This talk is on small bubbles…

Tim Salditt
on behalf of the small-bubble collaboration
XFEL UM , HH29.1.2020

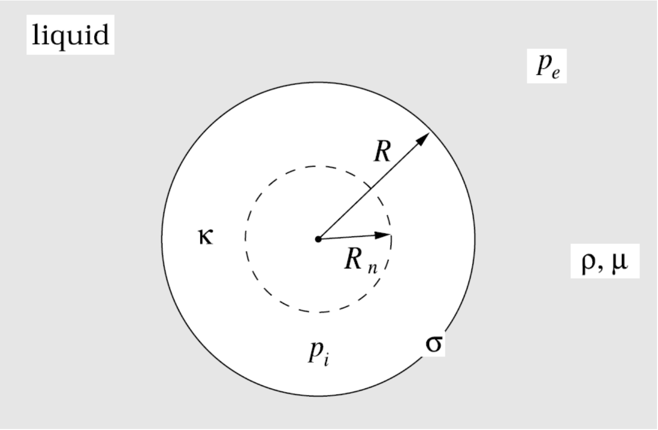
Malte Vassholz, Markus Osterhoff, Hannes Hoeppe, Juan Rosello, Robert Mettin, Thomas Kurz
Universität Göttingen, III-Phys. Inst.-Biophysik & Institut für Röntgenphysik

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 and Beamtime 10/ 2019 @17.5keV (p2207 & p2545 Hagemann/ Salditt)

Draw me a bubble…



- (quasi-) spherical gas phase in liquid
- Cavitation bubbles
  induced by hydrodynamic flow, optical breakdown, acoustic pressure
  when hydrostatic pressure falls below vapor pressure
- far from equilibrium, e.g. formed by
  ultrasound or optical breakdown (laser)
- ***Bubbles @ ocean – atmosphere interface***

  Evidence for the importance of bubbles in increasing air–sea gas flux
  DM Farmer, CL McNeil, BD Johnson - Nature, 1993

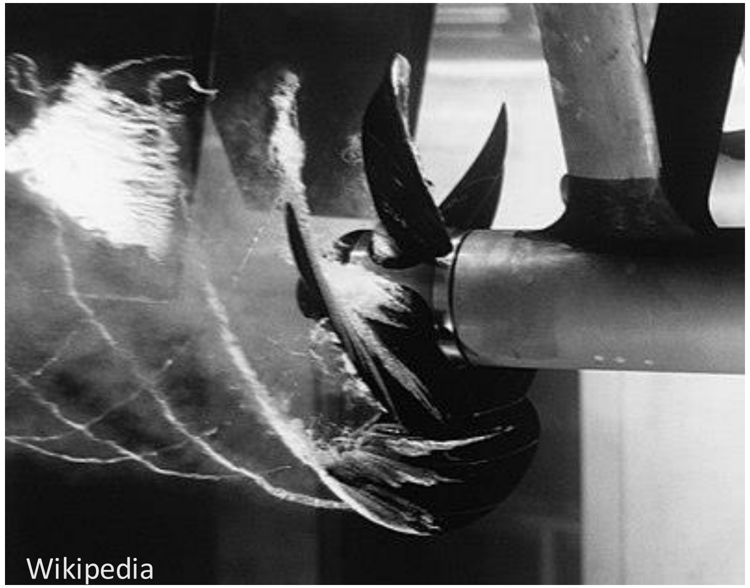
  Scale dependence of bubble creation mechanisms in breaking waves
  GB Deane, MD Stokes - Nature, 2002

  Gas transfer by breaking waves
  L Deike, WK Melville - Geophysical Research Letters, 2018

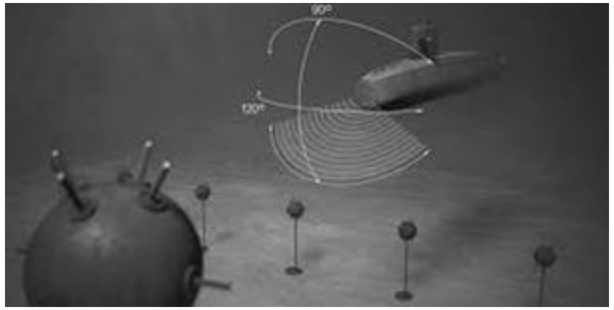
Katasushika Hokusai (1760-1849)

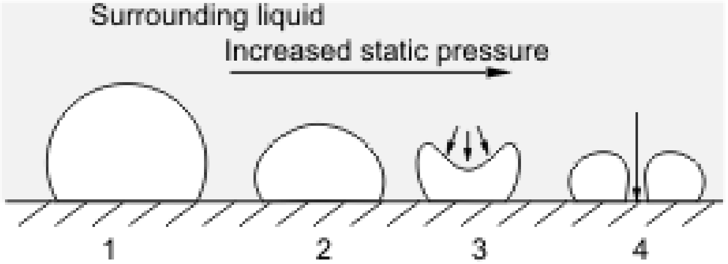
Important in climate models !

Cavitation in engineering


Wikipedia

Cavitation research started with technical fluid mechanics in particular in marine technology (propellors, sonar, underwater explosion)

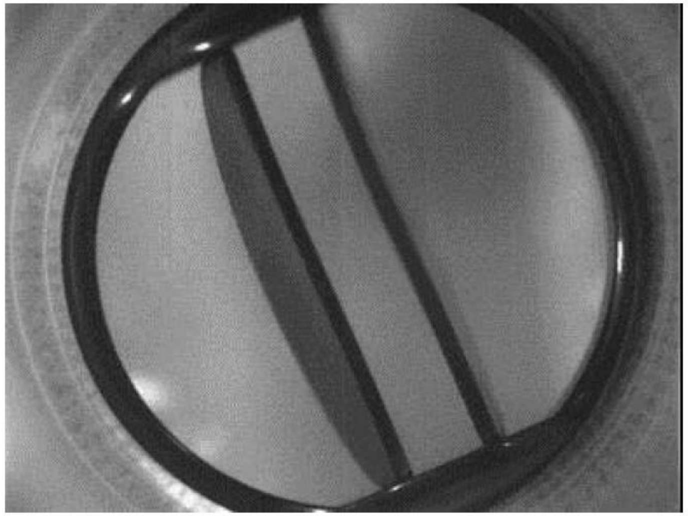




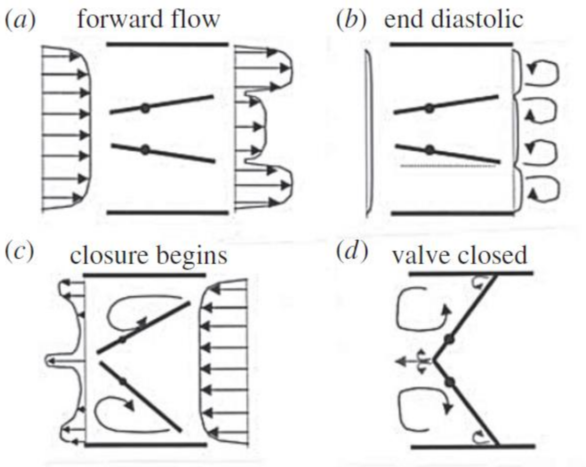
Cavitation bubble imploding close to a fixed surface generating a jet (4) of the surrounding liquid.

Cavitation limits performance of :
- ship propellors, blades
- pumps, motors

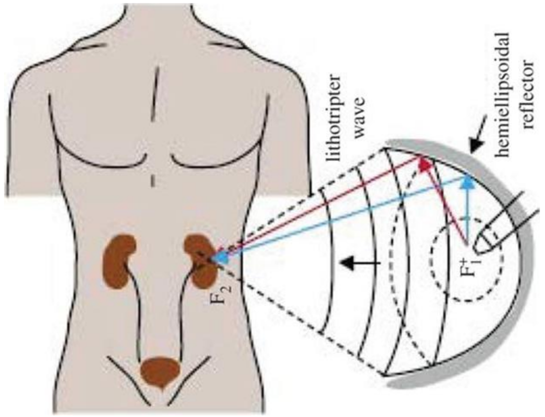
Cavitation enables:
- ultrasonic cleaning
- Laser ablation for drilling &hardening
- nano-particle production


CE Brennen, Interface Focus Roc. Soc. 2015

artificial heart valves



Cavitation in medicine and life science

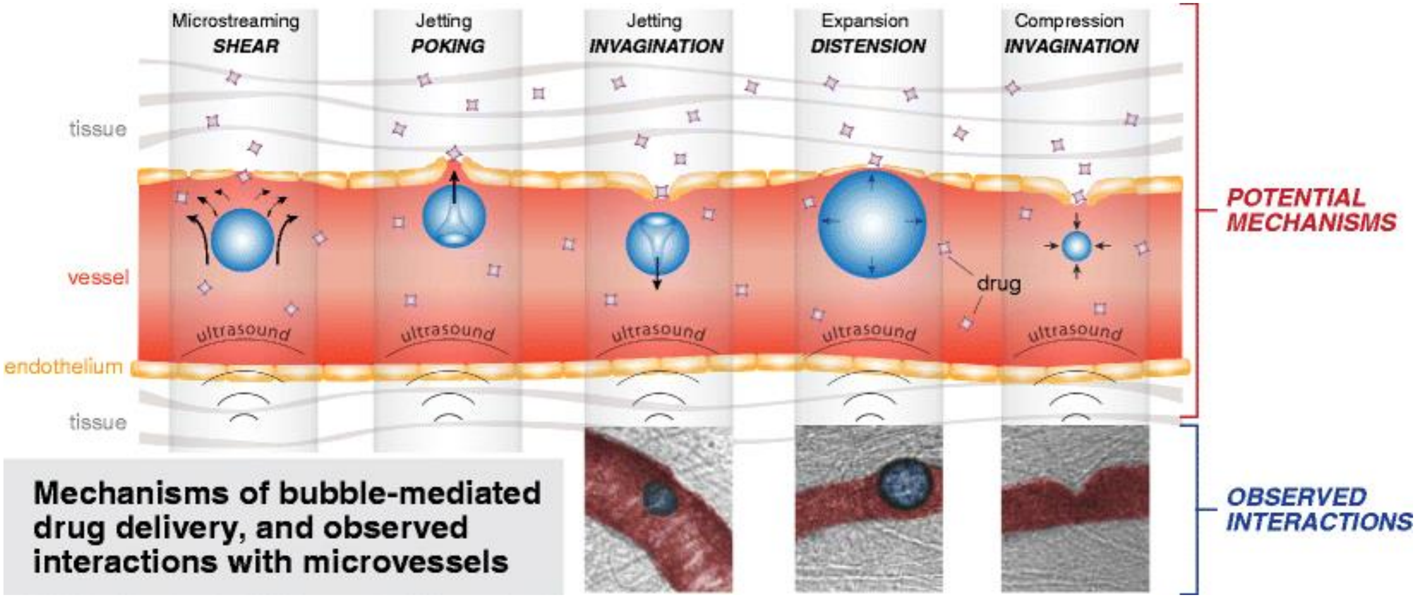


Lithotripter / phacoemulsificatin / ultrasound fat cavitation

Different biomedical applications:

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

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

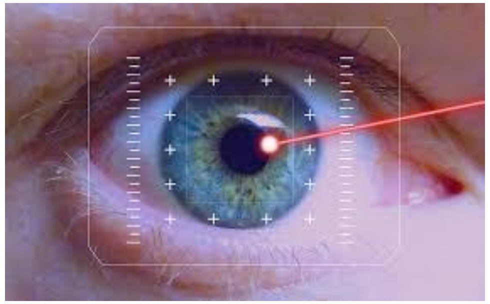


Mechanisms of bubble-mediated drug delivery, and observed interactions with microvessels

Cardiovascular applications of therapeutic ultrasound
Nazer et al. , Journal of Interventional Cardiac Electrophysiology, 2014,

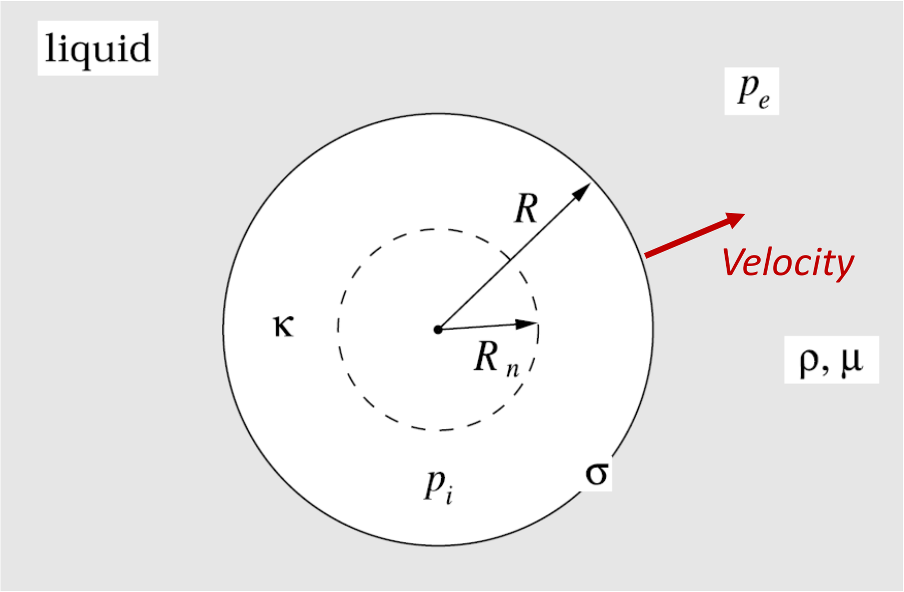
Surgery :

- 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!

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:

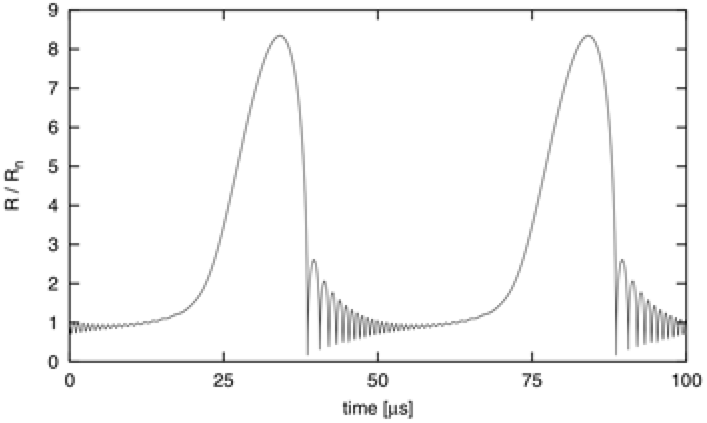
- bubble collapse: *T ? p ? R_{min} ?*
- *sonoluminescence*
- caviation in artifical heart valves
- nature of the interfaces
- equation of state of H_2O: beyond Tait

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

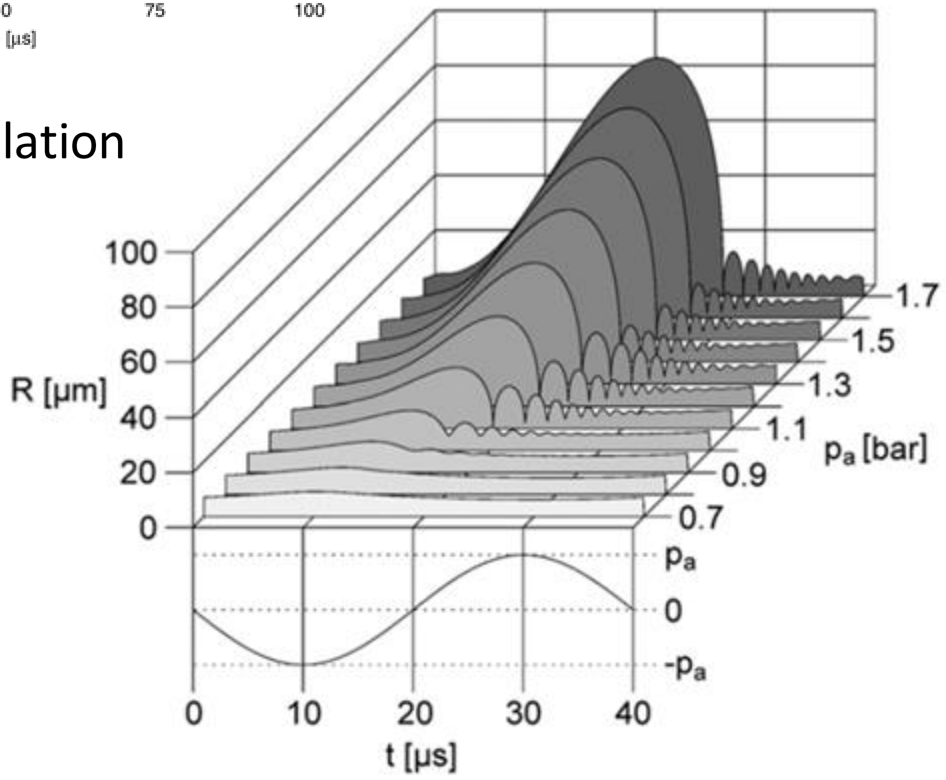
Physics of bubble oscillations, W. Lauterborn, T. Kurz Rep.Prog. Phys. 2010

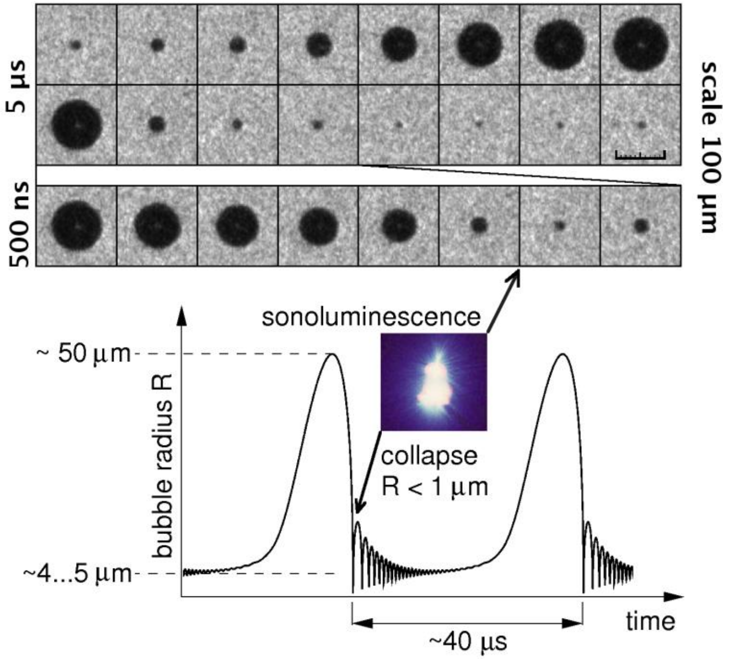
Nonlinear dynamics, synchronized by acoustics

- suitable synchronized observation
- sub-µm radius @ collapse ?
- *how small ? density ? pressure ?*



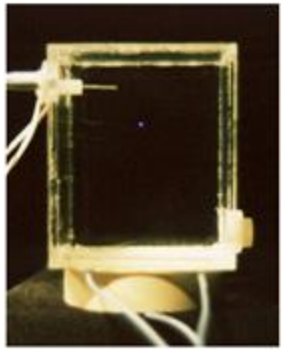
- numerical simulation





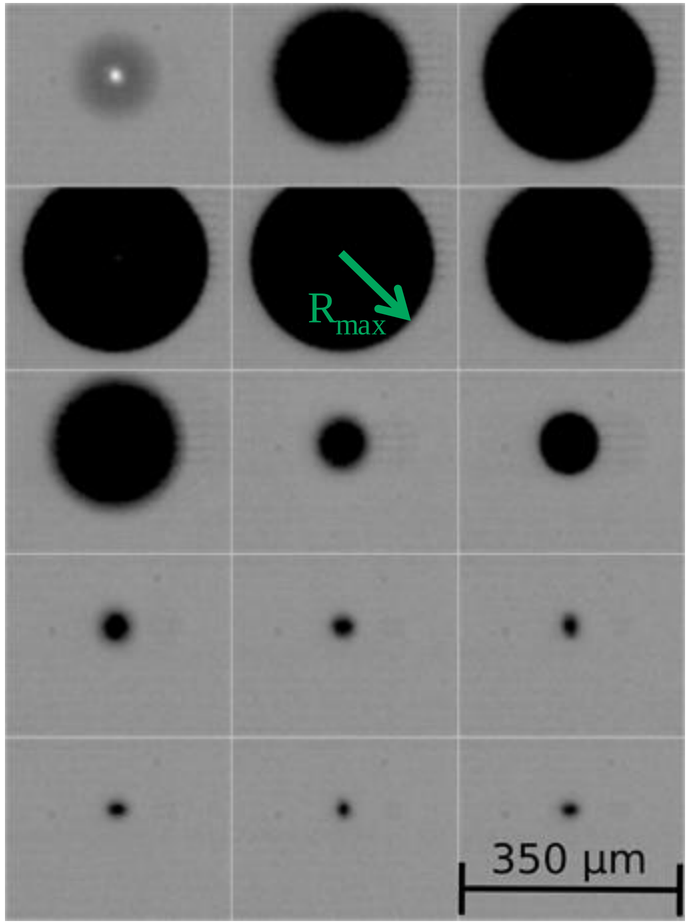
W. Lauterborn and T. Kurz,
Physics of bubble oscillations
Rep. Prog. Phys. 2010

- sonoluminescene

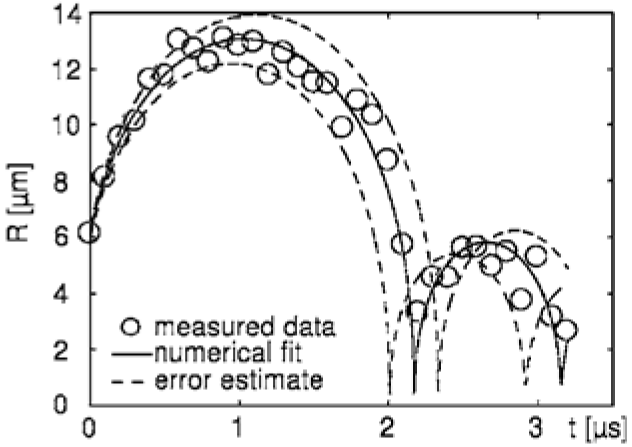


Bubble seeding, energy & oscillations

- bubble nutleation
  controlled by ps or ***ns- laser pulse)***
- initial stages: plasma
- accoustic trapping
- bubble collapse



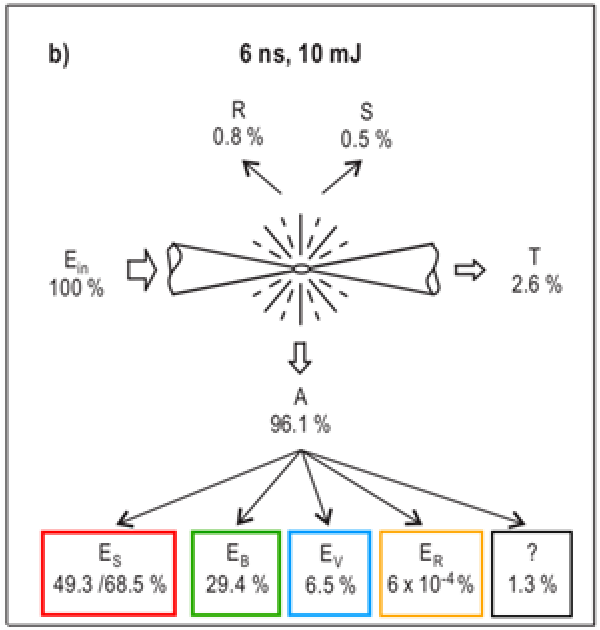
300 kfps, 1µs shutter speed



T. Kurz, D. Kröninger, R. Geisler, and W. Lauterborn, Phys. Rev. E (2006)

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

bubble energy determines maximum radius



~59 % Shockwave energy

~30 % Bubble Expansion energy

~7 % Evaporation energy

~$6*10^{-4}$% Radiation energy

~1,3 % Dark Energy

Vogel et al. Appl Phys B (1999)

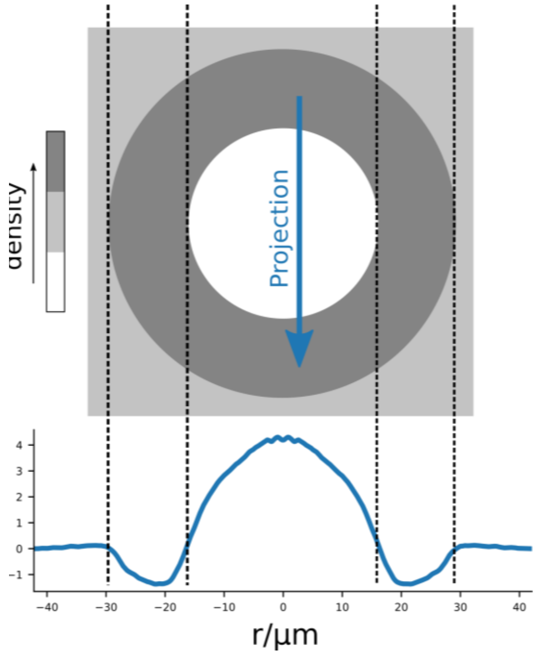
Research questions

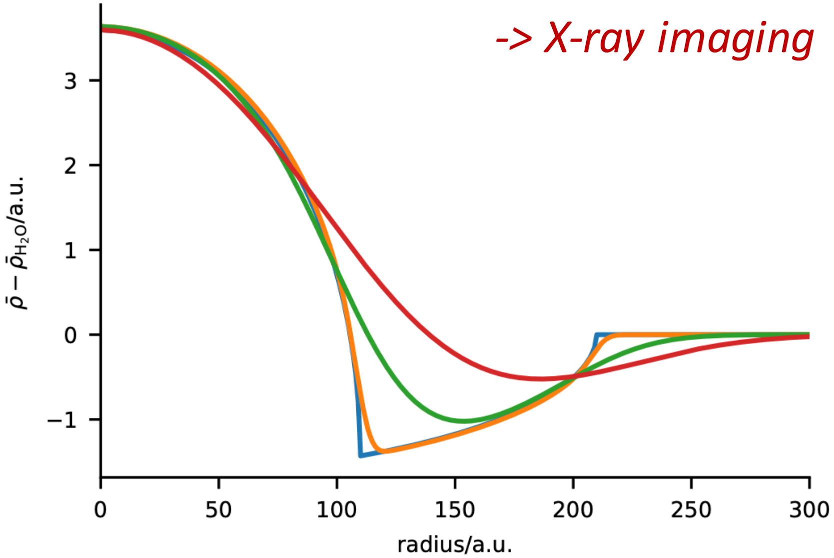
Plasma generated by
Optical breakdown
Multi-photon absorption
I > 10^{12} W/cm^2

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

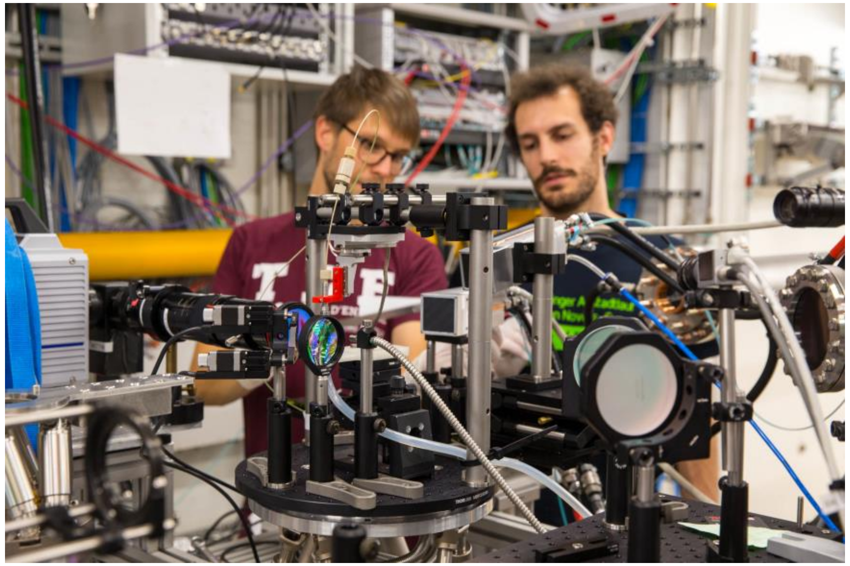




- bubble evolution
- density of the shockwave ?
- sharp interfaces gas/water ?

radial density profile !

email from XFEL (2.11.18) – a disruptive event



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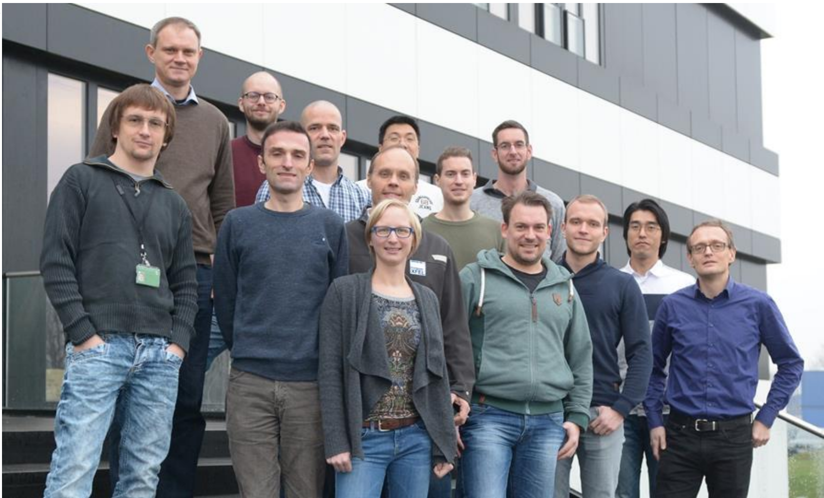
Am 02.11.18 um 14:42 schrieb European XFEL User Office:
> Main Proposer: Dr. Johannes Hagemann / email:
> johannes.hagemann@desy.de
>
> Principal Investigator: Prof. Dr. Tim Salditt / email: tsaldit@gwdg.de
>
> *Your Proposal No. 2207 at the European XFEL, allocation cycle 201802*
>
> *Title: Cavitation Dynamics Studied by Time-Resolved High-Resolution
> X-Ray Holography*
>
> **
>
> Dear Main Proposer and Principal Investigator for proposal No. 2207,
>
> Many thanks for submitting the above proposal in the 3^rd call for
> early user experiments at the European XFEL. It is our pleasure to
> confirm that the project has been allocated beamtime at the MID
> instrument as
> follows:
>
> *Start date: 05 June 2019 (Day shift) *
>
> *End date: 09 June 2019 (end of last shift) *
>
> *Total shift allocated: 5*
```

You cannot count on XFEL beamtime
For your Ph.D. or master project

… so when it comes, you have to change plans...



…disruptive for everybody!

large collaboration & strong individual contributions

Malte Vassholz, Markus Osterhoff, Hannes Hoeppe, Juan Rosello, Robert Mettin, Thomas Kurz, Tim Salditt
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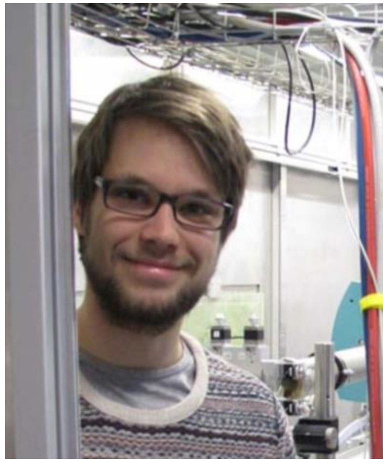
MID / XFEL

- UAC MID 06/2019 @14keV
- Beamtime 10/ 2019 @17.8keV

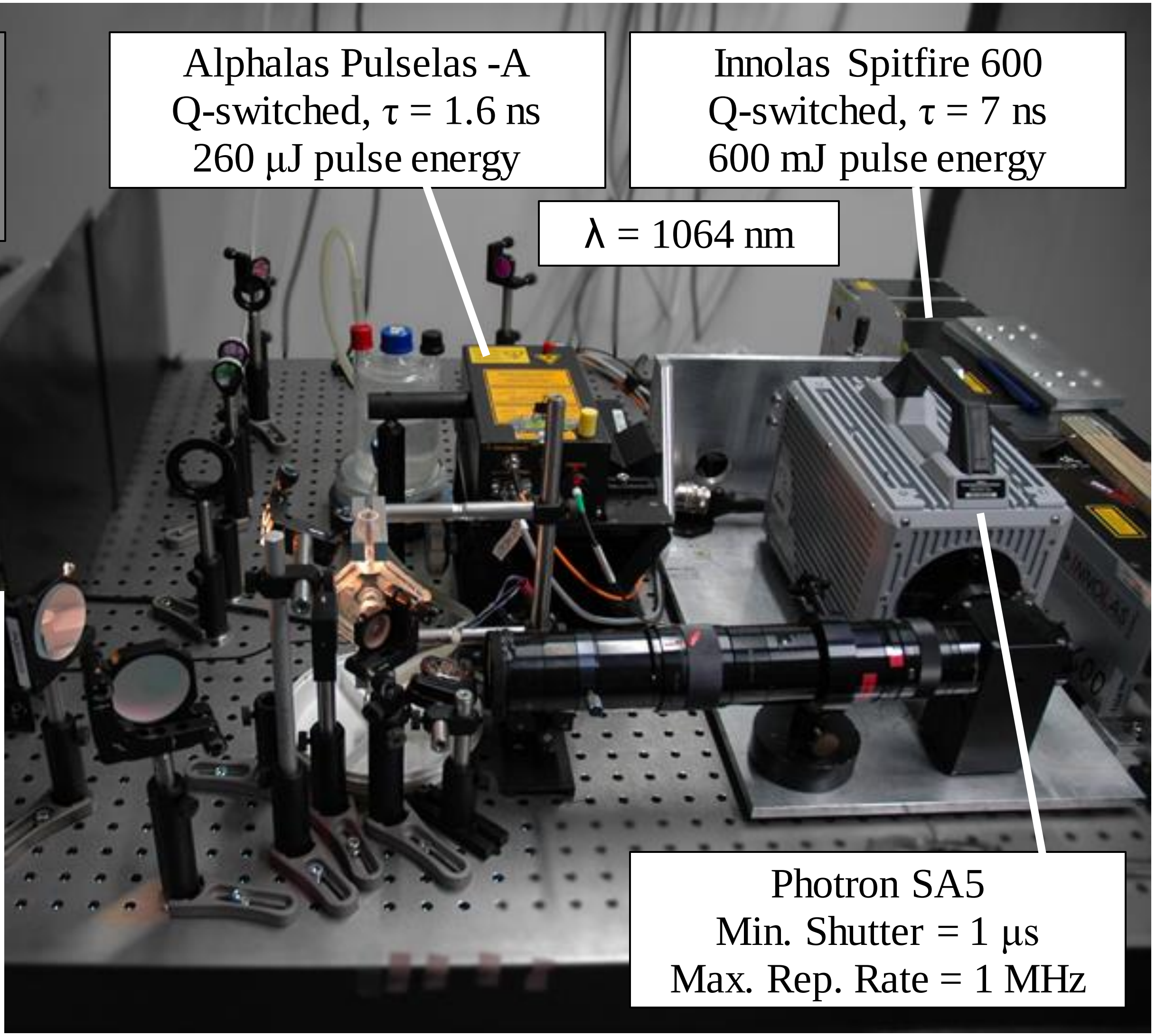
(p2207 & p2545 Hagemann/ Salditt)


Malte Vassholz


Johannes Hagemann


Markus Osterhoff

High speed optical imaging



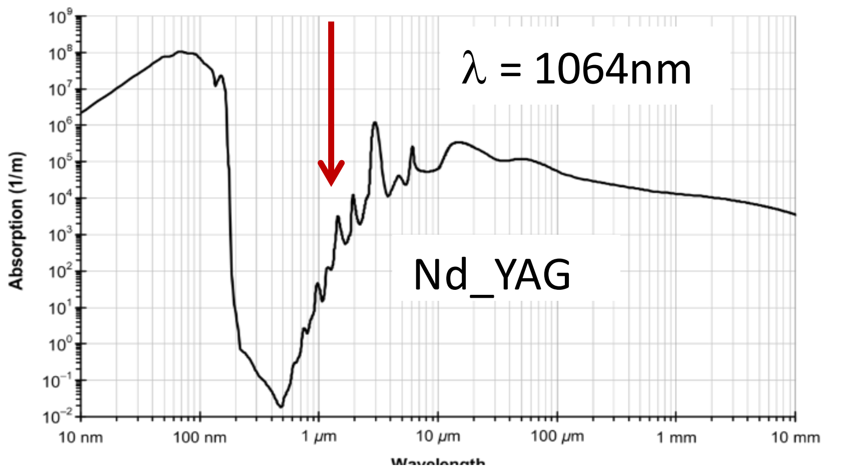
At XFEL:
Litron Nano L 200-10
Q-switched, τ = 4 ns
200 mJ pulse energy

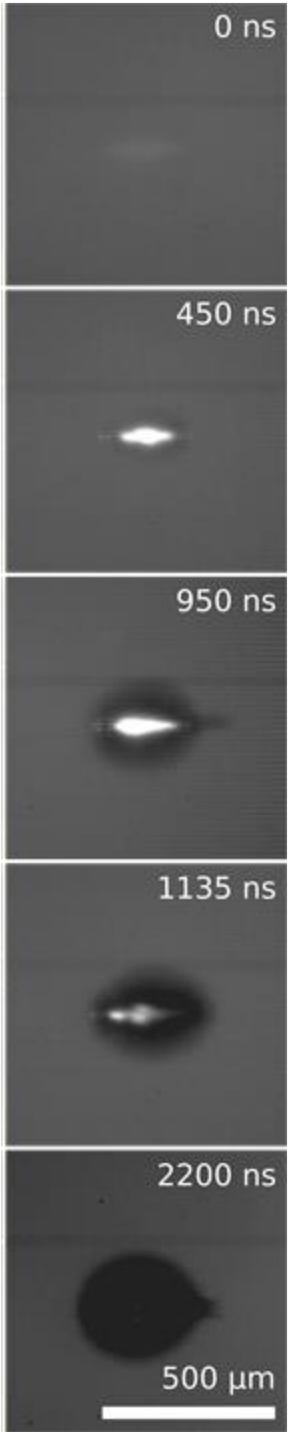
Alphalas Pulselas -A
Q-switched, τ = 1.6 ns
260 μJ pulse energy

Innolas Spitfire 600
Q-switched, τ = 7 ns
600 mJ pulse energy

λ = 1064 nm

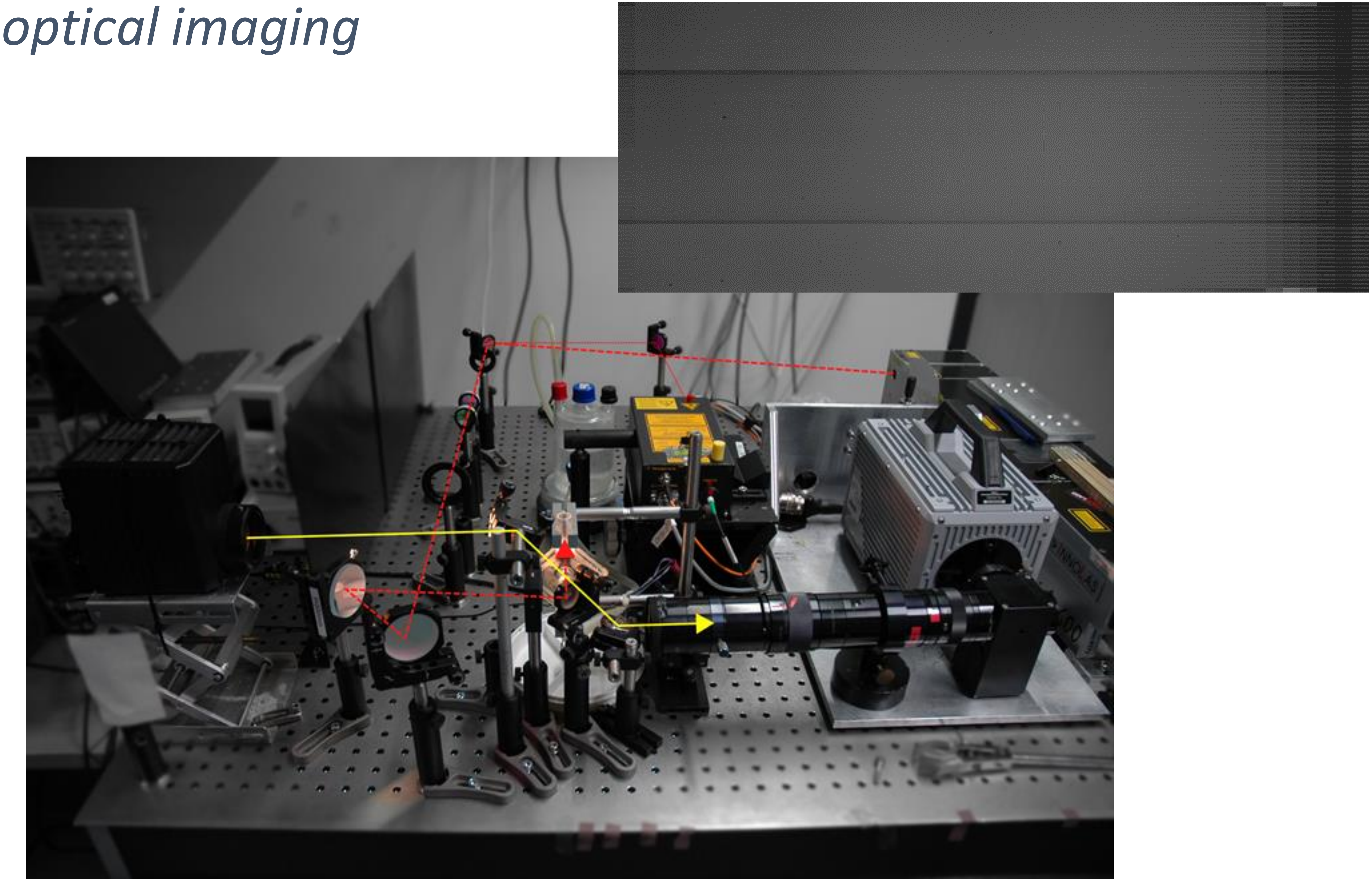
Photron SA5
Min. Shutter = 1 μs
Max. Rep. Rate = 1 MHz





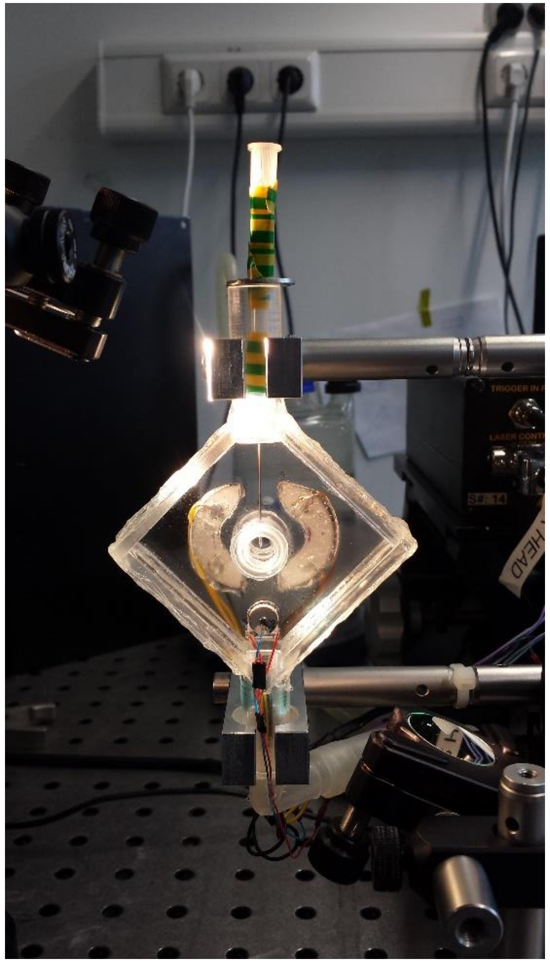
Hannes Hoeppe,Juan Rosello,

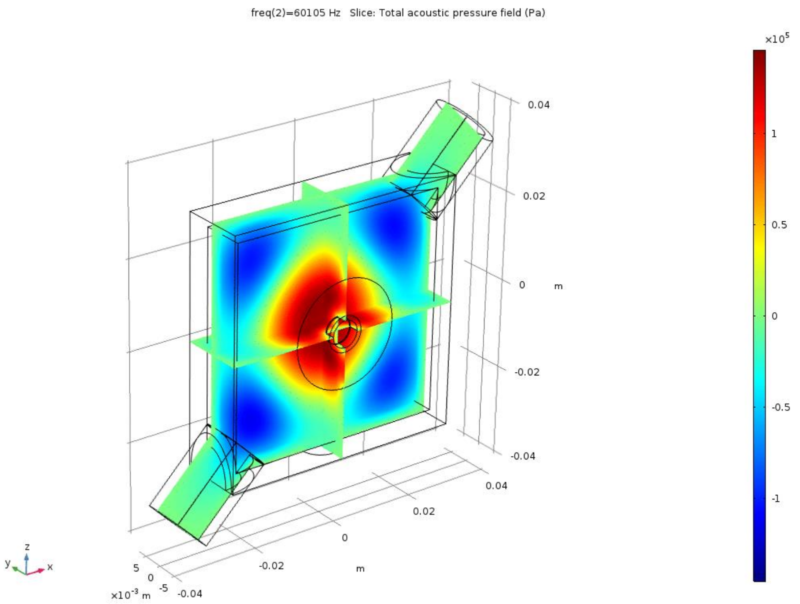
High speed optical imaging



Juan Rosello, Hannes Hoeppe

Cavitation cuvette x-ray compatible…



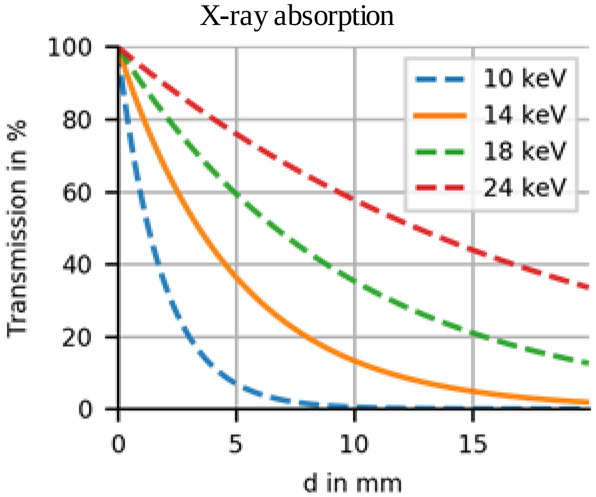


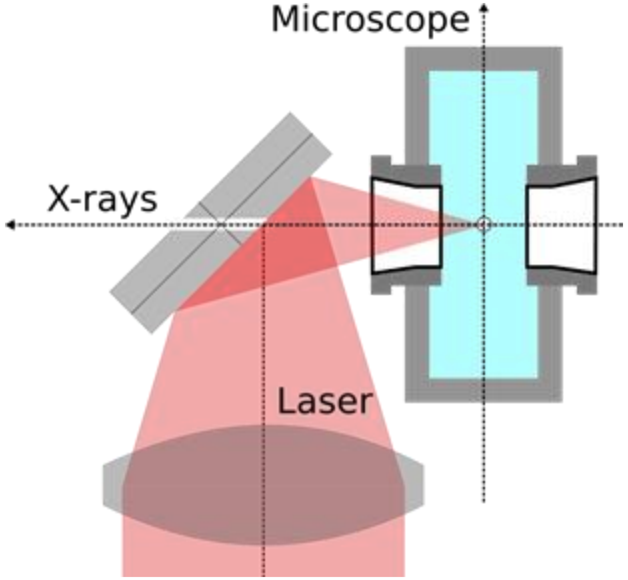
- suitable for accoustic driving /trapping
- ***Low x-ray absorption vs. Stability***

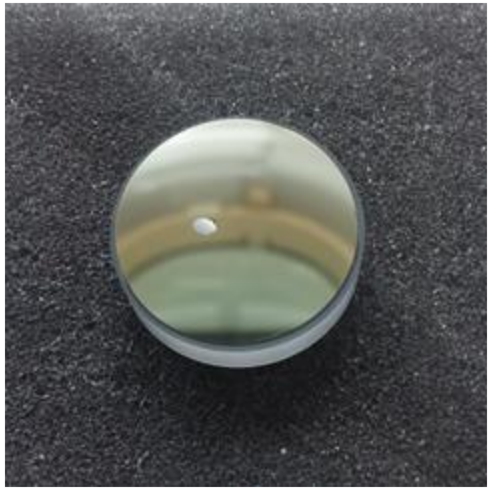
- compatible with XFEL defocused beam
- compatible with IR laser
- compatible speed optical camera

-> anti-parallel XFEL and IR-beams

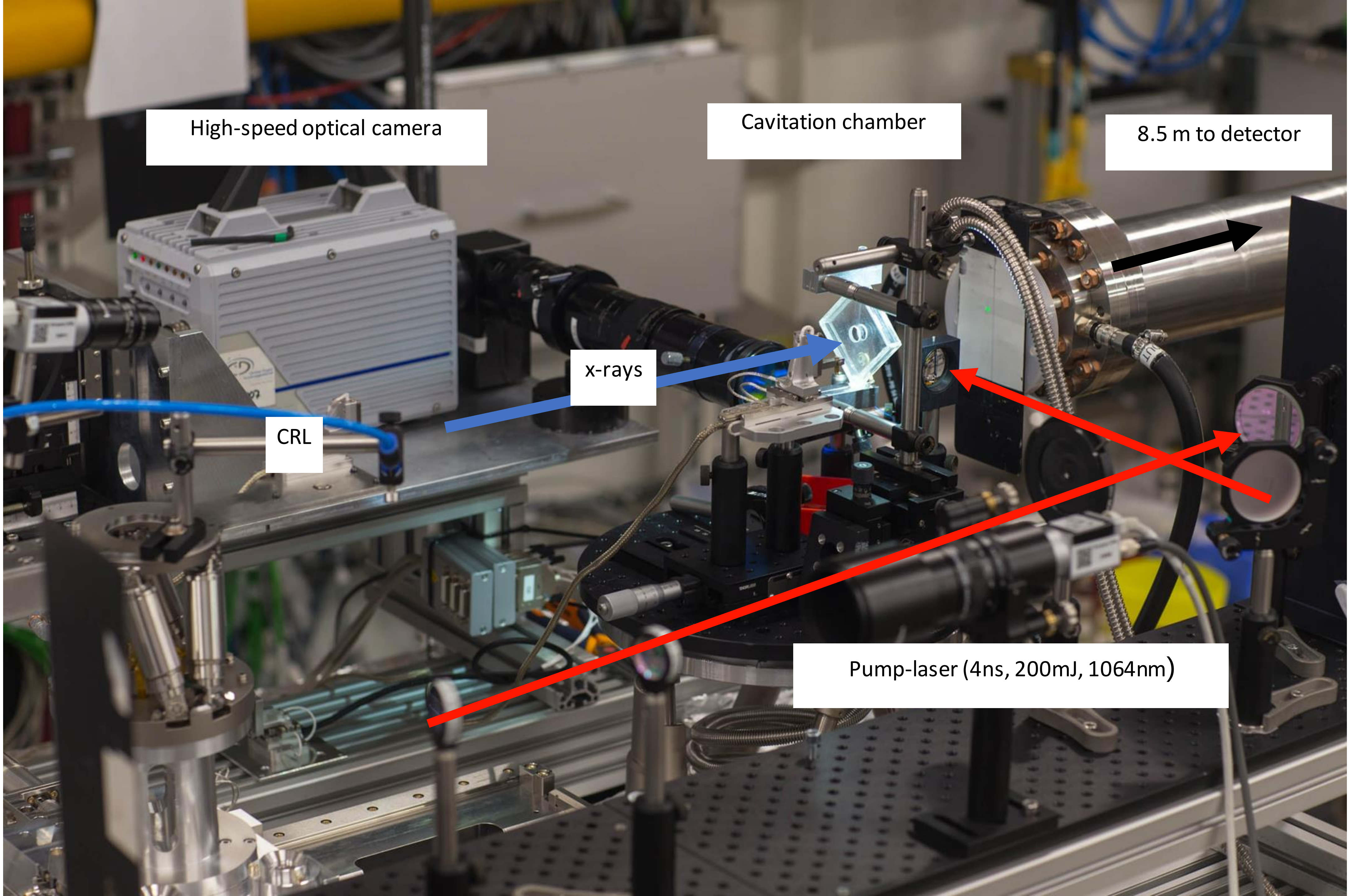
Mirror with drilled hole



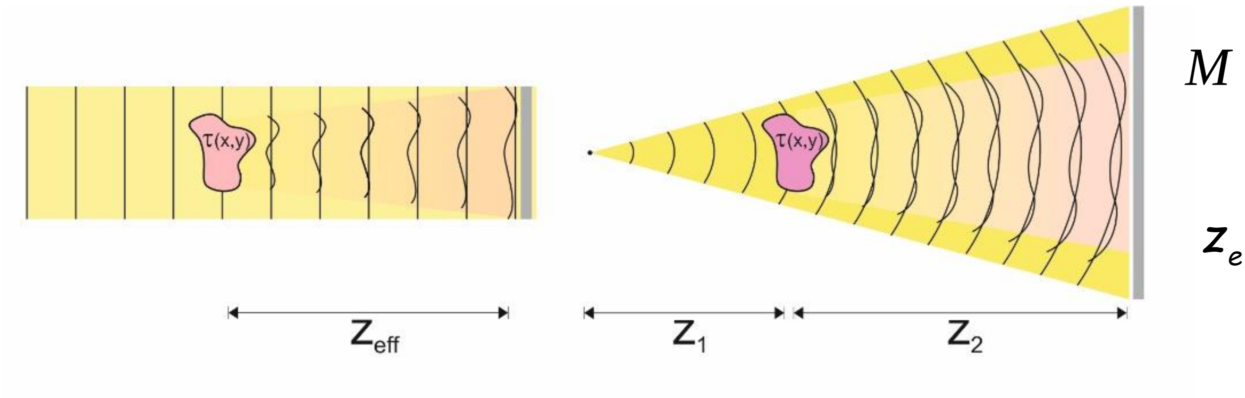




Malte Vassholz, Hannes Hoeppe

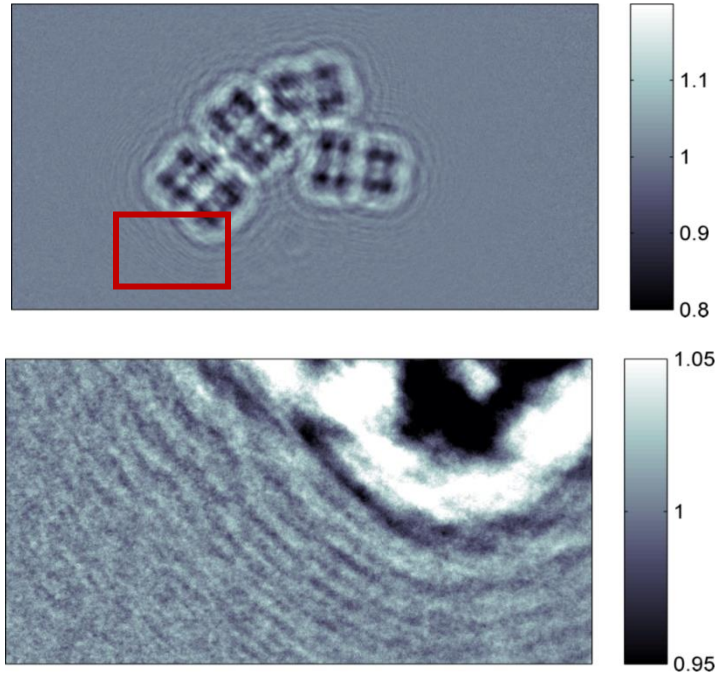

High-speed optical camera
Cavitation chamber
8.5 m to detector
x-rays
CRL
Pump-laser (4ns, 200mJ, 1064nm)

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



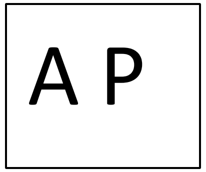
$$M = \frac{z_1 + z_2}{z_1}$$

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

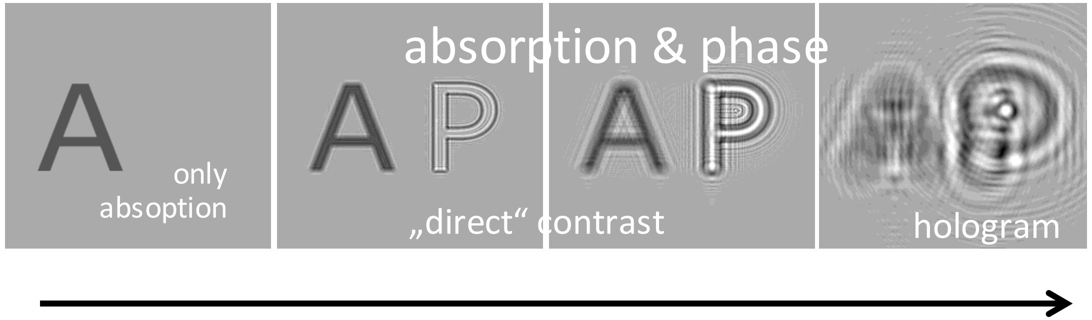


object with complex
transmission function τ(x,y)

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



Absorption Phase



Fresnel number F

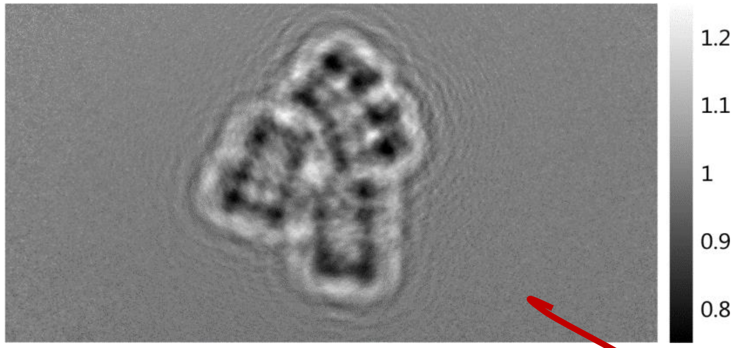
SR: Blurring of fringes !
Low signal in water

XFEL:

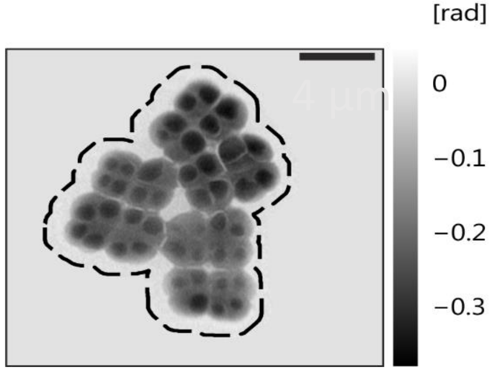
- ***no motional blurring,***
- ***ultimately sharp holograms !***
- ***outrun radiation damage***

Holographic phase retrieval

- high numerical aperture / high resolution
- quantitative reconstruction beyond linearisation
- probe abberations (wavefront, coherence)

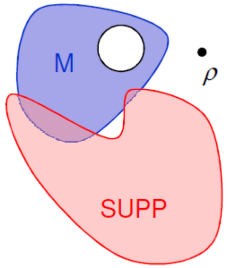


bacterial cells (Deinococcus radiodurans)

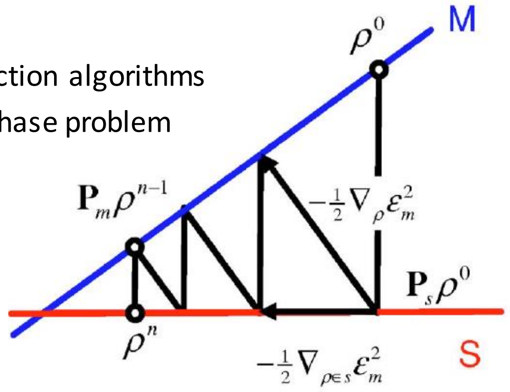


key challenge: phase retrieval !

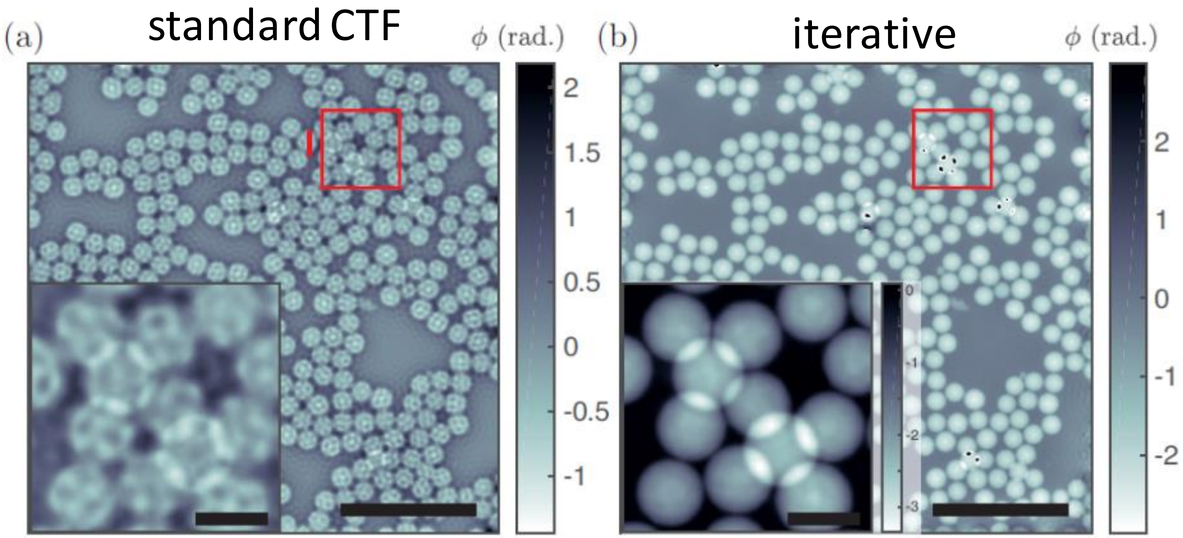
Bartels, Krenkel, Haber, Salditt Phys.Rev.Lett. 2015



iterative projection algorithms
to solve the phase problem

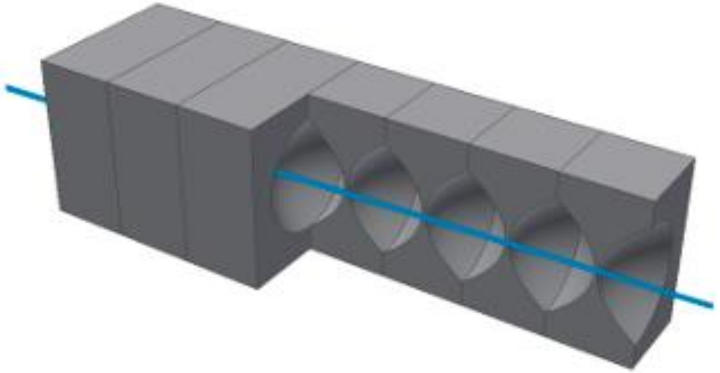


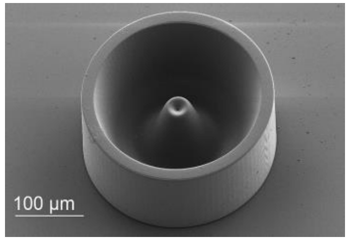
adaptation for near-field:
Giewekemeyer et al, PRA 2011; Hagemann et al. 2015, 2016;
Robisch et al.,2015; Krenkel et al. Acta Cryst 2017

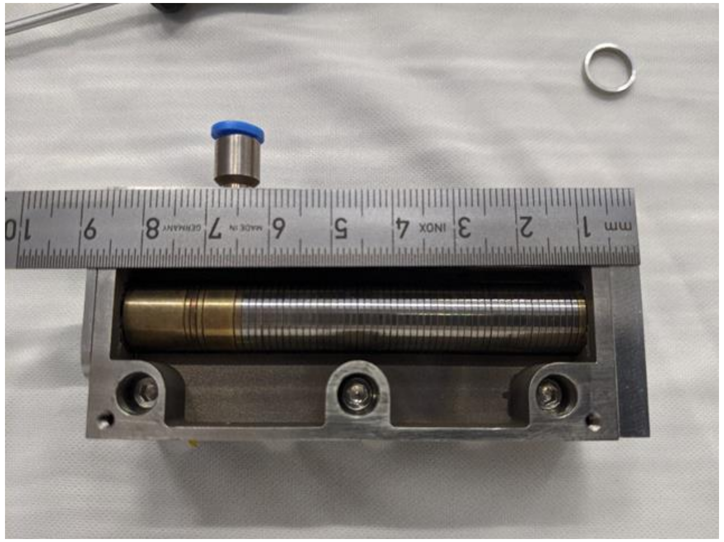


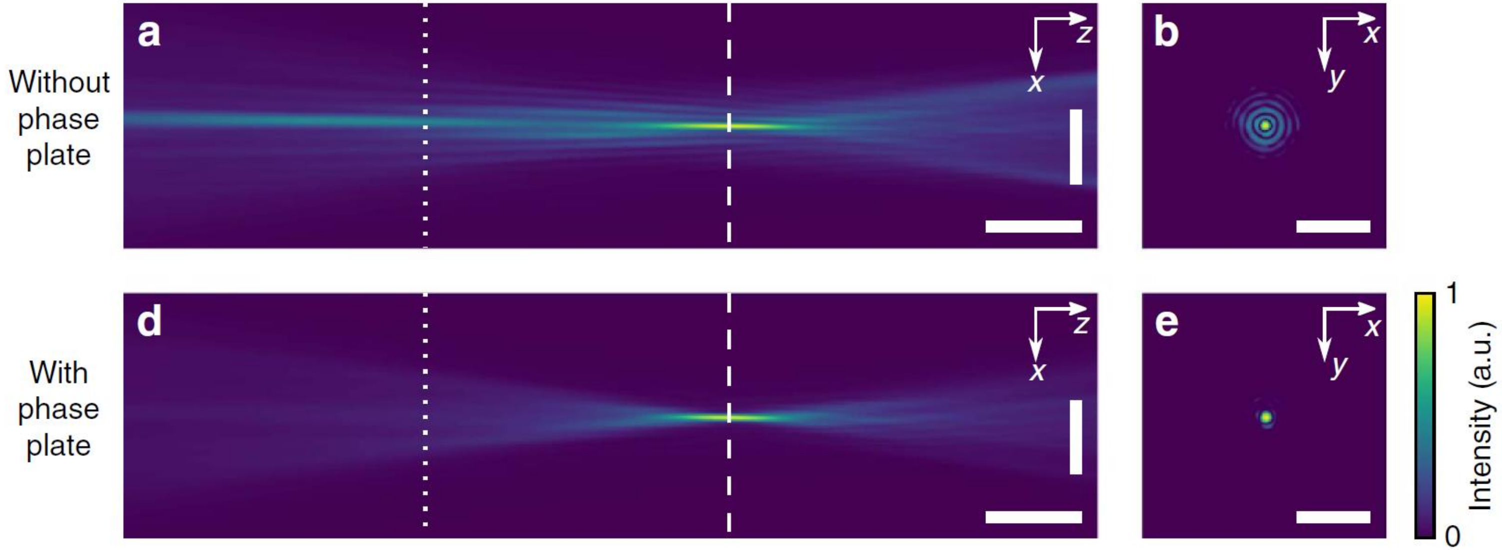
Hagemann, Töpperwien, Salditt Appl.Phys.Lett. 2018

CRL (Be) focusing to ~100nm







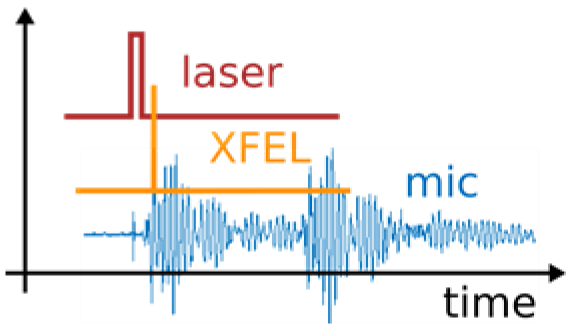


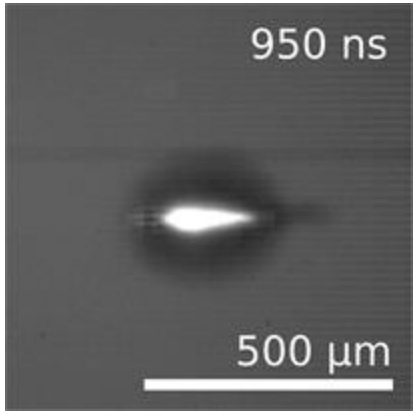
Seiboth et al., Nat. Comm. (2017)

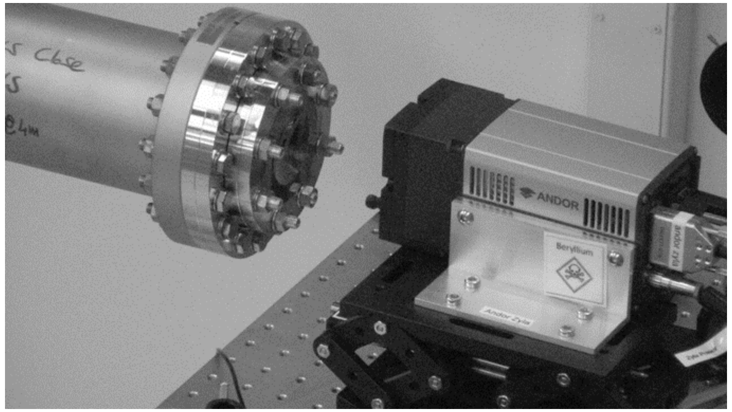
N=50 Be CRL
R=50µm
D=300µm
f=289mm
Δ ~ 100nm

Frank Seiboth, Andreas Schropp, Christian Schroer

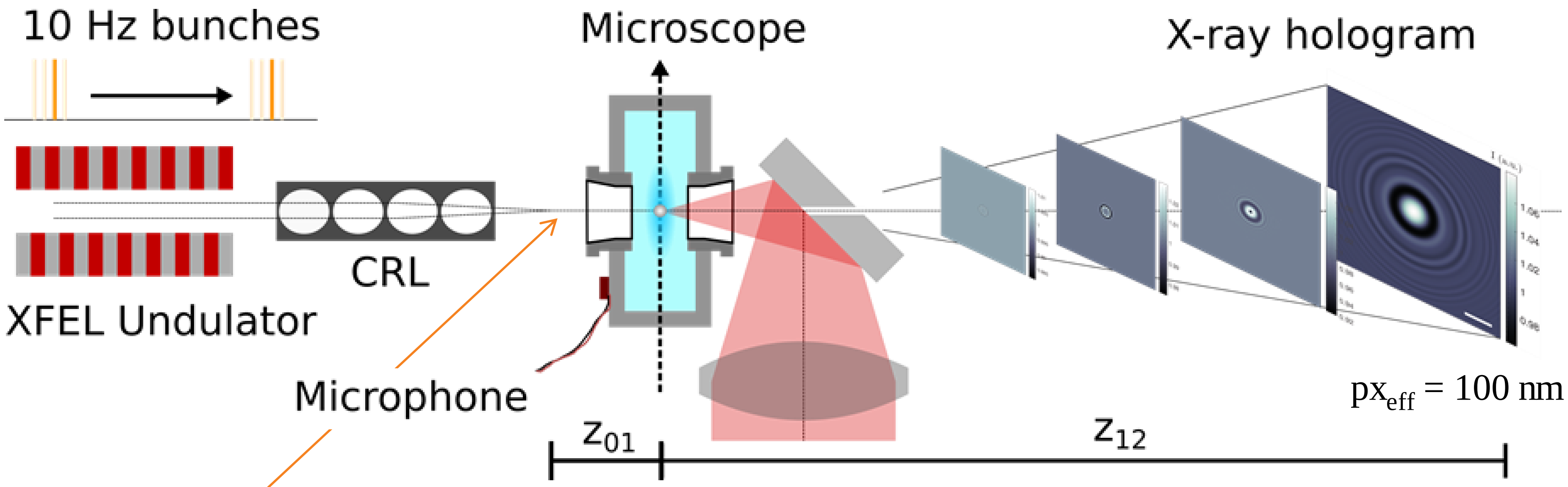
Settings at MID / exp. parameters







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

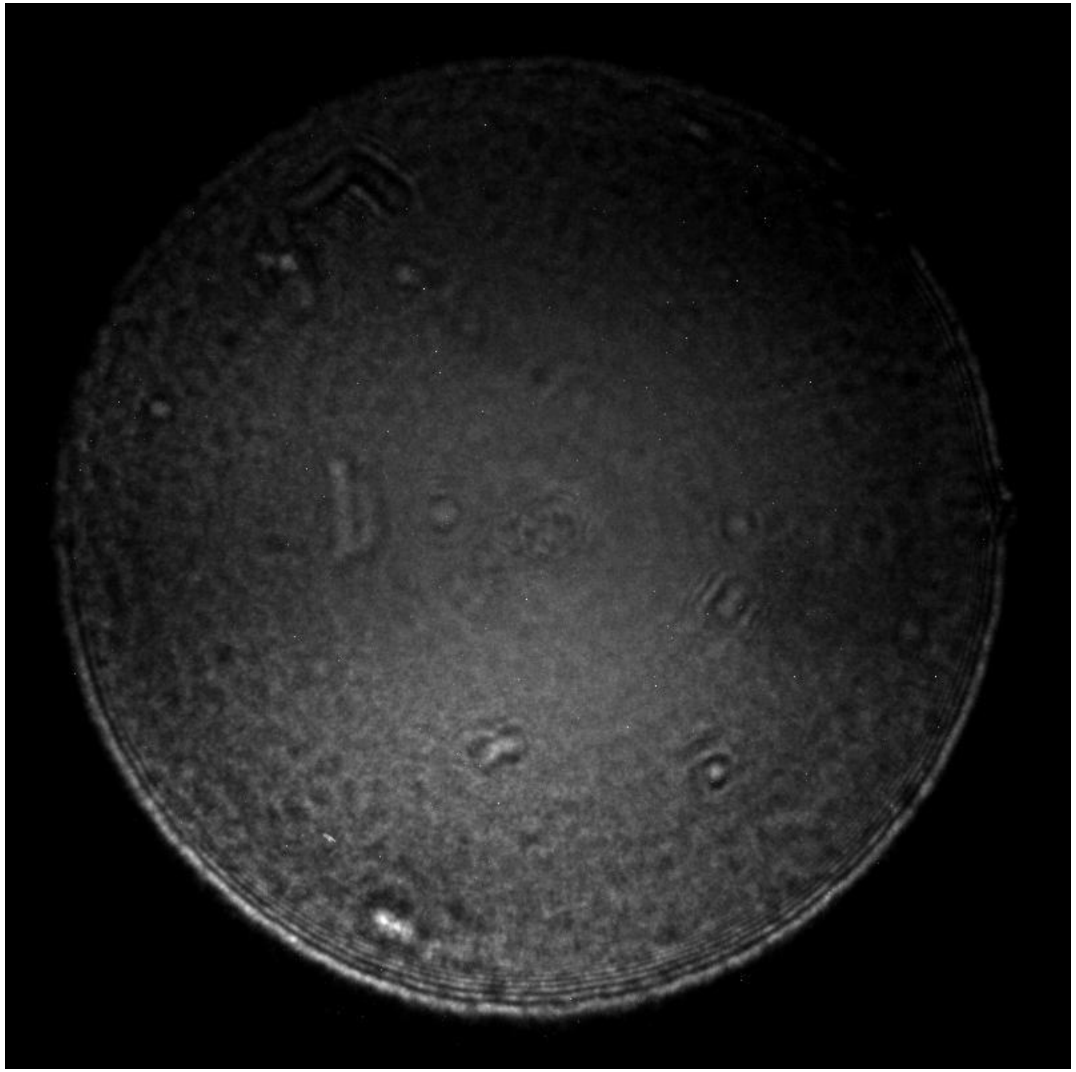
M =61 p_{xeff}=107nm

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

in terms of

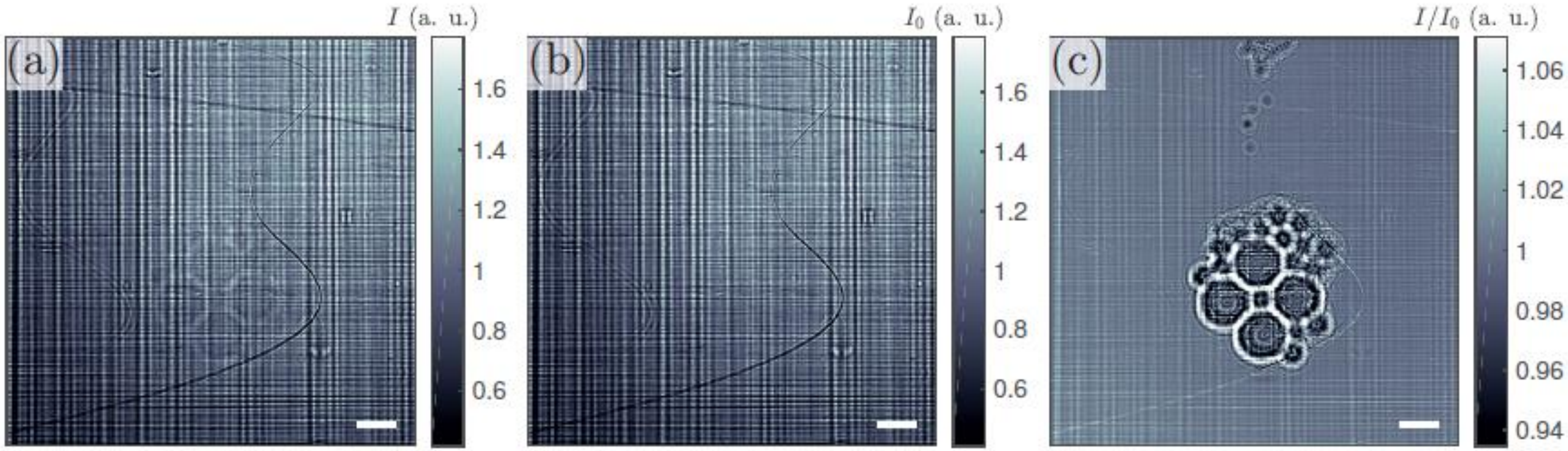
- *divergence,*
- *pointing stability*
- *signal*

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



But how to
perform the
flat field correction?

The empty beam problem in holography



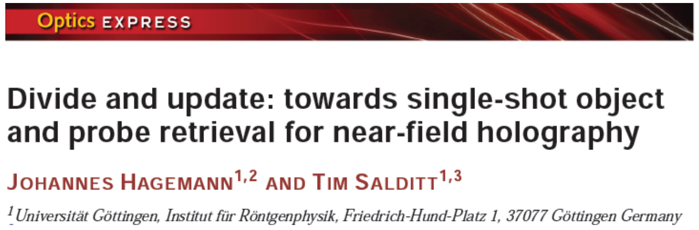
Simultaneous probe and object reconstruction for the near-field
A.L. Robisch, K. Kröger, A. Rack, T.Salditt, N.J.Phys. 2015

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

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

flat field correction
is flawed !

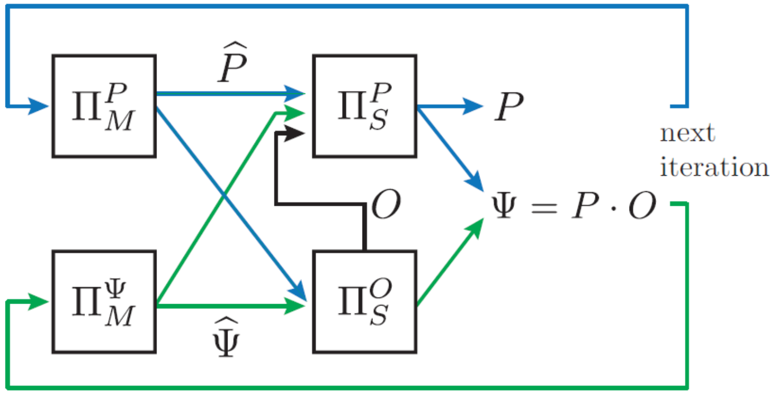


Optics EXPRESS

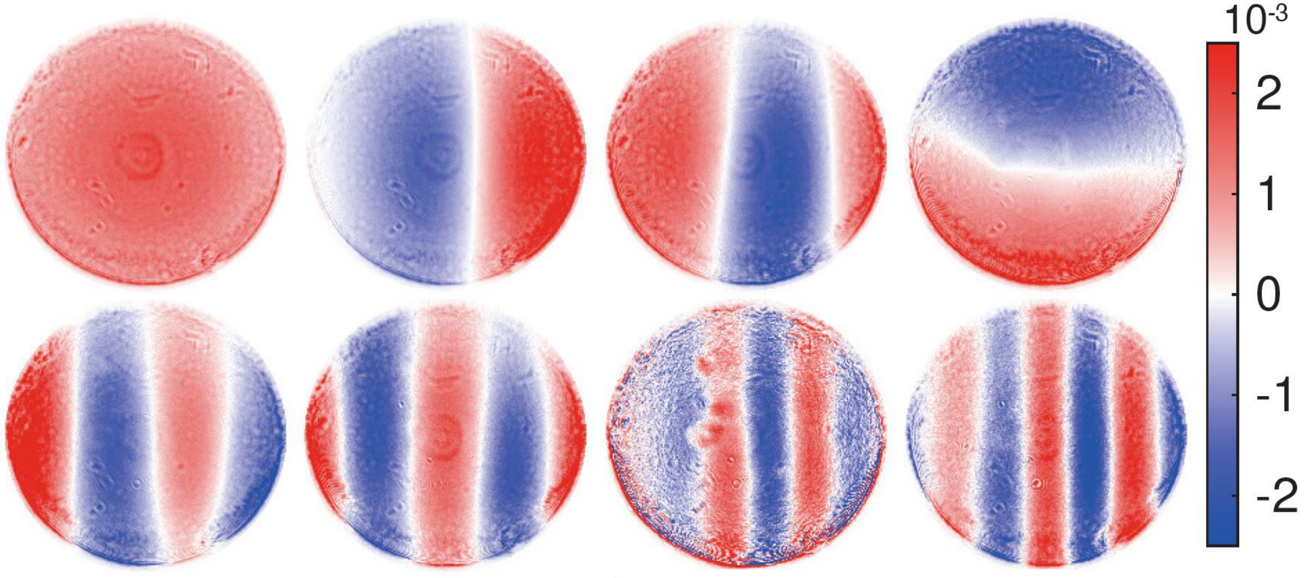
Divide and update: towards single-shot object and probe retrieval for near-field holography

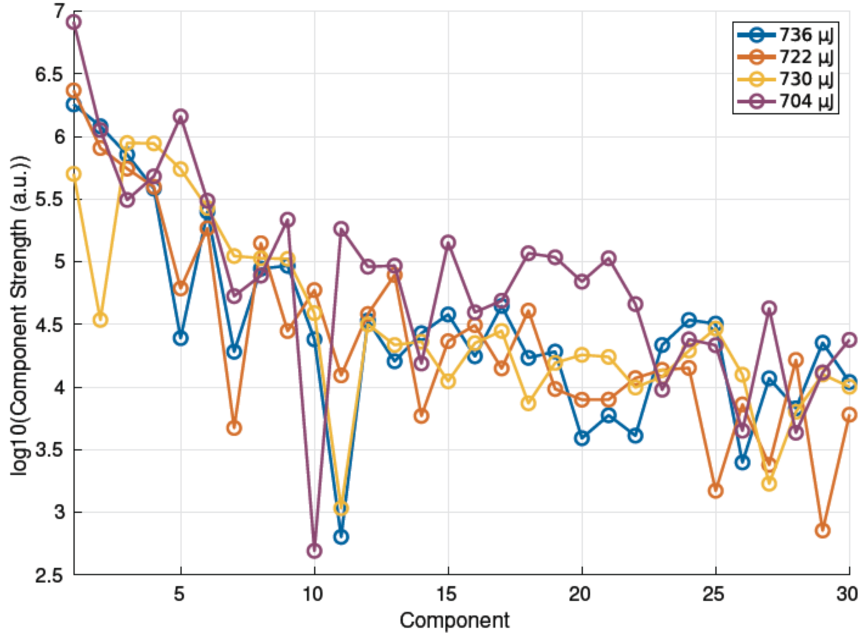
JOHANNES HAGEMANN[1,2] AND TIM SALDITT[1,3]

[1] *Universität Göttingen, Institut für Röntgenphysik, Friedrich-Hund-Platz 1, 37077 Göttingen Germany*



Let’s decompose (PCA analysis)





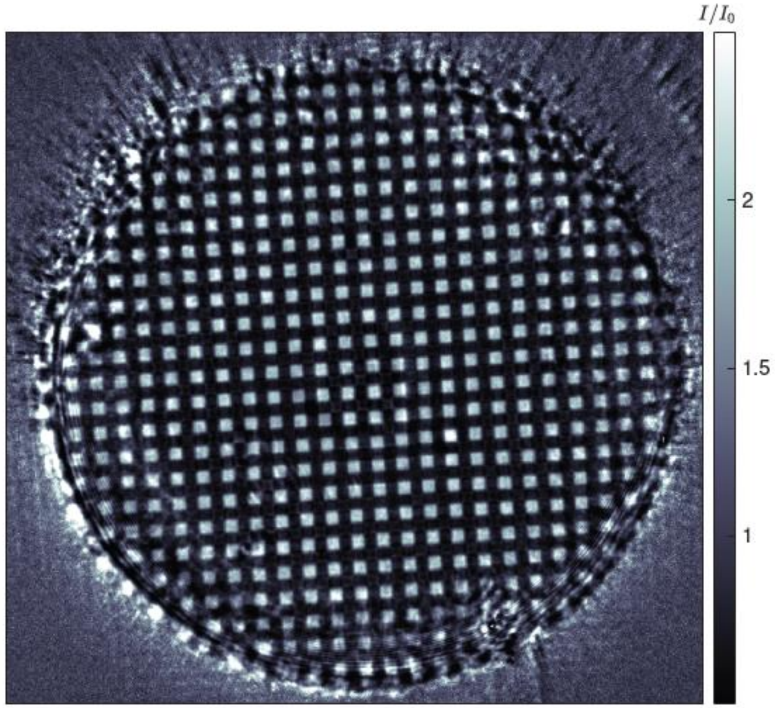
Based on:

Dynamic intensity normalization using eigen flatfields inX-rayimaging
V. V. Nieuwenhove et al. , Optics Express 23(21), 27975 (2015)

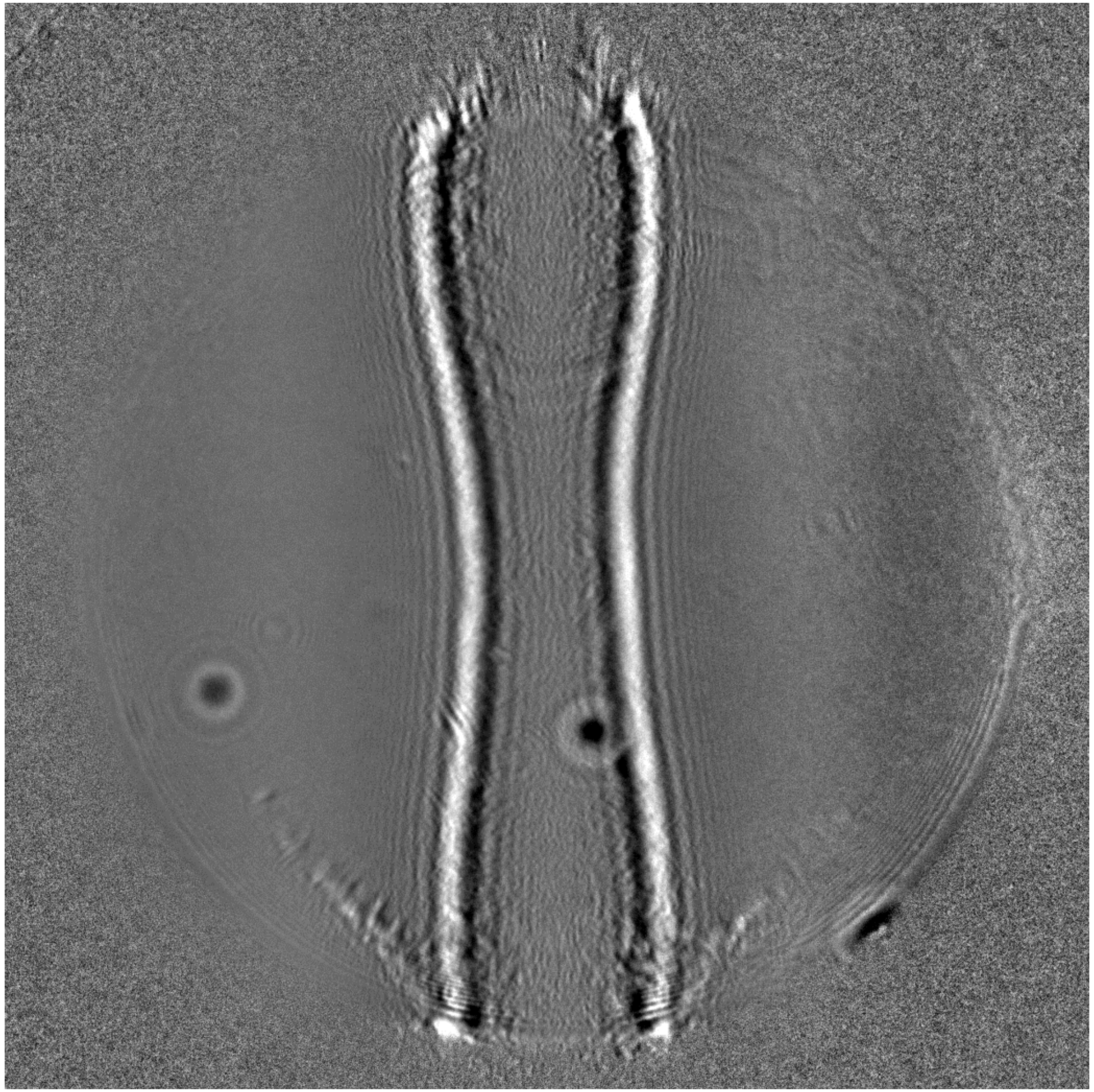
Johannes Hagemann

Let's decompose (PCA analysis)

now imaging works!



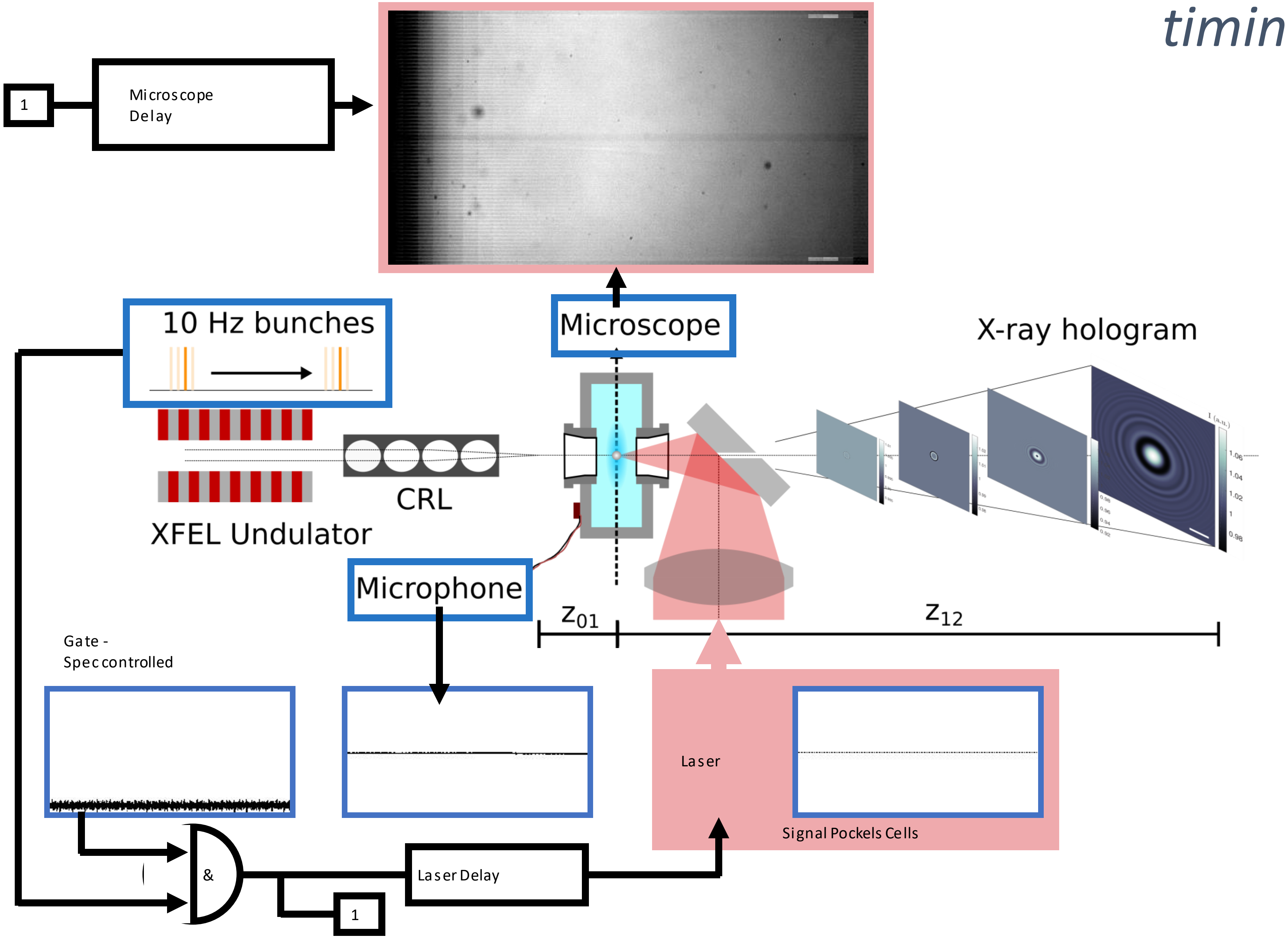
6µmAu mesh



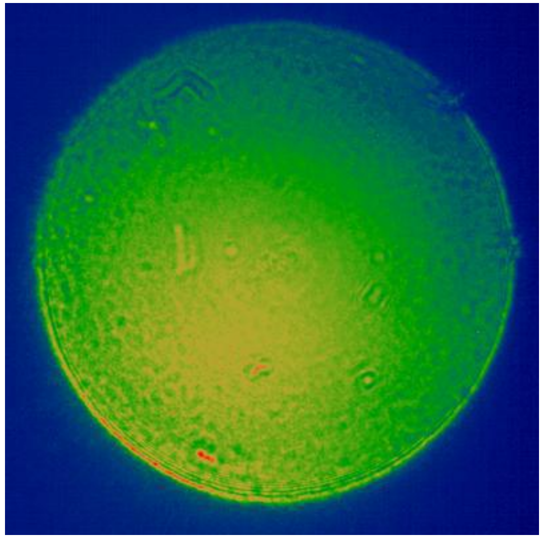
laminar water jet

Johannes Hagemann

timing&synchronisation



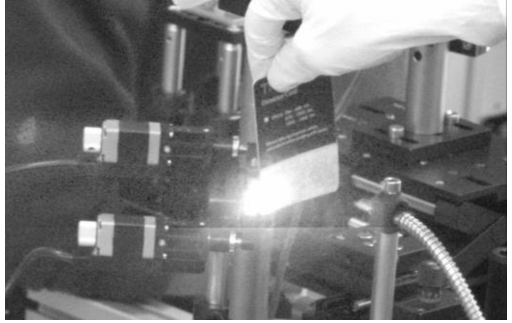
X-Ray Camera



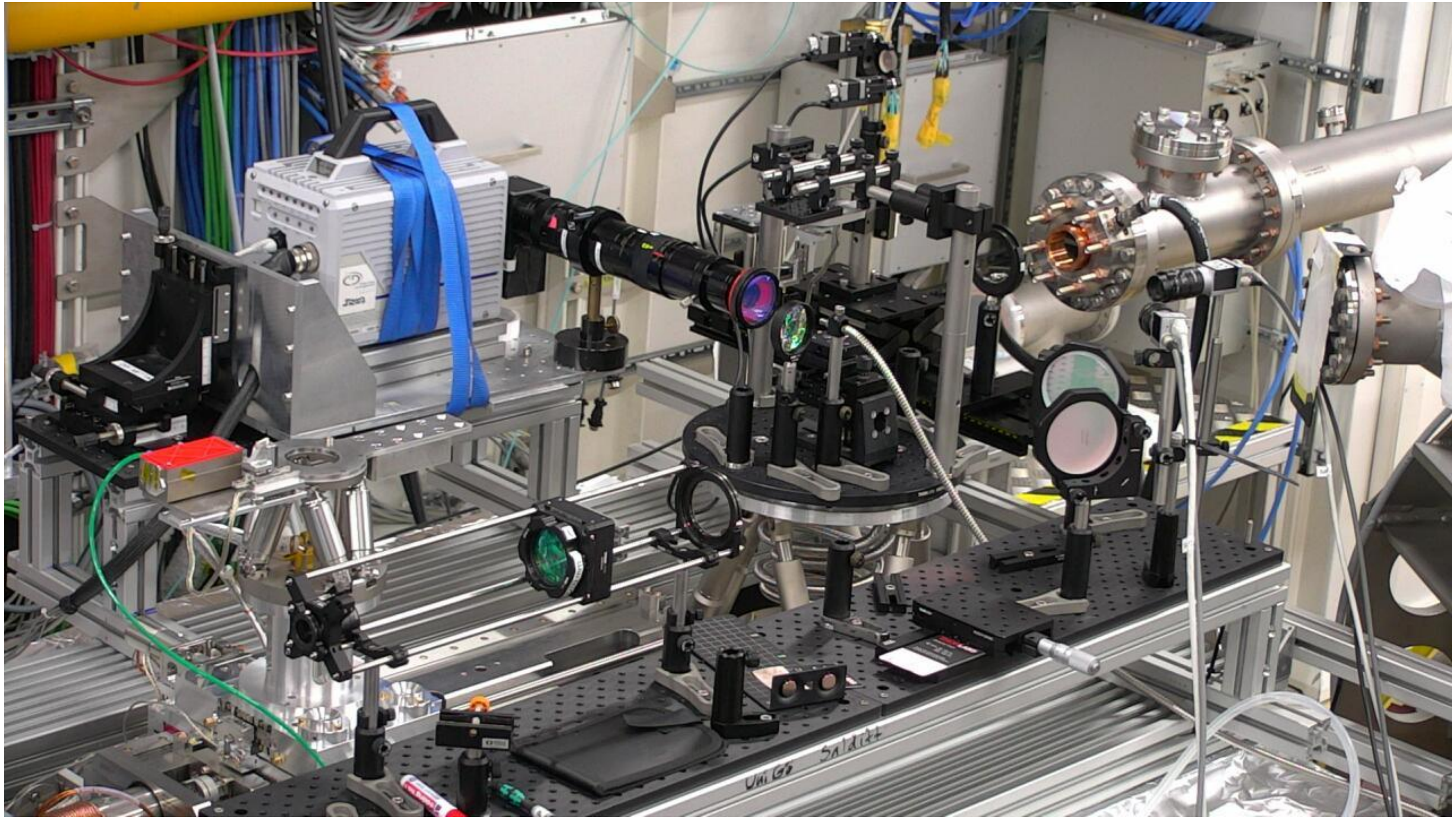
scheme works nicely –
but we miss the bubble

Markus Osterhoff , Malte Vassholz

A good timing scheme is not sufficient …



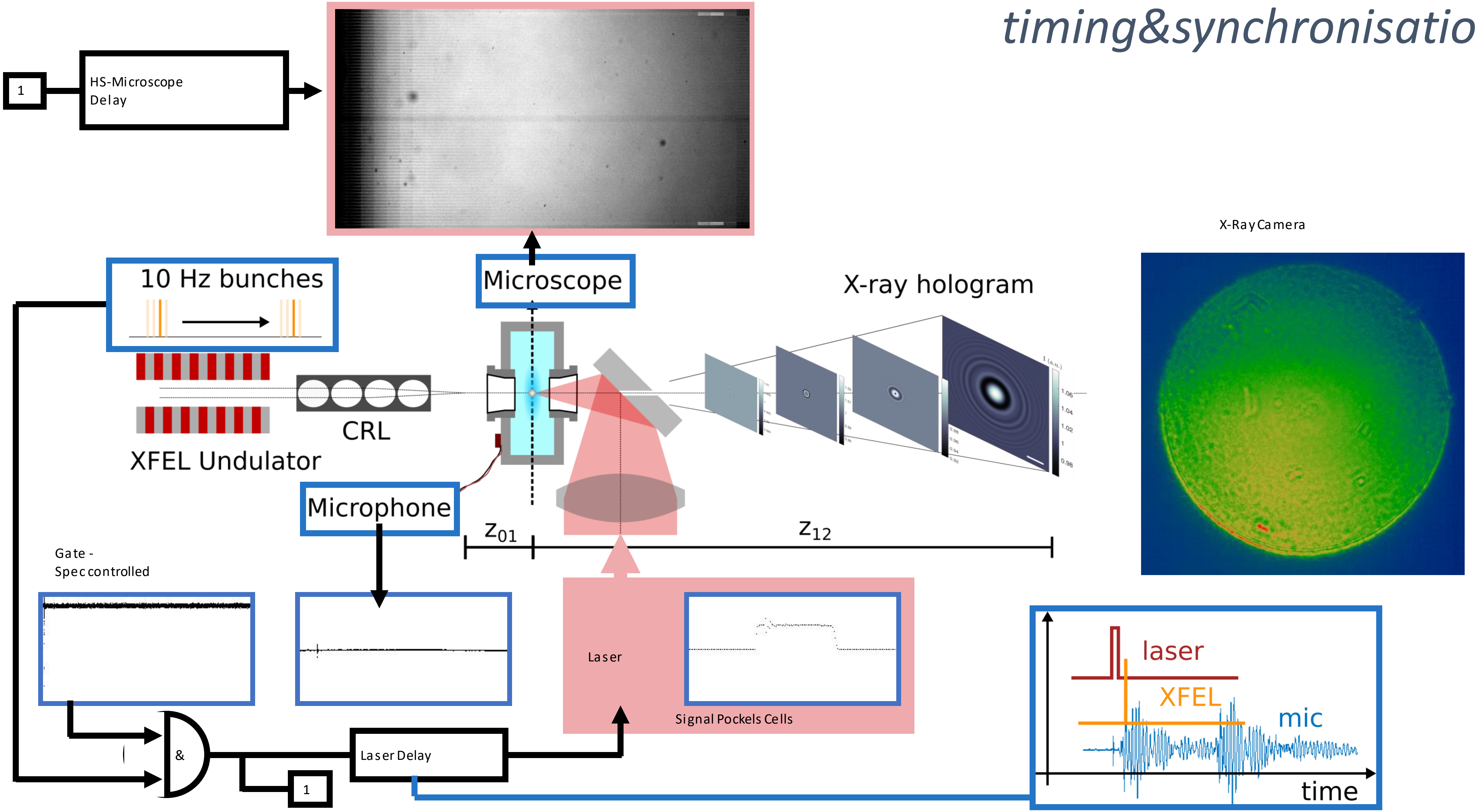
IR- alignment



you have to have spatial-tempral overlap !

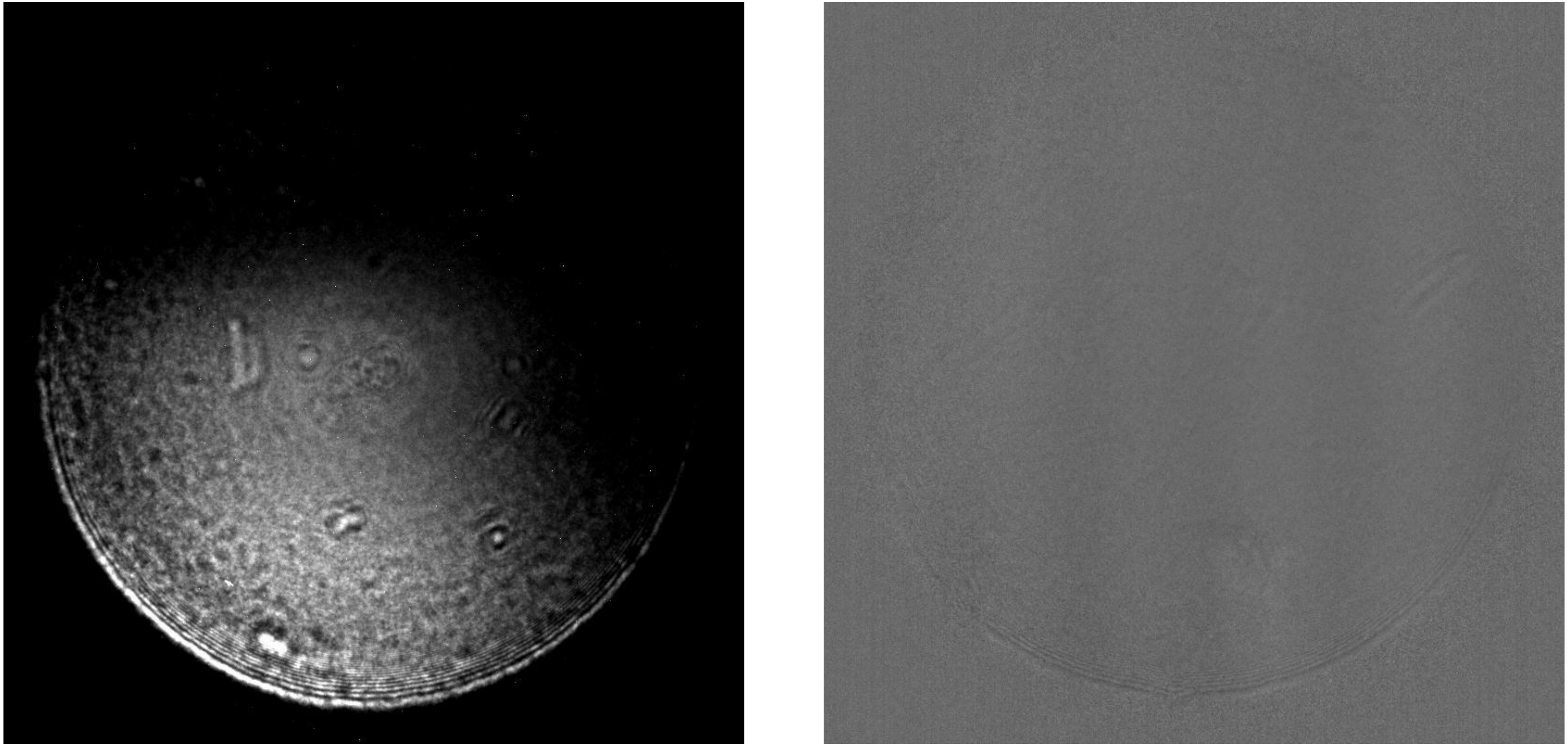
Malte Vassholz
Hannes Hoeppe

timing&synchronisation

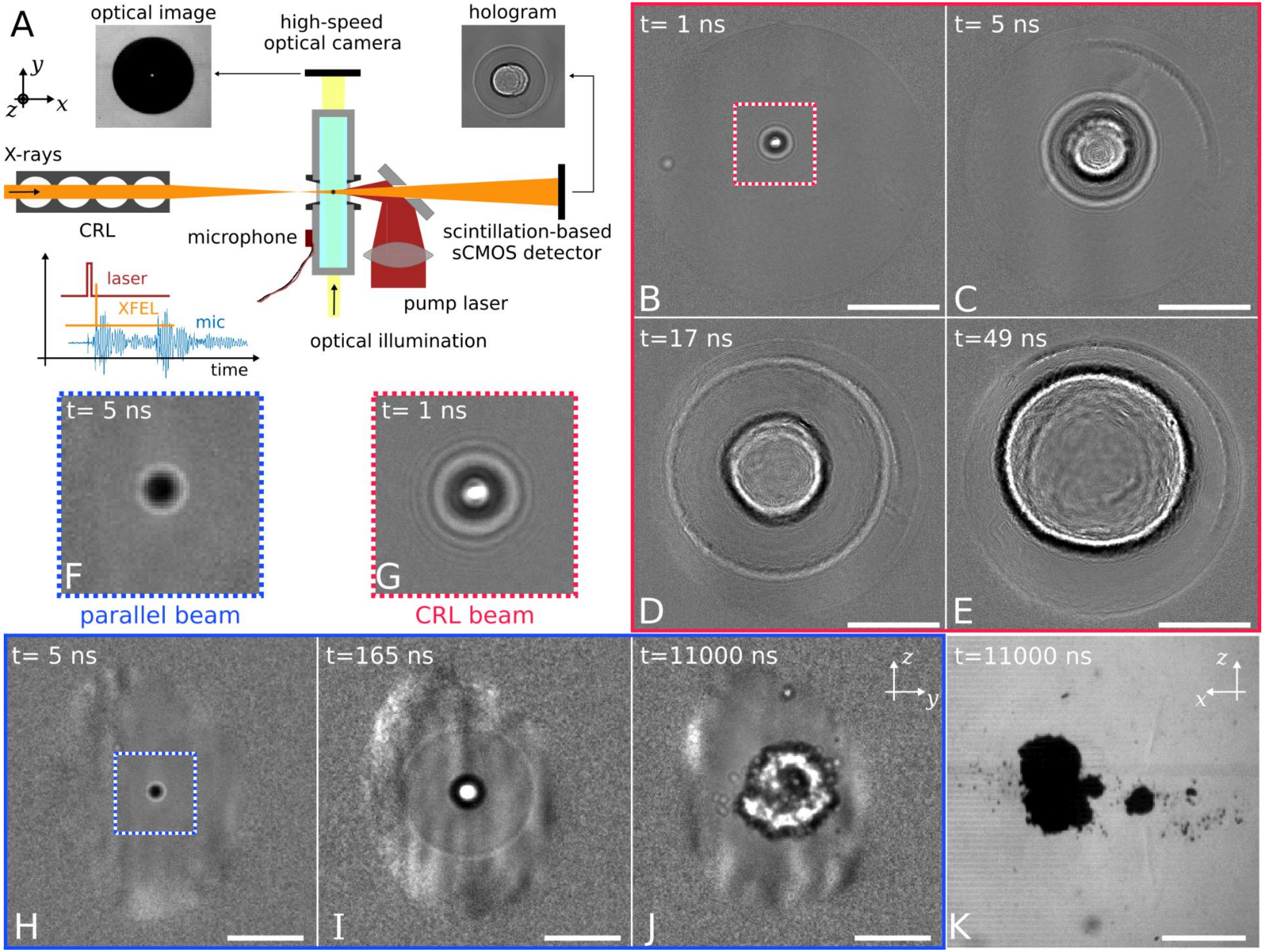


Markus Osterhoff , Malte Vassholz

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

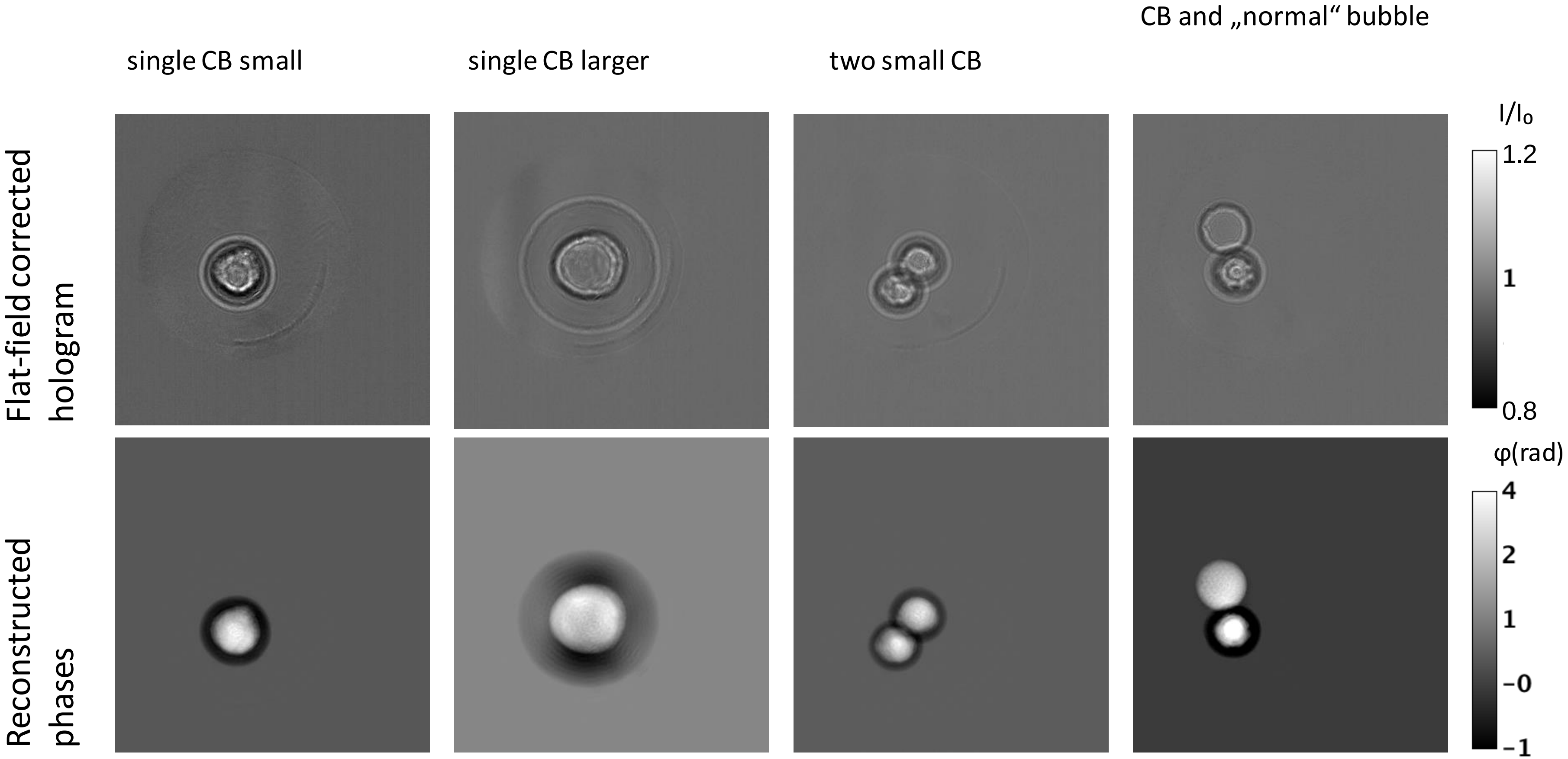


o.k.
now we 're
talking !



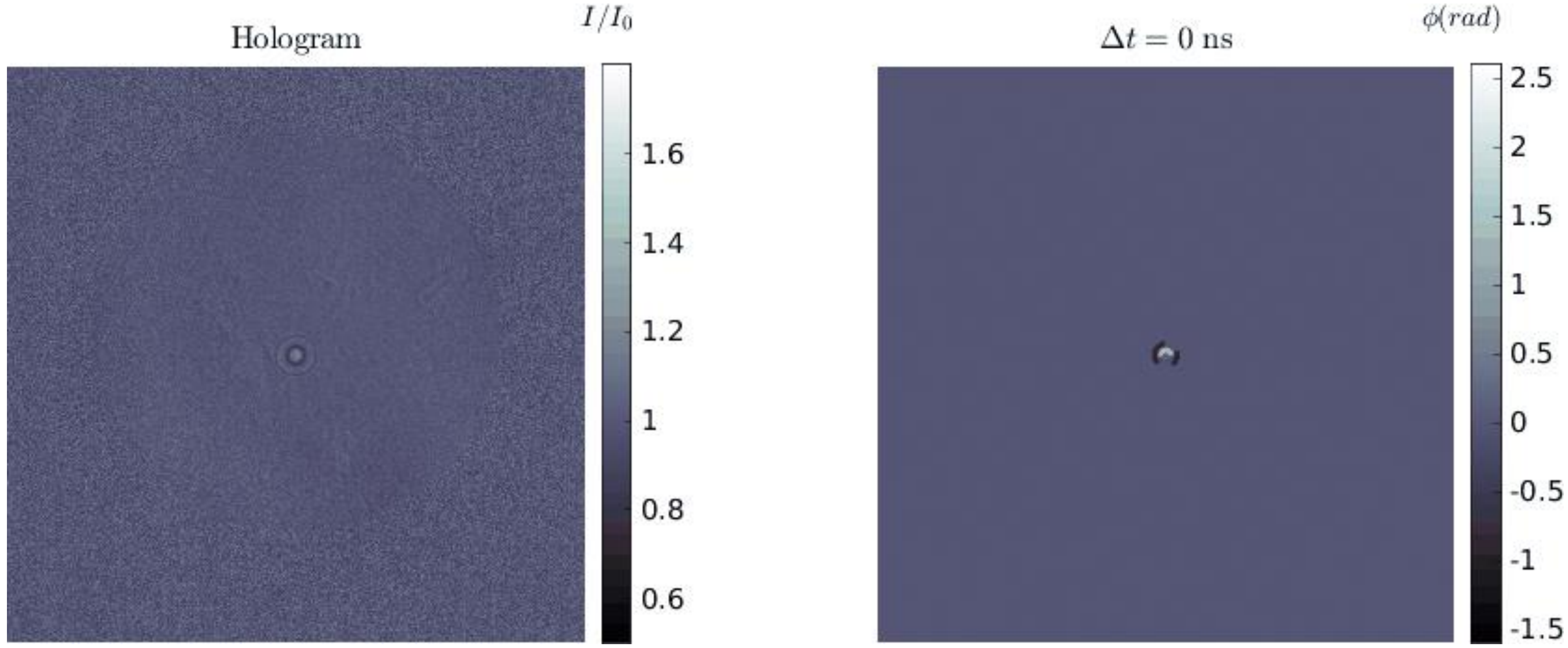
But how to
analyze all
of this?

Phase retrieval



@ Fresnel number $Fr = 0.8\cdot10^{-3}$ (with respect to the pixel size)
pixel size $\Delta x = 109$ nm, FOV = 140 µm

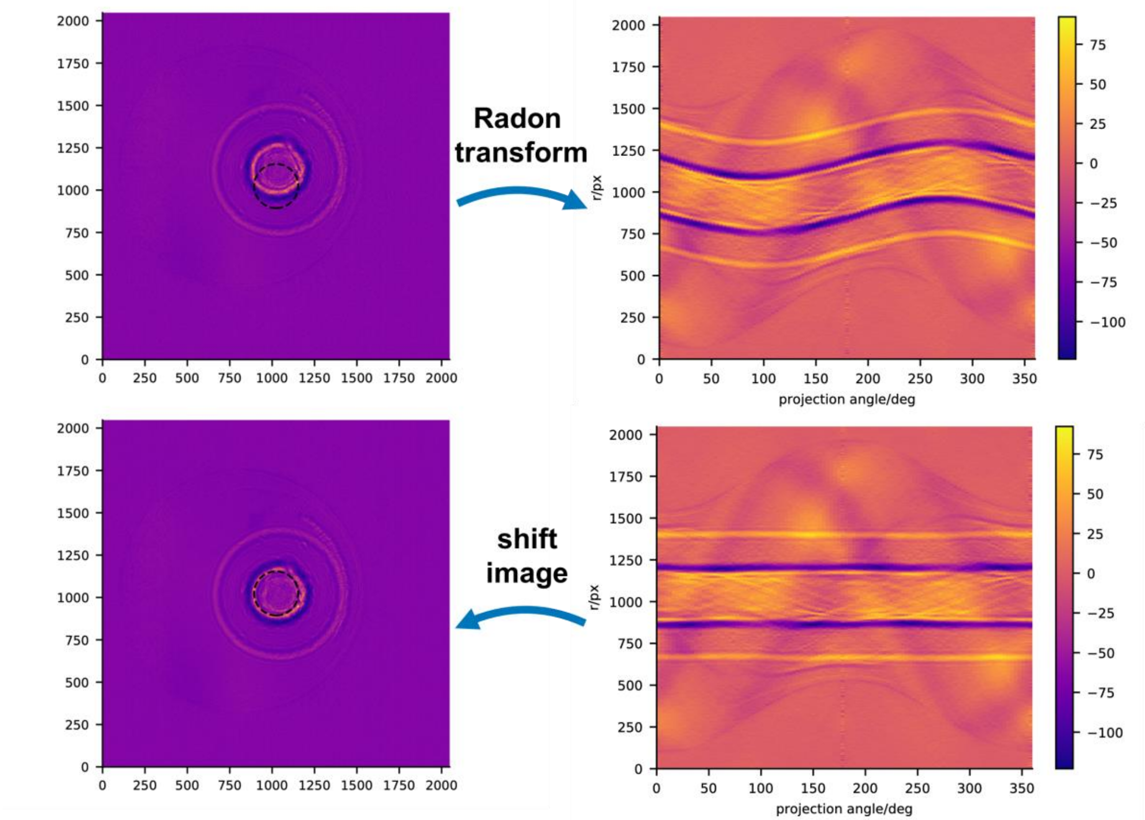
CB - Cavitation Bubble

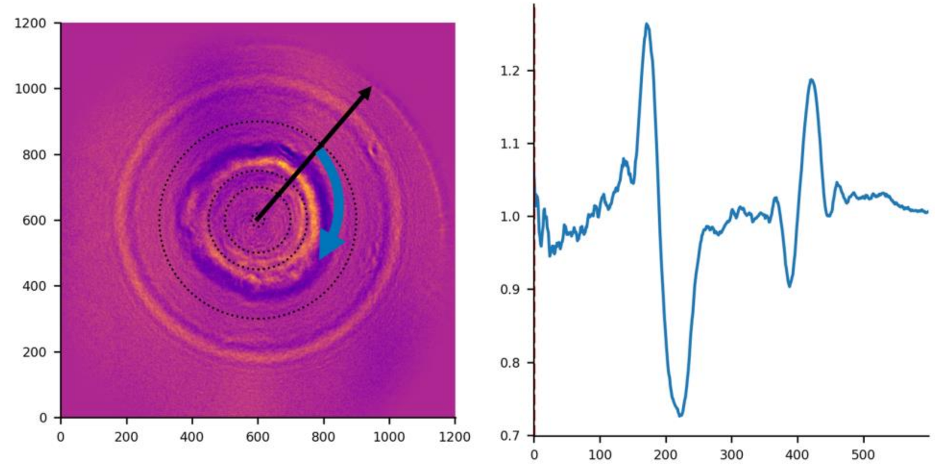


@ Fresnel number Fr = $7.6 \cdot 10^{-4}$ (with respect to the pixel size) pixel size $\Delta x = 97.7$ nm, FOV = 140 µm

Johannes Hagemann

Propagation of radially symmetric wavefunctions &data analysis




Integrate over polar angle

radial intensity

$$\tilde{g}(k) = 2\pi \int_0^\infty g(r) J_0(rk) r dr$$

$\tilde{g} = \mathcal{H}_0[g]$ Hankel transform with $\mathcal{H}_0^{-1} = \mathcal{H}_0$

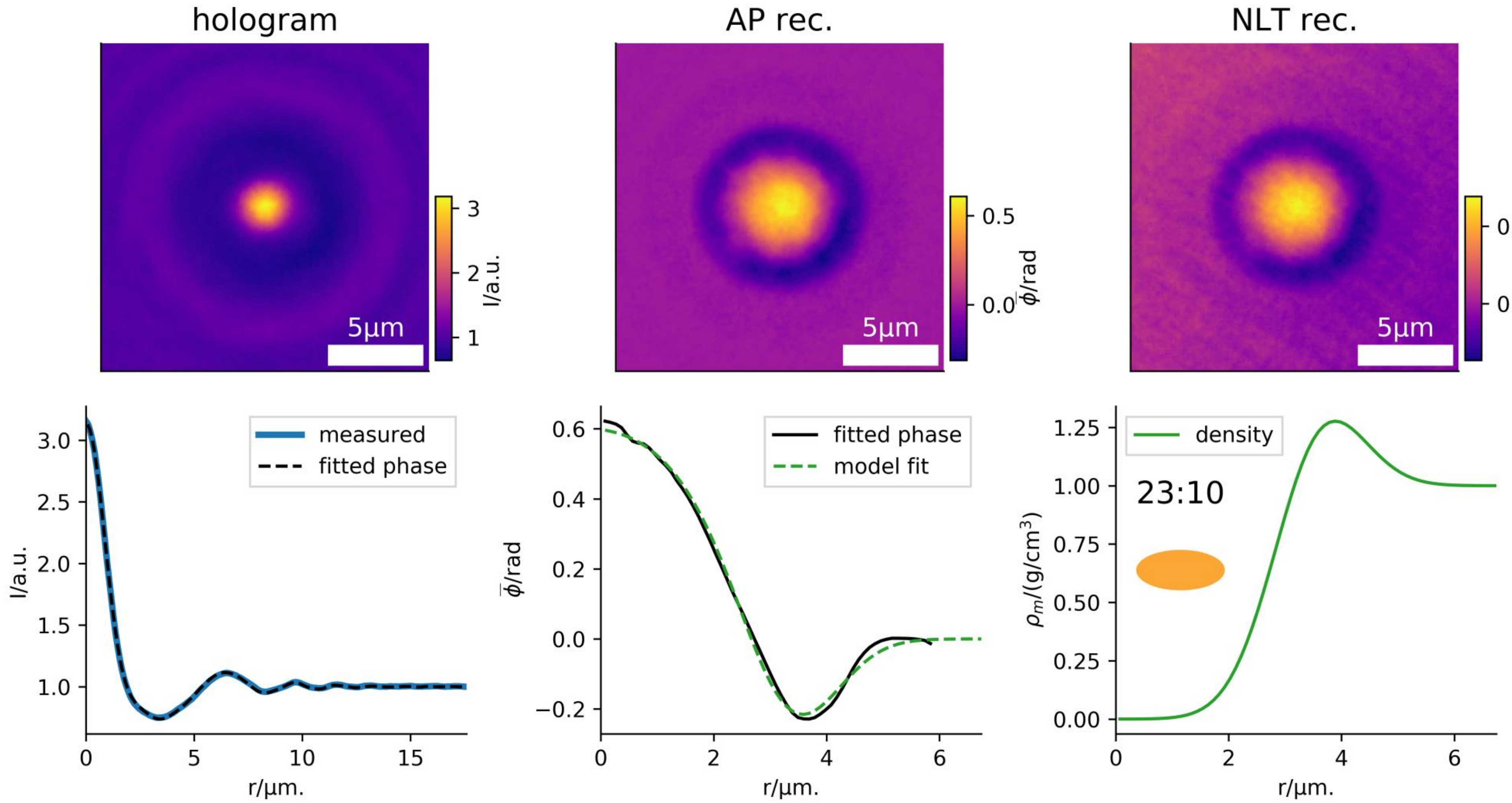
$$\psi(r_\perp, z) = \exp(ikz)\ \mathcal{H}_0 \left[\exp\left(\frac{-izk_\perp^2}{2k} \right)\ \mathcal{H}_0 \left[\psi(r_\perp, 0) \right] \right]$$

implemented on a discrete Hankel grid $\psi_i^{(z)} = M_{ij}\psi_j$

$\psi^* = argmin(|I_{exp} - (M\psi)^2|^2)$ plus reg.term if needed

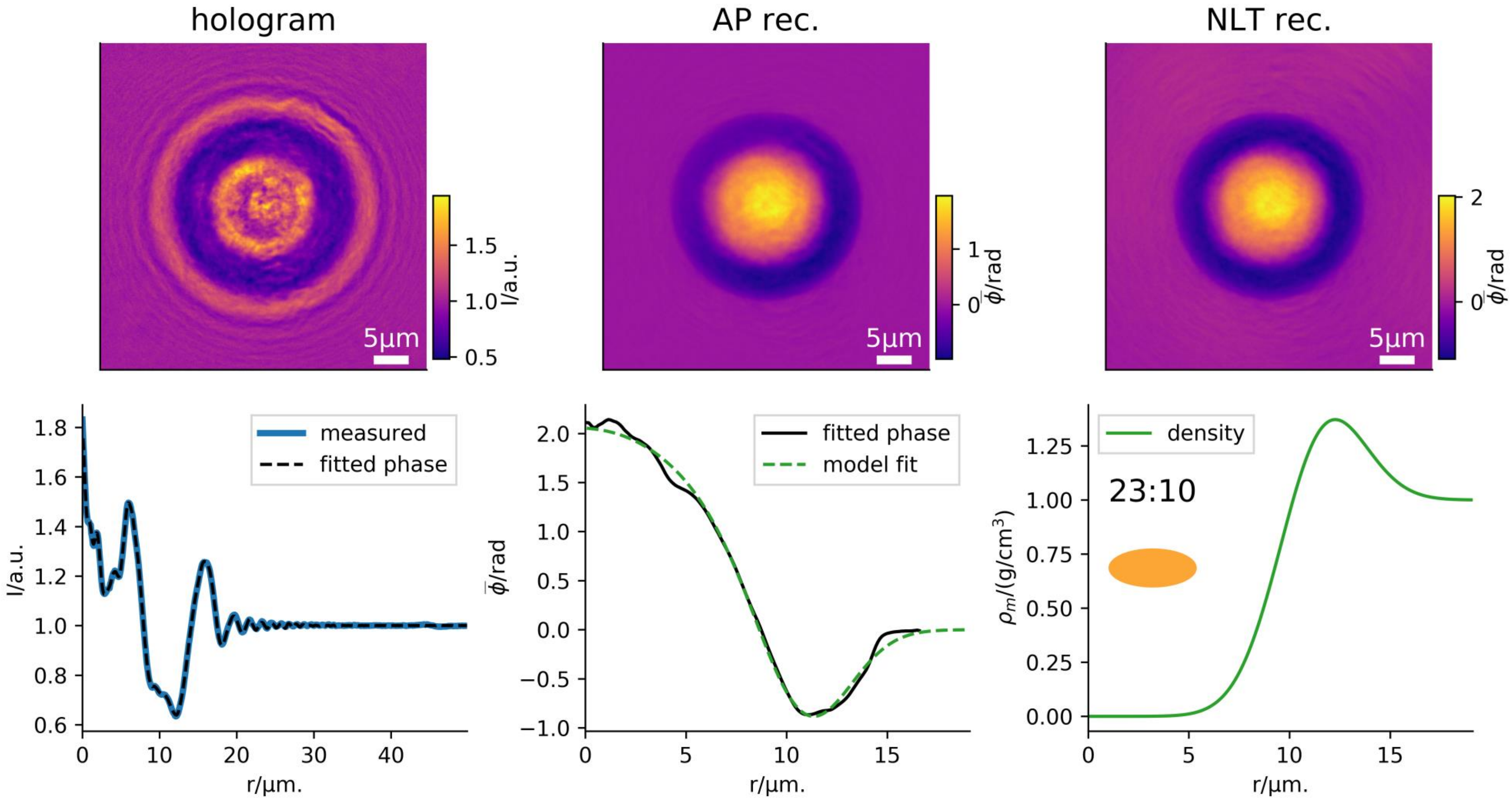
Malte Vassholz

τ=1ns



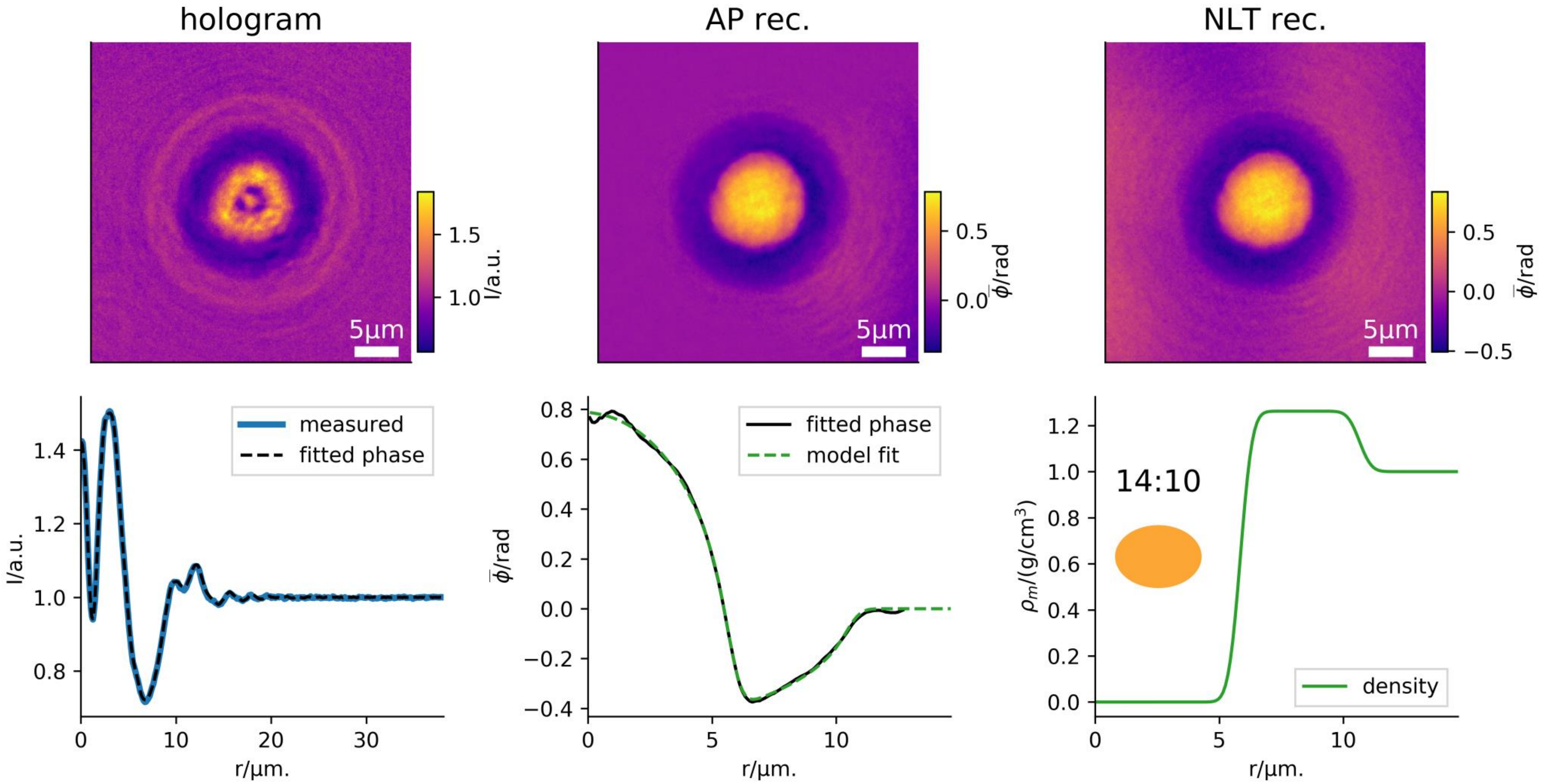
Malte Vassholz

τ=4ns



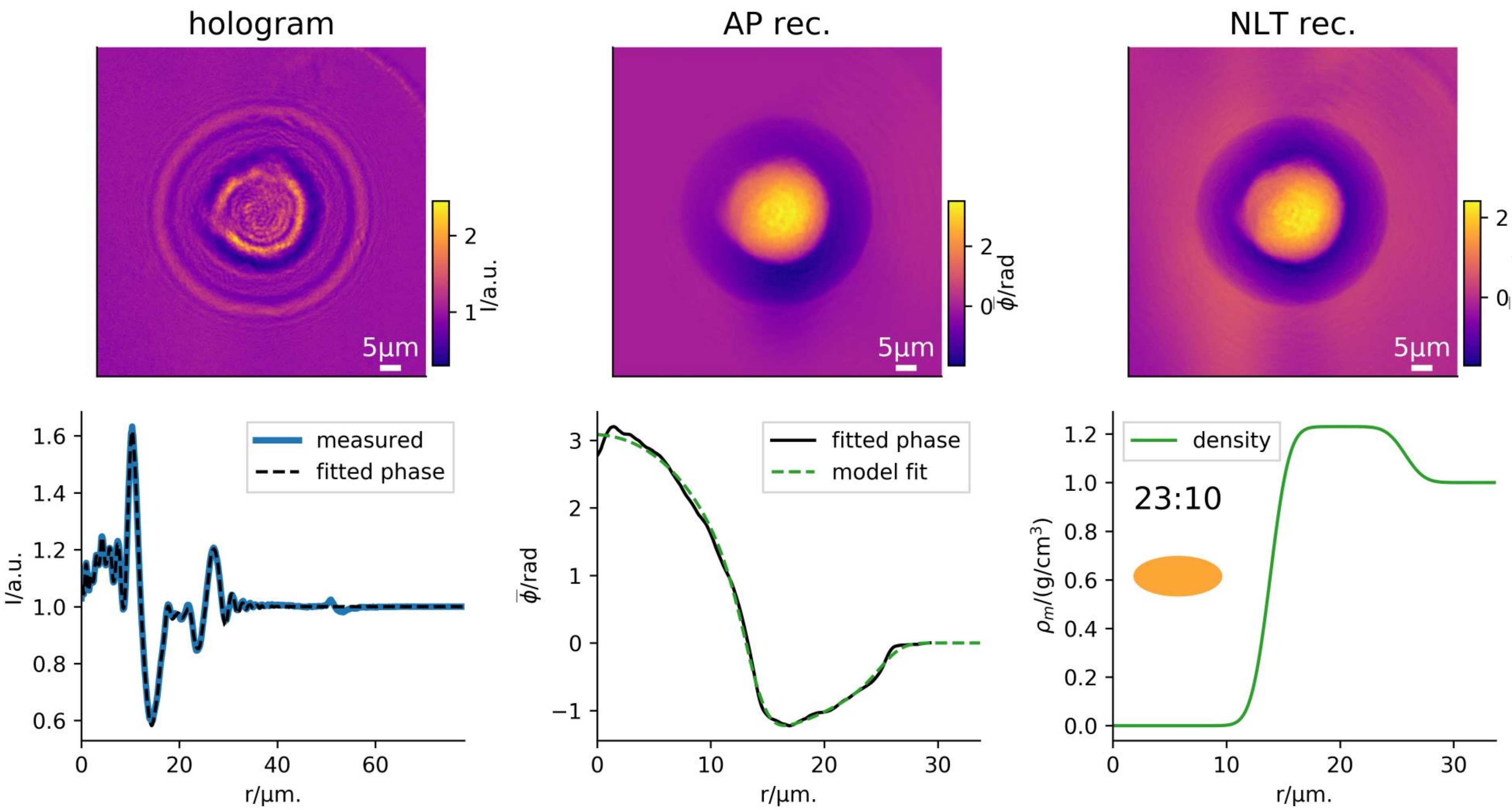
Malte Vassholz

τ=7ns



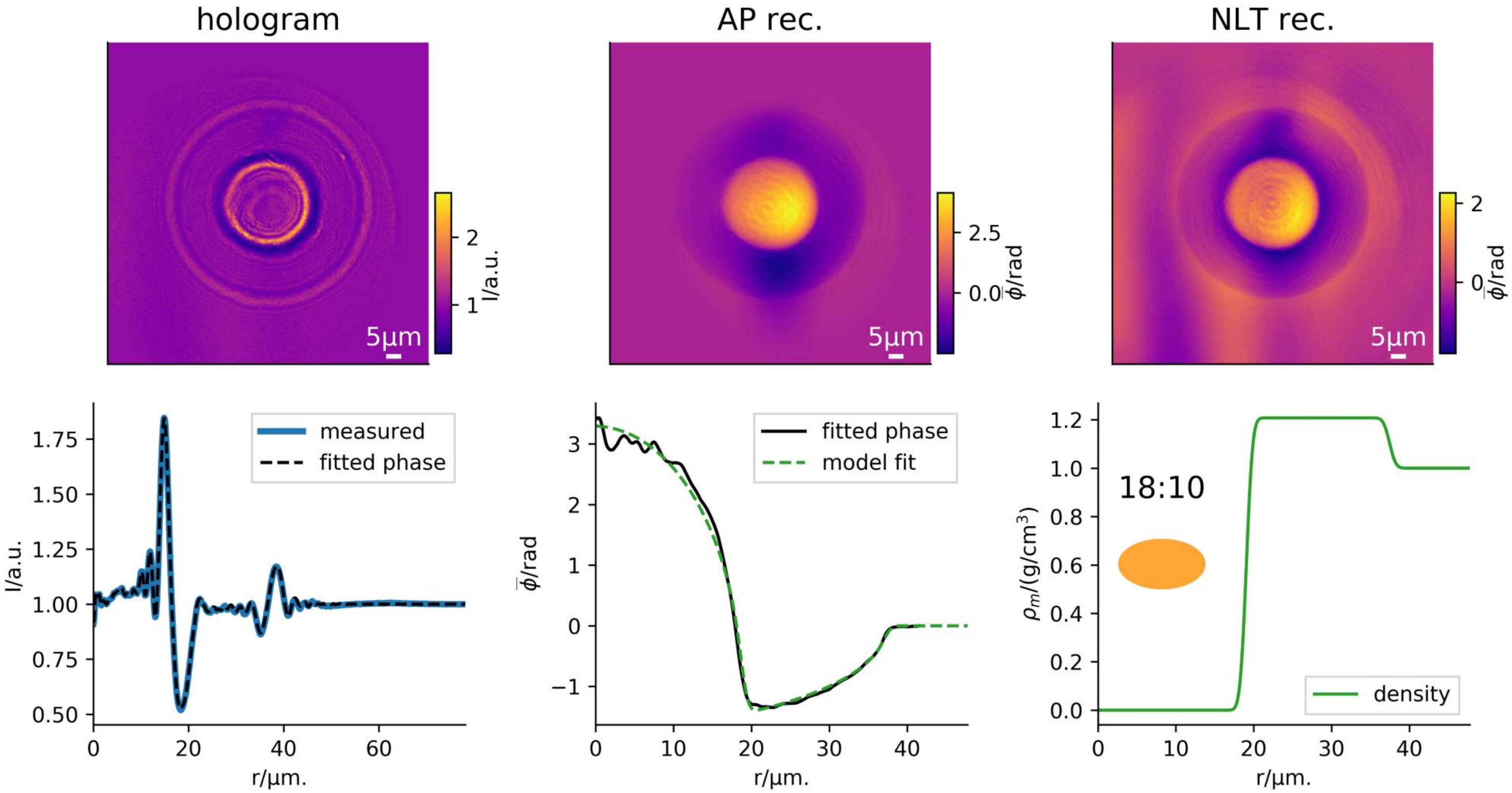
Malte Vassholz

τ=10ns



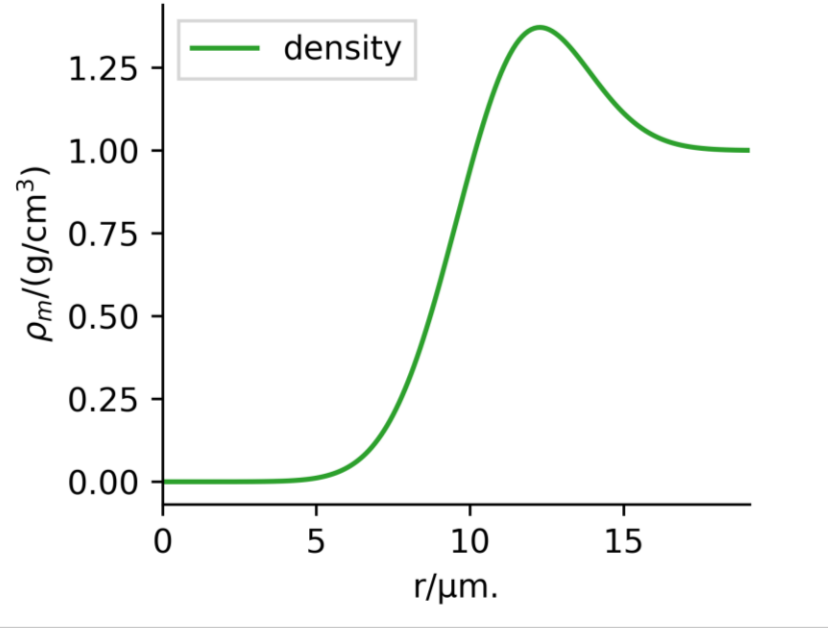
Malte Vassholz

τ=13ns

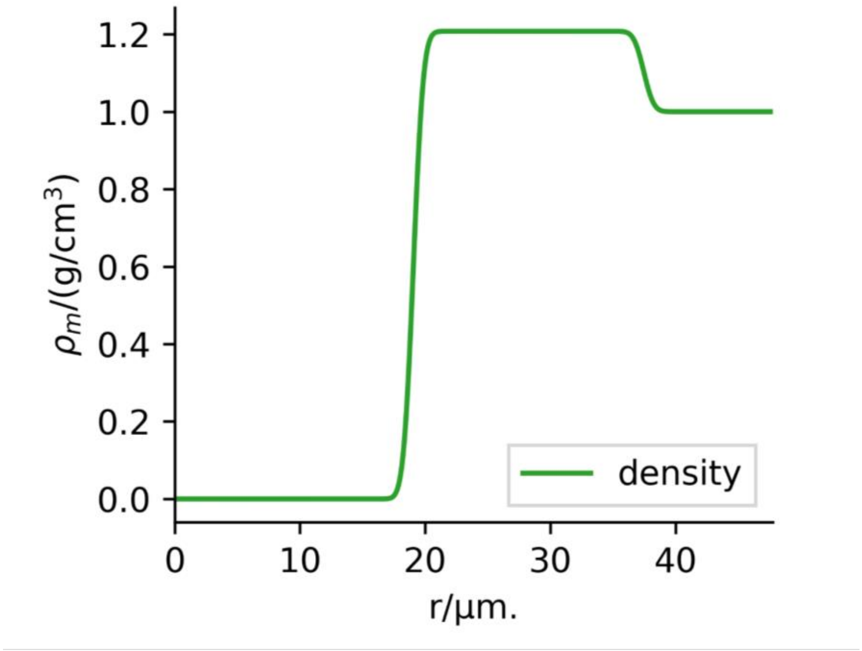


Malte Vassholz

τ=4ns



τ=13ns

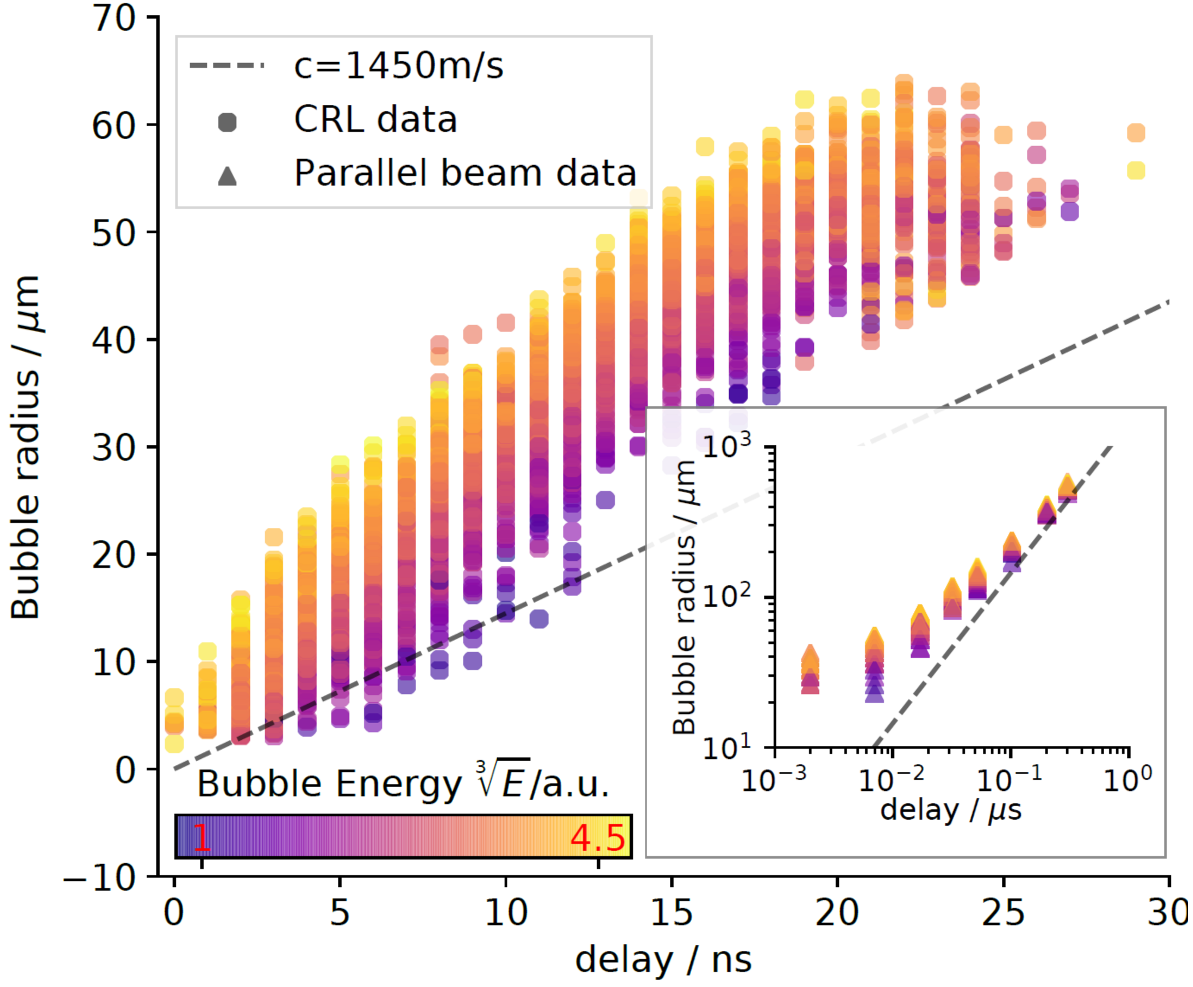


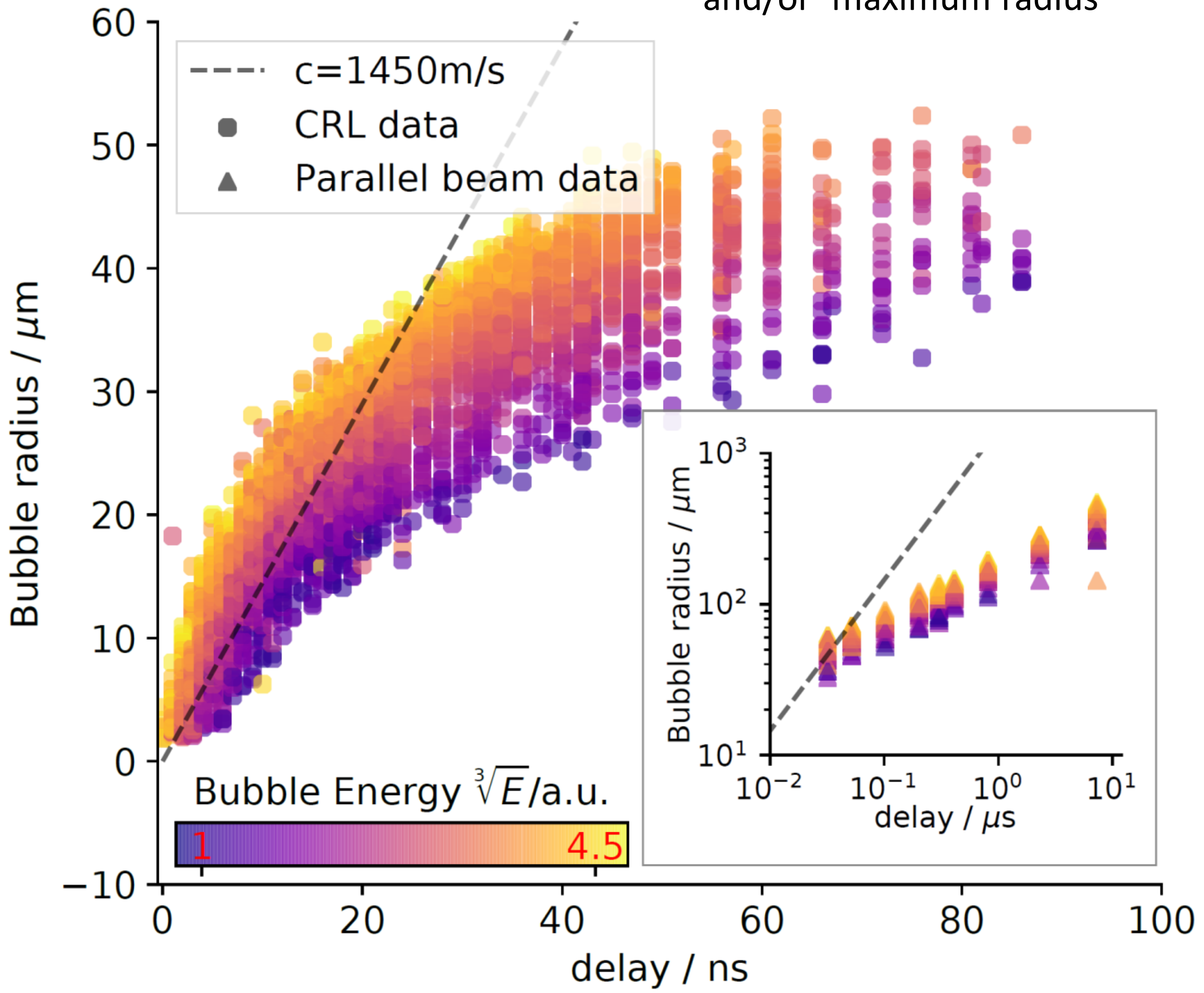
- *emergence of phase boundary / sharpening of the interface*
- *density of the shock wave -> equation of state*
- *Outlook: comparison with MD simulation*
- *Outlook: fs time scales / plasma dynamics / water structure in shock wave collapse of the bubble*

Malte Vassholz

Working out the entire ensemble / sorting for E_B

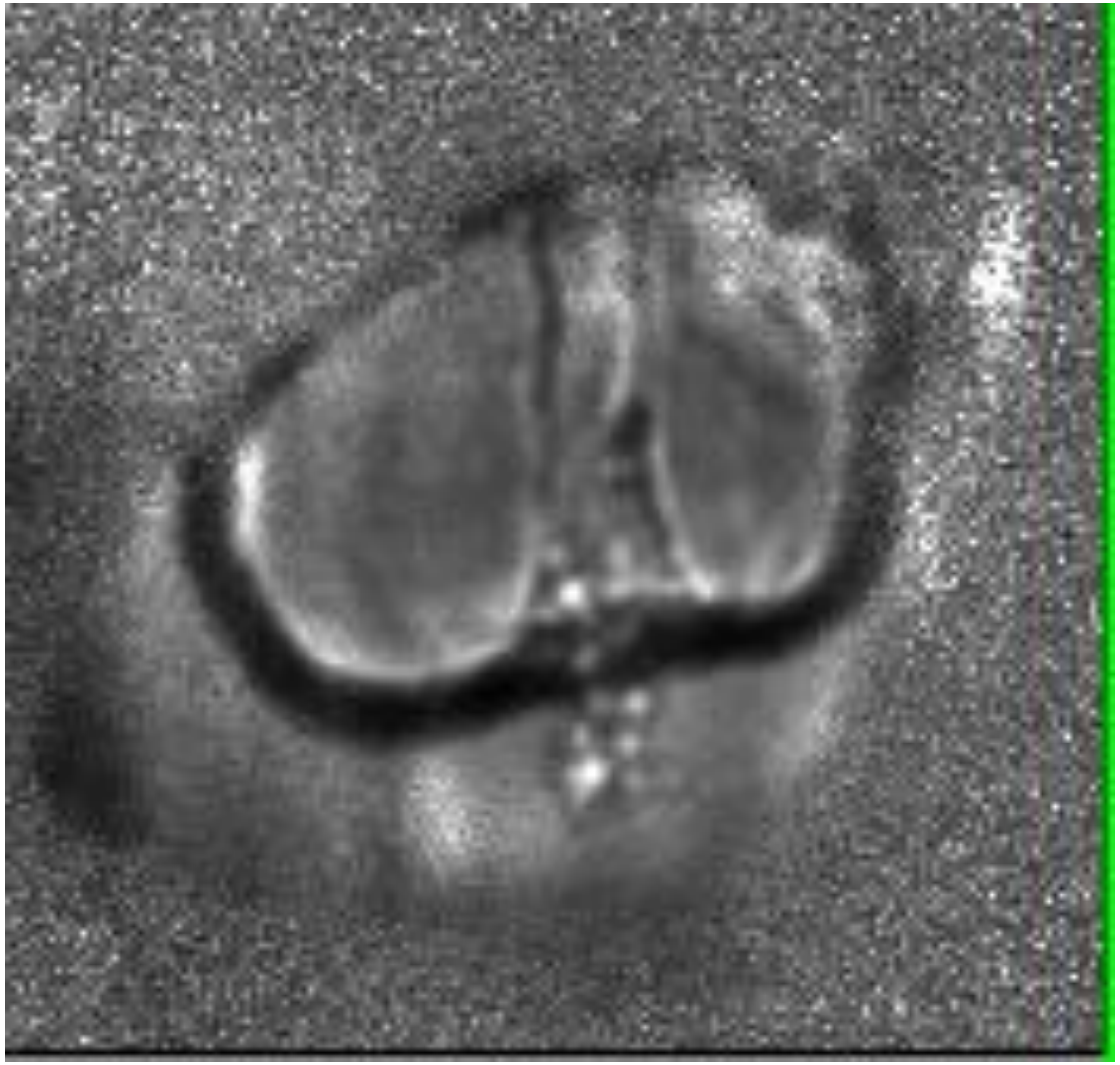
- maximum radius (photron)
- life time (microphone)
- bubble energy from life time and/or maximum radius





Malte Vassholz, Hannes Hoeppe, Markus Osterhoff

This is not only about spherical bubbles…jetting



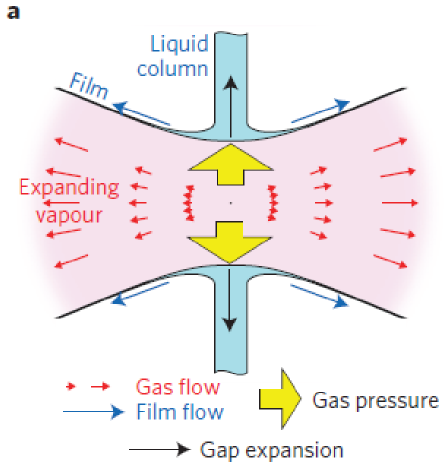
- cavitation bubbles near surfaces
- jetting
- parallel beam illumination

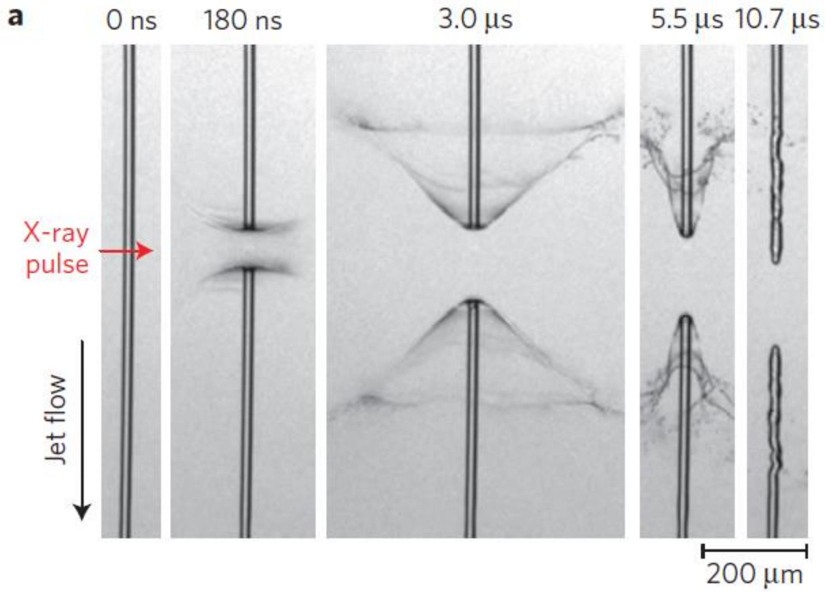
Juan Rosello

Cavitation in the microfluidic jet

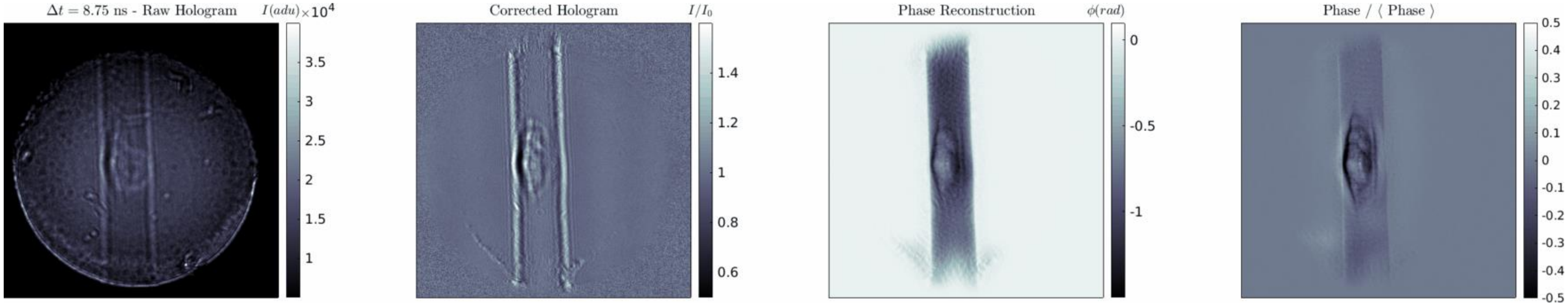
we can now observe the inverse

- *IR pump / x-ray probe*
- *density profiles*
- *Outlook: extend fs-regime*





Stan et al. Nat.Phys (2016)



Johannes Hagemann

Small bubble collaboration & Acknowledgements

Malte Vassholz, Markus Osterhoff, Hannes Hoeppe, Juan Rosello, Robert Mettin, Thomas Kurz, 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

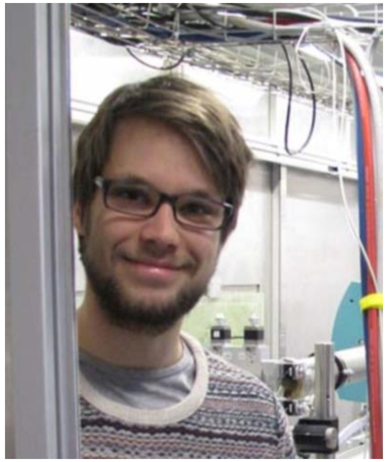
- UAC MID 06/2019 @14keV
- Beamtime 10/ 2019 @17.8keV

(p2207 & p2545 Hagemann/ Salditt)

MAX PLANCK SCHOOL of photonics

bmb+f

& the review panel for theit trust!



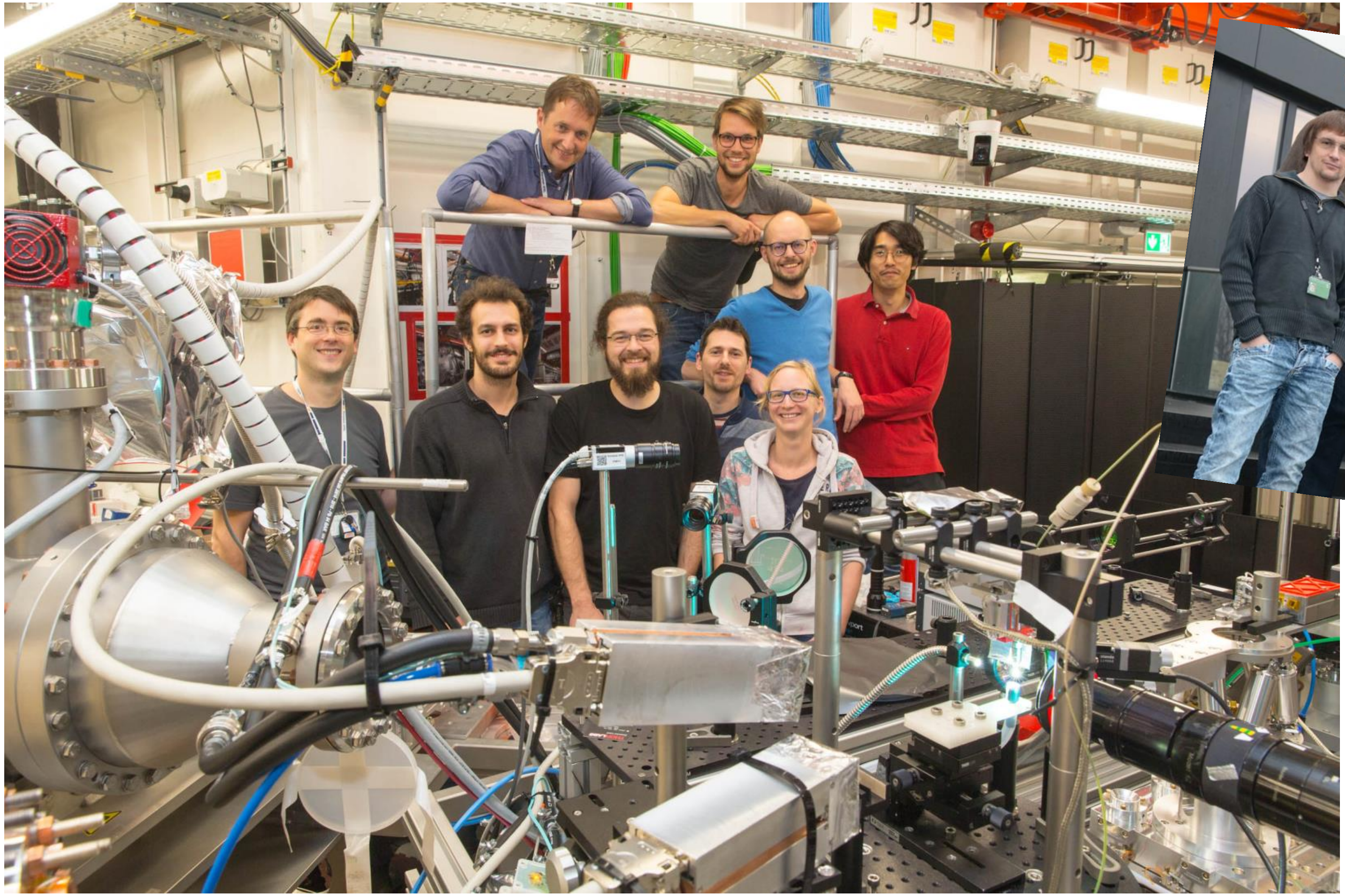
Vassholz *et al.*

Hagemann *et al.*

Osterhoff *et al.*

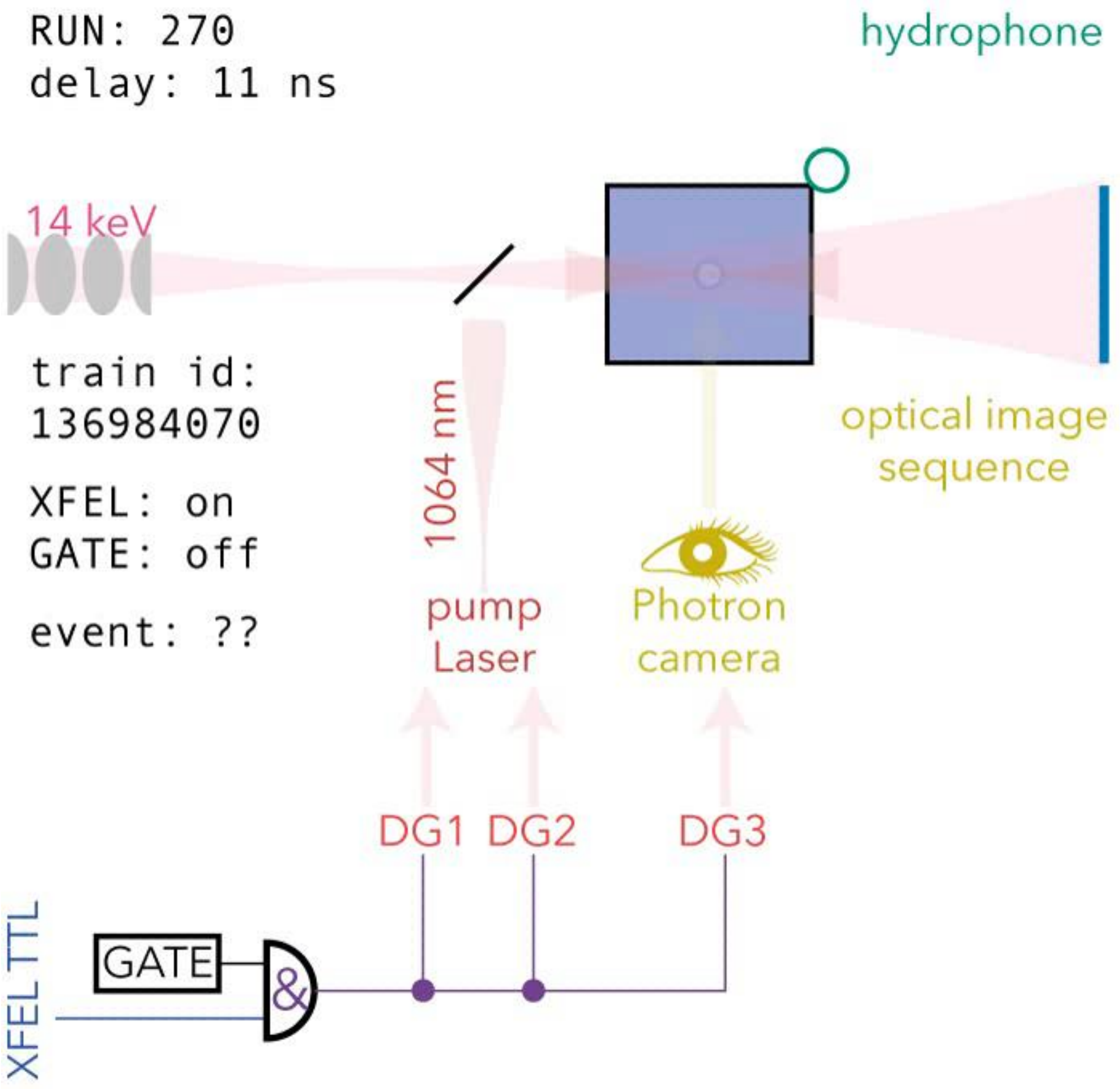
Manuscripts in preparation

Small bubble collaboration…



Many thanks to the MID team
for an amazing instrument
And frutiful collaboration

timing&synchronisation



X-ray raw data

hologram

phase image

M. Osterhoff et al., in preparation

Talk to the experts @ the posters!

#30 Timing (M. Osterhoff)
#249 Imaging (M. Vassholz)
#255 Dynamics (H. Hoeppe)