A talk on X-ray imaging of small bubbles in water…

Katasushika Hokusai (1760-1849)

small bubbles actually

cavitation bubble = (quasi-) spherical gas phase in liquid
when hydrostatic pressure falls below vapor pressure

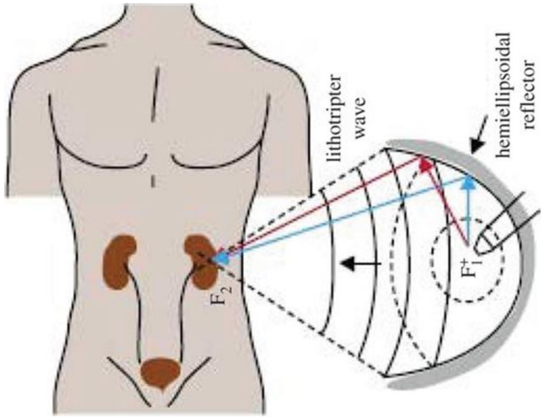
far from equilibrium -
created by laser pulse (optical breakdown)
of strong ultrasound field

Tim Salditt
Institut für Röntgenphysik, Universität Göttingen

MID workshop, XFEL/DESY User Meeting, 24.1.2022

learn about **cavitation**

relevant for engineering, life sciences & medicine

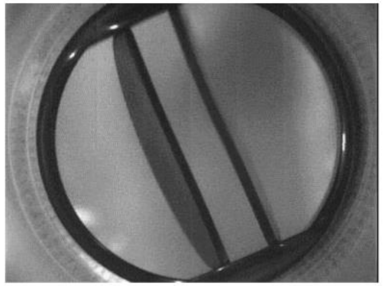


Cavitation limits performance of :

- ship propellors, blades
- pumps, motors

Cavitation enables:

- ultrasonic cleaning
- Laser ablation for drilling &hardening
- nano-particle production



artificial heart valves

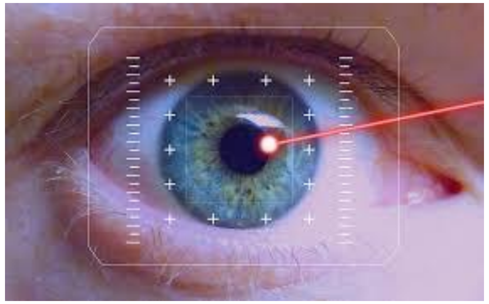
Different biomedical applications:

- Surgery / laser-tissue interaction
- drug delivery
- contrast enhancement in radiology

Lithotripter / phacoemulsificatin / ultrasound fat cavitation

Surgery :

- Ophtalmology
  (e.g. lens membrane destruction following cataract surgery)
- Urology and gastroenterology
  (e.g., kidney and gall stone ablation and fragmentation)
- Cardiology and vascular surgery
  (e.g., laser ablation, removal of fibro-fatty, calcified arterial plaque)



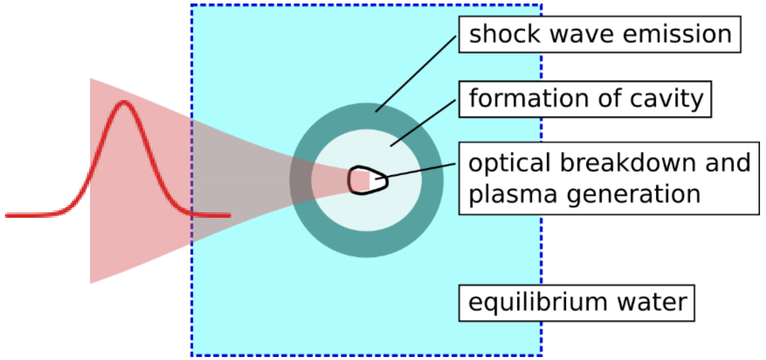
Laser-induced cavitation!

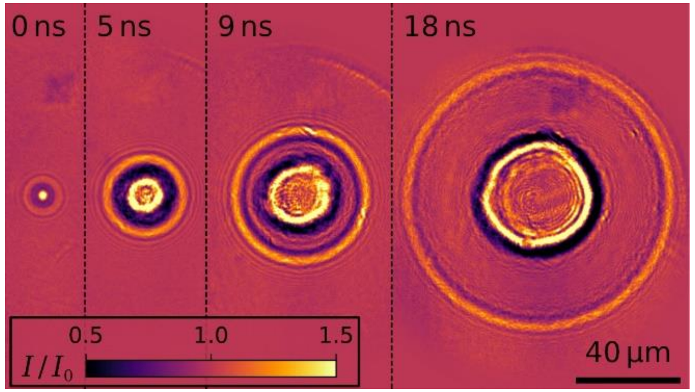
Cavitation in medicine
CE Brennen, Interface Focus Roc. Soc. 2015

and learn about **water** *under extreme conditions*

Single Pulse Full-field holographic X-ray imaging

controlled dynamics!

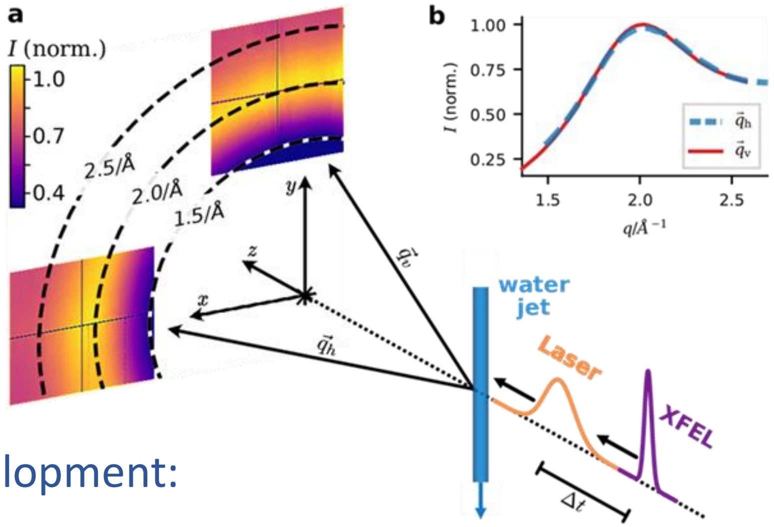




imaging & diffraction!

&

high spatial & temporal resolution !



recent results obtained at MID:

- shockwaves / equation of state @extreme conditions (p2207 & p2545)

Vassholz et al., *Pump-probe X-ray holographic imaging of laser-induced cavitation bubbles with femto-second FEL pulses.* Nature Communications 2021

Vassholz et al., unpublished MS

- laser-induced breackdown (p2807)
- cavitation bubble collapse (p2807)

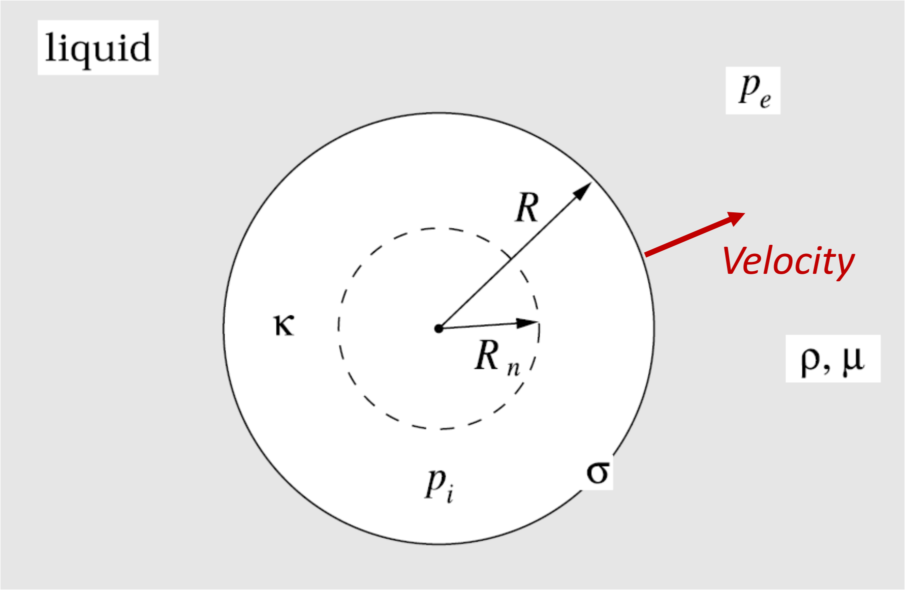
Hoeppe et al., in preparation

method development:

Osterhoff et al. *Nanosecond Timing and Synchronisation for Holographic Pump-Probe Studies at XFELs*. Journal of Synchrotron Radiation 2021

Hagemann et al., *Single-pulse phase-contrastimaging at free-electron lasers in the hard X-ray regime*. Journal of Synchrotron Radiation 2021.

Physics of bubbles and bubble oscillations



$$\rho R\ddot{R} + \frac{3}{2}\dot{R}^2 = p_i - p_e$$

Rayleigh equation (1917)

Rayleigh-Plesset equation

$$\rho R\ddot{R} + \frac{3}{2}\dot{R}^2 = p_{gn}\left(\frac{R_n}{R}\right)^{3\kappa} + p_v - p_{stat} - \frac{2\sigma}{R} - \frac{4\mu}{R}\dot{R} - p(t)$$

$$p - p_0 = B\left(\left(\frac{\rho}{\rho_0}\right)^m - 1\right)$$

Tait eq.

$$B = K/m \quad m = c_p/c_v \simeq 7$$

R: radius
R_n : radius at equilibrium
p_i: internal pressure
p_e: external pressure
σ: surface tension
κ: adiabatic exponent
ρ: density
μ: (dynamics) viscosity

Interesting and extreme physical states and phenomena:

- bubble collapse: *T ? p ? R_{min} ?*
- *sonoluminescence*
- caviation in artifical heart valves
- nature of the interfaces
- equation of state of H_2O: beyond Tait

…a lot is known, but all based on bubble trajectory, how about interior ? Always a clear phase separation ?

Physics of bubble oscillations, W. Lauterborn, T. Kurz Rep.Prog. Phys. 2010

Small bubble collaboration & Acknowledgements

Hannes Hoeppe, Markus Osterhoff, Malte Vassholz, Juan Rosello, Atiyeh Aghelmaleki, Robert Mettin, Tim Salditt
Universität Göttingen, III-Phys. Inst.-Biophysik & Institut für Röntgenphysik

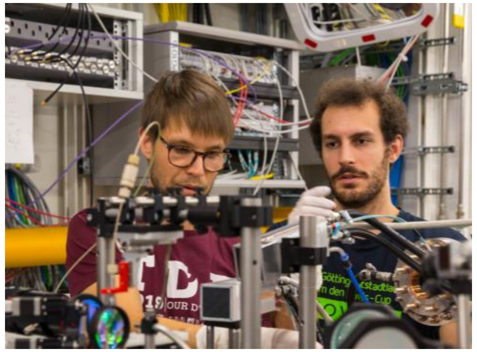
Johannes Hagemann, Frank Seiboth, Andreas Schropp, Christian G. Schroer, *DESY Photon Science*

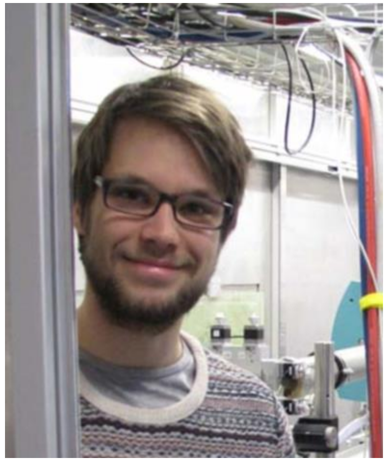
Johannes Möller, Jörg Hallmann, Ulrike Boesenberg, Chan Kim, Markus Scholz, Alexey Zozulya, Wei Lu, Roman Shayduk, Robert Schaffer, Anders Madsen
MID / XFEL

UAC MID 06/2019 @14keV
Beamtime 10/ 2019 @17.8keV
(p2207 & p2545)
Beamtime 10/2021 @18keV
(p2807)

MAX PLANCK SCHOOL of photonics

bmb+f





Hannes Paul Hoeppe Malte Vassholz Markus Osterhoff Johannes Hagemann

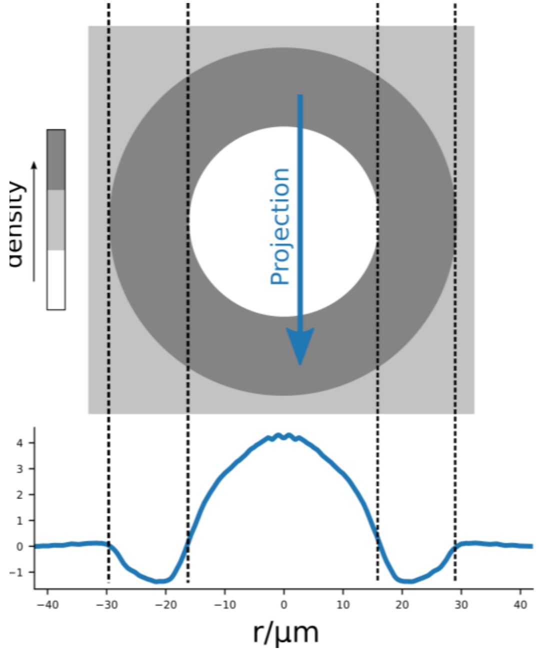
Research questions

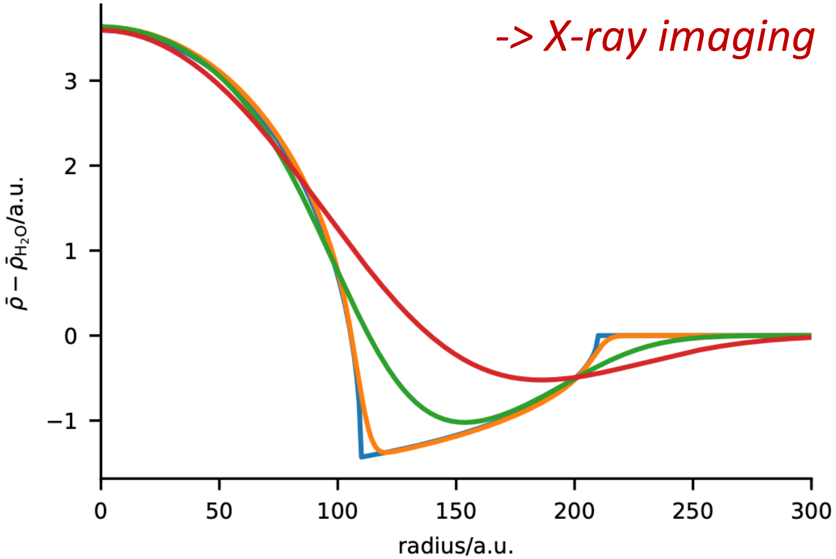
Plasma generated by
Optical breakdown
Multi-photon absorption
$I > 10^{12}$ W/cm^2

A) For laser-generated cavitation bubble:
better understanding of **transition from plasma to cavitation bubble**
B) Shock wave effets can be useful or unwanted depending on applications
-> detailed knowledge of the shock emission processes and the **properties of the shock wave** required
C) Fundamental physics: extreme conditions at **bubble collapse** (sonoluminescence, T> 10^4 K)

Challenge: Spatio-temporal resolution, contrast refraction, scattering, opacity, resolution –

-> X-ray imaging





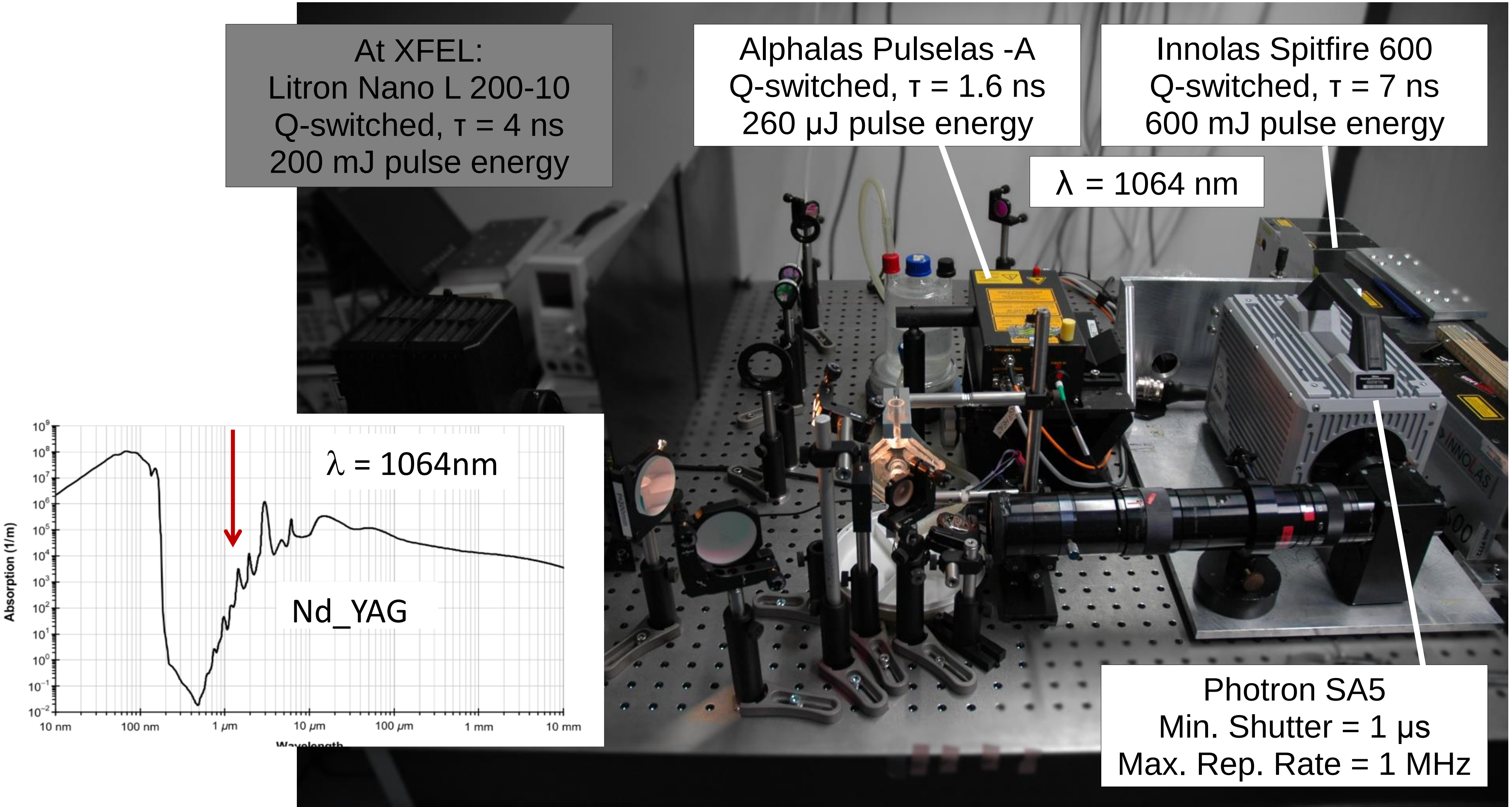
- bubble evolution
- density of the shockwave ?
- sharp interfaces gas/water ?

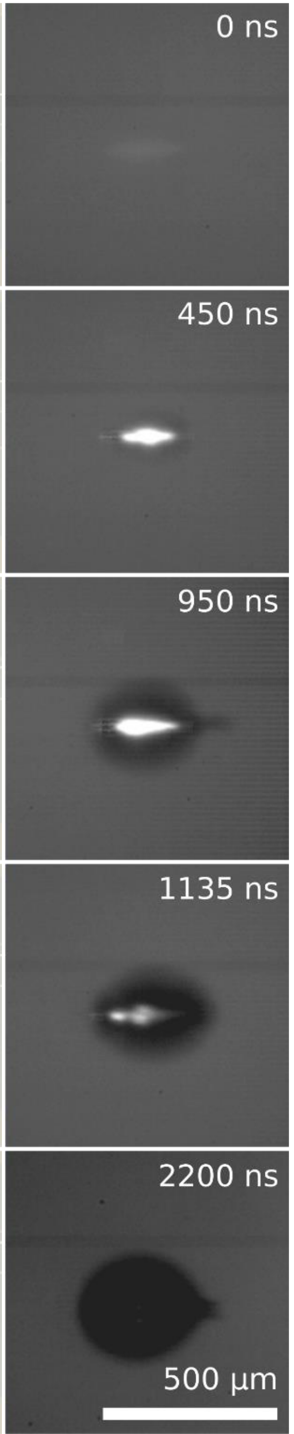
radial density profile !

High speed optical imaging

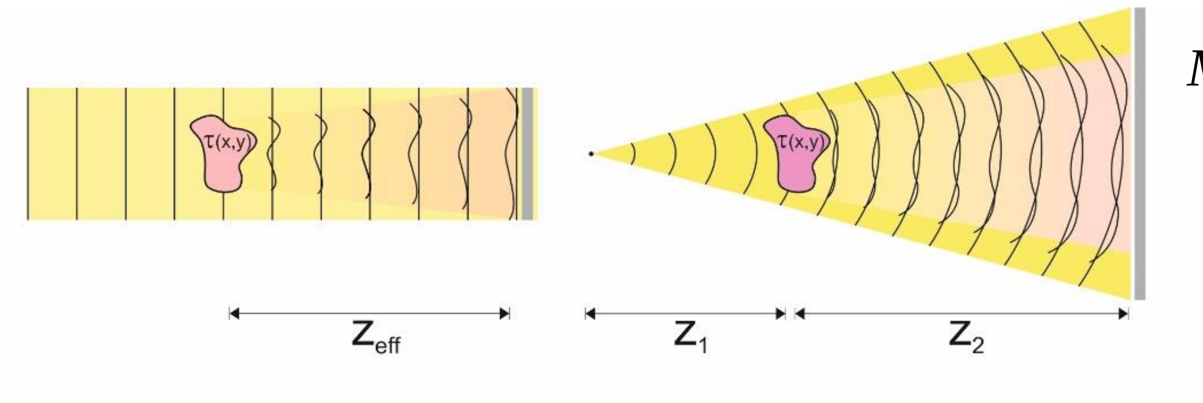
Hannes Hoeppe,
Juan Rosello

At XFEL:
Litron Nano L 200-10
Q-switched, τ = 4 ns
200 mJ pulse energy





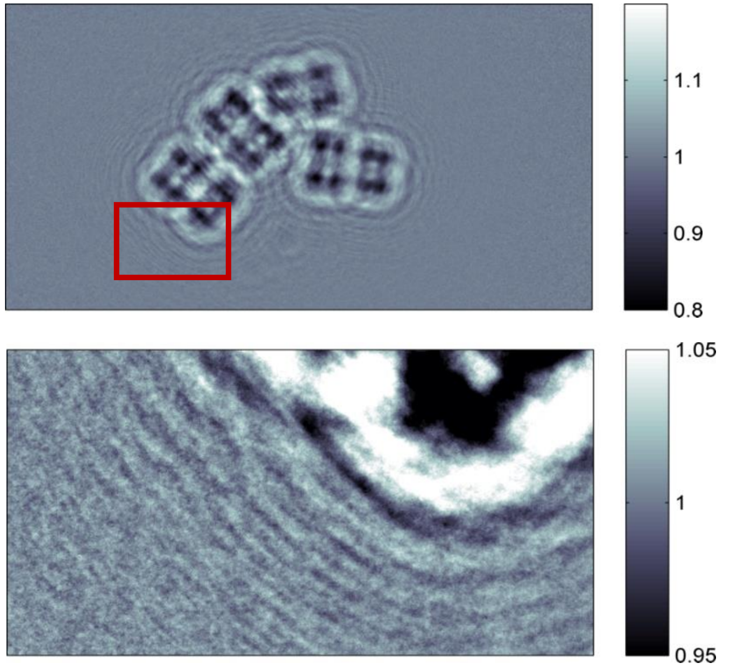
Full-field X-ray imaging / (inline) holography



$$M = \frac{z_1 + z_2}{z_1}$$

$$z_{eff} = \frac{z_1 z_2}{z_1 + z_2}$$

SR: Blurring of fringes & low signal in water

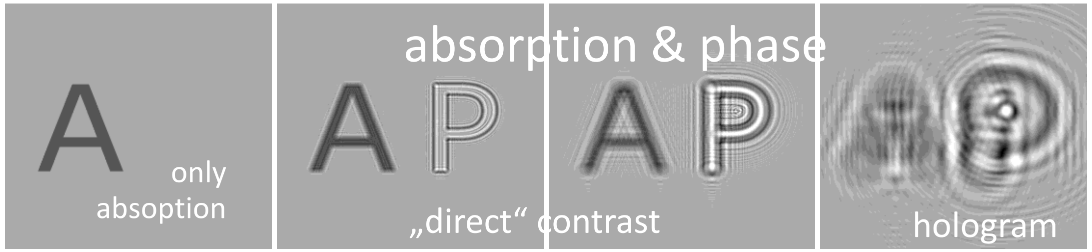


object with complex transmission function $\tau(x,y)$

$$\psi_z = FT^{-1}[\exp[iz\sqrt{k^2 - k_x^2 - k_y^2}]\, FT[\psi_0]]$$

A P

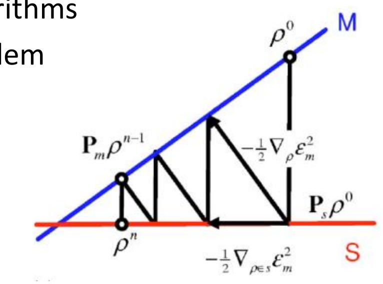
Absorption Phase



Fresnel number F

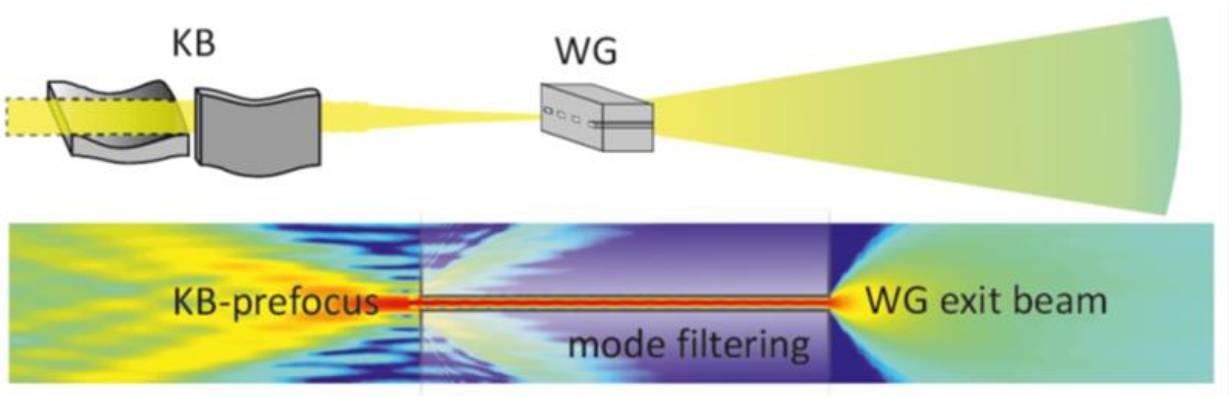
XFEL: no motional blurring,
sharp holograms, outrun radiation damage!

iterative projection algorithms
to solve the phase problem

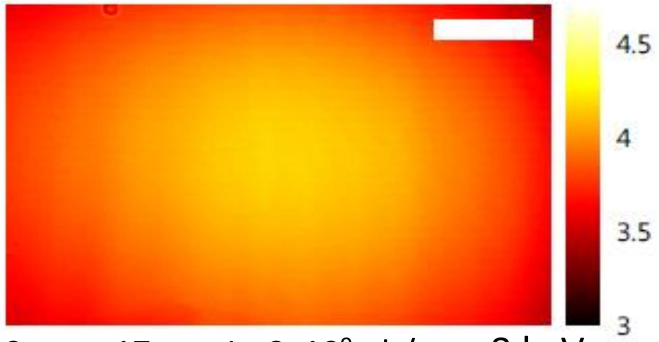


Lohse et al., *A phase-retrieval toolbox for X-ray holography and tomography*, Journal of Synchrotron Radiation (2020)

The empty beam problem in holography



waveguide farfield

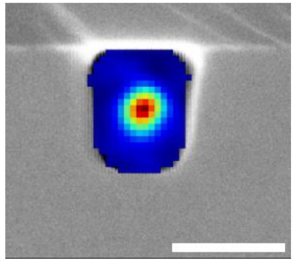


20 nm x 17 nm, $I_0=2x10^9$ ph/s   8 keV

waveguide optics to clean the probe !

Simultaneous probe and object reconstruction for the near-field
A.L. Robisch, K. Kröger, A. Rack, T.Salditt, N.J.Phys. 2015

Reconstruction of wave front and object for inline holography from a set of detection planes
J.Hagemann, A.L.Robisch et al., Optics express 2014



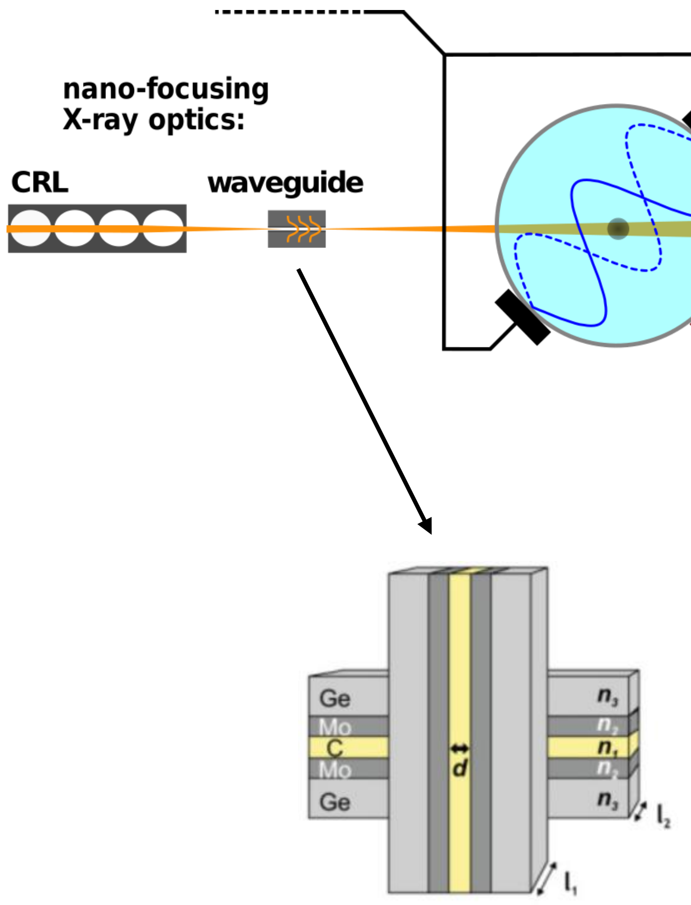
Validity of the empty-beam correction in near-field imaging
C. Homann, T.Hohage, J. Hagemann, A.L. Robisch, T.Salditt
Physical Review A 2014

Divide and update: towards single-shot object and probe retrieva for near-field holography
J. Hagemann, and T. Salditt   Opt.Expr. 2018

Holographic imaging with a hard x-ray nanoprobe: Ptychographic vs. conventional phase retrieval
A.-L. Robisch et al., J. Wallentin, A. Pacureanu, P. Cloetens, and T. Salditt   Opt.Lett. 2016

in 10 Hz MID beam (after alignment) !

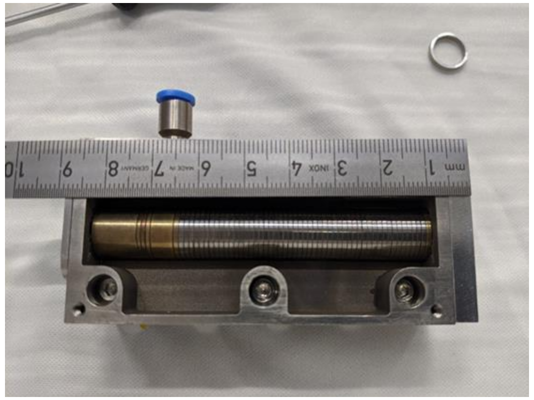
Waveguides at XFEL: first exposure

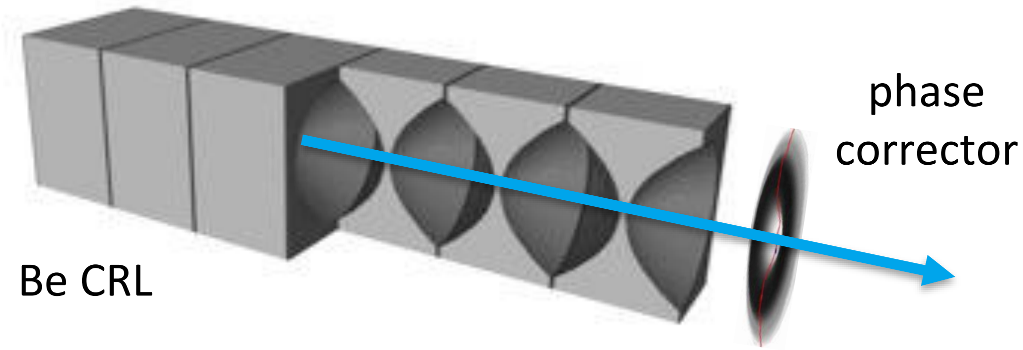


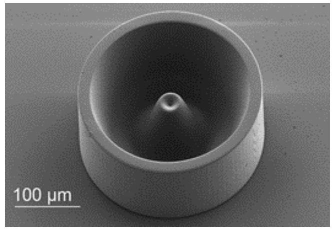
After alignment procedures

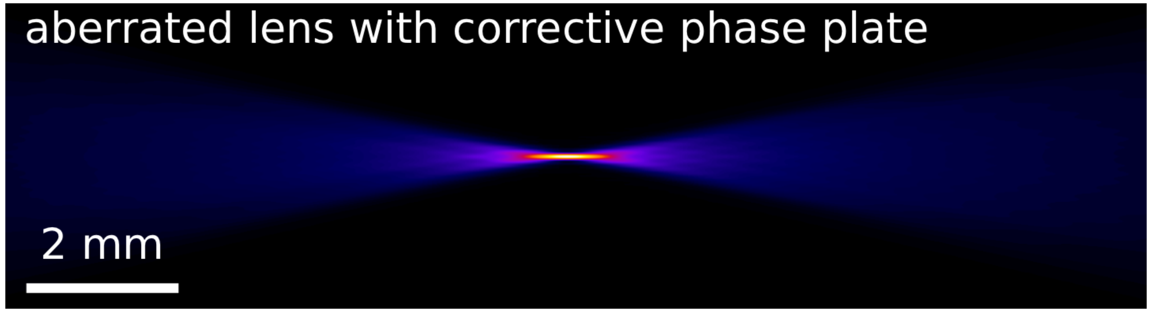
CRL (Be) focusing to ~80nm

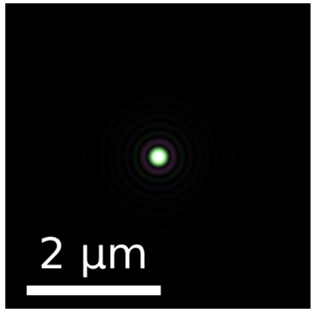
- stack of 50 Be lenses, 300 µm aperture
- f = 297 mm @ 14 keV
- spot size ~80 nm
- printed polymer phase plate
  to correct aberrations









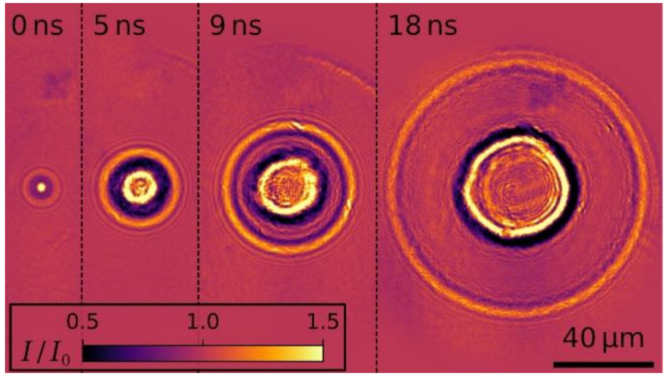


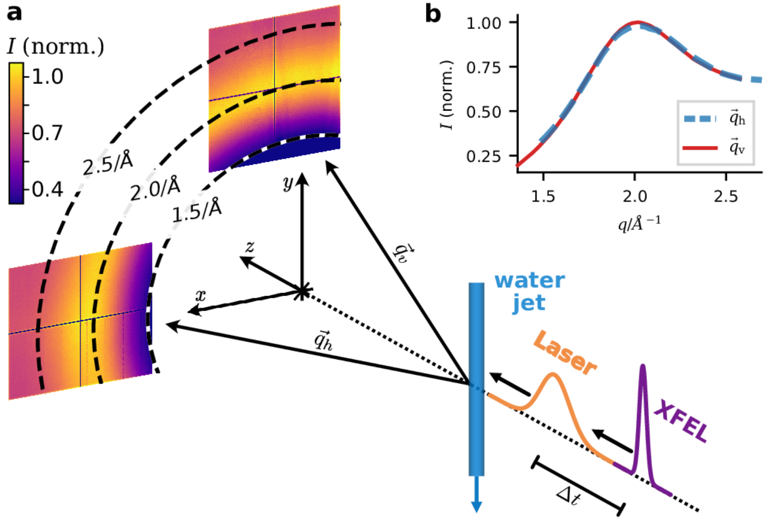
DESY.

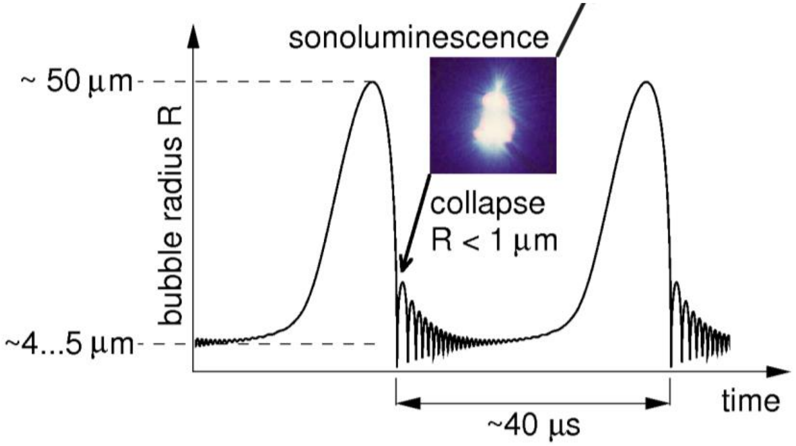
Seiboth, *et al.*, Nat. Comm. (2017); Hagemann et al, J.Synchr.Rad. 2021

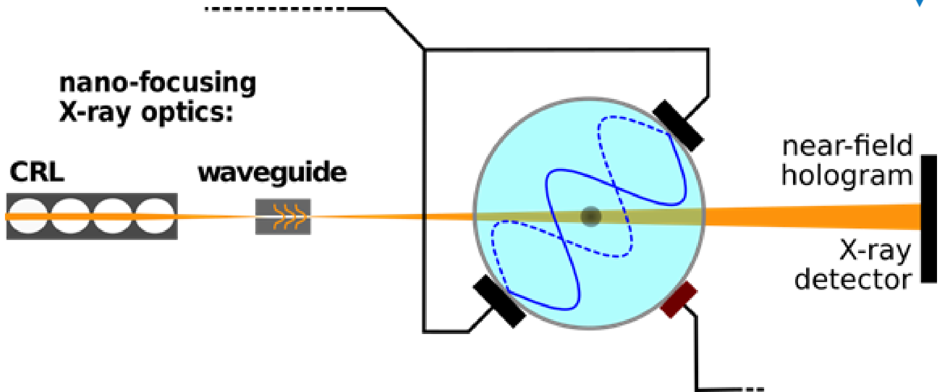
Outline

1) Recap 2019 experiments – *holography*
2) *diffraction from a shockwave*
3) Femtosecond laser-induced breakdown
4) Bubble collapse

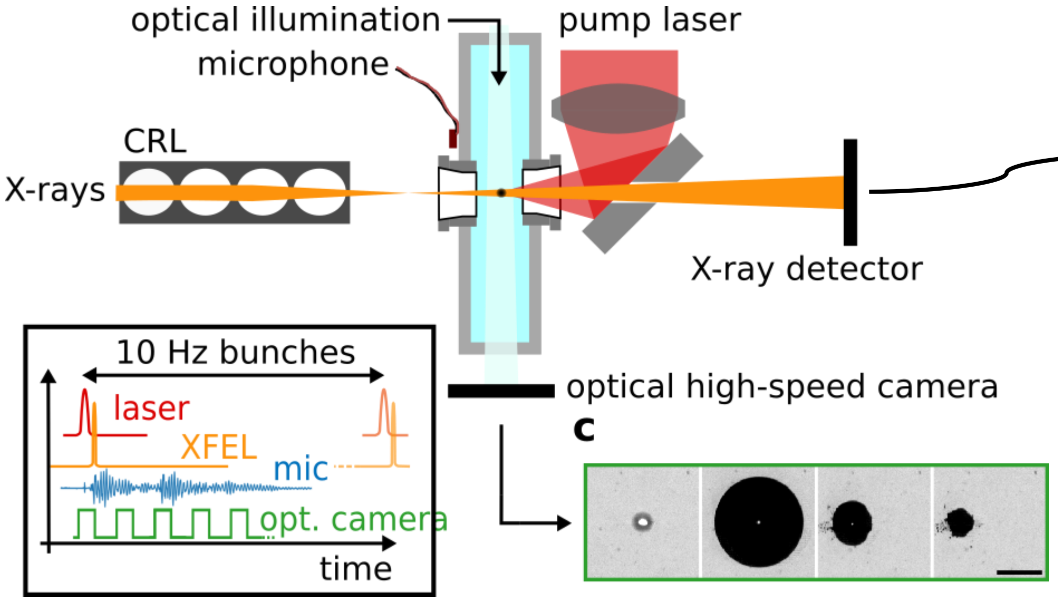




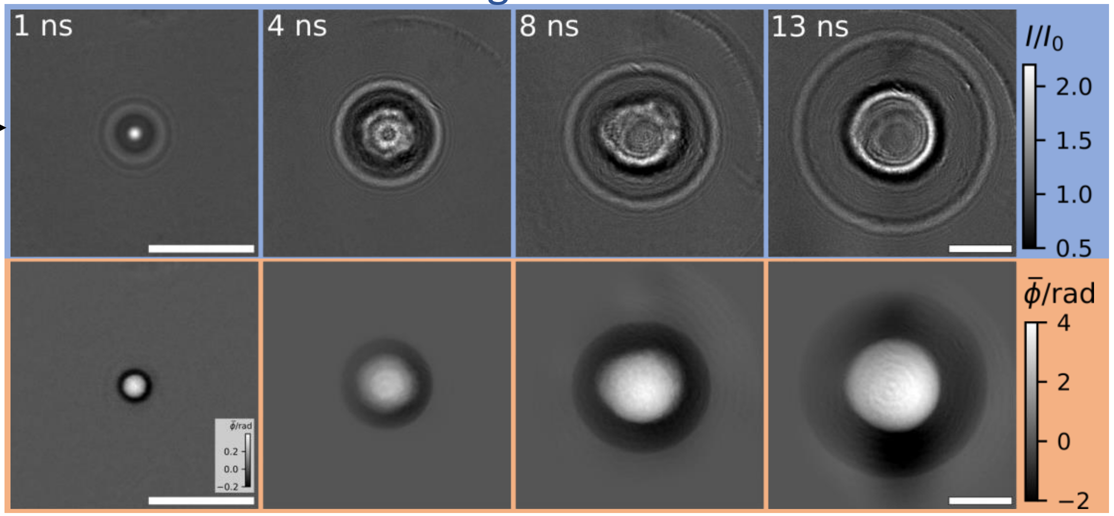




1. X-ray FEL imaging of nanosecond laser-induced cavitation (2019)



Flat-field corrected Holograms



AP phase reconstruction

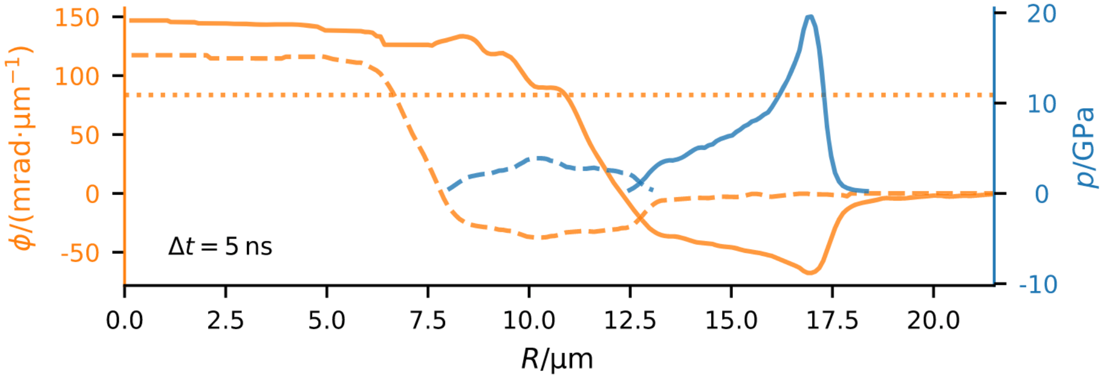
Scalebars: 25um

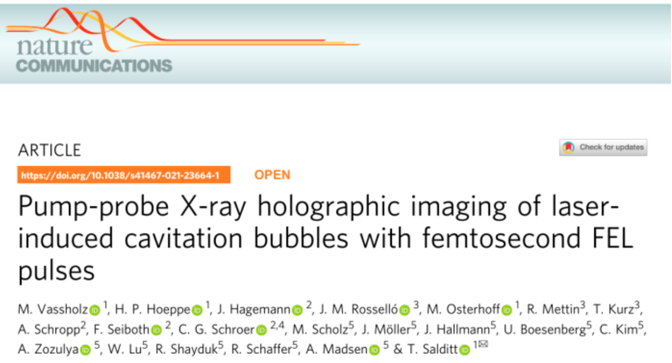
Mass density

$$\rho(R) = \rho_0 \left(1 - \frac{\phi(R)}{k\,\delta}\right)$$

Tait EOS

$$\frac{p(R) + B}{p_\infty + B} = \left(\frac{\rho(R)}{\rho_0}\right)^n$$




nature COMMUNICATIONS

ARTICLE

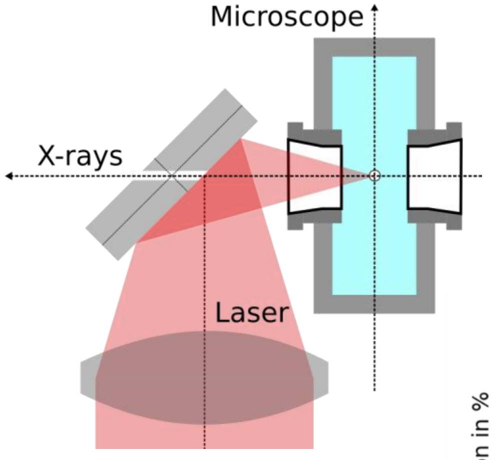
Check for updates

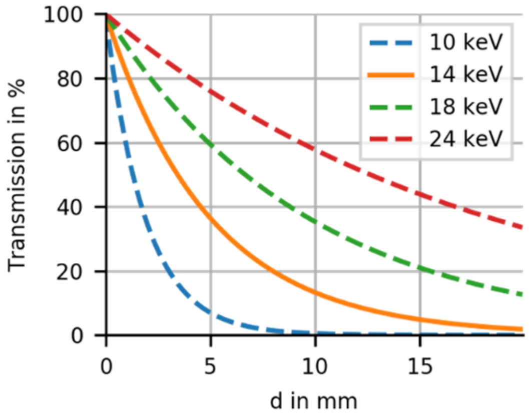
https://doi.org/10.1038/s41467-021-23664-1 OPEN

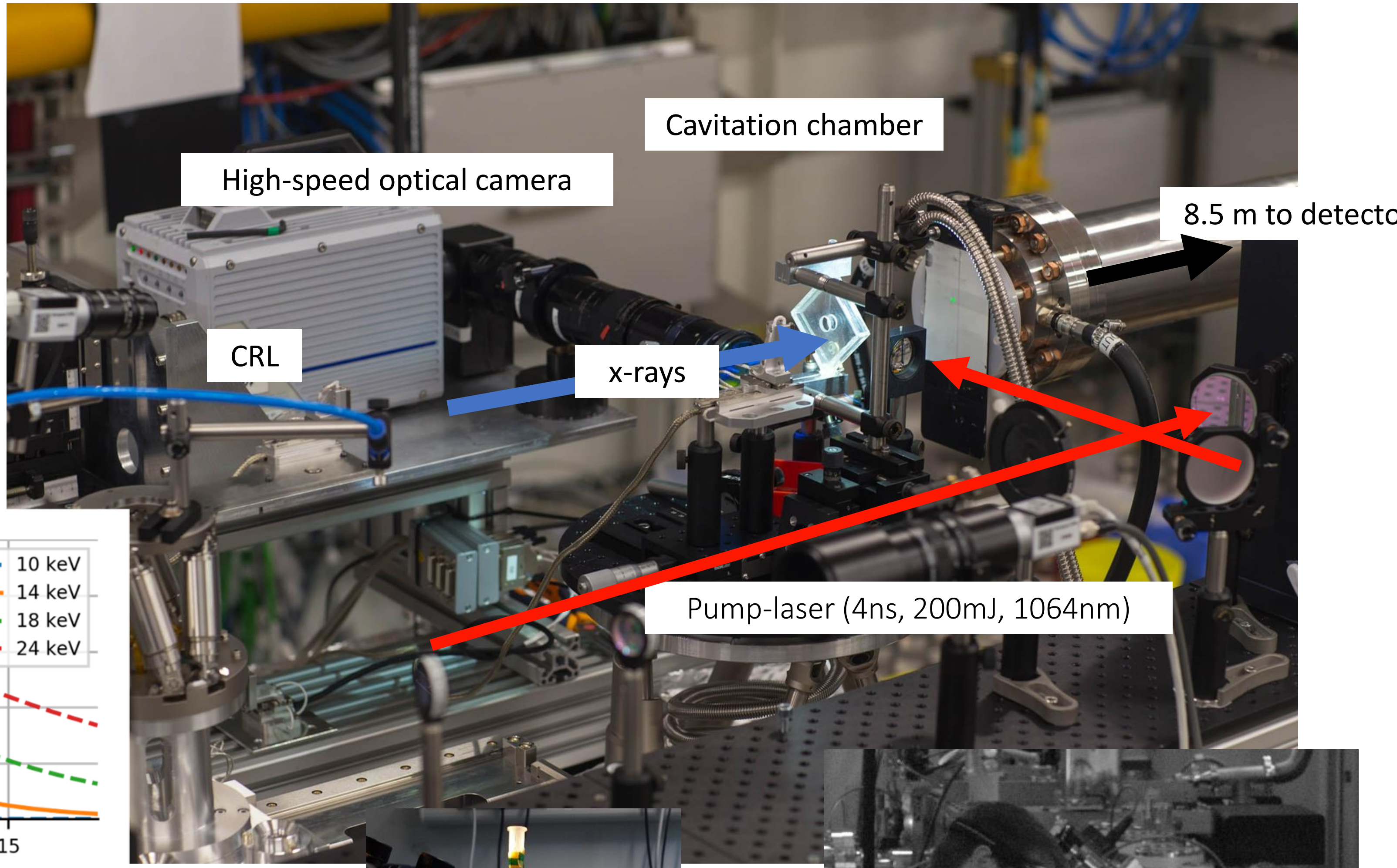
Pump-probe X-ray holographic imaging of laser-induced cavitation bubbles with femtosecond FEL pulses

M. Vassholz[1], H. P. Hoeppe[1], J. Hagemann[2], J. M. Rosselló[3], M. Osterhoff[1], R. Mettin[3], T. Kurz[3], A. Schropp[2], F. Seiboth[2], C. G. Schroer[2,4], M. Scholz[5], J. Möller[5], J. Hallmann[5], U. Boesenberg[5], C. Kim[5], A. Zozulya[5], W. Lu[5], R. Shayduk[5], R. Schaffer[5], A. Madsen[5] & T. Salditt[1]

Cavitation cuvette x-ray compatible…



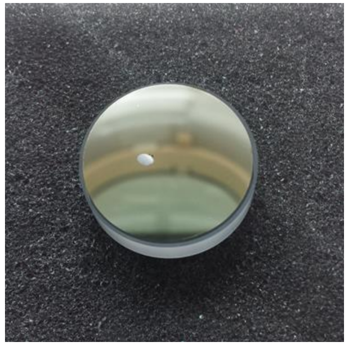


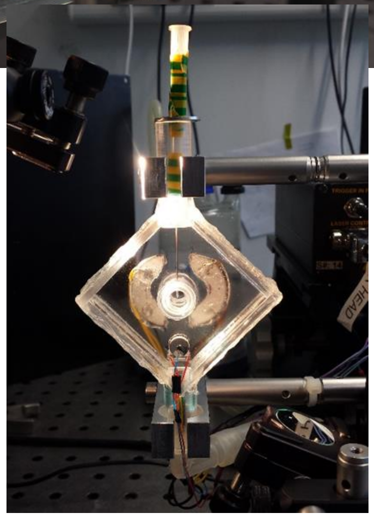


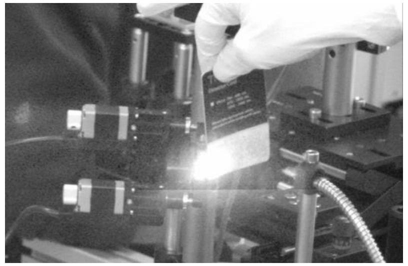
- compatible with XFEL defocused beam
- compatible with IR laser
- compatible with speed optical camera

-> anti-parallel XFEL and IR-beams

Mirror with drilled hole

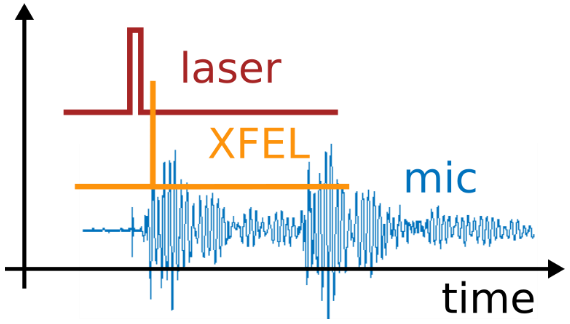


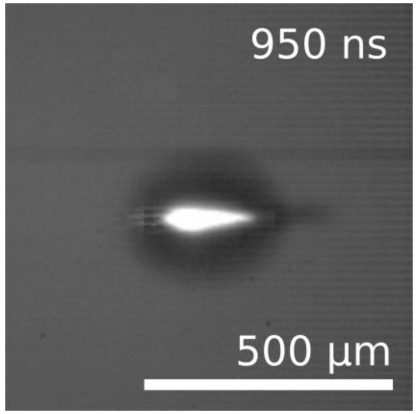


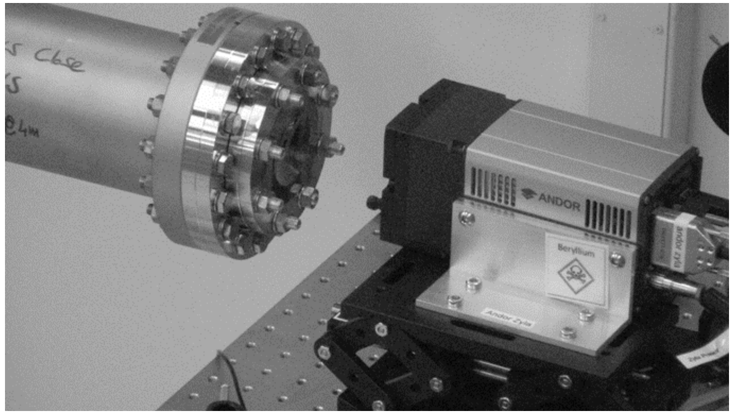


IR- alignment

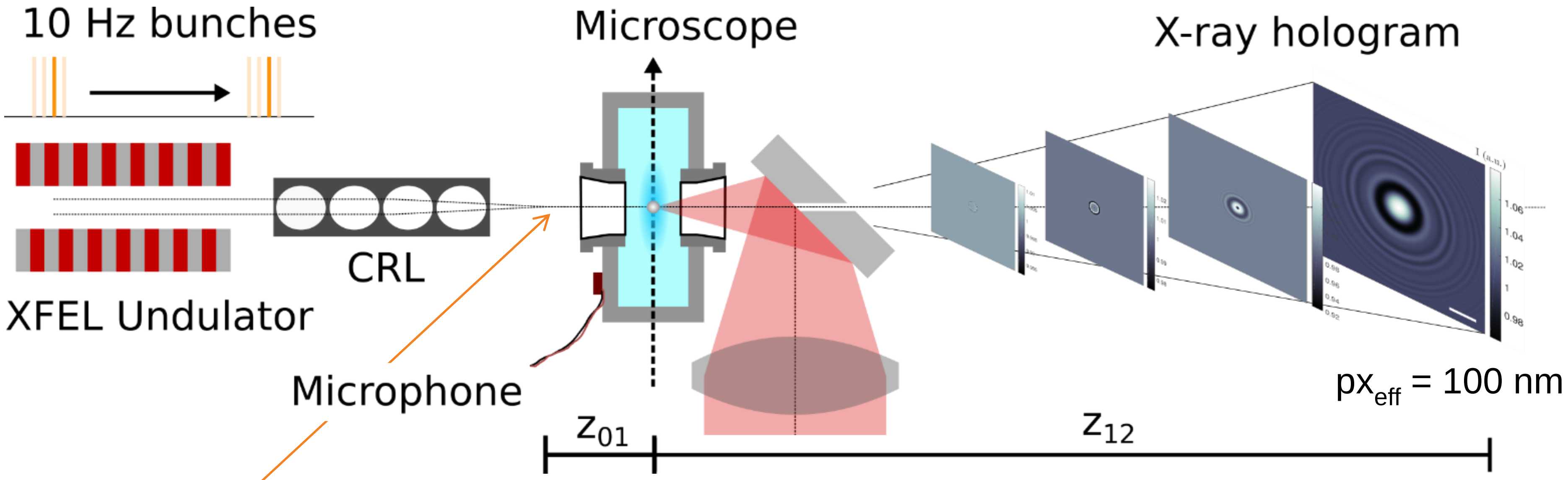
Settings at MID / exp. parameters







Andor Zyla 5.5 HF
20µm LuAG:Ce
px=6.5µm
z=8.859m



10 Hz
600 µJ / pulse
$3 \cdot 10^{11}$ ph / pulse
τ <100fs
E =14keV (UAC)
E= 18keV (Oct.19)

$W_{0,x}$ = 100 nm, div=0.6 mrad

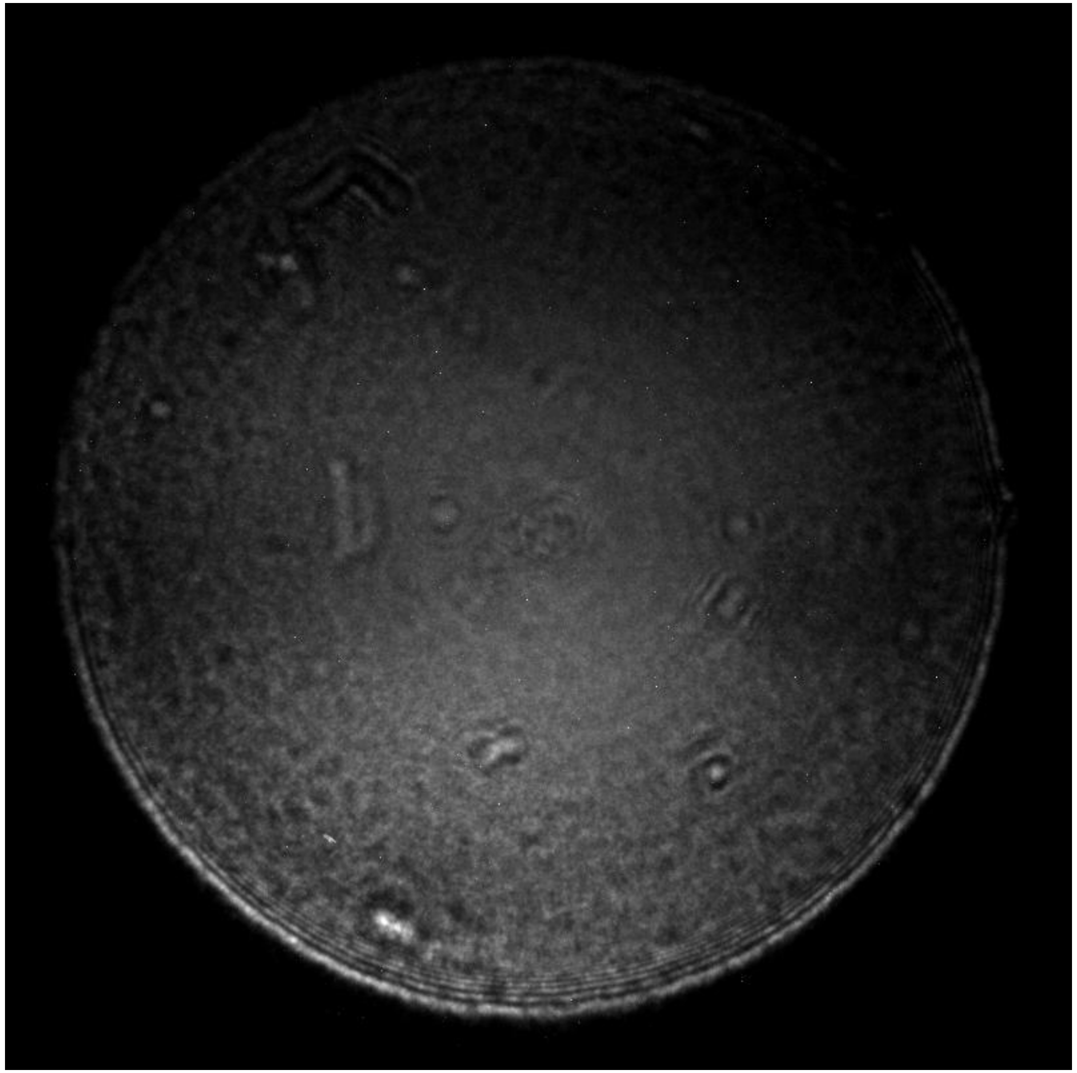
M =61 p_{xeff}=107nm

And this is how it looks – *meet your probe* !

in terms of

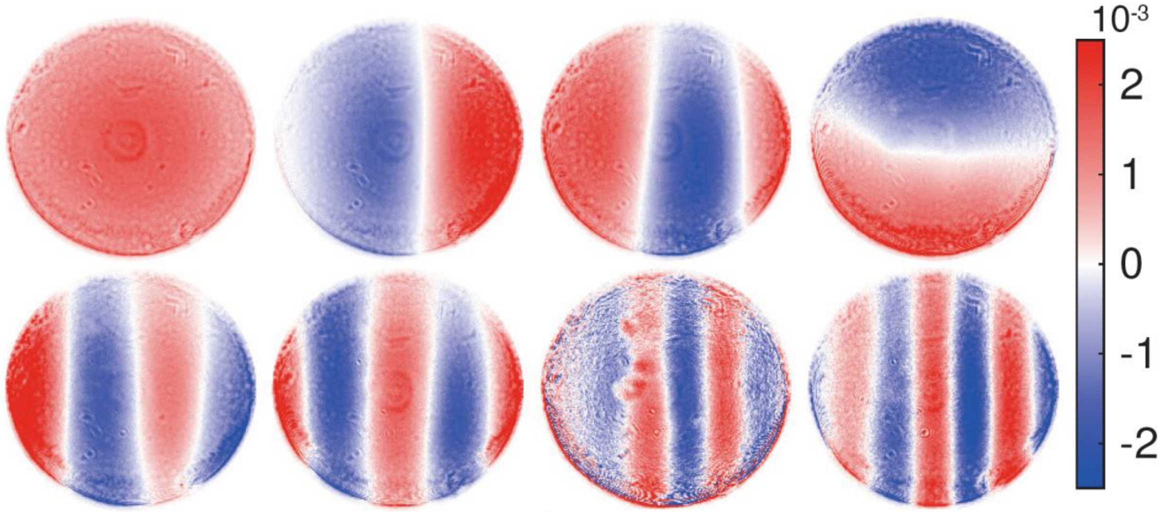
- *divergence,*
- *pointing stability*
- *signal*

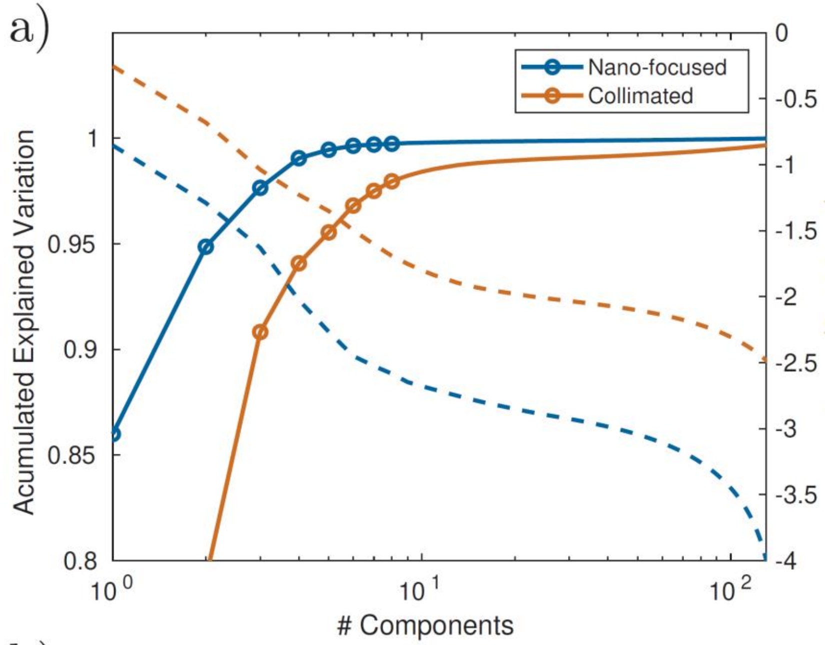
it is all actually
not too bad
for a single pulse!

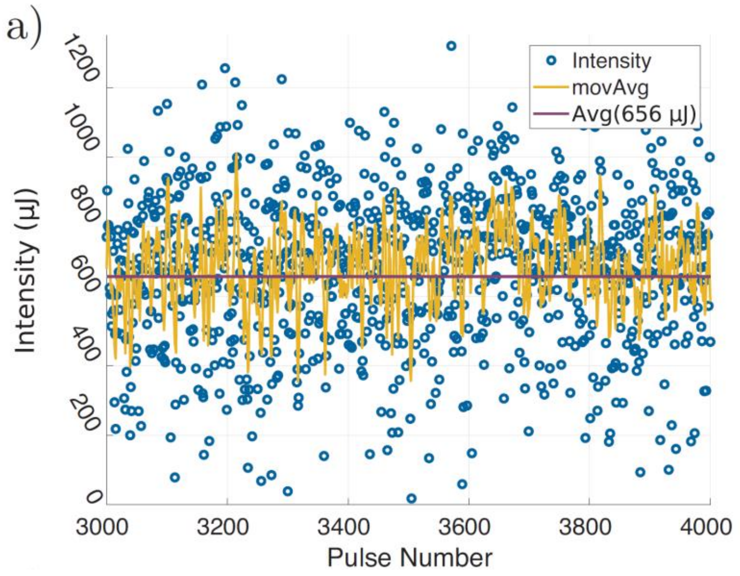


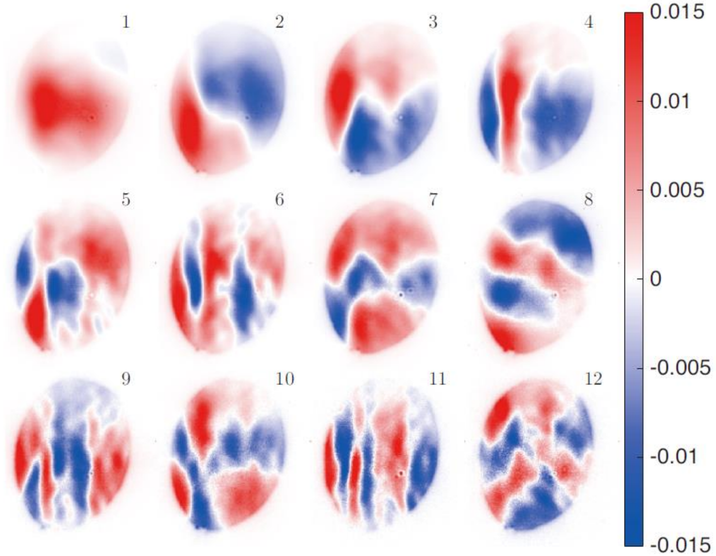
But how to
perform the
flat field correction?

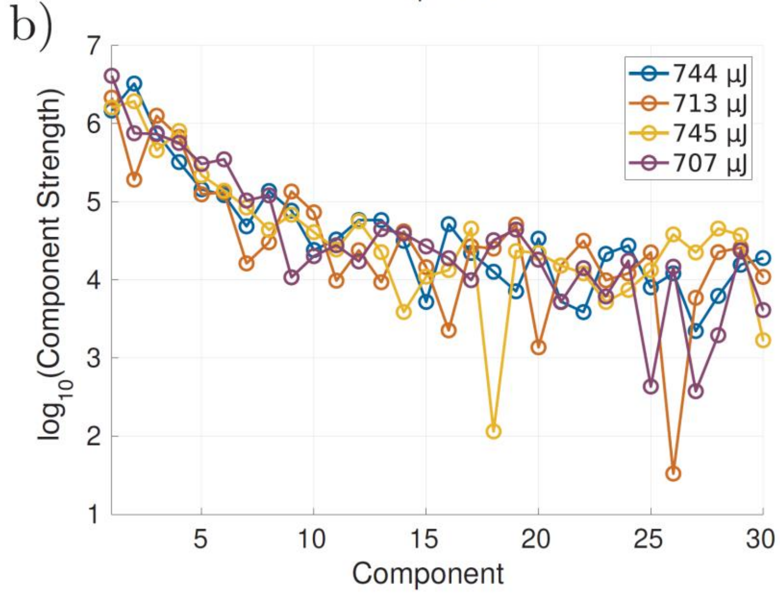
Let’s decompose (PCA analysis)







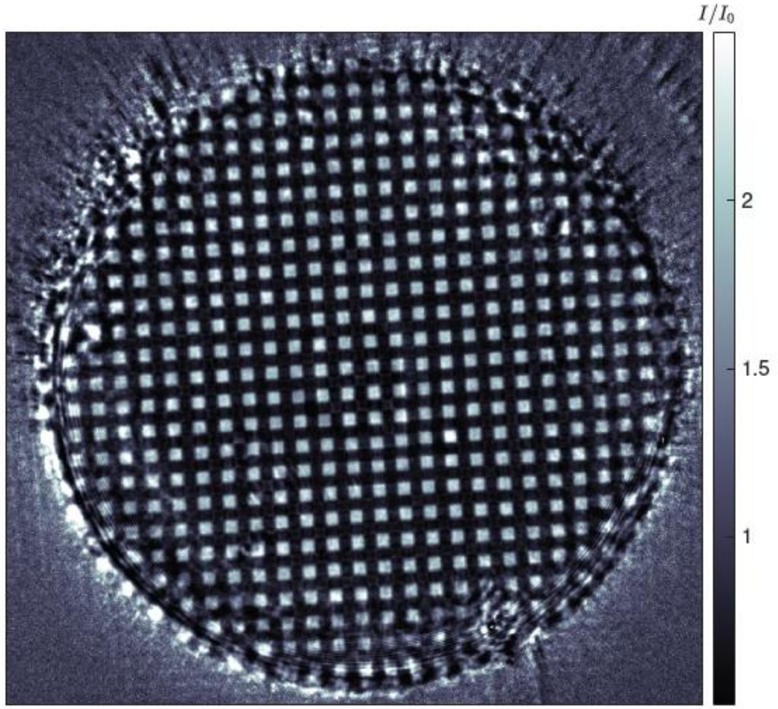




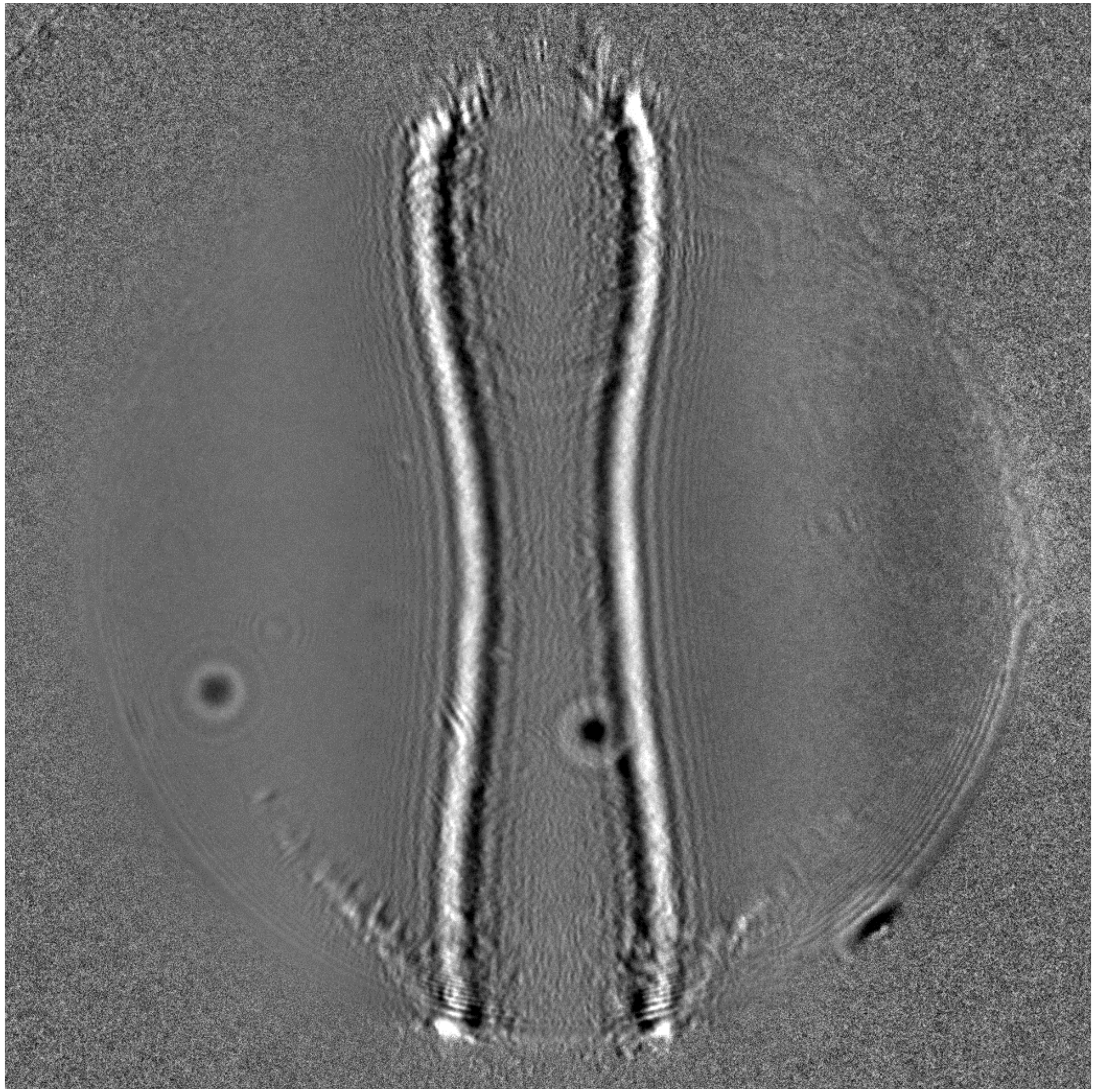
Single-pulse phase-contrast imaging at FEL in the hard X-ray regime
Johannes Hagemann et al. , J. Synchr. Rad. (2021)

Let’s decompose (PCA analysis)

now imaging works!



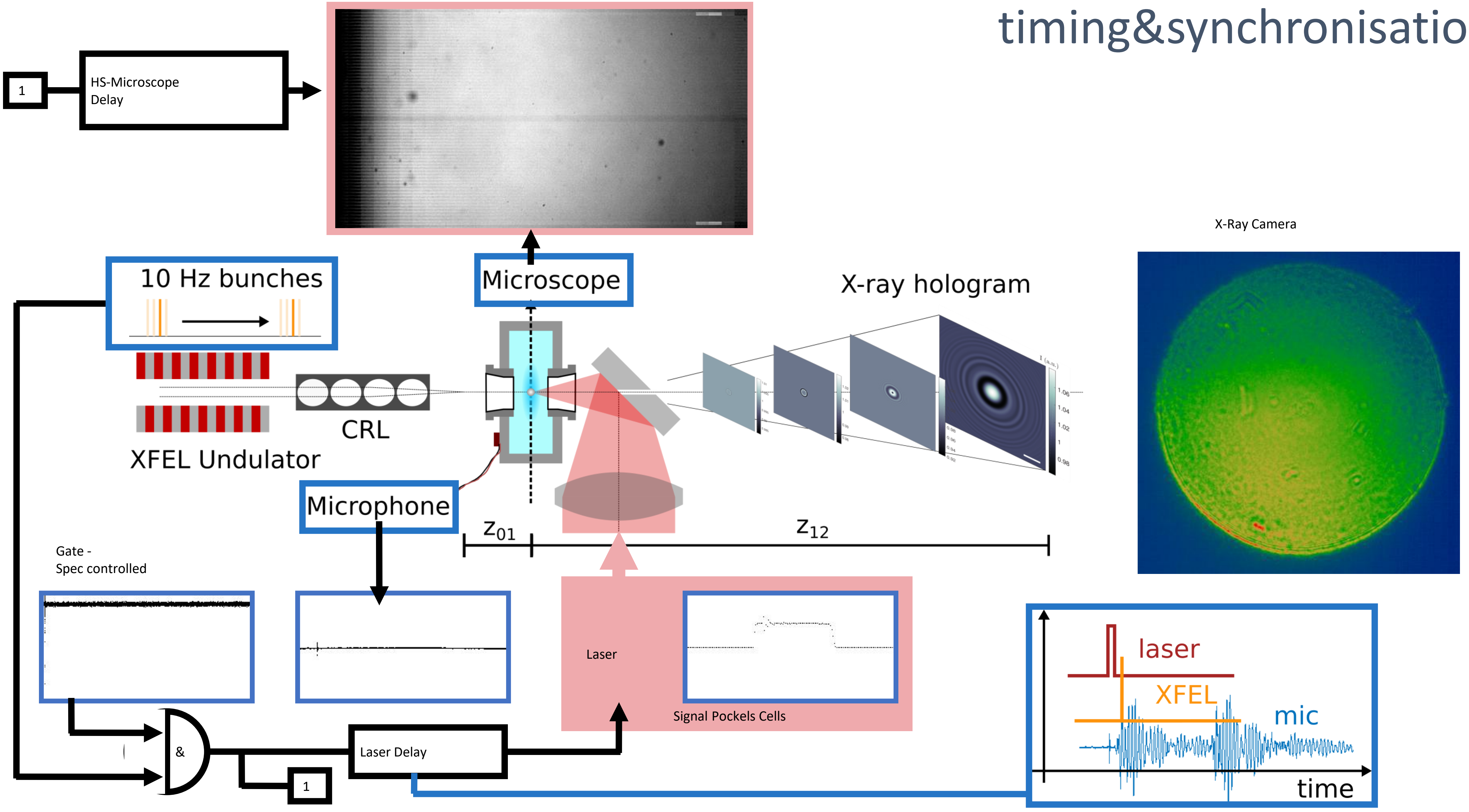
6µmAu mesh



laminar water jet

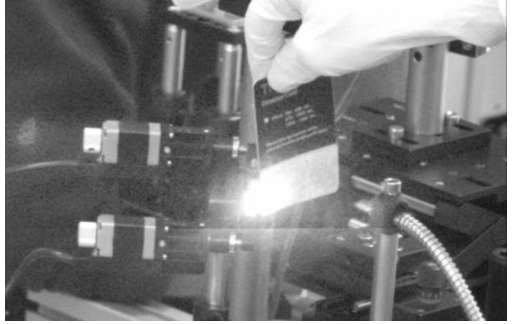
Johannes Hagemann

timing&synchronisation

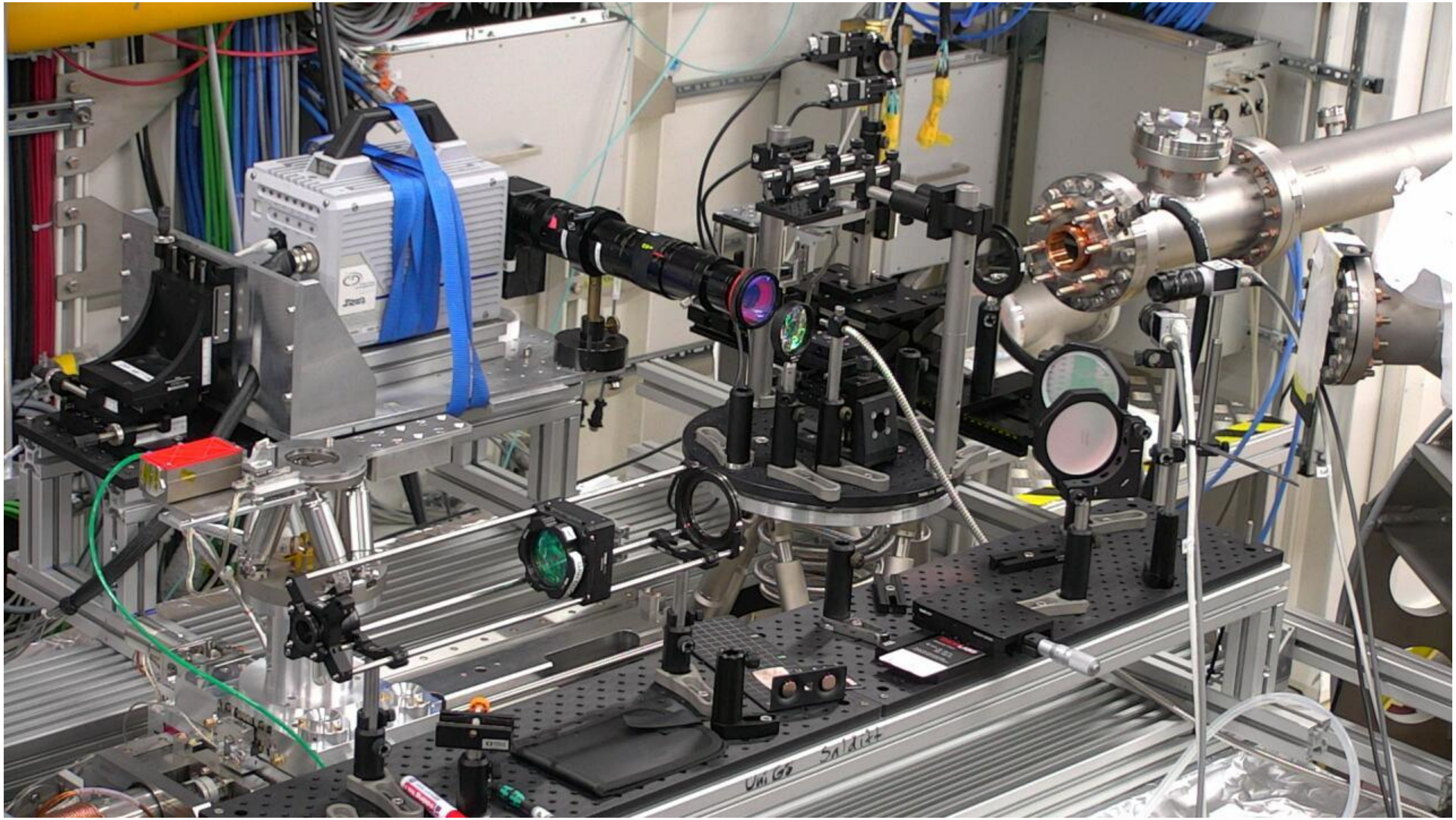


Markus Osterhoff et al., J. Synchr. Rad 2021

A good timing scheme is not sufficient …



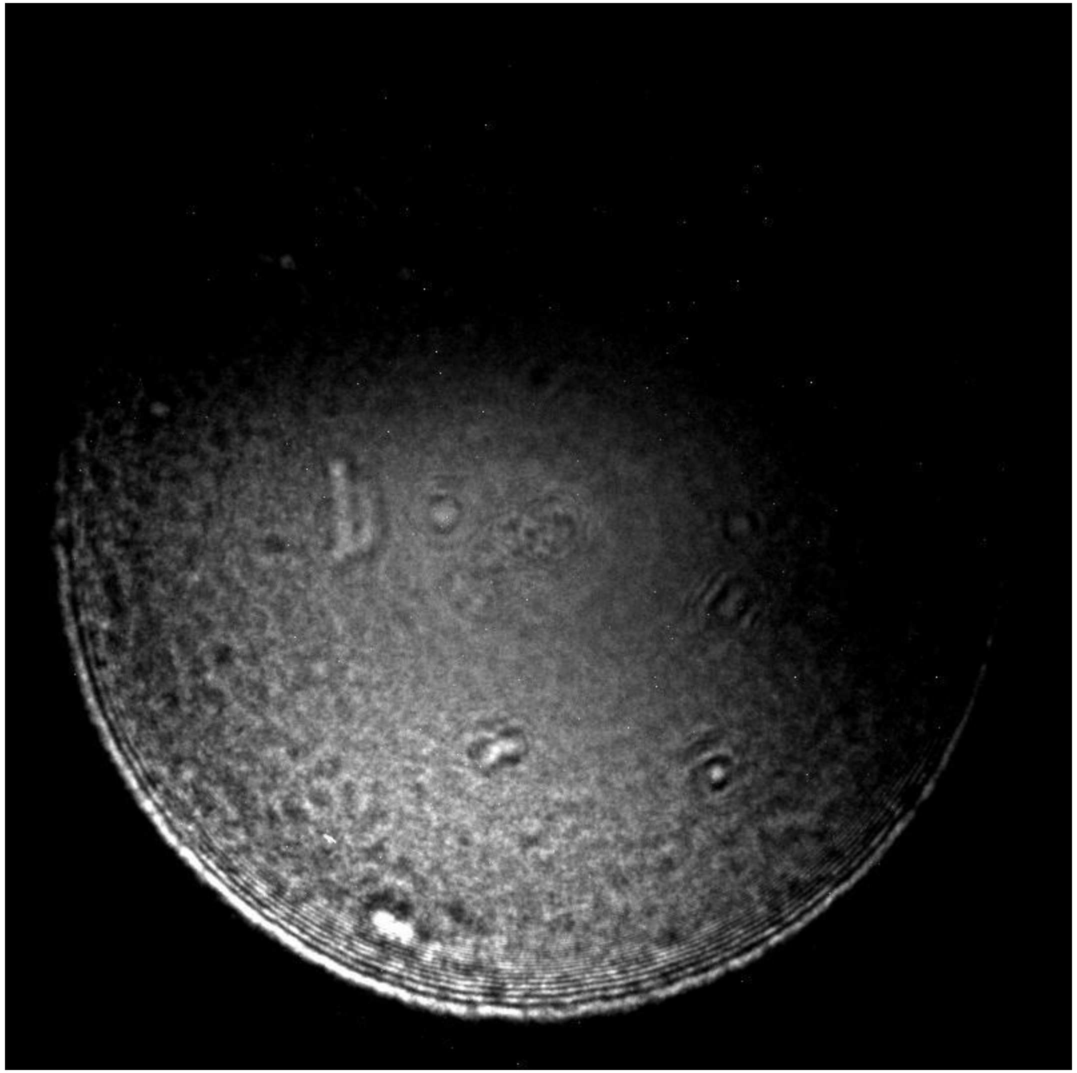
IR- alignment

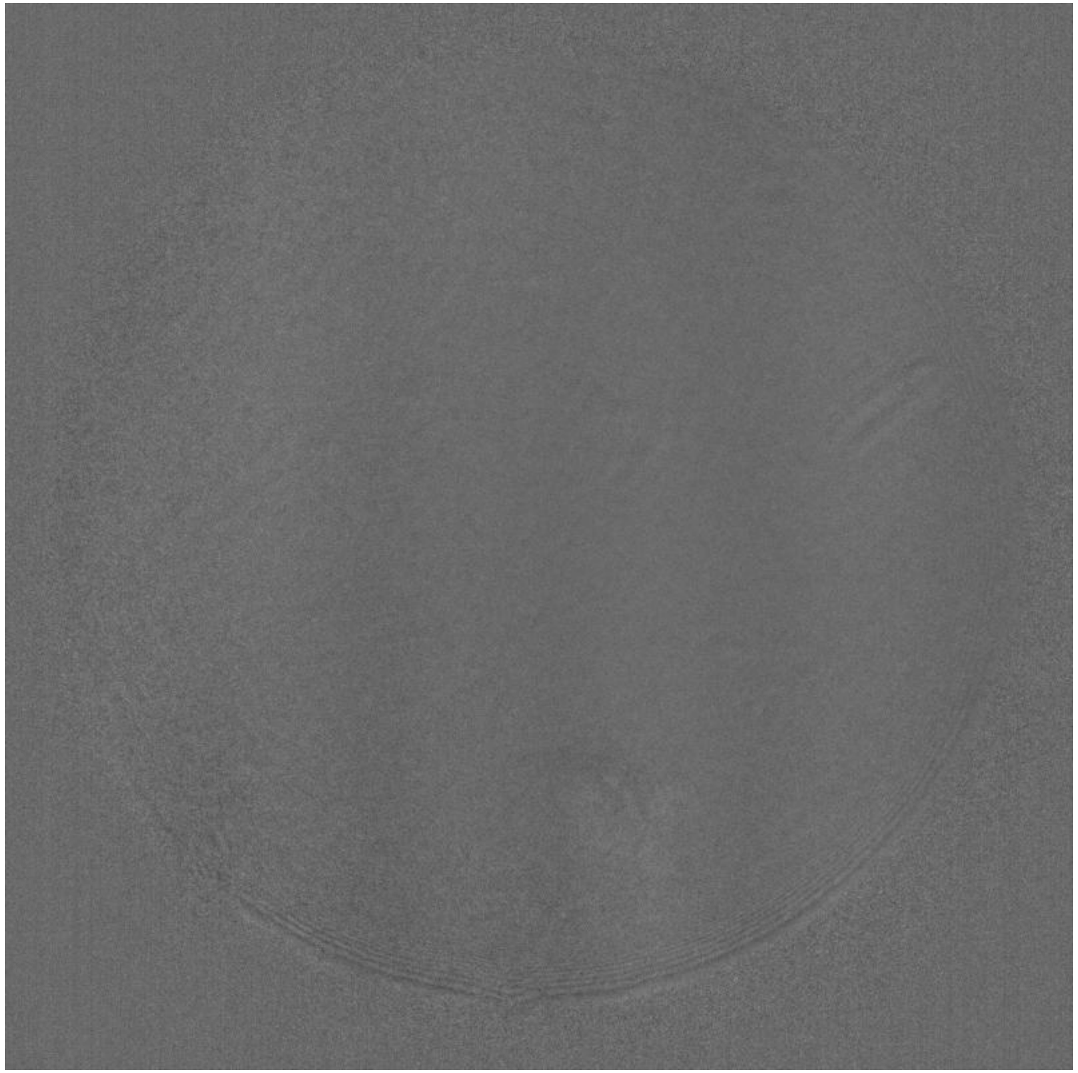


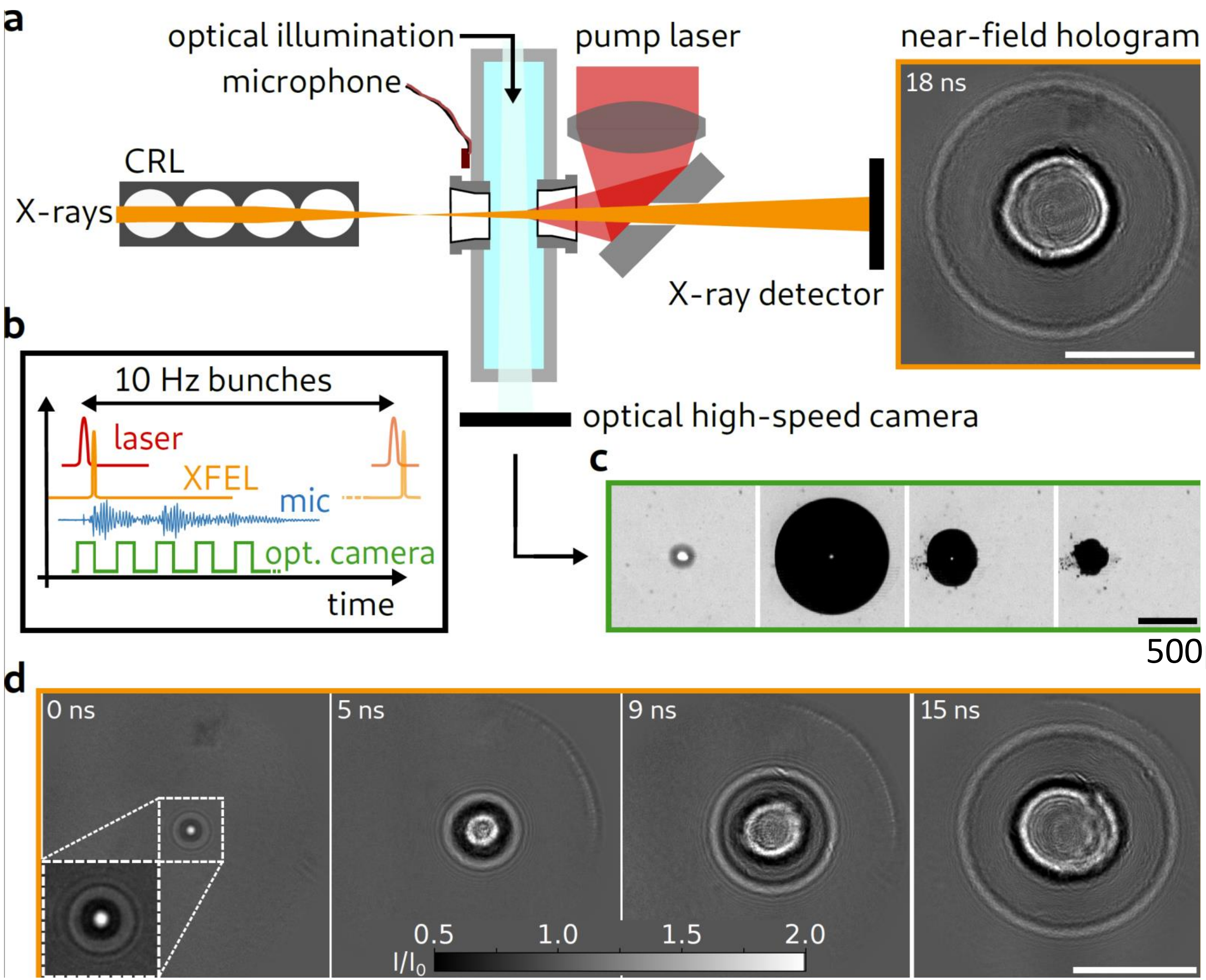
you have to have spatial-tempral overlap !

Malte Vassholz
Hannes Hoeppe

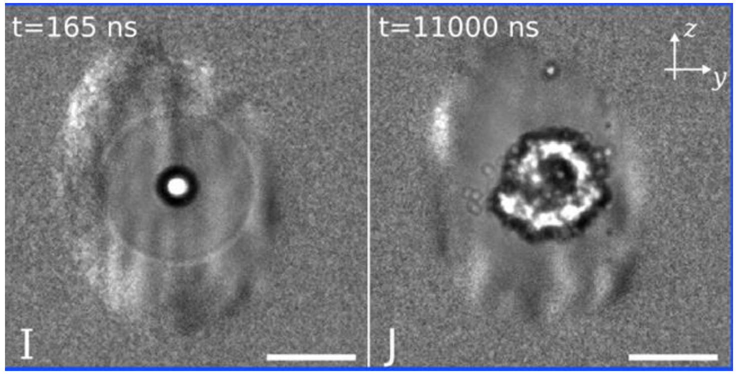
This is what we saw when we saw something (online analysis)







500µm

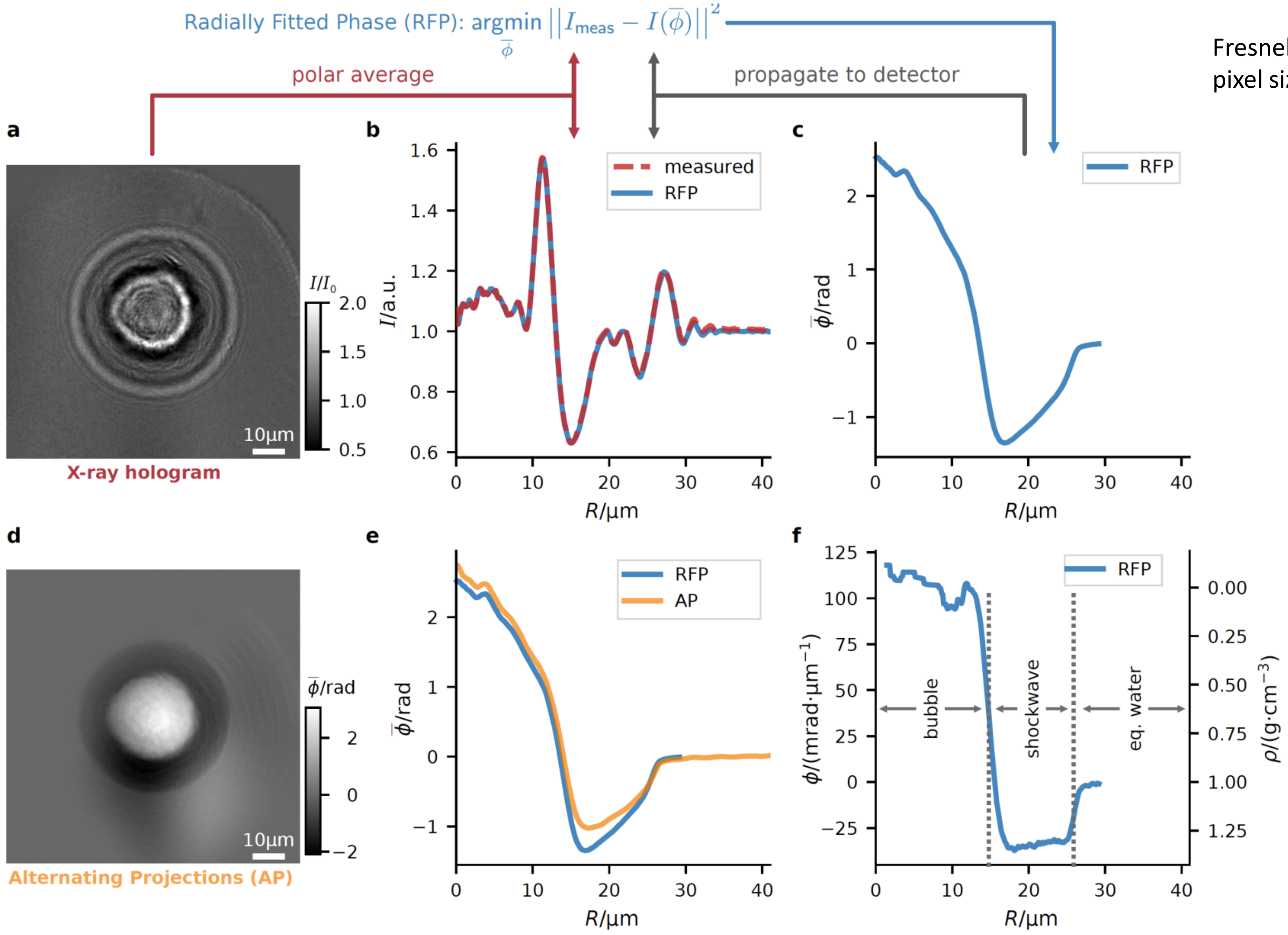


But how to analyze all of this?

50µm

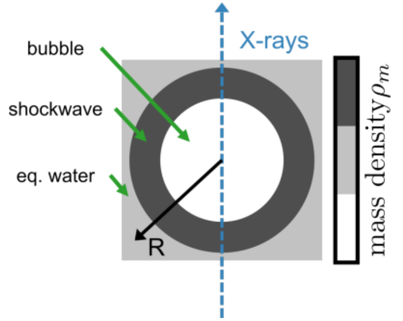
Phase retrieval

Fresnel number F = $0.8 \cdot 10^{-3}$
pixel size Δx = 109 nm, FOV = 140 µm



Malte Vassholz et al., *Pump-probe X-ray holographic imaging of laser-induced vavitation bubbles with femto-second FEL pulses* . Nat.Comm., in revision

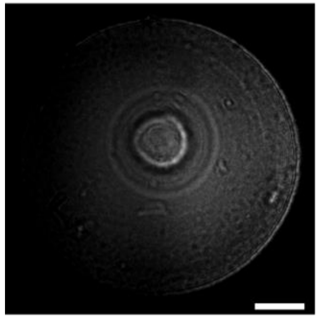
Phase retrieval in radial coordinates



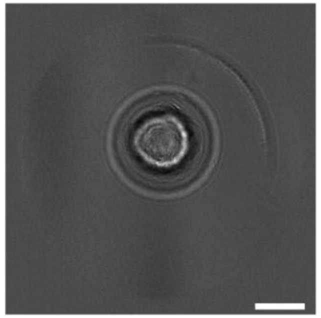
Radially Fitted Phase (RFP): $\text{argmin}_{\bar{\phi}} \left|\left| I_{\text{meas}} - I(\bar{\phi}) \right|\right|^2$

polar average

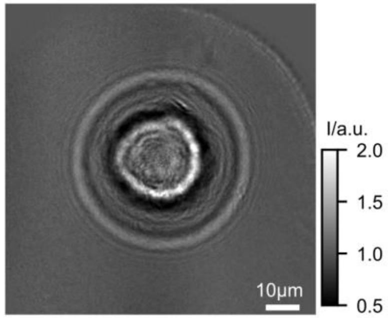
propagate to detector



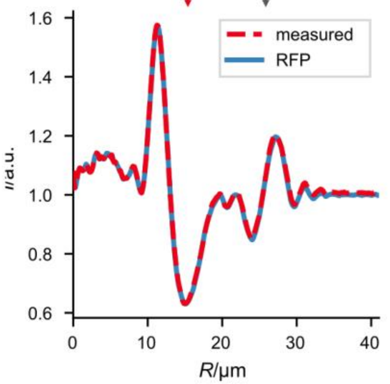
raw
X-ray hologram



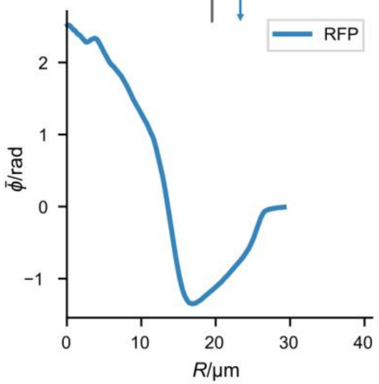
flat field corrected
X-ray hologram
(based on principal component analysis of a set of empty beams)



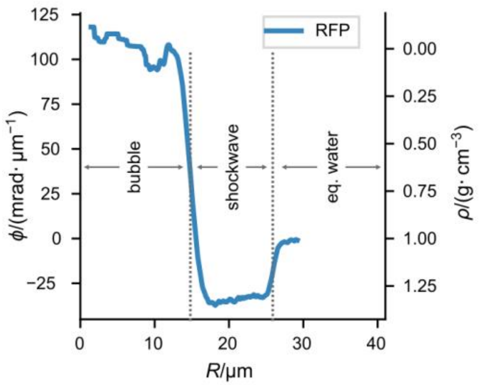
centered bubble
X-ray hologram



angular averaged intensity of measurement and fit (detector plane)



projected Radially Fitted Phase (RFP) (sample plane)



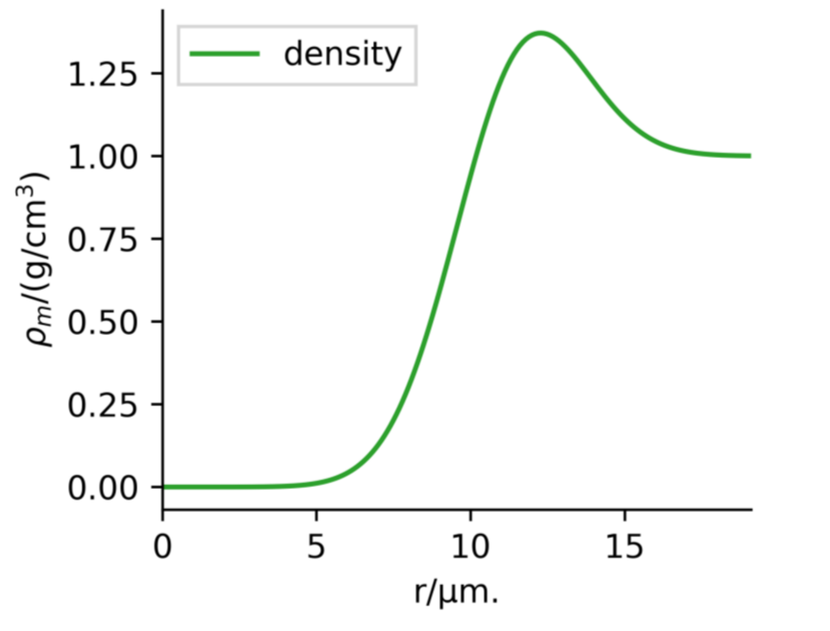
projection inversion of RFP, radial density distribution (sample plane)

⇕

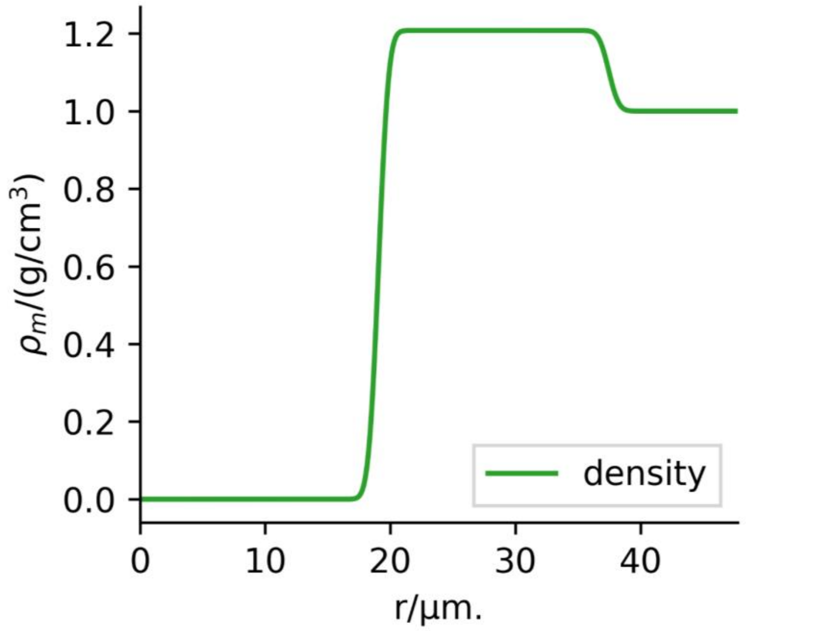
J. Hagemann et al., *Single-pulse phase-contrastimaging at free-electron lasers in the hard X-ray regime*. Journal of Synchrotron Radiation,28(1):52–63, 2021.

M. Vassholz et al., *Pump-probeX-ray holographic imaging of laser-induced cavitation bubbles with femto-second FEL pulses.* Nature Communications, 12(1):3468, 2021.

τ=4ns



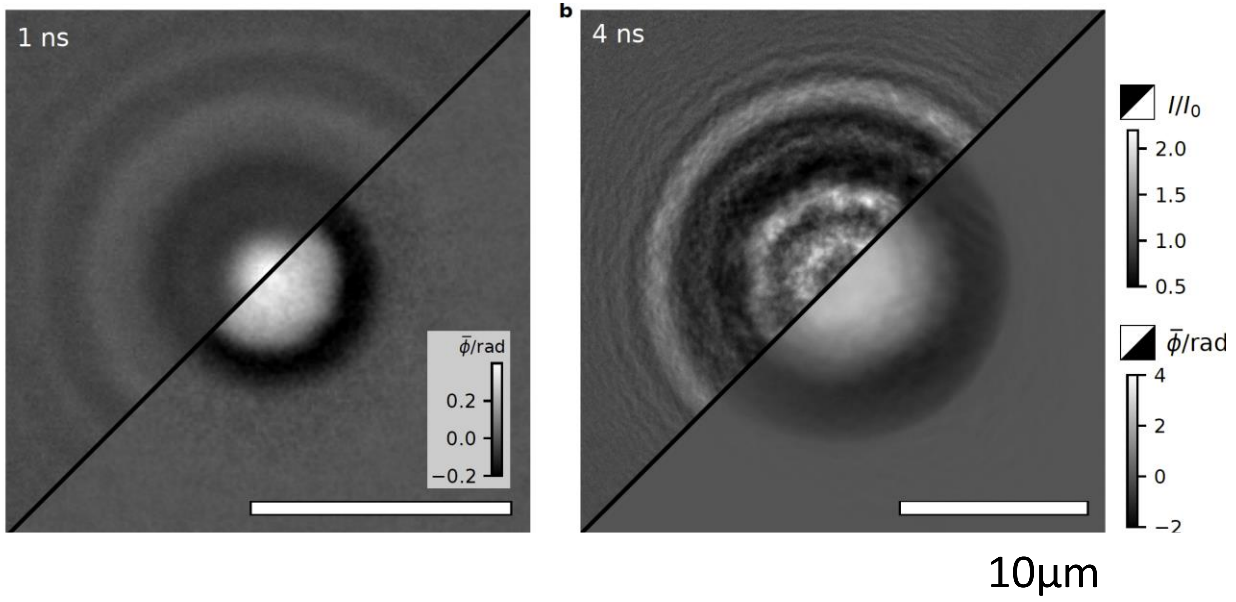
τ=13ns



- *emergence of phase boundary / sharpening of the interface*
- *density of the shock wave -> equation of state*
- *Outlook: comparison with MD simulation*
- *Outlook: fs time scales / plasma dynamics / water structure in shock wave collapse of the bubble*

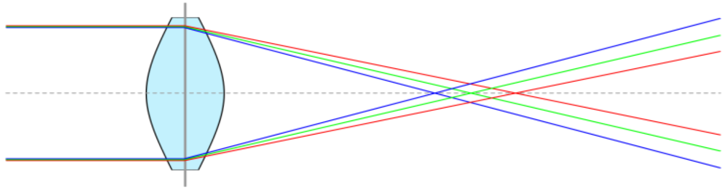
M. Vassholz et al. , in revision

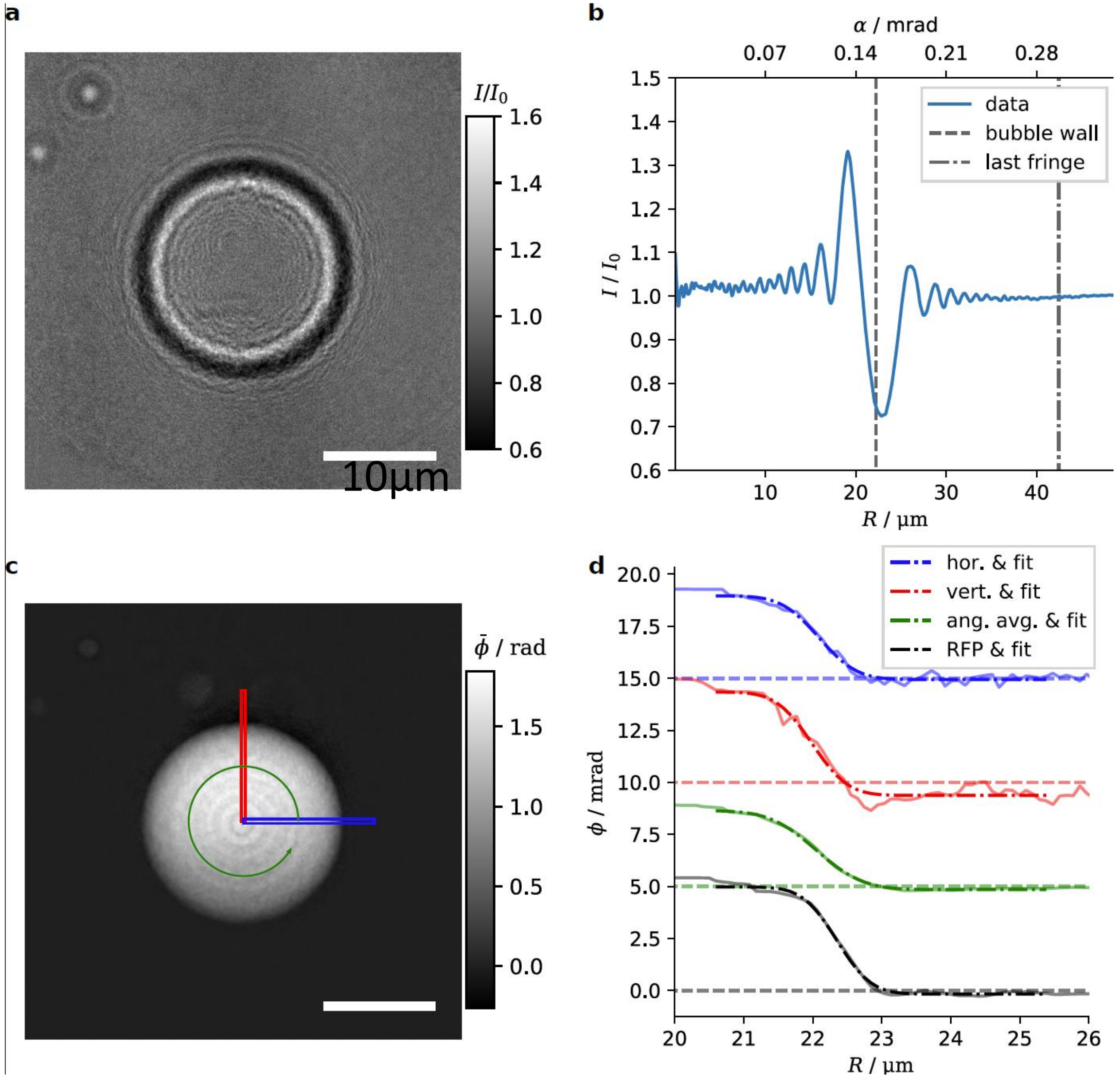
Phase retrieval /Resolution



@ Fresnel number Fr = $0.8 \cdot 10^{-3}$ (with respect to the pixel size)
pixel size Δx = 109 nm, FOV = 140 µm

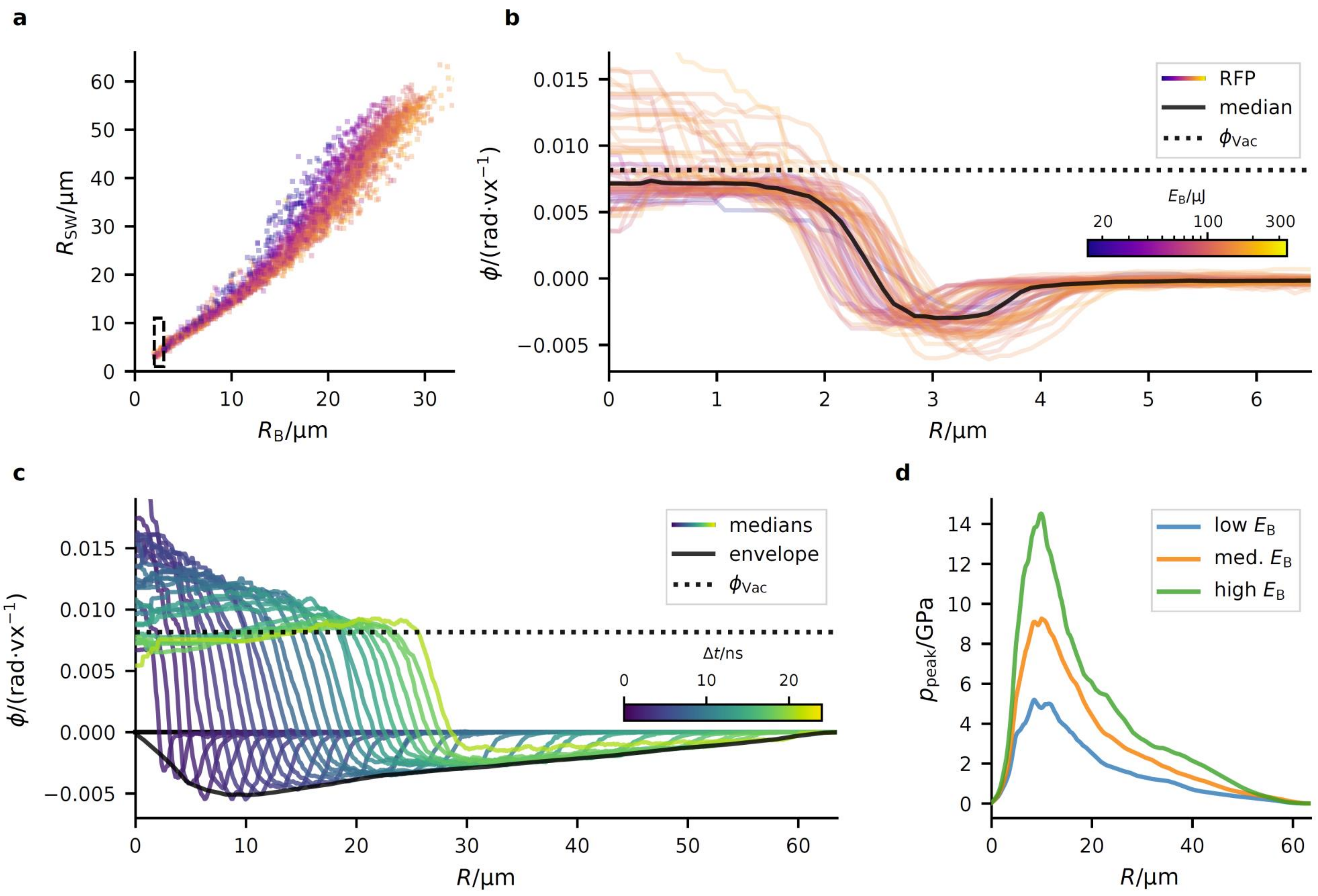
contrast sensitivity limited by wavefront stability!





resolution limited by dispersive optics !

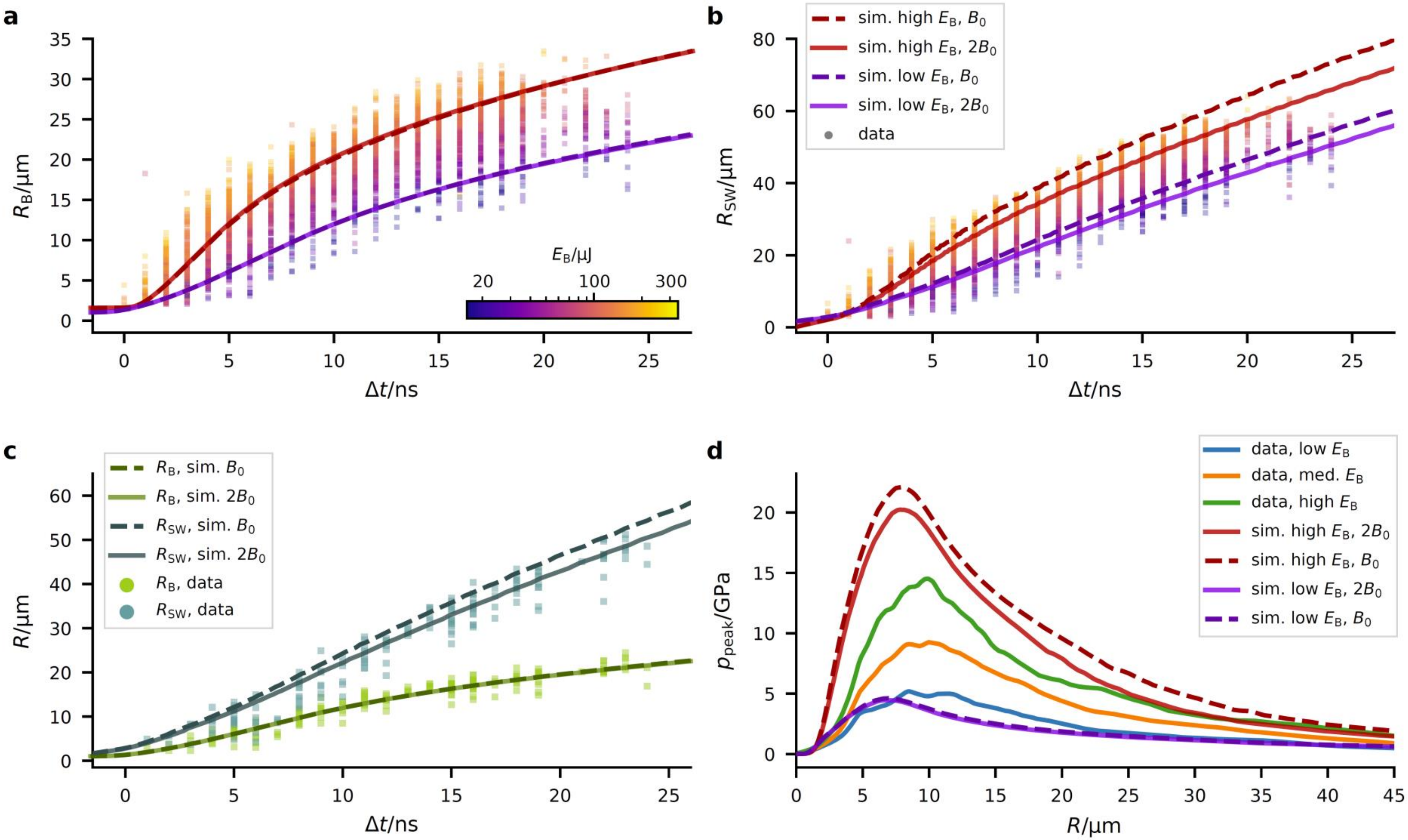
M. Vassholz et al. , in revision

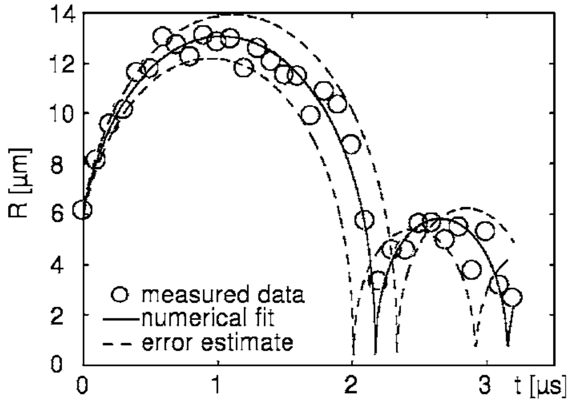


M. Vassholz et al. , in revision

Working out the entire ensemble / sorting for E_B

- maximum radius (photron)
- life time (microphone)
- bubble energy from life time and/or maximum radius





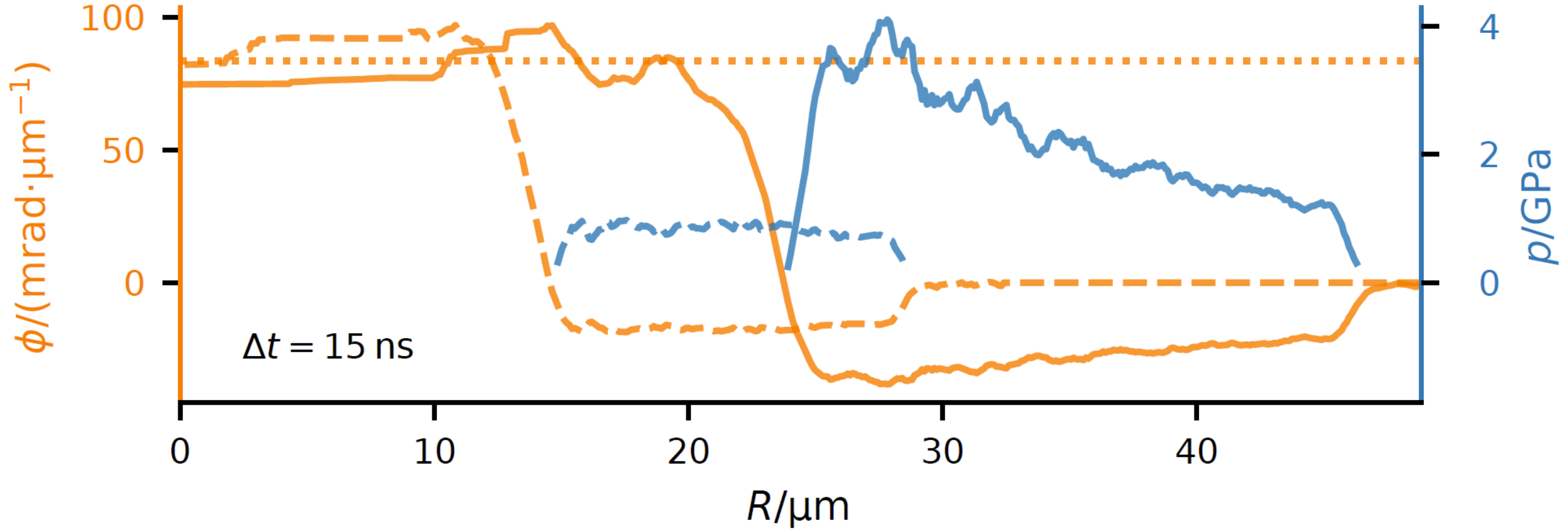
T. Kurz et al. Phys. Rev. E (2006)

bubble energy determines maximum radius

$$E_B = \frac{3\pi}{4}(p_0 - p_v)R_{max}^3$$

M. Vassholz et al. , Nat.Comm. 2021

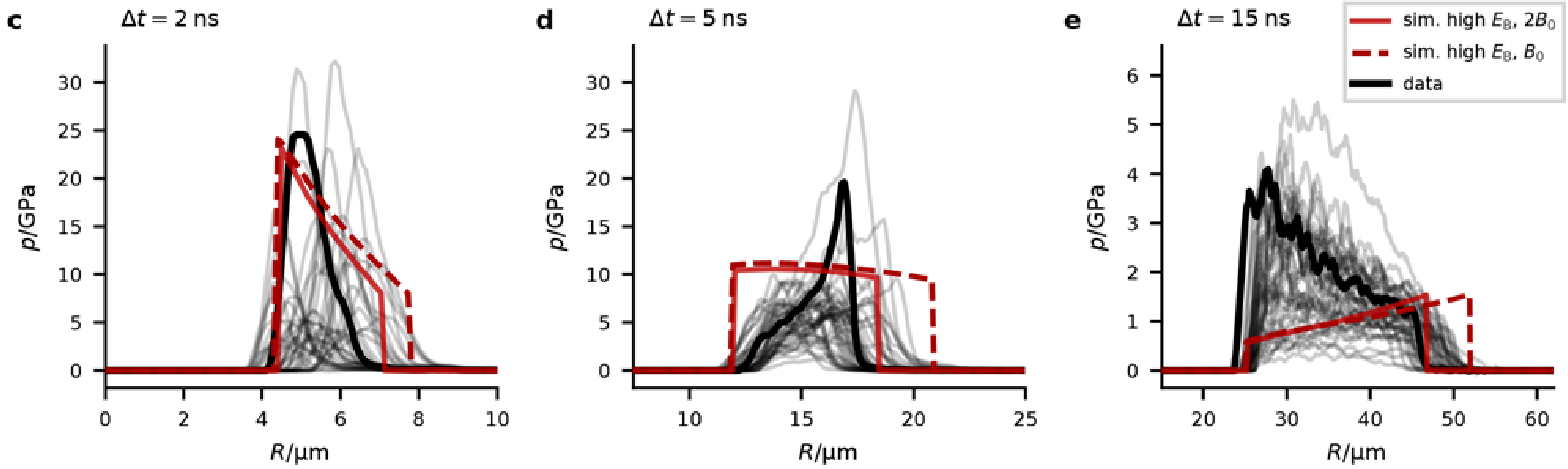
Results: Pressure profile of shock wave



$$p - p_0 = B\left(\left(\frac{\rho}{\rho_0}\right)^m - 1\right)$$

$$B = K/m \quad m = c_p/c_v \simeq 7$$

Tait eq.



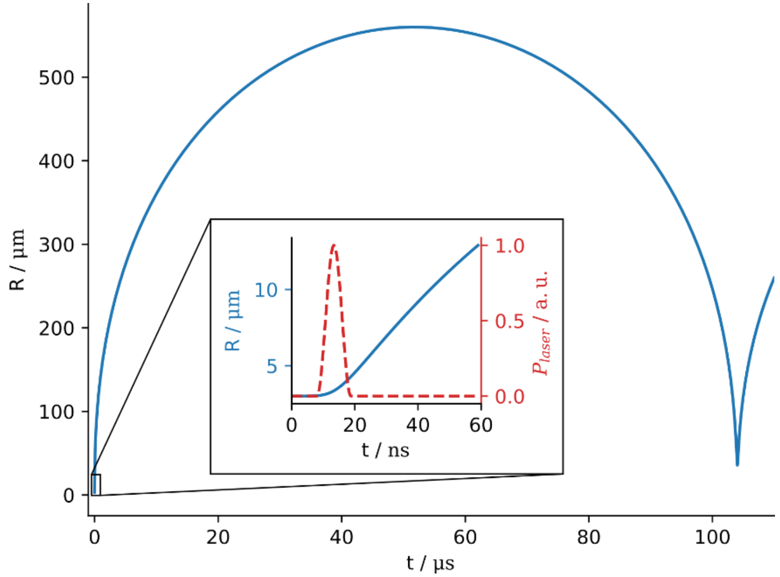
Gilmore model

-> data puts current hydrodynamic models of shock wave into question !

M. Vassholz et al. , Nat. Comm. 2021

The Gilmore model for cavitation dynamics

$$R\ddot{R}\left(1-\frac{\dot{R}}{C}\right)+\frac{3}{2}\dot{R}^2\left(1-\frac{\dot{R}}{3C}\right)=H\left(1+\frac{\dot{R}}{C}\right)+\frac{\dot{R}}{C}\left(1-\frac{\dot{R}}{C}\right)\frac{dH}{dR}$$



2. step: shock wave propagation based of the **Kirkwood-Bethe Hypothesis** and method of characteristics

$G = r(h + u^2/2)$ invariant quantity

$$\dot{r} = u + c$$

$$\dot{u} = \frac{1}{c-u}\left((u+c)\frac{G}{r^2}-\frac{2c^2u}{r}\right)$$

$$\dot{p} = \frac{\rho_0}{r(c-u)}\left(\frac{p+B}{p_0+B}\right)^{\frac{1}{n}}\left(2c^2u^2-\frac{c^2+uc}{r}G\right)$$

The pressure profiles are cuts at constant time in the three-dimensional space of all characteristics.

ρ water density

$n = 7 \hat{=}$ adiabatic index of water

$B = 314\,\mathrm{MPa} \hat{=} \frac{\rho_0 c_0^2}{n}$

σ surface tension

κ adiabatic index of air

η dynamic viscosity

$$p(\rho) = \left(\frac{\rho}{\rho_0}\right)^m (p_\infty + B) - B$$

Modified Tait equation of state

The Gilmore model for cavitation dynamics

$$R\ddot{R}\left(1-\frac{\dot{R}}{C}\right)+\frac{3}{2}\dot{R}^2\left(1-\frac{\dot{R}}{3C}\right)=H\left(1+\frac{\dot{R}}{C}\right)+\frac{\dot{R}}{C}\left(1-\frac{\dot{R}}{C}\right)\frac{dH}{dR}$$

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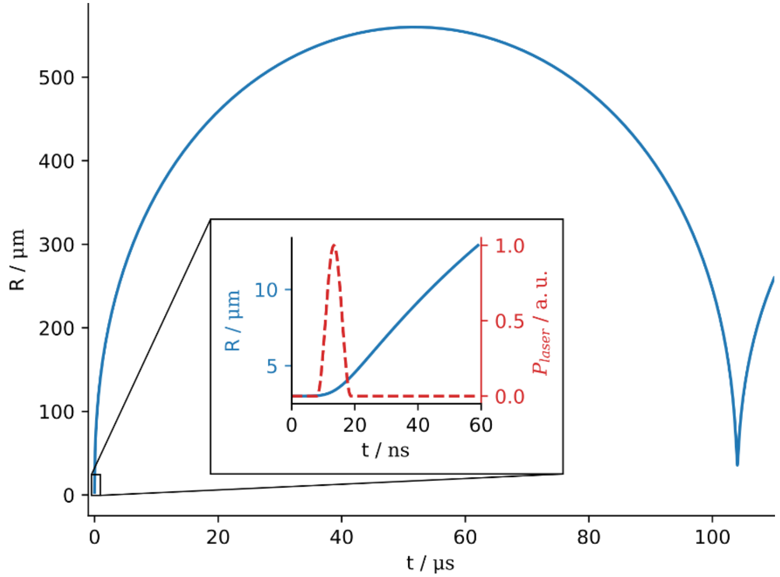
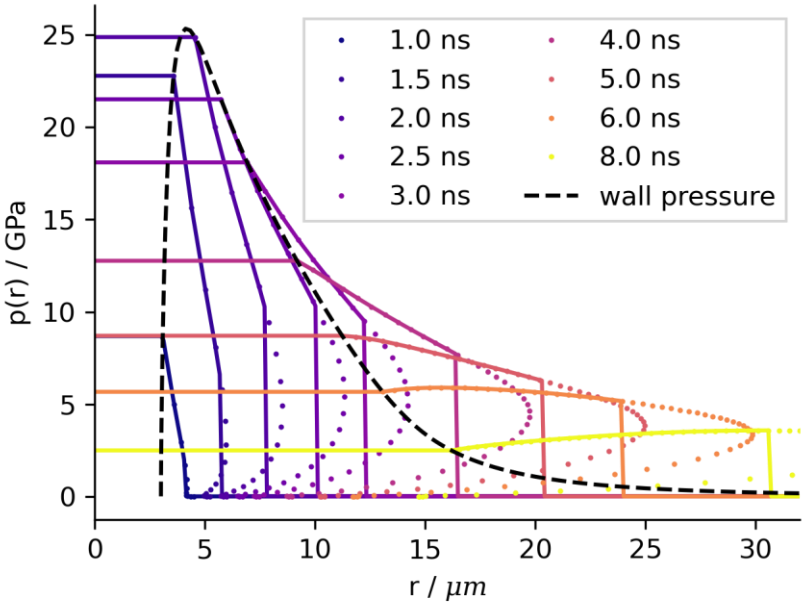
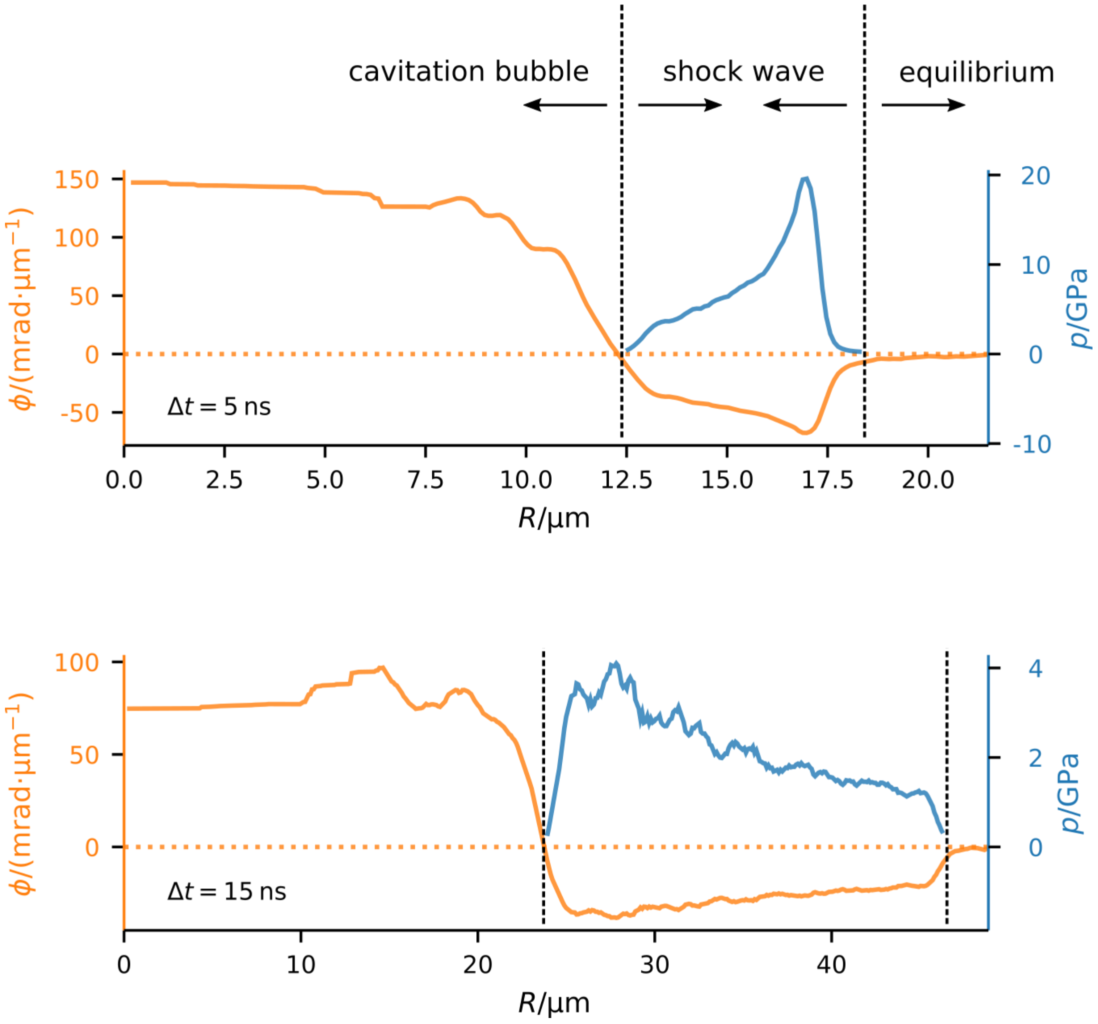




3d radial Phase, density & pressure



mass density:

$$\rho(R) = \rho_0 \left(1 - \frac{\phi(R)}{k\,\delta}\right)$$

k X-ray wave number

δ real part of the refractive index

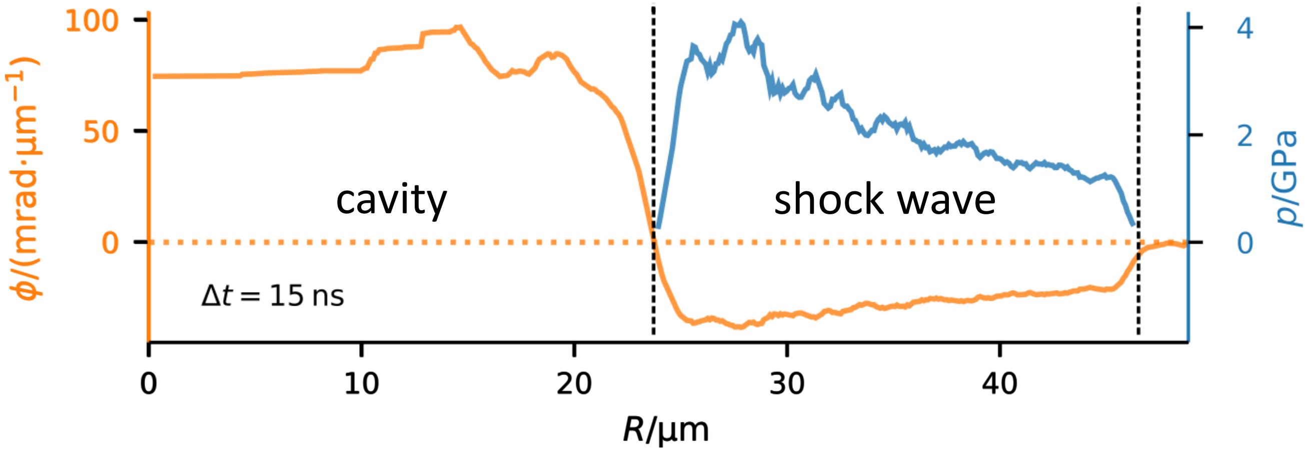
modified **Tait Equation of state,**
relates density to **pressure**:

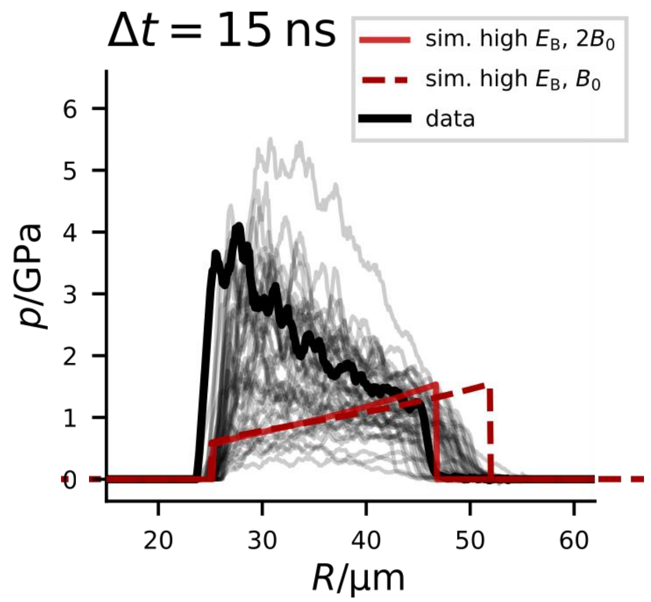
$$p(\rho) = \left(\frac{\rho}{\rho_0}\right)^n (p_\infty + B) - B$$

$n = 7 \mathrel{\hat{=}}$ adiabatic index of water

$B = 314\,\mathrm{MPa} \mathrel{\hat{=}} \frac{\rho_0 c_0^2}{n}$

3d radial Phase, density & pressure





mass density:

$$\rho(R) = \rho_0 \left(1 - \frac{\phi(R)}{k\,\delta}\right)$$

k X-ray wave number
δ real part of the refractive index

modified **Tait Equation of state (EOS),** relates density to **pressure**:

$$p(\rho) = \left(\frac{\rho}{\rho_0}\right)^n (p_\infty + B) - B$$

$n = 7 \hat{=}$ adiabatic index of water

$B = 314\,\mathrm{MPa} \hat{=} \frac{\rho_0 c_0^2}{n}$

Comparing with typical hydrodynamic models:

- Gilmore Model for cavitation dynamics
- Kirkwood & Bethe-based shock propagation

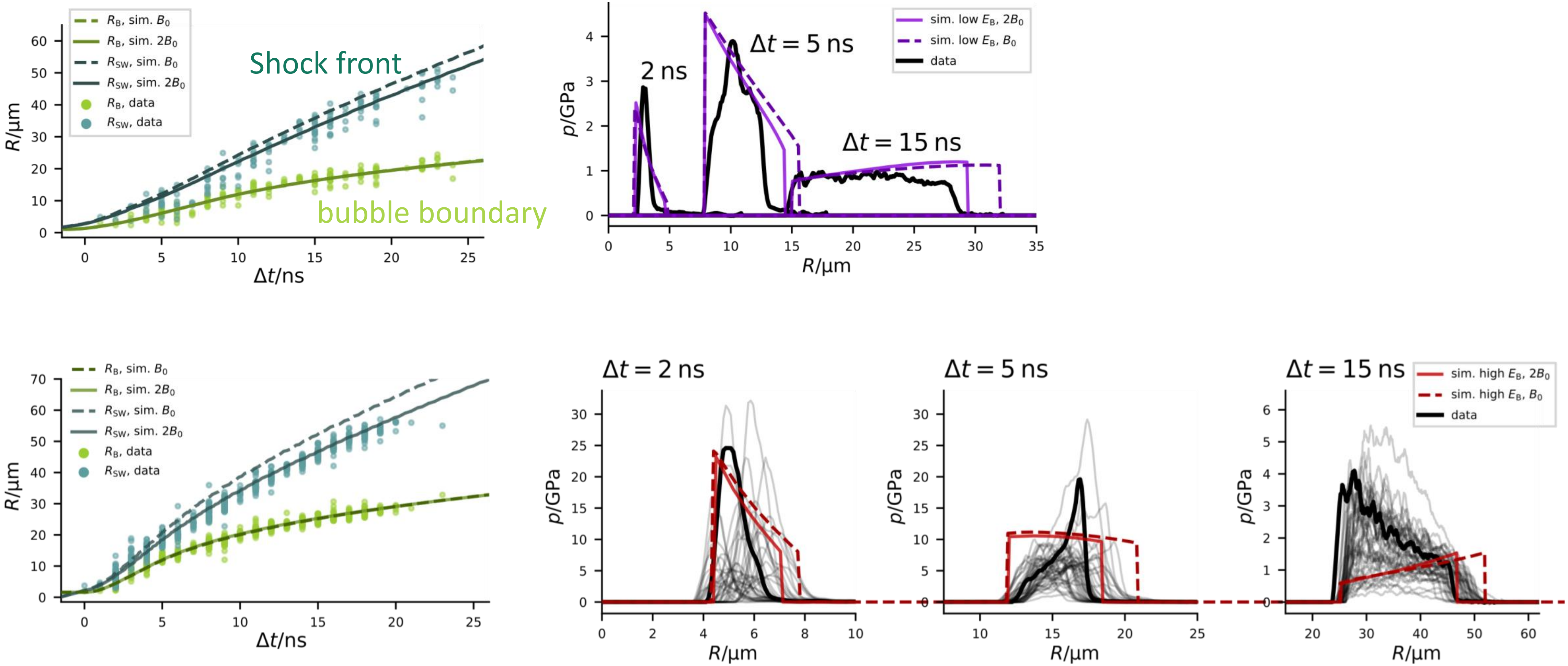
Discrepancies for high-energy events:

- Shape / slope
- peak pressures
- trajectory

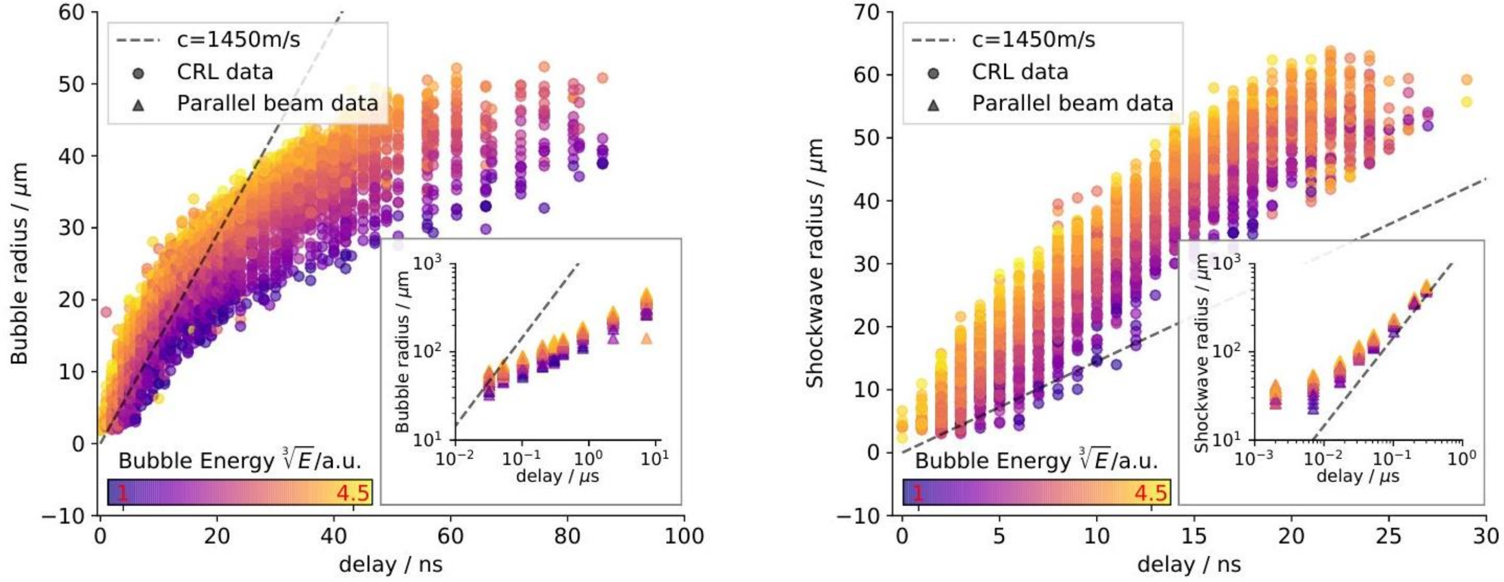
Shock wave structural dynamics, hydrodynamic simulations

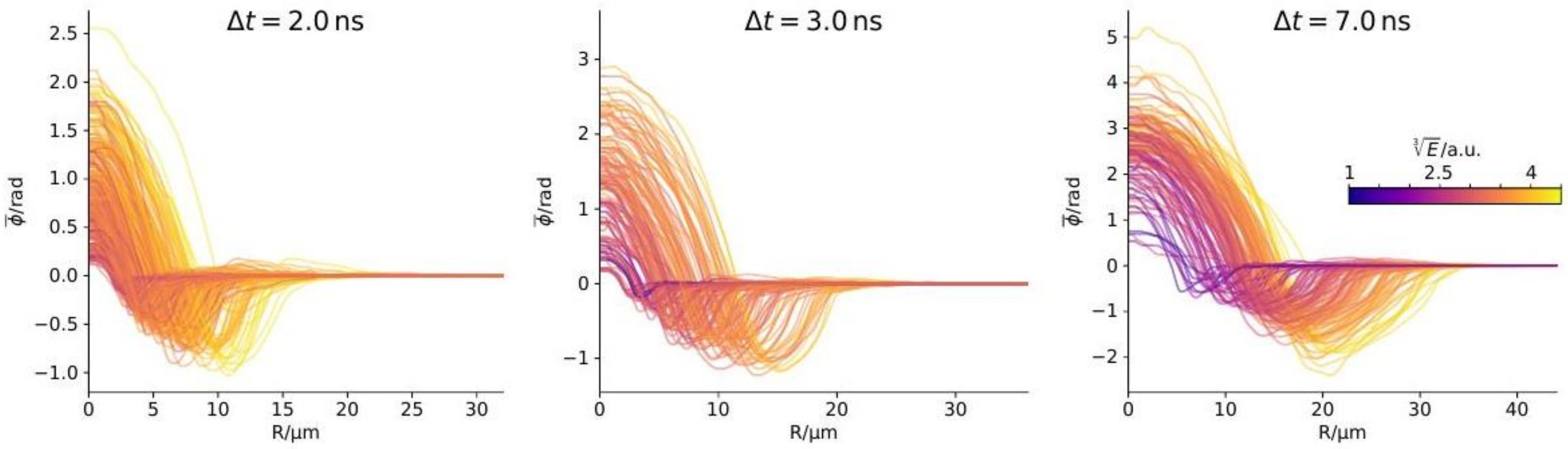
low E_B

high E_B

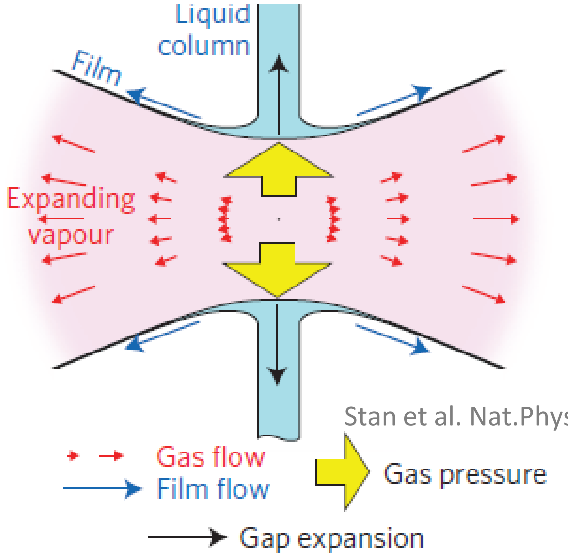


Shock wave structural dynamics, hydrodynamic simulations

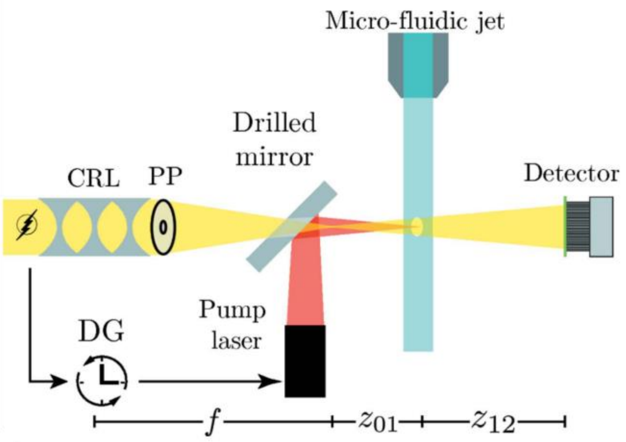


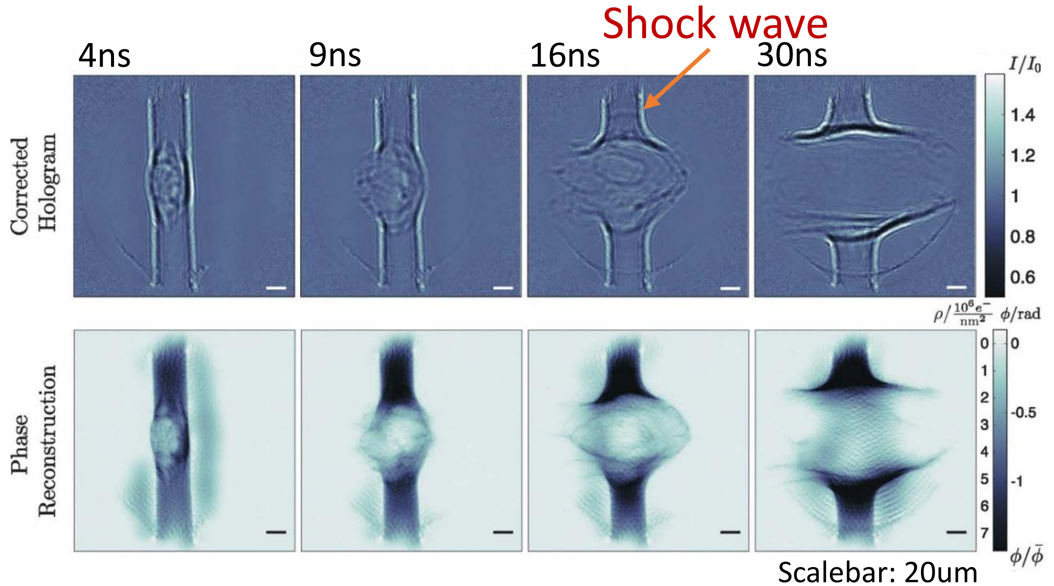


2. Cavitation in a liquid jet & molecular structure of water in the shockwave

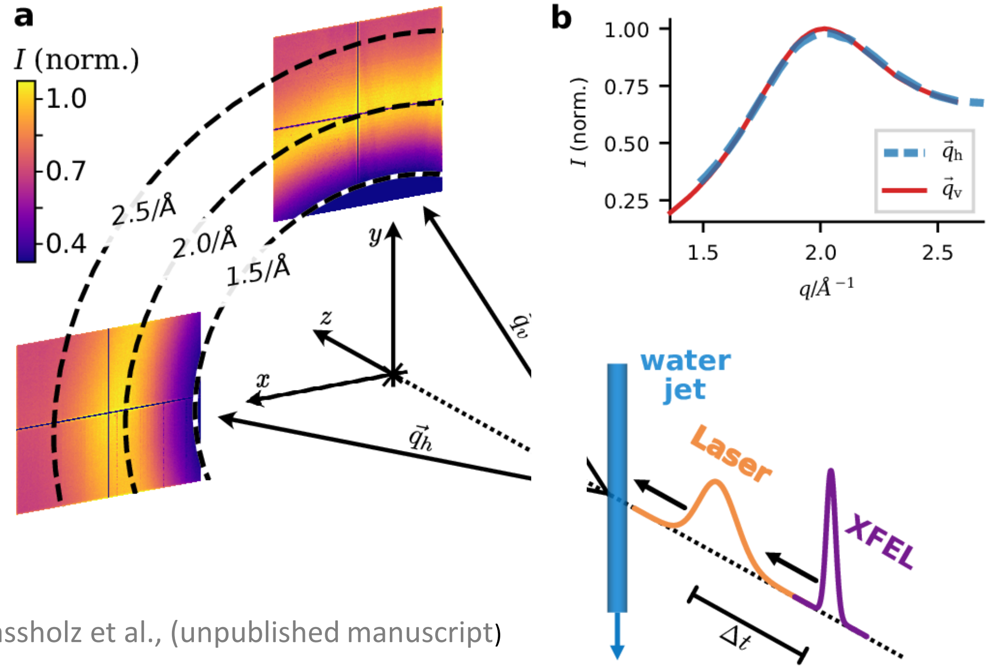


Stan et al. Nat.Phys (2016)



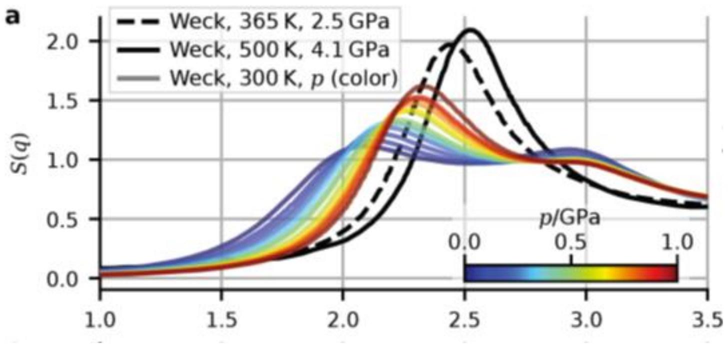


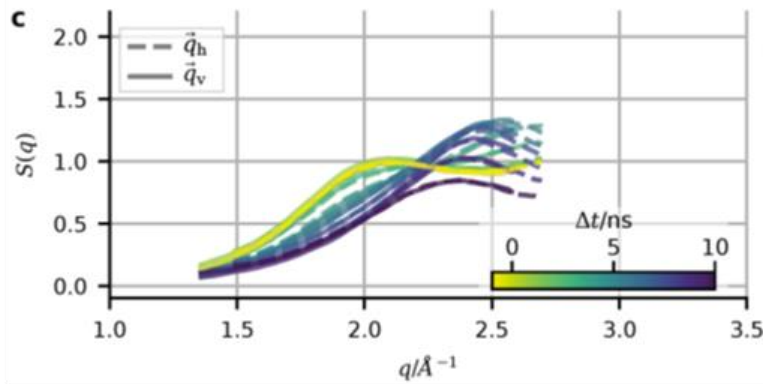
J. Hagemann et al., *Single-pulse phase-contrast imaging at free-electron lasers in the hard X-ray regime*. Journal of Synchrotron Radiation 2021.

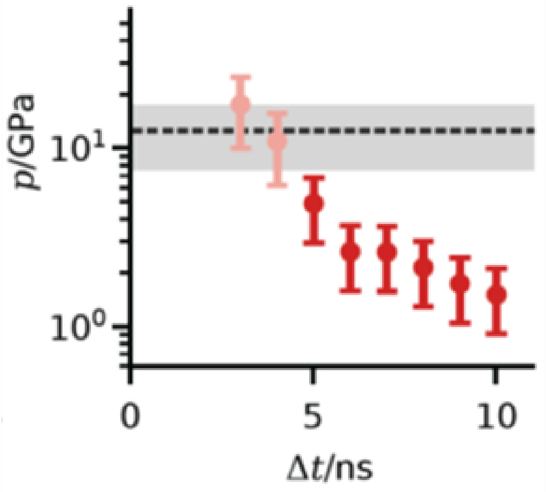


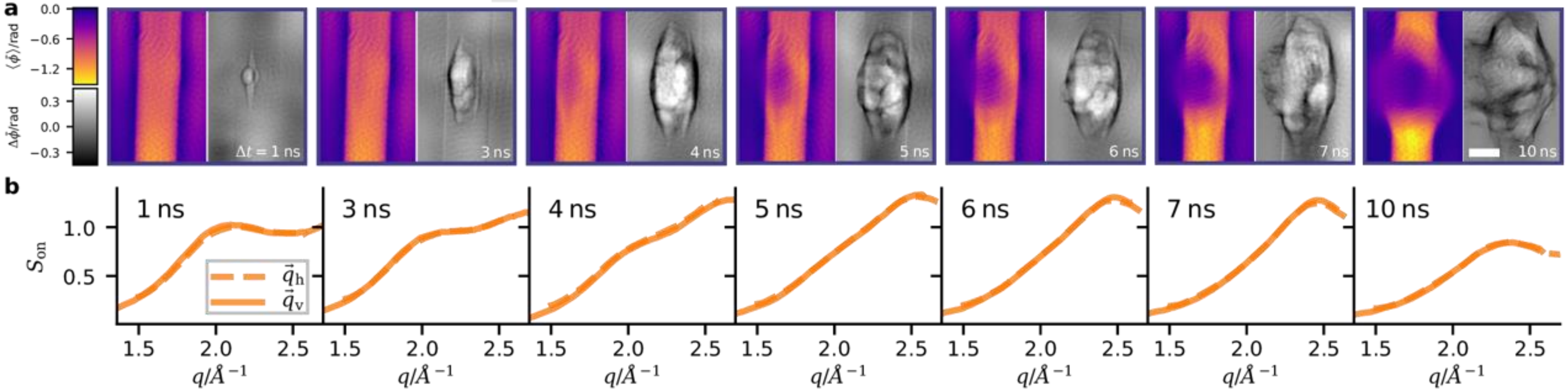
Vassholz et al., (unpublished manuscript)

Holography-assisted recording an interpretation of the diffraction signal



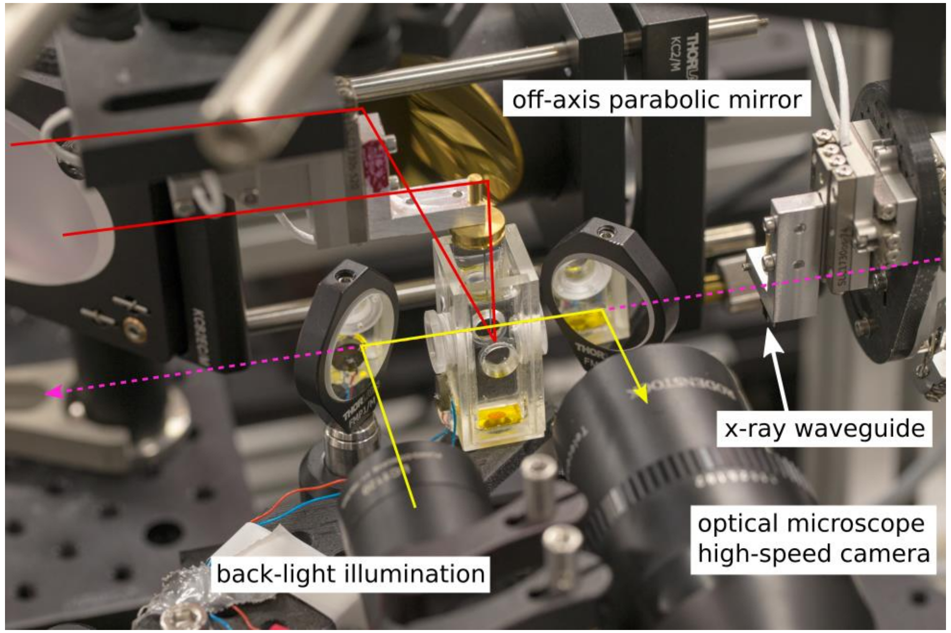


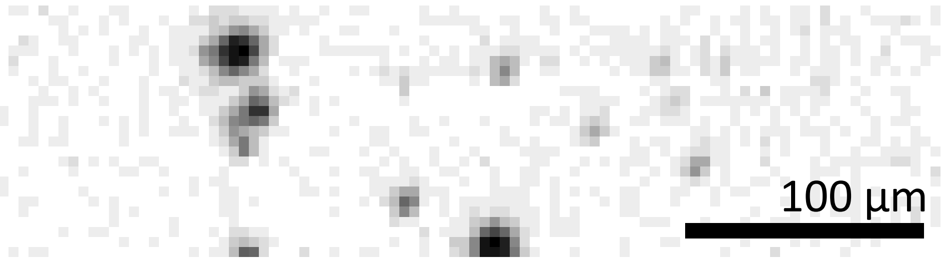




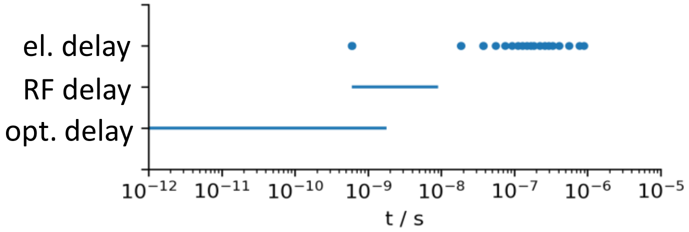
M. Vassholz Diss. 2021 , Vassholz et al., (unpublished manuscript)

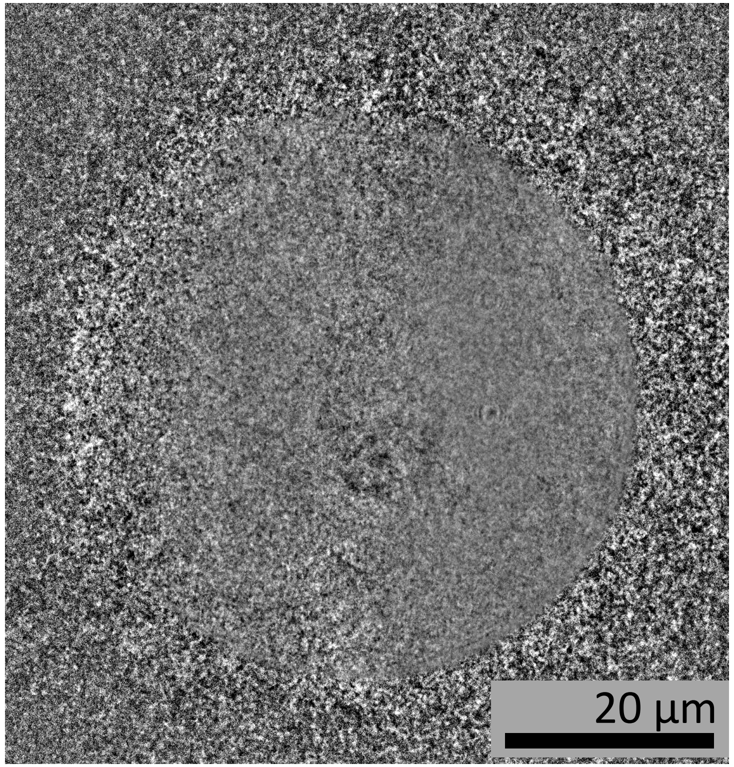
3. *Femtosecond* laser-induced cavitation (p2807 10/2021, MID)





Optical high-speed video:
160 ns shutter, 480.000 fps





Electronic delay: 1200 ns … 1 ns

MID fs-laser timing options:

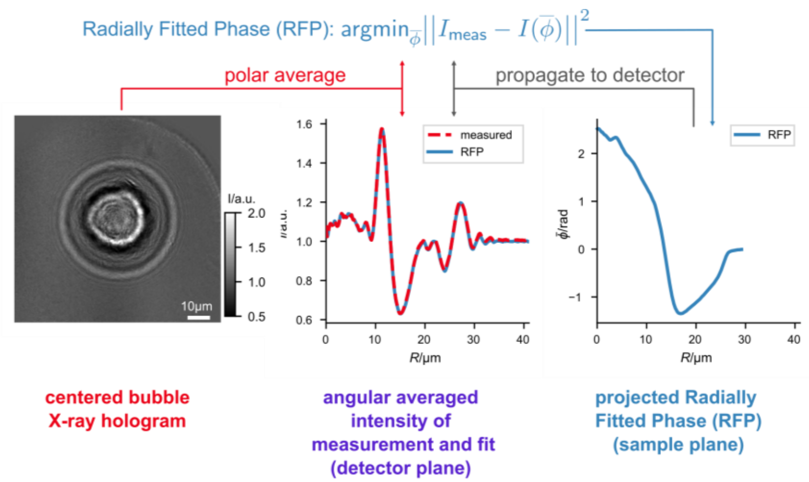
- Electronic trigger (18 ns steps)
- RF synchronization system (~ 1 ps steps)
- Optical delay line (fs precision)

X-ray parameters:
Eph = 18 keV
τ < 100 fs
frep = 10 Hz
<Ep> = 1 mJ

CRL Nanofocus:
M = 95.2
z01 = 102.5 mm
z12 = 9756 mm
peff = 68.23 nm

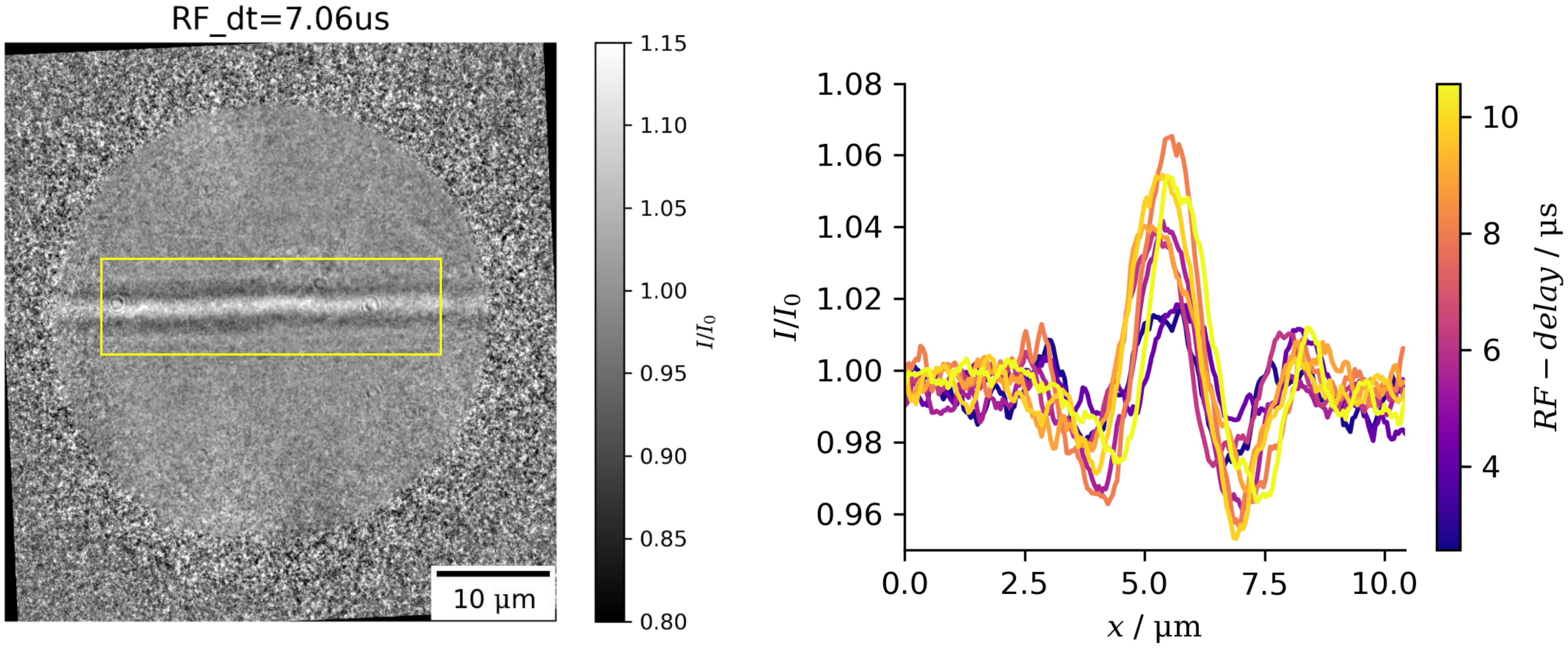
IR Pump laser:
λ = 800 nm
τ ≈ 60 fs
frep = 10 Hz
<Ep> = 3 µJ … 120 µJ

Analysis (ongoing)



Quantitative phase reconstruction:

- Alternating projections (AP) (2d)
- adapt radially fitted phase (RFP) for cylindrical symmetry

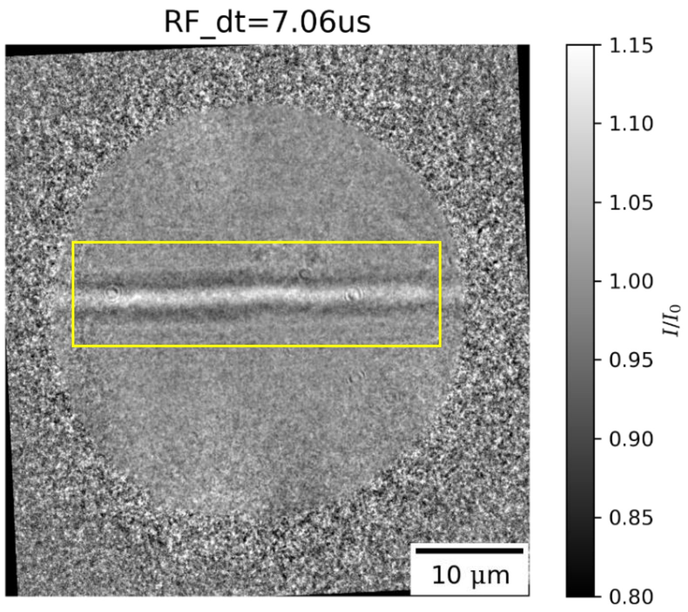


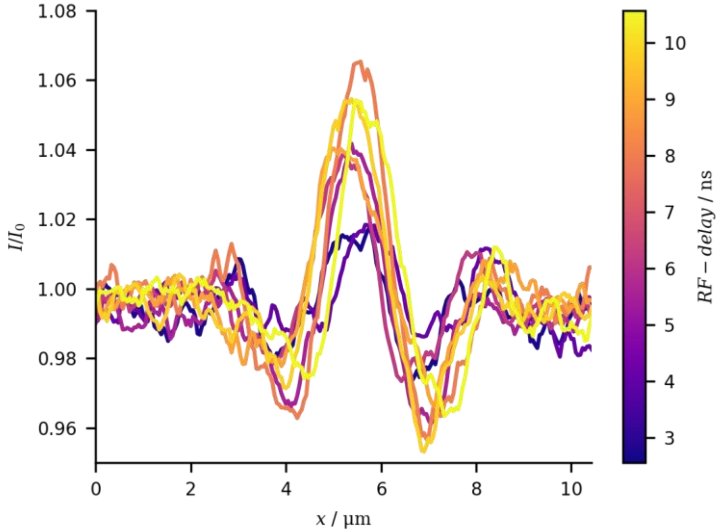
Investigating of:

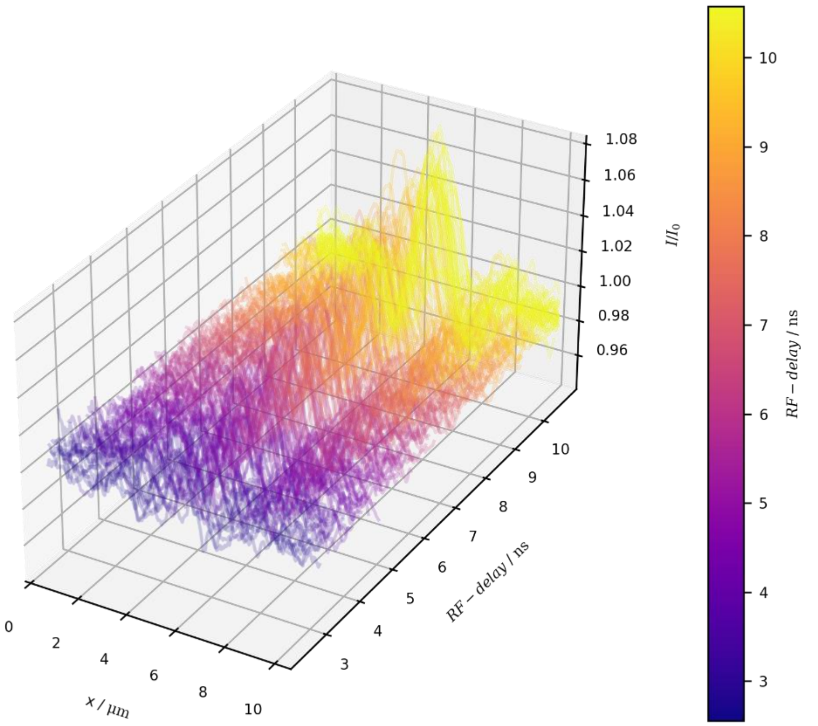
- optical breakdown
- filamentation
- plasma to vapour transition
- birth of cavitation bubble
- plasma and hydrodynamic simulations…

Hoeppe et al., (in preparation)

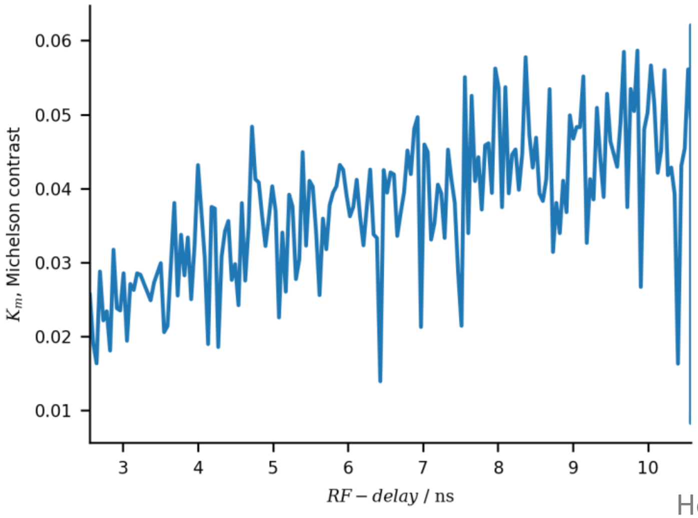
plasma to bubble transition





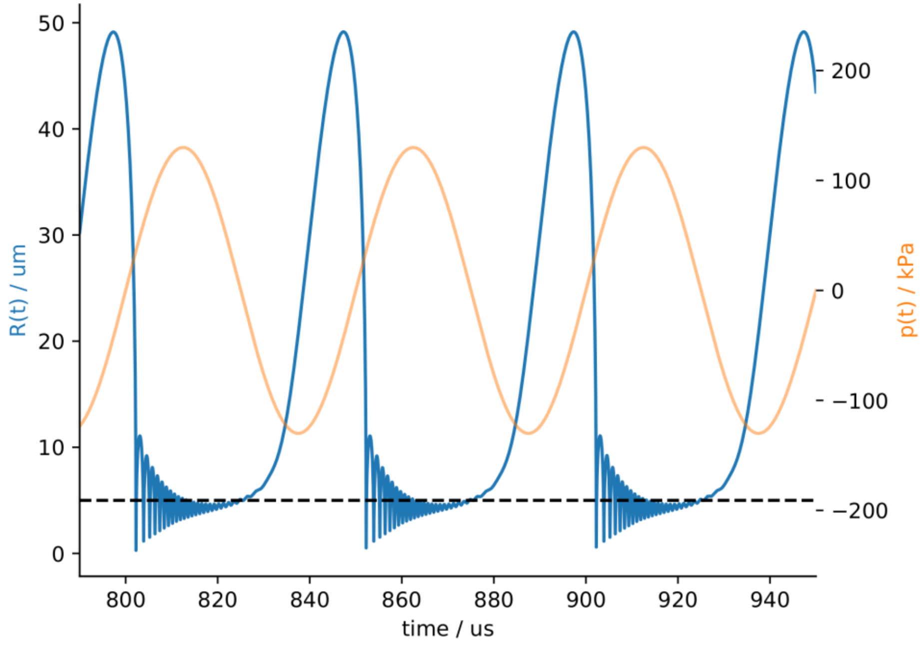


- **µs to ns dynamics:** (slow) bubble growth
- Shock wave emission?
- **ns & ps dynamics:** contrast increase (plasma cooling, recombination & transition to vapour cavity)
- -> laser surgery ! study of cavitation in tissues



Hoeppe et al., (in preparation)

3. Acoustic cavitation and trapping of a bubble



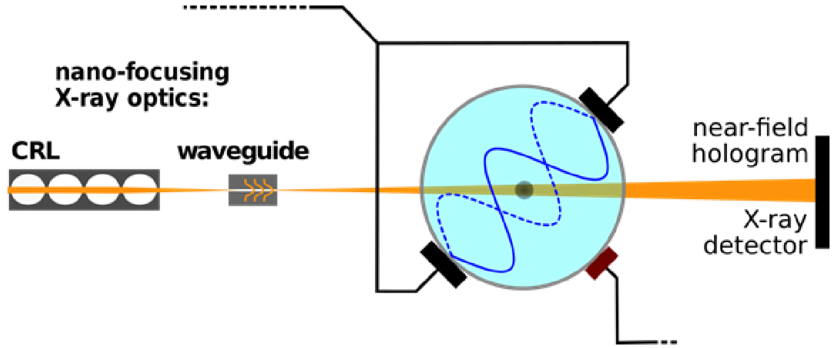
$$R\ddot{R} + \frac{2}{3}\dot{R}^2 = \frac{1}{\rho}\left(p_i - p_{stat} - \frac{2\sigma}{R} - \frac{4\eta}{R}\dot{R}\right)$$

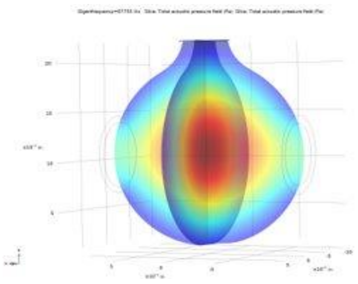
Main requirements for stable trapping:

- positional stability ↔ Bjernkes force
- Spherical stability ↔ surface modes
- Diffusional stability ↔ rectified diffusion

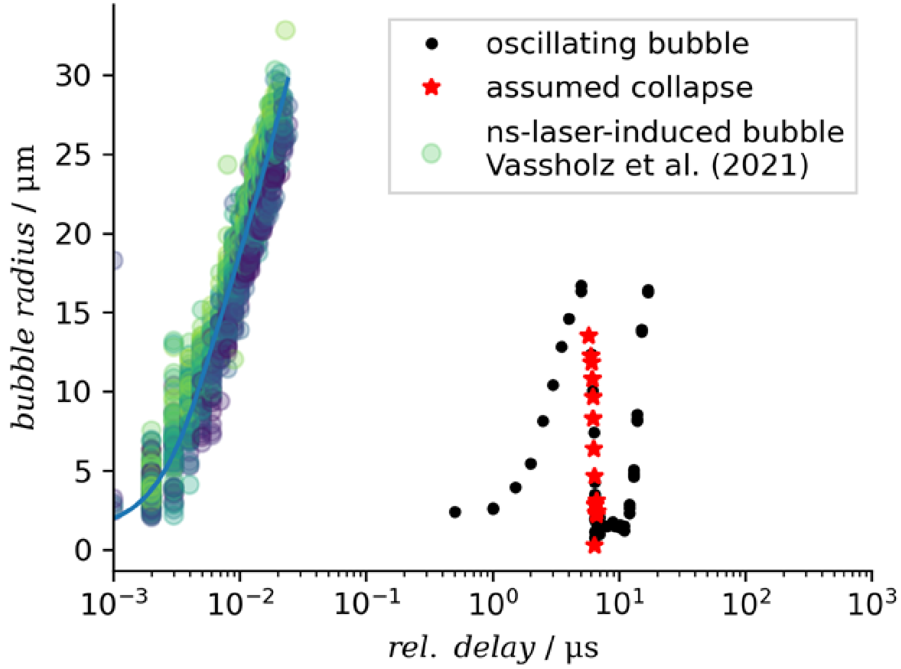
$$\boldsymbol{F}_{\mathrm{B}}(\boldsymbol{x}) = -\langle V(t)\,\nabla p_{\mathrm{ac}}(\boldsymbol{x}, t)\rangle_{\tau}$$

$$p_{\mathrm{ac}}(\boldsymbol{x}, t) = p_{\mathrm{a}}(\boldsymbol{x})\sin(\omega_{\mathrm{a}} t).$$

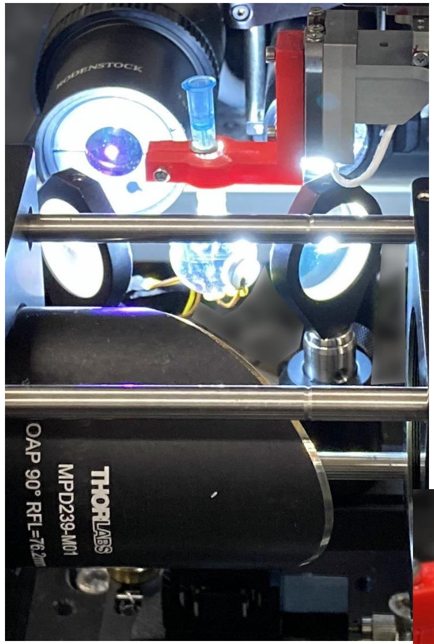


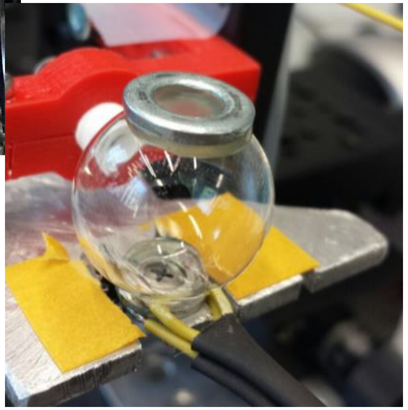


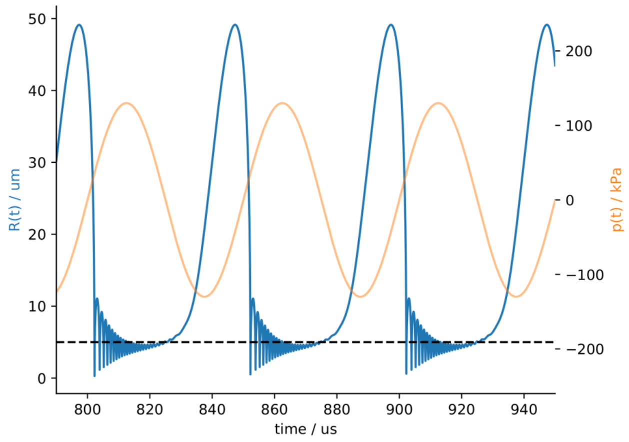
ultrasonic standing wave field



Imaging the bubble collapse – acoustic trapping & SBSL

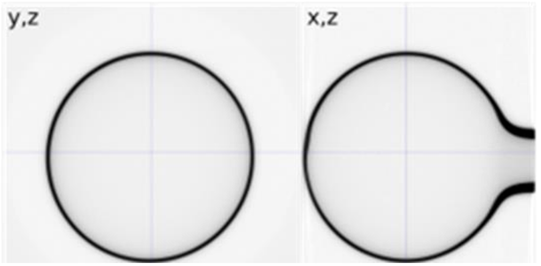


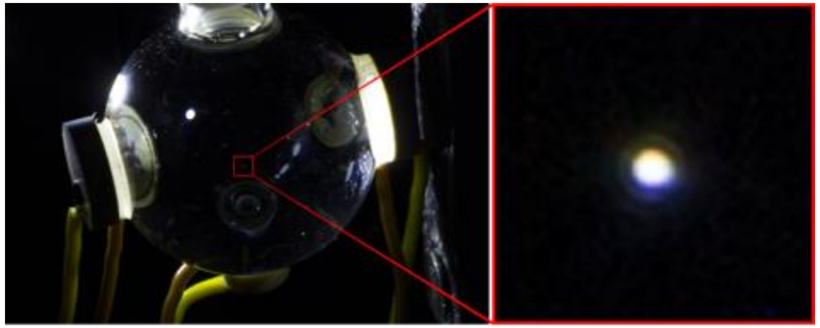




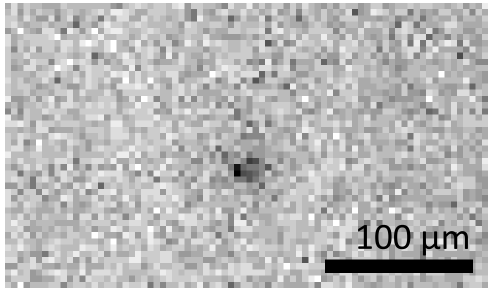
The non-linear bubble oscillator:

- **Expansion** to maximum radius, e.g. ~50µm
- **Collapse:** to extremely compressed bubble
  - T ≈ 4.000 - 10.000 K
  - Shock wave emission, ≈ 90% energy loss
  - Compression to almost liquid-like densities
  - Chemical dissociation reactions
  - sonoluminescence, thermal bremsstrahlung & radiative recombination?
- after-bounces and repeated expansion





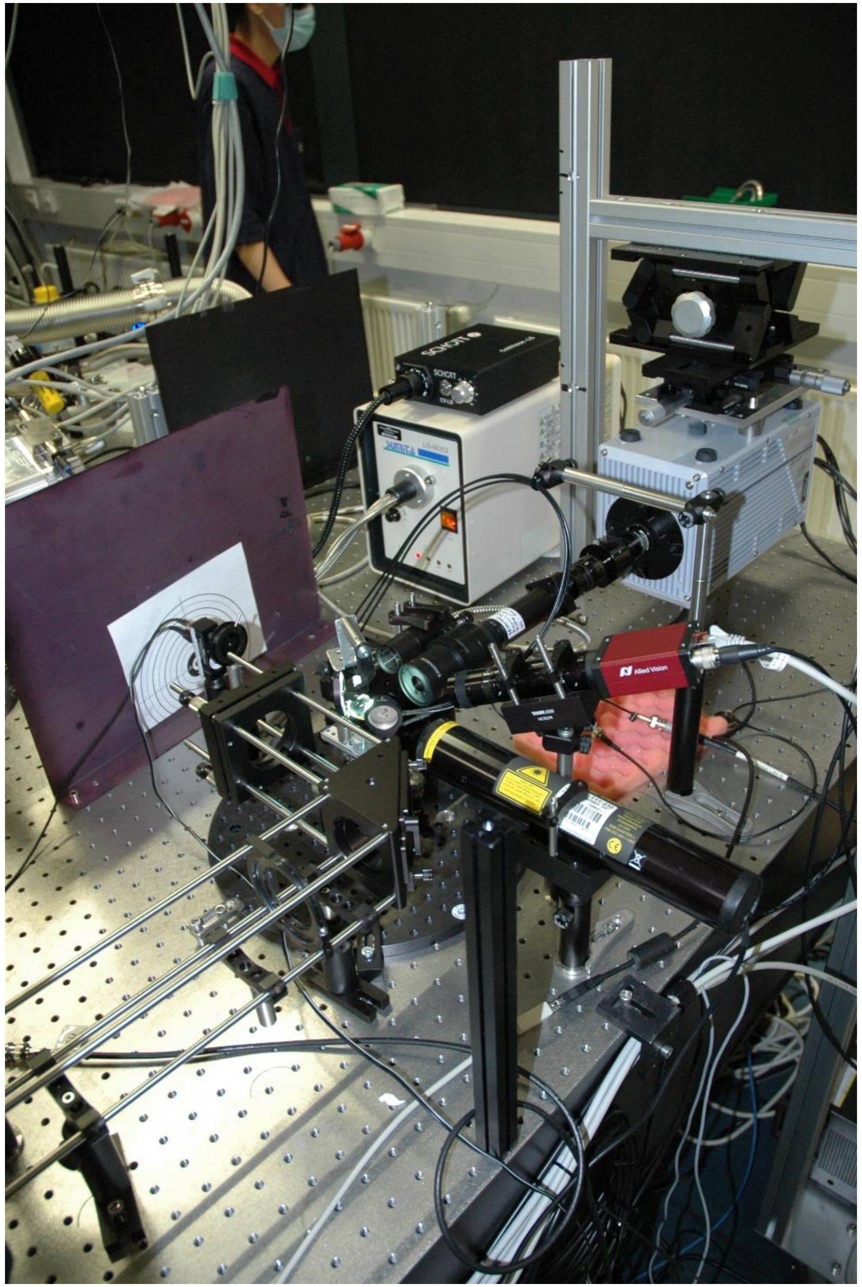
resonance chamber: d=19 mm cuvette with a trapped bubble at f=88 kHz

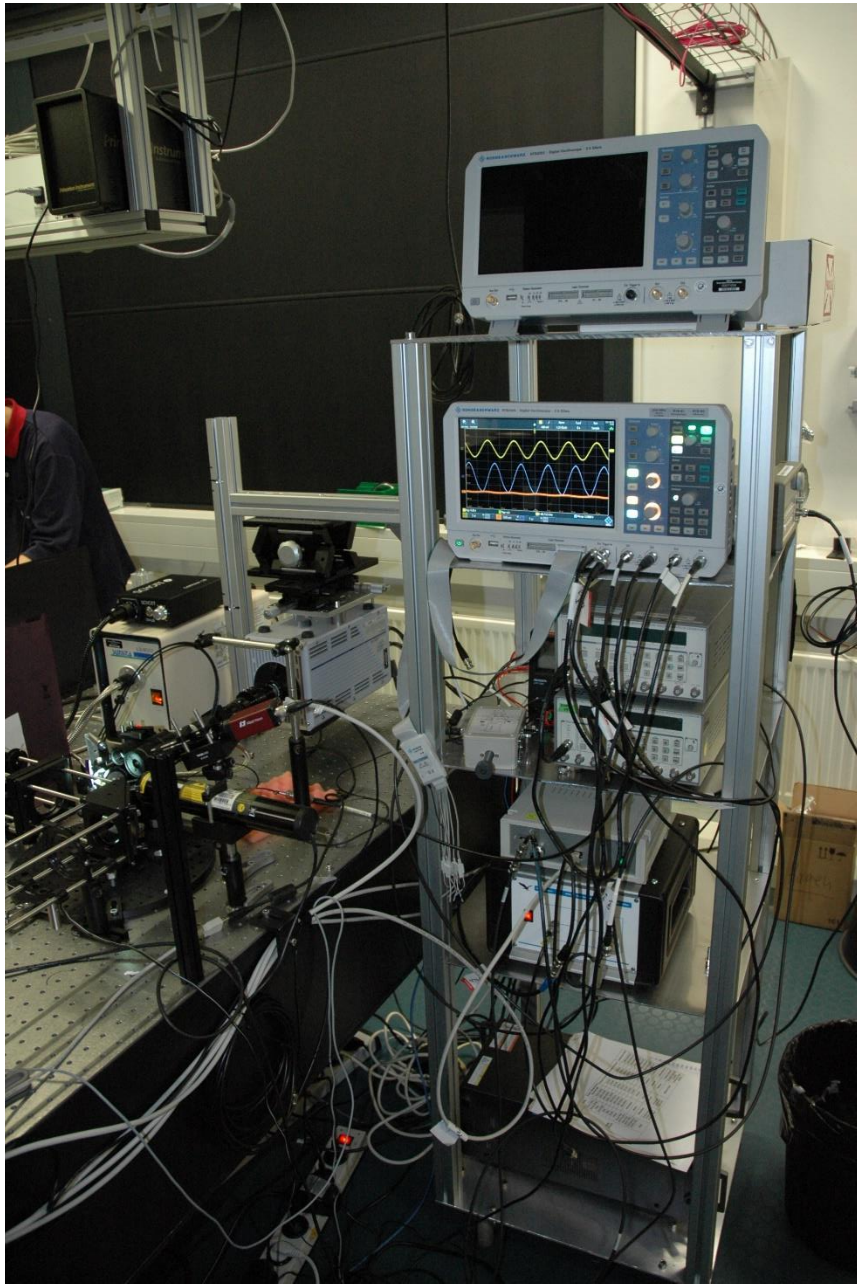


160 ns shutter, 480.000 fps
~ 88 kHz ultrasonic driving

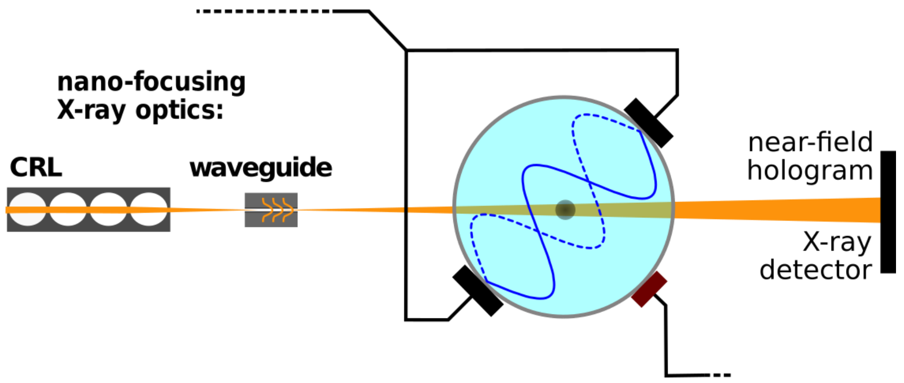
In-house setup

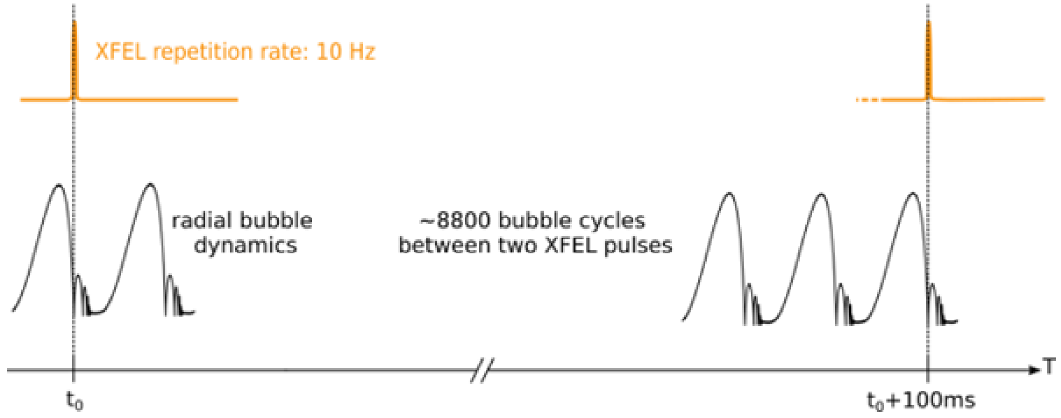
PXS lab:
TiSa fs laser (Coherent)
Acoustics & timing



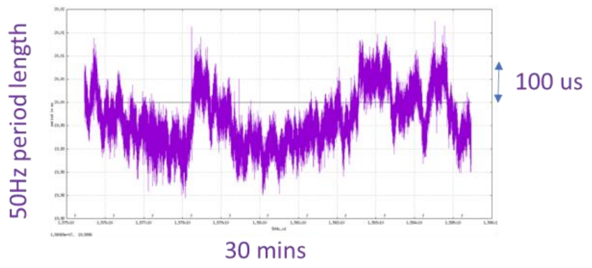


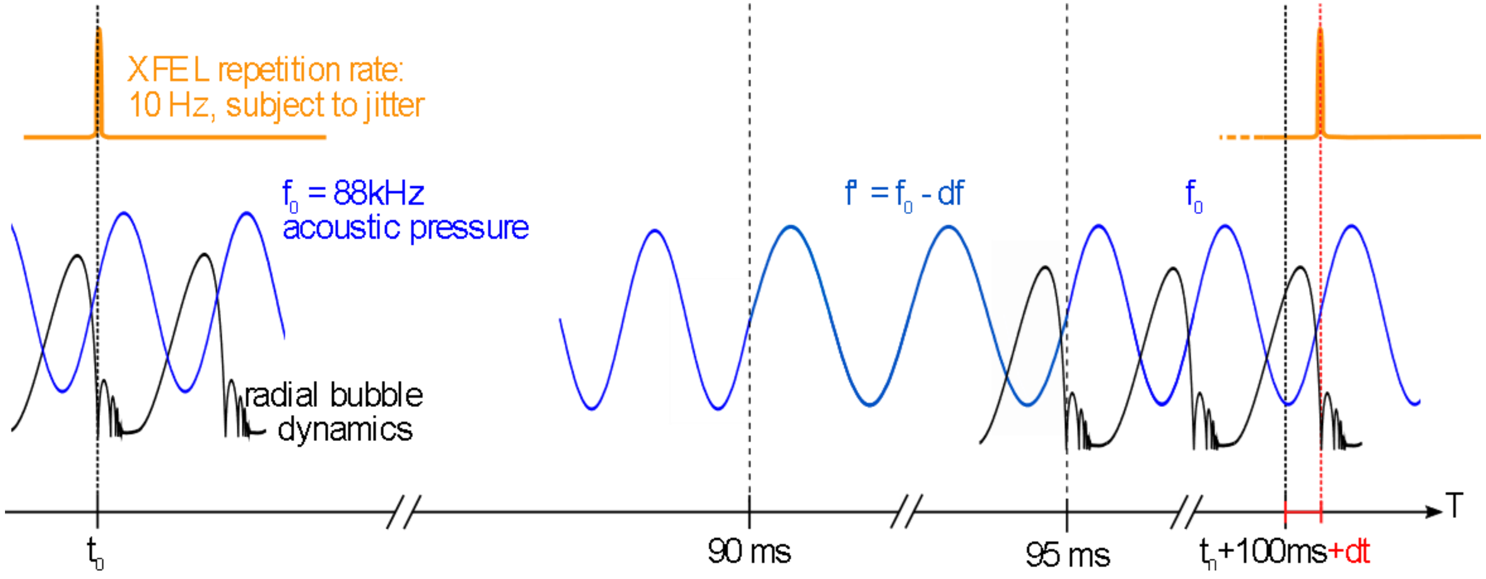
Acoustic synchronization & timing

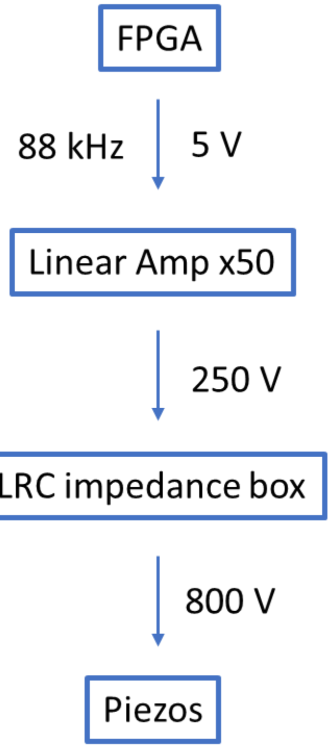




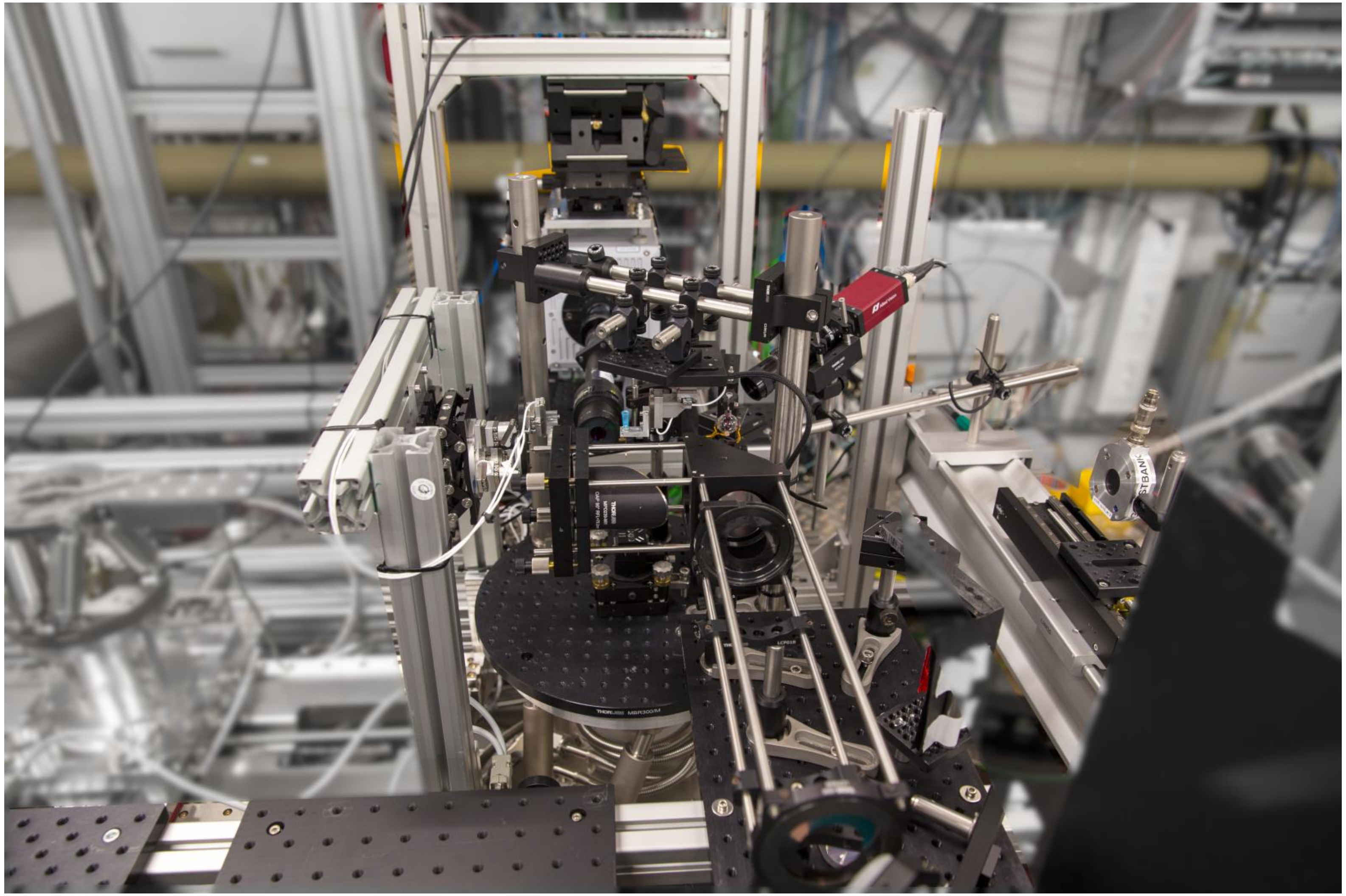
challenge: bunchclock synchr. to the mains: *jitter!*







XFEL beamtime p2807 10/21: Experimental parameters at MID



X-ray parameters:

E_{ph} = 18 keV
τ < 100 fs
f_{rep} = 10 Hz
$\langle E_p \rangle$ = 1 mJ

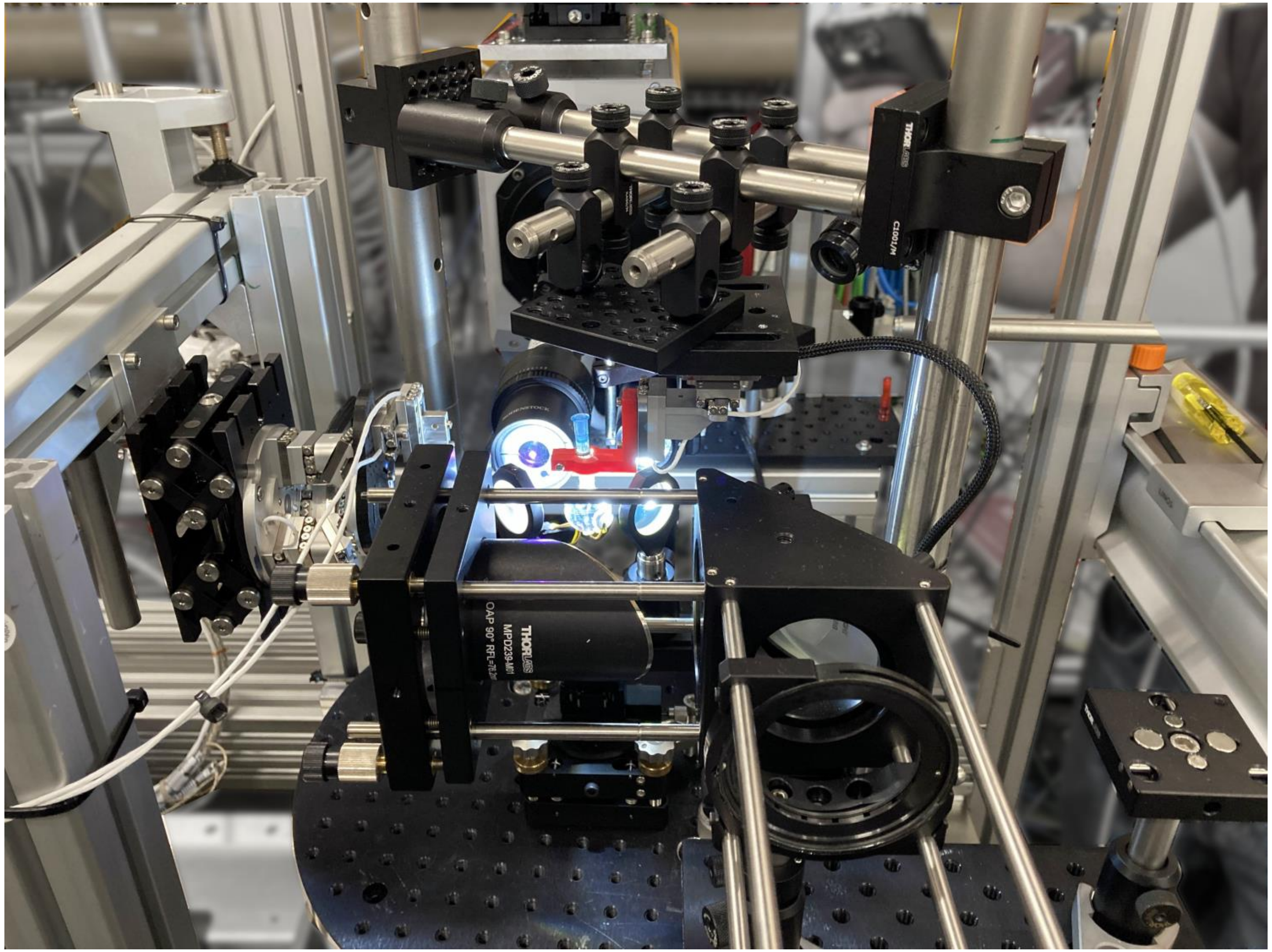
CRL Nanofocus:

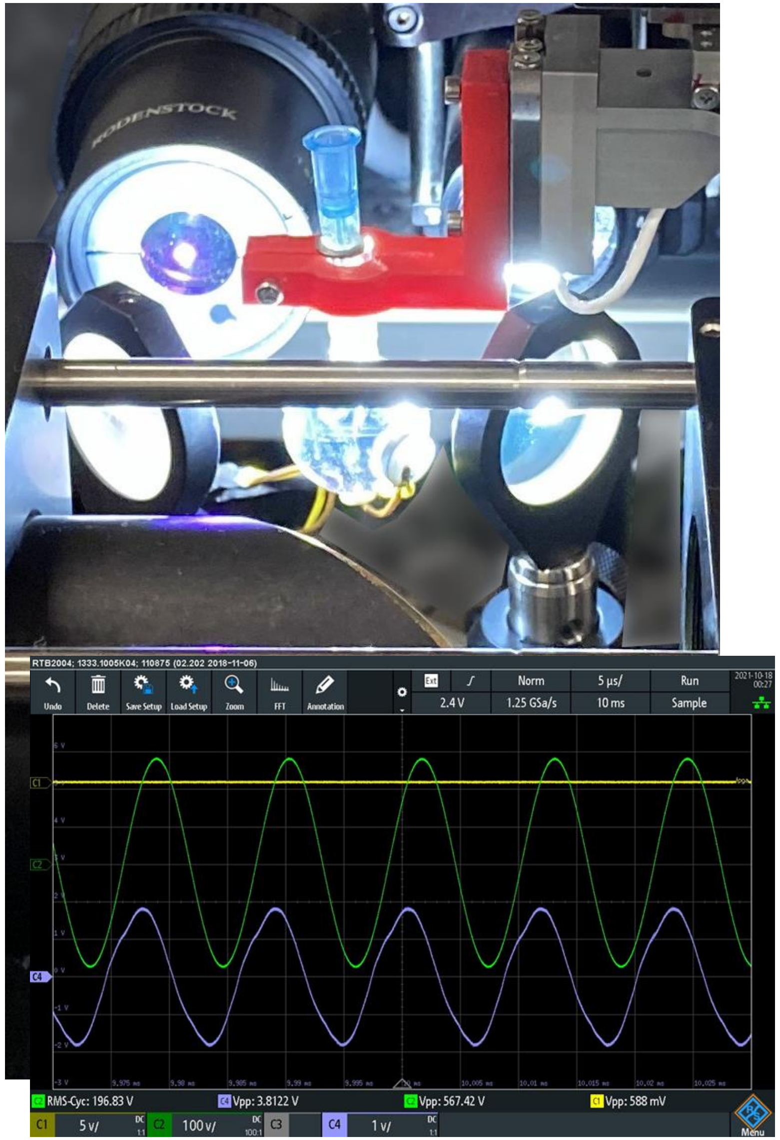
M = 95.2
z_{01} = 102.5 mm
z_{12} = 9756 mm
p_{eff} = 68.23 nm

IR Pump laser:

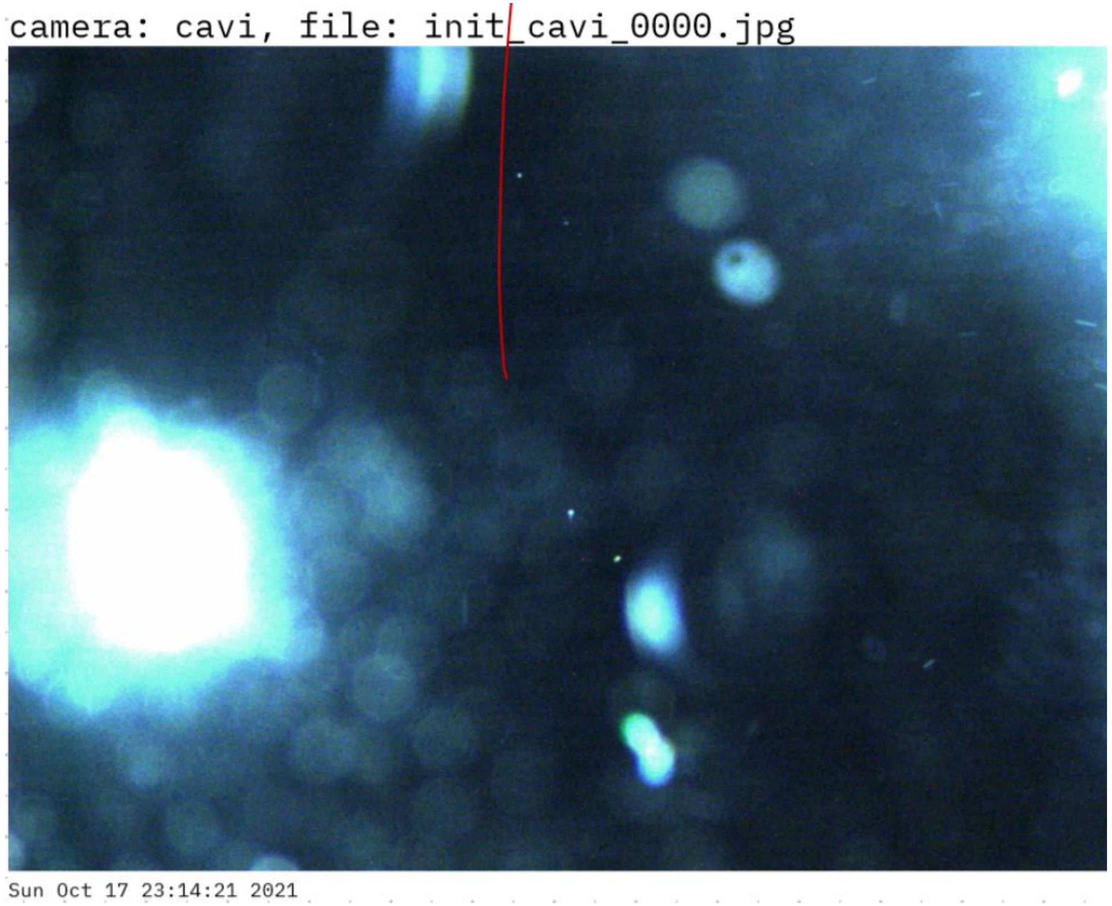
λ = 800 nm
$\tau \approx$ 60 fs
f_{rep} = 10 Hz
$\langle E_p \rangle$ = 3 µJ … 120 µJ

Experimental Setup for acoustic trapping installed at MID



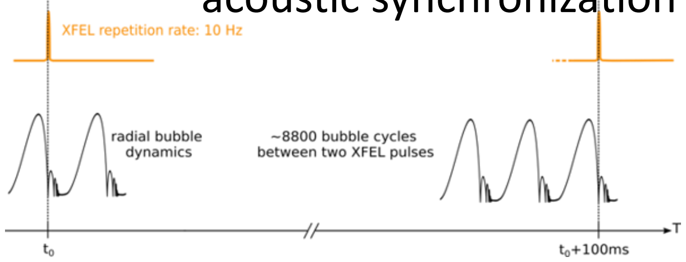


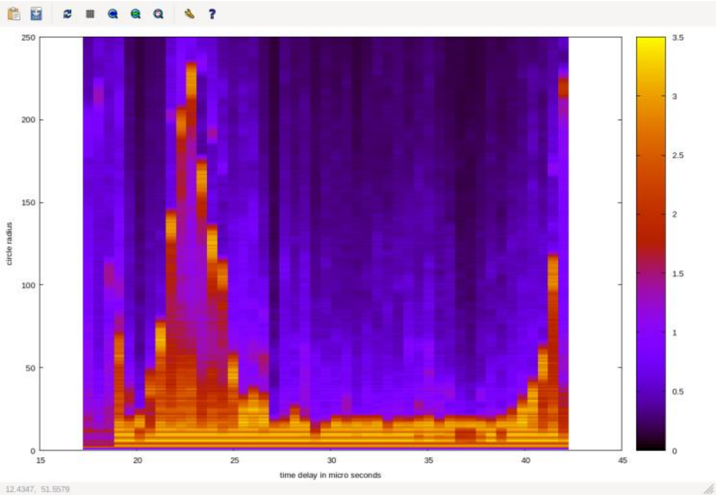
Live observation of luminescence



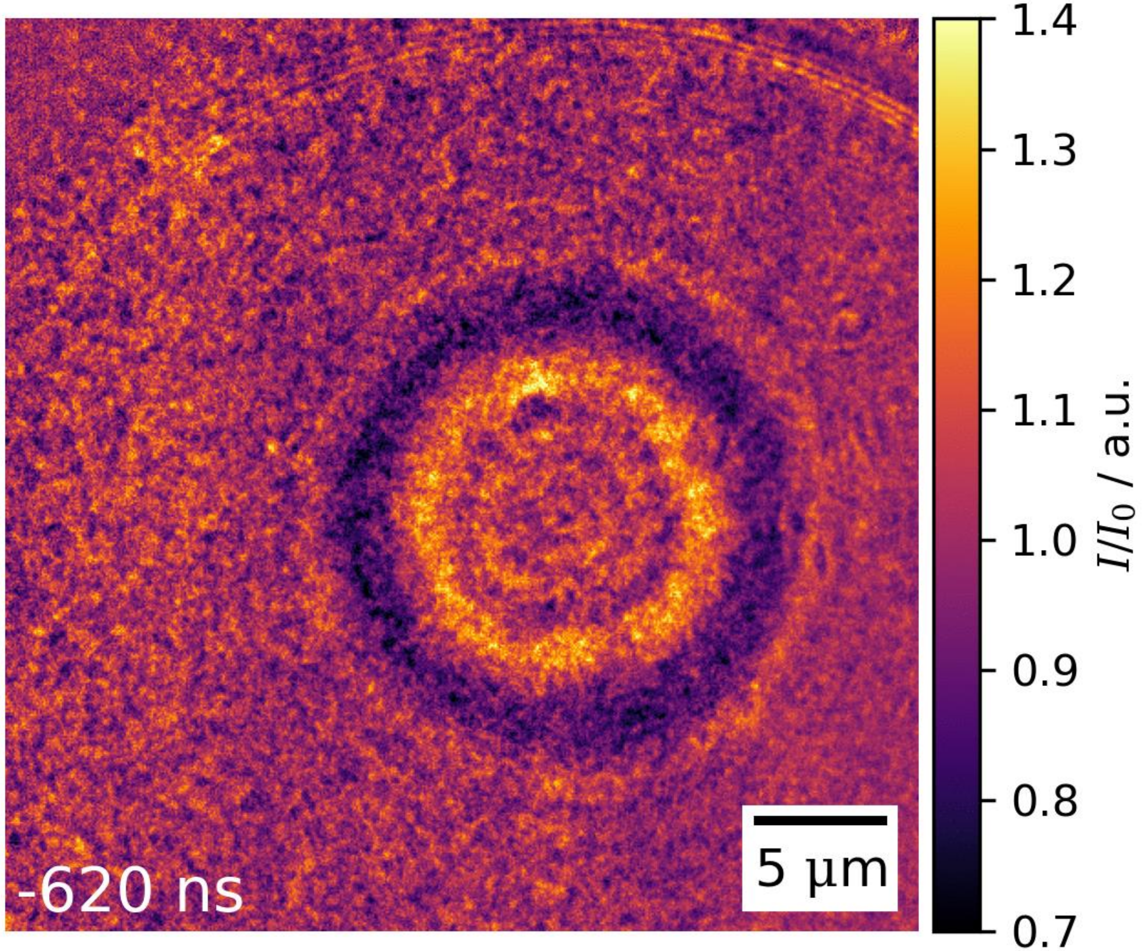
First results: sampling of the collapse

acoustic synchronization

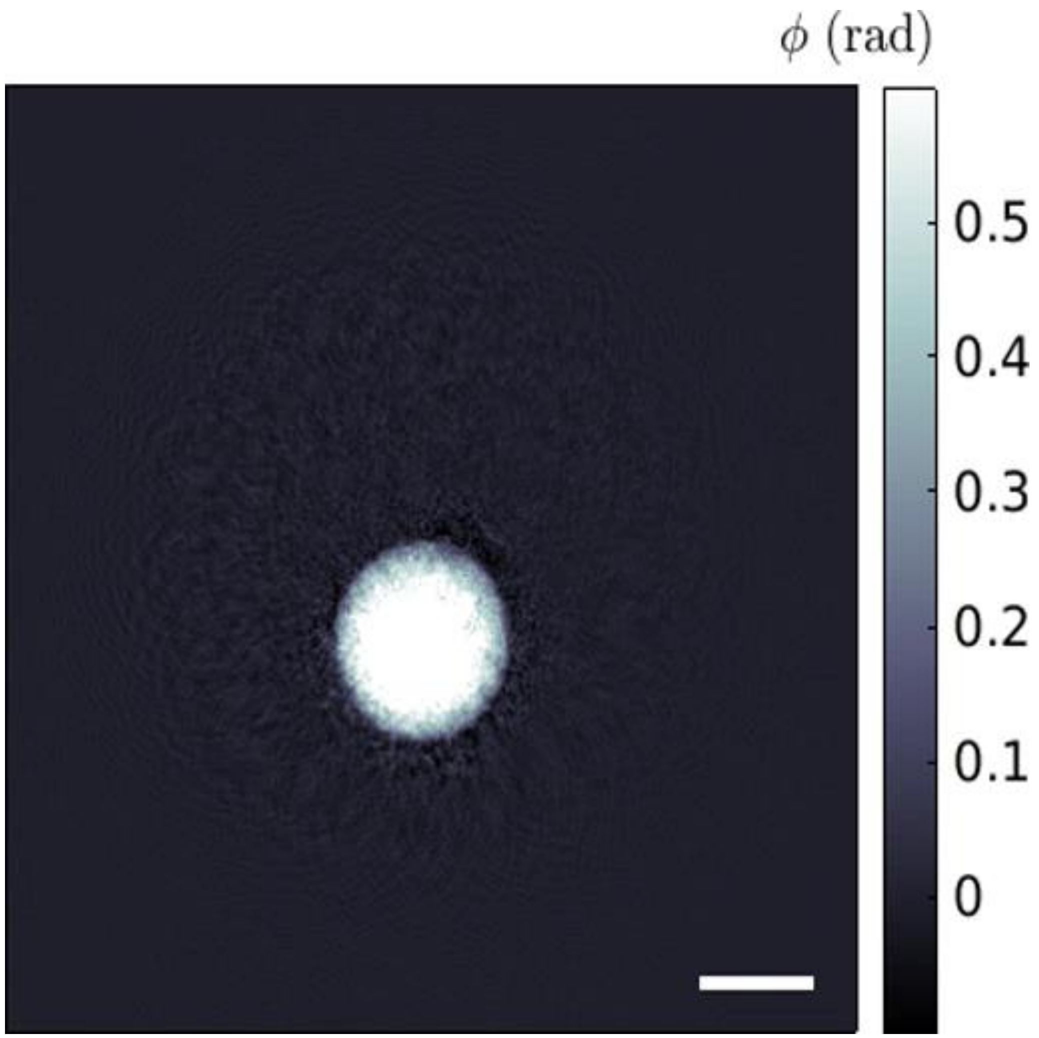


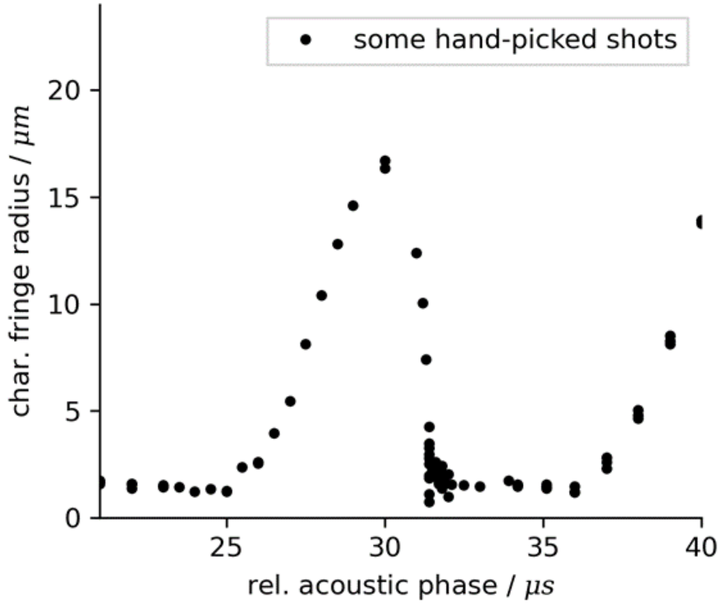


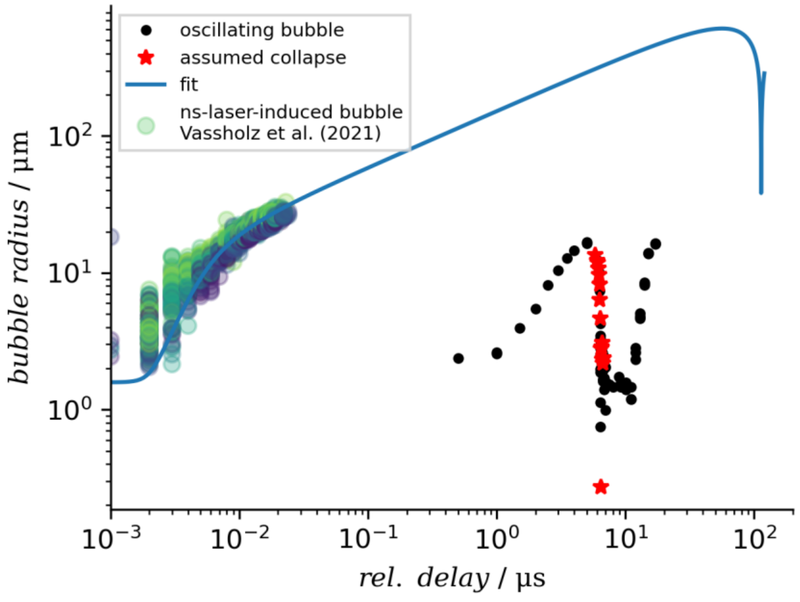
Acoustic delay / µs

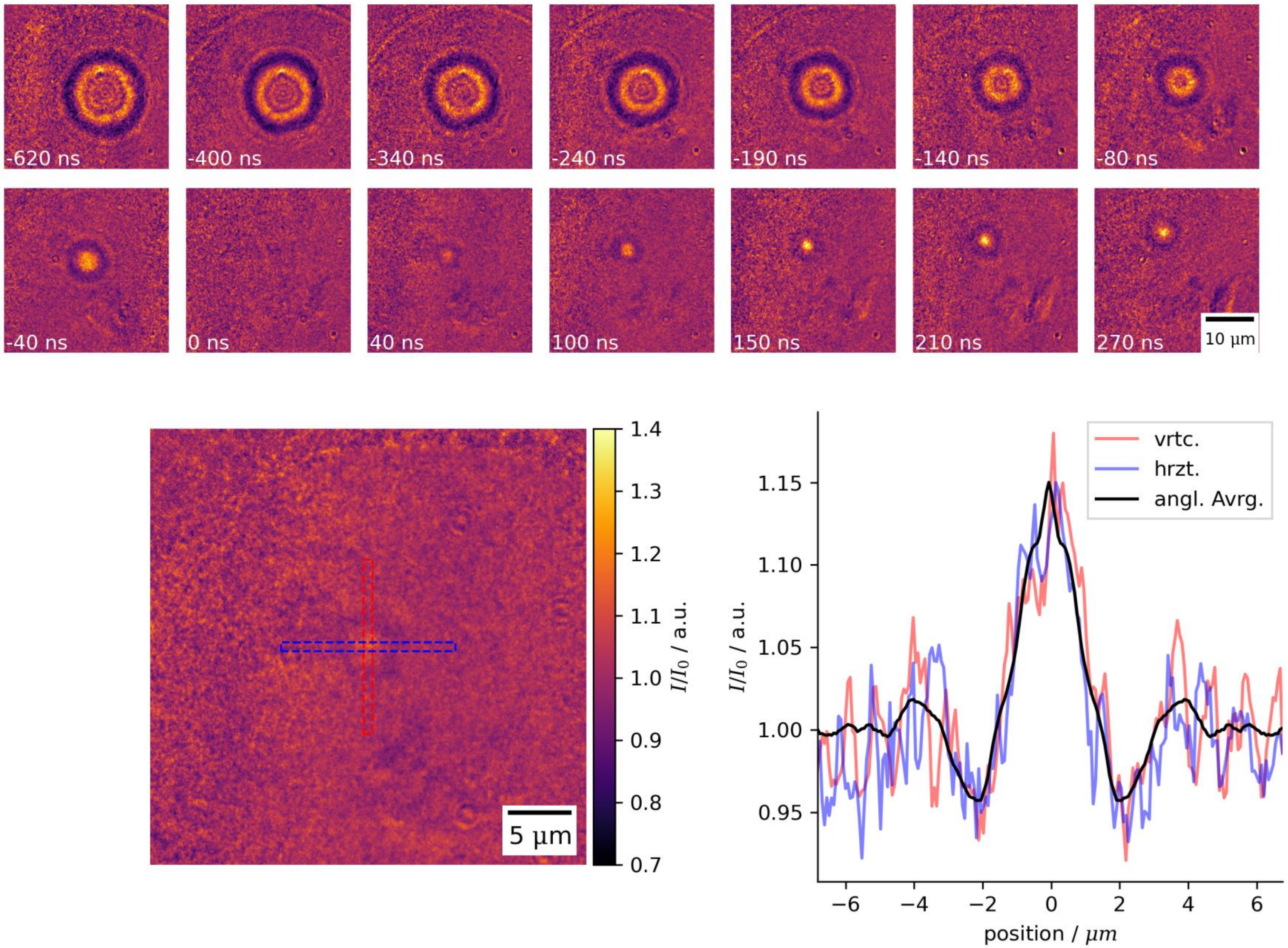


First results: phase reconstruction

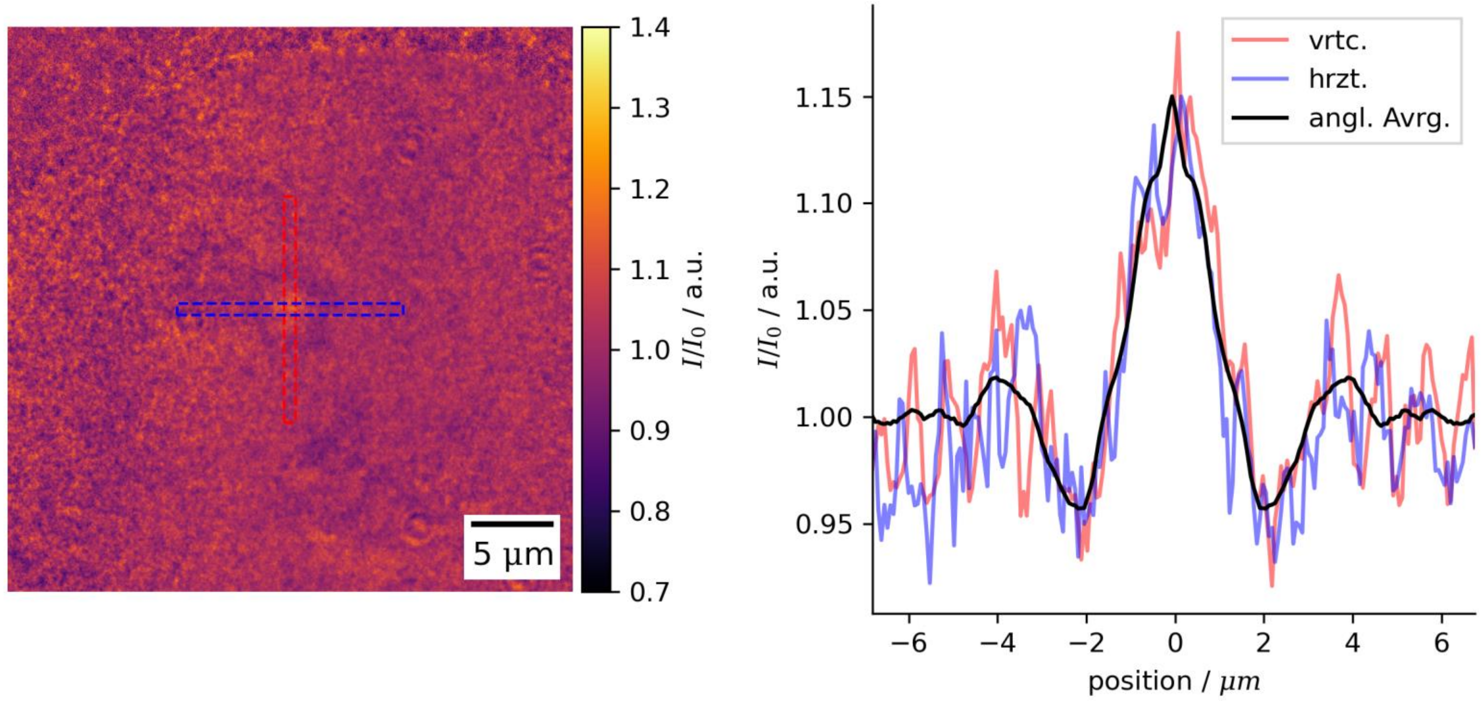




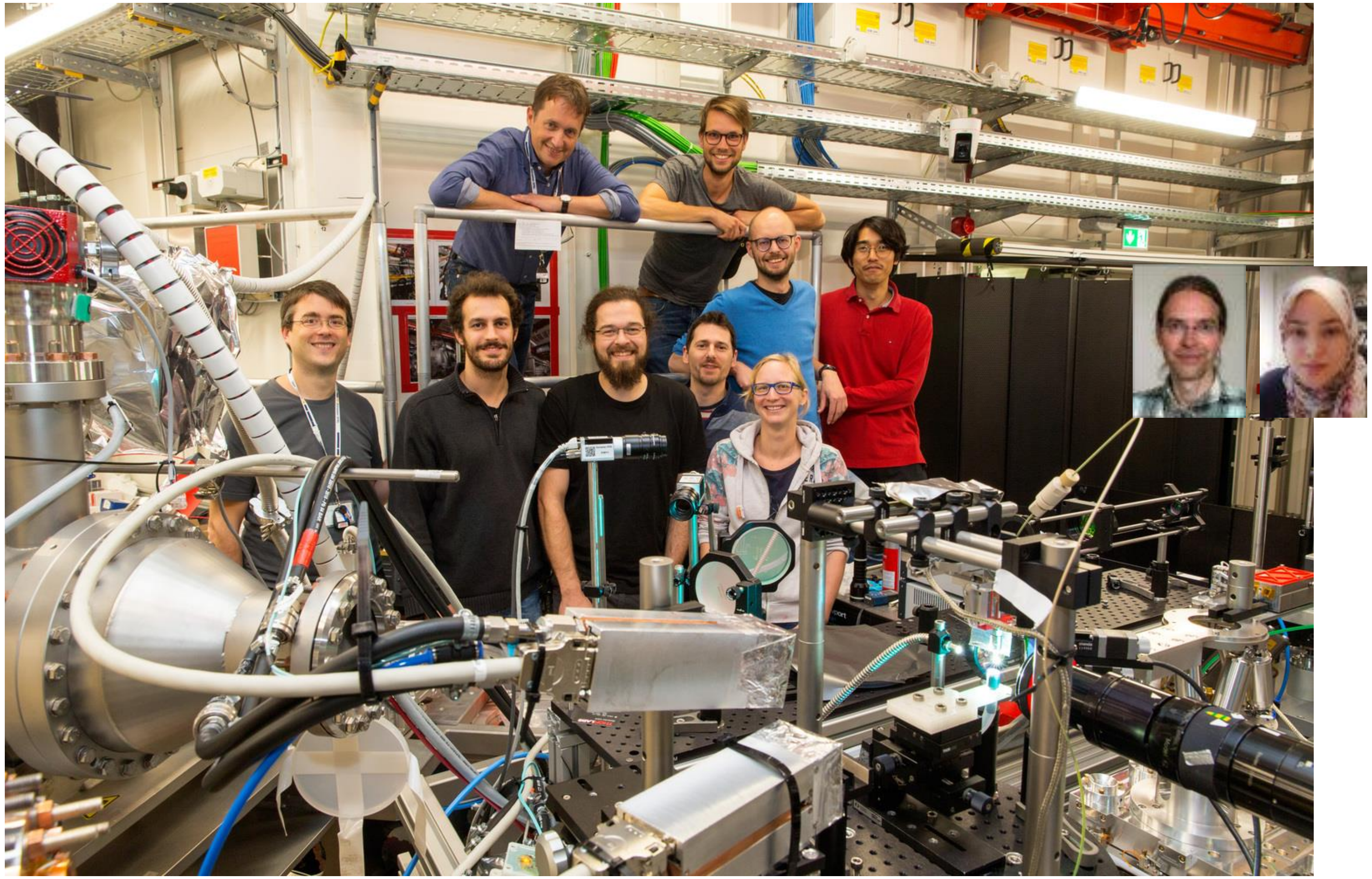




Hoeppe et al., (in preparation)


5 µm
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
I/I_0 / a.u.
vrtc.
hrzt.
angl. Avrg.
1.15
1.10
1.05
1.00
0.95
−6
−4
−2
0
2
4
6
position / μm

Team & Acknowledgements



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Max-Planck school of photonics

Bundesministerium
für Bildung
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