New science opportunities at XFELs:
probing ultra-intense laser-solid interactions

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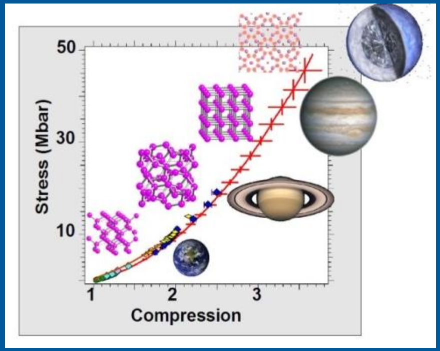
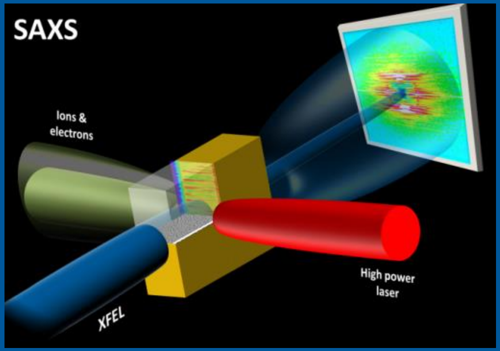
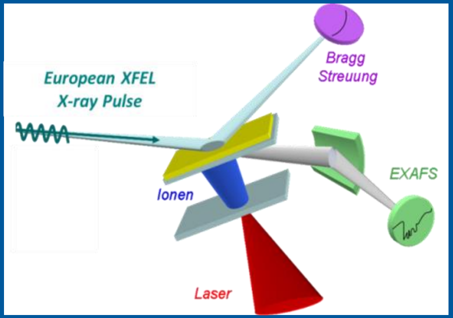
[1]HZDR, [2]TU-Dresden, [3]SIOM, [4]DESY, [5]Uni Siegen

on behalf of the Helmholtz International Beamline for Extreme Fields (HIBEF) at European XFEL





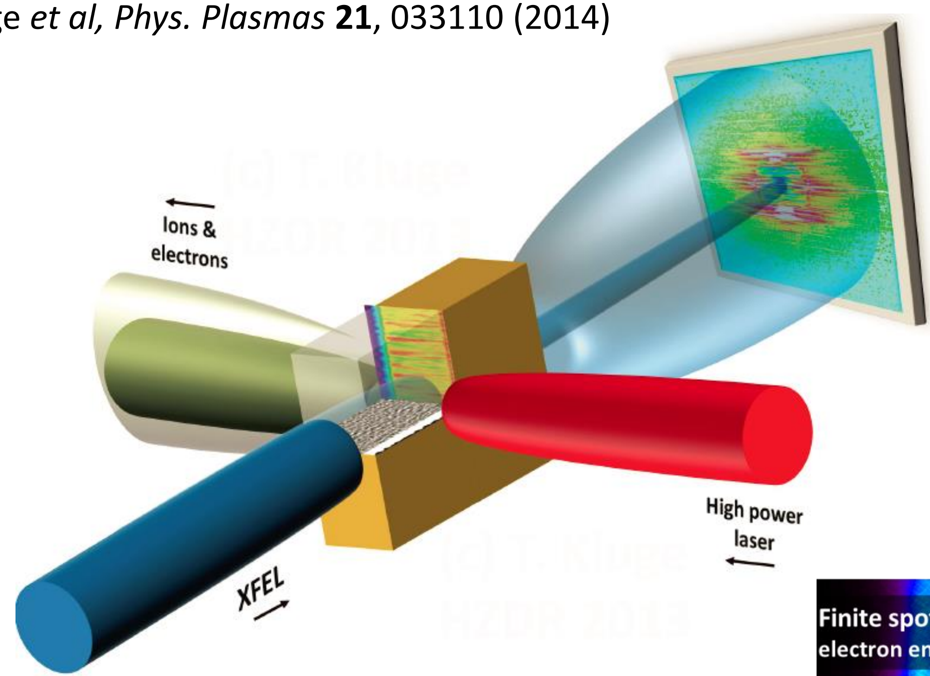


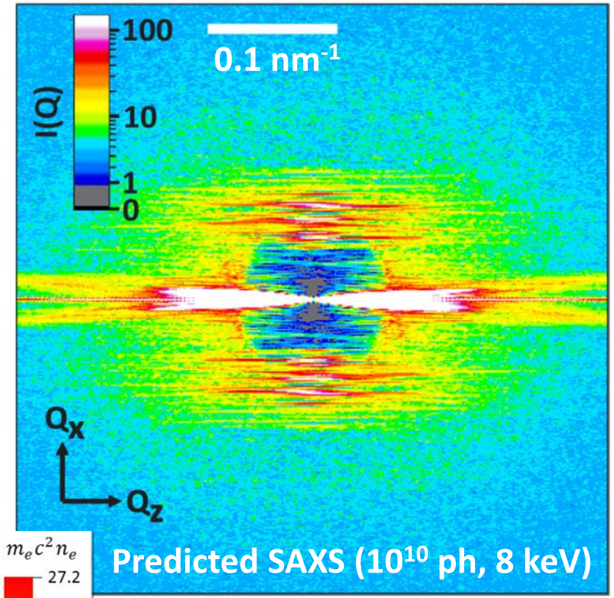
LA³NET TW3: Novel Acceleration Techniques
HZDR, Dresden
April 28-30, 2014

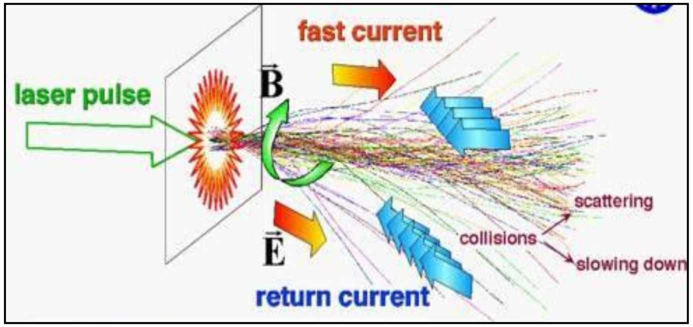
HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

HIBEF: Relativistic laser-matter interactions

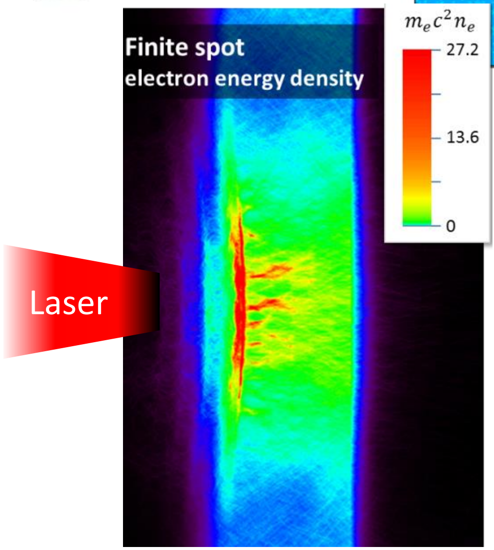
T. Kluge *et al*, *Phys. Plasmas* **21**, 033110 (2014)







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
- ....

Summary

Motivation:

Understand ultra-intense laser-matter interactions inside of solid density targets with *coherent* x-rays from XFELs

Examples:

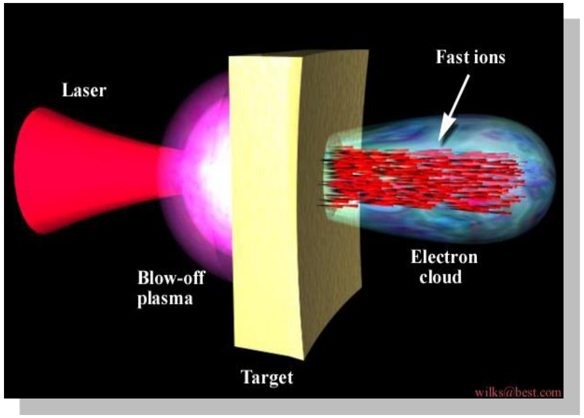
1. Physics at laser-matter-interface and in buried-layers
   [L. Huang et al., Phys. Plasmas **20**, 093109 (2013)]

2. Ultrafast electron dynamics at solid-density*
   [T. Kluge, C. Gutt, L. Huang et al., Phys. Plasmas **21**, 033110 (2014)]

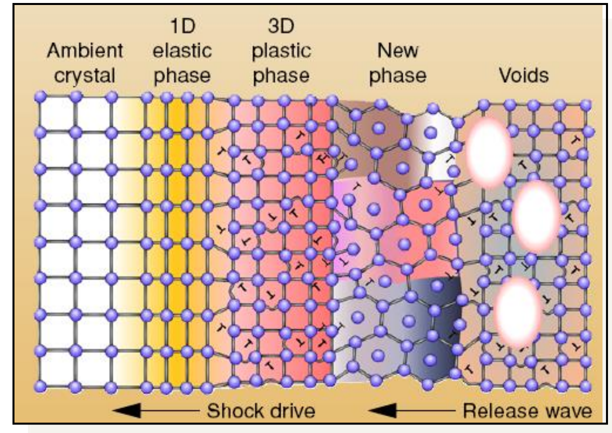
3. Ionization dynamics probed by resonant CXDI
   […work in progress…]

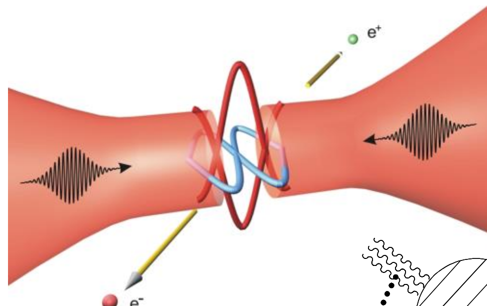
Extreme Conditions with Ultra-intense & High-energy Lasers

Extreme particle beams

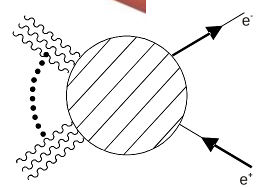


Extreme pressures

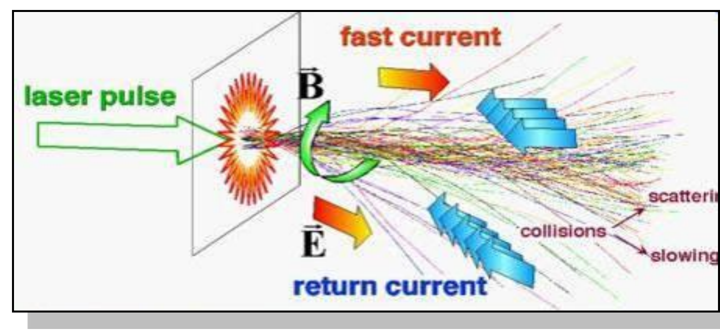


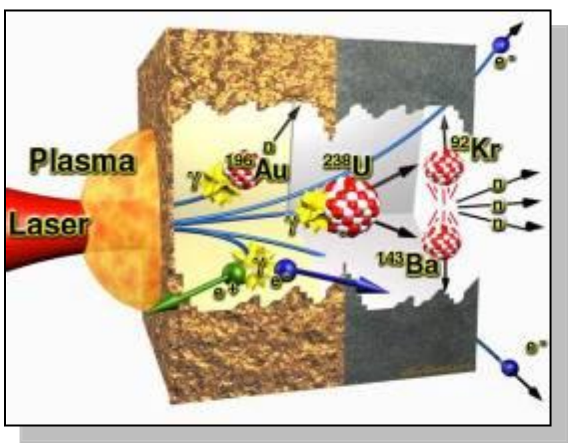


Strong Fields



Extreme currents





Extreme radiations

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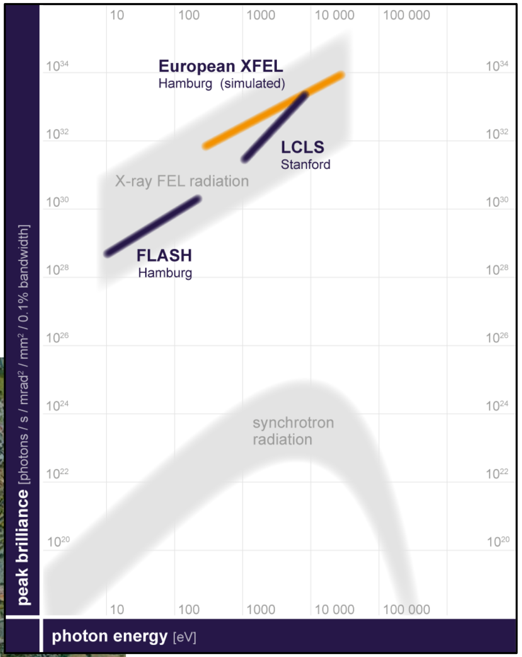
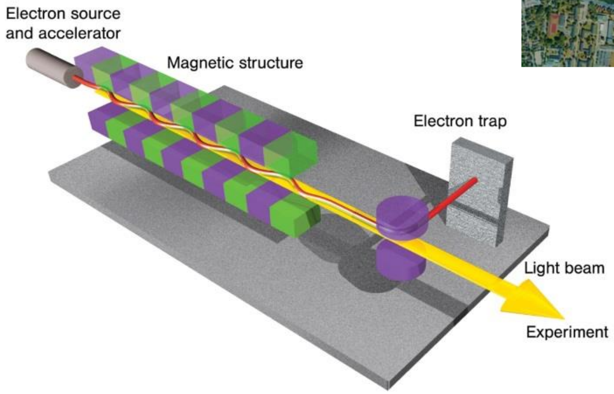
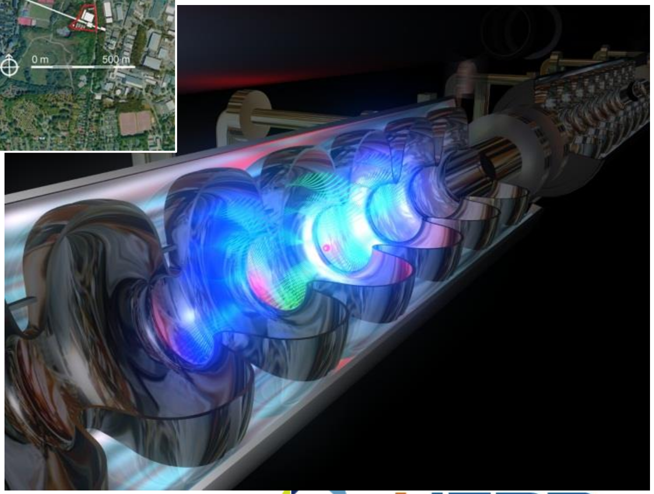
HIBEF at the European XFEL

European
XFEL







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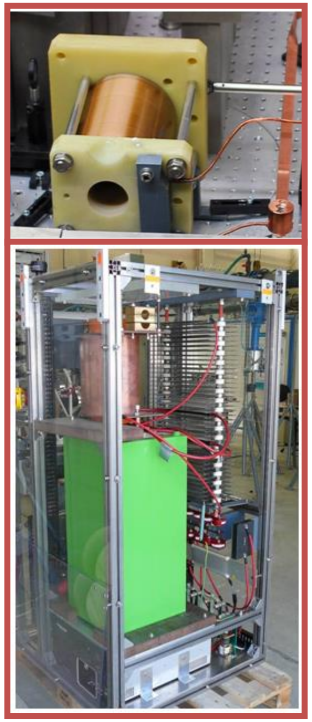
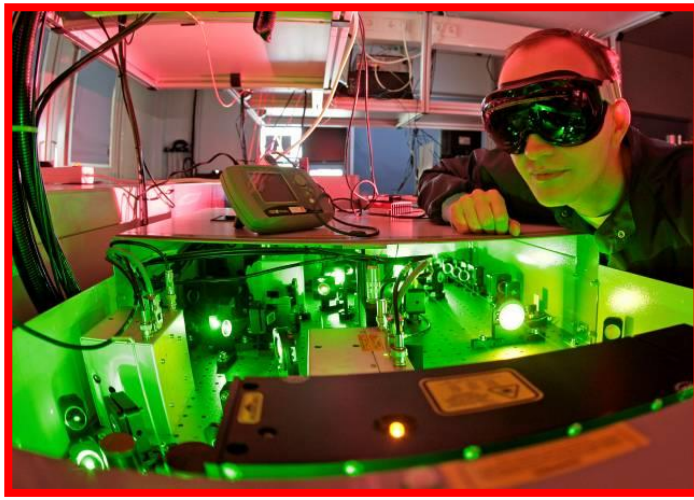
HZDR

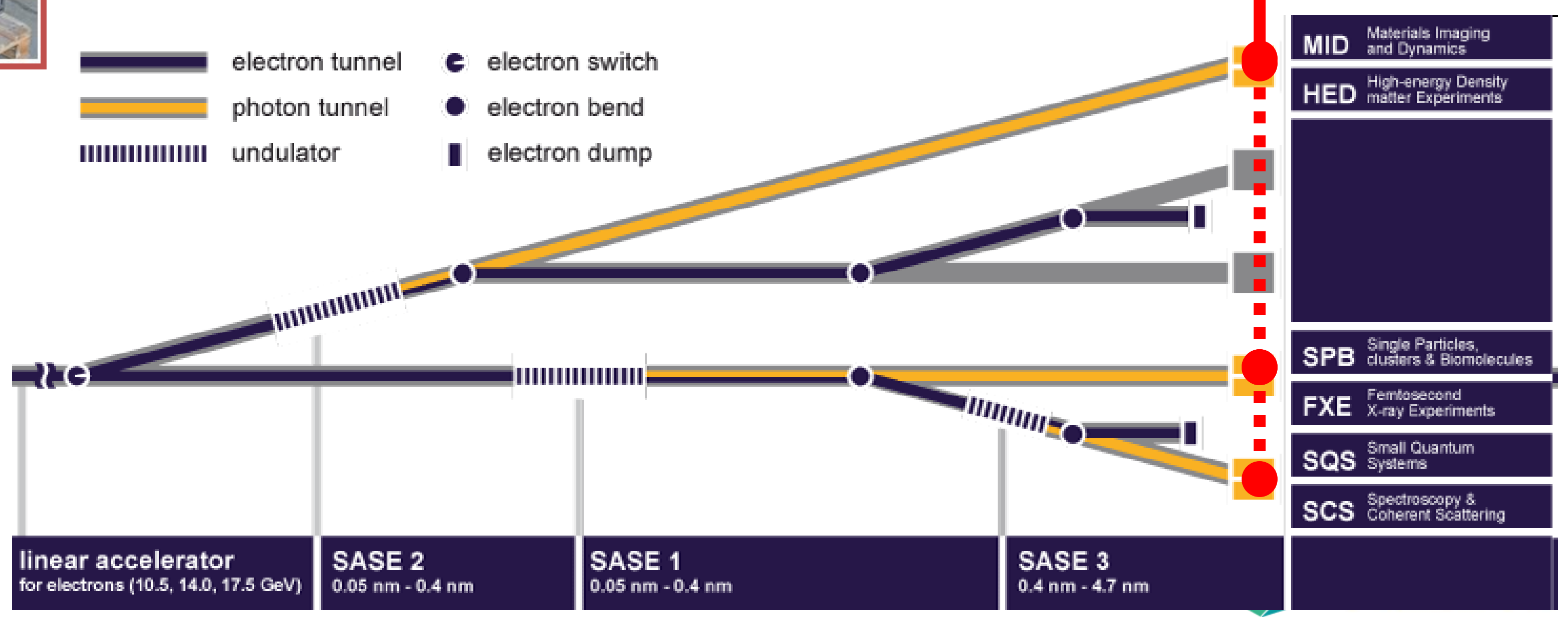
HIBEF at the European XFEL





Laser Options (~0.1 – 10 Hz)
~PW, 30 J/30 fs Ti:Sa
~kJ, ~2-20 ns shaped (DiPOLE-UK)
Pulsed Magnets (1 ms, ~50 T)

Optional target chamber for expt. staging



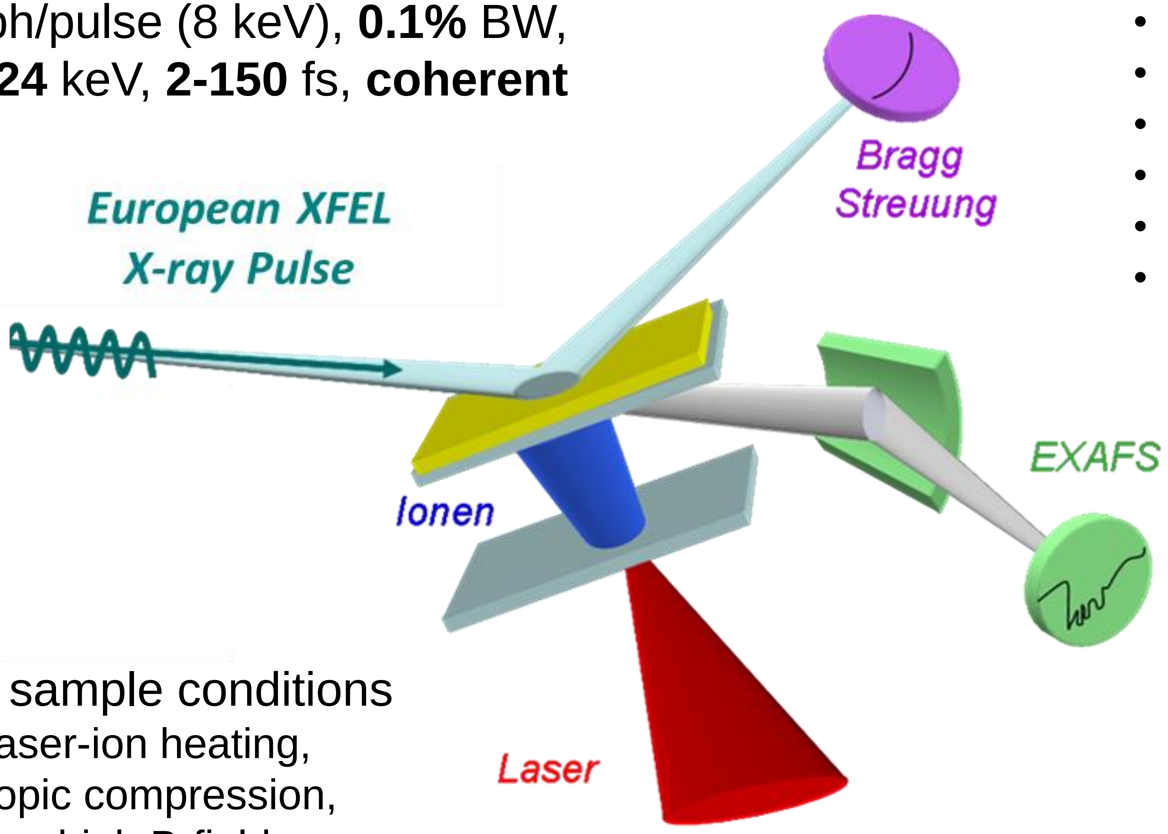
European XFEL

HIBEF: New Experimental Capabilities

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

X-FEL Probing:

- Bragg & Laue diffraction
- X-ray Thomson scattering
- Absorption spectroscopy
- Faraday Rotation
- Coherent X-ray imaging
- Correlation specroscopy

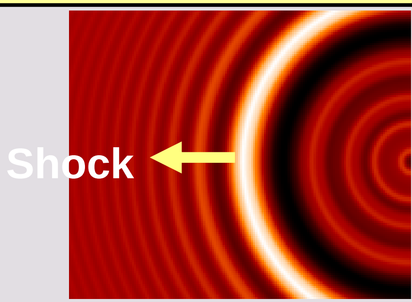


Extreme sample conditions
e.g., laser-ion heating,
isentropic compression,
shocks, high B-fields ...

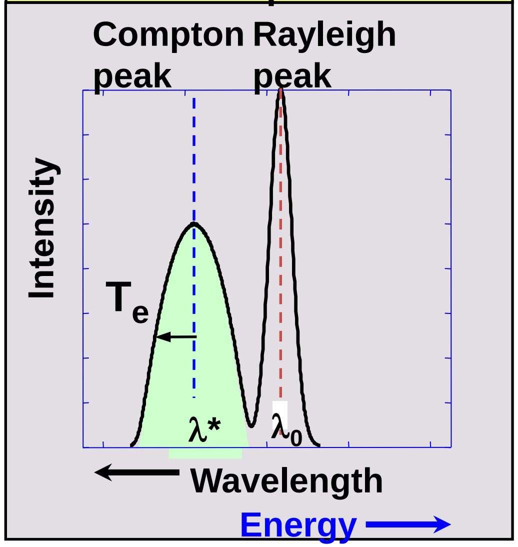
XFEL-based probing → faster, brighter (focused), coherent

XFEL combined with high-power laser drivers will open a new frontier of Science at Extreme Conditions

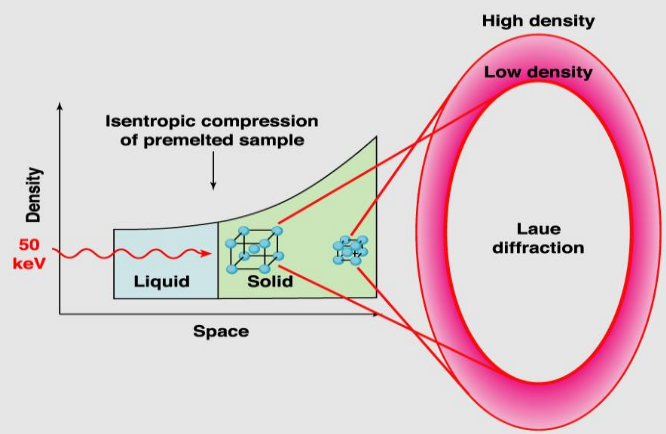
Diffractive imaging



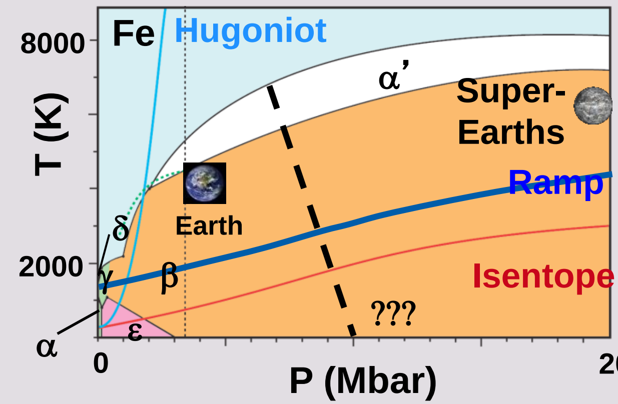
Compton scattering → Te, Z, ne, collision time of dense plasmas



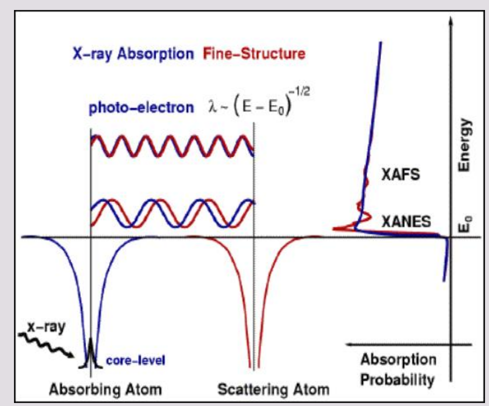
X-ray scattering → structure, chemistry, kinetics



Material phases, thermodynamic states



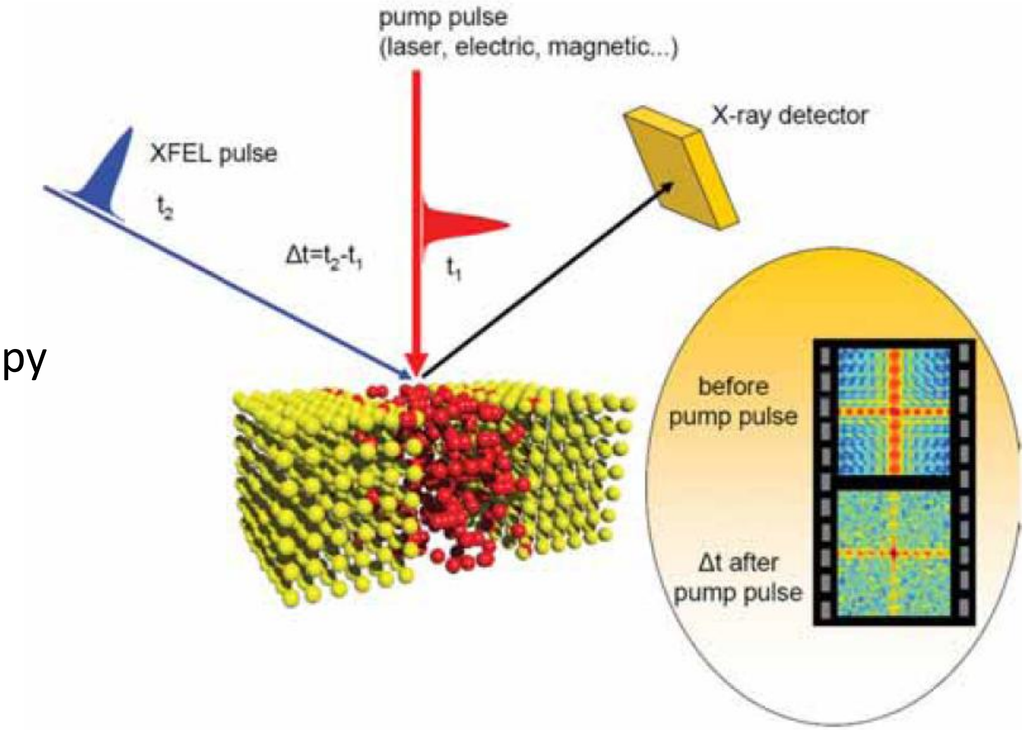
X-ray absorption spectroscopy → Melt, Chemistry



Courtesy G. Collins

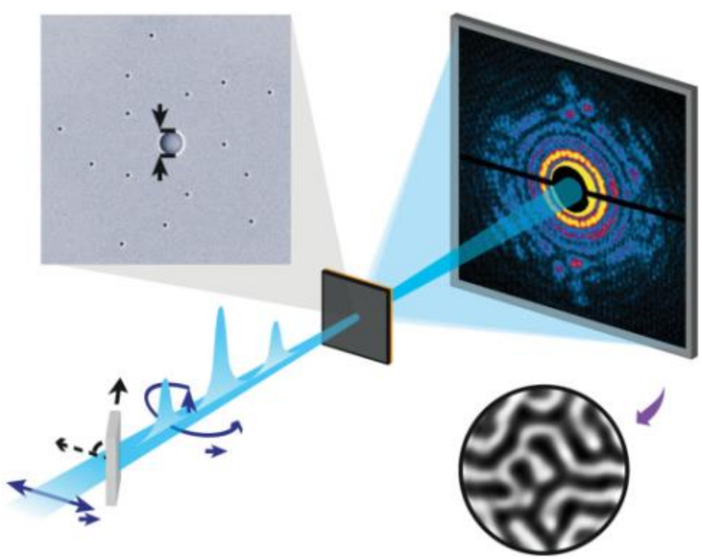
Important Challenge – Advancing hard X-ray Techniques

→ Adapting techniques from: Synchrotron-, Laser-, FEL-, & Ultrafast-science communities



Example: XPCS
X-ray Photon Correlation Spectroscopy

- Single-pulse x-ray Split & Delay
- Self-seeding (full coherence)



Small Angle X-ray Scattering (SAXS)
→ Coherent diffractive imaging
→ X-ray holography
→ e.g., XMCD for magnetic domain imaging
→ $S_{ee}(q)$ electron correlation function

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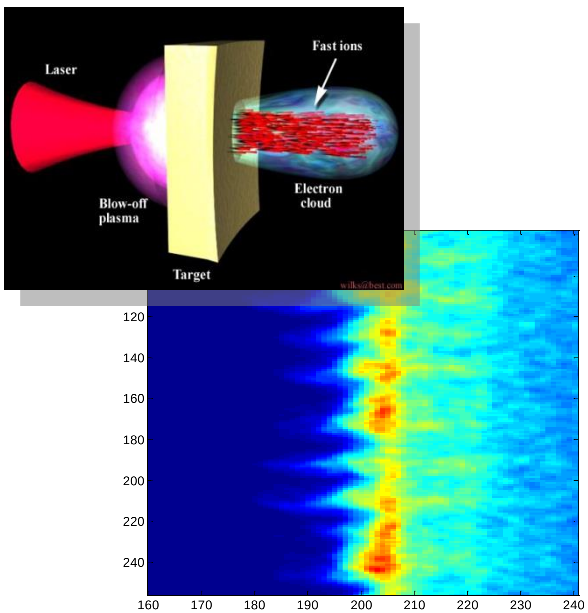
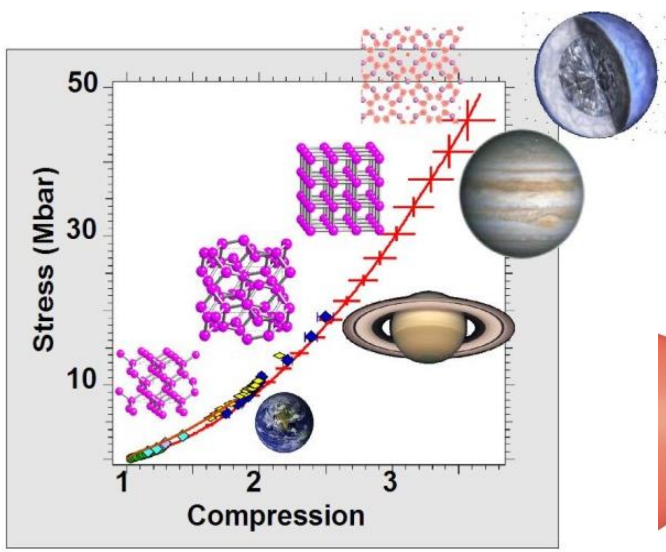
Unique Science Opportunities:

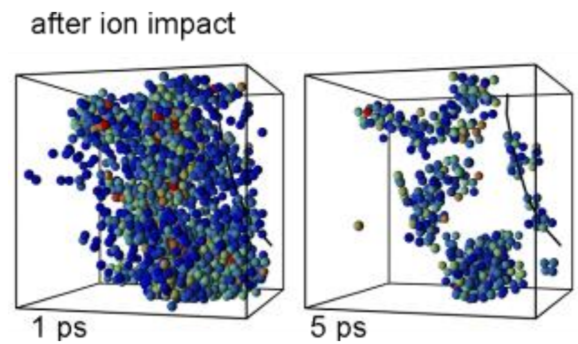
- Relativistic Laser-Plasmas
- New Phases of Matter
- Ultra-strong Field Physics
- Material Dynamics & Damage
- Element-selective Magnetism

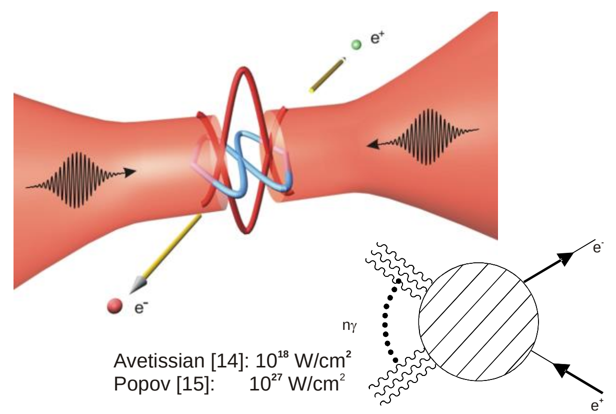
X-FEL User Consortium

HZDR, DESY, HIJ, XFEL, + over 90 institutions in 19 countries









HIBEF User Consortium

Co-PI's: *T.E. Cowan, U. Schramm (HZDR), E. Weckert (DESY), T. Stoehlker (HIJ), J. Wark (UK Consortium)*

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 Muenchen, 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, ESFR, 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: 10

SIOM, IOP-CAS, Peking Univ, SJTU (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)

		Nr	%	%
DE	HGF	74	10.9	33.3
	DE	152	22.4	
EU	UK	73	10.8	33.9
	FR	39	5.8	
	ES	29	4.3	
	SE	28	4.1	
	CH	10	1.5	
	CZ	10	1.5	
	PL	10	1.5	
	RU	10	1.5	
	HU	9	1.3	
	IT	6	0.9	
	XFEL	6	0.9	
Asia	CN	94	13.9	17.8
	JP	22	3.2	
	IN	5	0.7	
US	US	101	14.9	14.9

*as of 3/15/2012

>100 Institutions, >400 faculty/scientists, >300 students

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Summary

Motivation:

Understand ultra-intense laser-matter interactions inside of solid density targets with *coherent* x-rays from XFELs

Examples:

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

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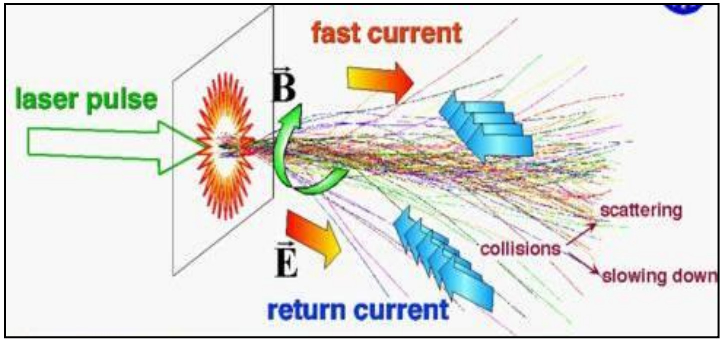
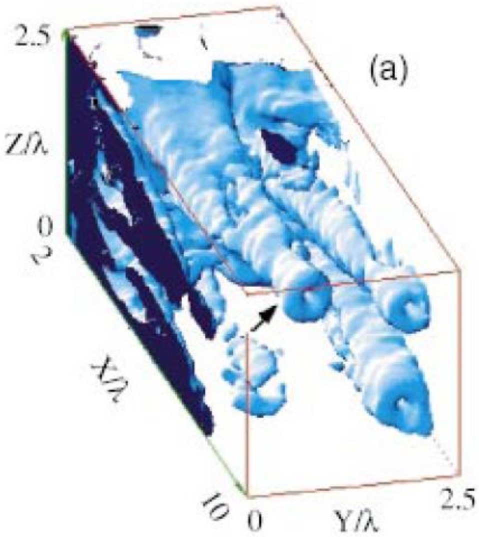
3. Ionization dynamics probed by resonant CXDI
   […work in progress…]

Ultra-Intense Laser-Matter Interactions – Key Challenges



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

→ **Current filamentation**
→ **Ionization dynamics**

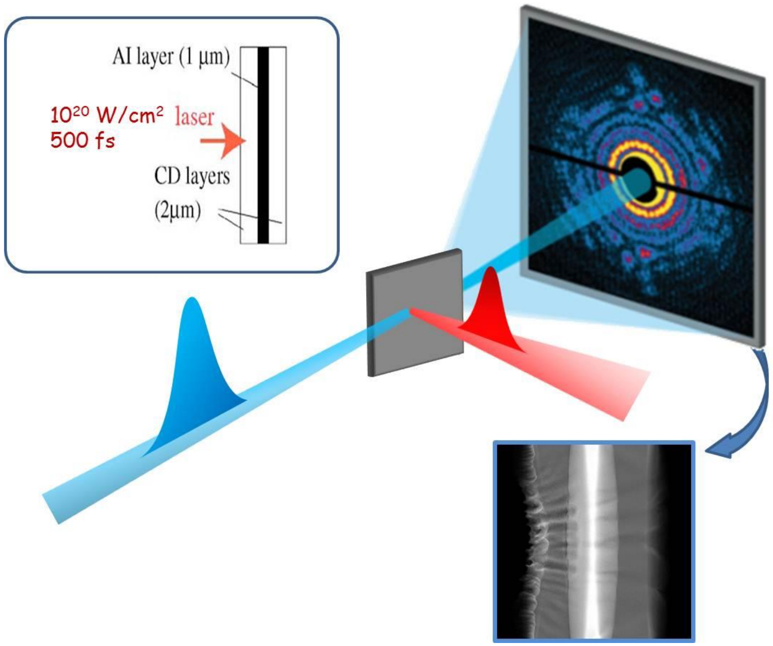


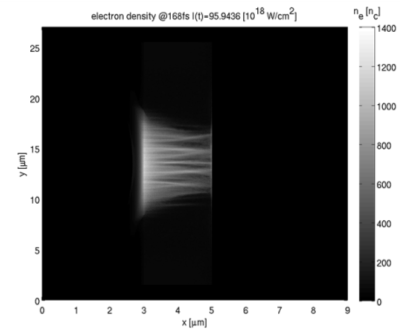
Essential Questions:
- return-current generation, neutralization (ionization, resistivity, heating)
- filament formation & propagation
- particle & energy transport
- e-e & e-i equilibration
- quasi-static resistive fields
- magnetic diffusion (relaxation, >6 ps)
- radiation transport
- …

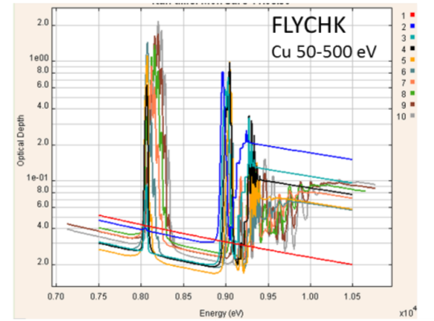
- Extreme transients & gradients
- Transition through cold-WDM-hot
- Extreme magnetizations

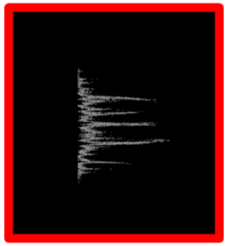
→ Ultrafast probing of Z*, j_e, T_e, B, inside solid-density plasma, time & space resolved, on the *plasma scale*

Small Angle X-ray Scattering & Coherent Diffraction Imaging

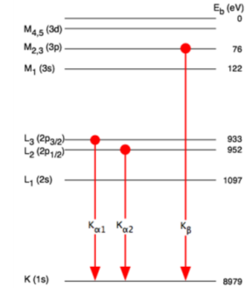


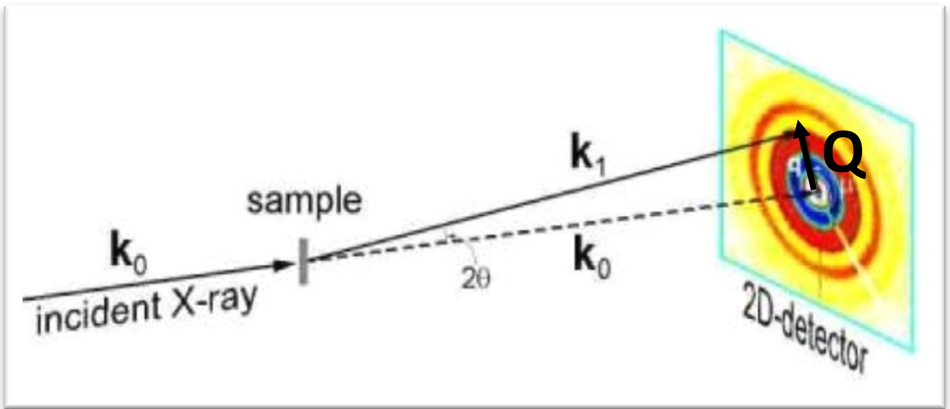






→ Isolate a specific charge-state by tuning to bound-bound resonance (e.g., $K\alpha$ or $K\beta$)





- SAXS: Small angle x-ray scattering
  Q-range < 0.3 nm^{-1}

- optical laser: λ =800 nm, Q=0.008 nm^{-1}
- plasma oscillations: λ_p~30 nm, Q~0.2 nm^{-1}

$$I(Q) \sim |f_0 + f' + if''|^2 \; S_{ii}(Q) \; + Z_f \, S_{ee}(Q)$$

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Understanding ultra-intense laser-matter interactions at solid density with coherent x-rays from XFELs

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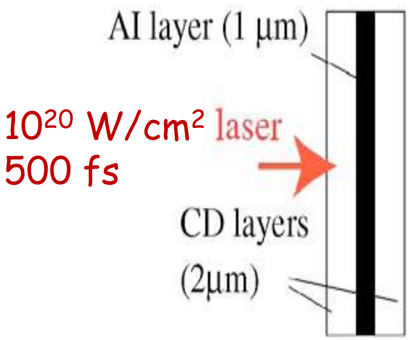
Example 1: Physics in buried layer targets

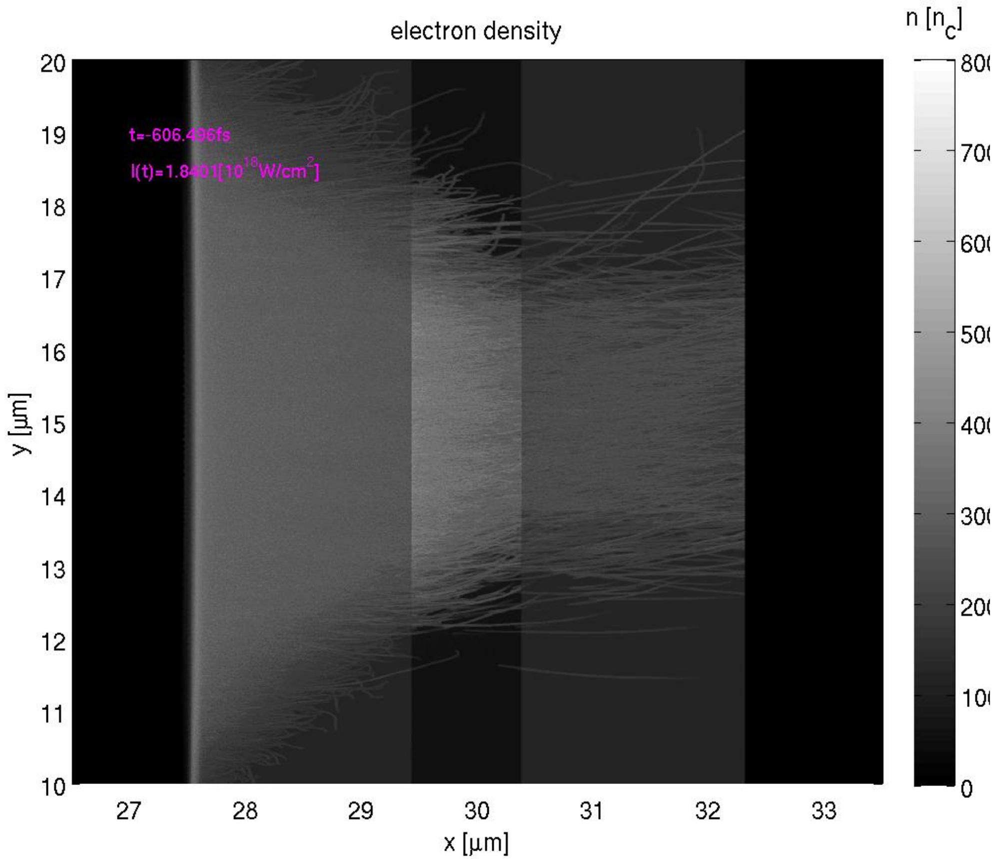


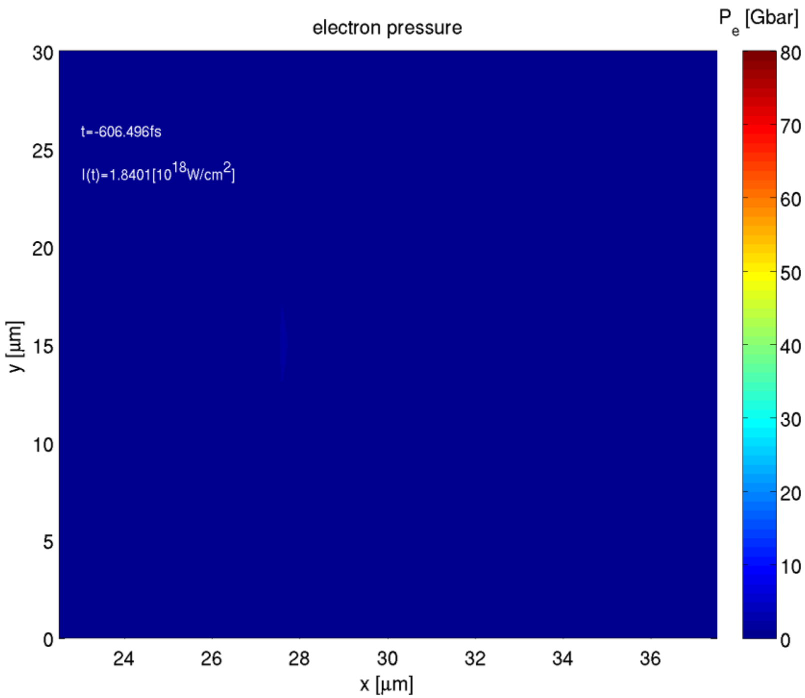
PICLS2d @ solid density
Ionization & collisions

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

Processes:

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



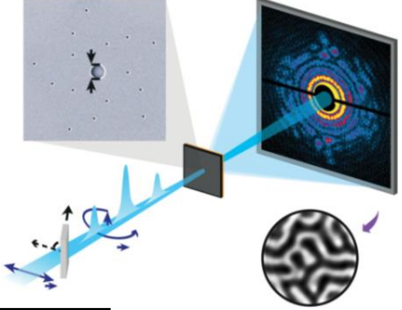


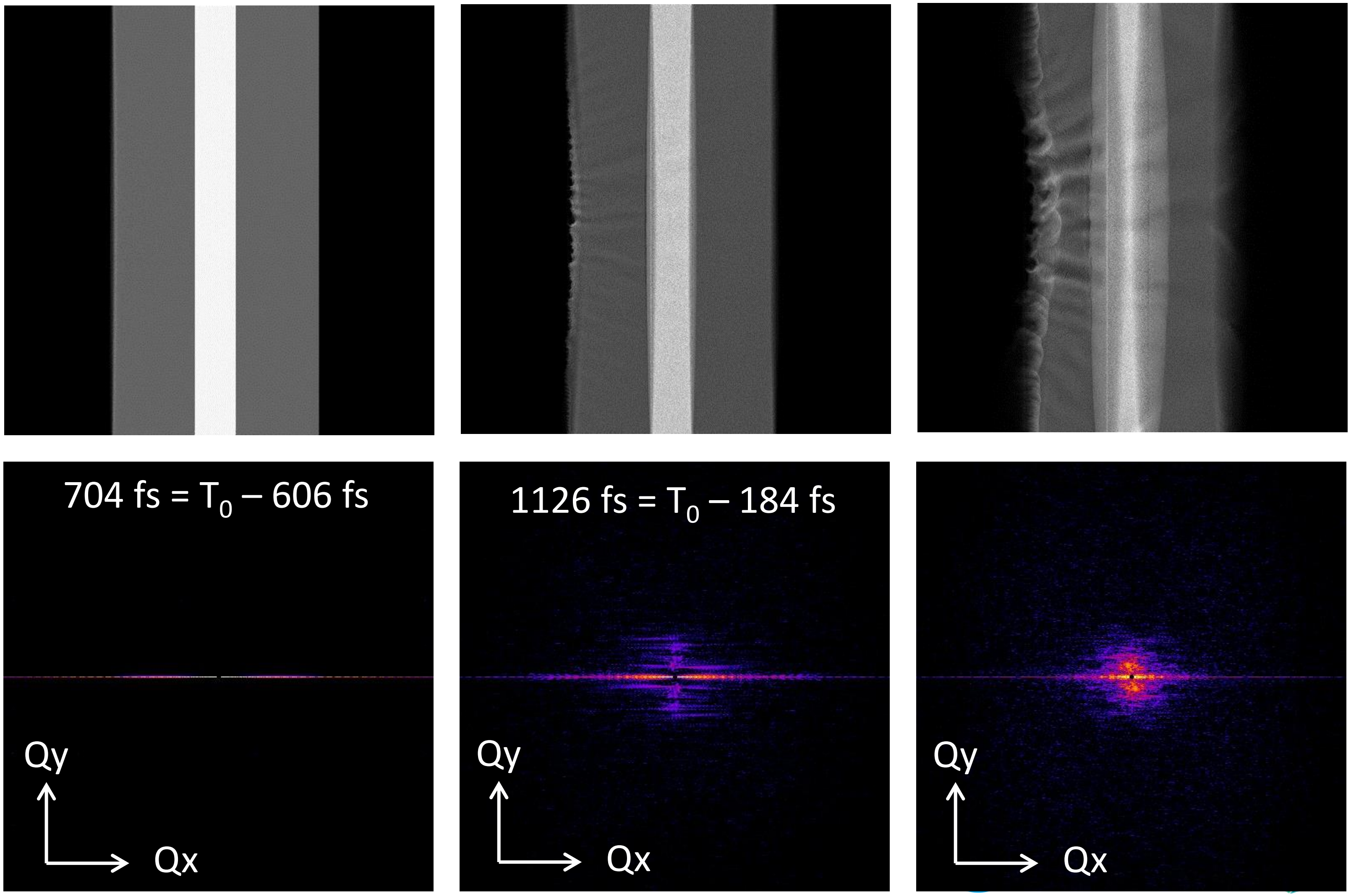
L. Huang et al., Phys. Plasmas **20**, 093109 (2013)

Example 1: Physics in buried layer targets

Small Angle X-ray Scattering (SAXS)

- spatial frequencies → mode structure of instabilities
- time history → growth rates, γ vs κ





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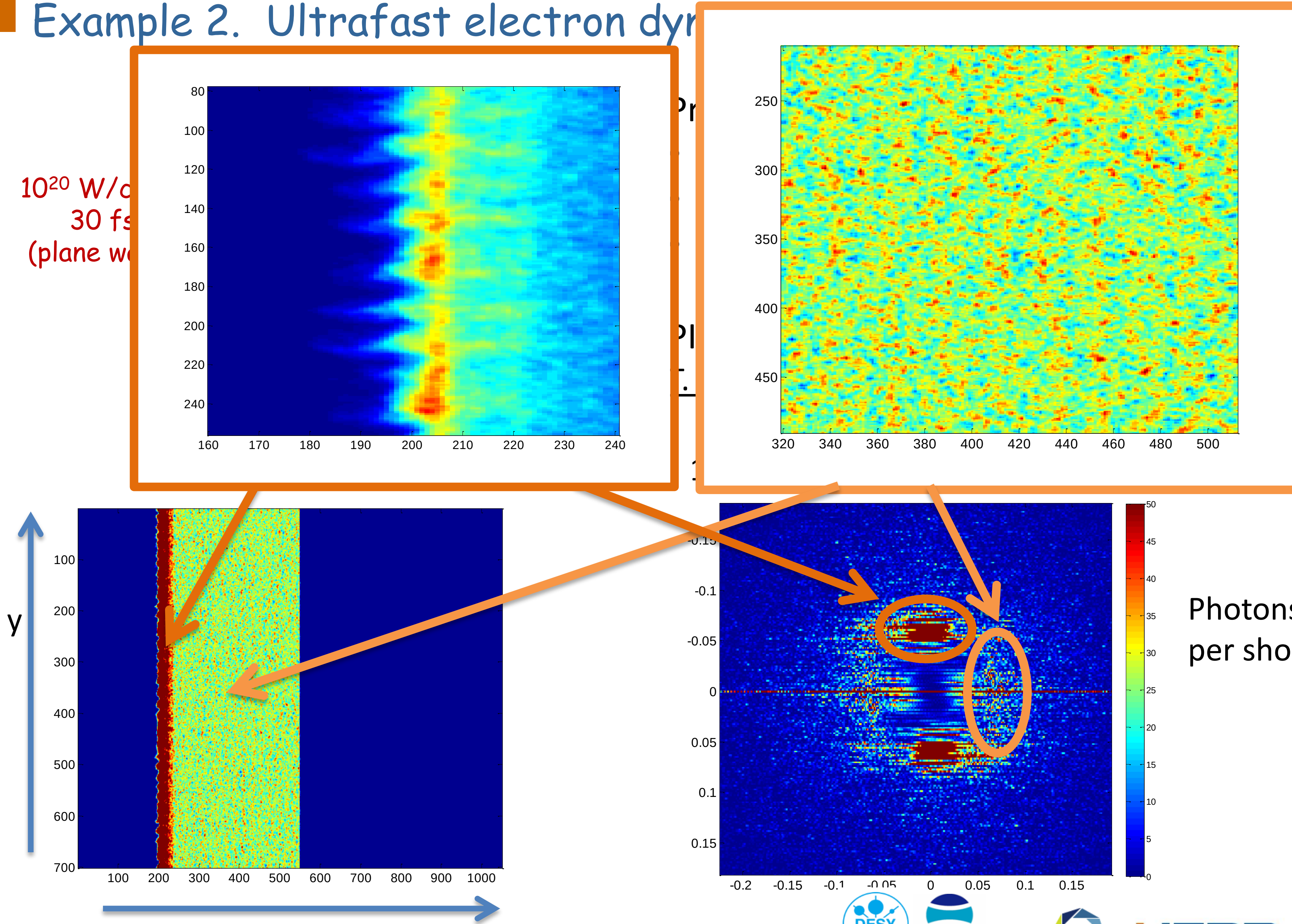
Example 2. Ultrafast electron dyn



T.Kluge, C. Gutt, L. Huang et al, arXiv:1306.0420

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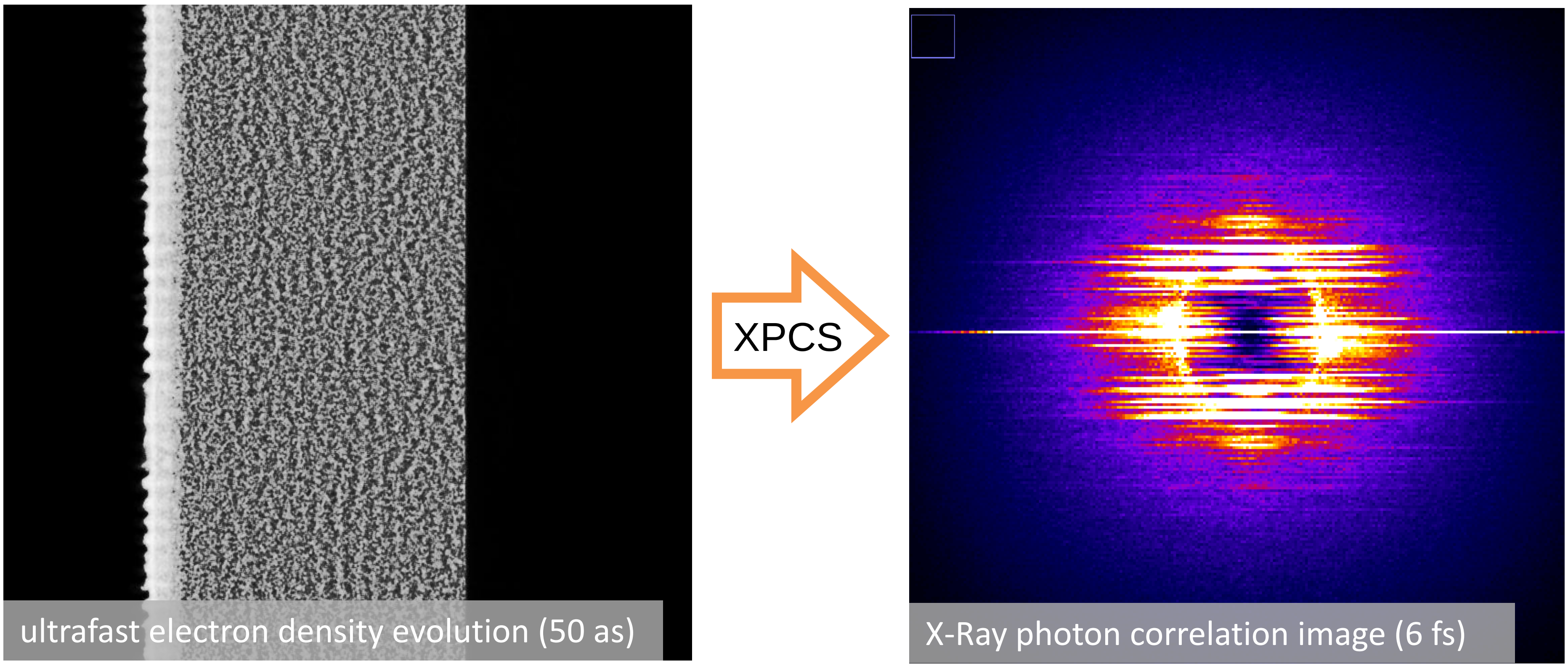
Example 2. Ultrafast electron dynamics at solid-density

Integration over XFEL pulse:

- Speckle blurring → loss of absolute position information
- But, retain full mode information → $S_{ee}(q)$, growth rate γ vs κ

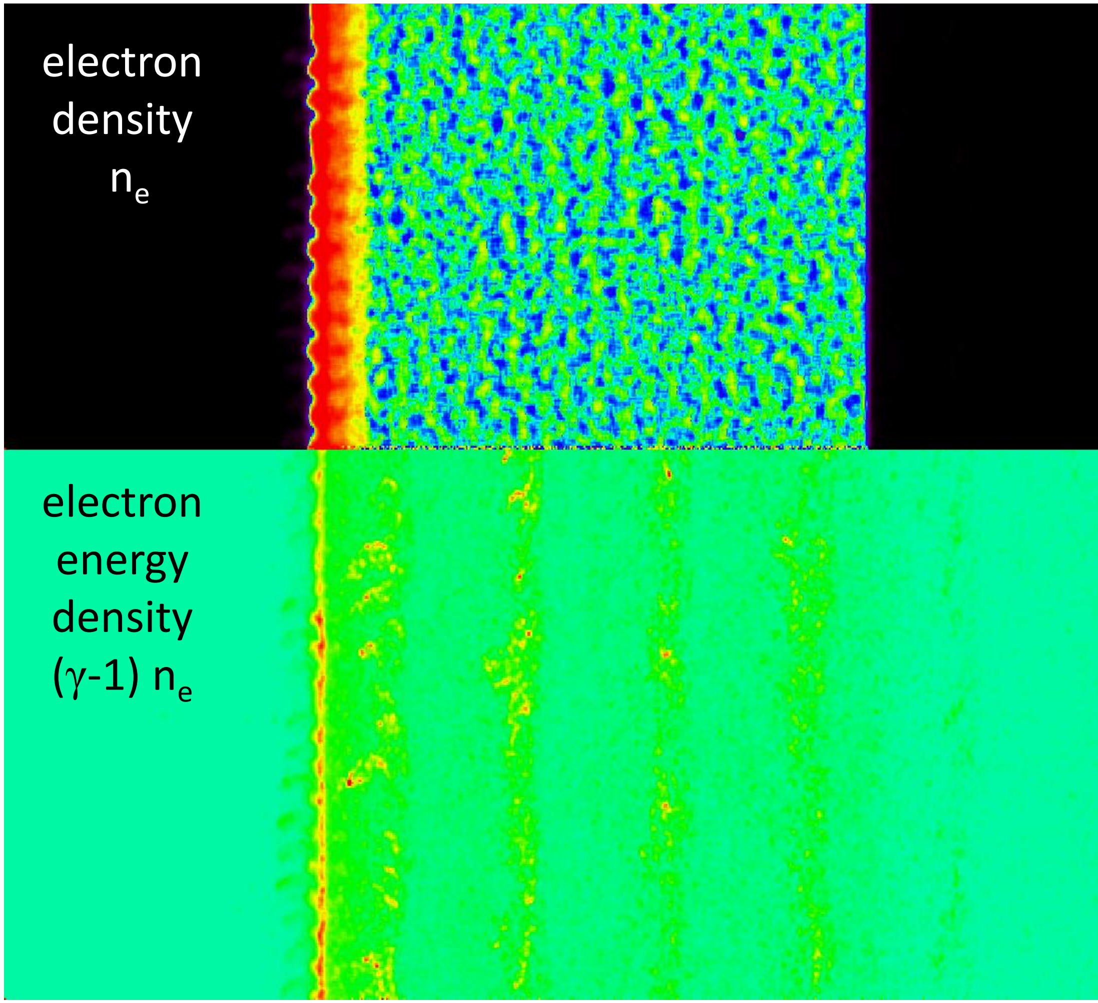


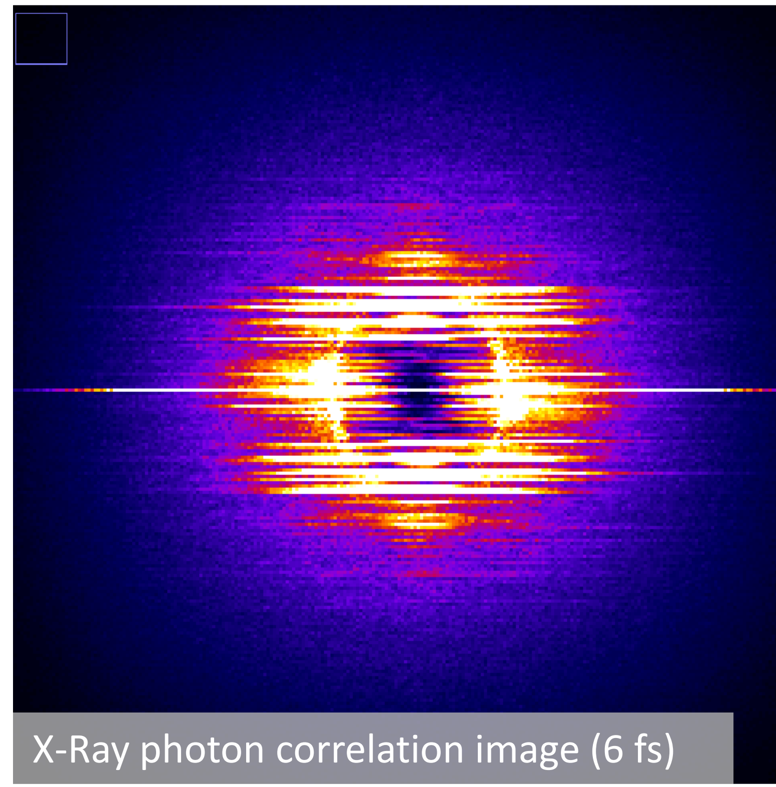
ultrafast electron density evolution (50 as)

X-Ray photon correlation image (6 fs)

Simulation (T. Kluge): 10^{20} W/cm^2, 30 fs plane wave on 2.5 μm Ti

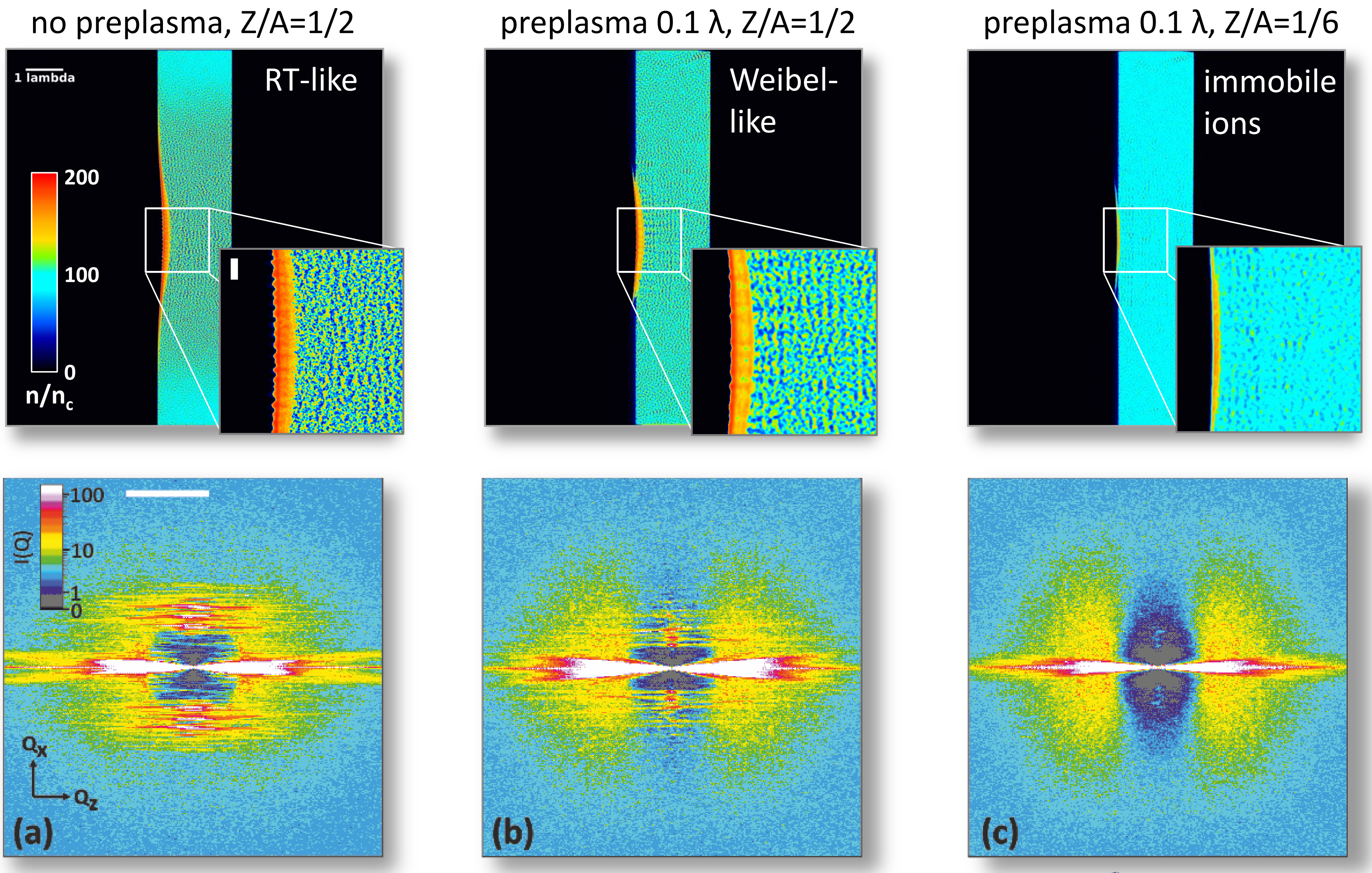
Example 2. Ultrafast electron dynamics at solid-density





Simulation (T. Kluge): 10^{20} W/cm^2 , 30 fs plane wave on 2.5 μm Ti

Example 2. High sensitivity to type of instability



T.Kluge, C. Gutt, L. Huang et al, arXiv:1306.0420

Outline

Motivation:

Understanding ultra-intense laser-matter interactions at solid density with coherent x-rays from XFELs

Examples:

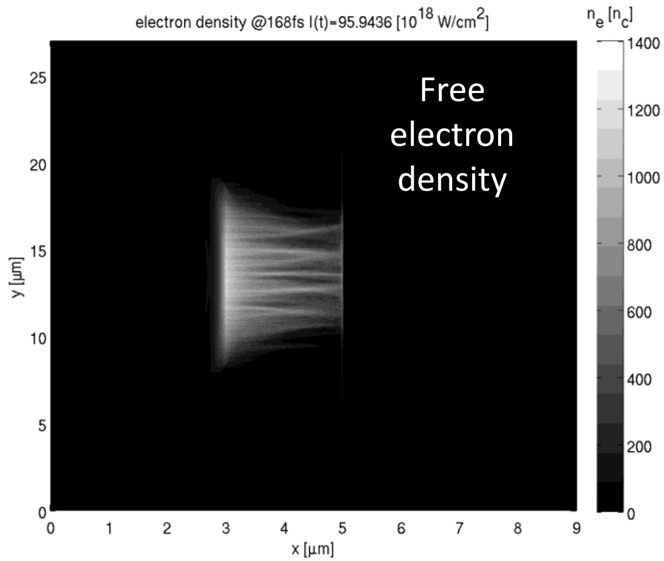
1. Physics at laser-matter-interface and in buried-layers
   [L. Huang et al., Phys. Plasmas **20**, 093109 (2013)]

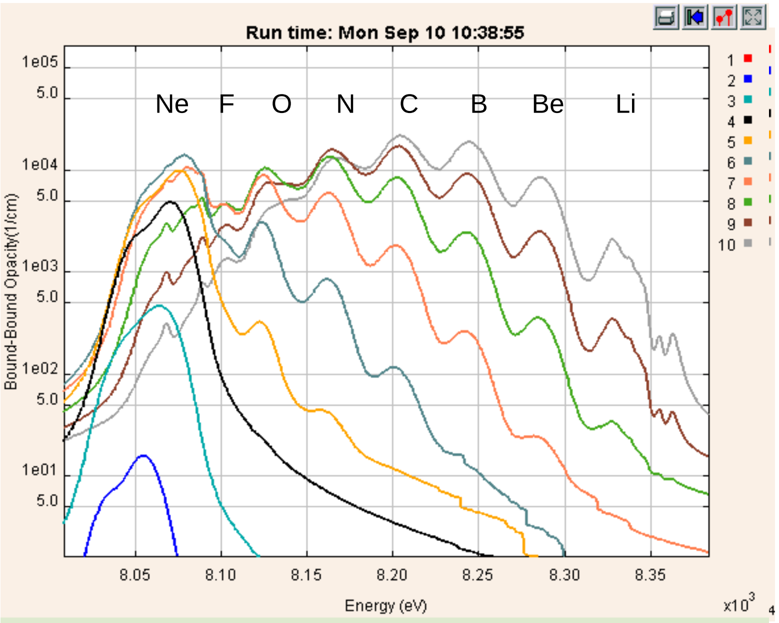
2. Ultrafast electron dynamics at solid-density
   [T. Kluge, C. Gutt, L. Huang et al., Phys. Plasmas 21, 033110 (2014)]

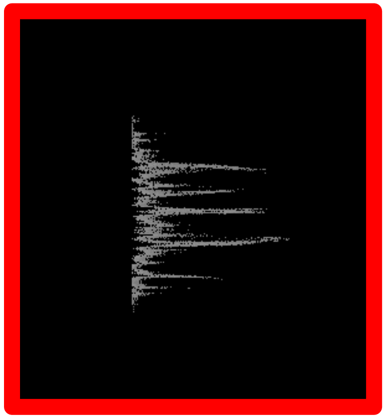
3. Ionization dynamics probed by resonant CXDI
   […work in progress…]

Example 3. Coherent imaging of ionization dynamics

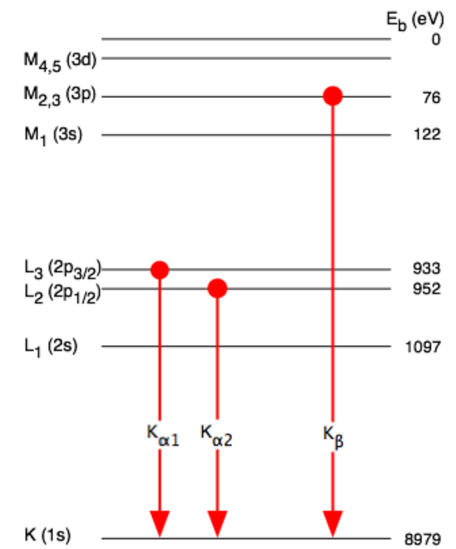
Free electron density related to ionization state, Z* (prior to ion motion)





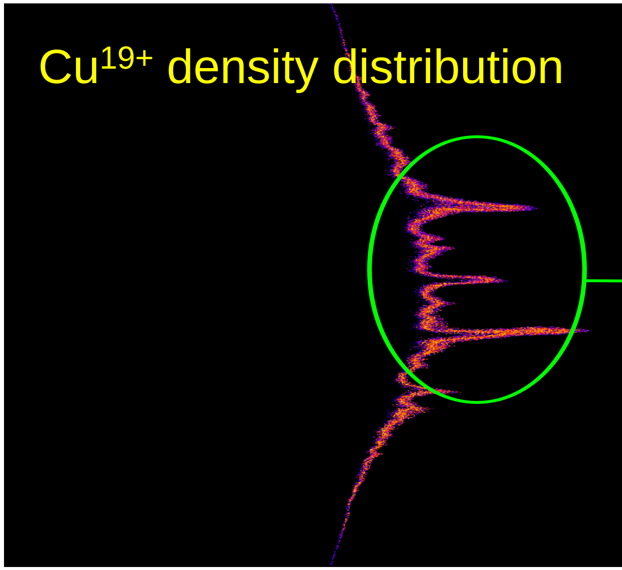


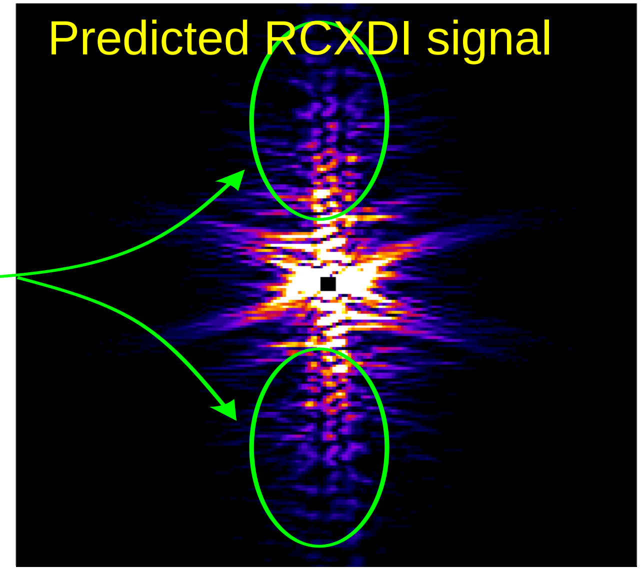
→ Isolate a specific charge-state by tuning to bound-bound resonance (e.g., Kα or Kβ)

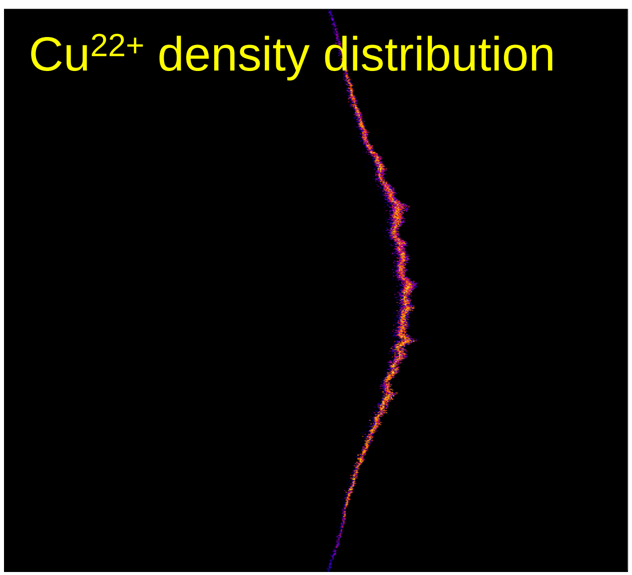


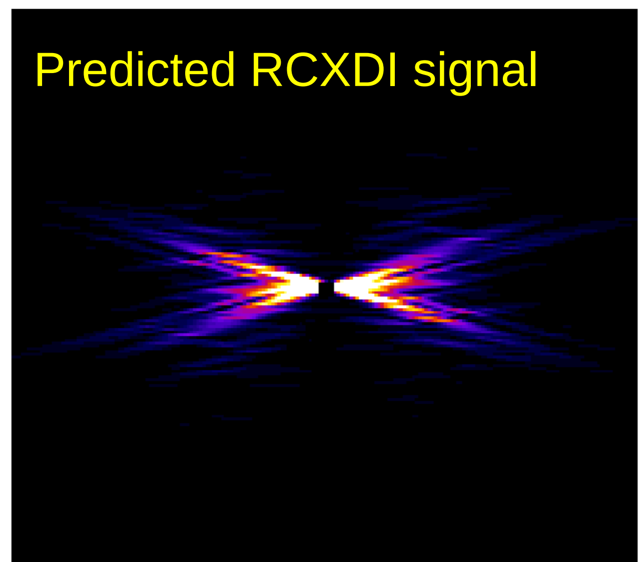
Simulation (L. Huang): 10^{20} W/cm^2, 50 fs → on 2.5 μm Cu

Example 3. Coherent imaging of ionization dynamics

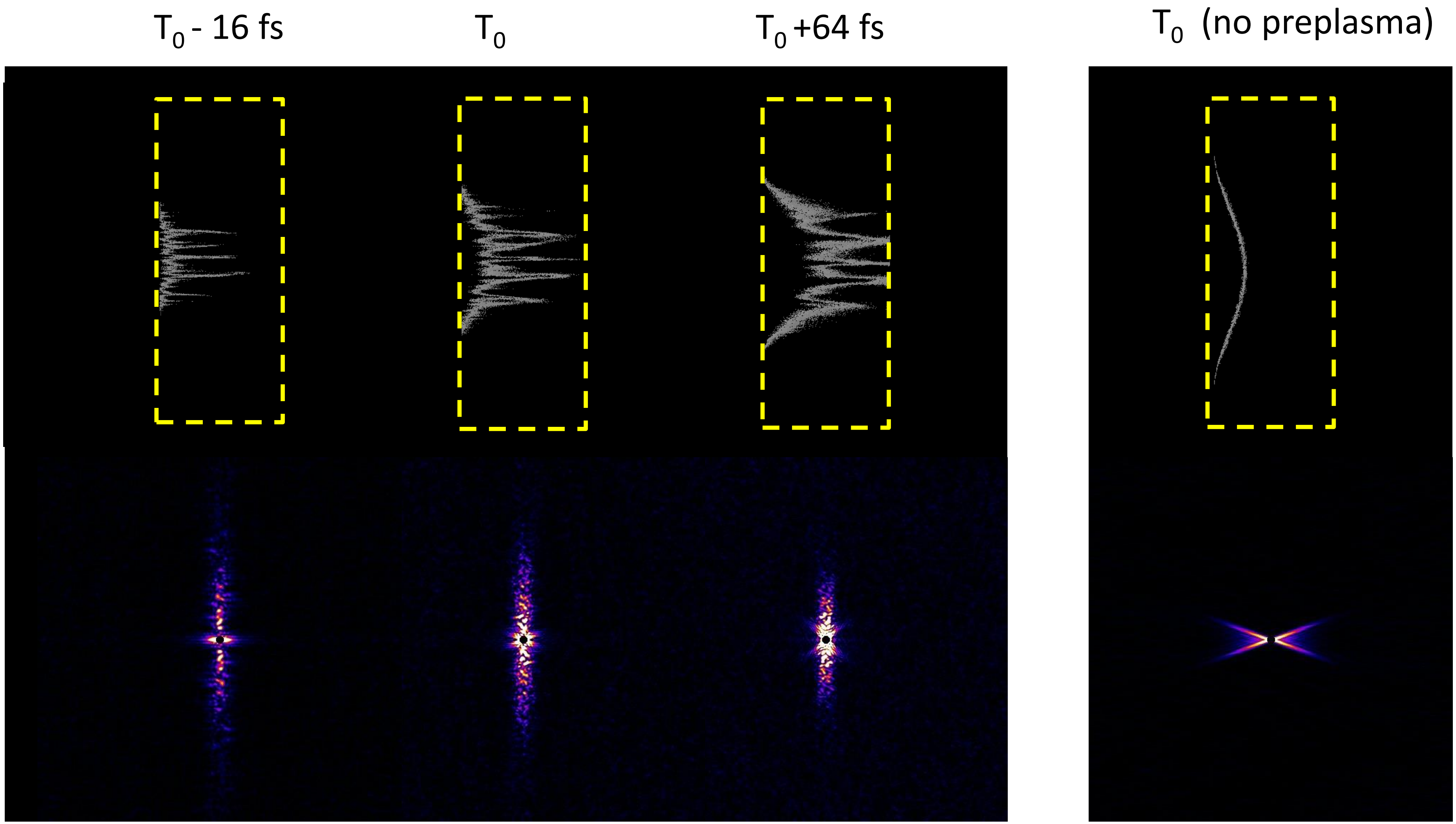








Example 3. Coherent imaging of ionization dynamics

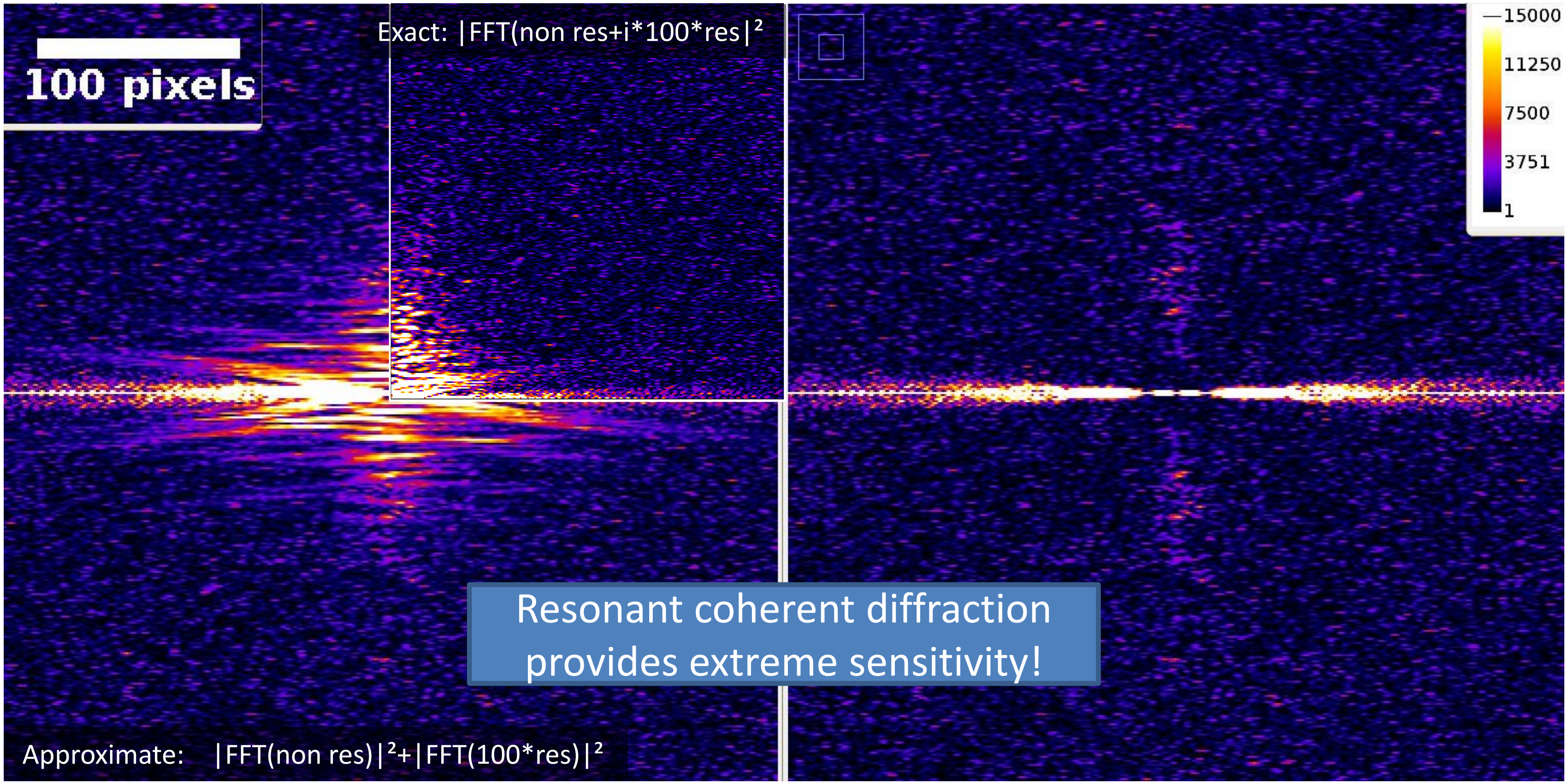


Example 3. Coherent imaging of ionization dynamics

$$I(\mathbf{q}) \sim |f_0(\mathbf{q}) + f' + if''|^2\ S_{ii}(\mathbf{q}) + Z_f\, S_{ee}(\mathbf{q})$$

for K-alpha resonance at Cu^{20+}, f” ~ 60 – 100 e/atom

with resonant @ Cu 20+ without resonant



XFEL: 8 keV, 10^{10} ph, 8.2x8.2 μm². Detector: 20 μm pixels @ 1 m.
Target: 1.6 μm thick, 6.4 μm deep (0.64 μm Cu). Solid density.

DRESDEN concept HZDR

HIBEF: Bringing New Communities to XFEL

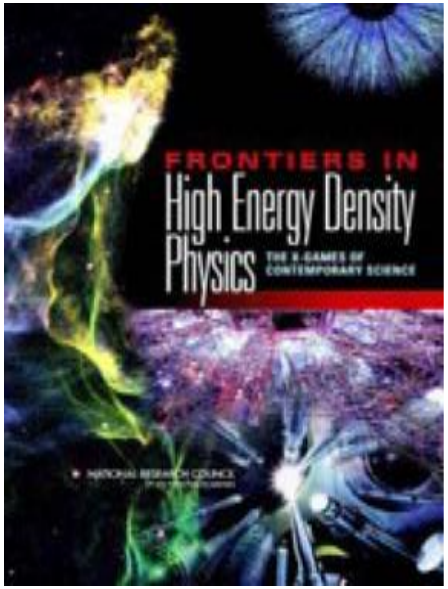
XFEL probing inside *dense plasma* or *dynamically compressed matter* (with time-resolved, brilliant, and fully coherent x-rays) will:

→ revolutionize our understanding of *laser-interactions* with matter, matter at *high pressure*, matter in *strong fields*, …

→ advance *high energy density* research at other facilities…

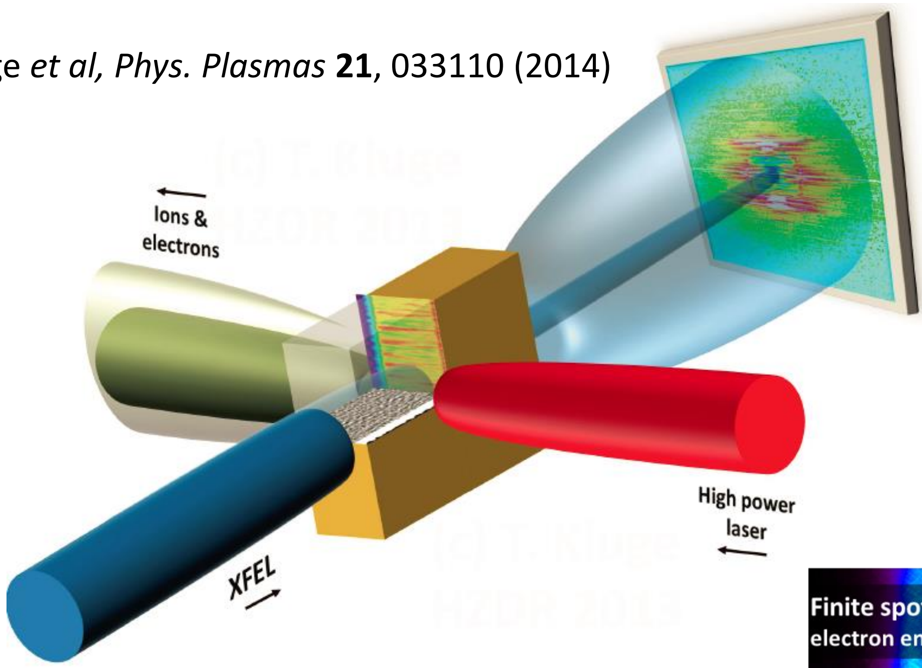
→ benefit *high-power laser* research worldwide, in many fundamental & applied areas…

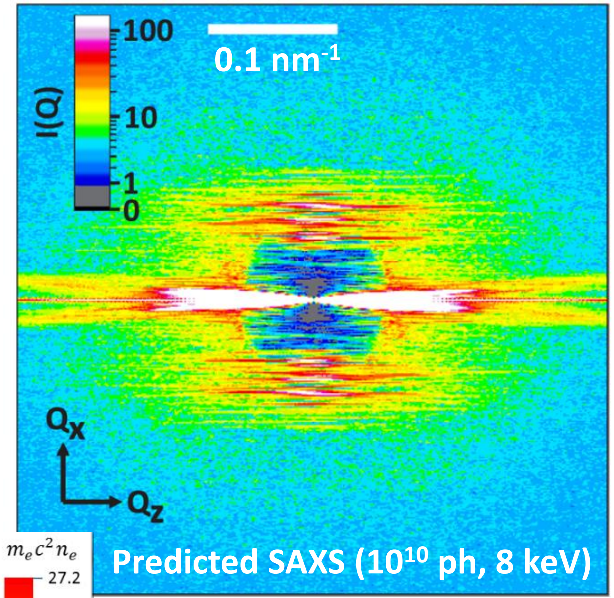
- *Compact accelerators*
- *Table-top light sources*
- *Radiation research in Oncology*
- *Fusion energy research*
- *Material dynamics & Ageing*
- *Ultrafast (fs-, as-) physics*
- *Geo- & planetary science*
- *Laboratory Astrophysics*

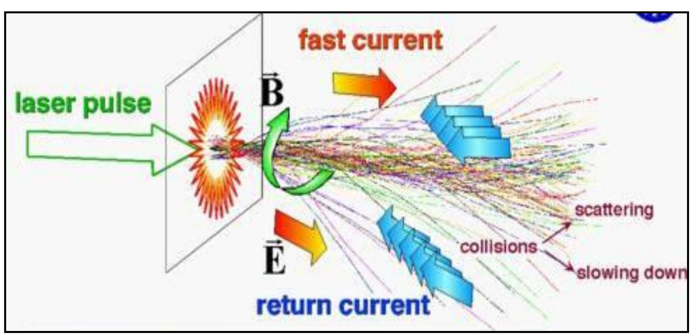


HIBEF: Relativistic laser-matter interactions

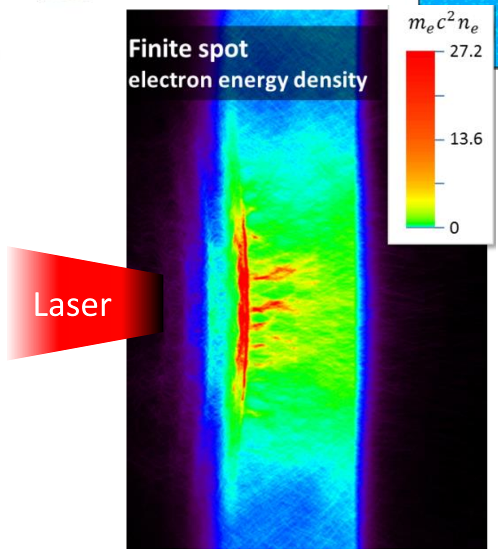
T. Kluge *et al*, *Phys. Plasmas* **21**, 033110 (2014)







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
- ....

Thank you for your attention…