Munich-Centre for Advanced Photonics

Quantitative X-Ray Phase-Contrast Microtomography from a Compact Laser Driven Betatron Source

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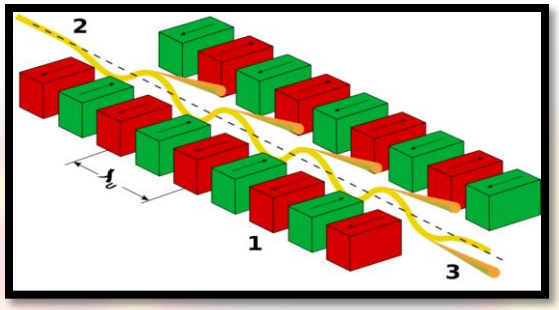
EAAC 2015, La Biodola, Isola d'Elba

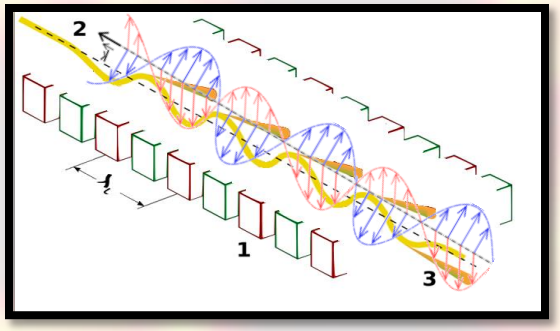
J. Wenz et al., Nature Comm. DOI:10.1038/ncomms8568 (2015

Sources of X-Ray Radiation from LWFA electrons

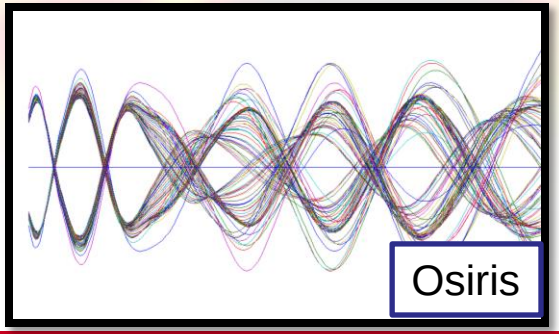


Based on electron oscillation due to

External magnetic field ➔ Undulator radiation



External laser field ➔ Thomson scattering



Internal EM fields ➔ Betatron radiation

Betatron Radiation

Electric Fields in the Plasma Wave

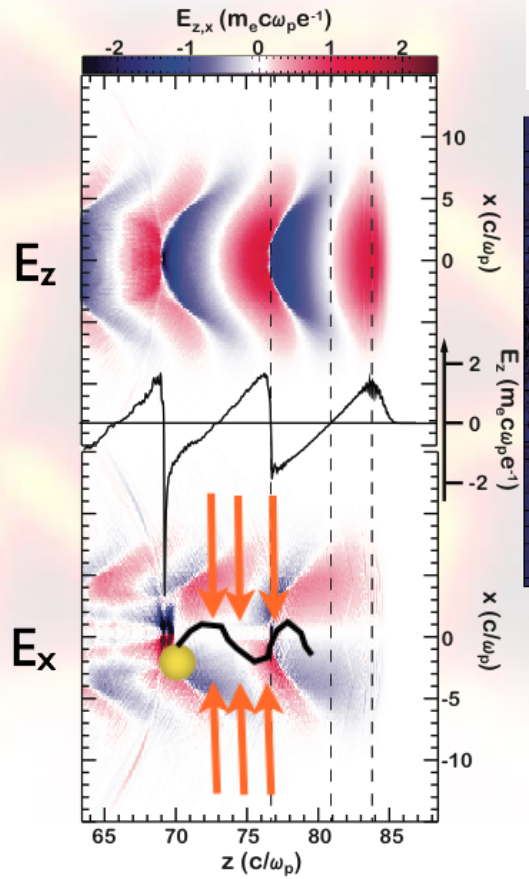
strong
transverse
focusing fields

\+ small source size

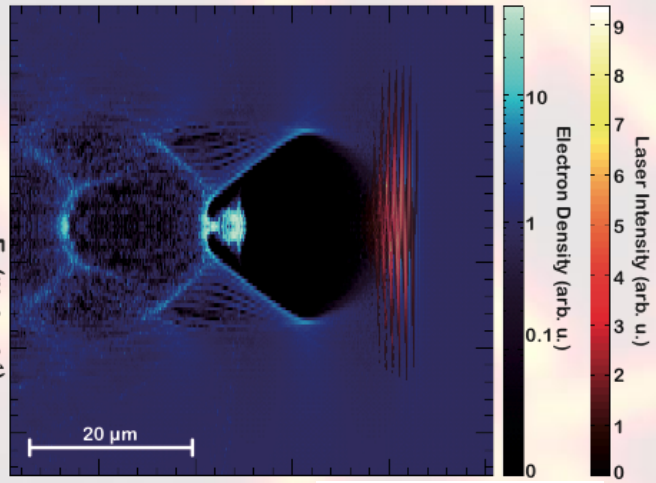
− increased divergence

BUT

Betatron Oscillation → X-ray radiation



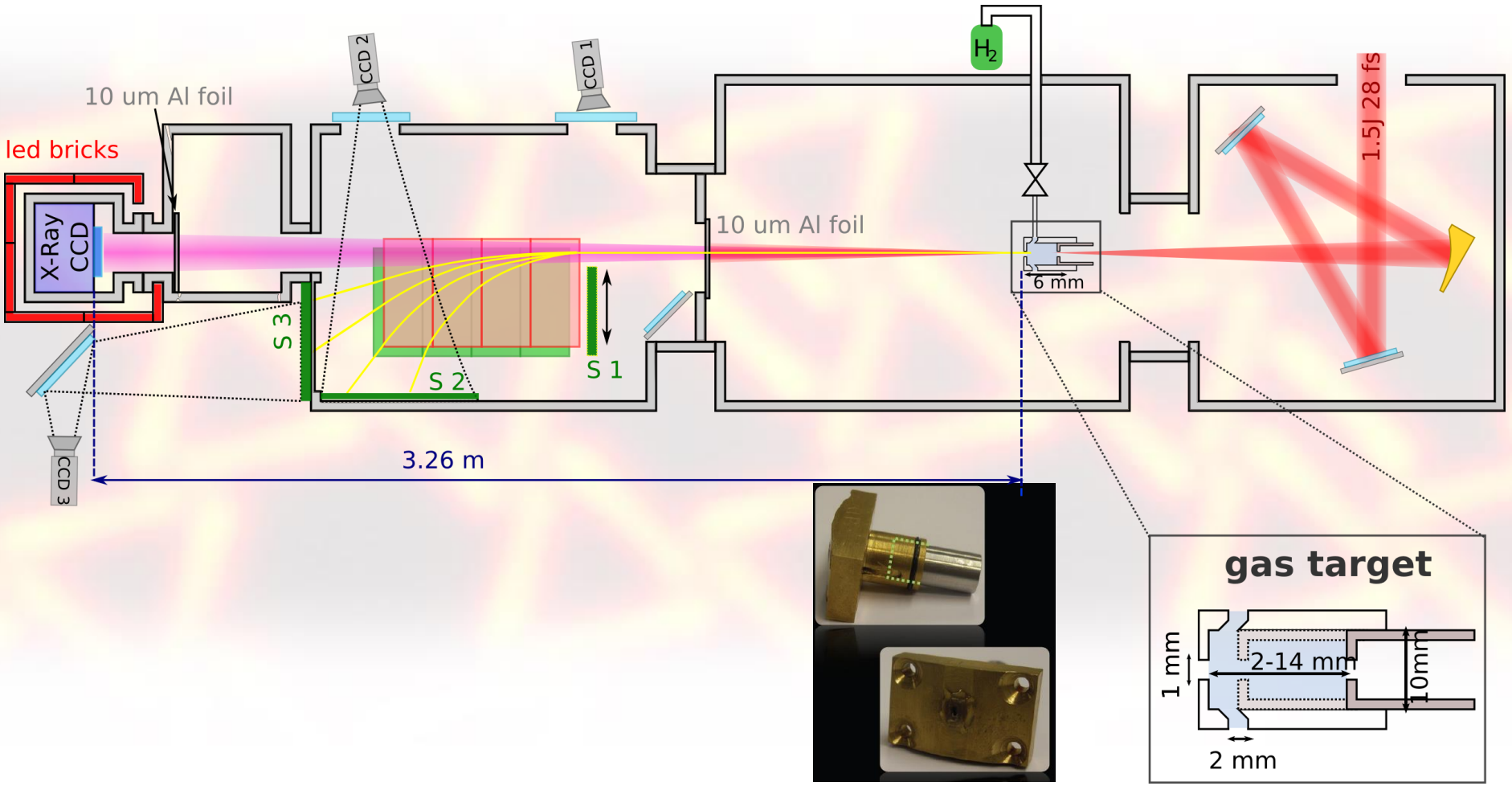
$$\lambda_\beta \approx \sqrt{2\gamma}\lambda_p \approx 300\ \mu m$$



$$K_\beta = \gamma r_\beta k_\beta$$

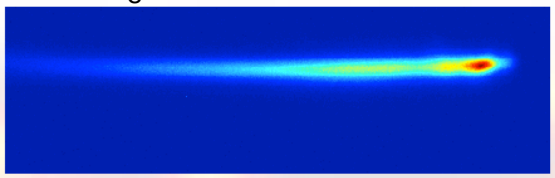
$$\lambda = \frac{\lambda_\beta}{n2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

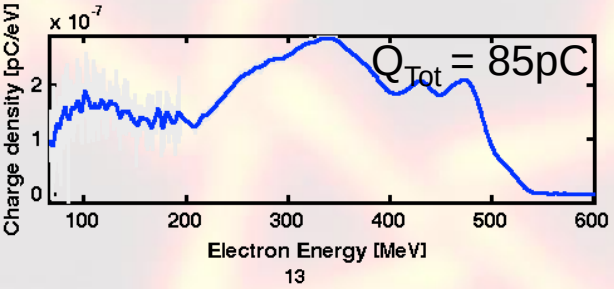
Experimental Setup

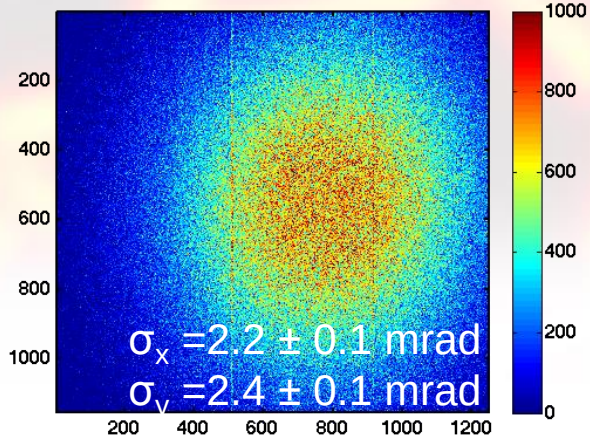


Betatron Beam Profile

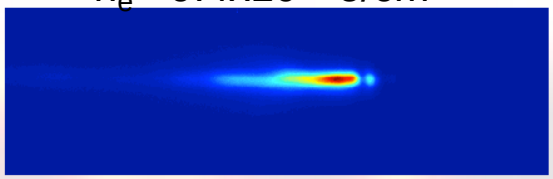
$n_e = 7.4 \times 10^{18}$ e/cm^3

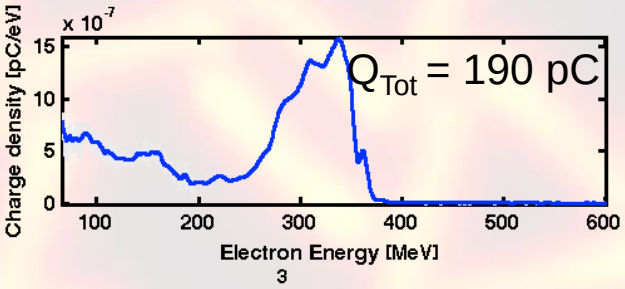


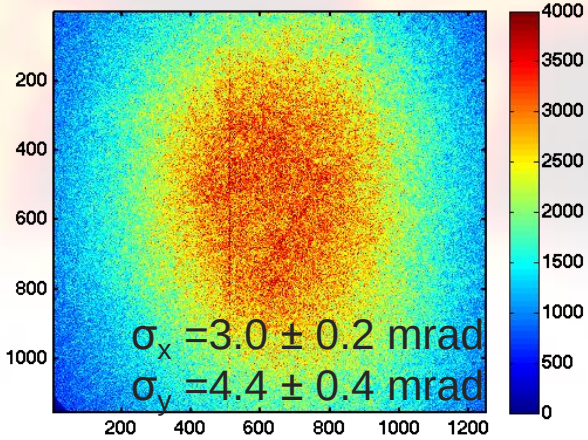




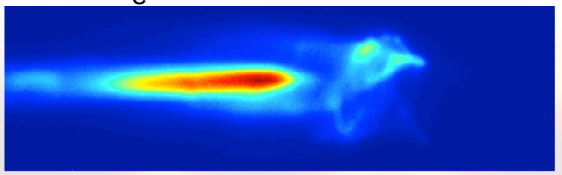
$n_e = 9.4 \times 10^{18}$ e/cm^3

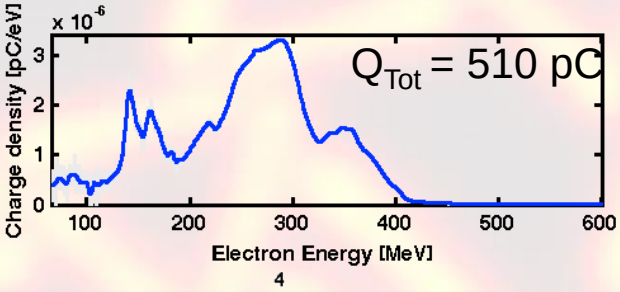


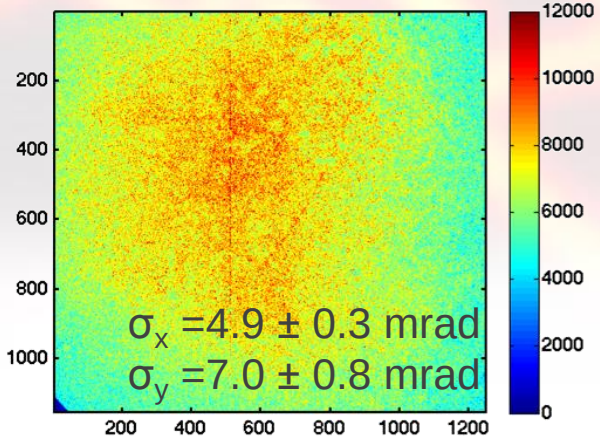




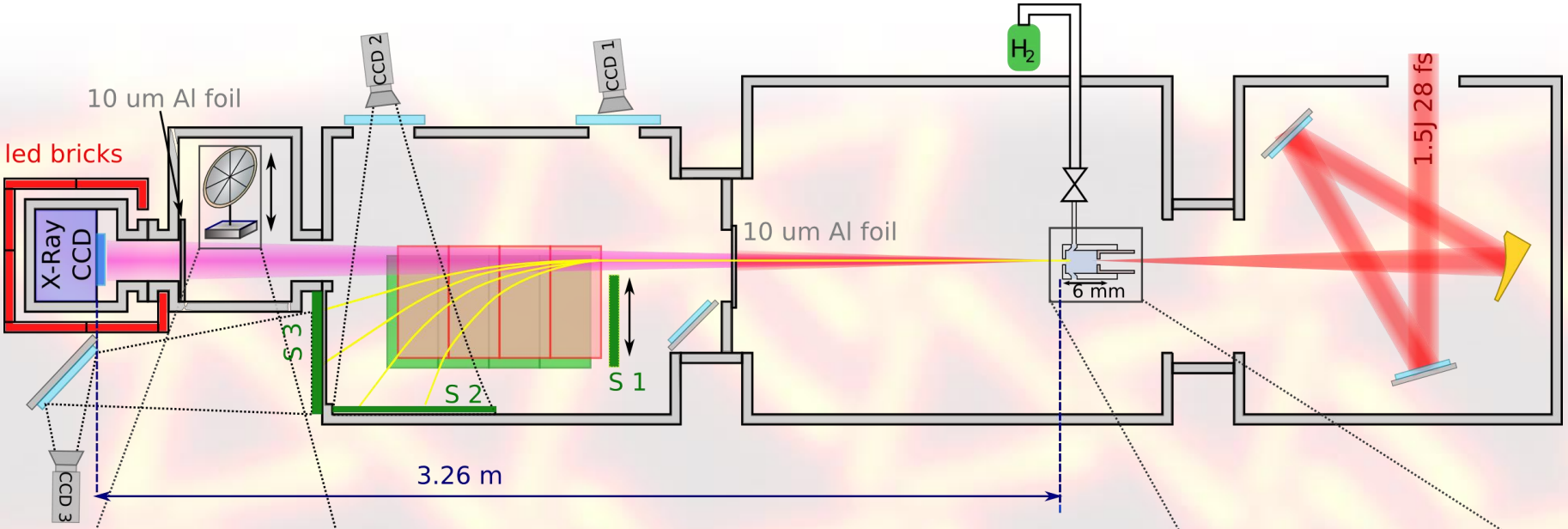
$n_e = 1.1 \times 10^{19}$ e/cm^3







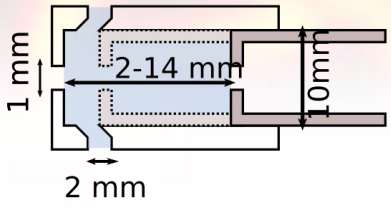
Single-Shot Characterization of the Betatron Spectrum



filter cake

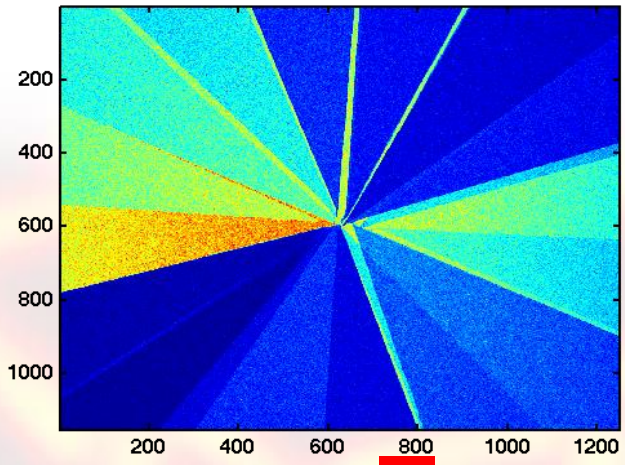
consisting of
Al pieces with thickness of 0-610 um

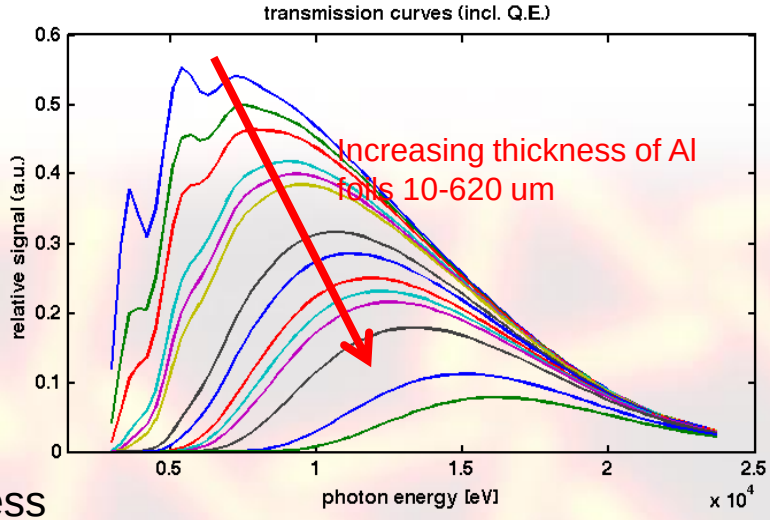
gas target



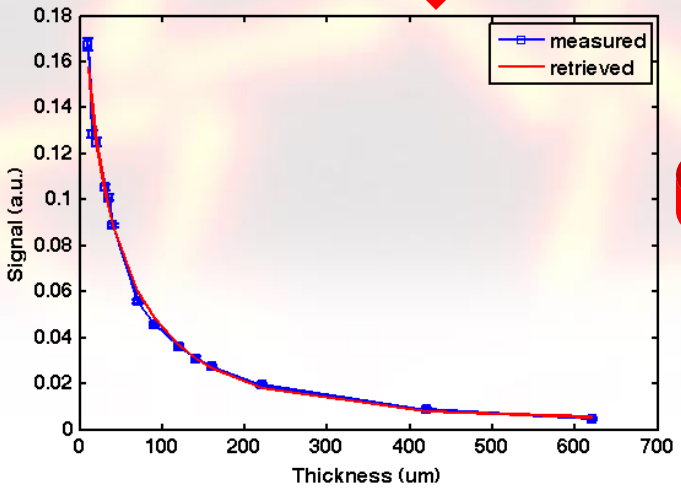
Sidky et al, J. Appl. Phys. 97, 124701 (2005)

Spectrum Reconstruction

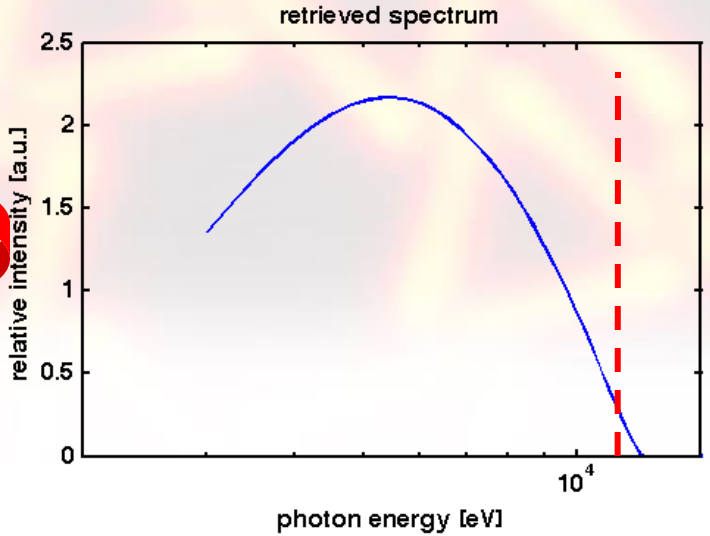




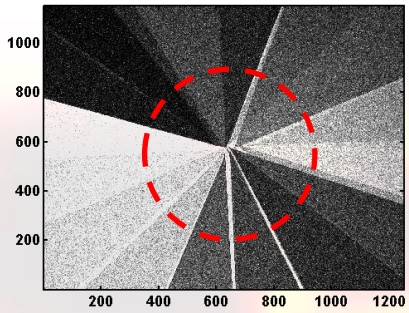
Different filter thickness
Different CCD counts

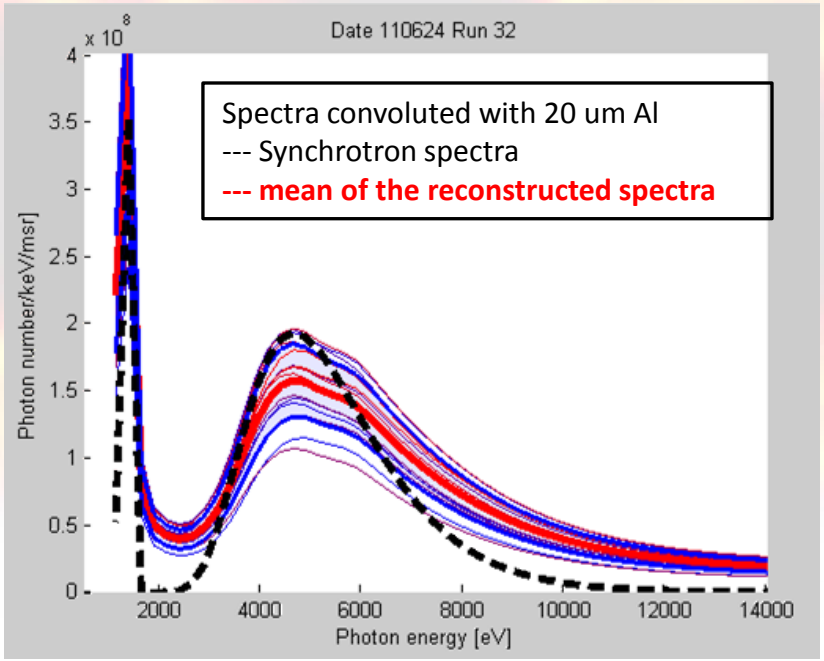


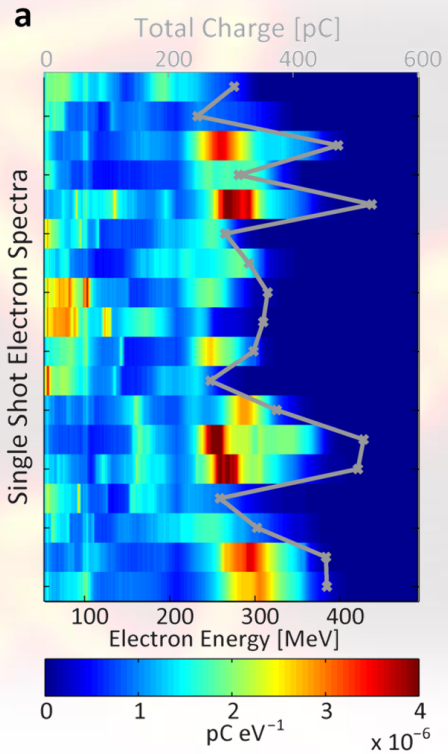
algorithm

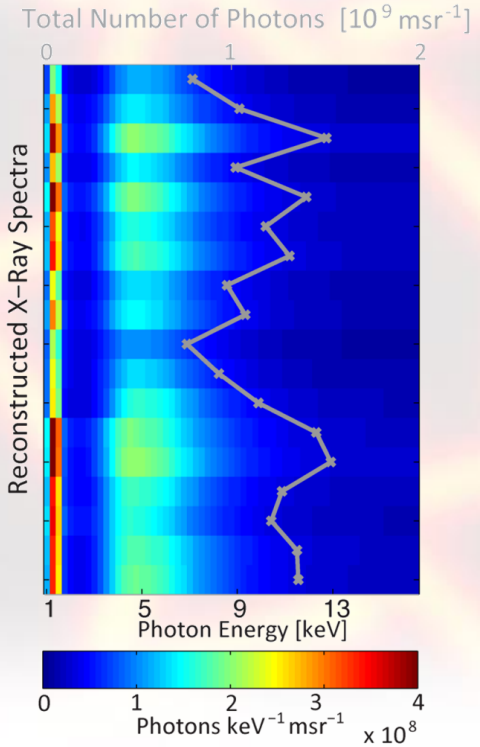


Reconstructed Betatron Spectrum

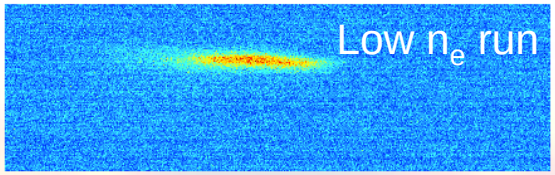


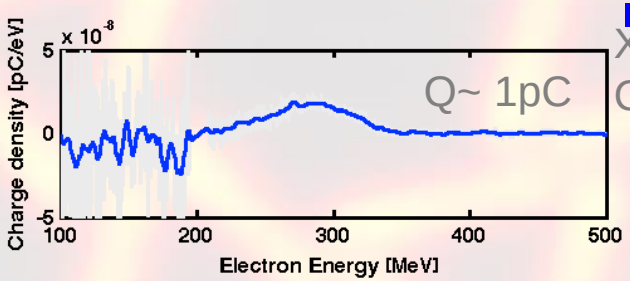




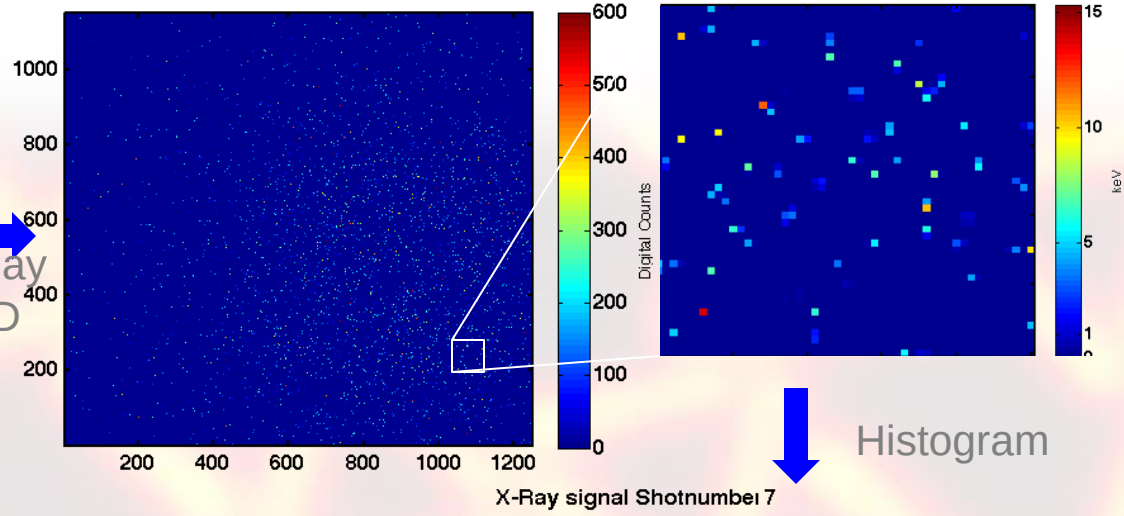


Single Pixel Counting–Method with low charge bunches

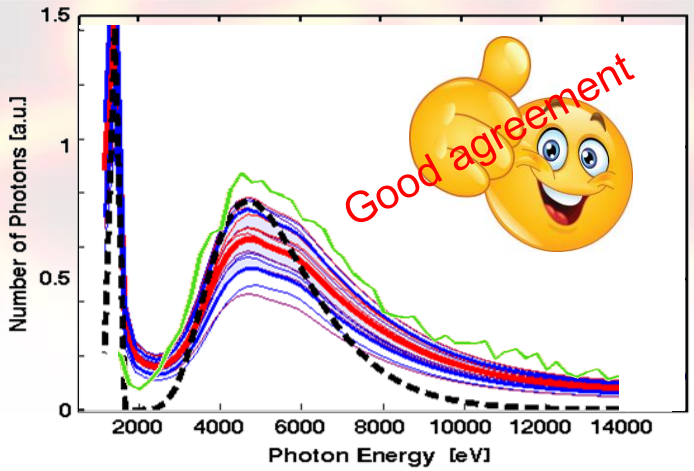




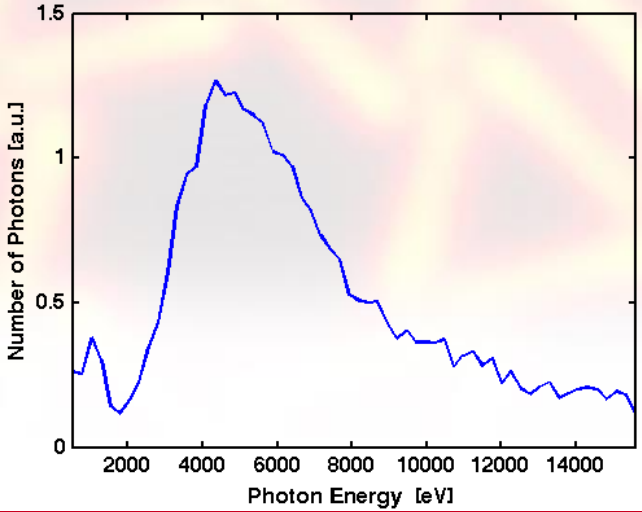
X-Ray CCD



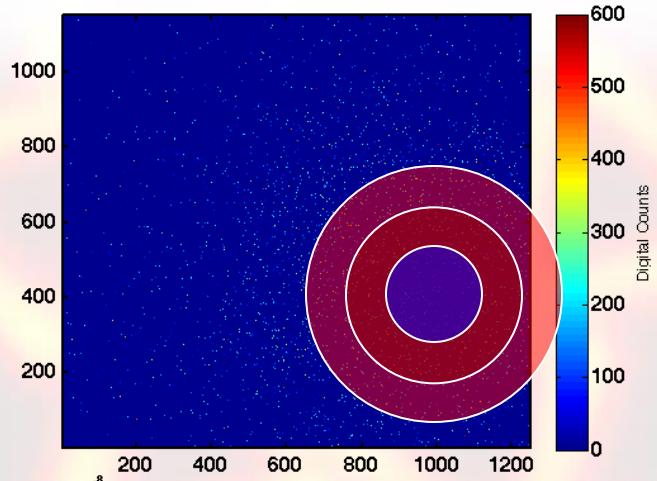
Histogram

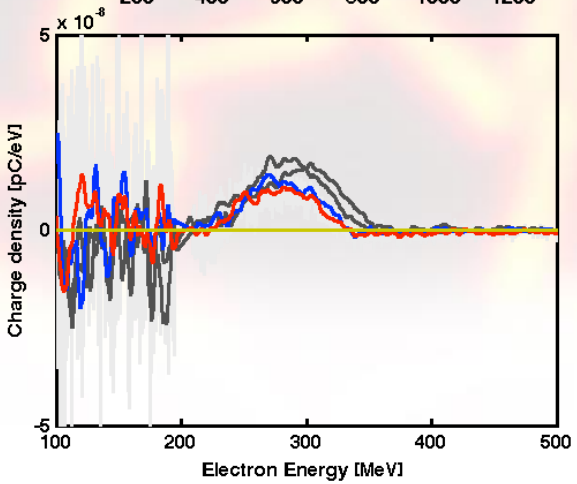


Comparison with Al-Cake



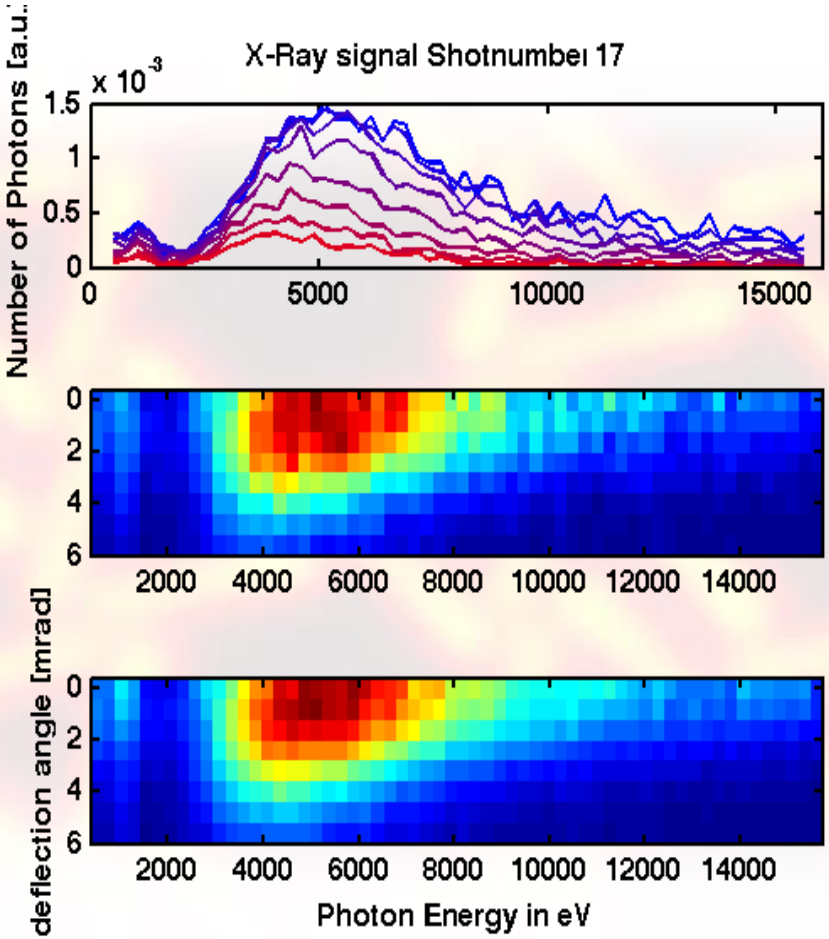
Angular resolved Photon Energies



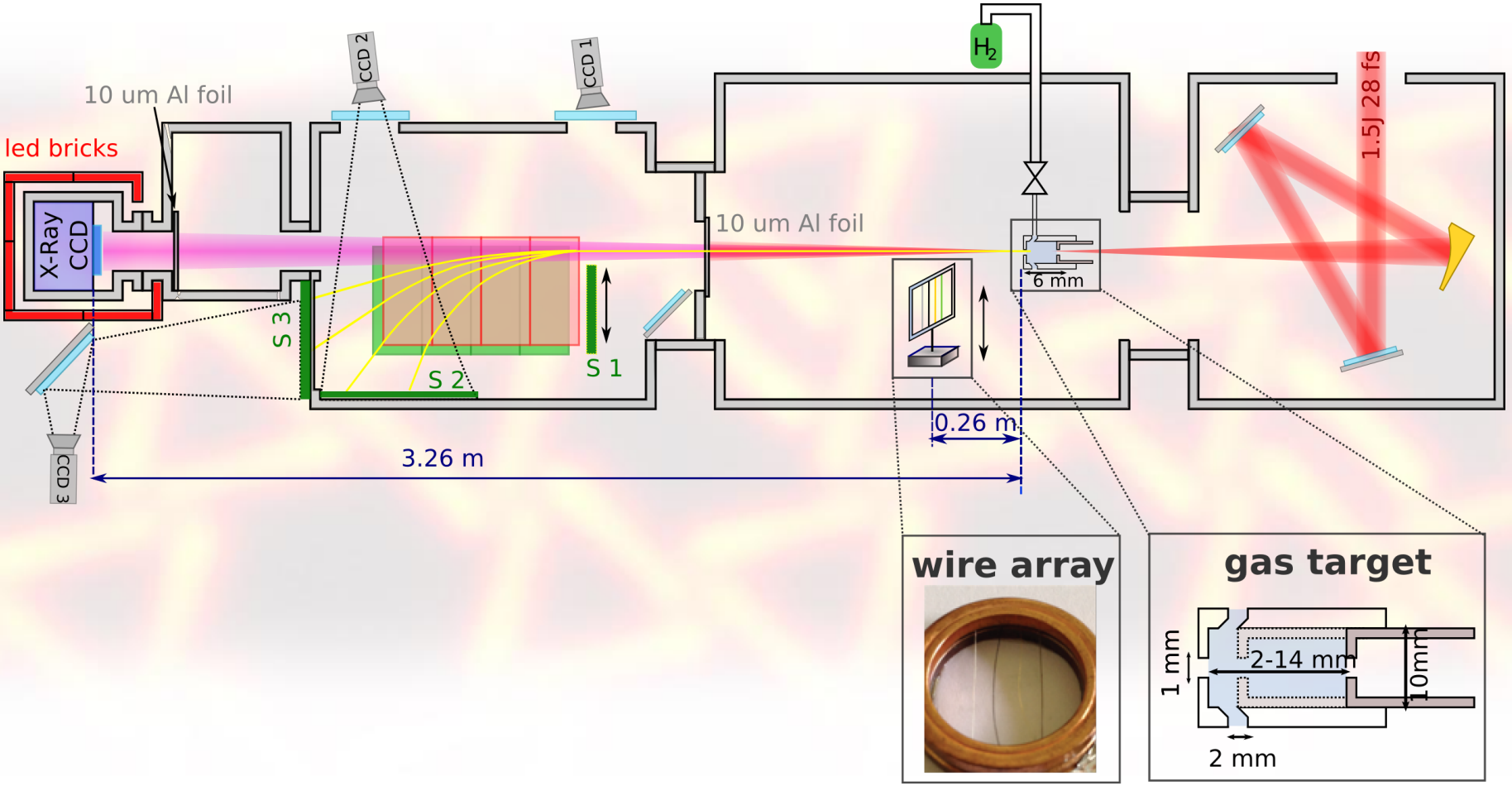


Single shot

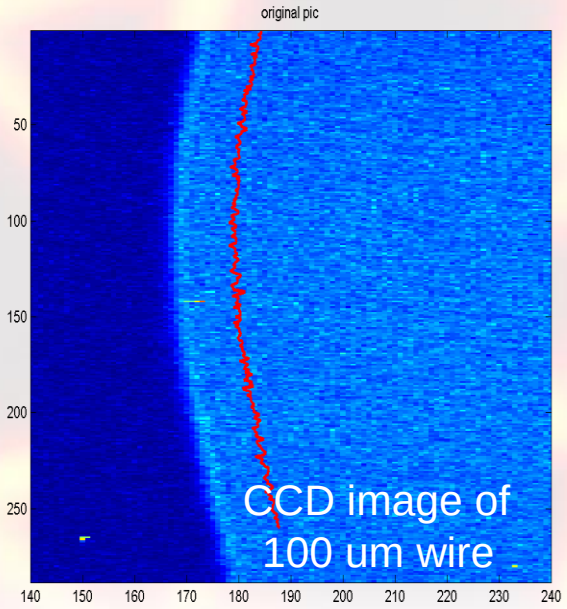
Average



Characterization of the Source Size

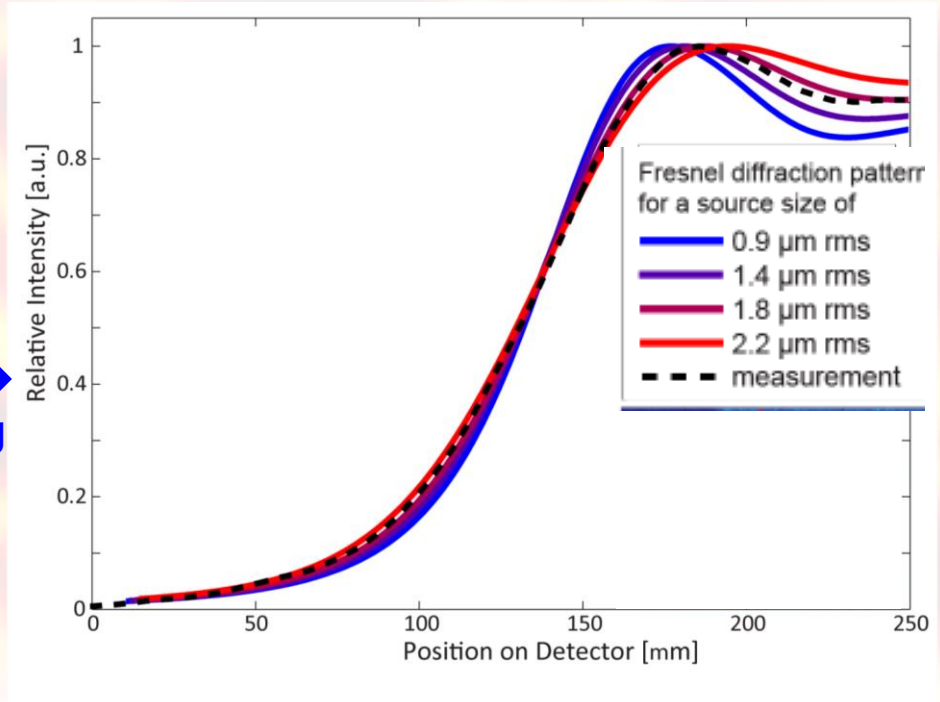


Source size reconstruction



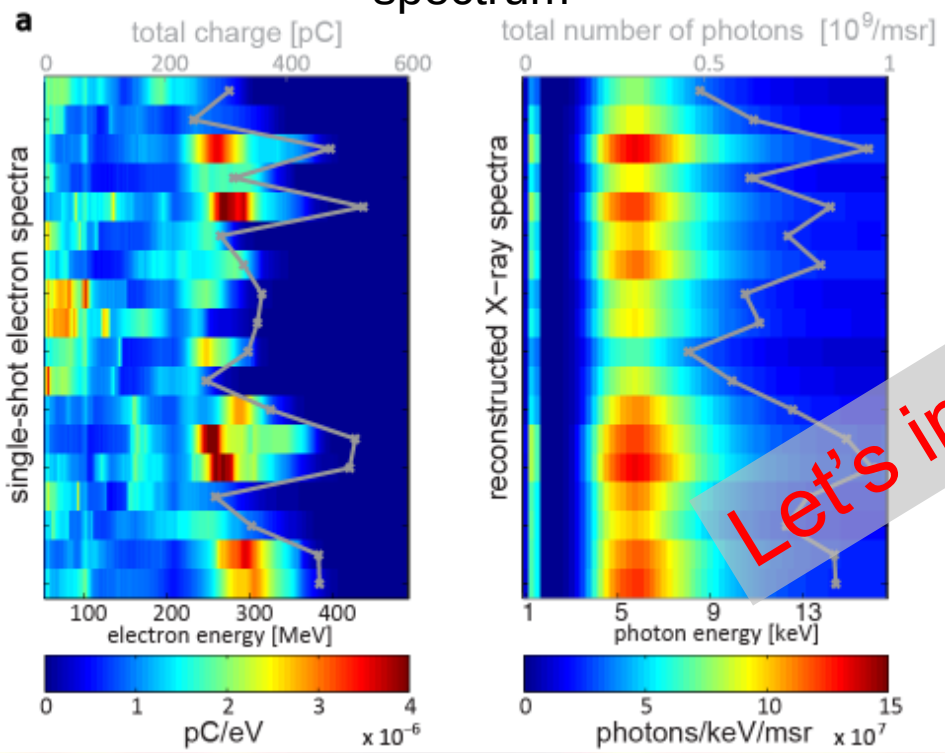
adding line outs

Fresnel modeling

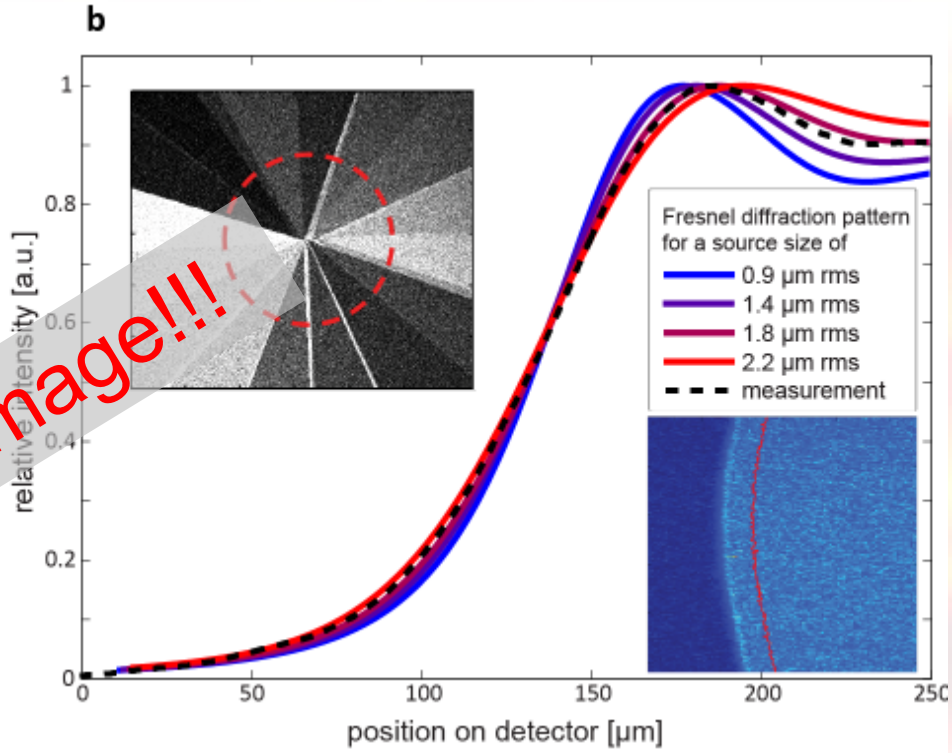


Betatron radiation source characteristics

spectrum



source size



Let's image!!!

peaks at 5.5 keV

best fit 1.8 μm

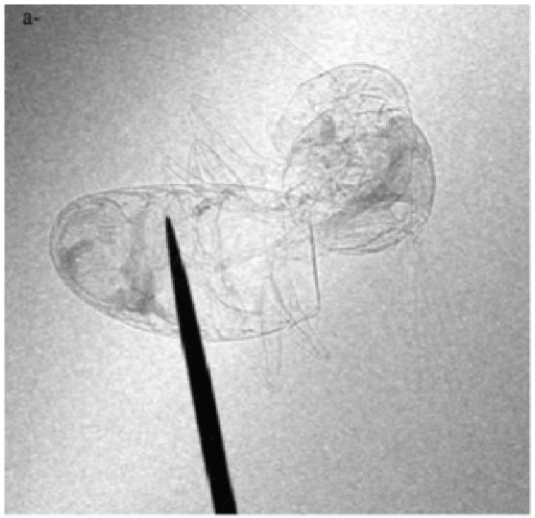
peak brilliance: 2×10^{22} ph s^{-1} mm^{-2} $mrad^{-2}$/0.1% BW (assuming pulse length of 10 fs)

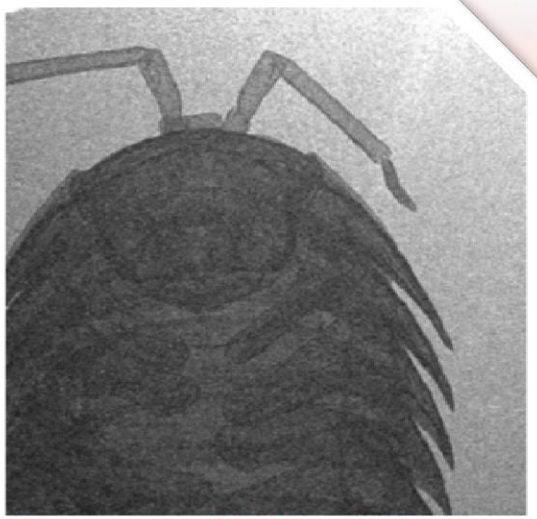
Previous work

First X rays betatron !
contrast images

S. Fourmaux *et al.*, !
Opt. Lett. **36**, 13 (2011)

S. Kneip *et al.*, Appl. Phys. !
Lett. **99**, 093701 (2011)





Courtesy of K. Krushelnick

V. Malka *et al.*, Nature Physics **4** (2008)!
E. Esarey et al., Rev. Mod. Phys. **81**, 1229 (2009)
S. Corde et al., Rev. of Modern Physics **85**, 1 (2013)

Propagation-based Phase-Contrast Imaging

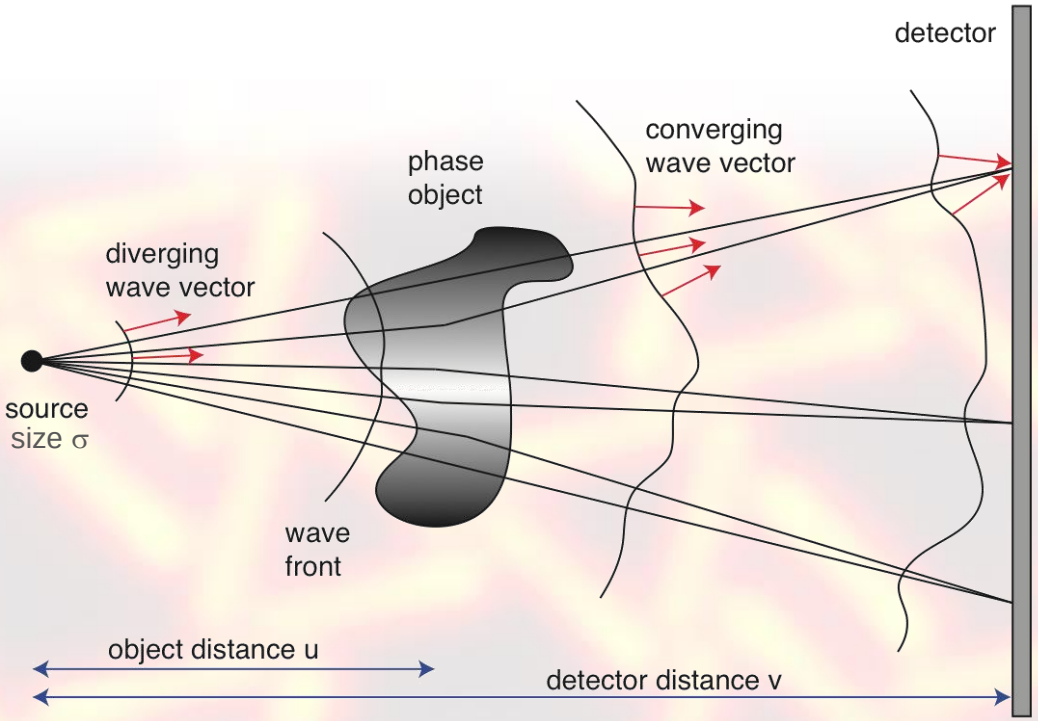
Requirements:

- sufficient degree of spatial coherence
  transverse coherence length l_t

$$l_t = \lambda v/\sigma > \sqrt{\lambda D}/(2\sqrt{2}) \approx O(1-10\,\mu m)$$

$$D = d(v-u)/(d+u)$$

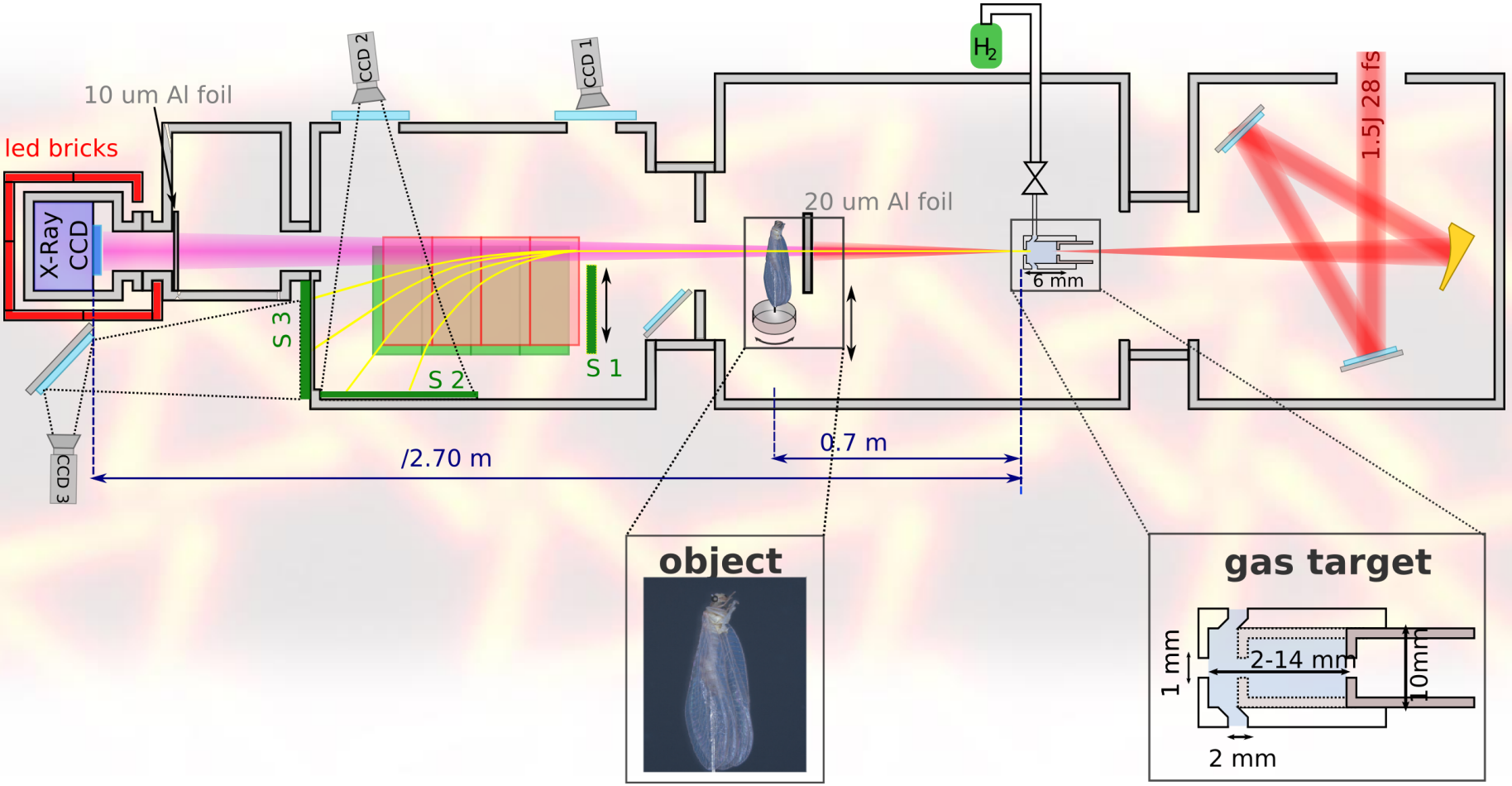
- a high resolution detector



The intensity distribution on the det-ector is a result of wavefront distortions introduced by phase object. The Transport of Intensity Equation relates sample thickness to measured inten-sity distribution:

$$T(\vec{r}) = -\frac{1}{\mu_{poly}} \times \ln\left(IFT\left\{ \frac{\frac{FT\left(I(v/u\cdot\vec{r})\right)}{I_0}}{1+\frac{(v-u)\delta_{poly}}{v/u\,\mu_{poly}}\left|\vec{k}\right|^2} \right\} \right)$$

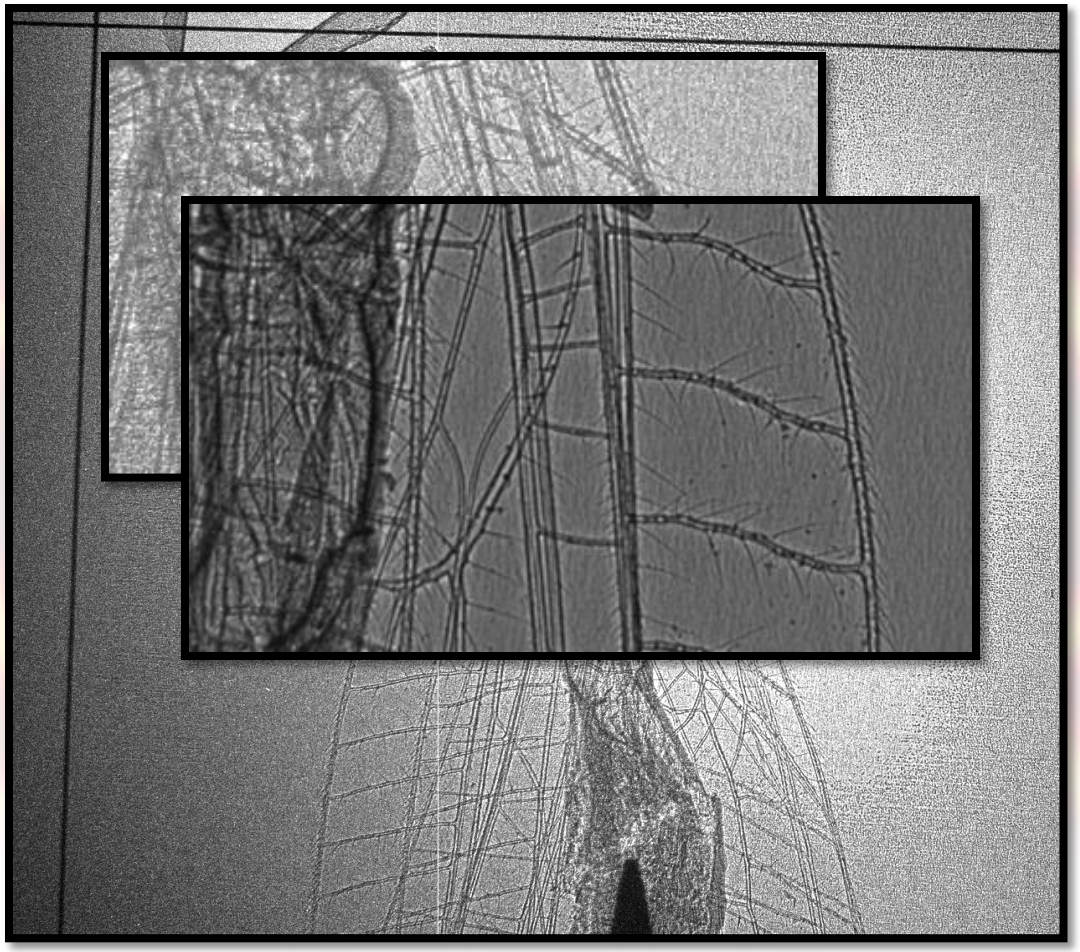
Experimental Setup- Phase Contrast Imaging



Going beyond the resolution of your detector

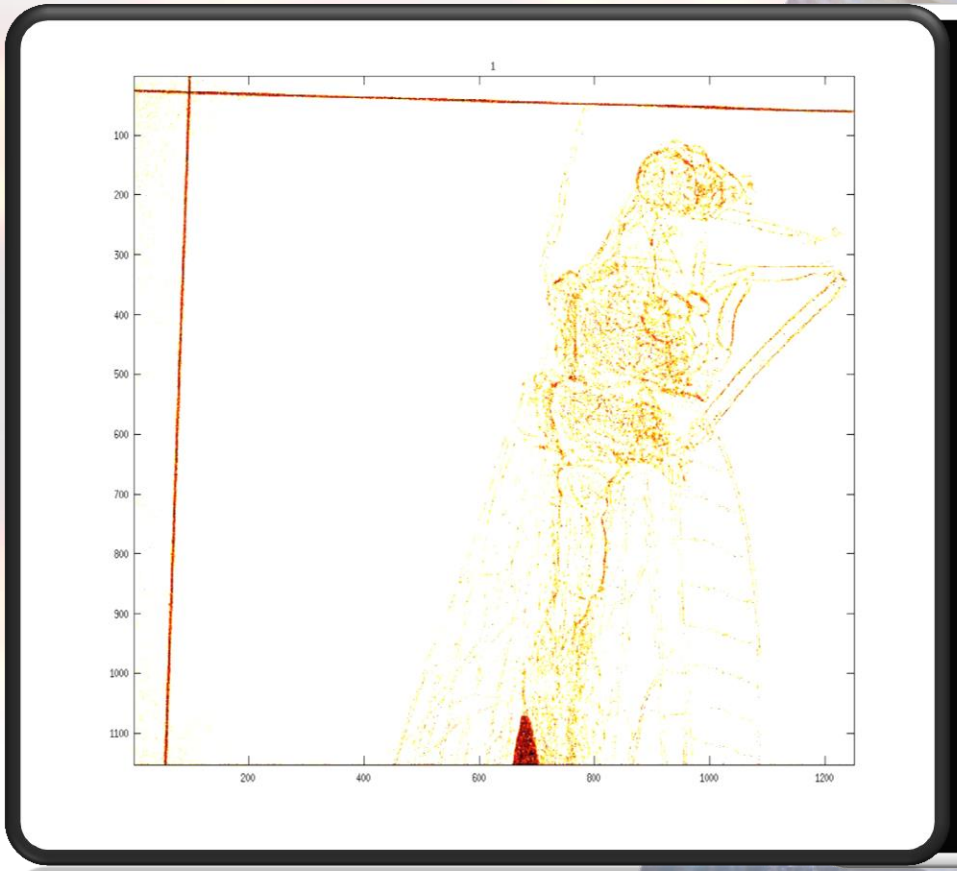
Adding and sub-sampling the 100 shots:

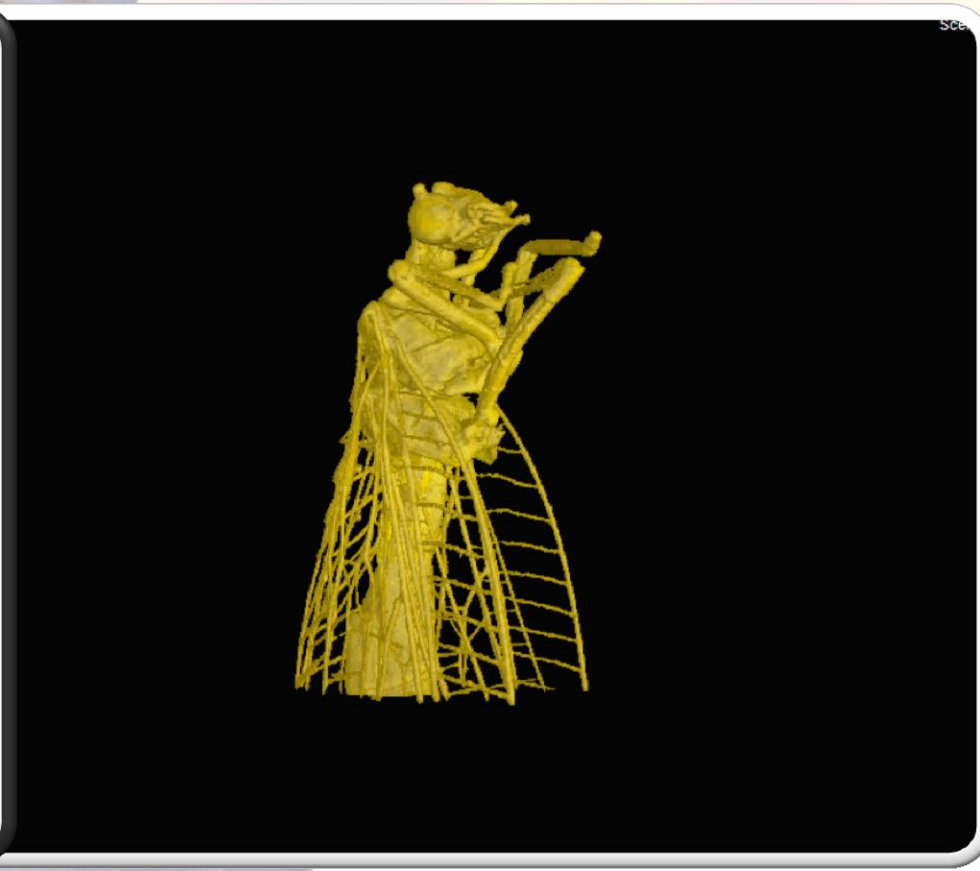
Single shot imaging



Phase contrast tomography of biological sample

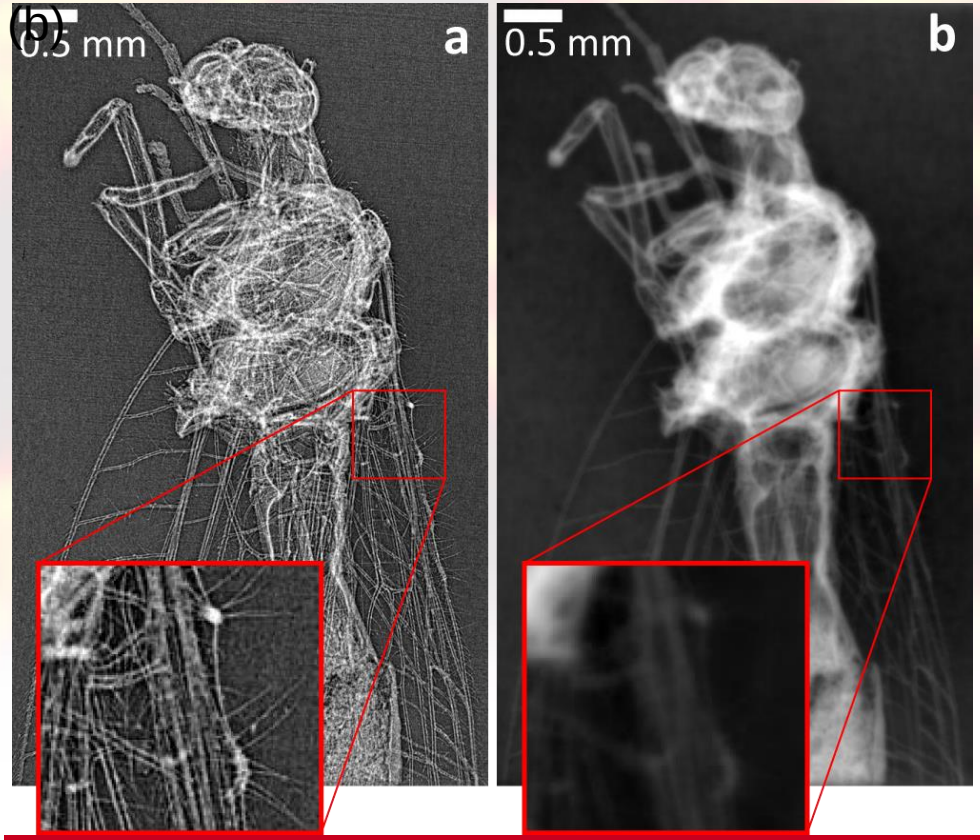
data analysis by the group of F. Pfeiffer



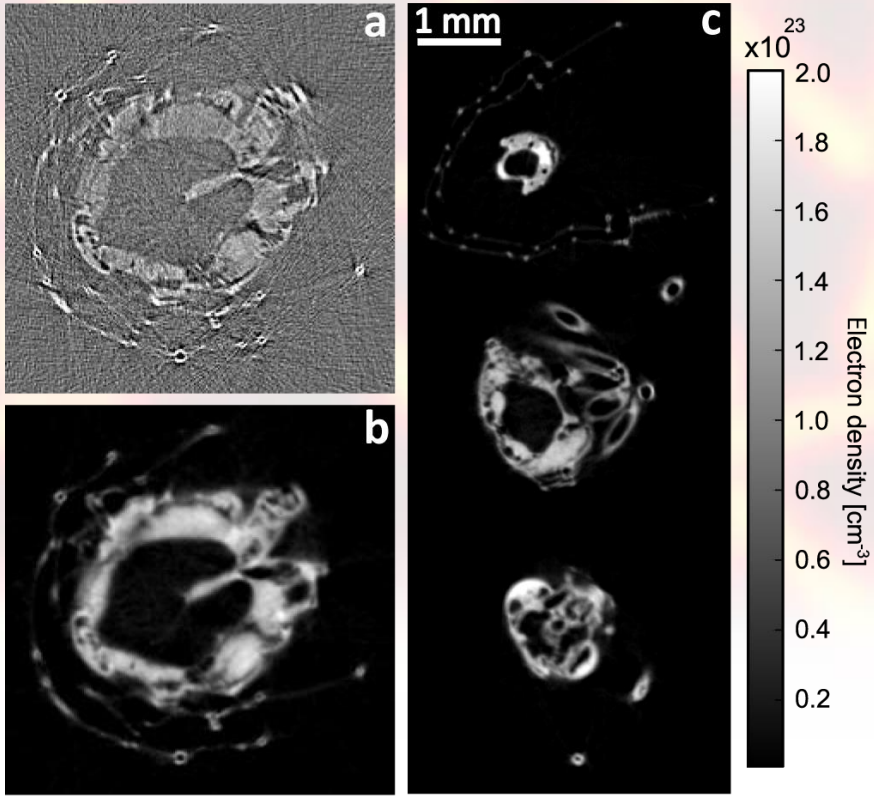


Quantitative Phase Map and Reconstruction

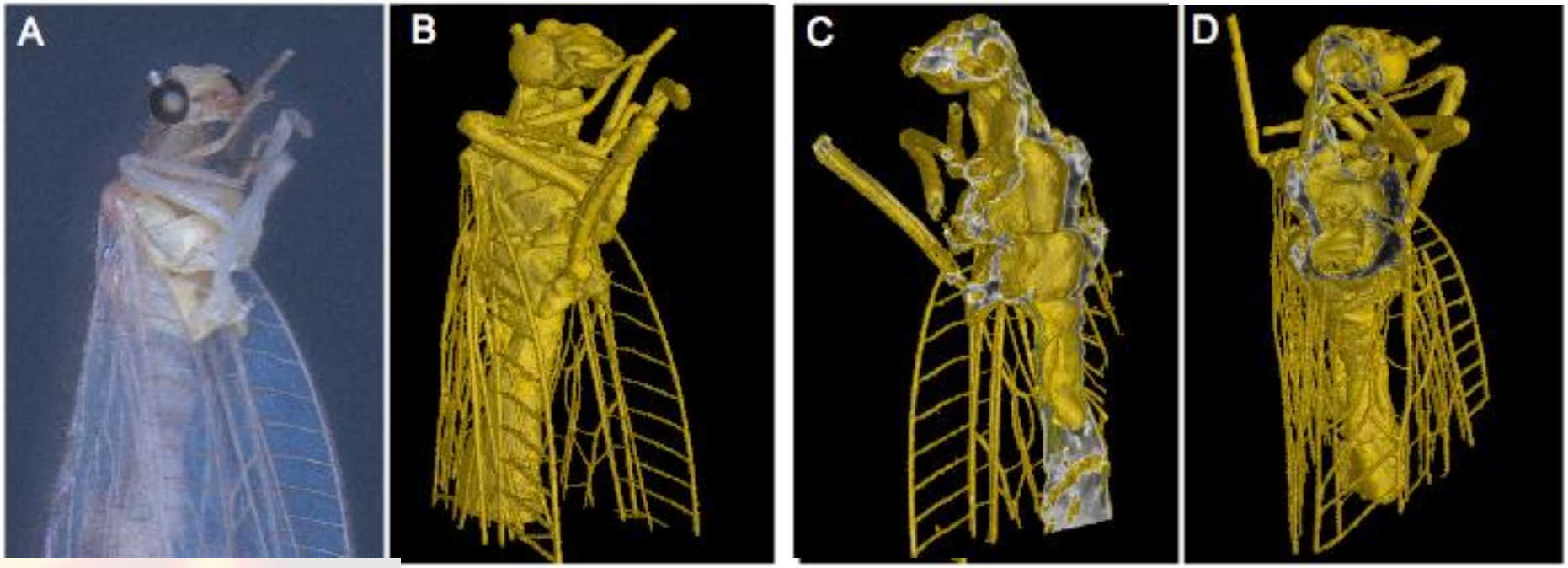
The transport-of intensity-equation (TIE) relates the edge-enhanced image at the detector (a) to the phase map of the insect (b)



tomographic reconstruction of 2-D projections yields cuts through sample (edge anhancement (a) and phase images (b,c))

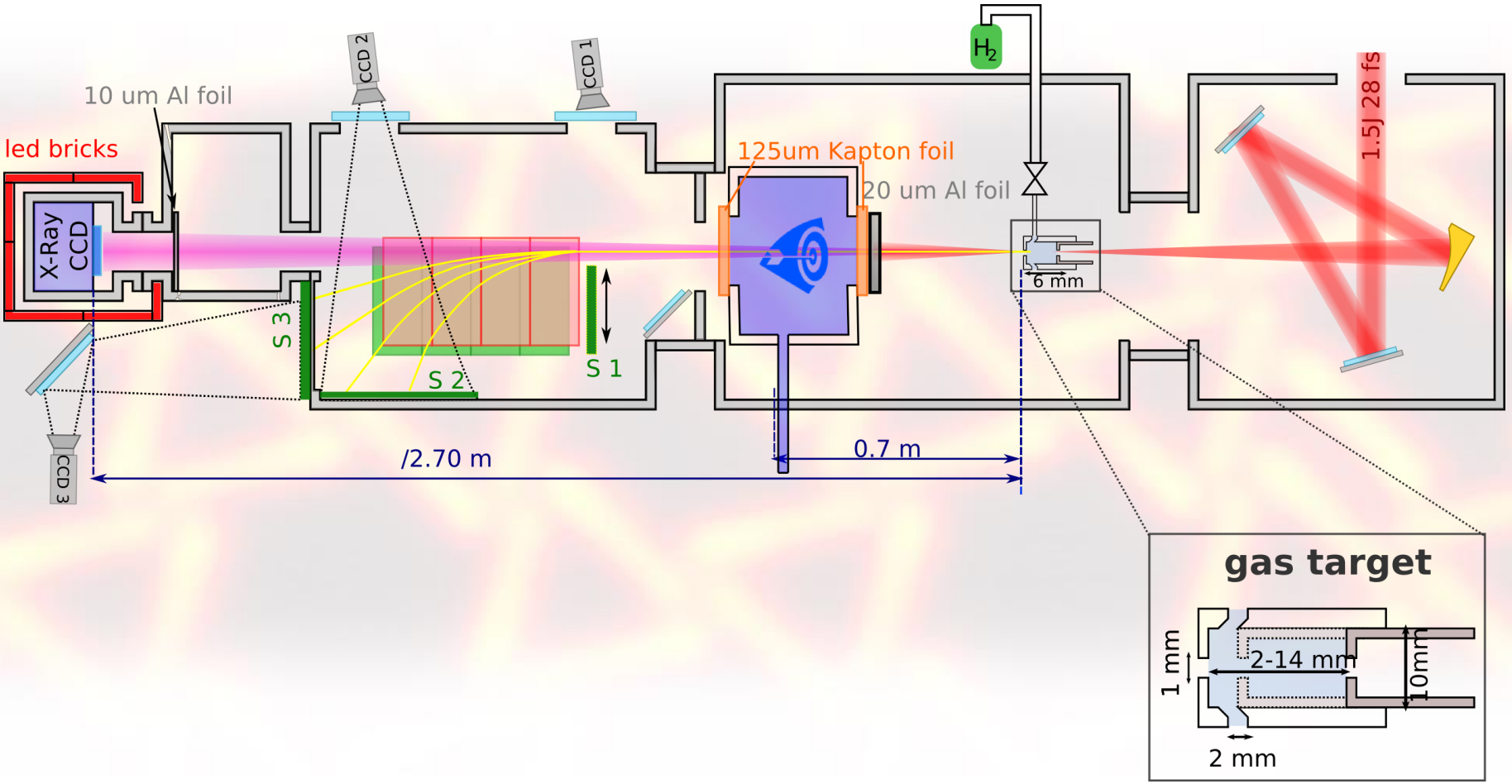


3D rendering of the fly

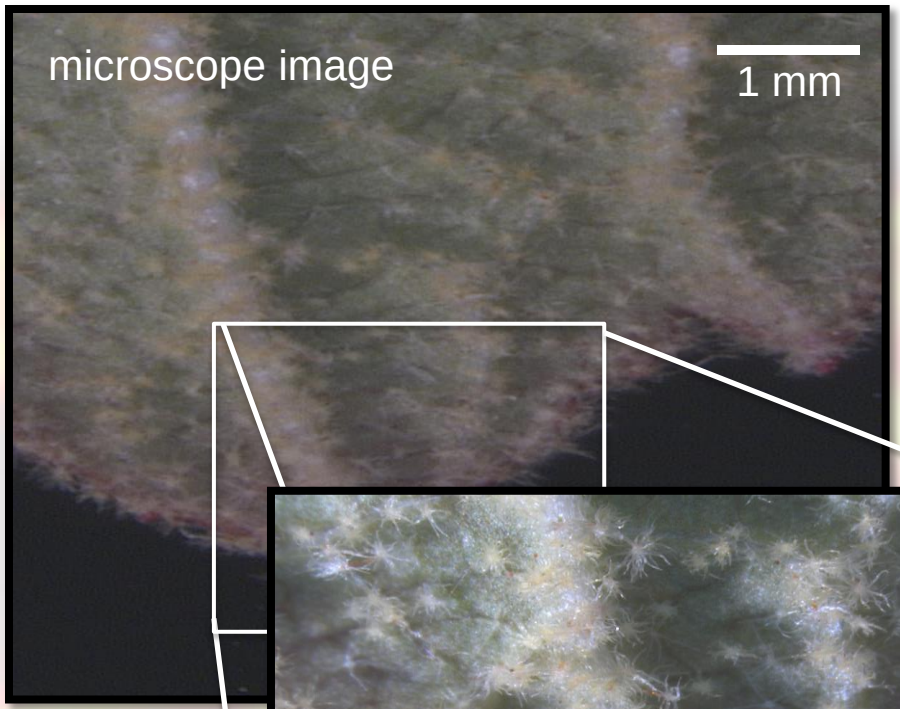


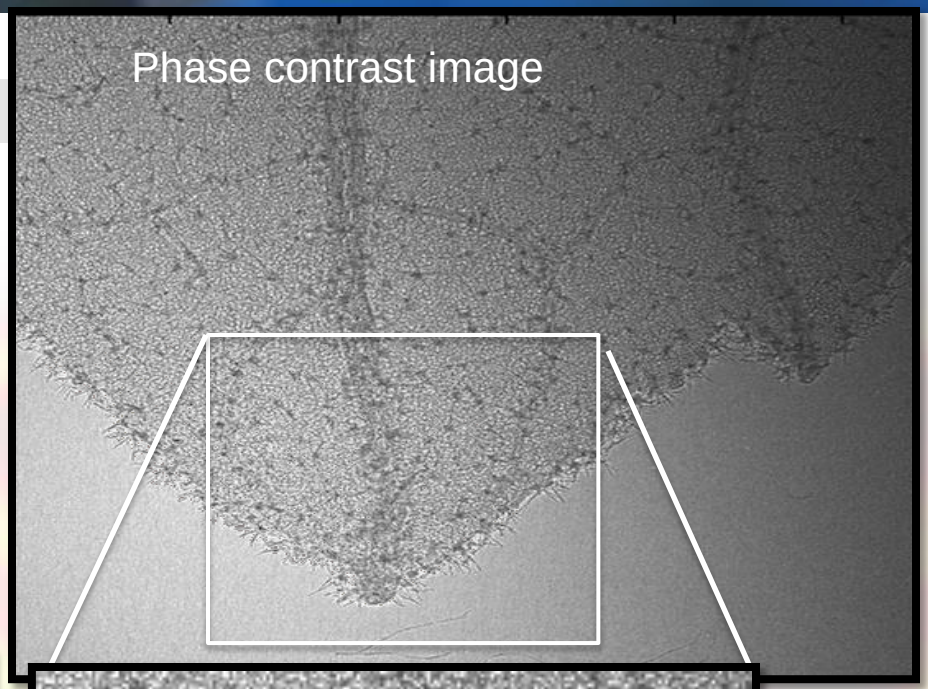
From background (void) of the reconstructed sample one can estimate a conservative limit for our measurement sensitivity of the electron density **sensitivity of 0.1×10^{23} cm^{-3}**

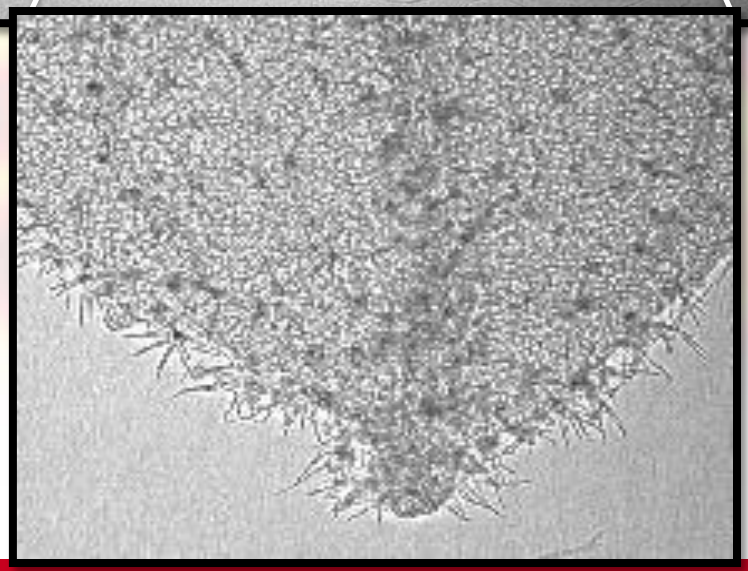
Reentrance setup for water containing samples



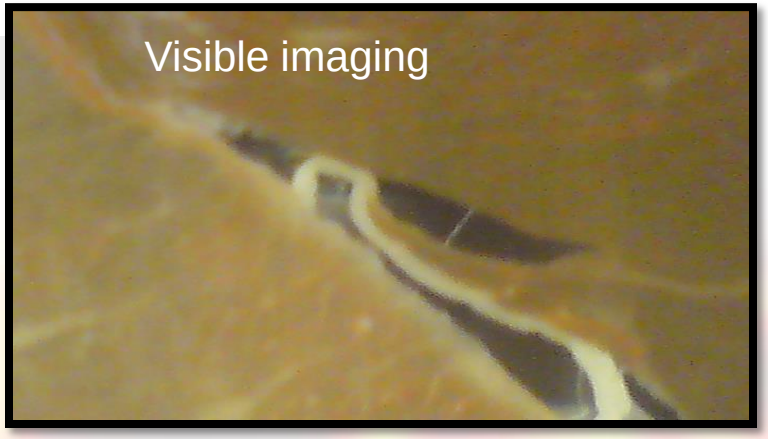
Water containing samples

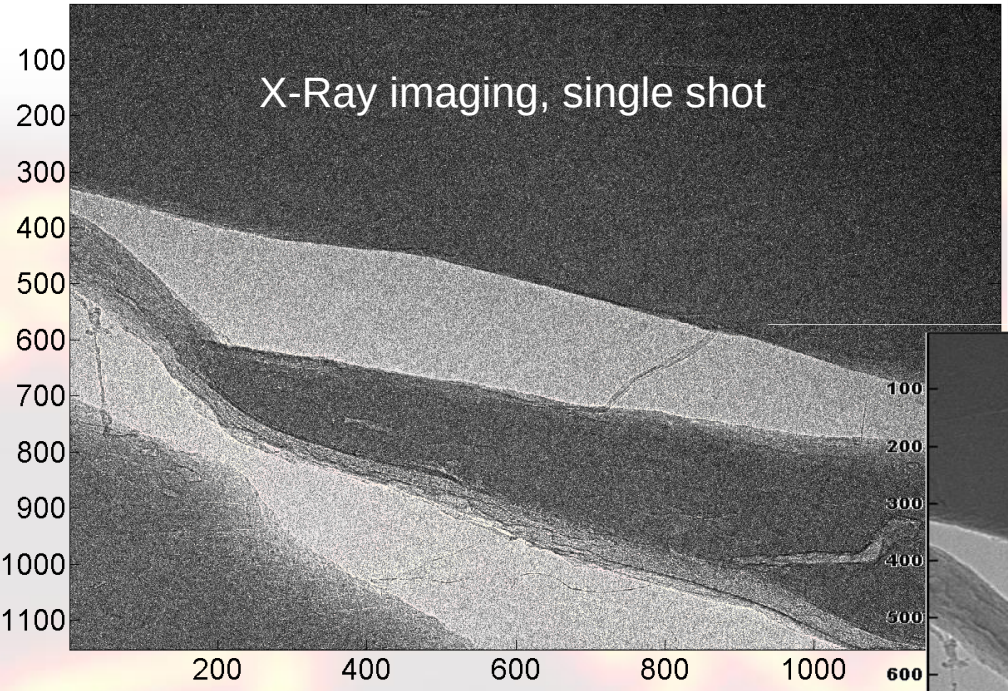


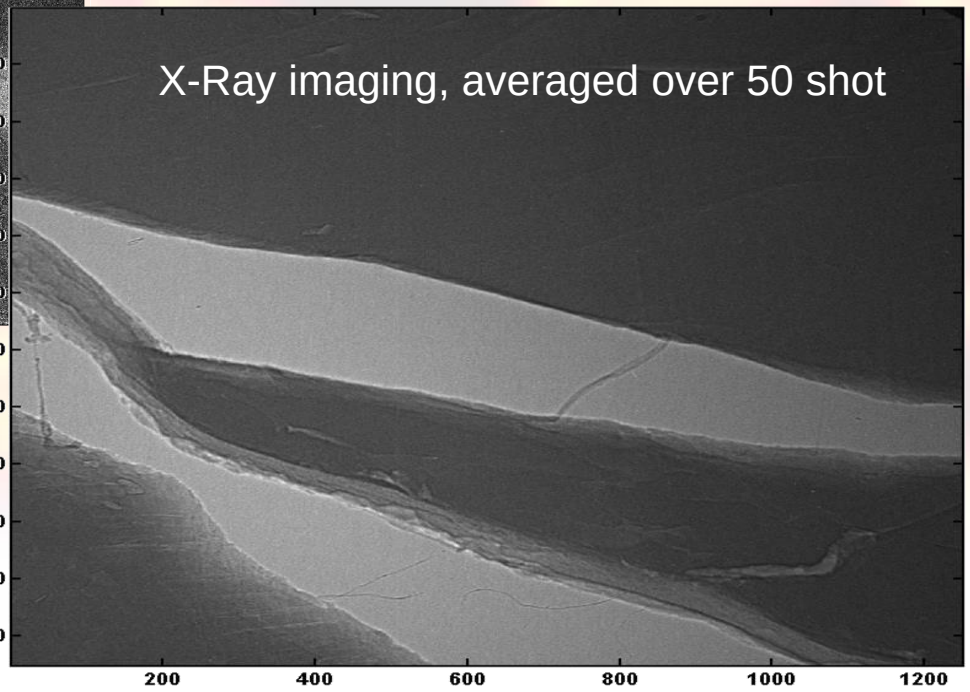




Hamon iberico







Summary

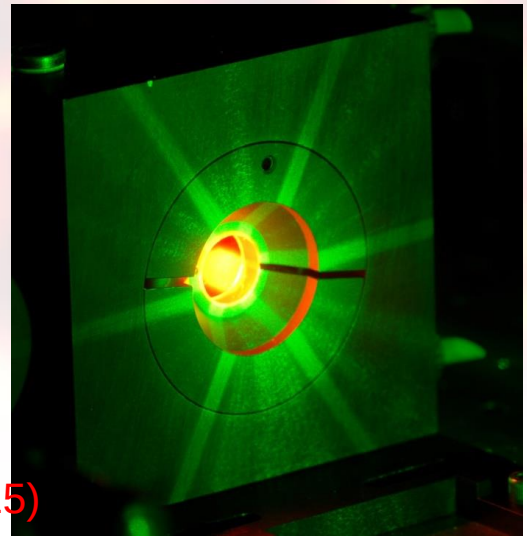
LWFA electrons are able to provide highly brilliant X-Ray sources enabling phase contrast tomography

Intrinsic properties of LWFA Betatron source:

Compact, high spatial coherence, low spectral fluctuation well suited for multi-exposure scans, fs duration

Source and spectral characterization enables reconstruction of absolute electron densities

complete tomography scan (1500 laser shots)



Thank you very much for your attention!!!

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