Magnified X-Ray Phase-Contrast Imaging at the LCLS

DyCoMaX

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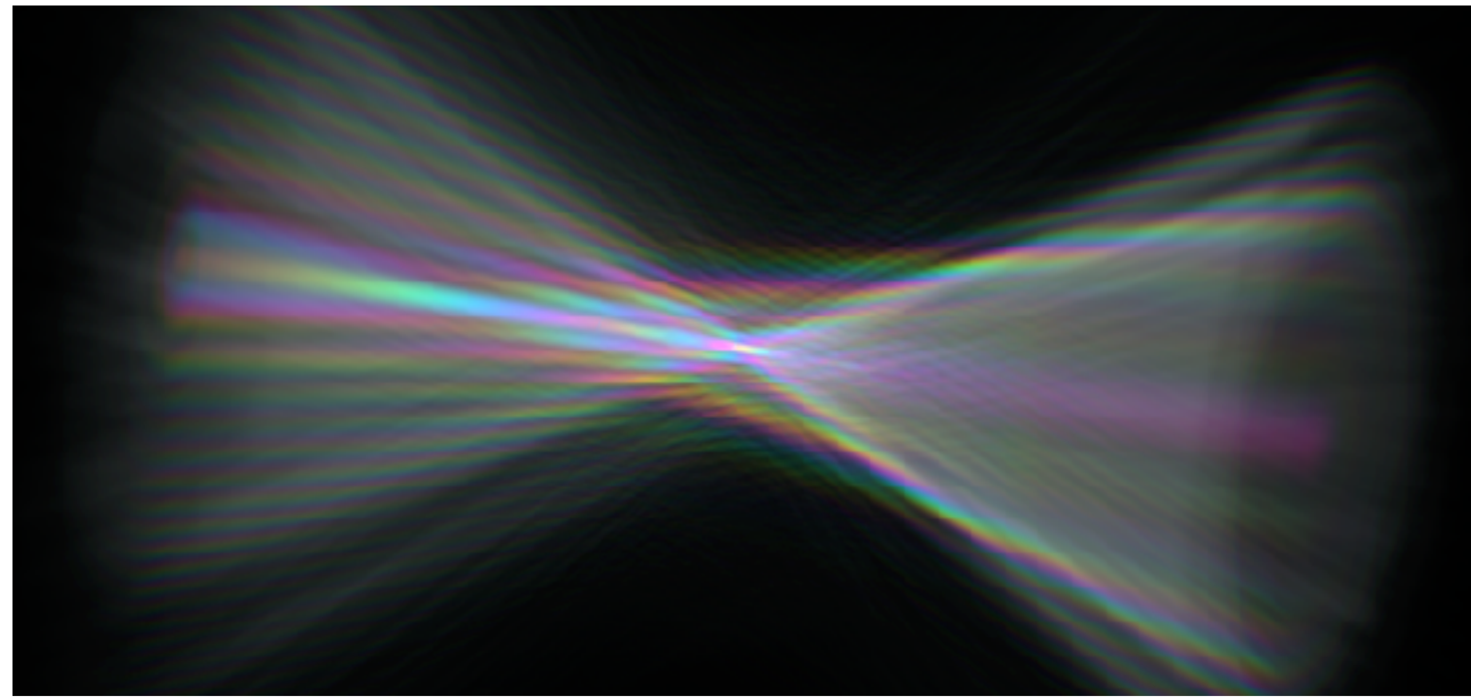
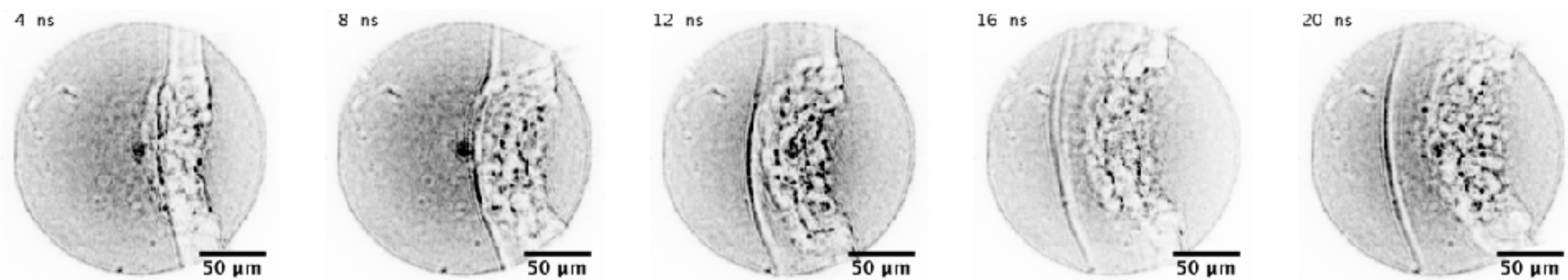




HELMHOLTZ | GEMEINSCHAFT

DESY

X-Ray Nanoscience and X-Ray Optics- and P06-groups

Prof. Dr. Christian G. Schroer (DESY and Uni HH)

Dr. Gerald Falkenberg (DESY - P06 beamline responsible)

S. Botta, D. Brückner, M. Döring, R. Döhrmann, J. Garrevoet, L. Grote, R. Hoppe, M. Kahnt, S. Klare, M. Lyubomirskiy, J. Reinhardt, D. Samberg, M. Scholz, A. Schropp, W. Schröder, F. Seiboth, M. Seyrich, K. Spiers, F. Wittwer

Scanning coherent X-ray micoscopy, using fluorescence (XRF), diffraction (SAXS, WAXS), absorption (XAS) and ptychographic (CXDI) contrast.

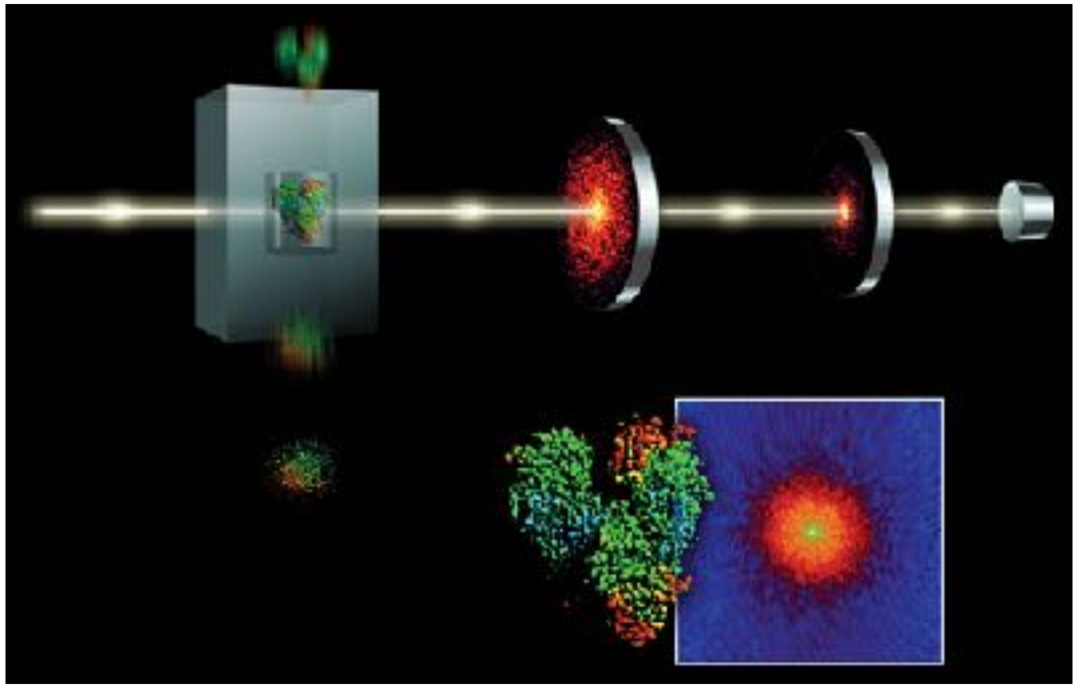
PETRA III (DESY, Hamburg)

ESRF (Grenoble)

LCLS (SLAC, Menlo Park)

High-Resolution Imaging at an XFEL

PPE-Fellowship: “Focusing X-ray free-electron laser beams for imaging and creating extreme conditions in matter”



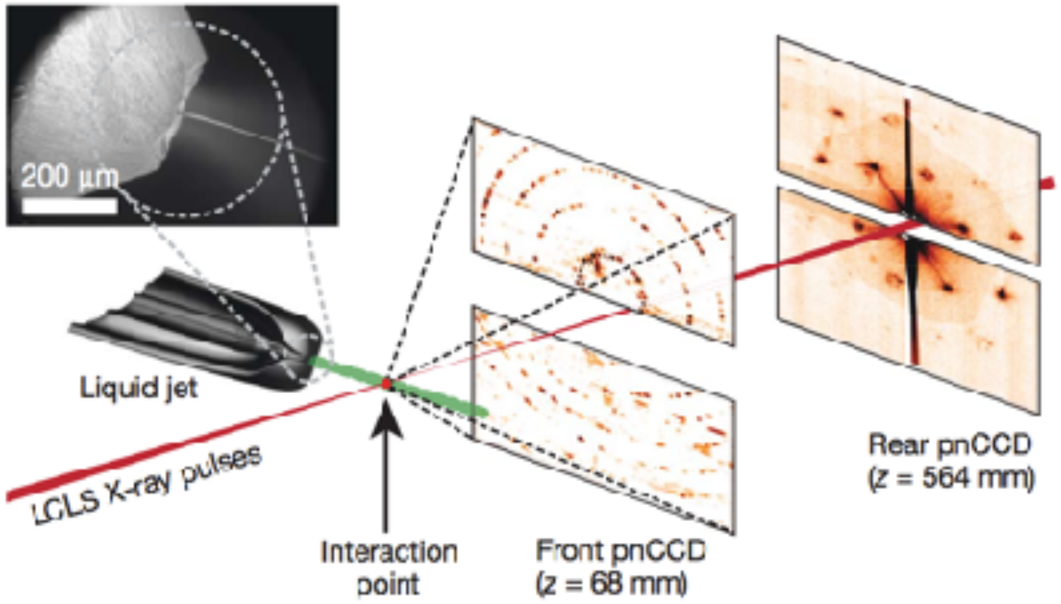
Advantages of an X-ray FEL

> short X-ray pulses (50 fs and below)
> high brilliance, intense beam
> highly coherent

➞ high temporal resolution (ultrafast)

Some experiments require high spatial resolution as well:

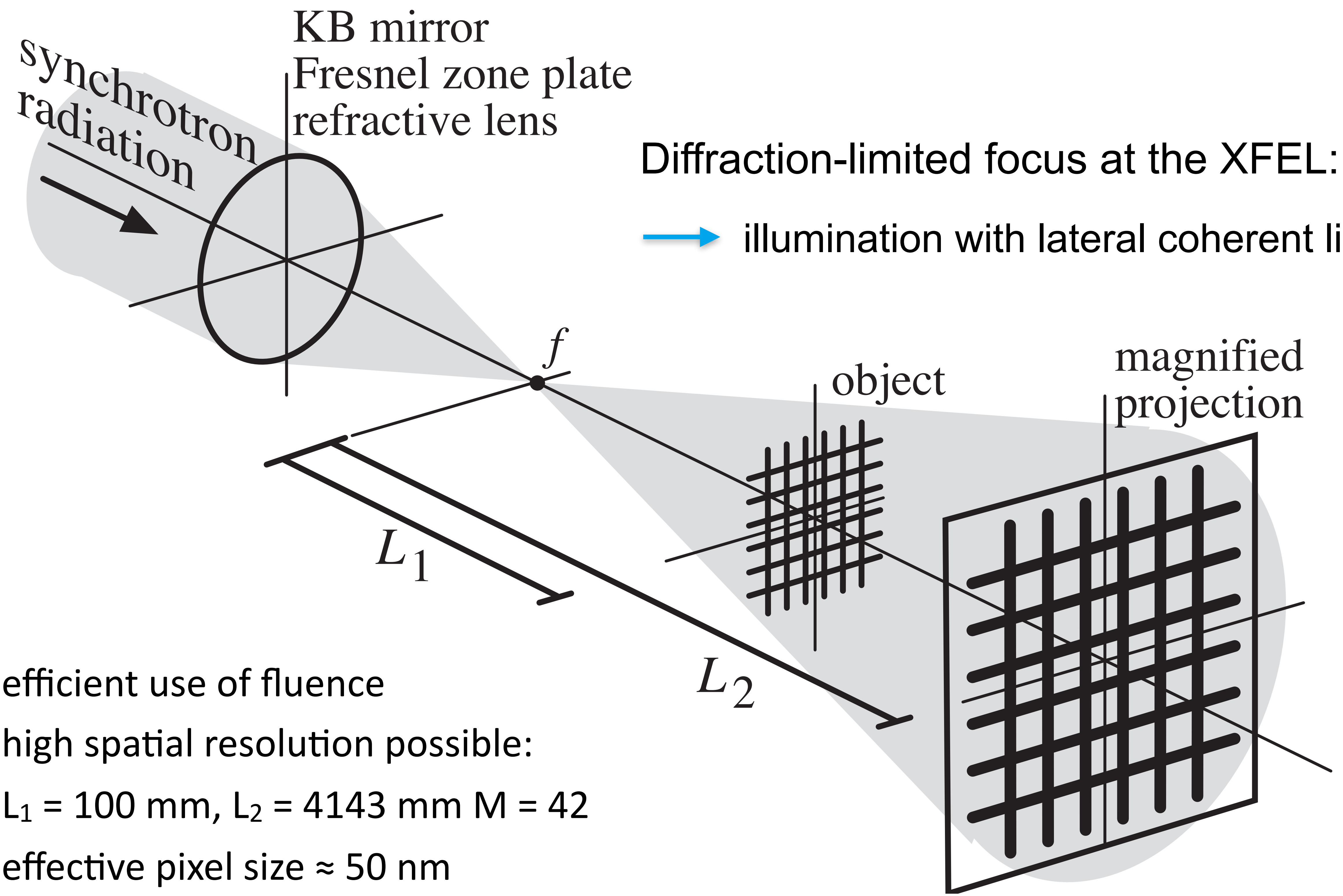
> diffraction imaging in reciprocal space
> magnified imaging in real space



H. N. Chapman et al., Nature **470**, 73-U81 (2011)

In either case, highest spatial resolution requires focusing the X-ray beam.

Magnified X-Ray Phase-Contrast Imaging



Diffraction-limited focus at the XFEL:

→ illumination with lateral coherent light

- efficient use of fluence
- high spatial resolution possible:
  L_1 = 100 mm, L_2 = 4143 mm M = 42
- effective pixel size ≈ 50 nm
- phase contrast: difficult to obtain quantitative results

Magnified X-Ray Imaging with Coherent Radiation

Imaging with curved wave field:

$$\psi_{z_0}(\vec{r}) = \frac{A}{\sqrt{r^2 + z_0^2}} e^{ik\sqrt{r^2+z_0^2}}$$

(spherical wave)

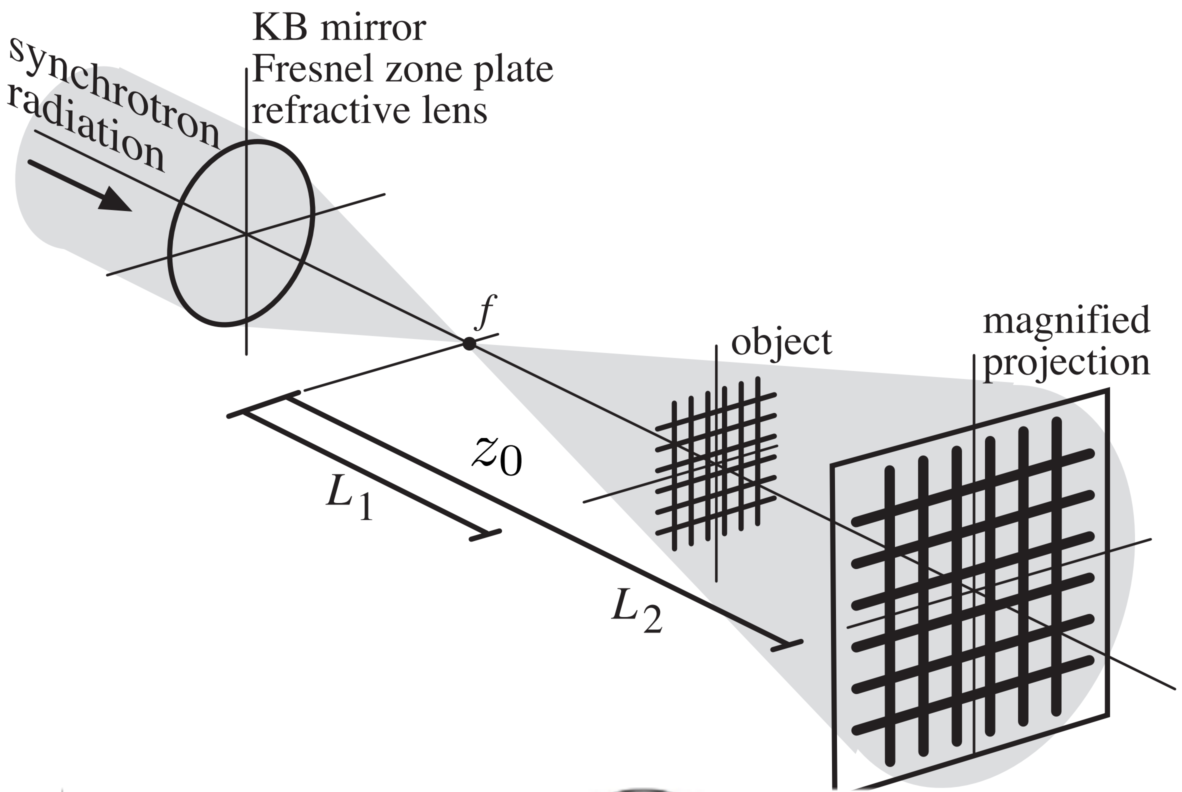
In paraxial approximation:

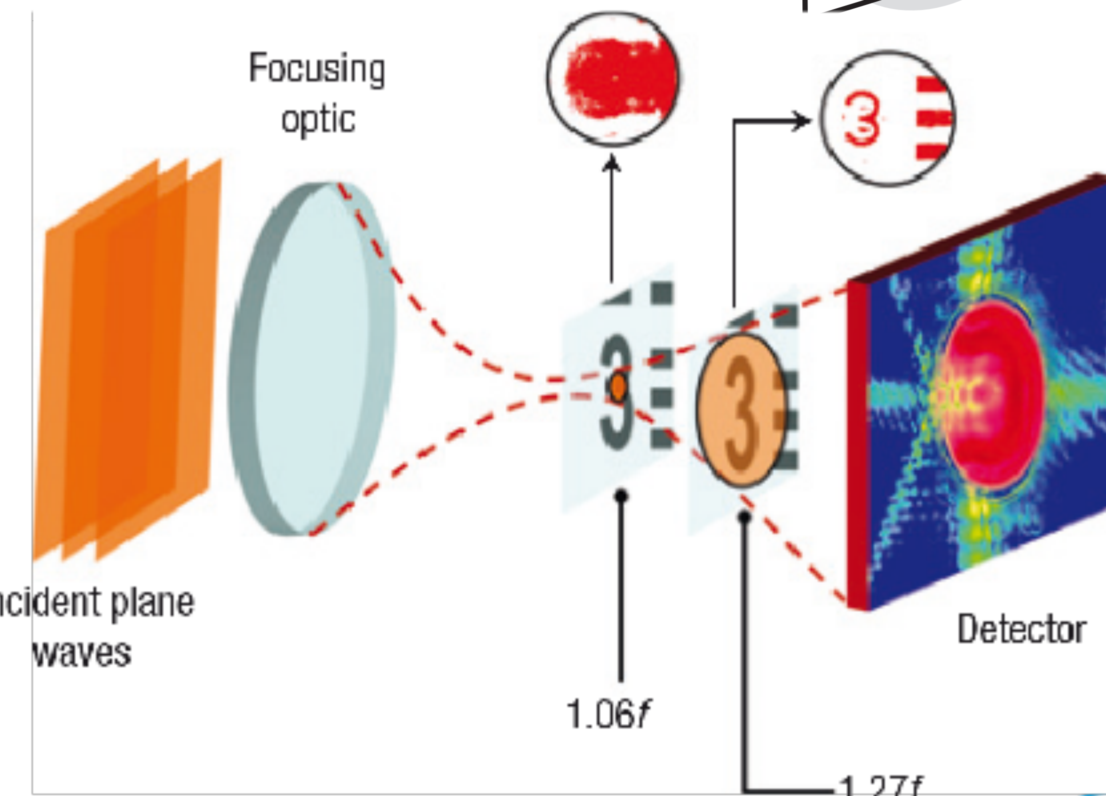
$$\psi_{z_0}(\vec{r}) = \frac{A}{z_0} e^{ik\frac{r^2}{2z_0}}$$

Thin object is modelled by a transmission function $T(\vec{r})$.

Wave front behind the sample:

$$\psi_{z_0+\delta}(\vec{r}) = \frac{A}{z_0} e^{ik\frac{r^2}{2z_0}} \cdot T(\vec{r})$$



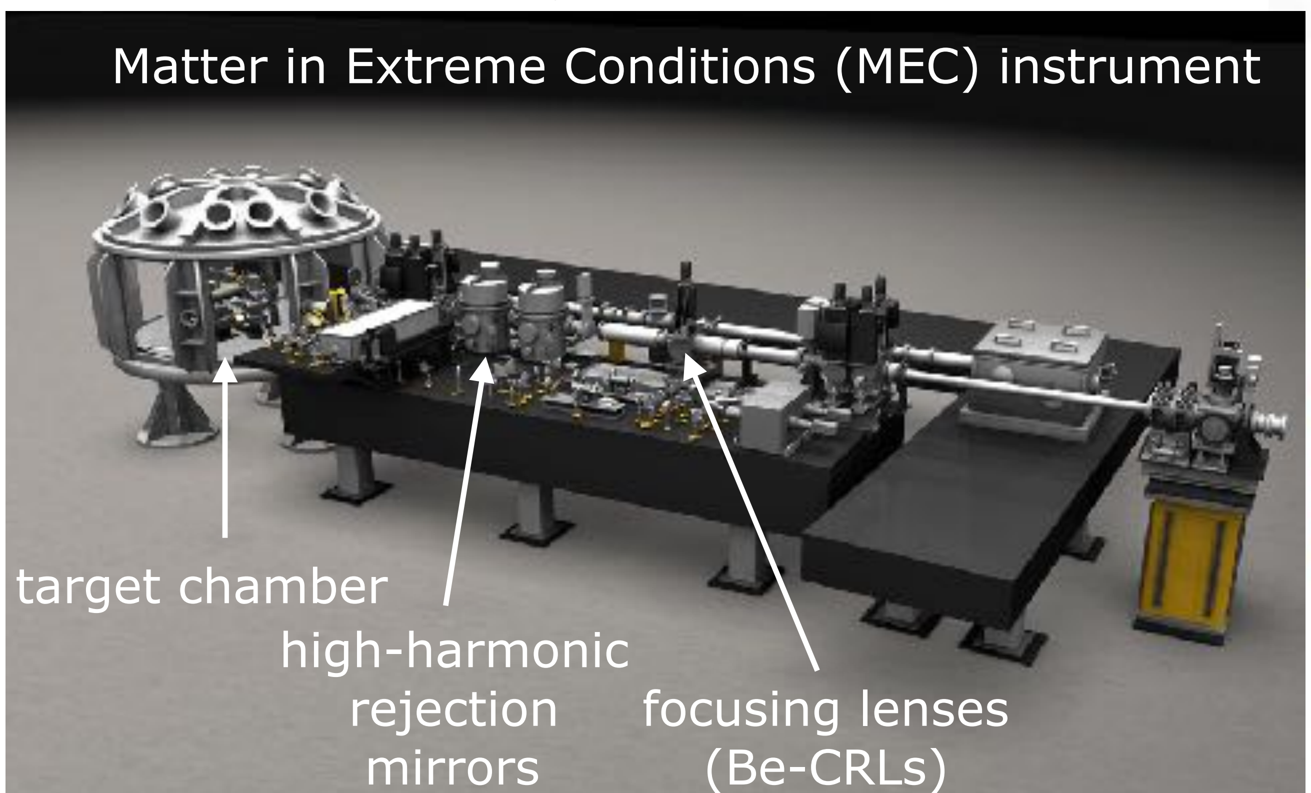


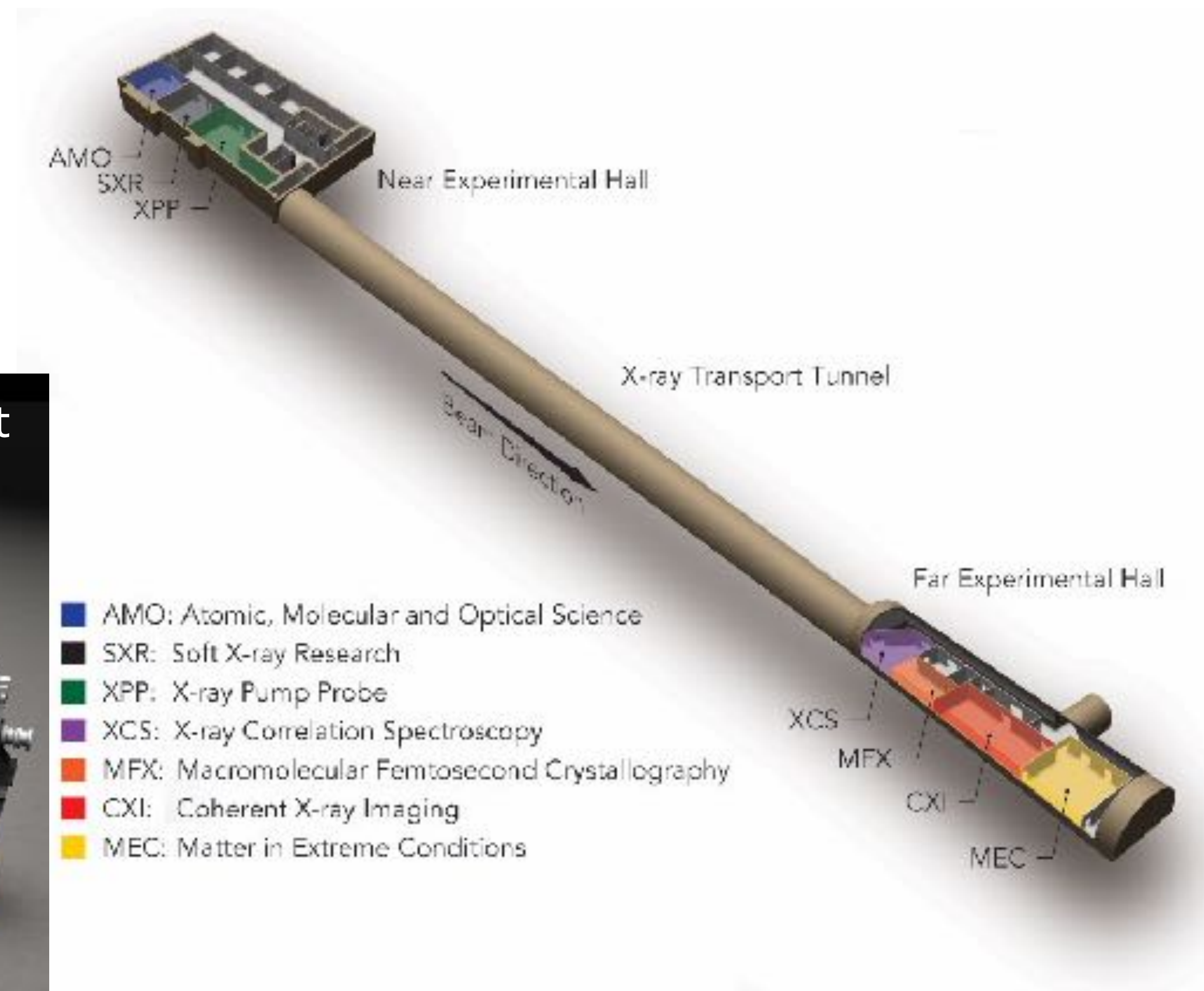
B. Abbey, et al., Nature Physics **4**, 394 (2008)

Linac Coherent Light Source (LCLS)

SLAC, Menlo Park

X-ray laser in operation at SLAC National Accelerator Laboratory since 2009 (Stanford University).





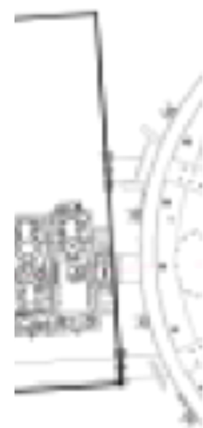
High-Power Optical Lasers at MEC

femtosecond laser

short pulse laser system

> wavelength: 800nm
> pulse length: ≤ 40fs
  (150ps uncompressed)
> maximum energy:
  150mJ per pulse
> repetiton rate: 10Hz
  Upgraded to 25TW!

TW-class short pulse laser for target driver and short pulse diagnostics

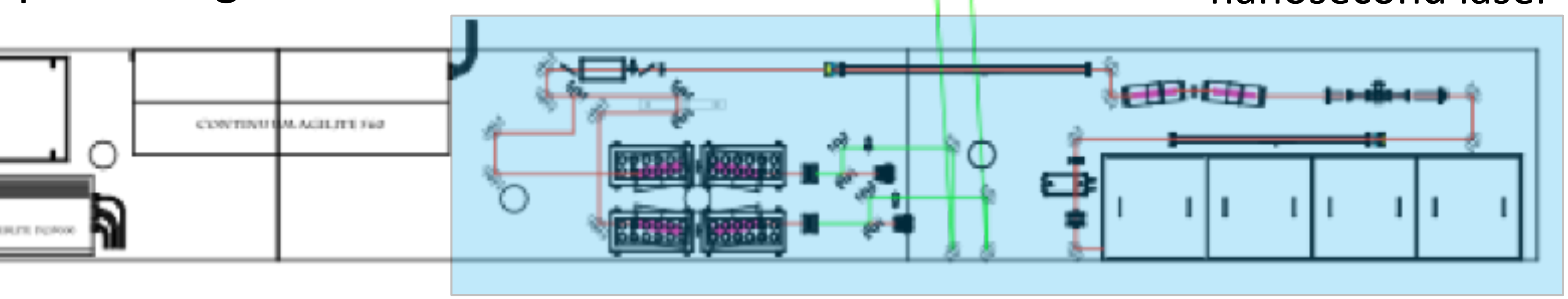


long pulse laser system

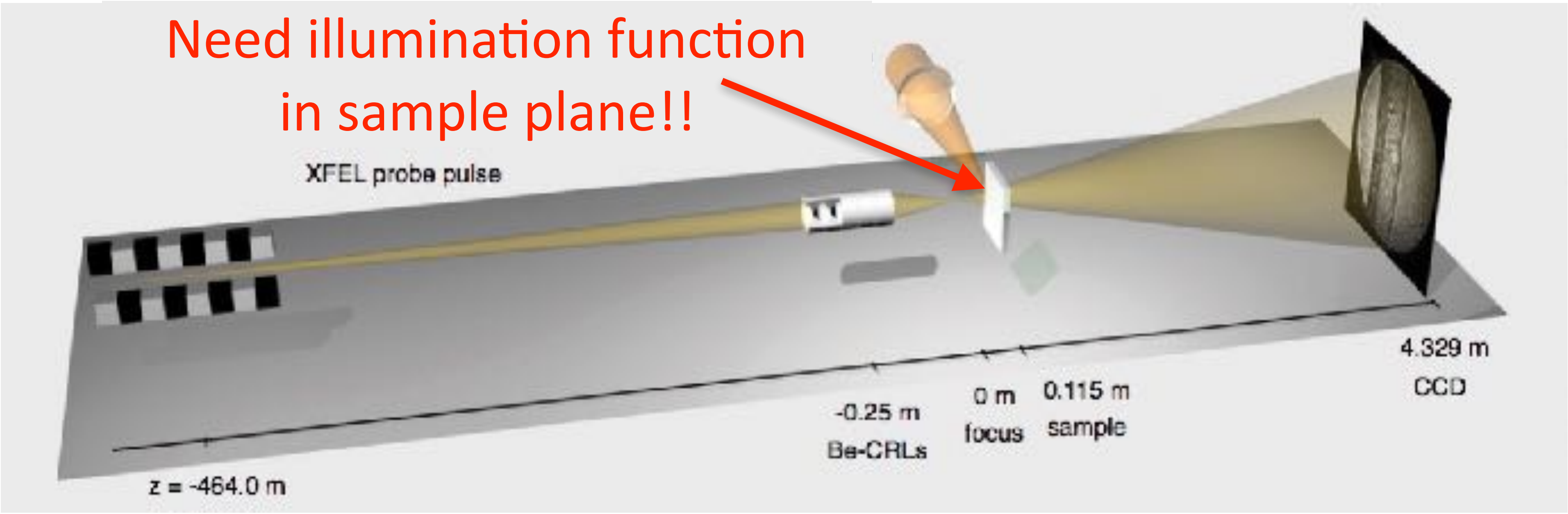
> wavelength: 527nm
> variable pulse length: 2-20ns
> variable temporal pulse shape
> energy: 4x10J
> one pulse every 10 minutes

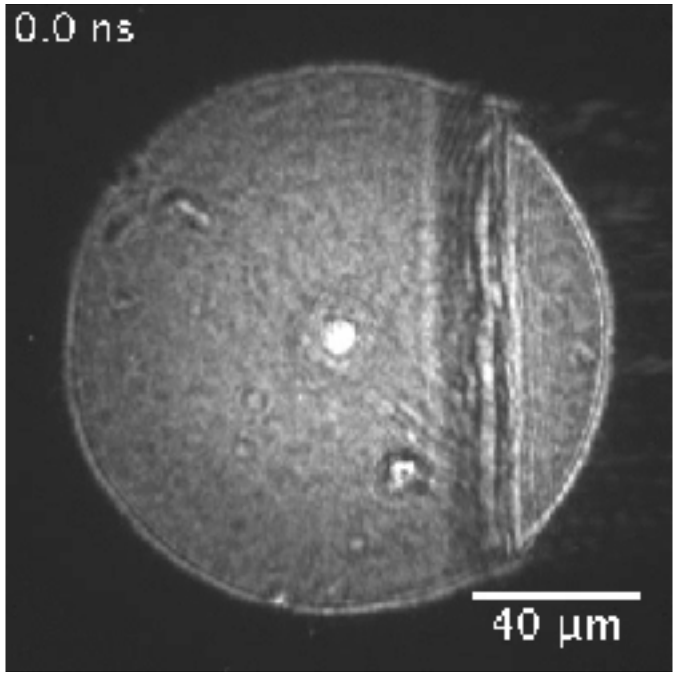
Multi-Joule high intensity shock driver for target interactions

nanosecond laser



Nanobeam Characterization by Ptychography

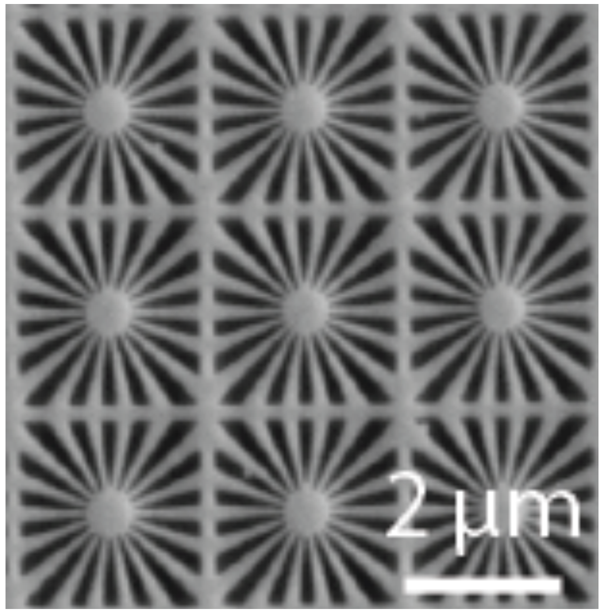




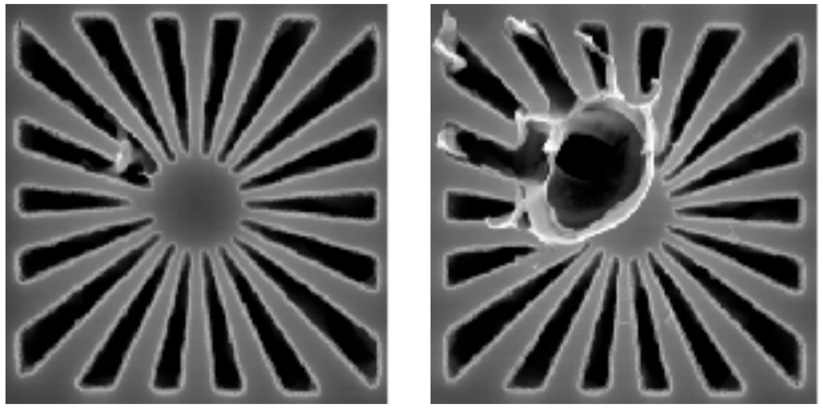
Using scanning coherent microscopy (ptychography) to determine the complex-valued illumination function.

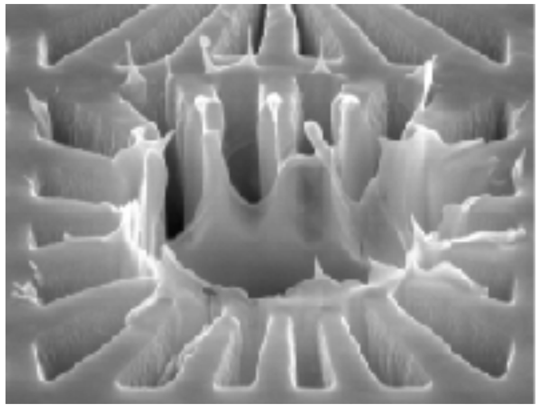
Tungsten test structures with 50 nm smallest feature size.

ptychography sample



SEM-image





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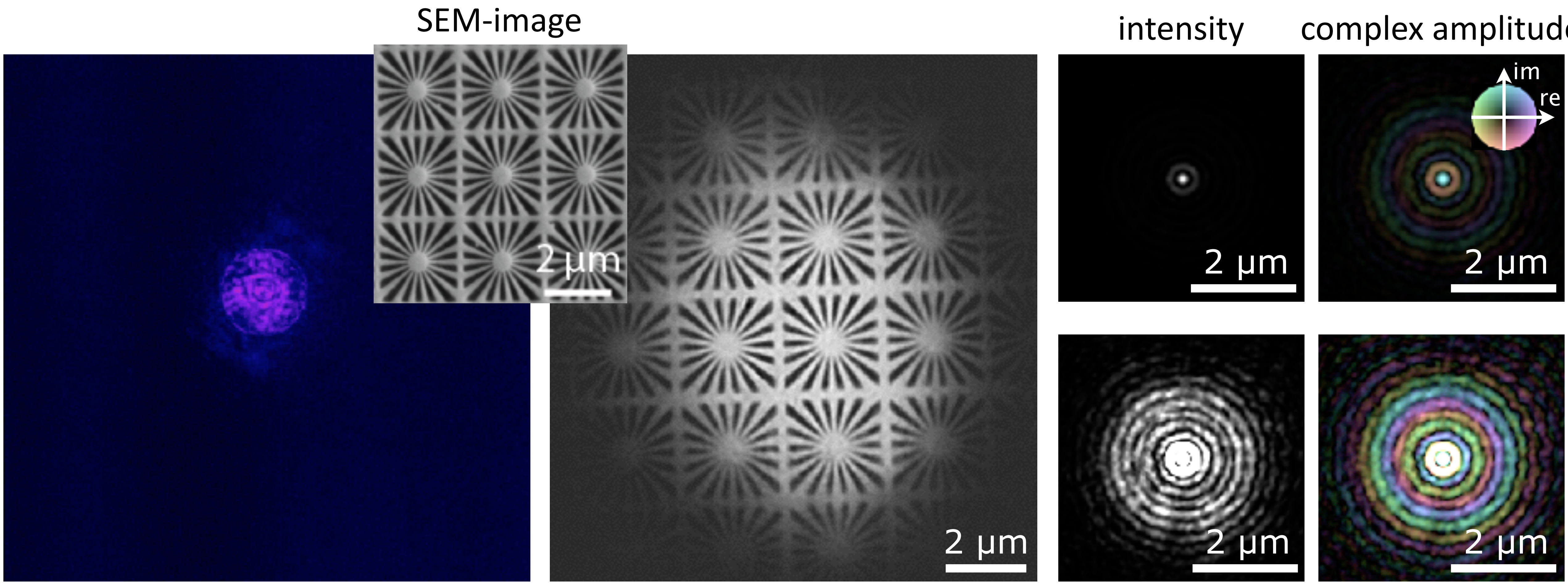


measured diffraction patterns from nano-structured sample

numerically retrieved object

intensity

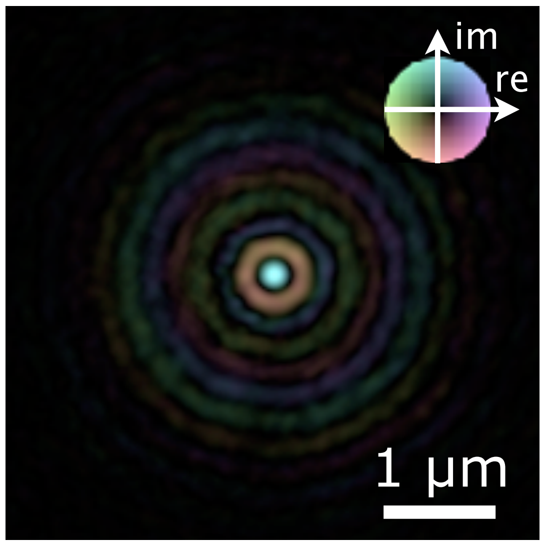
complex amplitude

- 125 nm (FWHM) central peak
- spherical aberration present, producing a series of side maxima
- important information required to improve the optics

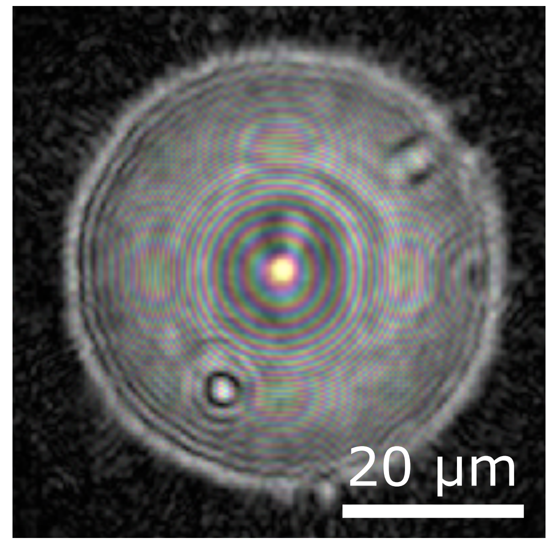
Schropp, A. et al., *Full spatial characterization of a nanofocused x-ray free-electron laser beam by ptychographic imaging*, Sci. Rep. **3**, 1633 (2013)

Influence of the Illumination Function

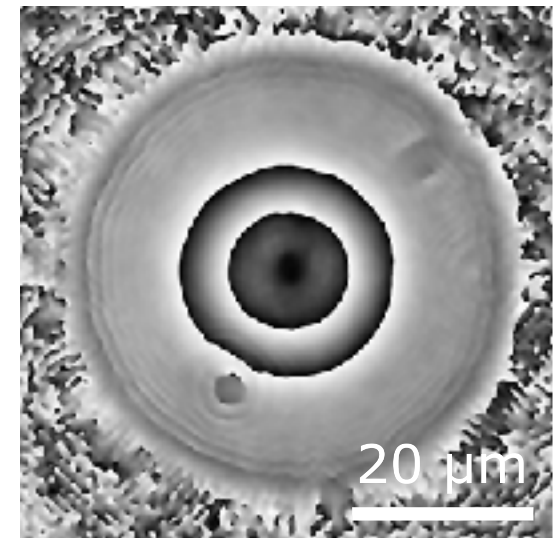
complex wave field

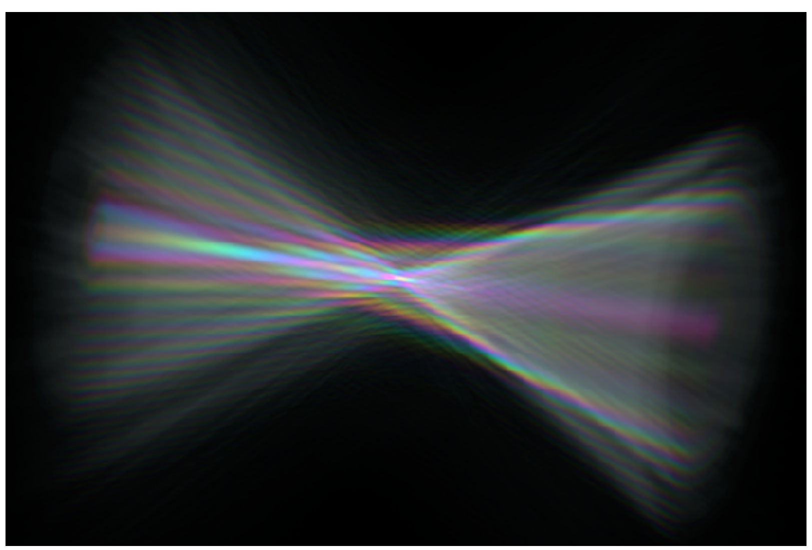


propagated into sample plane

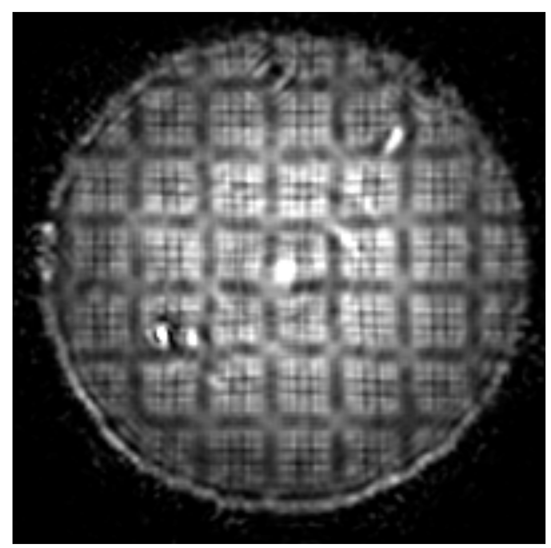


spherical wave subtracted

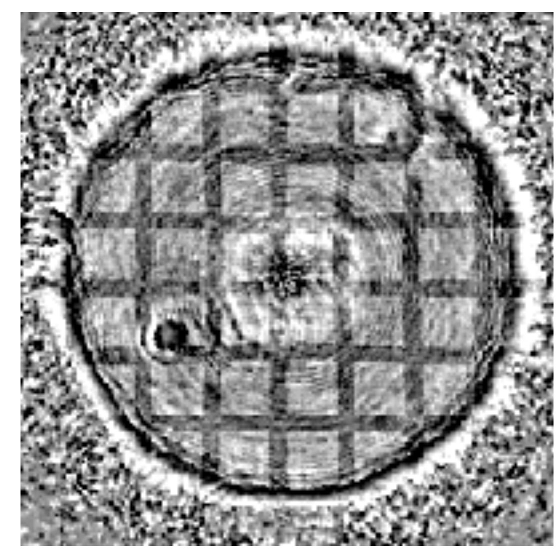




full caustic of nanofocused XFEL-beam

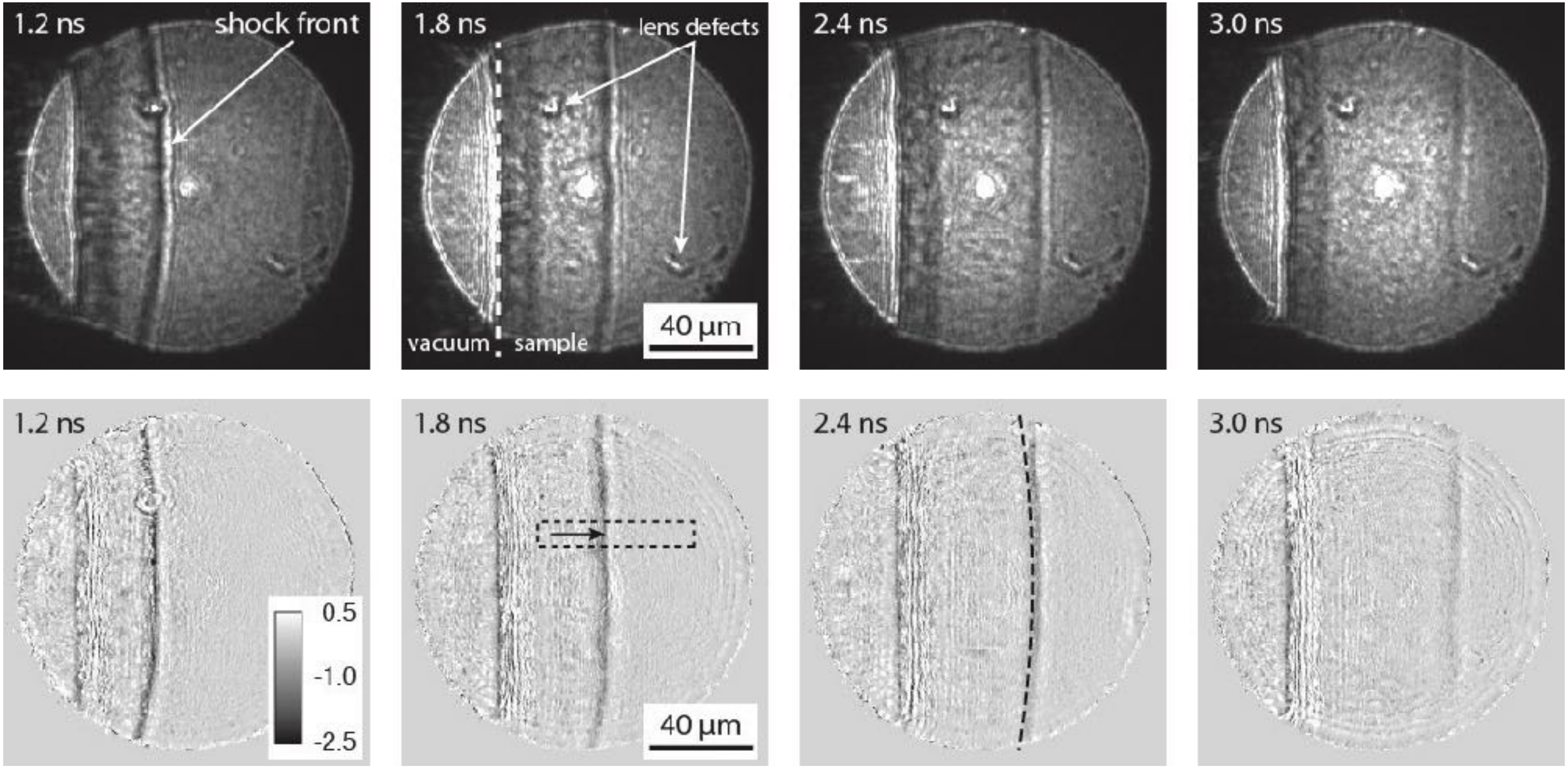


phase contrast image of Ni-mesh



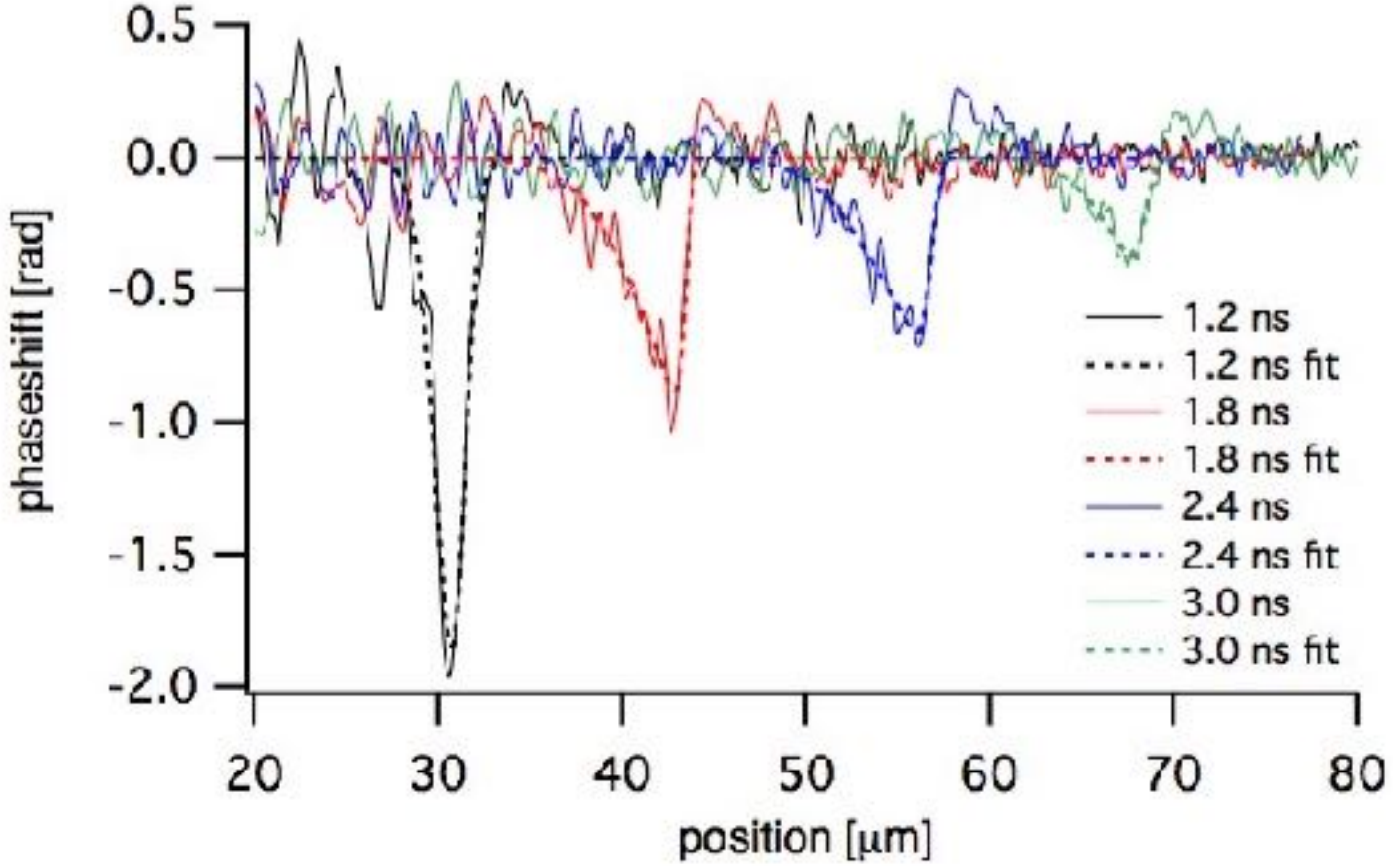
retrieved density without knowledge of illumination

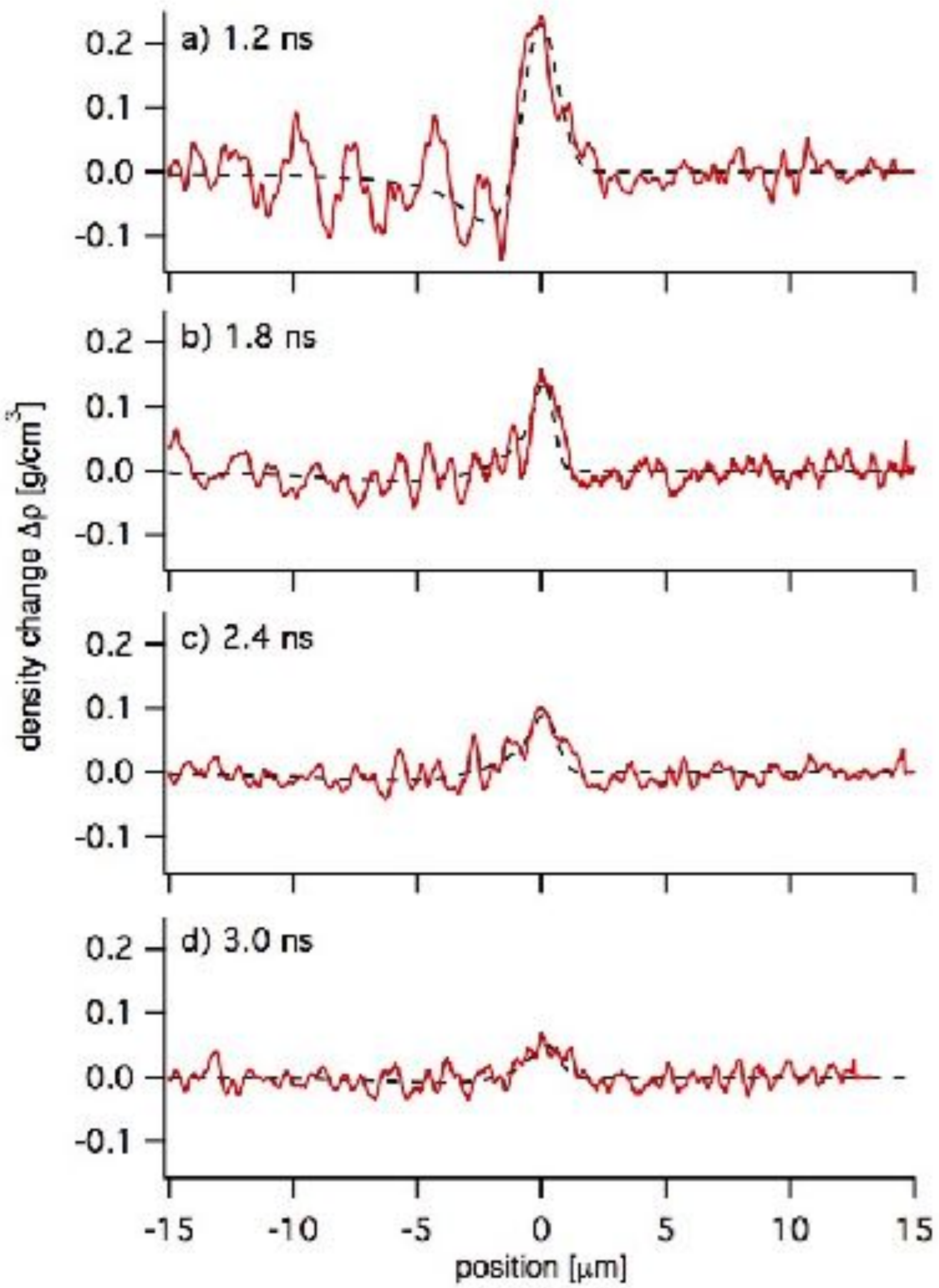
Transmission Function - Time Series



Tomographic Reconstruction of Density Profiles

Data contain structural information
with high spatial resolution!

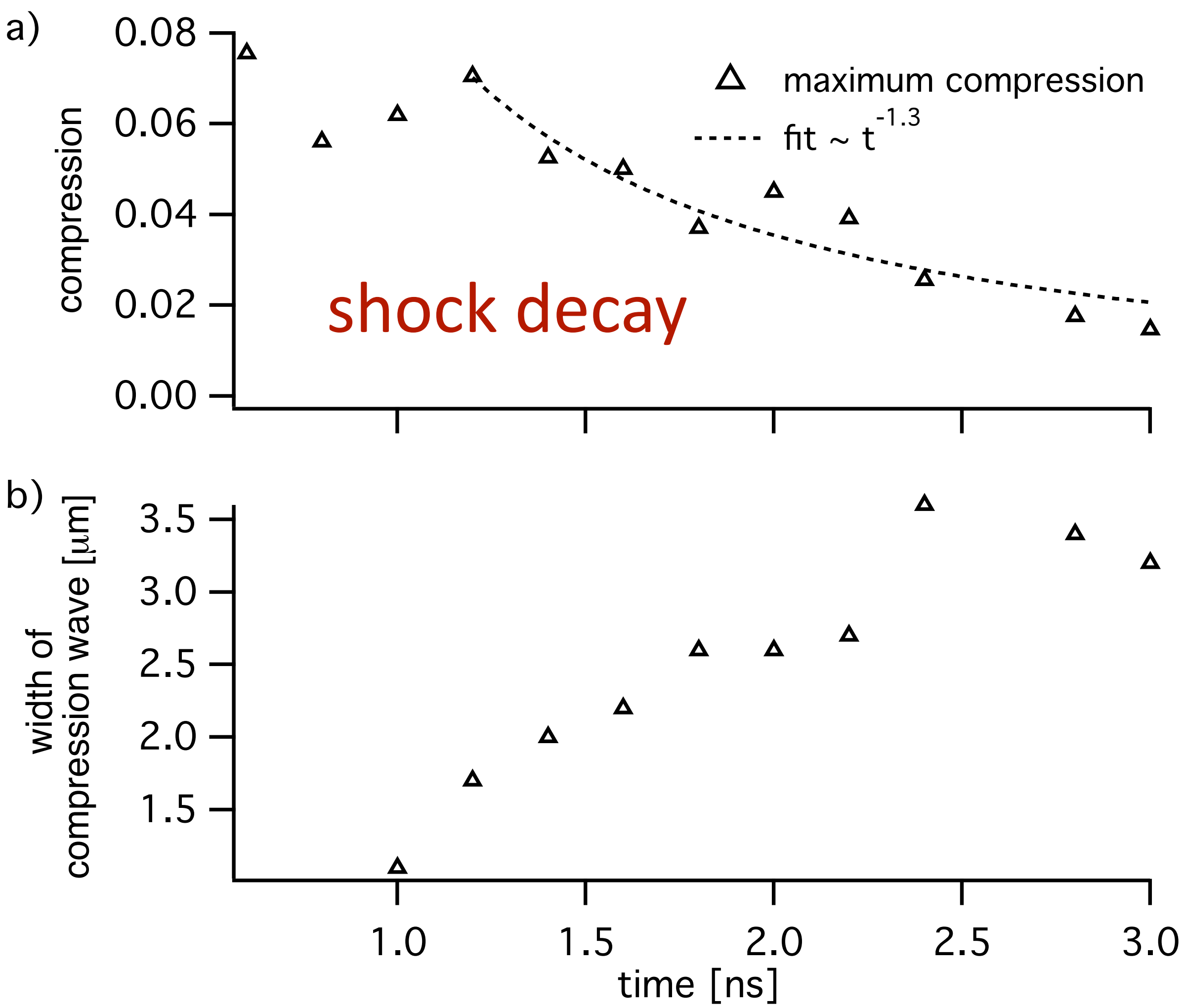


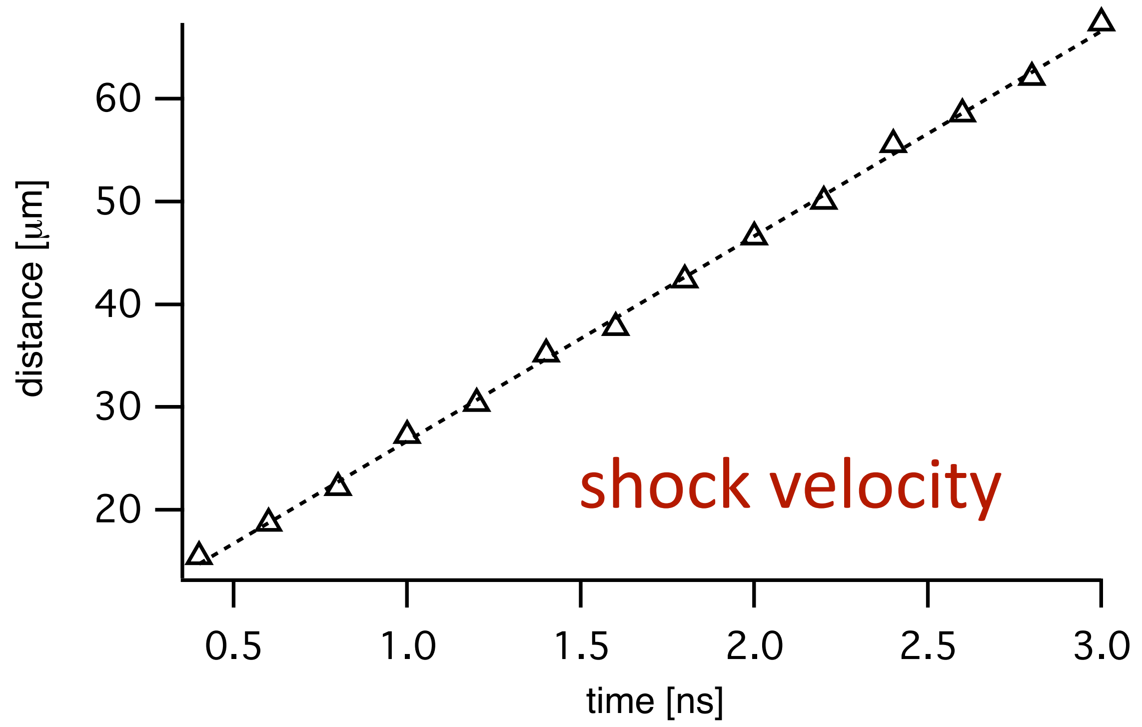


> quantitative values for the phase shift

Schropp, A. *et al.*, *Imaging Shock Waves in Diamond with Both High Temporal and Spatial Resolution at an XFEL*, Sci. Rep. **5**, 11089 (2015)

Elastic Wave in Diamond





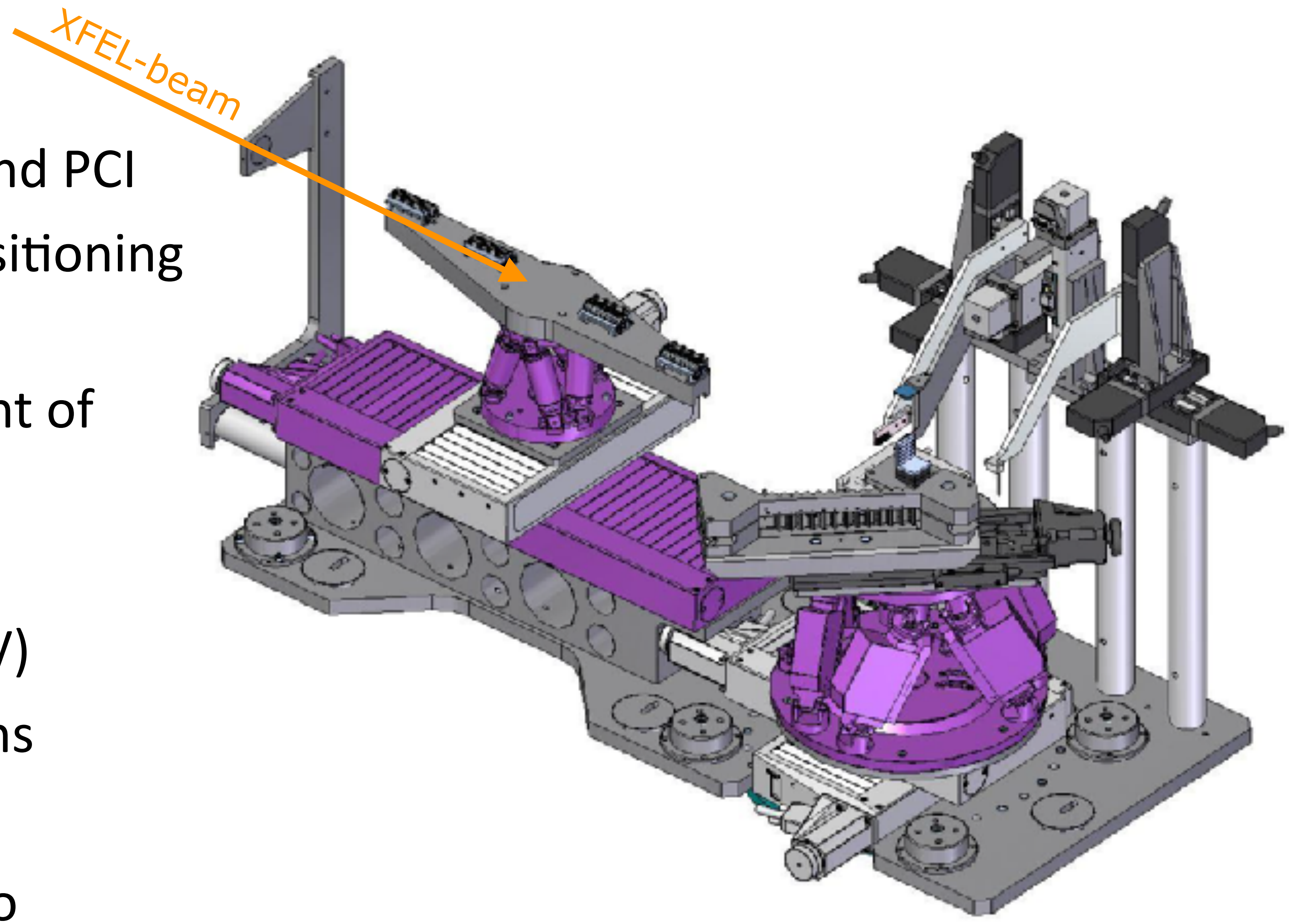
- shock velocity
- quantitative compression values
- spatial resolution of about 500nm (limited by the SASE bandwidth)

- characteristic time scale of shock decay
- PCI: high sensitivity of about 1% lattice compression (not visible in absorption!)

Schropp, A. *et al.*, *Imaging Shock Waves in Diamond with Both Temporal and Spatial Resolution at an XFEL*, Sci. Rep. **5**, 11089 (2015)

Nanofocusing Setup at MEC (PCI-Setup)

- combines ptychography and PCI
- improved stability and positioning accuracy
- hexapods for the alignment of Be-CRLs and sample
- long travel range for the alignment of Be-CRLs (FOV)
- cleaning aperture after lens
- beam stop
- compact design in order to enable a fast experimental set up



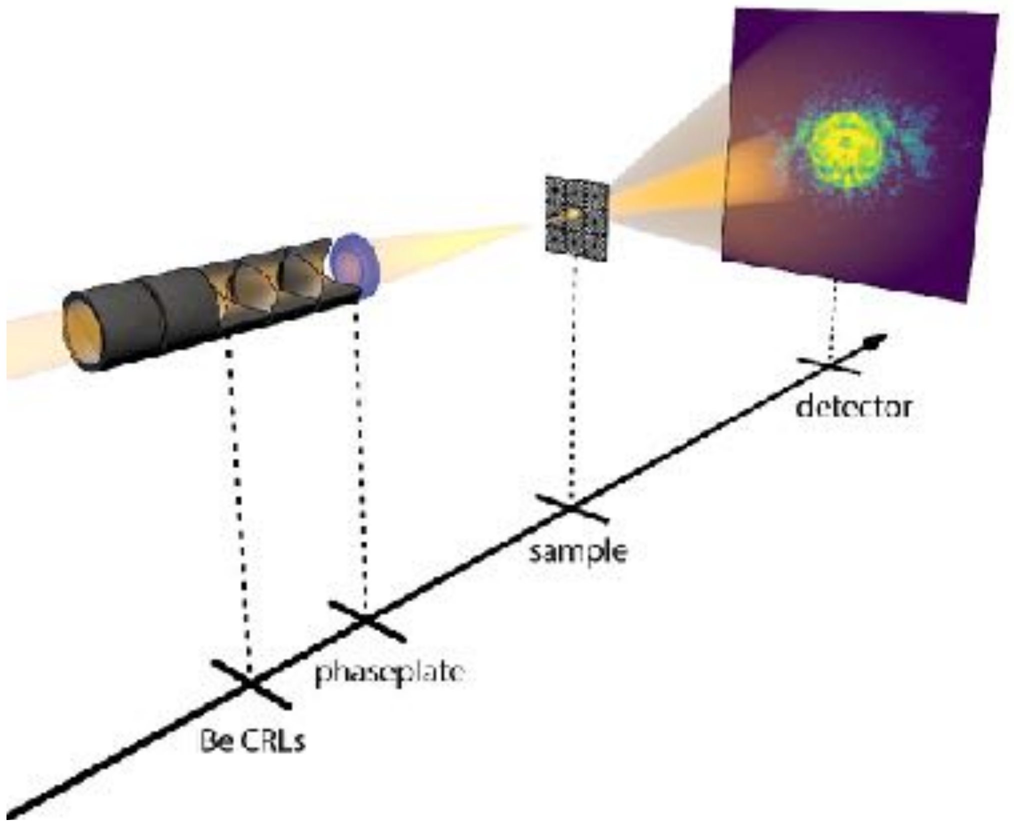
Will be redesigned and implemented at the MID- and HED-instrument of the European XFEL!

B. Nagler, *et al.*, *The phase-contrast imaging instrument at the matter in extreme conditions endstation at LCLS*, Rev. Sci. Instrum. **87**, 103701 (2016)

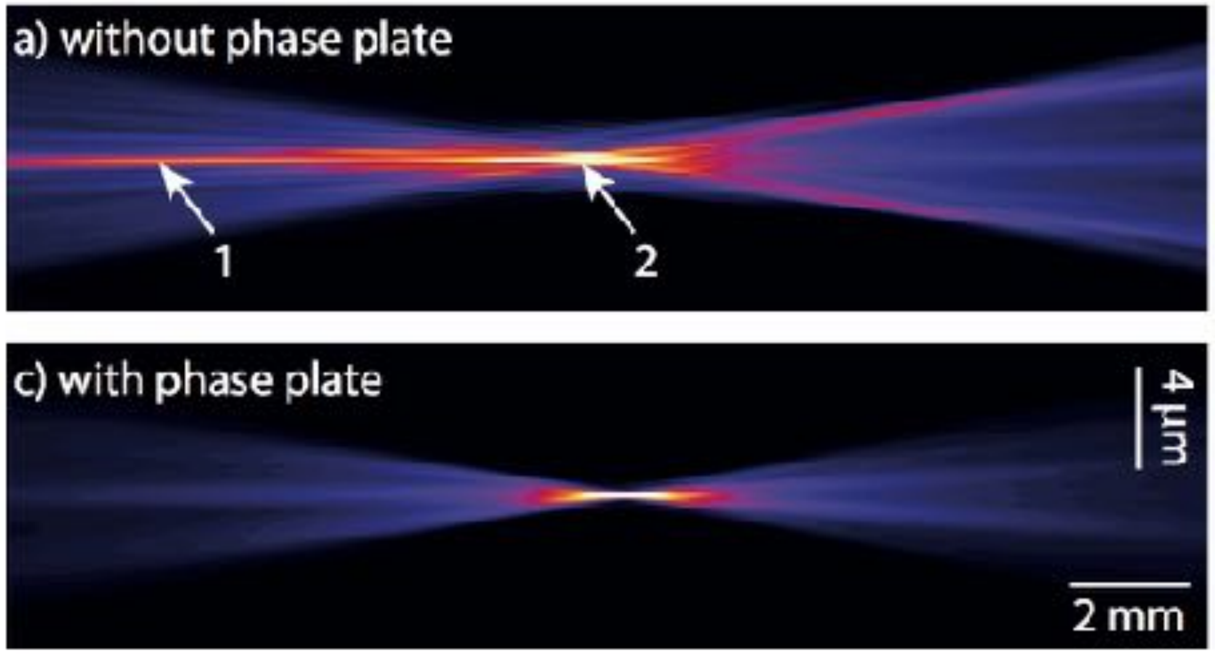
A. Schropp, *et al.*, *Developing a platform for high-resolution phase contrast imaging of high pressure shock waves in matter*, Proc. of SPIE, Vol. **8504**, 85040F (2012)

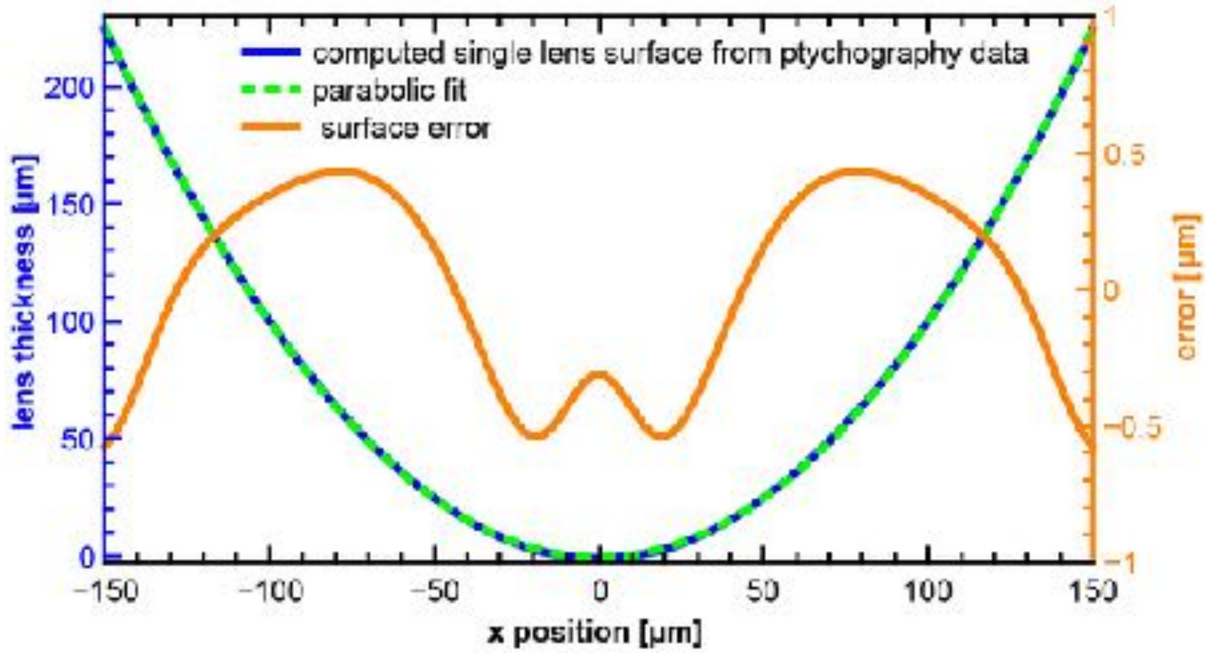
Perfect X-Ray Focusing

F. Seiboth *et al.*, "Perfect X-ray focusing via fitting corrective glasses to aberrated optics", Nat. Commun. **8**, 14623 (2017)



- Shape errors of single Be-CRLs are smaller than 500nm! Extremely challenging to improve!
- Corrective phase plate for the whole stack of the Be-lens relaxes the manufacturing requirements.
- Diffraction-limited and aberration-free X-ray focusing possible by inserting an additional phase plate made to measure.





XFEL vs Synchrotron Radiation — Peak Brilliance

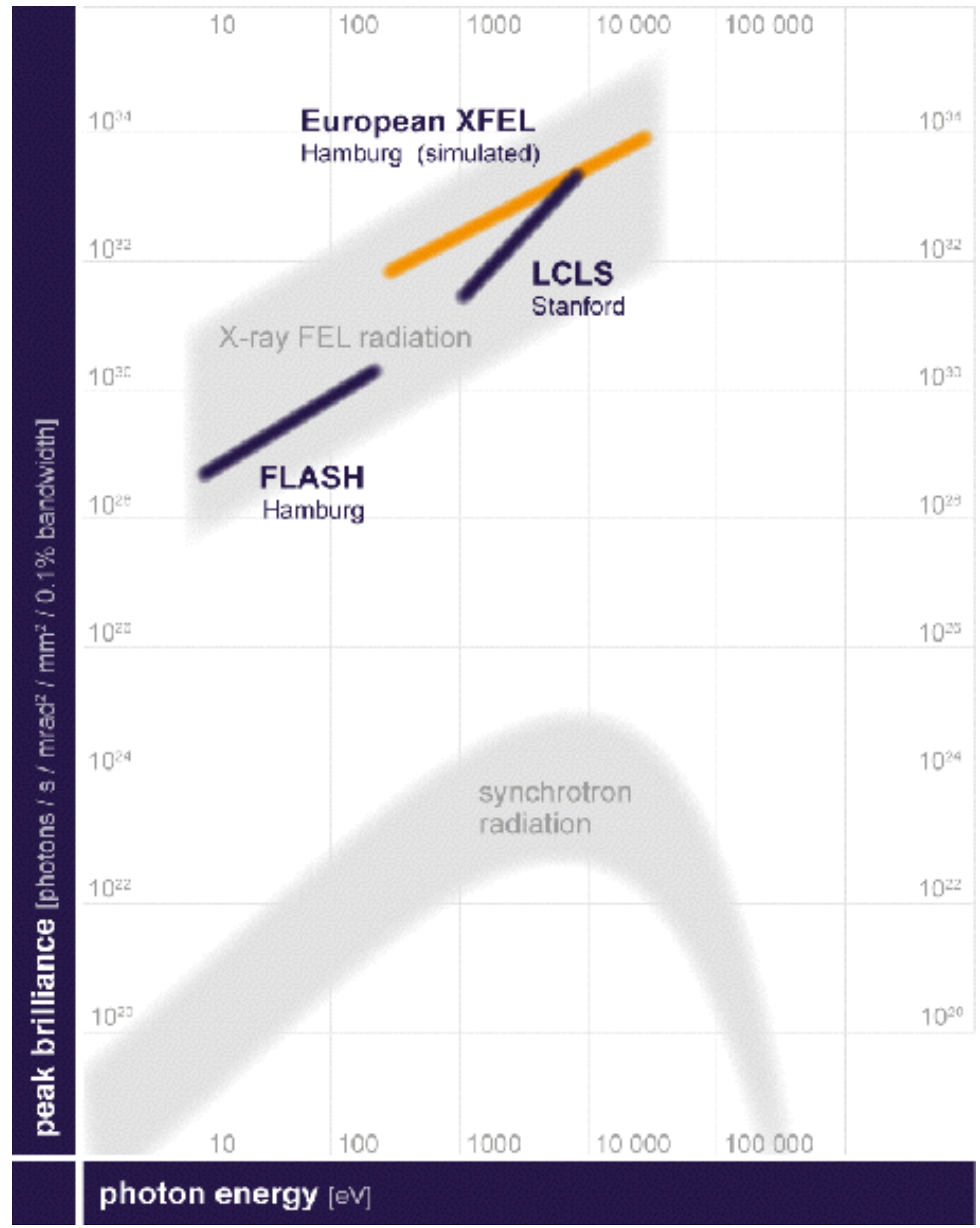
XFEL

- Time structure ≈ 100 fs
- Photon flux ≈ 10^{12} photons/pulse

Synchrotron Radiation

- Time structure ≈ 100 ps
- Photon flux ≈ 10^{9} photons/bunch

- Shocks propagate at about 10 km/s and faster, i.e., shock front moves about 1 nm within the XFEL-pulse duration and about 1 µm during a single synchrotron X-ray pulse.
- Shock front can be sharp on the atomic length scale.



http://www.xfel.eu/overview/in_comparison/

XFEL vs Synchrotron Radiation — Peak Brilliance

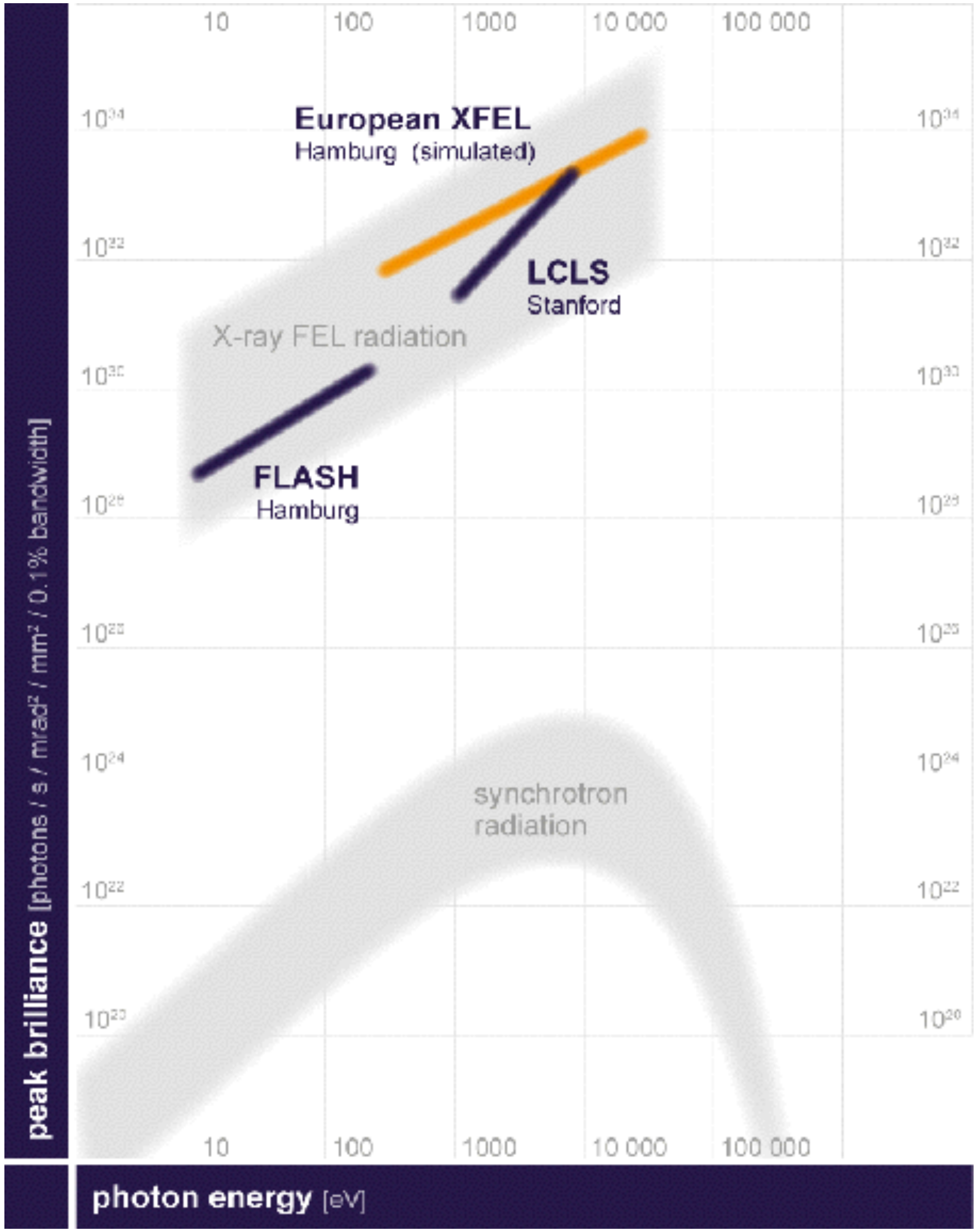
XFEL

- Time structure ≈ 100 fs
- Photon flux ≈ 10^{12} photons/pulse

Synchrotron Radiation

- Time structure ≈ 100 ps
- Photon flux ≈ 10^{9} photons/bunch

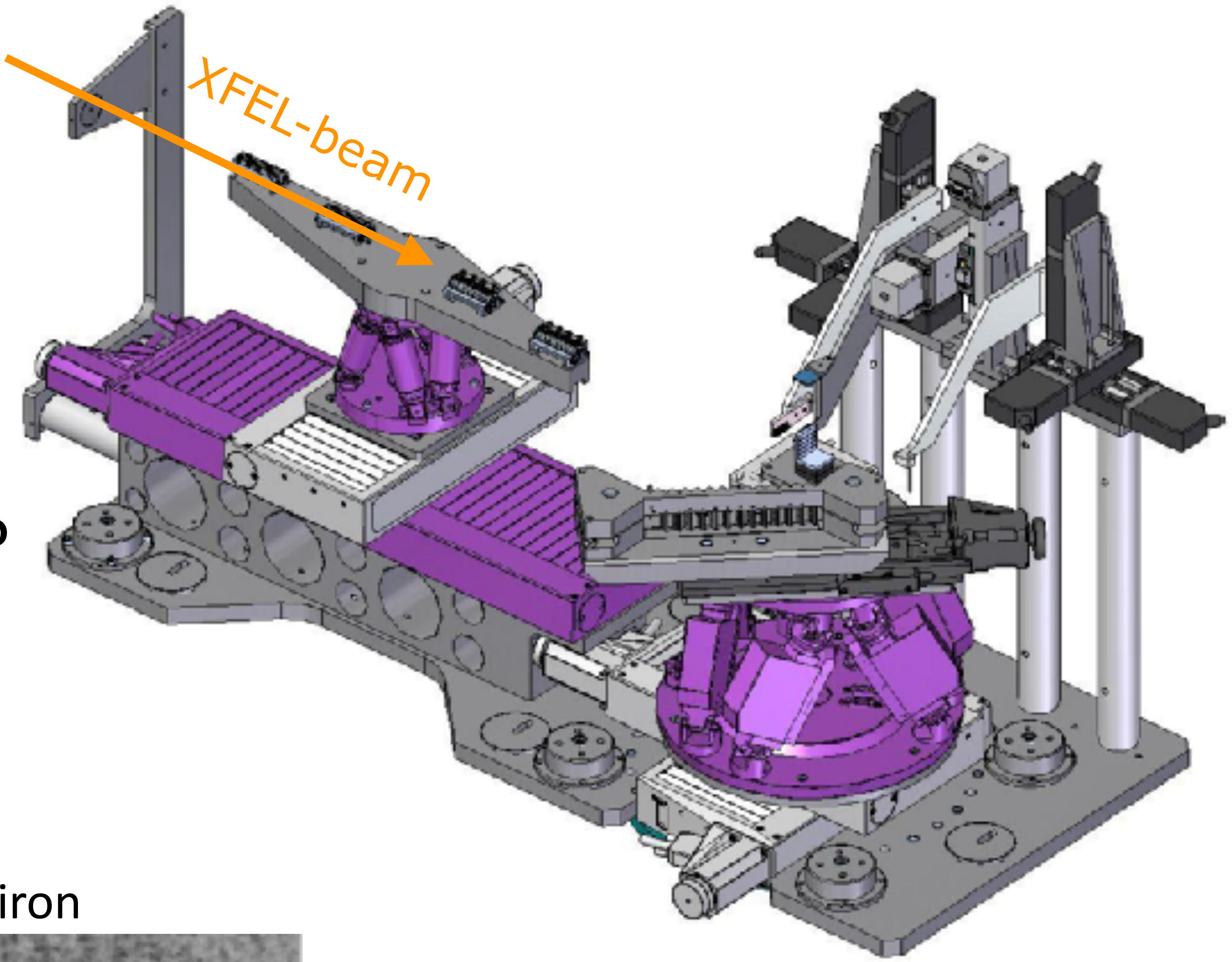
- Time-resolved imaging with moderate spatial resolution (> 1 µm) at the synchrotron?
  - improve quantum efficiency of the detector
  - direct imaging instead of PCI
  - pink beam?



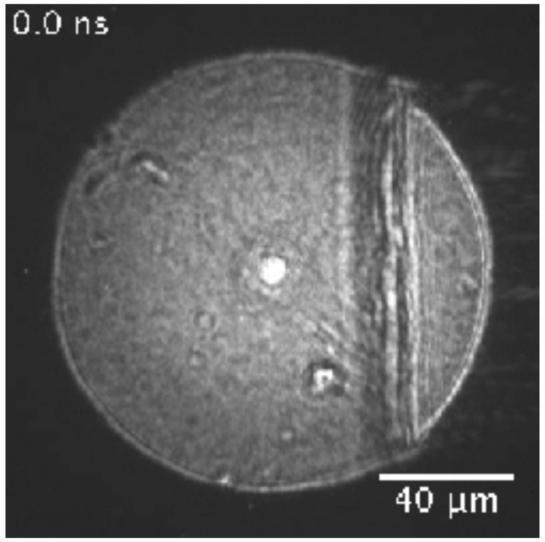
http://www.xfel.eu/overview/in_comparison/

Summary

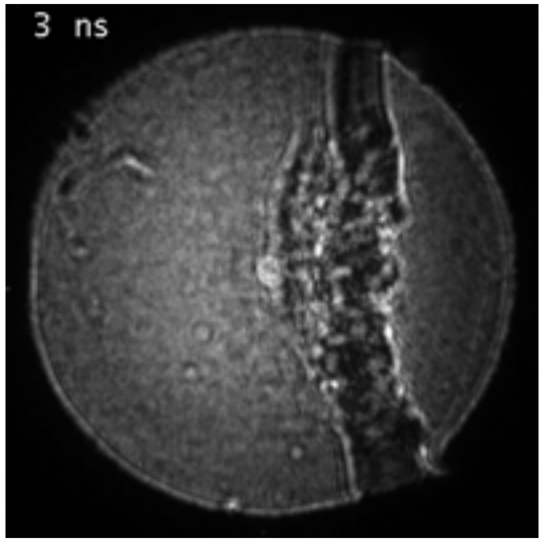
- XFEL: x-ray microscopy with both high spatial and temporal resolution.
- Beam characterization (ptychography) required to obtain quantitative results.
- PCI yields quantitative results on shock velocity, compression and timescale of shock decay.
- Time-resolved X-ray imaging on a moderate length scale at the synchrotron?



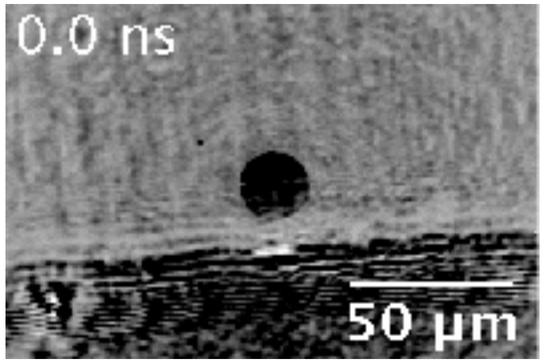
diamond



kapton



iron



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"Focusing X-ray free-electron laser beams for imaging and creating extreme conditions in matter"

At DESY and TUD
- Christian Schroer
- Frank Seiboth
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- Daniel Nilsson
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At LLNL
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- Yuan Ping
- Damien Hicks

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Thank you very much for your attention!