MHz X-ray Microscopy at Synchrotron and XFEL Facilities

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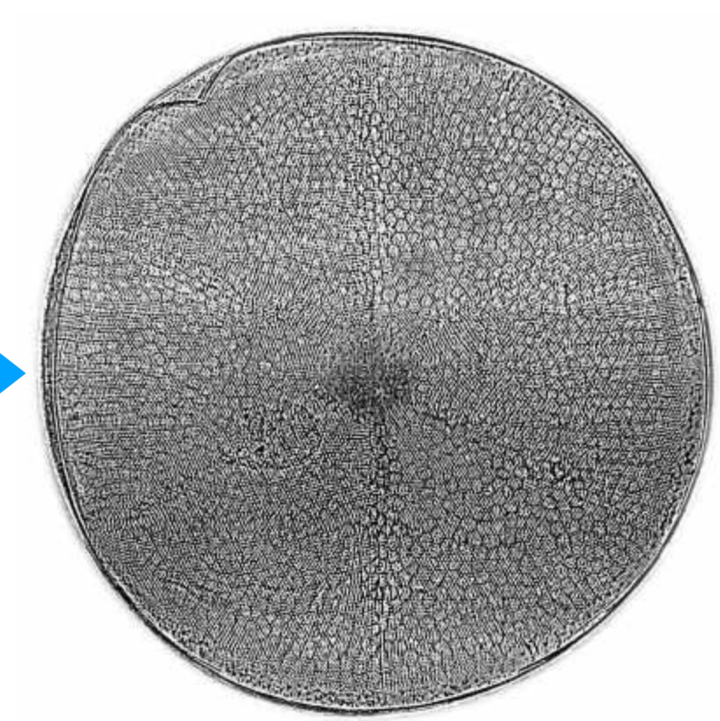
Contact: patrik.vagovic@cfel.de

Third generation X-ray sources impact on X-ray microscopy

“First light" on September 1994

“First light" on March 26, 1995

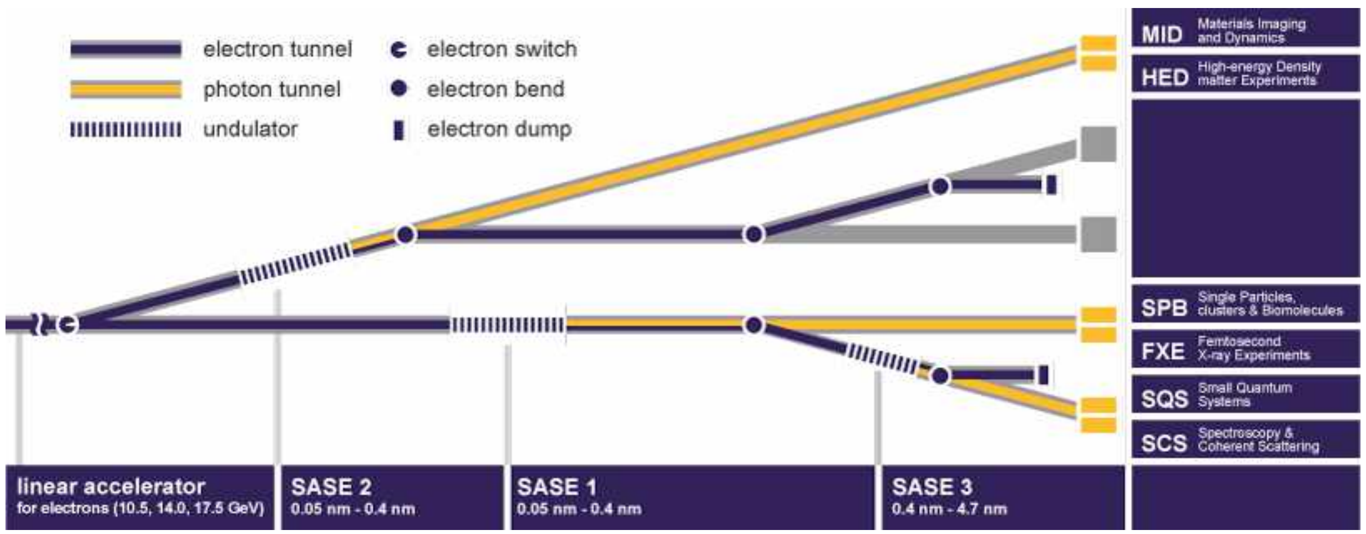
“First light” in 1999



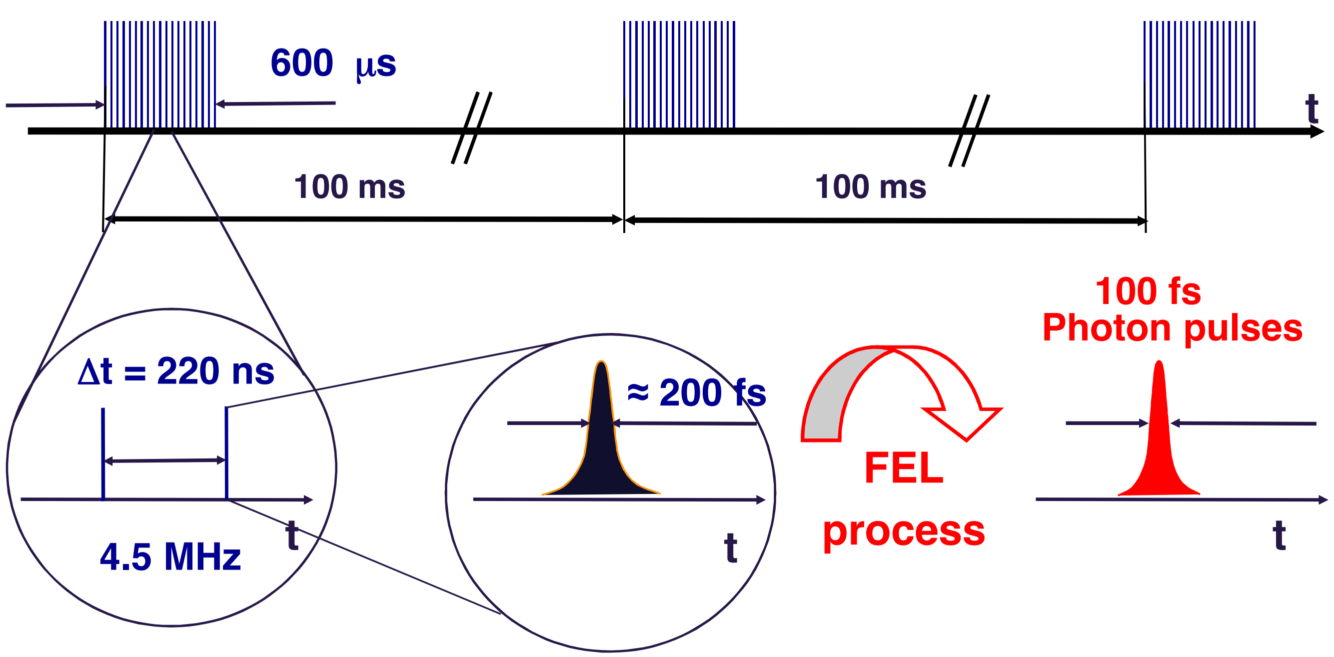
The silica shell of the diatom Actinoptychus senarius, measuring only 0.1 mm across, is revealed in fine detail in this X-ray hologram recorded at 5000-fold magnification with the new lenses. Credit: DESY/ AWI, Andrew Morgan/**Saša Bajt**/ **Henry Chapman**/Christian Hamm

25 years later …

4th generation sources:
X-ray Free-Electron Lasers



10Hz electron bunch trains
(with up to 2700 bunches à 0.1…1 nC)



What impact on X-ray microscopy we can expect?

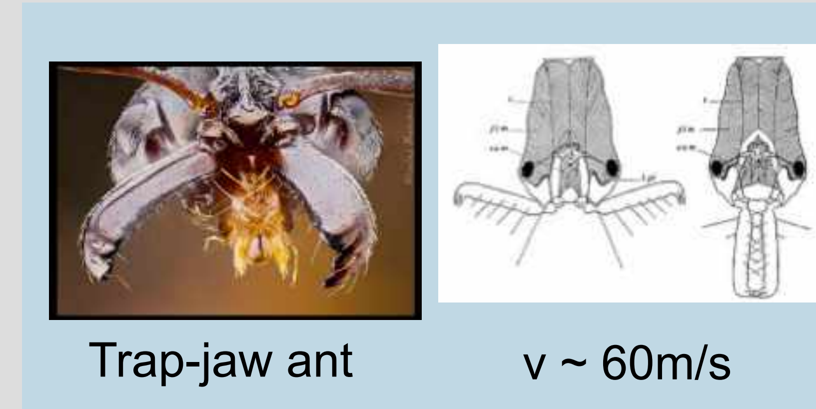
Unique X-ay beam properties:

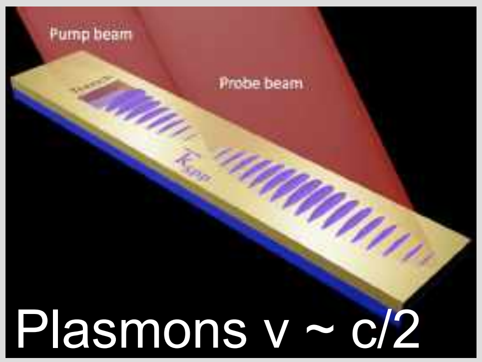
Number of photons per pulse: ~**10^{12}**
Bandwidth: **~ 10^{-2}**
Pulse rep. rate: up to **4.5 MHz**
Max. Photon energy: **25 keV possibly up to 100 keV with coming upgrades**
Pulse duration: **< 100 fs**

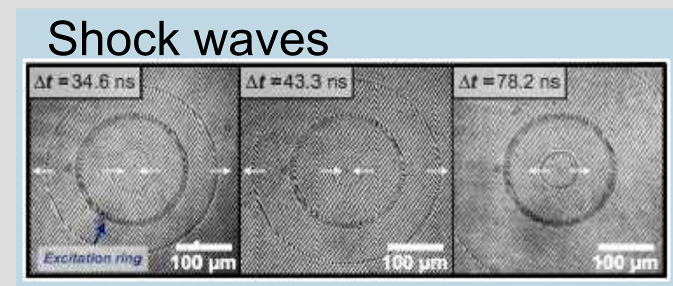
Focus on dynamics!?

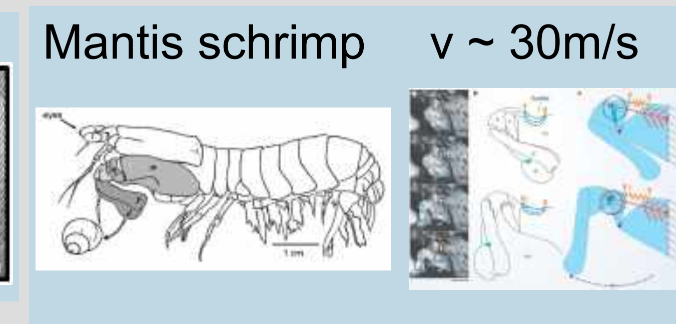
P. Vagovic, DESY Users Meeting, 2020 patrik.vagovic@cfel.de

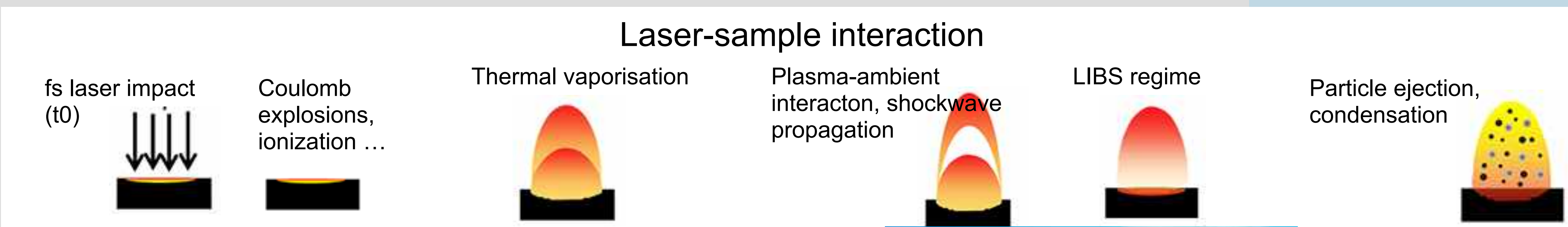
Ultra fast stochastic processes in material science and biology

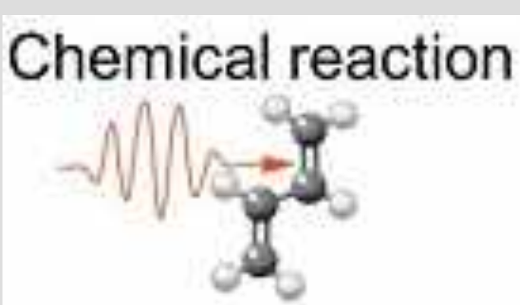


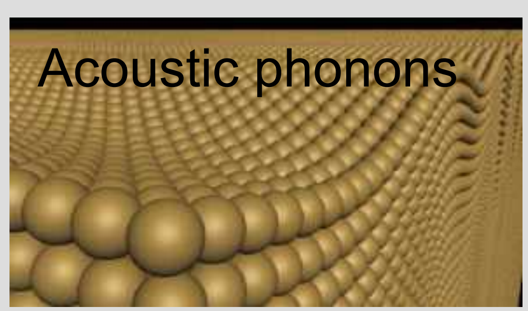


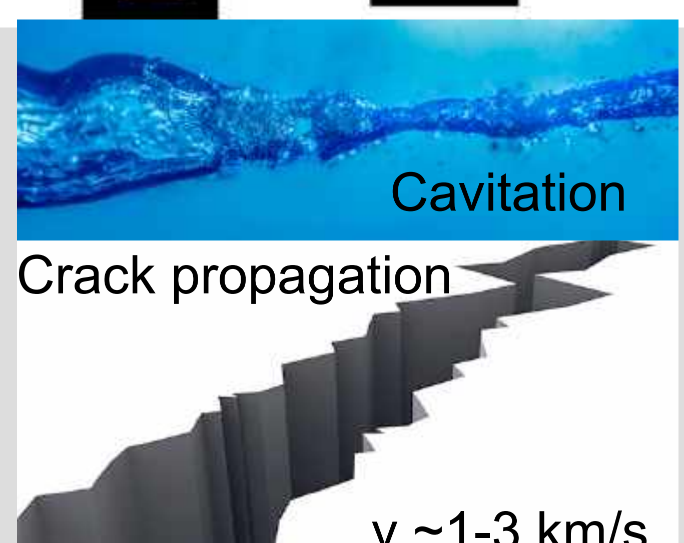


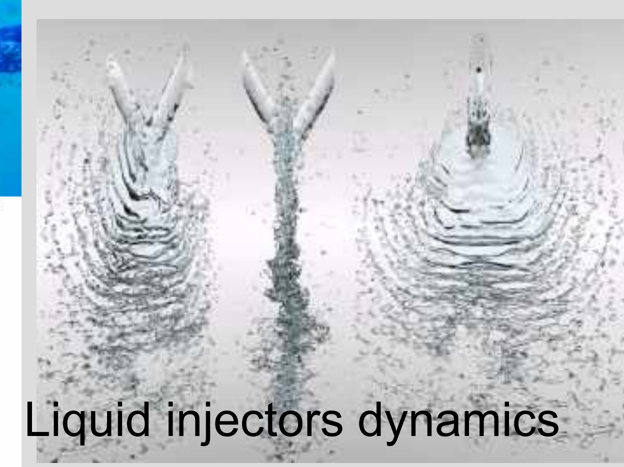


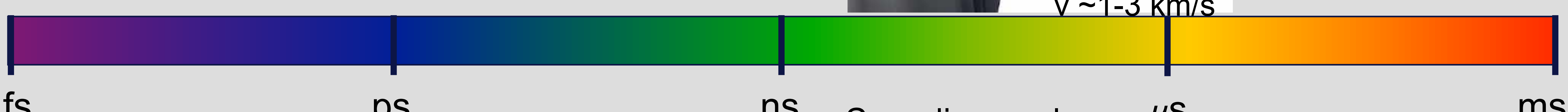








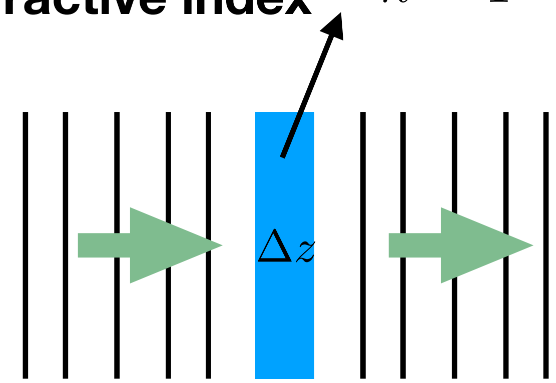




Principles of X-ray Microscopy

Wave field interaction with matter

Refractive index $n = 1 - \delta + i\beta$

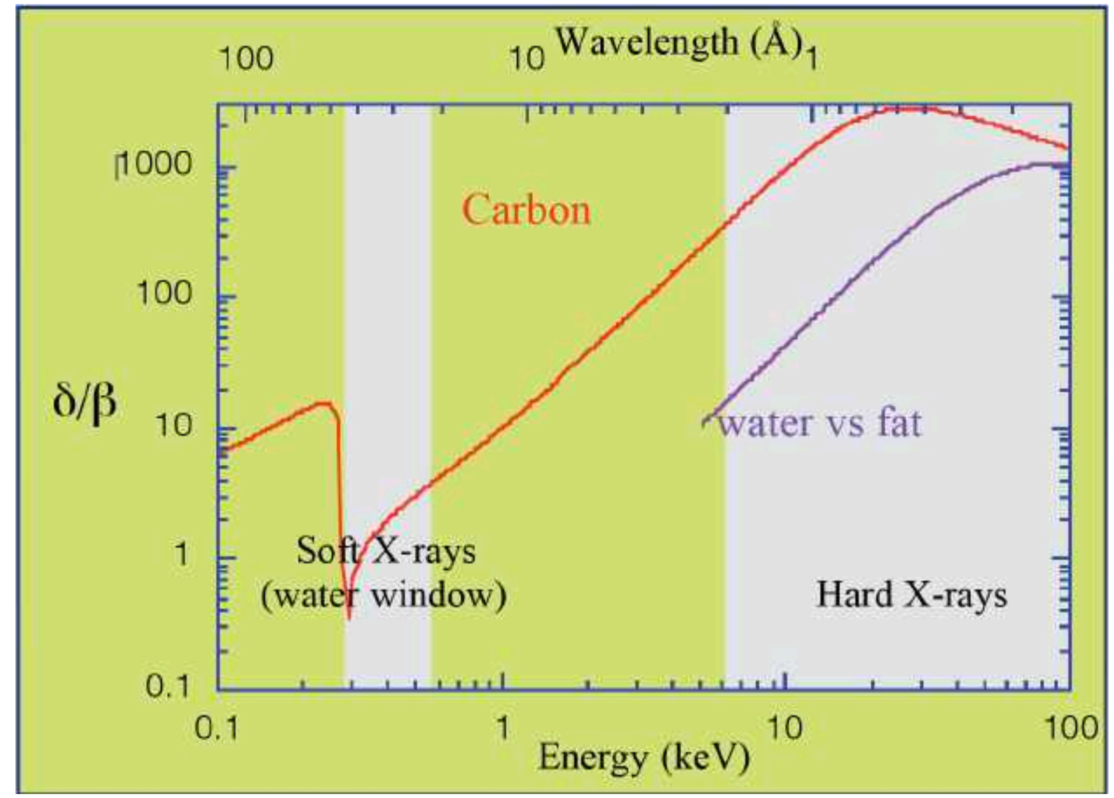


$$e^{ik\,n\,\Delta z} = e^{i\frac{2\pi}{\lambda}\,n\,\Delta z}$$

$$U_e(x, y) = T(x, y)U_0(x, y)$$

$U_0(x, y)$ $T(x, y)$ $T(x, y) = A(x, y)e^{i\phi(x,y)}$

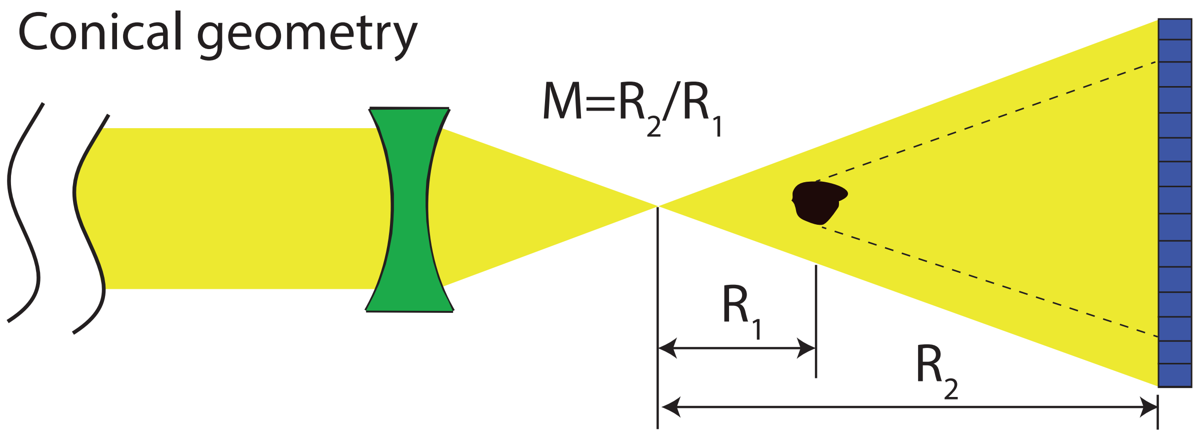
Phase vs Absorption



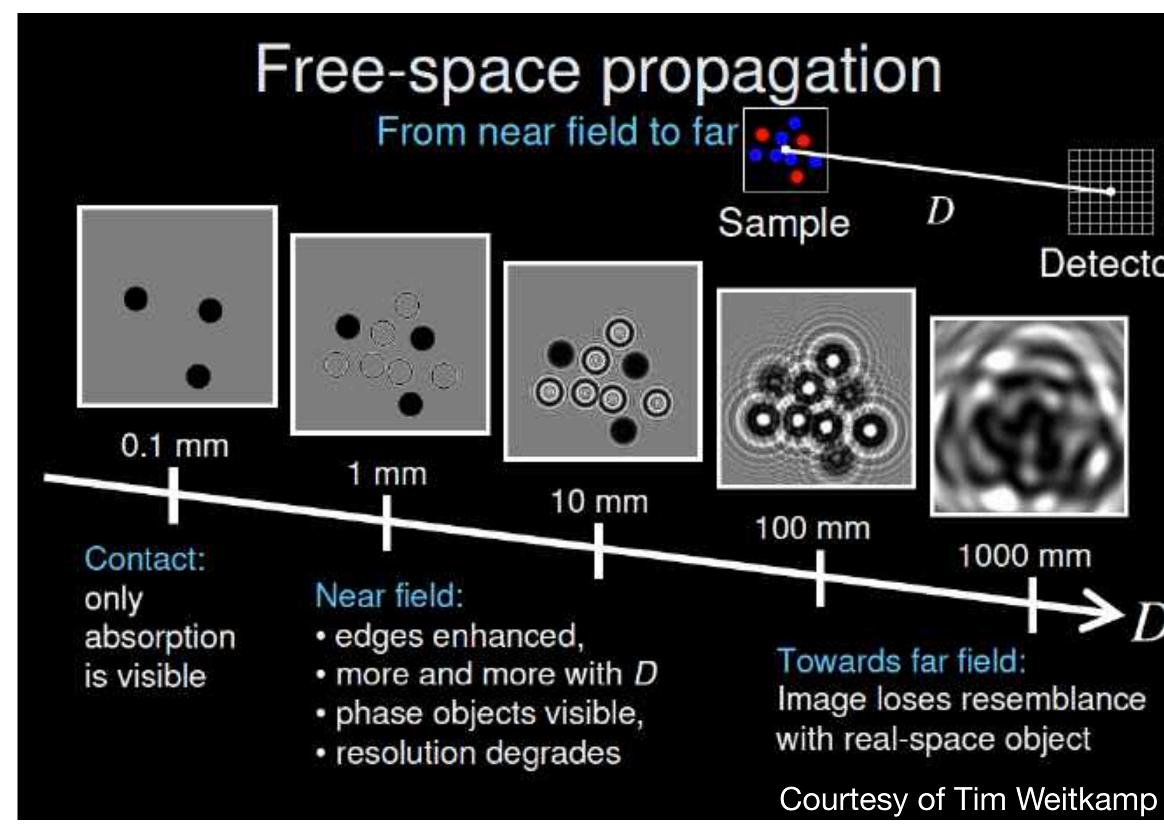
Gain 100 to 1000 !

Full-field X-ray microscopy using free space propagation

Conical geometry



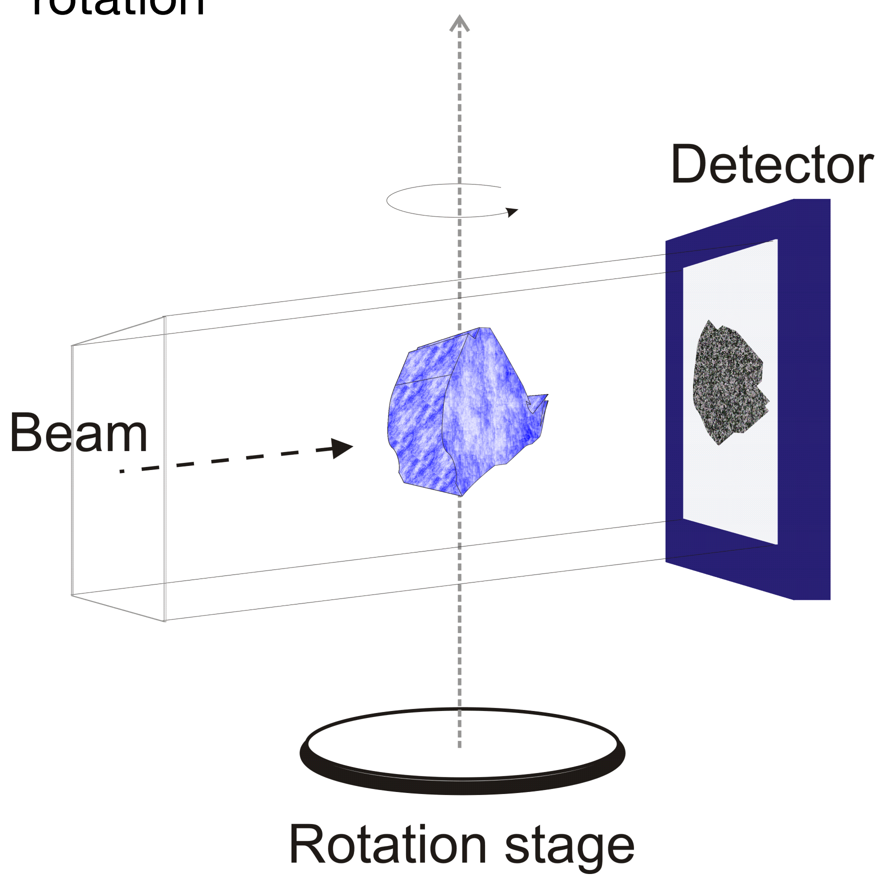
Parallel geometry



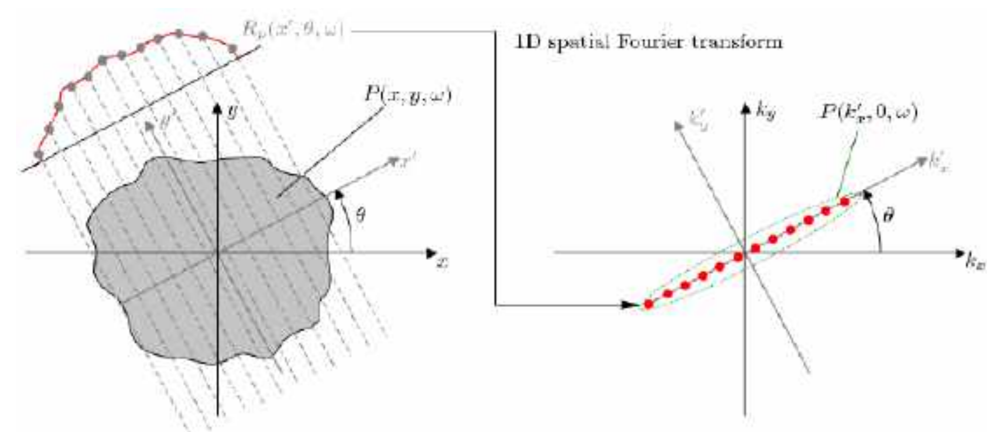
How we do 3D X-ray microscopy today

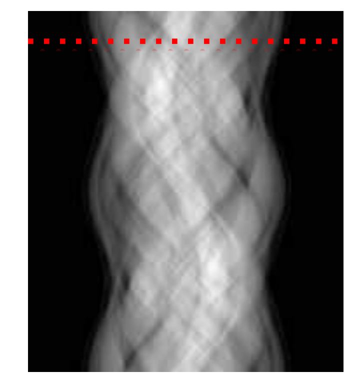
Computed tomography

Collection of projection images (radiograms) for various angles of rotation



3D reconstruction



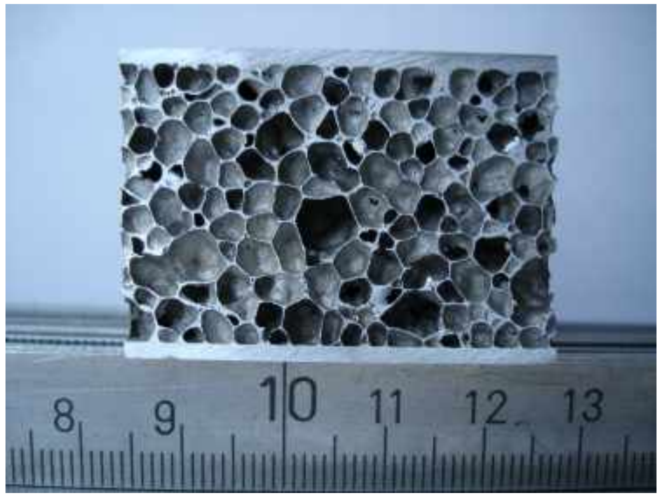


To obtain fast 3D images rotation of the sample must be fast!

World record in fast 3D tomography/tomoscopy: 208 (tomographic frames per second) tfs

García-Moreno, F., Kamm, P.H., Neu, T.R. *et al.* Using X-ray tomoscopy to explore the dynamics of foaming metal. *Nat Commun* **10,** 3762 (2019). https://doi.org/10.1038/s41467-019-11521-1

Fast dynamics in Al foams



Dynamics of wall rupture and coalescence in Al foaming process is not well understood.

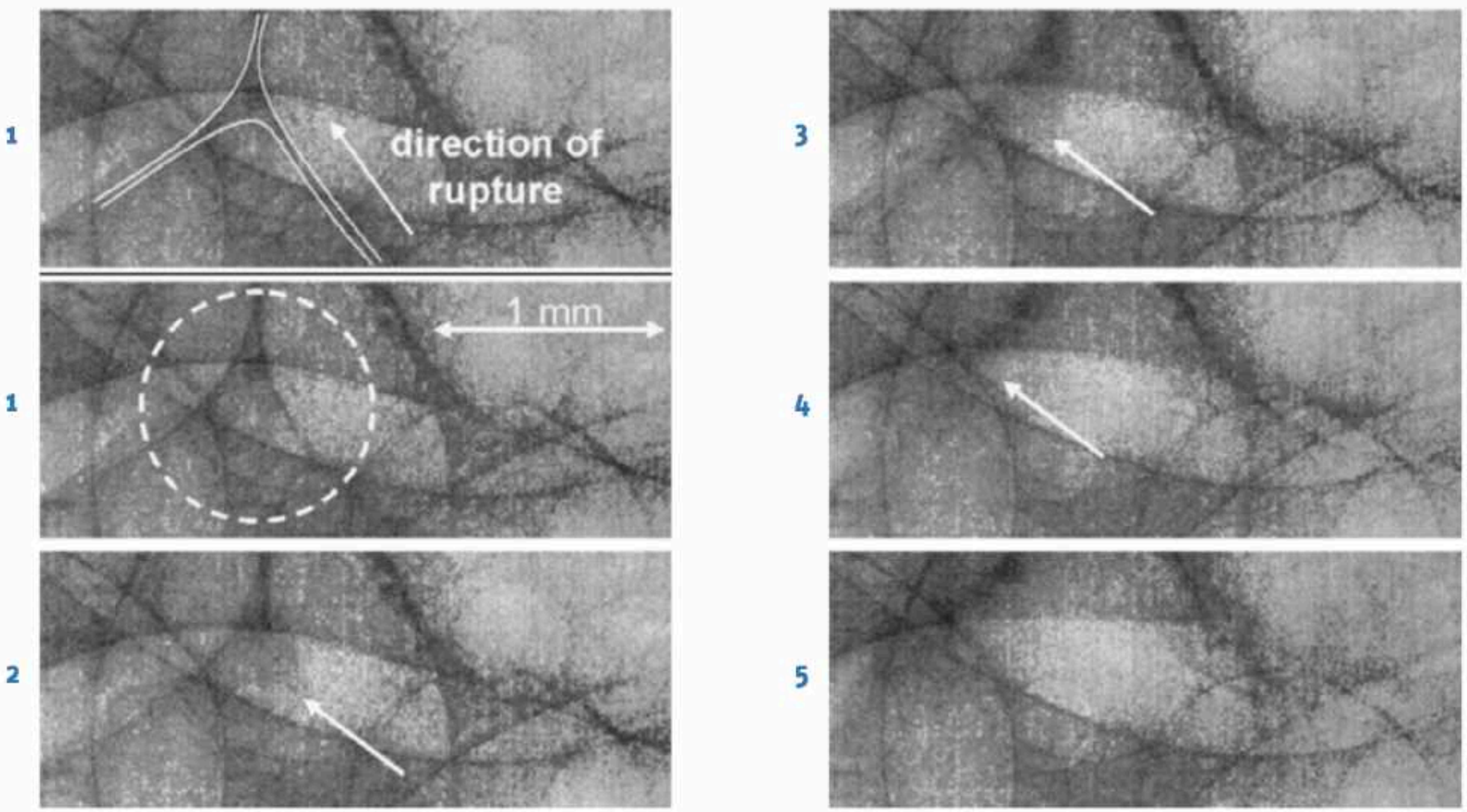
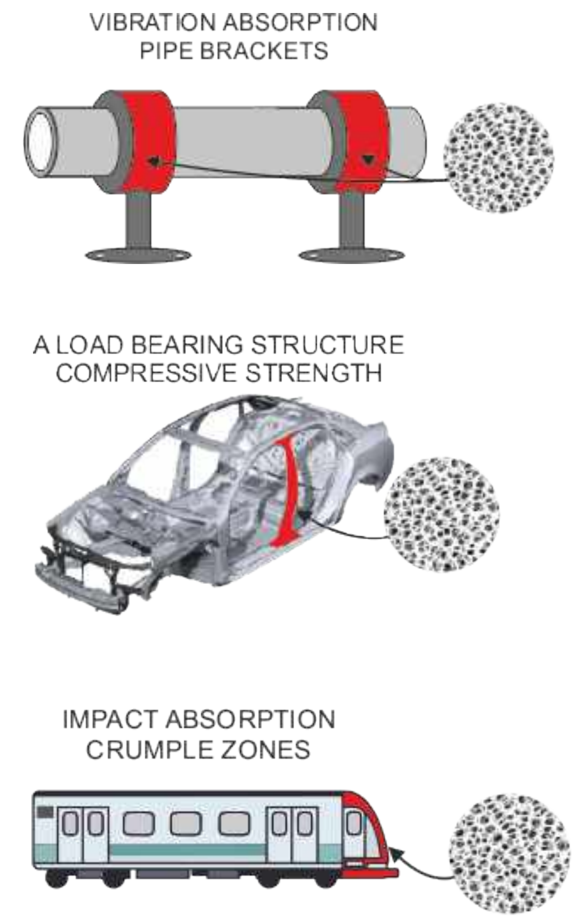


Fig. 1: Series of radiographies of a liquid metal foam featuring a rupturing film. Images are 200 m apart.* The lack of time resolution does not allow a proper analysis of the phenomena. * F. Garcia-Moreno, A. Rack, L. Helfen, T. Baumbach, S. Zabler, N. Babcsan, J. Banhart, T. Martin, C. Ponchut, M. Di Michiel, Fast processes in liquid metal foams investigated by high-speed synchrotron x-ray microradioscopy, Appl. Phys. Lett. 92 (2008) 3.

Industrial applications of Al foams



RÅC project INVISION

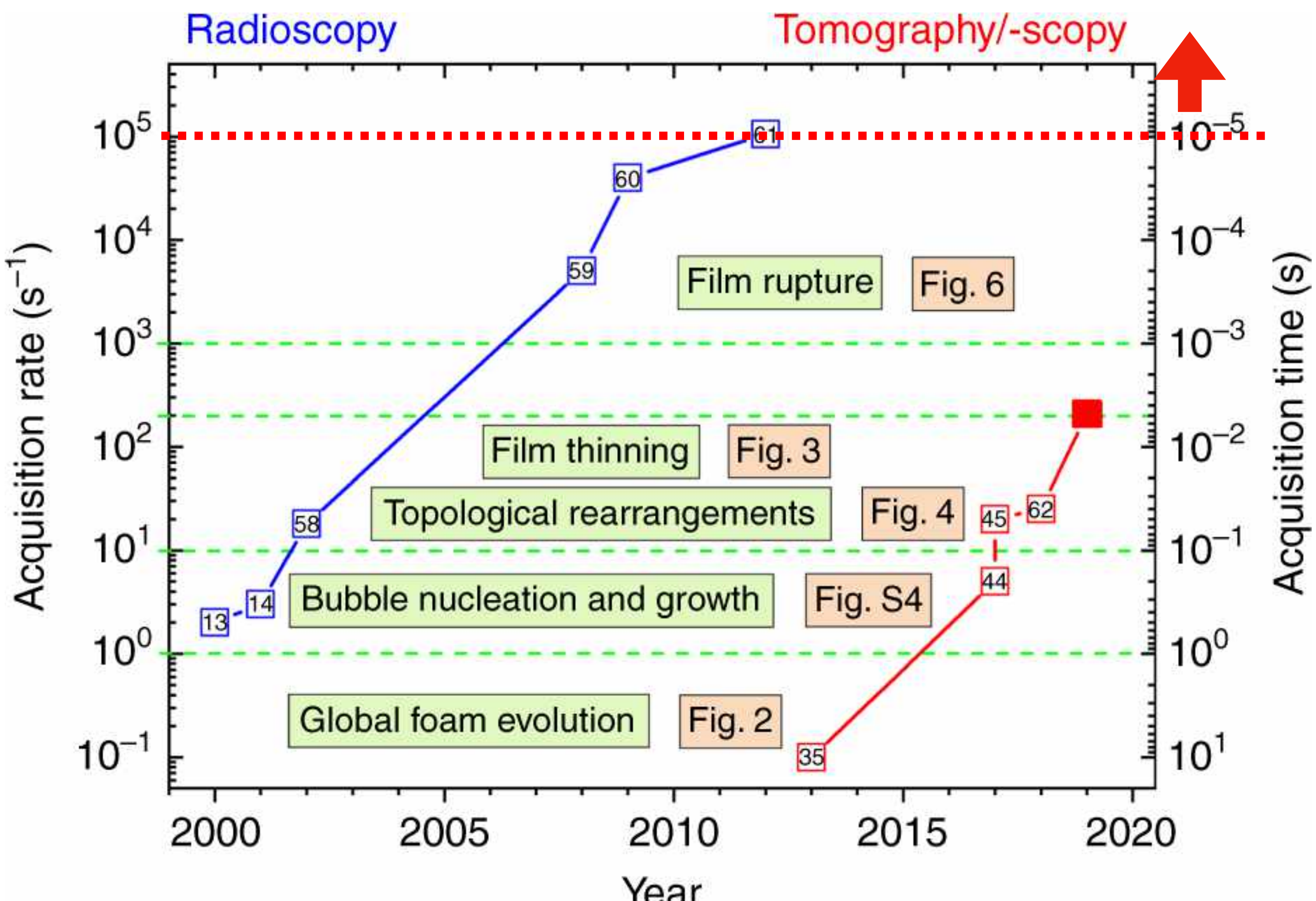


Prof. J. Banhart, Dr. F. Garcia-Moreno, Mike Noak
TU Berlin, HZB

Evolution of fast imaging in metallic foam research at synchrotrons

Fast 2D (radiography/radioscopy) and 3D (tomography and tomoscopy) imaging of Al foam dynamics

Terra incognita



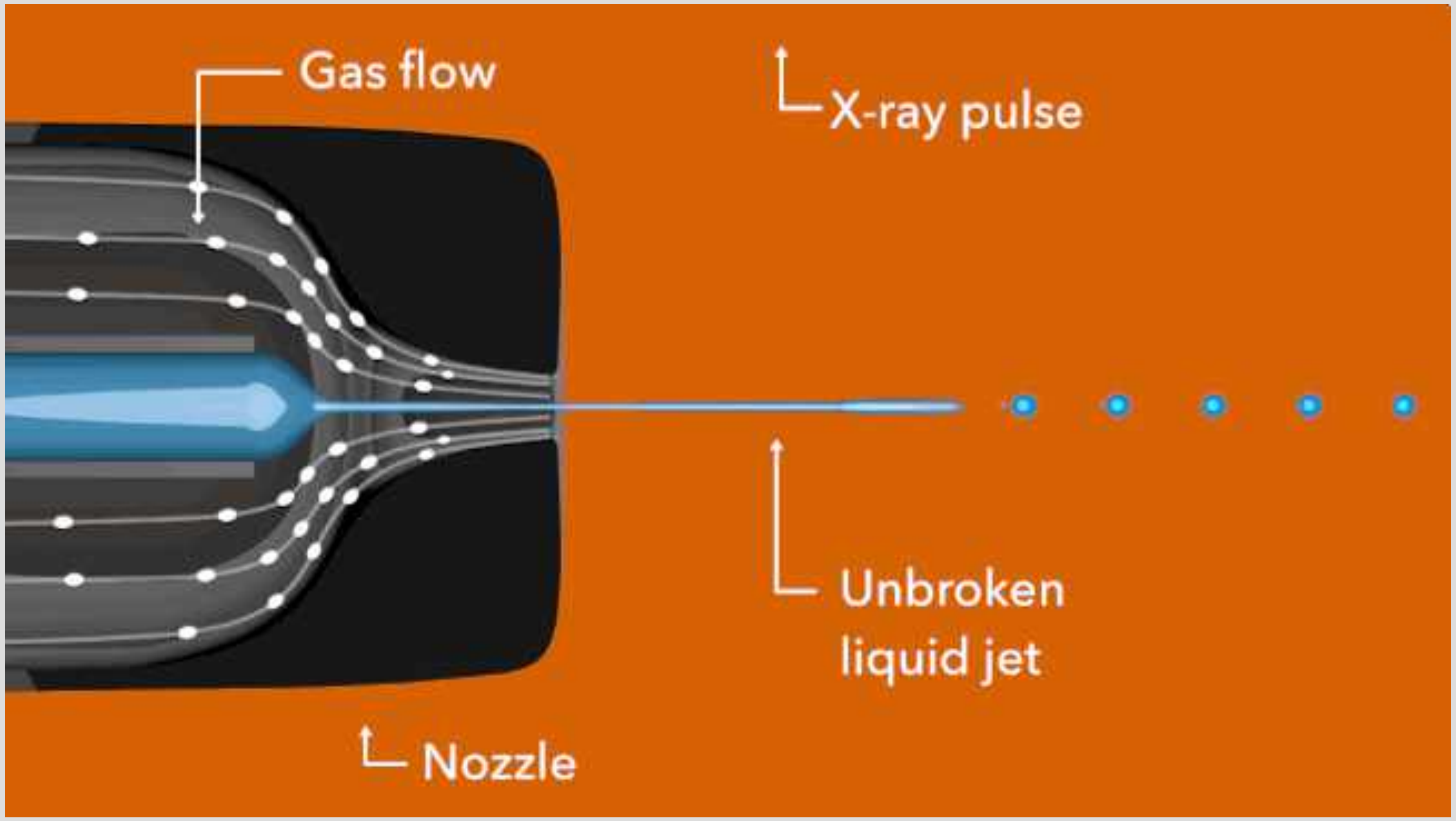
Garcia-Moreno, F., Kamm, P.H., Neu, T.R. *et al.* Using X-ray tomoscopy to explore the dynamics of foaming metal. *Nat Commun* **10,** 3762 (2019). https://doi.org/10.1038/s41467-019-11521-1

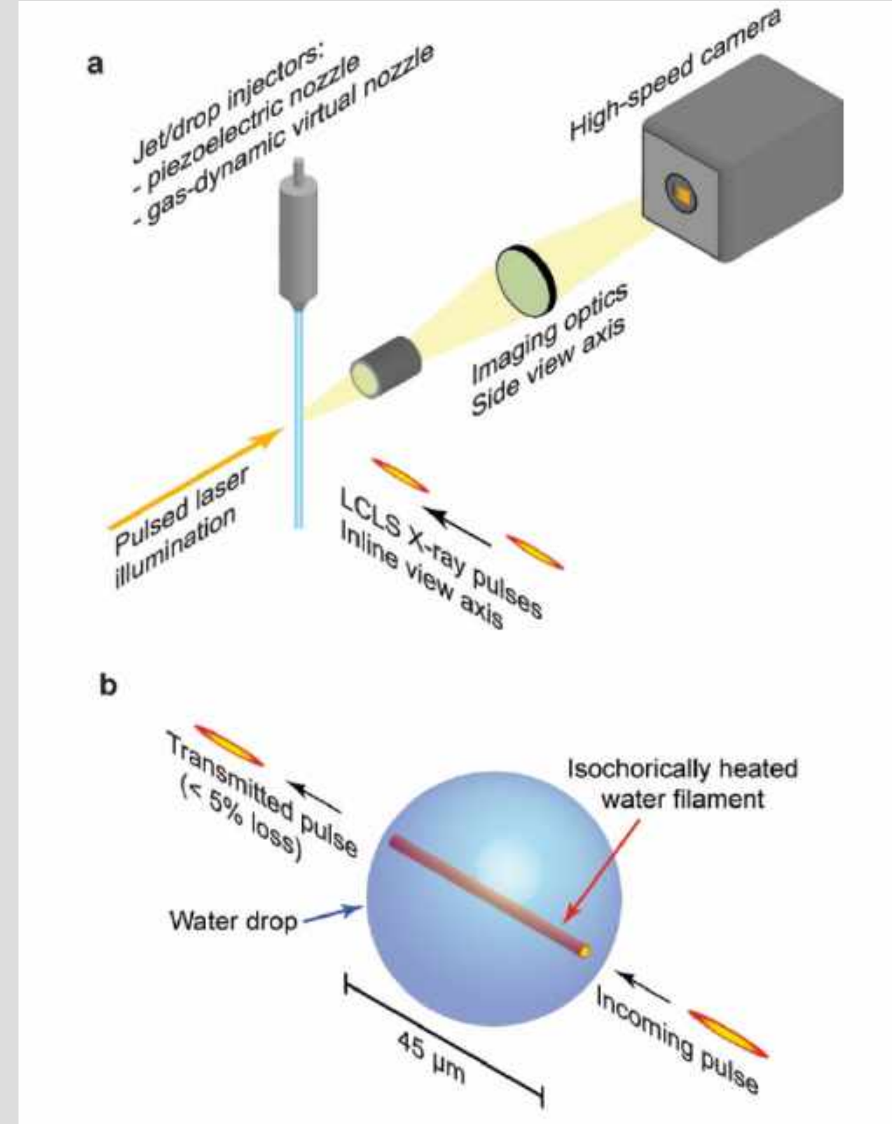
The coalescence and film rupture accessible only ~ MHz rate with single pulse illumination

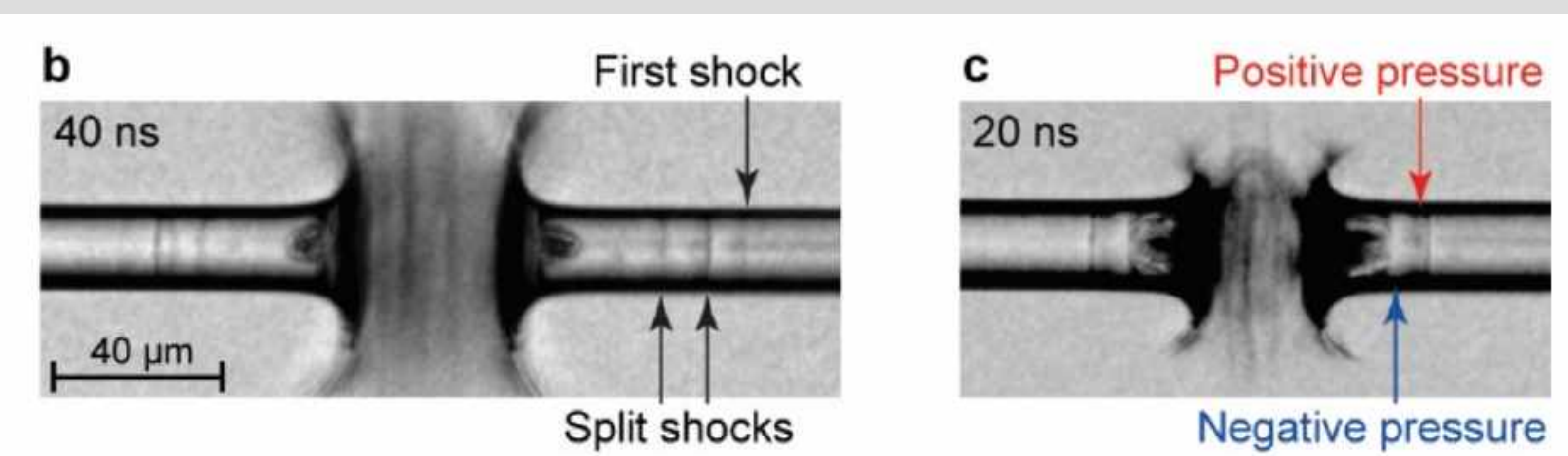
Can we exploit unique properties of EuXFEL and use it for MHz rate radioscopy or tomoscopy ???

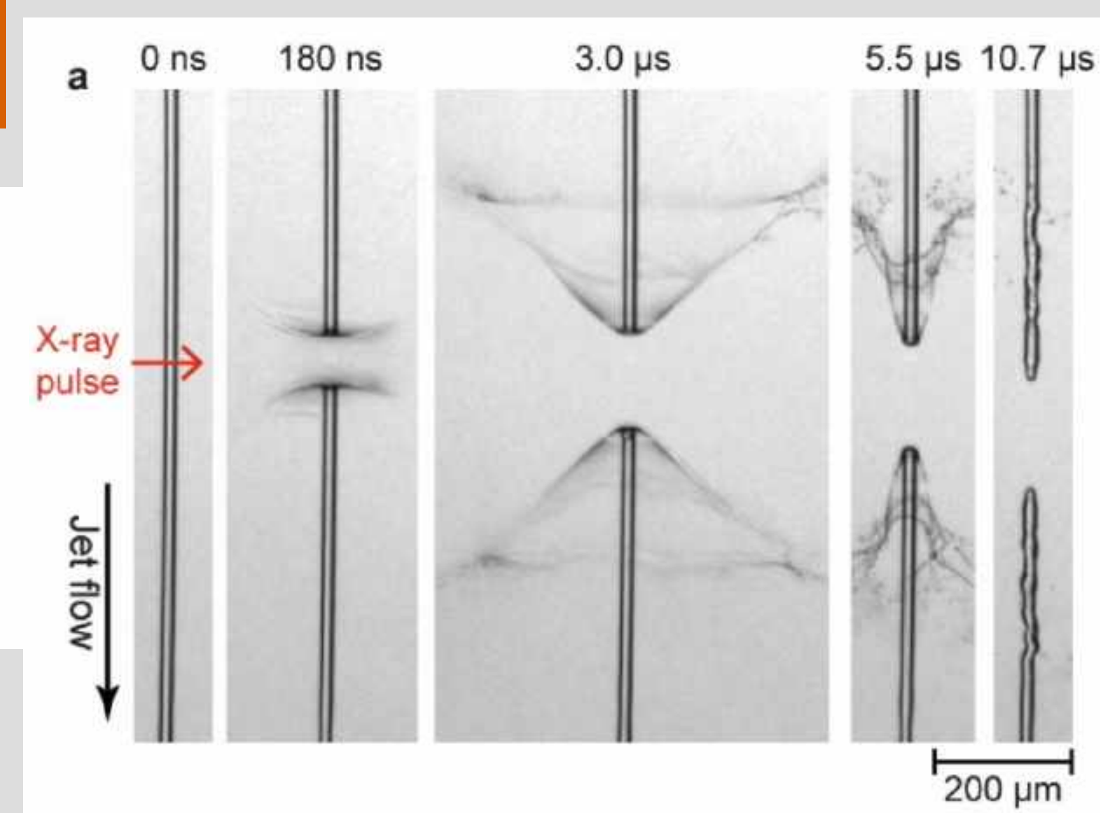
Fast dynamic in fluidics

Will liquid sample injectors work at 4.5 MHz rate ???









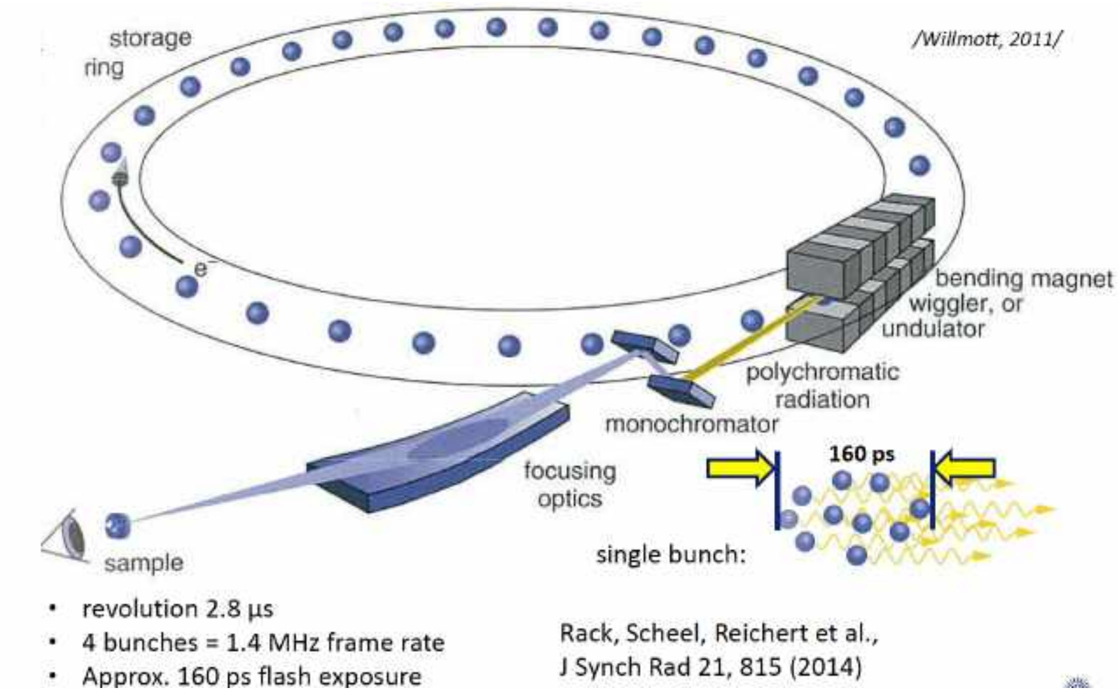
Required speed of the jet at 4.5MHz:

v = ~ **~>100 m/s**

Claudiu A. Stan et al.,   Nature Physics, 2016

MHz X-ray Microscopy at Synchrotrons

3rd generation sources:
Synchrotrons



Imaging synchronised to individual pulses was firstly pioneered at APS

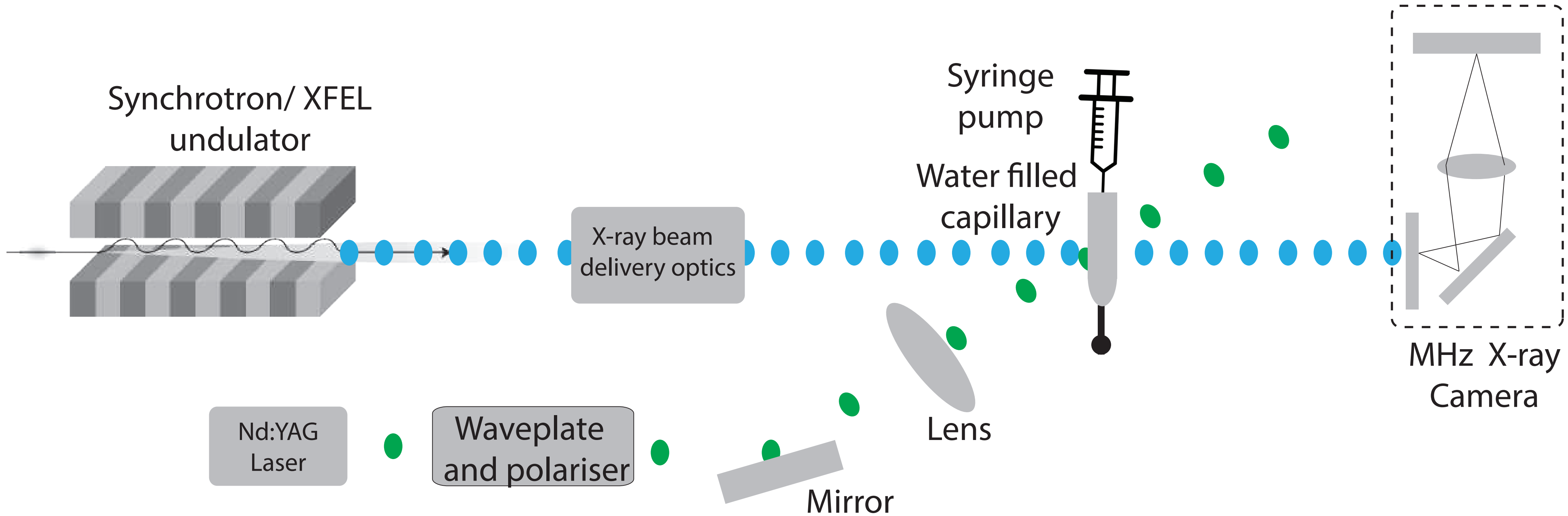
Wang, Y., Liu, X., Im, K. *et al.* Ultrafast X-ray study of dense-liquid-jet flow dynamics using structure-tracking velocimetry. *Nature Phys* **4,** 305–309 (2008).

~**1e9** photons per pulse, dE/E ~ 1e-2

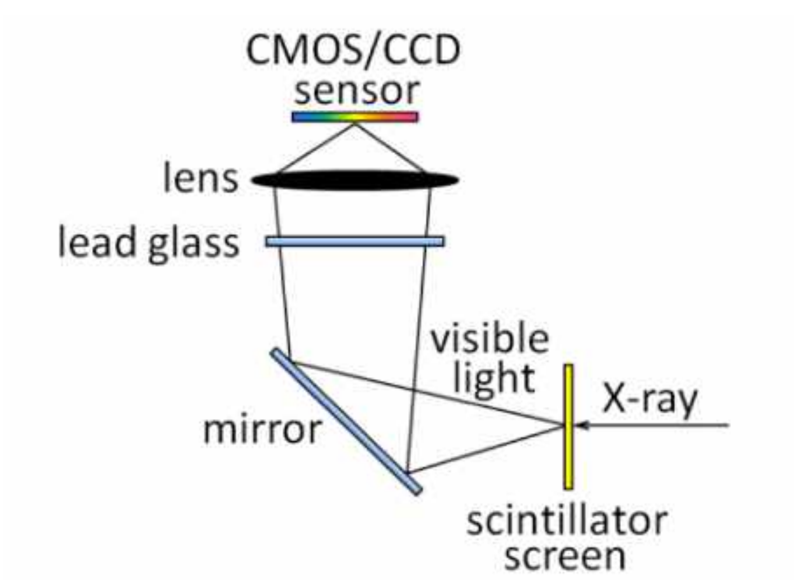
Later in 2016-2017 we explored MHz sampled imaging each frame with single pulse exposure at ESRF ID19

M. Olbinado, X. Just, J. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Mancuso, J. Morse, and A. Rack, "MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation," Opt. Express **25**, 13857-13871 (2017).

Fast Imaging at Synchrotrons synchronised to individual X-ray pulses

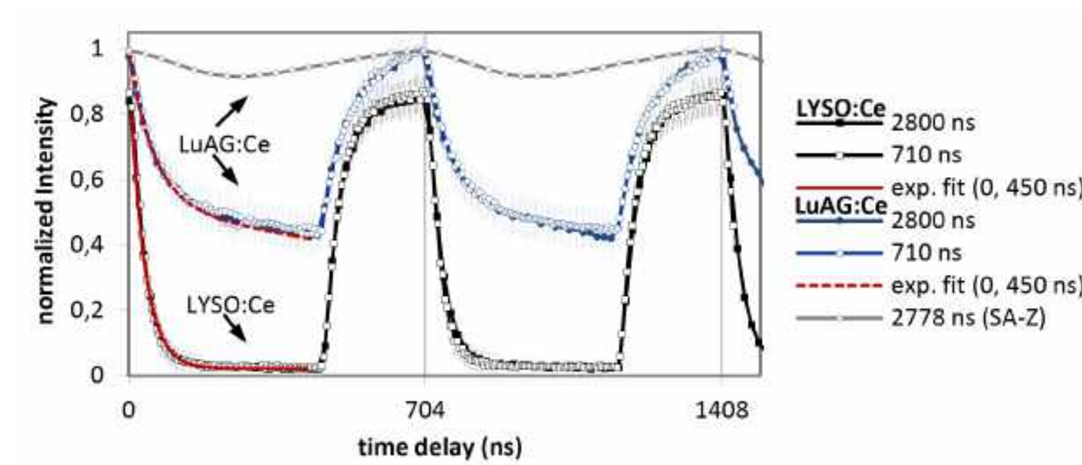


Time resolved X-ray radioscopy at ESRF ID19, (2016-2017) . Imaging of laser induced dynamics in water.
Laser wavelength: 532nm, X-ray energy: 30keV, full harmonics of the undulator.
Optical magnification: 4x, Effective pixel size: 8 um



X-ray imaging system based on scintillator

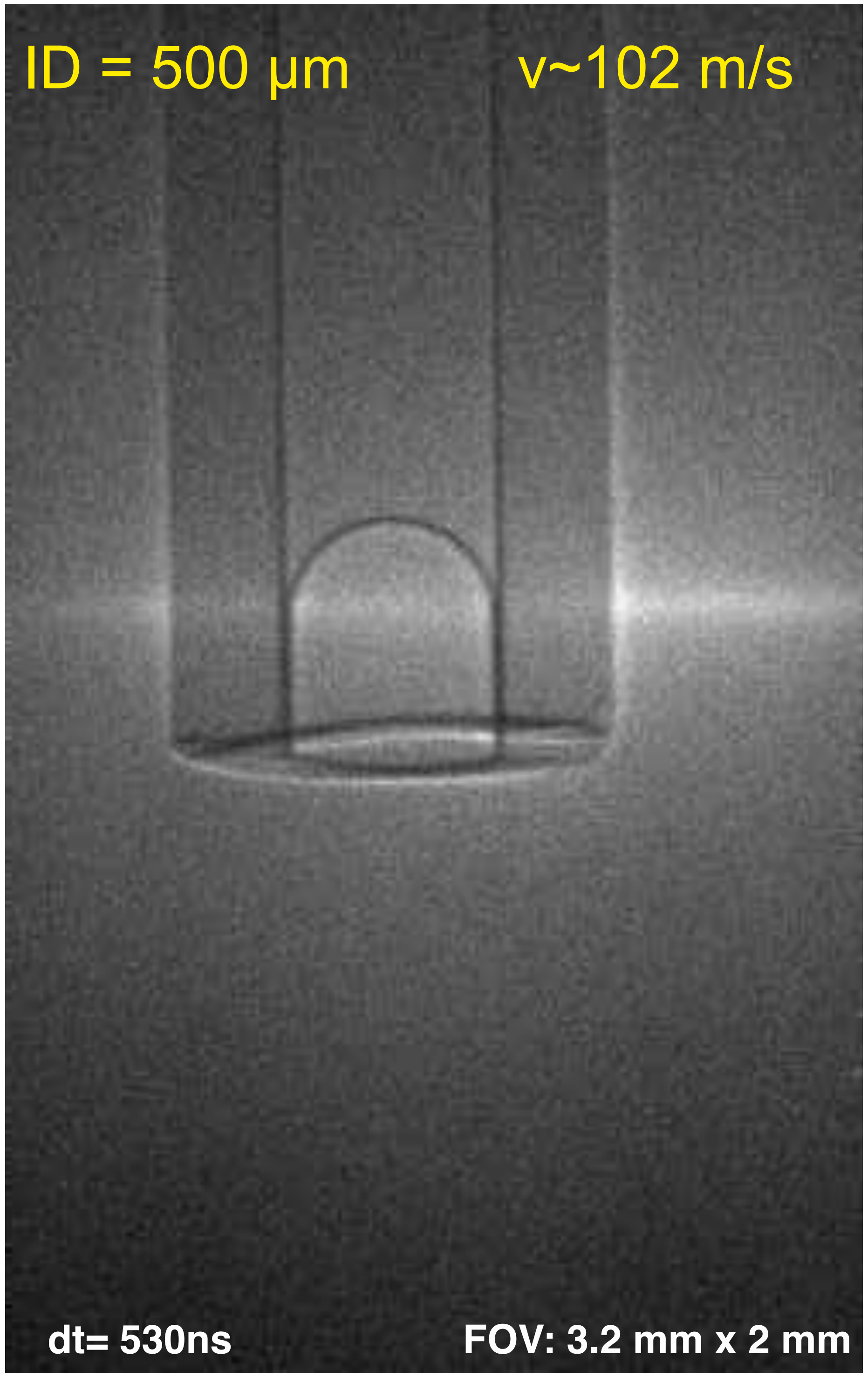
FT-CMOS Shimadzu HPV-X2 (Frame rate up to 10 MHz) 10bit dynamic range, 400x250 pixels



Scintillator response time resolved curves

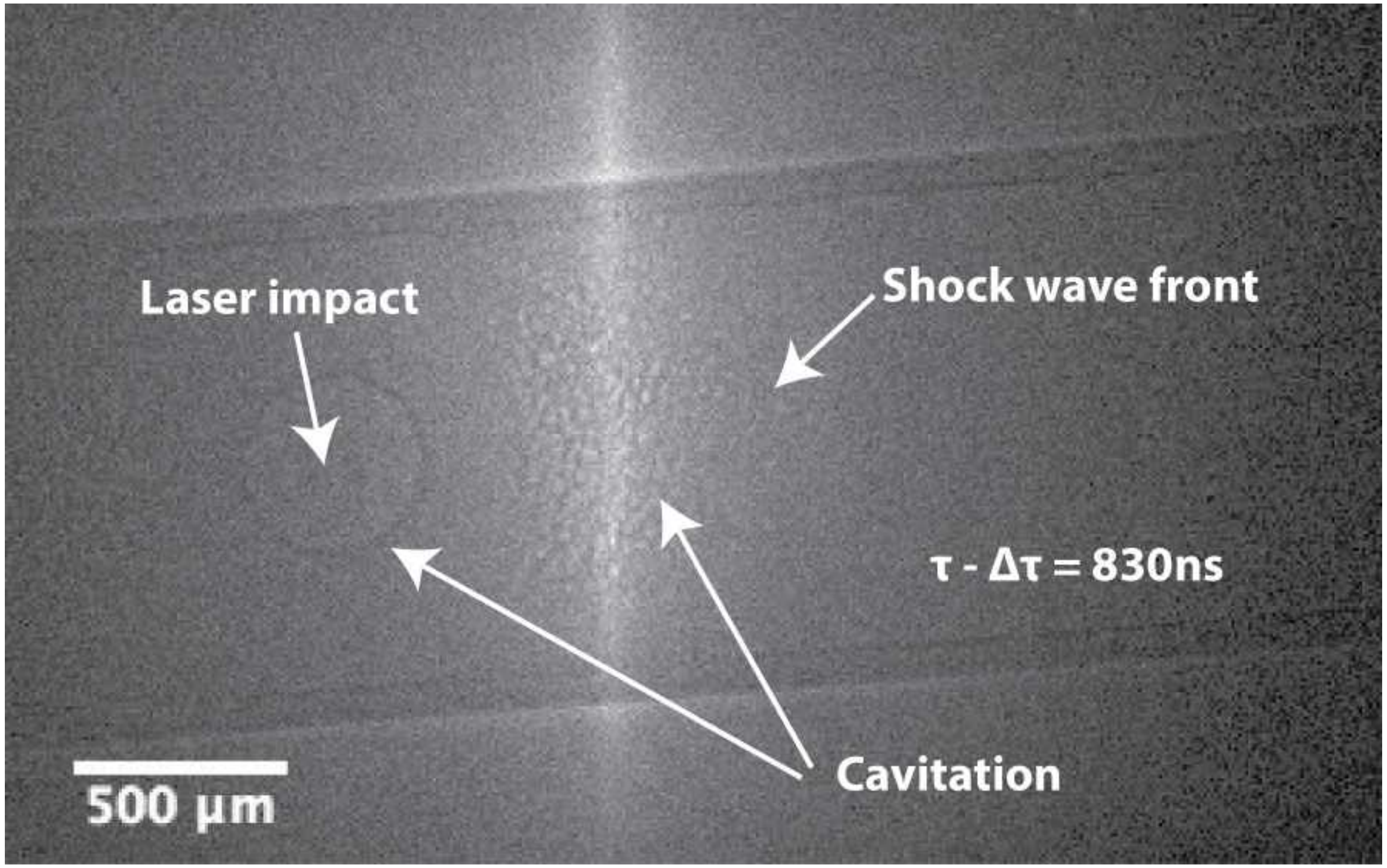
Laser induced dynamics in water filled capillaries

Cylindrical capillary



Successful jetting observed when ~2mJ laser power was absorbed in the liquid

Square capillary



Observation of the shockwave propagation (~1.4 km/s)

Time resolved X-ray radioscopy at ESRF ID19, (2017)
Imaging of laser induced dynamics in water.Laser wavelength: 532nm, X-ray energy: 30keV, full harmonics of the undulator.
Optical magnification: 4x, Effective pixel size: 8 um

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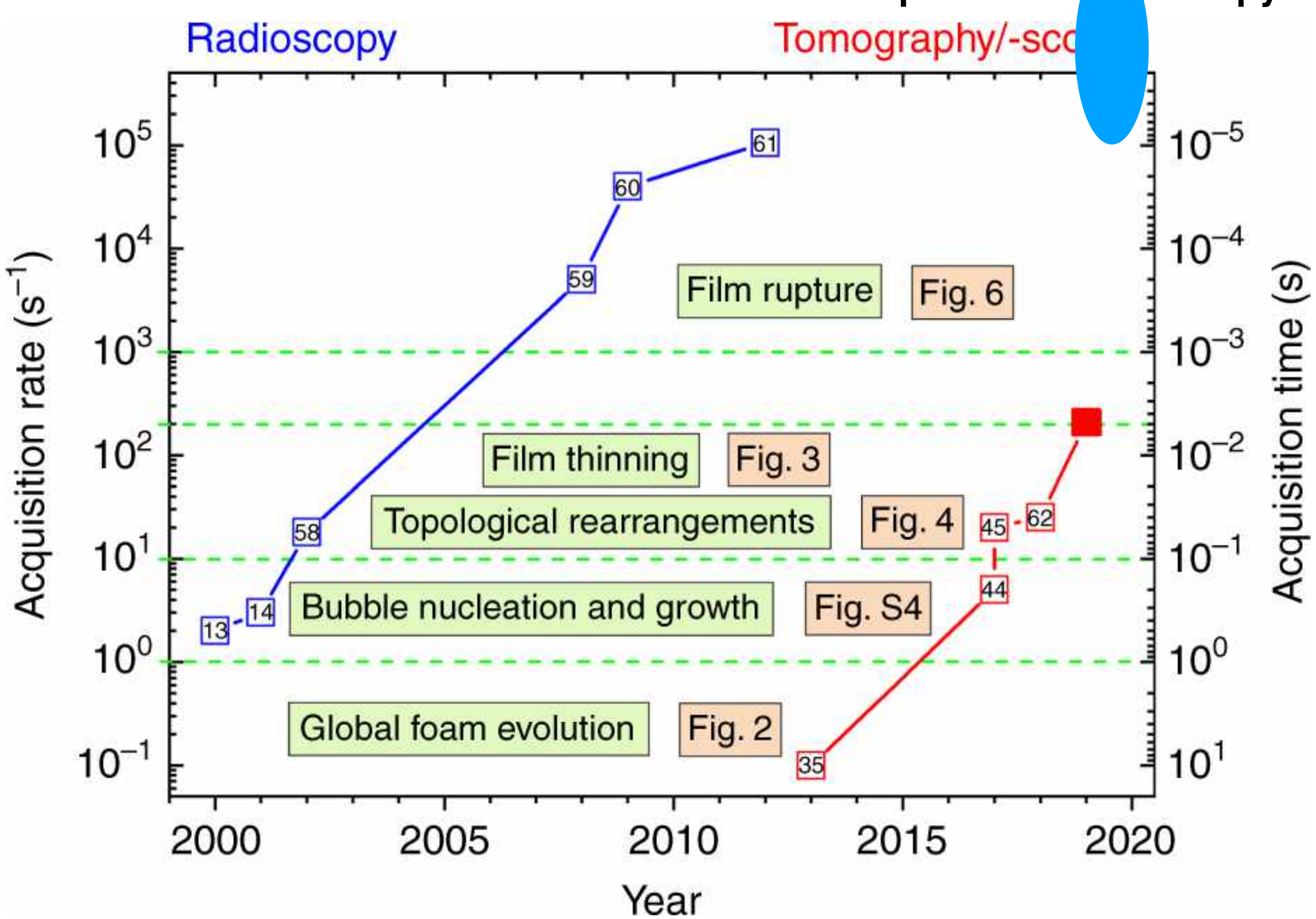
Exploring wall rupture dynamics in Al foams using pulsed synchronised imaging ~ MHz scale

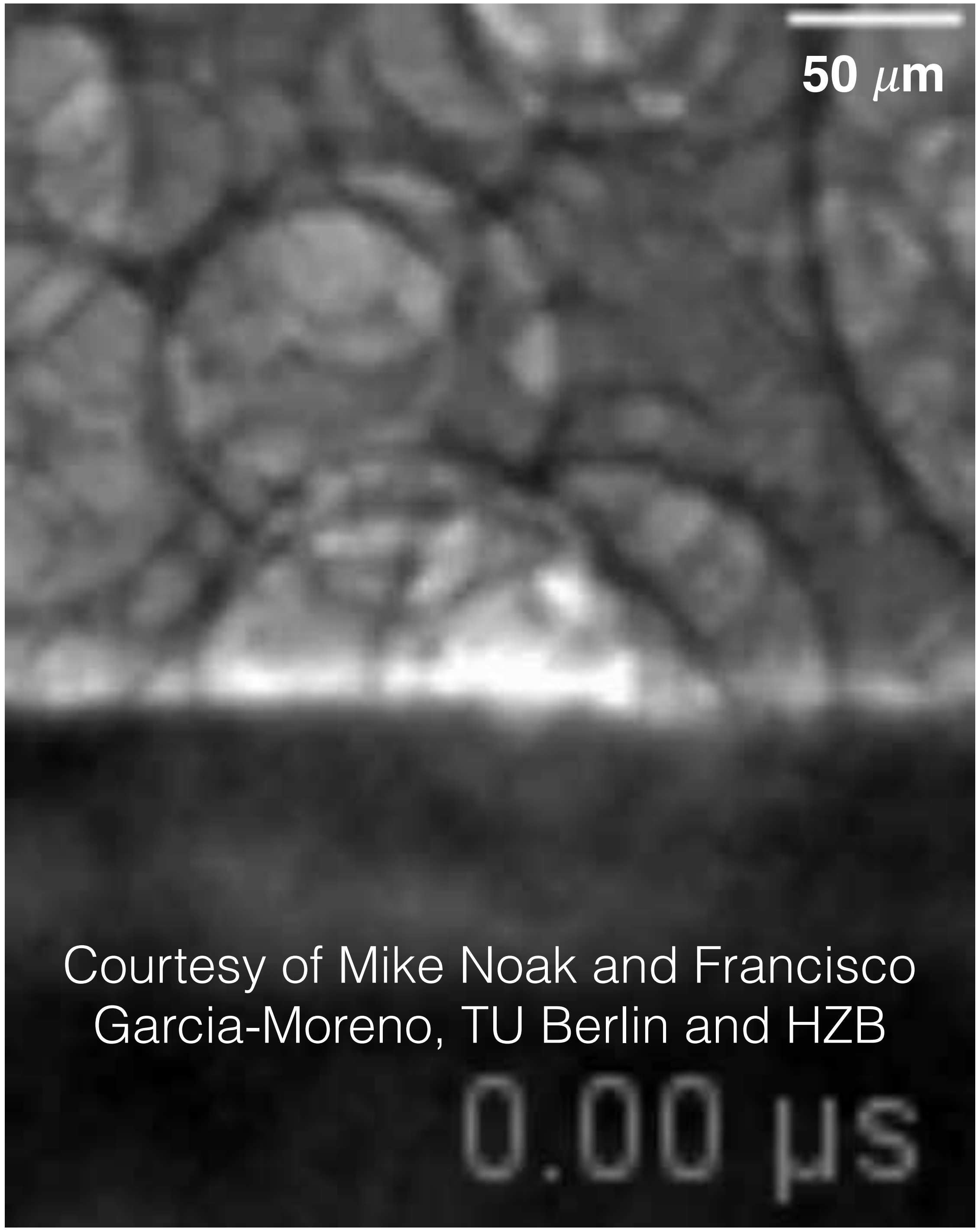
Preliminary results. Data analysis in progress

New data points on radioscopy curve



MHz imaging setup at APS 32ID (Dec 2019).
X-ray photon energy: 24 keV, Optical magnification: 10x,
Effective pixel size: 3.2 um

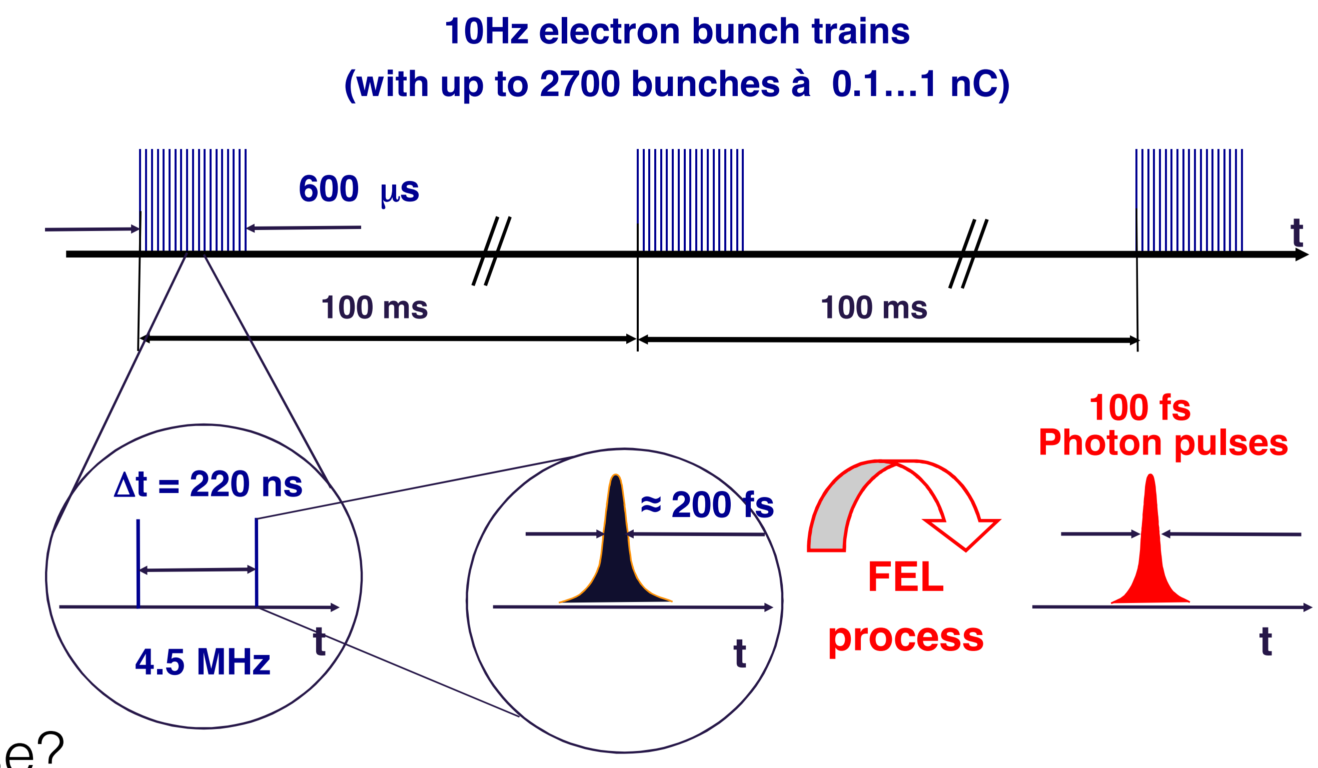
Capturing of wall rupture and bubble merging, APS 32 IDB, Dec. 2019, Δt = 4.61 μs



Can we do MHz rate X-ray microscopy at European XFEL?

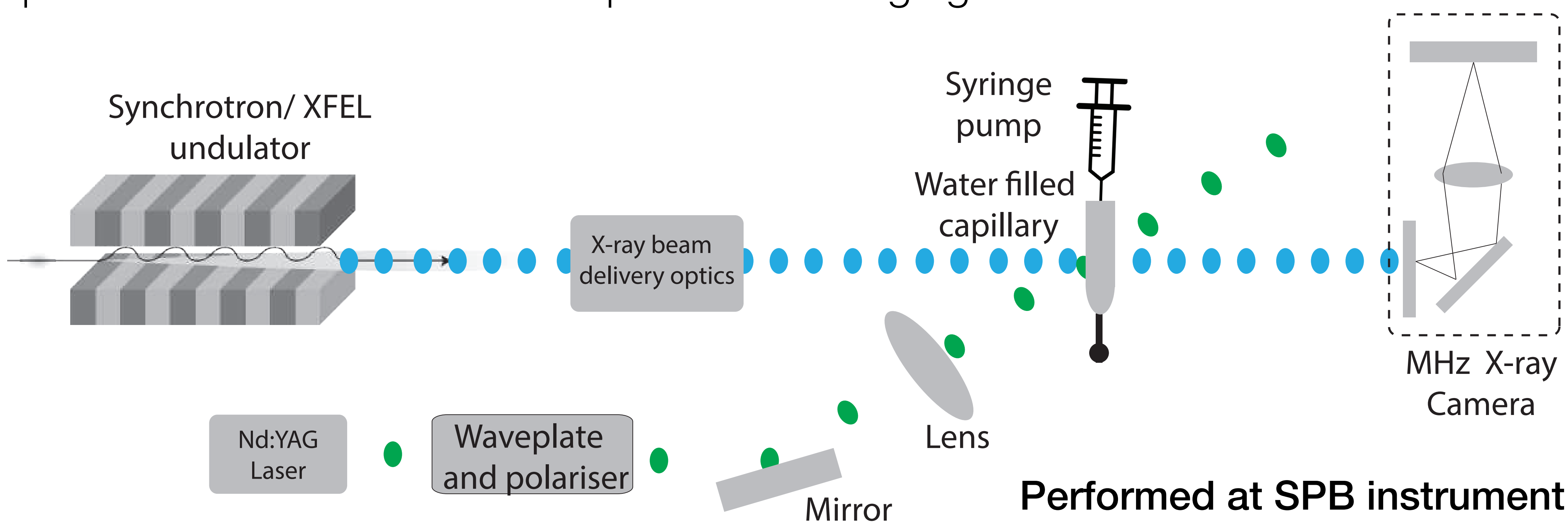
Unique X-ay beam properties:

Number of photons per pulse: ~$\mathbf{10^{12}}$
Bandwidth: **~ $\mathbf{10^{-2}}$**
Pulse rep. rate: up to **4.5 MHz**
Max. Photon energy: **25 keV**
Pulse duration: **< 100 fs**



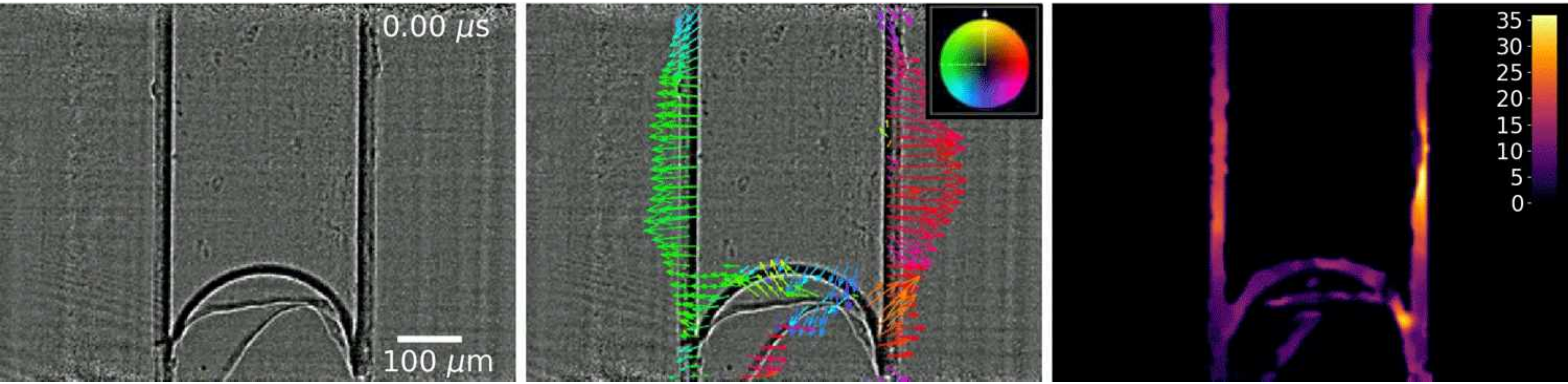
But XFEL's has also unique issues!

Will sample or optics evaporate after first pulse?
Will all possible fluctuations allow for quantitative imaging?



Performed at SPB instrument (2019)

First MHz rate X-ray microscopy at European XFEL

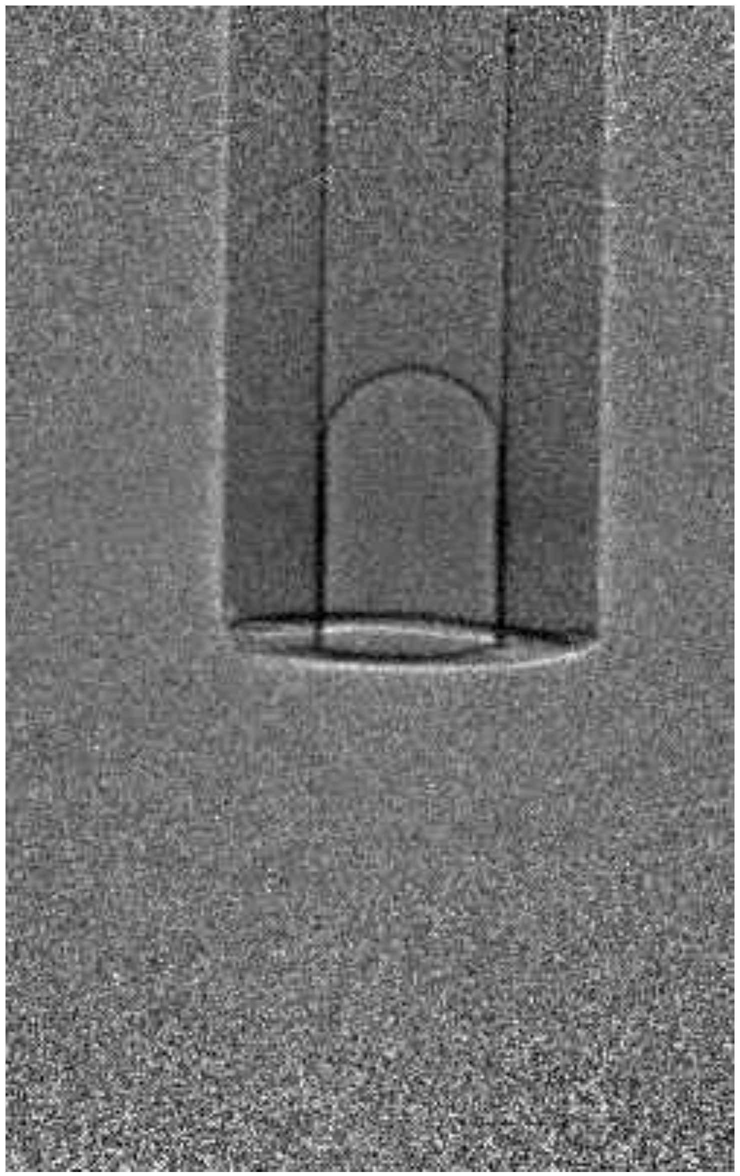


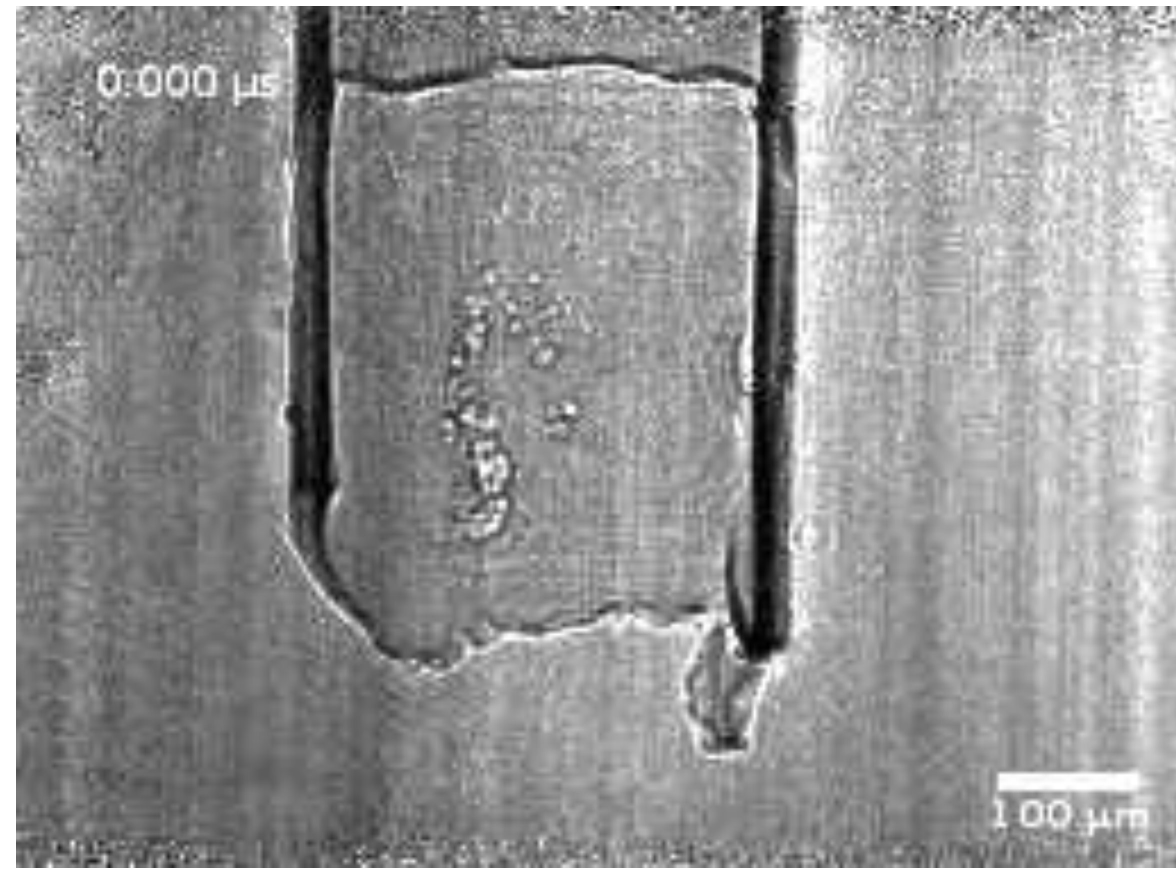
Laser induced capillary breakage filmed using 1.128 MHz sampling rate at EuXFEL. Middle figure shows displacement vectors of moving parts and figure on right shows velocities in m/s units. Performed at SPB instrument (2019)

P. Vagovic, T. Sato, L. Mikes, G. Mills, R. Graceffa, F. Mattsson, P. Villanueva-Perez, A. Ershov, T. Farago, J. Ulicny, H. Kirkwood, R. Letrun, R. Mokso, M. Zdora, M. Olbinado, A. Rack, T. Baumbach, J. Schulz, A. Meents, H. Chapman, and A. Mancuso, "Megahertz x-ray microscopy at x-ray free-electron laser and synchrotron sources," Optica **6**, 1106-1109 (2019).

Image quality (qualitative) comparison Synchrotron vs EuXFEL

Both sequences normalised in a same way by the background





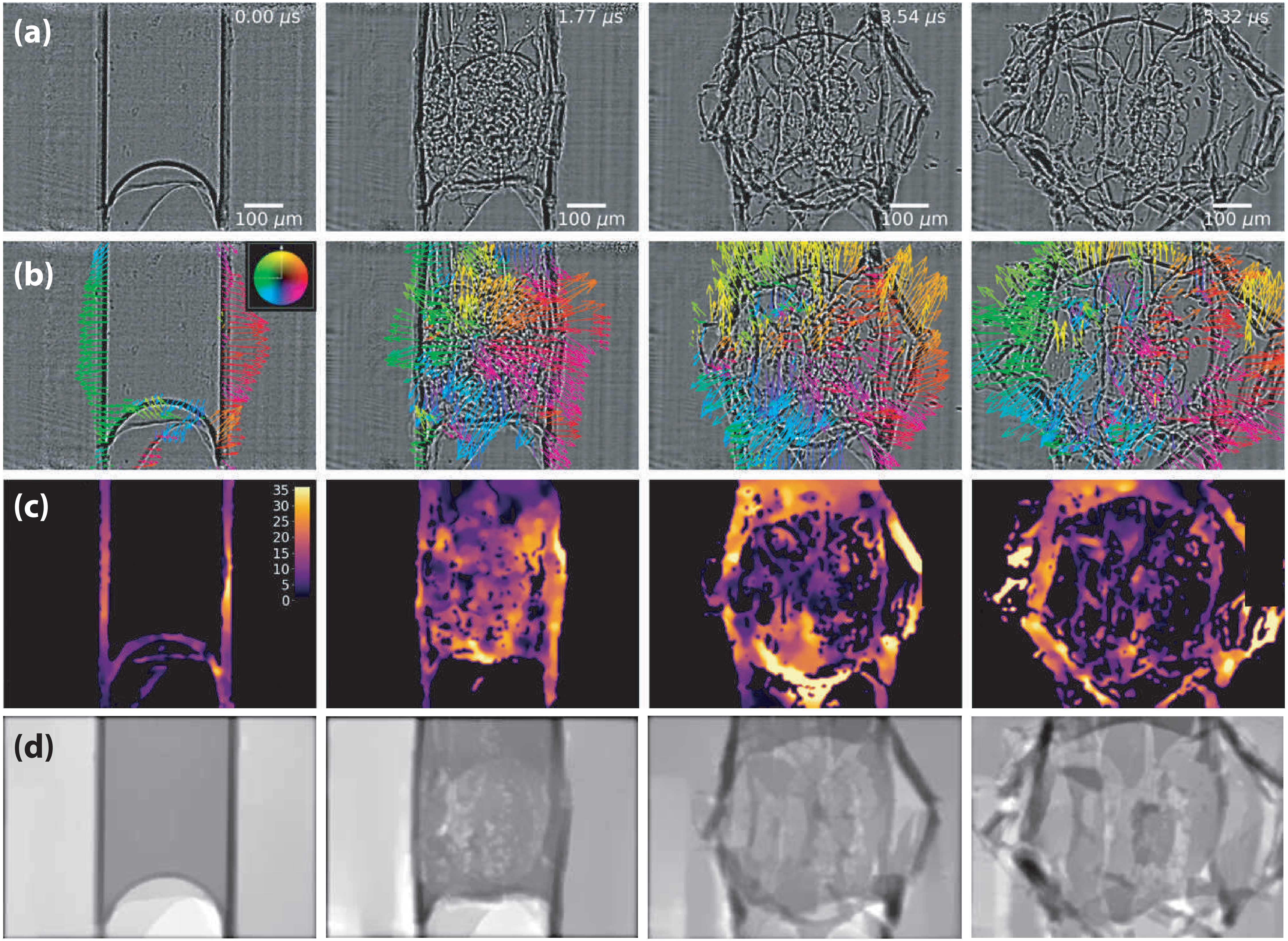
EuXFEL data
Optical magnification: 10x
Pixel size: 3.2 um
Scintillator thickness: 8um
Photon Energy: 9.3 keV

Synchrotron data:
Optical magnification: 4x
Pixel size: 8 um
Scintillator thickness: 100um
Photon Energy: 32 keV

+ For synchrotrons: very stable beams

+ For EuXFEL: much higher intensity

First MHz X-ray microscopy at hard X-Ray XFEL



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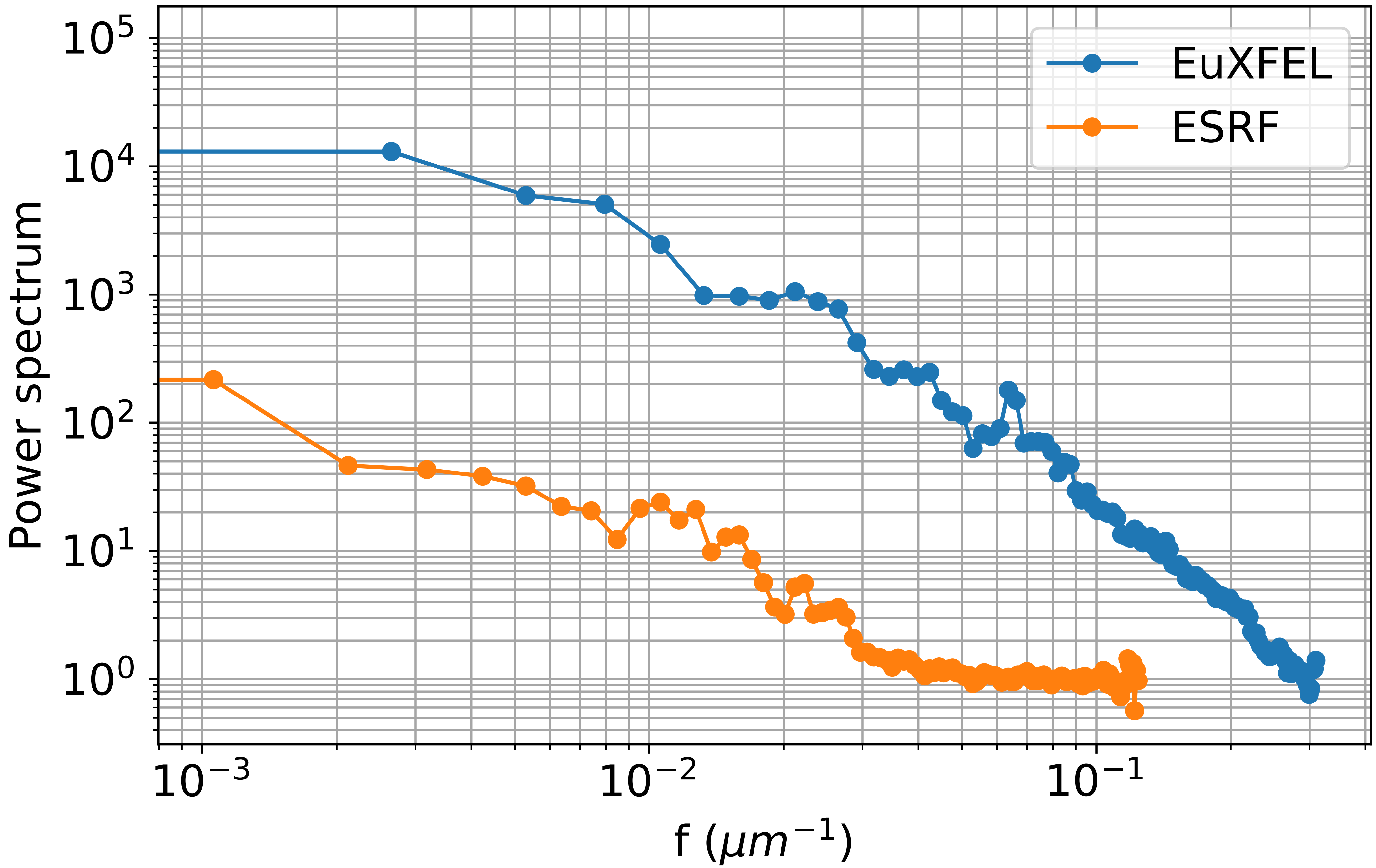
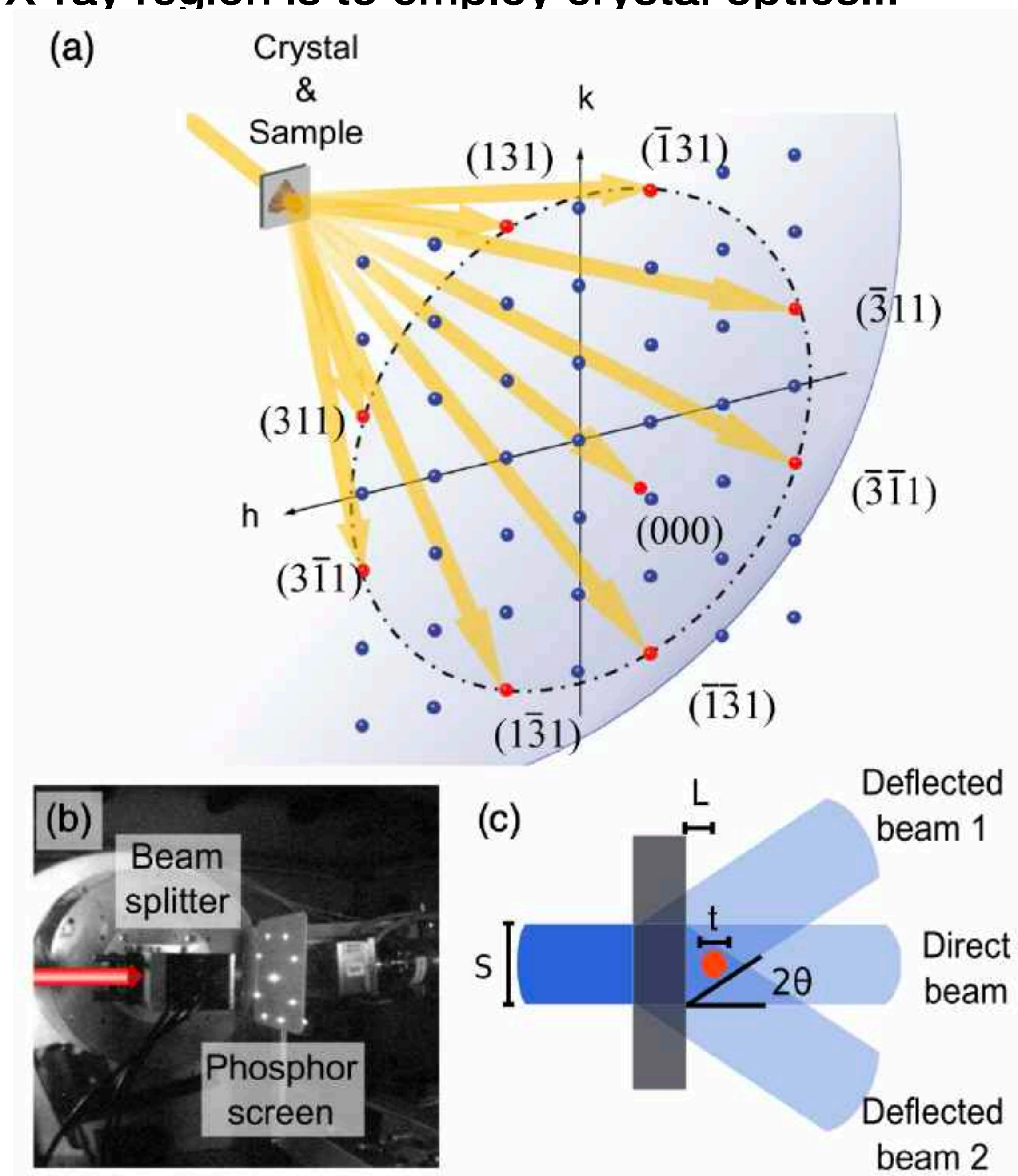


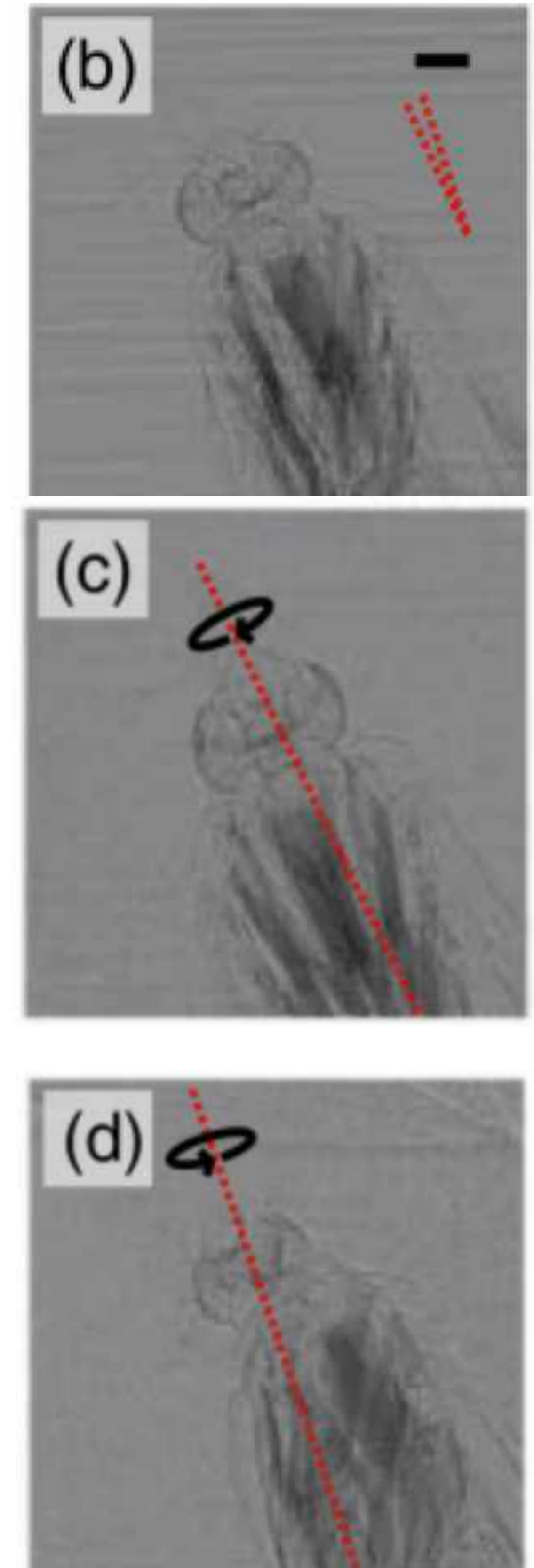
Two orders higher power spectrum at XFEL, even with higher resolution with much less efficient optical system!

We might be able to exploit high flux and MHz sampling at EuXFEL for MHz tomoscopy …. But how?

Towards MHz rate multi-projection imaging Or MHz rate tomoscopy

Only way for fast 3D imaging (>=1kHz sampling rate) in hard X-ray region is to employ crystal optics!!!





P. Villanueva-Perez, B. Pedrini, R. Mokso, P. Vagovic, V. Guzenko, S. Leake, P. Willmott, P. Oberta, C. David, H. Chapman, and M. Stampanoni, "Hard x-ray multi-projection imaging for single-shot approaches," Optica 5, 1521-1524 (2018).

Development of multi-projection MHz X-ray tomoscopy

Project **INVISION** supported by **RÅC (Röntgen-Ångström cluster)** for imaging of dynamics in metallic foams and granular structures. (Total budget~2M€)

Project **MHz X-ray Microscopy** supported by **Eu.XFEL R&D grant (Total budget~0.8M).**

Project partners

LUND UNIVERSITY

Stephen Hall

Pablo V.-Perez

TU berlin

J. Banhart F. Garcia-Moreno

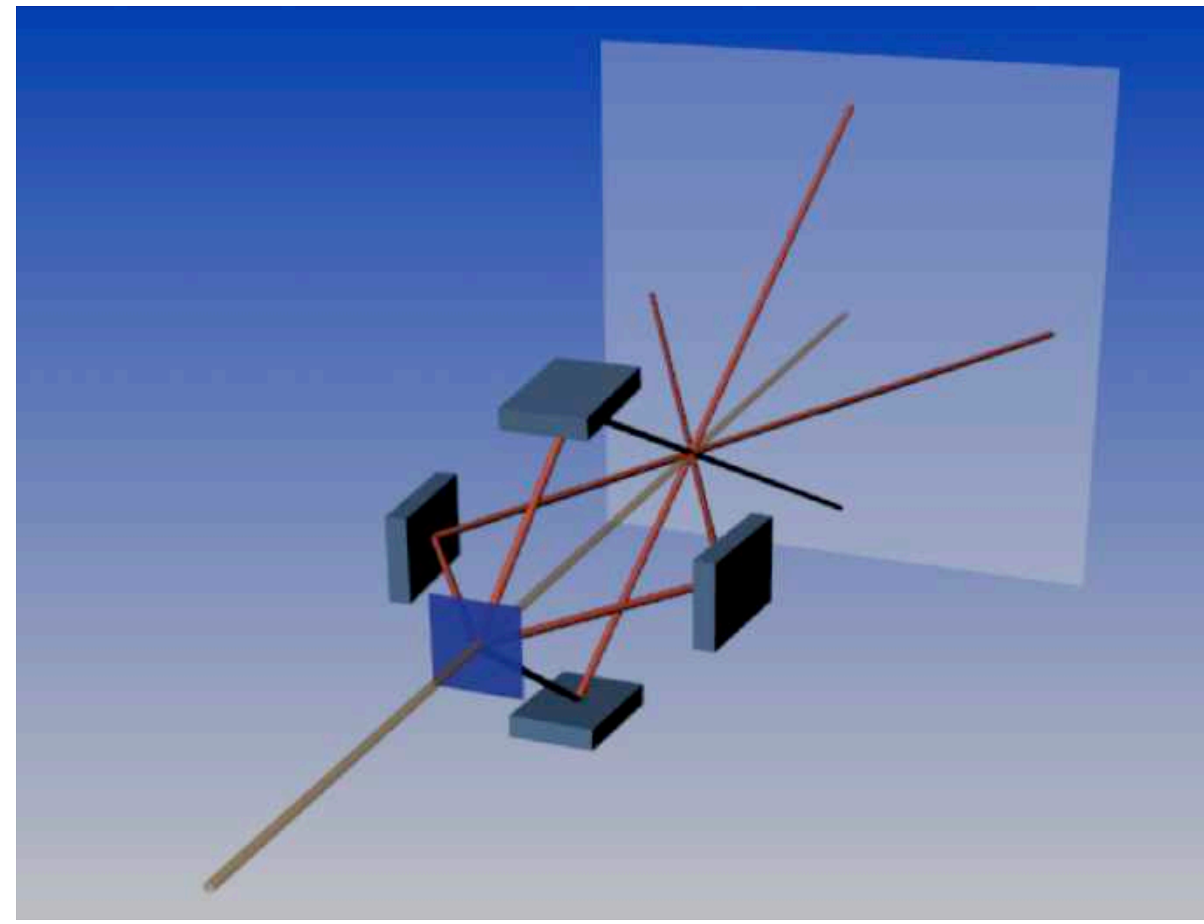
European XFEL

Valerio Bellucci

YOU?

MAX IV

Rajmund Mokso



Conceptual design of 4+1 projection demonstrator based on diamond 001 splitter and Si recombining crystals.

PostDoc position available!

Contact: patrik.vagovic@cfel.de

Summary

- Fast imaging with single pulse exposure and MHz sampling at synchrotrons is possible but with limited spatial resolution and limited only projection imaging

- EuXFEL MHz rate radiography/radioscopy we demonstrated at 1.13 MHz sampling rate, higher resolution and higher frame rate (up to 4.5MHz) is possible … but data treatment must be more sophisticated

- 3 orders higher flux may allow for tomoscopy using MHz sampling with single pulse exposure at EuXFEL

- Collaboration with industry is very welcome! In case of interest please contact EuXFEL Industrial Liaison Office:

antonio.bonucci@xfel.eu

- and in case of interest in scientific collaboration please contact me:

patrik.vagovic@cfel.de

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Margie Olbinado
Alexander Rack

APS
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Valerio Bellucci
Rita Graceffa
Romain Letrun
Henry Kirkwood
Mikako Makita
Joachim Schulz
Adrian P. Mancuso

Lund University

Pablo Villanueva-Perez
Rajmund Mokso
Frans Mattson

Karlsruhe Institute of Technology

Alexei Ershow
Tomas Farago
Tilo Baumbach

Diamond Light source

Marie-Christine Zdora
Silvia Cippiccia

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European XFEL
DESY
MAX-PLANCK-GESELLSCHAFT
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