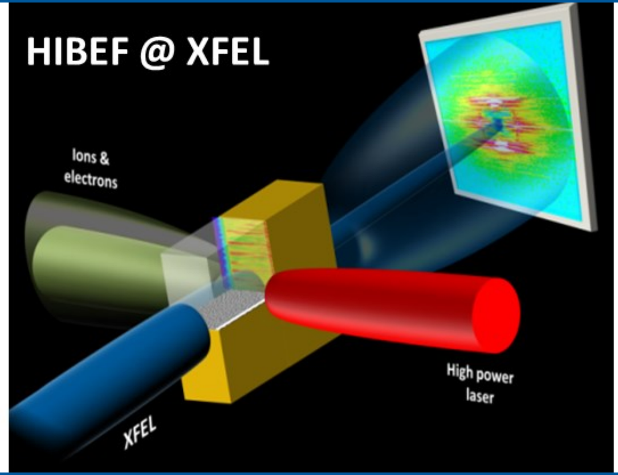
# Probing laser-driven extreme states of matter with HiBEF at European XFEL

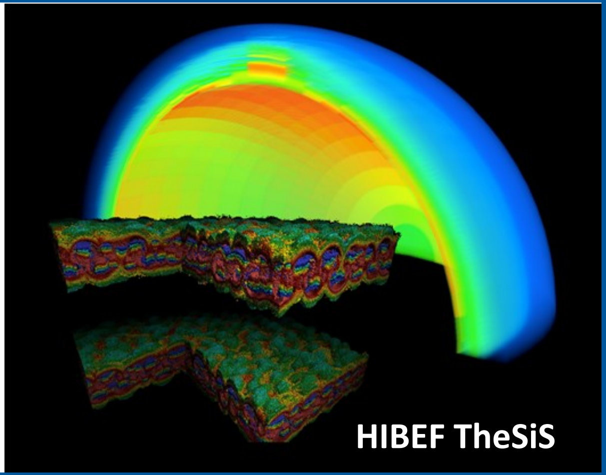
## *Helmholtz Intl Beamline for Extreme Fields*

T. E. Cowan[1,2]

*[1]Helmholtz-Zentrum Dresden-Rossendorf, [2]Technische Universität Dresden*

*and on behalf of the HIBEF User Consortium*




**AIRAPT 26**

***CNCC, Beijing***

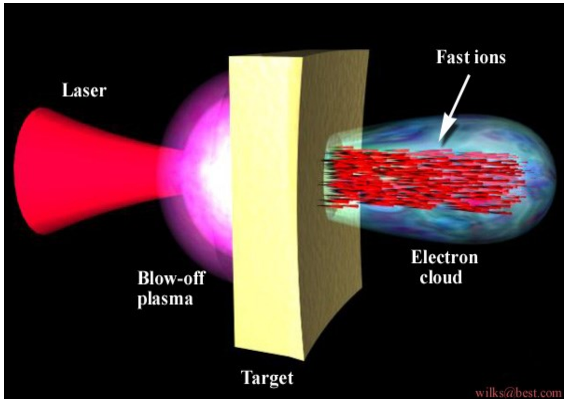
***20 August 2017***

HZDR

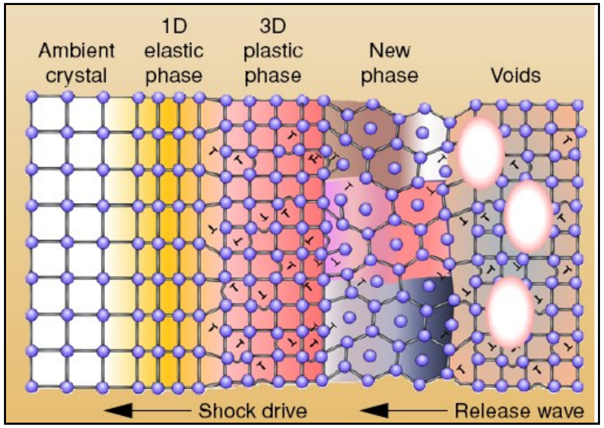
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

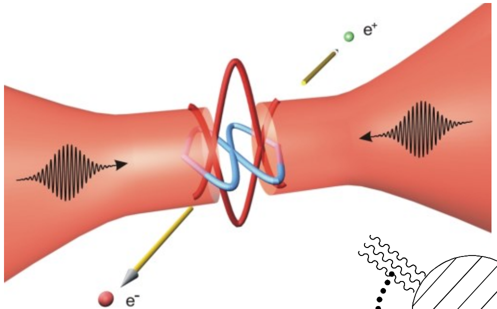
# Extreme Conditions driven by Ultra-intense & High-energy Lasers

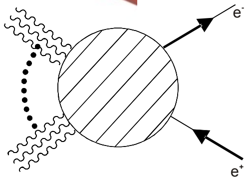
## Extreme particle beams




## Extreme pressures

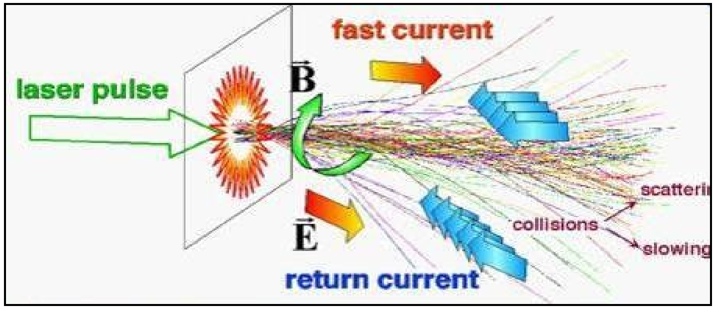


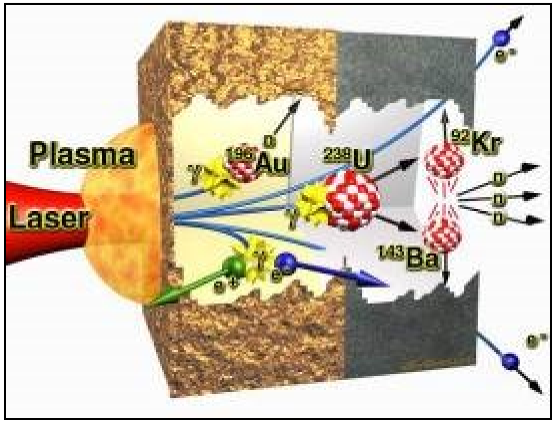




## Strong Fields

## Extreme currents



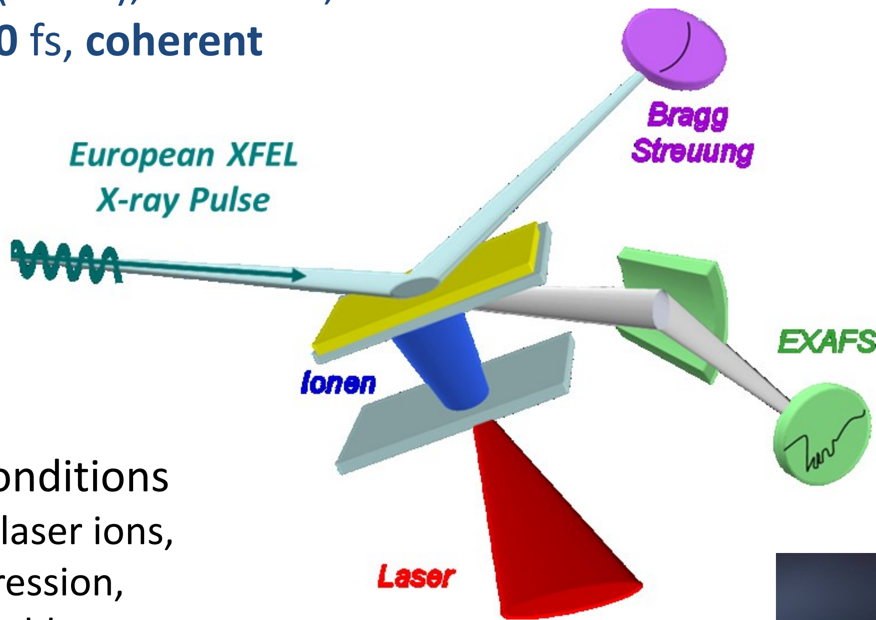




## Extreme radiations

# Brilliant X-FEL beams → advanced time-resolved techniques

Ultra-bright X-ray pulse
**$10^{12}$** ph/pulse (8 keV), **0.1%** BW,
**3-24** keV, **2-150** fs, **coherent**

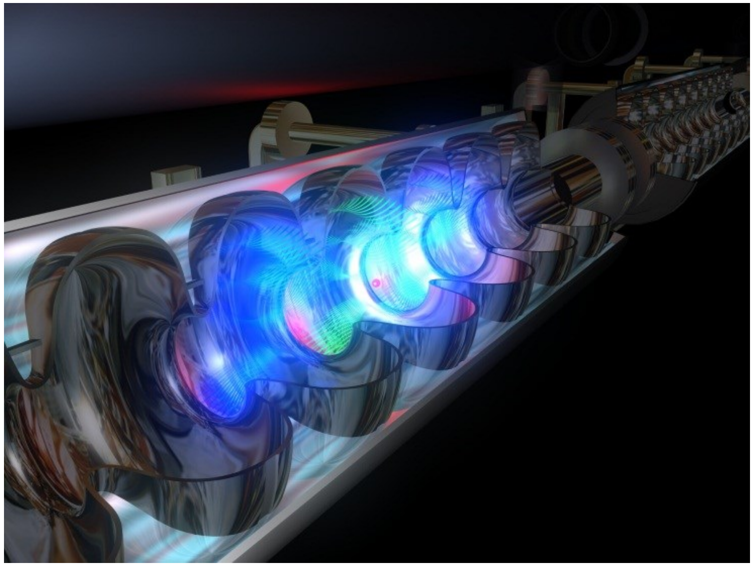
European XFEL




X-FEL probing techniques:

- Bragg & Laue diffraction
- Absorption spectroscopy
- X-ray Thomson scattering
- Phase Contrast Imaging
- Coherent X-ray imaging
- Small angle x-ray scattering
- X-ray Faraday Rotation
- Correlation specroscopy

Extreme sample conditions
relativistic laser, laser ions,
isentropic compression,
shocks, high B-fields ...



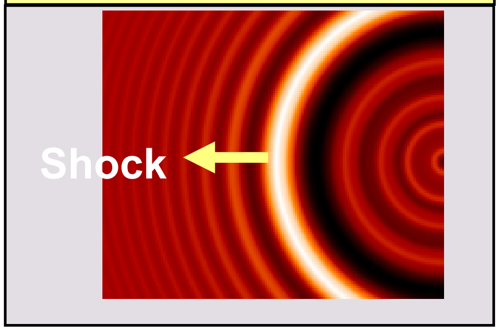
HED science at X-FELs versus Laser-only:
faster (→ fs), higher resolution (µm→nm),
atomic-selectivity, simpler targets, higher rep-rate

... from discovery science
to precision HED physics

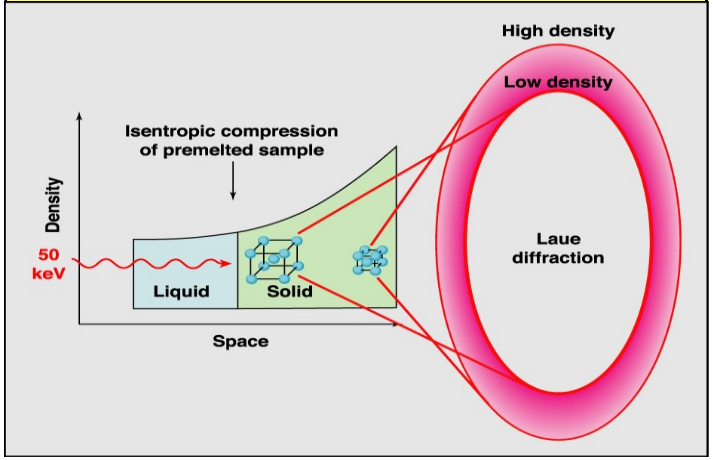
# High-power laser drivers combined with XFELs will open new frontiers of Science at Extreme Conditions

HiBEF

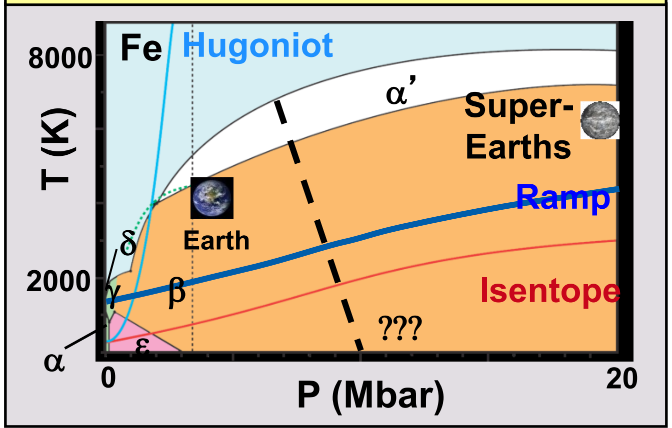
**Diffractive imaging (<µm)**



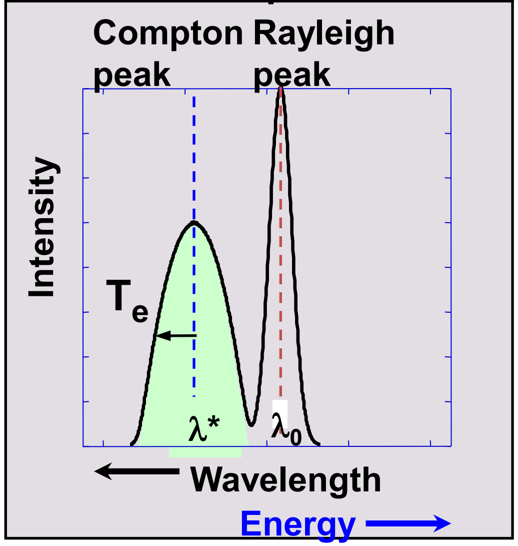

**X-ray scattering → structure, chemistry, kinetics**



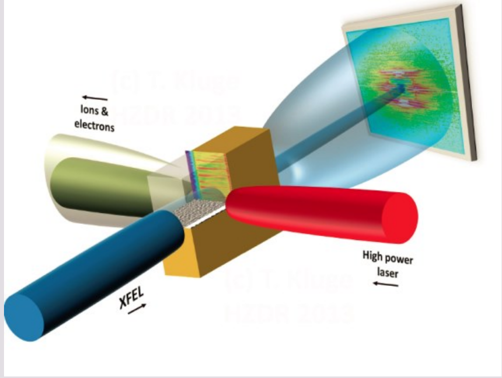

**X-Ray Diffraction → Material phases, thermodynamic states**



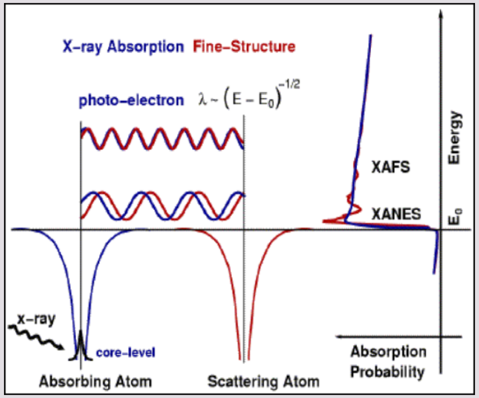

**Compton scattering → Te, Z, ne, collision time of dense plasmas**




**SAXS, CXDI, RCXD → plasma scale (~5 nm)**




**X-ray absorption spectroscopy → Melt, Chemistry**




Adapted from Rip Collins

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# Overview – this talk

- **Status of Helmholtz International Beamline for Extreme Fields (HiBEF) at European XFEL**

- **Science program with HED-HiBEF at XFEL & recent examples**

  - Shock physics – diamond “rain” in giant ice planets
  - Relativistic plasmas – nm sensitivity to plasma evolution (SAXS)
  - SAXS/CXDI in dynamic compression

# HIBEF - Helmholtz Int'l Beamline for Extreme Fields @ XFEL.EU

European XFEL

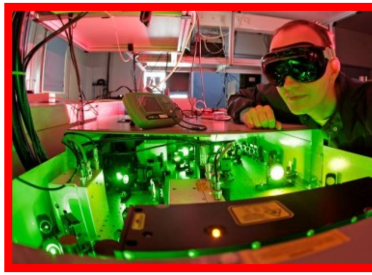
HiBEF User Consortium

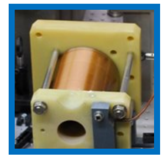
HED High-Energy Density science

HZDR DESY STFC, Oxford, CAEP

>80 institutions, 20 countries

(ca. 40 M€ committed, 12 M€ pending)





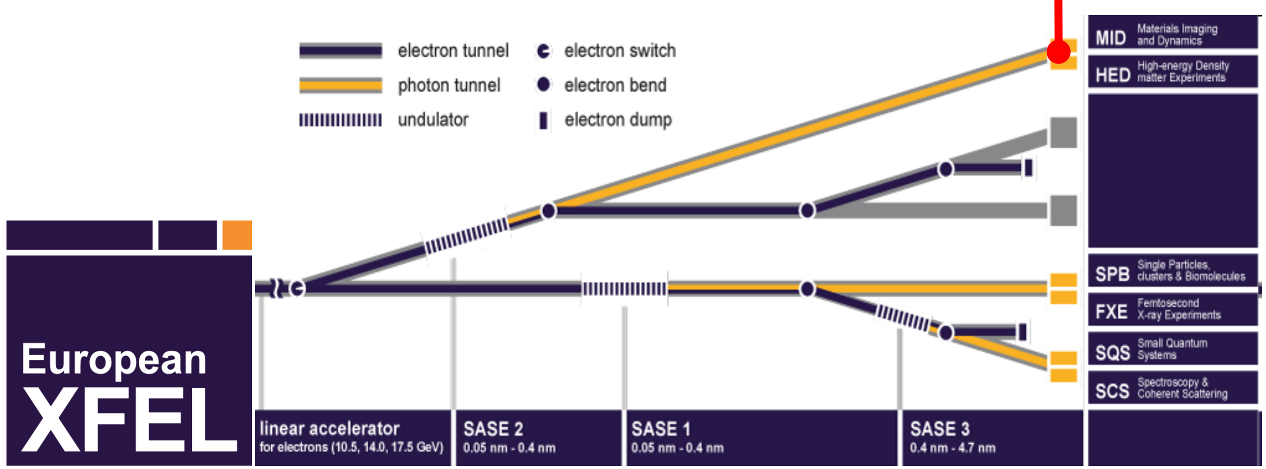
**HIBEF: Laser Systems (0.1-10 Hz)**

~PW, 30 J/30 fs (Ti:Sapphire)

~kJ, 2-20 ns shaped (Diode)

**Pulsed Magnets (60 T, 1 ms)**

1st lasing (SASE1)
04 May 2017

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# HiBEF - Helmholtz Int'l Beamline for Extreme Fields @ XFEL.EU

European XFEL | HiBEF User Consortium | HED High-Energy Density science

HZDR, DESY, STFC, Oxford, CAEP

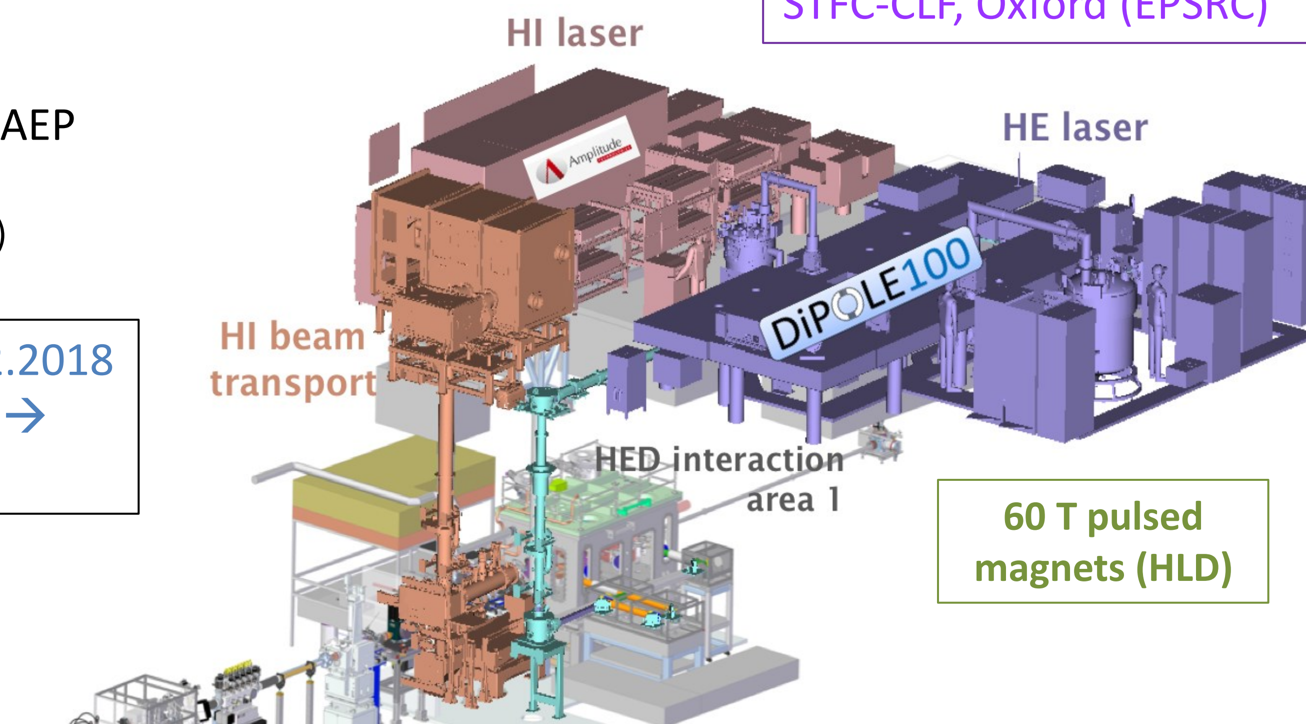
>80 institutions, 20 countries

(ca. 40 M€ committed, 10 M€ pending)

- Phase 1 construction → Q2.2018
- Commissioning, Q3.2018 →
- User Operation, 2019 →

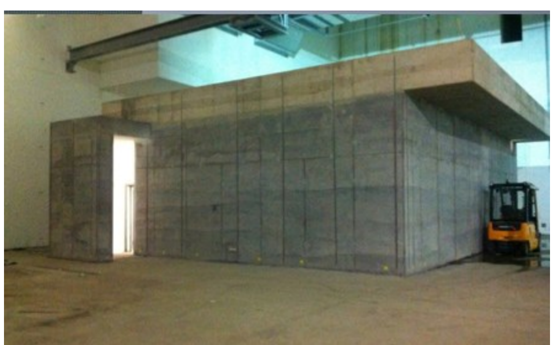
300 TW Ti:Sapphire laser (7.5 J / 25 fs)

UK DIPOLE 100-X: diode pumped 100 J, 10 ns laser STFC-CLF, Oxford (EPSRC)




60 T pulsed magnets (HLD)

1st lasing (SASE1)
04 May 2017



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1st lasing (SASE1)
04 May 2017

**Management Board:** *T.E. Cowan (HZDR), E. Weckert (DESY), J. Wark (Oxford), R. Redmer (Rostock), T. Tschentscher (XFEL-observer)*
**HiBEF Coord:** *C. Baehtz (HZDR),* **Laser Dir:** *T. Toncian (HZDR)*
**HED Lead Scientist:** *U. Zastrau (XFEL)*

Germany: 27
CFEL, DESY, FZJ, GFZ, GSI, HIJ, HZB, HZDR, MBI, MPIC, MPIK, MPI-S, MPQ, MPSD, Bayreuth, HU Berlin, TU Darmstadt, TU Dresden, Duisburg, Frankfurt, Freiburg, Hamburg, FSU-Jena, LMU-Munich, TU München, Rostock, Siegen

Europe & Assoc. Countries: 42
PSI, EP-Lausanne (CH); IOP-ASCR, CTU-Prague (CZ); CLPU-Salamanca, UPM-Madrid (ES); IRAMIS-CEA, CEA-Arpajon, CELIA-Bordeaux, ESRF, Jussieu, LULI, UPMC, LNCMI, U Toulouse (FR); U Pecs, U Szeged (HU); Weizmann (IS); Sapienza-Rome (IT); MUT-Warsaw, NCBJ-Swierk, U Wroclaw (PL); IST-Lisbon (PO); JIHT-RAS (RU); Stockholm, Umea, Uppsala (SE); Cambridge, Edinburgh, Imperial College, Queen's Univ Belfast, University College London, Oxford, Plymouth, STFC-RAL, SUPA, Strathclyde, Warwick, York (UK); Eu-XFEL, ELI-DC, EMFL (EU)

Asia: 11
**SIOM**, IOP-CAS, Peking Univ, SJTU, **CAEP** (CN); Tata IFR, RRCAT (IN); GSE Osaka, ILE-Osaka, KPSI-JAEA, Univ. Kyoto (JP)

North America: 17
Alberta (CAN), BNL, UC Berkeley, Carnegie Inst. Wash., General Atomics, LANL, LBL, LLNL, U. Michigan, ORNL, OSU, Rockefeller U, SLAC, UCSD, UNR, UT Austin, WSU (US)

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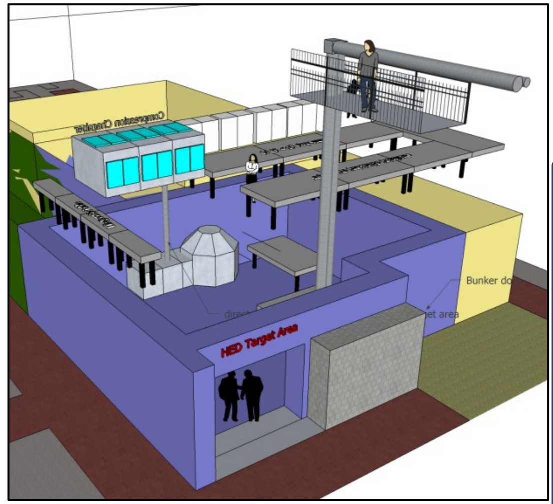
# HiBEF at HED Instrument of European XFEL

**Phase 1 (2018-2020):**
**Laser Lab in XHEXP Hall**

→ 300 TW Ti:Sa (7.5 J, 25 fs, 5 Hz)
(max. **400 TW, 10 J, 25 fs**, 5 Hz )
→ 100 J ns-pulse (2-20 ns, 10 Hz)*
→ 200 kJ magnet pulser (50 T, 1 ms)
→ 2-stage and dynamic DACs

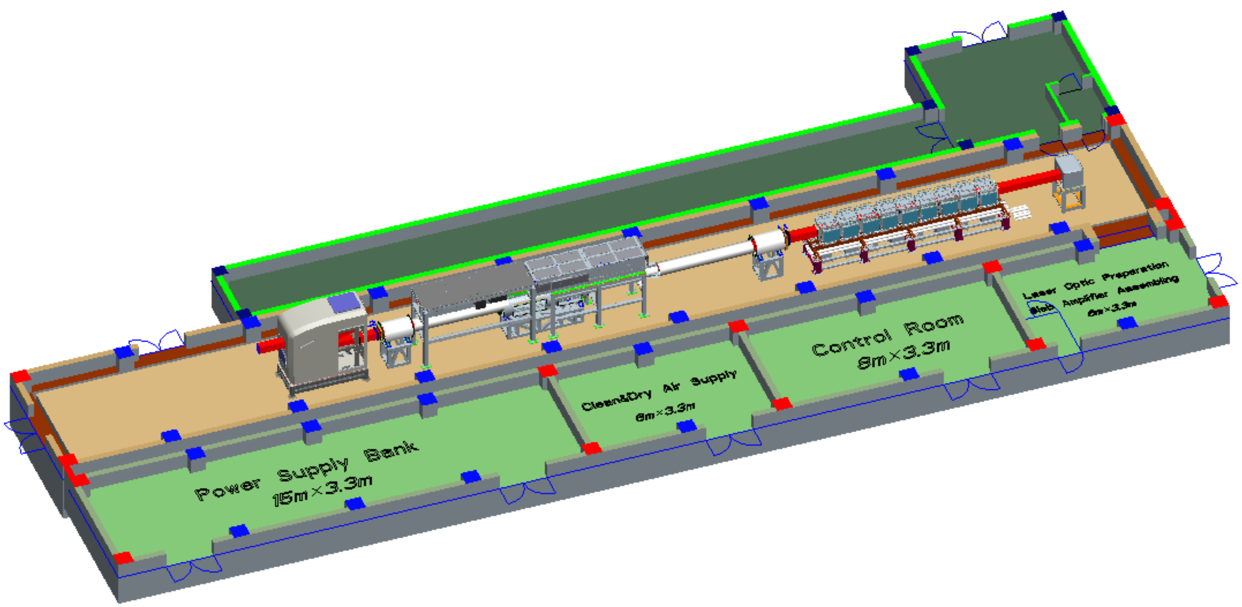
*STFC DiPOLE laser (UK)




**Phase 2: external laser laboratory (2021 - )**

→ kJ shaped ns-pulses*
→ PW (30 J, 30 fs, 1 Hz)
→ MJ pulser (60 T, 0.1 s)

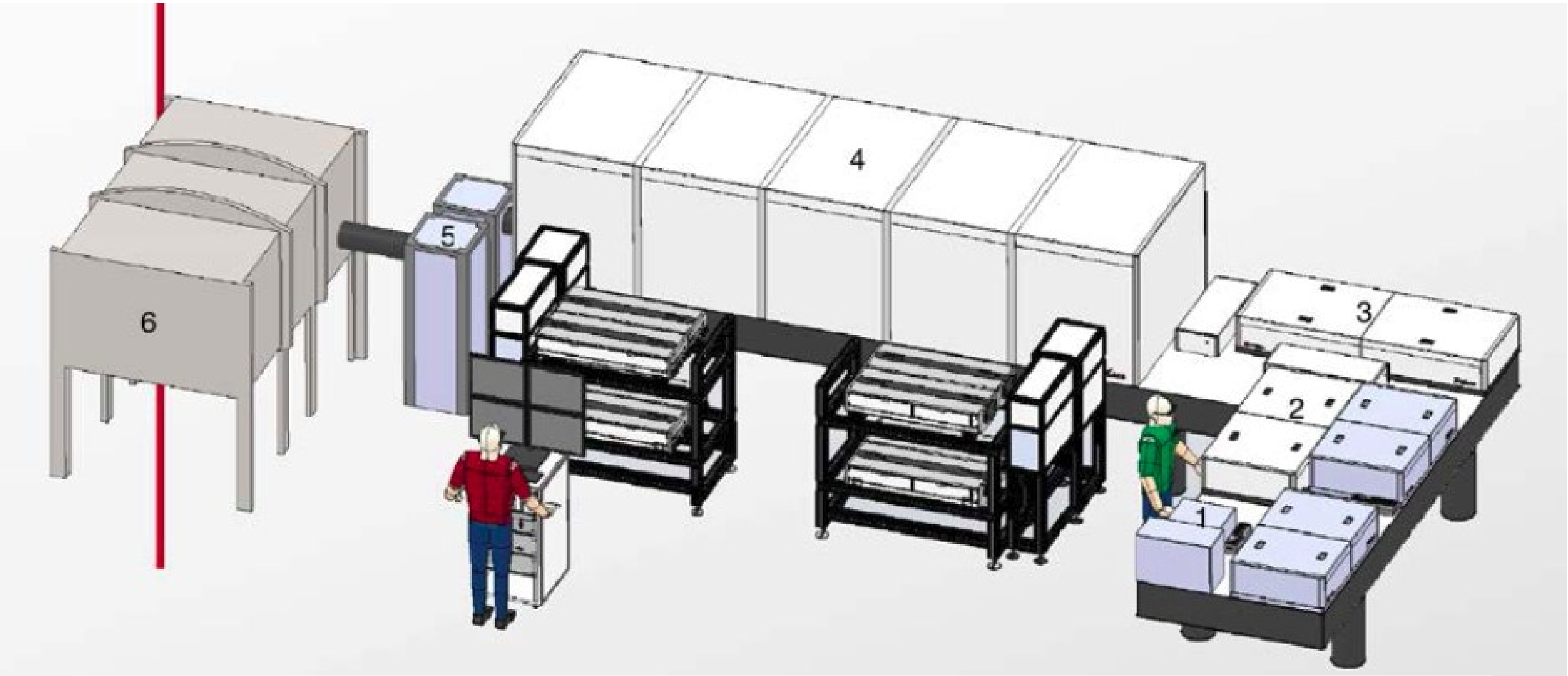
*CAEP kJ laser (CN)




~ 2-10 ns
> 2 kJ at 1 μm
> 1 kJ at 0.5 μm
Shot per hour

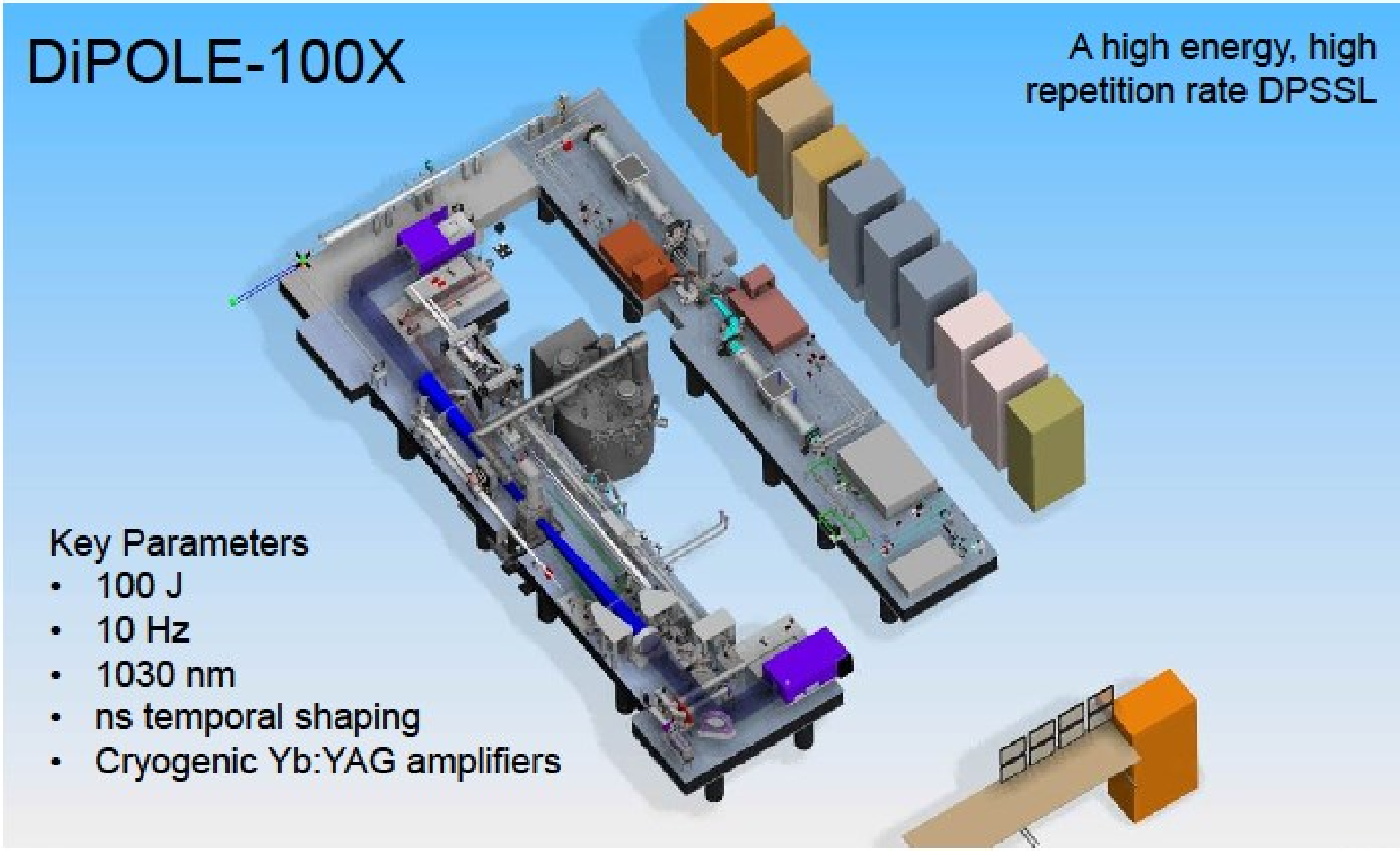
*Research Center of Laser Fusion CAEP*

# HiBEF – HI Laser: Amplitude Technologies




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

# HiBEF – HE Laser: DiPOLE-100X




Science & Technology Facilities Council

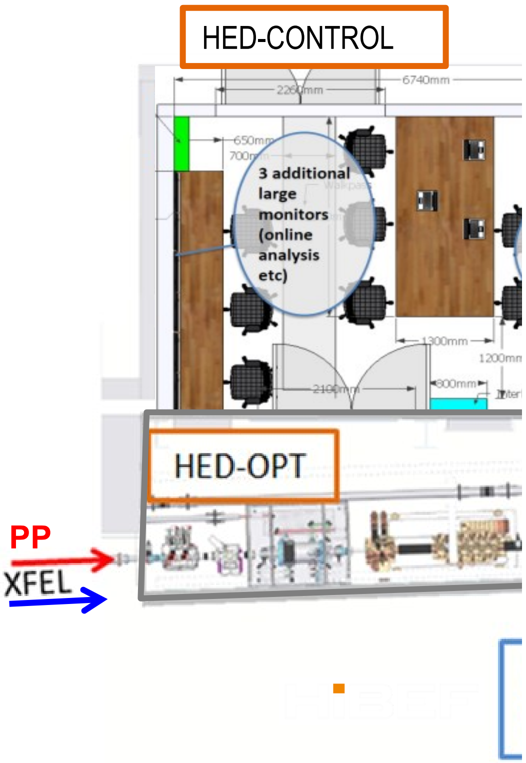
EPSRC Engineering and Physical Sciences Research Council

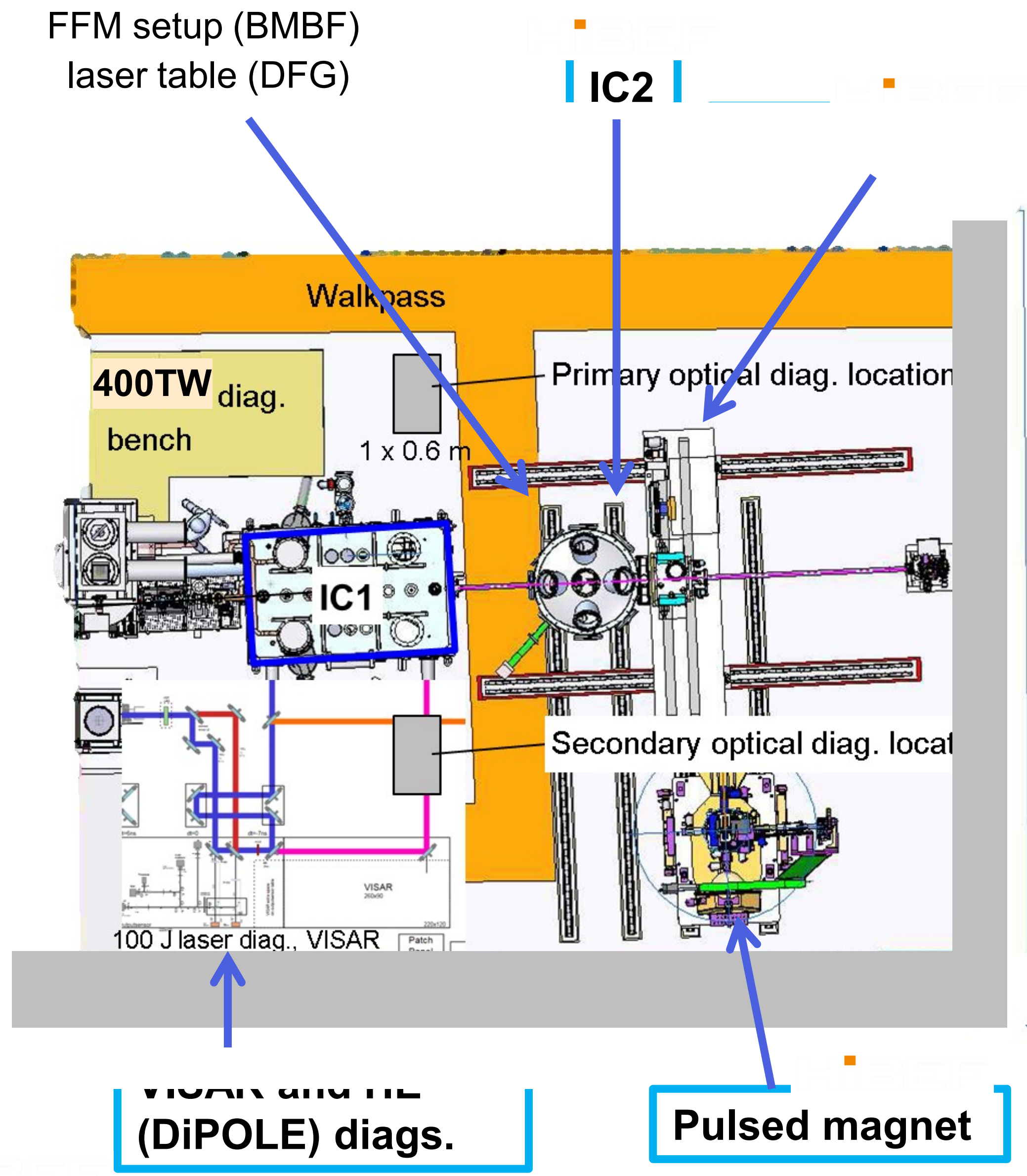
European XFEL

DiPOLE100

Science & Technology Facilities Council Central Laser Facility

# HED control room, optics hutch, and enclosure



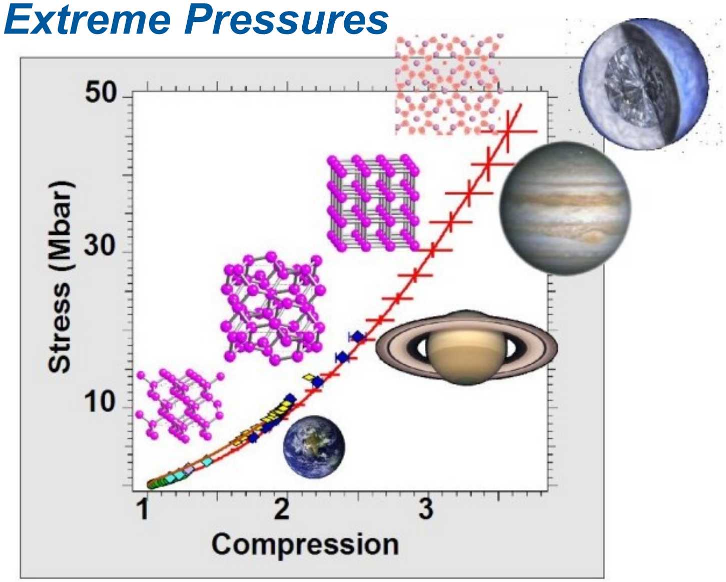
# HiBEF / HED development timeline

Interaction chamber
IC1 installation

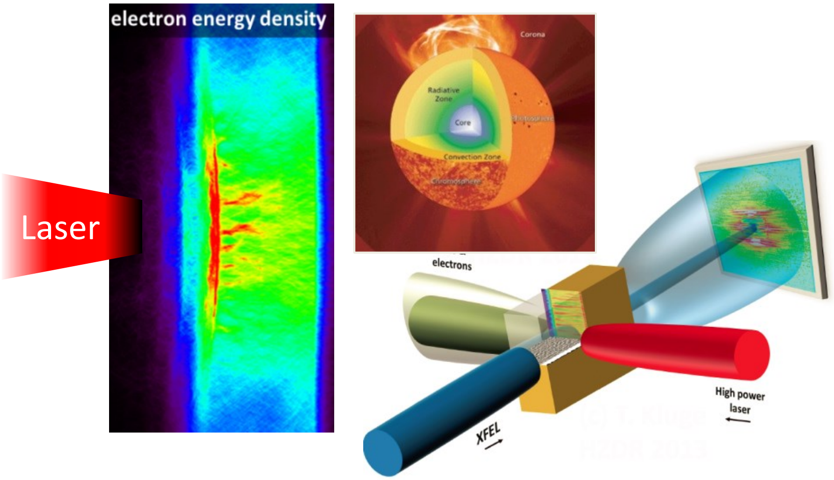

| | |
|---|---|
| June 2017 | - begin cave installations |
| April 2018 | - 300 TW laser Factory Acceptance Test / shipping |
| June 2018 | - DiPOLE-100X commissioning at STFC (UK) |
| Oct 2018 | - 300 TW installation complete at XFEL |
| Dec 2018 | - Installation of DiPOLE-100X at XFEL |
| Winter 2018/19 | - Laser commissioning |
| | - First x-ray only experiments at HED |
| Summer 2019 | - First experiments with HiBEF lasers |
| 2020 | - External Building (approximate) |
| 2020-21 | - kJ-class Laser installation (approximate) |

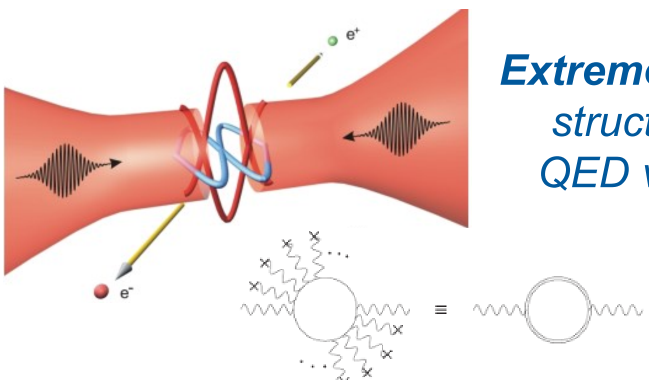
# HIBEF – Exploring New Phases of Matter

## *Extreme Pressures*




## *Extreme Plasmas & Temperatures*

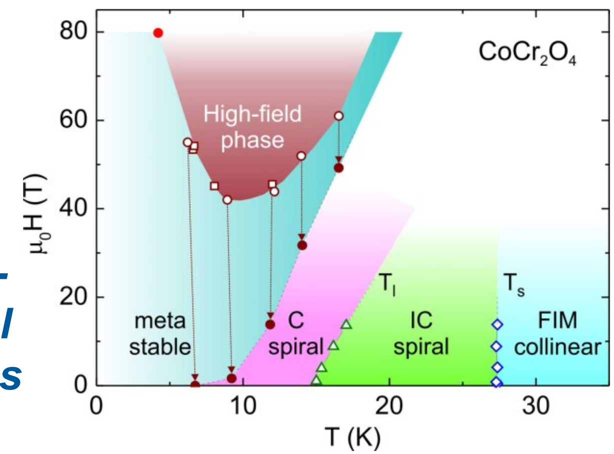



## *Extreme Fields:*

*structure of QED vacuum*

## *Magneto-structural transitions*




Nat Mater **9** (2010) 624; Rev Mod Phys **84** (2012) 1607 (2012), Nat Comm 7 (2016) 10970 (2016); Phys Plasmas **21** (2014) 033110, Phys Plasmas **23** (2016) 033103 ; New J Phys **16** (2014) 023008; Phys Scr **91** (2016) 023010; Phys Rev Lett **110** (2013) 115502

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# HED Science at HIBEF: Demixing in planetary atmospheres

## Recreating diamond rain predicted to happen inside giant planets

D. Kraus & team

HZDR

Berkeley UNIVERSITY OF CALIFORNIA

Lawrence Livermore National Laboratory

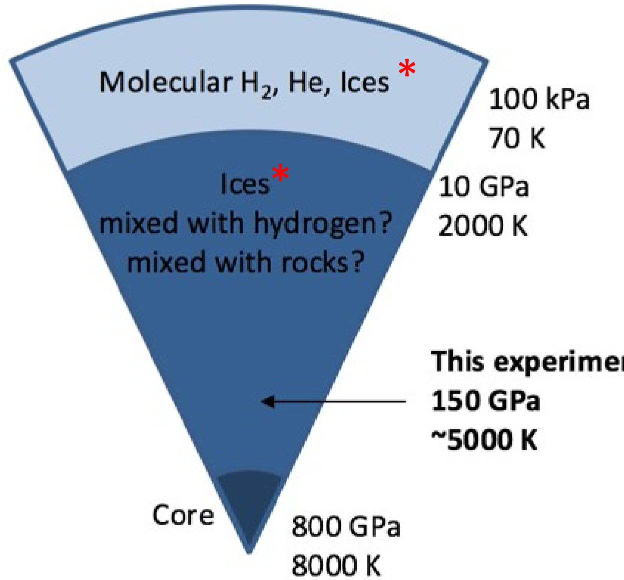
SLAC

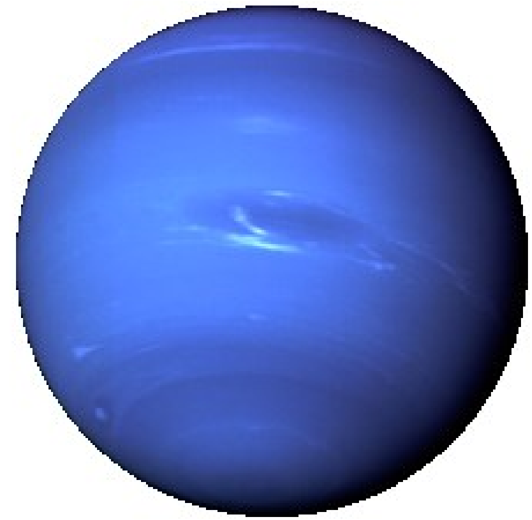
GSI

TECHNISCHE UNIVERSITÄT DARMSTADT

大阪大学 OSAKA UNIVERSITY

WARWICK THE UNIVERSITY OF WARWICK



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

MARVIN ROSS

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

**letters to nature**

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

*Ices := $H_20$, $NH_3$, $CH_4$

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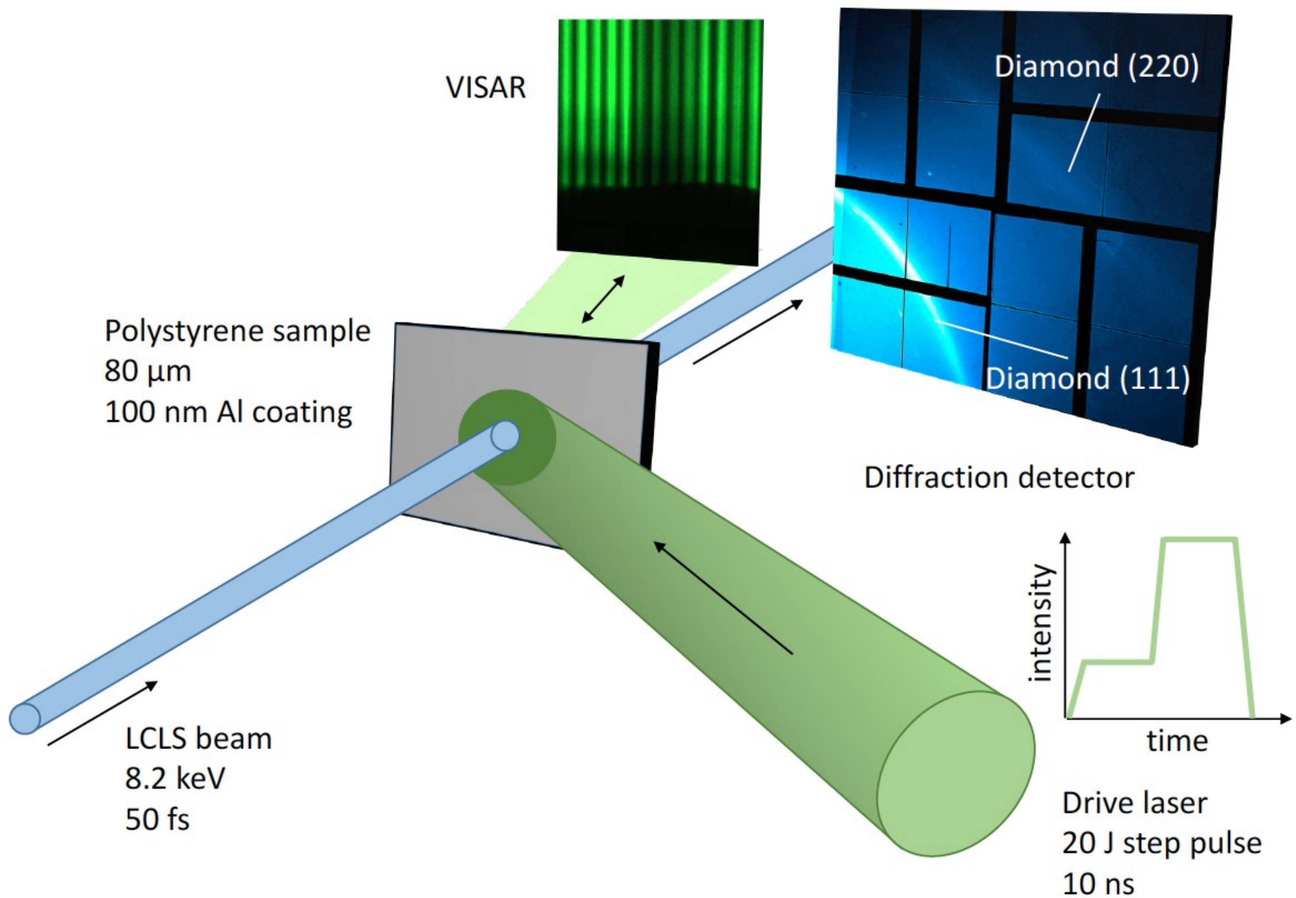
# HED Science at HIBEF: Demixing in planetary atmospheres

## Recreating diamond rain predicted to happen inside giant planets

D. Kraus & team



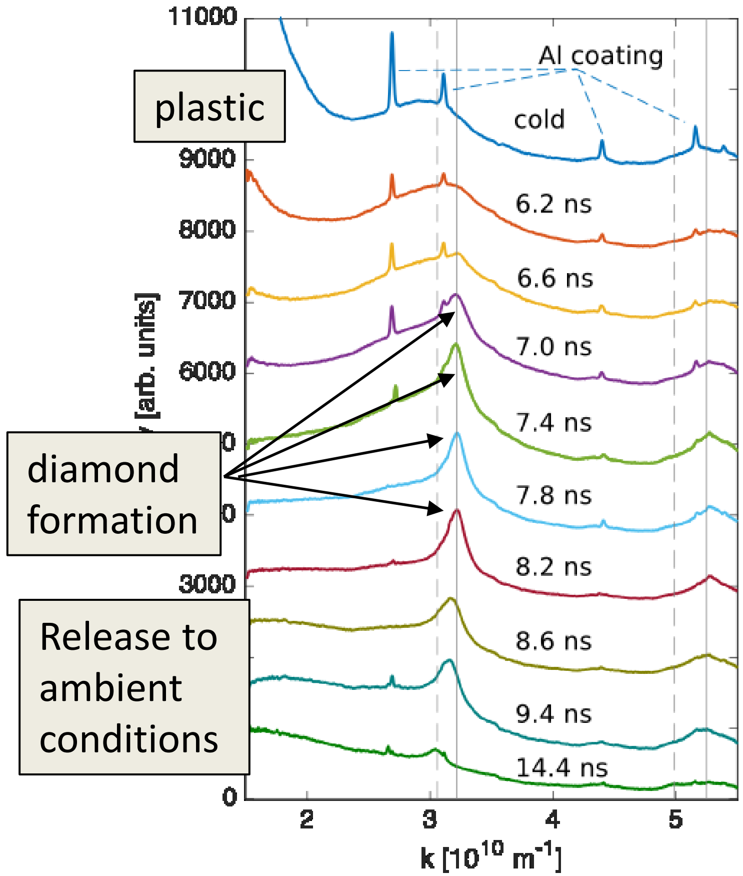

*Ices := $H_2O$, $NH_3$, $CH_4$

→ polystyrene (CH) as surrogate for $CH_4$

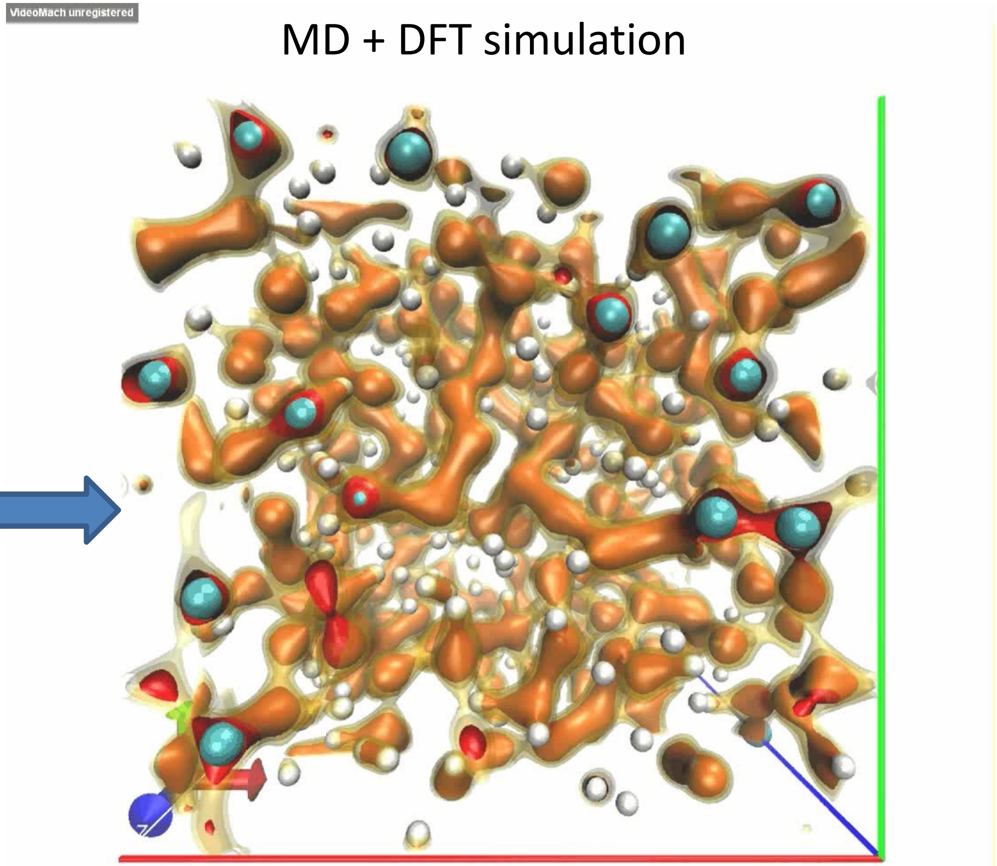
# HED Science at HIBEF: Demixing in planetary atmospheres

## Recreating diamond rain predicted to happen inside giant planets

Experiment




MD + DFT simulation




cyan: C, white: H; Orange: isoelectronic contours

D. Kraus et al., accepted for publication in Nature Astronomy

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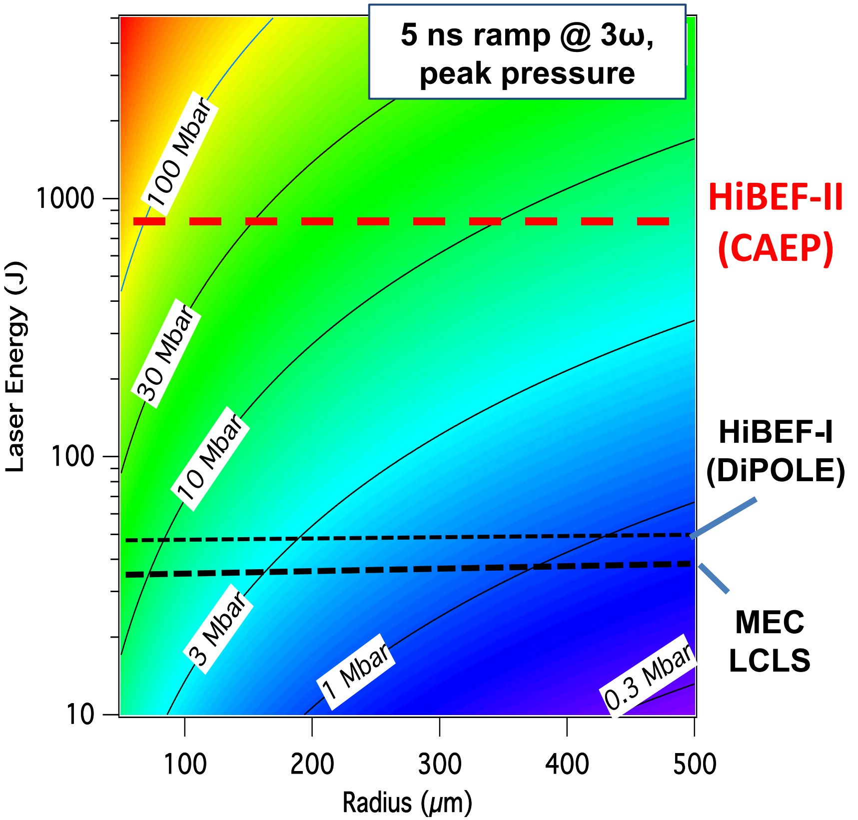
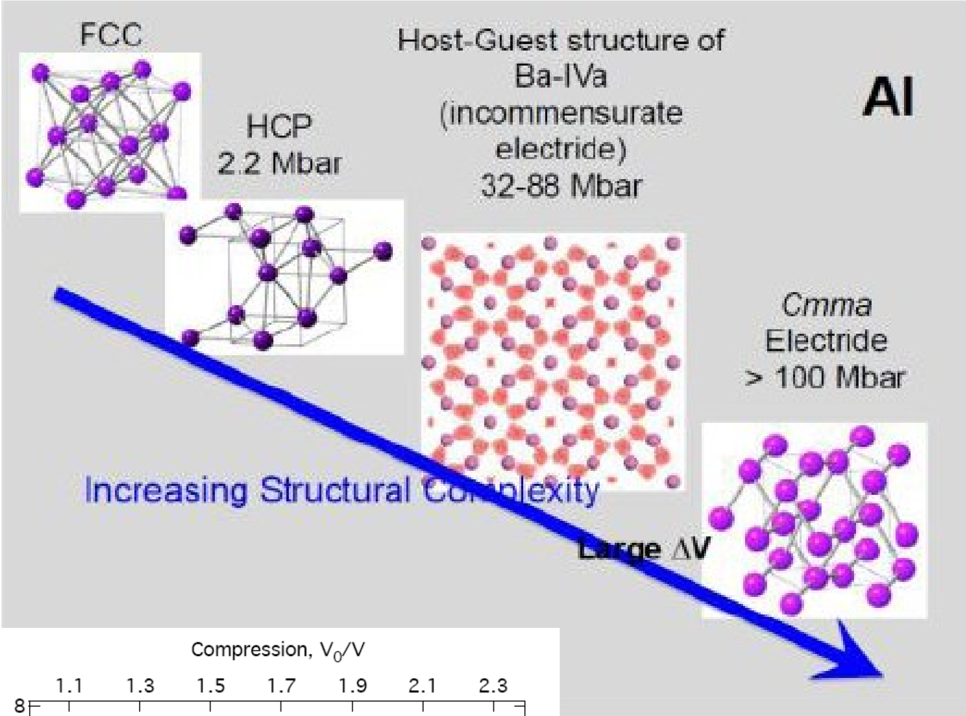
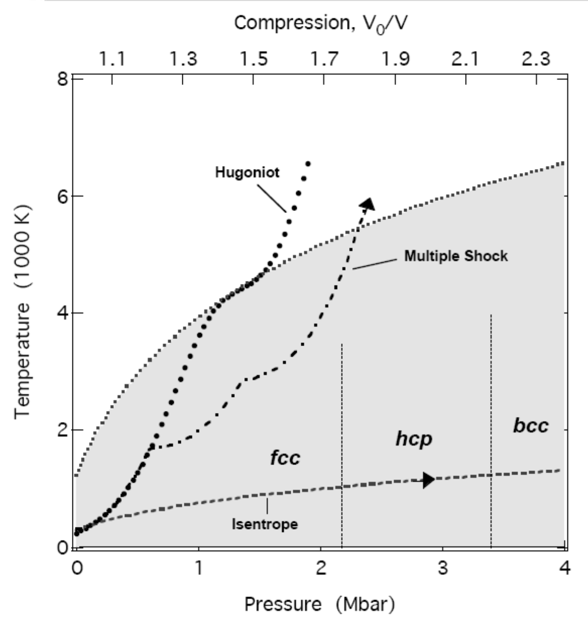
# HiBEF – Ramp Compression to beyond TPa



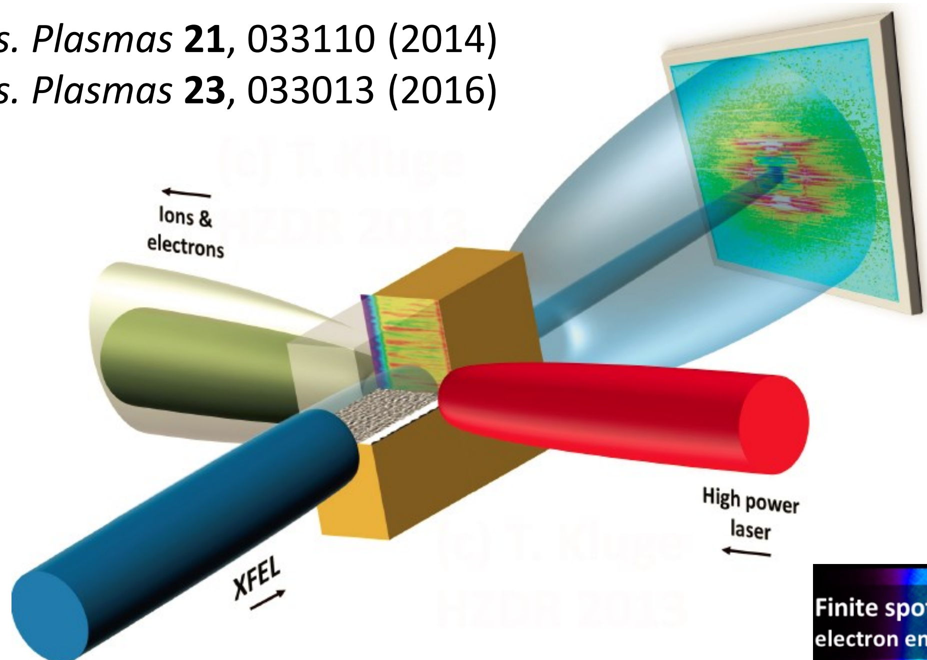



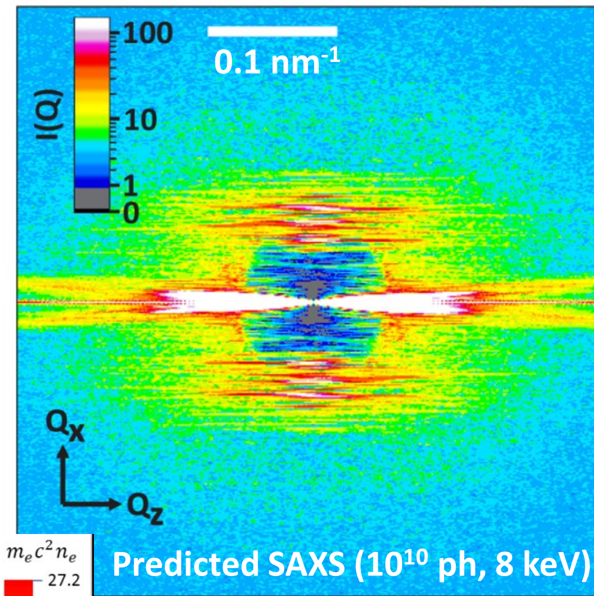

C. J. Pickard & R. J. Needs, Nat Mater 9, 624 (2010)

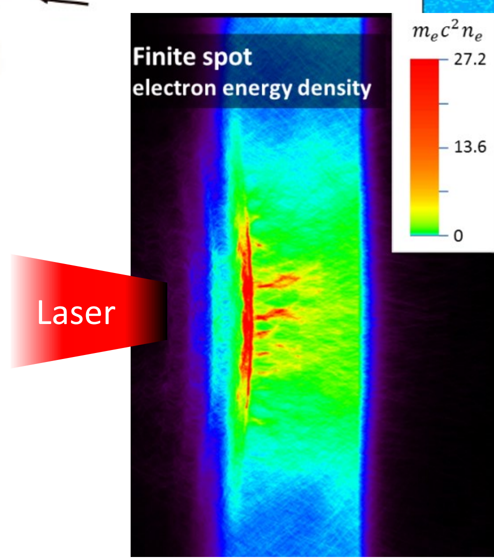
*Can predicted new exotic phases be produced?*
*Nucleation & growth times?*
*Metastability & recovery?*

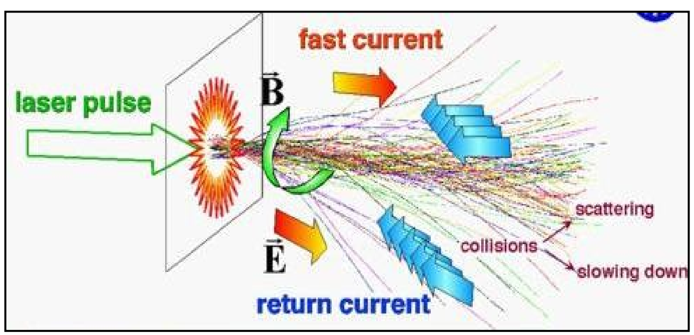
# HED Science at HIBEF: Relativistic laser-matter interactions
## Probing solid-density plasma with coherent x-ray diffraction

*Phys. Plasmas* **21**, 033110 (2014)
*Phys. Plasmas* **23**, 033013 (2016)




$10^{13}$ A/cm$^2$, > 1000 T, $10^{13}$ V/m, ~keV solid density

- ionization dynamics, heating & resistivity
- electron transport, return current neutralization
- filamentation, hole boring
- e-e & e-i equilibration
- quasi-static fields
- ....

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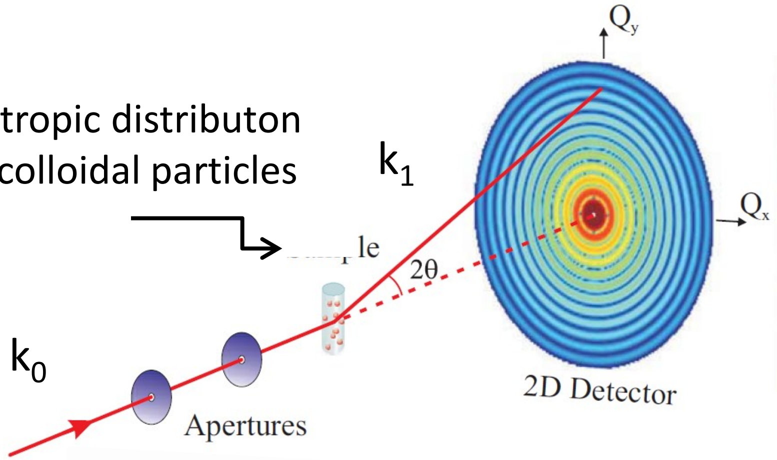
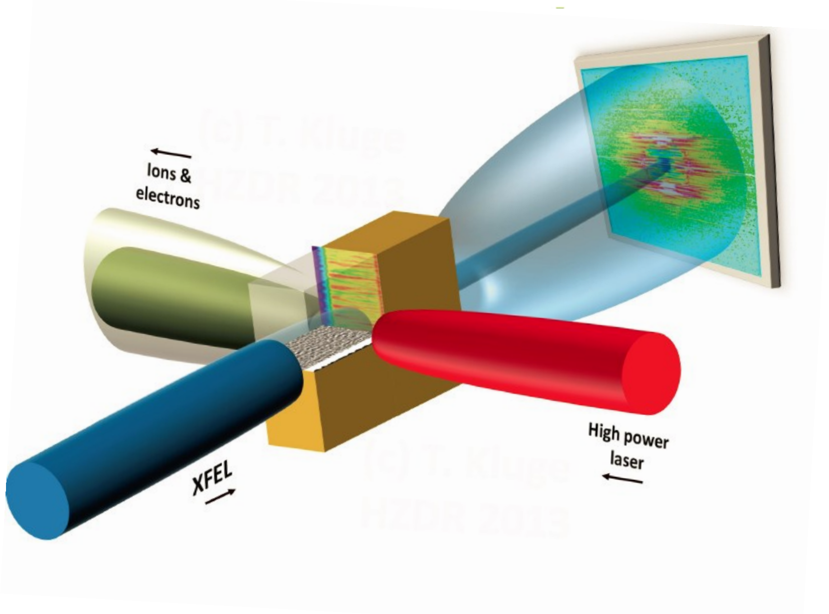
# HED Science at HIBEF: Relativistic laser-matter interactions
## Probing solid-density plasma with coherent x-ray diffraction

### Small angle X-ray scattering   (SAXS, CXDI, RCXDI, …)

isotropic distributon
of colloidal particles




Typical scales / quantities:

Wave vector transfer Q

$$Q = 2k_0 \cdot \sin\theta \approx k_0 \cdot 2\theta$$

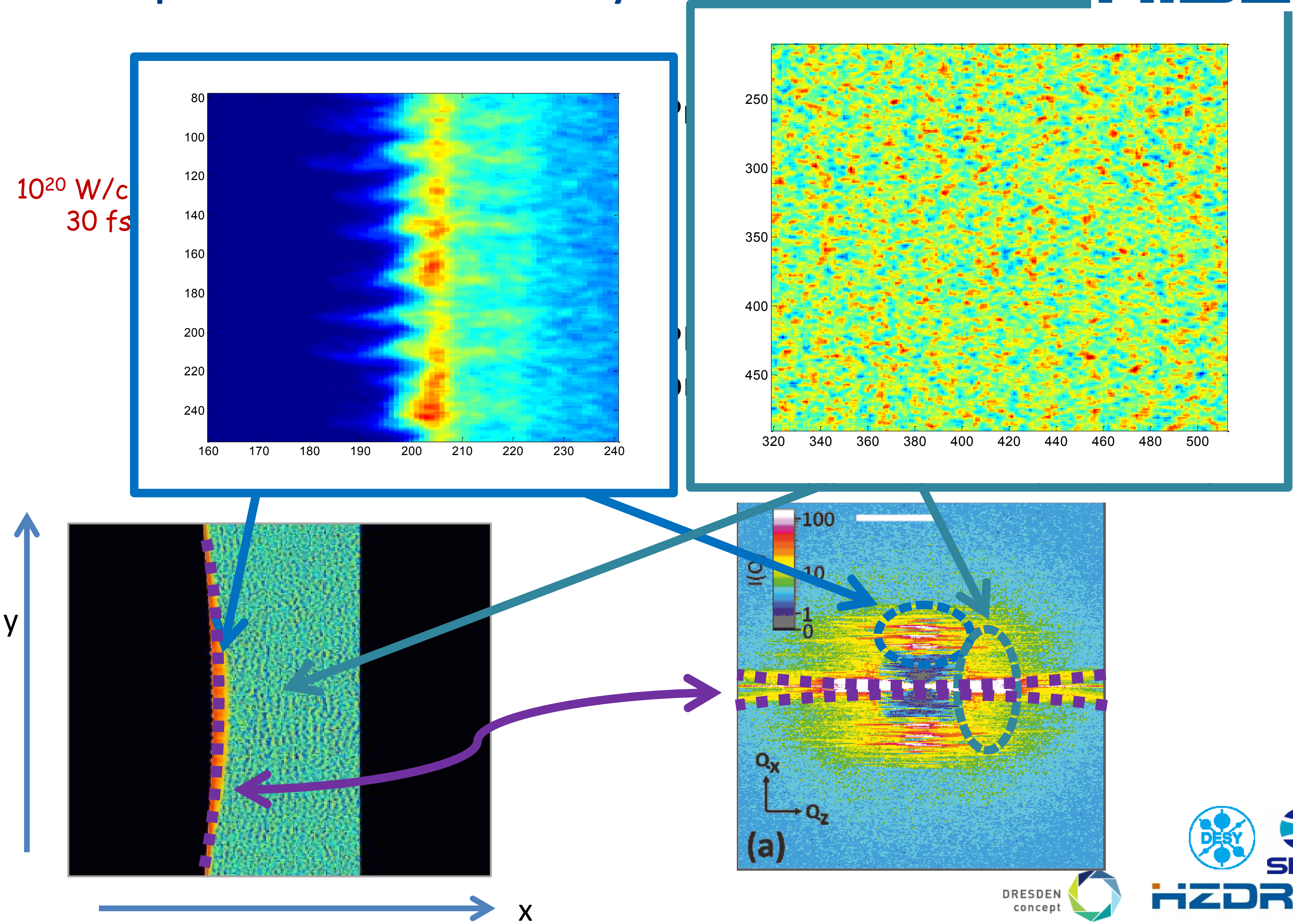
Diffraction pattern in Q-space →
Fourier transform of the electron distribution in real space
$I(Q,t) = r_e^2 \, |FT\{n(r,t)\}|^2$

Example: 8keV, 0.15 nm, $k_0$ = 40 $nm^{-1}$

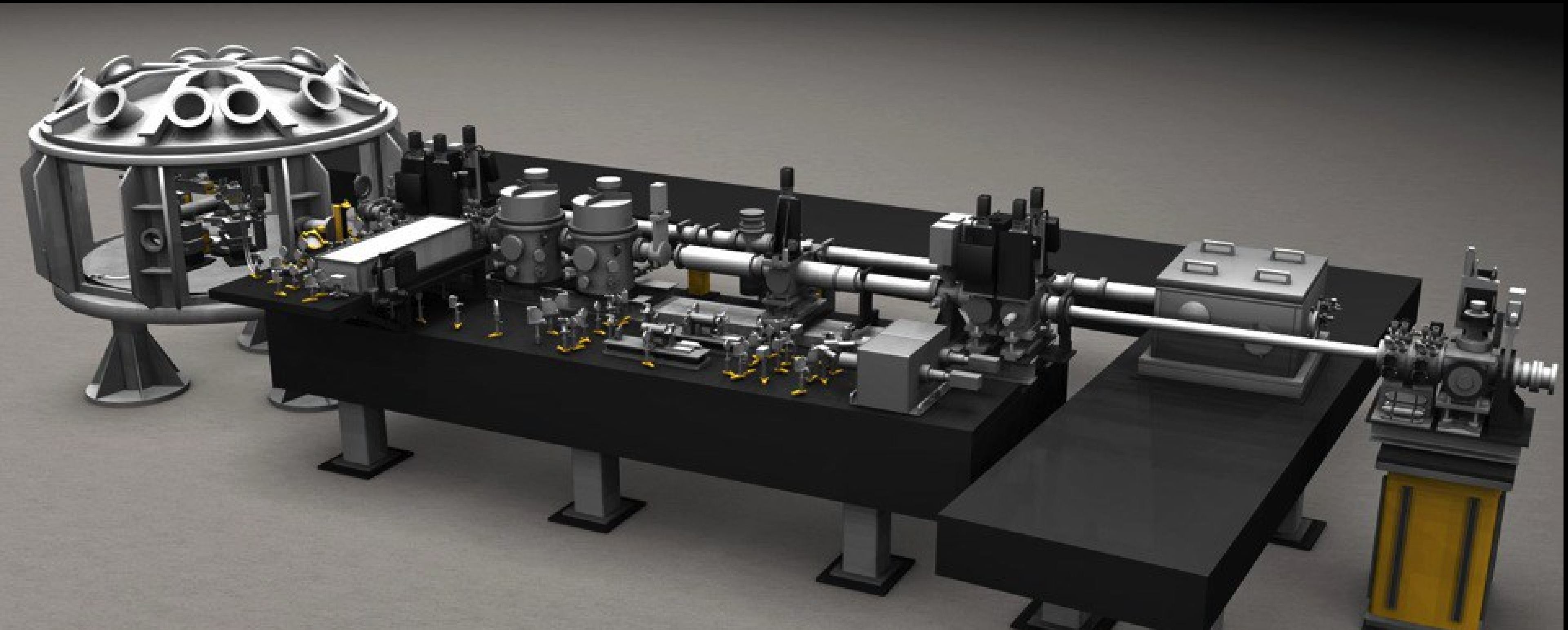
plasma oscillation d ~ 60 nm →
Q ~ 2π / d ~ 0.1 $nm^{-1}$
θ ~ 2.5 mrad

Also, ~nm features in dynamic compression

# Example:  Relativistic electron dynamics



# LCLS Experiment – MEC LN04

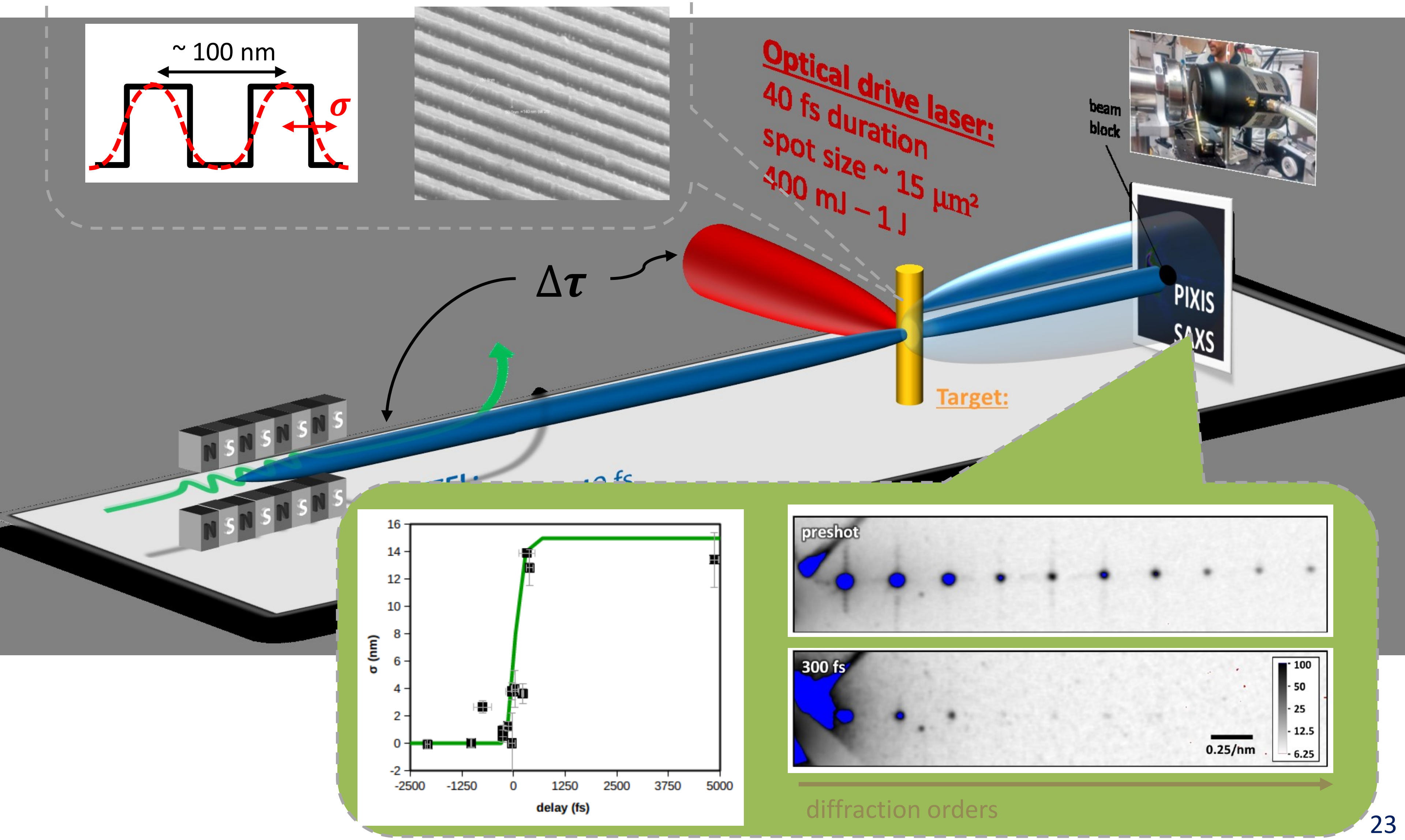


Aim of campaign:

"Establish SAXS method for fs probing of laser-driven plasmas on few nm scale in-between PCI (few hundred nm) and WAXS diffraction (angstrom)."

# Time-resolved plasma evolution on the fs & nm scales

- *tailored targets: gratings*



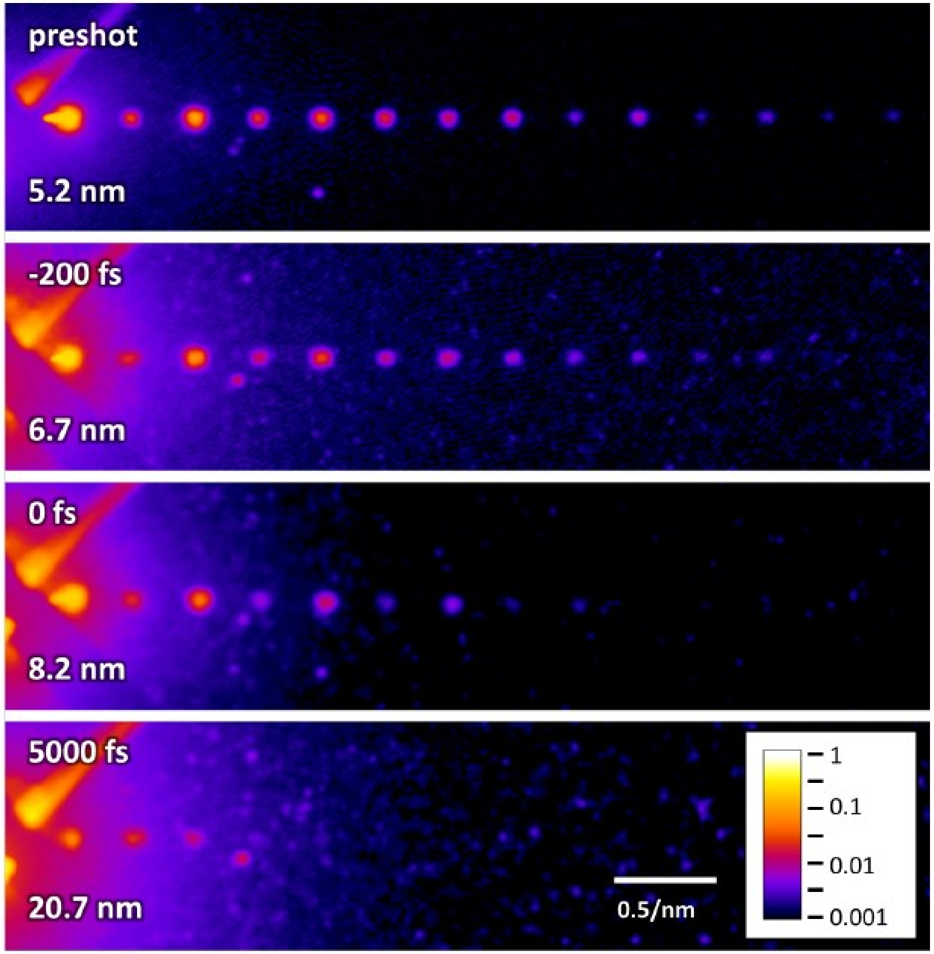
# Overview – this talk

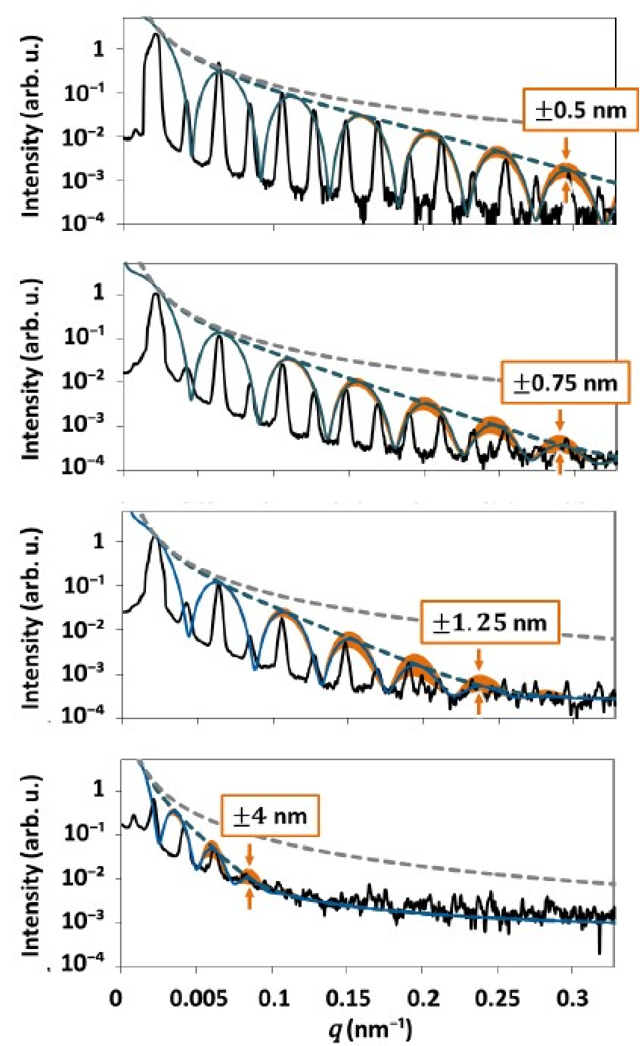
- Status of Helmholtz International Beamline for Extreme Fields (HiBEF) at European XFEL

- **Science program with HED-HiBEF at XFEL & recent examples**

  - Shock physics – diamond "rain" in giant ice planets
  - Relativistic plasmas – nm sensitivity to plasma evolution (SAXS)
  - SAXS/CXDI in dynamic compression

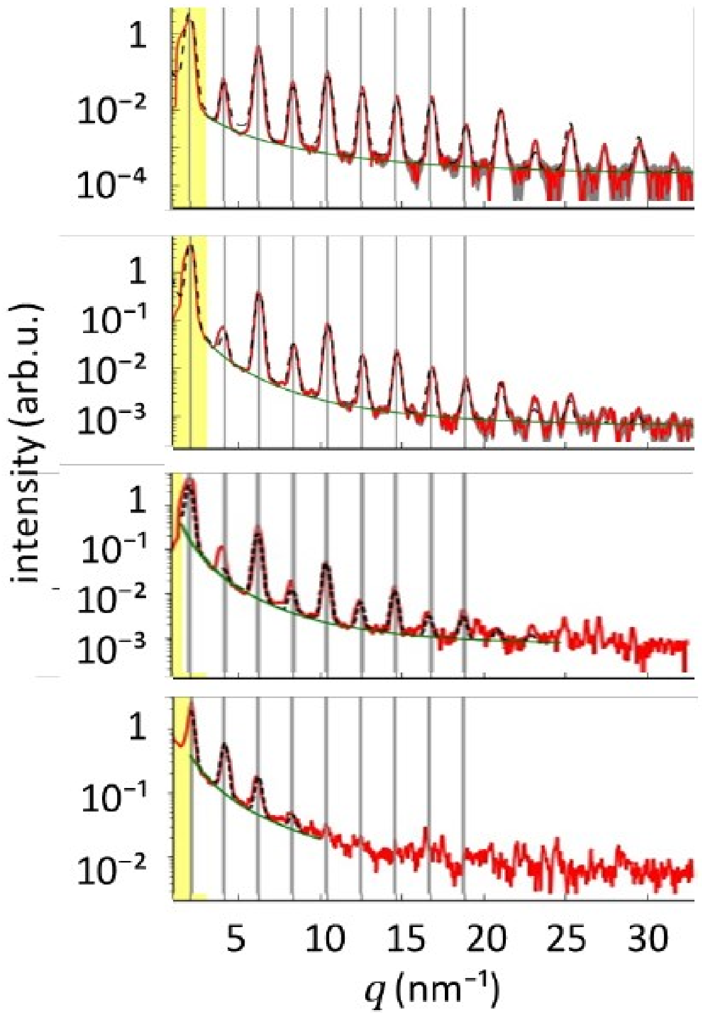
# Time-resolved plasma evolution on the fs & nm scales

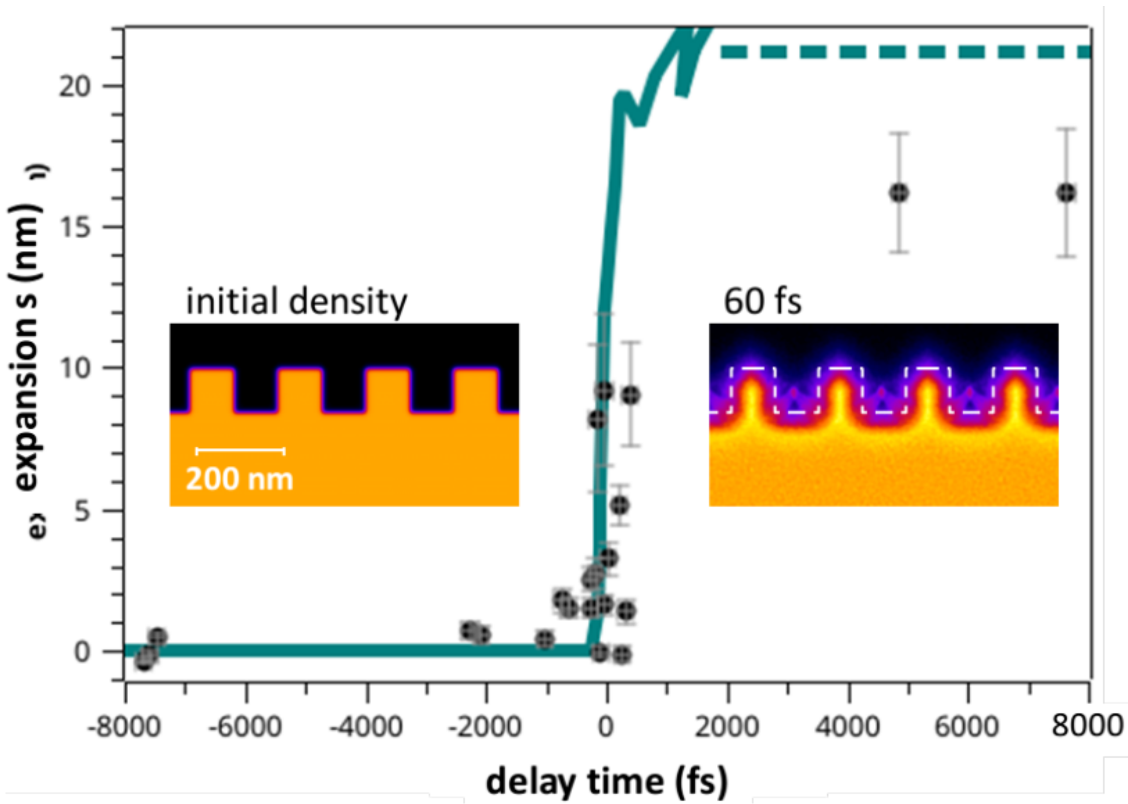


# Time-resolved plasma evolution on the fs & nm scales

HiBEF



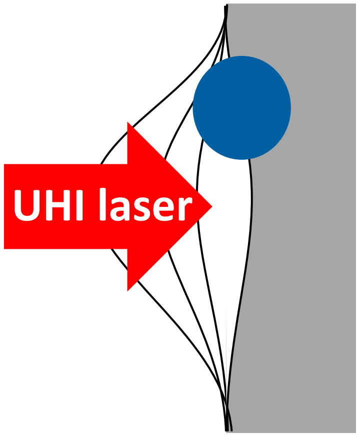

DRESDEN concept

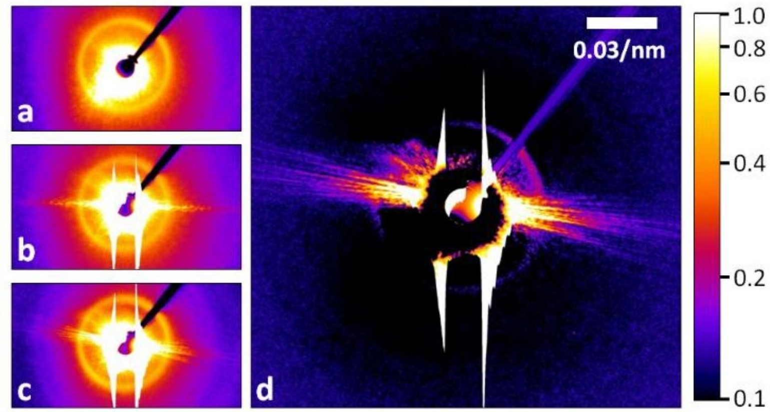
HZDR


Mitglied der Helmholtz-Gemeinschaft

# Time-resolved plasma evolution on the fs & nm scales

- Hole-boring (T. Kluge, MEC-LCLS LN04), ablation (L. Fletcher, MEC-LCLS LF20)



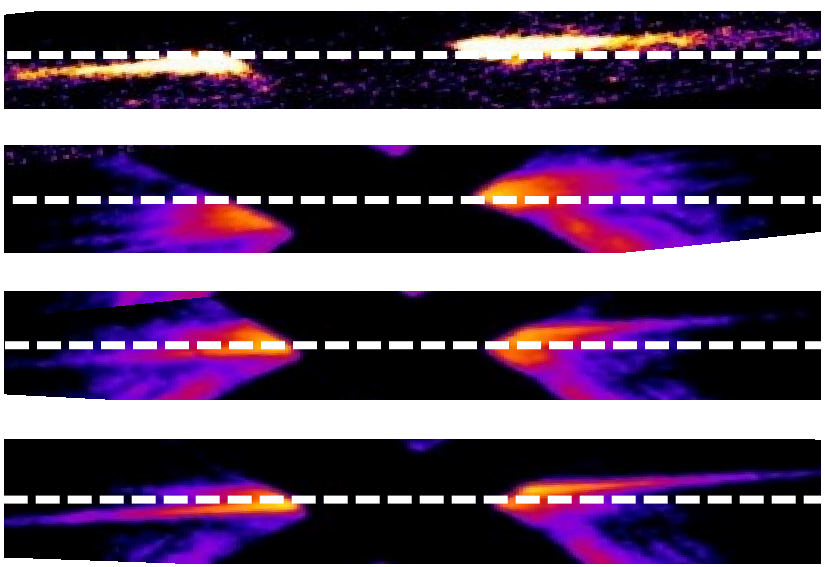



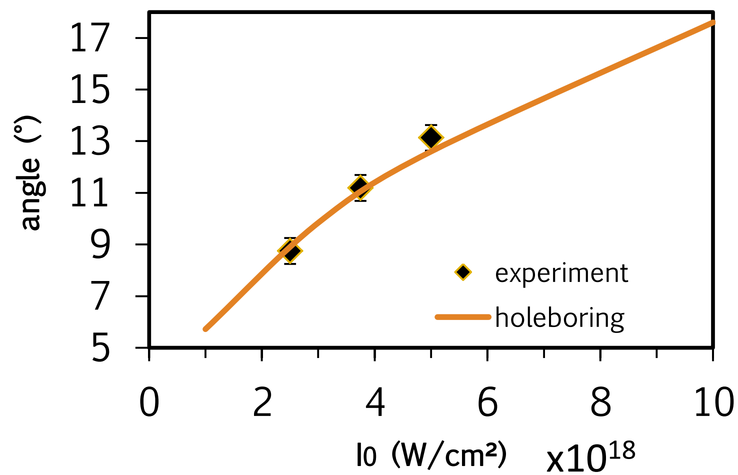

**un-pumped**

**Pumped**
**100%, $5 \times 10^{18}$**
**13.2°**

**Pumped**
**75%, $3.75 \times 10^{18}$**
**11.2°**

**Pumped**
**50%, $2.5 \times 10^{18}$**
**8.7°**



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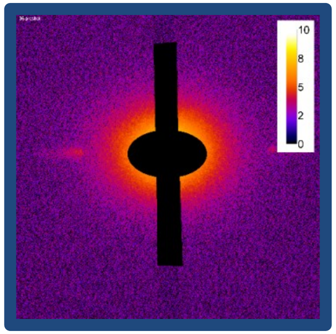
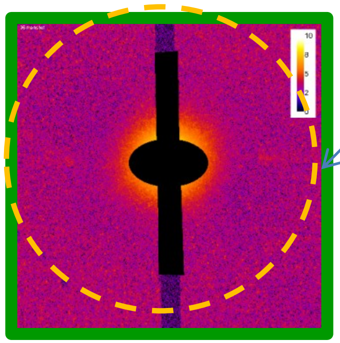
HZDR

# Time-resolved SAXS in dynamic compression

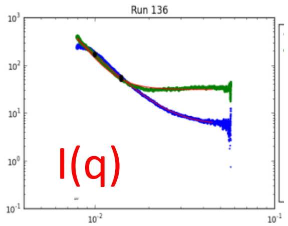
- Shock-induced demixing in hydrocarbons (D. Kraus et al, MEC-LCLS LP34)
  - Size distribution of diamond nanocrystals formed in shocked plastic

Pre-shot

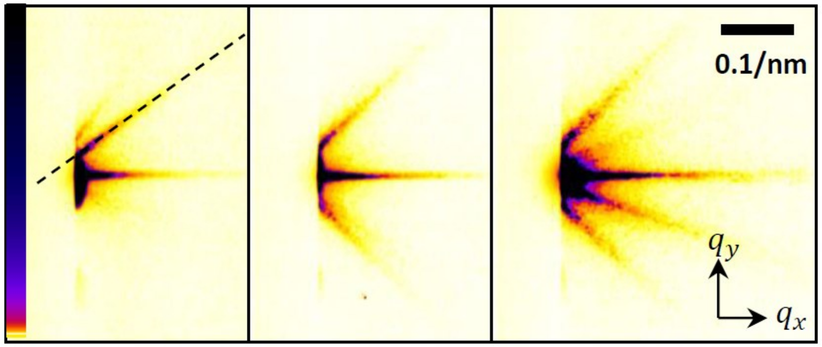


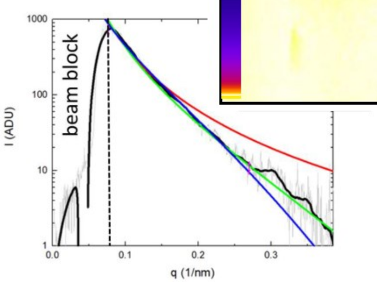


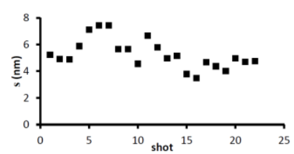
Compressed diamond powder diffraction

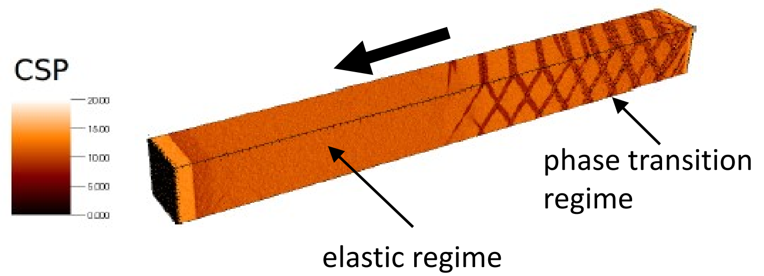



- High pressure phase in shocked Si (E. McBride et al, MEC-LCLS LH88)
  - *Oriented* diffraction steaks < *5 nm* density transition width




J. Appl. Phys. 114, 133504 (2013)
G. Mogni et al., PRB **89**, 064104 (2014)

DRESDEN concept HZDR

# Summary

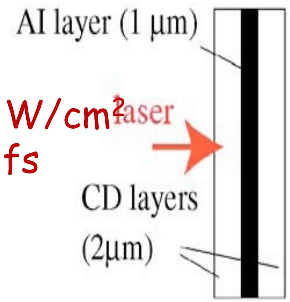
- **HiBEF / HED is** on track for laser commissioning winter 2018/2019
  - User Operation from mid 2019 (up to 300 TW; up to 100 J ns)
  - Phase II from ~2022 (kJ, ... PW)

- **Preparatory experiments (LCLS, SACLA) show great promise**
  - shock compression becoming routine at xfel's
  - nm-scale resolution of plasma evolution demonstrated
  - nm-scale SAXS promising technique for dynamic compression

→ **High Power Lasers at XFEL's *will revolutionize* High Energy Density science**

**Thank you for your Attention**

# Time-resolved plasma evolution on the fs & nm scales

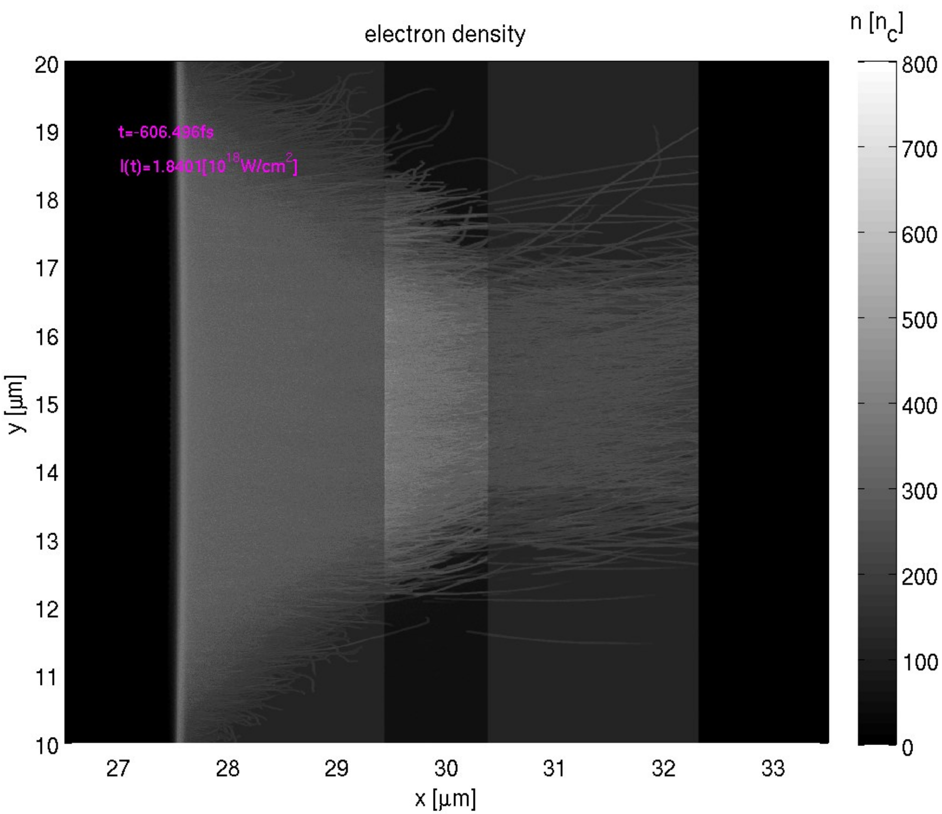


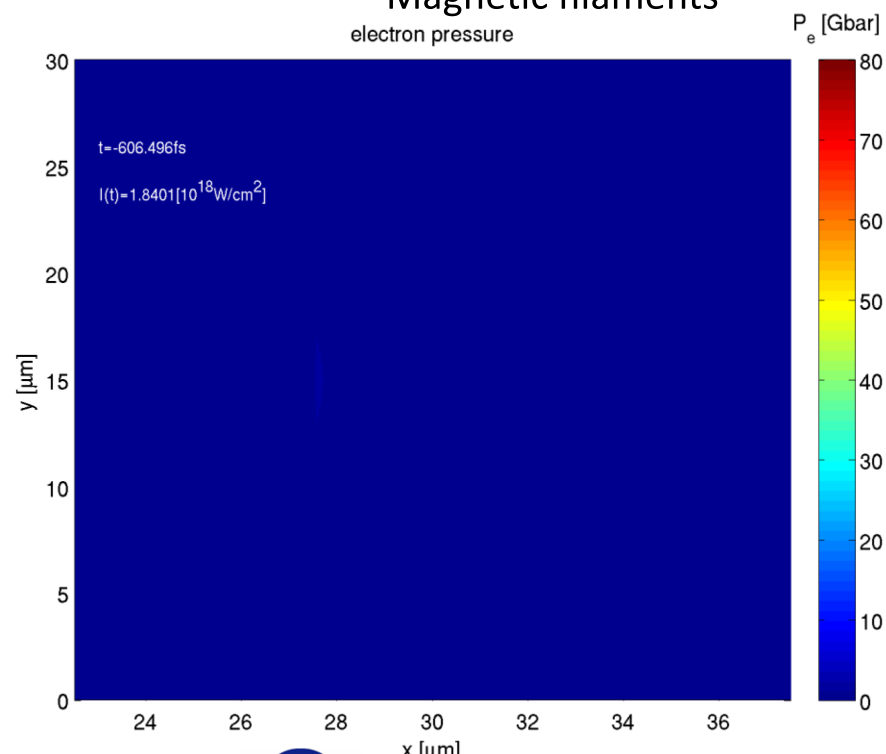

$10^{20}$ W/cm²
500 fs

PICLS2d @ solid density
Ionization & collisions

L. Huang, M. Bussmann et al., Phys. Plasmas **20**, 093109 (2013)

- Ionization dynamics
- $e^-$ filamentation
- Hole-boring
- Channeling (hydro)
- Ion heating
- Interface "shocks"
- Colliding shocks
- Magnetic filaments




L. Huang et al., Phys. Plasmas **20**, 093109 (2013)

# Acknowledgements:

**HiBEF Project Team** *(HZDR, DESY)*
C. Baehtz, T. Toncian, K. Knoefel, A. Pelka, W. Seidel, J. Dreyer, H. Hoeppner, M. Toncian, D. Moeller, J. Hauser, A. Winter, A. Ferrari, T. Herrmannsdoerfer *(HZDR)*
H.-P. Liermann, A. Schropp, J. Strempfer, M. van Zimmermann *(DESY)*

**HED Instrument Team** *(XFEL)*
U. Zastrau, M. Nakatsutsumi, K. Appel, S. Goede, Z. Konopkova, M. Makita, I. Thorpe, A. Schmidt, K. Sukharnkov, T. Feldmann, E. Martens, G. Priebe, T. Tschentscher *(XFEL)*

**Collaborators:**
T. Kluge[1], M. Roedel[1], J. Metzkes[1], A. Pelka[1], A. Laso Garcia[1], I. Prencipe[1], M. Rehwald[1], T. Schoenherr[1], A. Erbe[1], C. Gutt[3] , E. Galtier[4], I. Nam[4], H. J. Lee[4], S. Glenzer[4] U. Huebner[5], C. Roedel[6], E. McBride[4,7], M. Nakatsutsumi[7], N. Hartley[1], M. Garten[1], M. Zacharias[1], M. Bussmann[1], K. Zeil[1], U. Schramm[1,2], T.E. Cowan[1,2],
L. Huang[1], J. Grenzer[1], B. Nagler[4], E. Gamboa[4], W. Schumaker[4], L.B. Fletcher[4], M. Harmand[8], A. Krygier[8], A. Higgenbotham[9]
D. Kraus[1,2], K. Rohatsch[1], A. Schuster[1] and LP34 collaboration

*[1]HZDR, [2]TU Dresden, [3]U Siegen, [4]SLAC, [5]LIPhT, [6]FSU Jena, [7]XFEL, [8]UPMC, [9]York*