DEPARTMENT OF MEDICAL PHYSICS AND BIOMEDICAL ENGINEERING

X-ray imaging techniques and their application to novel light sources

Silvia Cipiccia

ADVANCED X-RAY IMAGING

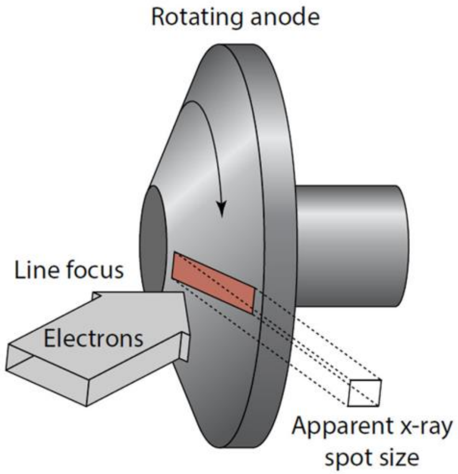
AXIM

ADVANCED X-RAY IMAGING

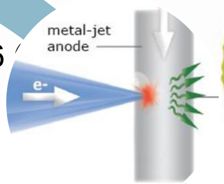
X-ray imaging

M.E. Couprie
Journal of Electron
Spectroscopy and
Phenomena 196

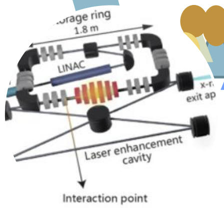
Laboratory sources



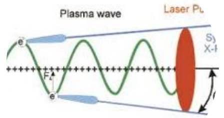
Novel
sources



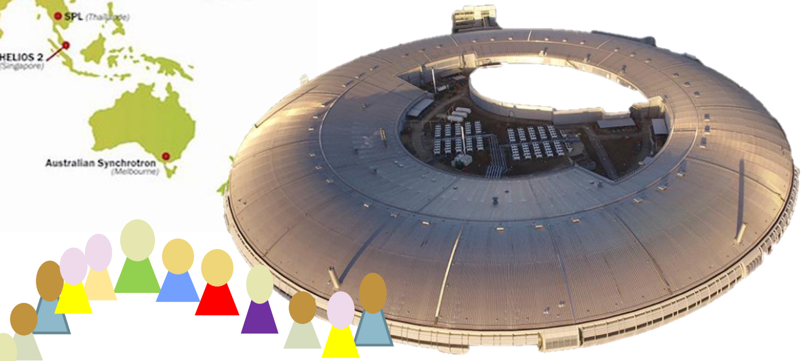
Liquid
metal-jet



Inverse
Compton
Scattering



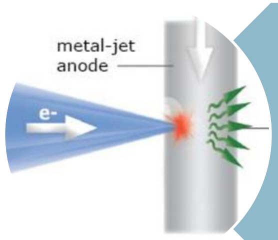
Laser-
driven
sources



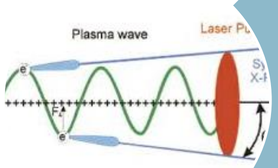
SYNCHROTRON

XFEL

- Each source has different specific features
- Not a solution fits all



Coherent diffraction imaging



Multimodal imaging with incoherent sources

ADVANCED X-RAY IMAGING

Coherence

- Quality of the beam: high coherence =
- Spatial coherence:
  - tells us how c
    focus your sc
- Temporal coherence:
  - tells us how r
- Definition of coherence: same frequer
- Signature of coherence: interference

an

van Cittert- Zernike theorem: An incoherent source will manifest a coherent wavefront at large distance

Generation of spatially coherent water waves from randomly distributed wave disturbances produced by 13 ducks jumping into a pool at time 00:47:12. The frame times are indicated.

Spatial coherence from ducks FREE

Wayne H. Knox; Miguel Alonso; Emil Wolf

Check for updates

Physics Today **63** (3), 11 (2010);
https://doi.org/10.1063/1.3366225

Spatial Coherence

- The source is monochromatic

$$\Delta p = \frac{d}{2} \sin\theta$$

$$S_2P_1 - S_2P_2 = d\sin\theta$$

$$S_1P_1 - S_2P_1 = 2d\sin\theta$$

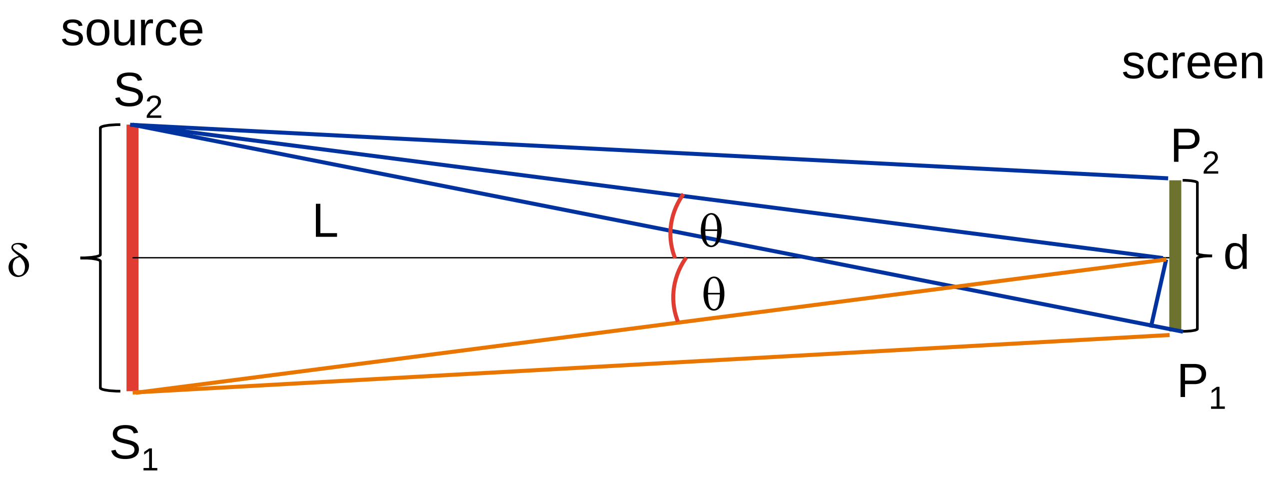
$$\Delta\varphi = \frac{2\pi}{\lambda} 2d\sin\theta$$

$$\sin\theta \approx \frac{\delta}{2L}$$

$$\Delta\varphi = 2\pi \frac{d\delta}{L\lambda}$$

When $\Delta\varphi = \pi$ out of phase

$$lateral\ coherence\ length = \frac{L\lambda}{2\delta}$$



- Similarly, can be calculated for the temporal coherence length

Example

- **Synchrotron**
- Source size~ 100 um
- Wavelength 8 keV -> 0.155 nm
- Distance 100 m

- Spatial coherence length: 80 um

- **X-ray laboratory source**
- Source size~ 200 um
- Wavelength 8 keV -> 0.155 nm
- Distance 2 m

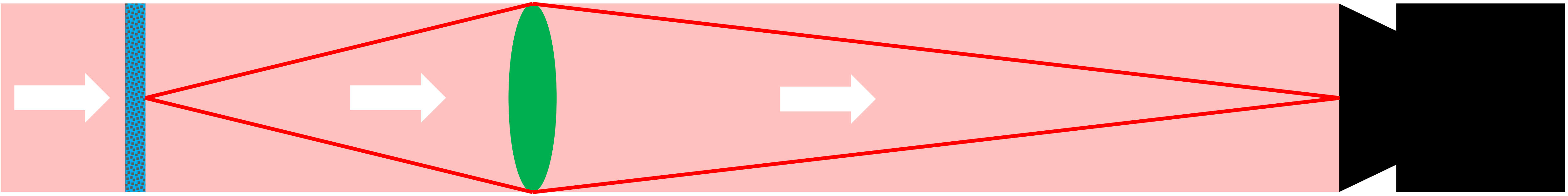
- Spatial coherence length: 0.8 um

- **Laser driven source (betatron)**
- Source size~ 2 um
- Wavelength 8 keV -> 0.155 nm
- Distance 2 m

- Spatial coherence length: 80 um

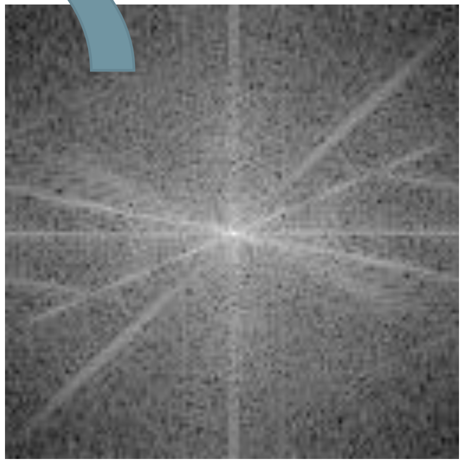
Conventional Microscopy
Coherent diffraction imaging

- Radiation is scattered from a sample and is focussed through a lens into an image plane
- The detector is placed in the image plane and captures the intensity image (lost phase information)
- The image is limited in resolution by the quality of the lens profile to the high scatter angles

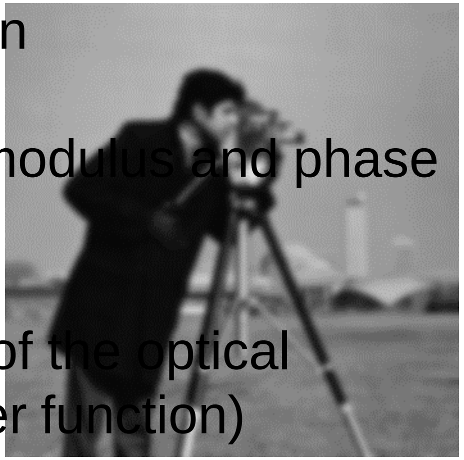


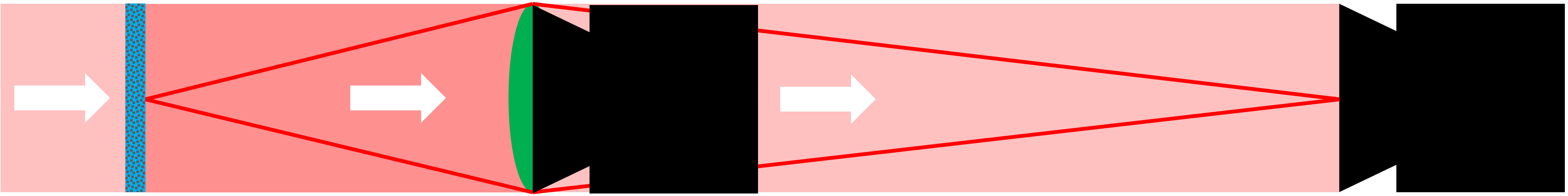
Coherent diffraction imaging

Recover the relative phase

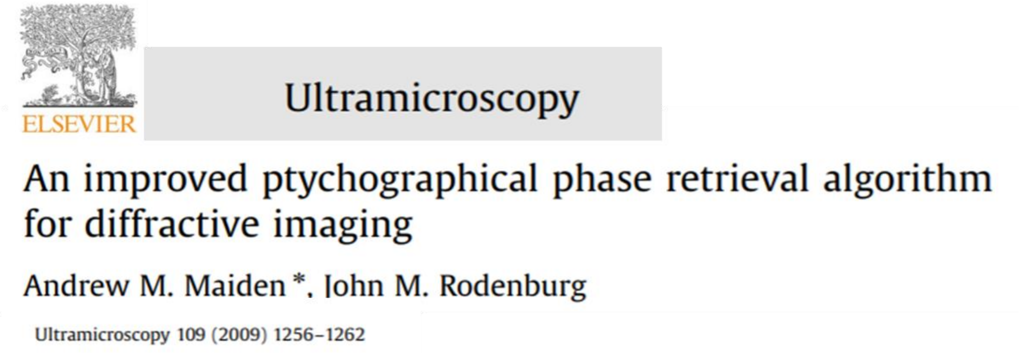


- Replace the function of the lens with a computational reconstruction
- Allows to recover both the modulus and phase components of the wave
- Is not limited by the quality of the optical components (perfect transfer function)





Ptychography:
Scanning Coherent Diffraction Imaging



ELSEVIER

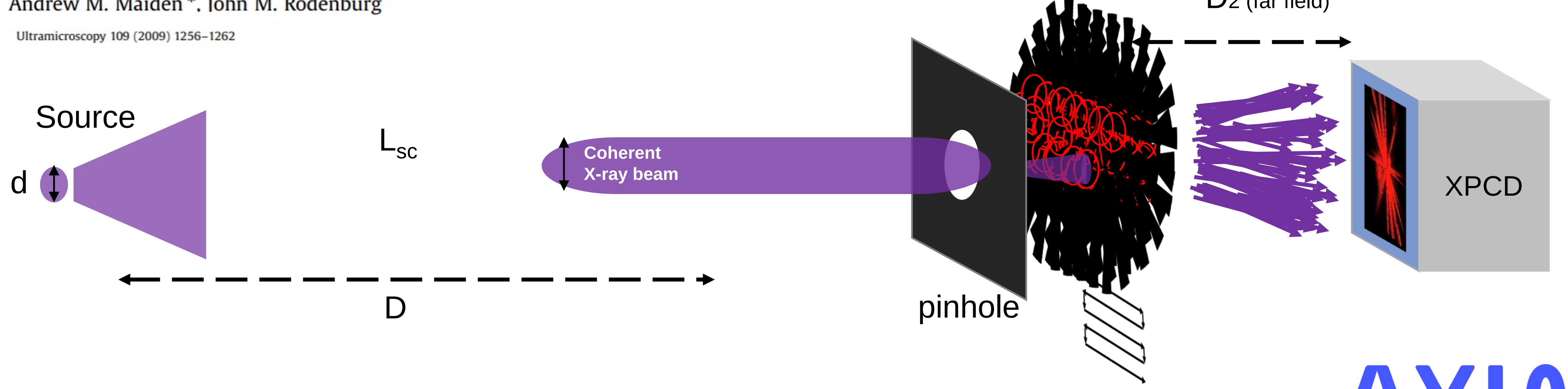
Ultramicroscopy

An improved ptychographical phase retrieval algorithm for diffractive imaging

Andrew M. Maiden *, John M. Rodenburg

Ultramicroscopy 109 (2009) 1256–1262

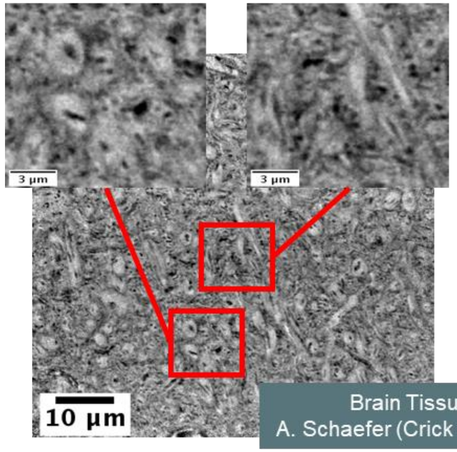
- Extends the coherence by scanning
- Does not require pre-knowledge of the illumination



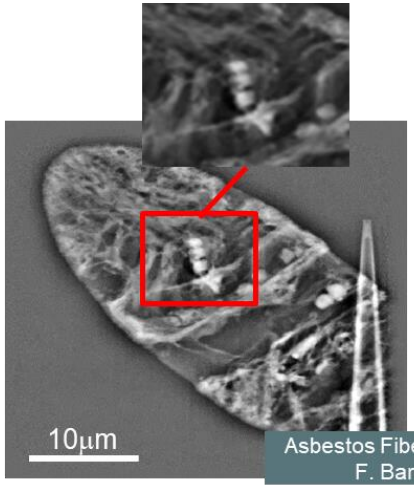
X-ray ptychography

- Nanoscale resolution
- Sensitive to small changes in electron density
- Quantitative

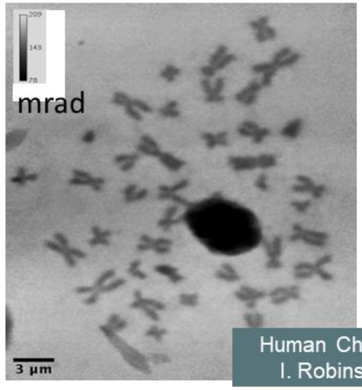
- Requires high quality beam:
- high coherence



Brain Tissue
A. Schaefer (Crick Institute)



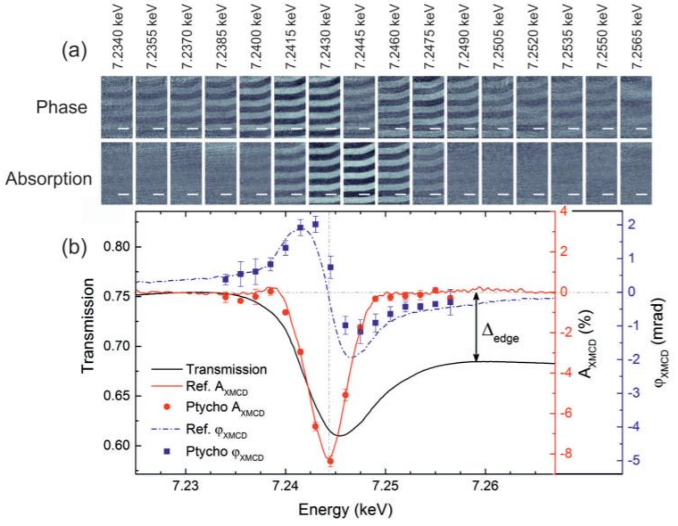
Asbestos Fibers In Lung Tissue
F. Bardelli (CNR)



Human Chromosomes (stain-free)
I. Robinson, A. Bhartiya (UCL)

X-ray ptychography

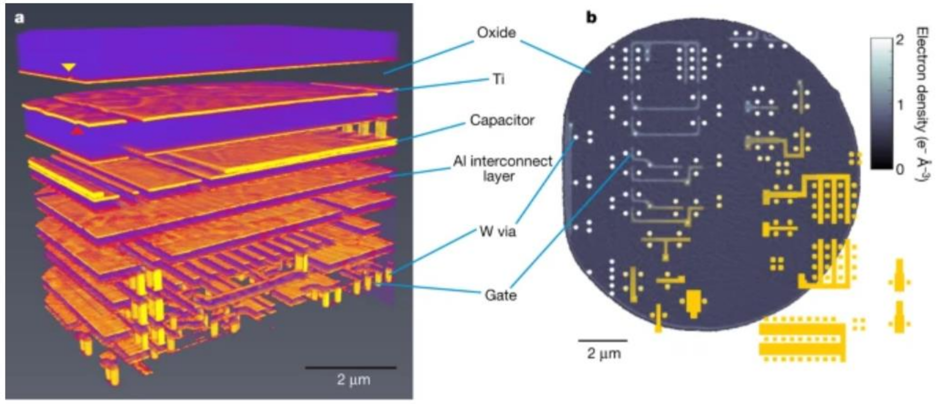
Magnetic domain imaging



CLAIRE DONNELLY *et al.*
PHYSICAL REVIEW B **94**, 064421 (2016)

Electronic science

Figure 2: PXCT of detector ASIC chip.

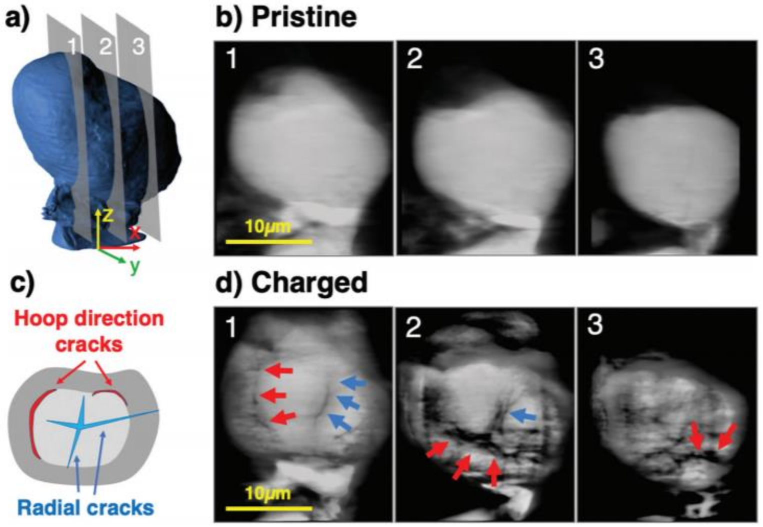


High-resolution non-destructive three-dimensional imaging of integrated circuits

Mirko Holler[1], Manuel Guizar-Sicairos[1], Esther H. R. Tsai[1], Roberto Dinapoli[1], Elisabeth Müller[1], Oliver Bunk[1], Jörg Raabe[1] & Gabriel Aeppli[1,2,3]

NATURE | VOL 543 | 16 MARCH 2017

Batteries



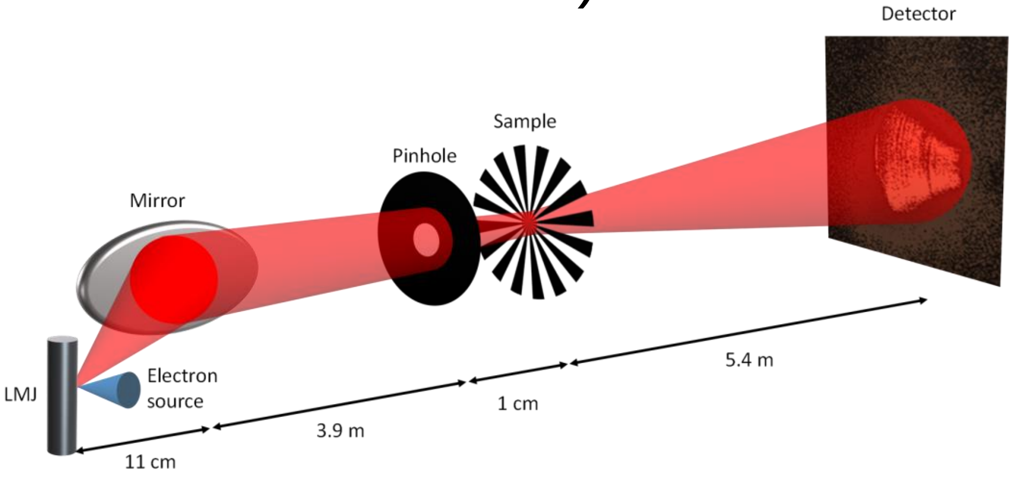
Synchrotron X-ray quantitative evaluation of transient deformation and damage phenomena in a single nickel-rich cathode particle†

León Romano Brandt,*[a] John-Joseph Marie,[b] Thomas Moxham,[a] Dominic P. Förstermann,[b] Enrico Salvati,[ac] Cyril Besnard,[a] Chrysanthi Papadaki,[a] Zifan Wang,[a] Peter G. Bruce[bdef] and Alexander M. Korsunsky[a]

Coherent diffraction imaging with an LMJ

Can be performed outside a synchrotron?

- YES
- SMALL laboratory Sheffield: Sasha Mykhaylyk
- Brilliance 10^{11} photons/(0.1%BW s mrad^2 mm^2)

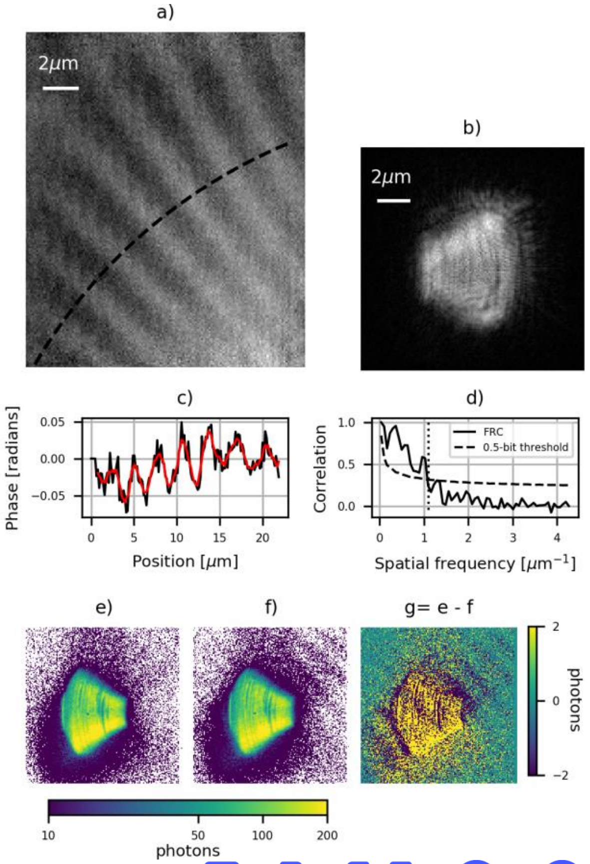


PHYSICAL REVIEW LETTERS

X-Ray Ptychography with a Laboratory Source

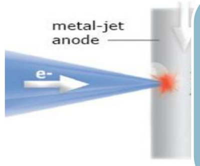
Darren J. Batey, Frederic Van Assche, Sander Vanheule, Matthieu N. Boone, Andrew J. Parnell, Oleksandr O. Mykhaylyk, Christoph Rau, and Silvia Cipiccia

Phys. Rev. Lett. **126**, 193902 – Published 12 May 2021



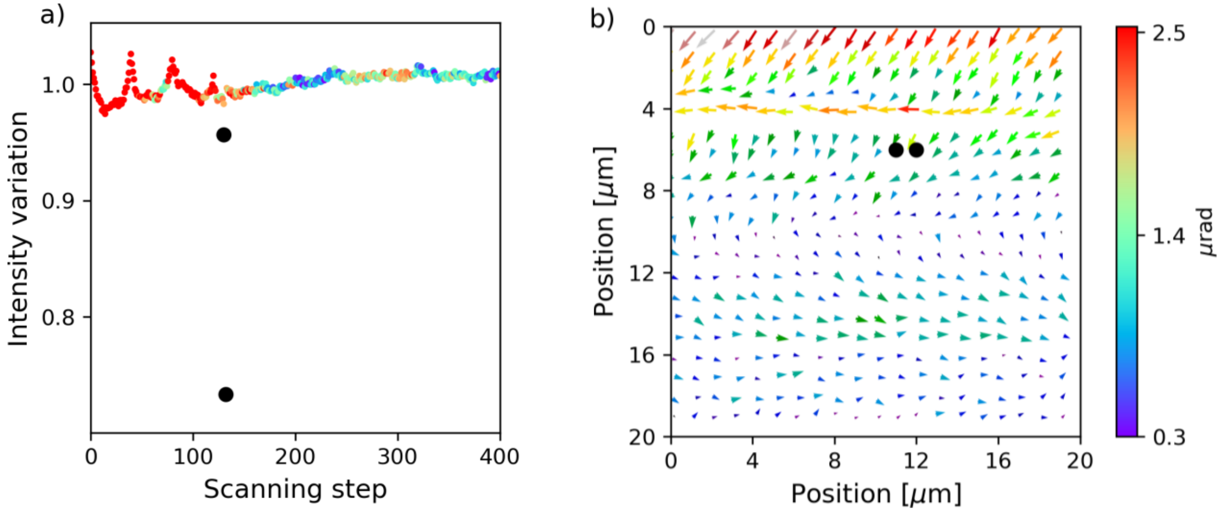
Coherent diffraction imaging with an LMJ

Main Challenge

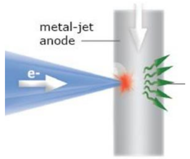


Long acquisition
Source instability

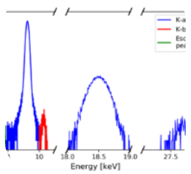
PTY REX



Next steps



Increase usable flux



Broadband

- Hyperspectral detector
- Algorithm

AXIM ADVANCED X-RAY IMAGING

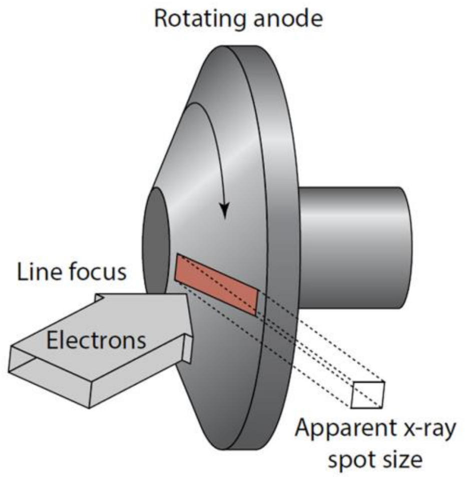
Imaging with incoherent light sources

- Large source size: spatially incoherent
- Polychromatic: temporally incoherent

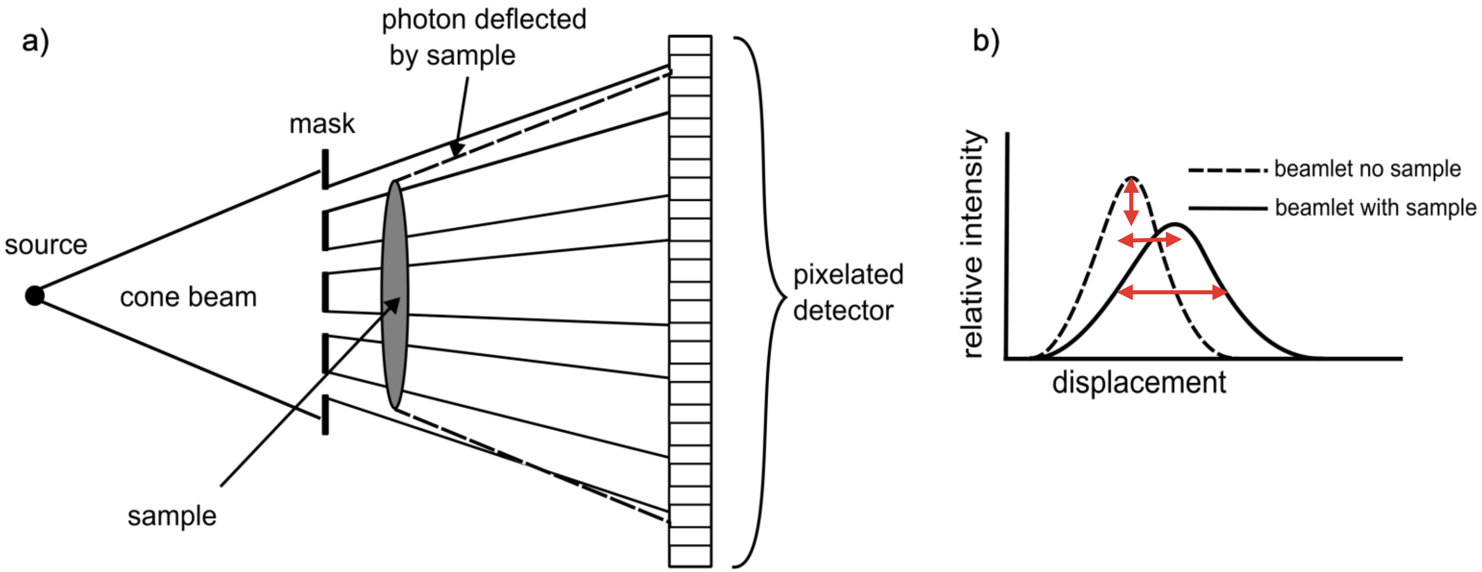
- Standard imaging: absorption imaging
- widely used for medical and industrial applications

Is it possible to extract more information?

Laboratory sources

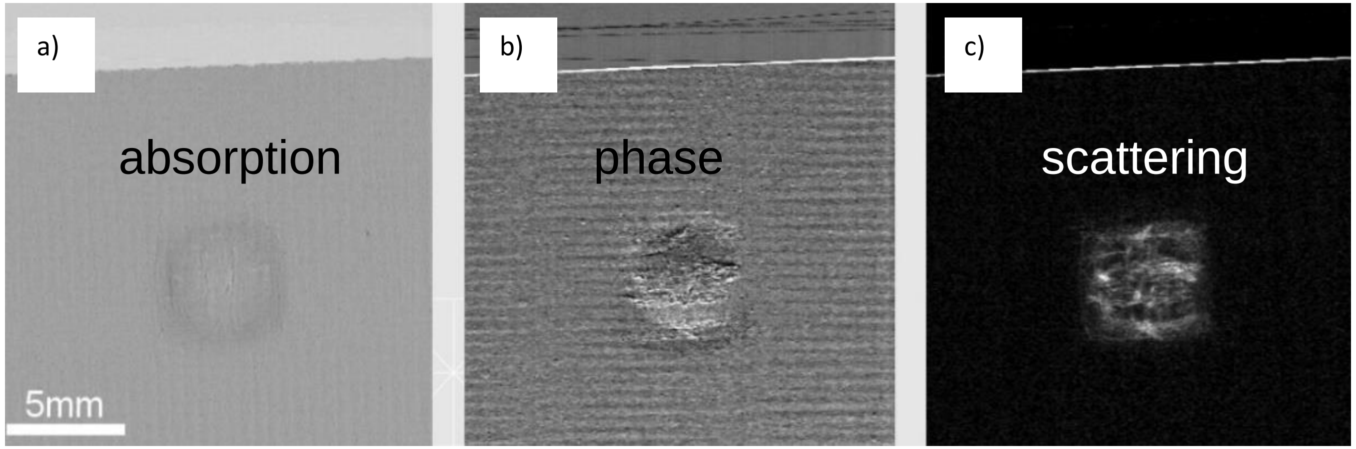


Edge Illumination-Beam Tracking



Robust

- Fully achromatic
- Low spatial coherence (large source size)



Edge-illumination x-ray phase-contrast imaging

Alessandro Olivo[3,2,1]

Published 13 July 2021 • © 2021 The Author(s). Published by IOP Publishing Ltd

Journal of Physics: Condensed Matter, Volume 33, Number 36 Intense Radiation Sources in Condensed Matter and Materials Physics

Citation Alessandro Olivo 2021 J. Phys.: Condens. Matter **33** 363002

DOI 10.1088/1361-648X/ac0e6e

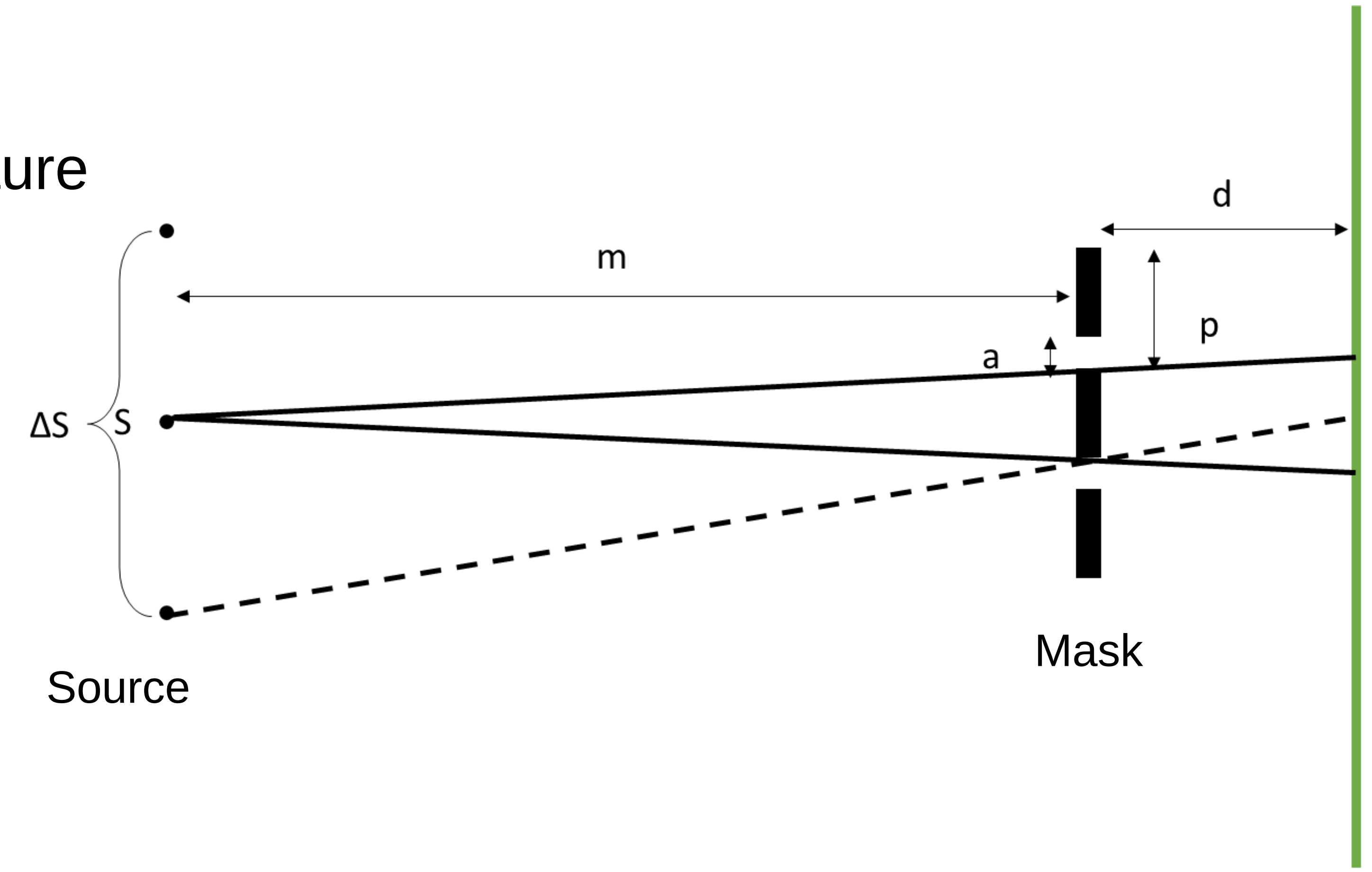
AXIM ADVANCED X-RAY IMAGING

Limits of the technique

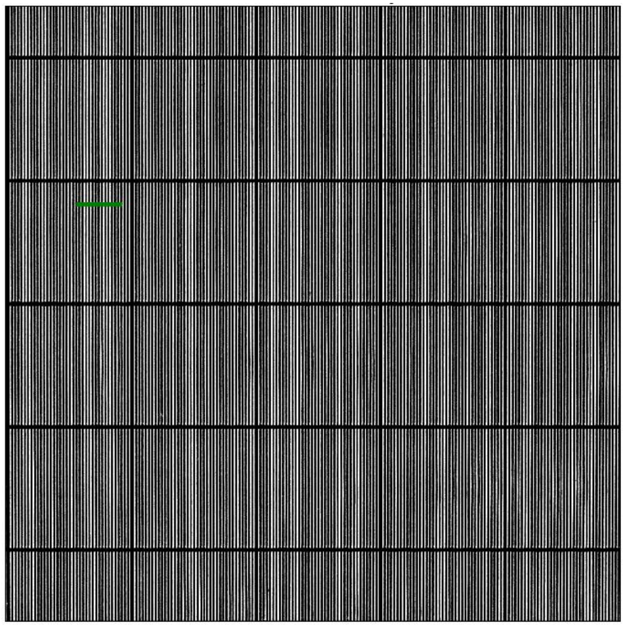
- Resolution:
- Single shot: mask period
- Dithering (scanning): mask aperture
- Geometrical limits:

$$\frac{\Delta S}{m} < \frac{(p-a)_1}{d}$$

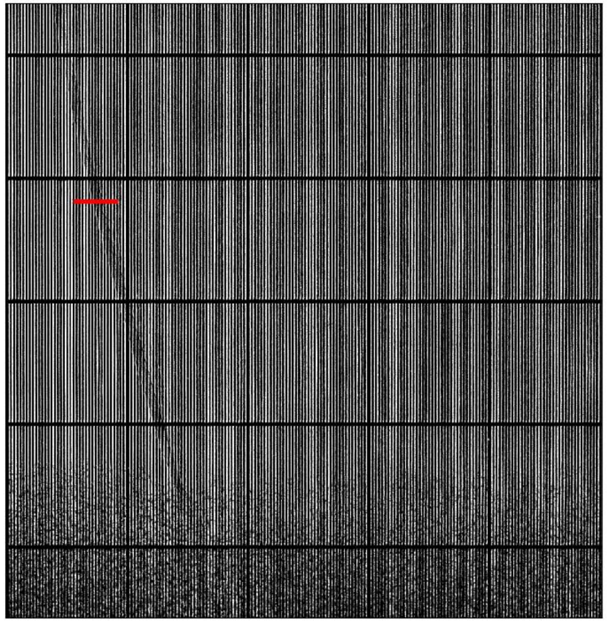
$$(p-a)_1 = \frac{(p-a)}{m} * (m+d)$$



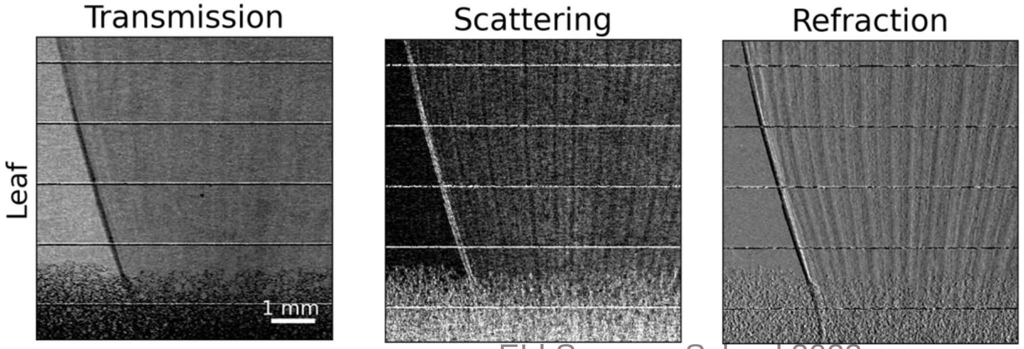
How it looks like

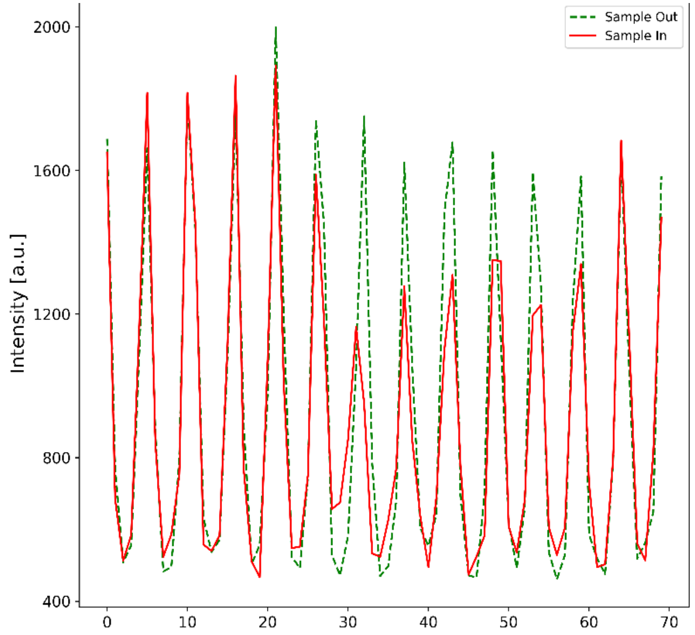


Mask



Mask + sample



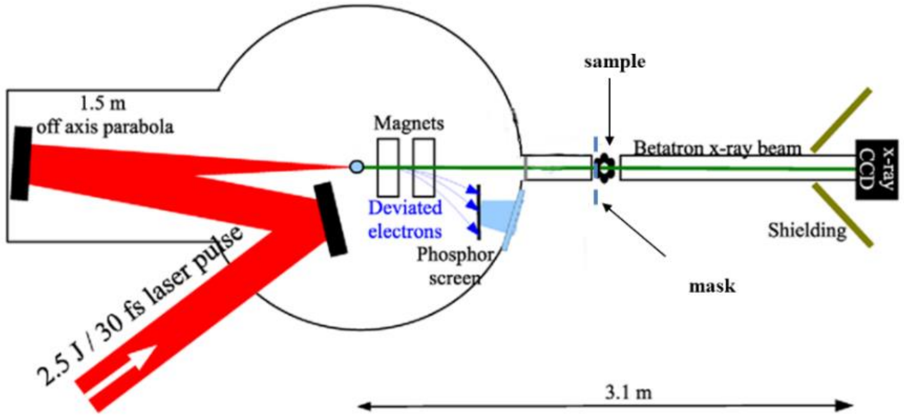


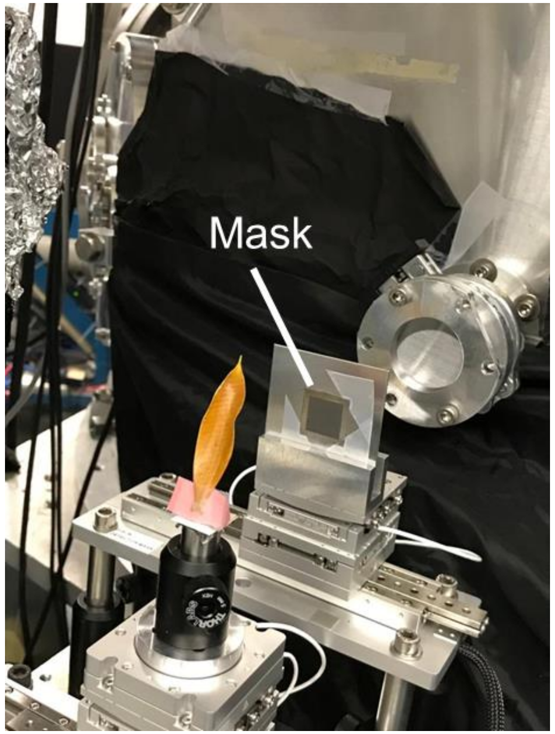
Beamlets with and without sample

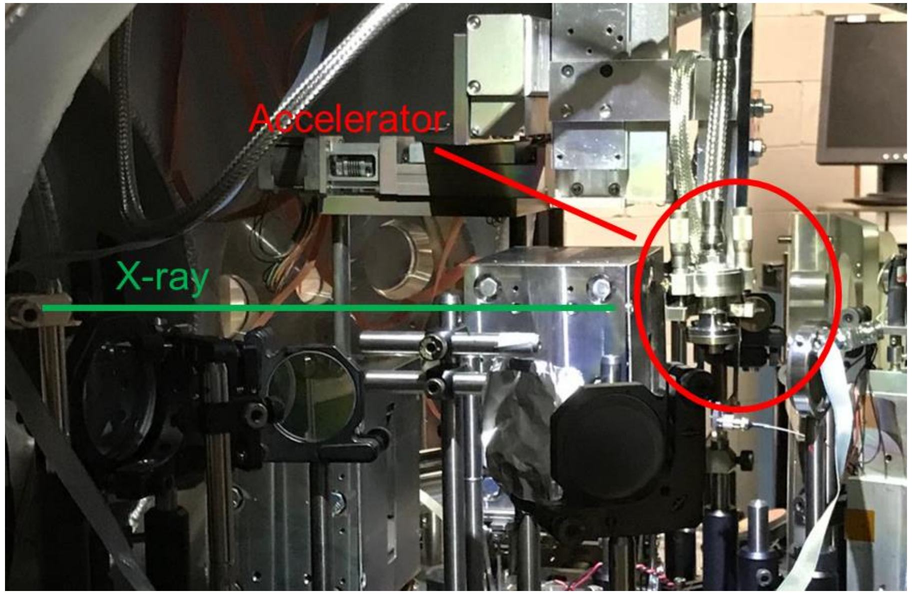
Beam Tracking with a laser-driven source

INRS Institut national de la recherche scientifique

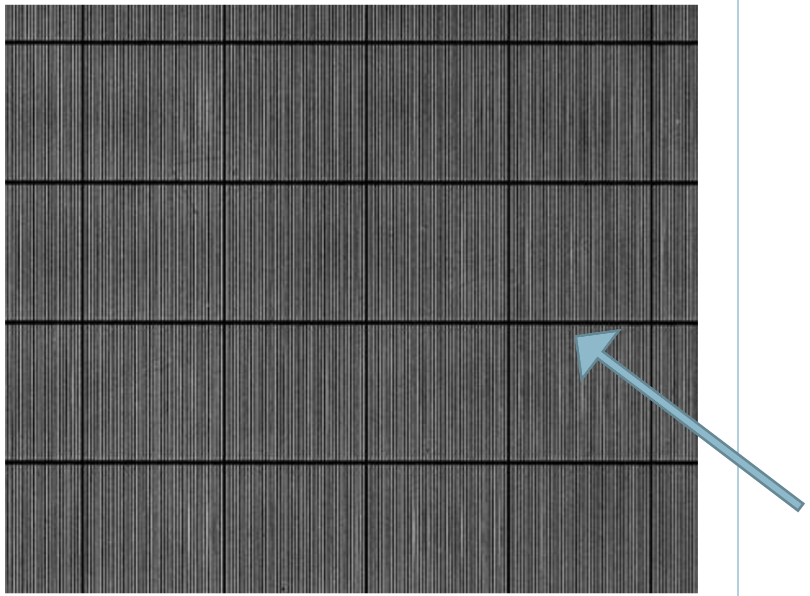
ALLS Advanced Laser Light Source







Beam Tracking with a laser-driven source



Tungsten mask: 12 um aperture, 39 um period. Laser micromachined by Scitech Precision

Bridges to reinforce the self-standing structure

Detector

- Andor Ikon L
- 1024x1024 pixels, 13 um pixel size

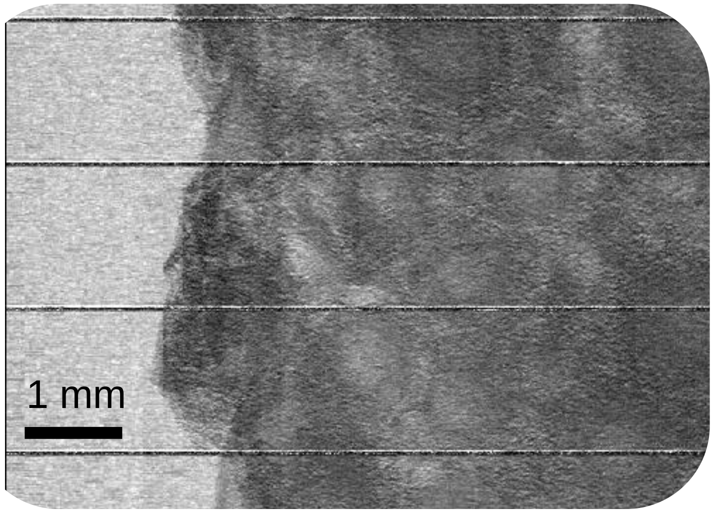
Resolution

- Single shot: mask period
- Dithering: mask aperture

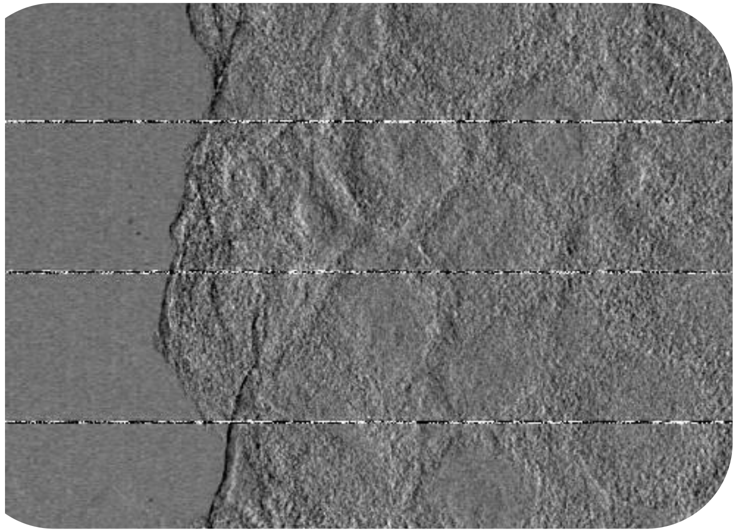
Dithering acquisition

Parameters

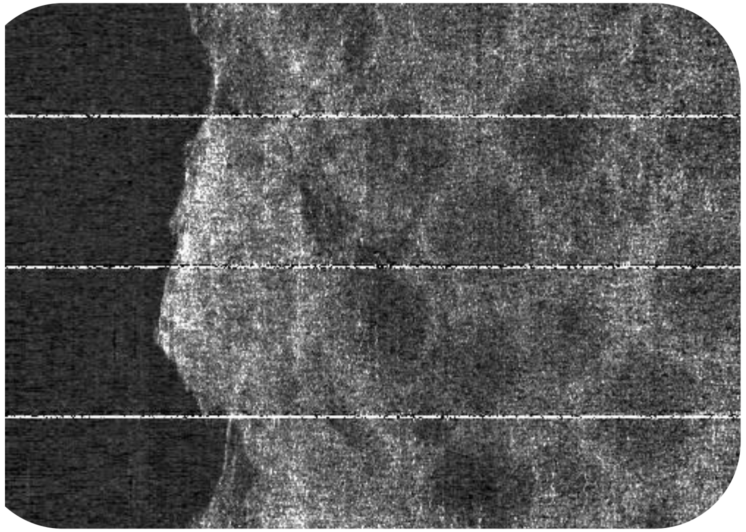
- Sample orange peel
- 4 dithering steps
- Pixel size 10.7x30 um
- 100 cumulated shots per dithering step



Transmission



Refraction



Scattering

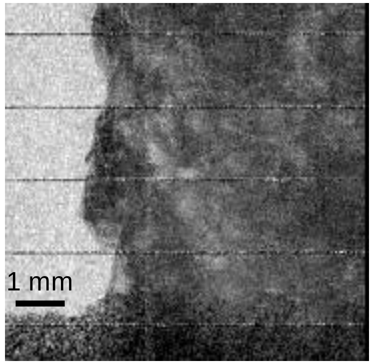
A. Doherty et al. *'Femtosecond multimodal imaging with a laser-driven x-ray source'.*
Comm. Physics, in review

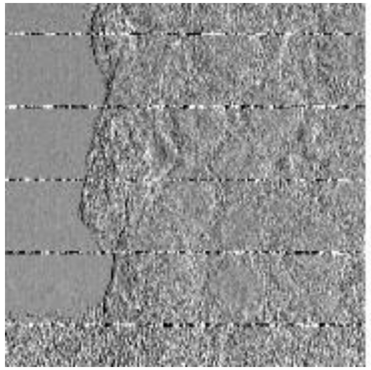
No dithering

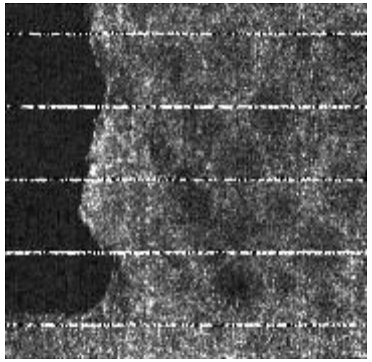
50 shots

Parameters

- Binning 2: Pixel size 39x30 um







Transmission

Refraction

Scattering

Single shot

Parameters

- Binning 8: Pixel size 39x120 um

Factor 12 in statistics

Scaling

- Laser power: 145 TW 750W, factor 3
- Tailored plasma: up to factor 100
- More efficient detector

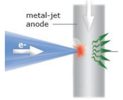
Resolution

- Masks: 2 um aperture, 7 um period
- Similar statistics
- Higher resolution

A. Doherty et al. *'Femtosecond multimodal imaging with a laser-driven x-ray source'.* Comm. Physics, in review

Challenges:

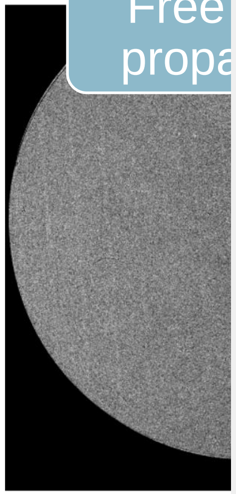
Main Challenge



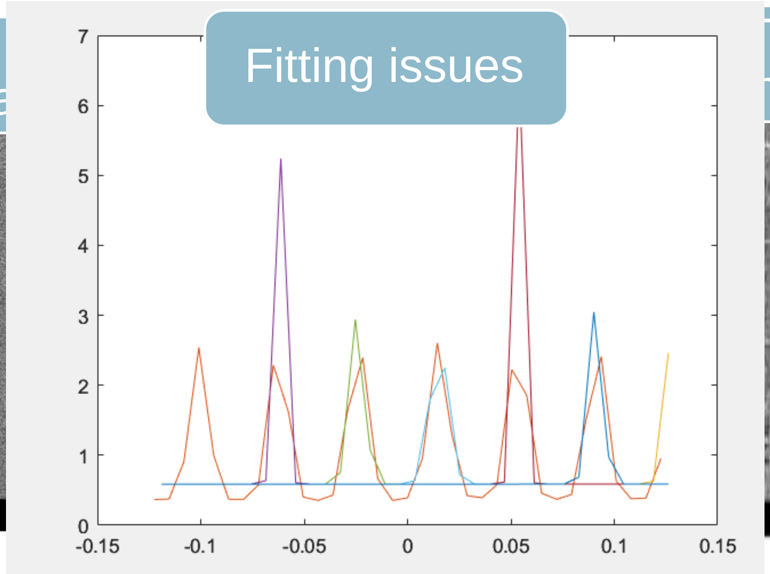
Spectral variations

More robust fitting

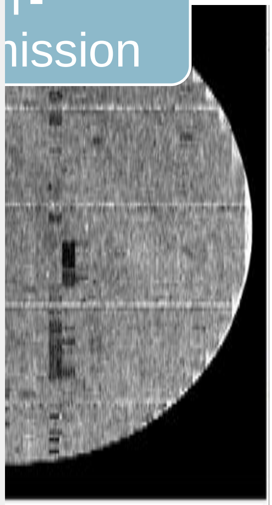
Flat battery cell 8 mm diameter



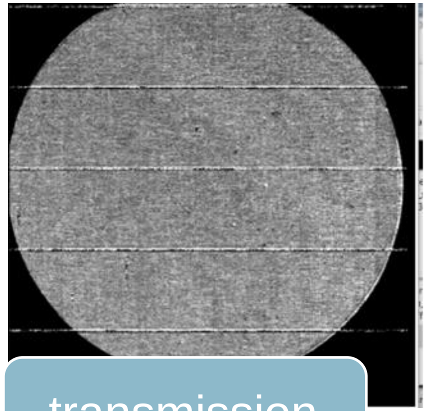
Free propa



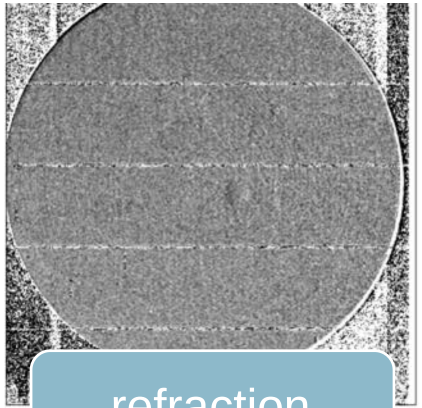
Fitting issues



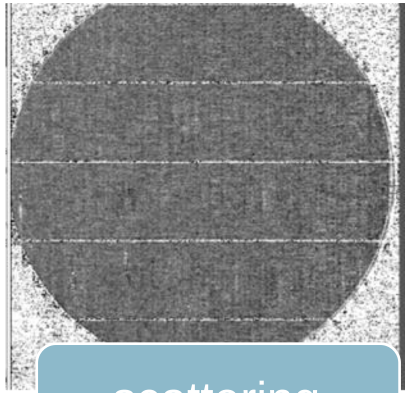
T-
nission



transmission



refraction



scattering

ADVANCED X-RAY IMAGING

Thank you!

University of Sheffield
Imperial College London
UKRI Science and Technology Facilities Council | Central Laser Facility
HZB Helmholtz Zentrum Berlin
INRS Institut national de la recherche scientifique
ALLS Advanced Laser Light Source
diamond
GHENT UNIVERSITY
UKRI Engineering and Physical Sciences Research Council
THE ROYAL SOCIETY
wellcome trust
Royal Academy of Engineering

https://www.ucl.ac.uk/medical-physics-biomedical-engineering/research/research-groups/advanced-x-ray-imaging-group-axim

s.cipiccia@ucl.ac.uk

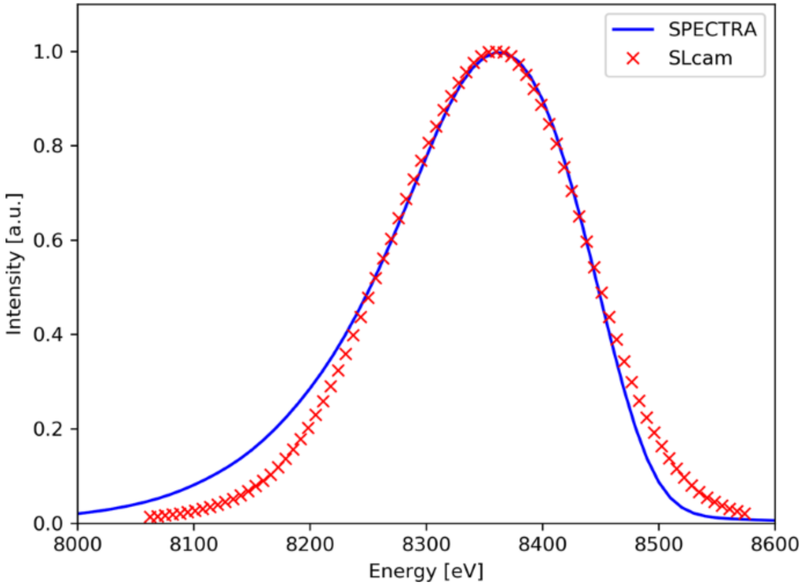
AXIM
ADVANCED X-RAY IMAGING

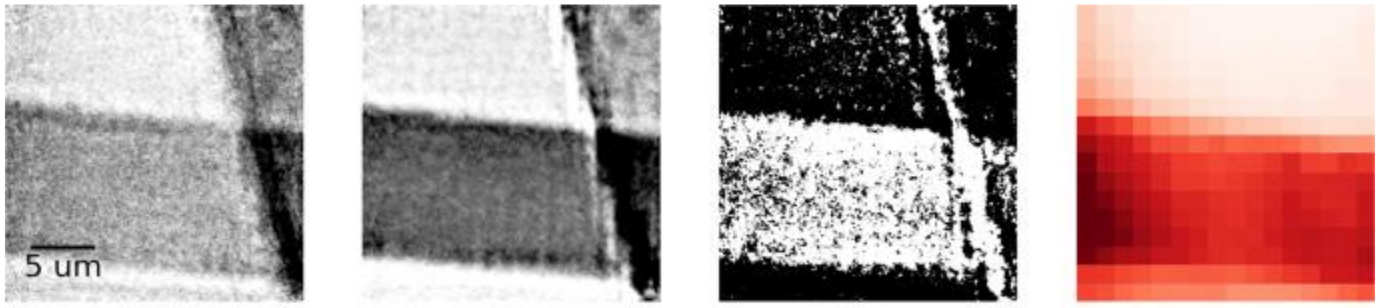
GHENT UNIVERSITY | diamond | UKRI Science and Technology Facilities Council | UCL

Broadband ptychography

Detector as monochromator

- Hyperspectral detectors (e.g. Hexitec, SLcam)
- Edge subtraction
- Scanning Ni edge in a single acquisition
- Limitation:
  - Not compatible with high flux
  - Resolution limited by the detector bandwidth





(a) (b) (c) (d)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Spectroscopic imaging with single acquisition ptychography and a hyperspectral detector

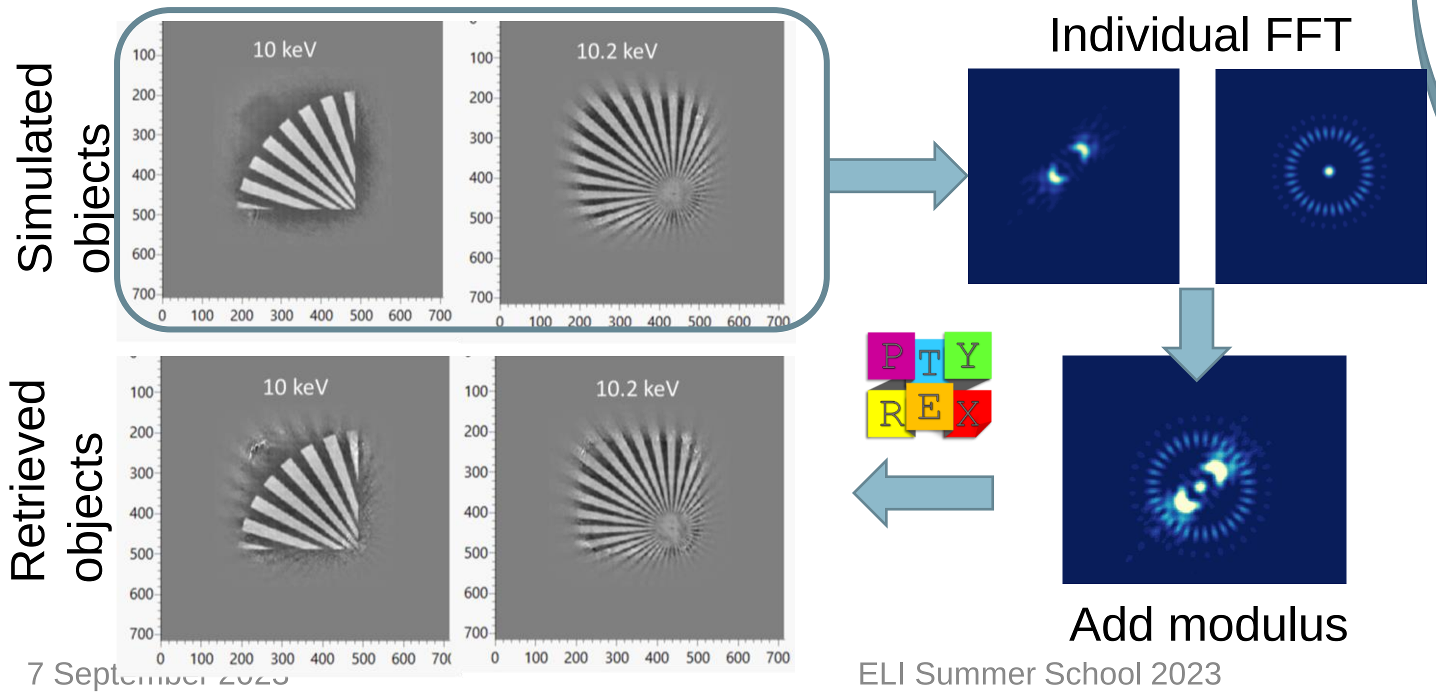
Darren J. Batey, Silvia Cipiccia, Frederic Van Assche, Sander Vanheule, Juriaan Vanmechele, M…thieu N… Boone & Christoph Rau

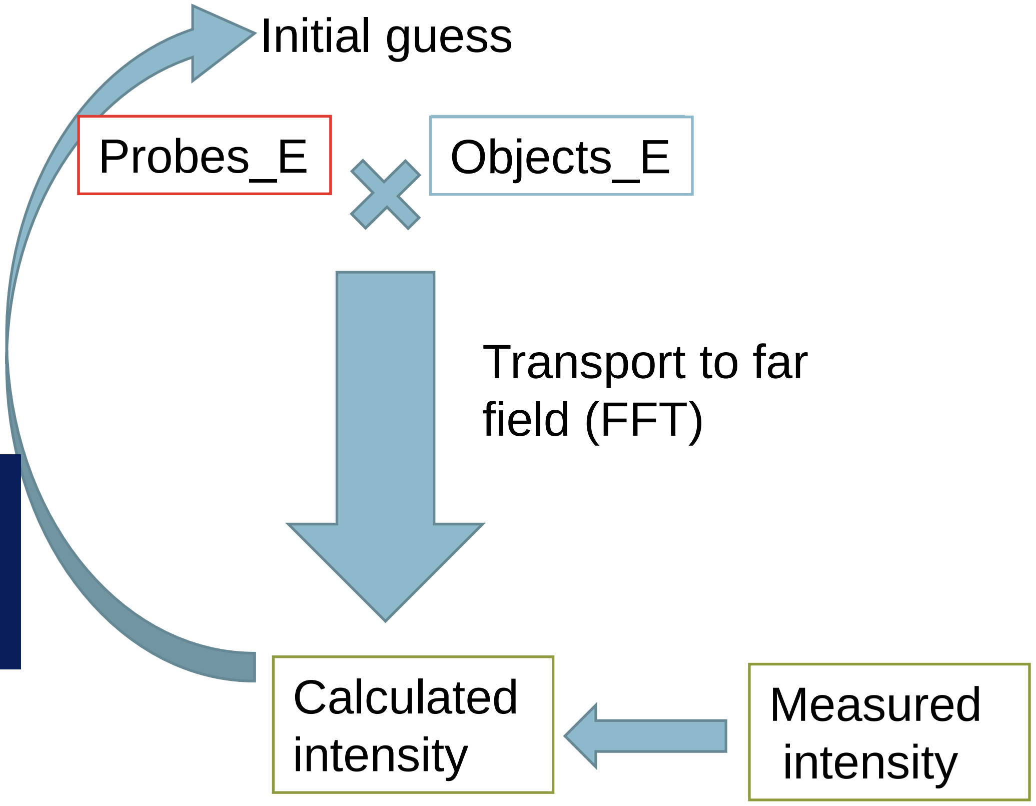
AXIM ADVANCED X-RAY IMAGING

Broadband ptychography

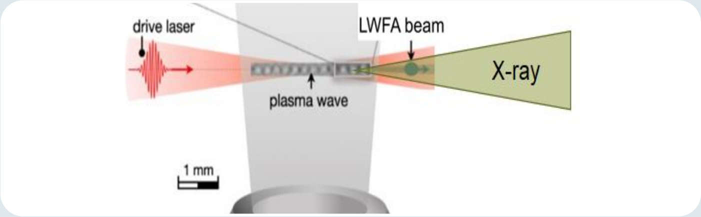
Algorithm as monochromator

- Modify standard algorithm
  - Multiple illuminations (one per energy)
  - Multiple objects (one per energy)





Laser-driven x-ray sources



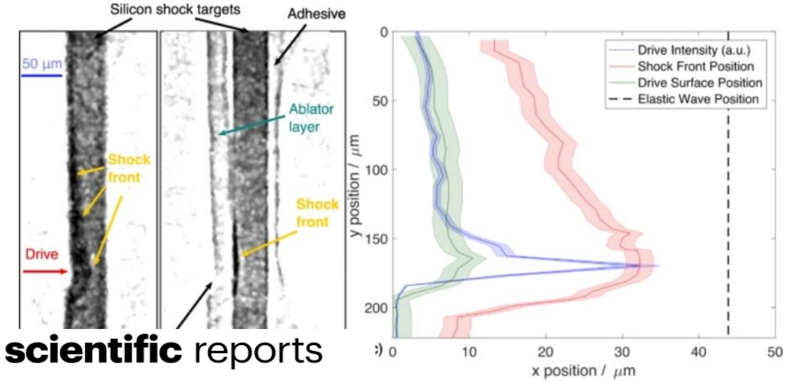
Unique Features

- Compact
- Femtosecond pulse duration
- Small source size → high spatial coherence

To exploit at the best:

- Single-shot: to make sue of the femtosecond time resolution
- Multimodal: access multiple information in one acquisition

Ultra-fast imaging



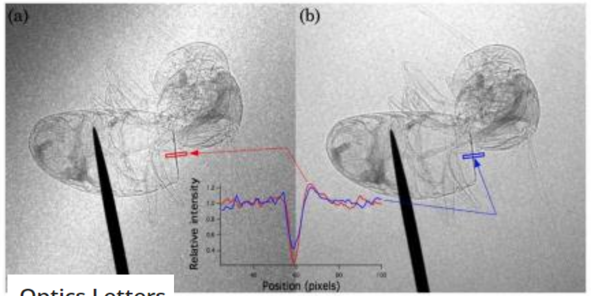
scientific reports

Ultrafast Imaging of Laser Driven Shock Waves using Betatron X-rays from a Laser Wakefield Accelerator

J. C. Wood, D. J. Chapman, K. Poder, N. C. Lopes, M. E. Rutherford, T. G. White, F. Albert, K. T. Behm, N. Booth, J. S. J. Bryant, P. S. Foster, S. Glenzer, E. Hill, K. Krushelnick, Z. Najmudin, B. B. Pollock, S. Rose, W. Schumaker, R. H. H. Scott, M. Sherlock, A. G. R. Thomas, Z. Zhao, D. E. Eakins & S. P. D. Mangles

Scientific Reports 8, Article number: 11010 (2018) | Cite this article

Phase Contrast



Optics Letters

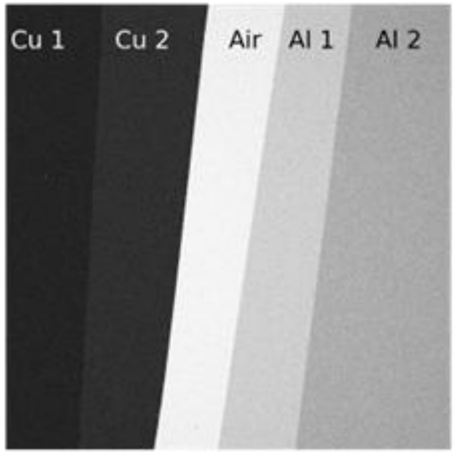
Single shot phase contrast imaging using laser-produced Betatron x-ray beams

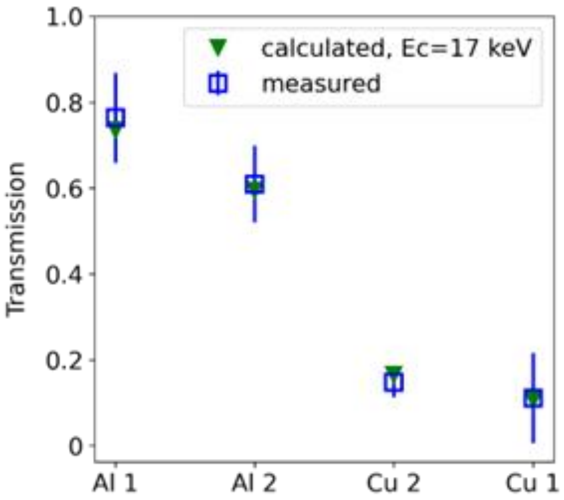
S. Fourmaux,[1,*] S. Corde,[2] K. Ta Phuoc,[2] P. Lassonde,[1] G. Lebrun,[1] S. Payeur,[1] F. Martin,[1] S. Sebban,[2] V. Malka,[2] A. Rousse,[2] and J. C. Kieffer[1]

AXIM ADVANCED X-RAY IMAGING

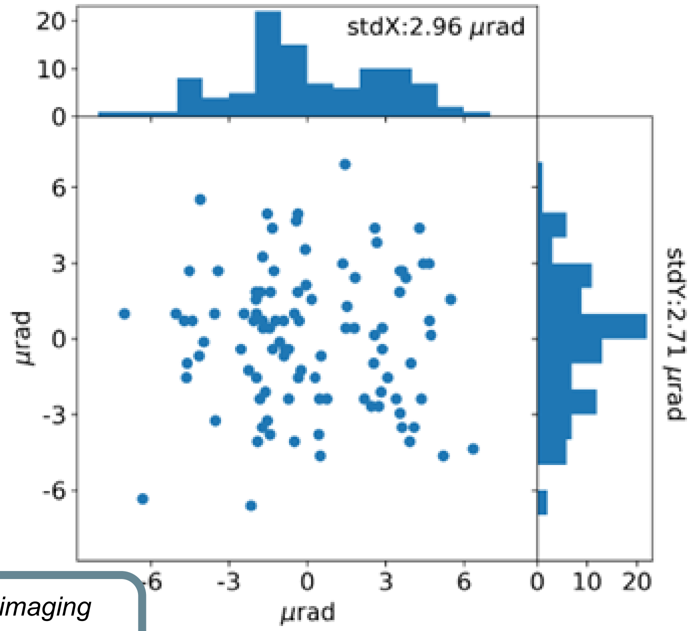
Source characterization

Energy Spectrum





Source pointing



A. Doherty et al. *'Femtosecond multimodal imaging with a laser-driven x-ray source'.*
Comm. Physics, in review