X-Ray Phase-Contrast Imaging of Strong Shock Waves

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Now at:
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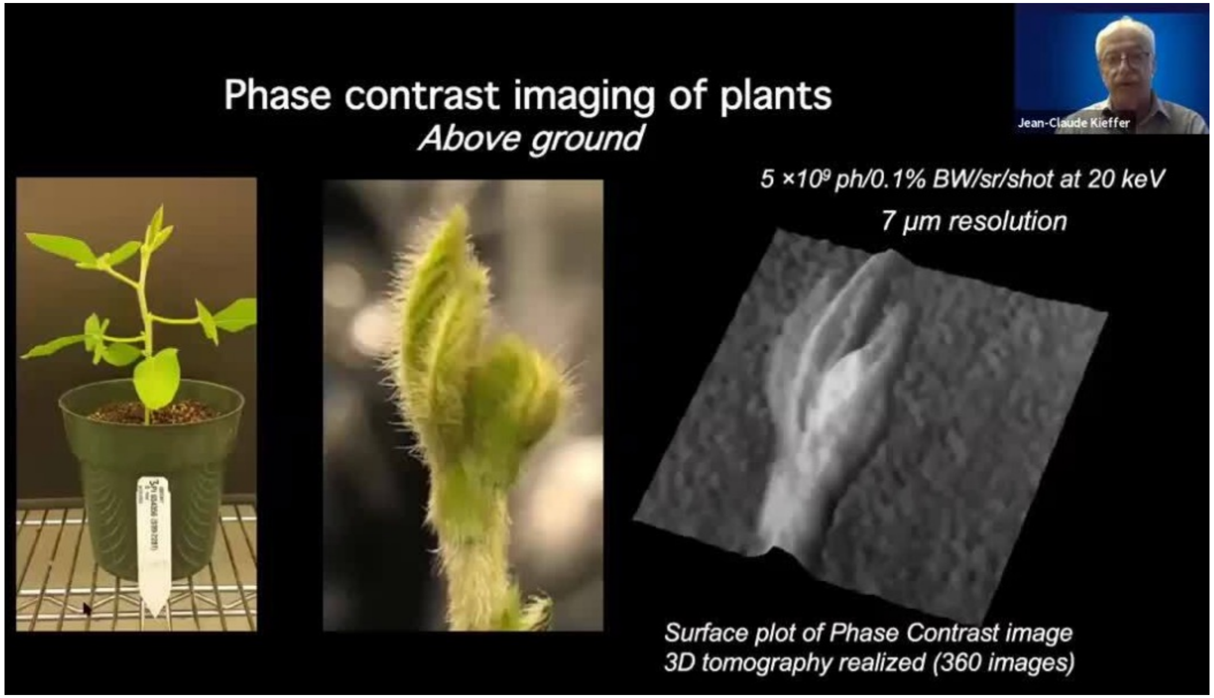
Message of the talk:

1) **X-Ray Phase-Contrast Imaging (XCPI) is an extremely important diagnostic for HED physics**

   - First experiment at Phelix, GSI, to study the dynamics of single shocks
   - Experiment at Omega, Rochester, to study the dynamics of two consecutive shocks (clearly important for the shock ignition approach to ICF)

2) **XPCI can be implemented on LMJ using PETAL as a backlighter source**

XPCI is an imaging technique successfully used in several domains of science from biology to material science using conventional X-ray sources, laser-plasmas, XFELS...



There are not many applications of XPCI to HED physics using high-energy laser systems and laser-plasmas as a backlighting source

What is XPCI ?

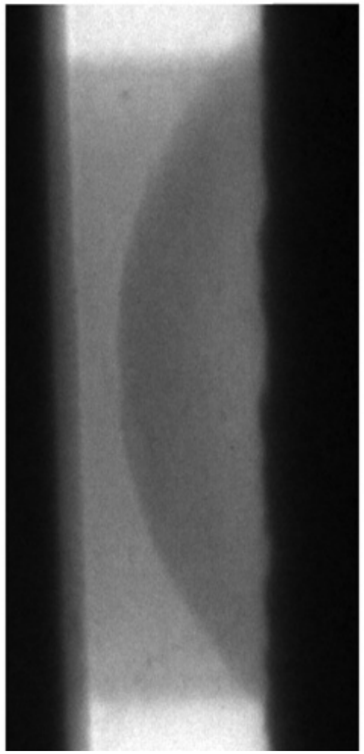
- The refractive index of matter (including plasmas) has a real and imaginary part

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

- **X-ray radiography** is based on the differences in the absorption coefficient of matter ($\mu = 2k\beta$) which is proportional to density ρ

- In order to probe large / dense samples you need high-energy X-rays but then the differences in β are not large enough to allow getting a good contrast

8 Mbar shock propagating in 250 µm plastic (Δt = 4.7 ns)



LULI laser

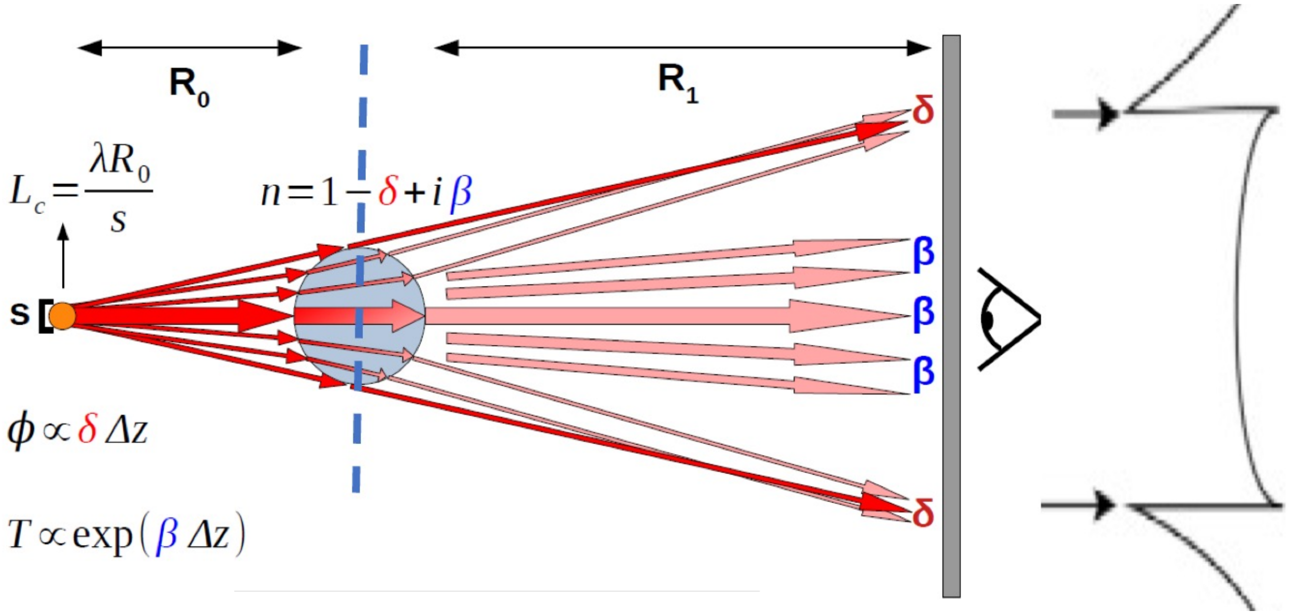
L. Antonelli , et al. «Laser-driven shock waves studied by x-ray radiography» PHYSICAL REVIEW E 95, 063205 (2017)

What is XPCI ?

- XPCI depends on the real part of the refraction index, i.e. on δ which produces a phase shift in the probing e.m. wave ($\Delta\phi = knx$) and ray refraction, according to Snell-Descartes law ($i/r \approx n_r/n_i$)

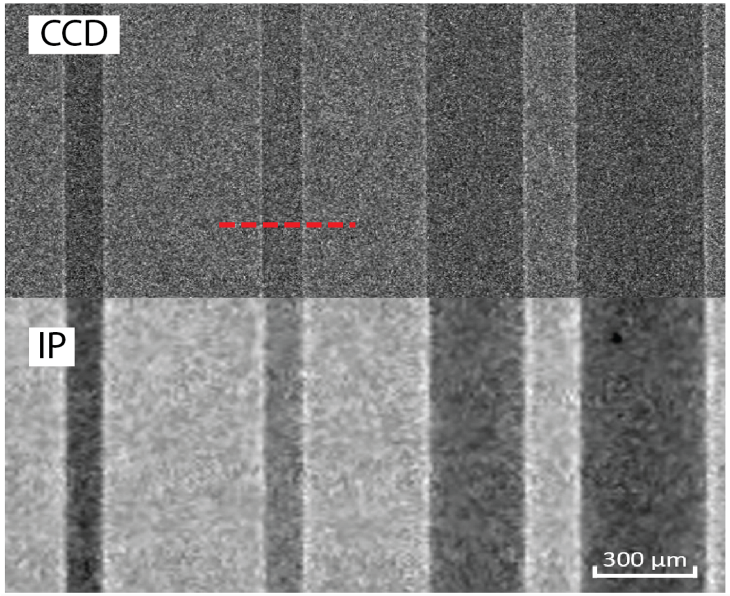
- XPCI is therefore very sensitive to the presence of strong gradients in the refraction index (i.e. in the density) as those produced by shock waves

- The typical feature of XPCI is the localized enhancement in the image contrast

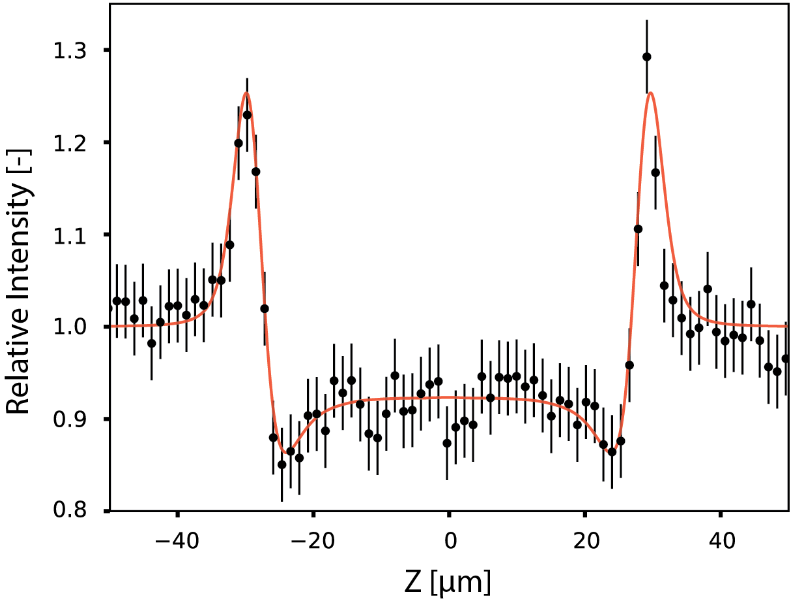


XPCI: Example with static target

We performed a first test using a static object, a nylon wire:



a)



b)

L. Antonelli, et al. «X-ray phase-contrast imaging for laser-induced shock waves» EPL, 125 (2019) 35002

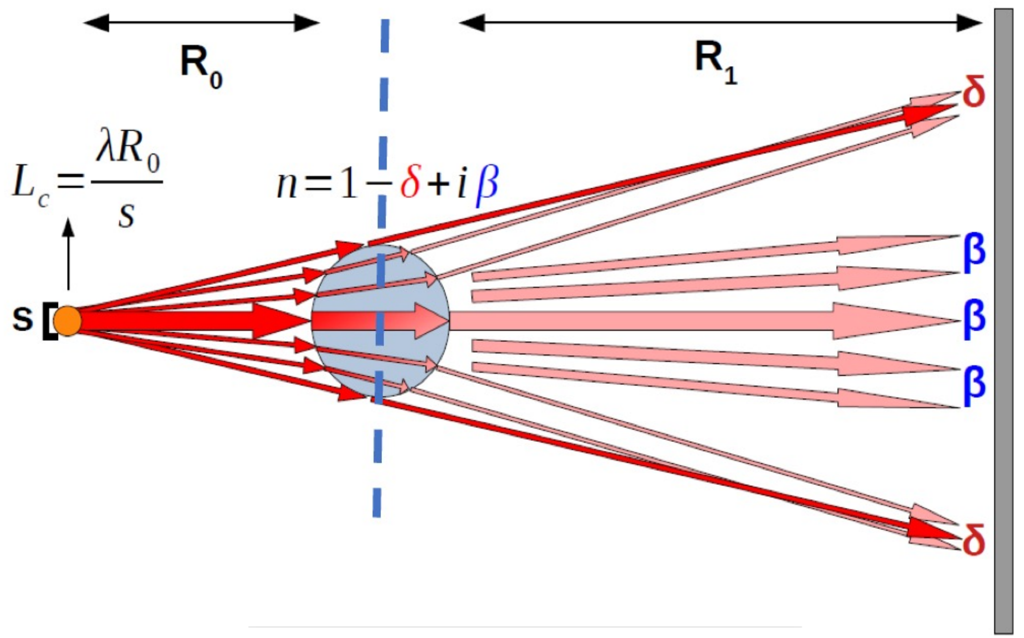
Good signal in a single shot.
Agreement between simulation and experimental data.

XPCI: importance of the coherence length

The recorded pattern on detector results from the superposition of waves coming from a «coherence area» defined as

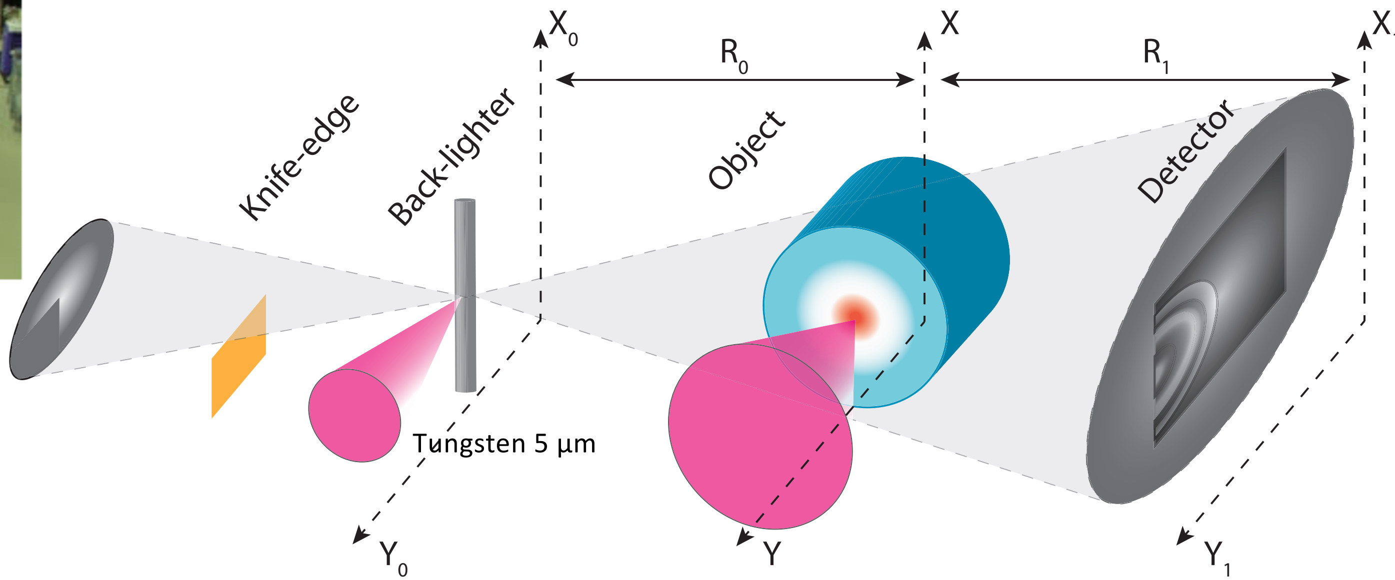
$$L_c = \frac{\lambda R_o}{s}$$

R_o is the source to sample distance, s the source size and λ the X-ray wavelength.
L_c has to be larger than the scale length of the structures to be resolved



Need small source size

Experiment at GSI (Phelix laser)



Short pulse:

- $\lambda[\mu m]$: 1
- E[J]: 25
- τ[ps]: 0.5
- $width[\mu]$: 5

Source:

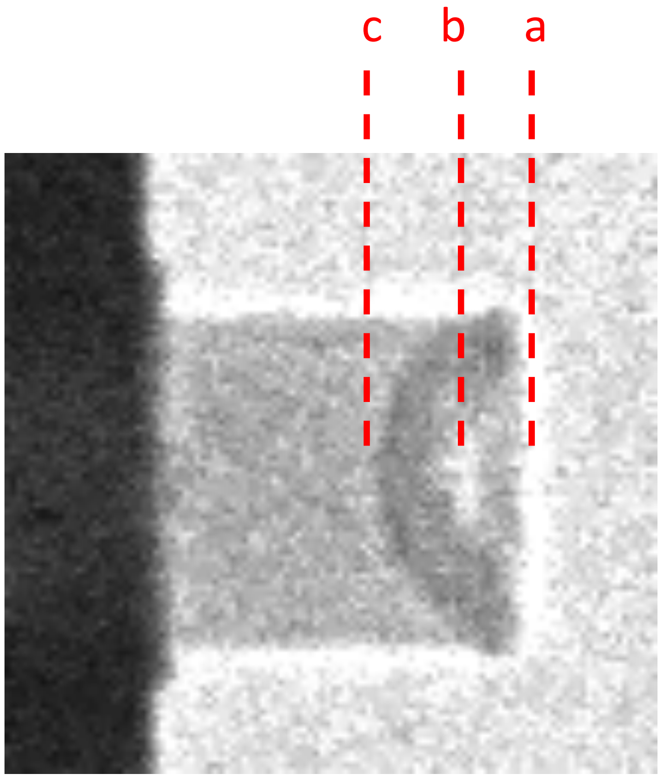
- R_0[cm]: 27
- R_1[cm]: 94
- $width_x[\mu m]$: 30
- $width_y[\mu m]$: 5

Long pulse:

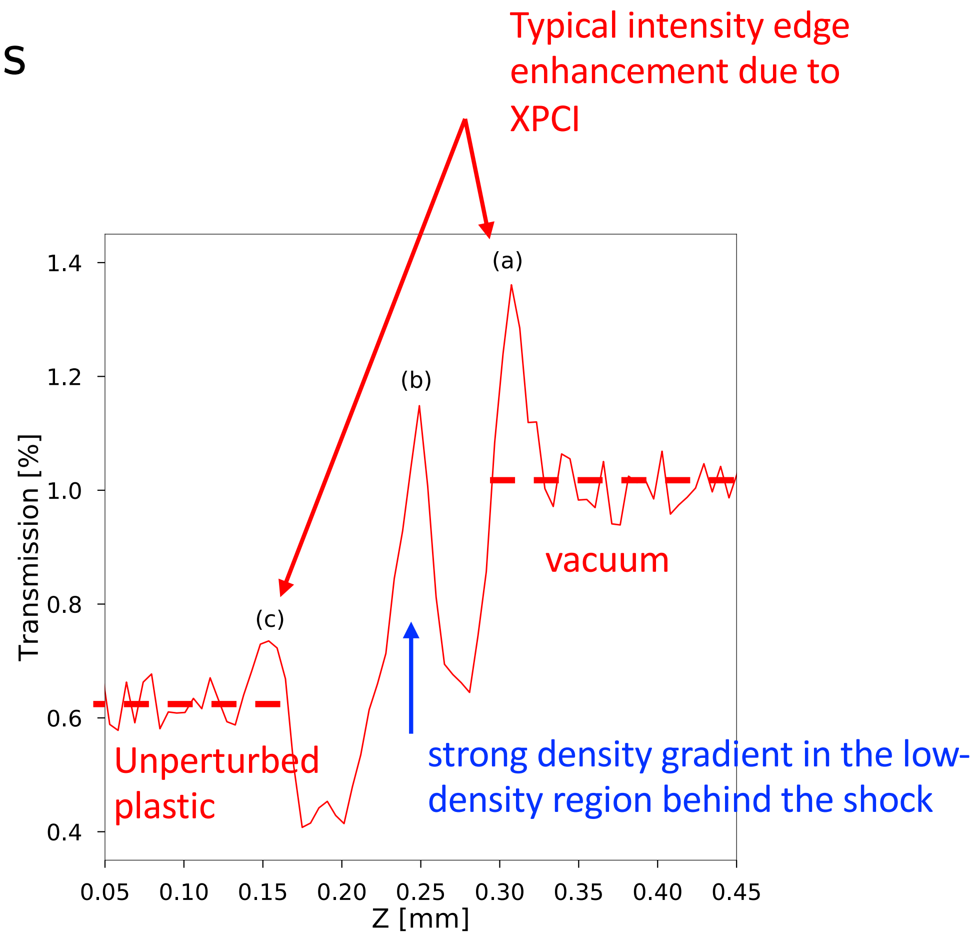
- $\lambda[\mu m]$: 1
- E[J]: 25
- τ[ps]: 2000
- $width[\mu]$: 50

Shock Wave propagation

Shock-wave generated at $5 \times 10^{14}\ Wcm^{-2}$
Delay between laser pulses 8 ns



Experimental image

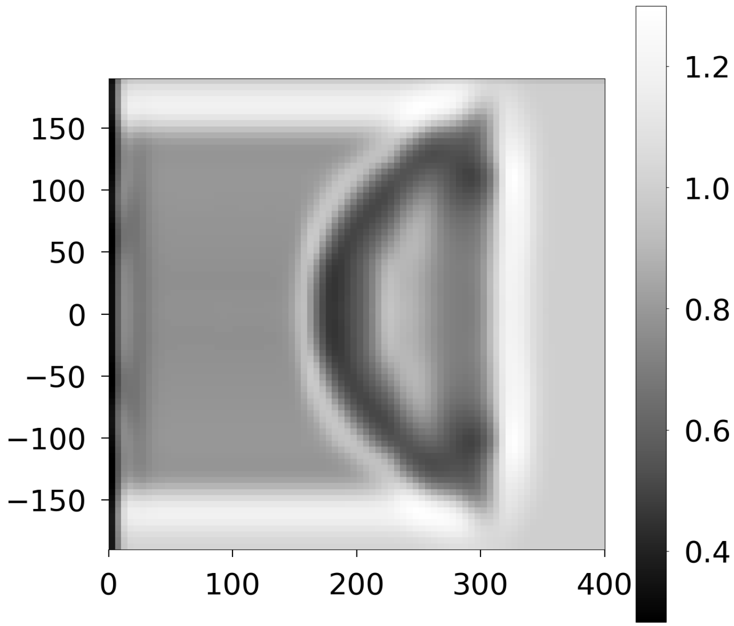


Experimental profile on axis

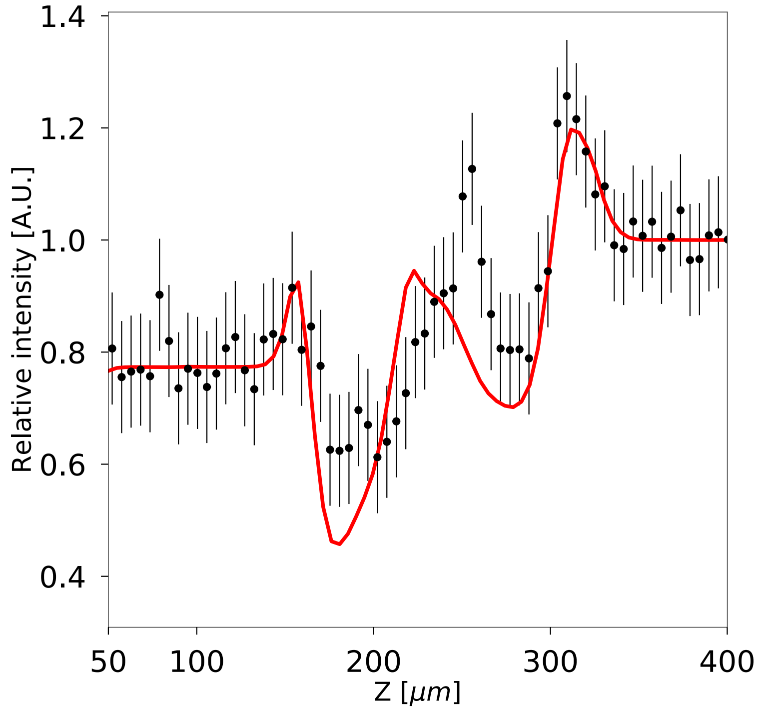
Shock Wave propagation

Comparison with hydro simulations (DUED)

S.ATZENI *Comput. Phys. Commun.* **43,** 107 (1986)



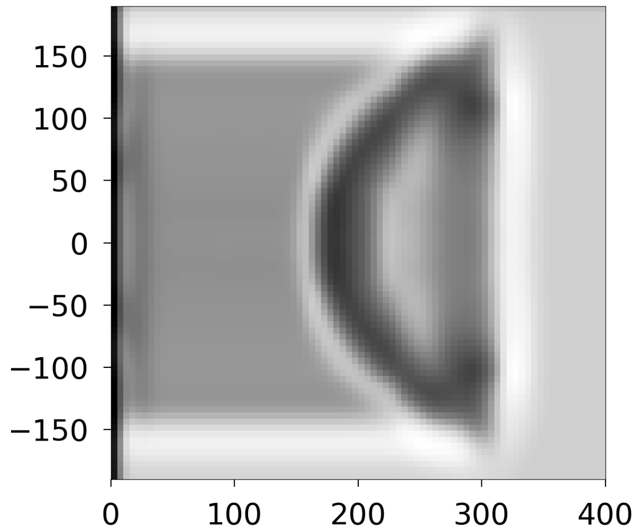
DUED simulation + phase-contrast module

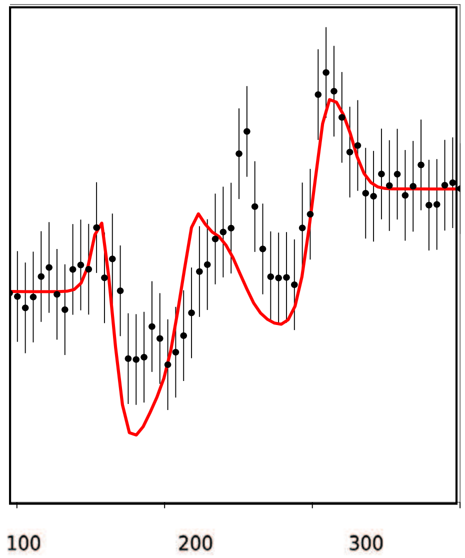


Experimental profile on axis (black dots) and numerical profile (red line)

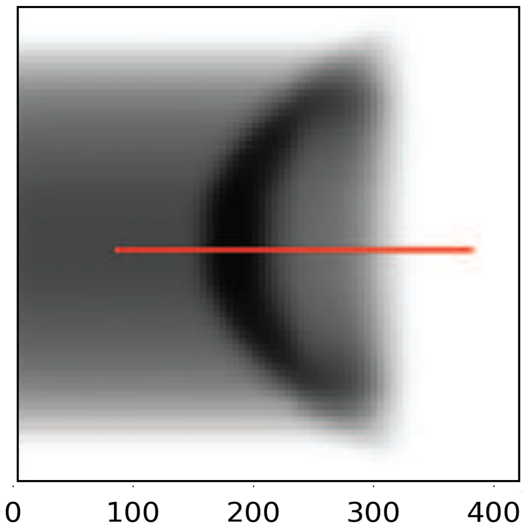
Simulation used reduced spot size to improve the agreement with experimental results

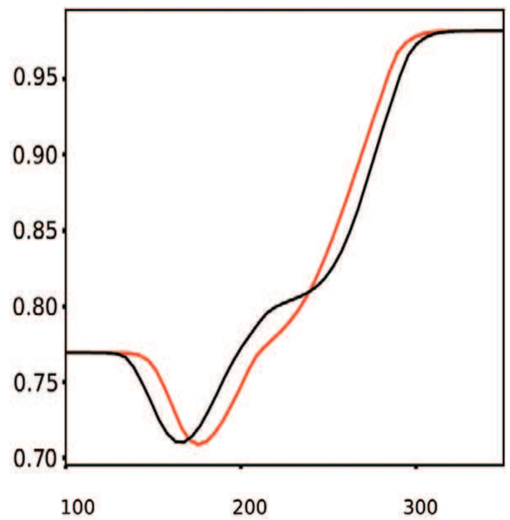
Do we get more information?





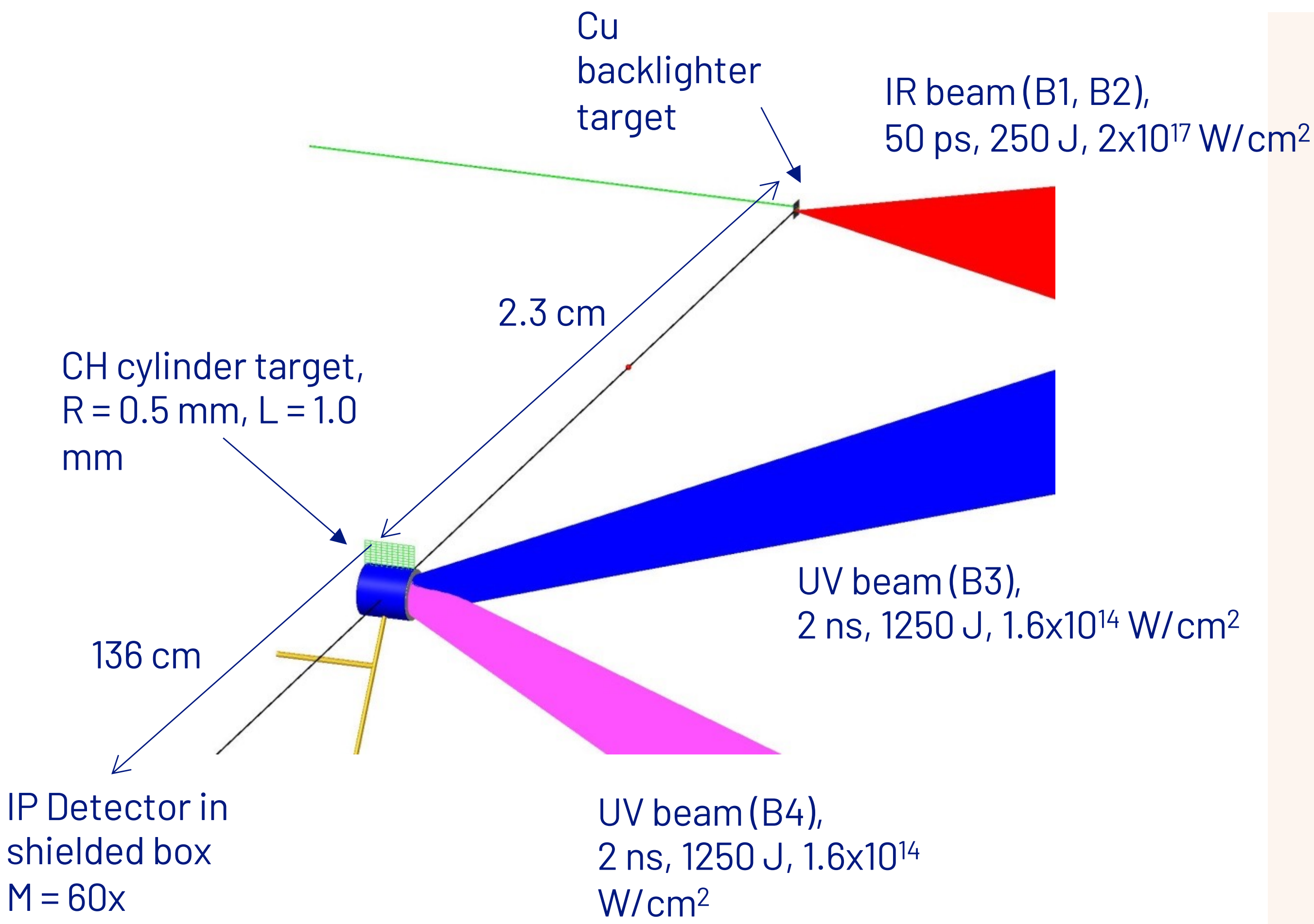
XPCI

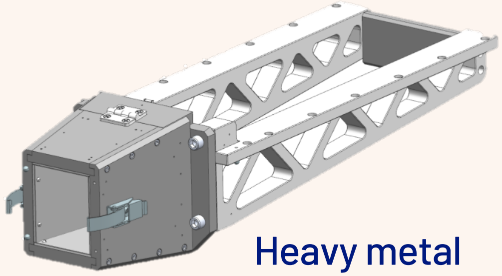




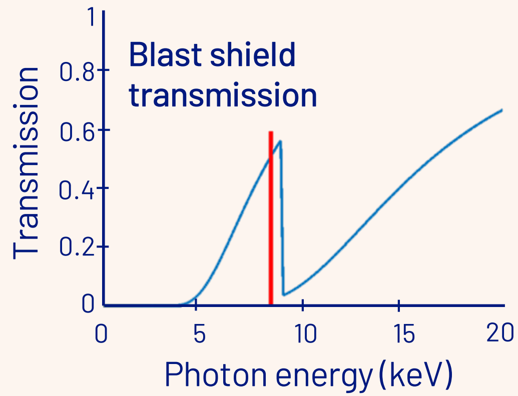
X-ray radiography

XPCI experiment at Omega

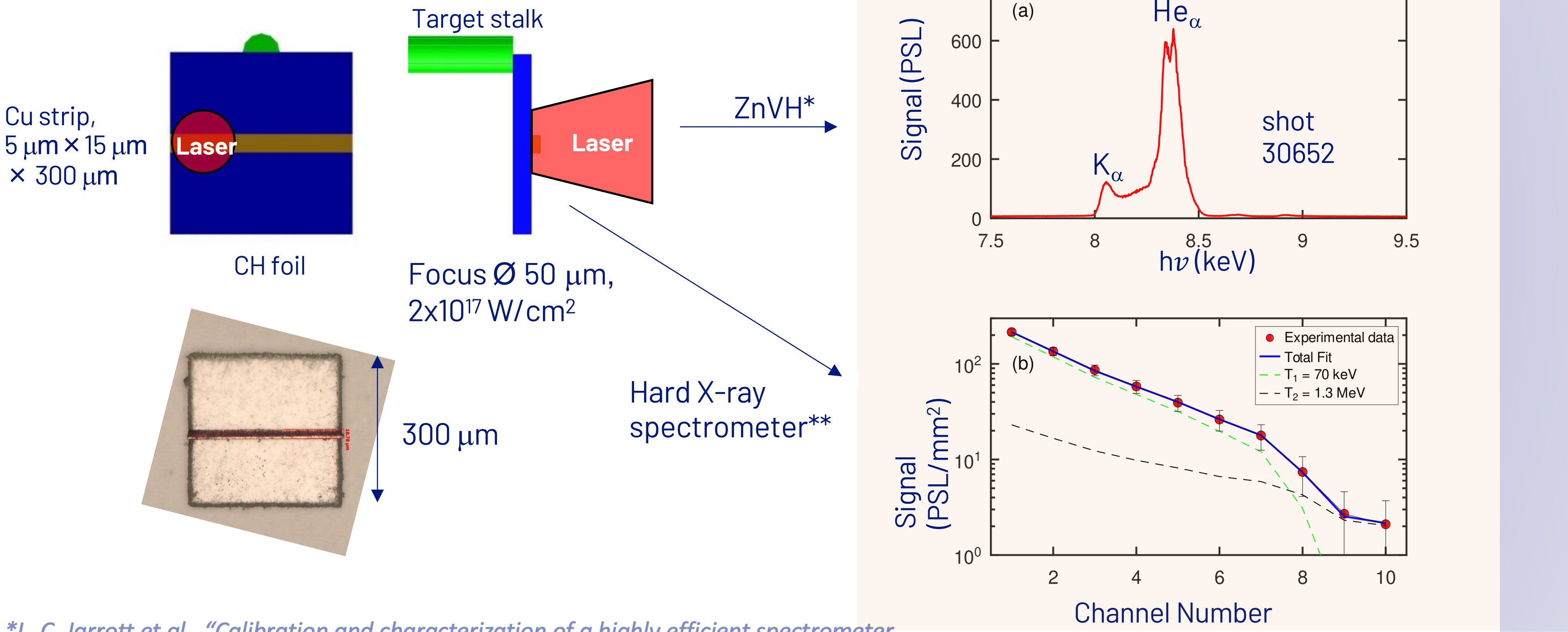




Heavy metal shielded box for IP detector

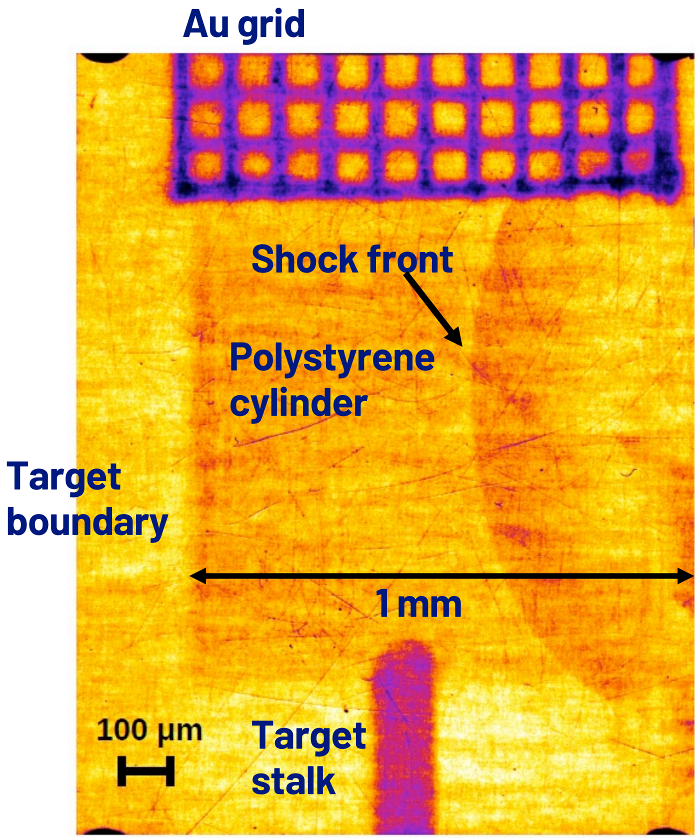


The backlighter beam focused on a thin Cu wire or a Cu strip onto a thin CH substrate



*L. C. Jarrott et al., "Calibration and characterization of a highly efficient spectrometer in von Hamos geometry for 7-10 keV x-rays," Rev. Sci. Instrum. 88, 043110 (2017)
** C. D. Chen, "A Bremsstrahlung spectrometer using k-edge and differential filters with image plate dosimeters,"Rev. Sci. Instrum. 79, 10E305 (2008).

Phase contrast imaging reveals the position of the shock front and its curvature



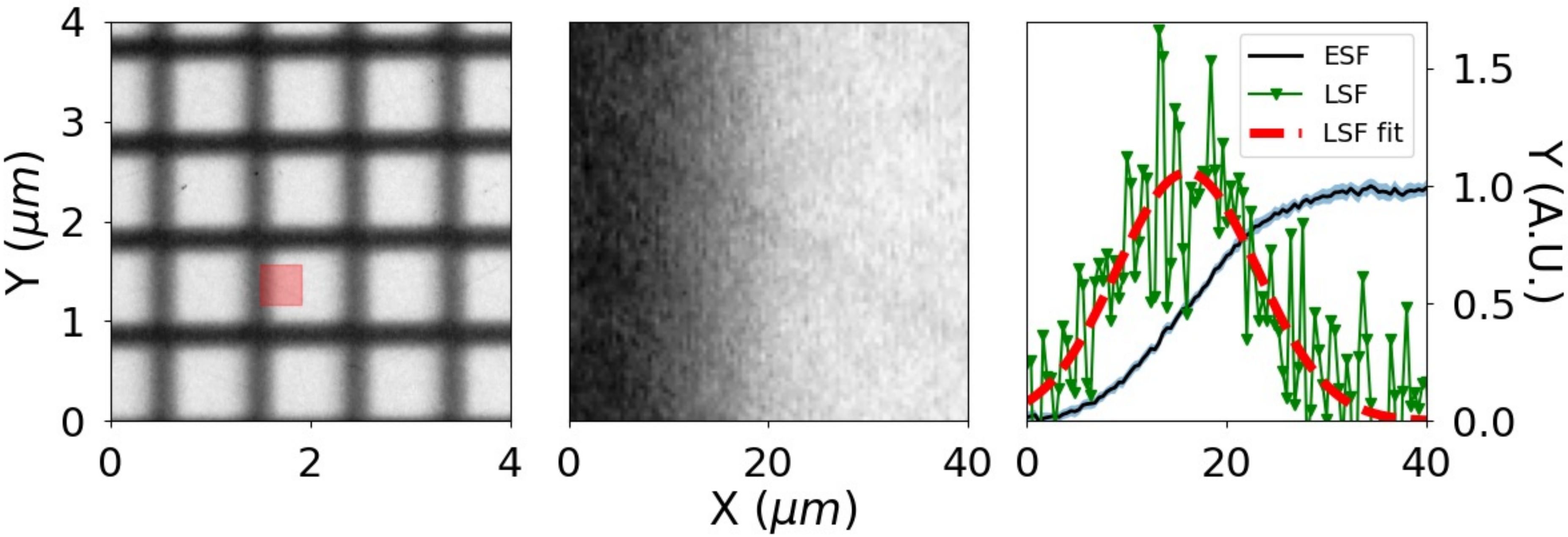
Shot 30658

$I = 1.6 \times 10^{14}$ W/cm^2

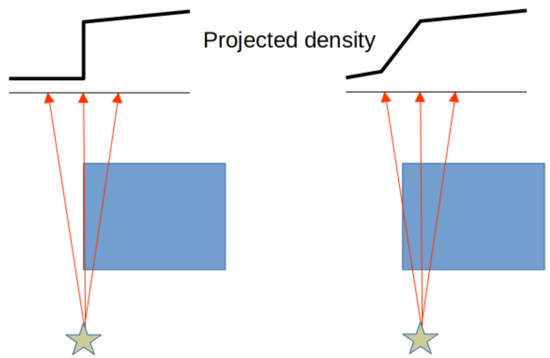
$\Delta t_{back} = 10.0$ ns, $\langle v_{shock} \rangle = 40 \pm 4$ μm/ns

Probing the plasma at higher photon energies helps to mitigate the strong x-ray self-emission produced by the drive beams

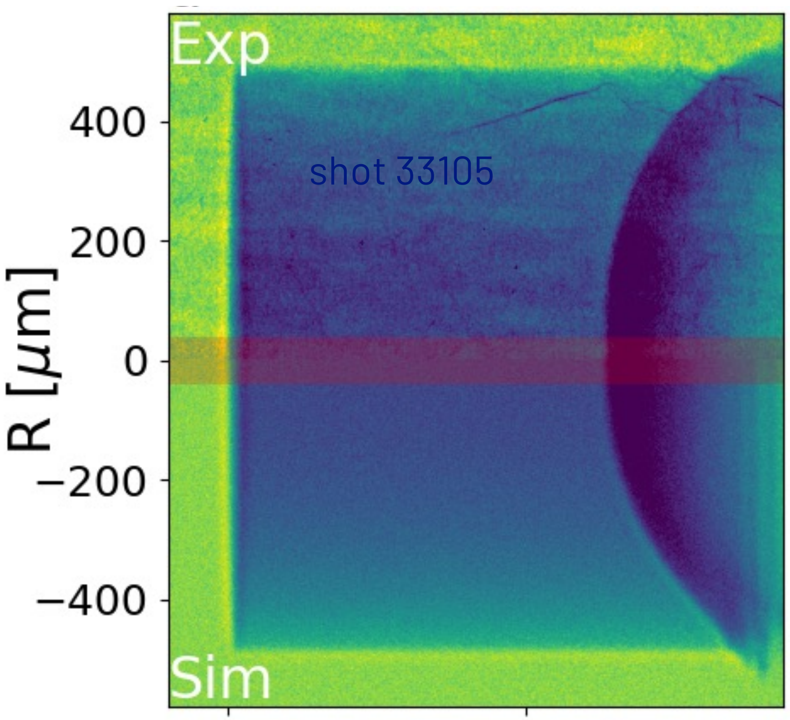
A spatial resolution of 15 µm was measured using a static Au grid target

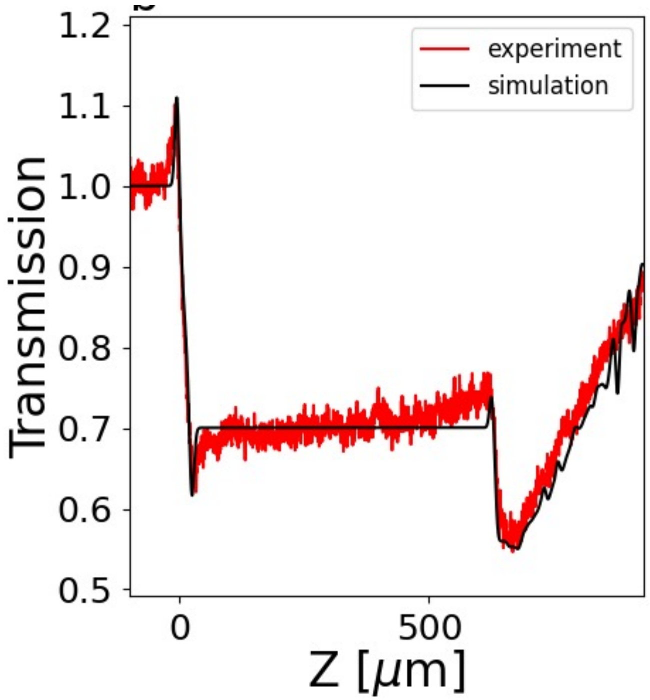


No evidence of edge enhancement in grid image:
- Too high absorption in the grid (killing phase contrast effect)
- Misalignment between source and grid producing an "longer" projected gradient



DUED simulations + Phase Contrast module

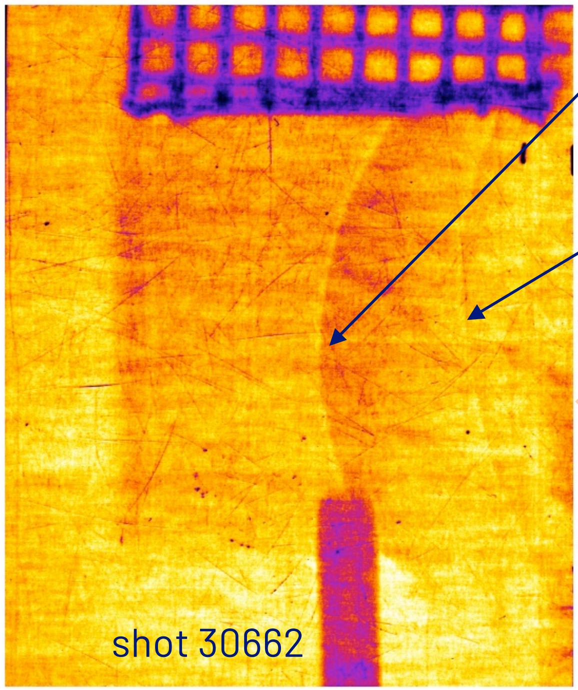




UV beam (B4), 2 ns, 495 J, 6x10^{13} W/cm^2
Δt_{probe} = 15 ns, $\langle v_{shock} \rangle$ = 25 ± 2 μm/ns

The image quality was significantly improved by using a fresh image plate detector and by reducing the drive laser intensity

XPCI imaging of double shocks



1st shock
36 ± 2 μm/ns

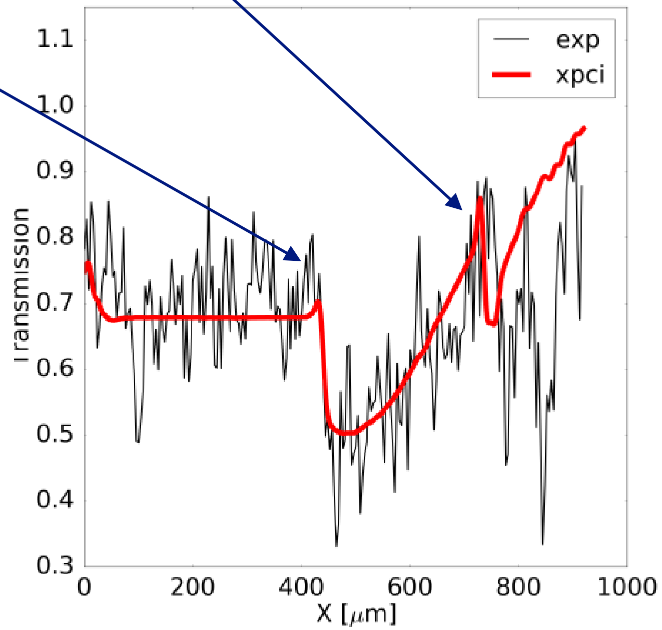
2nd shock
77 ± 12 μm/ns

1.6 × 10^{14} W/cm^2

1.6 × 10^{14} W/cm^2

Δt_{driver} = 12.0 ns

Δt_{back} = 15.0 ns

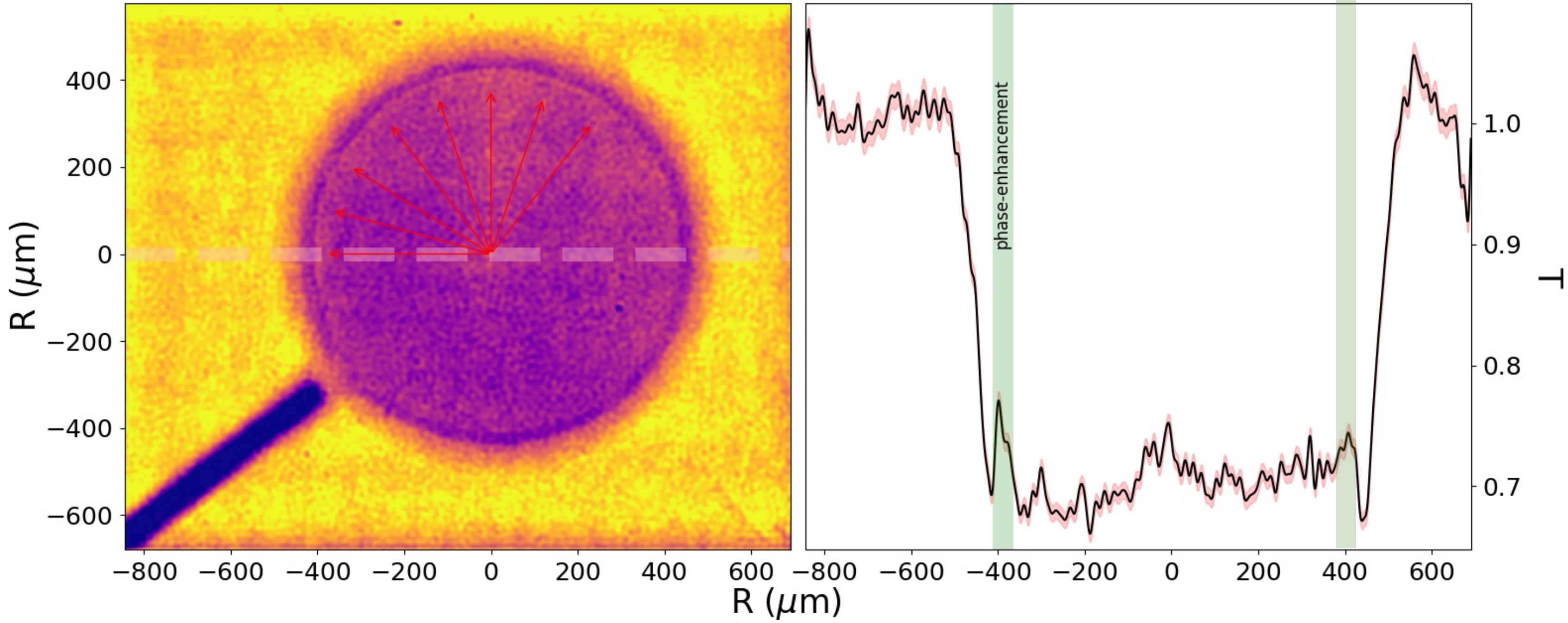


- Contrast for the second shock is a factor of 3x higher with phase-enhancement (21% of source intensity) compared to absorption only radiography (only 7%)
- This might open the possibility to use XPCI for shock-timing measurements in ICF – especially relevant for the shock ignition approach

Omega – preliminary test for imaging spherical implosions

Radiographs on IP indicate some phase contrast enhancement of the imploding shock wave

Driven CH solid sphere, 1 mm dia.



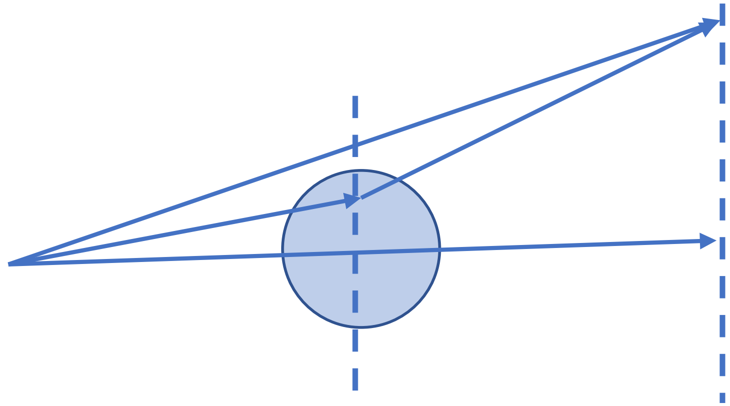
UV drive: 640 J, 2×10^{13} W/cm^2

Courtesy W. Theobald

How to obtain XPCI synthetic images?

Many codes but usually not adapted for HED applications and not interfaceable with hydro codes

Two approaches:



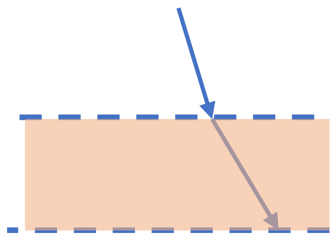
- **Ray tracing (geometrical optics)**

  A.Kar, T.R.Boehly, P.B.Radha, D.H.Edgell, S.X.Hu, P.M.Nilson, A.Shvydky, W.Theobald, D.Cao, K.S.Anderson, V.N.Goncharov, and S.P.Regan, "Simulated refraction-enhanced X-ray radiography of laser-driven shocks" Phys. Plasmas 26, 032705 (2019)

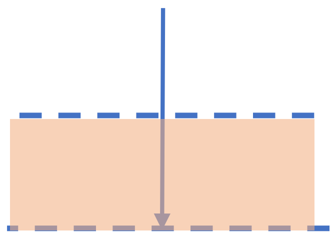
- **Wave optics (code *PhaseX*)**

  F.Barbato, S.Atzeni, D.Batani, and L.Antonelli, Optics Express 30, 3388–3403 (2022).

  Computationally heavier but more precise



Phase change and deviation



No deviation but still there is a phase change

How to obtain XPCI synthetic images?

- **Wave optics (code *PhaseX*)**

F.Barbato, S.Atzeni, D.Batani, and L.Antonelli, Optics Express 30, 3388–3403 (2022).

First the field transmitted to the sample is calculated as

$$E = A\exp(-\Delta\varphi)\,E_0$$

$$A = exp\int -k\beta(r,\lambda)d\vec{r}$$

$$\Delta\varphi = \int -k\delta(r,\lambda)d\vec{r}$$

Then the field is propagated in vacuum to the detector using the Fresnel approximation

$$E(x,y,z) = \frac{e^{ikz}}{i\lambda z}\iint_{-\infty}^{+\infty} E(x',y',0)e^{\frac{ik}{2z}\left[(x-x')^2+(y-y')^2\right]}\,dx'dy'.$$

Issue: describing the refraction index of the plasma

Conclusions

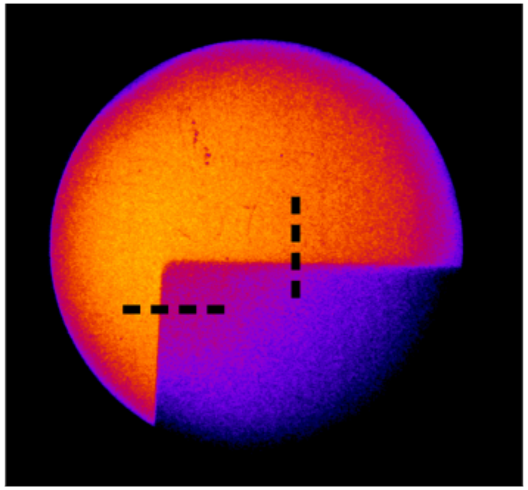
1) X-Ray Phase-Contrast Imaging (XCPI) is an extremely important diagnostic for HED physics

Images of double shocks have not been obtained before (previous attempt at Gekko using absorption X-ray radiography in the framework of "Shock ignition")

2) XPCI experiments on LMJ using PETAL as a backlighter source appear to be feasible

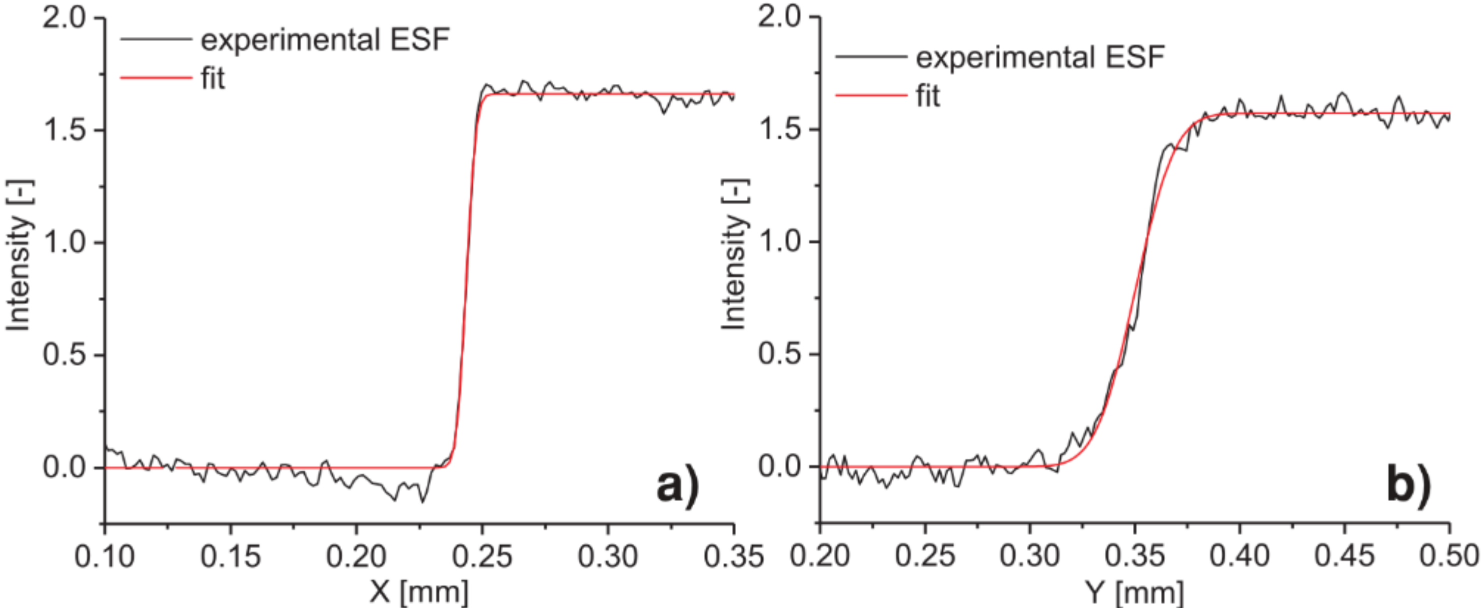
Thank you !!

X-ray source characterization



Source characteristics:

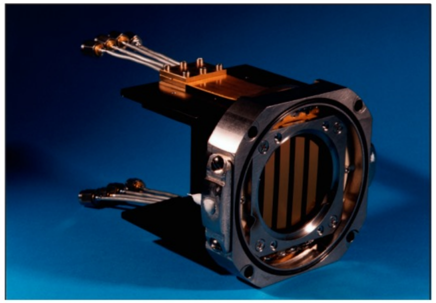
- Backlighter: Tungsten
- Horizontal dimension: 5 µm
- Vertical dimension: 30 µm
- Bremsstrahlung emission until 15 keV
- L-shell emission between 8 and 9 keV

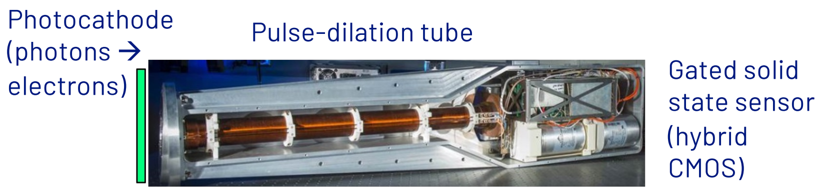


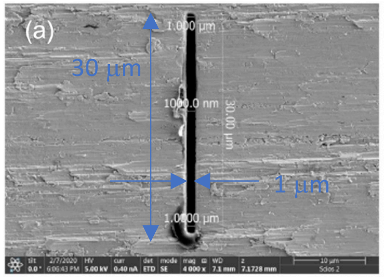
Further improvements of the technique are required

Mitigate radiation background in kJ facilities by replacing the time-integrating detector with a time-gated detector.

- x-ray framing cameras
- Nanosecond-gated burst-mode hybrid CMOS imaging senso
- pulse dilation tube imagers







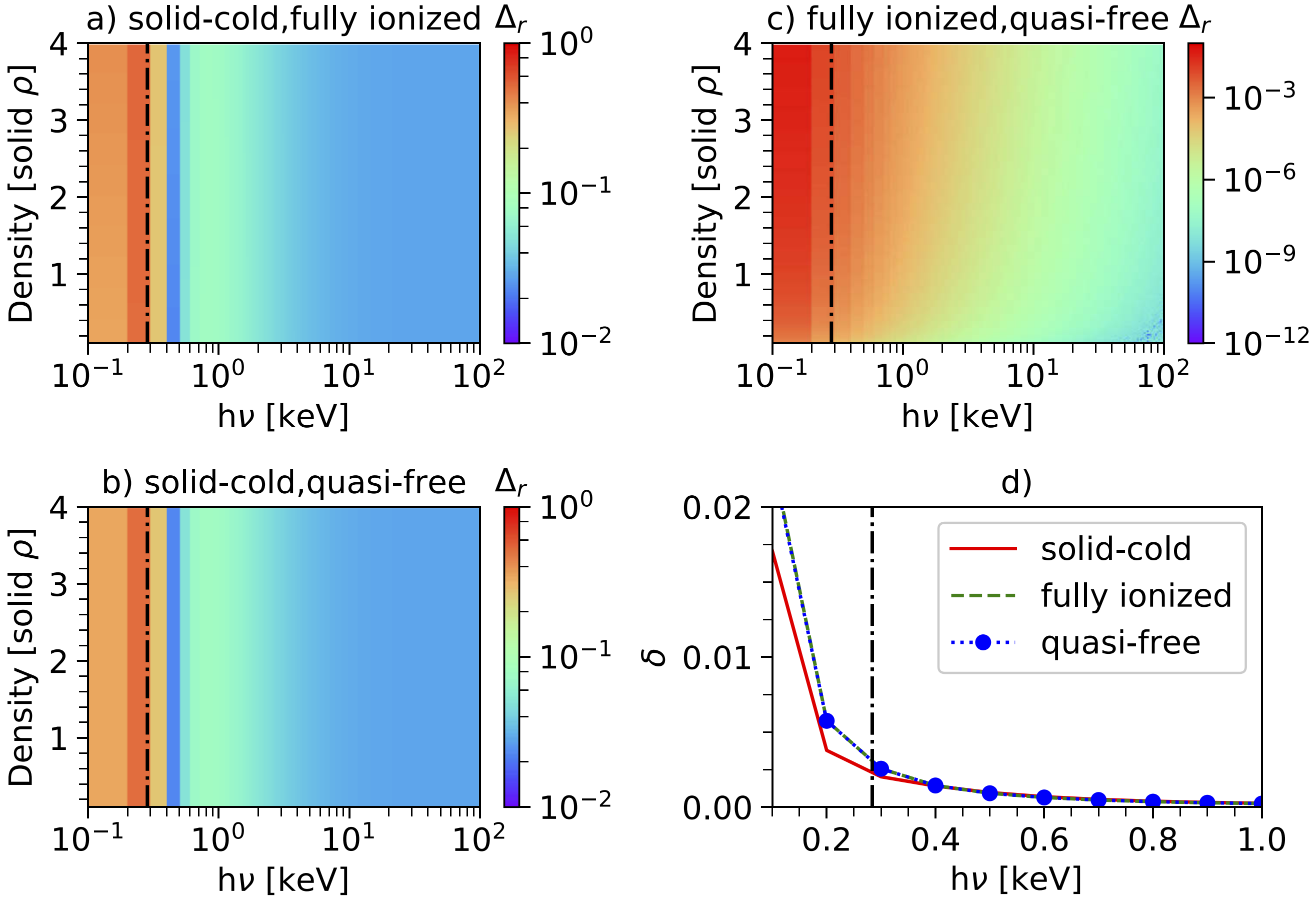
Reduce backlighter source size for better spatial resolution

- Thinner Cu strips
- Placing Cu foil behind a micron-wide pinhole in Ta plate fabricated with a focused ion beam

An increase in useful signal intensity might be achieved by focusing the short-pulse beam to a line focus instead of a point focus

Courtesy W.Theobald

Issues related to refraction index



Comparison between models to calculate δ, test material polystyrene ρ = 1.05 g/cm^3. The color maps show the discrepancy Δ*r* = (δ1(*E*, ρ) − δ2(*E*, ρ))/δ1(*E*, ρ) between models as function of photon energy and mass density given in unit of the solid density. a) solid-cold vs. fully ionized, b) solid-cold vs. quasi-free, c) fully ionized vs. quasi-free; the vertical dot-dash line shows the carbon *K*-edge. d) zoom of δ(*E*) around the C *K*-edge at solid density.