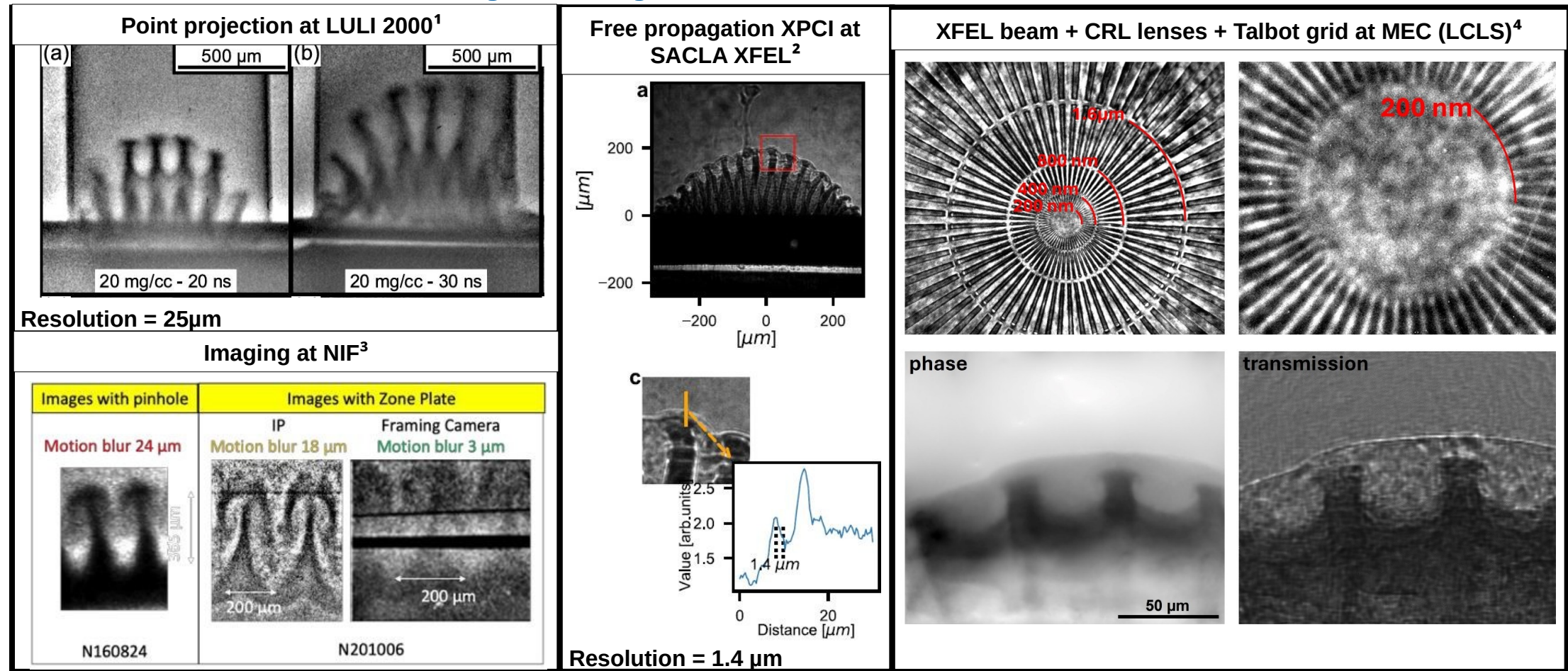


Applications and potential of XFEL radiation for foams and hydrodynamic instabilities



Victorien Bouffetier, HZDR, FWKX, HIBEF

¹G. Rigon et al, Physical Review E, 104, 4, (2021)

²G. Rigon et al, Nature Communication, 12, 1, (2021)

³ A. Do et al, Rev. Sci. Instrum. 92, 053511 (2021)

⁴ V. Bouffetier et al, (in preparation)

Collaborators and institutions

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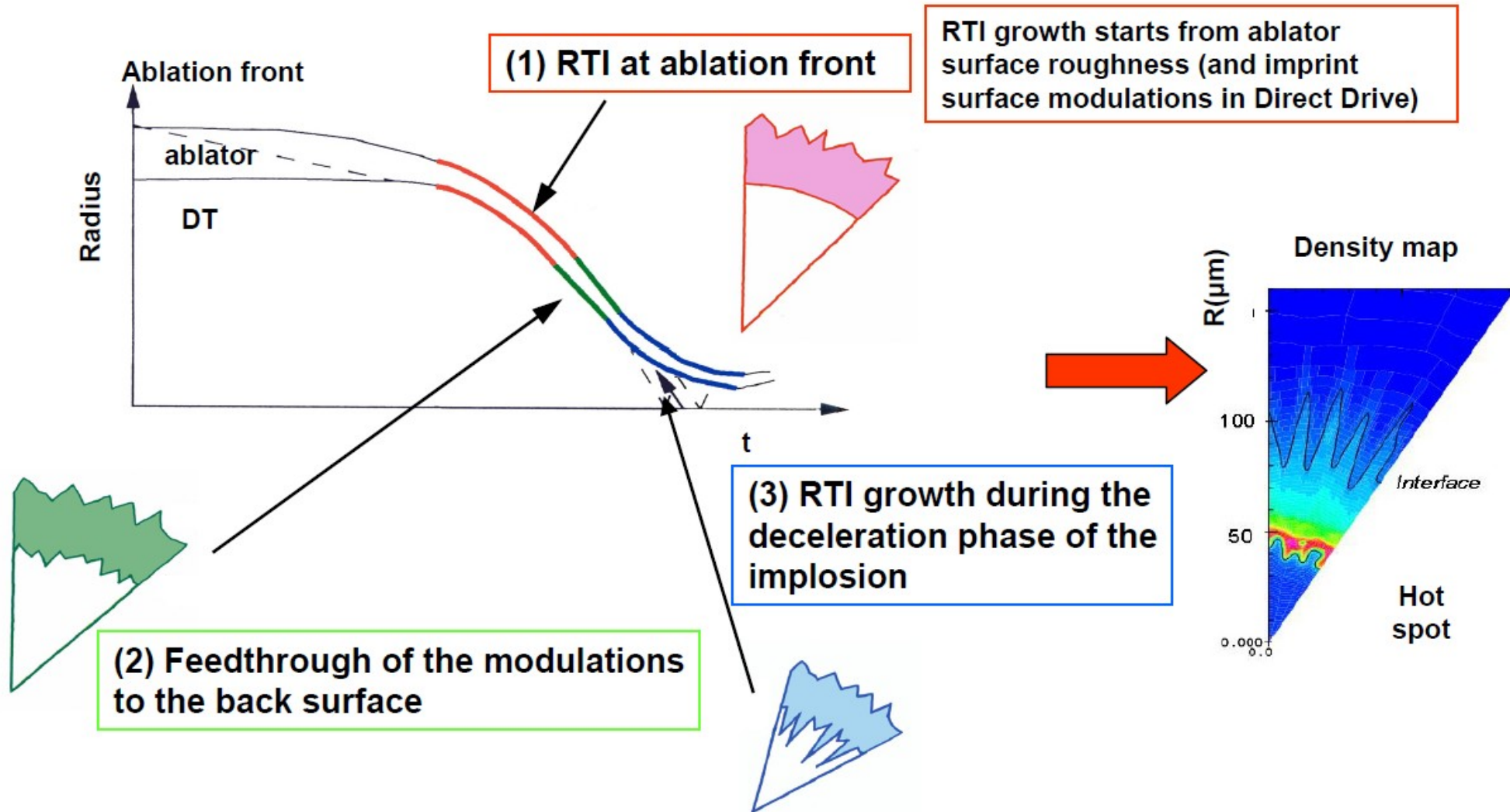
⁽¹³⁾ *Focused Energy GmbH, Im Tiefen See 45, 64293 Darmstadt, Germany*

⁽¹⁴⁾ *York Plasma Institute, School of Physics, Engineering and Technology, University of York, York YO10 5DD, United Kingdom*

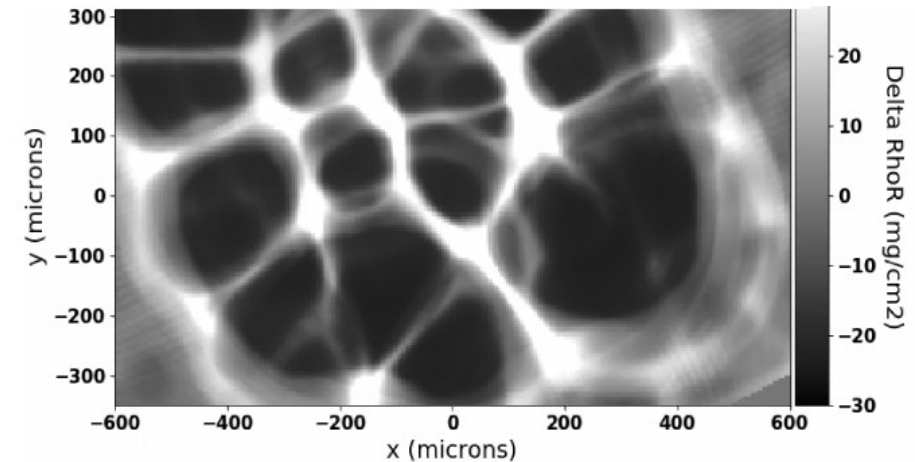
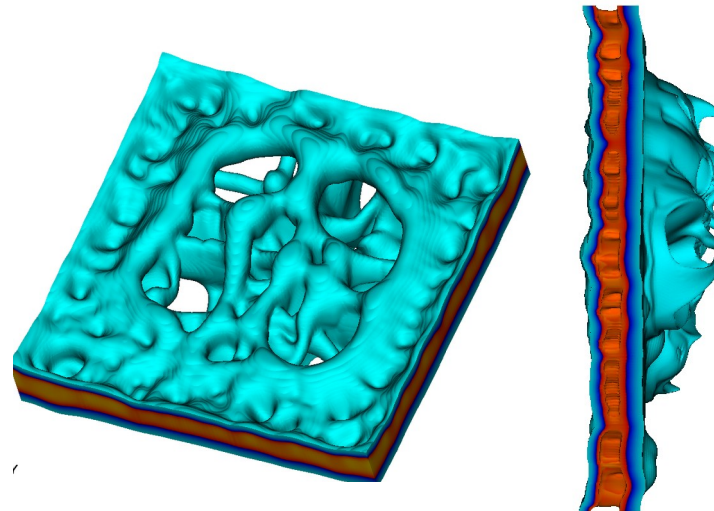
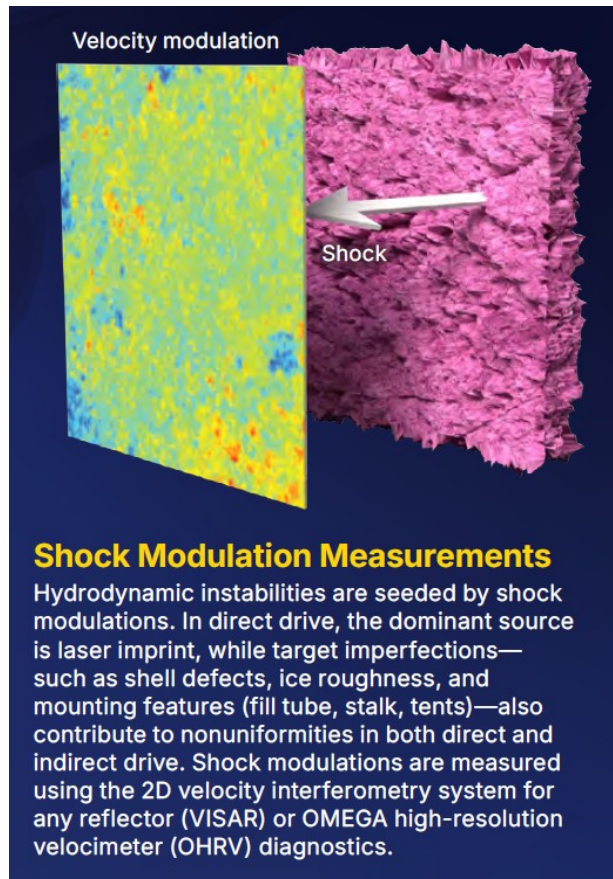
⁽¹⁵⁾ *Dipartimento SBAI, Università degli Studi di Roma "La Sapienza," Via Antonio Scarpa 14, 00161 Roma, Italy*

⁽¹⁶⁾ *CEA, DAM, DIF, F-91297 Arpajon, France*

Initial seeds are amplified during the convergence



Laser imprint is only visible after RTI amplification



- ❑ Could we find a way to initialize DD hydro simulations with the speckle pattern of the drive beam ?

Advanced IFE concepts rely on ablators with internal defects, microstructures

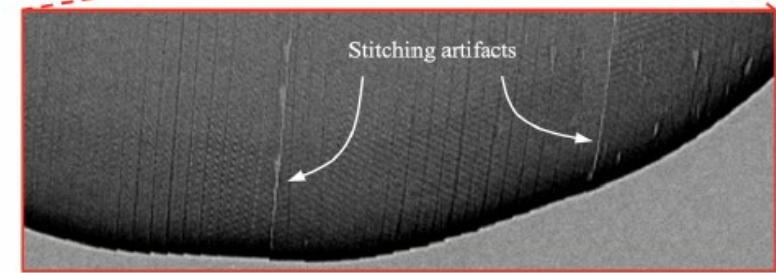
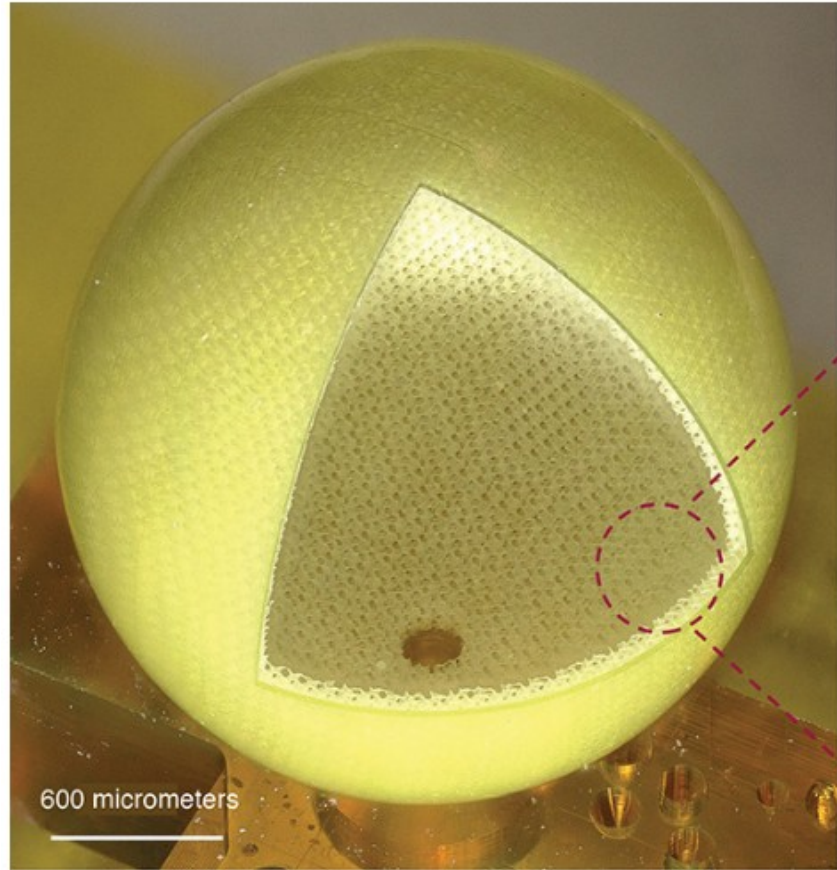
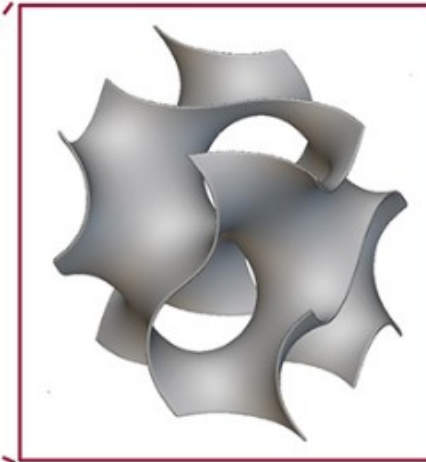
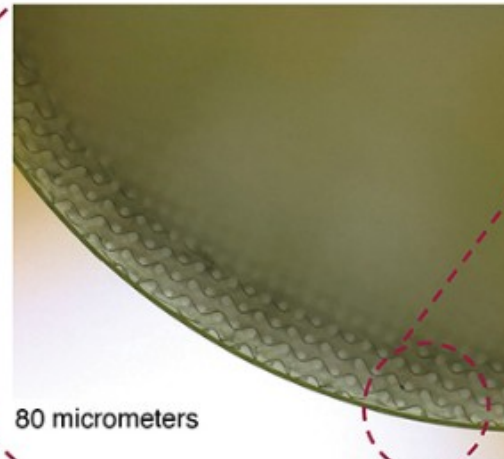


FIG. 2. The original prototype 2PP PDD-WF capsule (A. Haid, GA) presented by Olson *et al.*²⁰ was not gas-tight due to stitching artifacts as evidenced by an x-radiograph.



X-ray phase contrast imaging for optically thin sample

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

~Electron density ← refraction absorption → ~Ion density

Free propagation



Absorption

Phase



Detector

Sample

X-rays

Transport of intensity equation:

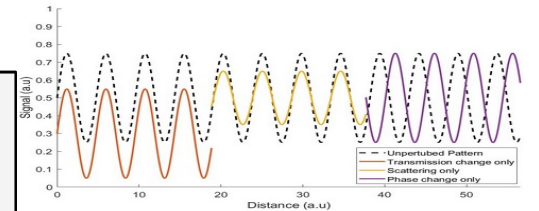
$$I_{XPCI}(x, y, z) = \underbrace{I_0 \exp[-\mu R(x, y)]}_{\text{Transmission}} - \underbrace{\frac{z I_0 \delta}{\mu} \nabla_{\perp}^2 \exp[-\mu R(x, y)]}_{\text{« Phase »}}$$

Grating X-ray interferometry (ex: Talbot):

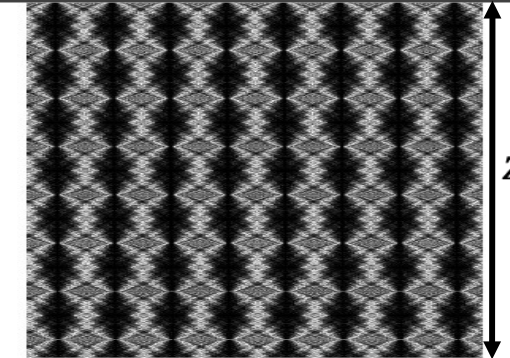
$$I(x, y, z) = I_{XPCI}(x, y, z) + B(x, y, z) \cdot \sin \left[\frac{2\pi x}{p} + \frac{\lambda \cdot \nabla \phi_{\text{samp}}}{W_{\text{eff}}} \right]$$

With I_0 the illumination function, $\mu = 4\pi\beta/\lambda$ the absorption coefficient, and W_{eff} the effective angular resolution, $R(x, y)$ the integrated thickness of the sample

$$\phi_{\text{samp}} = \frac{2\pi}{\lambda} \int \delta dz \begin{cases} \text{cold} & \delta = \frac{r_e \lambda^2}{2\pi} n_e \\ \text{plasma} & \delta = 1 - \text{Re} \left[\sqrt{1 - \frac{\omega_p^2}{\omega^2 + v_{ei}^2} \cdot \left(1 - i \frac{v_{ei}}{\omega}\right)} \right] \end{cases}$$



Detector



Sample

X-rays

DRESDEN
concept
SCIENCE AND
INNOVATION CAMPUS



HZDR

Propagation-based X-ray phase contrast imaging analysis

$$I_{XPCI}(x, y, z) = I_0 \exp[-\mu R(x, y)] - \frac{z I_0 \delta}{\mu} \nabla_{\perp}^2 \exp[-\mu R(x, y)]$$

How to
extract
 ϕ_{smp} ?

$$\phi_{smp} = \frac{2\pi}{\lambda} \int \delta dz$$

With $\delta = \text{constante}$:

$$\phi_{smp} = \frac{2\pi\delta}{\lambda} R(x, y), \quad \text{with } R \text{ the projected thickness}$$

For collimated beam

$$R(x, y, z_D) = \frac{1}{\mu} \ln \left(\mathcal{F}^{-1} \left\{ \mu \frac{\mathcal{F}[I_{XPCI}(x, y, z_D)/I_0]}{z_D \delta |k_{\perp}|^2 + \mu} \right\} \right)$$

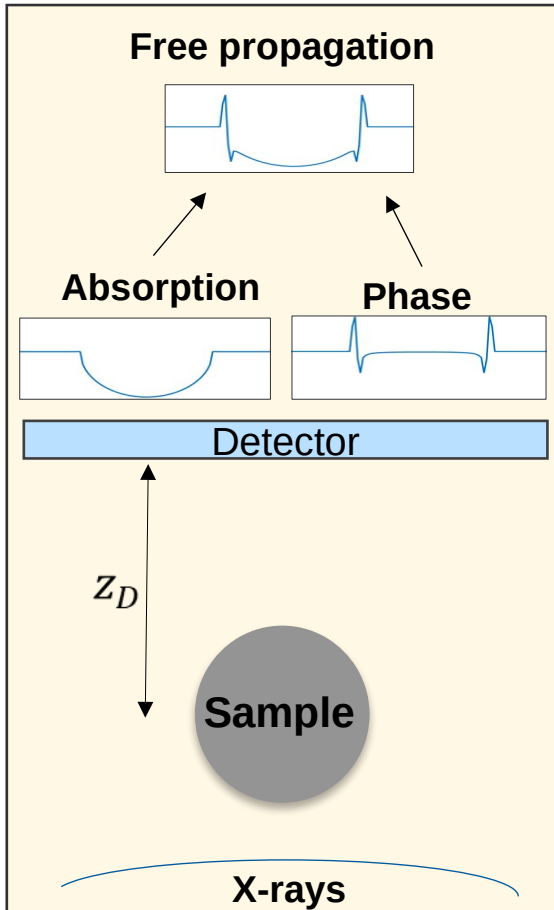
For diverging beam,

$$R_M(x, y, z_D) = \frac{1}{\mu} \ln \left(\mathcal{F}^{-1} \left\{ \mu \frac{\mathcal{F}[M^2 \cdot I_{XPCI}(x, y, z_D)/I_0]}{z_D \delta |k_{\perp}|^2 / M + \mu} \right\} \right), \quad \text{With } M \text{ the magnification}$$

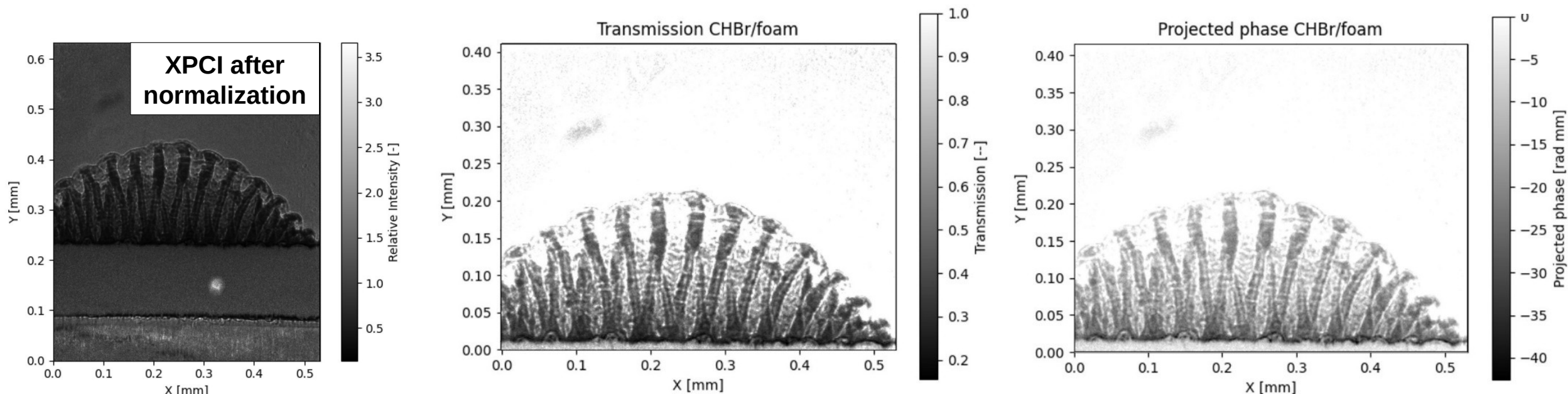
$$\begin{cases} T_{smp} = e^{-\mu R(x, y)}, \\ \phi_{smp} = \frac{2\pi\delta}{\lambda} R(x, y). \end{cases}$$

Low-pass filter : the postprocessing will always be lower resolution than the raw data

Drawback of the method: μ and δ have to be known



Example of RTI developments observed at the BL3-EH5 SACLA



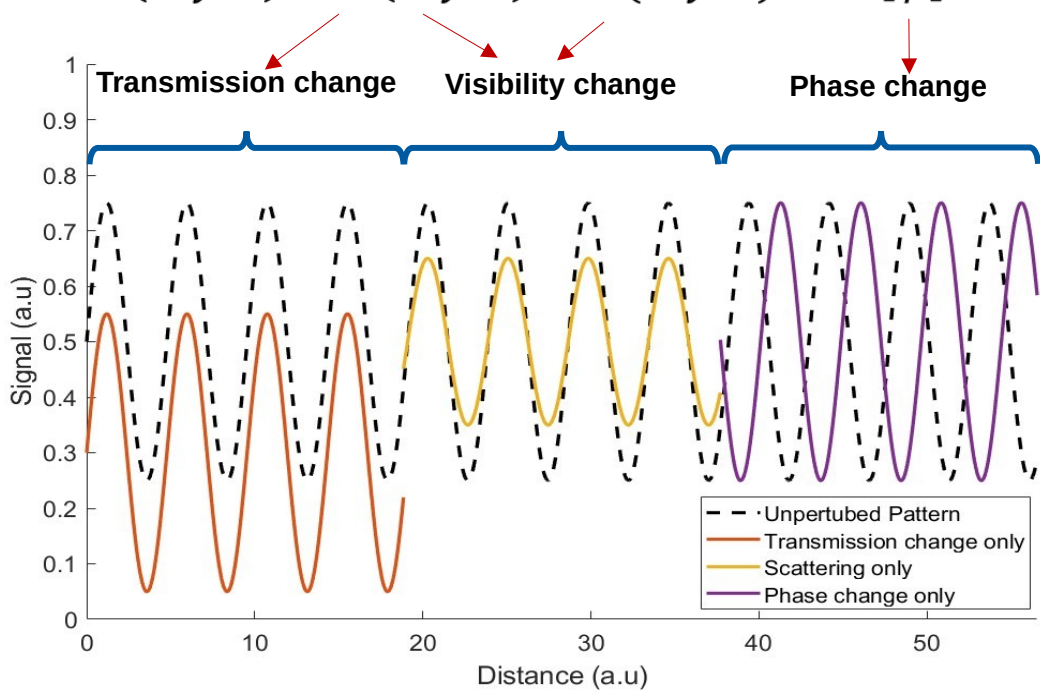
Post processing: F. Barbato from data in ²G. Rigon et al, Nature Communication, 12, 1, (2021)

XPCI enables net enhancement of interfaces due to réfraction happening at the edges of the RTI fingers.

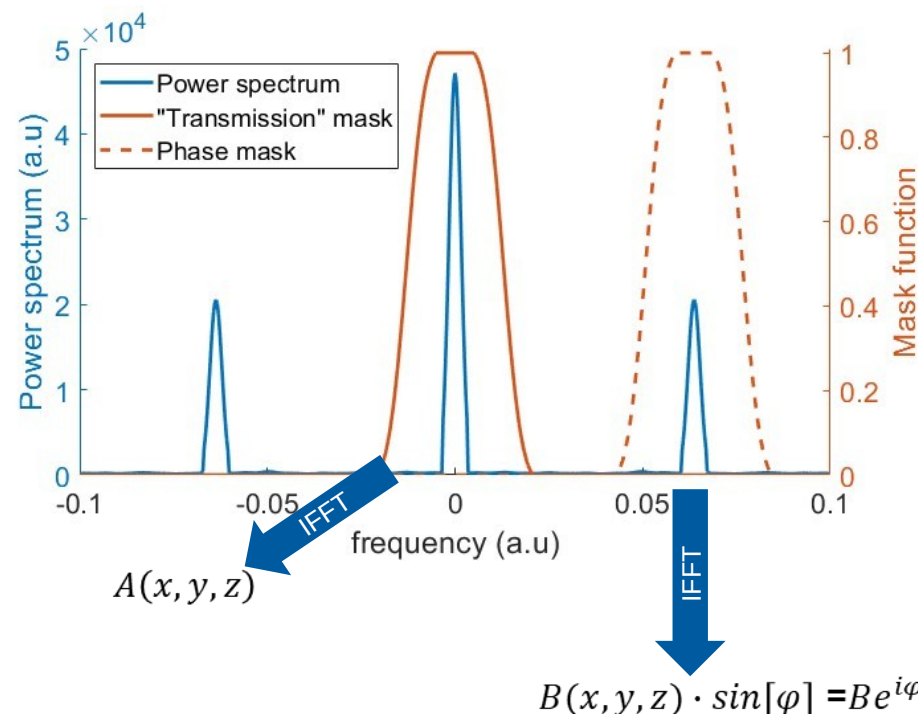
No additional features which is not already enhanced and visible in the raw image will be added after the phase retrieval compared to transmission.

X-ray grating interferometry analysis using FFT

$$I(x, y, z) = A(x, y, z) + B(x, y, z) \cdot \sin[\varphi]$$



Fast Fourier Transform



Transmission (mass density):

$$T = \frac{A_{per}}{A_{ref}}, \text{ with } A = I_{XPCI}(x, y, z)$$

Dark field (small angle X-ray scattering):

$$DF = \ln\left(\frac{V_{per}}{V_{ref}}\right) = \ln\left(\frac{B_{per}}{B_{ref}} \cdot \frac{1}{T}\right), \text{ with } V = \frac{B}{A} \text{ the fringe visibility}$$

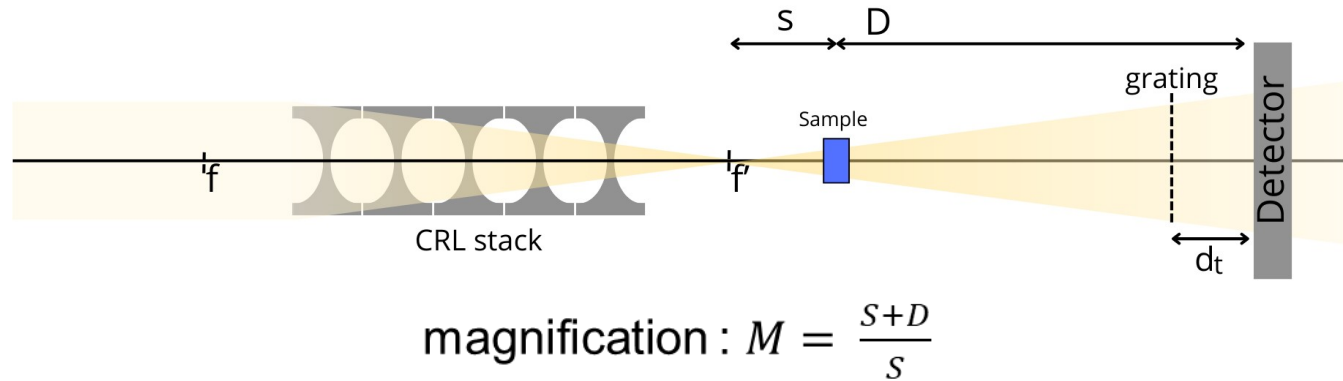
Phase difference (electron density):

$$\Delta\varphi = \varphi_{per} - \varphi_{ref} = \frac{\lambda \nabla \phi_{samp}}{w_{eff}}, \text{ with } \varphi \text{ the interferogram's phase, and } \phi \text{ the X-ray wavefront's phase}$$

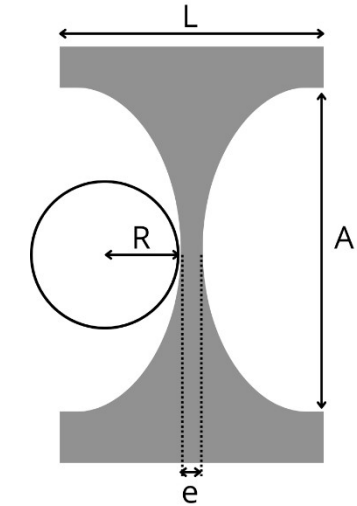
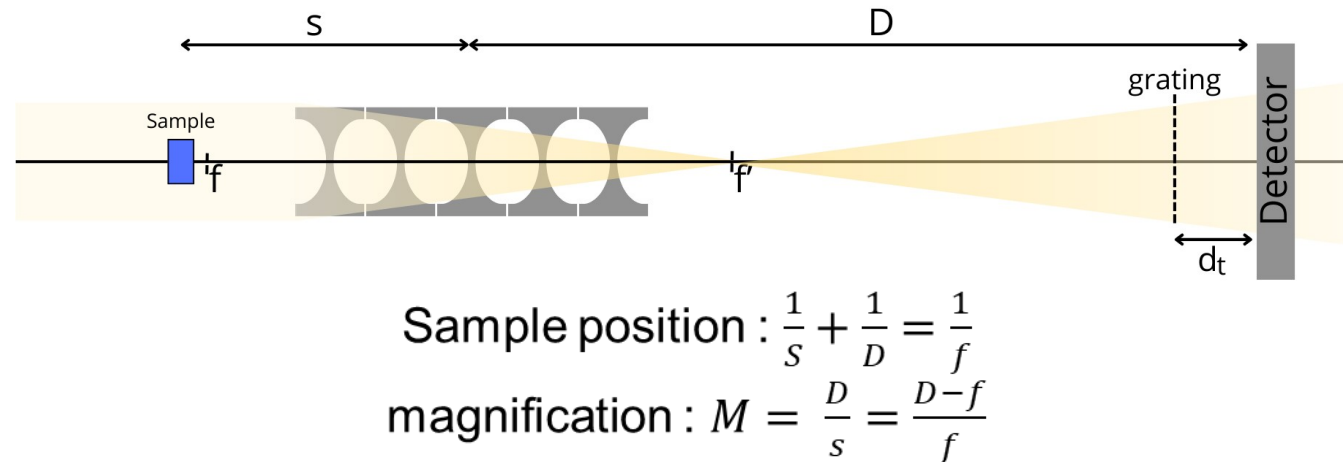
using:
 $\ln(Be^{i\varphi}) = \ln(B) + i\varphi,$
 The fringes' amplitude and phase can be splitted.
Not of caution : φ still needs to be unwrapped

Compound refractive lens based imaging

- Point projection scheme



- Direct imaging scheme



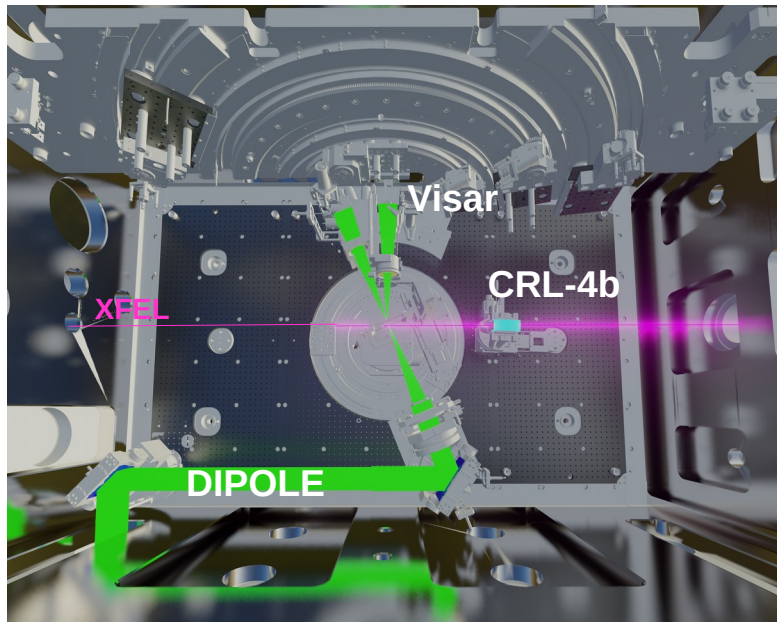
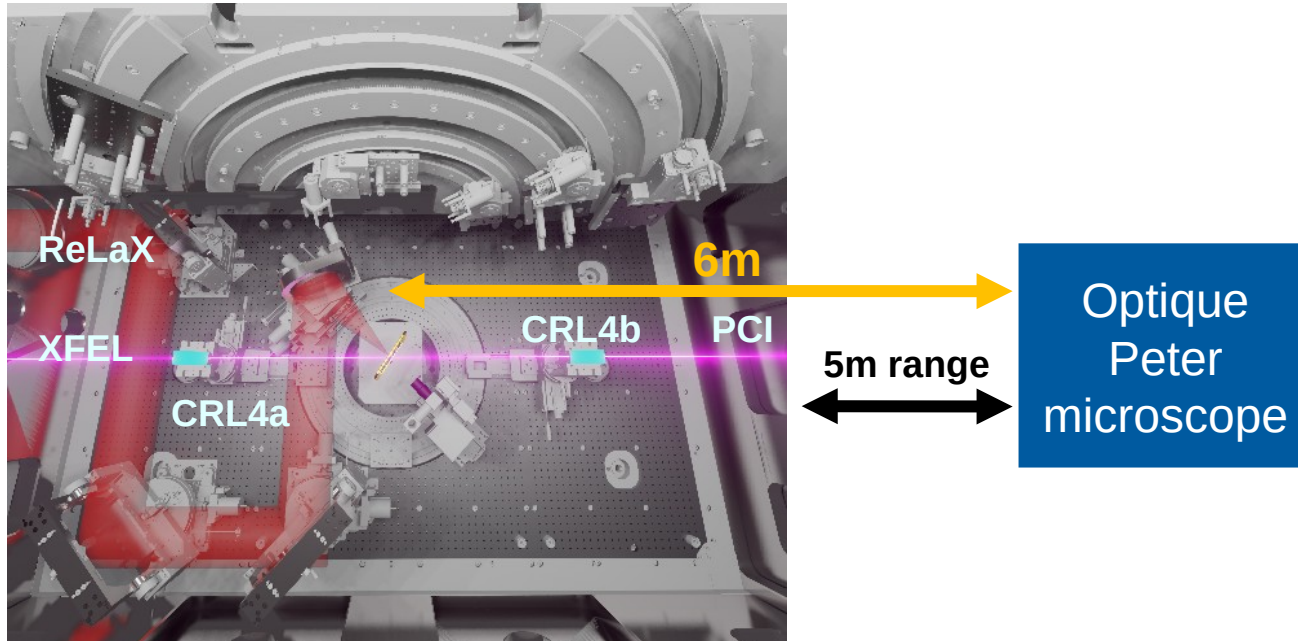
Focusing capabilities of a CRL stack:

Focal length : $f = \frac{R}{2N\delta}$

Curvature radius

Number of lenses

THE INTERACTION CHAMBER : SUB-MICROMETER RESOLUTION IMAGING PLATFORM



3 schemes:

- Point-projection (CRL4a):
< 1 μ m – 100 μ m FoV on target
- Imaging (CRL4b):
>100 μ m FoV on target
- Combination of both (CRL4a + CRL4b):
<1 μ m – 100 μ m FoV on target

In all cases we attain resolution < 1 μ m (limited by SASE bandwidth)

- Optique Peter microscope:
 - Zyla camera: 6.5 μ m pixel size
 - microscope objective 2X, 7.5X, 10X

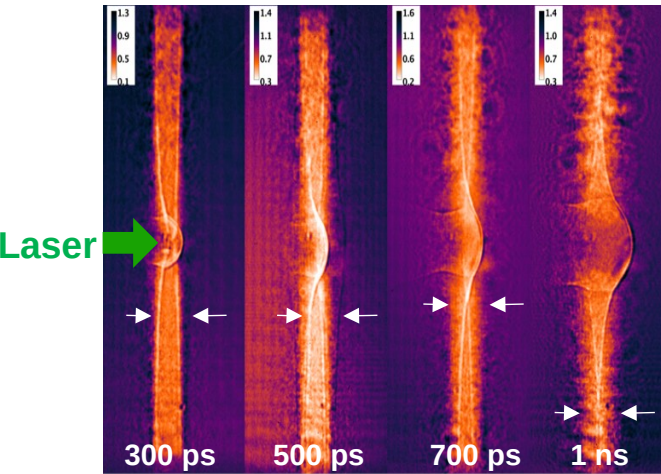
For Imaging demonstrated:

- ~500 nm with SASE
- ~200 nm monochromated beam

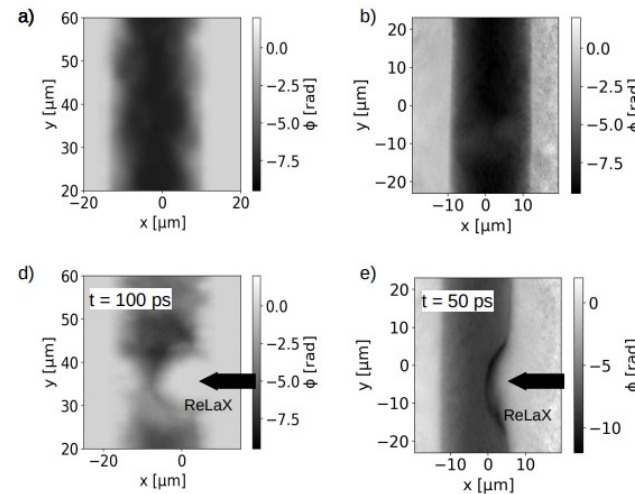
X-ray imaging in IC1

Wire compression using RELAX laser

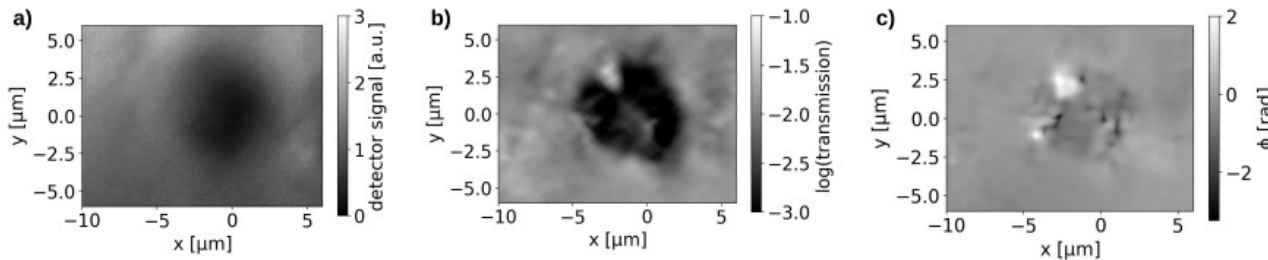
*Direct imaging:



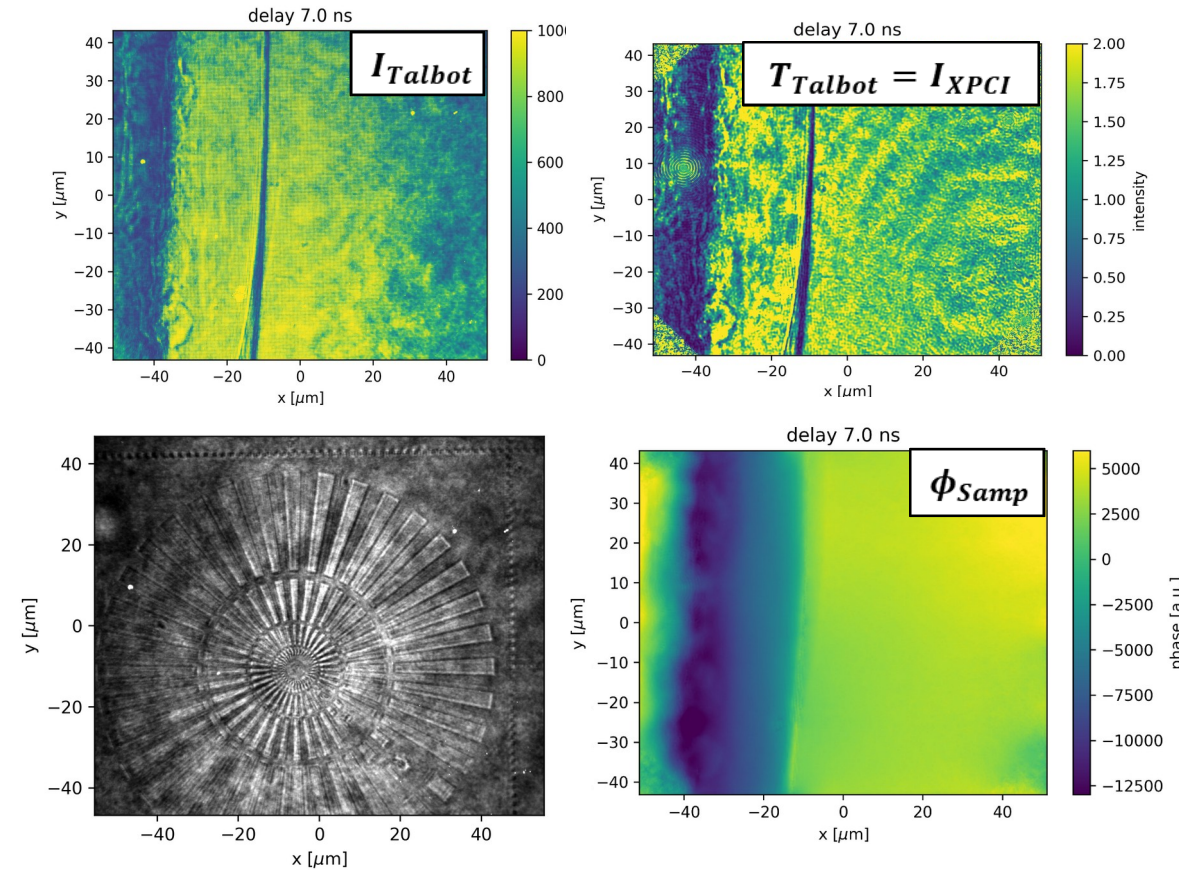
**Direct vs Talbot imaging:



**Talbot resonant imaging:



** Imaging shocks in polystyrene generated with DIPOLE laser using Talbot interferometry

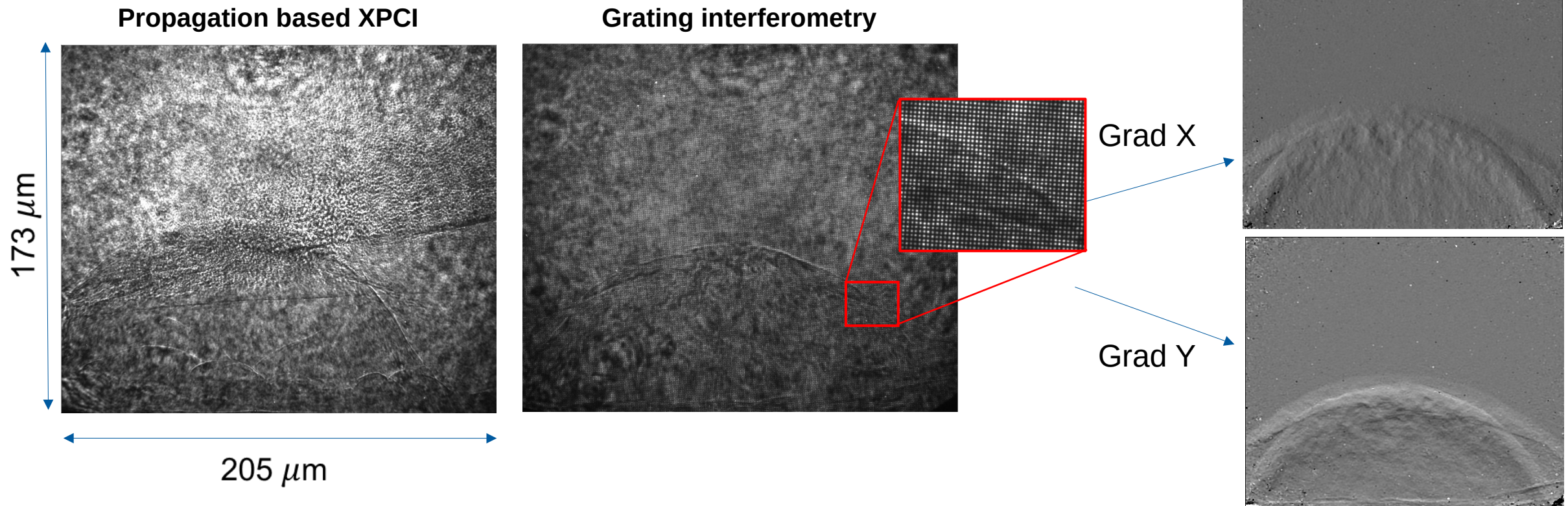


*A. Laso Garcia, et al, *Nature Communications* 15.1 (2024): 7896.

** A. Laso Garcia, et al, *arXiv preprint arXiv:2601.14028* (2026).

Free propagation imaging vs grating interferometry

Grating interferometry enables better sensitivity to retrieve features not visible even with propagative XPCI

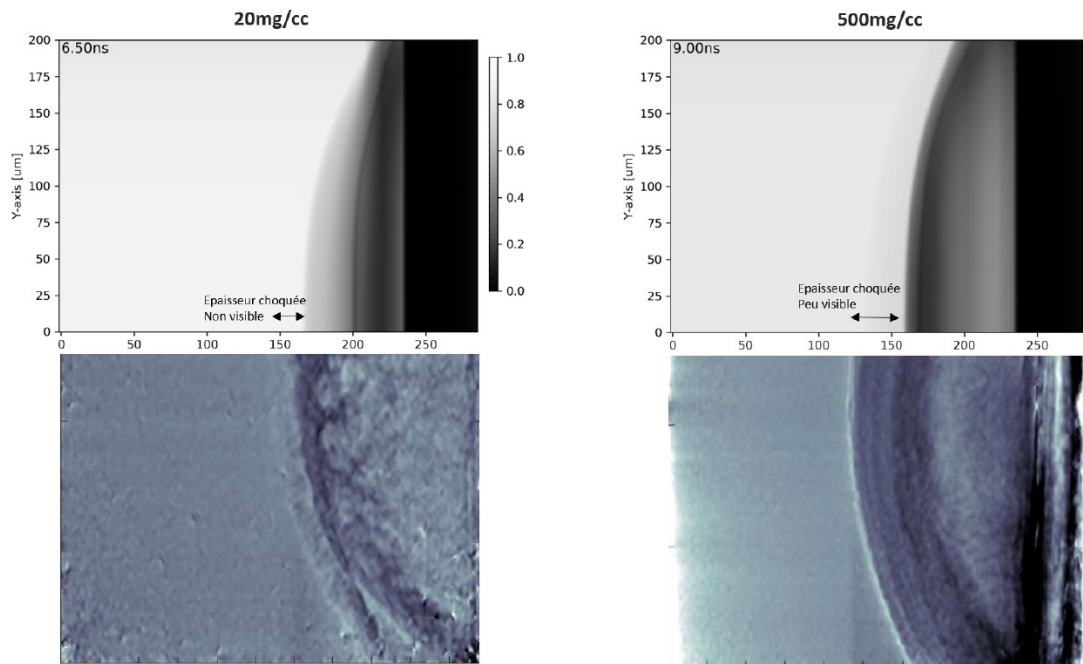


Phase imaging of shocks with Talbot Grating Interferometry

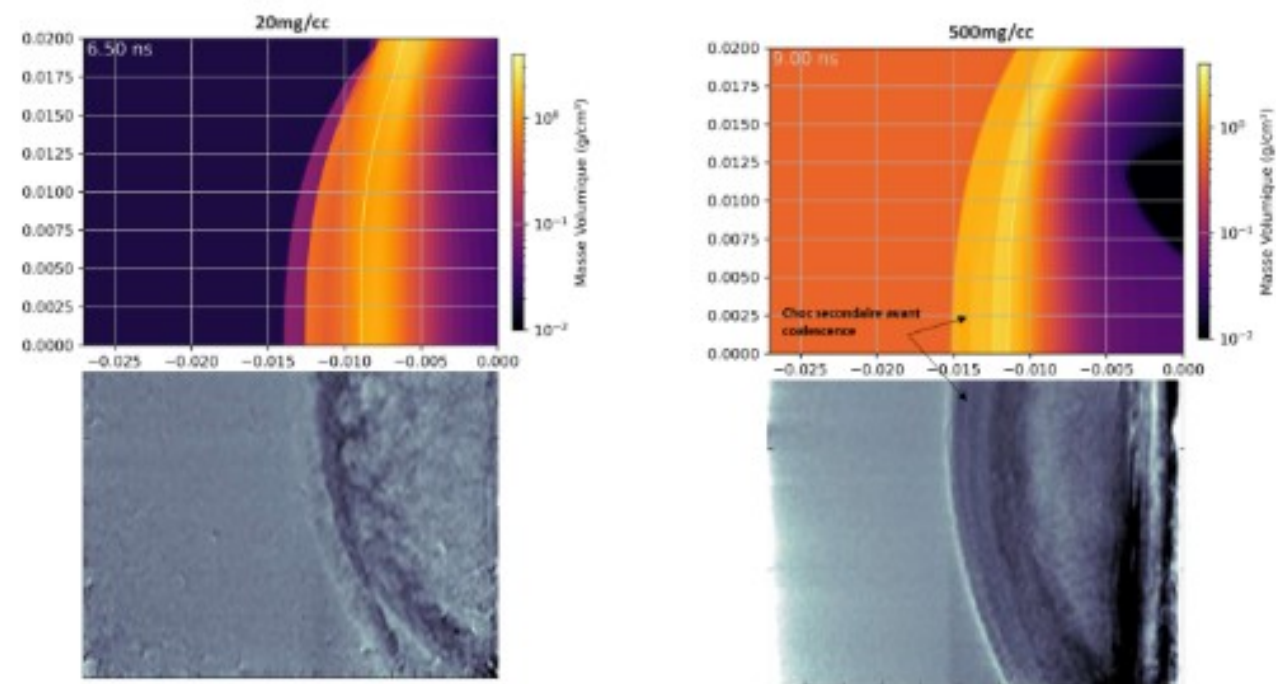
Comparison of differential phase from grating interferometry vs simulated absorption imaging

Simulation

Experiment



Comparison of differential phase from grating interferometry vs volumic mass maps



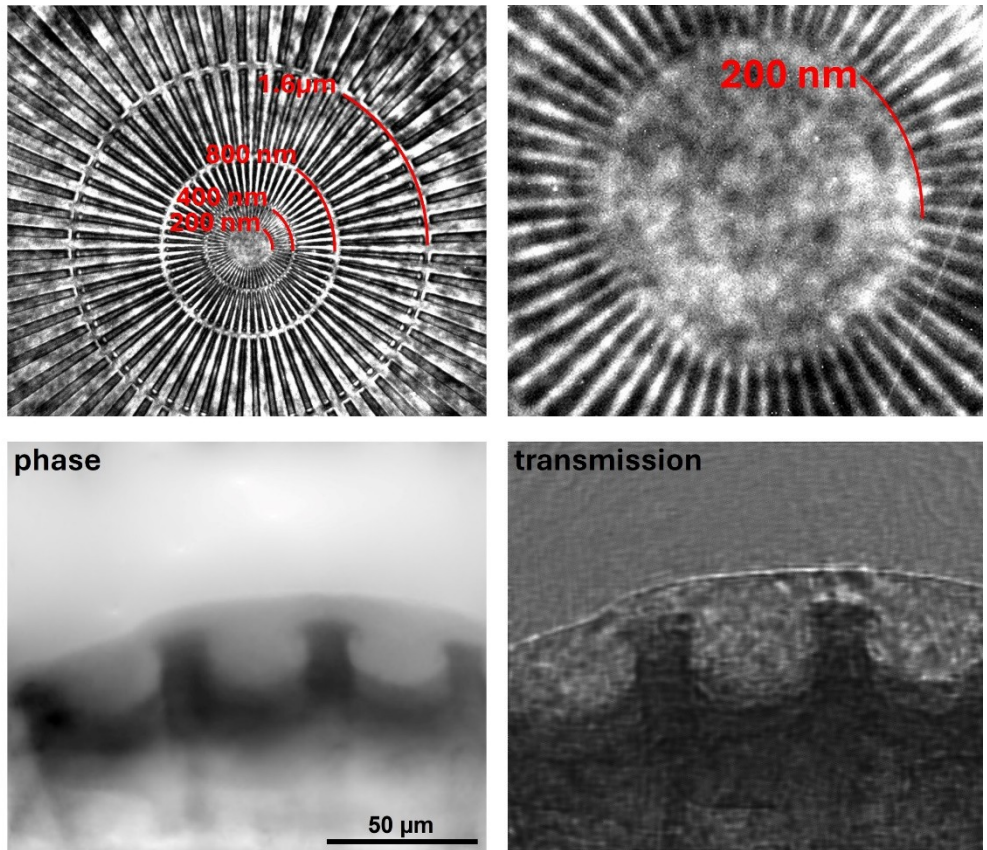
* Simulation: T. Goudal

Additional images and descriptions in C. Parisuana et al, PoP, (2025)

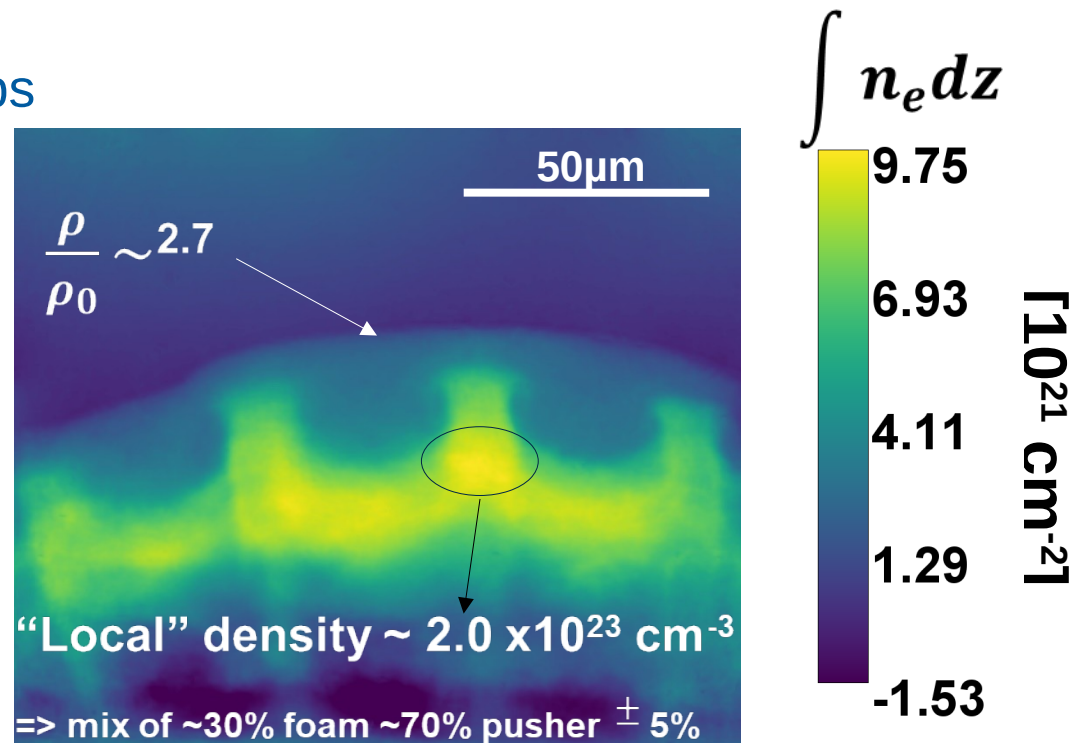
The greater sensitivity in phase contrast imaging enables a more direct comparison between simulations and experiments thanks to the greater details in hydrodynamic structures

Advanced characterization of turbulent mixing with X-ray interferometry

Density retrieval from phase maps



Postprocessing: M.P. Valdivia

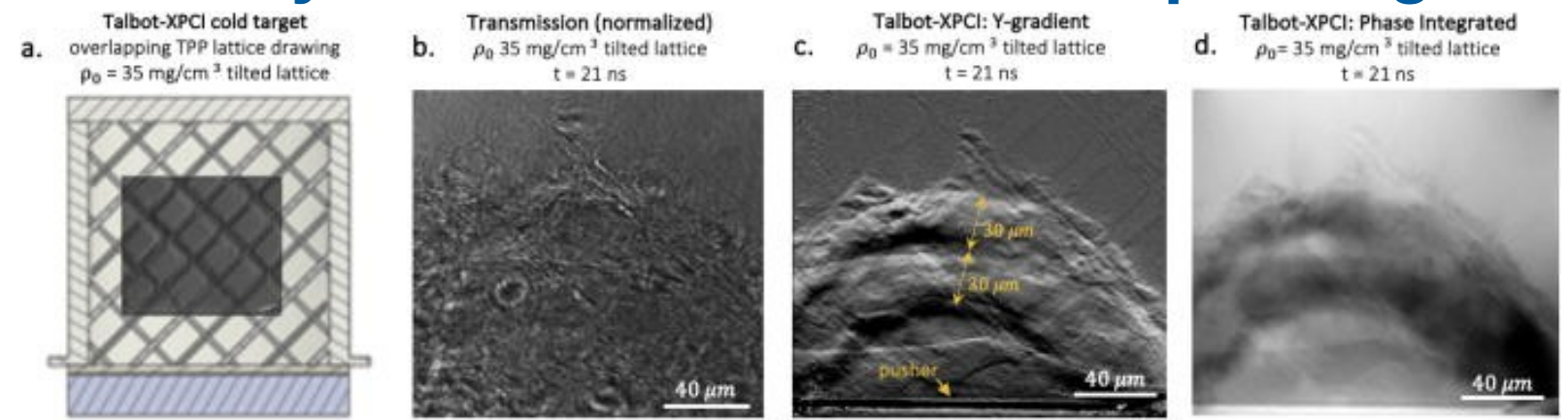


Retrieval of electron density from phase maps (as shown above) and ion density from transmission will enable to retrieve local average Z to characterize the mixing induced by RTI.

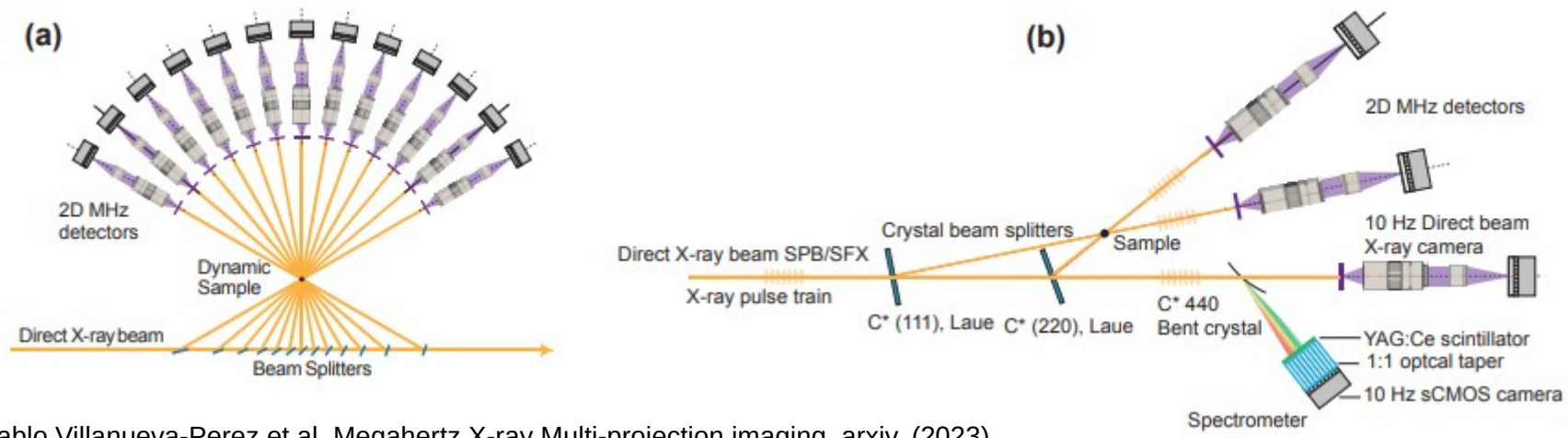
Conclusions and perspectives

- **XFEL provide highly coherent light which is ideally suited for phase sensitive imaging**
- **XFEL light can enable submicron resolution down to a few hundred nm (no motion blurr)**
- **Advanced phase imaging techniques enable to retrieve subtil changes in density maps**
- **3D probing may enable to improve our understanding of plasma hydrodynamics in near future**

XFEL facilities may enable to overcome 2D probing limitations



C. Parisuana et al, PoP, 2025



Pablo Villanueva-Perez et al, Megahertz X-ray Multi-projection imaging, arxiv, (2023)

Instabilities are inherently 3D. 2D maps from radiography only offer limited information due to depth integration over the target

3D imaging will be tested at HED in spring 2027 to overcome this aspect