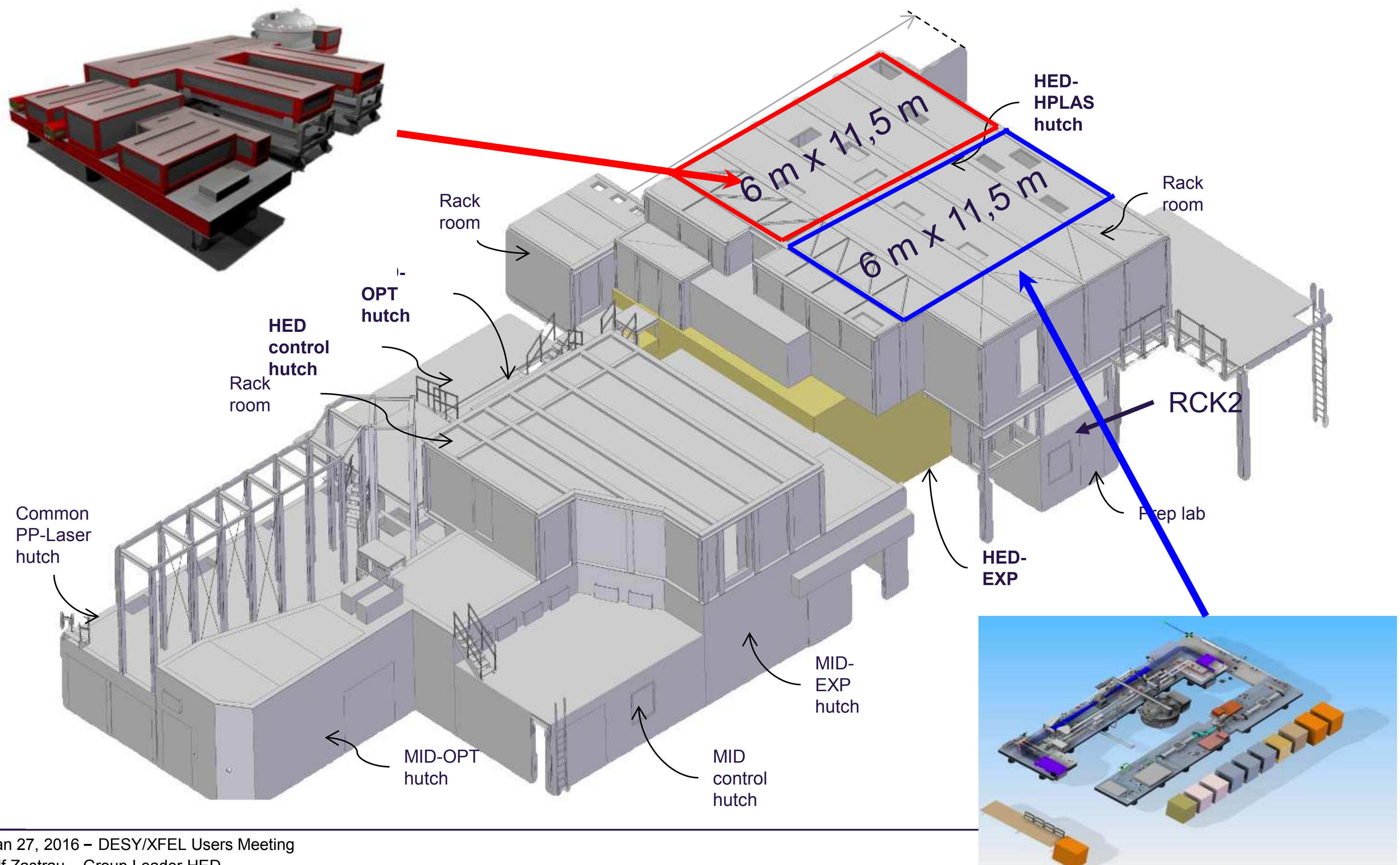
LN_2 based helium cryo-cooler
    Low risk, low cost technology

100 J Amplifier:

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

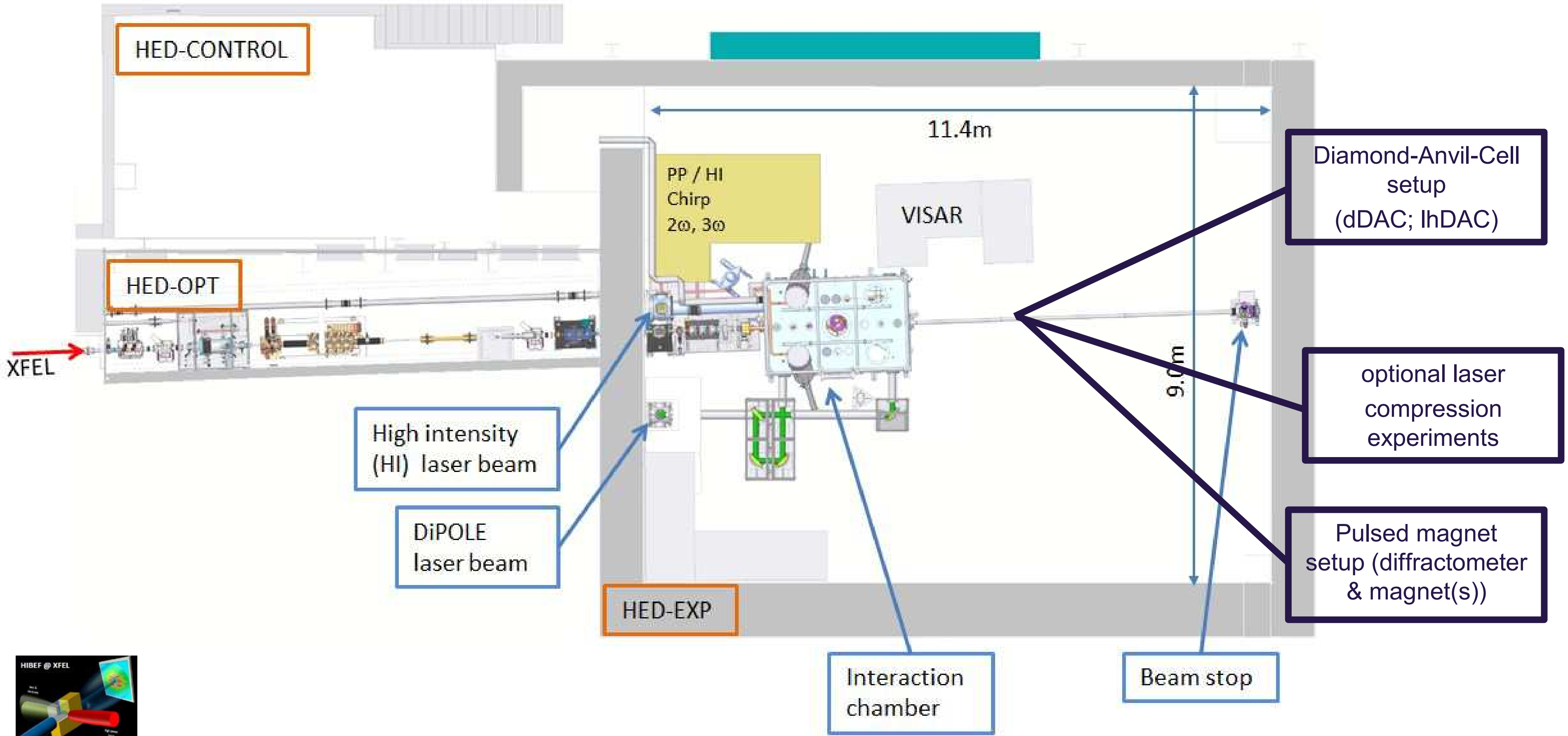
Output: 100J @ 10Hz
Wavefront corrected, Position stabilised

High-Energy and High-Intensity Lasers (HIBEF)

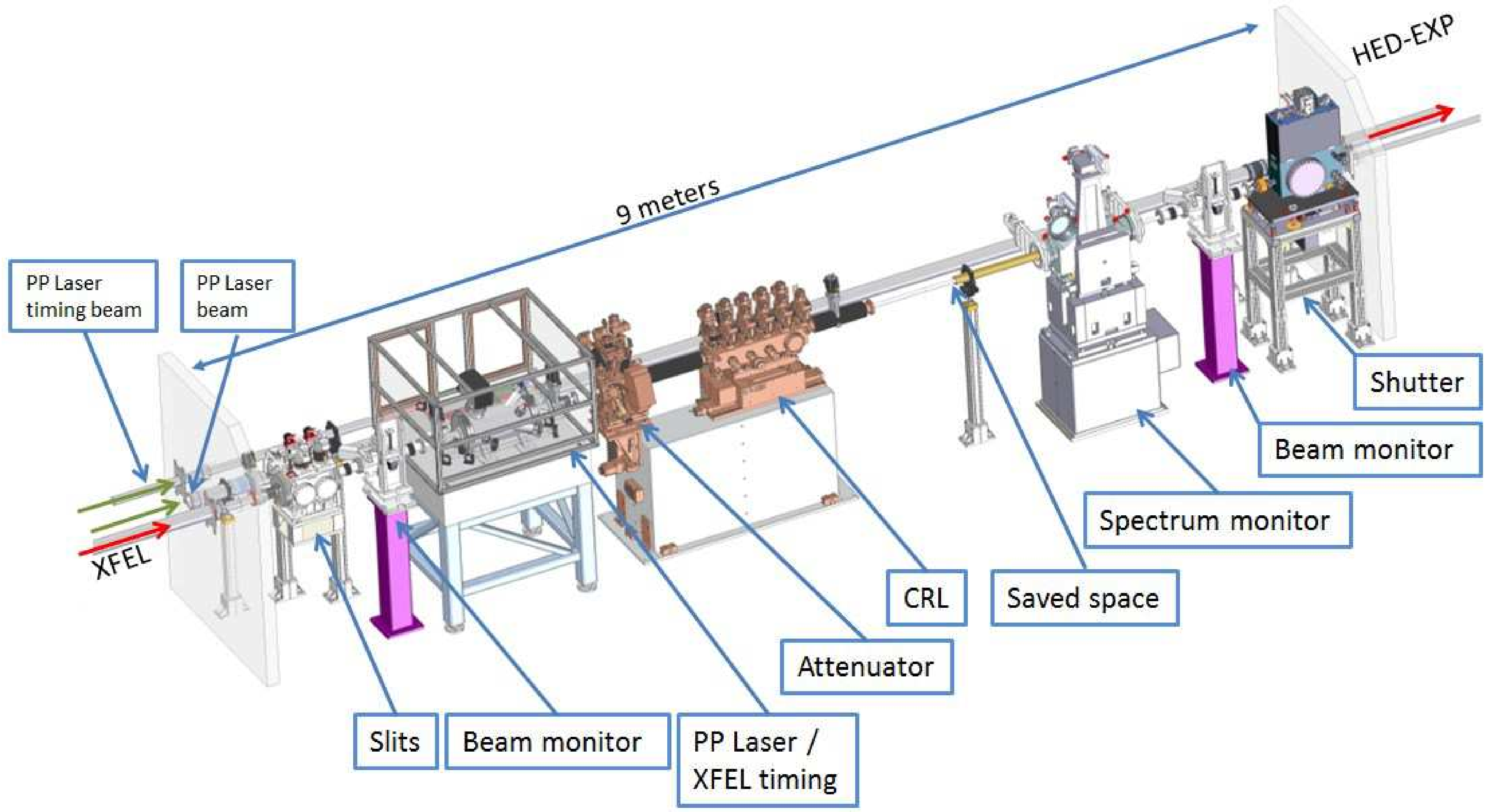


X-ray room layout

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

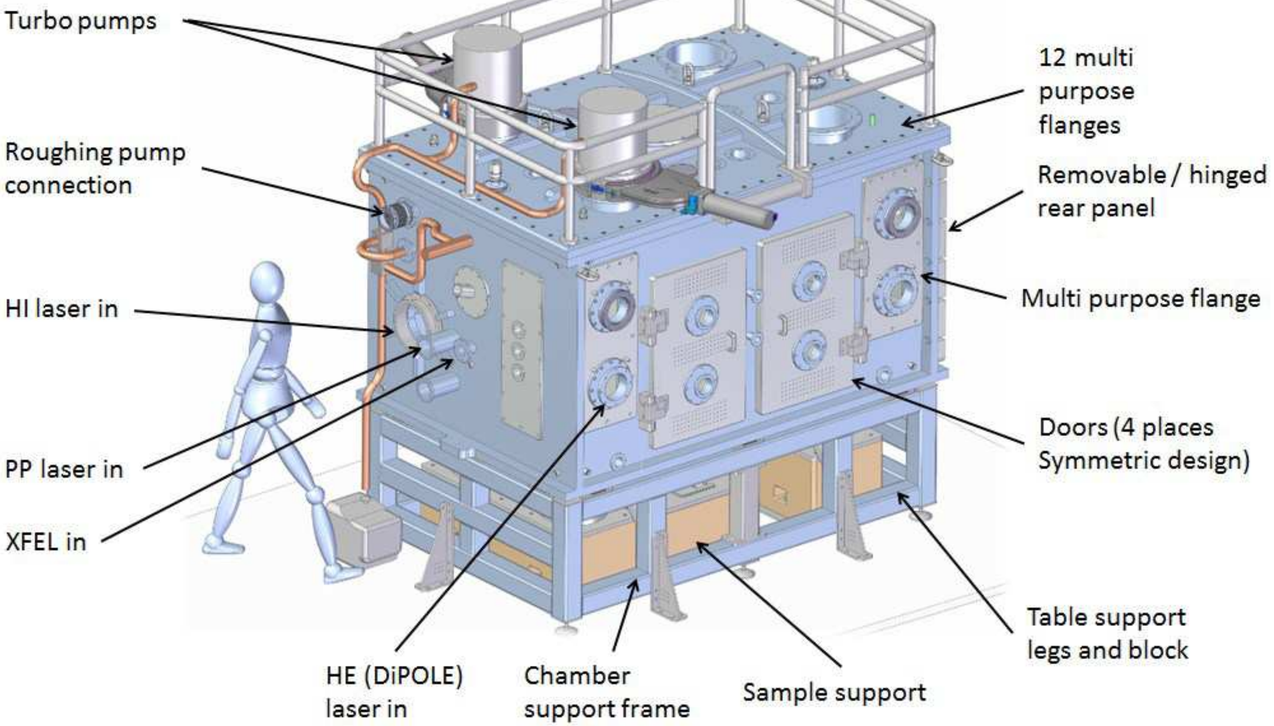


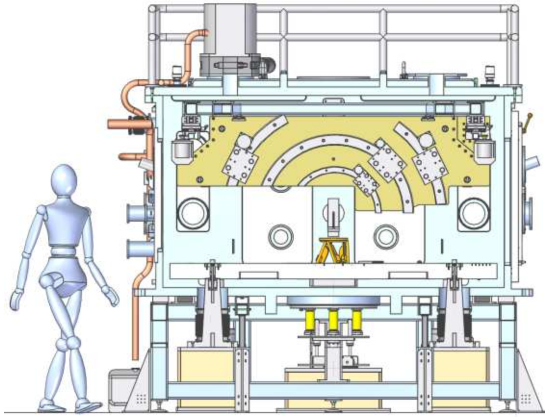
X-ray transport optics hutch



Interaction Chamber 1

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





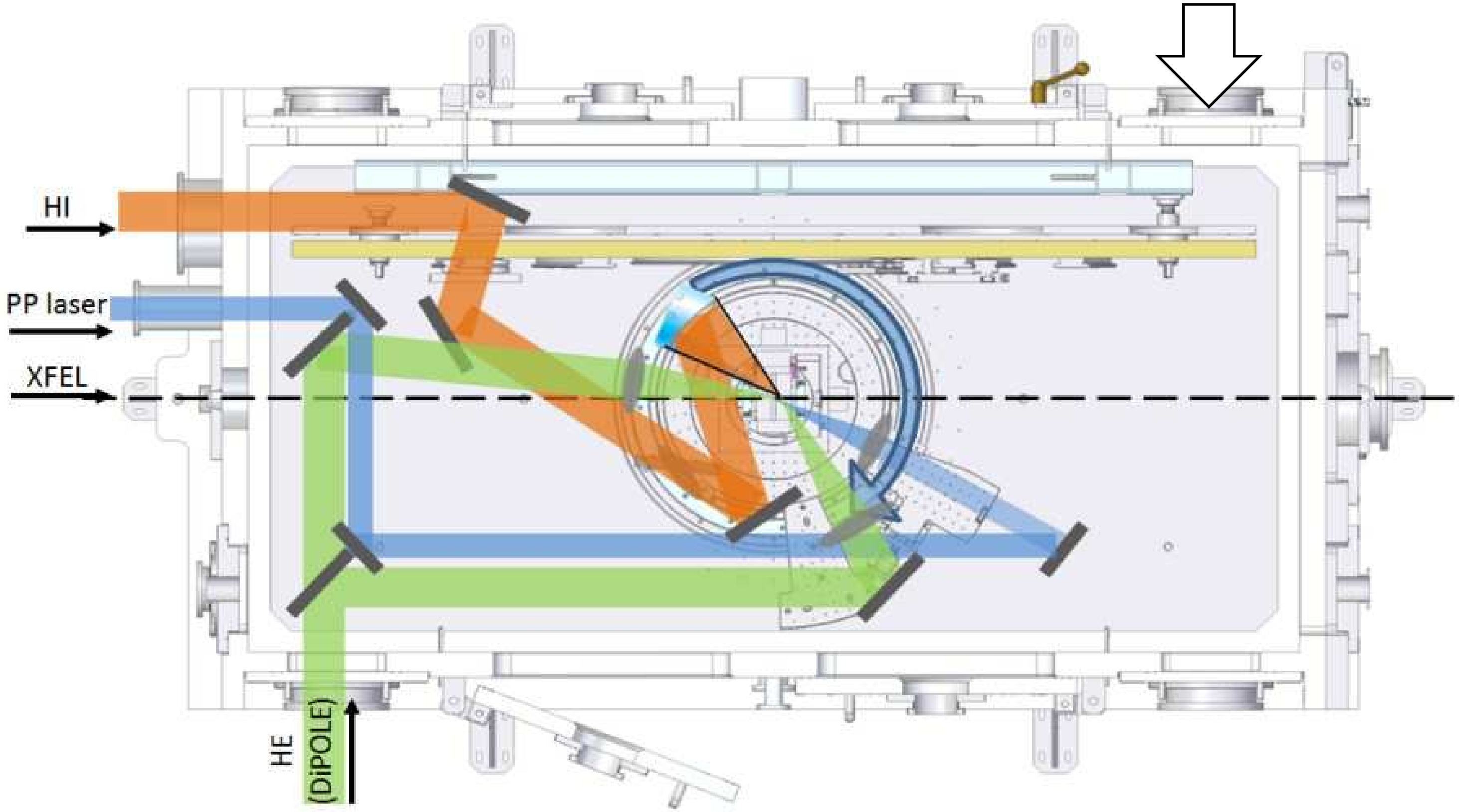
Side cut

- 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

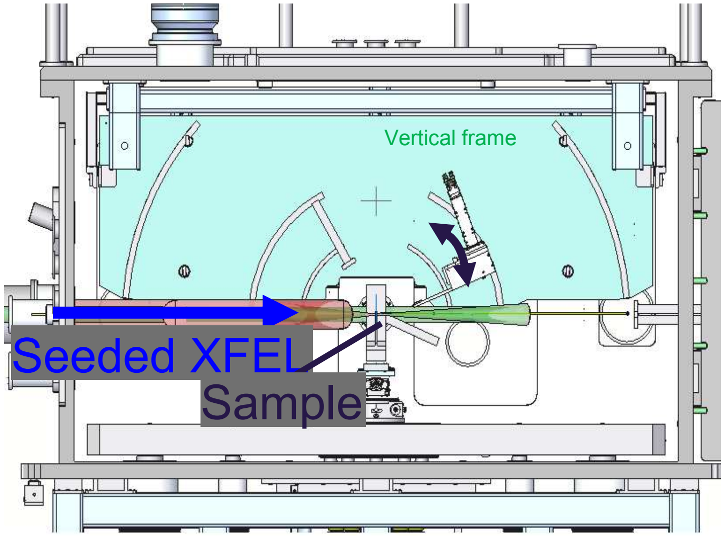
Optical probe out



XFEL beam: fixed

Optical beams: highly flexible

X-ray diagnostics



- Inside vacuum chamber:

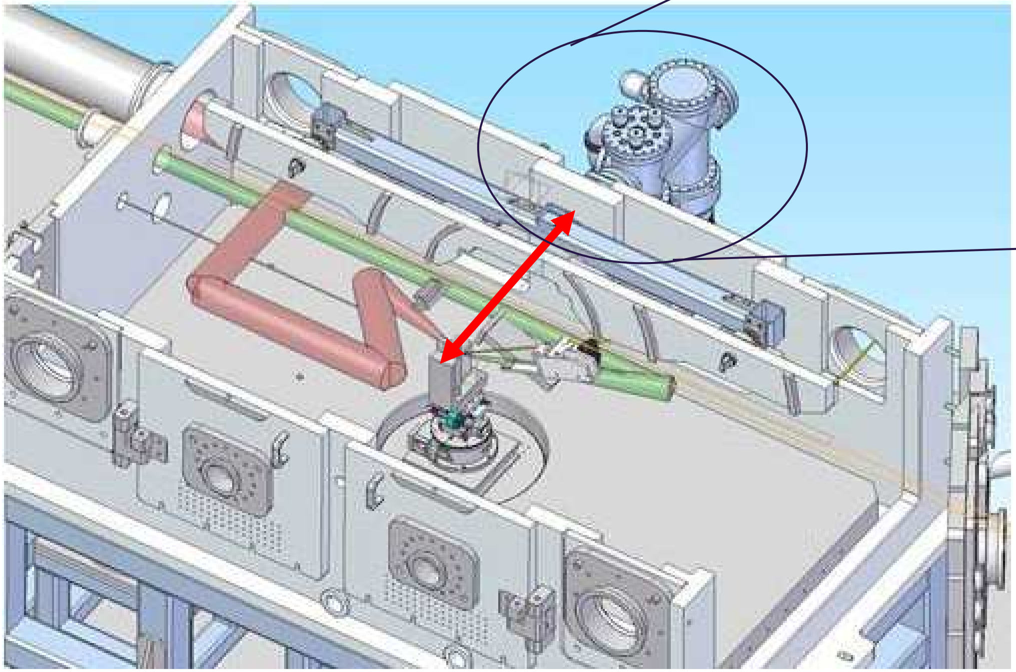
- HAPG X-ray spectrometer (ΔE = 10 eV)
- High-resolution X-ray scattering
- set-up (down to 40 meV) (BMBF?)
- X-ray diffraction area detectors

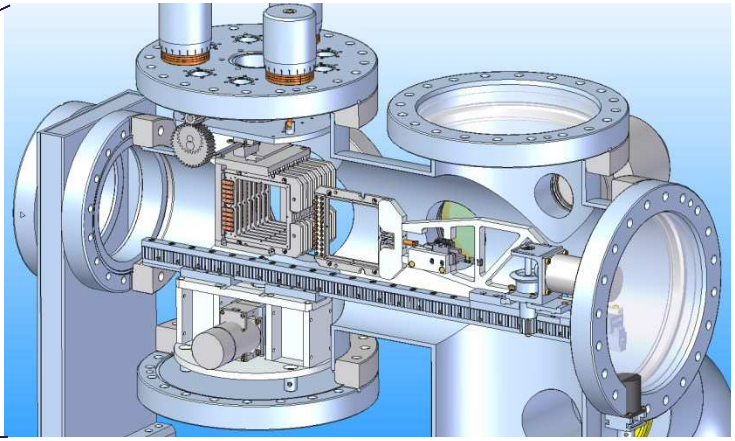
- Outside vacuum chamber (Detector Bench), HIBEF:

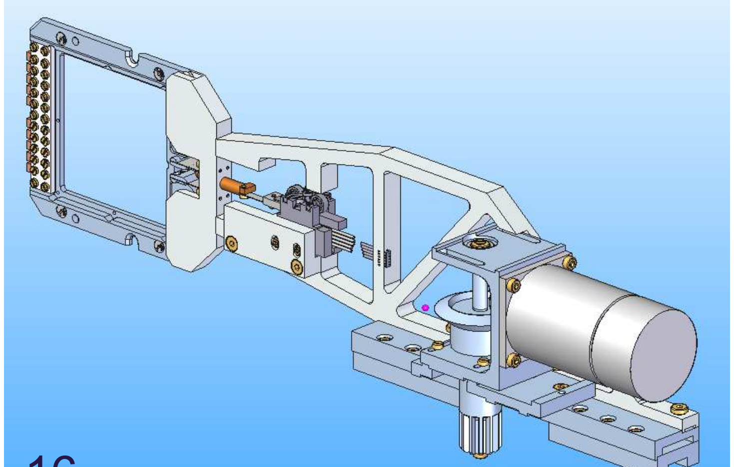
- X-ray spectrometer for XANES (upstream and downstream)
- SAXS detector at 2.5 – 6.5 m downstream from sample (HIBEF)
- Ptychography X-ray detector at 4 m downstream of the sample (HIBEF)
- Phase contrast imaging detector at 4 m downstream of sample (HIBEF)
- X-ray diffraction area detector (HIBEF)

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

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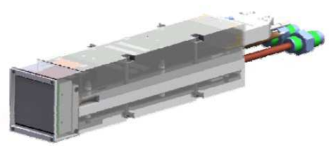
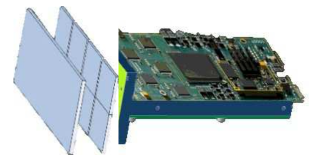
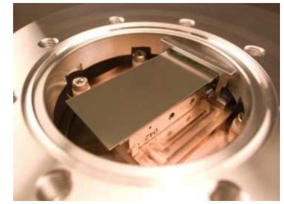
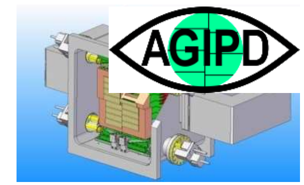
Current design is for SCS instrument

X-ray detector choices



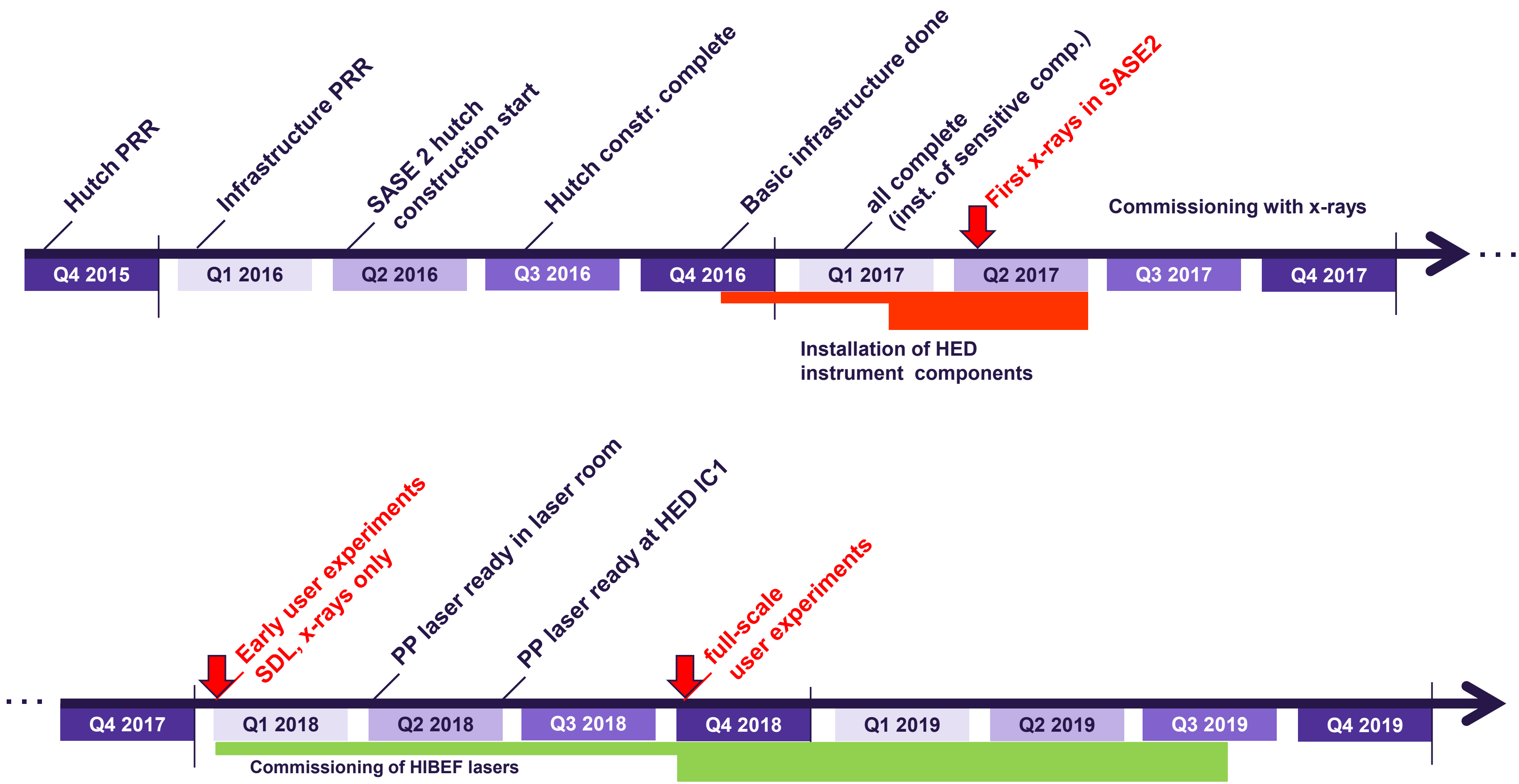






Parameter	ePix100 / 10k	Jungfrau	MPCCD	AGIPD
	LCLS	PSI	SACLA	PSI
Sensor	500 µm Si	450 µm Si	300 µm Si	500 µm Si or GaAs
Repetition	120 Hz	2000 Hz	60Hz	4.5 MHz
Pixel size	50/100 µm	75 µm	50 µm	200µm
Dyn. range at 12keV	$10^2/10^3$	10^4	10^3	10^4
Vacuum?	Yes	Maybe	Yes	Yes
EMP resistance	*HED group initiated international 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



European XFEL

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

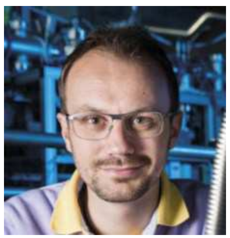
DAC experiments: dynamic DAC and double stage at 8.4 keV

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

Status of HIBEF - User Consortium

C. Baehtz

Helmholtz **I**nternational **B**eamline for **E**xtreme **F**ields

- 29.1.2015: Last HIBEF Meeting
- 29.1.2015: HGF ranking no. 2.
- 24.6.2015: HIB proposal accepted (HIBEF 20.5 Mio €).

MOUs

- LANL, LLNL (US); SIOM (CN),
- HIB-MOU DESY, xFEL and HZDR
- University of Oxford (HIBEF-UK leading Institute)
- Universities: Erlangen (D), OSU (US), Osaka….

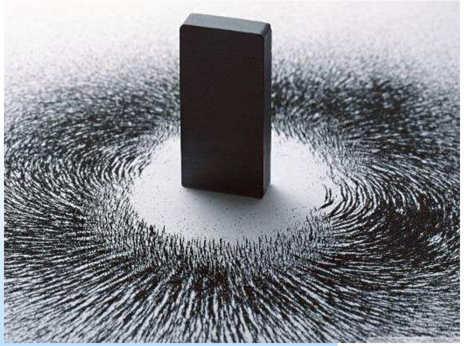
China Academy of Engineering Physics

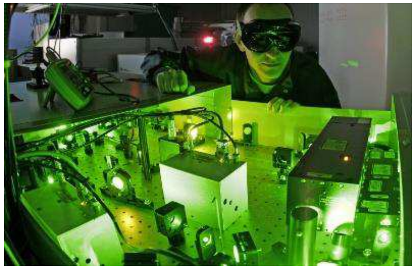
Formal signing ceremony at the China Embassy in Hamburg 29.1.2016.

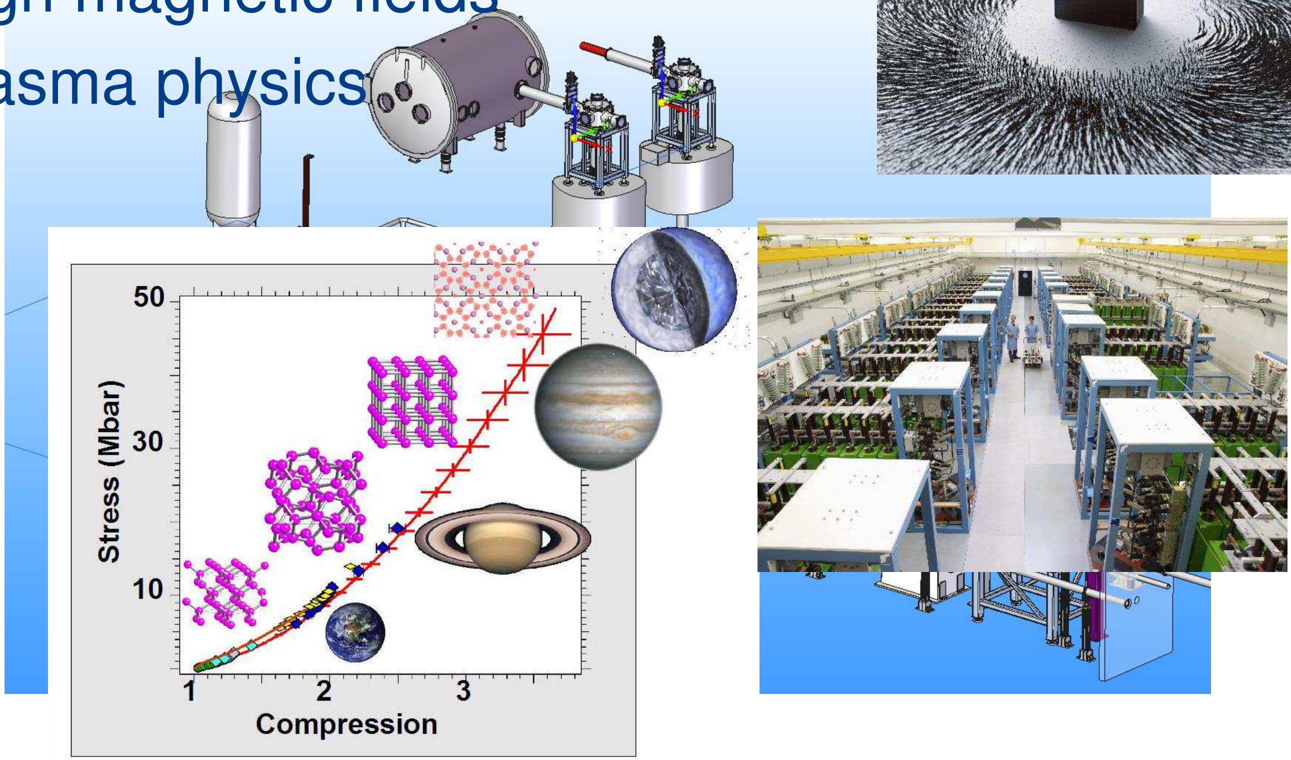
Helmholtz International Beamline for Extreme Fields

And all needs to fit in here…

- High pressure sciences
- High magnetic fields
- Plasma physics







DRESDEN concept

HZDR

HIBEF – Personal (HZDR)

- 2 Laser scientists
- 2 Laser technician
- Scientist in the field of pulsed magnetic fields
- Scientist in the field of high pressure experiments
- Plasma physicist
- Technician

… for construction and operation!

- Project Manager, controlling; coordination of in-kind contribution …

www.hibef.eu

DRESDEN concept

HZDR

HIBEF Organisation Chart

Management Board
J. Wark Oxford, E. Weckert DESY, T. Cowan HZDR,
R. Redmer Rostock

xFEL observer
U. Zastrau, T. Tschentscher

(xFEL Contact)

Scientific advisory Committee
Chair: G. Gregori
M. I. McMahon (Edinburgh)
M. von Zimmermann (DESY)
R. Cauble (US - LLNL)
B. Kaempfer (HZDR)
P. McKenna (Strathclyde)
P. Audebert (France - LULI)
K. Appel (xFEL)

Technical advisory Committee
Chair: A. Higginbotham
H. P. Liermann (DESY)
S. Toleikis (DESY)
J. Strempfer (DESY)
U. Schramm (HZDR)
J. H. Eggert (LLNL)
C. Hernandez-Gomez (CLF)
M. Nakatsutsumi (xFEL)

HIBEF coordination
C. Bähtz, W. Seidel (U. Zastrau)

Targets
A. Pelka (M. Nakatsutsumi)

High-Energy Laser
T. Butcher CLF (G. Priebe)

DAC
H.P. Liermann DESY (K. Appel)

Magnetic fields
T. Herrmannsdörfer (J. Moore)

X-Ray instr.
A. Schropp DESY (K. Appel)

High-Intensity Laser
U. Schramm (G. Priebe)

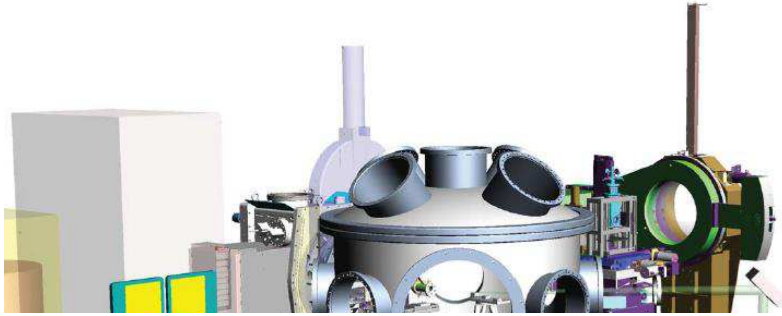
Res. Tech.
P. Kaever

Control Systems
J. Dreyer (B. Heisen)

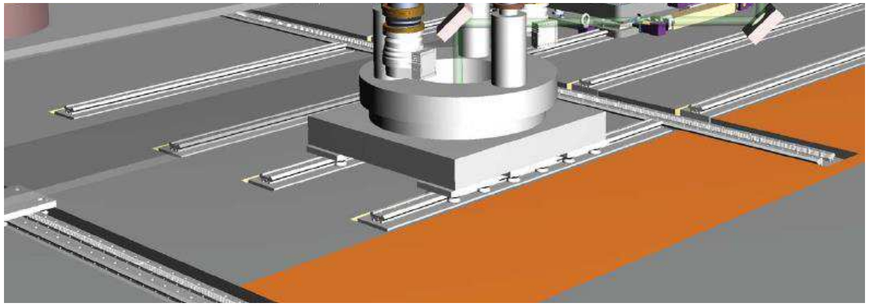
Building
D. Reichelt

Diamond **A**nvil **C**ell setup for HIBEF at HED/xFEL

Workshop at the 26.1.2016 @ DESY / xFEL-UM



1. HIBEF - Workshop about instrumentation

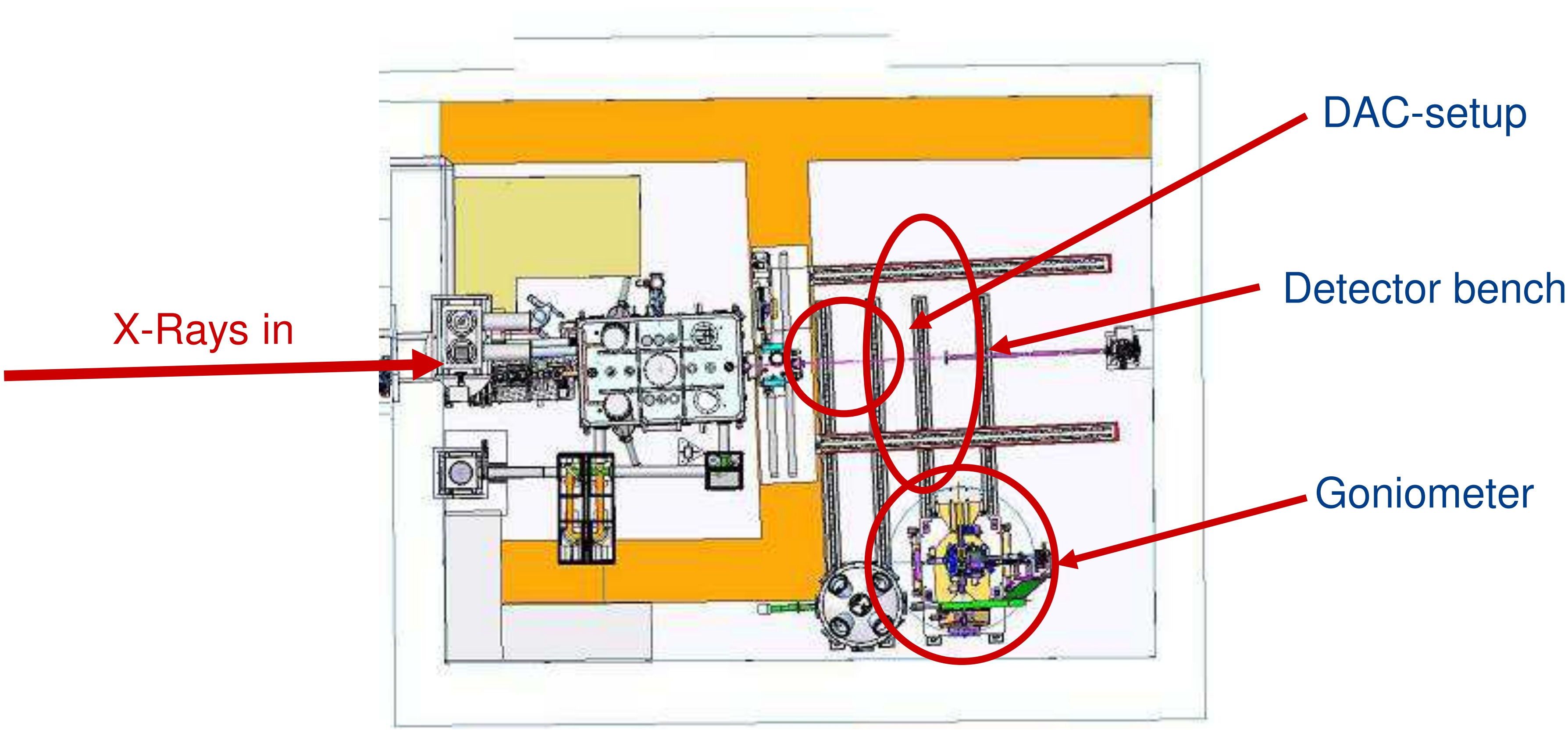


"Conceptual design of the DAC-setup at HIBEF"

by Hanns-Peter Liermann DESY

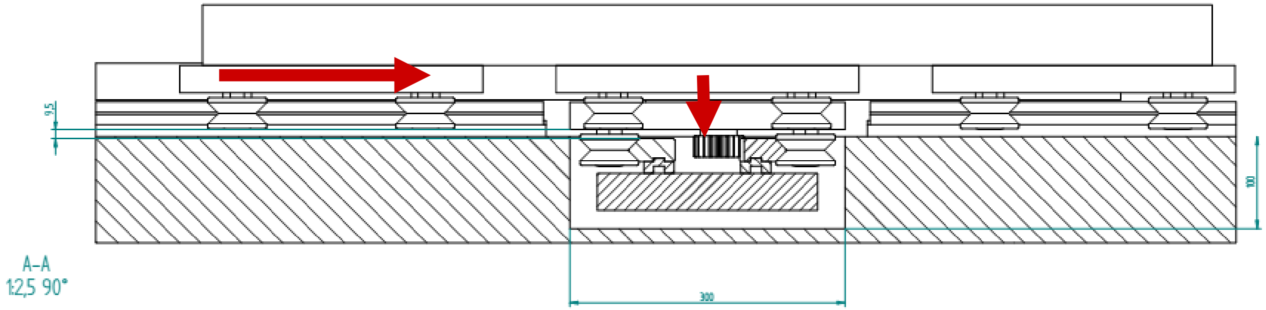
X-Ray Instrumentation

- Exchange of the different experimental setups
- Manually movable DAC setup and goniometer
- Motorized detector bench

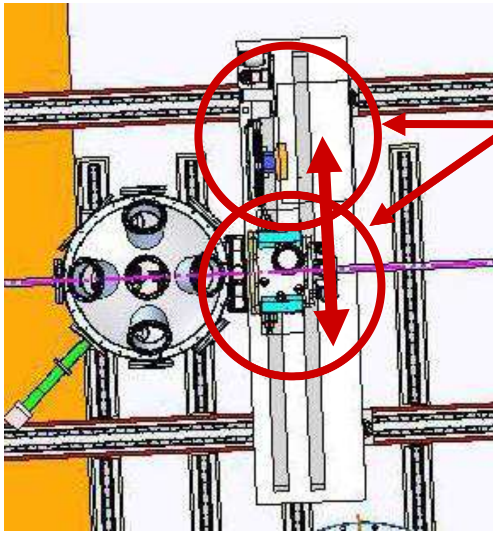


X-Ray Instrumentation – Rail system

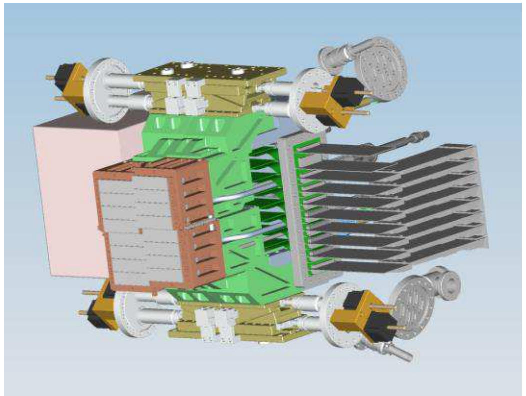
- Rails in different high
- DAC setup and goniometer - interrupted rails
- Motorized detector bench – unbroken rail system
- Detector bench rails at ground level



X-Ray Instrumentation – Detector bench



- 2 Positions for detector
- Travel range perp. beam ca. 140 mm
- AGIPD permanently
- Second position is flexible equipped.
- Second table behind the detector bench



Detector	Sensor	Pixel	Repetion	Misc.	Method
AGIPD	GaAs (Si)	200 µm	4.5 MHz	300kg; in vac.	XRD; high Q-range
PE 0822	amorph. Si	200 µm	25-100 Hz	only 2.2 cm thick	XRD; high Q-range
Spectrometer	"The single-shot incident spectrometer at HED" Bolun Chen CAEP				
Jungfrau	Si	75 µm	2kHz		PCI/XRD
FLI / PCO	4k*4k CCD	9 µm	0.3 Hz		PCI
PIXIS 2048b	2k*2k	13 µm	0.3 Hz		PCI / SAX

Member of the Helmholtz Association
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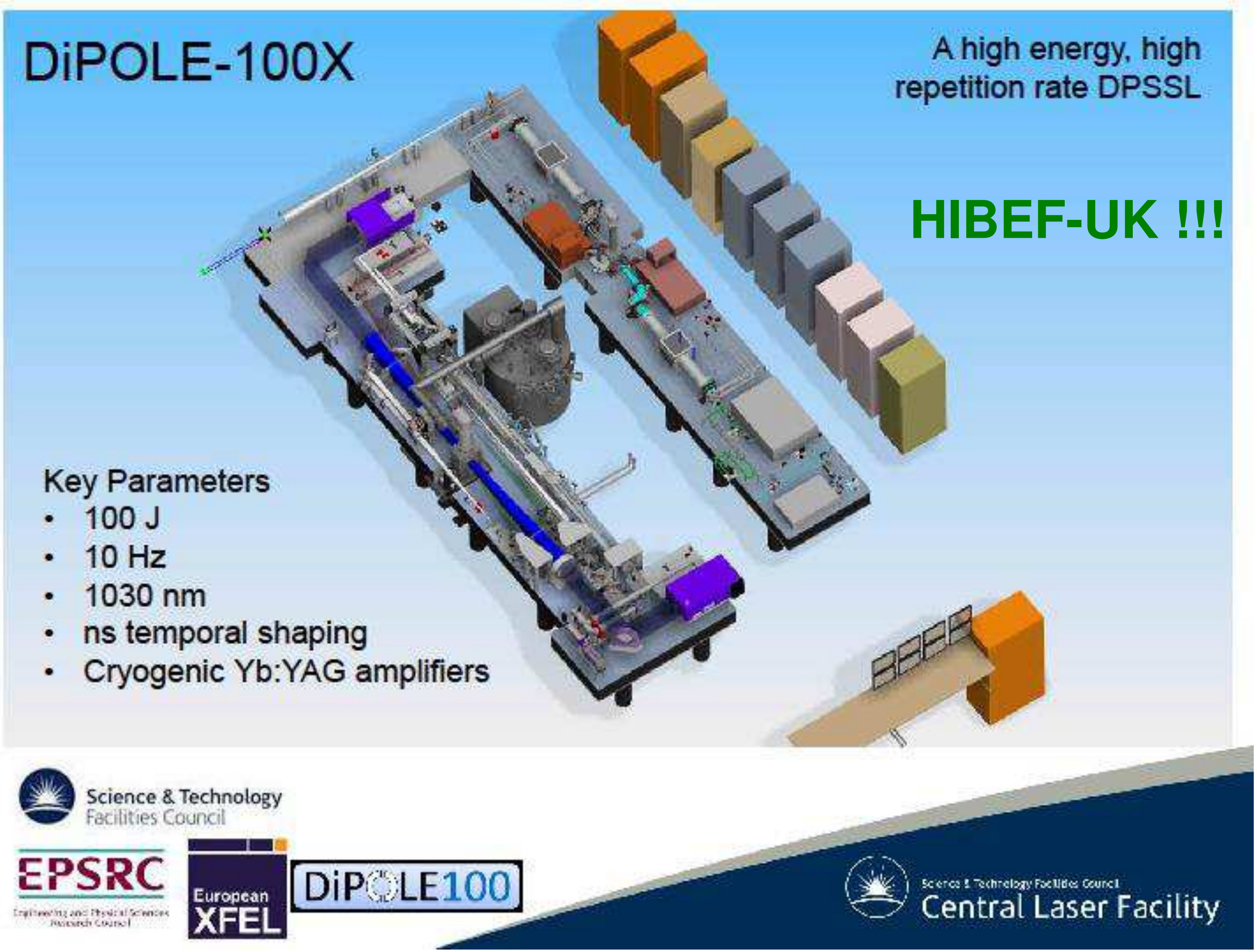
High Energy Laser



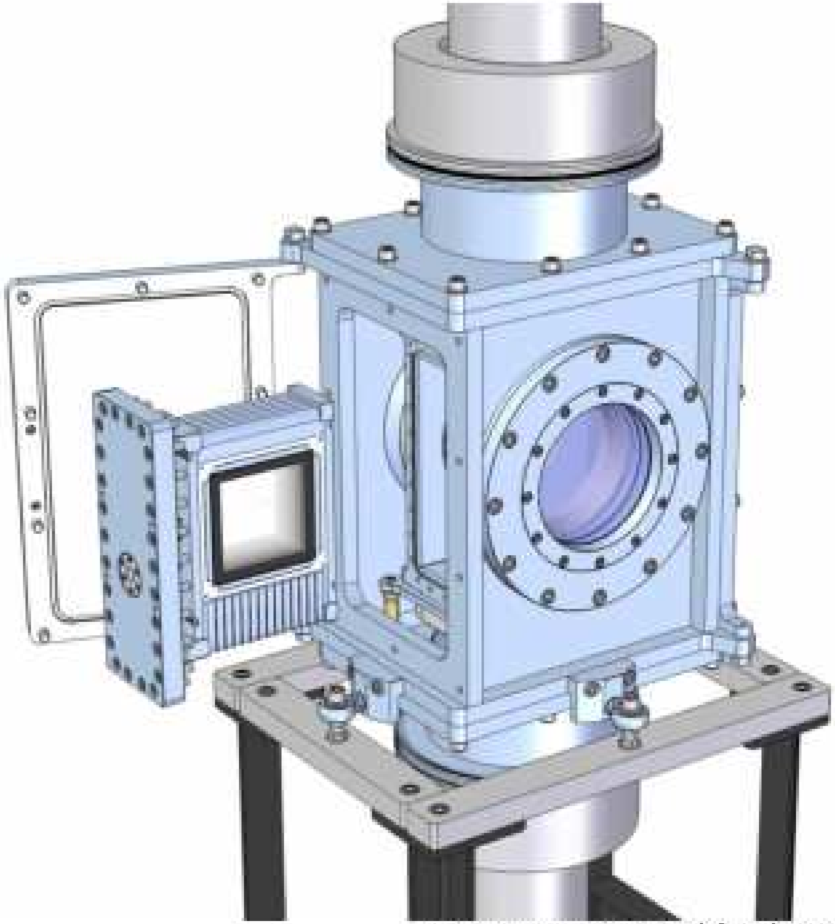
T. Butcher

High Energy Laser

Key Parameters

- 100 J
- 10 Hz
- 1030 nm
- ns temporal shaping
- Cryogenic Yb:YAG amplifiers

100 J DiPOLE system for HiLASE delivered.



100J cryogenic amplifier head

High Intensity Laser

Laser parameter

- Pulse duration 25f
- Peak Power 100TW at sample position
- 10 Hz operation; single trigger option
- Fail safe long term operation (spare pump lasers)
- State-of-the-art intensity contrast

Amplitude TECHNOLOGIES Nothing but ultrafast.

Continuum

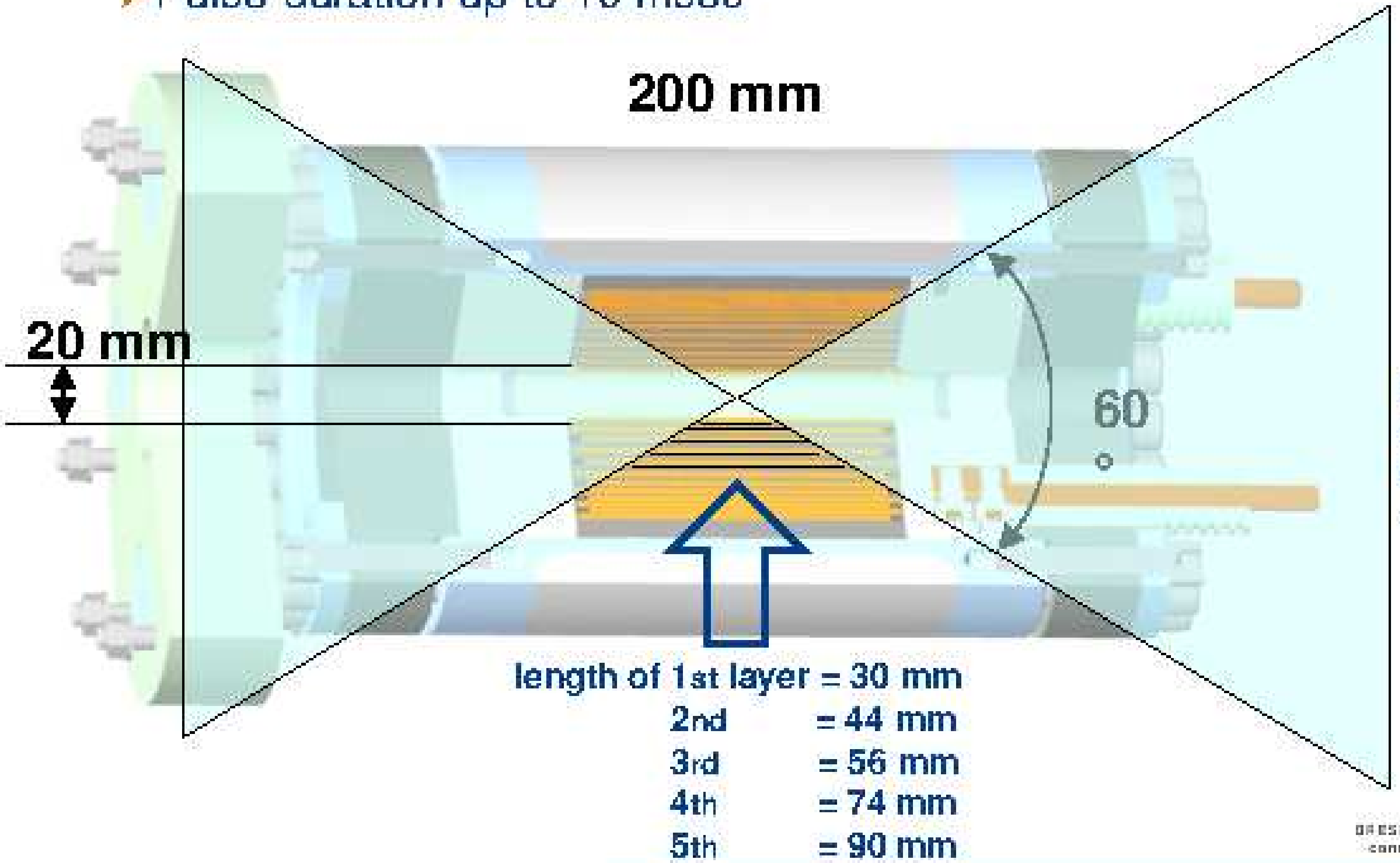
THALES

DRESDEN concept HZDR

Pulsed Magnetic fields

Coil parameter:

- Max. 60 T; 1 % field homogeneity over the sample
- 8 mm^3 sample volume; 10-20 mm bore size
- ±30 degree opening angle
- Pulse duration up to 10 msec



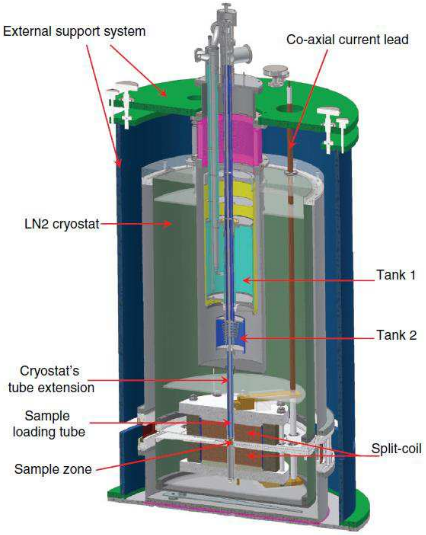
$L = 1.45$ mH
$B \sim 50$ T @ $I_{max} = 22$ kA
$t(I_{max}) = 3.3$ ms
$s_{vM} \sim 3$ GPa

Dr. C. Baehtz| Institute of Radiation Physics | www.hzdr.de

Pulsed Magnetic fields

Pulser

- 1 MJ – 100kA – 24kV
- 20*0.175 mF capacitors

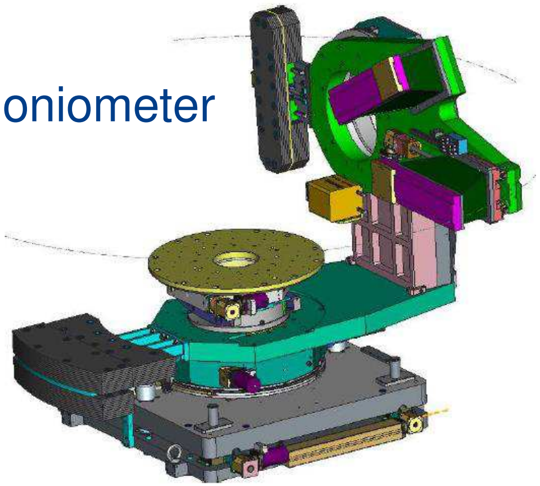


Cryo

- 2-300K sample temperature

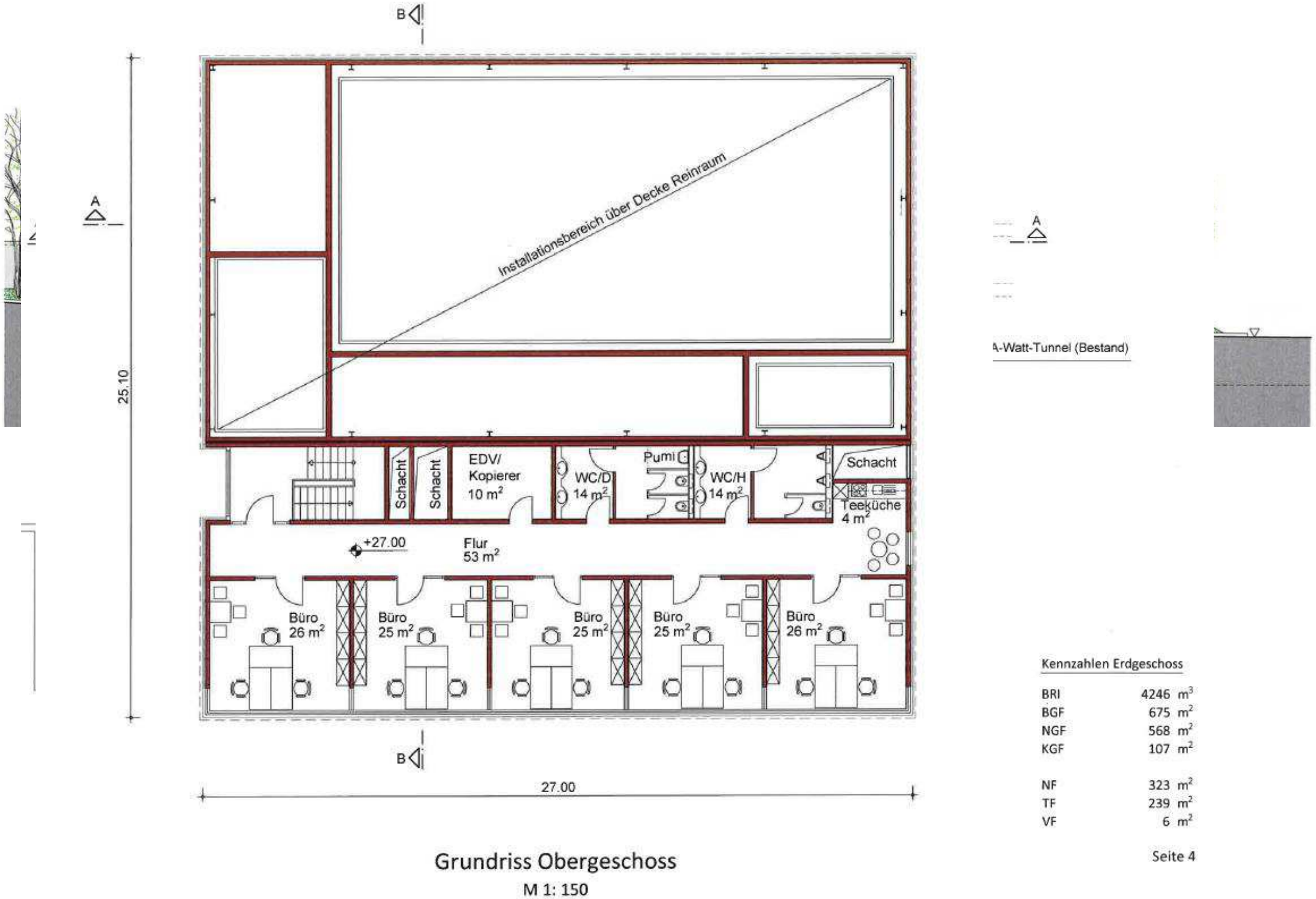
XRD

- Heavy load 6-circle goniometer
- AGIPD-Module
- Fast APD or similar
- Phase retarder



HIBEF Building

- Laser room for future upgrade
- Clean room
- Pulser
- Offices



Targets for Advanced Laser Light Sources Workshop
29-30 August 2016
HZDR, Institute of Radiation Physics

… how to develop a network for target preparation?
… what are the requirements on targets for advanced laser light sources?

Join the discussion!

for further information
i.prencipe@hzdr.de

HZDR
Laserlab Europe
ESRF
eli Nuclear Physics
EUCALL
eli beamlines
Science & Technology Facilities Council
DRESDEN concept
scitech PRECISION MICRO LASER TARGETS

Credits Anna Ferrari

HIBEF: US Constortium

Robert Cauble
Jupiter Laser Facility Director
LLNL

28 January 2016

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

LLNL-PRES-681209

US partners

- The US consortium is bureaucratically complex and still evolving
- Los Alamos National Laboratory has signed an MOU with HZDR
- Lawrence Livermore National Laboratory has signed an MOU with HZDR
- Ohio State University will participate (MOU)
- Stanford Linear Accelerator Laboratory will participate (doesn't need MOU)
- Lawrence Berkeley National Laboratory expects to participate
- Laboratory for Laser Energetics (Rochester) is still in discussion

Most of these institutions are funded by the US Department of Energy

US DOE has confirmed that participation in HIBEF is appropriate

LANL has a keen and focused interest in HED XFEL experiments

MOU 0081 with HZDR to collaborate on Extreme-Matter Research

Parallels scientific mission of **MaRIE: Ma**tter and **R**adiation **I**n **E**xtremes

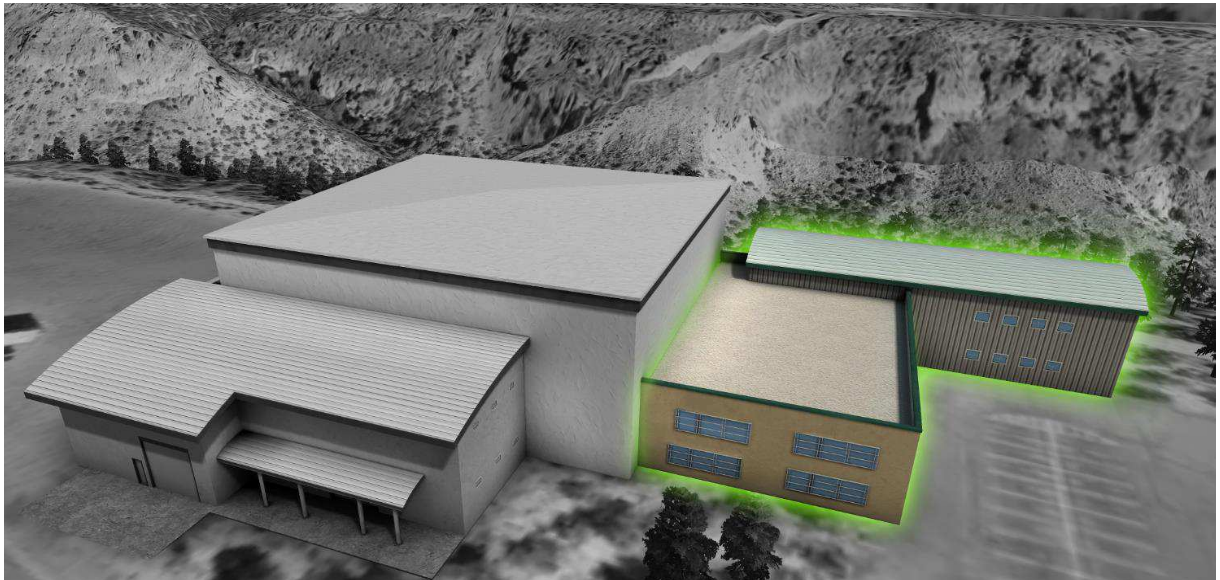
- MaRIE is $2B LANL signature facility proposed to DOE
- CD0 (mission need) approval imminent
- Study materials in extremes

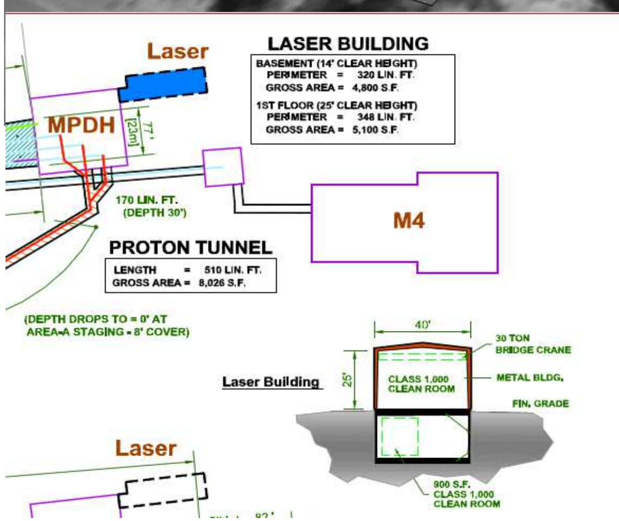
Scientific topics include:

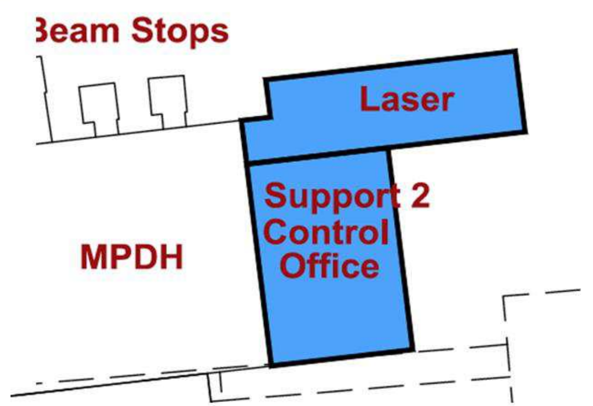
- High Energy Density Physics
  including Warm Dense Matter and mix at interfaces
- Dynamic materials including phase transitions
- Magnetic phenomena, including functional magnetic materials and
  f-electron phenomena

Courtesy Juan Fernandez

LANL has a keen and focused interest in HED XFEL experiments; MaRIE plans to include an XFEL







Courtesy Juan Fernandez

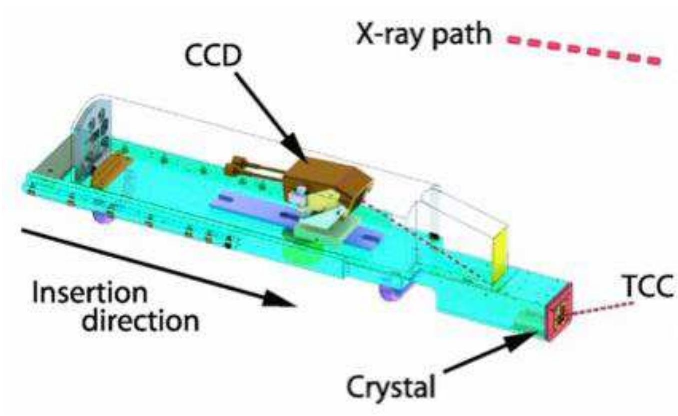
LANL plans in-kind contributions to HIBEF aimed at a program to explore extreme matter with x-rays

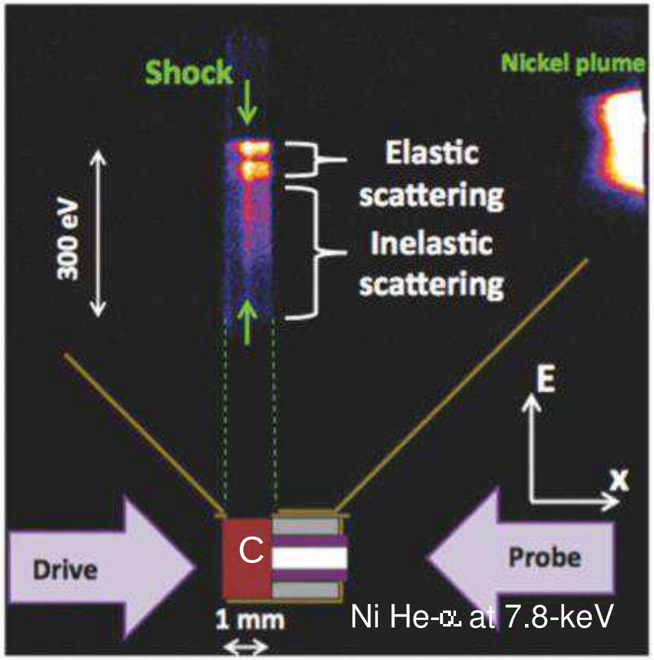
- Advancing scientific program with x-ray probing
  - X-ray Thomson scattering (XRTS) development
    - Warm-dense matter characterization
    - Bulk probing (e.g., temperature) of dynamic materials
  - Coherent & high-resolution imaging
    - Dynamic materials (e.g., phase transitions)
    - Interface mix in WDM and plasmas
- Contributions in kind
  - X-ray spectrometer for 1D spatially resolved XRTS
    - $1M+ in development & commissioning @ Trident and Omega
  - Postdoc + 0.25 Mentor, physically @ HIBEF part-time to commission & use
    - $300k / year

Courtesy Juan Fernandez

LANL plans in-kind contributions to HIBEF aimed at a program to explore extreme matter with x-rays

iXRTS





"Imaging x-ray Thomson scattering spectrometer design and demonstration,"
E.J. Gamboa et al., Rev. Sci. Instrum. 83, 10E108 (2012).

Courtesy Juan Fernandez

LANL anticipates capabilities and conditions of extreme matter worth investigating on E-XFEL

- Isochoric heating
  - Create WDM and sharp plasma interfaces
  - Subject materials to off-Hugoniot loading paths
  - Study phase-transition dynamics, etc.

- High-pressure dynamic loading
  - Up to ~ 1 Mbar
  - Strain rates ~ 10^6 – 10^9

- Warm-dense matter conditions
  - Quasi-homogeneous, ~ solid density
  - Few – tens of eV
  - Area ~ $(100mm)^2$, thickness ~ 10mm

Courtesy Juan Fernandez

LLNL understands that XFELs offer a new window into extreme science

Unlike LANL, LLNL has no plans to build an XFEL but LLNL scientists have and will continue to find enormous utility in XFELs

- Collaborating with LCLS from its design stage
- Signed MOU with HZDR

Scientific topics include:

- High Energy Density Physics in all regimes
- Dynamic materials including phase transitions
- Effects of strong magnetic fields on plasma, and *vice versa*

LLNL in-kind contributions are geared toward making HIBEF/E-XFEL more viable for all users

- Contributions may include:

  - LPOM-lite for DiPOLE (pulseshaping)
  - T-REX sub-1-ps resolution x-ray streak camera + 0.5 postdoc in place at E-XFEL
  - dynamic DAC + postdoc in place at E-XFEL
  - 0.5 FTE to assess long-pulse beam transport, liaise with HIBEF/E-XFEL,
  - frequency doubling crystal for DiPOLE

- Development of LPOM for NIF took 50 man-years. We think we can produce a "lite" version for smaller lasers

- X-ray streak camera is a several-$M effort

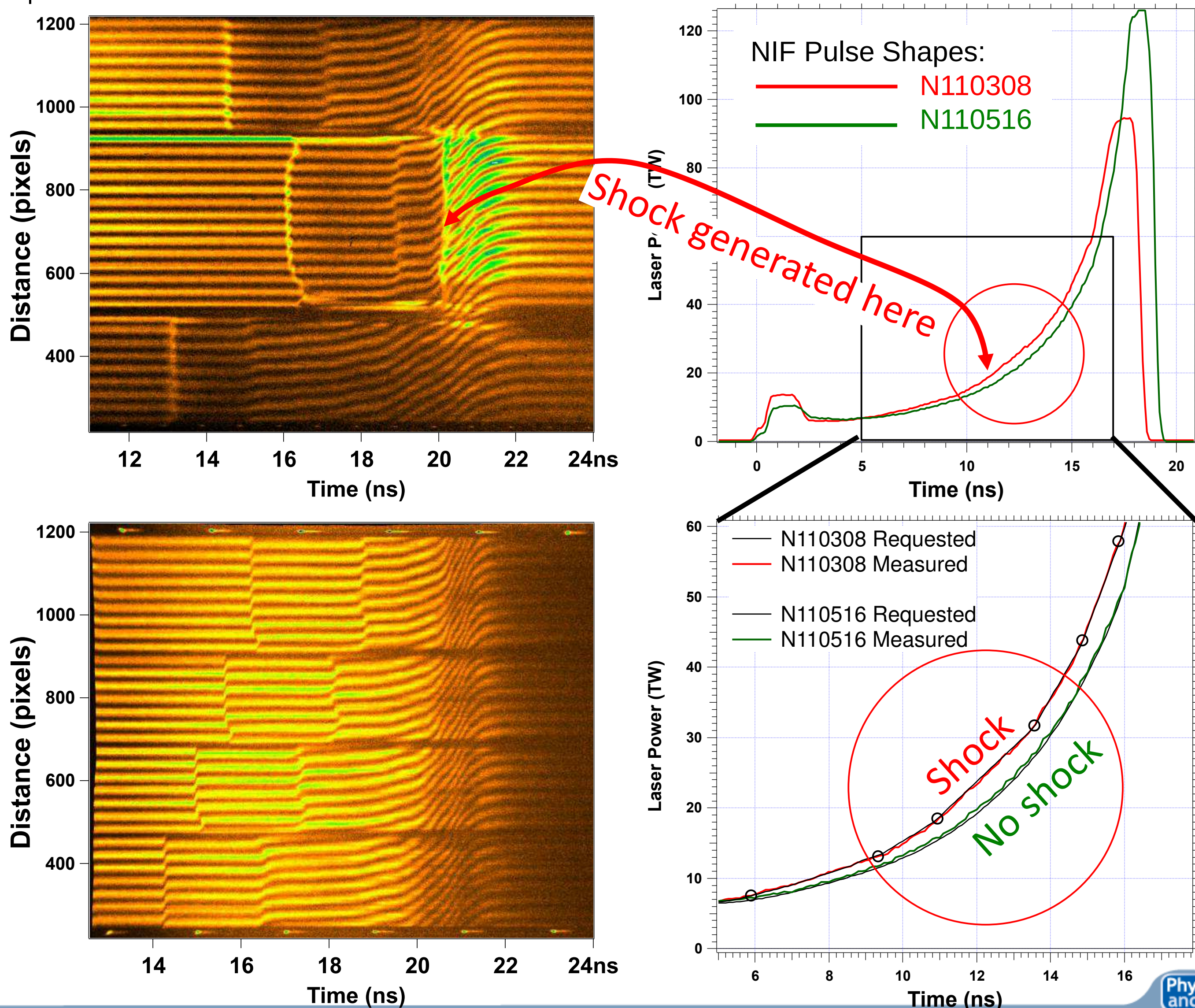
- d-DAC development is a several man-year effort

Laser Performance Optimization Module - LPOM

NIF ramp EOS measurements on diamond

N110308
27 Mbar

N110516
37 Mbar

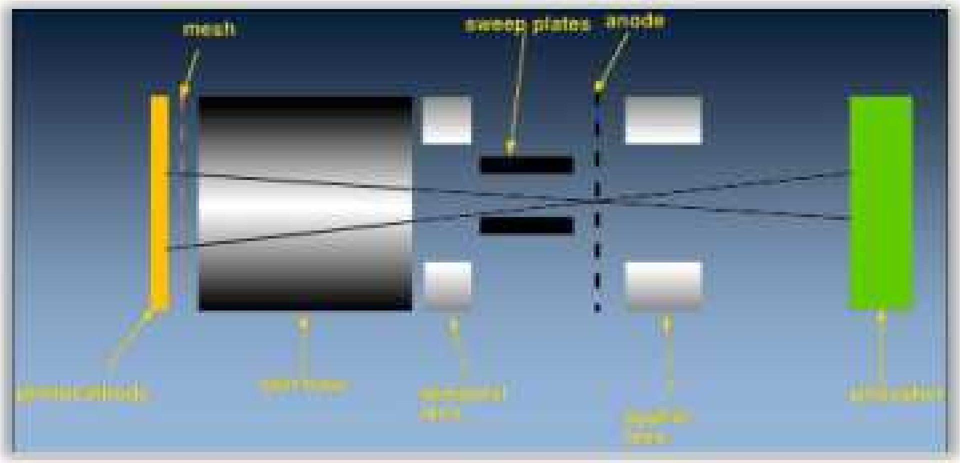


Laser Performance Optimization Module - LPOM

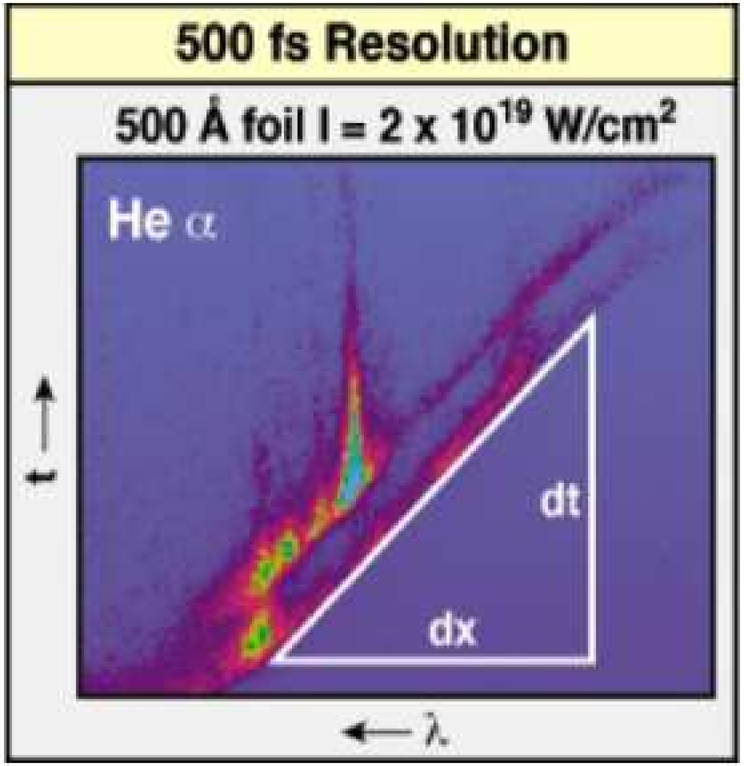
- Capability to modify pulse shape as needed and on the fly
- Keeps laser system from propagating a damaging pulse
- LPOM consists of some pick-off optics and software for backward prediction
- ~ One year to develop from present NIF-LPOM configuration
- Specialized for DiPOLE

Ultra-fast x-ray streak camera – T-REX

- T-REX streak camera designed for sub-ps resolution
  - spatial and temporal lenses separated (reduces curvature but difficult to model)
  - uses a pulsed charge cathode (faster electron extraction, faster resolution)

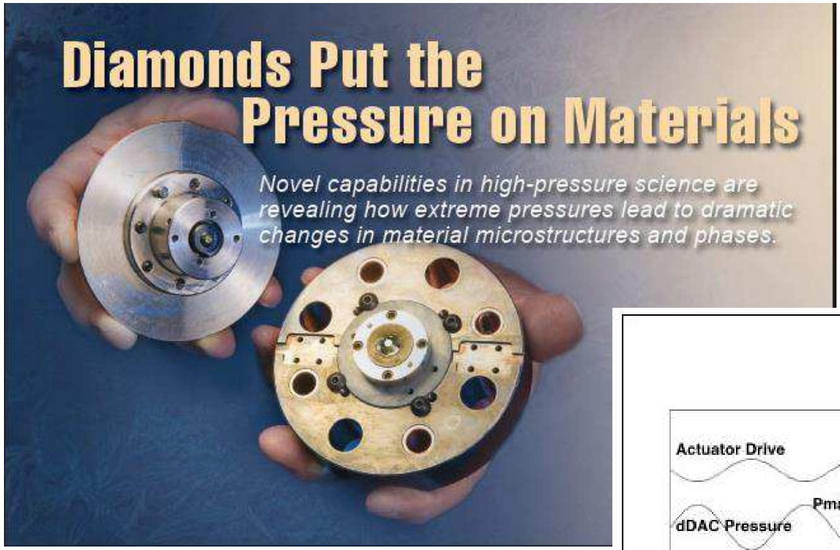


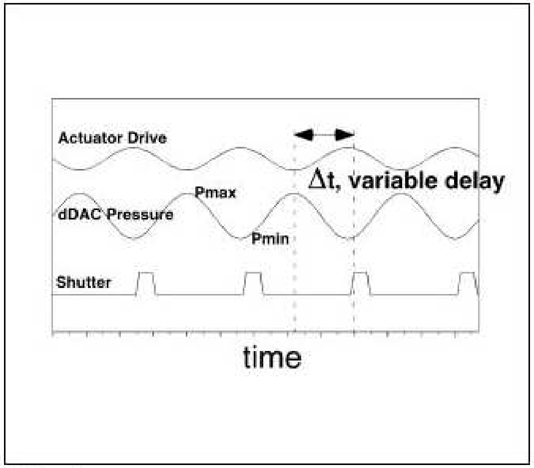
E.V. Marley et al., "Ultrafast x-ray streak camera for ten-inch manipulator-based platforms," Rev. Sci. Instrum. **83**, 10E106 (2012)

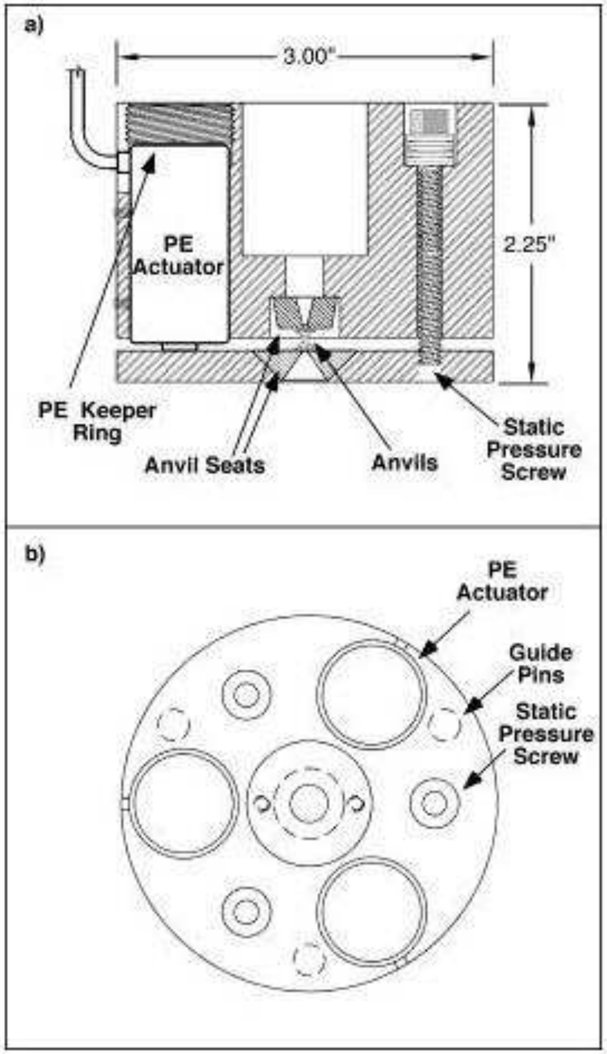


Dynamic diamond anvil cell

- Robust design by Will Evans' group
- Expect to place a postdoc at DESY for DAC expts

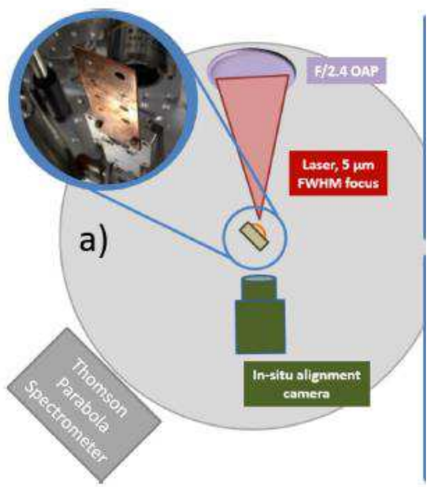


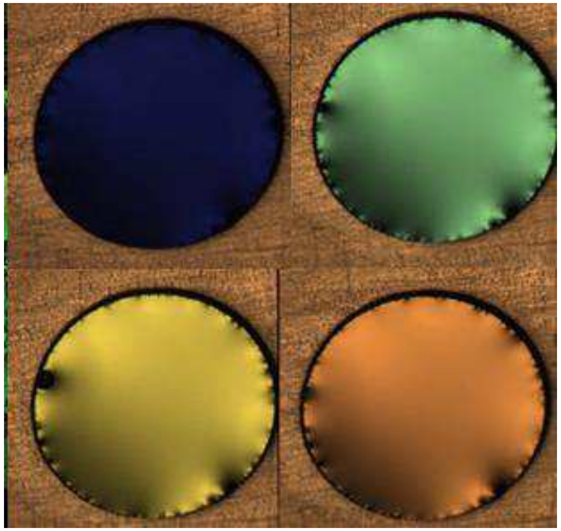




Ohio State will contribute an on-demand device for solid, variable-thickness targets at high-rep-rate

- **Ohio State has begun development of a technique for producing liquid crystal** targets with thicknesses of 50 to 5000 nm
- **Present configuration is low**-Z only, with a rep-rate of ~ 1/minute
- **Rep**-rate is up-scaleable, certainly to 0.1-1 Hz. Looking at ways to incorporate higher-Z components





P. L. Poole et al., " Liquid crystal films as on-demand variable thickness (50-5000 nm) targets for intense lasers," Phys. Plasmas **21**, 063109 (2014)

Courtesy Douglass Schumacher

SLAC expects to field cryogenic H_2 jet capability

- A prototype unit has been fielded at LCLS, Jupiter Laser Facility, HZDR
- Roughly \$0.5M

Jet source assembly

Cryostat on XYZ manipulator

Hydrogen Jet

Courtesy Siegfried Glenzer

LBNL in-kind contributions are being discussed

- What has been proposed:

  - x-ray spectrometers developed at the Advance Light Source

  - spectroscopic analysis codes

  - 0.5 postdoc situated at E-XFEL

- No MOU yet. Working with University of California office. No problems expected.

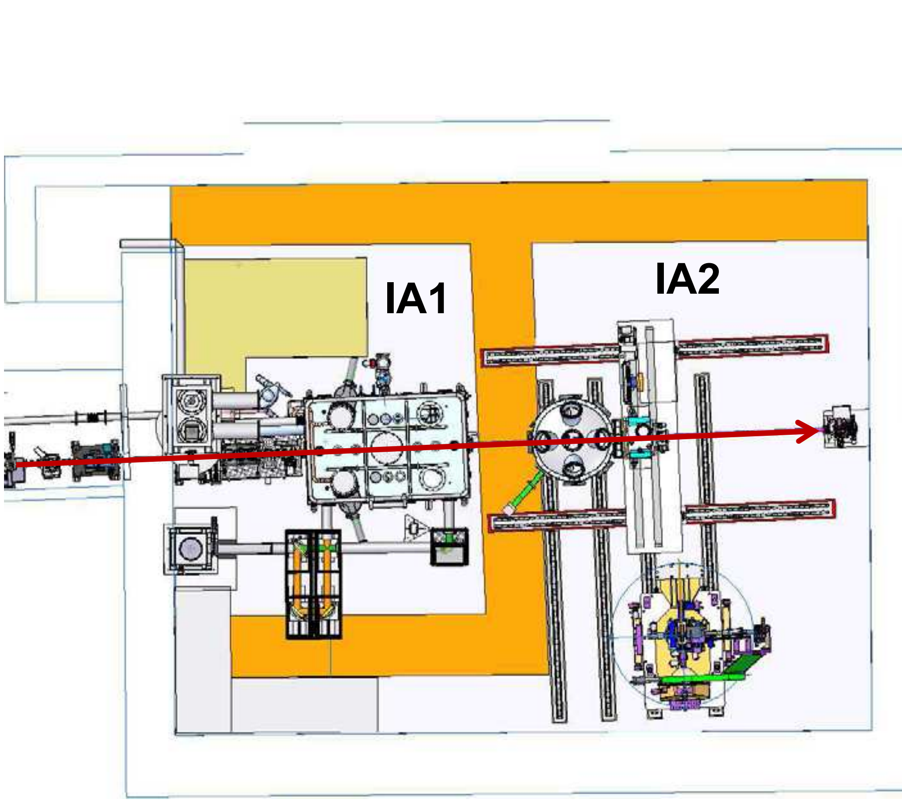
To conclude, what we plan to provide

- iXRTS Thomson scattering spectrometer (LANL)
- LPOM-lite pulse-shaping capability (LLNL)
- T-REX sub-ps resolution streak camera (LLNL)
- Dynamic DAC (LLNL)
- Ensuring 2ω operation for DiPOLE
- Liquid crystal, high-rep-rate target mechanism (OSU)
- Various spectrometers (LBNL)
- Spectroscopic analysis codes (LBNL)
- Cryogenic H_2 jet system (SLAC)
- Up to 3 postdocs on-site (LANL, LLNL, LBNL) + 0.5-0.75 senior personnel (LANL,LLNL)

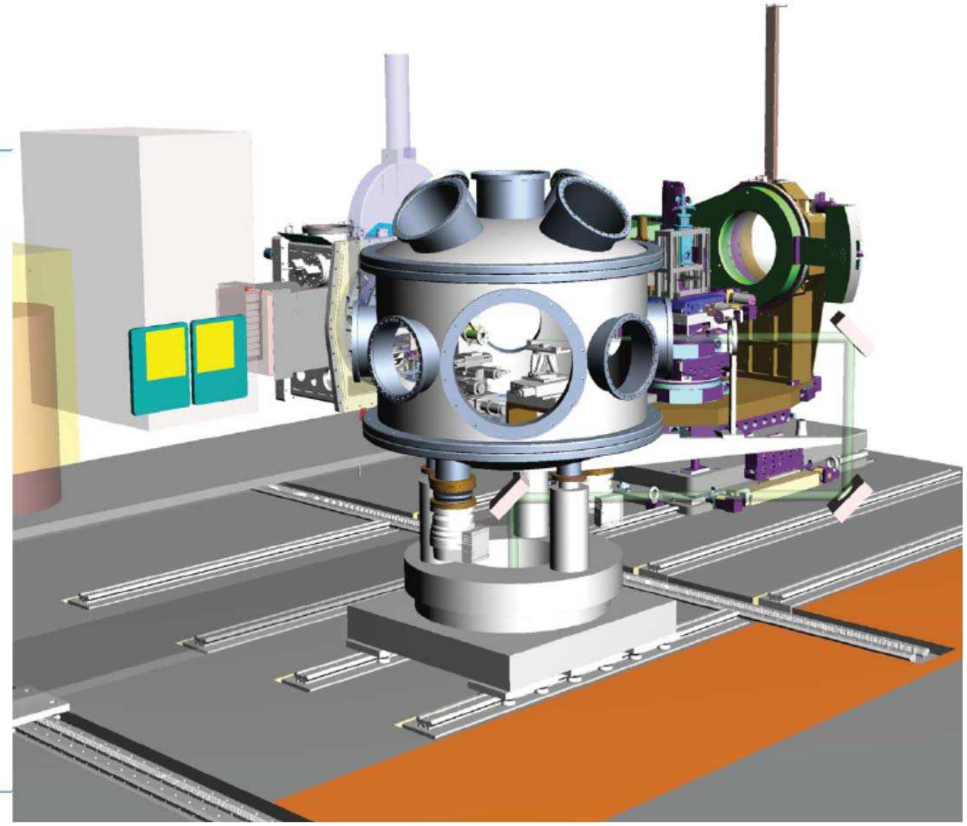
Still under discussion

- A wide variety of items from LLE

Summary of the Workshop “Conceptual Design Report (CDR) Diamond Anvil Cell Setup for HIBEF at the HED/XFEL”



Top view of the HED Hutch



Side view of the DAC Chamber at HED

H. P. Liermann, H. Damker, Z. Konôpková, K. Appel, A. Schropp, C. Baehtz

HELMHOLTZ | GEMEINSCHAFT

DESY

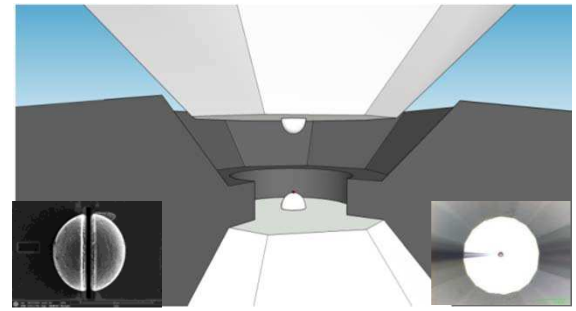
Summary Workshop "Conceptual Design Report (CDR) Diamond Anvil Cell Setup for HIBEF at the HED/XFEL"

Task of the Workshop

1st Part => Sharpened the Science Case

- Reiterated and expanded the science case
- Identified priority experiments
- Identified ultimate experiments

=> to be able optimize experimental setup

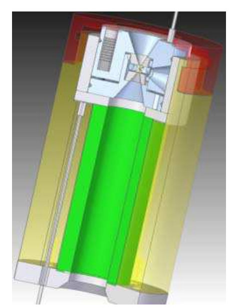


Dubrovinsky et al. 2012, 2015 & submitted.

dsDAC

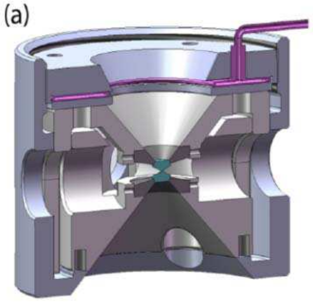
2nd Part => Review technical plans of a DAC setup at the HED

- Status of the DAC, mDAC, dDAC and dsDAC in conjunction with pulsed laser and resistive heating
- Identified the limits of "dynamic" DAC experiments at 3rd generation sources
- Experimental concept to conducted DAC experiments at the HED
- Discussed limitation of the DAC experiments at the XFEL
- Talked about the current design of the DAC setup
  - o Vacuum Chamber
  - o Detectors and access to reciprocal space
  - o Time Line



dDAC

(a)



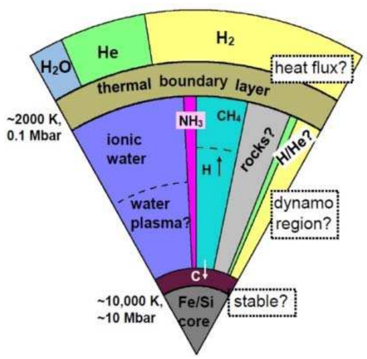
Sinogeikin et al. 2015

mDAC

Summary Workshop "Conceptual Design Report (CDR) Diamond Anvil Cell Setup for HIBEF at the HED/XFEL"

Sharpen existing science cases and add new once

- Exploration of physical properties and stabilities of phases at the pressure/temperature/strain rate condition of the interior of extrasolar planets
- Exploration of compression rate dependence on physical properties and stability of phases in the strain rate regime above 10^{-1}/s to 10^{4}/s
- Study of electron ion relaxation in the pulse laser heated or isochoric heated DAC
- Study of early stages of crystallization or phase separation by means of phase contrast Imaging in normal and radial geometry
- Study of thermal transport properties (diffusion) in the DAC at high P and T
- Determination of strain distribution using coherent imaging and characterization of nano particle systems
- Study of phase transition kinetics and intermediate states on the ps time scale



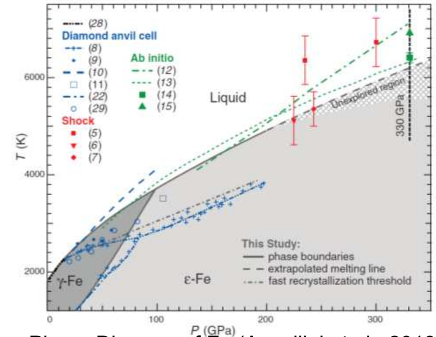
Ice Giant Planet like Uranus
(courtesy of N. Nettelmann)

Summary Workshop “Conceptual Design Report (CDR) Diamond Anvil Cell Setup for HIBEF at the HED/XFEL”

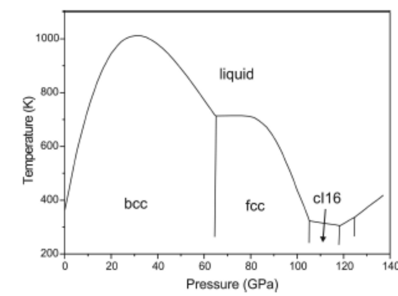
Priority Experiments

(feasible & major impact)

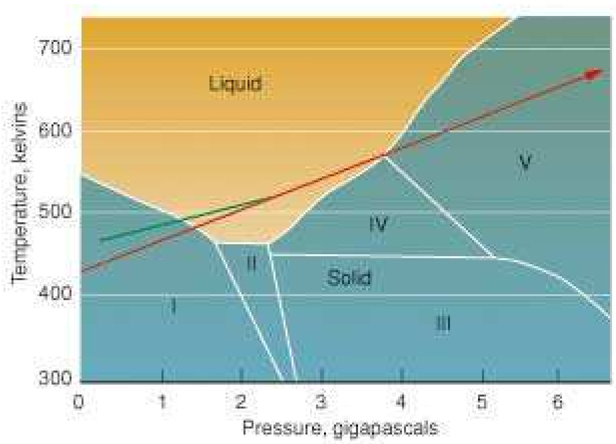
- Study melt relations and kinetics of Na and Fe at P > 2 Mbar in the convention DAC with pulsed laser heating
- Physical properties & stability fields of H_2O above 1 Mbar with the dDAC
- Structure and phase stability of Fe, (Mg, Fe)O, & Si-PPv at pressures above 4 Mbar within the pulsed laser heated dsDAC
- Ps shocks and heating on Bi (going from iii to V) in the DAC



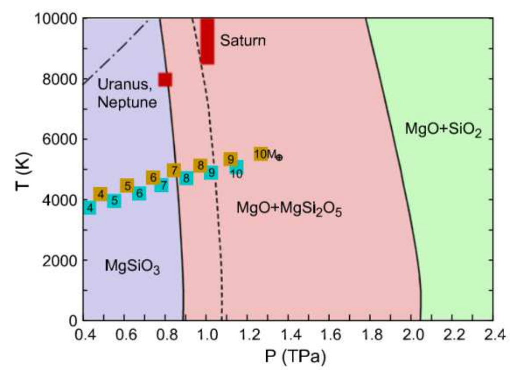
Phase Diagram of Fe (Anzellini et al., 2013)



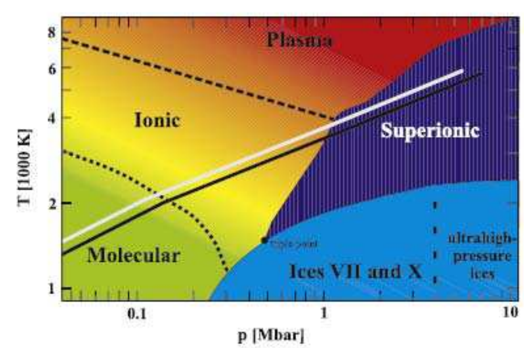
Phase Diagram of Na (McMahon et al., 2007)



Phase Diagram of Bi (



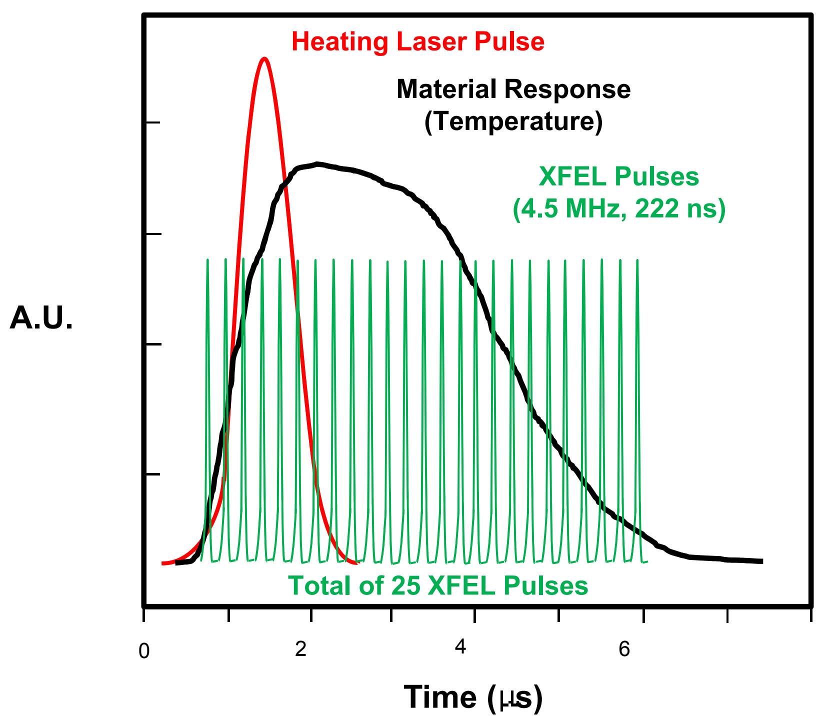
Phase Diagram of MgSiO3 PPv (Umemoto et al. 2011)



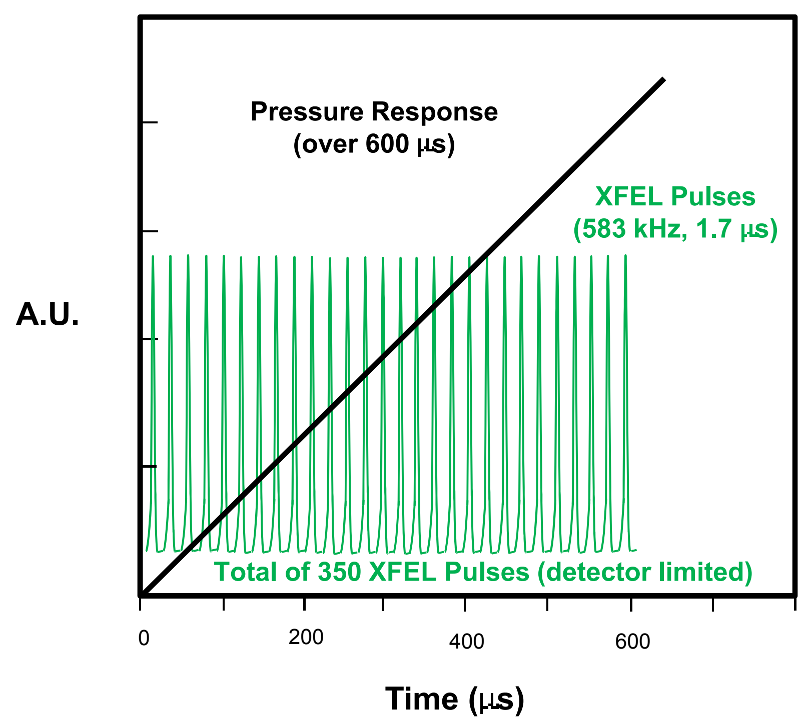
Phase Diagram of H_2O (Redmer et al, 2011)

Experimental Concept of dDAC and dsDAC Experiments at HED

dsDAC Experiments



dDAC Experiments



For dsDAC experiments:

⇒ Fastes scenario get 25 pulses with rep. of 4.5 MHz (every 222 ns) over 6 µs

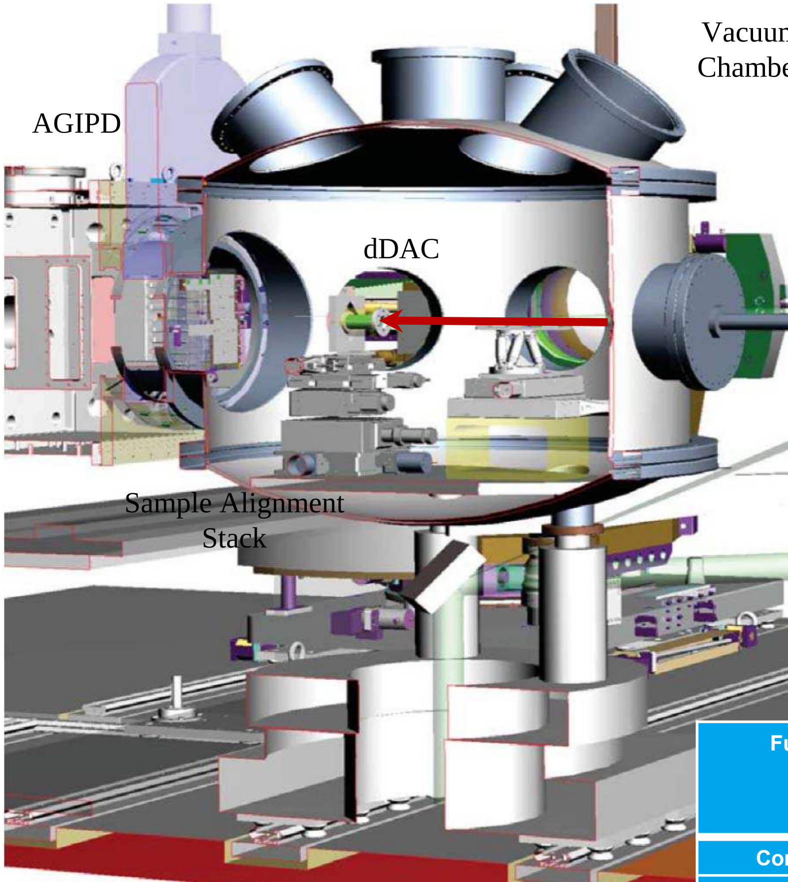
⇒ Can always go slower with less pulses

For dDAC experiments:

⇒ Slowest possible scenario get 350 pulses with rep. of 583 kHz (every 1.7 µs) over 600 µs

⇒ Can always go faster (less time covered)

Summary Workshop "Conceptual Design Report (CDR) Diamond Anvil Cell Setup for HIBEF at the HED/XFEL"



Chamber and Sample Stack requirements

- Alignment of dsDAC and dDAC requires:

⇒ high stability of support with respect to incident beam => decoupling of vacuum chamber from sample support and stack (100 nm or less)

⇒ small step size for sample stack (100 nm)

⇒ for fast turn around use turret with 4-6 DAC => high stability required (100 nm or less)

Pinhole and Beamstop

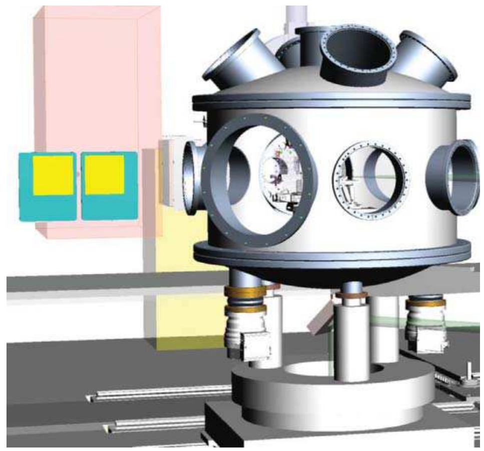
- Pinhole necessary to clean tails => working on concept
- Beamstop at the end of HED Hutch => low scattering

Function	Alignment of Rotation Center into XFEL beam	Vertical Alignment	Rotation	Sample alignment into rotation center
Component	Huber XY 5102.30	Micos NPE-200	Micos PRS-200	Micos LS-110
Weight (kg)	15	9.2	8	2.7
Load Capacity (kg)	200	30	50	10
Travel (mm)	15	13	360 degrees	26
Resolution (μm)	0.1	0.05	0.001 degrees	0.05
Bi-directional Repeatability (μm)	0.1	+/- 0.04	+/- 0.001 degrees	0.1
Wobble (μrad)	n.a.	n.a.	± 17.5	n.a.

Summary Workshop “Conceptual Design Report (CDR) Diamond Anvil Cell Setup for HIBEF at the HED/XFEL”

Detectors for Different Repetition Rates

XRD 0822 from Perkin Elmer

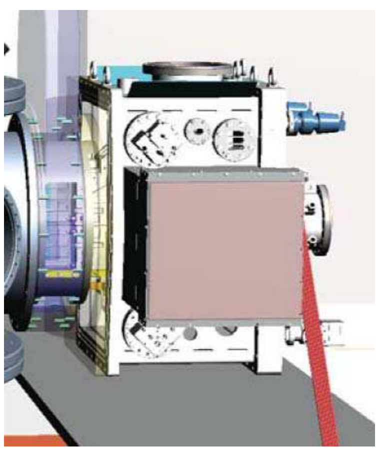


may be
funded

Specification
ScI sensor (max sensitivity @ 60keV)
Pixel: 0. 2 x 0.2 mm^2
Size: 1024 × 1024 (200 x 200 mm active area)
Max frame rate: 25 Hz (full resolution)
Vacuum Incompatible

AGIPD

(Adaptive Gain Integrating Pixel Detector)



Funded through HIBEF

Specification:
GaAs sensor (100 % QE @ 25 keV)
Single photon counting up to ~10^4 ph/pixel/frame
Pixel 0. 2 x 0.2 mm^2 pixel size
Size: 1024 × 1024 (200 x 200 mm active area)
Max frame rate: 4.5 MHz (burst mode)
Vacuum Compatible

Jungfrau from PSI

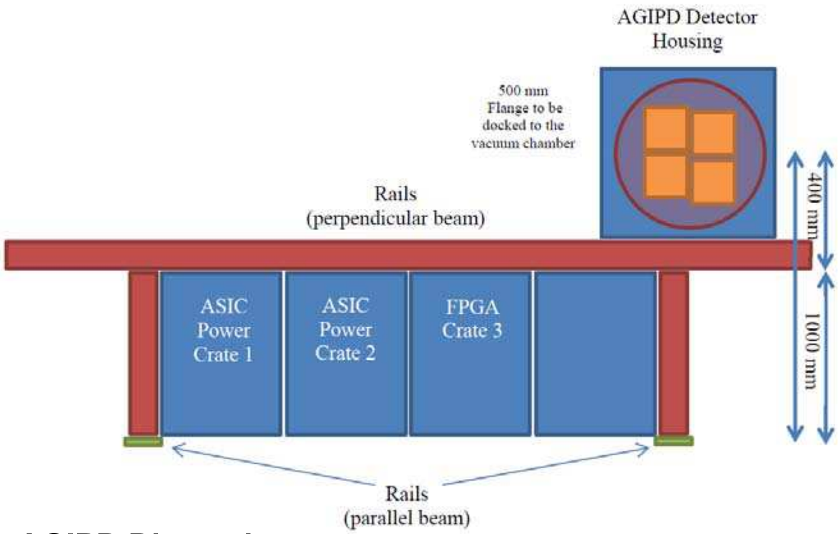
(adJUstiNg Gain detector FoR the Aramis User station)

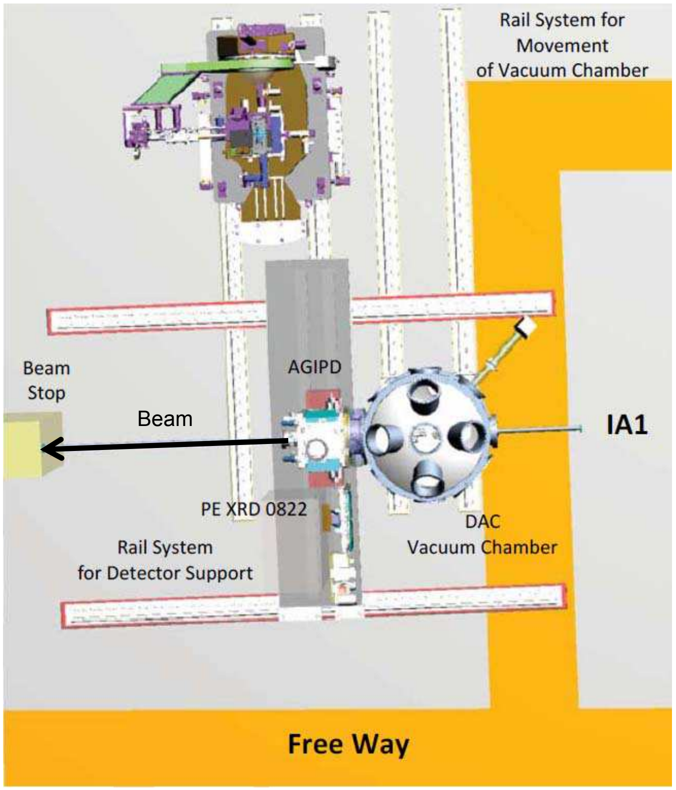
Specification:
Si sensor (15% QE @ 45 keV)
Pixel: 75 µm x 75 µm
Size: 2048 x 2048 (153 x 153 mm)
Max frame rate: 2.7 kHz (MHz ??)
Vacuum Compatible

not funded

Summary Workshop "Conceptual Design Report (CDR) Diamond Anvil Cell Setup for HIBEF at the HED/XFEL"

Proposed Detector Bench for AGIPD (& other Detectors)





AGIPD Dimension

- 1M is 500 kg heavy
- Dimensions ca. 1 x 1 x 1.5 m^3
- Requires 3 Crates => underneath Main part of Detector
- Extra Oil Cooling away from detector location

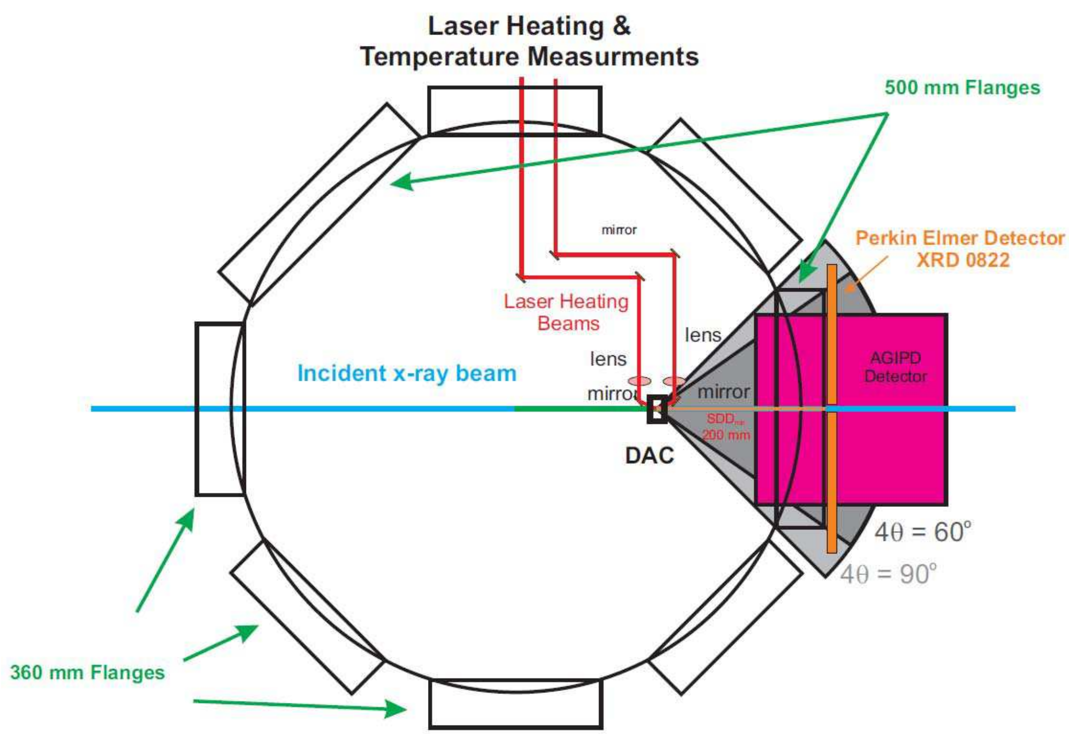
Detectors Positioning

- On motorized rails ⊥ beam
- On motorized rails ∥ beam
- No motorized vertical system for AGIPD

⇒ Can be flanged to DAC Vacuum Chamber
⇒ Can be flanged to IA1 Vacuum Chamber
⇒ Can be positioned to other setup with a X-ray trans. Window
⇒ Can be changed reproducible during experiment

- ∥ Detector Rail System submerged in floor
  => plated covered => no obstruction
- ⊥ Detector Rail System on top of bench
  => no obstruction
- Bench can be moved all the way back
  => Out of the way from other setups

Access to Reciprocal Space in the DAC Vacuum Chamber



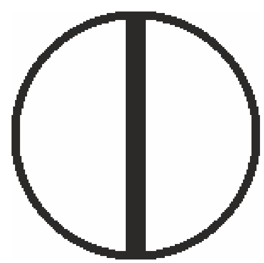
Requirements

- 4θ angle limited by DAC opening (90°)
- 4θ = 90° covers d = 0.648 Å or Q = 9.7 Å^{-1} @25 keV
- To cover 90° opening with a PE or AGIPD SDD = 200mm
- Difficult when DAC in the center => move DAC 300 mm from the center

Design Established

⇒ AGIPD can reach SDD = 200 mm

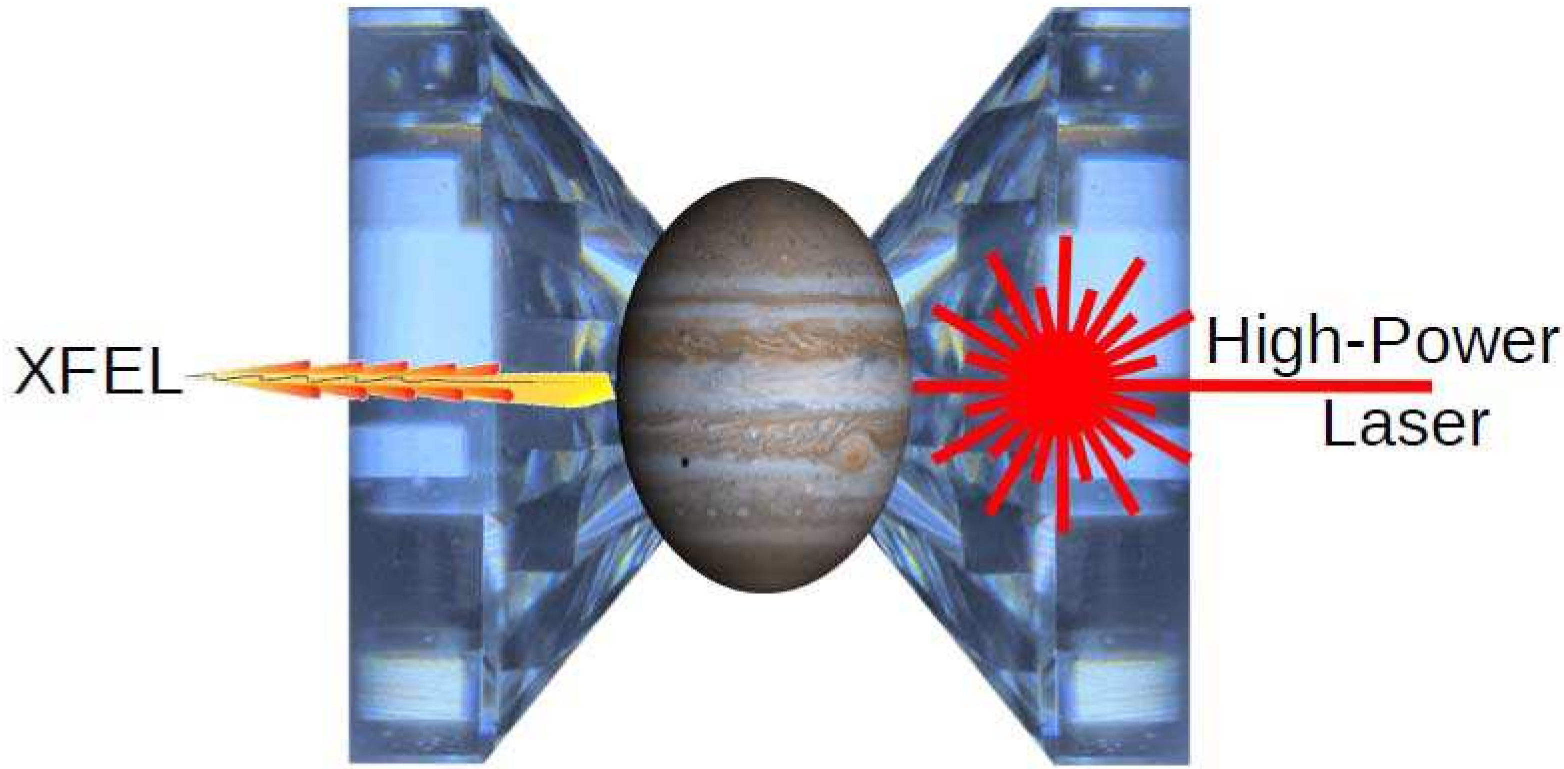
⇒ PE XRD 0822 cannot => vacuum incompatible => 4θ = 60° => Q = 6.56 Å^{-1} @ 25 keV



Envisioned Flange
Window for PE XRD 0822

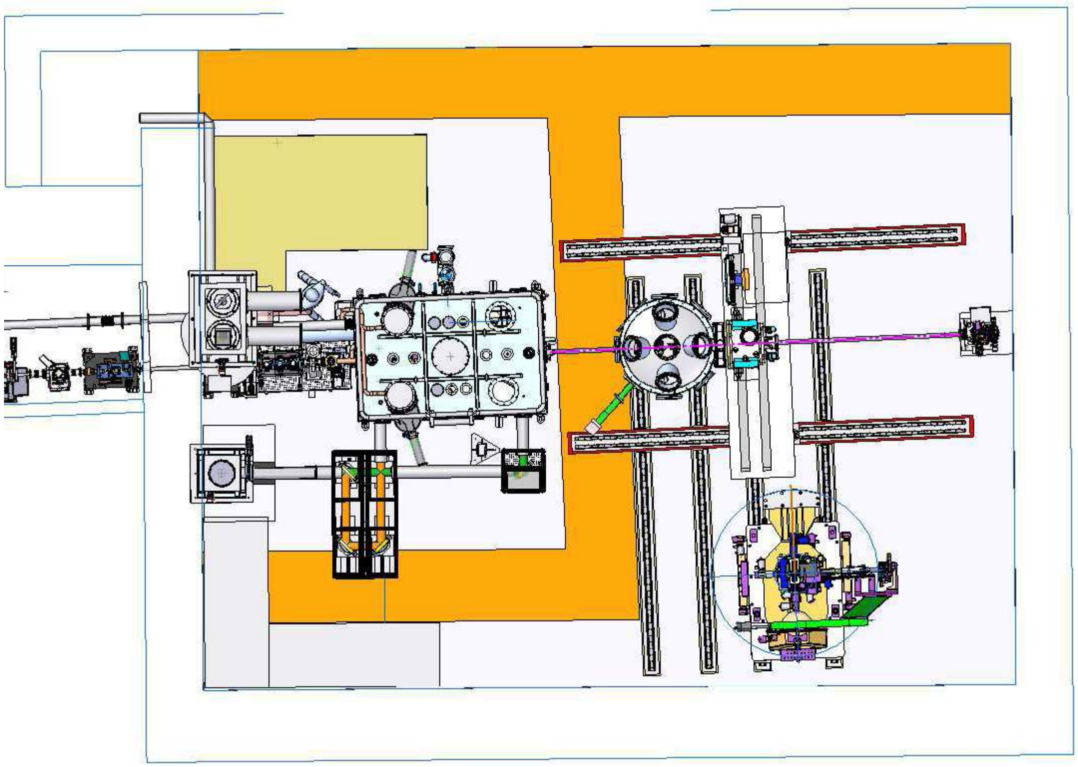
Summary Workshop "Conceptual Design Report (CDR) Diamond Anvil Cell Setup for HIBEF at the HED/XFEL"

5th Joint Workshop on High Pressure, Planetary, and Plasma Physics (HP4)



14-16th of September 2016 in Hamburg on DESY Grounds
(jointly organized by European XFEL and DESY)

Workshop on the Conceptual Design of the Shock Compression Setup for HIBEF at the HED/XFEL



13th of September 2016 in Hamburg on DESY Grounds (jointly organized by HZDR and DESY)

Thank you for your Attention!!!!

Thank you for contributing

Z. Konopkova	J. Eggert
C. Baehtz	W. Evans
H. Damker	R. Redmer
K. Appel	W. Morgenroth
U. Zastrau	L. Dubrovinsky
T. Tschentscher	H. Marquardt
E. McBride	A. Goncharov
S. McWilliams	…

(sorry if I forgot someone)

The single-shot incident spectrometer at HED

Bolun Chen

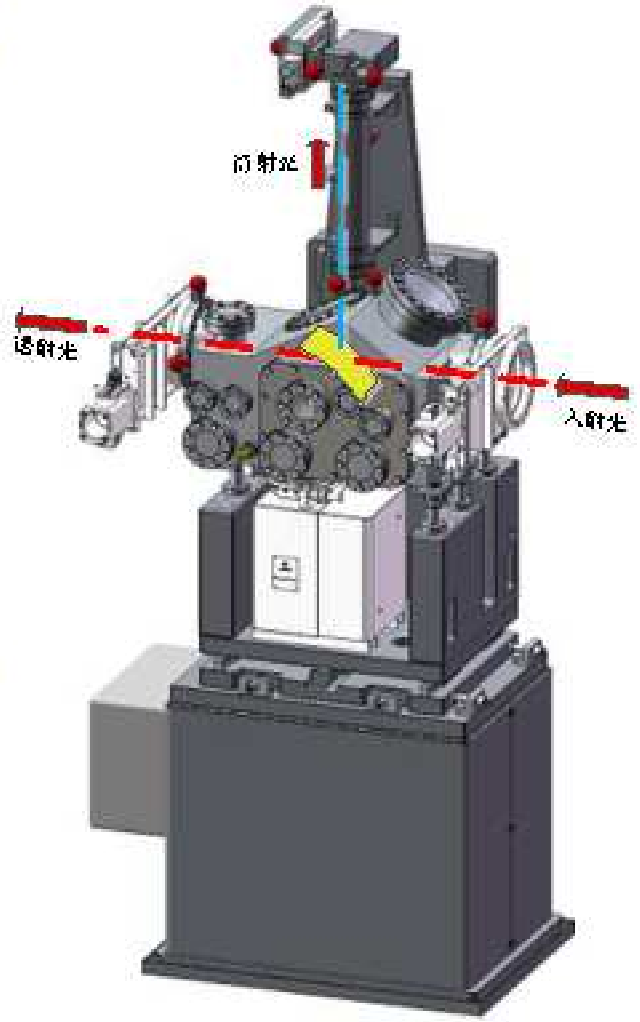
Laser Fusion Research Center, CAEP

Presentation Outline

- Introduction
- Conceptual design
- Technical design
- Acknowledgement

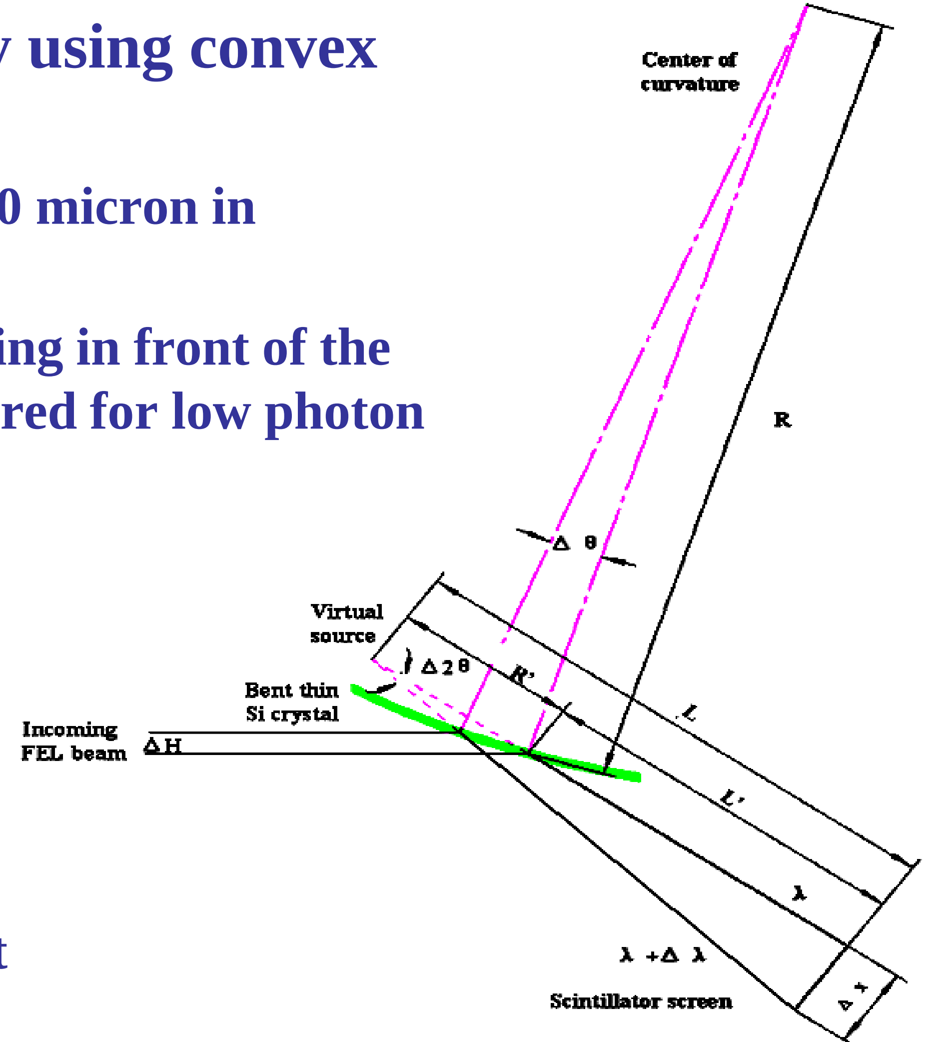
Introduction

- The single-shot incident spectrometer
  - X-ray spectrometer for HED instrument of European XFEL
  - The precise knowledge of incident X-ray spectra is crucial for normalization of absorption spectra
  - The spectrometer will be implemented in the HED optics hutch (HED-OPT)
  - Design and built by CAEP in close collaboration with HED group



Principle of Operation

- A defocusing geometry using convex crystals
  - Crystal membrane of 10 micron in thickness
  - An update using a grating in front of the spectrometer is considered for low photon energies
- The crystal curvature and detector distance impact energy range, sensitivity, and resolution
  - Idea already realized at LCLS and SwissFEL



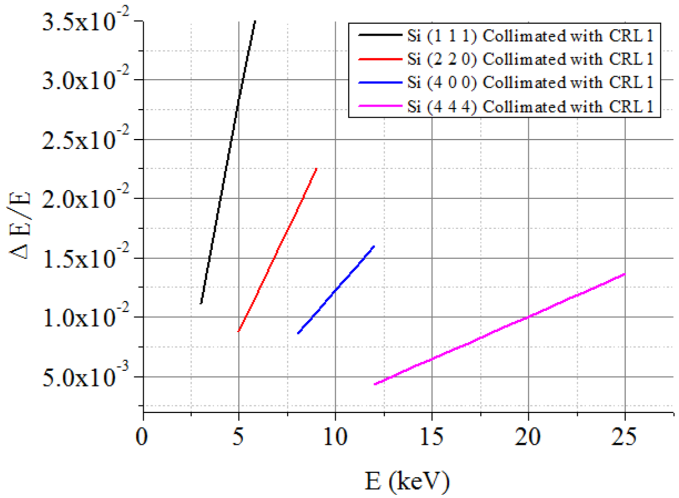
D. Zhu *et al.*, APL. **101** 034103 (2012)

Conceptual design

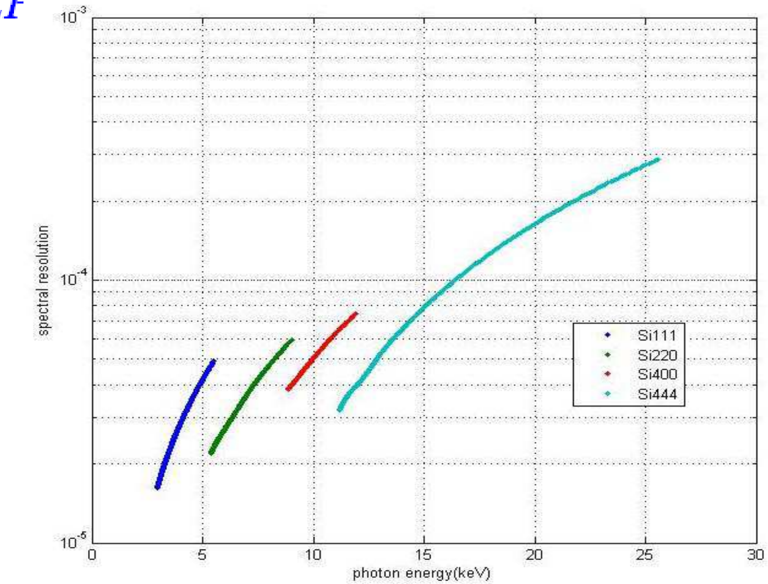
- **Four different cuts of silicon crystals are used**
- **The Bragg angles are set to vary in a small range for different crystals to keep the spectrometer compact**
- **Gotthard and CCD detector will be used**
- **The RoC is set to 200mm. The distance between the detectors and the surface of the bent crystal is ~850mm**

crystal	2d（Å）	energy（keV）	Bragg（°）
Si (1 1 1)	6.27	3~5.5	41.23° ~21.07°
Si (2 2 0)	3.84	5.4~9	36.72° ~21.02°
Si (4 0 0)	2.72	8.85~11.9	31.06° ~22.56°
Si (4 4 4)	1.57	11.7~25	42.53° ~18.44°

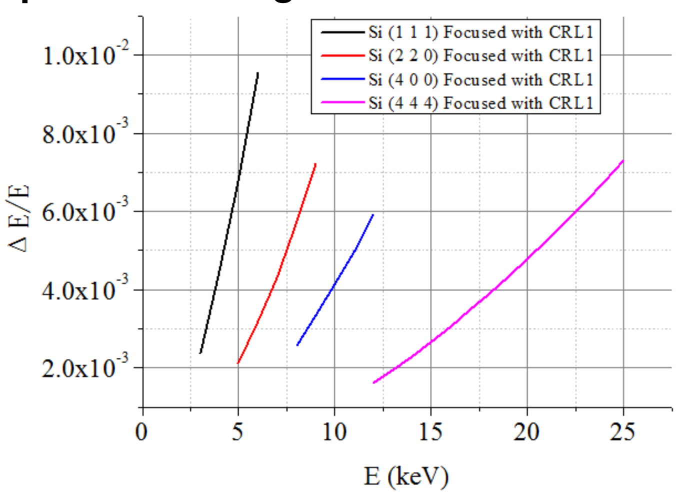
Requirements



Spectral coverage collimated with CRL1



Spectral resolution of the spectrometer



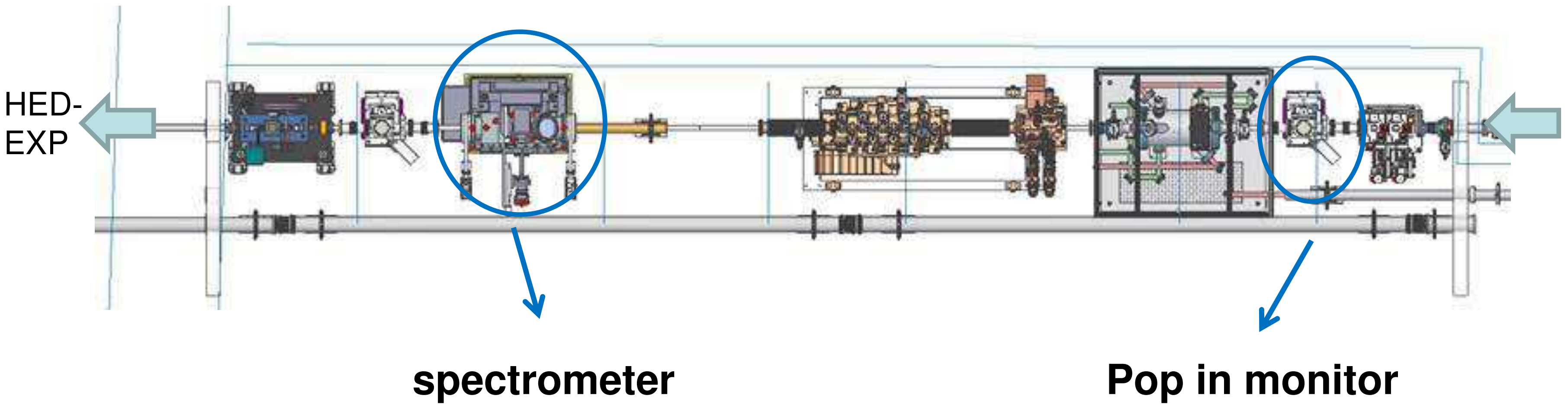
Spectral coverage focused with CRL1

- Photon energy: 3~25keV
- Spectral resolution: $\Delta E/E \sim 5\times10^{-5}$ (3~15keV)
- Energy coverage: $\Delta E/E > 10^{-3}$
- The transmission is only 3 % to 30 % for 3-5keV

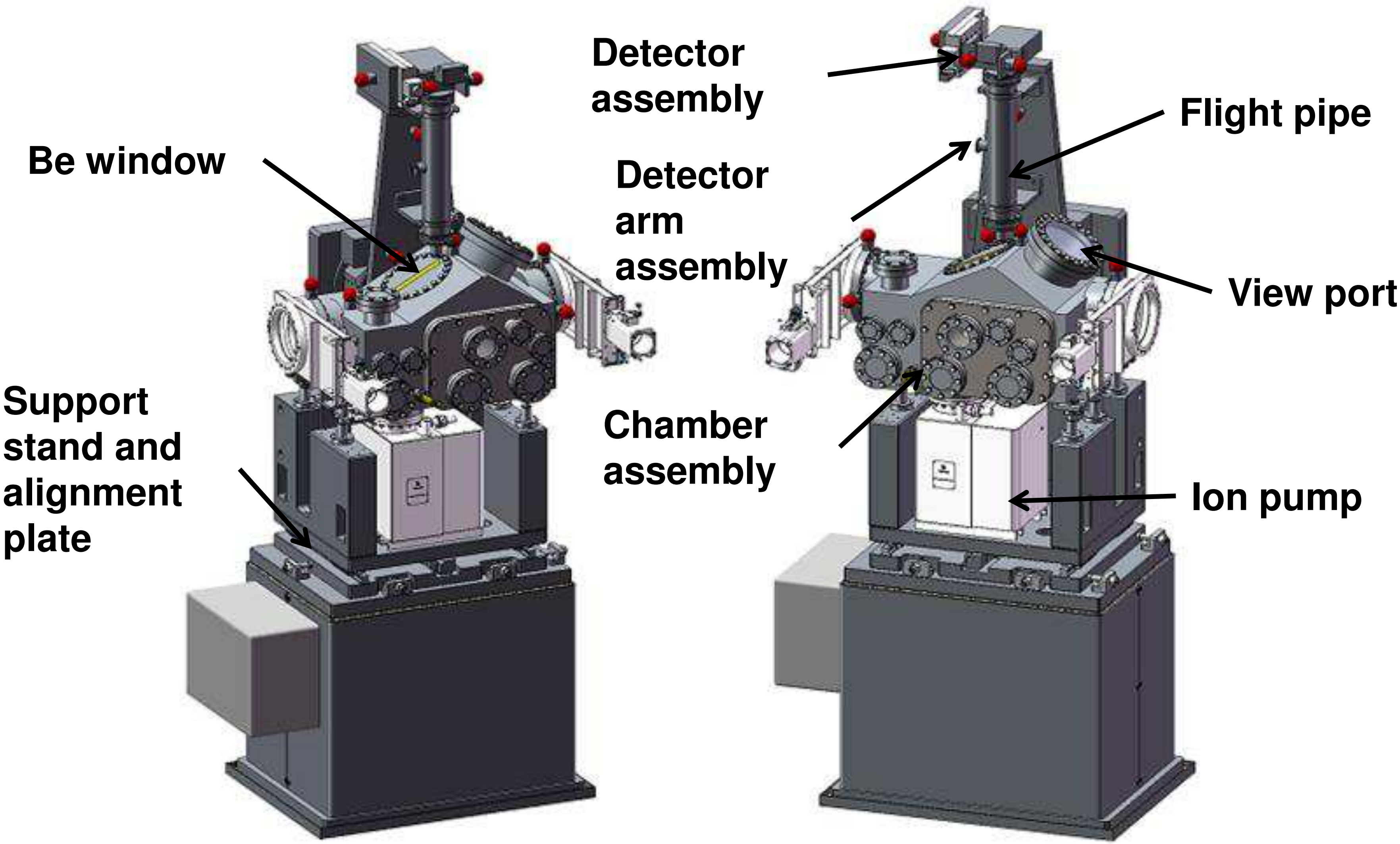
Consideration of the update design

- For lower photon energy
  - Add a diamond grating mounted on the position monitor located at the beginning of the HED-OPT
  - The distance will be about 7m

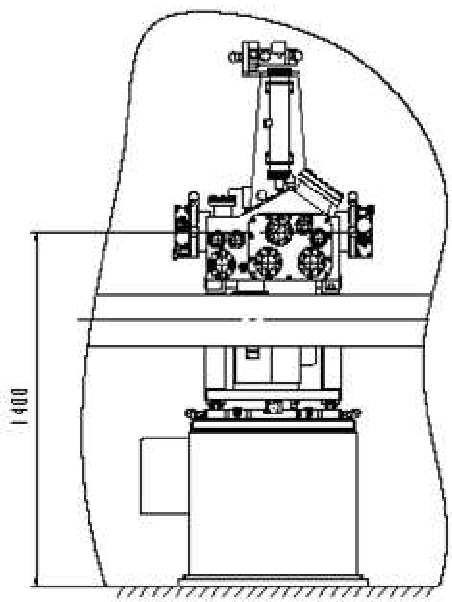
	3keV	4keV	5keV	6keV	7keV	8keV
150nm	19.29	14.47	11.57	9.64	8.27	7.23
200nm	14.47	10.85	8.68	7.23	6.20	5.42
250nm	11.57	8.68	6.94	5.79	4.96	4.34

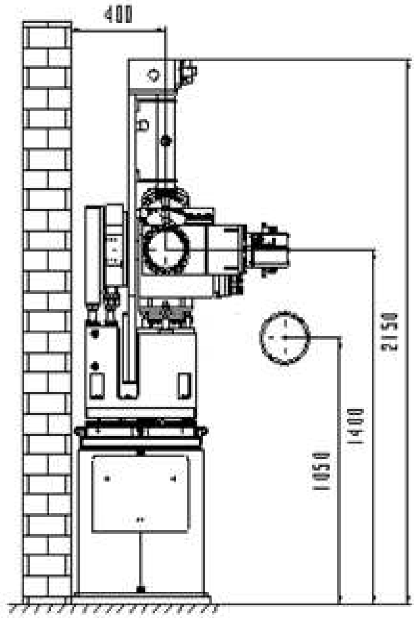


First Technical Design

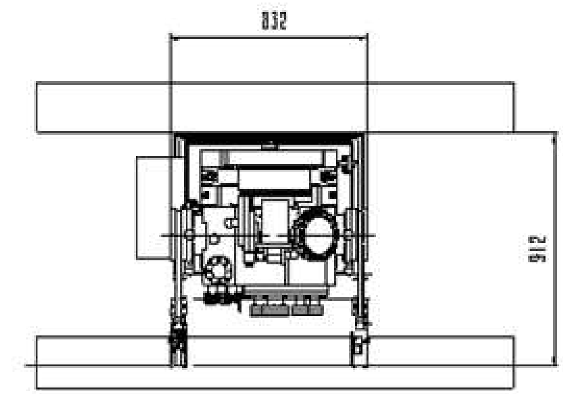


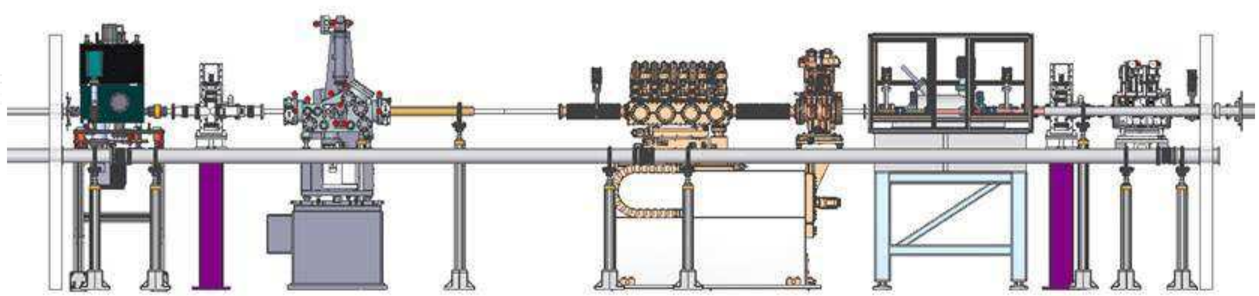
Layout





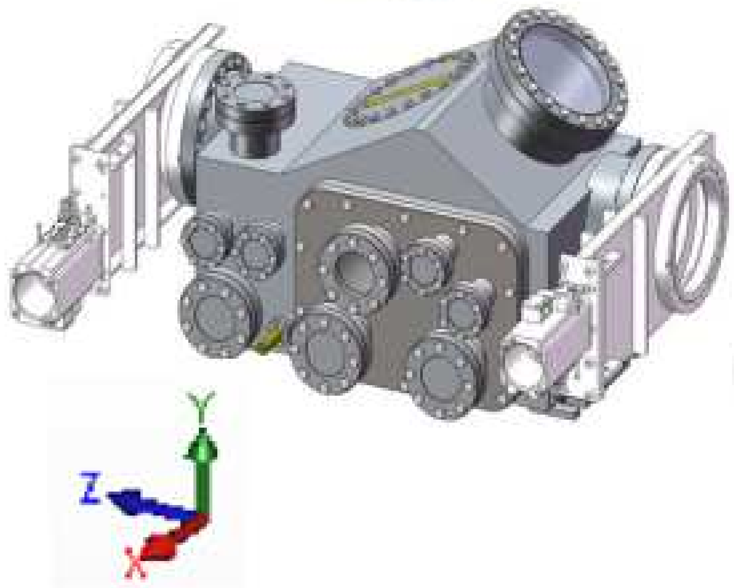
- Located at HED optics hutch
- ~985m from the source
- 400mm from one side wall
- The length should be less than 0.9m

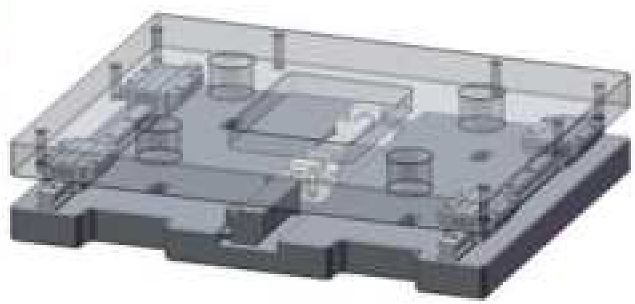




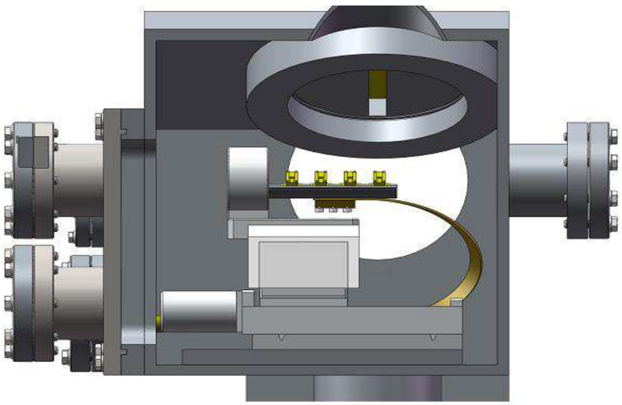
Proposed chamber assembly

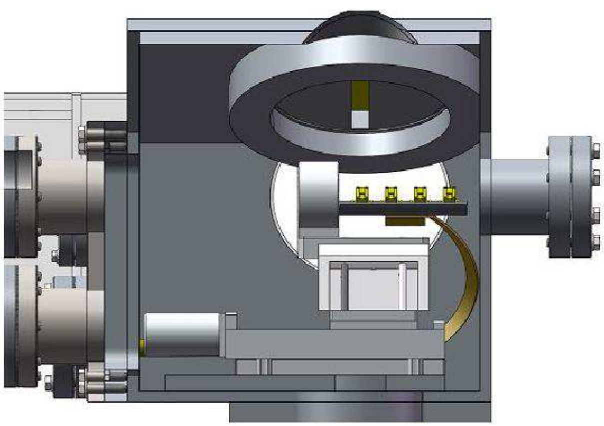
- One big flange holds several smaller flanges on the side wall
  - Can be used to change the crystals
- Be window for reflection beam
- One view port on top of the chamber
- A motorized linear stage is used to move the chamber in x direction.

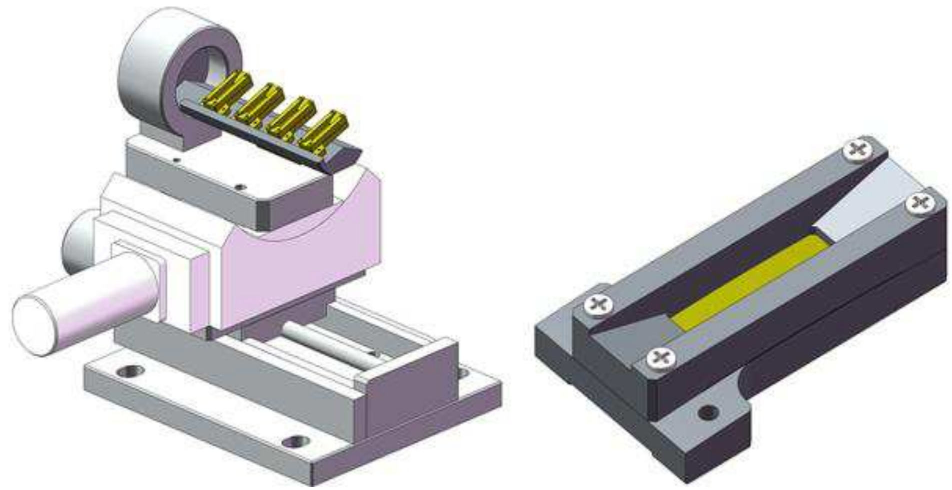




Crystal stage assembly



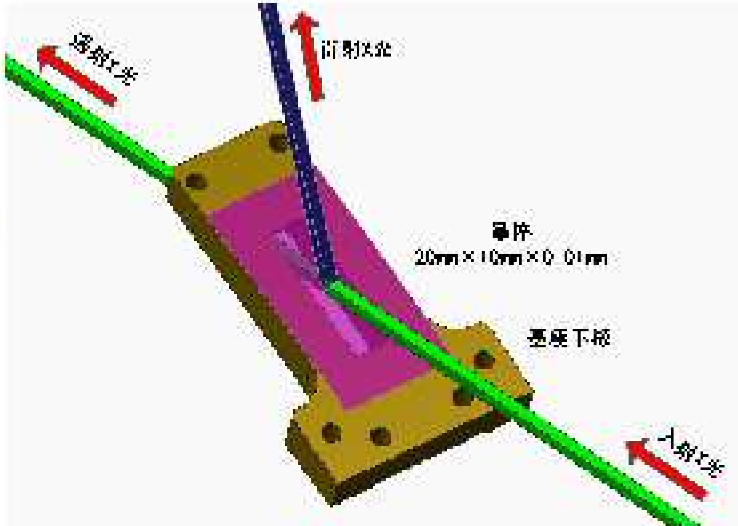


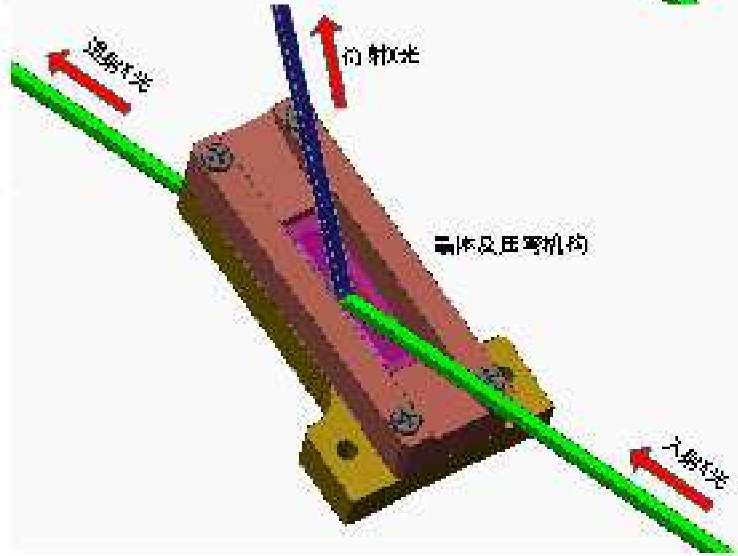


- **Put the complete mechanics in to vacuum**
- **The assembly carries up to four crystals benders**
- **The X axis allows one of the crystals to be brought into the beam**

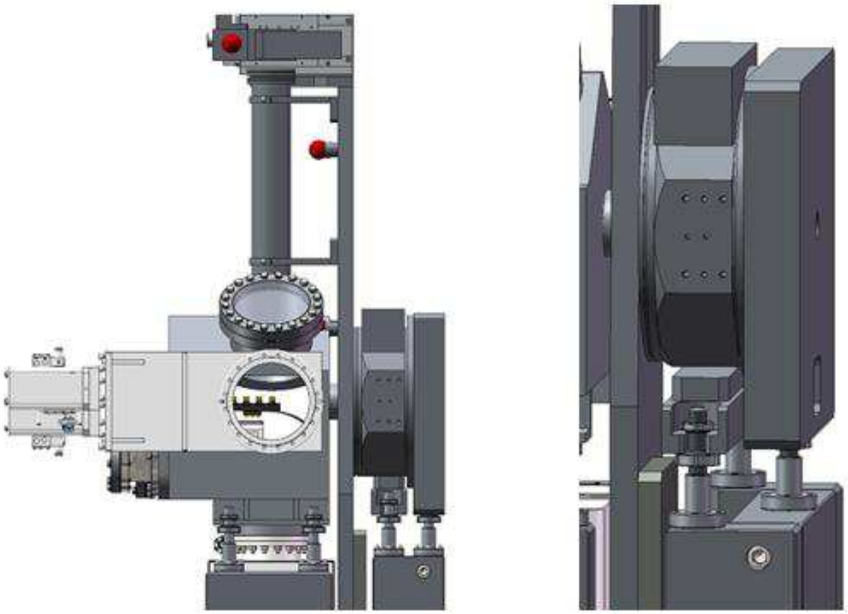
Crystal assembly

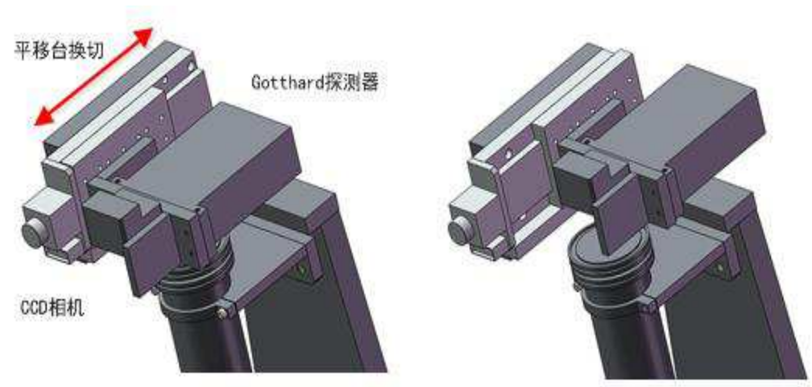
- The size of the crystal membranes are 20*10mm
- The bent crystal holders will be tested for an optimum design
- Try to find the easiest mounting method

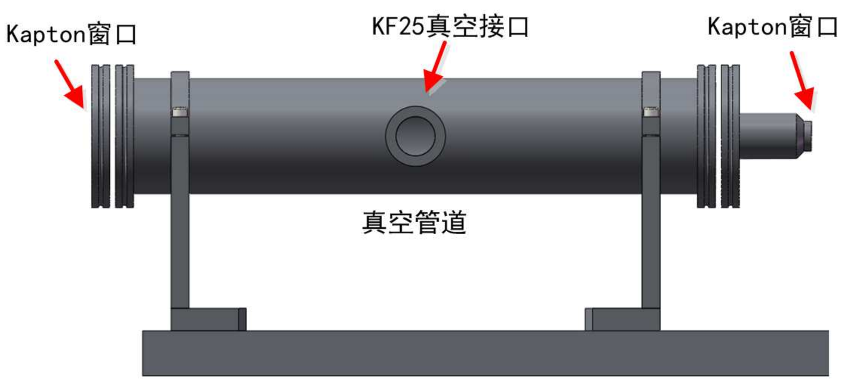




Detector assembly







- The detectors are positioned at a distance of 850mm
- Rotated about the X axis by a large high precision goniometer
- the detector X stage carrying the Gotthard and YAG/ CCD

Collaboration

- On 26 March, 2015, representatives of CAEP signed a framework collaboration agreement with European XFEL at the Consulate of the P. R. China in Hamburg.

- The agreement formalizes CAEP's future involvement in the X-ray free-electron laser facility and is intended to provide the basis for future exchange of staff and students and the development of instrumentation for European XFEL.

Team

中国工程物理研究院
CHINA ACADEMY OF ENGINEERING PHYSICS

Shenye Liu	(Leader)
Zhenghua Yang	(engineer)
Xing Zhang	(engineer)
Minxi Wei	(engineer)
…	

European XFEL

HED group

Ulf Zastrau	(Group leader)
Karen Appel	(Scientist, X-ray transport)
Ian Thorpe	(Instrument engineer)
Motoaki Nakatsutsumi	(Scientist, lasers)
…	

Acknowledgements

Jianfeng Li (Scientist of CAEP)

Qiuping Wang (Scientist of USTC)

Junhua He, Min Zhang (Engineer of XIOPM, CAS)

Naresh Kujala (Spectrometry Scientist of EU-XFEL)

Lewis Batchelor (Instrument Engineer of EU-XFEL)

Diling Zhu (Scientist of LCLS)

Marion Harmand (Scientist of IMPMC)

CAEP introduction

- **China Academy of Engineering Physics (CAEP) is a major research centre that operates 12 research institutes and 15 national laboratories across China.**

Thank you for your kind attention

Institut für Optik & Quantenelektronik JENA
Friedrich-Schiller-Universität

Ion dynamics using highest-resolution inelastic x-ray scattering

I. Uschmann, R. Lötzsch, G.G. Paulus

Friedrich-Schiller-Universität Jena

In collaboration with

U. Zastrau, H. Sinn and HED-team

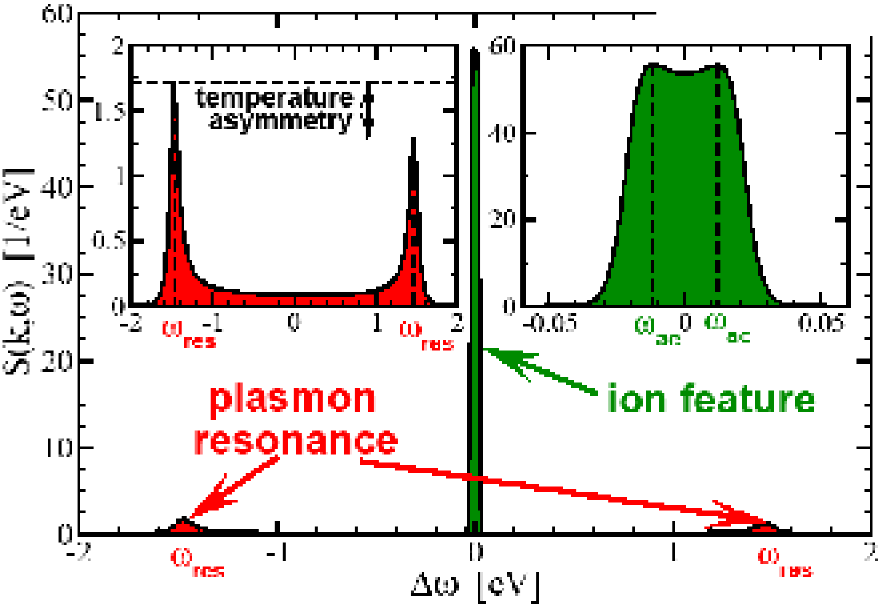
R. Redmer

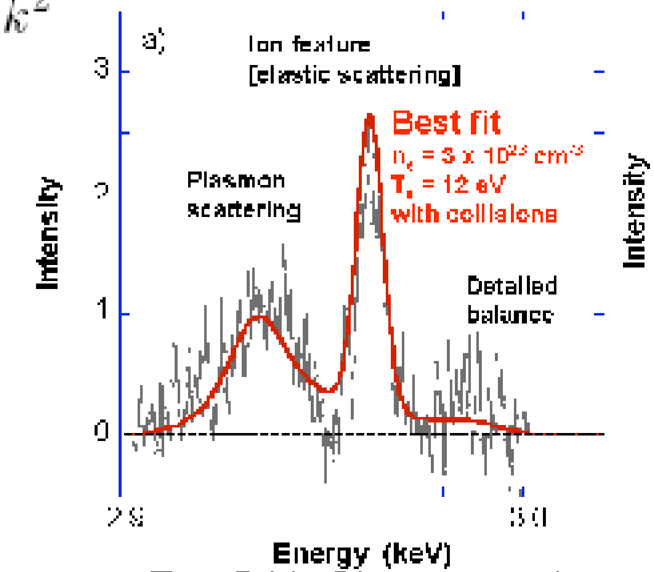
WDM diagnostics based on Dynamic structure Factor $S_{ee,ac}(k,\omega)$

electron collective modes: plasmons (~eV),ion system: ion acoustic modes (~10 meV)

Te via detailed balance relation: $$Y(\mathbf{k},\omega) = \frac{S^0_{ee}(-\mathbf{k},-\omega)}{S^0_{ee}(\mathbf{k},\omega)} = \exp\left(-\frac{\hbar\omega}{k_B T_e}\right)$$

Peak positions give ne: $$\omega^2_{\mathrm{GB}}(k) = \omega^2_{pi} + \frac{3k_B T_e}{m_e}k^2$$





Be: S.H. Glenzer et al., PRL **98**, 065002 (2007)

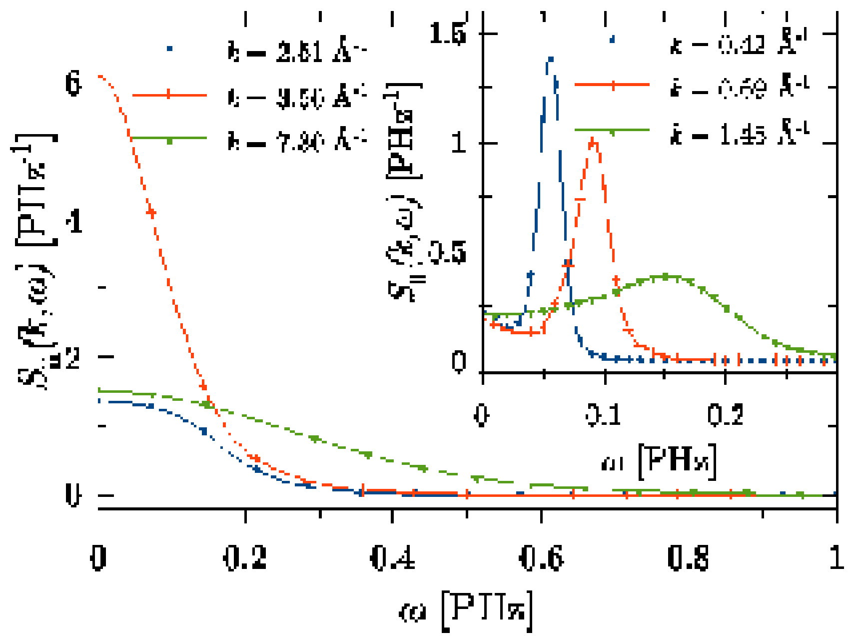
A. Höll et al., High Energy Dens. Phys. **3**, 120 (2007)
R. Thiele et al., Phys. Rev. E **78**, 026411 (2008)
S.H. Glenzer, R. Redmer, Rev. Mod. Phys. **81**, 1625 (2009)

courtesy R. Redmer

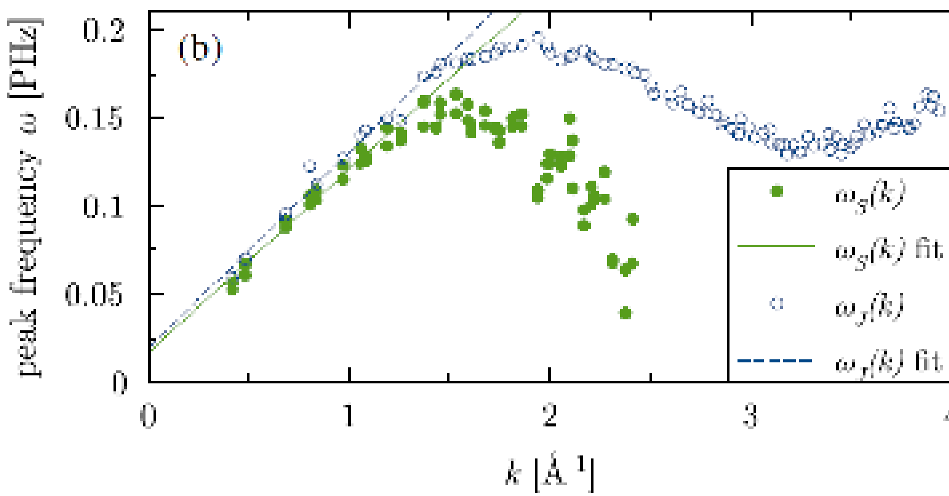
Sii(k,ω) in the warm dense matter region (Al): dispersion

T=3.5 eV, ρ=5.2 g/cm3

typical for recent XRTS experiments (spectrum), see Ma et al. (2013), Fletcher et al. (2015)



H.R. Rüter, R. Redmer, PRL **112**, 145007 (2014)



Ion acoustic modes: ωs

Long. current correlation function: ωl

TABLE I. Adiabatic and apparent sound velocity for liquid (1000 K, 2.3565 g/cm^3) and warm dense aluminum (40 600 K, 5.2 g/cm^3).

T (K)	ϱ (g/cm^3)	c_s (m/s)	c_l (m/s)
1000	2.3565	4860	5010
40 600	5.2	10 380	11 070

courtesy R. Redmer

Why IXRS at FELs (Example)

From simulations for WDM

→ derive EOS data, electronic transport

→ ion dynamics and material properties like DT, η, cs

→ derive generalized hydrodynamic model

High-resolution X-ray Thomson scattering at seeded FELs

→ reveals ion dynamics in WDM

→ benchmark for theory, DFT-MD simulations

→ test validity of hydrodynamic model

Planetary physics

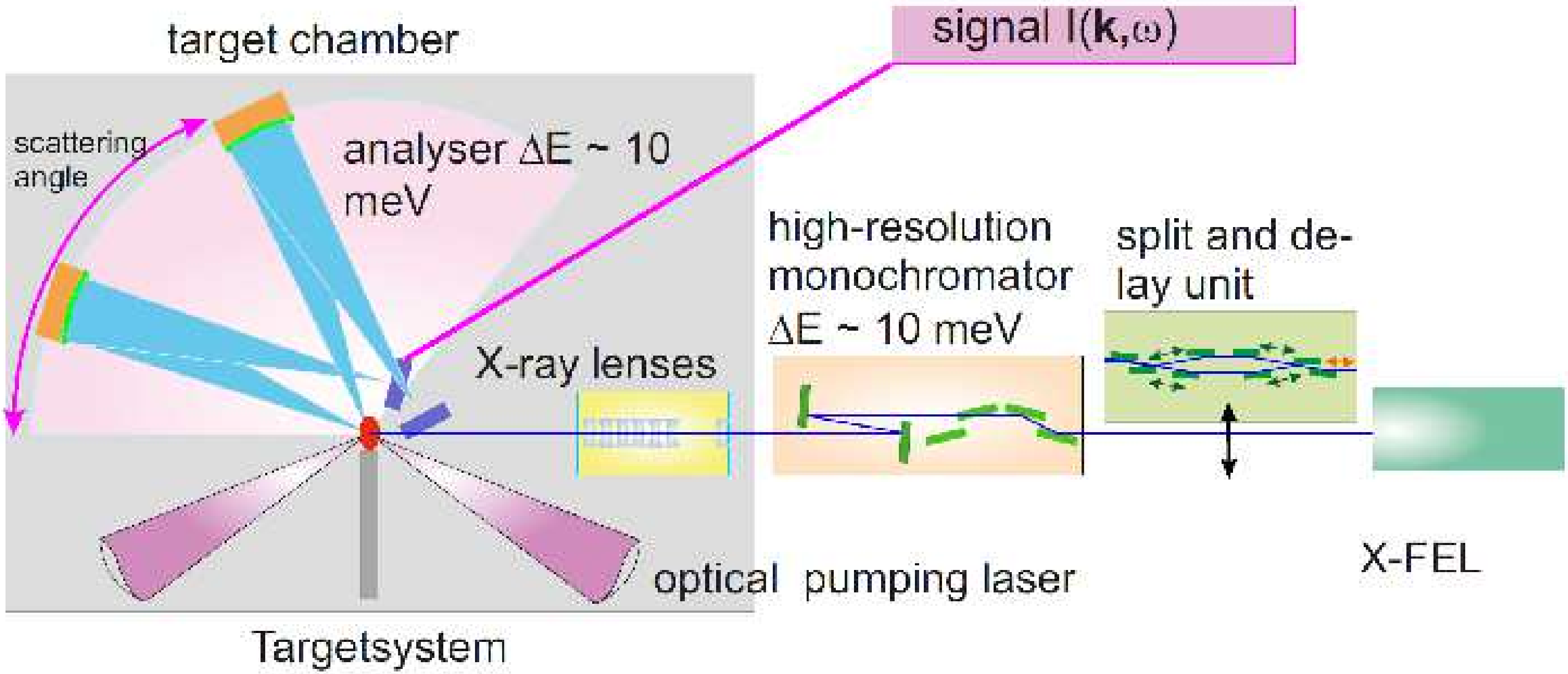
→ input for interior, evolution and dynamo models

→ better understanding of planets and planetary systems

Aim of the project

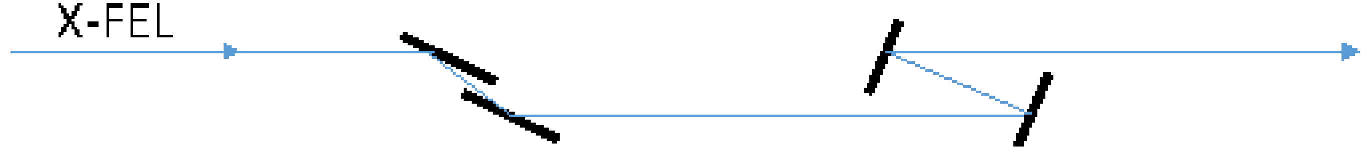
- Measure the dynamic structure factor angularly resolved to investigate conventional matter up to extreme states of condensed matter under high pressure
- Provide the necessary X-ray optics
  - High resolution monochromator
  - High resolution analyzer
- Measure k-dependent

Measuring scheme



High resolution monochromator

Two stage design to prevent beam offset



ΔE ≈1 eV

ΔE ≈10...40 meV

- Silicon 111 monochromator

- First phase: high orders of silicon 111
- Later: other reflections to prevent higher harmonics contributions
- Very large crystals necessary

Channel cut crystals

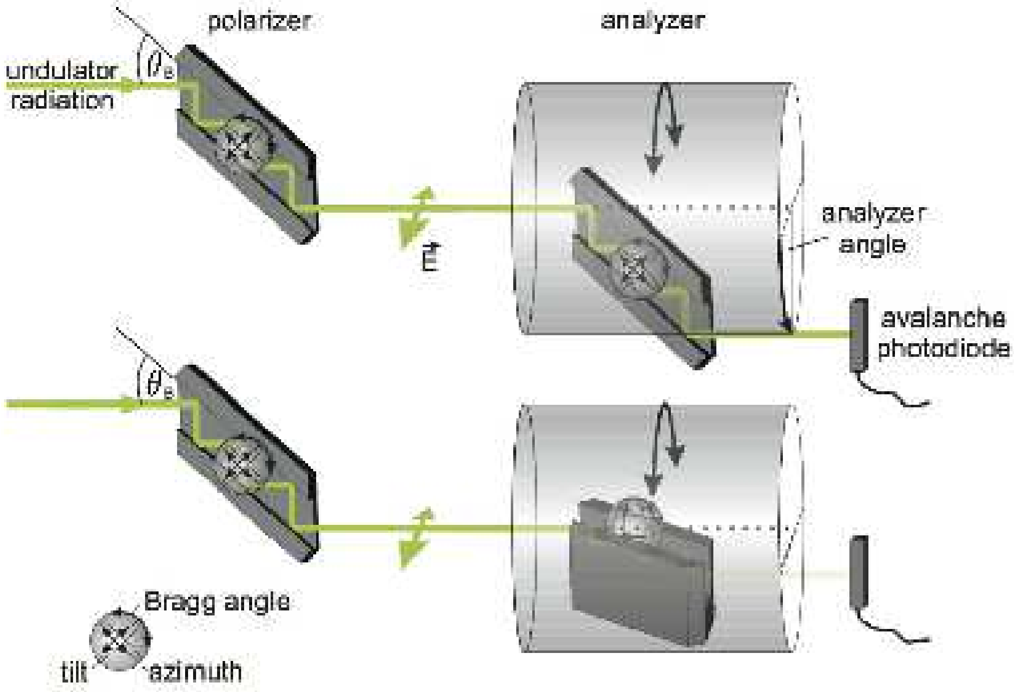
Channel cut crystals

- High stability
- Not easy to prepare perfect inner faces

Channel-cut crystal

High resolution monochromator near 90°
(ESRF)

Channel cut polarimeters

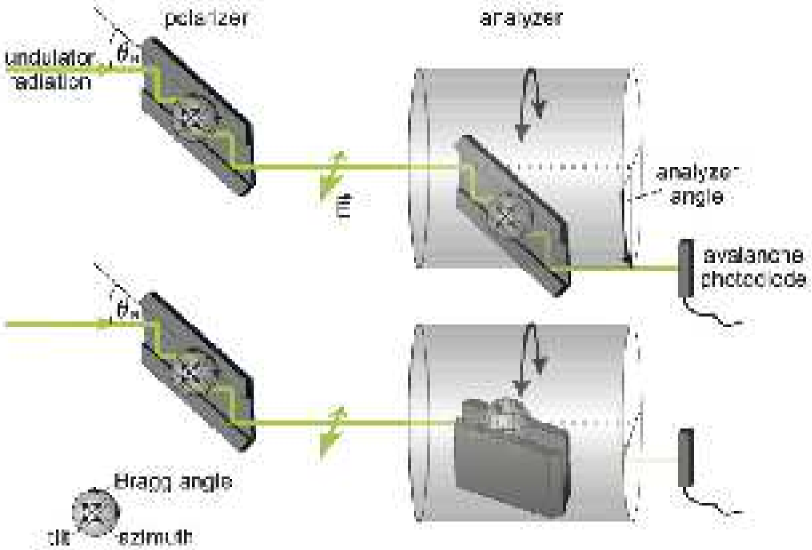


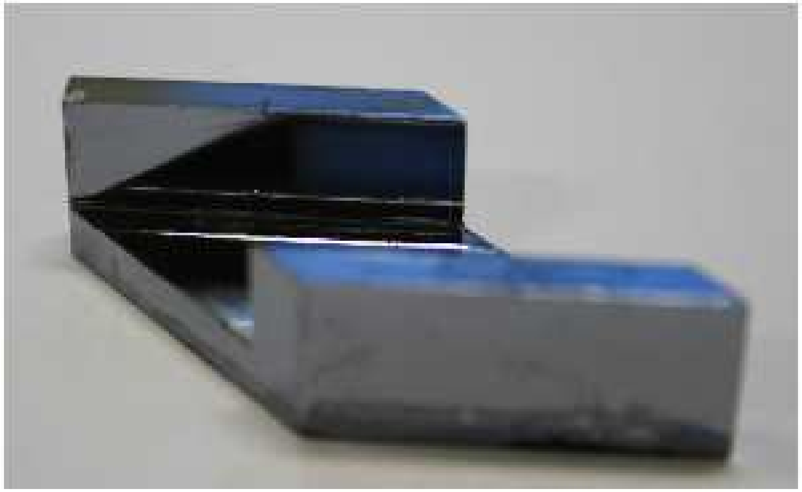
- Multiple Bragg reflections at 45° allow for high purity polarimetry.
- Measured **Ix/I0 = 2.4 · 10^{-10}** at ID06 ESRF (Eph= 6457 eV, 400 silicon reflection, 6 reflections per crystal)
- **A channel cut polarimeter will be installed at MID**

B. Marx, K.S. Schulze, *et al.*, PRL 110, 2013

![ioQ JENA logo]

Channel cut polarimeter at LCLS





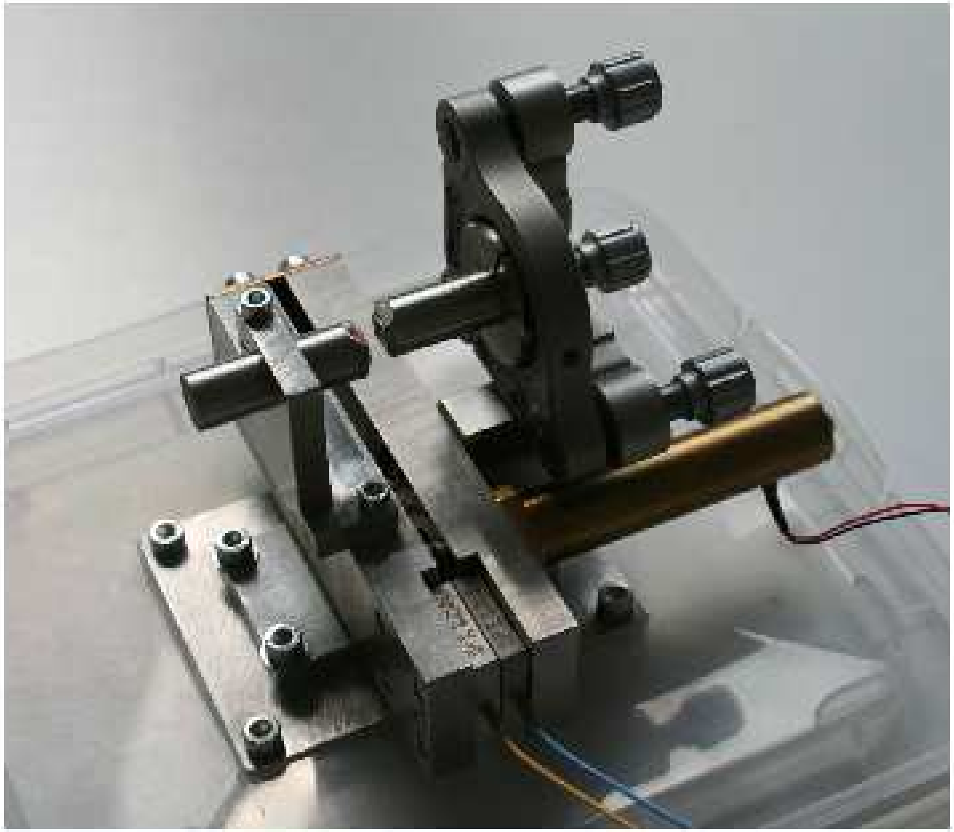
Eph = 6457 eV, silicon 400, two reflections

polarization purity: Ix/I0 = 1,5 · 10^{-5}

Quasi channel cuts

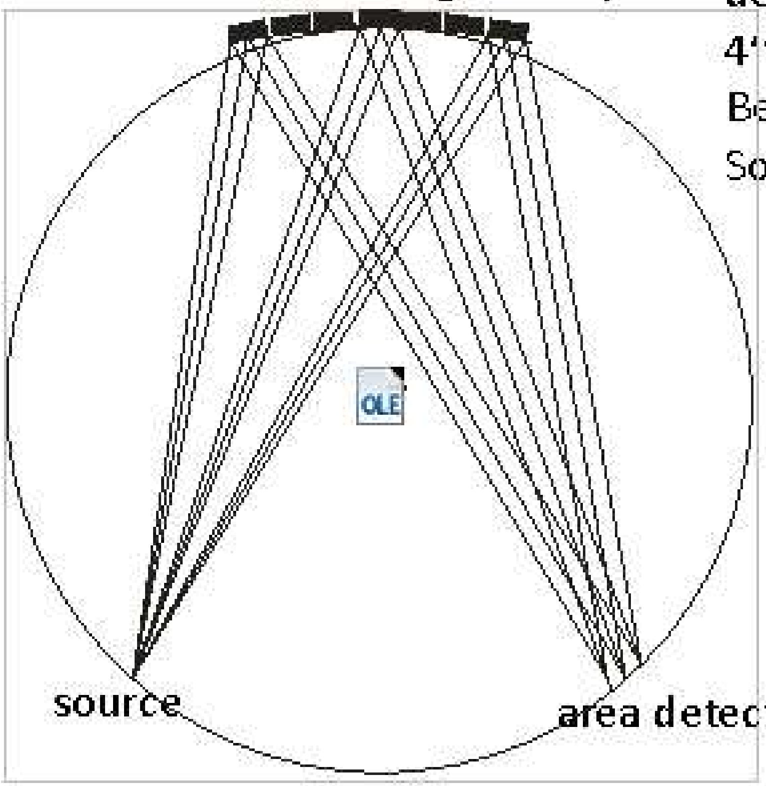
Quasi channel cuts

- Allows to use flat, perfect crystals
- Active stabilisation

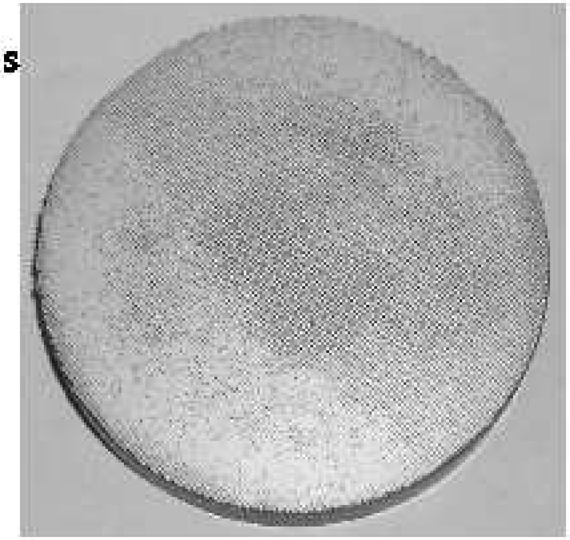


Analyser crystals

Rowland circle geometry



Spherical Diced silicon crystals
developed at the ESRF
4'' diameter
Bending radii ~ 1 m
Solid angle ~100 mrad^2



Reflection	Energy (keV)	2.5 m Vertical Arm	
		ΔE (meV)	$\Delta E/E$
Si(7,7,7)	13.840	8.6 ± 1.0	$6.2\cdot10^{-7}$
Si(8,8,8)	15.817	8.0 ± 1.0	$5.1\cdot10^{-7}$
Si(9,9,9)	17.794	5.2 ± 0.5	$5.5\cdot10^{-7}$
Si(11,11,11)	21.747	–	–
Si(12,12,12)	23.724	–	–
Si(13,13,13)	25.704	–	–

Verbeni et al.: Journal of Physics and Chemistry of Solids 66 (2005) 2299–2305

Mascuiovecchio et al. Nucl. Instr. and Meth. B 111 (1996), 181

Conclusion

- We want to develop the instrumentation for high-resolution inelastic X-ray scattering at HED
- A high resolution monochromator with ΔE ~10…40 meV will be build.
- A high resolution analyzer crystal will be purchased from the ESRF.
- The analyser will be mounted on a rail system for k-dependent measurements.

Dynamic Warm Dense Matter Research at XFELs

Dominik Kraus
Department of Physics
University of California, Berkeley

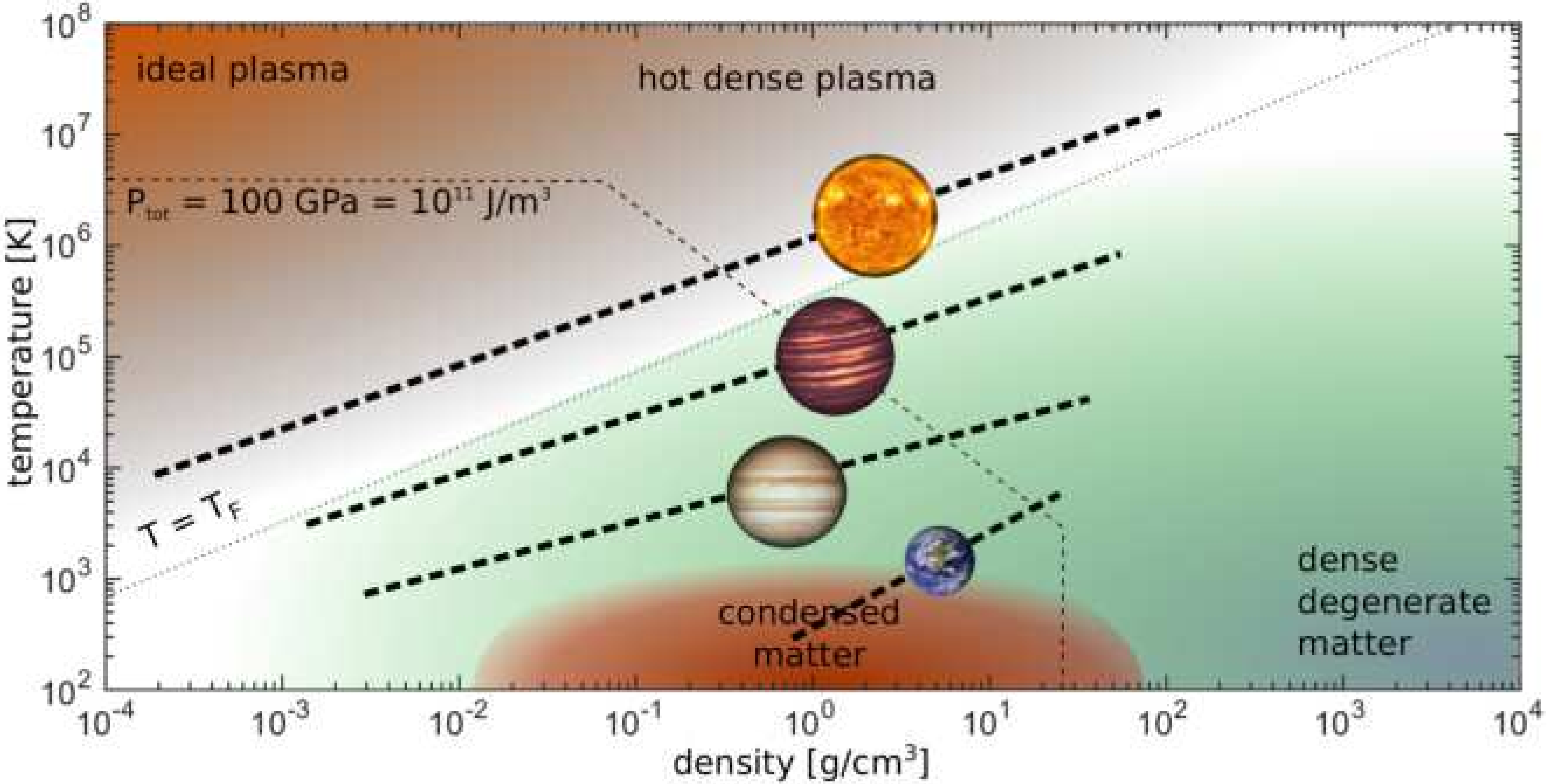
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

HELMHOLTZ GEMEINSCHAFT

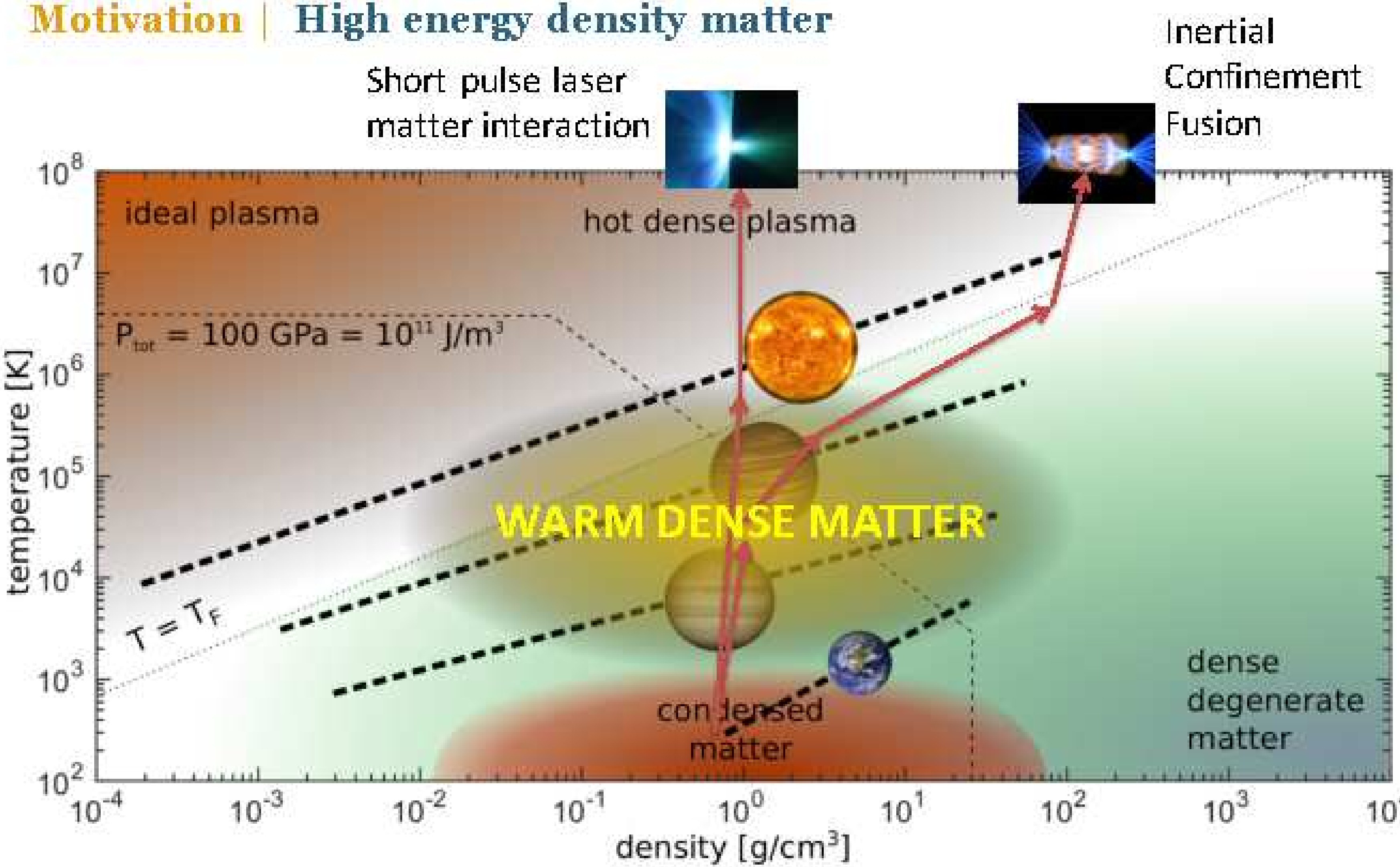
Helmholtz Young Investigator Group
"Dynamic Warm Dense Matter Research with HIBEF"
starting 03/16

Berkeley UNIVERSITY OF CALIFORNIA

Motivation | High energy density matter



Motivation | High energy density matter



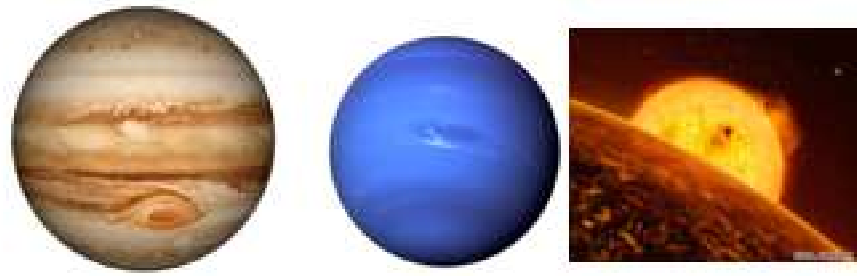
Motivation | Warm dense Matter (WDM)

transition regime
solid state $\Longleftrightarrow$ hot dense plasma

properties:

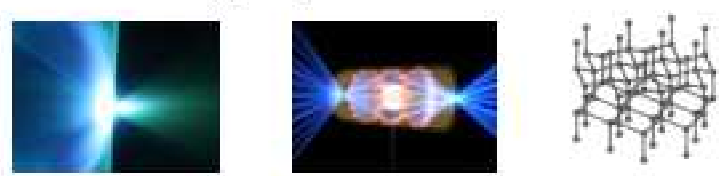
- 0.1 – 10 times solid state density
- temperature: ~5000 K up to ~10^6 K
- pressure: ~1 GPa up to ~10 TPa
- partially ionized
- partially degenerate $n_e \lambda_{th}^3 \approx 1$
- strongly coupled ions

gas giants / ice giants / brown dwarfs

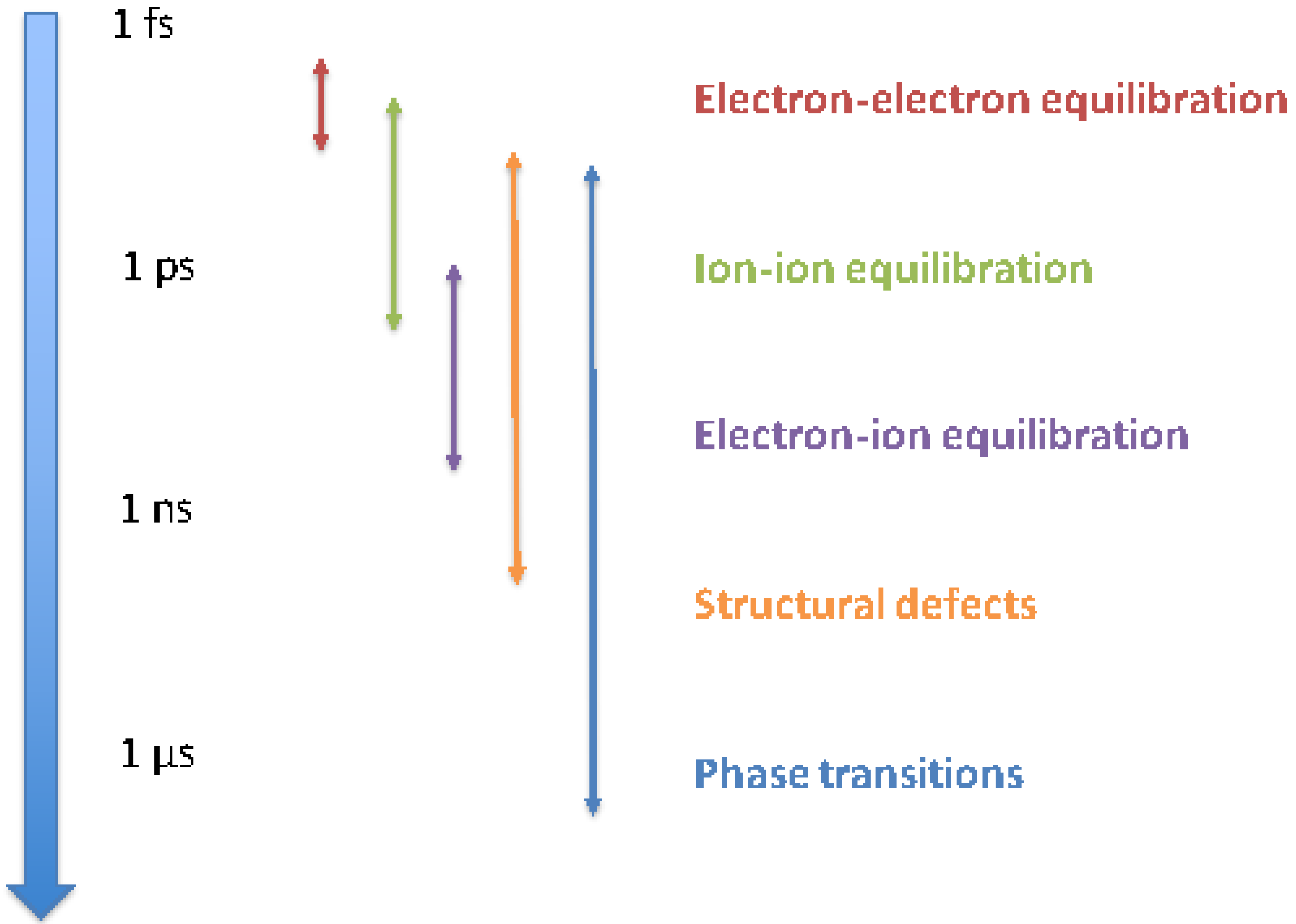


impacts

Laboratory experiments



Motivation | Time scales



Motivation | Warm dense matter

What do we need?

- Equation of State
- Energy absorption rates
- Relaxation rates
- Response functions

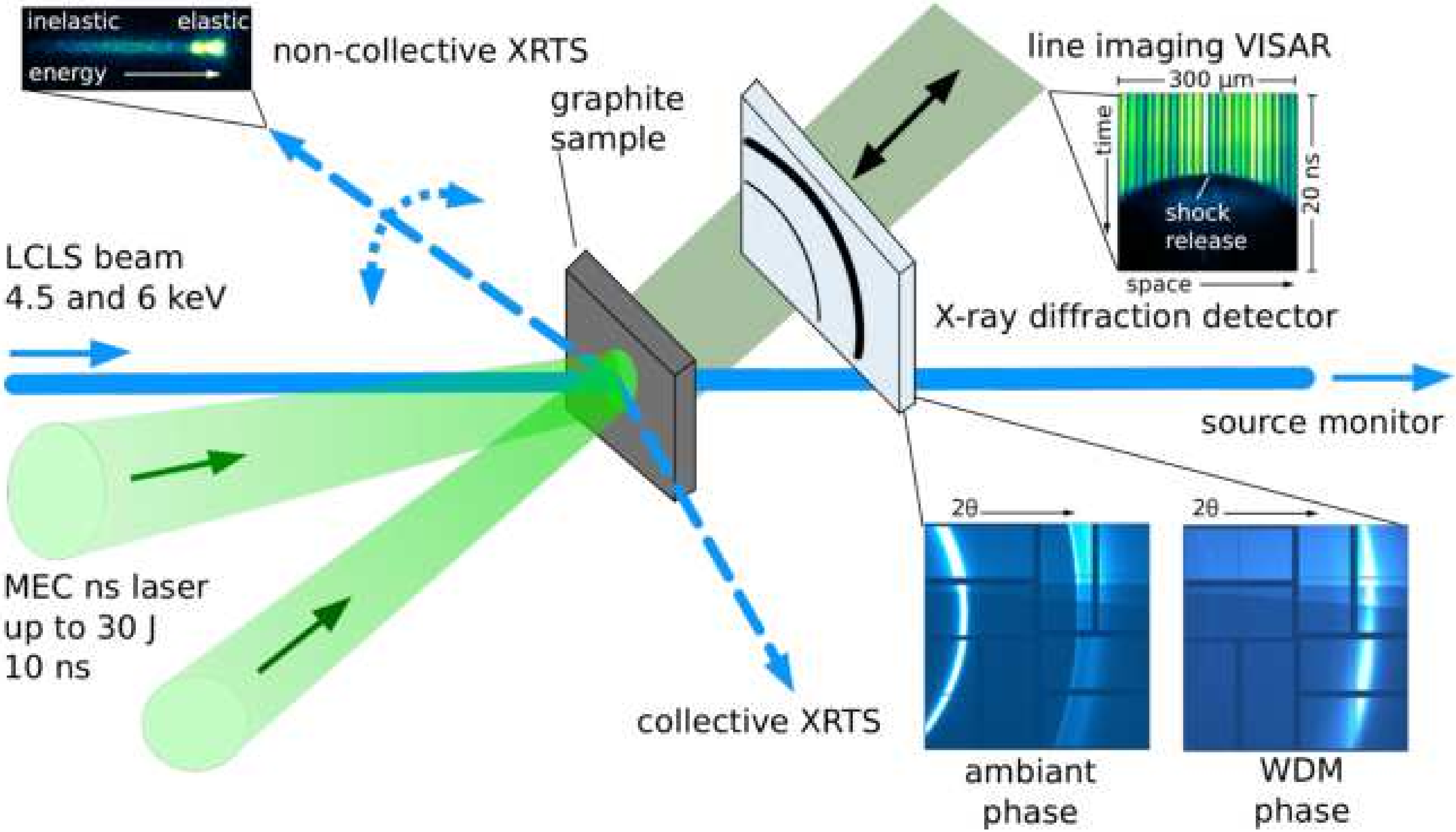
Underlying physics

- Strong interactions (ions)
- Bound states / ionization balance
- Quantum degeneracy
- Structure

Measurements are usually not "theory-free"

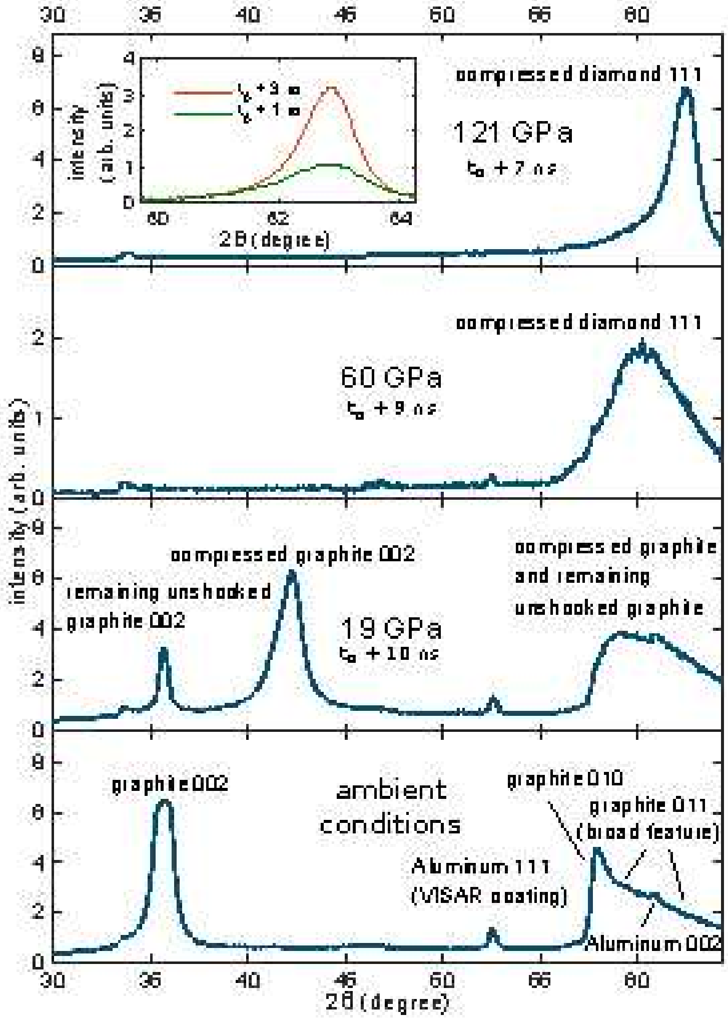
- "Over-diagnose" experiments
- Homogeneous samples
- High temporal resolution
- Cover broad parameter space

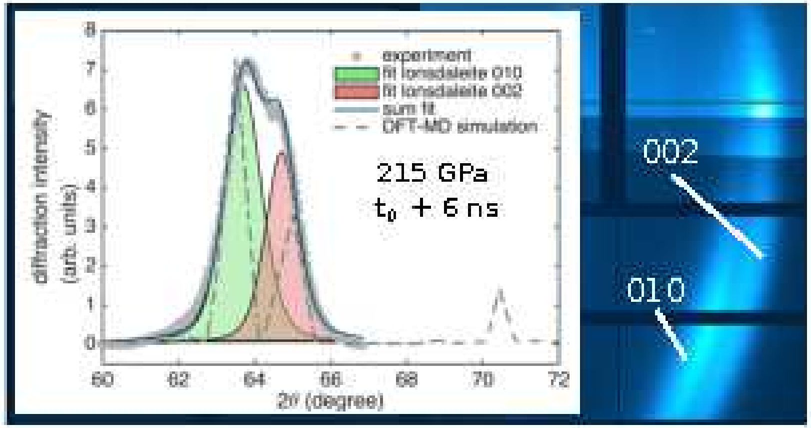
LCLS experiment | Setup



D. Kraus et al., Nature Communications (2016)

LCLS experiment | X-ray Diffraction: ns-formation of diamond

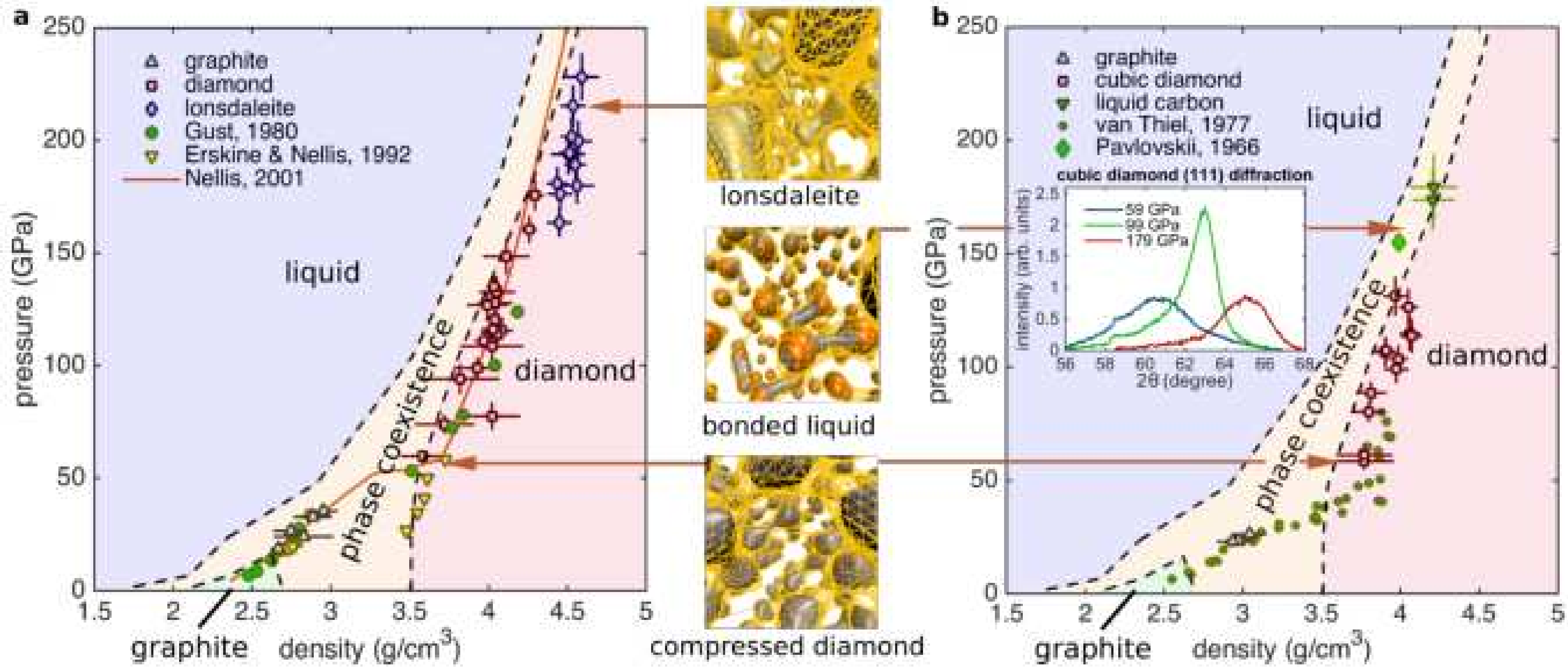




- First direct in-situ observation of the shock-induced transition from graphite to diamond.
- Pyrolytic graphite compressed above ~170 GPa: formation of lonsdaleite structure.

D. Kraus et al., Nature Communications (2016)

LCLS experiment | X-ray diffraction from porous samples



Isochoric heating using shorts pulse lasers can access different parameter regimes!

D. Kraus et al., Nature Communications (2016)

slide removed

- High porosity samples → liquid
- Low porosity samples → liquid (but cooler)
- Pyrolytic graphite → solid, close to melting

LCLS experiment | Diffraction + Absorption

slide removed

Spectrally resolved X-ray scattering was also anticipated, but no space left in target chamber

B. Barbrel, UC Berkeley
F. Albert, LLNL
W. Schumaker, SLAC
…

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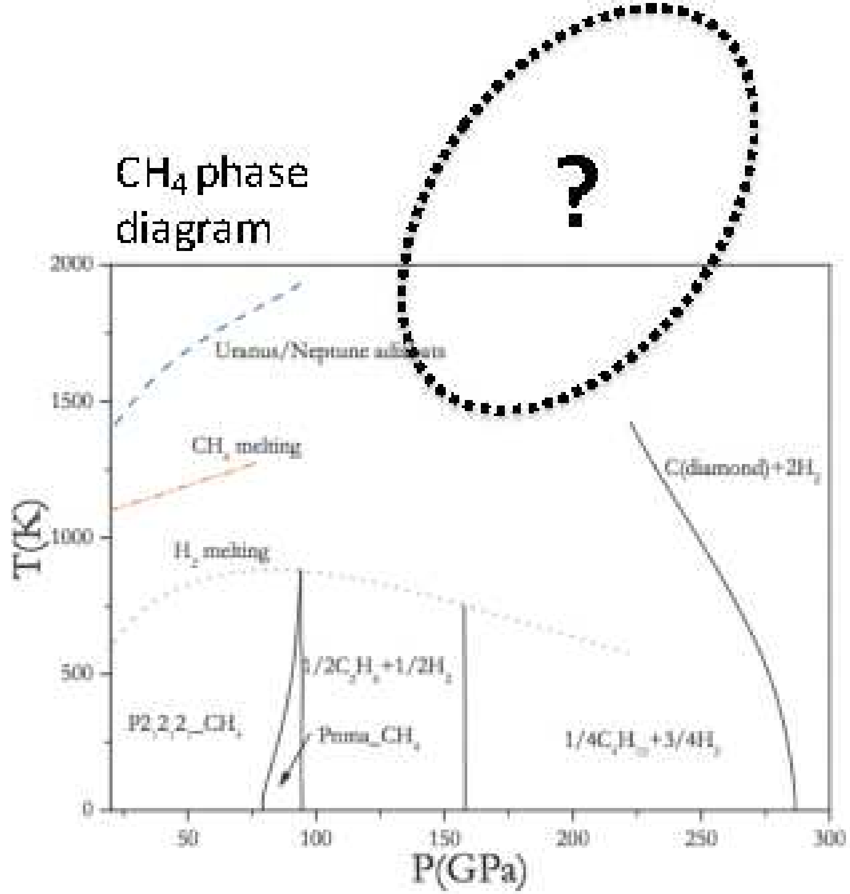
LCLS experiment | CH phase separation



G. Gao et al., J. Chem. Phys. 133, 144508 (2010)

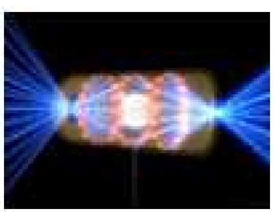
letters to nature

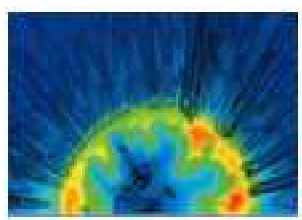
Nature **292**, 435 - 436 (30 July 1981); doi:10.1038/292435a0

The ice layer in Uranus and Neptune—diamonds in the sky?

MARVIN ROSS

University of California, Lawrence Livermore National Laboratory, Livermore, California 94550, USA

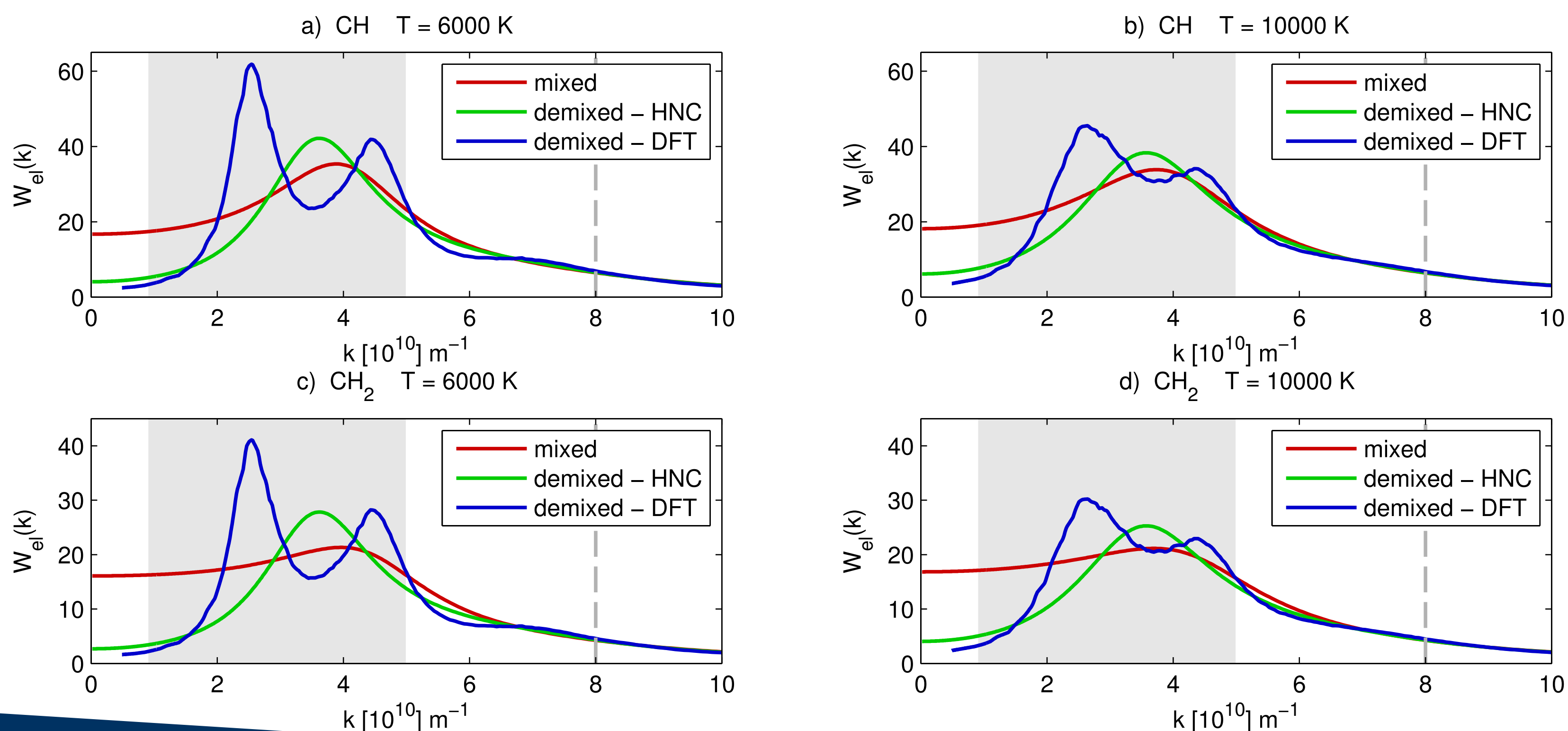




Elastic scattering amplitude is very sensitive for de-mixing (especially at small k).

picture removed

Will use large k for normalization.



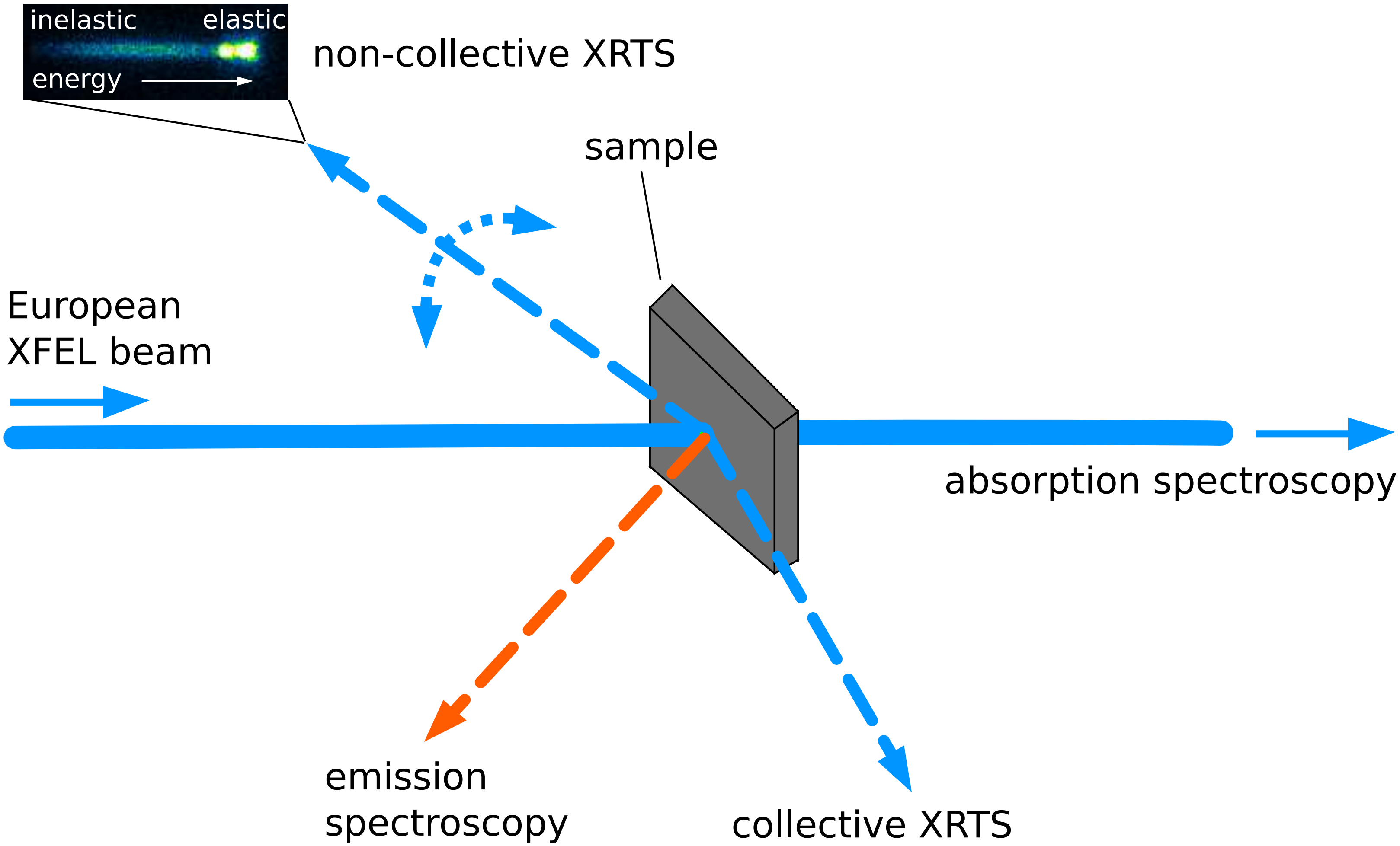
 CH phase separation - DFT-MD simulations

150 GPa
5000 K

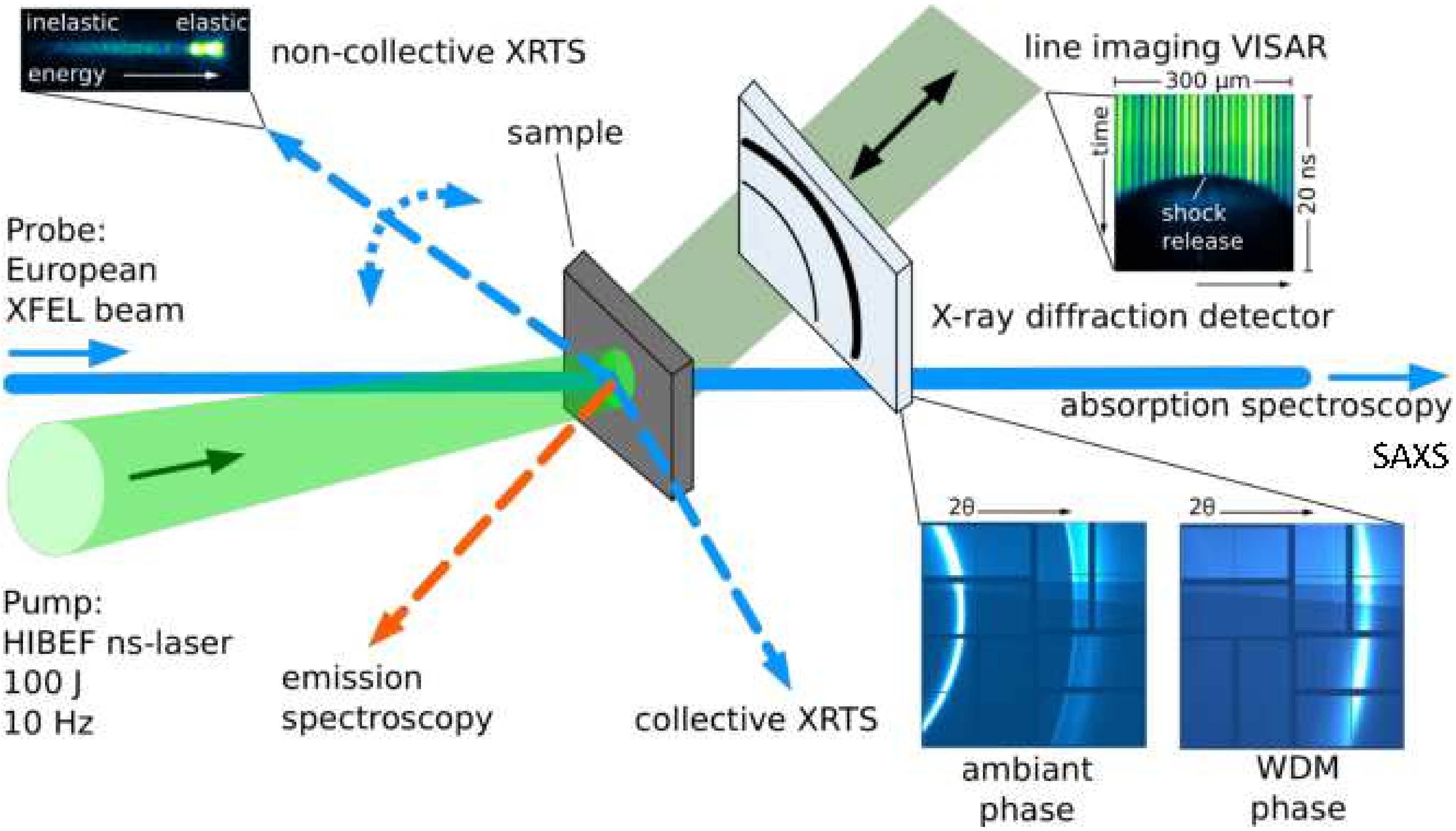
slide removed

J. Vorberger, HZDR

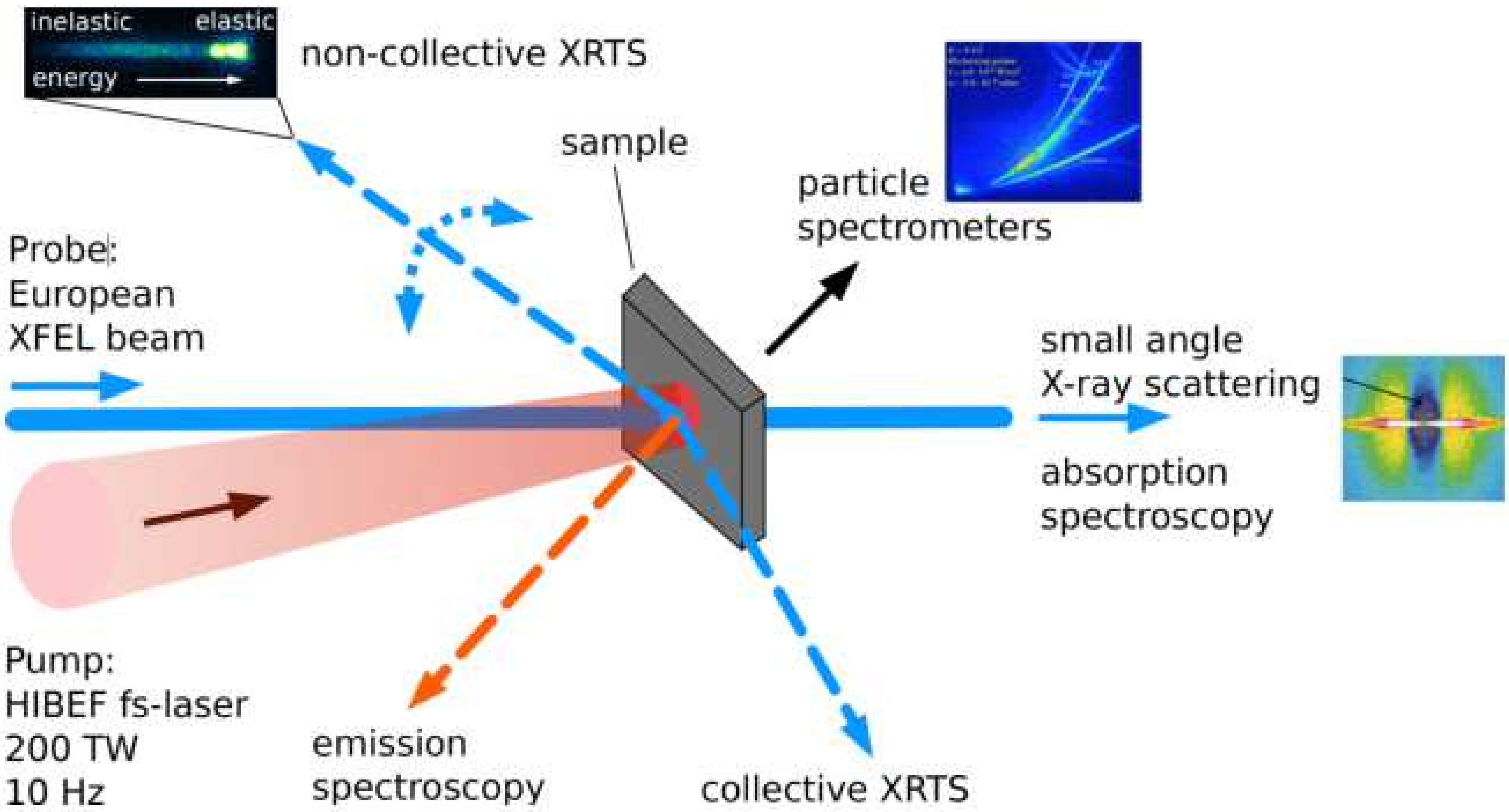
slide removed


inelastic
elastic
energy
non-collective XRTS
sample
European XFEL beam
absorption spectroscopy
emission spectroscopy
collective XRTS

HED at XFEL / HIBEF | Anticipated future experiments



HED at XFEL / HIBEF | Anticipated future experiments



Outlook | Advertisment

High Energy Density at European XFEL – Helmholtz International Beamline for Extreme Fields

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

HELMHOLTZ GEMEINSCHAFT

Job openings: now: postdoc & laser engineers

more soon


Thanks

First results from the HED group at MEC, LCLS

Siegfried H. Glenzer

(SLAC, Stanford University)

January 28th, 2016

Presentation to:

XFEL workshop on the HED instrument, Hamburg

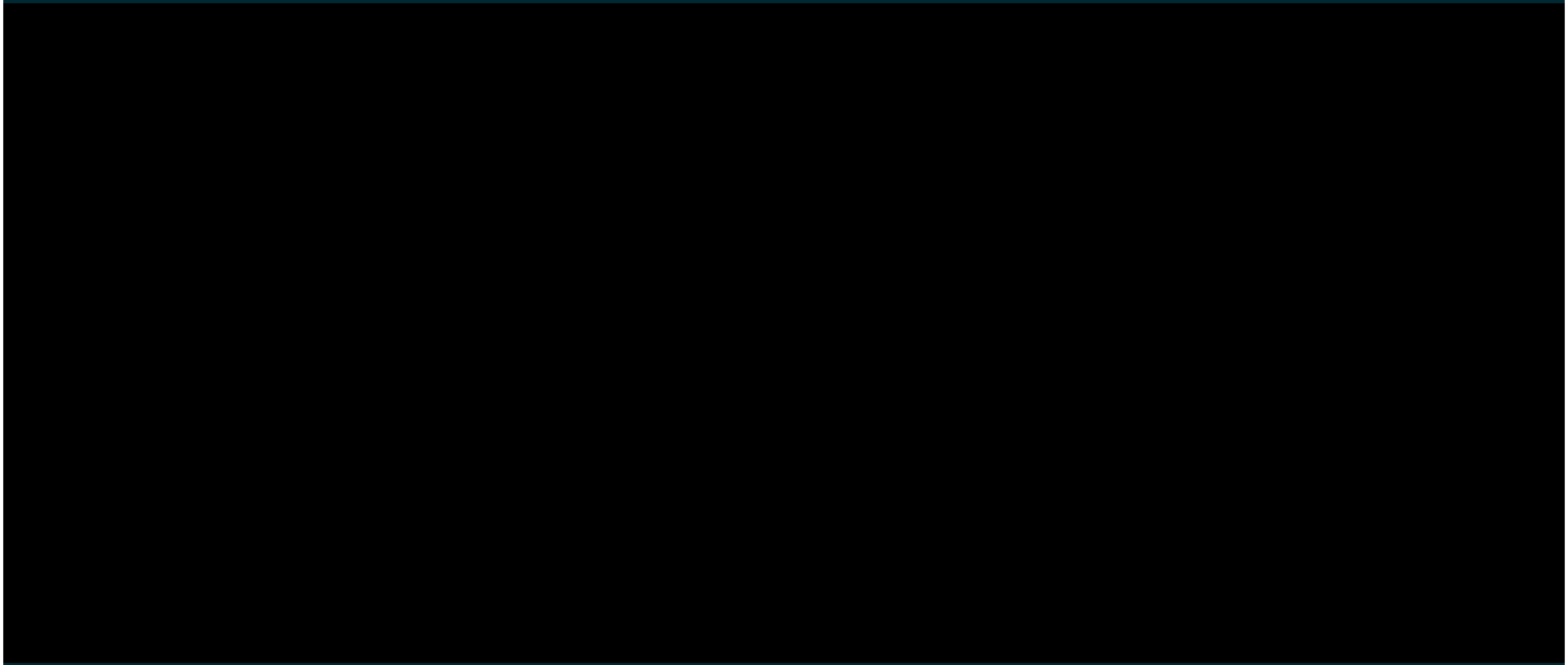
The LCLS x-ray laser enables scientific discoveries in Matter under Extreme Conditions

SLAC

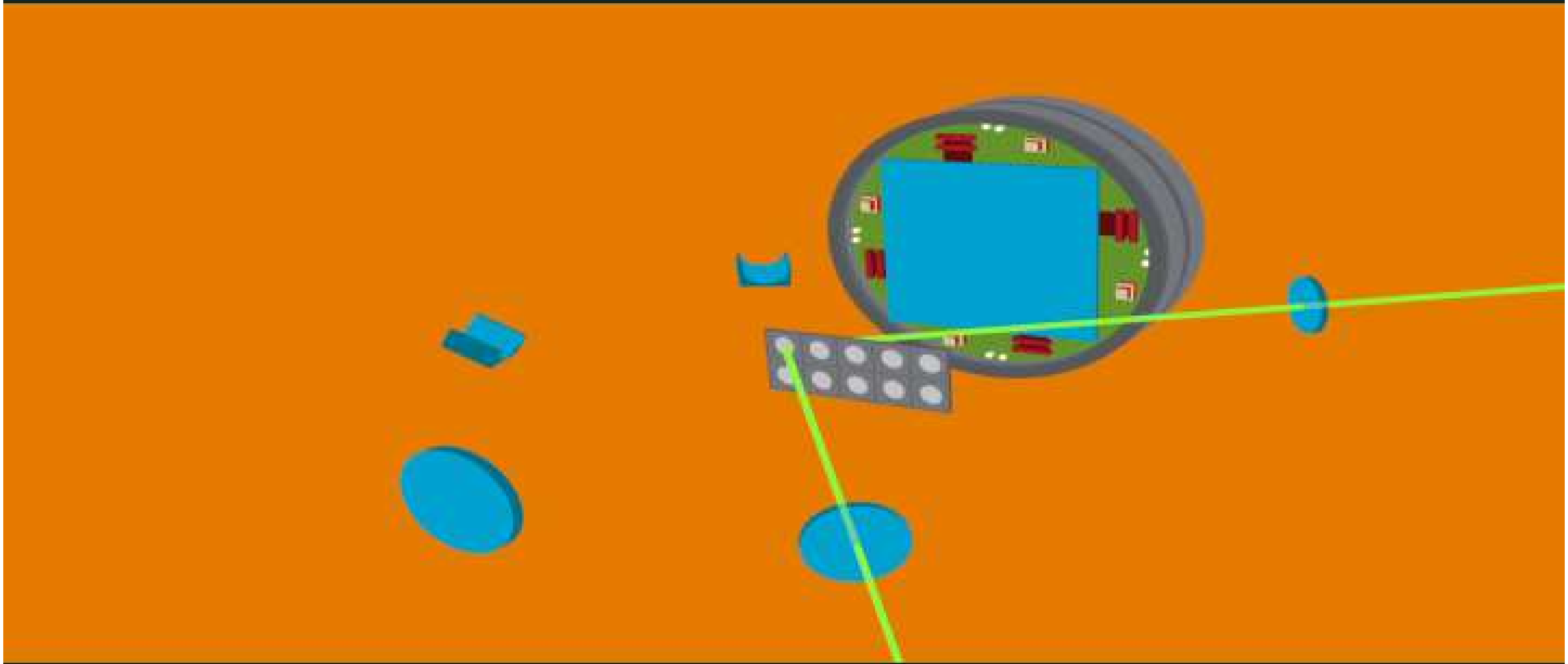
- New capabilities at the LCLS Free Electron Laser
  - 10^{12} focused x-ray photons (4-10 keV) with unprecedented resolution
    - Space (200 nm)
    - Time (50 fs)
    - Energy ($\Delta E/E = 10^{-4}$)
- Coupling LCLS x rays with nanosecond shock driver lasers
  - Determine the properties of matter at high densities and at high pressures
- Coupling LCLS x rays with high-power short-pulse lasers
  - Visualize laser-matter interaction with ultrafast pump-probe experiments
- Summary and outlook towards LCLS-II

The coupling of high-power optical lasers with LCLS x-rays is pushing the HED science frontier

Matter in Extreme Conditions (MEC)

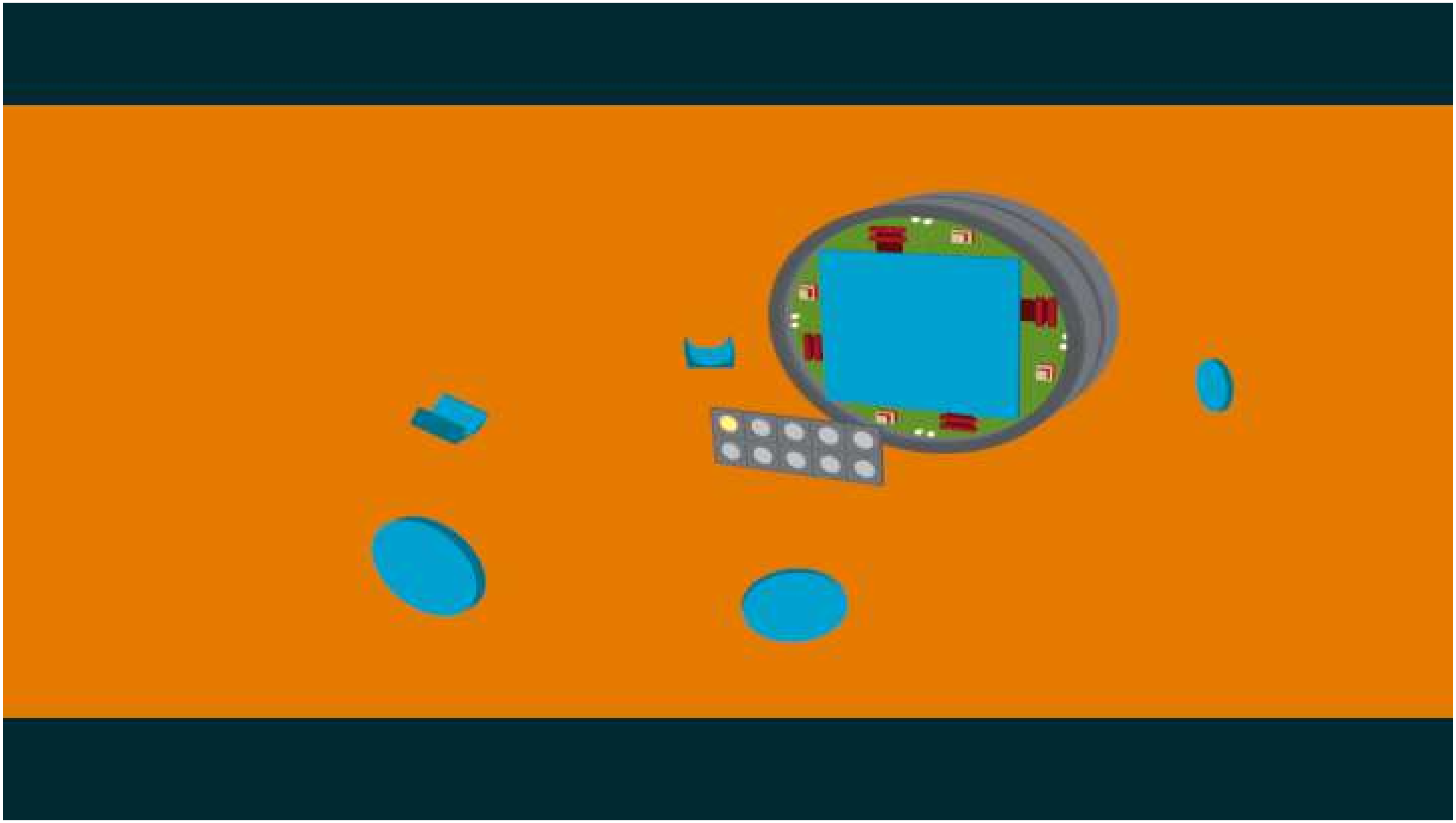


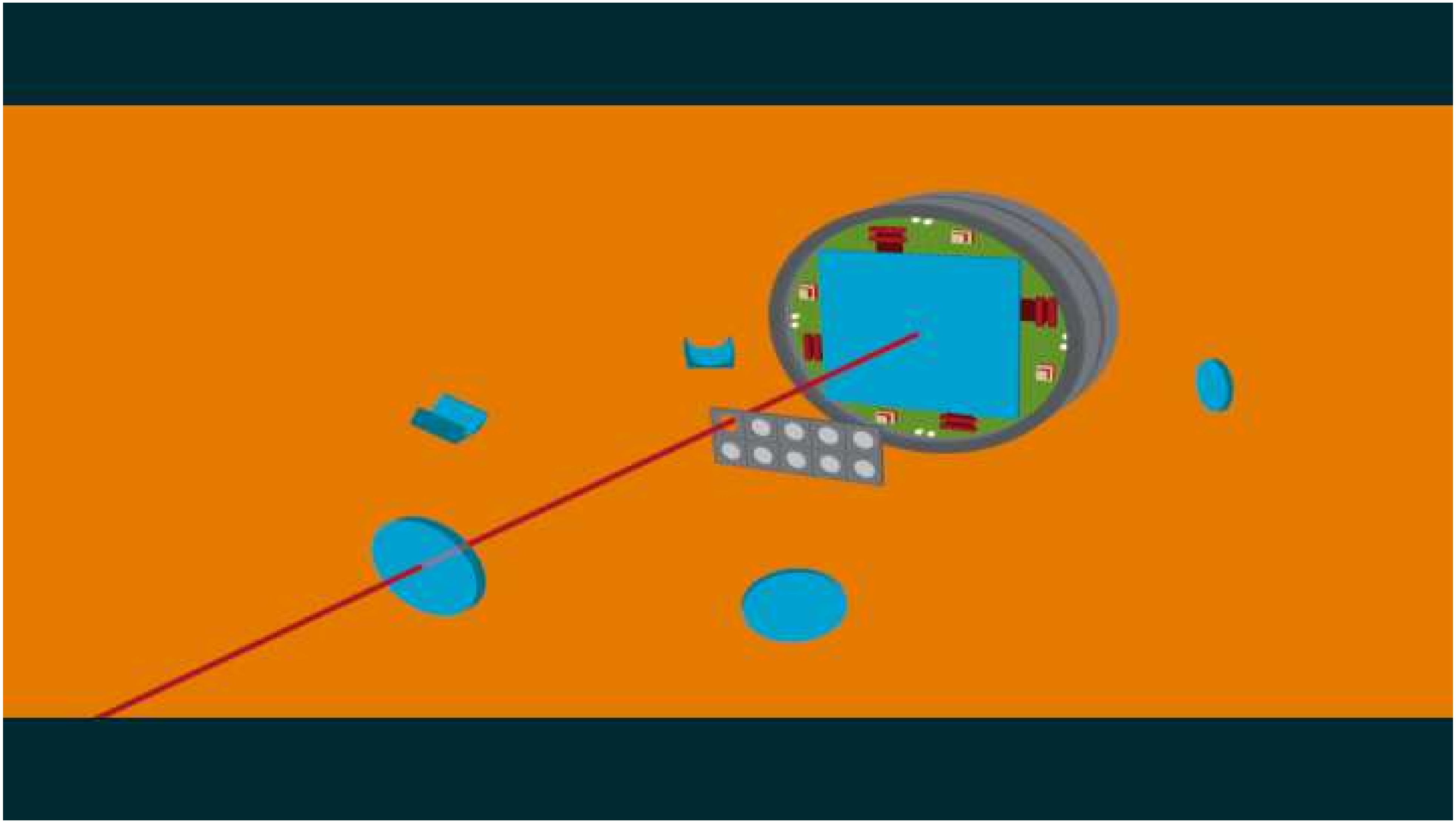
Shaped nanosecond glass laser: 1 GW = 1,000,000,000 W = 1 billion W

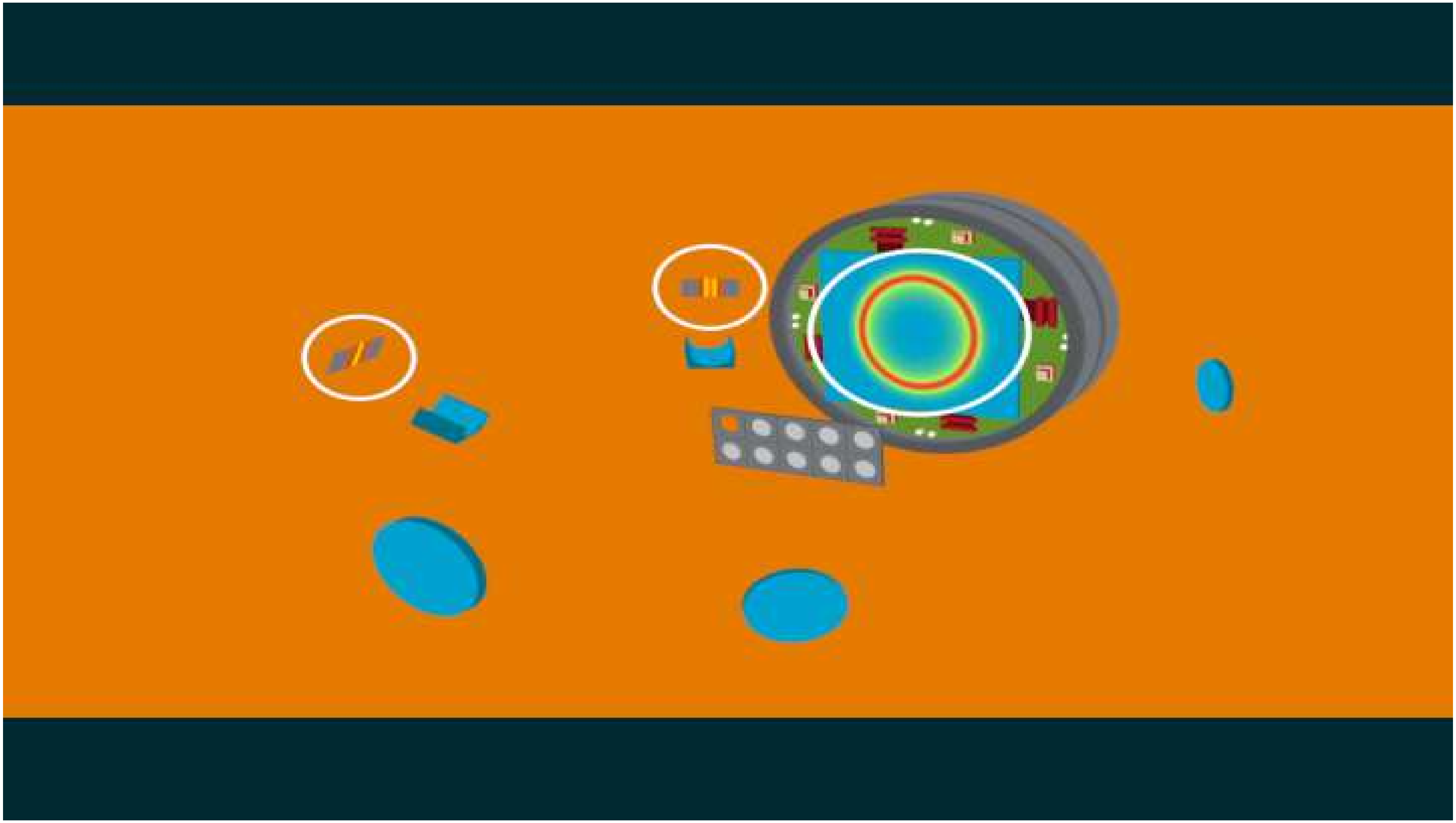


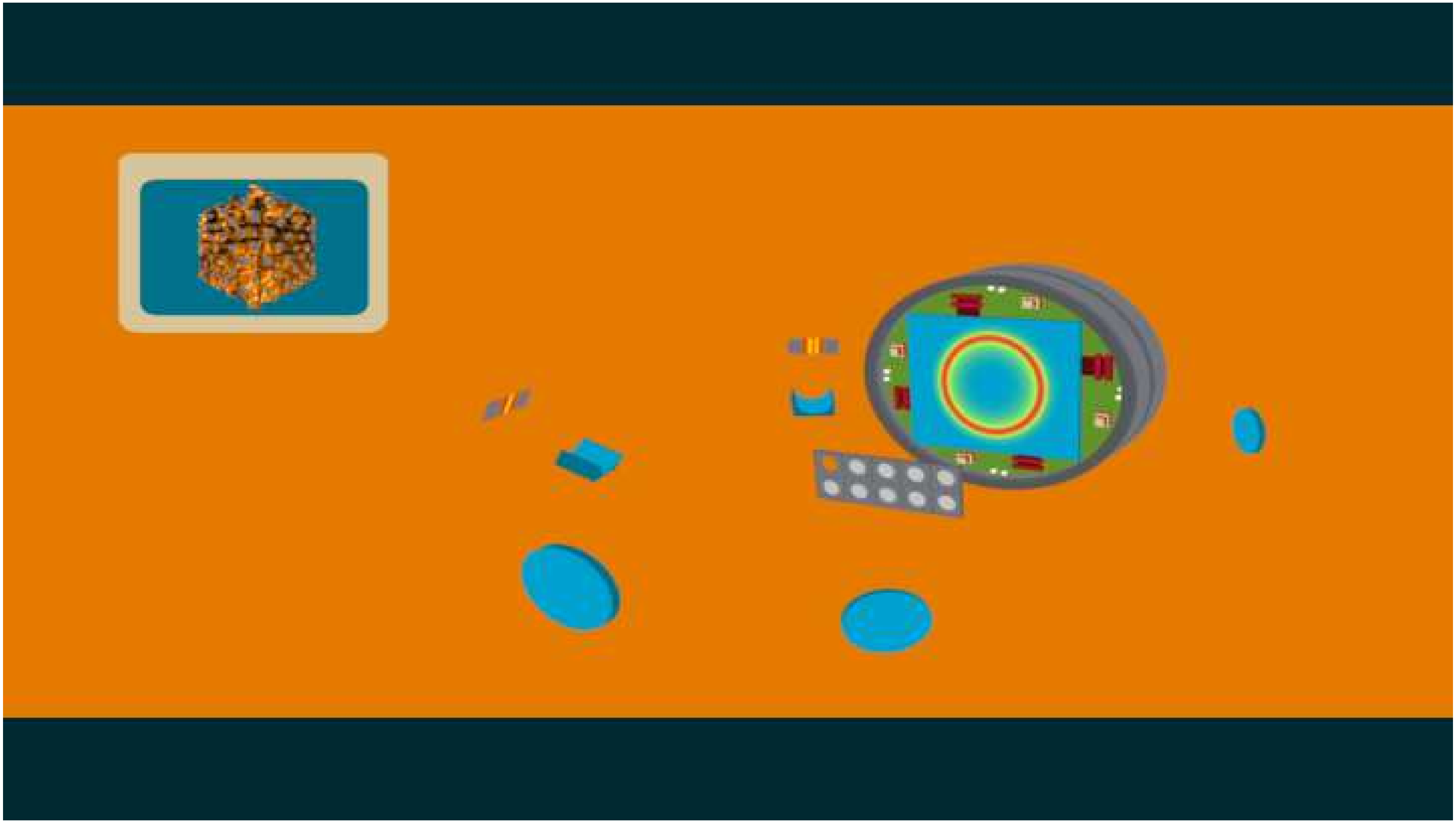
Newton's third law:

Action = Reaction



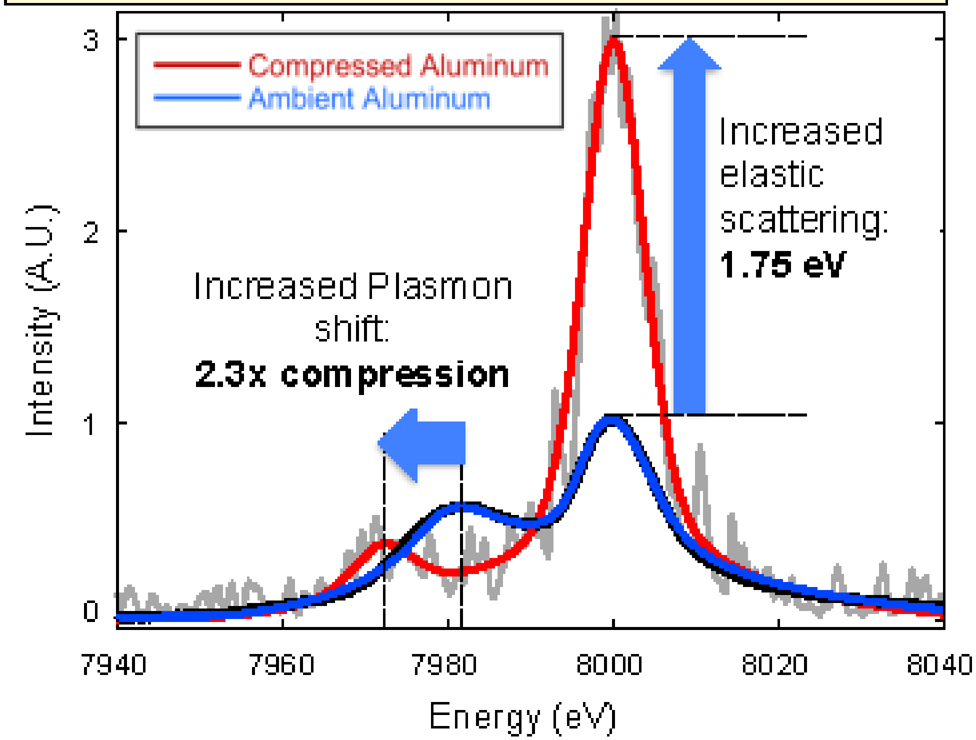


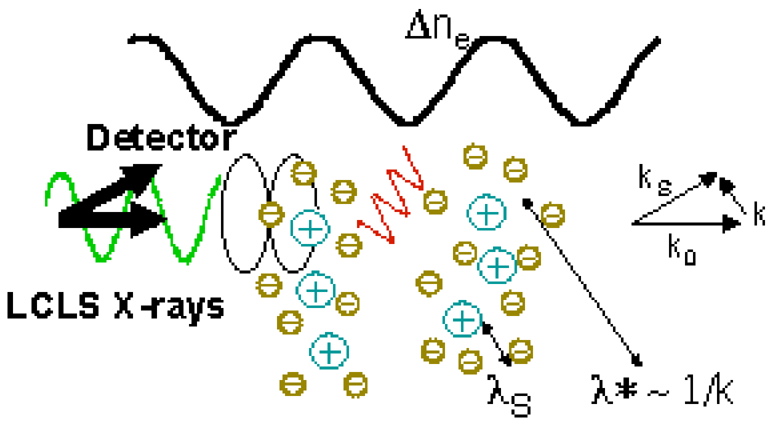




Plasmon measurements accurately determine 3x compressed Al at temperatures of 1.75 eV

Plasmon (forward scattering) spectra



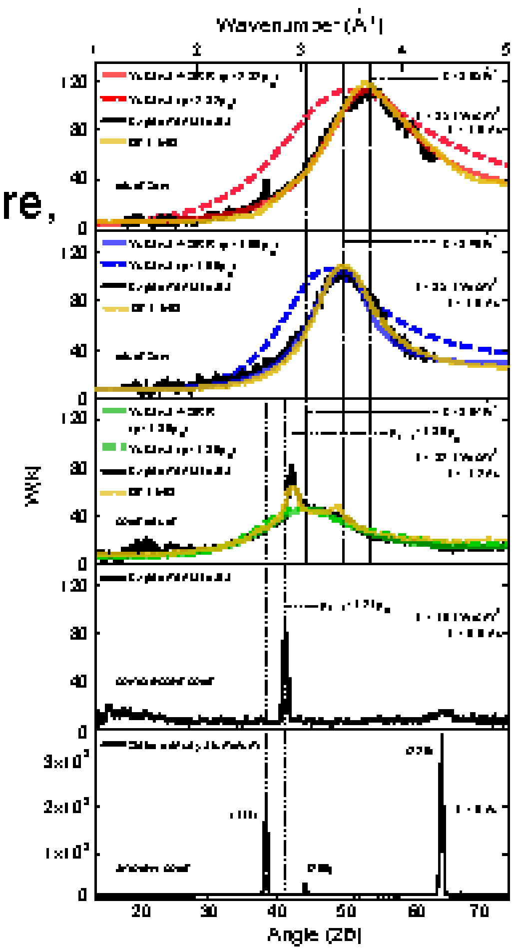


- Plasmon shift determined by plasma frequency $\omega_{pe} = [n_e e^2/m_e \varepsilon_0]^{1/2}$

First-principals method to determine conditions: $n_e = 5.4 \times 10^{23}$ cm^{-3} ± 5%

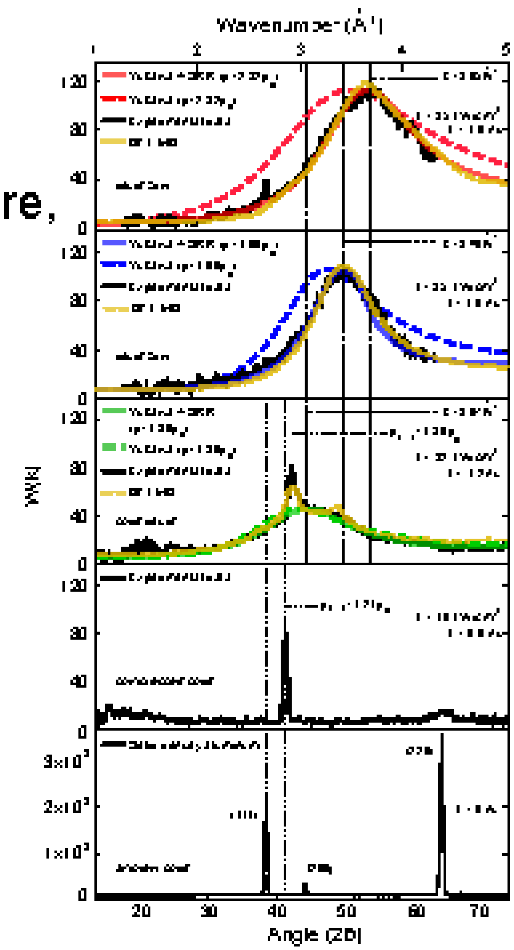
X-rays visualize Matter in Extreme Conditions

Density,
Temperature,
Pressure



X-rays visualize Matter in Extreme Conditions

Density,
Temperature,
Pressure



Let us first have a look at low temperature/pressure conditions

X-rays visualize Matter in Extreme Conditions

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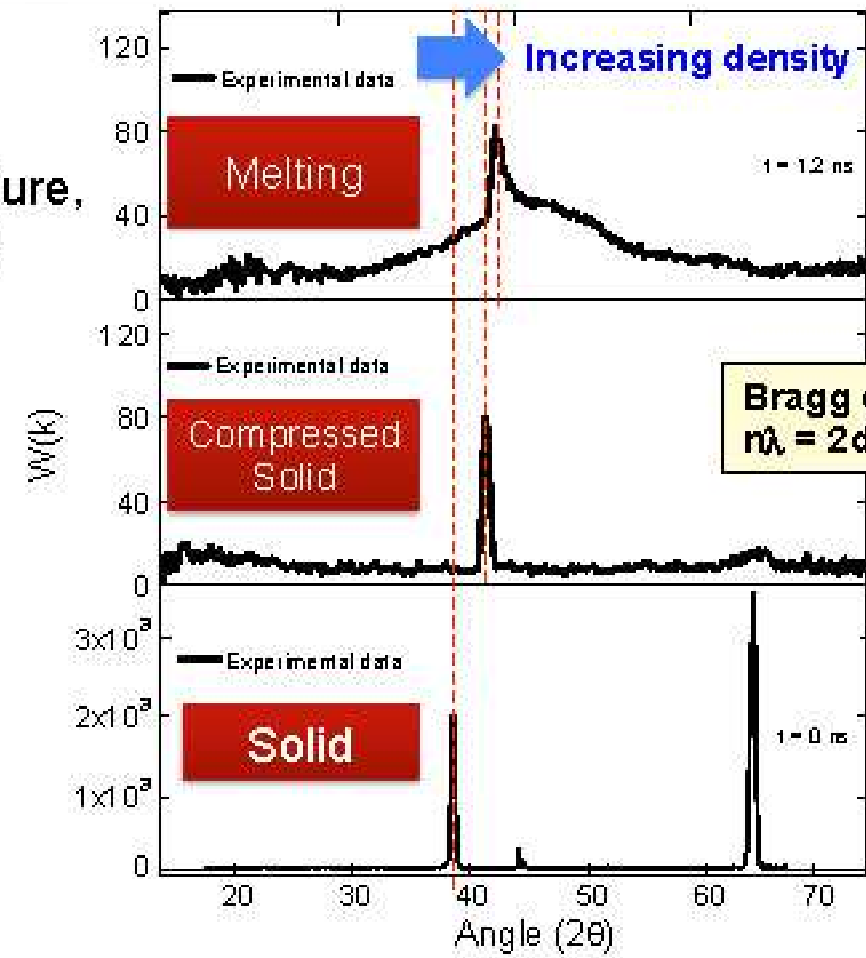
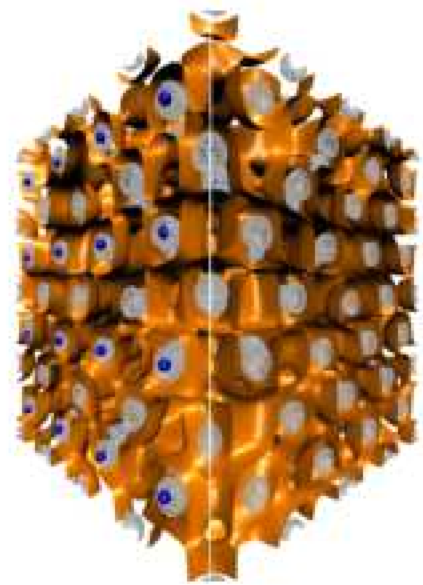
Density,
Temperature,
Pressure



Bragg equation:
$n\lambda = 2d \sin\theta$

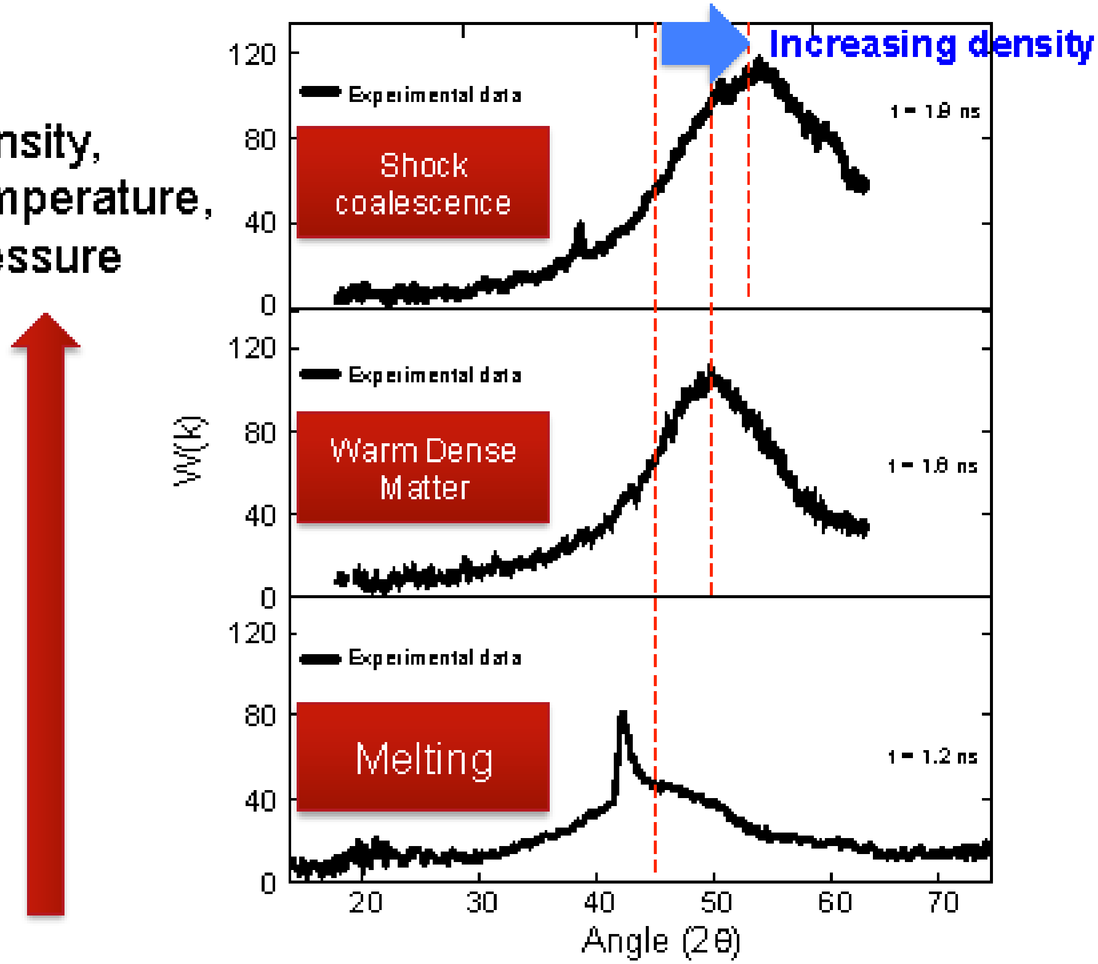
Solid Aluminum



- **Orange: isosurface of the n_e (delocalized electrons)**
- **Grey: 2nd isosurface (n=1,2 localized electrons)**
- **Blue sphere: Al nuclei**

X-rays visualize Matter in Extreme Conditions

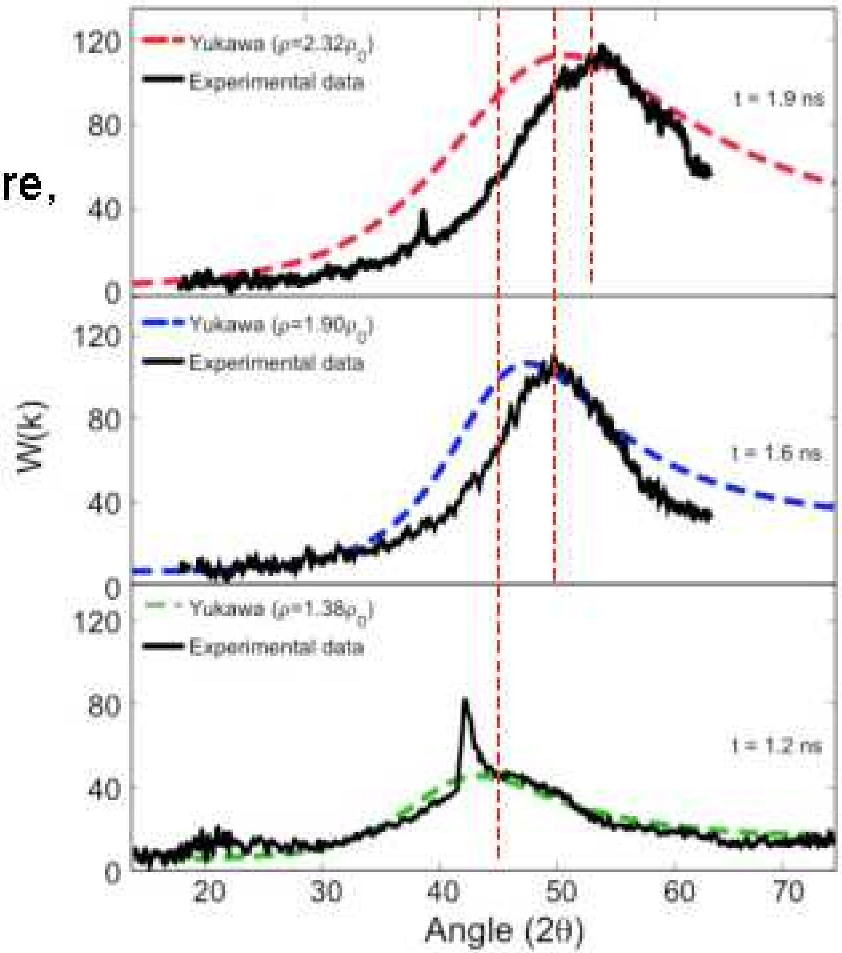
Density, Temperature, Pressure



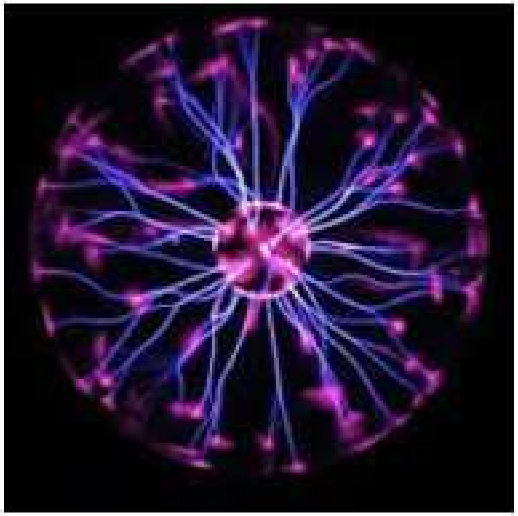
When Bragg peaks disappear a broad fluid peak takes over – this feature contains information about the structure of Warm Dense Matter

Plasma Theory does not agree with data

Density, Temperature, Pressure



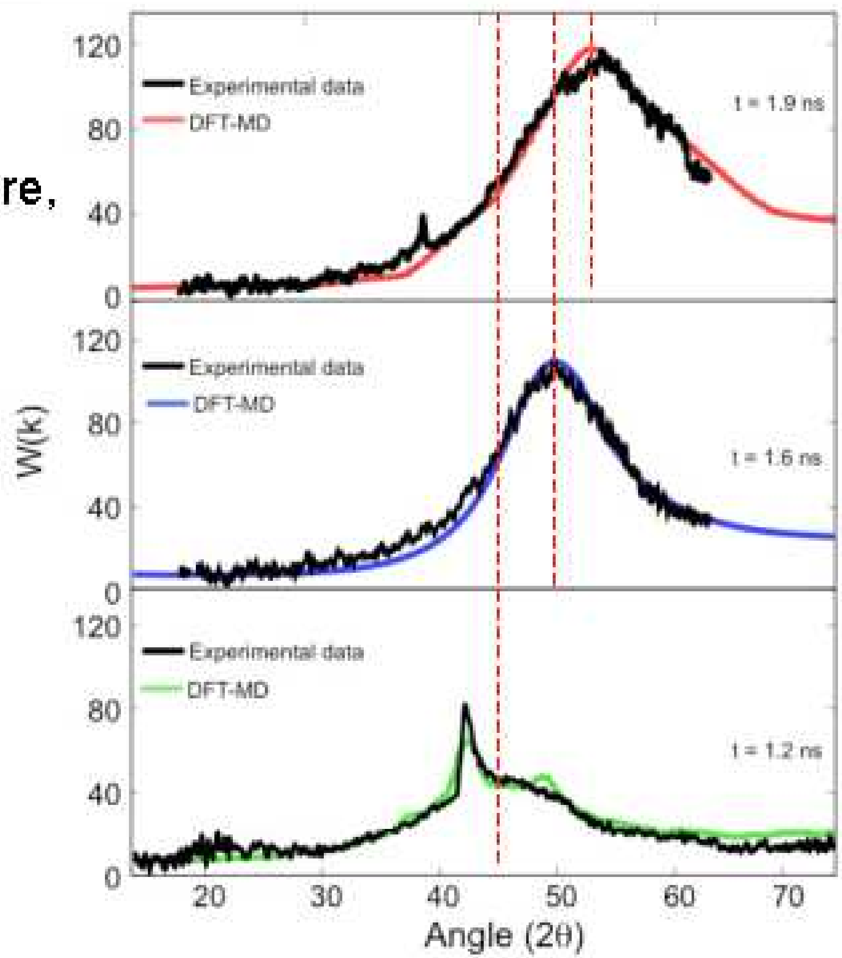
Ideal Plasma Theory



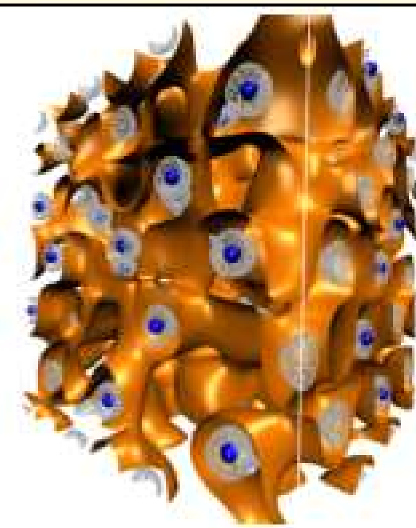
- **Theory includes screening by free electron, but no short-range repulsion**

Warm dense matter property: Screening and Repulsion

Density,
Temperature,
Pressure



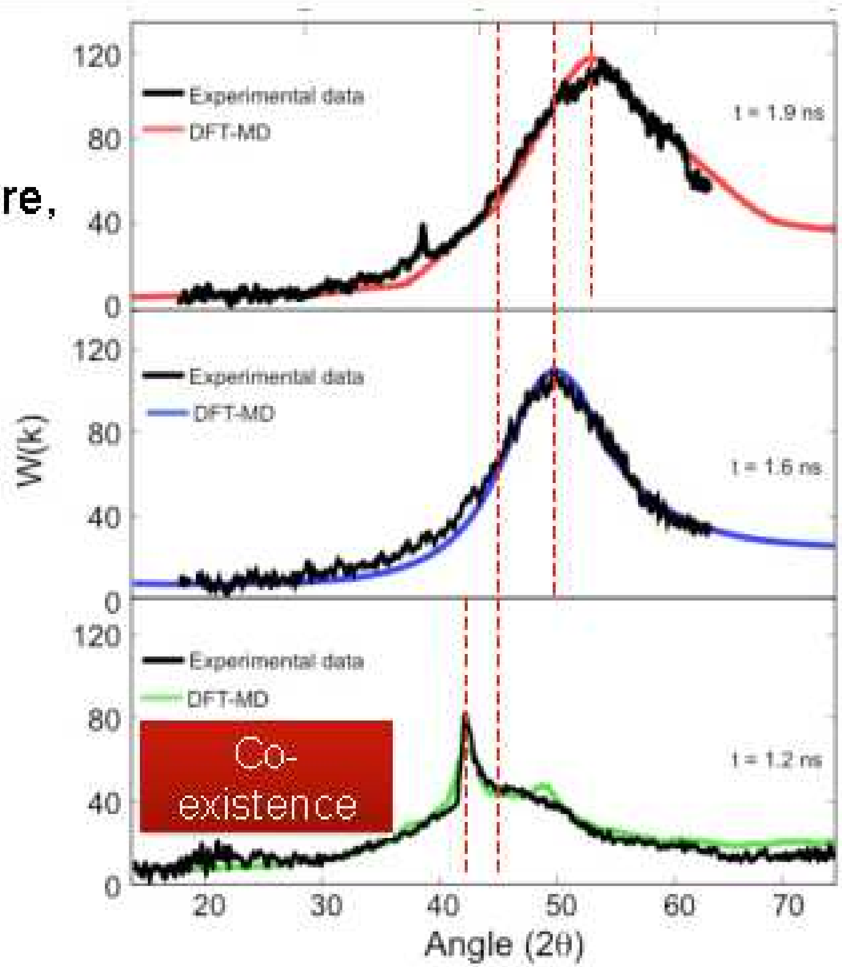
DFT-MD simulations of warm dense matter



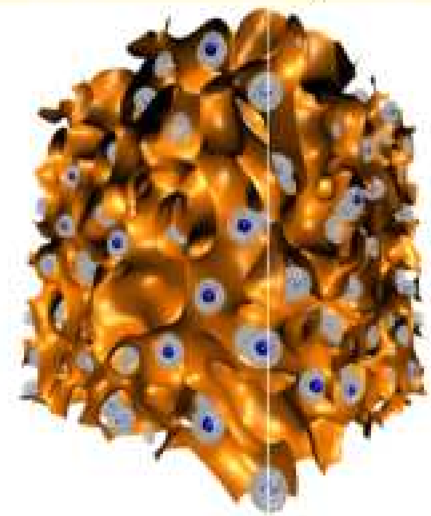
- **Delocalized e- are disturbed from the very regular structure in the lattice**
- **Properties of both**
  - **Hot dense gas or plasma**
  - **Solid**

Date show that we can now study co-existence

Density,
Temperature,
Pressure



DFT-MD simulations show co-existence regime



- **Simulations show Bragg peak and broad fluid peak**
- **Warm Dense Matter co-exists with a compressed solid**

Pseudo-Atom Molecular Dynamics shows agreement with our findings

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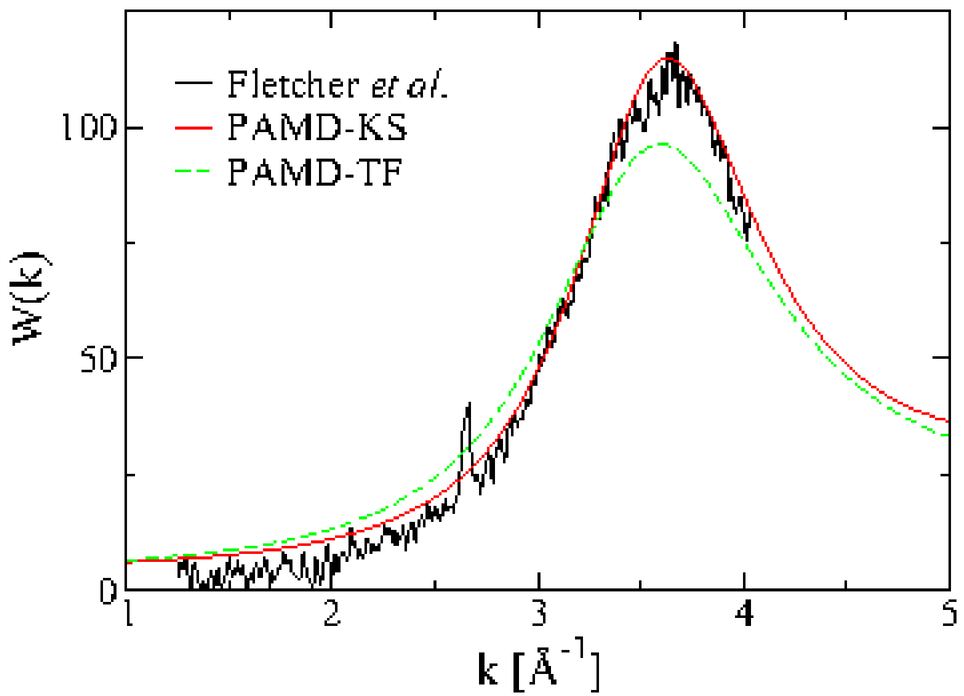
PAMD performed for n_e and T_e from Plasmon scattering measurement



PHYSICAL REVIEW E 92 033101 (2015)

Models of the elastic x-ray scattering feature for warm dense aluminum

C. E. Starrett and D. Saumon
Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87545, USA

- **Excellent agreement with Kohn-Sham**
  - **Detailed configuration accounting**
- **Inadequacies using Thomas-Fermi functional**
  - **Orbital free modeling**
  - **Not suitable for warm dense matter modeling with <50 eV**

We determined the structure factor: a critically important quantity describing the microphysics

SLAC

- **Pressure**

Total

$$P_{TOT} = P_i + P_e$$

Ion pressure

$$P_i = p^{x} + P_G$$

Excess ion pressure

$$p^{x} = \frac{n_i U^{(0)}}{3N} - \frac{n_i (Ze)^2}{12\pi^2} \int_0^\infty S(k) \frac{k_e^4}{(k^2 + k_e^2)^2} \partial k$$

Ideal gas pressure

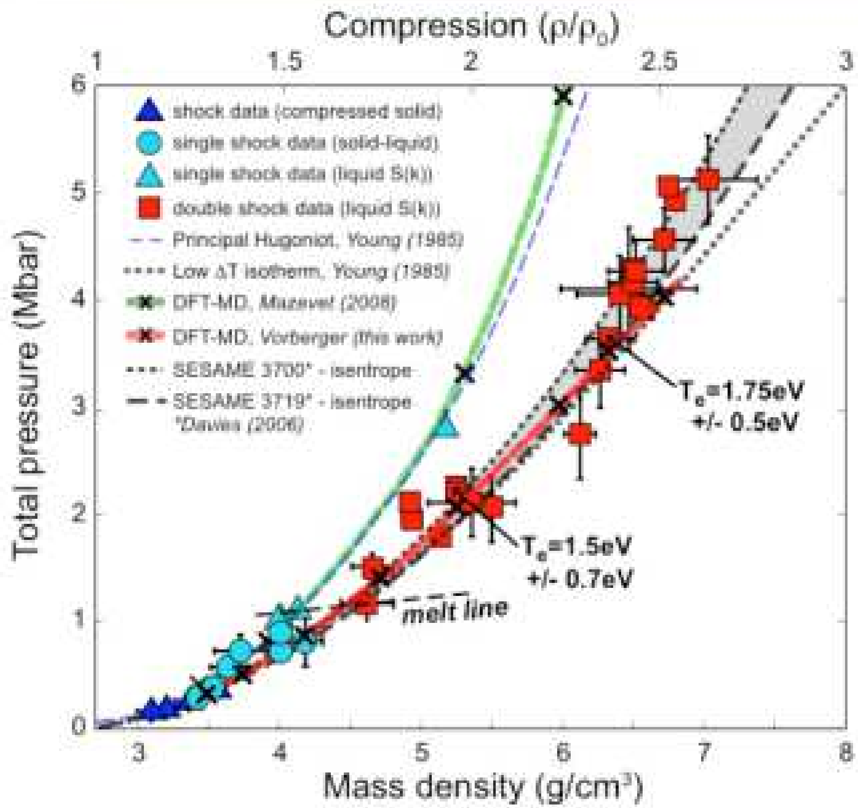
$$P_G = n_i k_B T_i$$

- **Collisions**

$$\nu^{B}(\omega) = -i \frac{\varepsilon_0 \Omega_0^2 n_i}{6\pi^2 e^2 m_e n_e} \int_0^\infty dk k^6 [V_{ei}^S(k)]^2 S_{ii}(k) \frac{1}{\omega} [\varepsilon_e^{\mathrm{RPA}}(k,\omega) - \varepsilon_e^{\mathrm{RPA}}(k,0)]$$

Equation of State, Line broadening, Stopping Powers, Transport, Opacity,…

First application of a measured dynamic structure factor to determine the pressure of compressed matter



- Use novel *in situ* measurements of the electron temperature and density in the warm dense regime
- Tested microphysical models and determined the physics properties of matter in extreme conditions
- Use data to determine pressure of the shock Hugoniot and isentrope of Aluminum

L. Fletcher *et al. Nature Photonics* **9**, 274 – 279 (2015)
D. Chapman *et al. Nature Comm* **6**, 6839 (2015)

X-ray scattering (Bragg, Thomson) observes novel physical properties of warm dense matter

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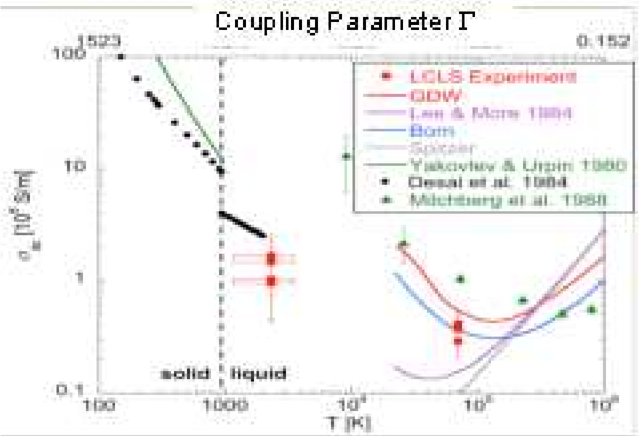
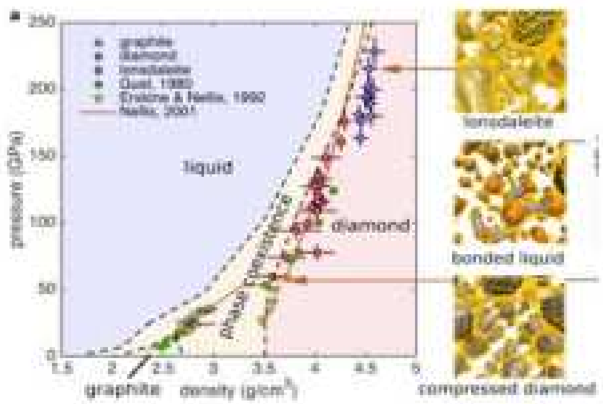
Plasmon damping determines conductivity



- Solid Al at T = 6 eV
- First *Conductivity* measurements with independent T_e, n_e data

P. Sperling, PRL **115**, (2015)

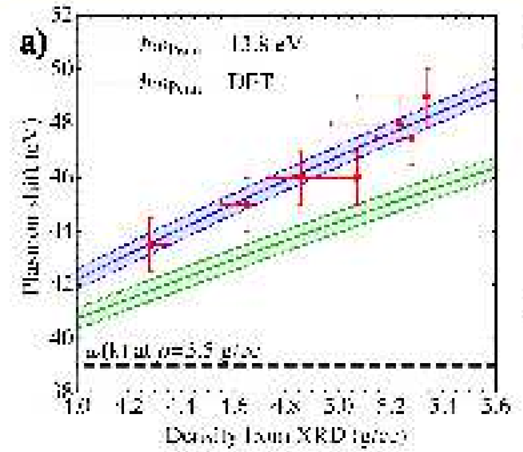
Graphite to diamond transition



- At ~1 Mbar, pyrolytic graphite to diamond
- At ~2 Mbar, first observation of hexagonal C: *Lonsdaleite*

D. Kraus, *Nature Comm.*, in review

Bragg & Plasmon show increasing band gap in C

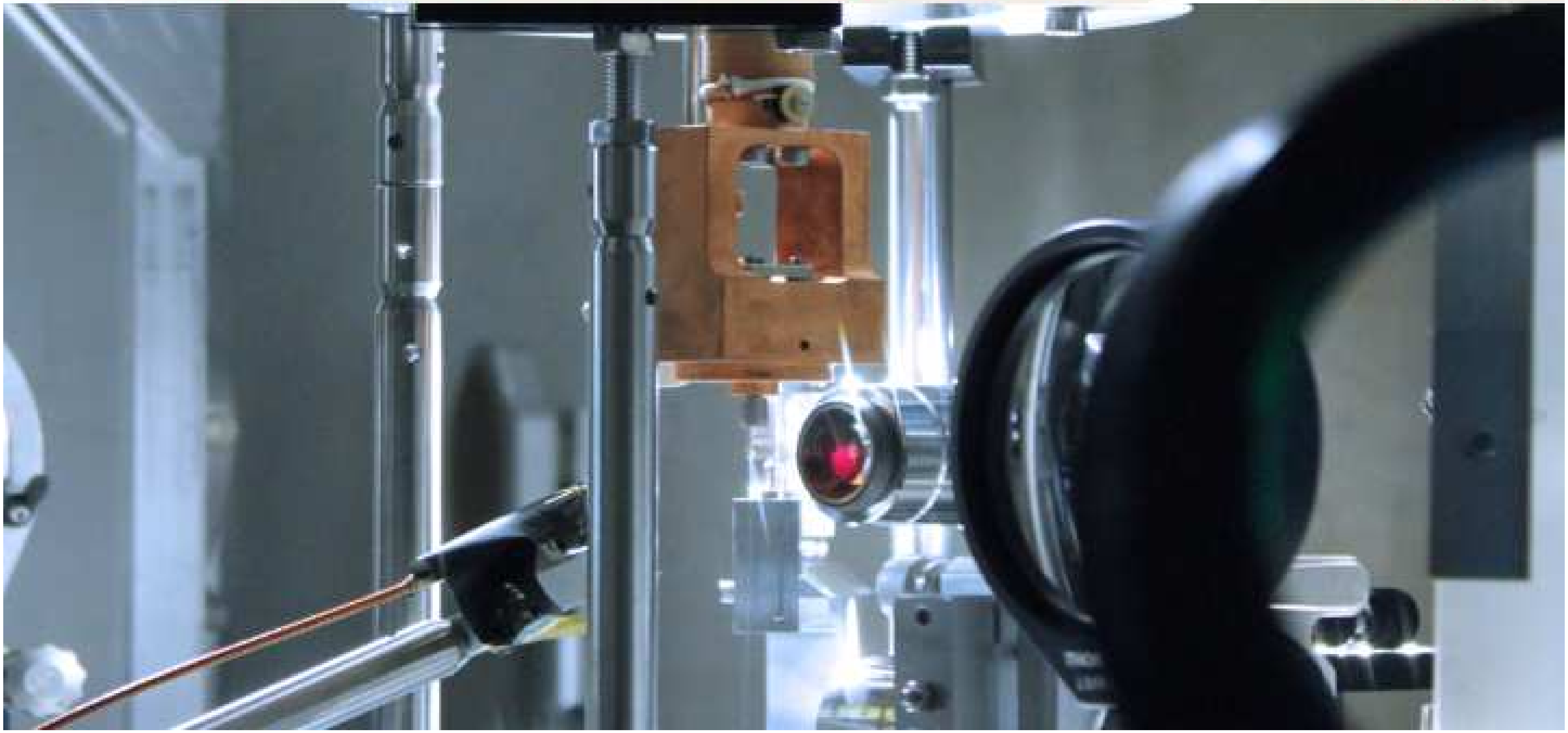


- Diamond shows an increasing band gap
- Diamond remains insulator at 4 Mbar

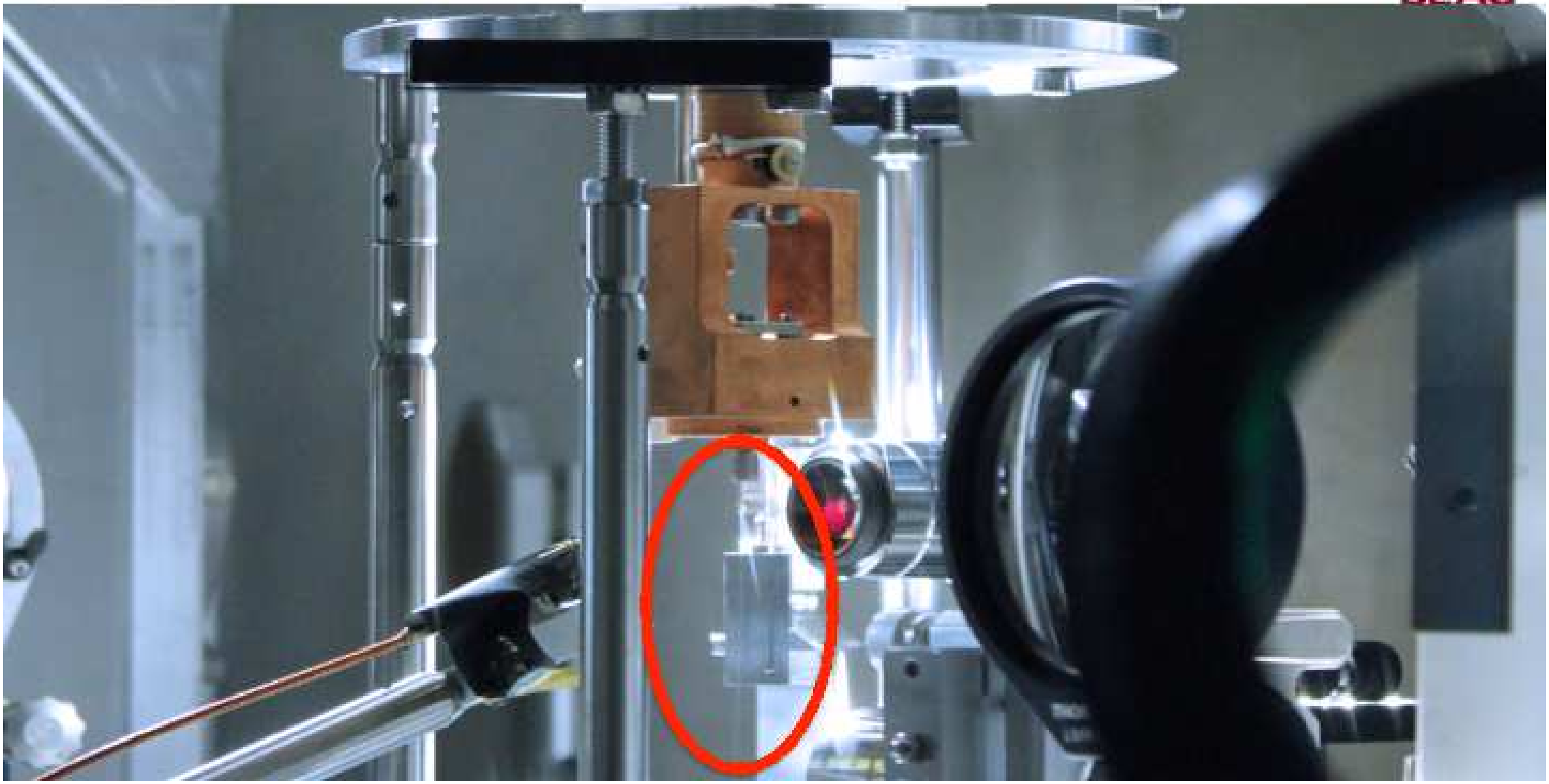
E. Gamboa, *Nature Comm.*, in review

A true high-repetition rate target for high-power short pulse laser interactios: Hydrogen jet

SLAC

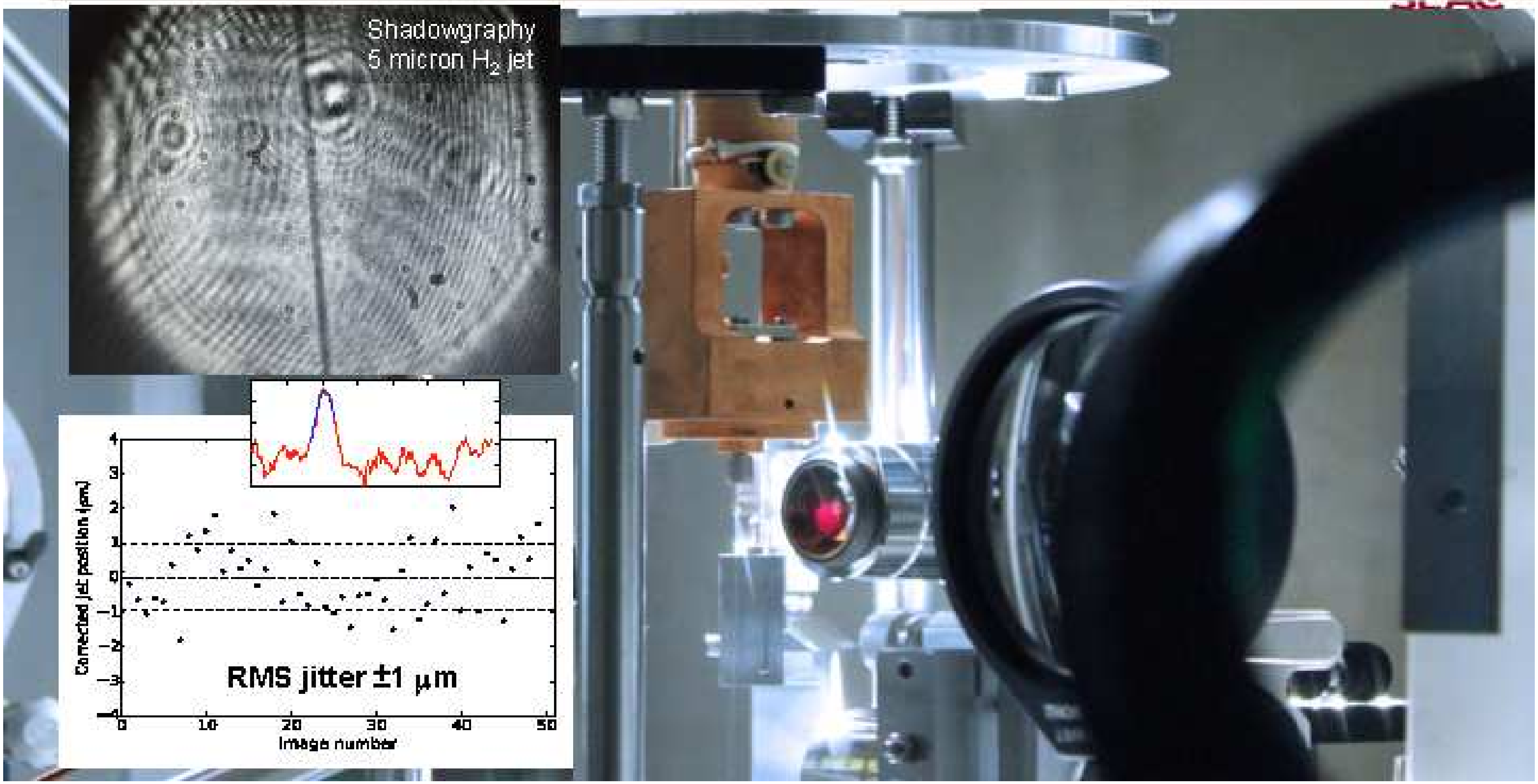


Super-cooled hydrogen icicle




You see with your eyes:
1/10th the diameter of a human hair
Jet: 5 μm
Human hair: ~50 μm

Super-cooled hydrogen icicle



Unprecedented explorations of solids and HED plasmas using x-ray scattering

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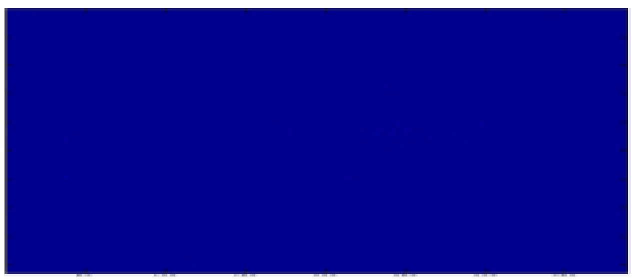
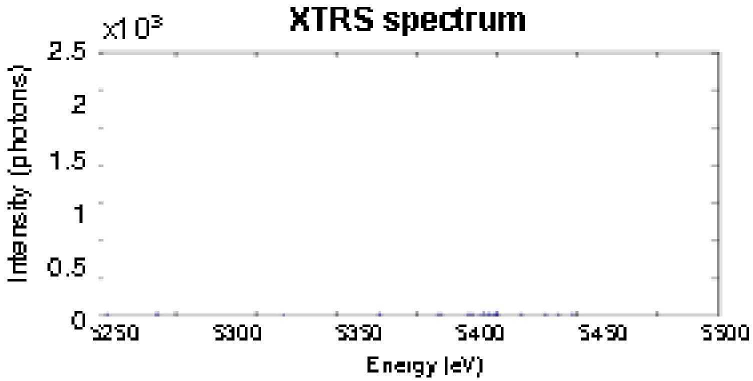
Inelastic single photon x-ray scattering (170°) @ 120 Hz

Single crystal x-ray diffraction (30°-55°) @ 120 Hz

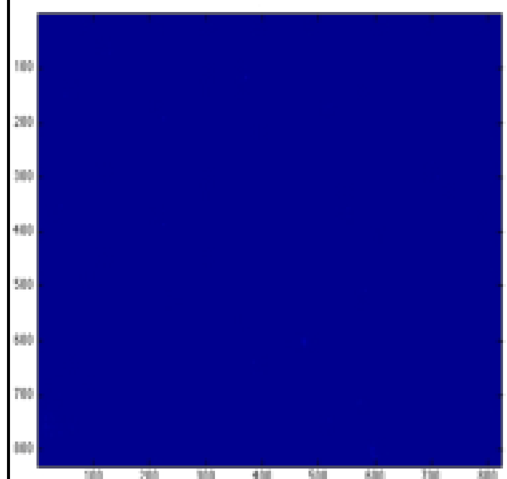
PI-CCD image



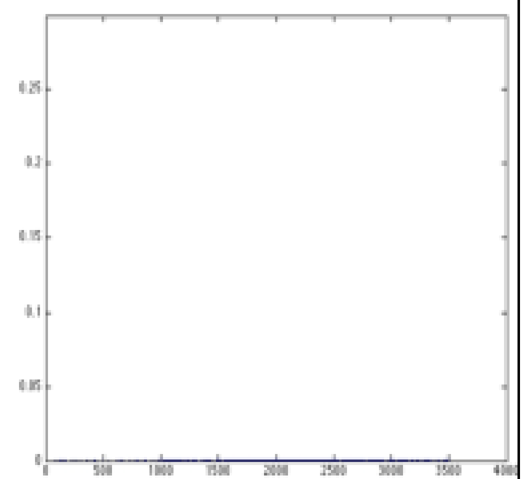
XTRS spectrum



CSPAD image

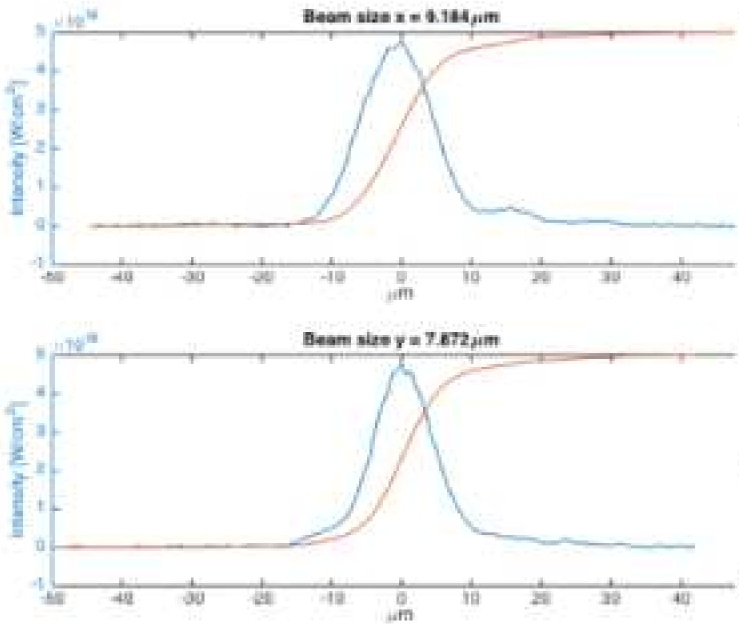


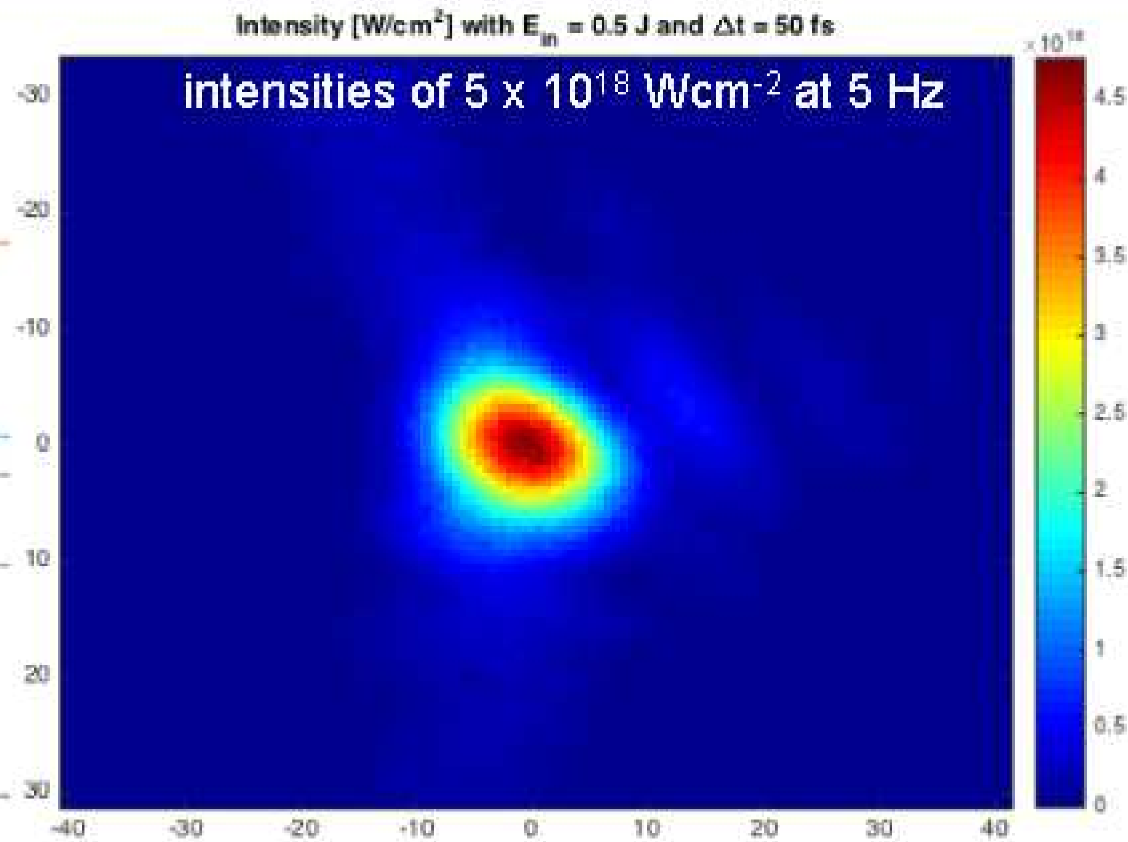
Radial (2θ) lineout



	500 shots	5,000 shots
120 Hz	4 seconds	40 seconds
5 Hz	2 minutes	17 minutes

We recently commissioned a 30 TW laser for high-power laser-matter interaction experiments at LCLS

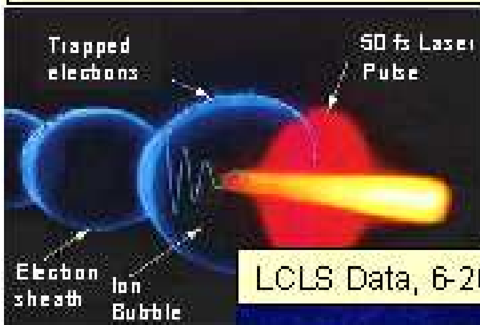




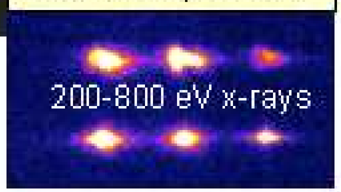
We have begun ultrafast pump-probe experiments using LCLS and high-power lasers

SLAC

Betatron radiation at MEC



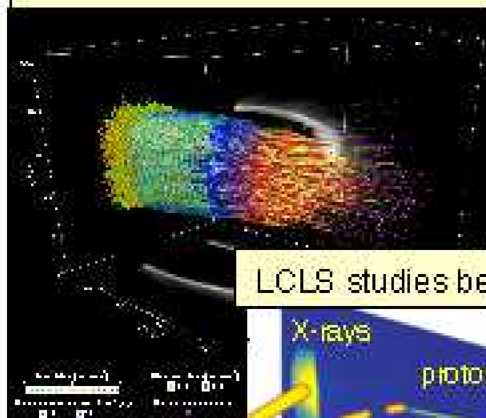
LCLS Data, 6-2015



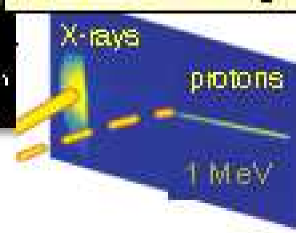
- 150 MeV e- from He-N gas cell
- High-energy betatron probing

W. Schumacher, F. Albert et al.

1 Hz MeV proton acceleration at MEC



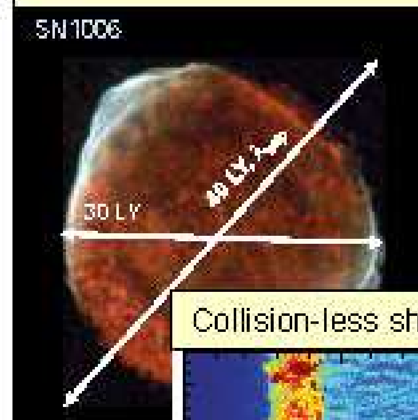
LCLS studies begun



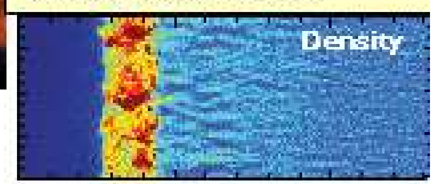
- Isochoric heating
- Imaging

J. Kim, S. Goede, M. Gauthier et al.

Laboratory Astrophysics at MEC



Collision-less shocks



- Ultrafast x-ray Imaging with 200 nm resolution

F. Fiuza, C. Ruyer et al.

The LCLS x-ray laser enables scientific discoveries in Matter under Extreme Conditions

SLAC

- New capabilities at the LCLS Free Electron Laser
  - 10^{12} focused x-ray photons (4-10 keV) with unprecedented resolution
    - Space (200 nm)
    - Time (50 fs)
    - Energy ($\Delta E/E = 10^{-4}$)
- Coupling LCLS x rays with nanosecond shock driver lasers
  - Determine the properties of matter at high densities and at high pressures
- Coupling LCLS x rays with high-power short-pulse lasers
  - Visualize laser-matter interaction with ultrafast pump-probe experiments
- Summary and outlook towards LCLS-II

The coupling of high-power optical lasers with LCLS x-rays is pushing the HED science frontier

Collaborators

SLAC

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