

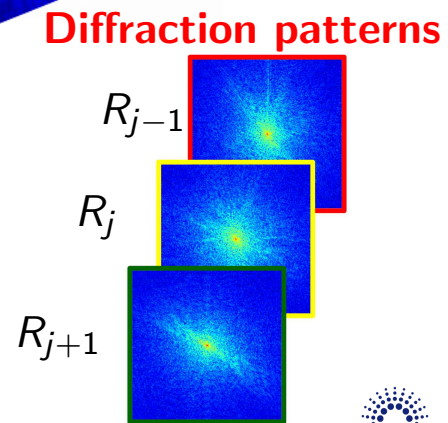
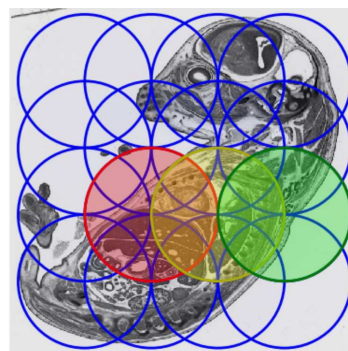
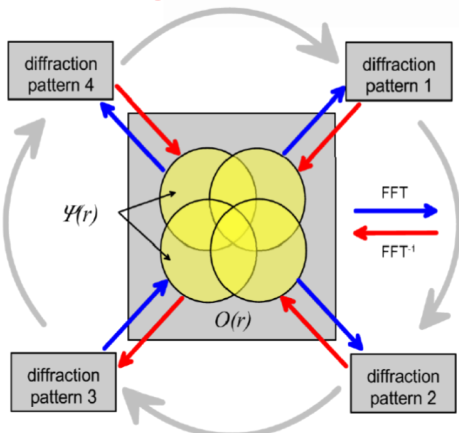
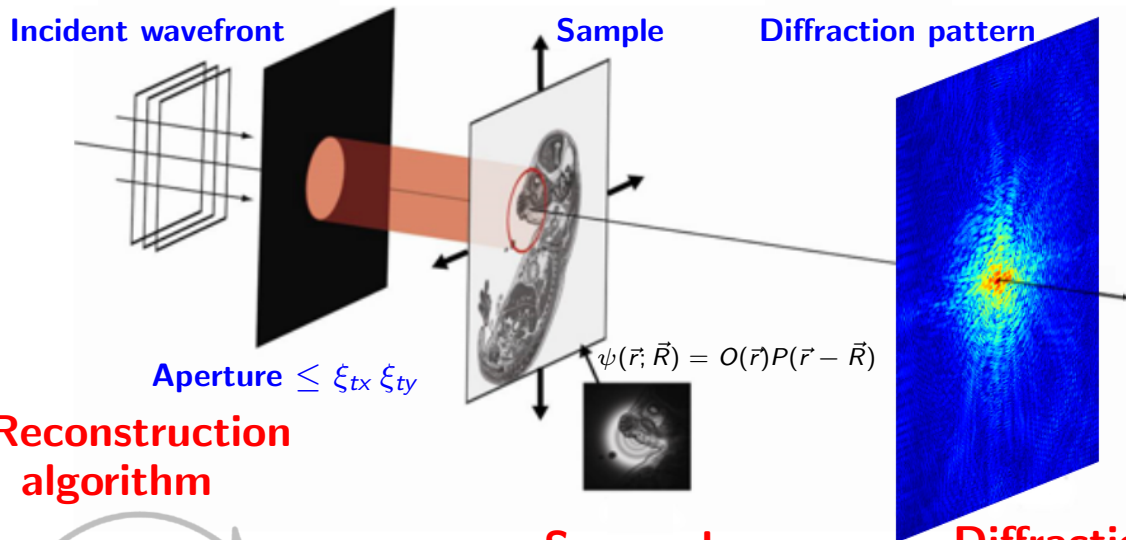
Quantitative X-ray ptychographic imaging: present and future innovations

Julio Cesar da Silva^{1,*}

¹ID16A Nano-imaging beamline
ESRF - The European Synchrotron, France

*e-mail: jdasilva@esrf.fr

Transverse diversity - Far-field X-ray Ptychography exploiting the transverse diversity

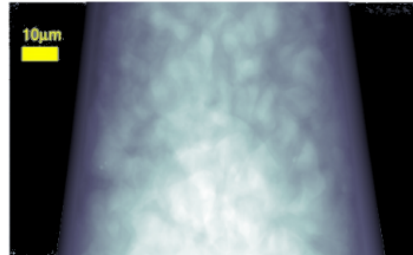


Welcome to the third dimension

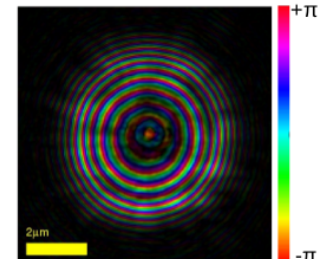
Amplitude



Phase



Probe



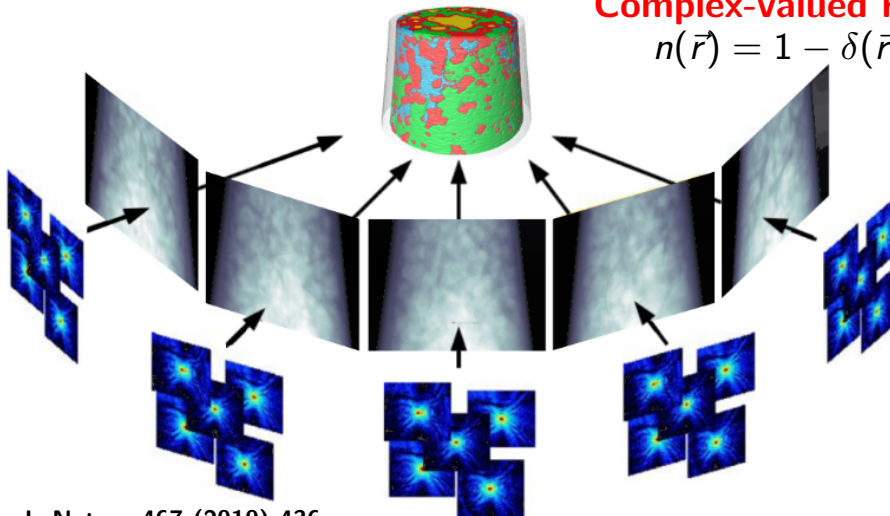
J. C. da Silva et al. Langmuir 31 (2015) 3779

brightness : amplitude
color : phase

Ptychographic X-ray Computed Tomography (PXCT)

Complex-valued refractive index

$$n(\vec{r}) = 1 - \delta(\vec{r}) + i\beta(\vec{r})$$

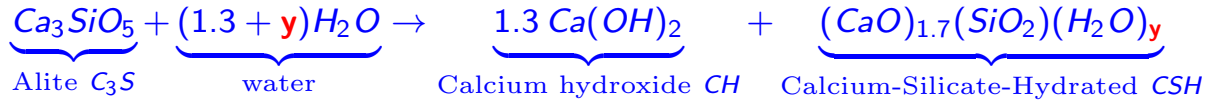


M. Dierolf et al. Nature 467 (2010) 436

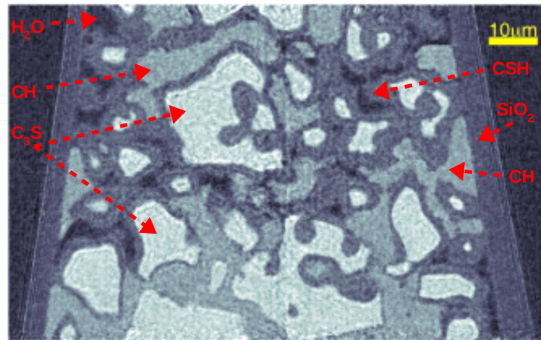


ESRF

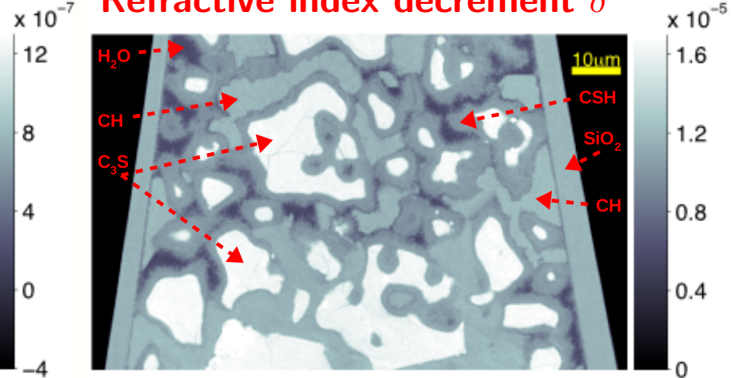
Chemical imaging of hydrated ordinary cement



Absorption index β



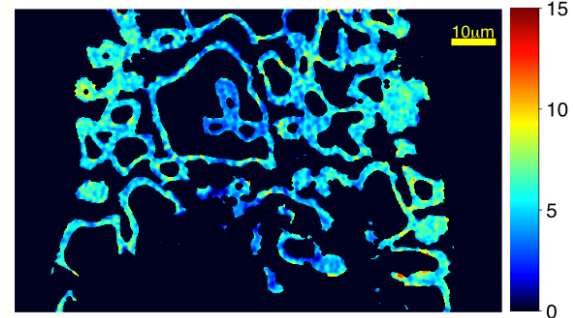
Refractive index decrement δ



$$\left(\frac{\mu}{\rho}\right)_{CSH} = \omega_{CaO} \left(\frac{\mu}{\rho}\right)_{CaO} + \omega_{SiO_2} \left(\frac{\mu}{\rho}\right)_{SiO_2} + \omega_{H_2O} \left(\frac{\mu}{\rho}\right)_{H_2O}$$

Materials	ρ ($g.cm^{-3}$)	$\rho_{att.}$ ($g.cm^{-3}$)
Water	0.99 ± 0.01	1.00
CH	2.18 ± 0.01	2.211
C ₃ S	3.10 ± 0.01	3.064
Capillary	2.19 ± 0.01	2.203
CSH _(y=5.2±0.4)	1.83 ± 0.01	$1.83(y = 5)$

Water content of CSH:

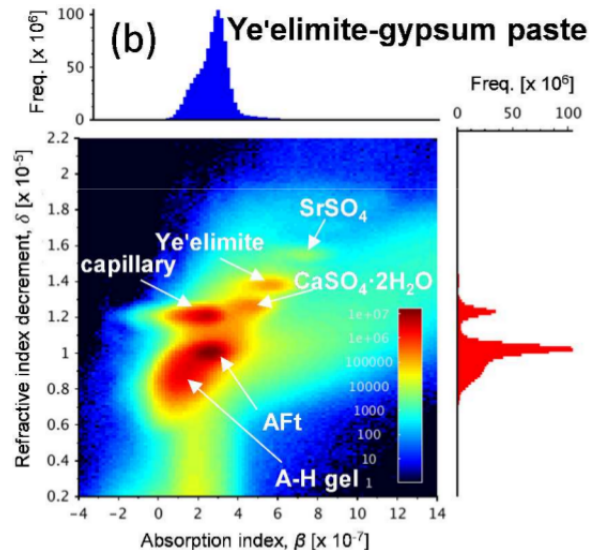
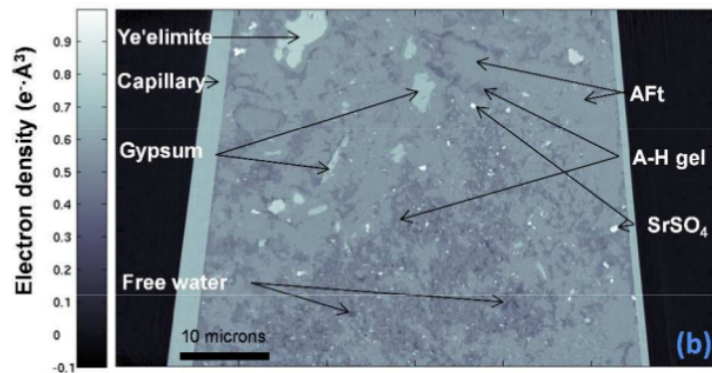
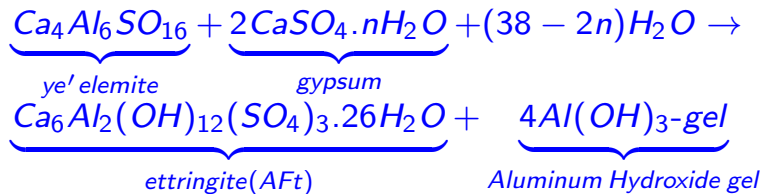


J. C. da Silva et al., Langmuir 31 (2015) 3779.



ESRF

Hydration of eco-friendly cement based on ye'elemite



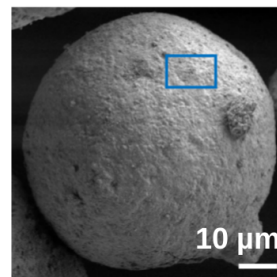
Materials	vol%	mass density ($g \cdot cm^{-3}$)	Expected ($g \cdot cm^{-3}$)
Ye'elemite	3.6	2.58	2.60
Ettringite (AFt)	69.7	1.77	1.78
Al hydroxide gel ^α	25.4	1.48	1.53

$\alpha: (CaO)_{0.04}Al(OH)_3 \cdot 2.3H_2O$

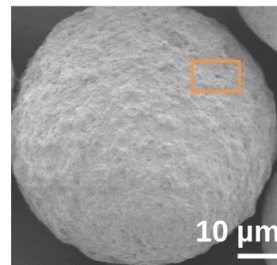
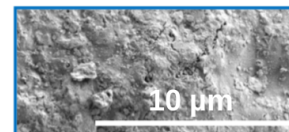
A. Cuesta et al. J. Phys. Chem. C 121, 3044-3054 (2017).



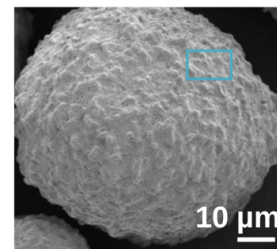
Fluid Catalytic Cracking (FCC) catalysis



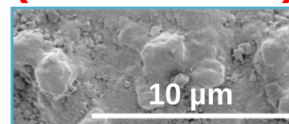
Pristine



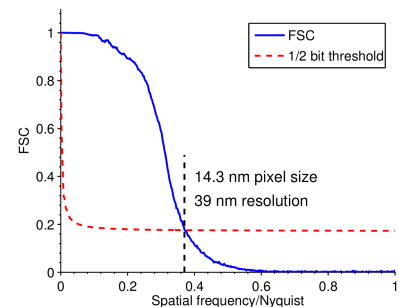
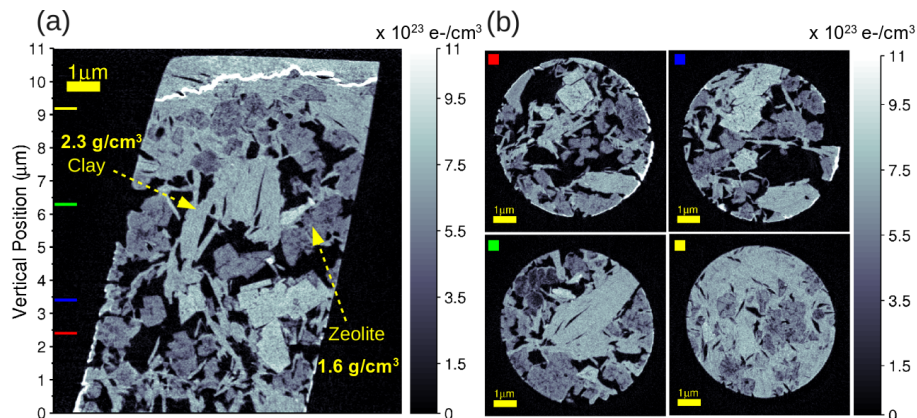
**Middle
life**



**End of life
(deactivated)**

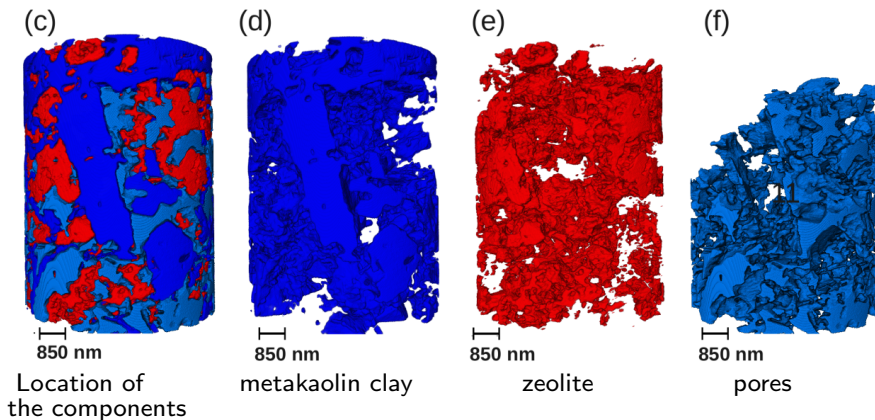


PXCT - pre-shaped FCC catalyst - pristine



M. van Heel, M. Schatz,
J. Struc. Biol. 151 (2005) 250.

gitlab.com/jcesardasilva/FSCimaging



$E = 6.2 \text{ keV}$ ($\lambda = 2 \text{ \AA}$)
419 diff. patterns per proj.
450 projections
 $12 \times 12 \times 11 \mu\text{m}^3$
14.3 nm of voxel size
39 nm of spatial resolution

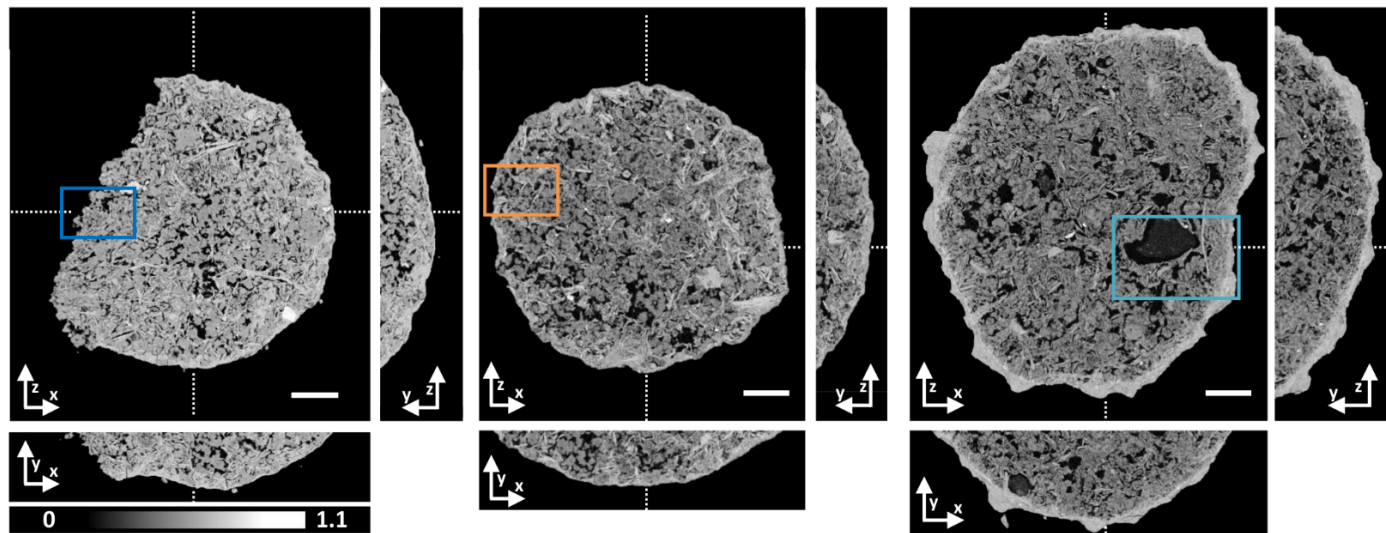
J. C. da Silva et al, ChemCatChem 7, (2015), 413.

FCC – Coked and uncoked catalysts

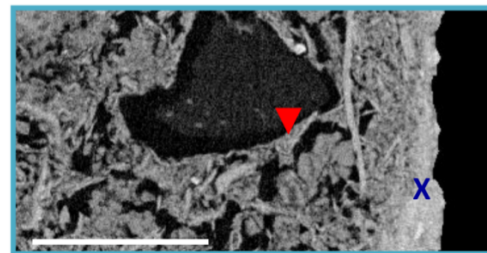
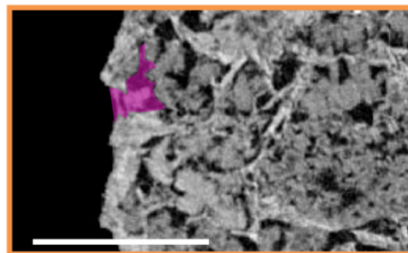
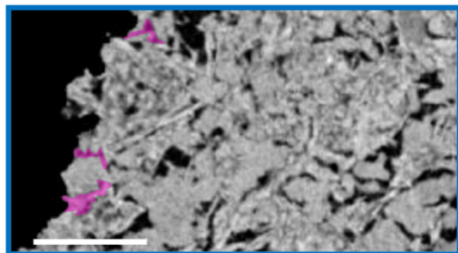
Pristine

Middle life

End of life (deactivated)



Electron Density / Å⁻³



Scale bar 5 μm

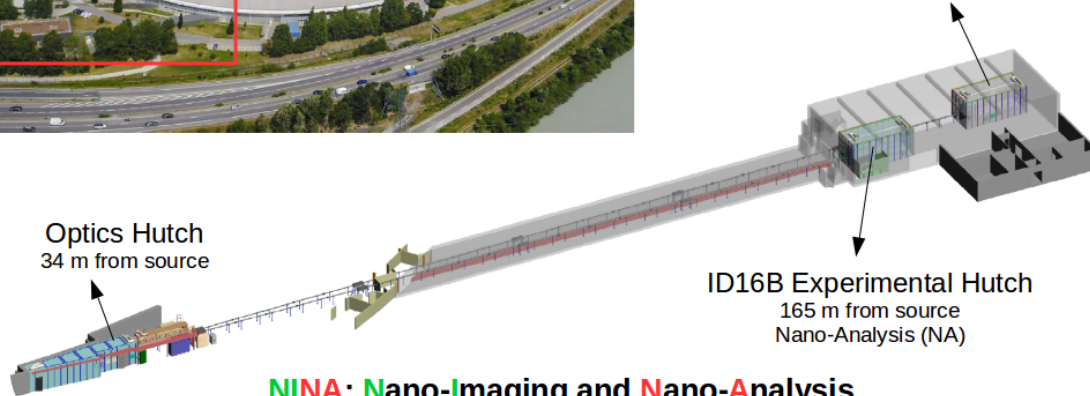
J. Ihli et al., Nature Communications 8, 809 (2017).



ID16A nano-imaging beamline



ID16A Experimental Hutch
185 m from source
Nano-imaging (NI)



Optics Hutch
34 m from source

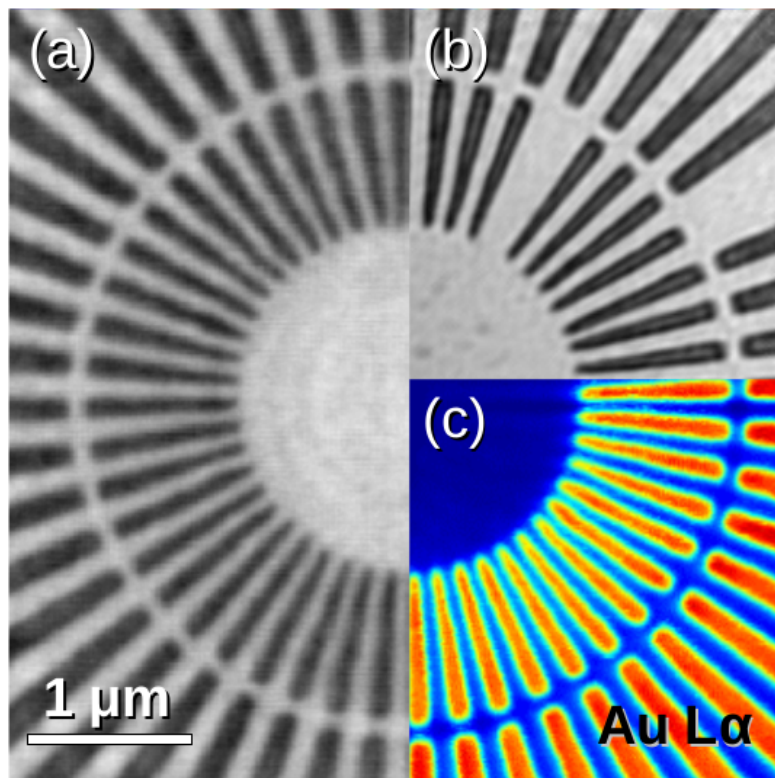
ID16B Experimental Hutch
165 m from source
Nano-Analysis (NA)

NINA: Nano-Imaging and Nano-Analysis

J. C. da Silva et al., Proc. SPIE 10389, 103890F (2017).

Holography

- full field microscopy
- large FOV
- quantitative



Ptychography

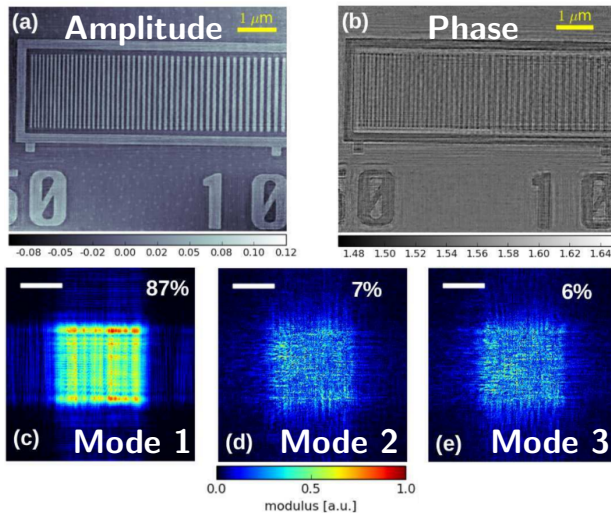
- scanning microscopy
- high resolution
- high sensitivity
- fully quantitative

Fluorescence

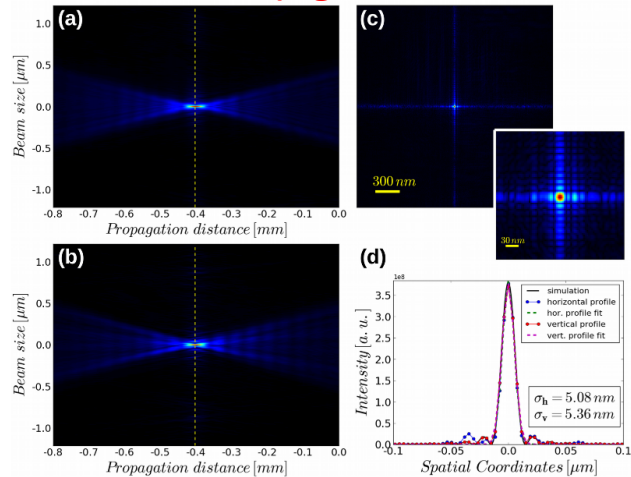
- scanning microscopy
- elemental sensitivity

J. C. da Silva et al., Proc. SPIE 10389, 103890F (2017).

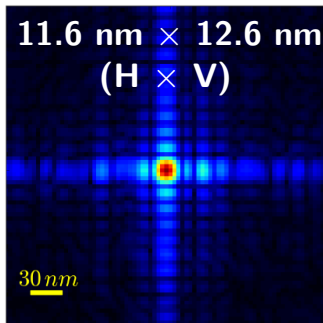
Smallest ever high energy (33.6 keV) focal spot



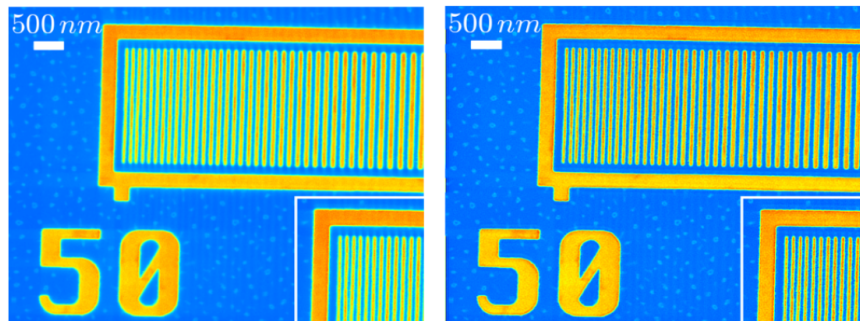
Wave Propagation



Focal spot



Deconvolution of XRF data

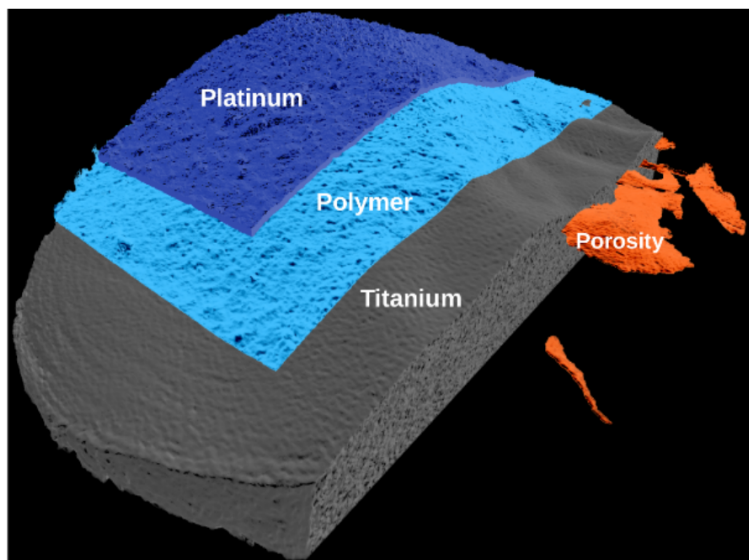
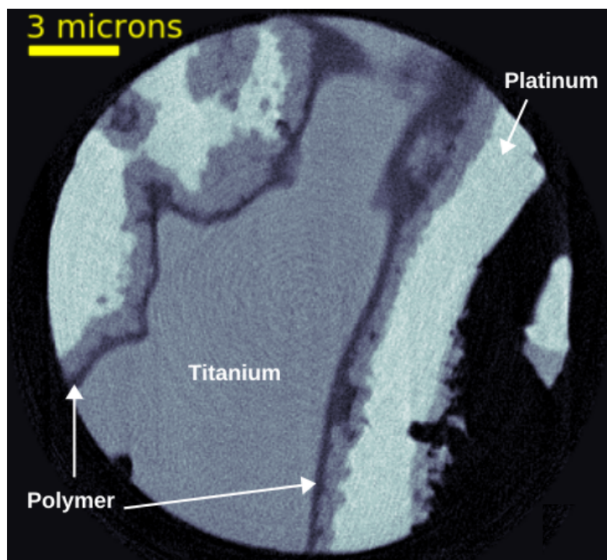
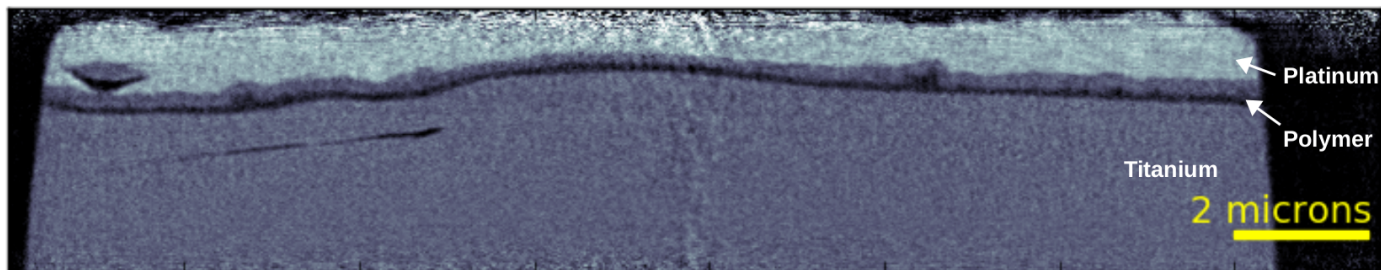


Original

Deconvolved

J. C. da Silva et al., *Optica* 4(5), 492-495 (2017).

PXCT application case: polymer infiltration in metals

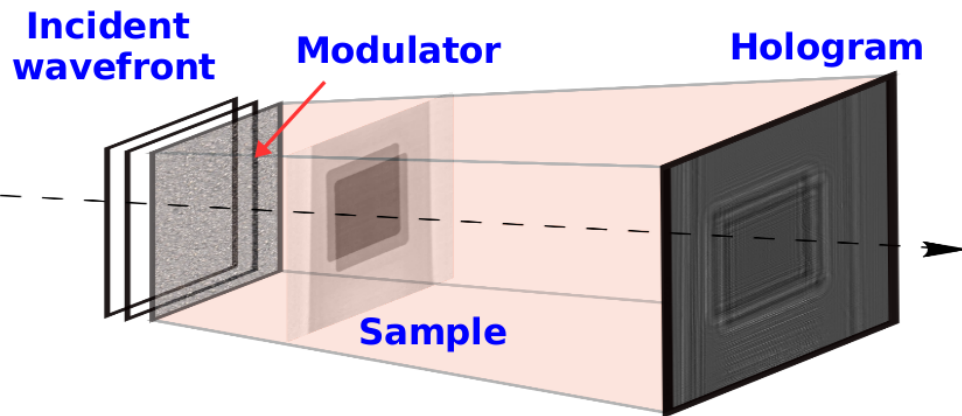


J. Haubrich et al., *Applied Surface Science* 433, 546-555 (2018).

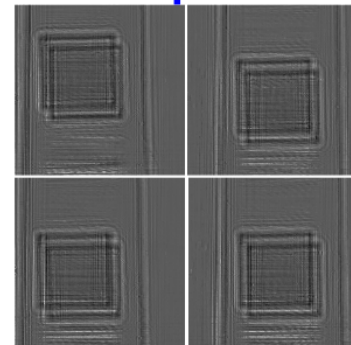
J. C. da Silva et al., *Proc. SPIE* 10391, 1039106 (2017).

Near-field ptychography

another way to exploit the transverse diversity

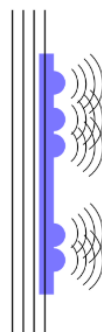


Lateral positions

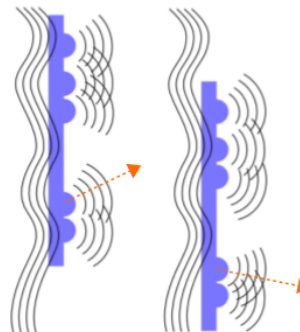


Transverse diversity

Plane wave



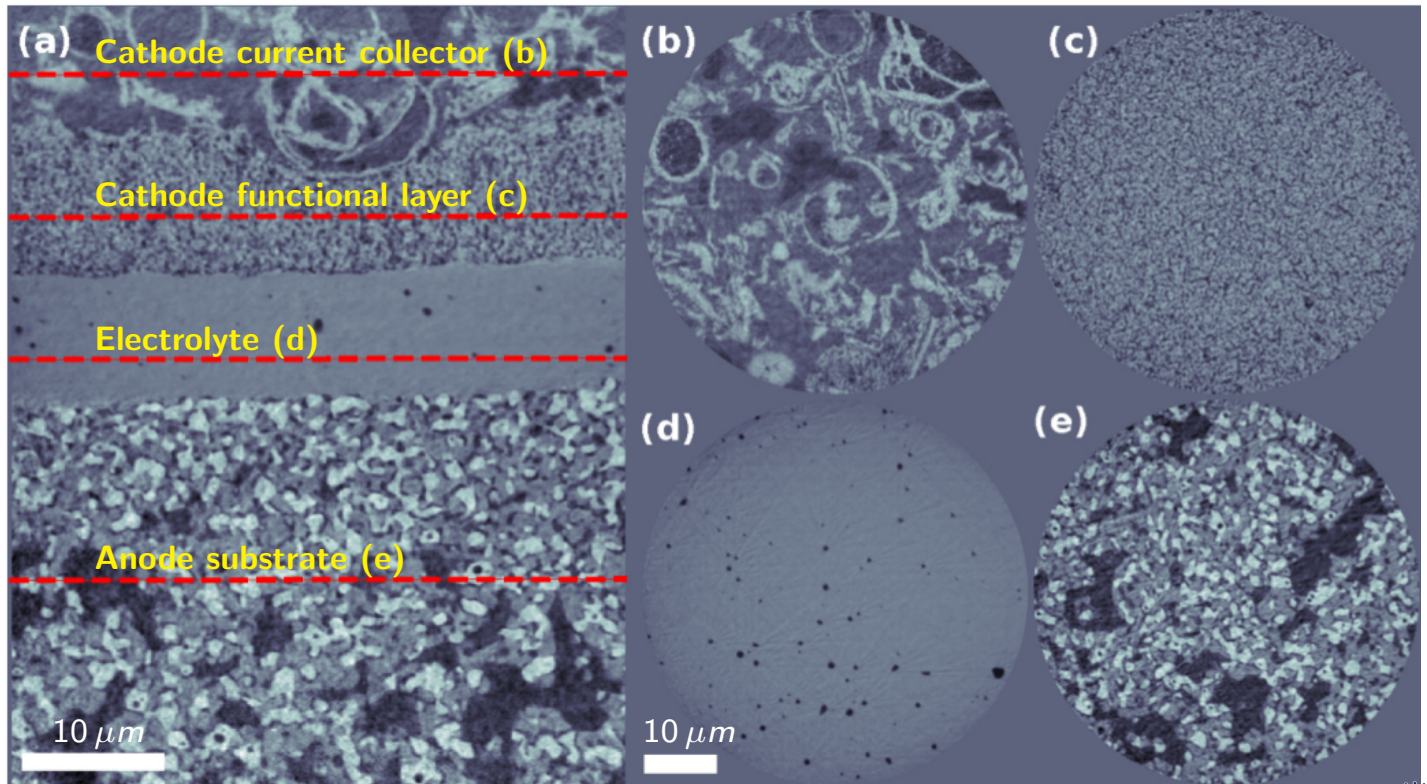
Structured beam



M. Stockmar et al., *Sci. Rep.* 3, 1927 (2013)

The different structures of a SOFC

SOFC: Solid Oxide Fuel Cell

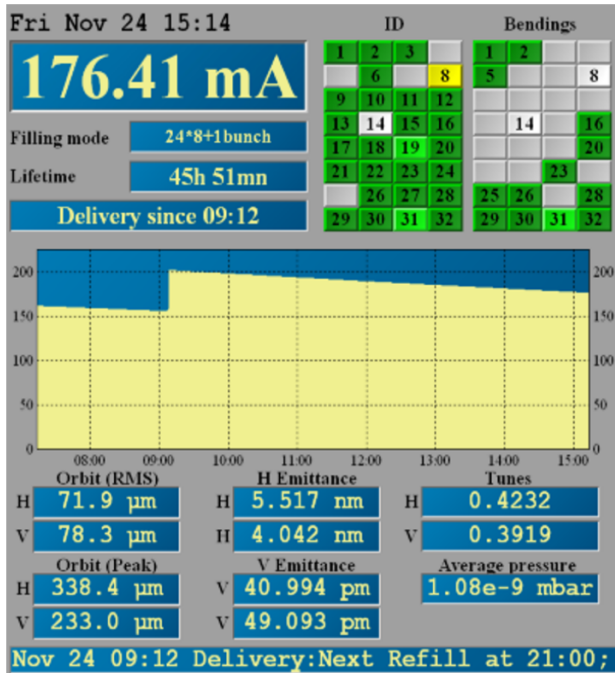


M. Stockmar et al., *Opt. Express* 23(10), 12720 (2015)

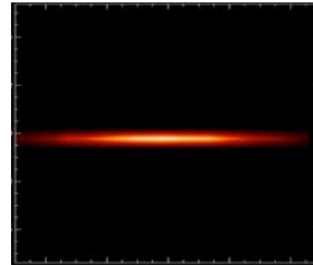


ESRF

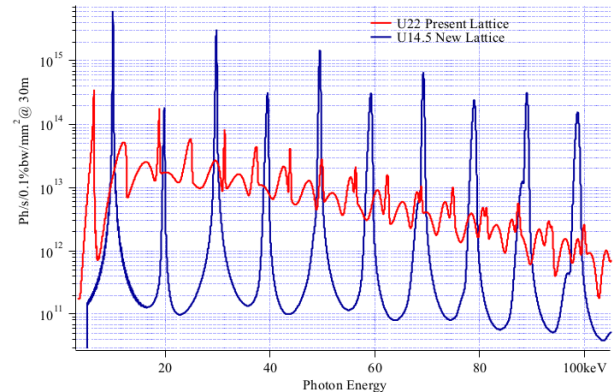
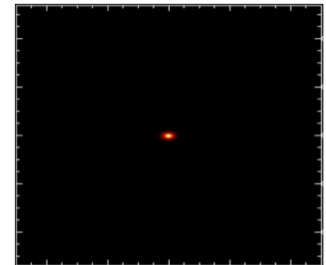
ESRF - Extremely Brilliant Source (EBS)



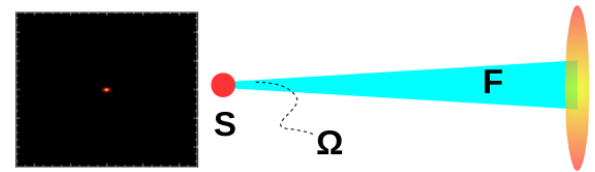
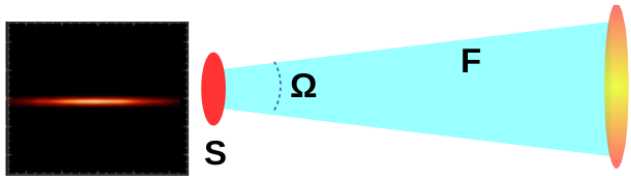
Current source



New source (Expected)



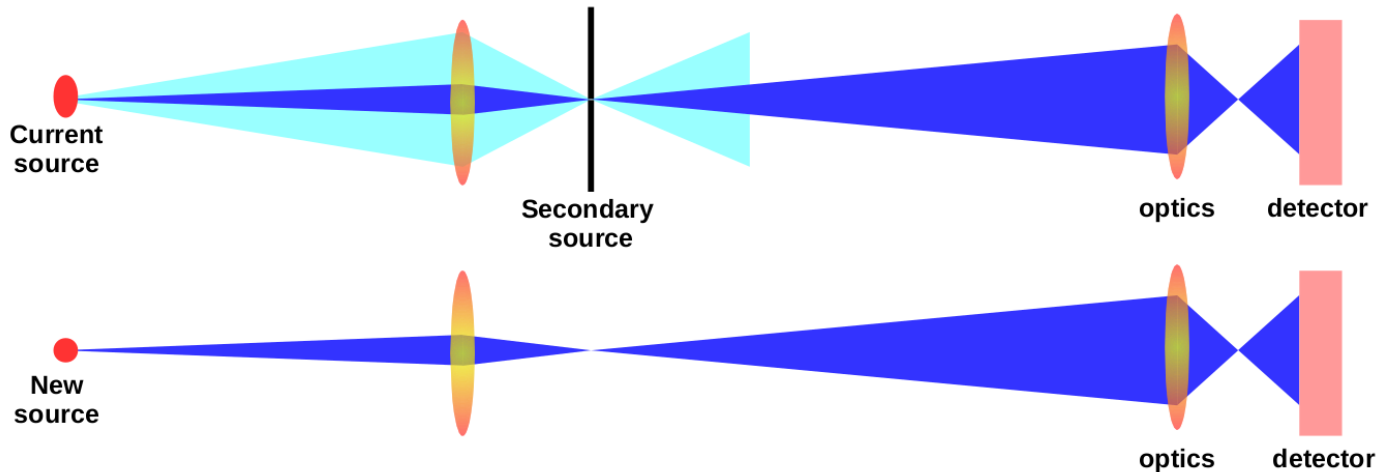
More brilliance and transverse coherence



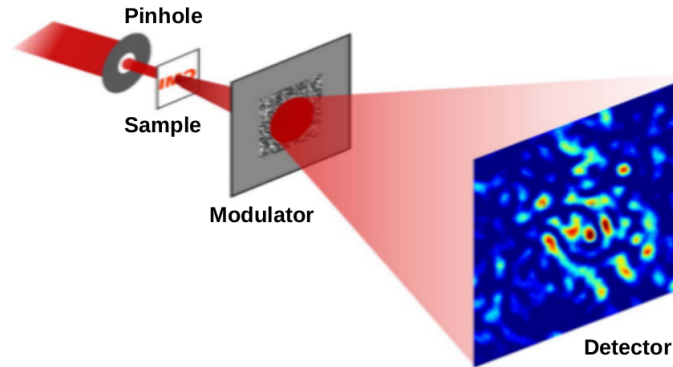
Ω = angular divergence
 S = source area
 F = Flux

$$\text{Brilliance} = (\text{const.}) \times \frac{F}{S\Omega}$$

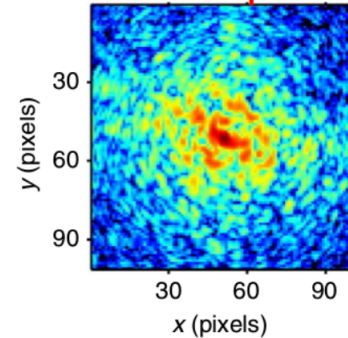
$$\text{Emittance} = S\Omega$$



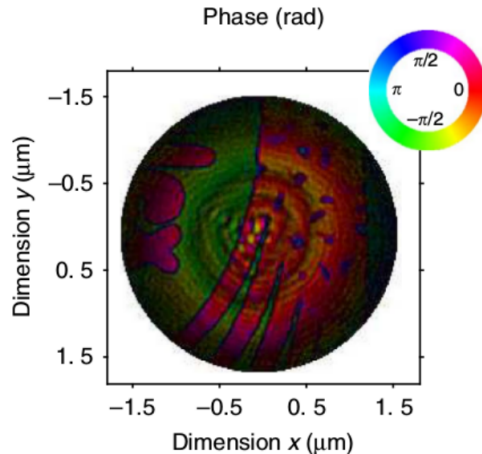
Innovation I: Coherent X-ray modulation imaging



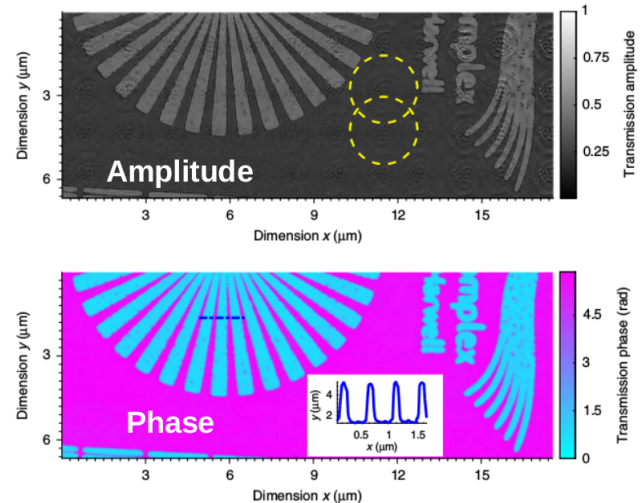
Diffraction pattern



Wavefield past the sample



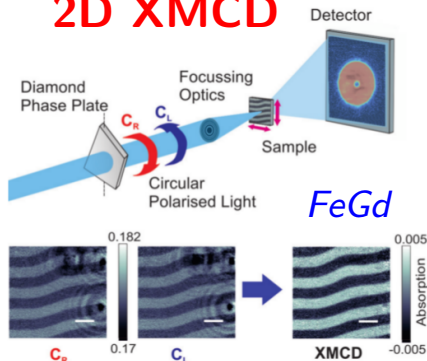
CMI reconstruction



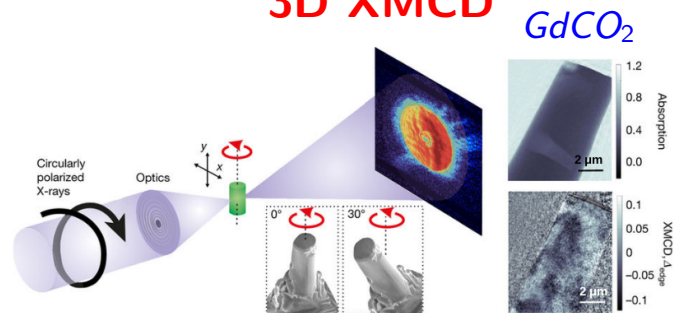
F. Zhang et al., Nature Communications 7, 13367 (2016).

Innovation II: Magnetic imaging via ptychography

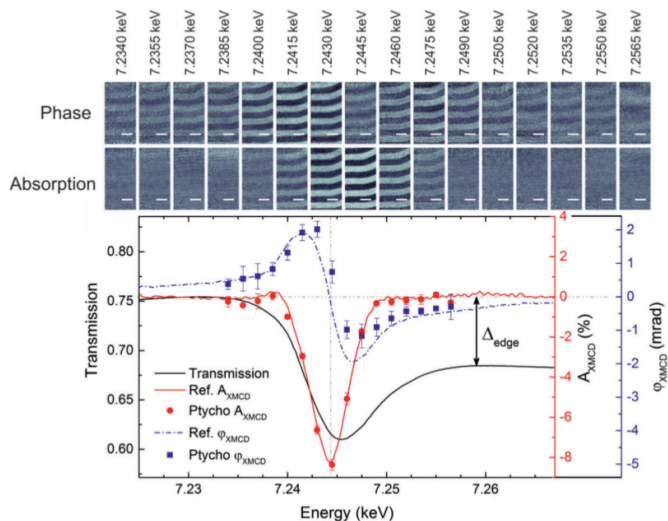
2D XMCD



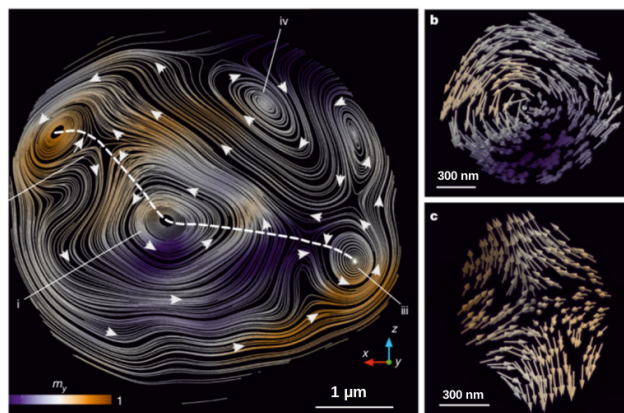
3D XMCD



Reconstructed magnetization vector field



C. Donnelly et al., Phys. Rev. B 94, 064421 (2016)

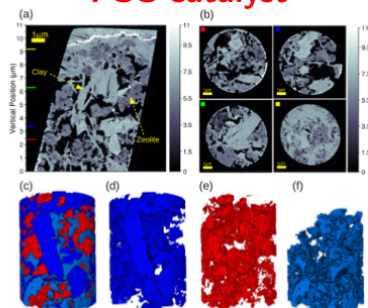


C. Donnelly et al., Nature 547, 328-331 (2017)

Ptychography is already an established imaging technique

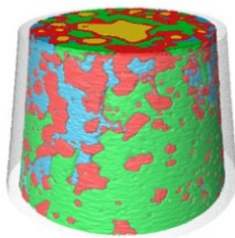
Some Application Cases of X-ray ptychography

FCC catalyst



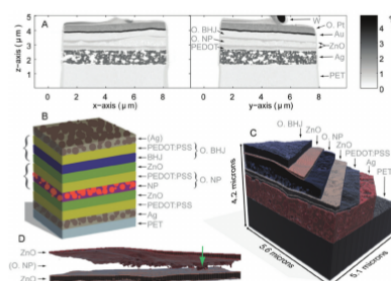
J. C. da Silva et al.,
ChemCatChem 7 (2015) 413.

Cement hydration



J. C. da Silva et al.,
Langmuir 31 (2015) 3779.

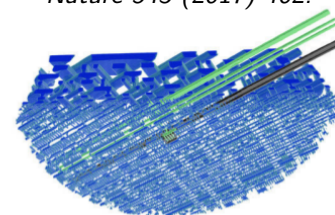
Tandem solar cells



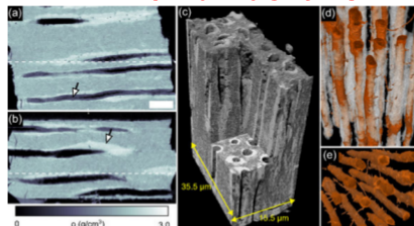
E. B. L. Pedersen et al.,
Nanoscale 7 (2015) 13765.

Microelectronics

M. Holler et al.,
Nature 543 (2017) 402.

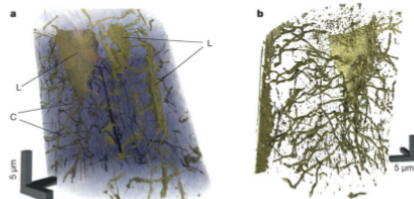


Human dentine



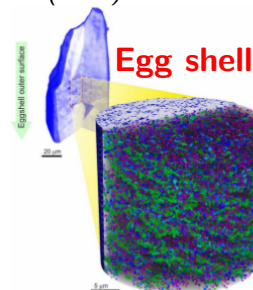
I. Zanette et al.,
Sci. Rep. 5 (2015) 9210.

Bones



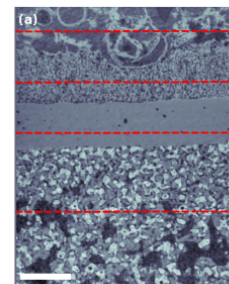
M. Dierolf et al.,
Nature 467 (2010) 436.

Egg shell



M. Guizar-Sicairos et al.,
Optica 2 (2015) 259.

SOFC



M. Stockmar et al.,
Opt. Express 23 (2015) 12720.

Thank you for your attention!



Dynamics and Imaging Using Coherent X-rays at the European Synchrotron

V. Favre-Nicolin, Y. Chushkin, P. Cloetens, J. C. da Silva, S. Leake, B. Ruta & F. Zontone

Synchrotron Radiation News 30(5), 13-18 (2017).

Contact: jdasilva@esrf.fr



ESRF

**Thank you for your
attention!**