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X-ray speckle-based phase-contrast imaging – state of the art and future

Marie-Christine Zdora[1,2,3], Pierre Thibault[1], Irene Zanette[1]

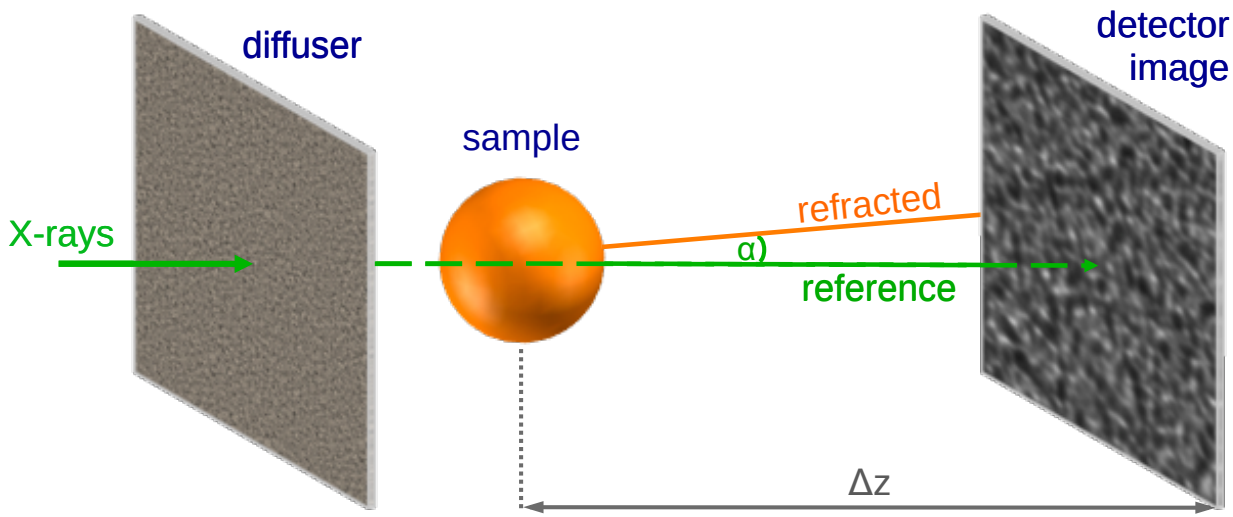
m.zdora@soton.ac.uk

[1]Department of Physics & Astronomy, University of Southampton, SO17 1BJ, UK
[2]Department of Physics & Astronomy, University College London, WC1E 6BT, UK
[3]Diamond Light Source, Harwell Science and Innovation Campus, OX11 0DE, UK

Workshop on Coherence at ESRF-EBS

10 September 2019

X-ray speckle-based imaging



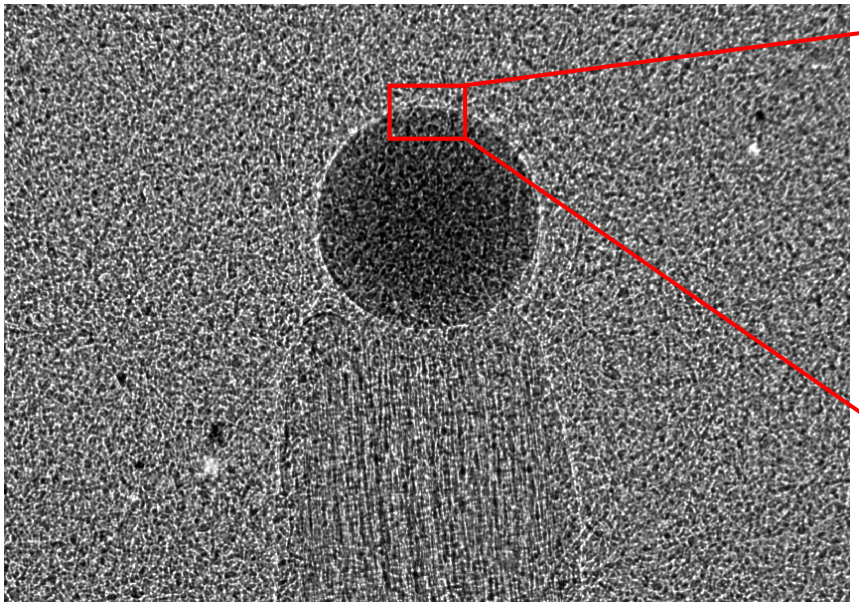
S. Berujon et al., Phys. Rev. A 86, 063813 (2012).

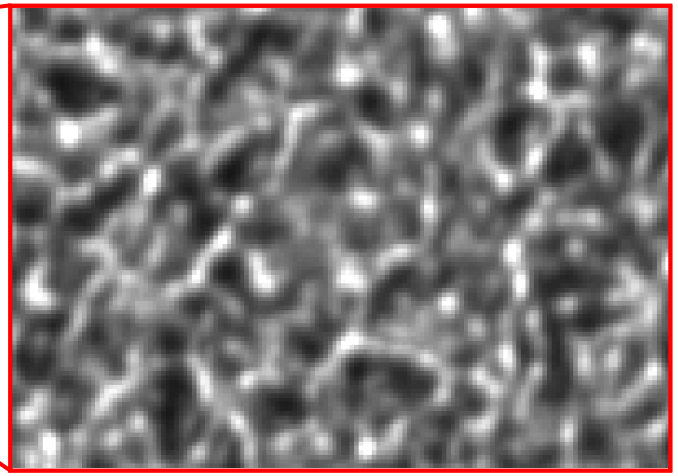
K. Morgan et al., Appl. Phys. Lett. 100, 124102 (2012).

refraction in sample

$$\alpha_{x,y} = \frac{1}{k}\frac{\partial \Phi}{\partial x, y} = \frac{v_{x,y}}{\Delta z}$$

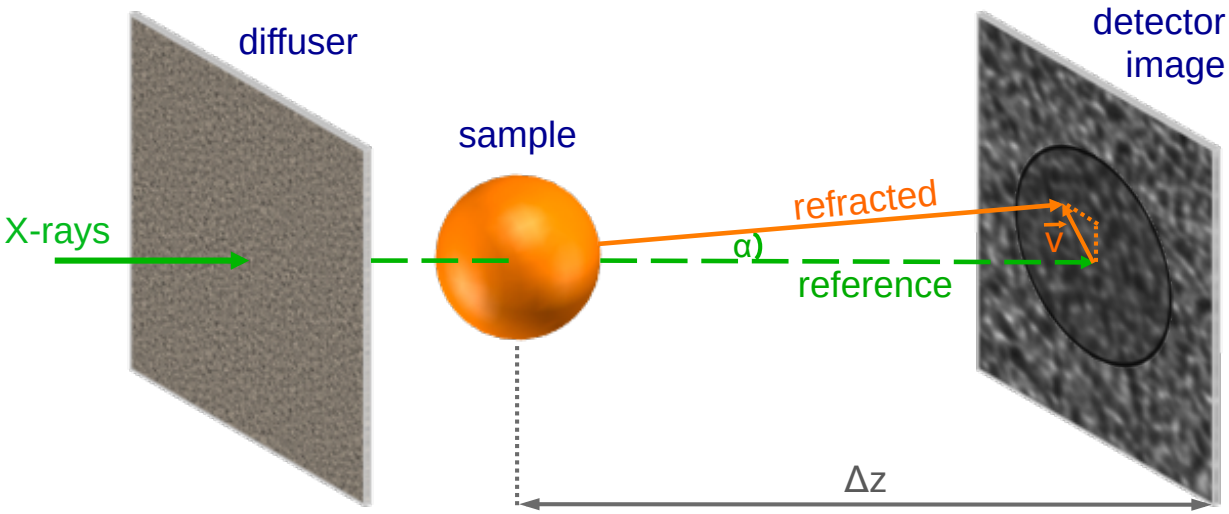
displacement of speckle pattern





M. Zdora et al., J. Instrum. 13, C05005 (2018).

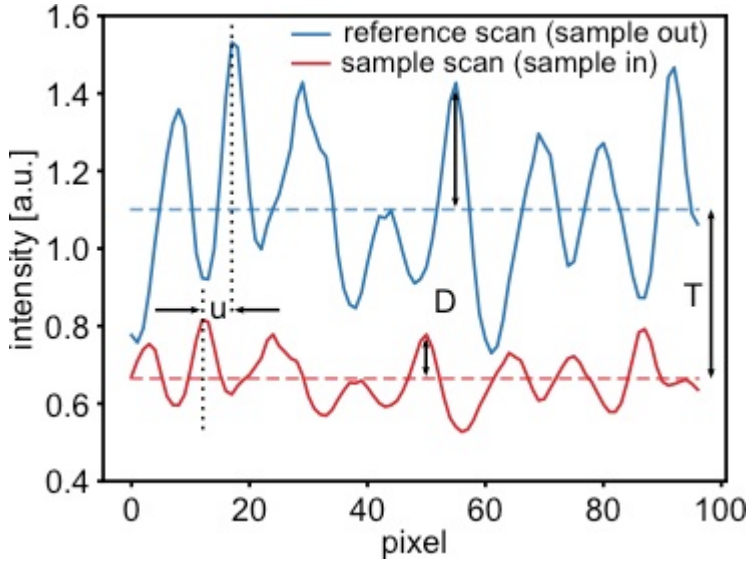
X-ray speckle-based imaging



S. Berujon et al., Phys. Rev. A 86, 063813 (2012).

K. Morgan et al., Appl. Phys. Lett. 100, 124102 (2012).

$$\alpha_{x,y} = \frac{1}{k}\frac{\partial \Phi}{\partial x, y} = \frac{v_{x,y}}{\Delta z}$$



3 complementary image signals:

- Differential phase in horizontal *and* vertical direction
- Transmission
- Dark field (small-angle scattering)

M. Zdora et al., J. Instrum. 13, C05005 (2018).

X-ray speckle-based imaging

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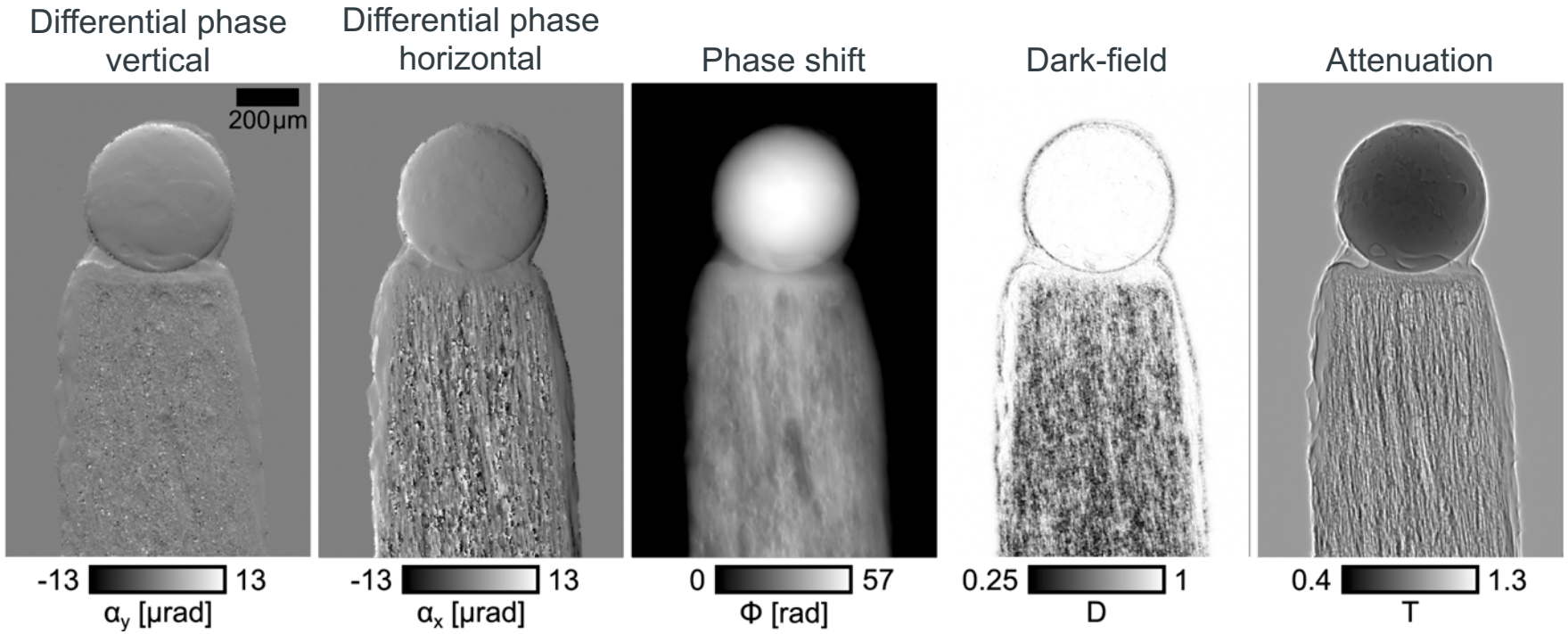

M. Zdora et al., J. Instrum. 13, C05005 (2018).

3 complementary image signals:

- Differential phase in horizontal *and* vertical direction
- Dark-field (small-angle scattering)
- Attenuation

State of the art of speckle imaging

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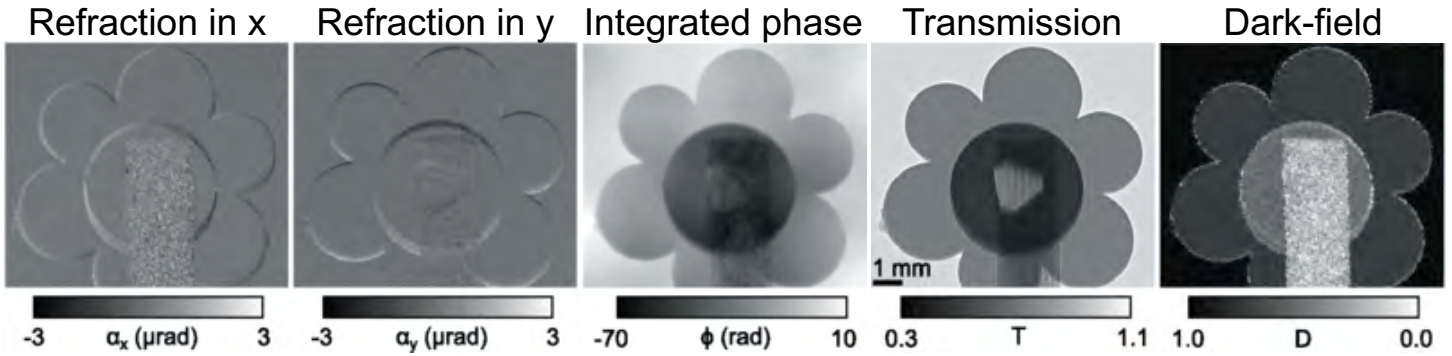
M. Zdora, J. Imaging 4, 60 (2018) [review article].

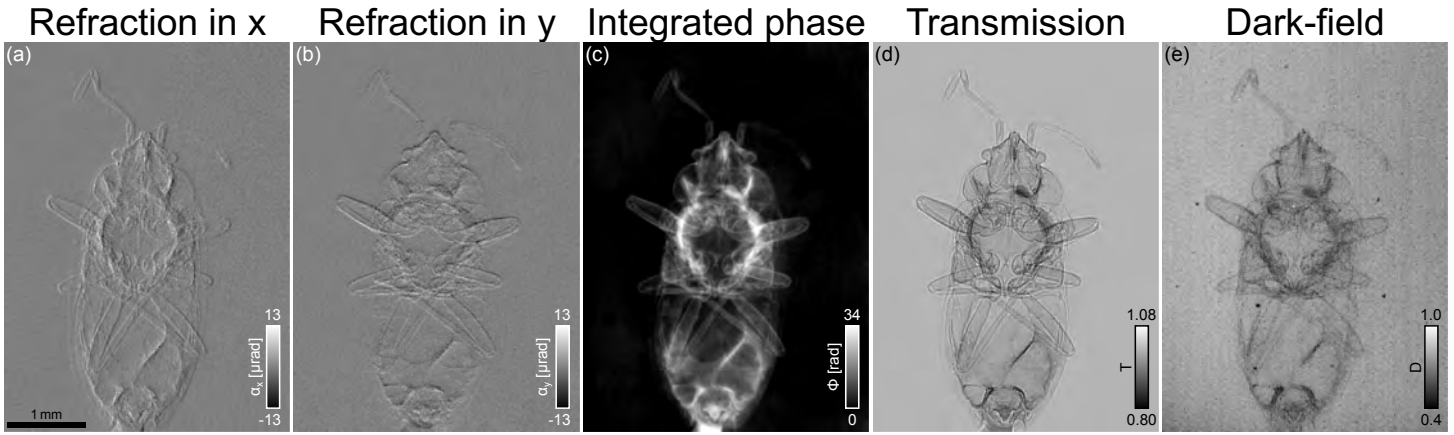
Developments:

- Translation to polychromatic laboratory sources

Plastic flower on wooden support and bug imaged at liquid-metal-jet sources (Excillum)



I. Zanette et al., Phys. Rev. Lett. 112, 253903 (2014).



M. Zdora, PhD thesis (2019).

State of the art of speckle imaging

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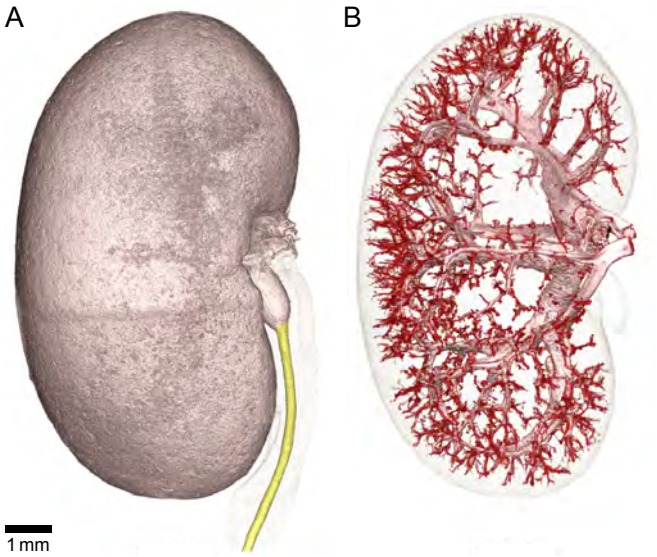
Developments:

- Translation to polychromatic laboratory sources
- Speckle-based tomography

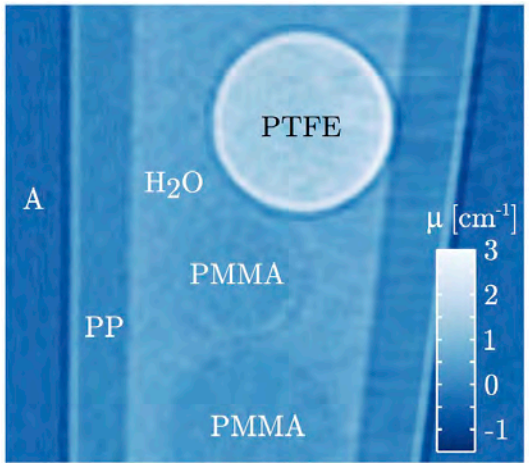
Speckle tomography of a mouse kidney



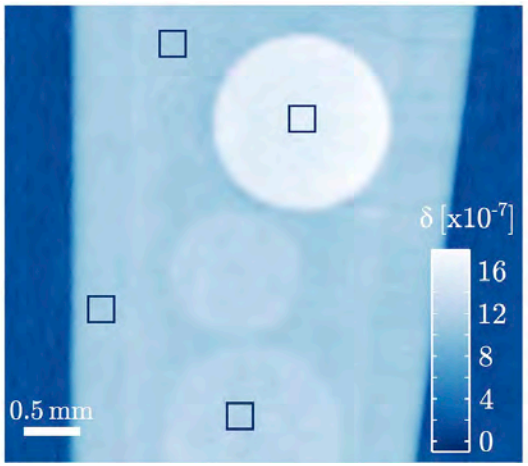
M. Zdora et al., submitted.

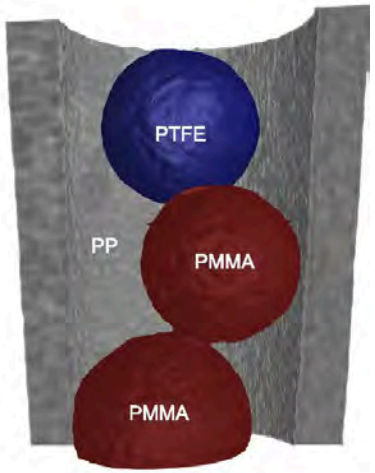
Speckle tomography of plastic spheres at a liquid metal-jet source (Excillum)

Absorption tomogram



Phase tomogram





I. Zanette, M. Zdora et al., Proc. Natl. Acad. Sci. USA 112, 12569-12573 (2015).

State of the art of speckle imaging

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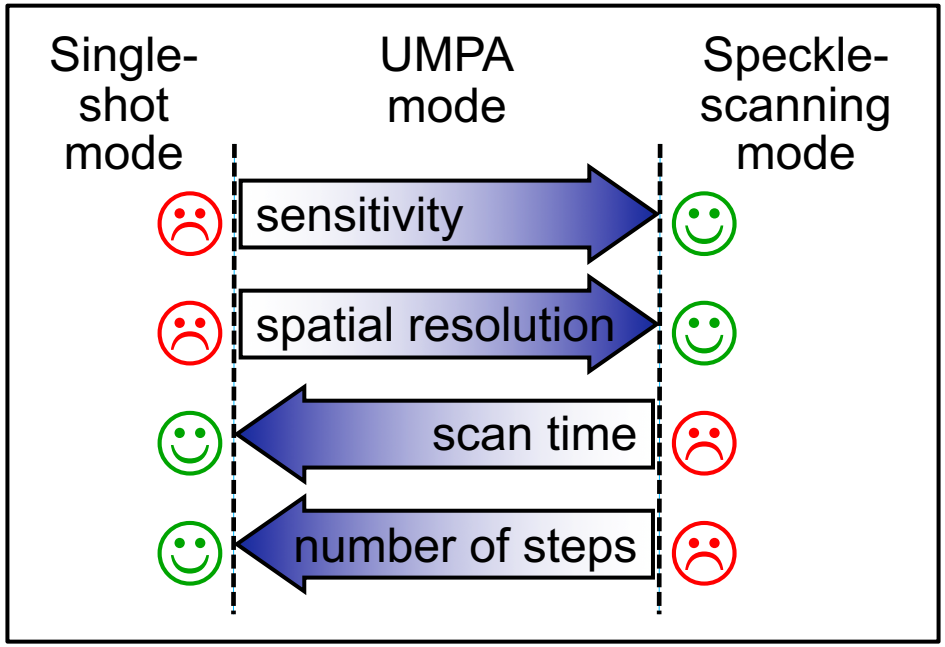
Developments:

- Translation to polychromatic laboratory sources
- Speckle-based tomography
- Progresses in data acquisition schemes and reconstruction algorithms



State of the art of speckle imaging

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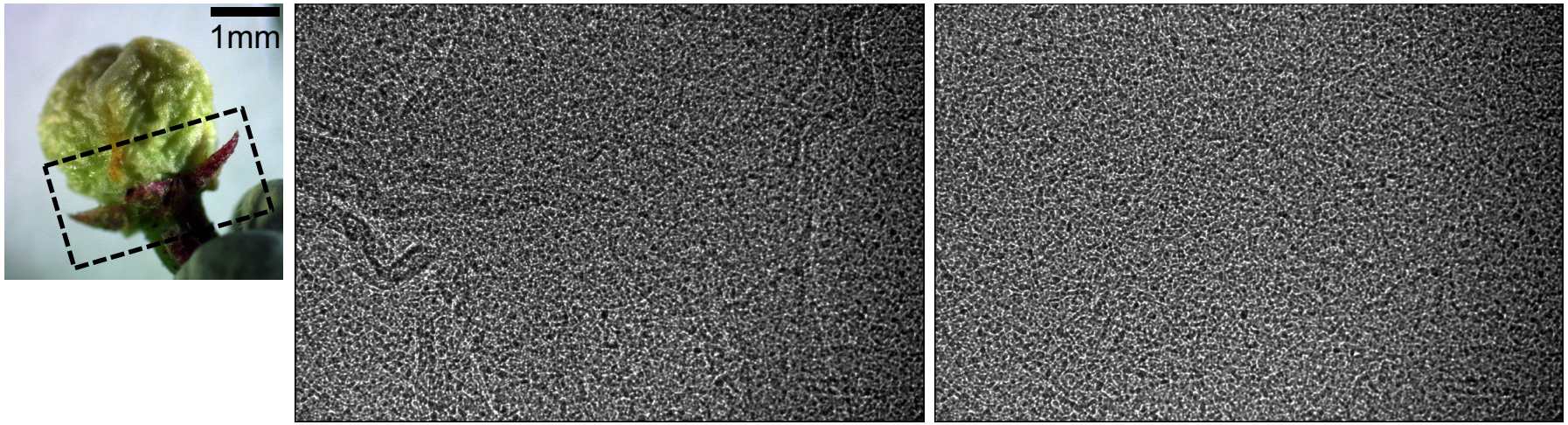
Developments:

- Translation to polychromatic laboratory sources
- Speckle-based tomography
- Progresses in data acquisition schemes and reconstruction algorithms

UMPA:

- Random step pattern
- Large step sizes
- Small number of steps
- Tuning of sensitivity, resolution, scan time
- Random as well as periodic reference patterns

Data acquisition with the unified modulated pattern analysis (UMPA)



M. Zdora et al., Phys. Rev. Lett. 118, 203903 (2017).

X-ray energy: 19 keV; Effective pixel size: 0.40 µm;
Sample-detector distance: 34 cm

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M. Zdora, J. Imaging 4, 60 (2018) [review article].

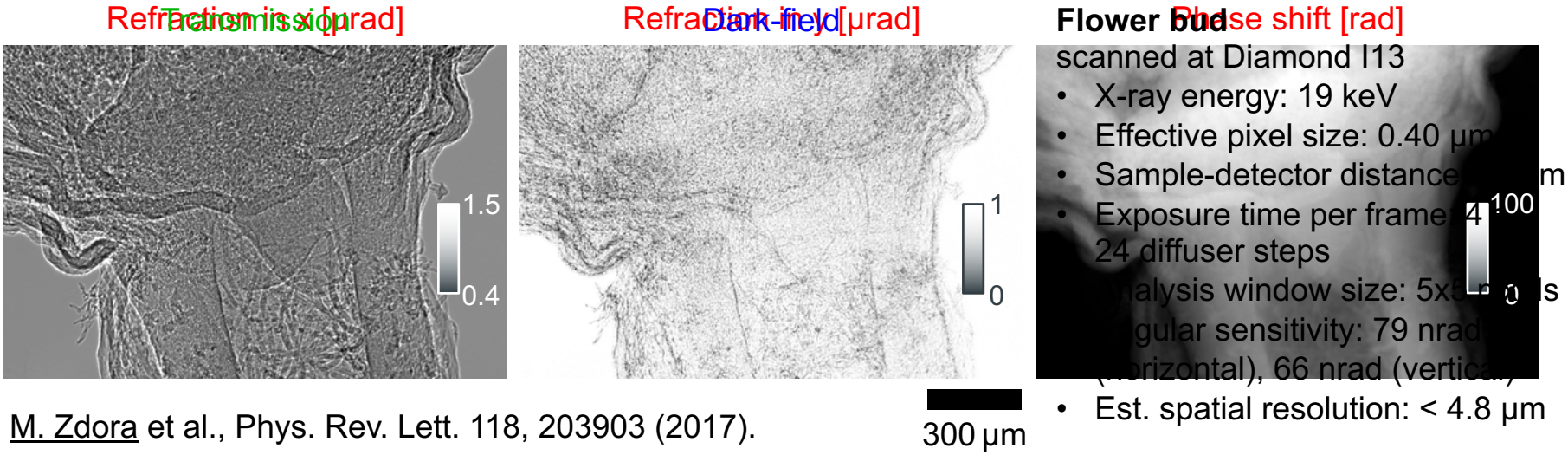
Developments:

- Translation to polychromatic laboratory sources
- Speckle-based tomography
- Progresses in data acquisition schemes and reconstruction algorithms

UMPA:

- Random step pattern
- Large step sizes
- Small number of steps
- Tuning of sensitivity, resolution, scan time
- Random as well as periodic reference patterns
- Differential phase (x and y), transmission and dark-field

Data reconstruction with the unified modulated pattern analysis (UMPA)



Flower bud
scanned at Diamond I13

- X-ray energy: 19 keV
- Effective pixel size: 0.40 µm
- Sample-detector distance m
- Exposure time per frame 4
  24 diffuser steps
  nalysis window size: 5x8 s
  gular sensitivity: 79 nrad
  (horizontal), 66 nrad (vertical)
- Est. spatial resolution: < 4.8 µm

M. Zdora et al., Phys. Rev. Lett. 118, 203903 (2017).

State of the art of speckle imaging

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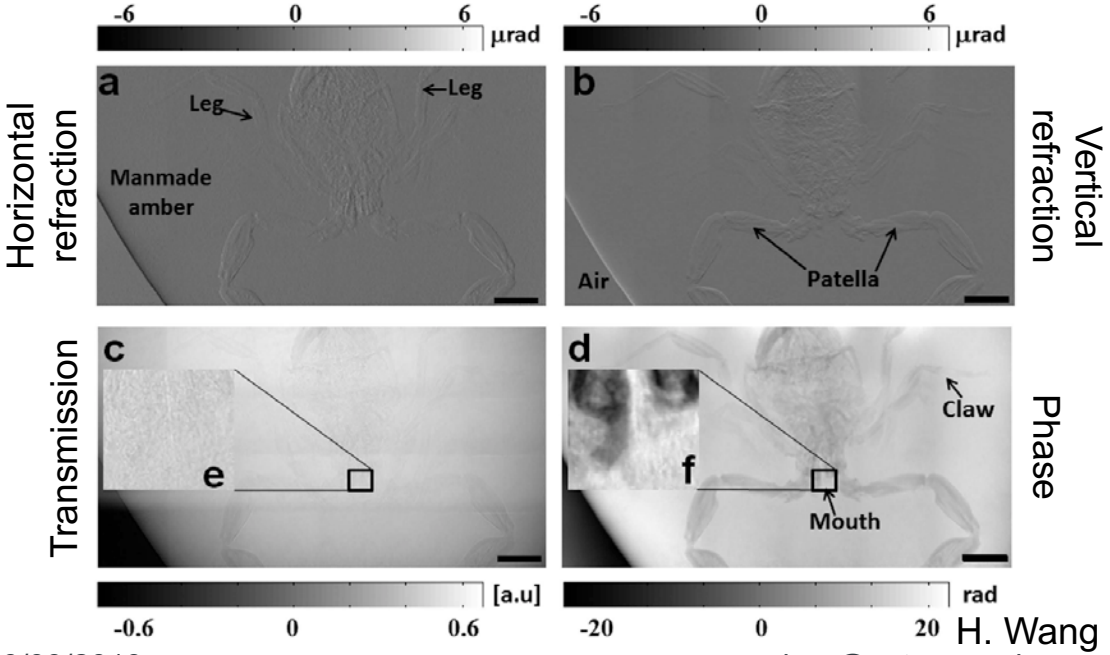
M. Zdora, J. Imaging 4, 60 (2018) [review article].

Developments:

- Translation to polychromatic laboratory sources
- Speckle-based tomography
- Progresses in data acquisition schemes and reconstruction algorithms
- Extension to high-energy X-rays

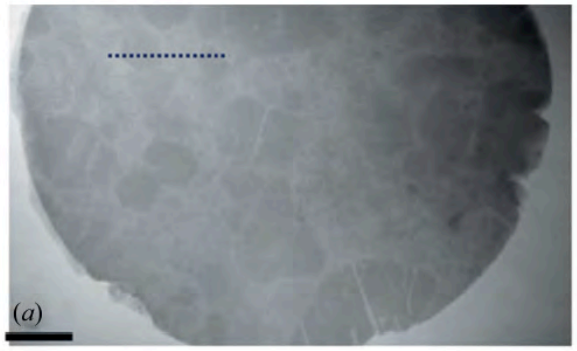
Imaging of a scorpion in manmade amber at 60 keV



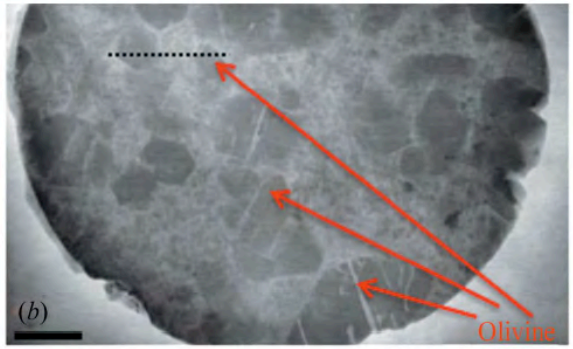
H. Wang et al., Sci. Rep. 6, 30581 (2016).

Imaging of a thin slice of picrite rock at 53 keV

Transmission



Phase



H. Wang et al., J. Synchrotron Radiat. 25, 1182-1188 (2018).

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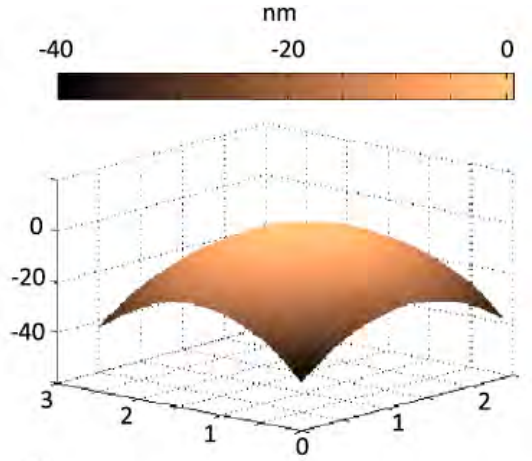
M. Zdora, J. Imaging 4, 60 (2018) [review article].

Applications:

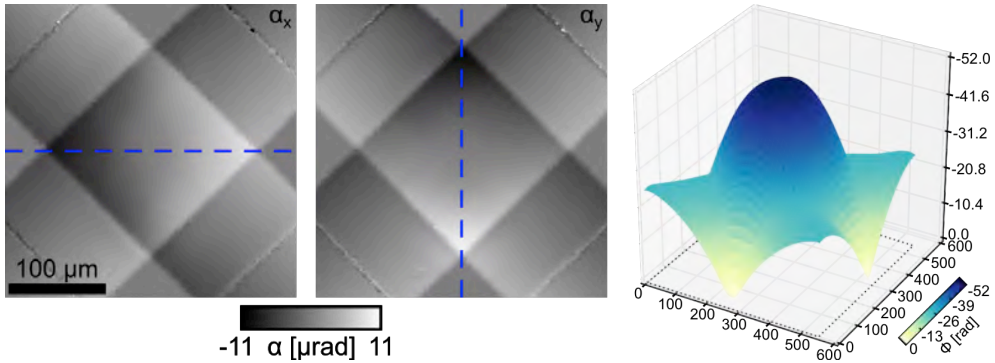
- Optics characterisation & beam phase sensing

Reconstruction of an X-ray wavefront

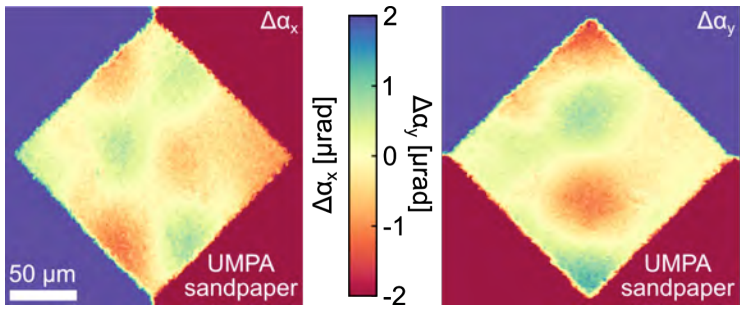


S. Berujon et al., Phys. Rev. Lett. 108, 158102 (2012).

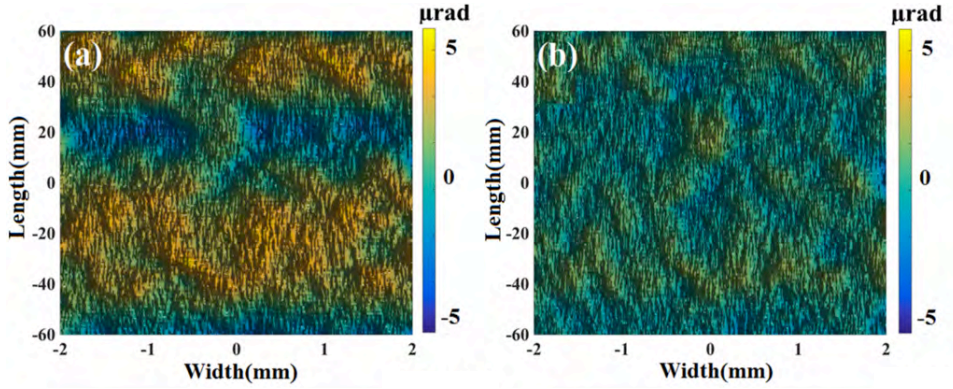
Characterisation of an X-ray refractive lens



Optimisation of a bimorph mirrors



M. Zdora et al., Phys. Rev. Lett. 118, 203903 (2017).
M. Zdora et al., Opt. Express 26, 4989-5004 (2018).



Y. Kashyap et al., Rev. Sci. Instrum. 87, 052001 (2016).

State of the art of speckle imaging

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M. Zdora, J. Imaging 4, 60 (2018) [review article].

Applications:

- Optics characterisation & beam phase sensing
- Biomedical imaging

Virtual histology of an unstained, hydrated mouse kidney

Parameters: @ESRF ID19

- Mean X-ray energy: 25.6 keV (single harmonic undulator)
- Effective pixel size: 3.1 µm
- Sample-detector dist: 0.65 m
- Exposure time: 50 ms
- 20 diffuser steps
- Analysis window: 5x5 pixels

State of the art of speckle imaging

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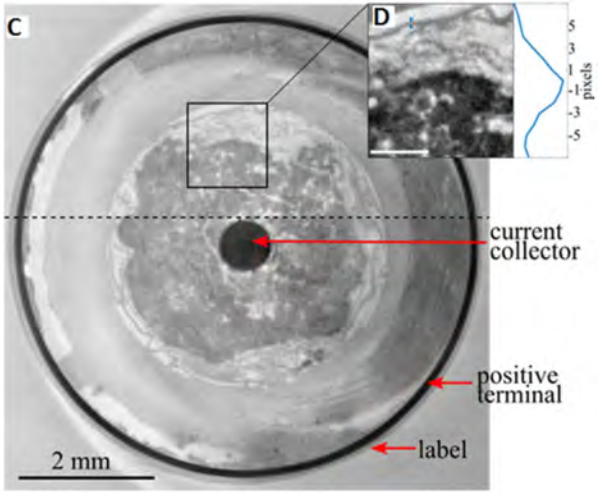
M. Zdora, J. Imaging 4, 60 (2018) [review article].

Applications:

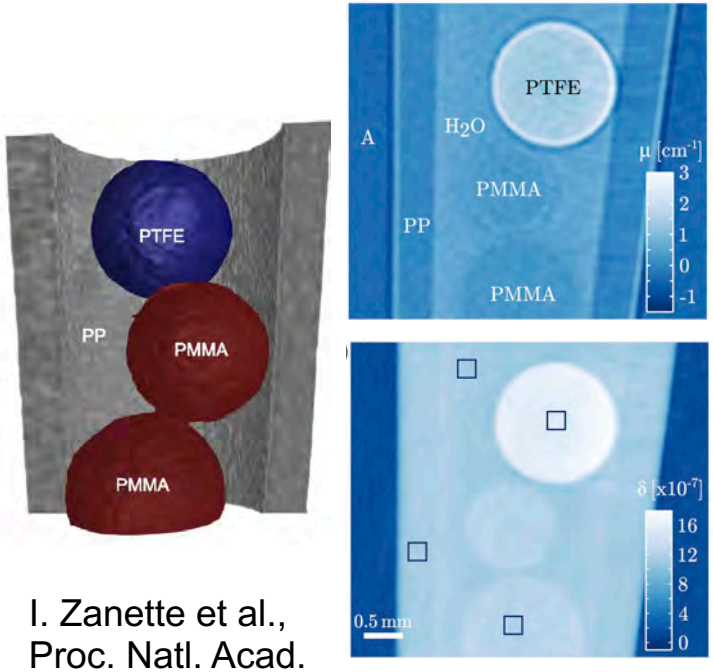
- Optics characterisation & beam phase sensing
- Biomedical imaging
- Materials science and material characterisation

Phase tomography of a battery



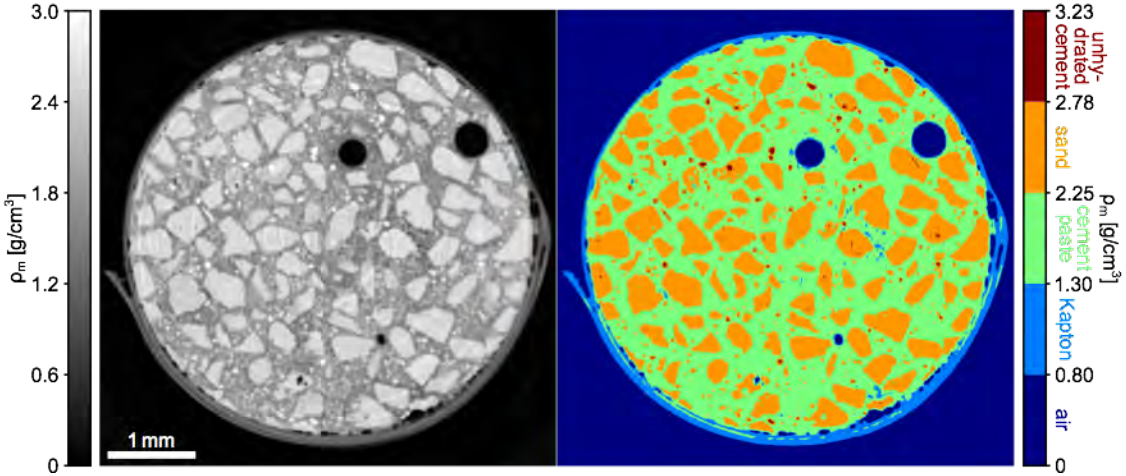
H. Wang et al., Sci. Rep. 9, 8913 (2019).

Identification of different types of plastic



I. Zanette et al., Proc. Natl. Acad. Sci. USA 112, 12569-12573 (2015).

Identification of different components in a mortar sample



M. Zdora, PhD thesis (2019).

State of the art of speckle imaging

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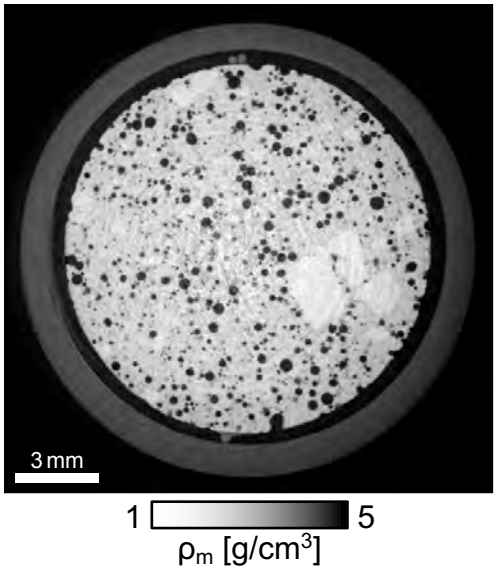
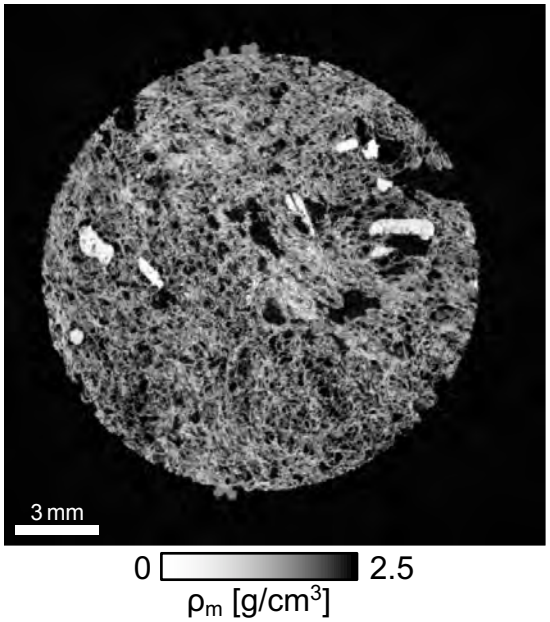
M. Zdora, J. Imaging 4, 60 (2018) [review article].

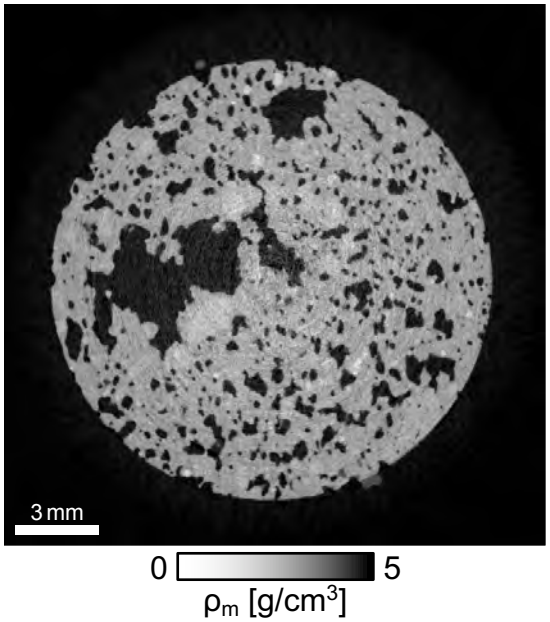
Applications:

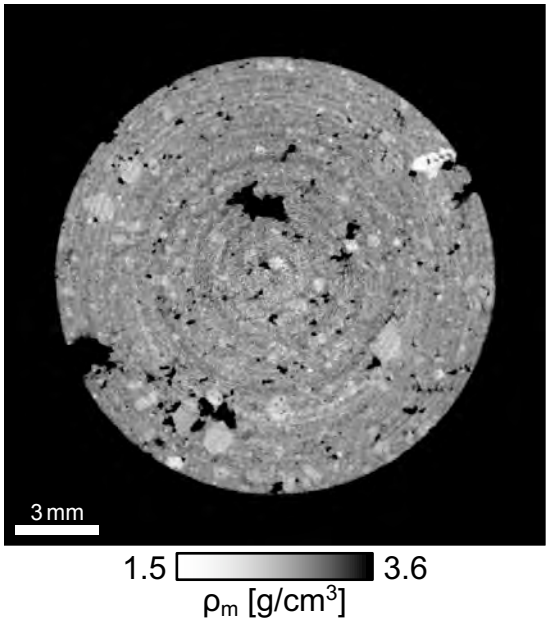
- Optics characterisation & beam phase sensing
- Biomedical imaging
- Materials science and material characterisation
- Geology



Phase tomography of volcanic rocks at 53 keV







M. Zdora, PhD thesis (2019).

Potential of speckle imaging at ESRF-EBS

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Benefits and possibilities of high transverse coherence and coherent flux

- High visibility of the speckle pattern, well-defined speckles
  → improved sensitivity
- Improved speckle visibility at high X-ray energies
  → new applications (thicker, denser samples), materials science, geology, …
- Longer transverse coherence length → feasibility of using larger diffuser grains
  → possibility of larger field of view, wider samples
- Combination of speckle-based imaging with other techniques relying on spatial coherence, e.g. holotomography, (near-field) ptychography, …
- Faster scans → higher sample throughput

Caveats

- More Fresnel fringes around sample features upon propagation
  → artefacts at interfaces
- More interference fringes from optical components

Future directions for speckle-based imaging at ESRF-EBS

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- Theoretical evaluation/simulations of speckle visibility under conditions of increased coherence
- Extension of reconstruction algorithms to handle strong Fresnel fringes at interfaces
- First tests on combining speckle imaging with other techniques for multi-scale imaging approaches and improved image quality
- Speckle-based imaging as a tool for beam phase sensing and coherence measurement
- Megahertz frame rate speckle-based differential phase-contrast imaging for time-resolved studies
- Further work on technique development of speckle-based imaging, such as dark-field imaging, optimisation of diffusers and setups, algorithms etc.

Acknowledgements

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Frieder Koch

excillum
REDEFINING THE X-RAY TUBE

Fei Yang

IMT

Arndt Last

Thank you for your attention!