Coherent imaging of magnetic domains on Sextants beamline

Synchrotron SOLEIL (SEXTANTS)
Horia Popescu,
Nicolas Jaouen,
Victor Pinty

INSP, Paris
Maurizio Sacchi

CSNSM, Orsay
Franck Fortuna

LCPMR, Paris VI
Renaud Delaunay,
Jan Luning, Regis Vacheresse,
Bertrand Pilette

ELETTRA, Trieste
Carlo Spezzani

sextants

Soft x-ray EXperimenT resonANT Scattering

SOLEIL SYNCHROTRON

Beamline team:

R. Gaudemer => Assistant Engineer

H. Popescu => Scientist in charge Coherent Scattering/FTH

A. Nicolaou => Scientist in charge of RIXS

N. Jaouen => Principal beamline scientist

J.Y Chauleau => Post Doc RESOXS

K Ruotsalainen => Post Doc RIXS

Research Associates:

(LCPMR, Paris): S. Chiuzbaian, J. Lüning, R. Delaunay, JM Mariot

(I. Néel, Grenoble): J.M. Tonnerre

(INSP, Paris): M. Sacchi

Outline:

- Sextants beamline

- **Coherent scattering instruments on Sextants :**
    - **COMET : transmission**
    - **IRMA2 : reflectivity**

- **Coherent imaging techniques :**
    - **Holography**
    - **Ptychography**

- **Conclusion: - transmission ok**
    - reflectivity : we need the round beam ☺ !!

Soft x-ray EXperimenT resonANT Scattering

SEXTANTS Beamine

- **Beamline of phase 2** : (R. Gaudemer, H. Popescu, A. Nicolaou, N. Jaouen)

  First Experiment: End 2010

  First expert users: first semester 2011

  (open to users **2011)**
- **Energy range** : **50-1800 eV** (N, O, F, transition metals, rare earth, S, …),
- **High flux** : **>10^{13} ph/s** on the sample,
- **Resolving power $\Delta E/E \geq 8000$** over the whole energy range,
- **Variable polarization: linear and circular**:
  - **2 Apple-II undulator**: circular +/-, variable linear

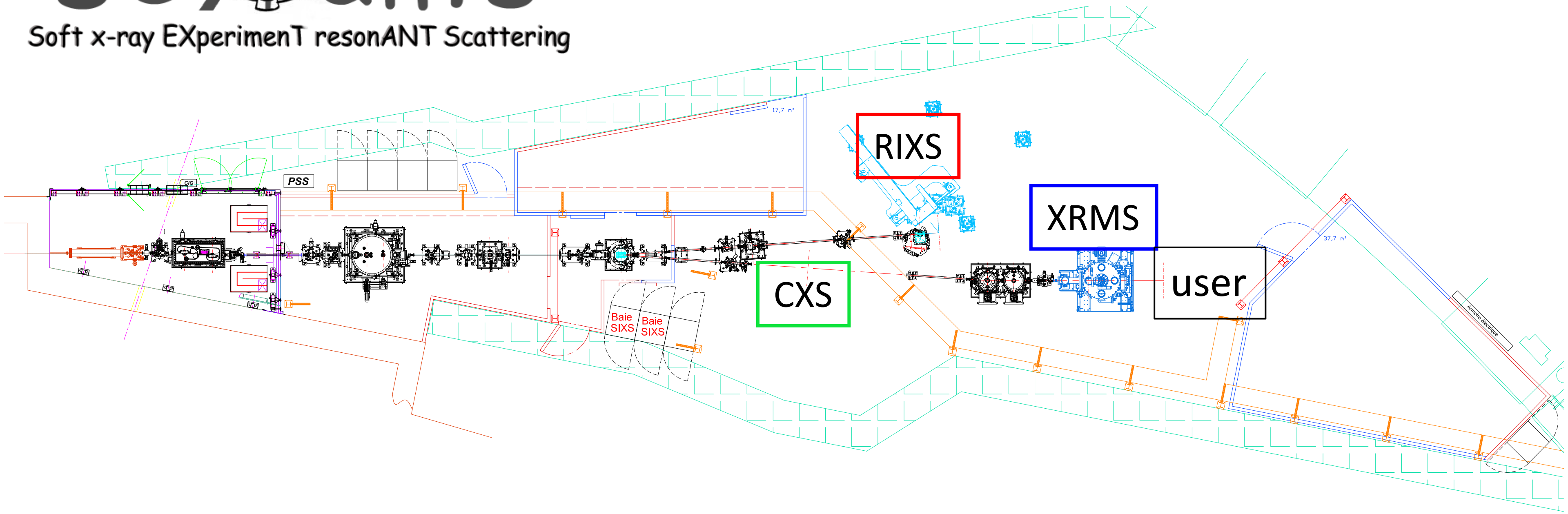
    HU80 + HU44: the whole energy range in first harmonic

    $\Rightarrow$ Maximize flux and polarization
- **Two branches and 3+1 experimental stations** (UHV)**:**
  - **High resolution RIXS Spectrometer**
  - **Two UHV diffractometers**
  - **One set-up for coherent imaging in transmission**
  - **User set-up.**

H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

SEXTANTS Beamline

sextants
Soft x-ray EXperimenT resonANT Scattering



Three main techniques:

- Soft X-ray resonant magnetic scattering (XRMS)

(Magnetic multilayers, nanostructures, single crystal diffraction)

- Resonant Inelastic X-ray Scattering (RIXS)

Strongly correlated systems, non-solid systems (gaz/liquide)

- Coherent X-ray scattering (CXS)

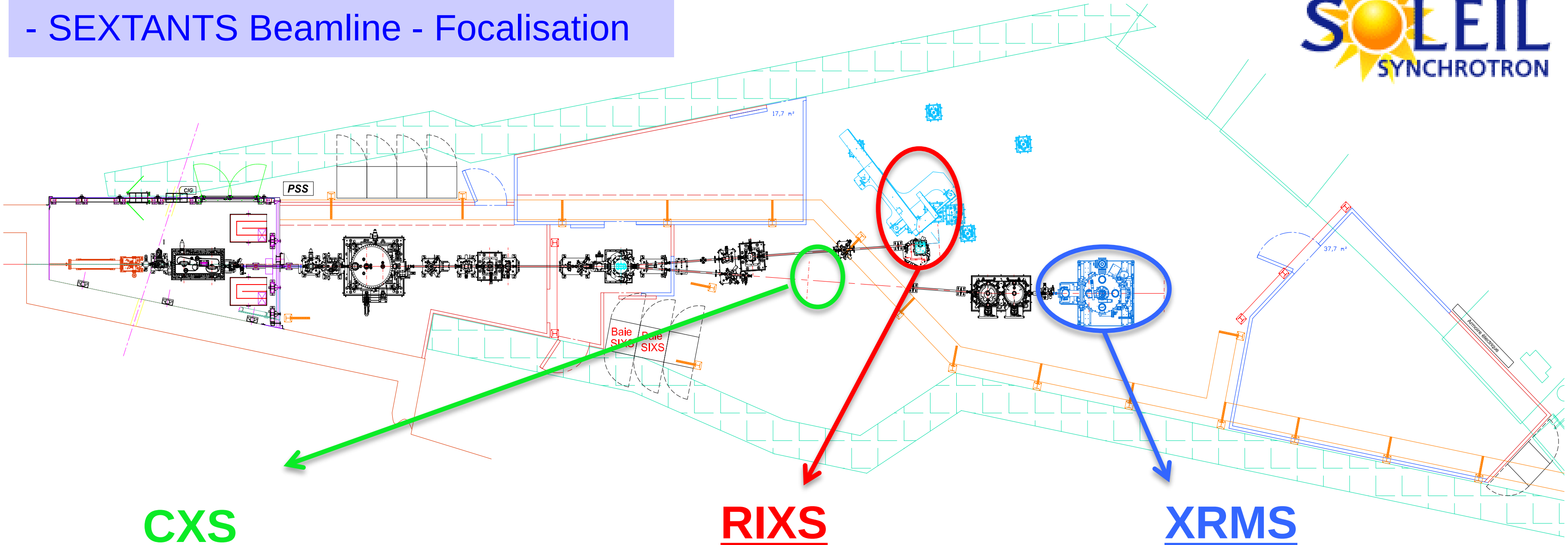
(Lensless microscopy, dynamical studies in imaging)

One experimental point open for user set up

H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

- SEXTANTS Beamline - Focalisation

SOLEIL SYNCHROTRON

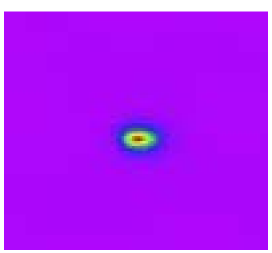


CXS

Horizontal x Vertical

Measured:

80µm x 50µm

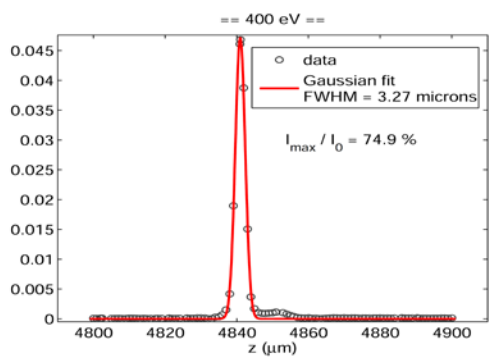


RIXS

Vertical (FWHM)

Calculated : 1.5µm

Measured ≈ 1.9µm



XRMS

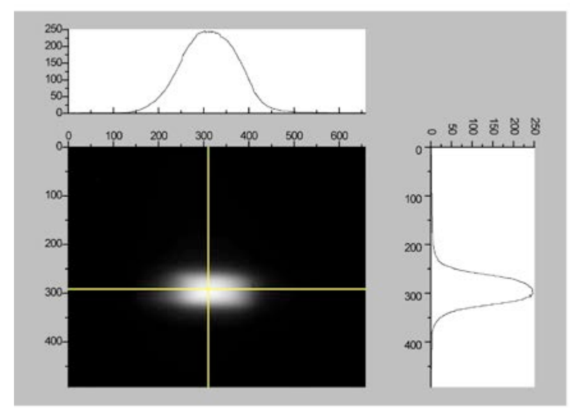
h-slit = 40µm / v-slit 10µm

Calculated @2.2m from M8

18µm * 7µm FMHM

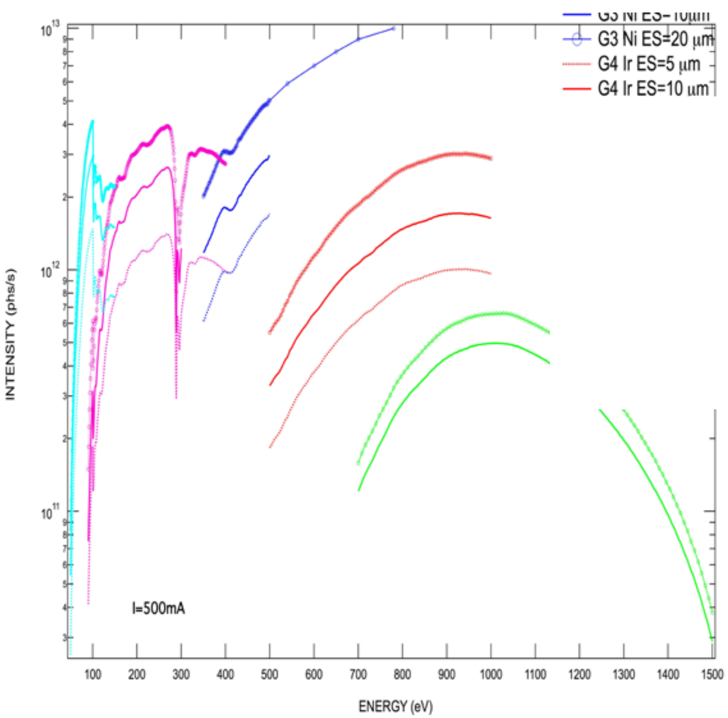
Measured @ 2.2m from M8

17.3µm * 7.4µm



H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

FLUX



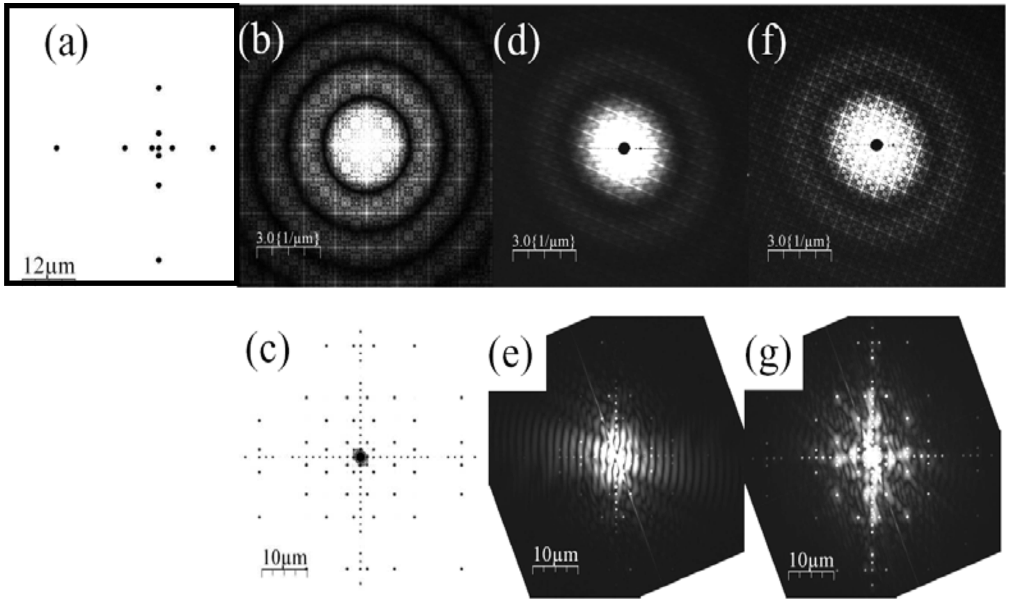
Flux measured @ sample position after 5 mirrors and one grating:

In excess of 3 10^{12}ph/s in the 50-1000eV energy range

COHERENCE:

- for full beamline angular acceptance
- Reduce acceptance (close beamline slits)

	Angular Acceptance	
MaskCalc.	150×150 µrad^2	40×40 µrad^2



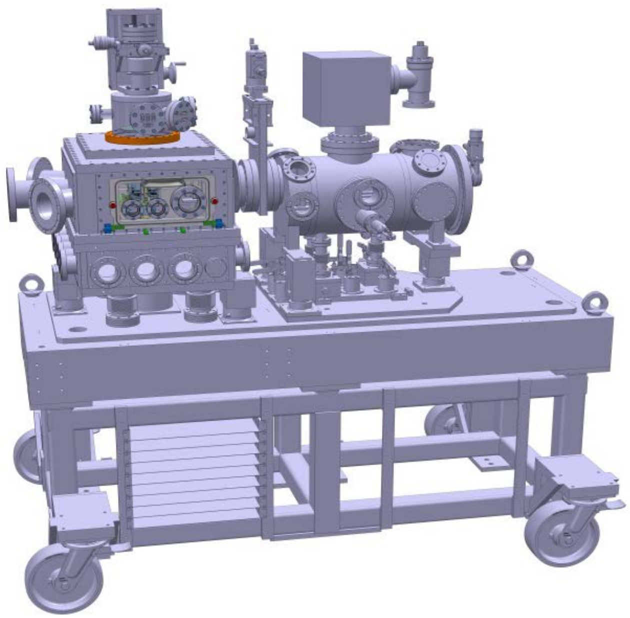
Estimated transverse coherence at 778 eV (hor. × vert.)

- **8µm × 15 µm** @ full acceptance
- **25 µm × 25 µm** @ 40 × 40 µrad^2

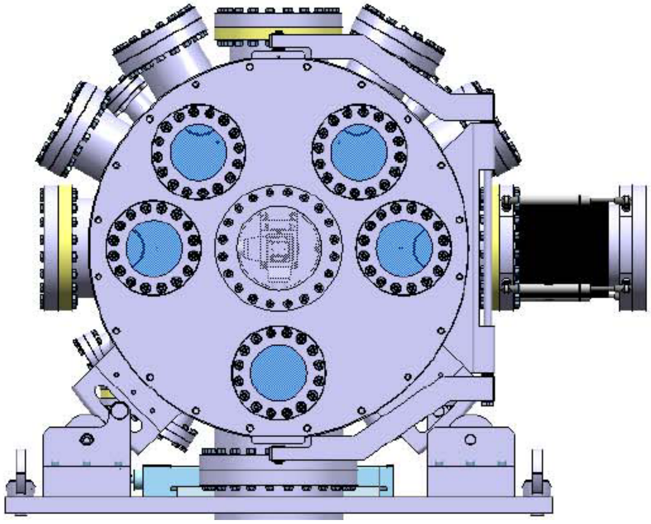
M. Sacchi, H. Popescu, F. Fortuna, R. Delaunay, N. Jaouen
J. Phys. Conf. Series, 2012

Coherent scattering instruments on Sextants:

COMET : transmission



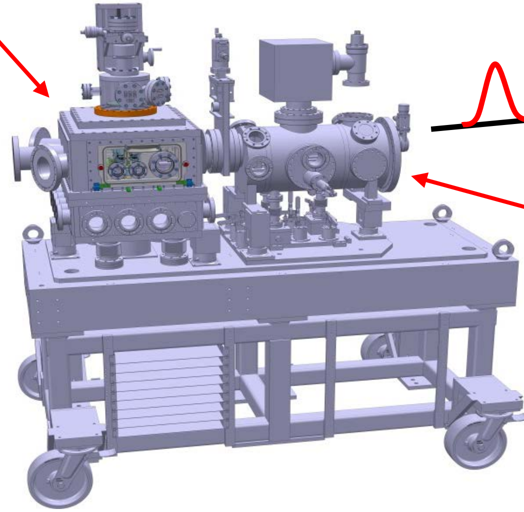
IRMA2 : reflectivity



COMET instrument : Coherent Magnetic scattering Experiments in Transmission

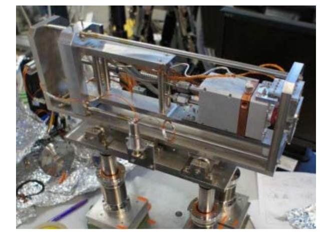
sample chamber

x-rays in



outgoing x-rays towards the KB end-station

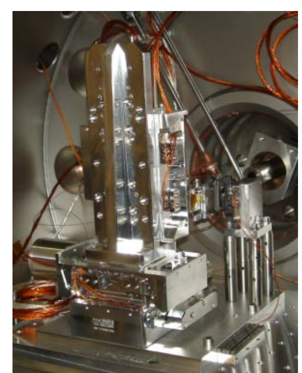
removable 2D detector



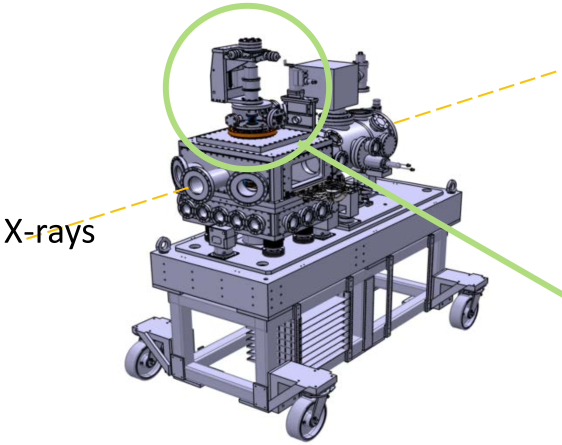
Collaboration LCPMR : J. Luning, R. Delaunay, R. Vacheresse, B. Pilette, J. Perron

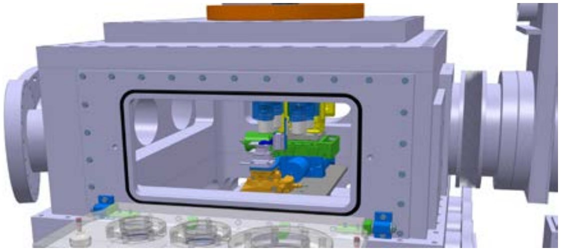
- Imaging by Fourier Transform Holography (FTH) and Ptychograpgy
- Integrated or separated mask/sample approach
- extandable field of view
- Normal or tilted transmission geometry for imaging out-of-plane or in-plane magnetic domains, respectively
- Magnetic field: 500 Oe in pulsed mode (1 T static in 2017)
- Low temperature: 100K (20K in 2017)
- regular spatial resolution: ~ 30 nm (with standard masks available for users)

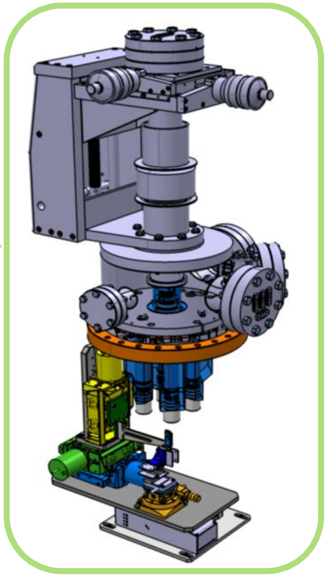
Internal mechanics:

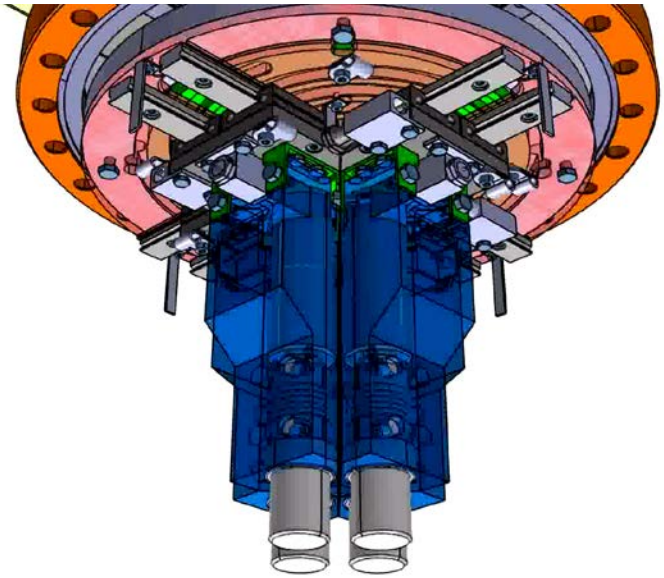


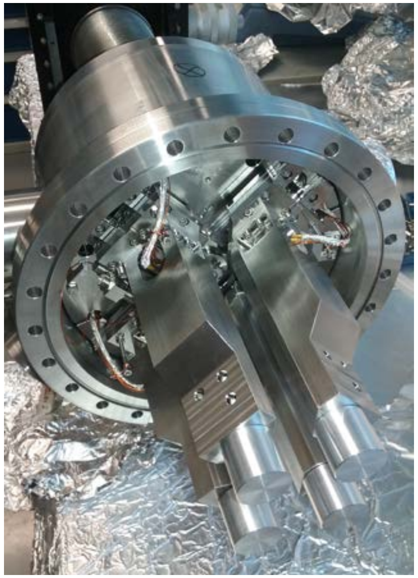
In 2017 : 1 Tesla and He temperature









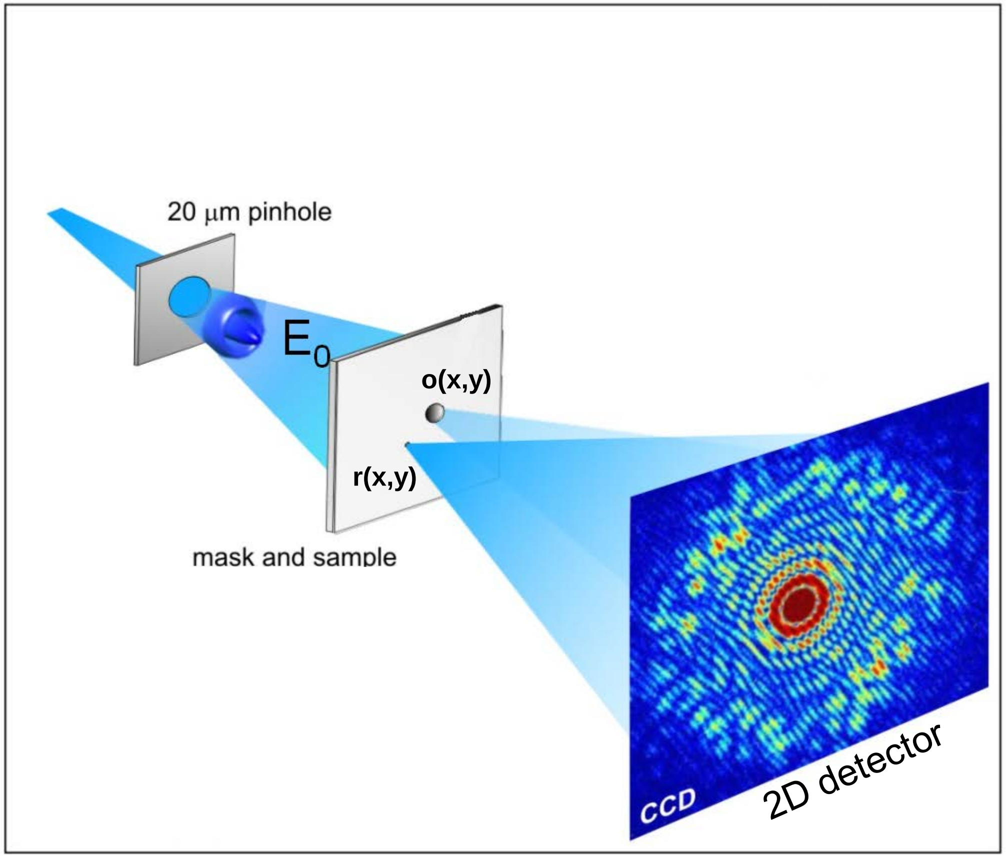


4 permanent magnets:

- tunable intensity
- all horizontal directions
- each magnet is motorized around it's axis

- commercial He cryostat + flexible stripes

Fourier Transform Holography (FTH) imaging technique



S. Eisebitt et al., Vol 432, 2004, Nature

object: $o(x,y) = E_0\, t_o(x,y)$

reference: $r(x,y) = E_0\, t_r(x,y)$

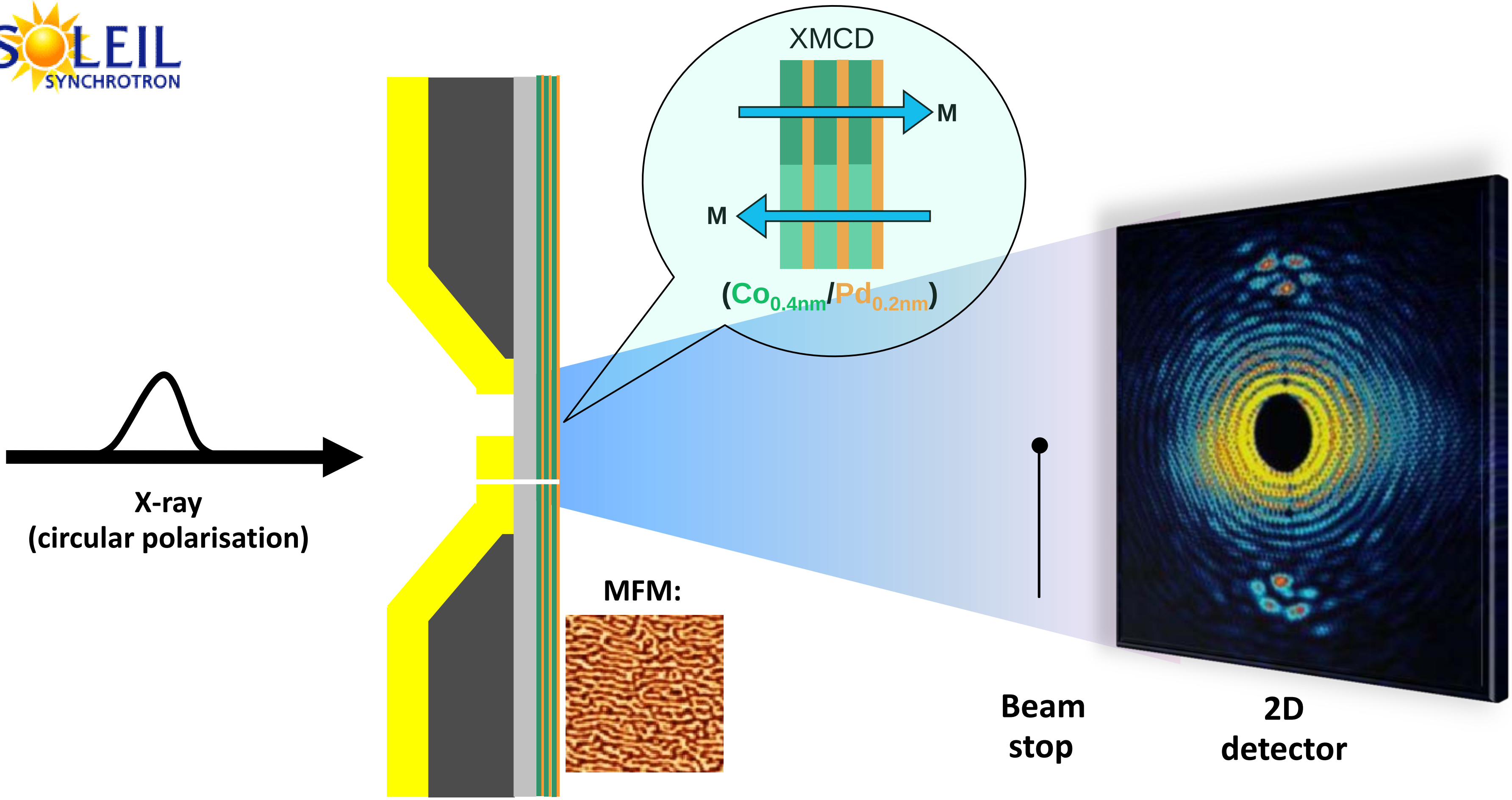
Hologram intensity:

$$= |\,\mathbf{F}\{r + o\}|^2$$
$$= |R + O|^2$$
$$= |R|^2 + |O|^2 + OR^* + RO^*$$

Reconstructed real space images:

$$\mathbf{F}\{\text{Hologram intensity}\}$$
$$= r \star r + o \star o + o \star r + r \star o$$

Integrated mask/sample approach in normal transmission geometry

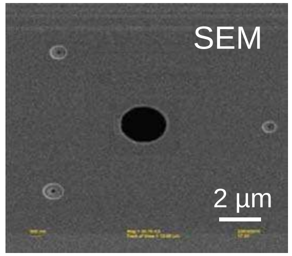


Advantages: - easy to align,
- stable against vibrations
- sample environment (temperature, magnetic fields, etc.)

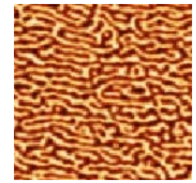
Disadvantage: fixed field of view, difficult fabrication

FTH Imaging of perpendicular magnetic domains using circular polarization

FIB fabricated mask

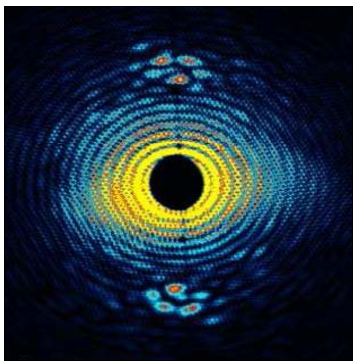


MFM

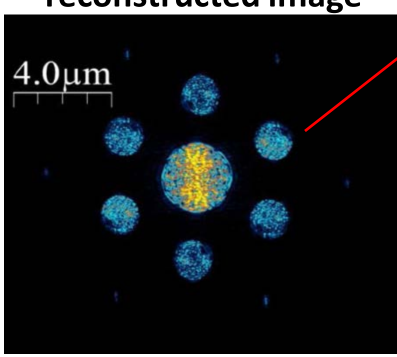


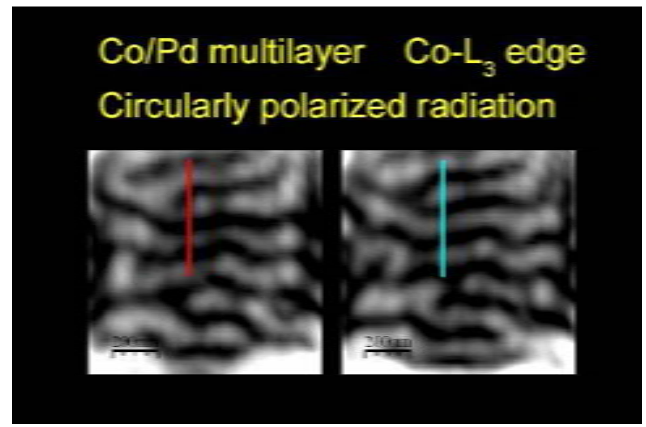
Co/Pd multilayer
- **perpendicular magnetization**
- **meander domains**

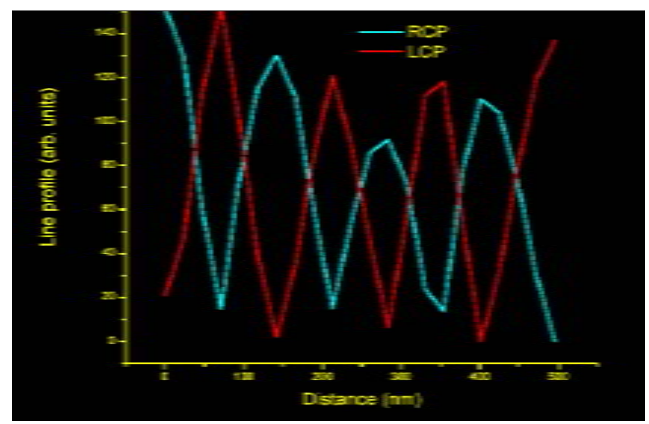
diffraction diagram



reconstructed image

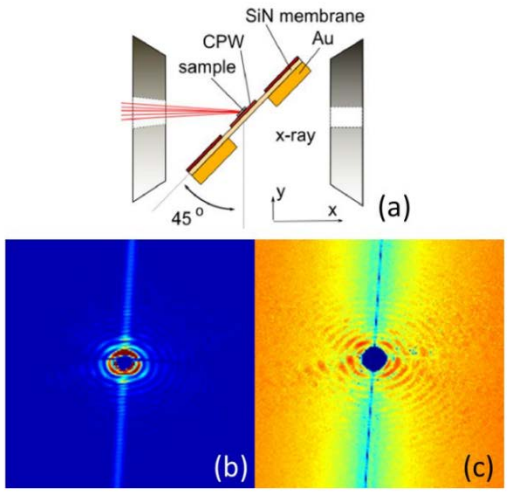


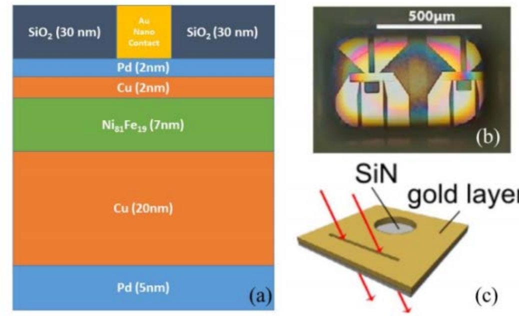


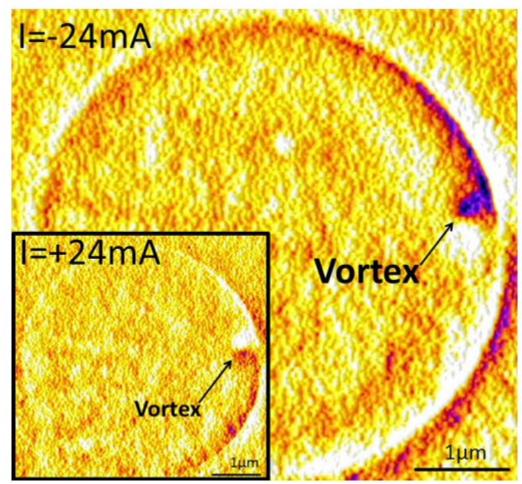


H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

Holographic magnetic imaging of single layer nano-contact spin transfer oscillators





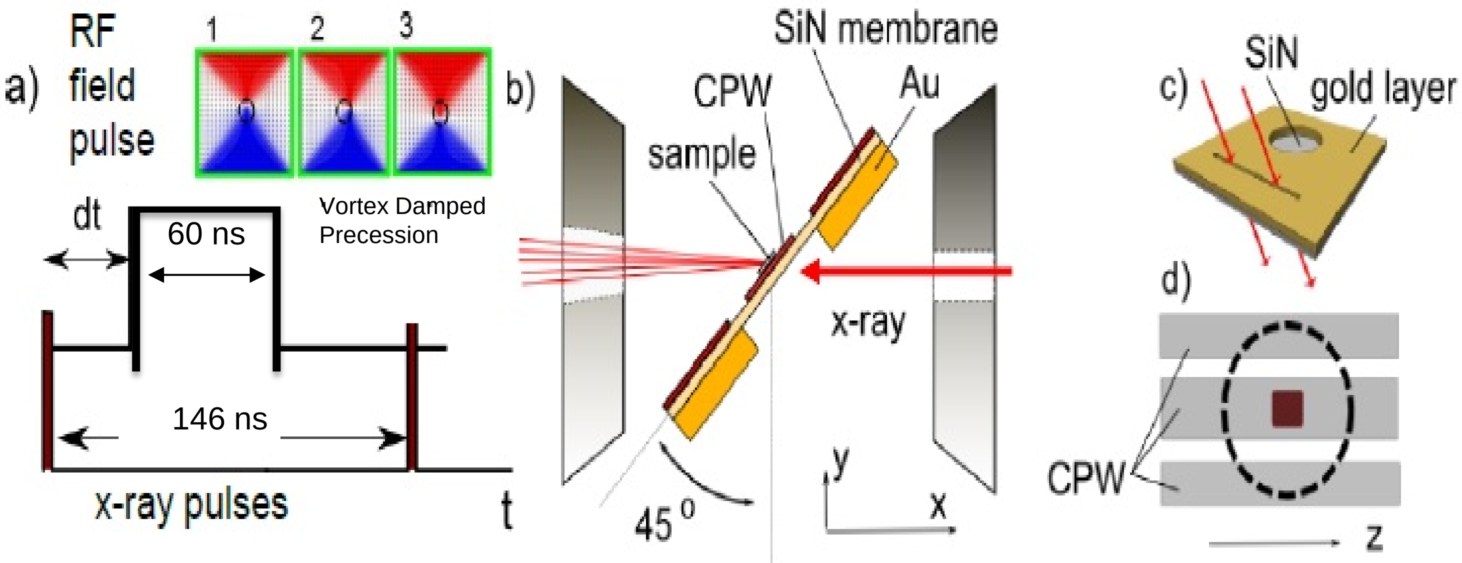


15 nm spatial resolution !

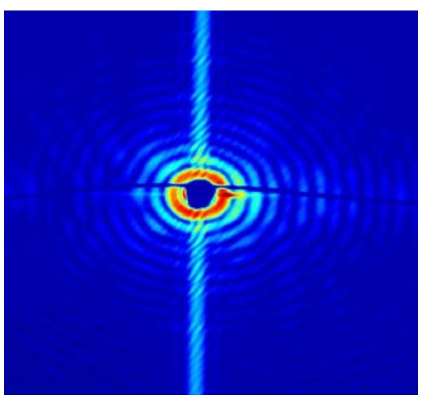
(using a slit for the reference beam)

E. O. Burgos Parra et al., IEEE Transactions on Magnetics, Volume PP, Issue 99 (2016)

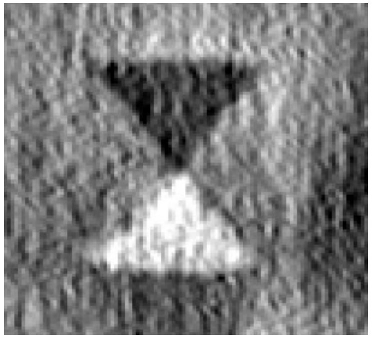
Experimental Principle



Static Measurement



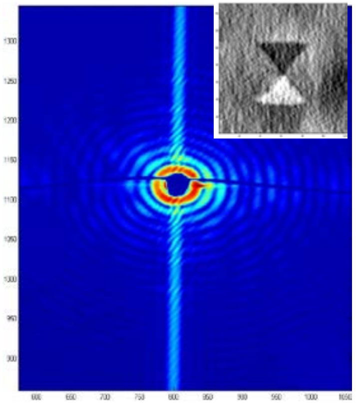
FFT



F Ogrin (Exter, UK)
G van der Laan (DLS, UK)
G Beutier (Grenoble, France)

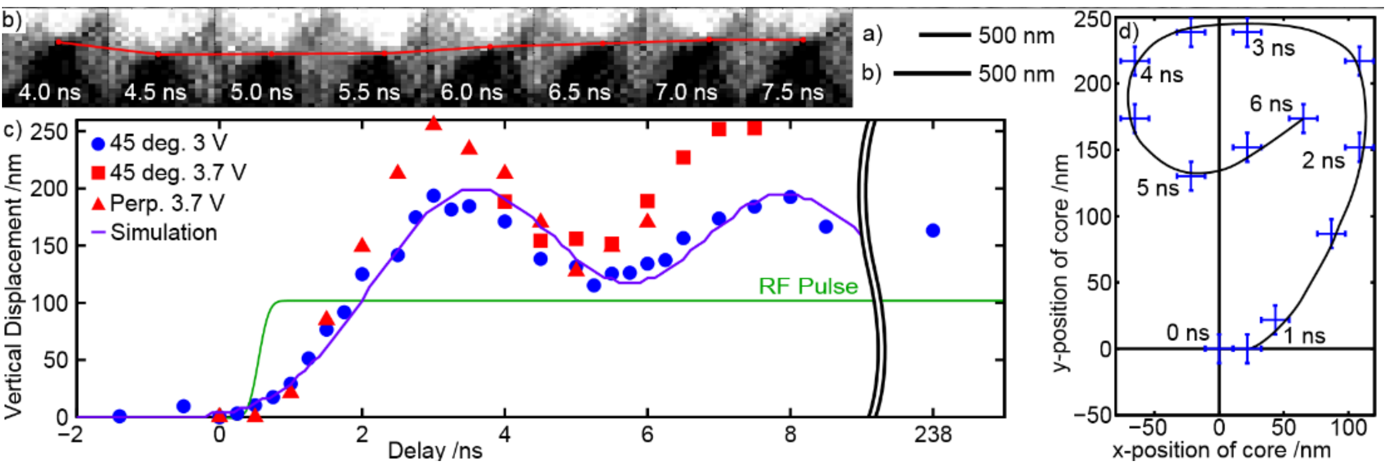
- Time resolved imaging of Vortex Dynamic

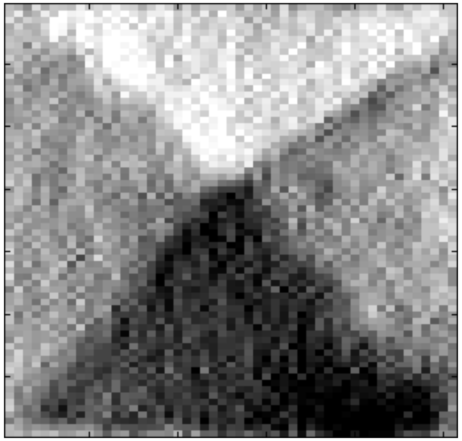
Static image



- 8 bunch @ SEXTANTS beamline; 146 ns delay
- 2 µm x 2 µm Py square, ~50 nm thick
- Spatial Resolution: **35 nm** per pixel
- Temporal Resolution: **250/500 ps**
- An RF pulse (60ns width, 1ns rise time) excited core gyration

In plane: Vortex Dynamic



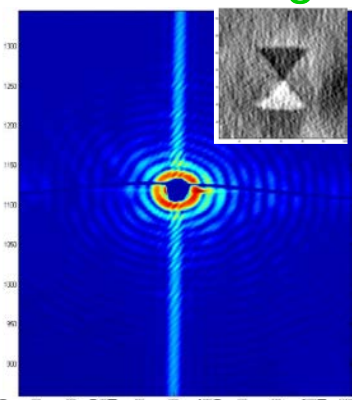


SCIENTIFIC REPORTS

N bukin et al, *Scientific Reports, 2016, 6: art.n° 36307*

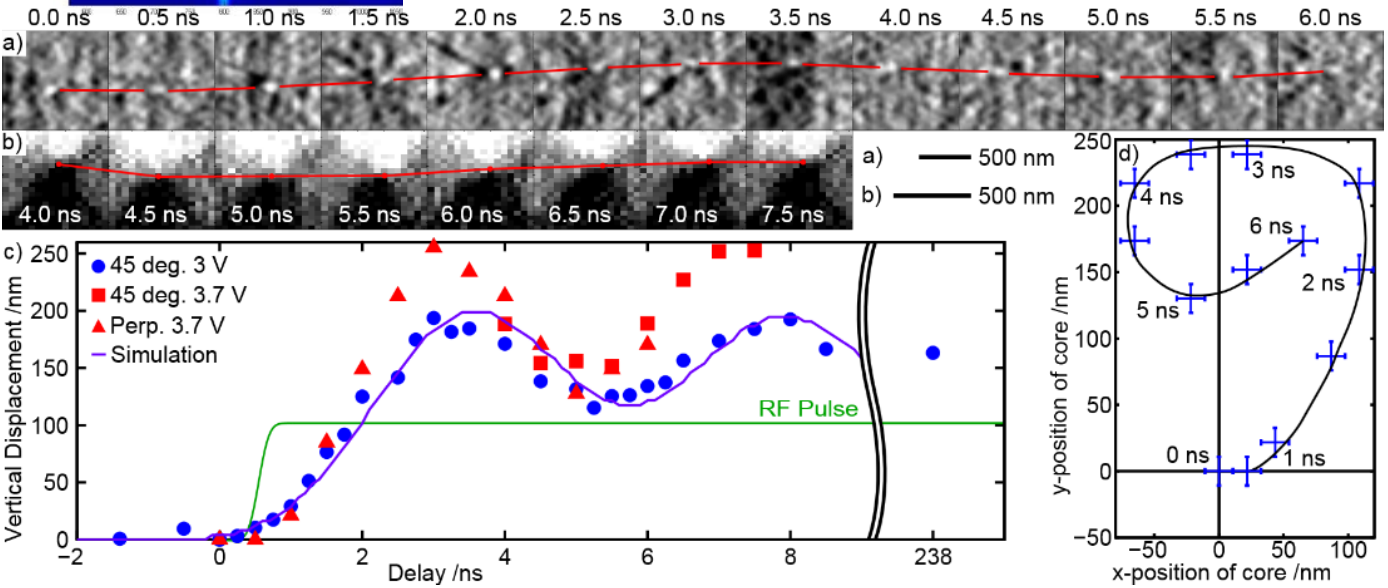
- Time resolved imaging of Vortex Dynamic

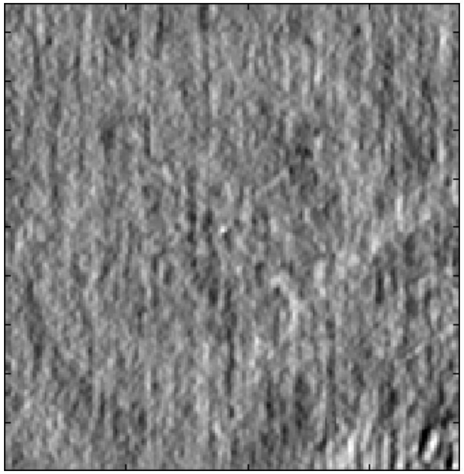
Static image



- 8 bunch @ SEXTANTS beamline; 146 ns delay
- 2 µm x 2 µm Py square, ~50 nm thick
- Spatial Resolution: **25 nm** per pixel
- Temporal Resolution: **250/500 ps**
- An RF pulse (60ns width, 1ns rise time) excited core gyration

Out of Plane: Vortex + DW Dynamic

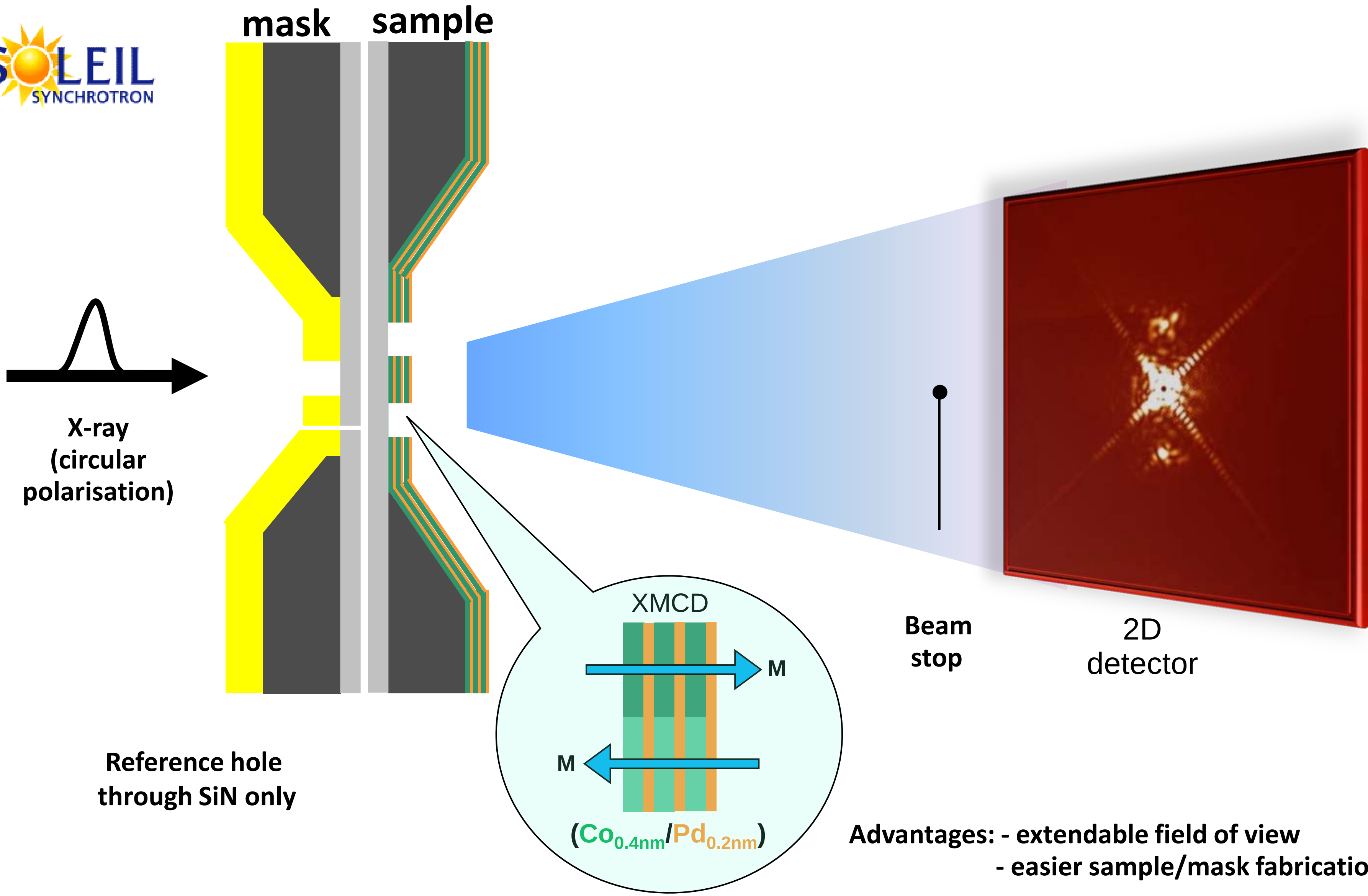




SCIENTIFIC REPORTS

N bukin et al, *Scientific Reports, 2016, 6: art.n° 36307*

Holography: separated mask/sample approach



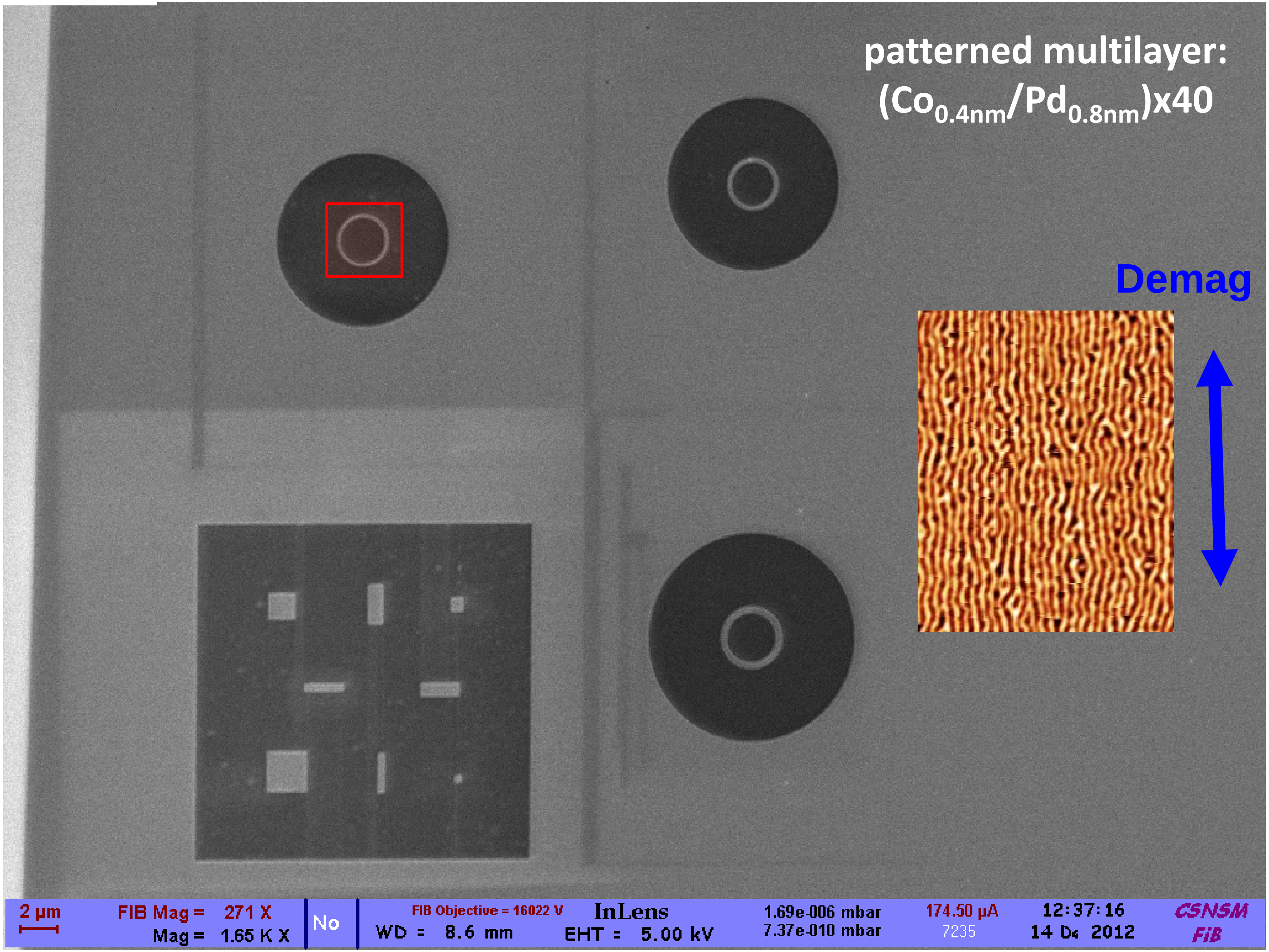
Reference hole
through SiN only

Advantages: - extendable field of view
- easier sample/mask fabrication

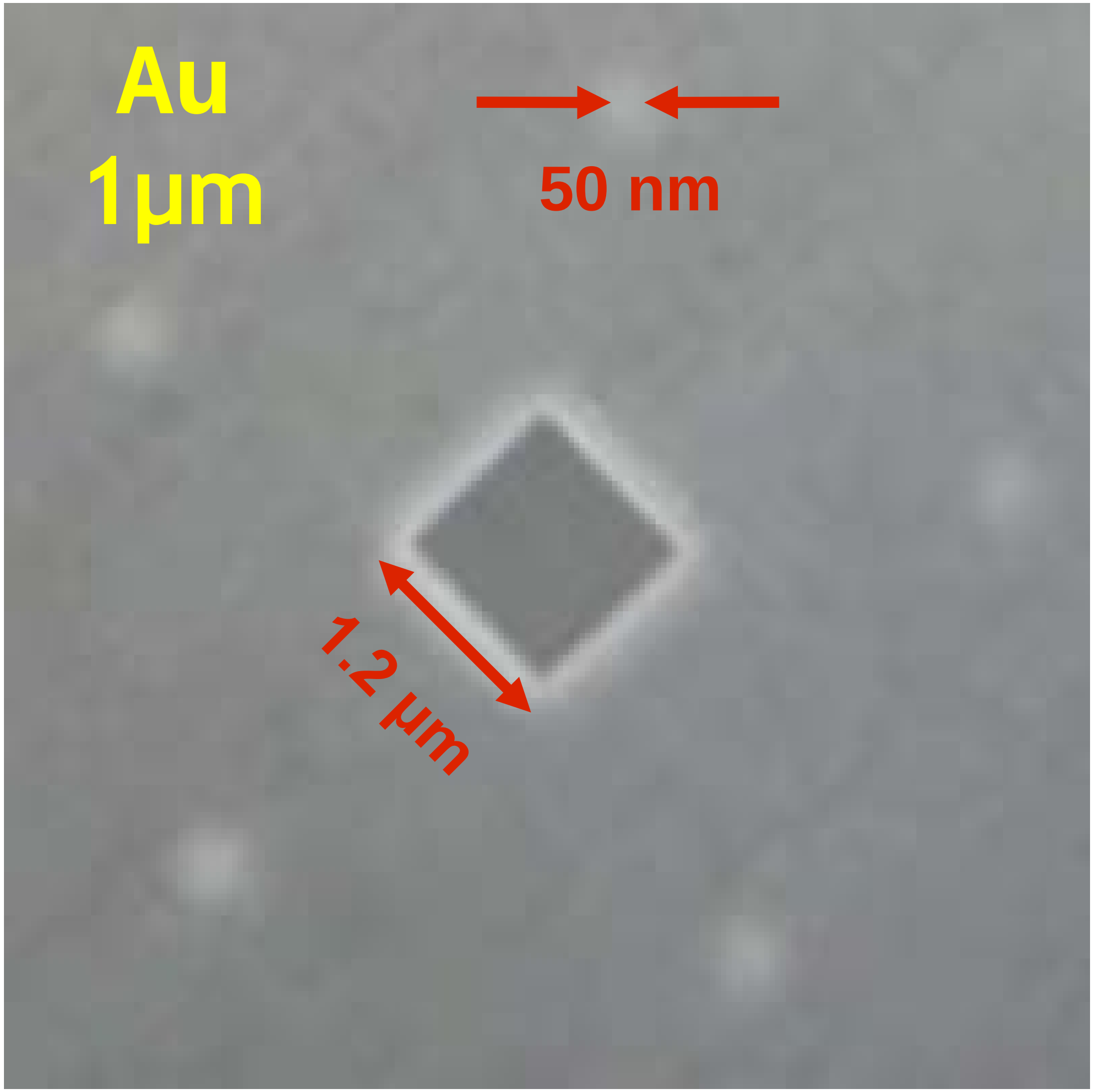
Disadvantage: challenging alignment, stability

H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

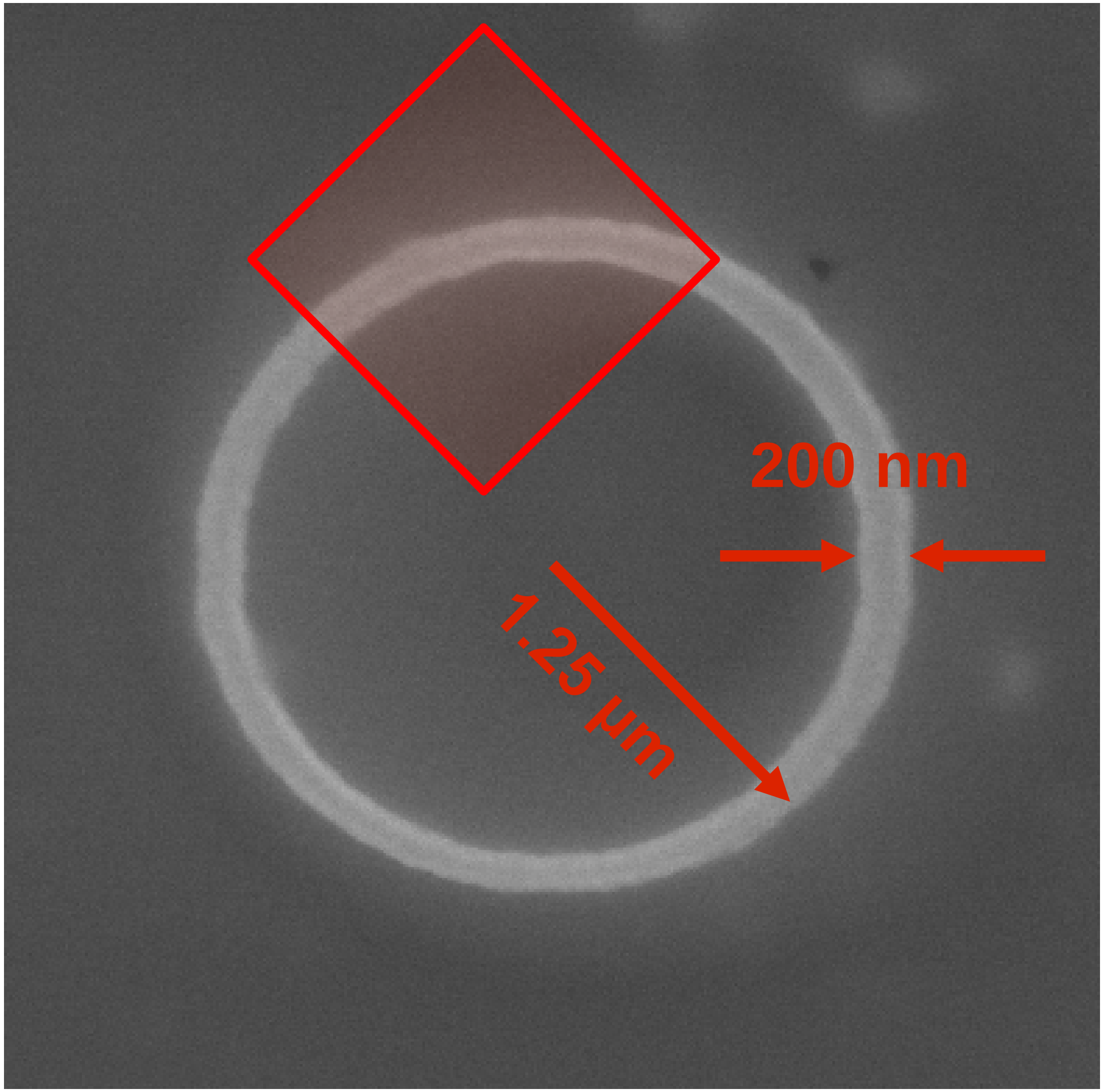
Holography: separated mask/sample approach



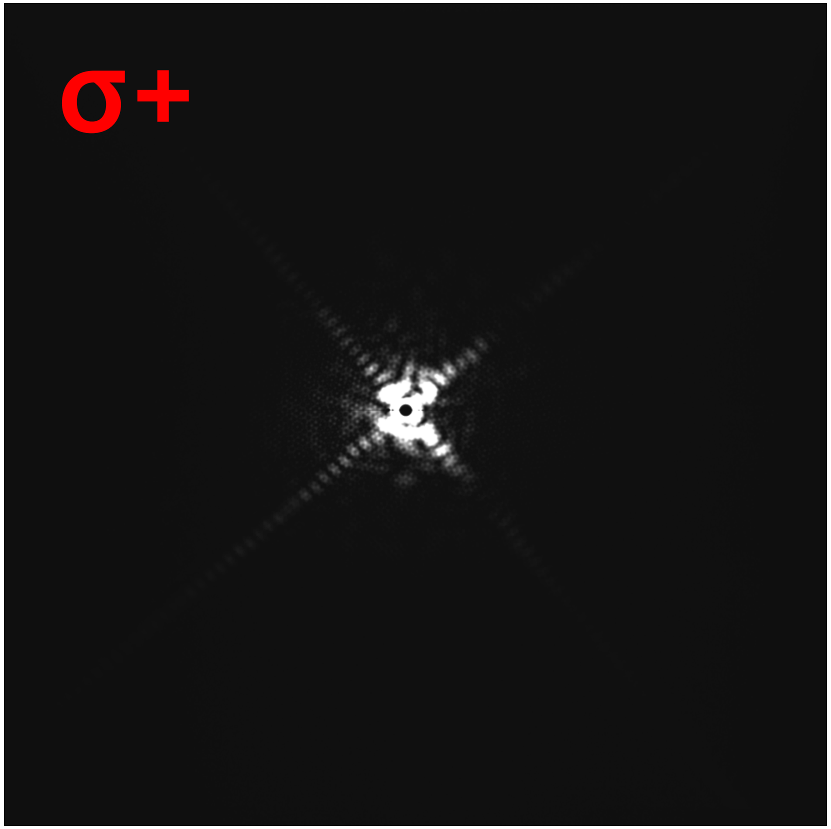
Holography: separated mask/sample approach

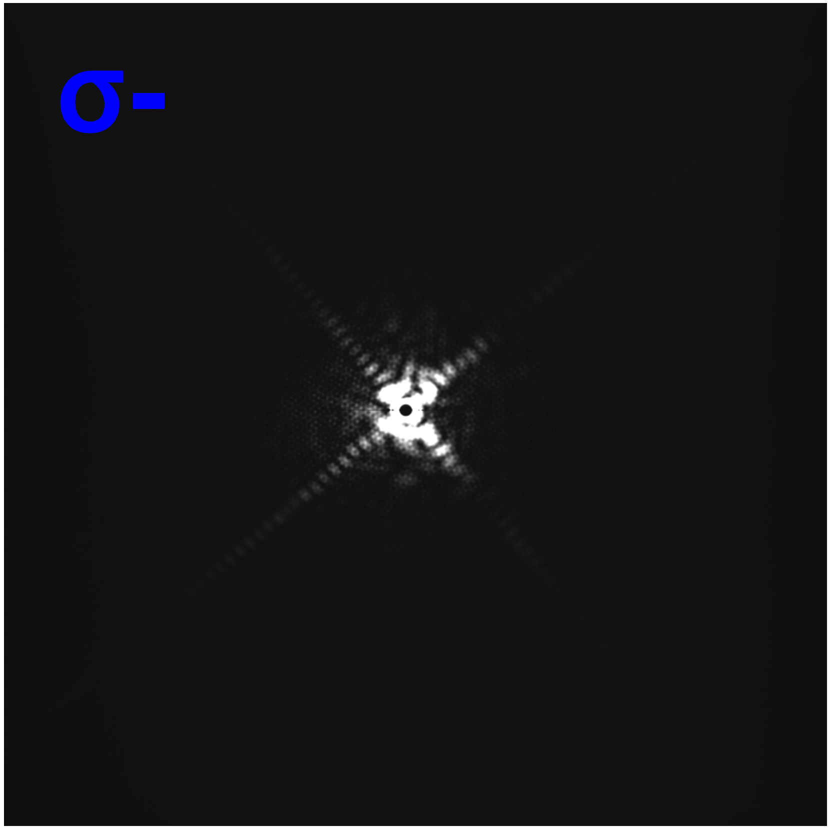


Holography: separated mask/sample approach

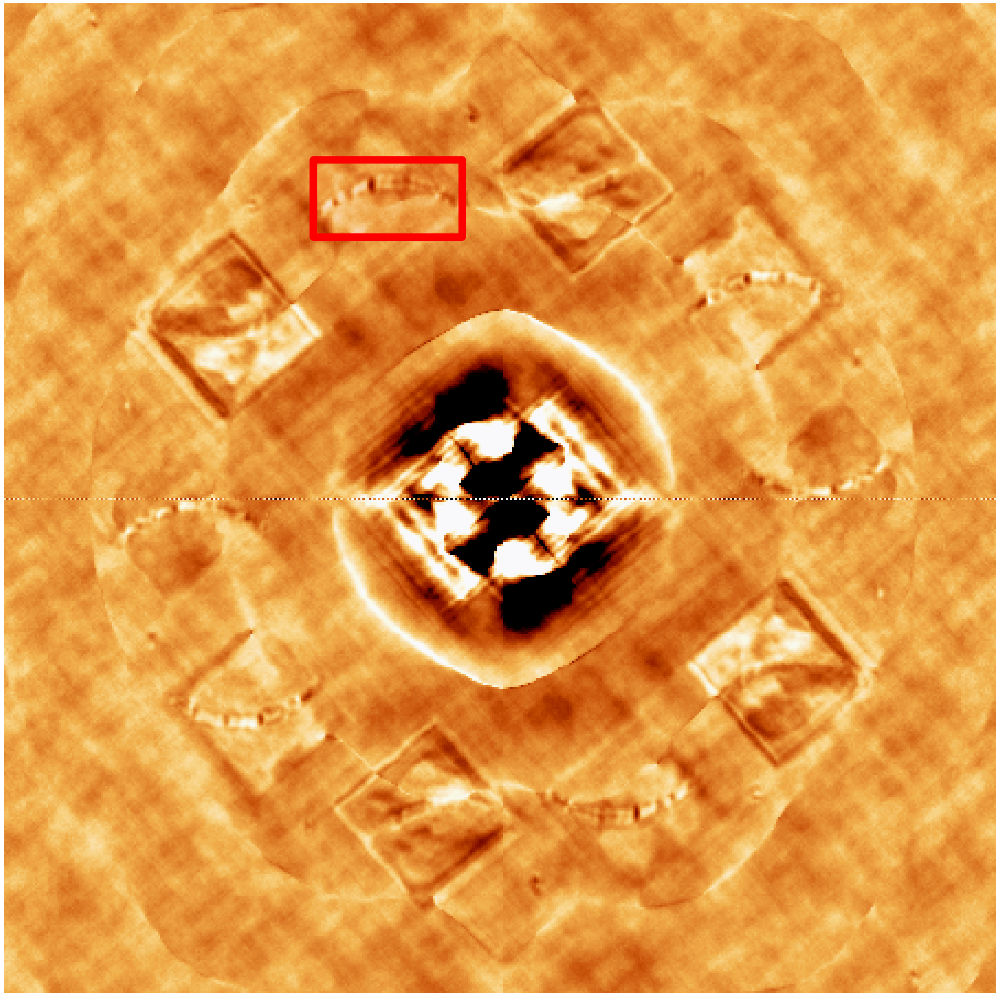


Holography: separated mask/sample approach

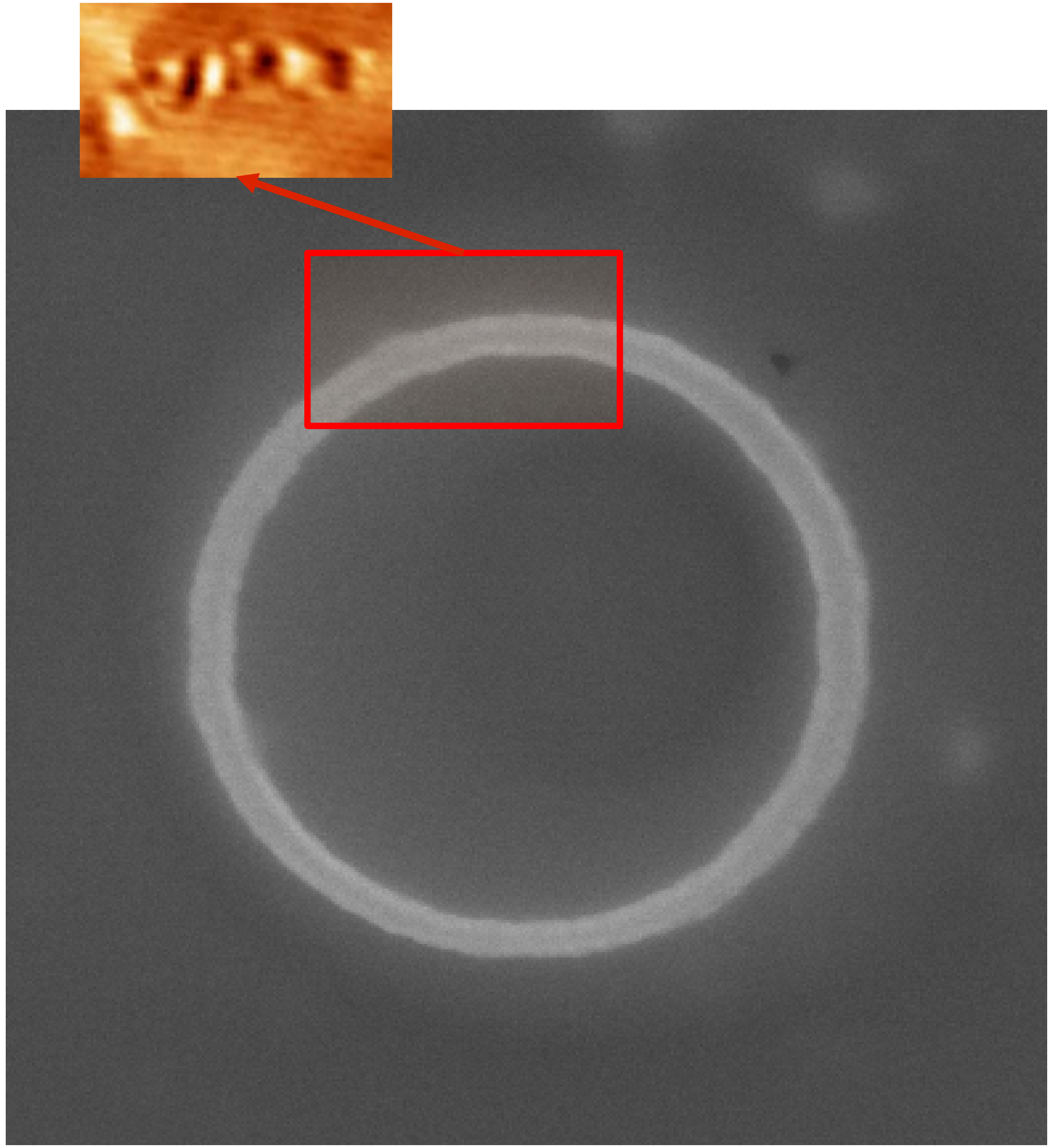




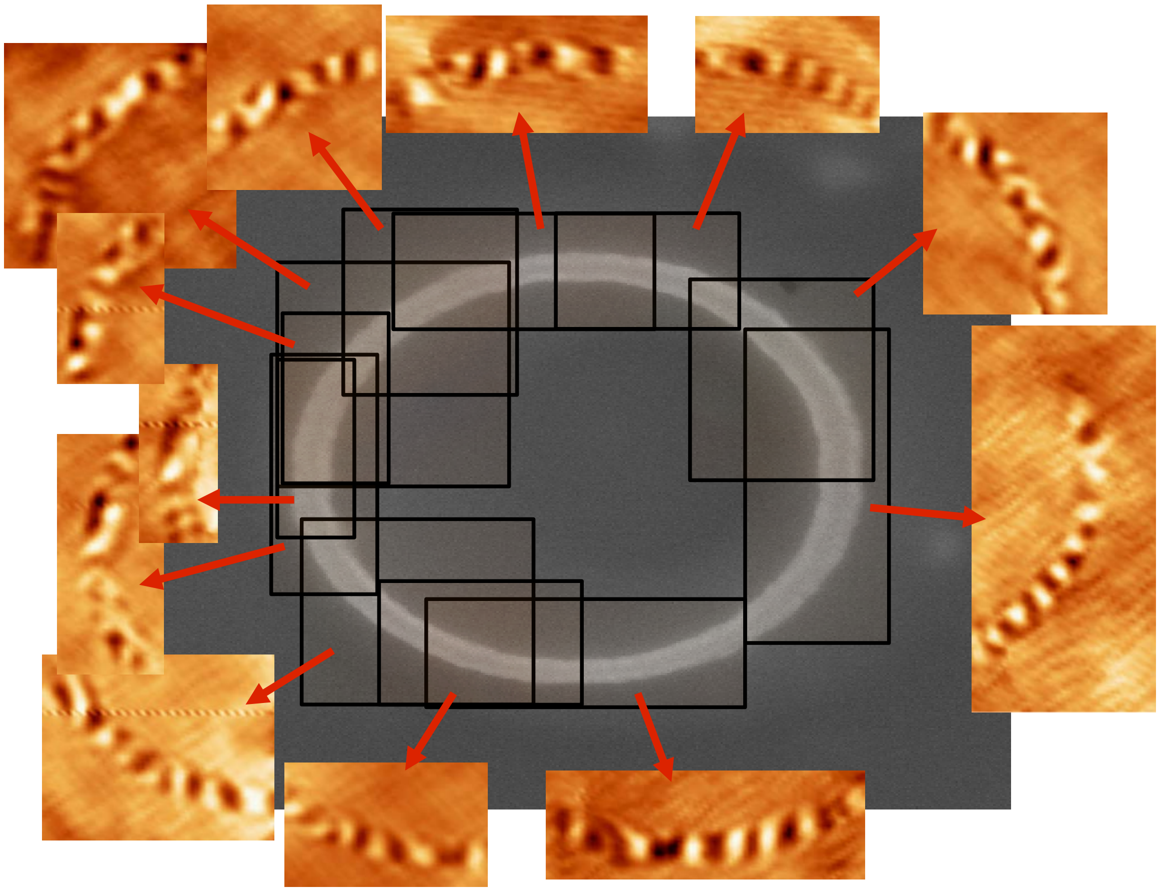
Holography: separated mask/sample approach



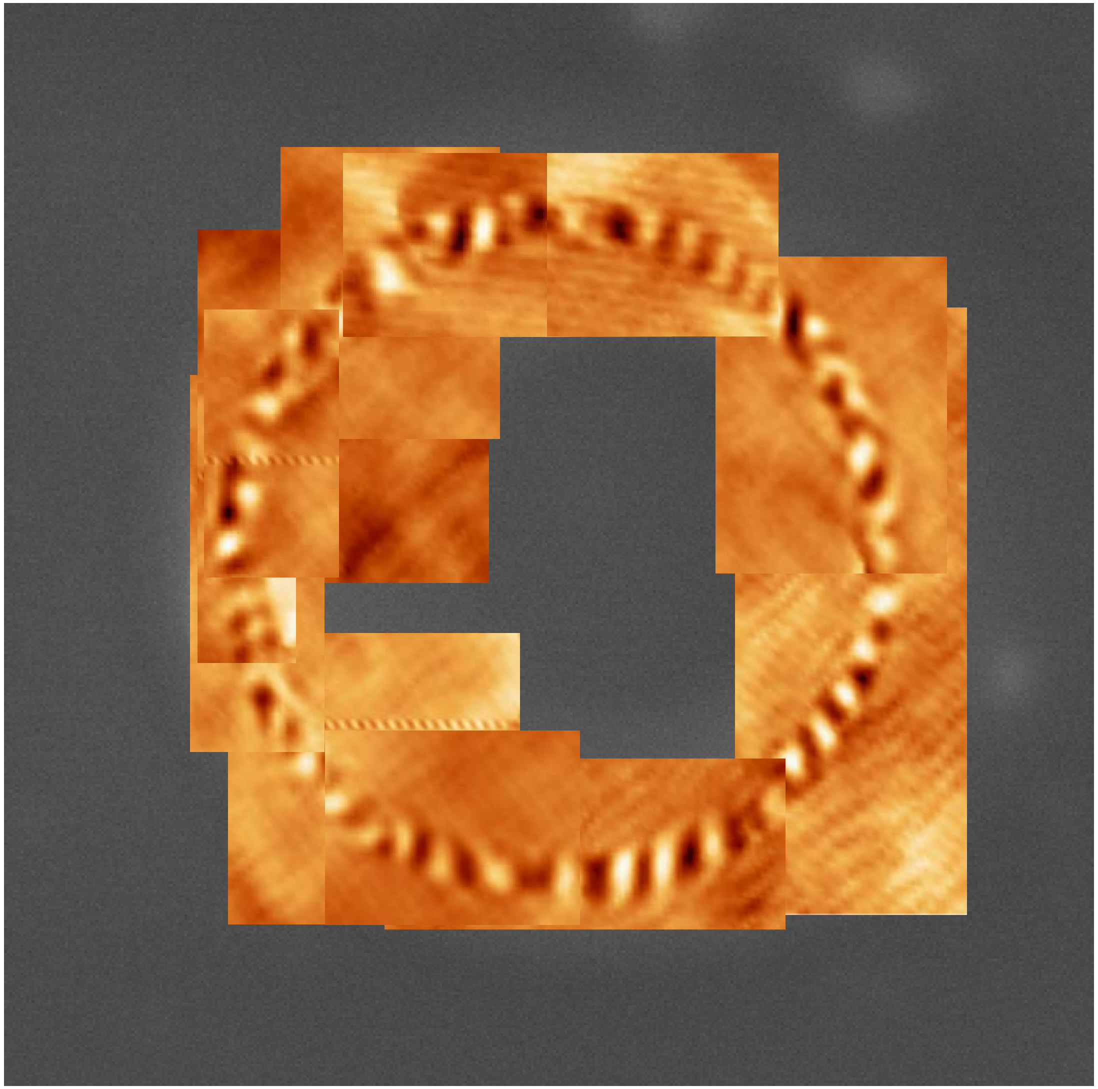
Holography: separated mask/sample approach



Holography: separated mask/sample approach

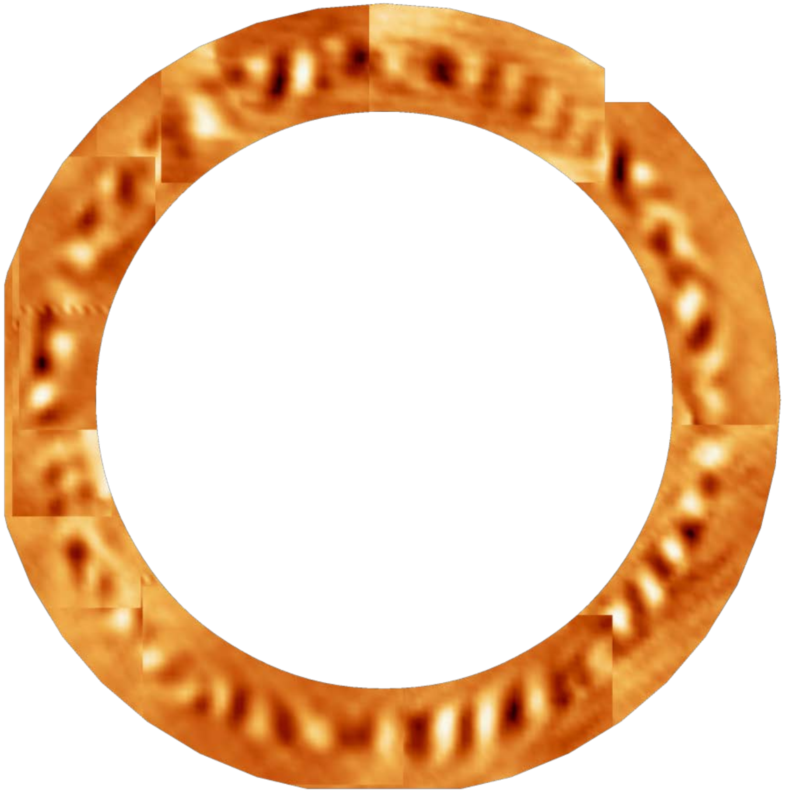


Holography: separated mask/sample approach



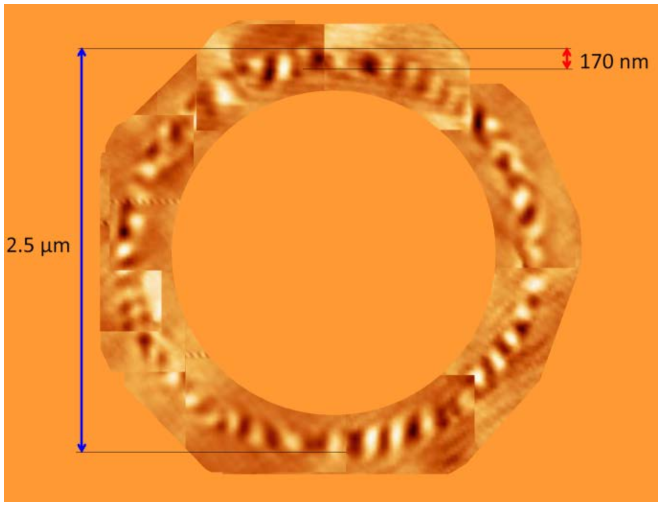
H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

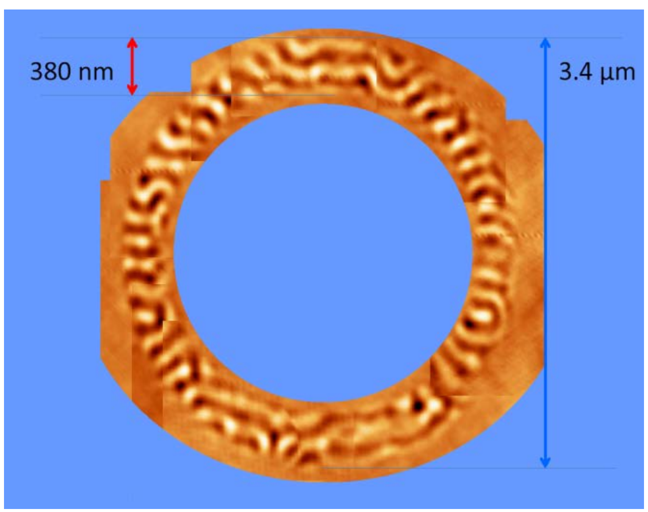
4 - CXS @ Sextants– Holography: Extended Field of view



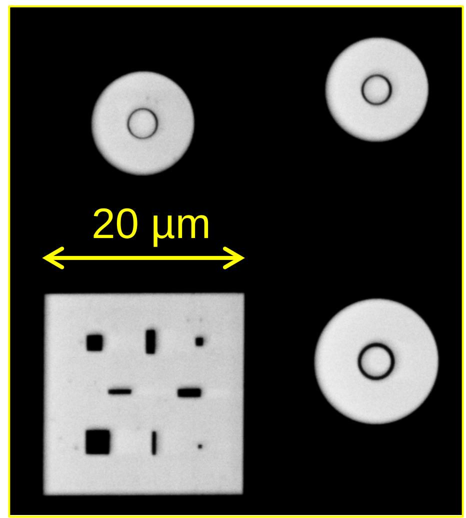
H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

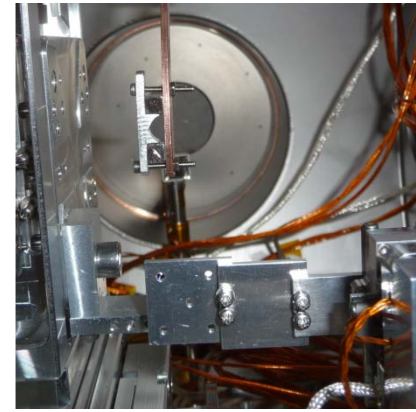
FTH imaging of perpendicular magnetic domains using the extended field of view

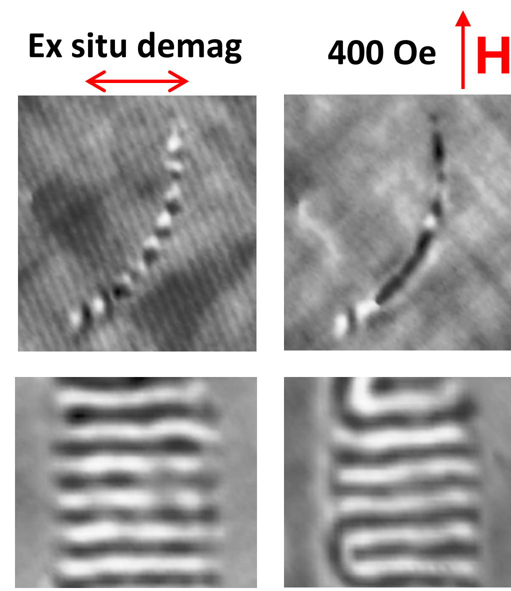




patterned multilayer:
$(Co_{0.4nm}/Pd_{0.8nm})x40$



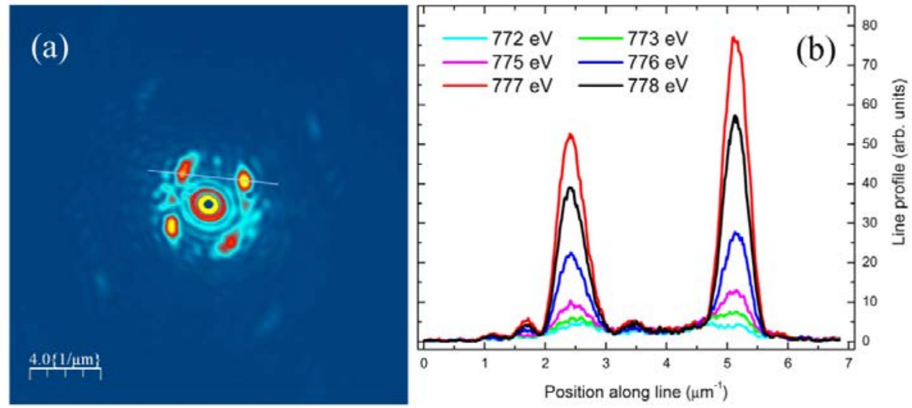




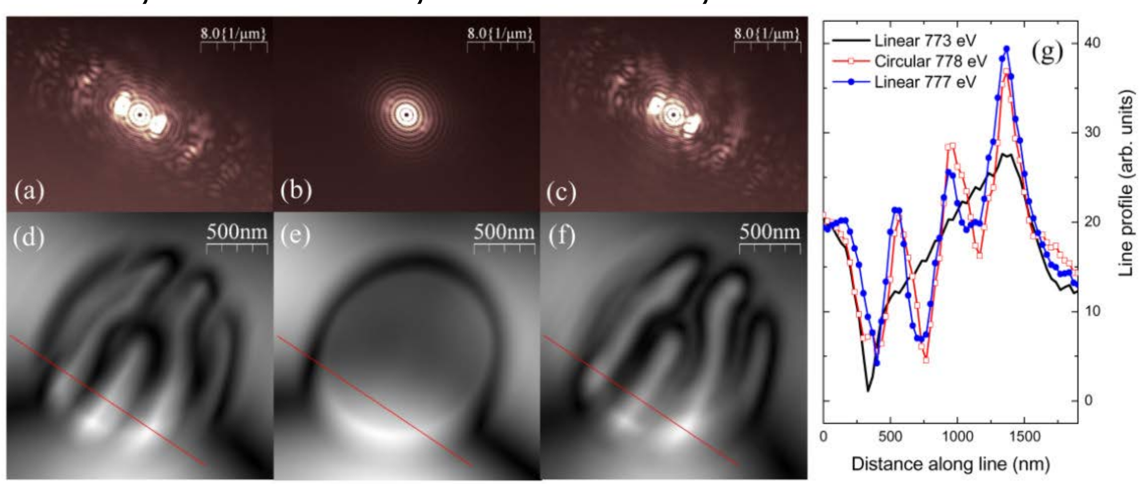
H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

Linear polarization in normal incidence for out of plane magnetization (interest for FEL and HHG surces)

General idea:
the reference wave is also crossing the magnetic layer



777eV, LP 773 eV, LP 778 eV, CP

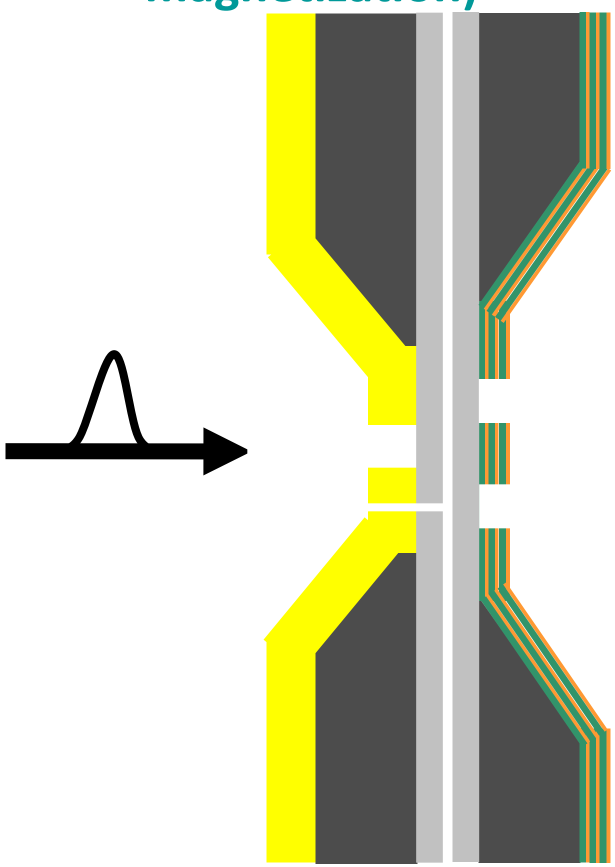


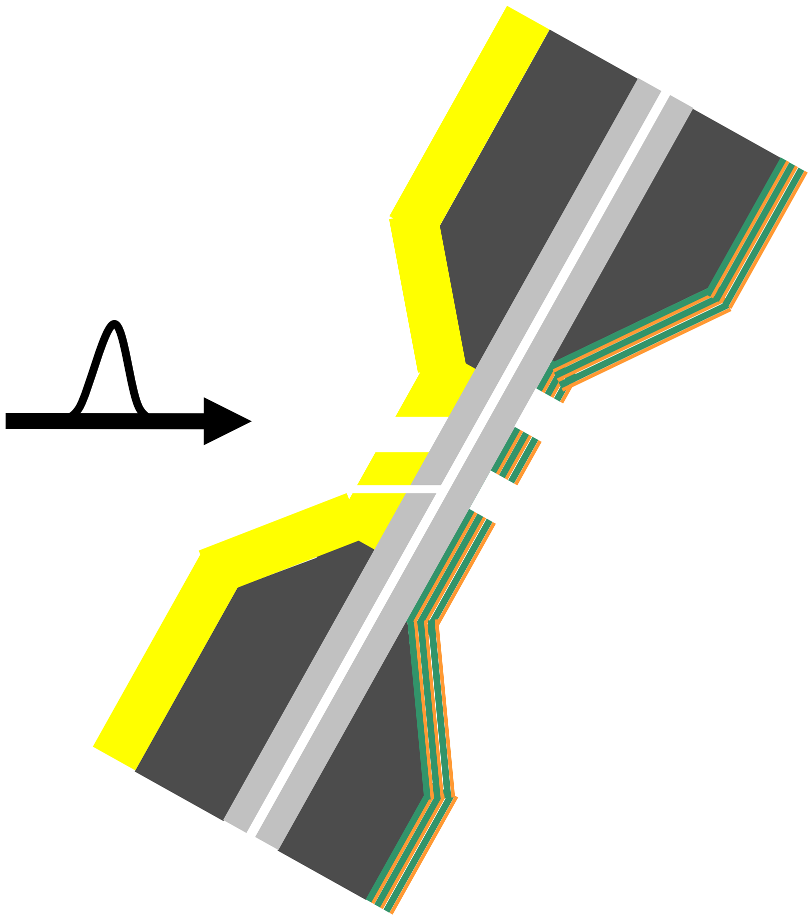
Vol. 20, No. 9 / OPTICS EXPRESS 9776 (2012)

Transmission geometries :

normal incidence
(out of plane magnetization)
magnetization)

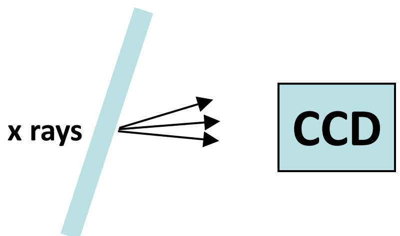
tilted geometry
(in plane



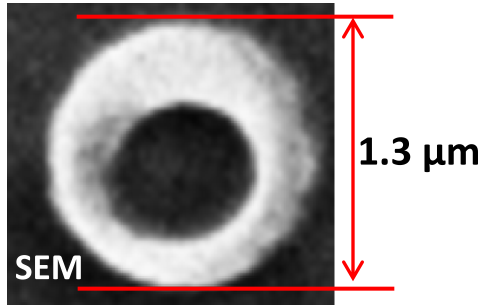


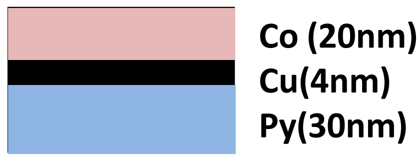
H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

Holographic imaging of in-plane magnetic domains at tilted geometry (30°) with movable field of view

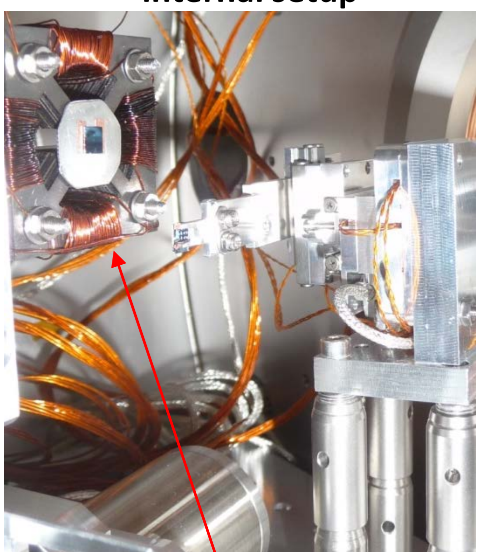


Co L3, 778 eV, circular polarisation



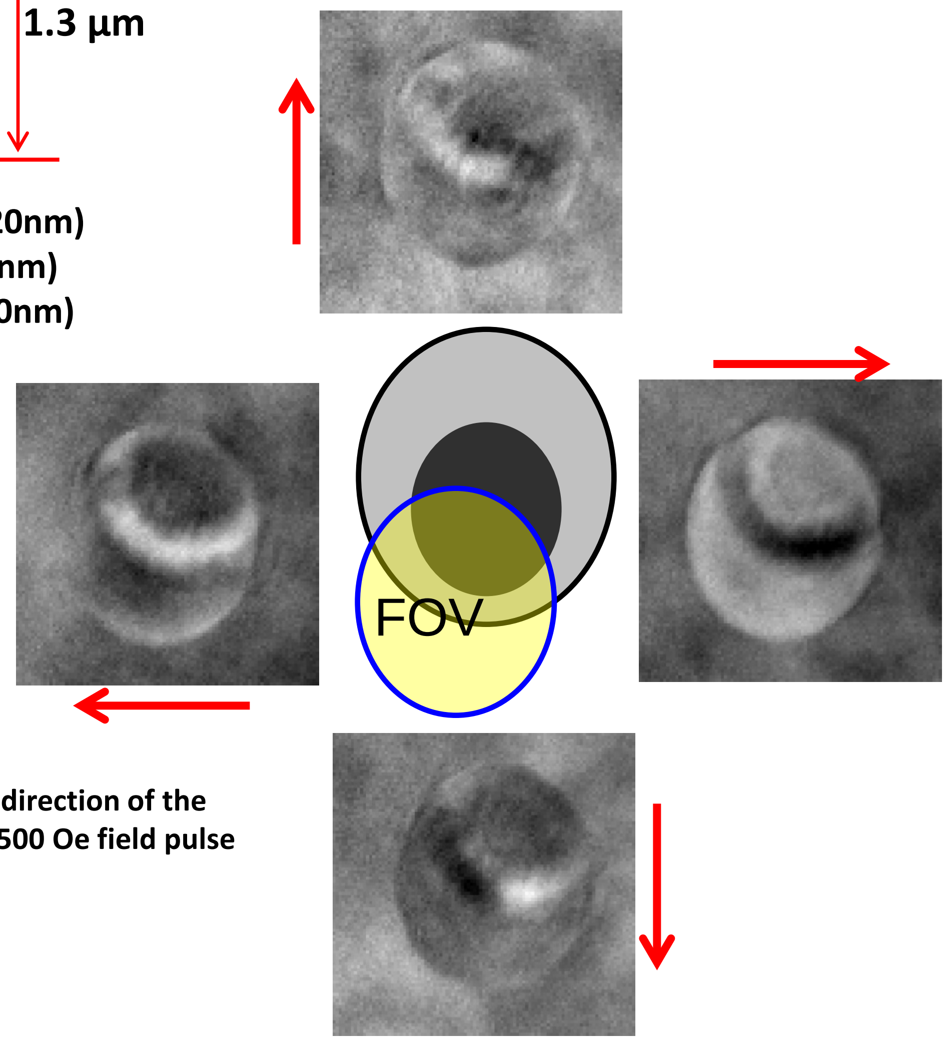


internal setup



500 Oe (pulsed mode)

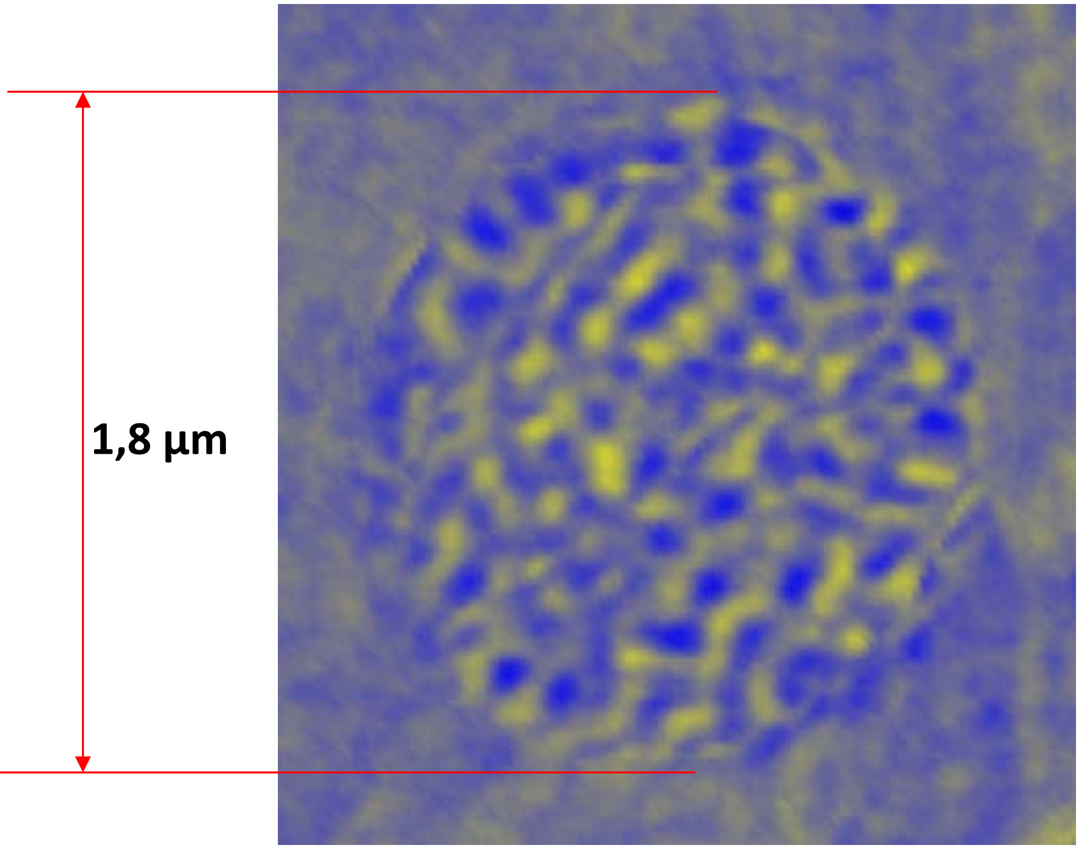
Four remanent states



red arrows: direction of the 500 Oe field pulse

H. Popescu et al., APL 107 (20) 2015

Holography with separated mask : ‘magnetic bubles’



Sample
(Co0.6/Pt1)x30

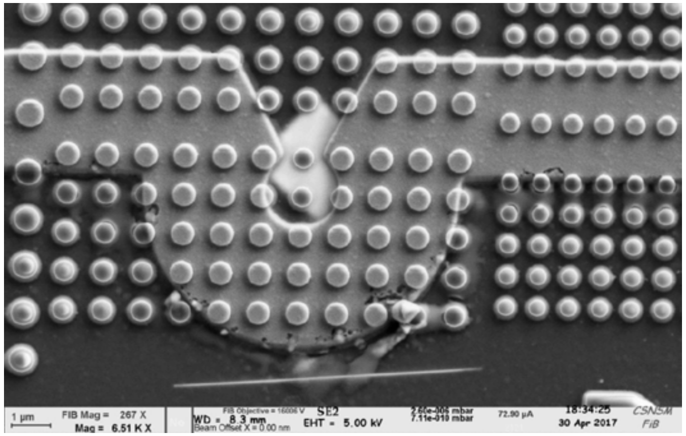
90nm magnetic bubbles

Coll. N Reyren, V. Cros
UMPhy CNRS-Thales

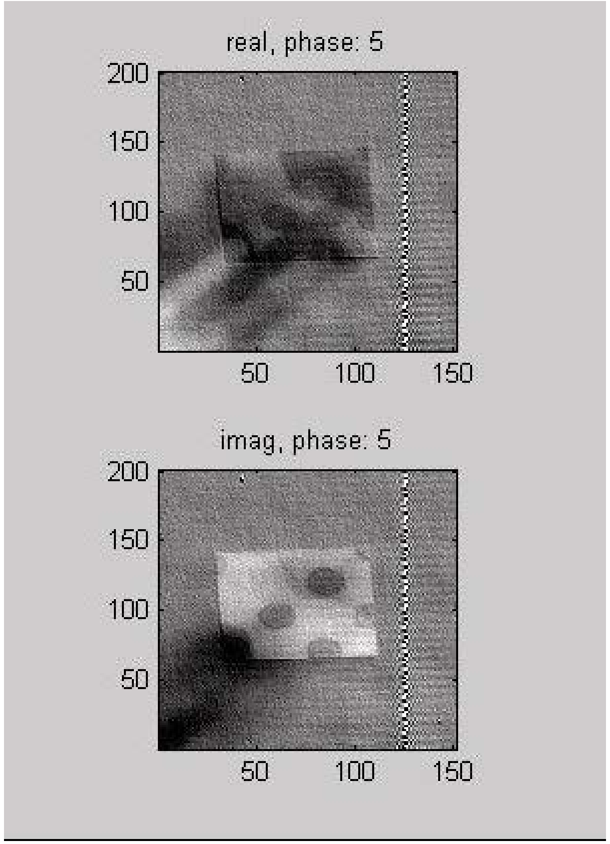
FLAG-ERA
Joint Transnational Call 2015

Holographic imaging of 600 nm dots with integrated mask and Heraldo technique

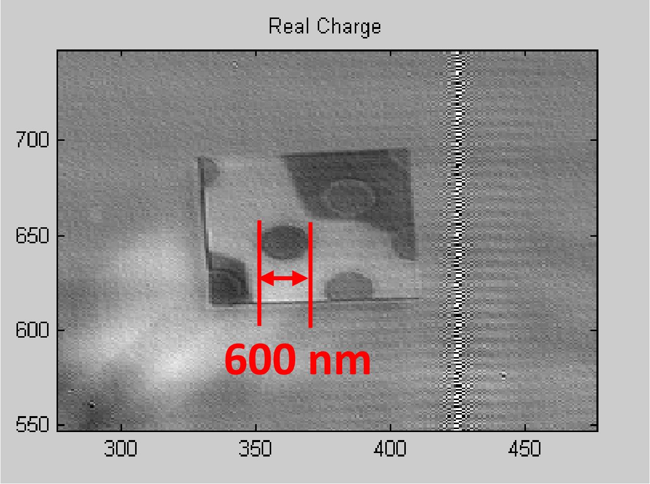
Sample $(Ta_1/Co_{0.6}/Pt_1)x5$



Reconstructed image (phase scan):



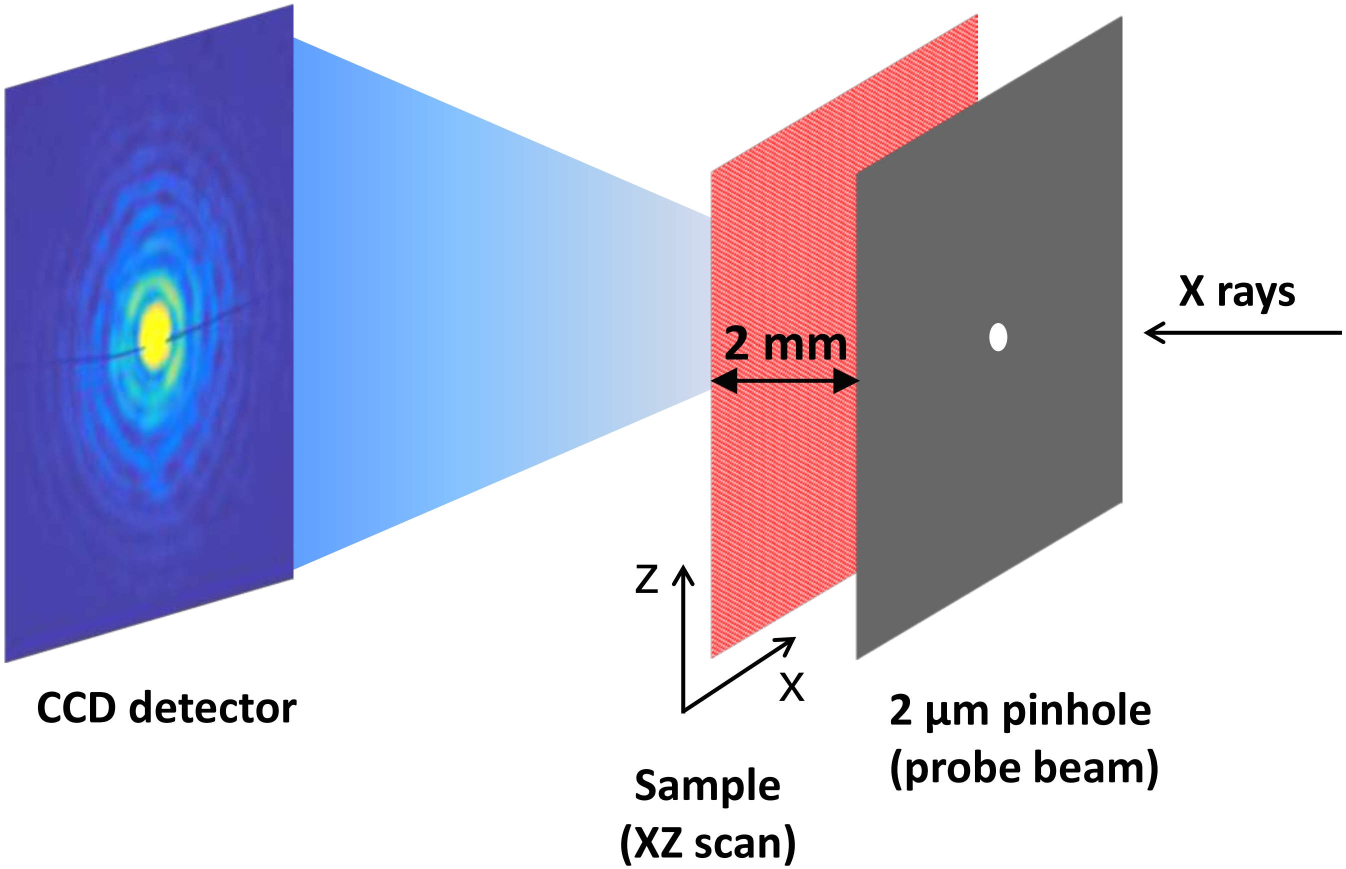
Reconstructed image:



25 nm resolution

H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

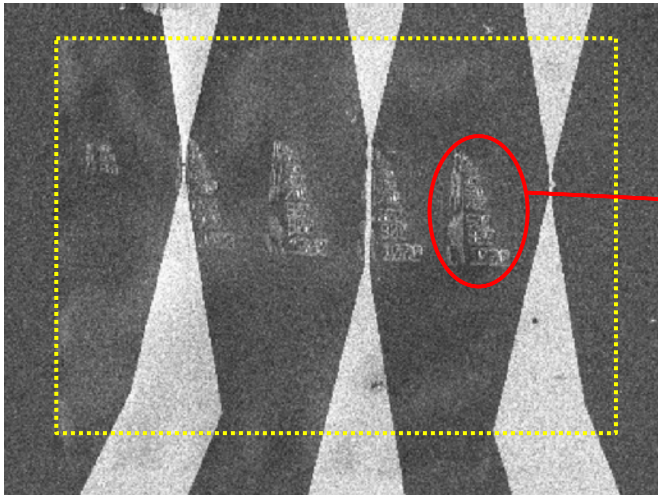
Ptychography imaging technique:

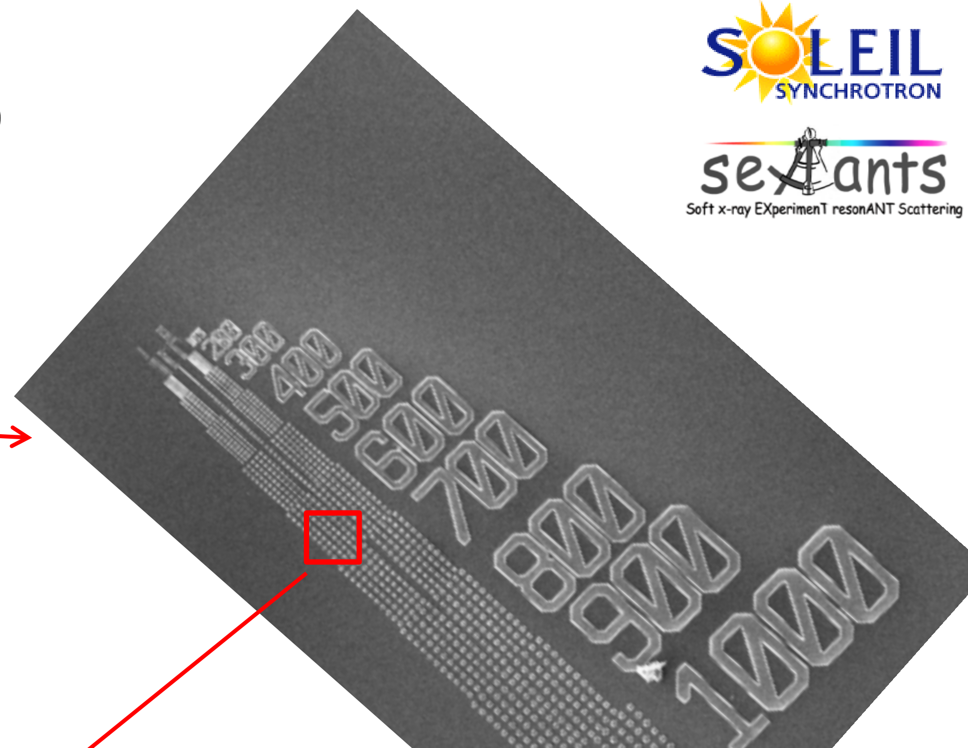


A 2D diffraction diagram is recorded for each sample position. If enough overlap, by iterative algorithmes the sample transmission can be reconstructed.

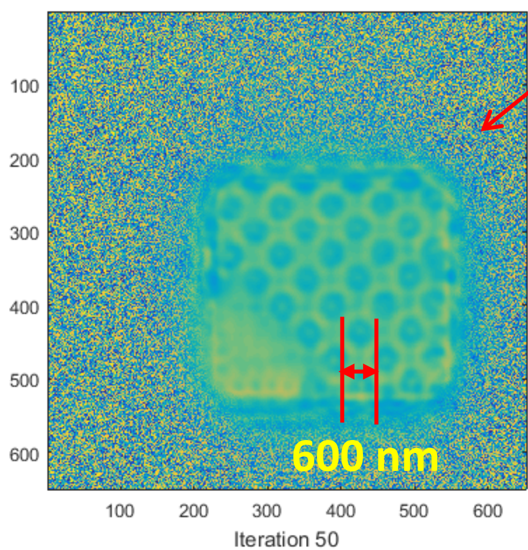
Ptychography imaging technique

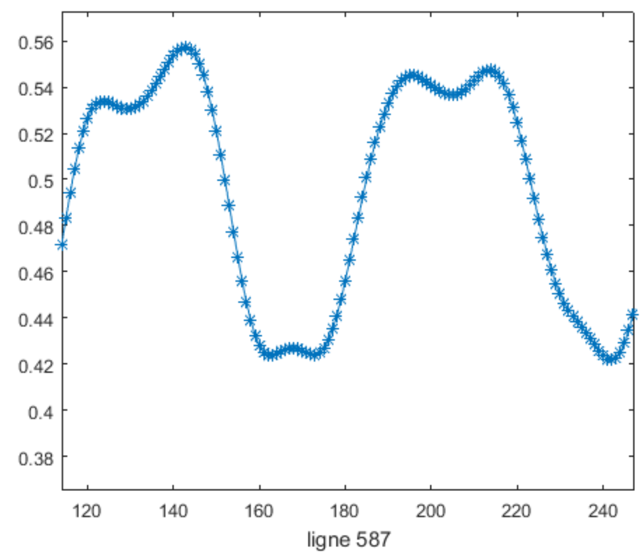
(reconstruction algorithmes by Kadda Medjubi)





200 nm resolution





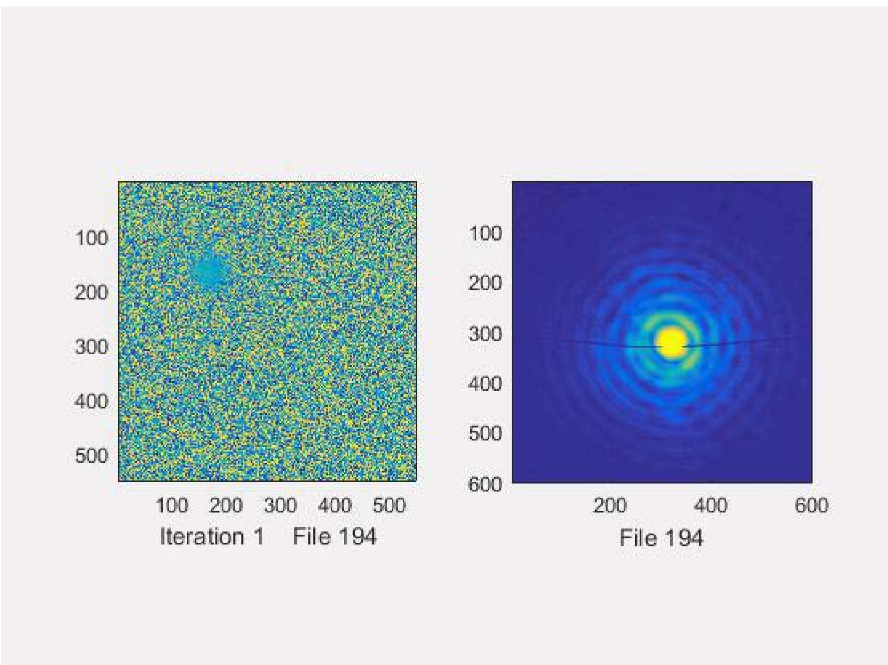
H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

Ptychography imaging technique:

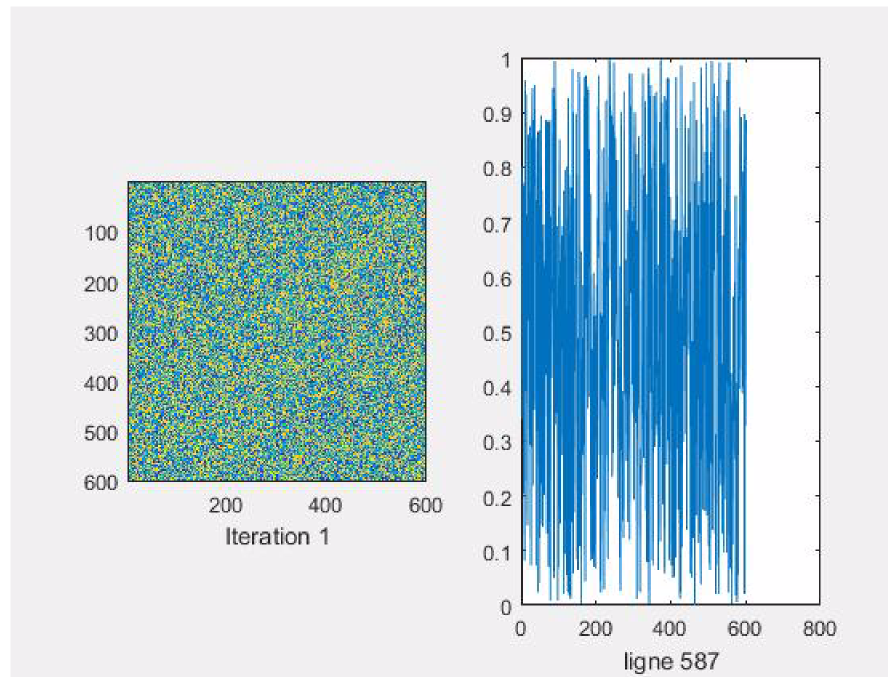
(reconstruction algorithmes by Kadda Medjubi)

Probe beam: 2µm pinhole placed
at 2 mm from the sample
Sample XZ scan with 500 nm steps

Image reconstruction : detail of first 3 iterations

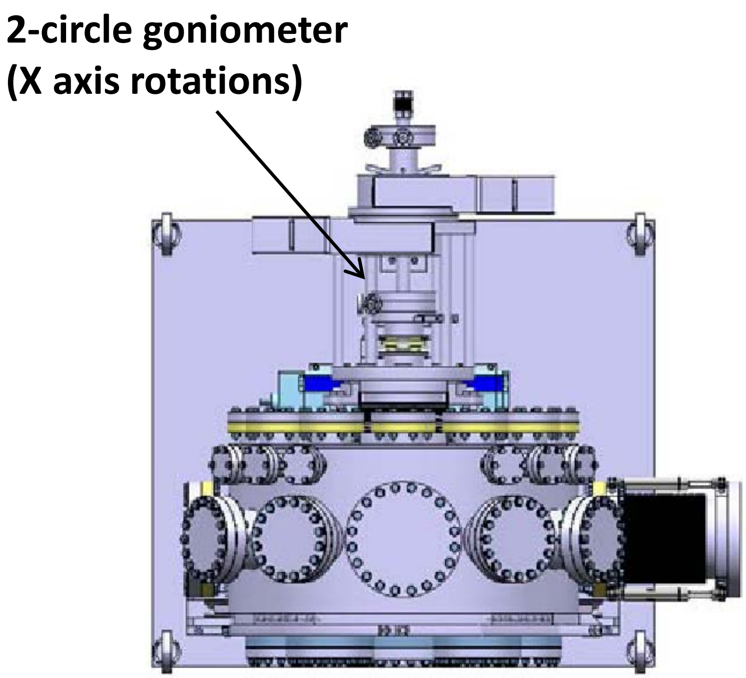


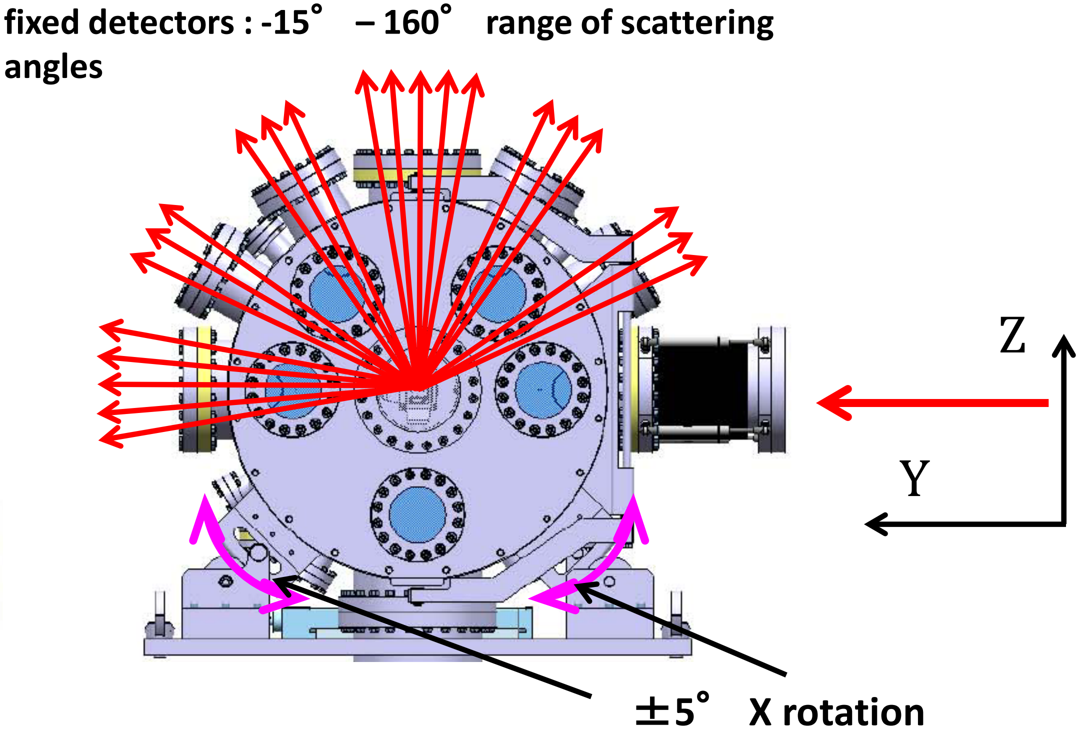
Evolution to 50 iterations



IRMA2 - Instrument pour la Refléctivité MAgnetique

Reflectivity, Diffraction, Coherent scattering, X-ray imaging

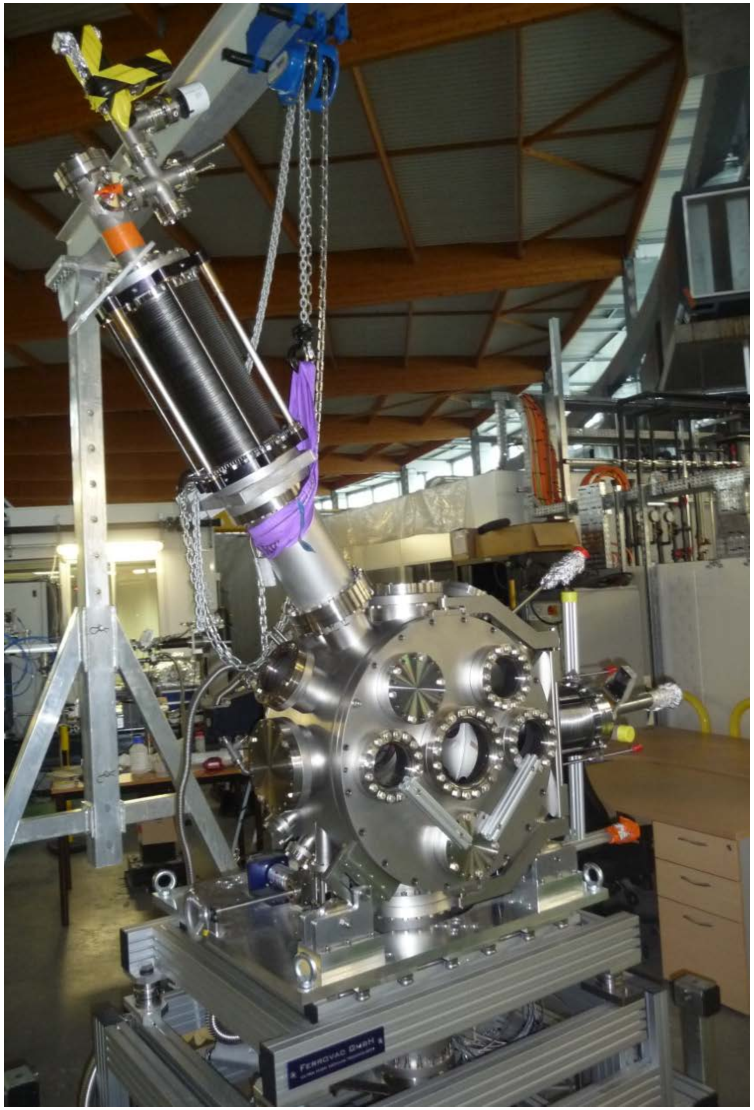




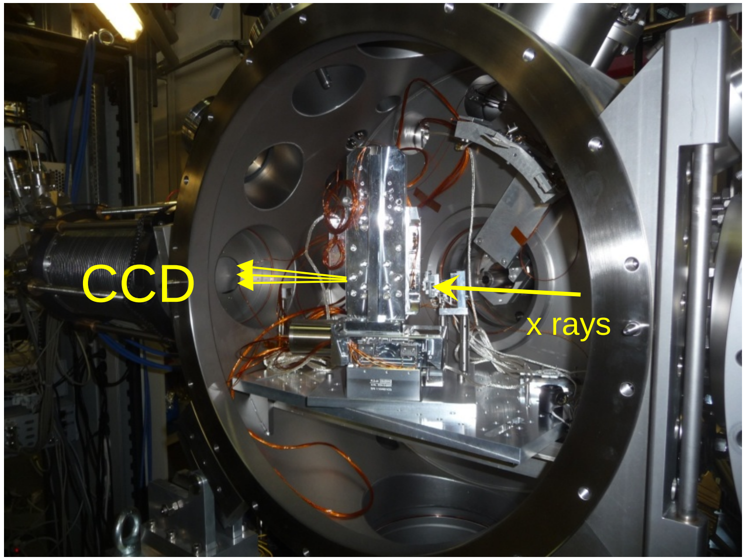
M. Sacchi, H. Popescu, F. Fortuna, R. Delaunay, N. Jaouen, J. Phys. Conf. Series, 2012

IRMA2 instrument: 2D detector positions

2D detector at 60°



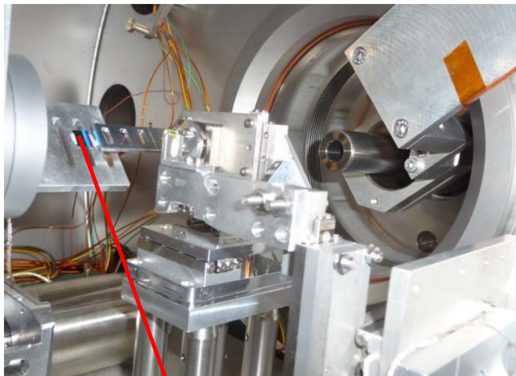
2D detector in transmission



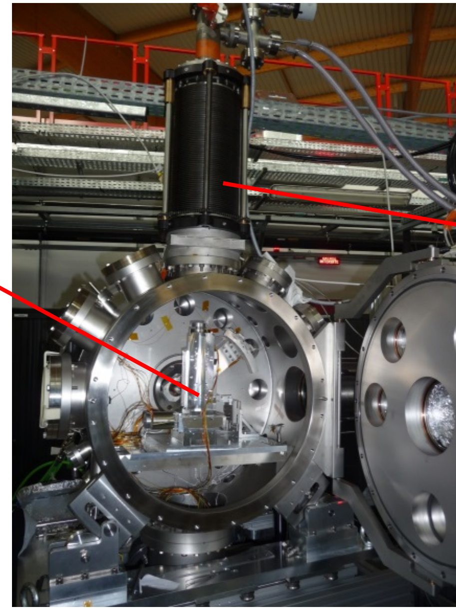
H. Popescu, Workshop Round Beam, Soleil (14/06/2017)

Ptycography test in reflectivity

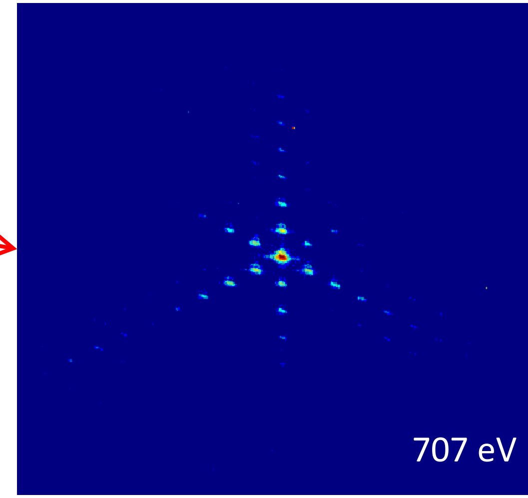
internal setup:

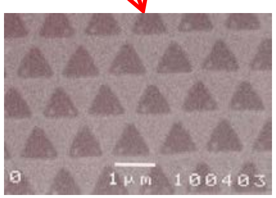


IRMA2



2D detector at 90° :

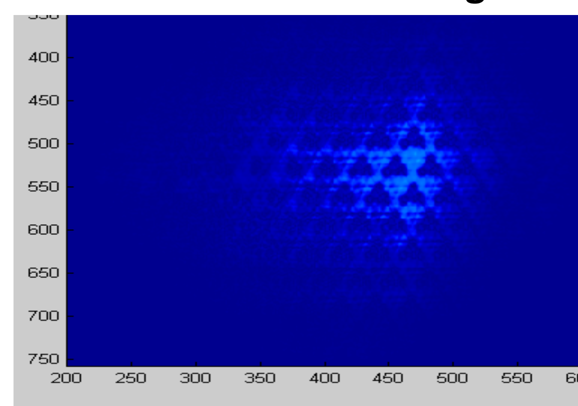




Py pattern

probe beam : 5 µm pinhole
step_x : 1.1 µm
step_z: 1.3 µm
reconstructed pixel size: 27 nm

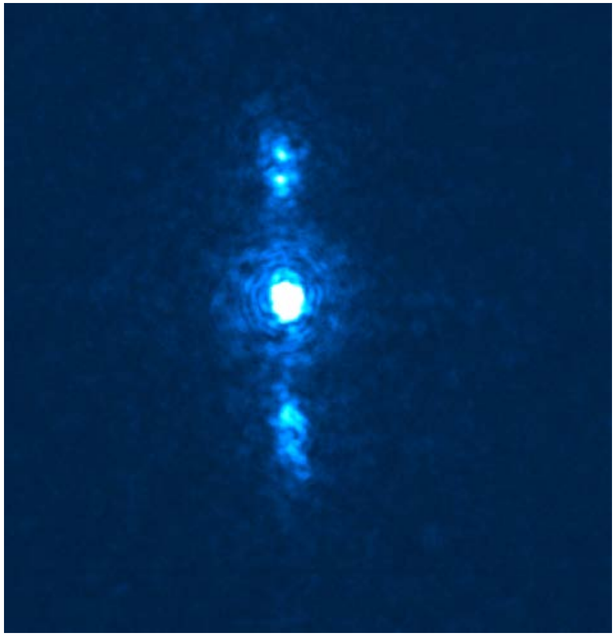
Reconstructed image:



(reconstruction algorithmes by Kadda Medjubi)

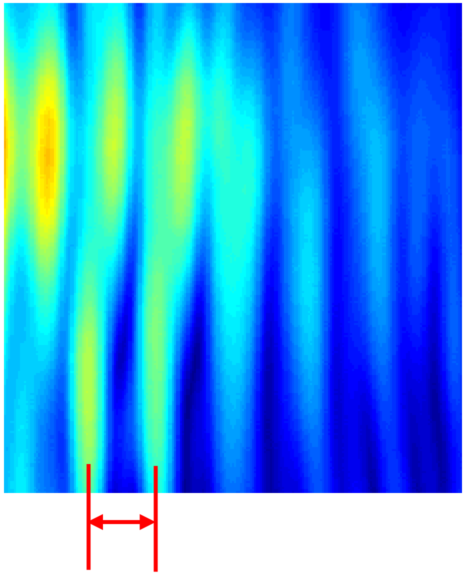
Ptychography in reflectivity on a real magnetic sample: (MnAs/GaAs, alpha/beta stripes with 900 nm period)

Diffraction diagram in reflectivity at 90°

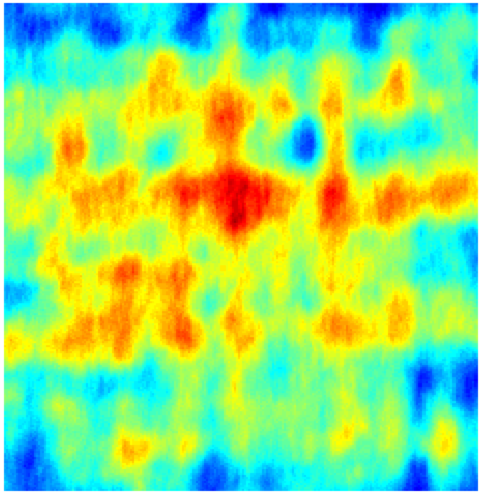


with 22 microns pinhole

Structural (Alpha and Beta stripes) (CL + CR)



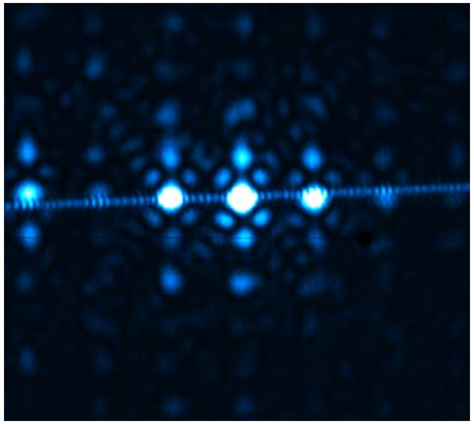
Magnetic domains (CL – CR)



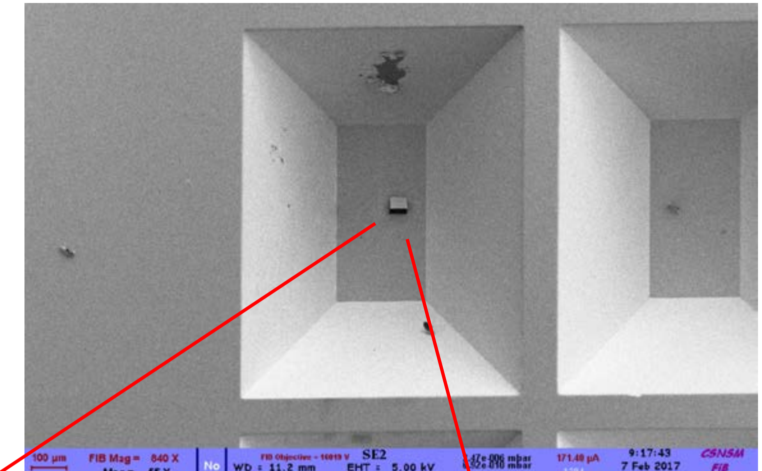
CL : circular left
CR: circular right

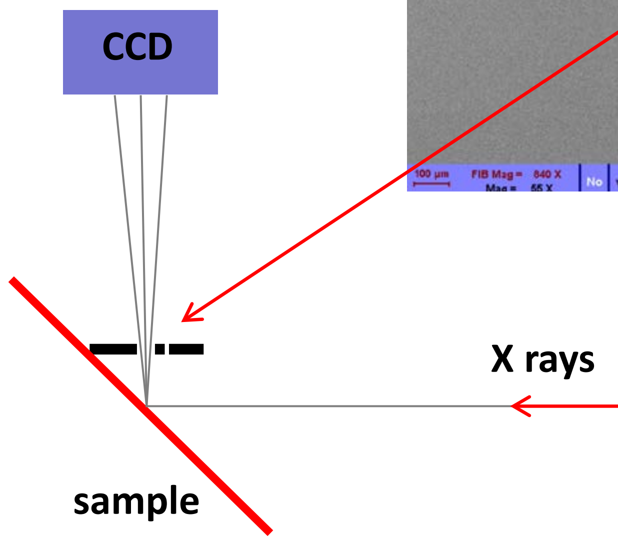
Holography in reflectivity with movable field of view

Diffraction diagram

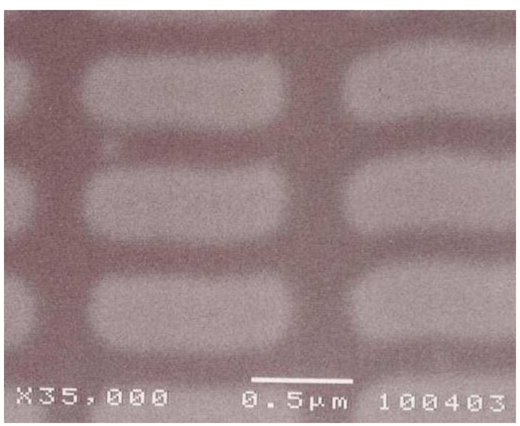


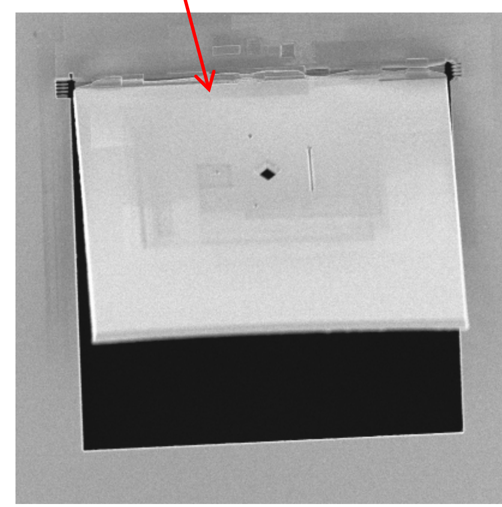
mask





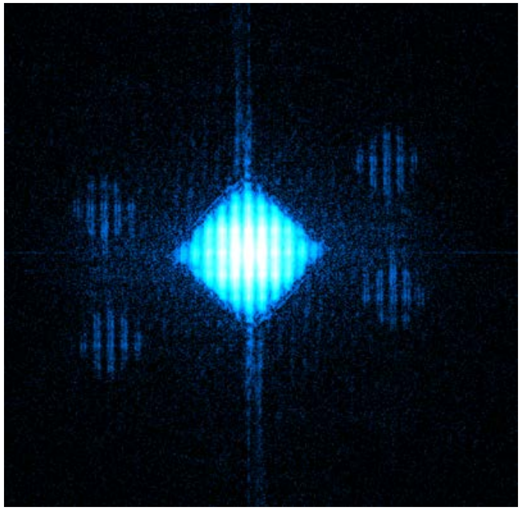
Patterned sample
(CoCu multilayer)



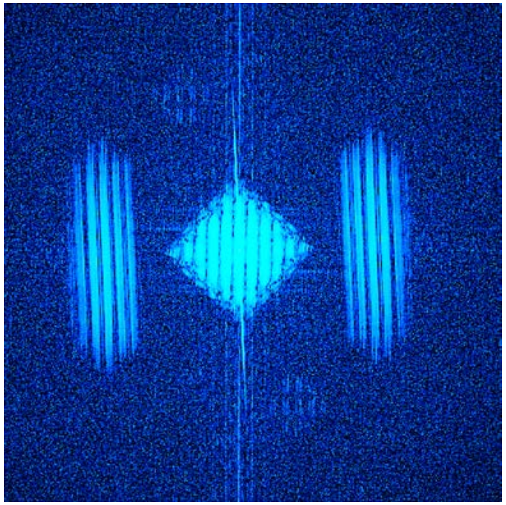


Holography in reflectivity with movable field of view

Reconstructed image with slit reference
(Heraldo linear differential filter)



Reconstructed image with classic referece hole
(simple Fourier transform)



Conclusion:

Sextants beamline is adapted for coherent diffraction imaging

Coherent scattering instruments on Sextants

- **COMET : transmission**
- **IRMA2 : reflectivity**

Imaging techniques :

- **Holography (state of the art 15 nm resolution)**
- **Ptychography (under developpement)**

Geometries:

- **In transmission : ok !**
- **In reflectivity : we really need the round beam !!**