Imaging Magnetic Domains by X-ray Spectro-Holography

Stefan Eisebitt

BESSY

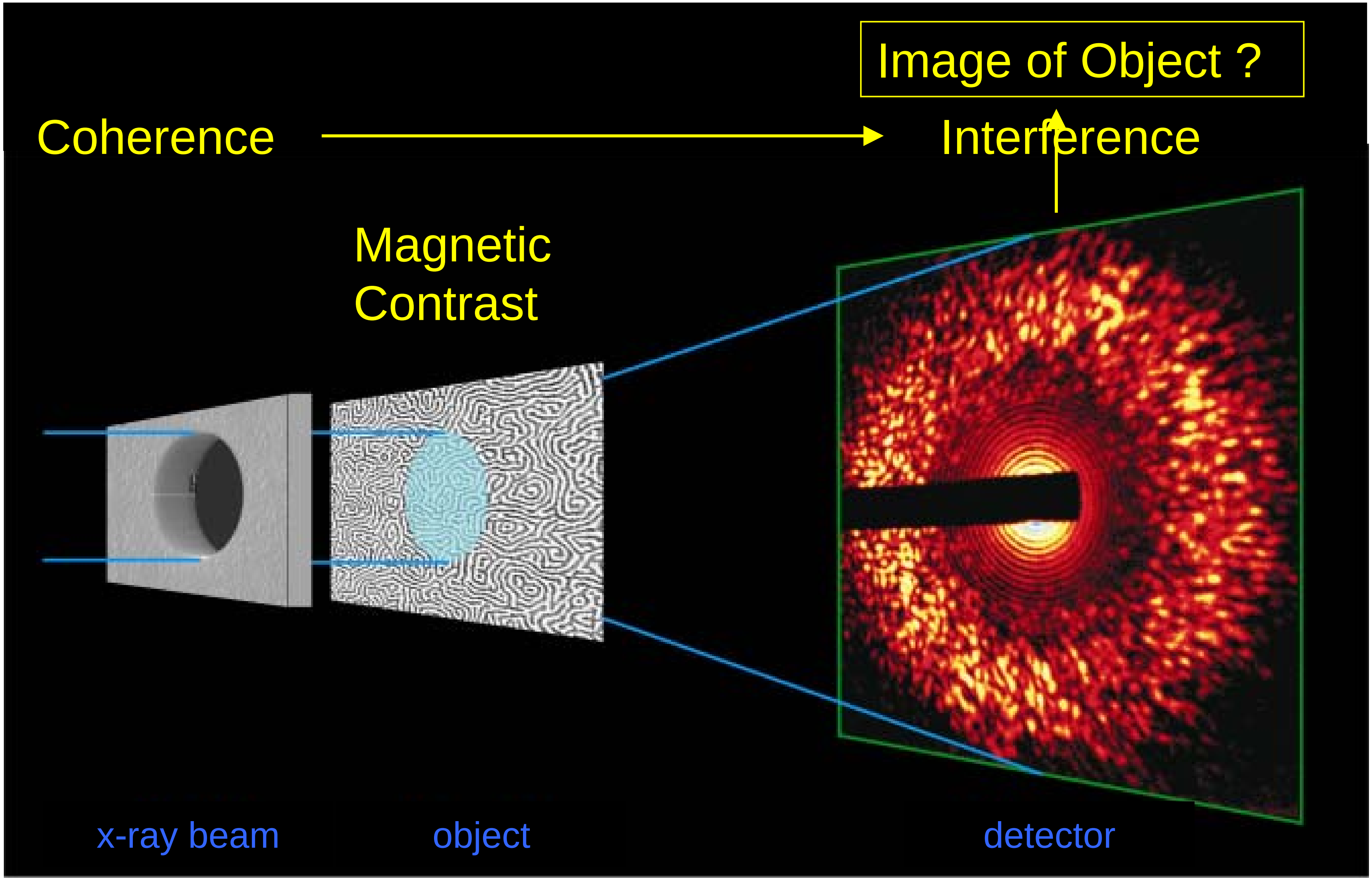
O. Hellwig
M. Lörgen
W. Eberhardt

J. Lüning
W. F. Schlotter
J. Stöhr

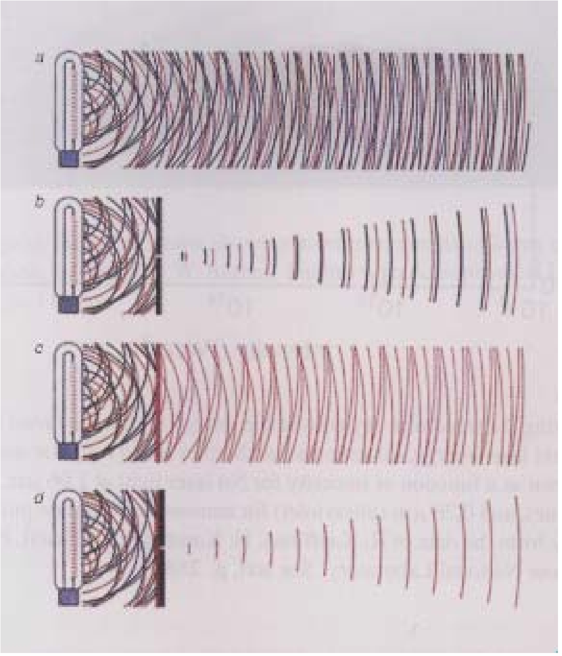
HITACHI
Inspire the Next

E.E. Fullerton

Lensless Imaging of Magnetic Structures



Coherent X-rays



A. Schawlow,
Sci. Am. **219**, 120 (1968)

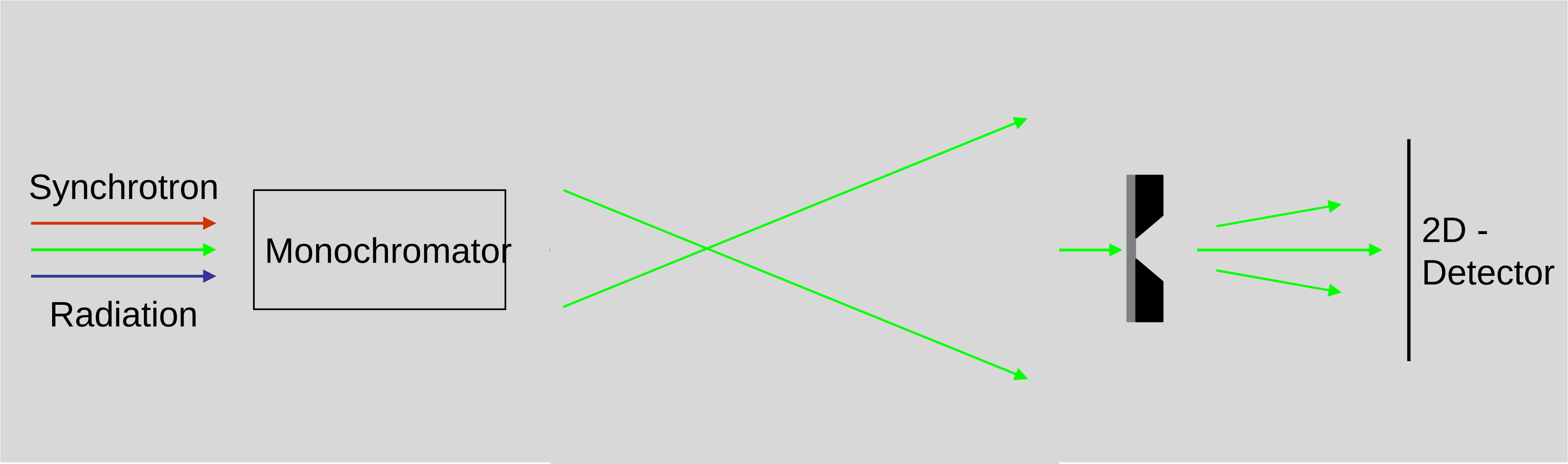
Current x-ray sources are not intrinsically coherent

Synchrotron Radiation

Synchrotron is a chaotic source, but:

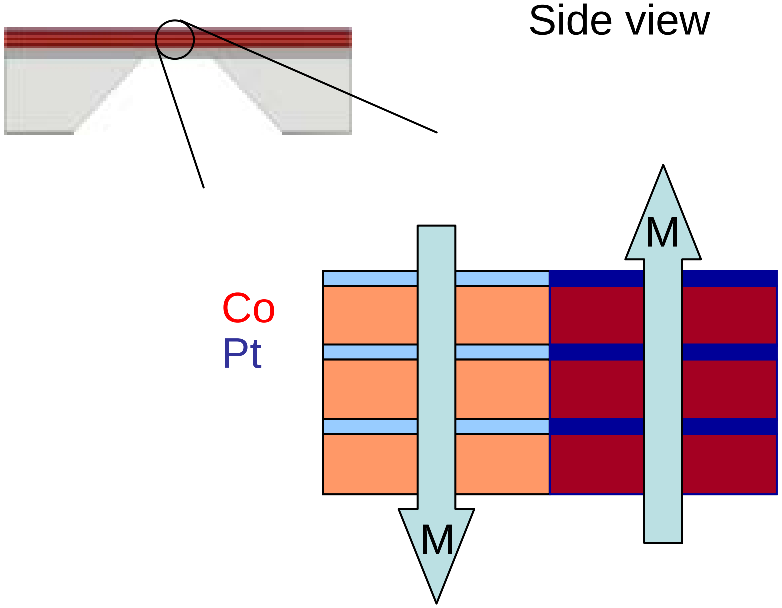
Undulator source at 3rd generation synchrotron allows to extract a high coherent flux

Photons in coherence volume
~ Brightness · λ^3



Magnetic Labyrinth Nanostructures - CoPt

Side view



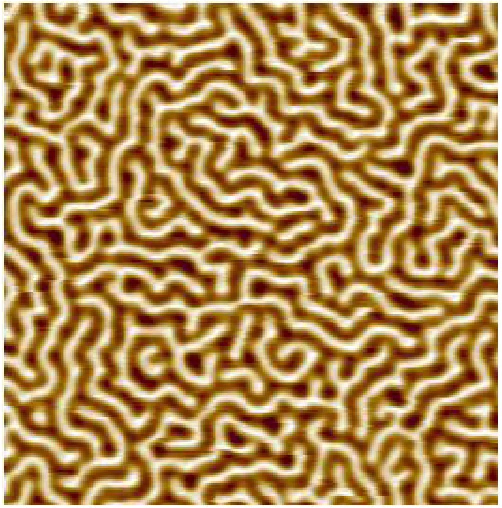
Sample: O. Hellwig

SiN_x / Pt (24 nm) /
[Co (1.2 nm) / Pt (0.7 nm)]$_{50}$ /
Pt (1.5 nm)

perpendicular anisotropy

magnetic storage media

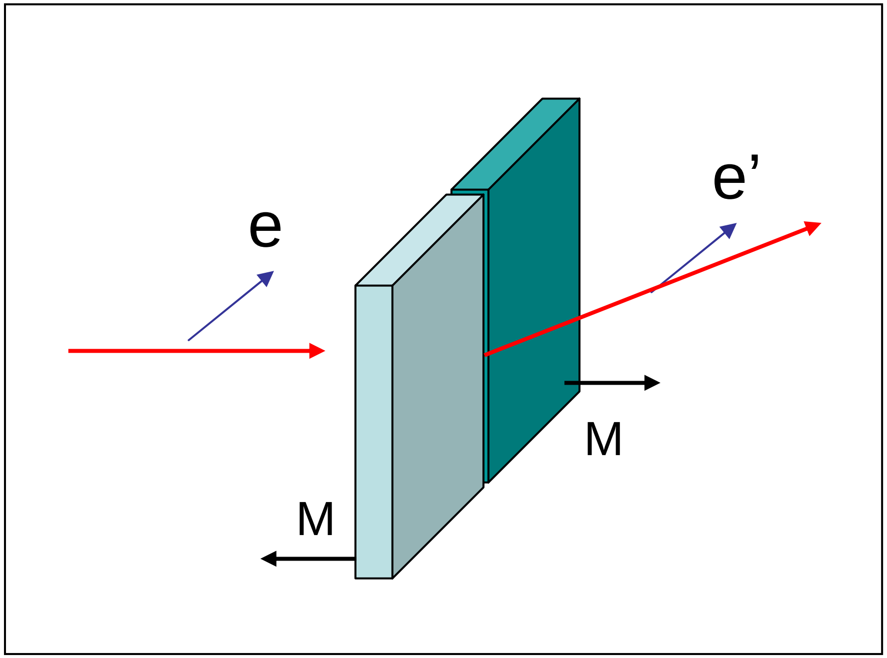
MFM, top view

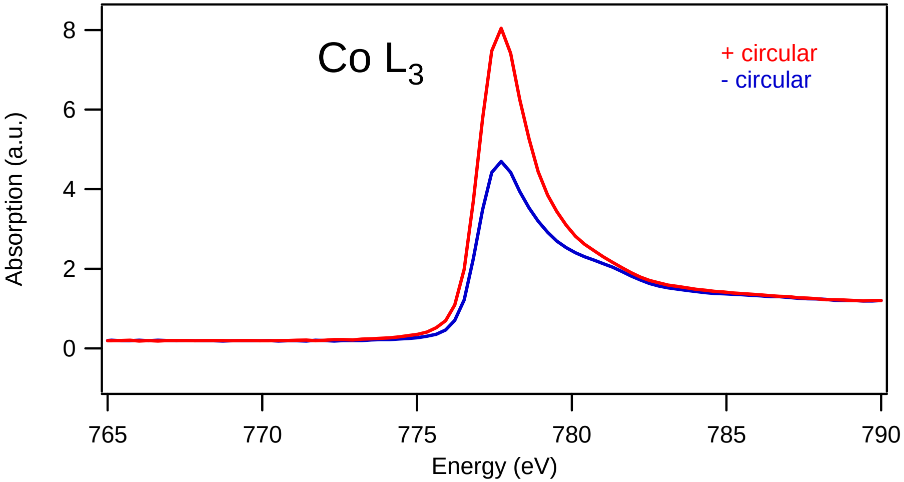


5 μm x 5 μm

Contrast mechanism:
Circular magnetic dichroism

Resonant Magnetic Scattering





Soft x-rays give strong magnetic contrast

charge, magnetic, magnetic

$$I \propto \left| \sum_n \exp(i\mathbf{q}\cdot\mathbf{r}_n) f_n \right|^2$$

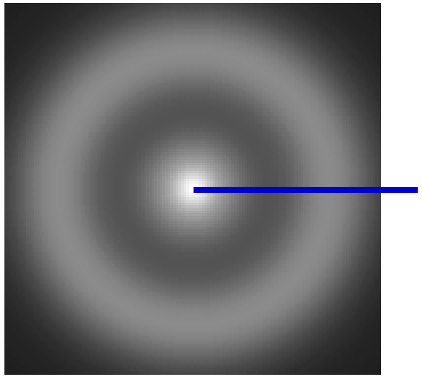
$$f_n = \mathbf{e}'\cdot\mathbf{e}\, F_n^c - i(\mathbf{e}'\times\mathbf{e})\cdot\mathbf{M}_n F_n^{m1} + (\mathbf{e}'\cdot\mathbf{M}_n)(\mathbf{e}\cdot\mathbf{M}_n) F_n^{m2}$$

zero in our geometry

J. P. Hannon, G. T. Trammell, M. Blume, D. Gibbs, Phys. Rev. Lett 61, 1245 (1988)

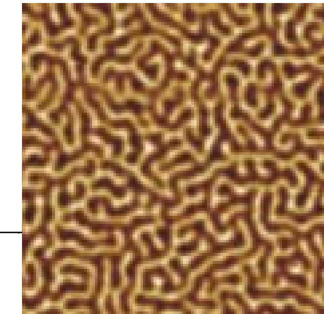
Magnetic Small Angle Scattering

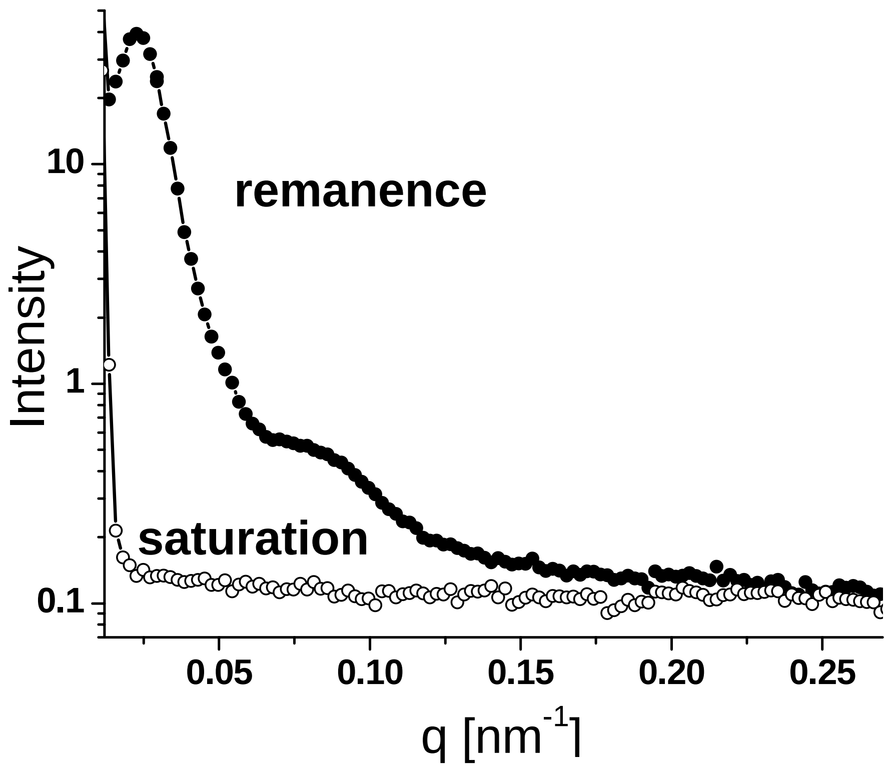
(incoherent)

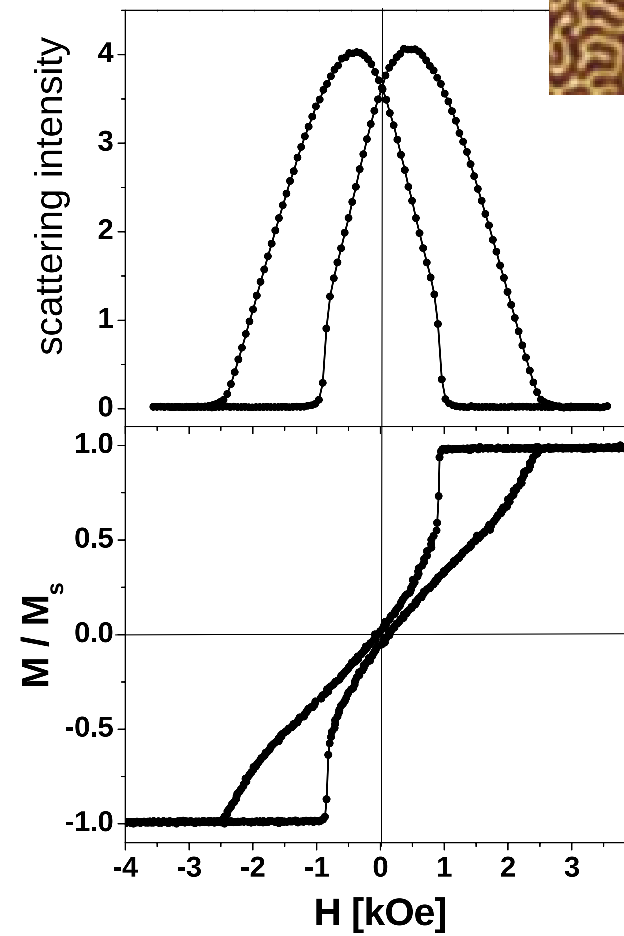


q-Dependence

Hysteresis-Loops







SAS H-scan

polar MOKE

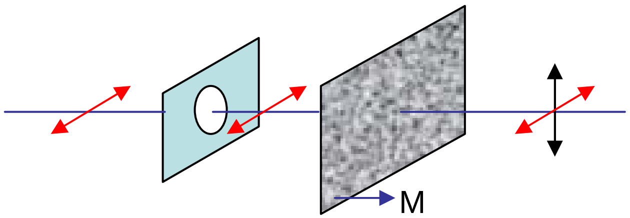
element specific

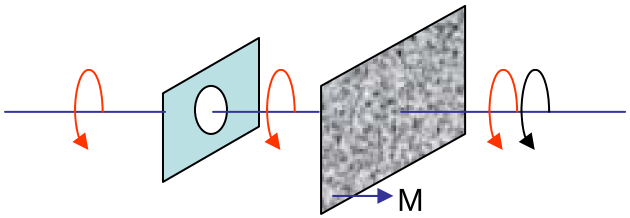
Polarization Effects: Switch Interference On / Off

linear

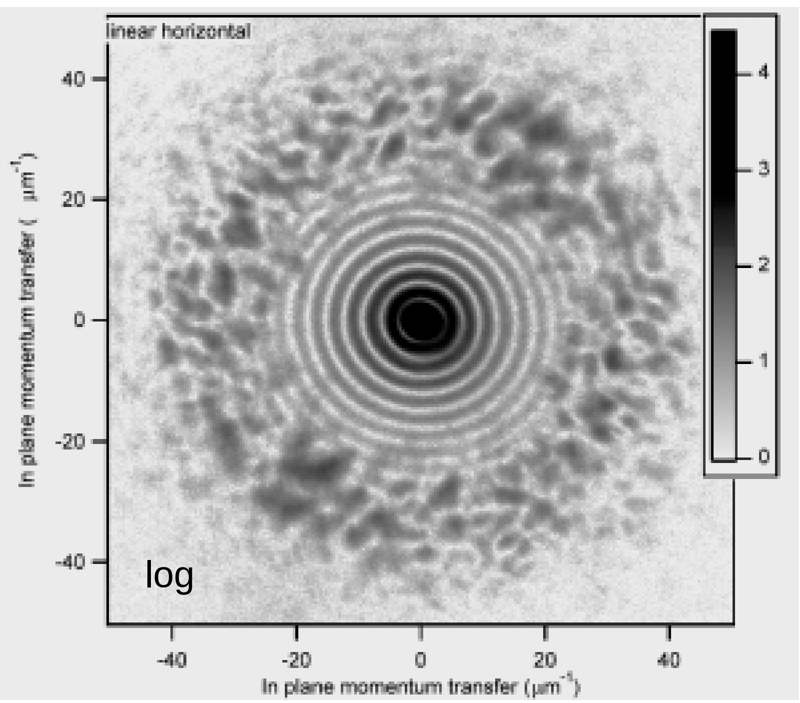
$$f_n = \mathbf{e}'\cdot\mathbf{e}\, F_n^{c} - i(\mathbf{e}'\times\mathbf{e})\cdot\mathbf{M}_n F_n^{m1}$$

right circular

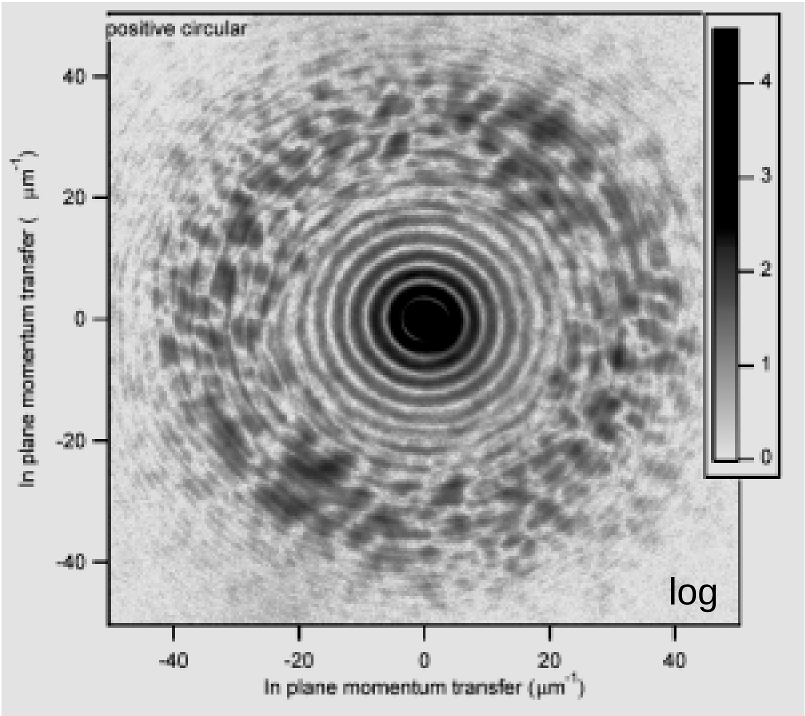




In-line geometry

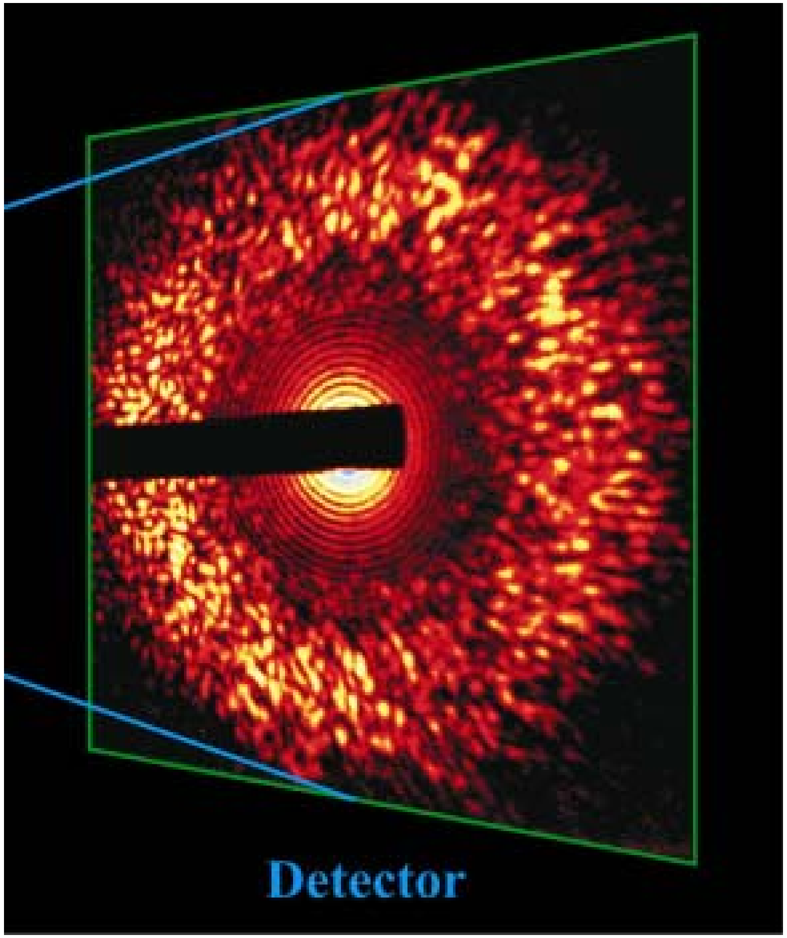


778 eV
1.6 nm



S. Eisebitt *et al.*, Phys. Rev. B **68**, 104419 (2003)
A. Rahmim *et al.*, Phys. Rev. B **65**, 235421 (2002)

Solving the Phase Problem



?

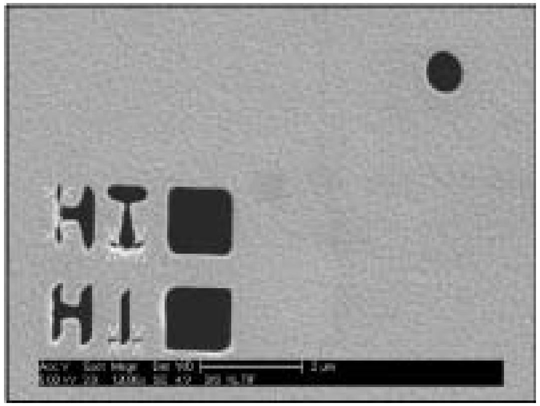
(a) Iterative phase retrieval:
oversampling phasing

Image of Object

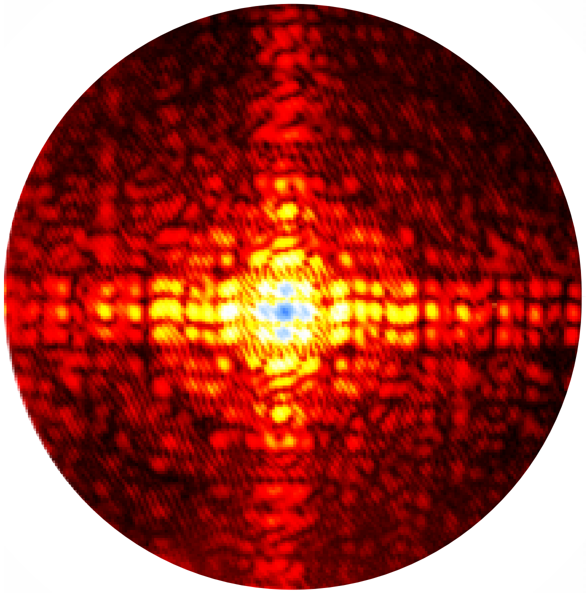
(b) Encode the phase:
holography

Iterative Phase Retrieval

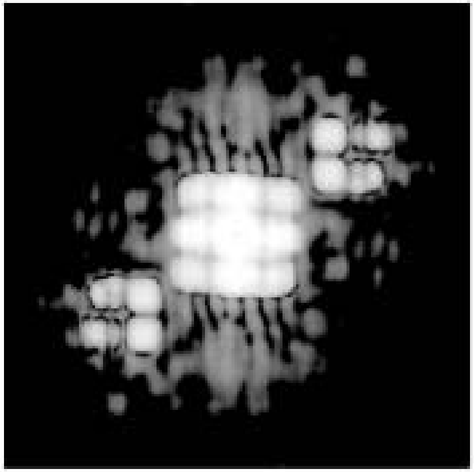
from coherent x-ray scattering *alone*



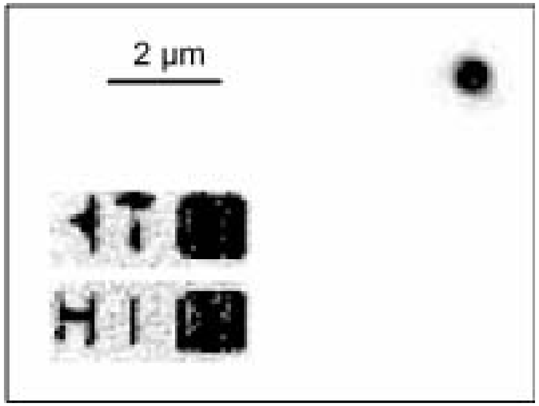
Sample



Coherent Scattering



Patterson map
= autocorrelation



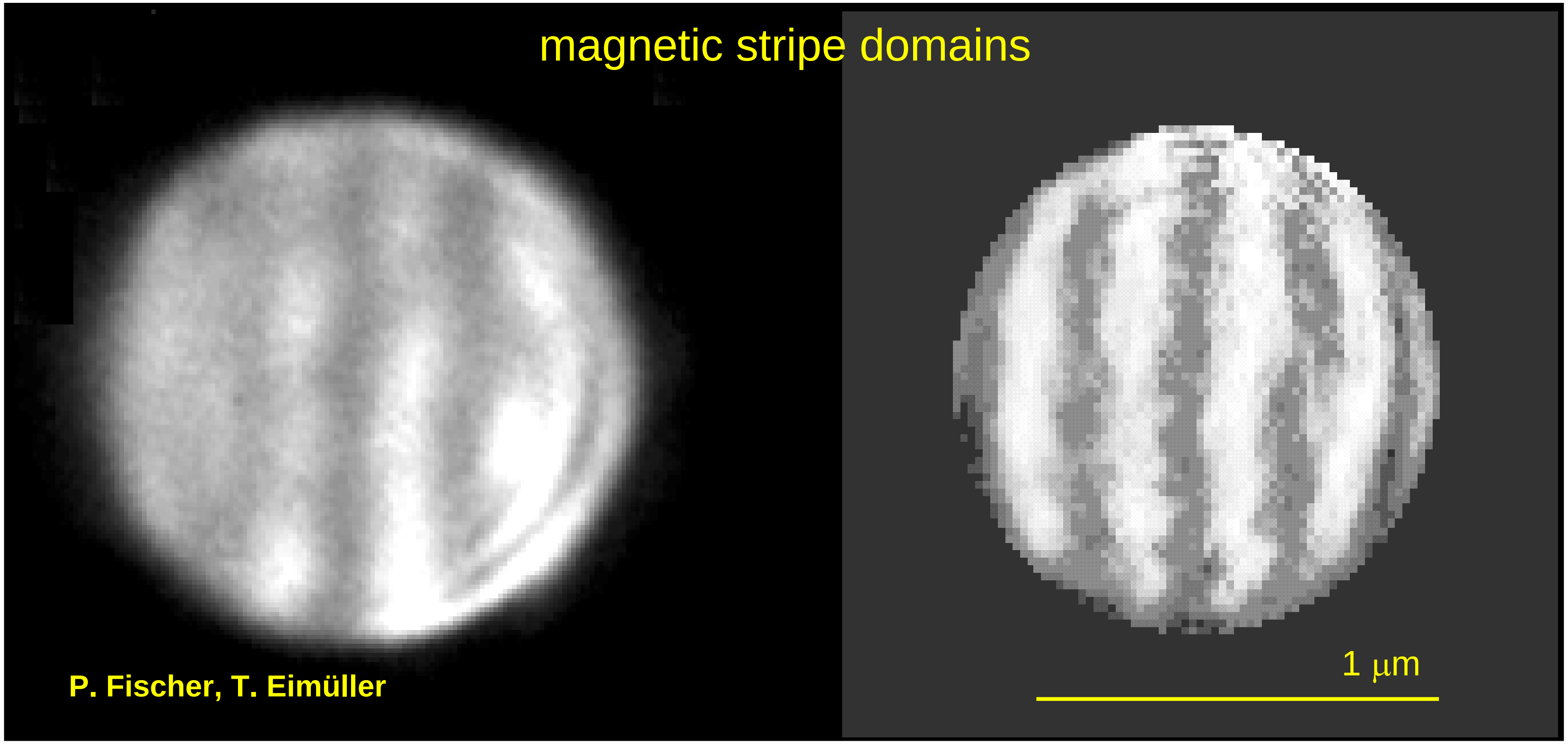
Reconstruction

see S. Marchesini *et al*, PRB **68** 140101(R) (2003)

S. Eisebitt et al. Appl. Phys. Lett., **84**, 3373 (2004)

Iterative Phase Retrieval: Magnetic Domains

magnetic sample: complex scattering factor

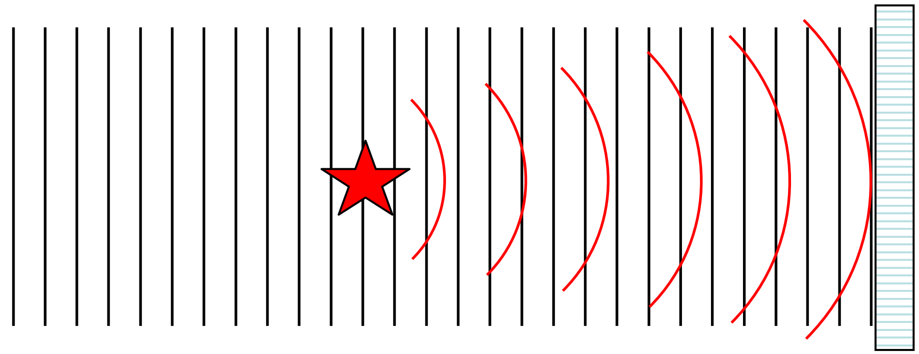


M. Lörgen et al, BESSY Highlights 2003 (2004)

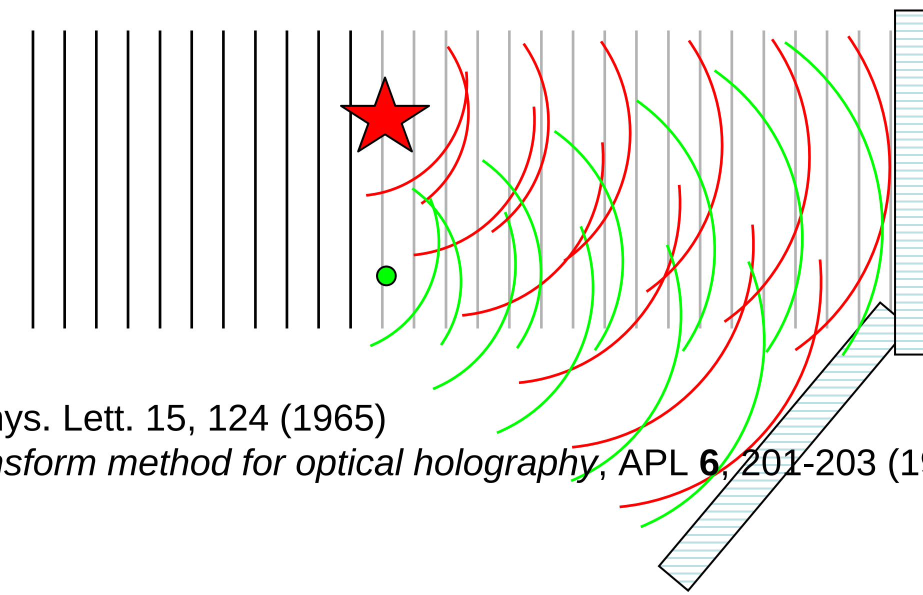
- resolution only limited by momentum transfer
- is the solution unique?

Holography

In-line
„Gabor-H.“



Off-axis
„Leith-Upatnieks-H.“
„Fourier-transform-H.“



J.T. Winthrop, C.R. Worrington, Phys. Lett. 15, 124 (1965)
G.W. Stroke, *Lensless Fourier-transform method for optical holography*, APL **6**, 201-203 (1965)

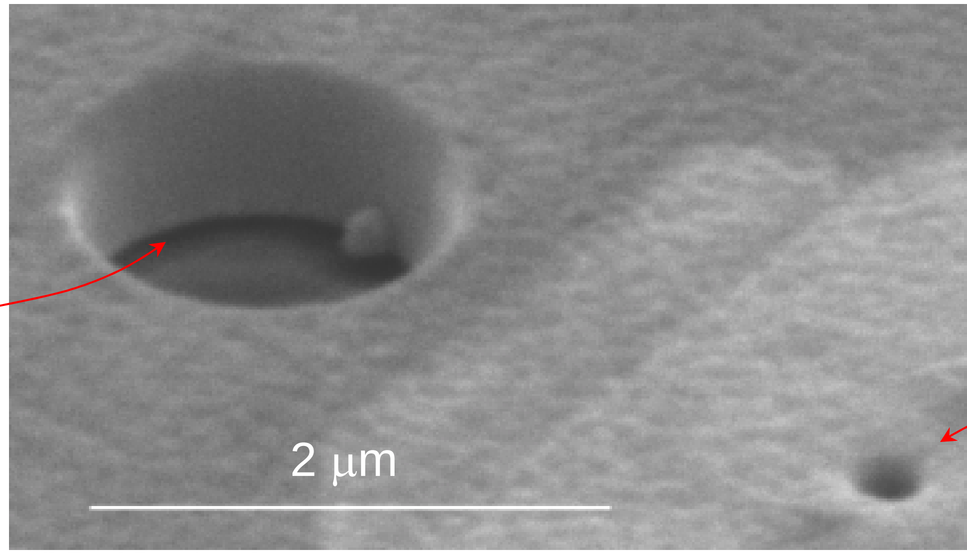
X-rays: - difficult, few experiments
- state of the art resolution: 60 nm: **FT** I. McNulty et al. Science 256, 1009 (1992)
G S. Lindaas et al. J. Opt. Soc. Am. A 13, 1788 (1996)

X-ray Fourier Transform Holography Mask

Microstructured Mask

Focussed Ion Beam:
W.F. Schlotter

perspective



Object area
∅ 1.5 μm

Reference hole
∅ 100 nm

side

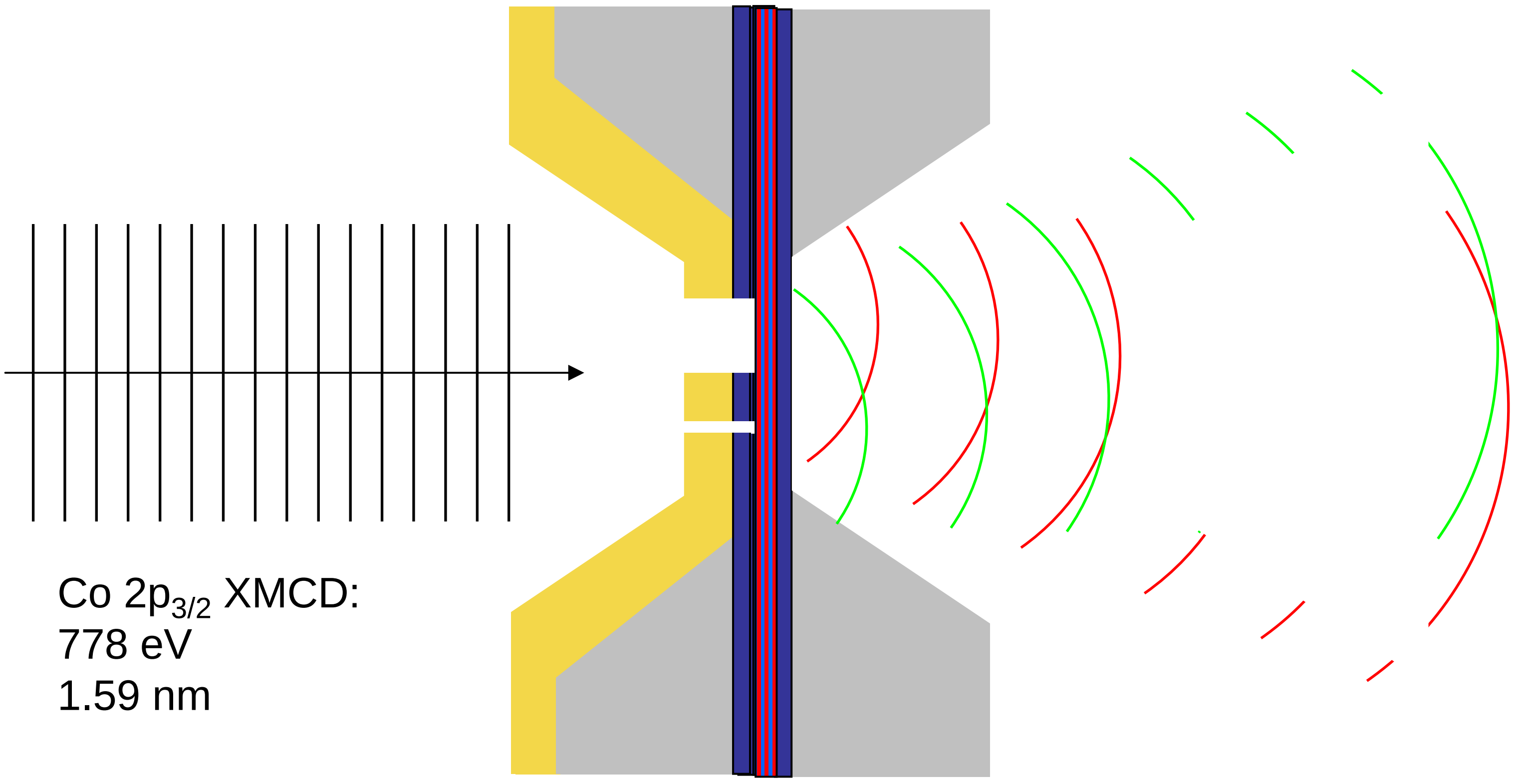
Au (600nm)

Si Substrate

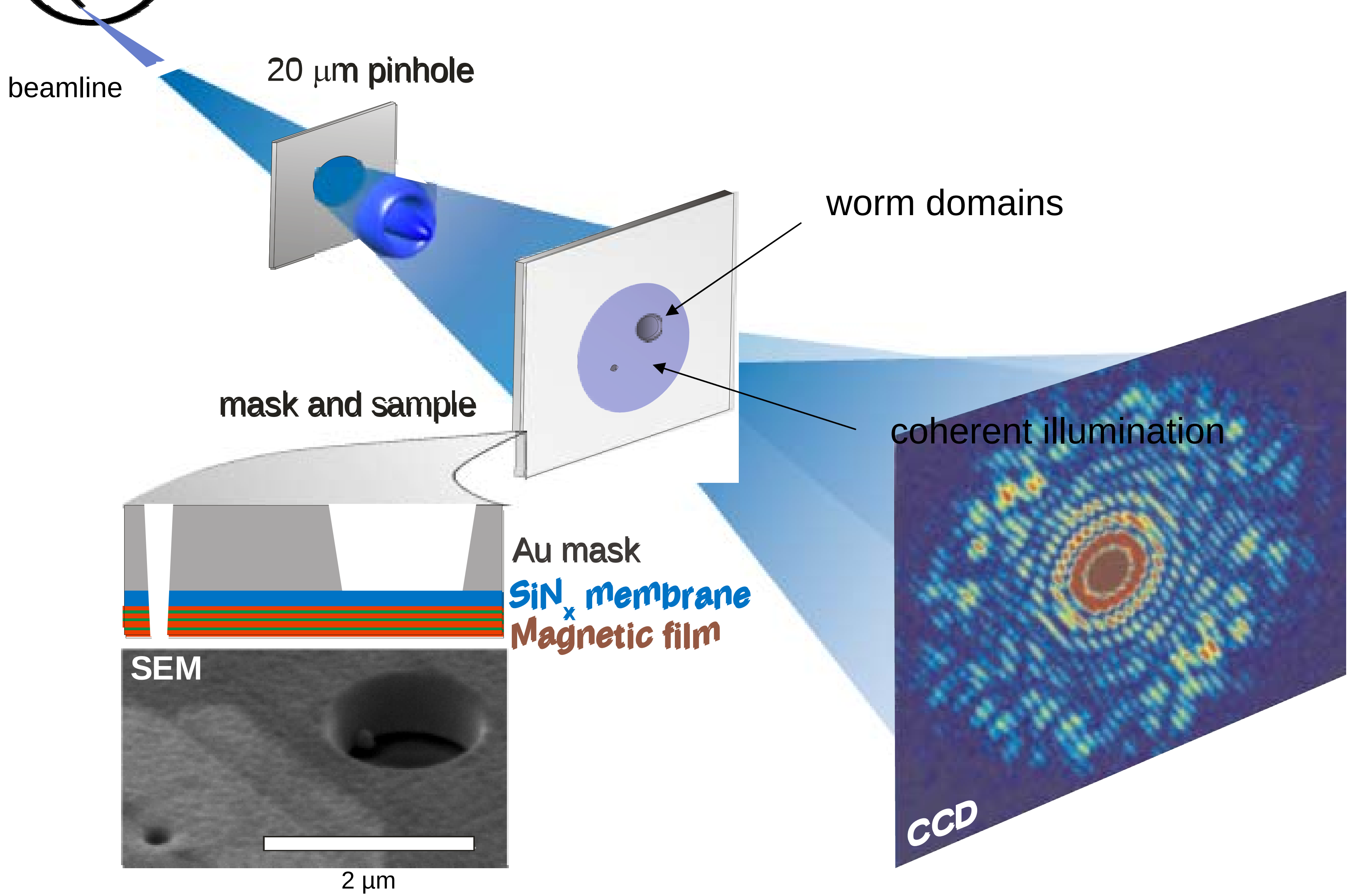
Si_3N_4 (100nm) Membrane

Fourier Transform Holography at λ=1.6 nm

Mask Approach



Setup

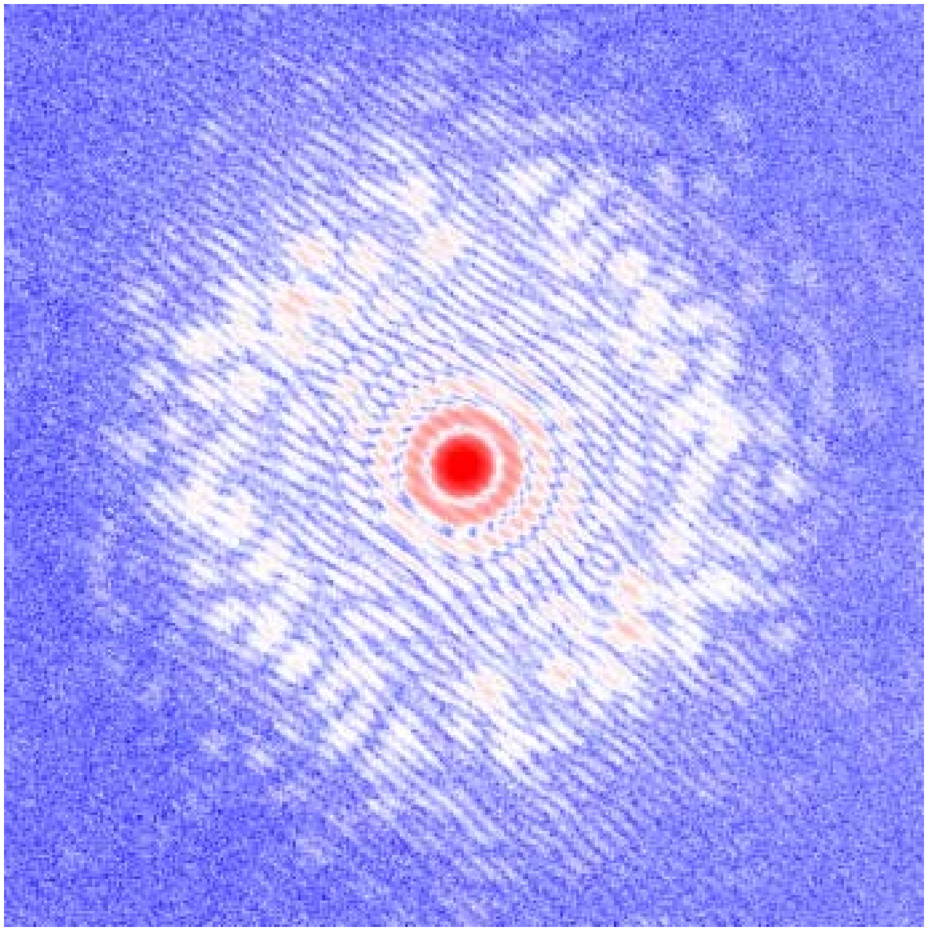


S. Eisebitt, Coherence 2005, Porquerolles June ‘05

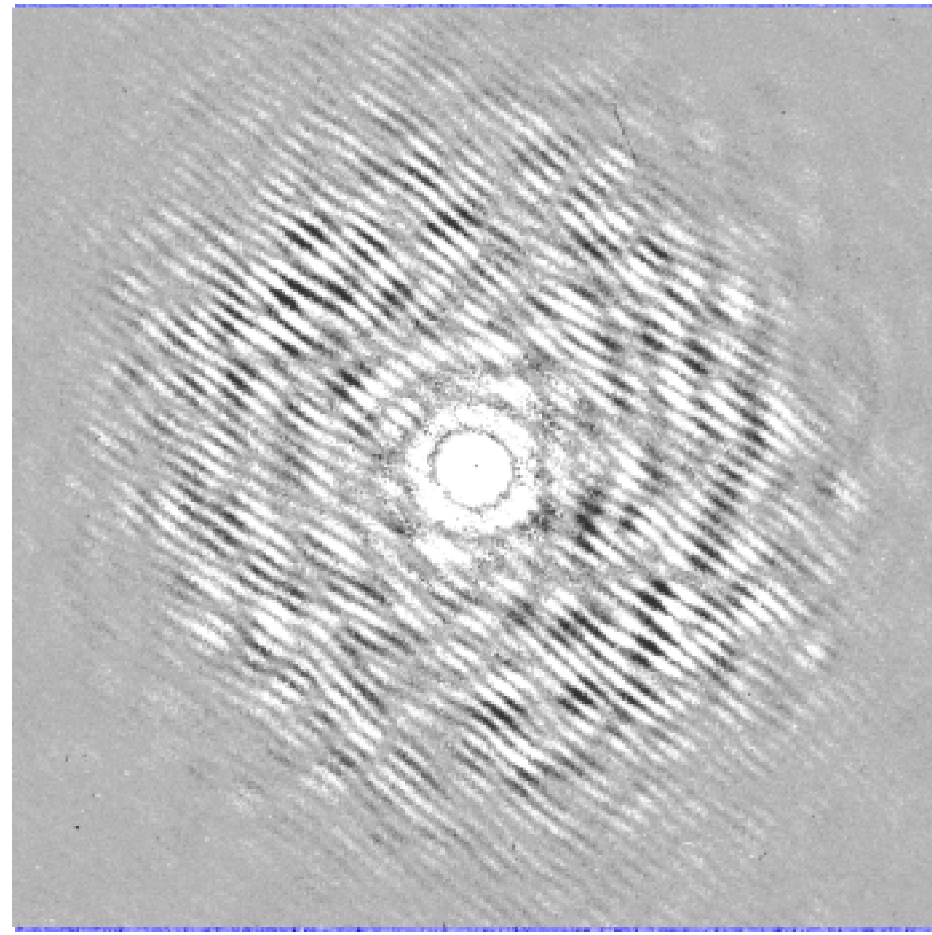
Dichroic Hologram

CCD Detector Image

Right circular polarized



Difference (RCP – LCP)

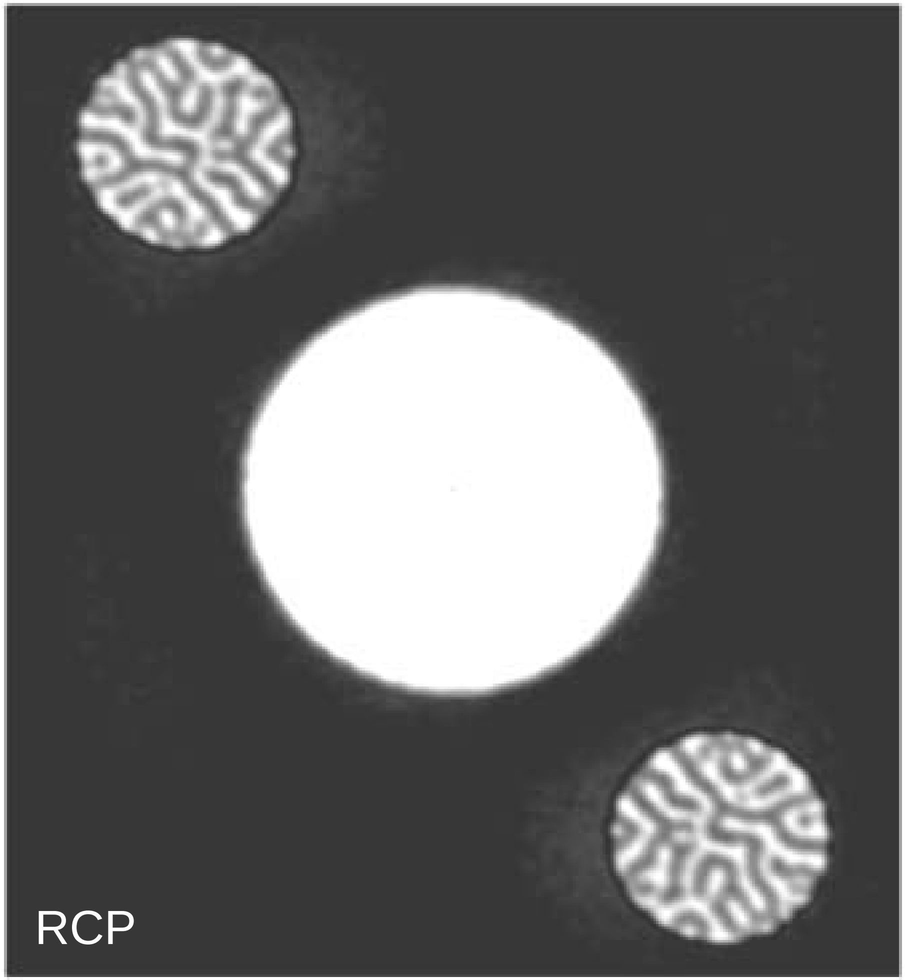


500 sec total exposure

log z-scale

Digital Image Reconstruction

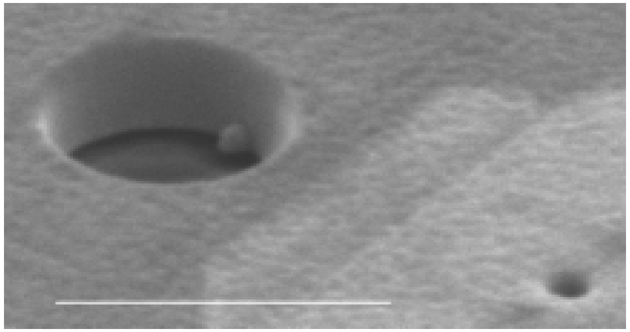
FFT = Patterson Map



Convolution theorem applied to diffraction:
FT(diffraction) = Autocorrelation (Object)

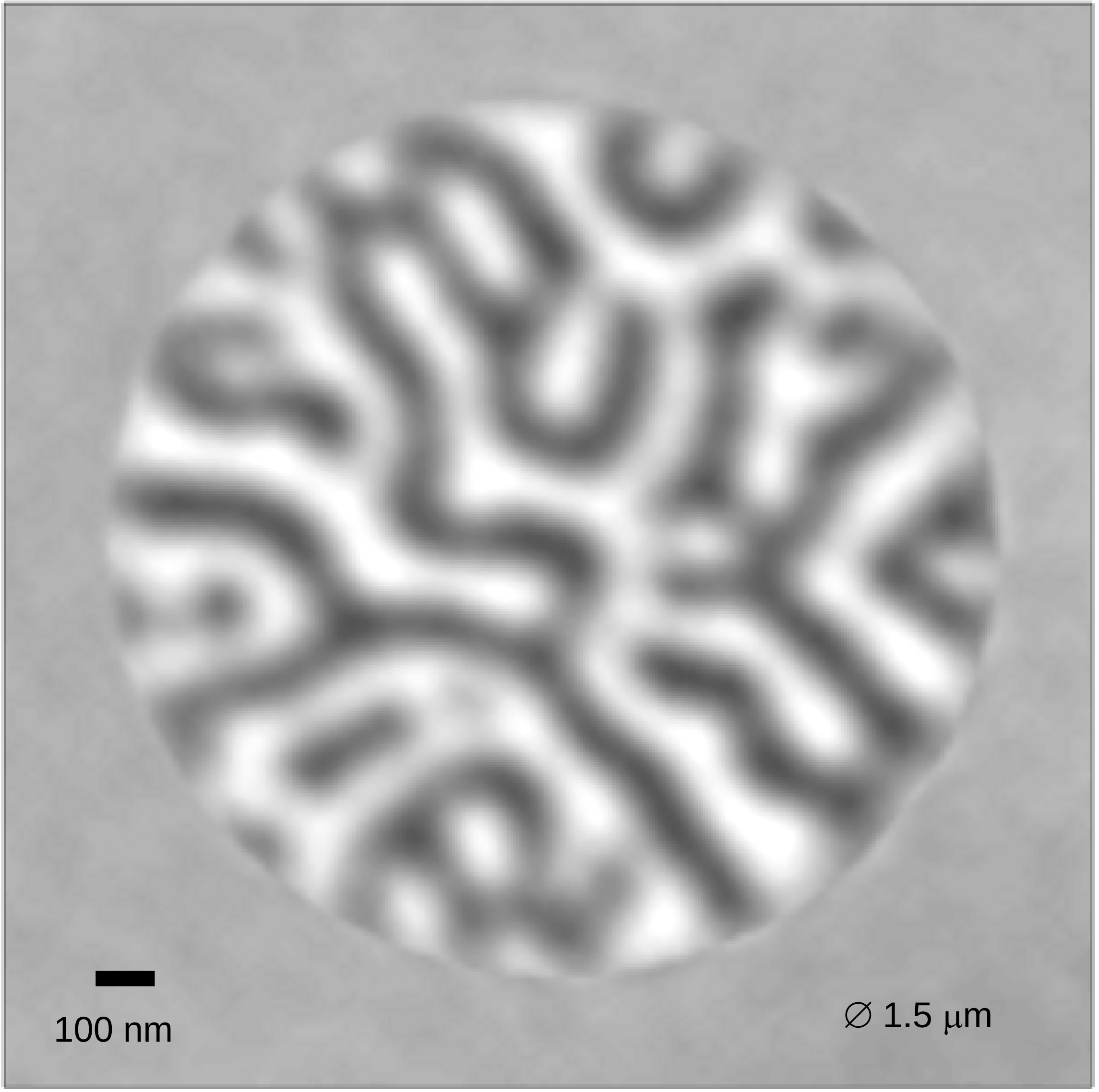
$FT(a \otimes b) = FT(a) \cdot FT(b)$

$(a \otimes a) = FT^{-1}\{FT(a) \cdot FT(a)\}$



a	real space object
$FT(a) \cdot FT(a)$	diffraction intensity

X-Ray Spectro-Holography

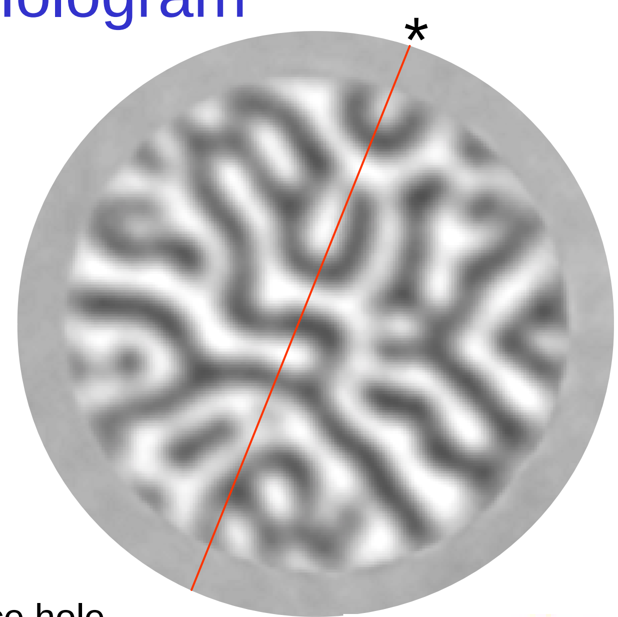


RCP-LCP

500 sec

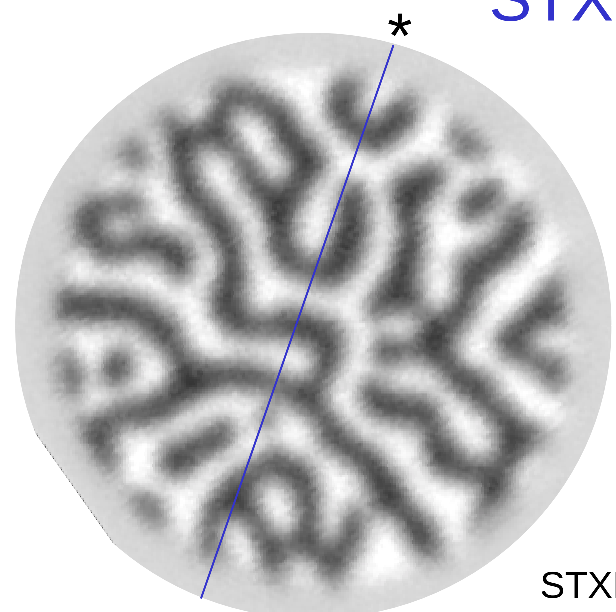
Is it good? / Is it real?

FT Hologram



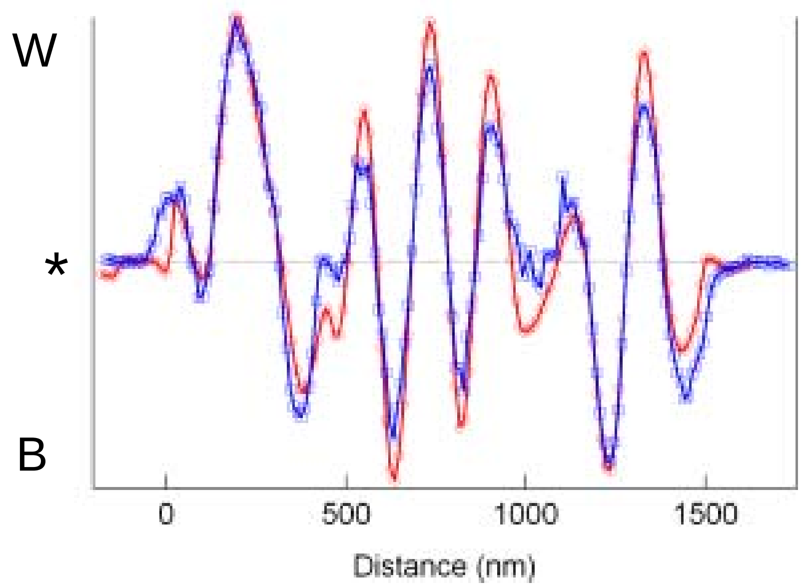
Reference hole
∅ 100 nm

STXM



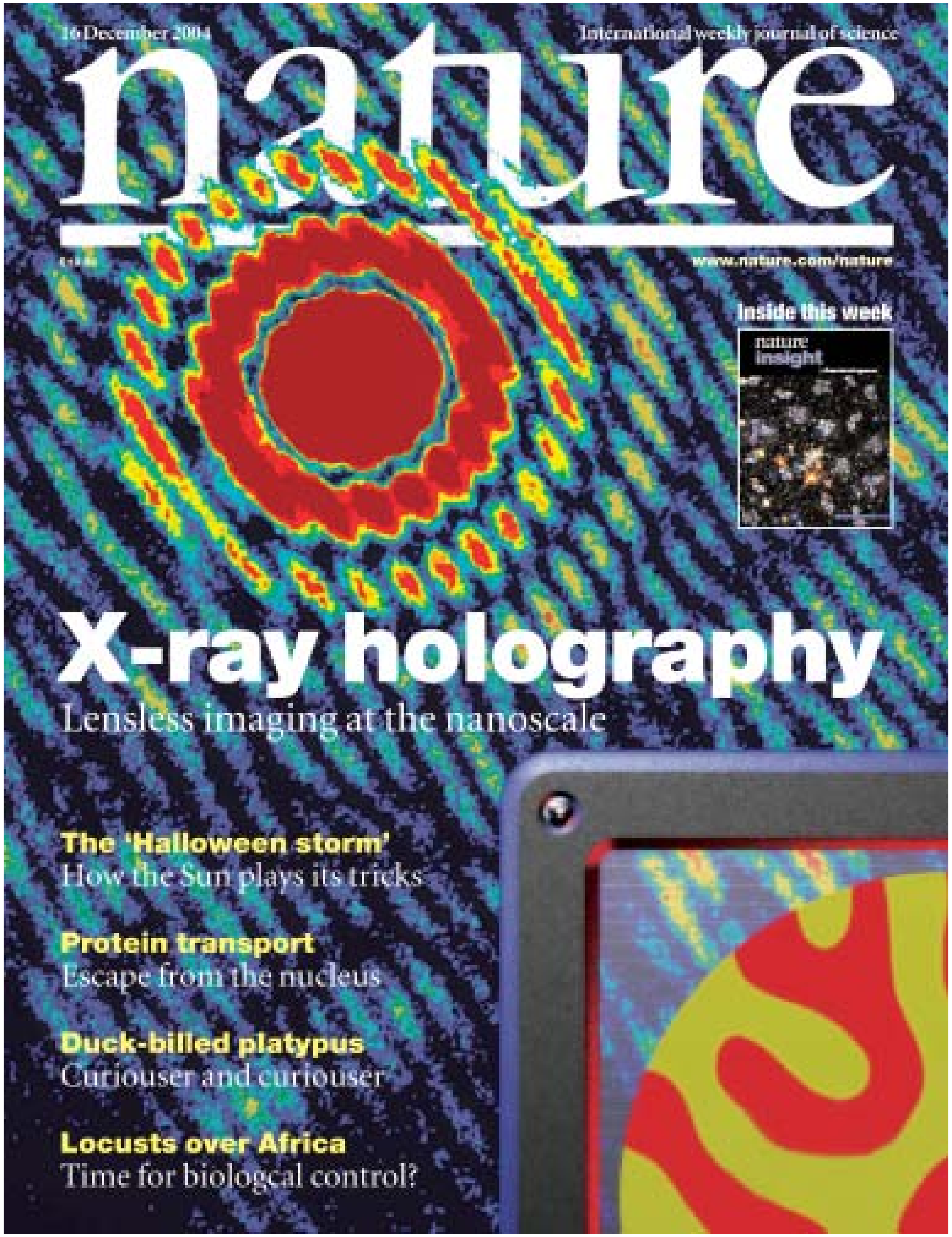
STXM @ ALS
W. F. Schlotter
Y. Acremann

Resolution
30 - 40 nm



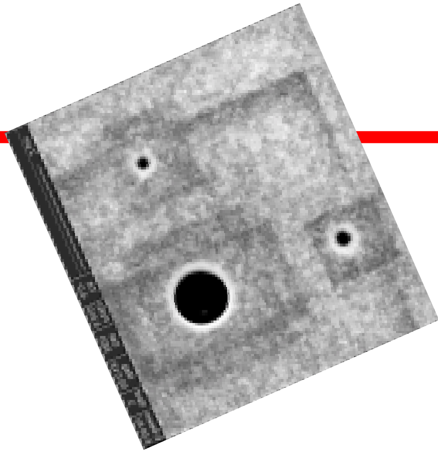
Holographic Image:
50 nm resolution

S. Eisebitt, J. Lüning, W. F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt, J. Stöhr, ***Nature* 432**, 885 (2004)



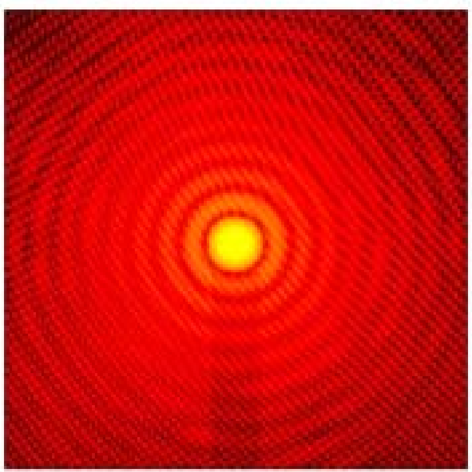
Nature **432**, 885-888
16. Dec.2004

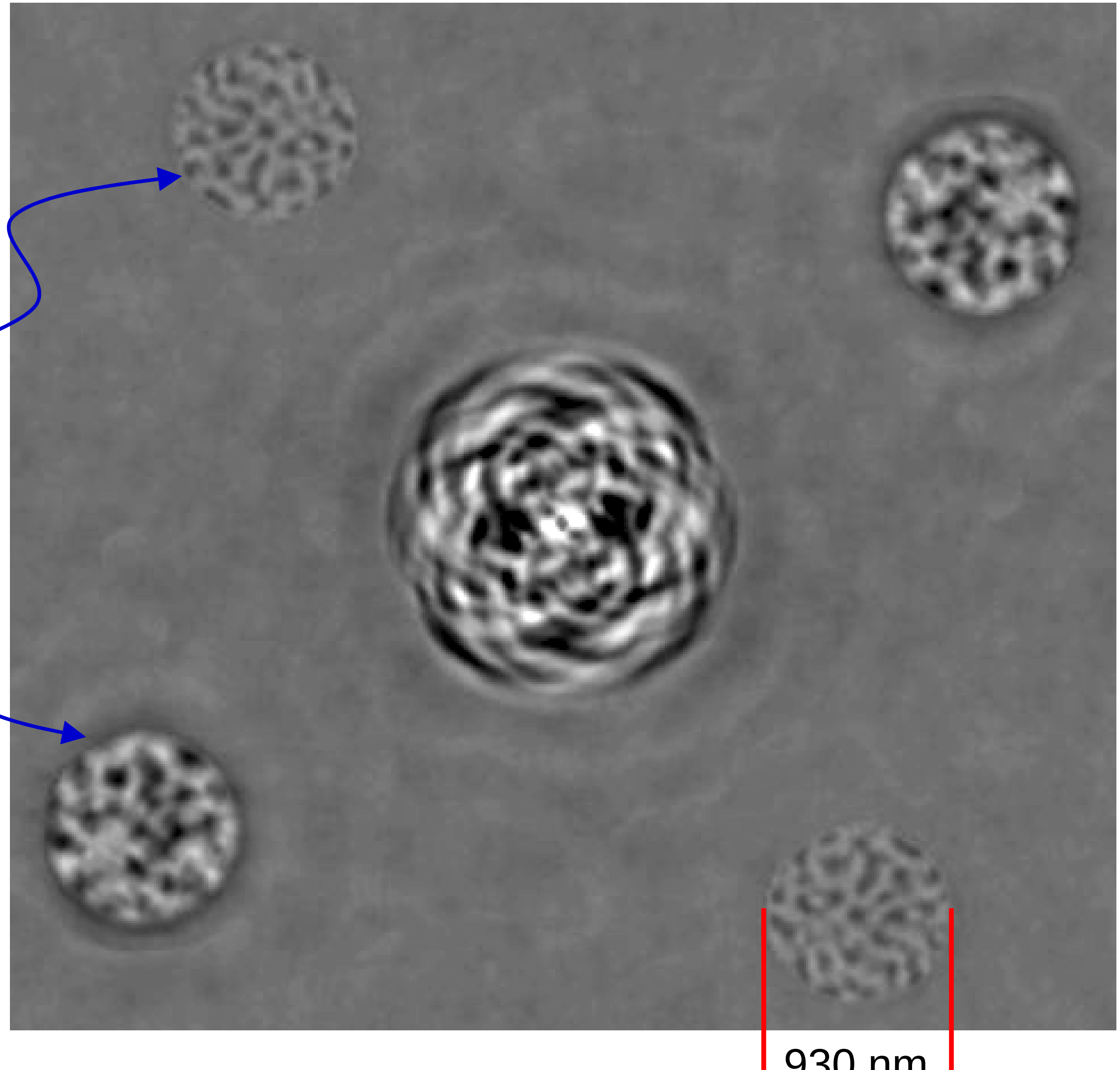
Multiple Reference FT Holograms



high resolution

high intensity



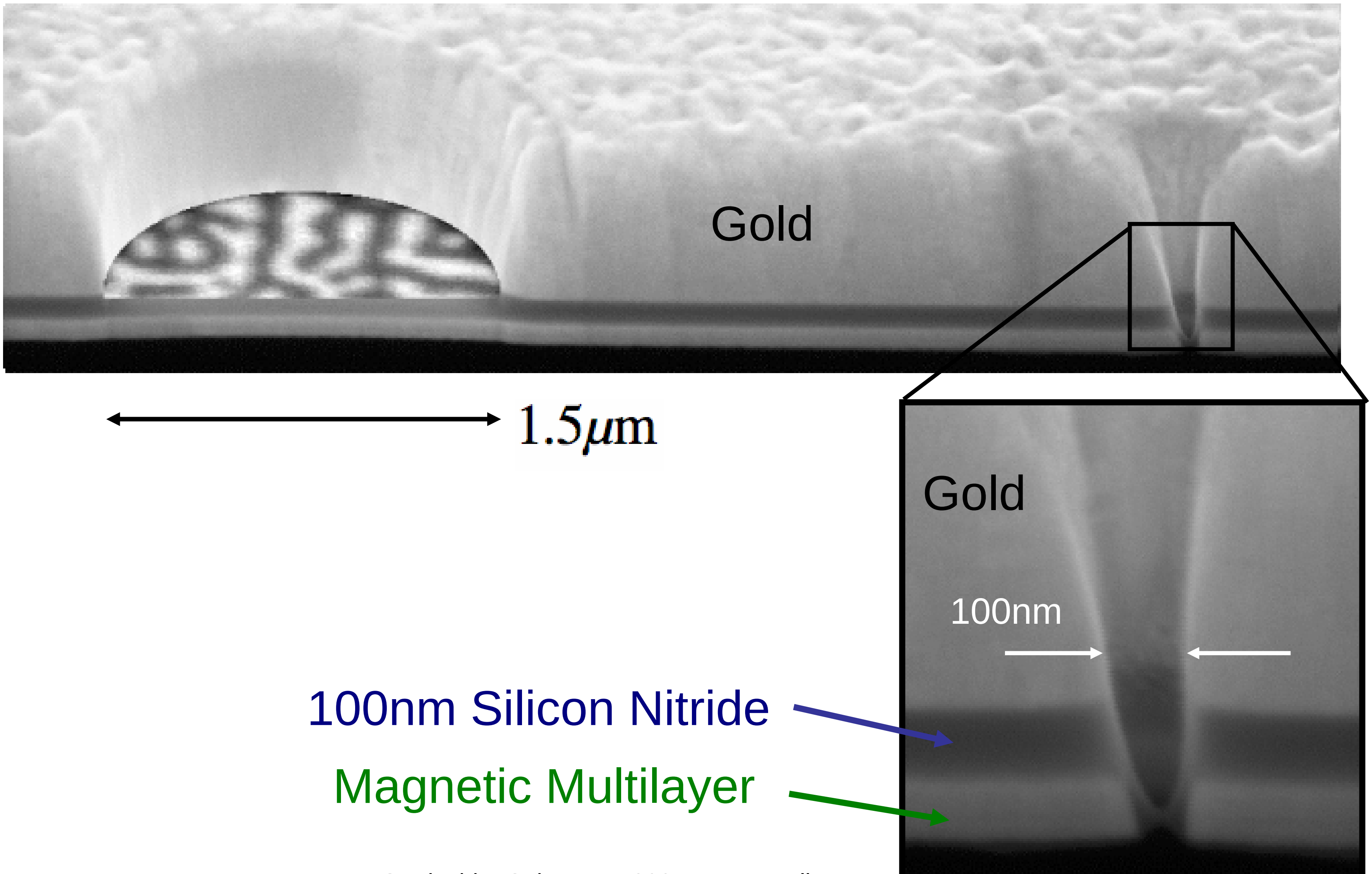


W.F. Schlotter, S. Eisebitt, O. Hellwig, J. Lüning (unpublished)

Integrated Sample Structure

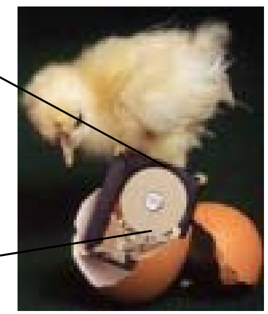
Patterned with Focused Ion Beam

W.F. Schlotter



Magnetic Data Storage

60 cm



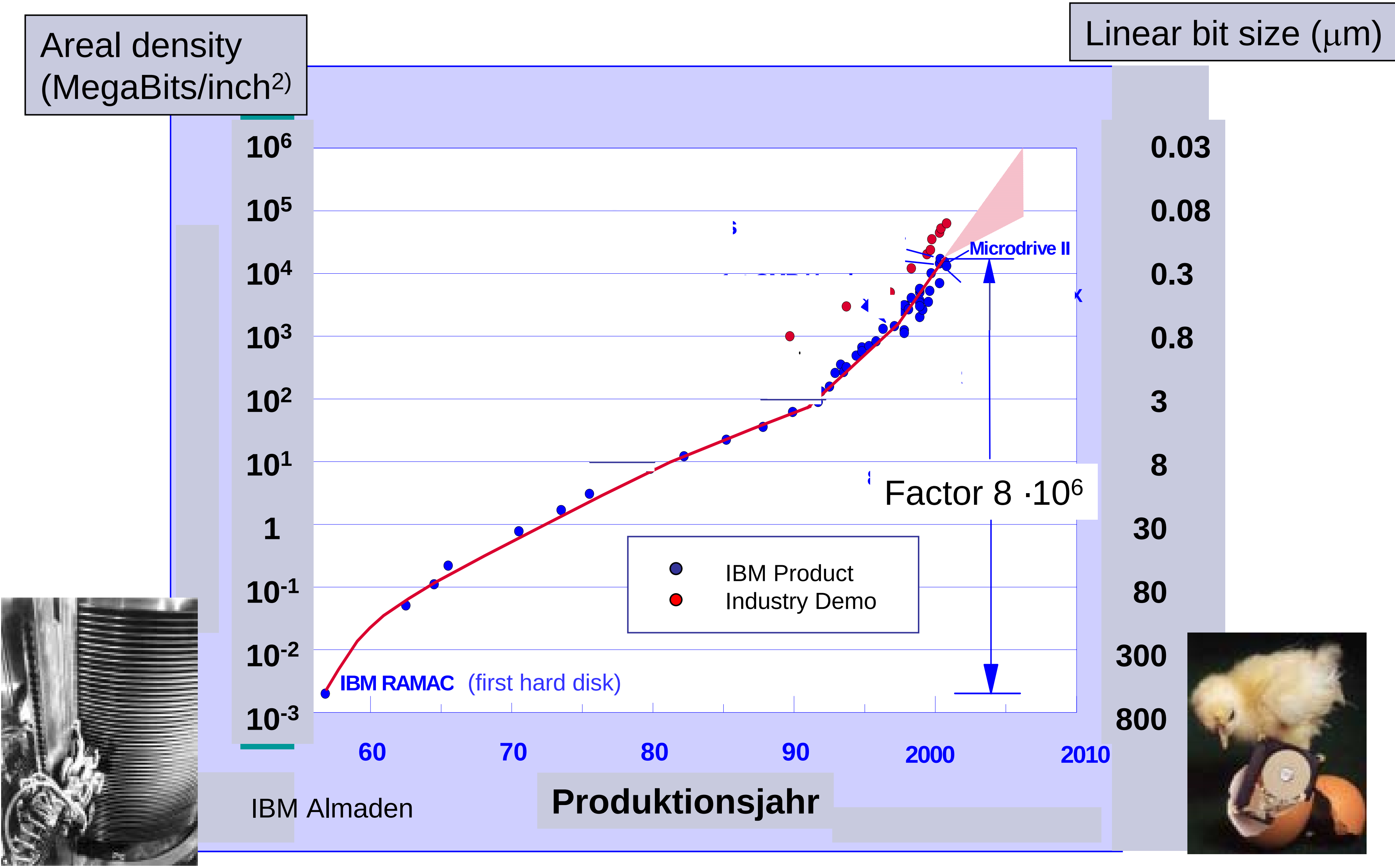
2,5 cm

?

1956: RAMAC
5 M byte
10.000$ / Mb

2003: Microdrive (iPod)
4 G byte
1$ / Gb

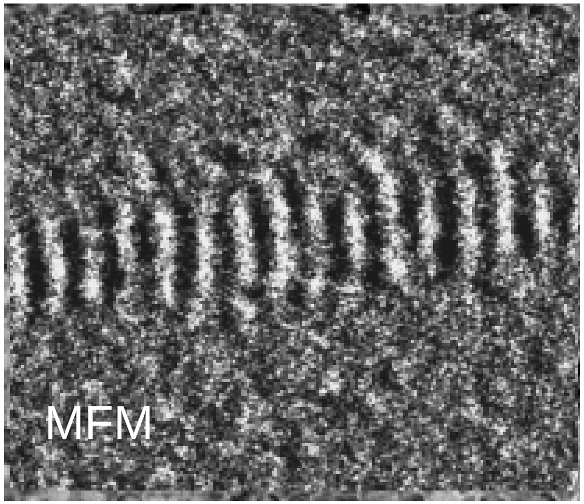
Hard Disks: Storage Density



S. Eisebitt, Coherence 2005, Porquerolles June '05

Media Development

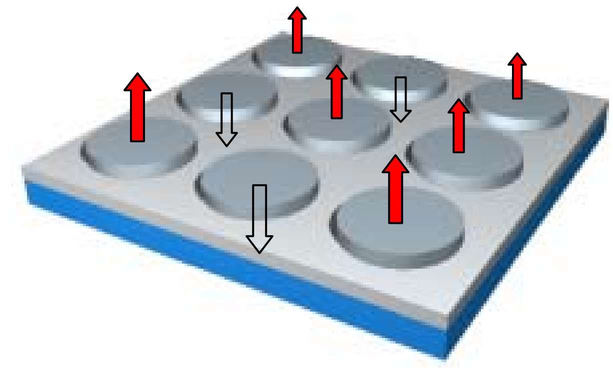
granular & in plane

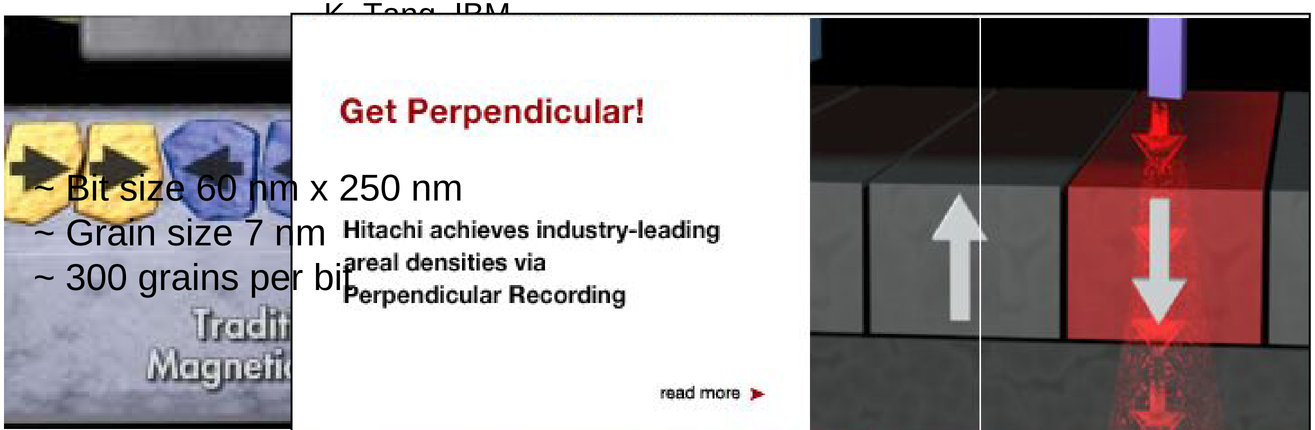


1000 nm

CoPtCrB
35 Gbit/in^2 demo
K. Tang, IBM

structured & perpendicular



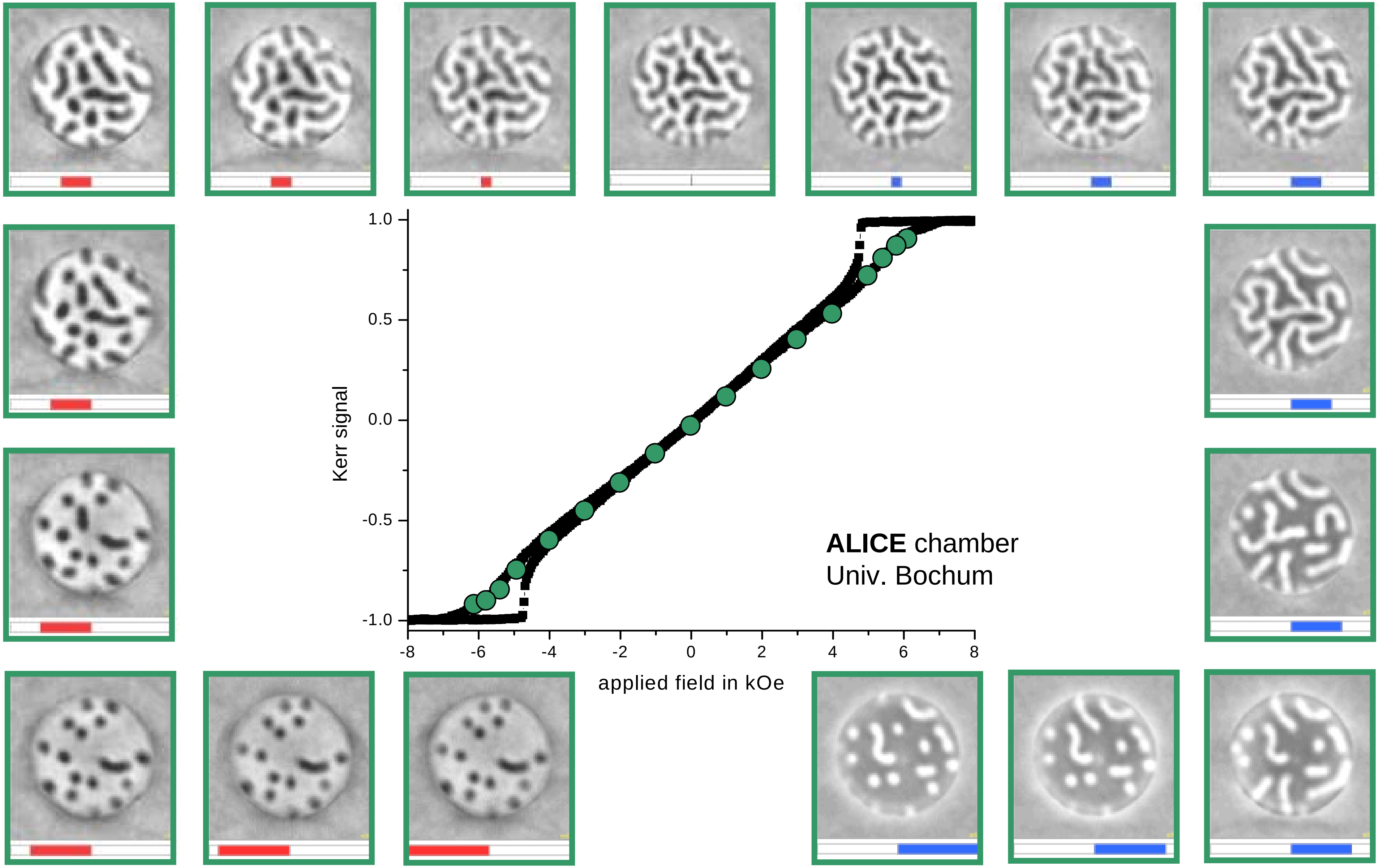


~ Bit size 60 nm x 250 nm
~ Grain size 7 nm
~ 300 grains per bit

230 Gbit/in^2

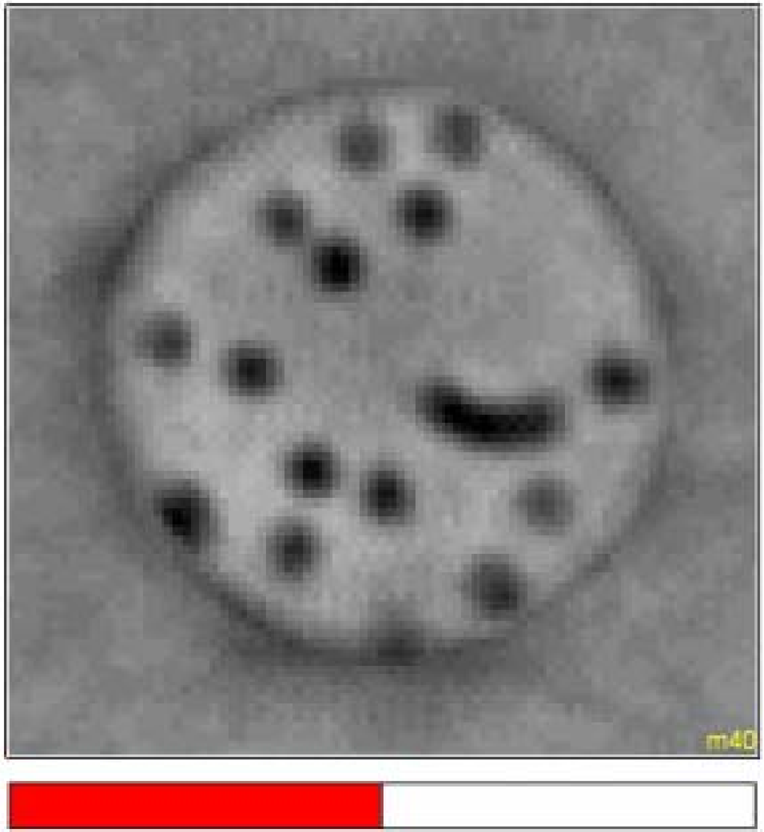
IBM / Hitachi

Reversal of a CoPt multilayer

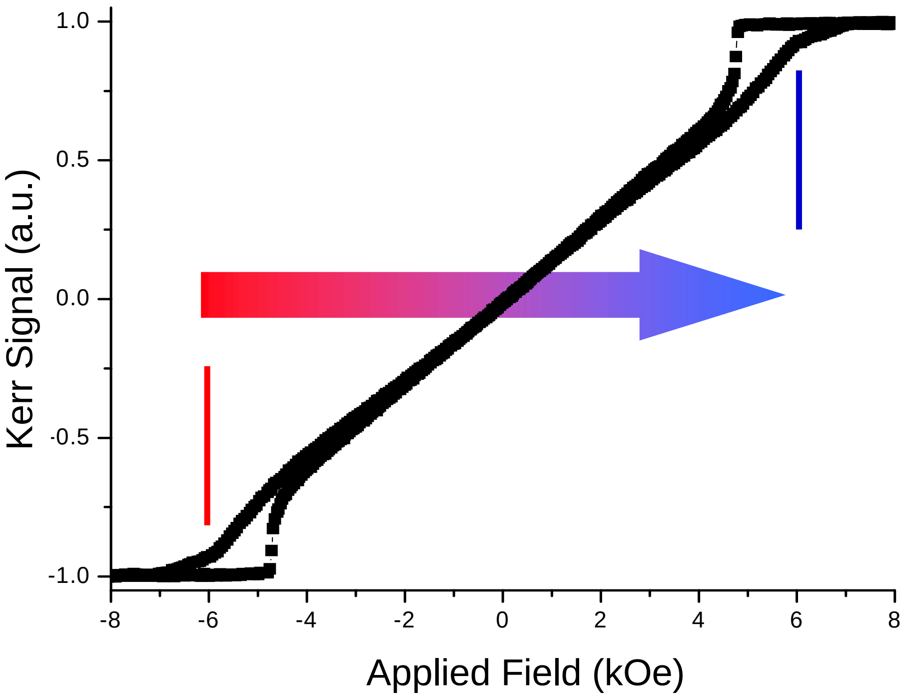


Reversal of a CoPt multilayer

perpendicular



2 min / image
60 nm Co

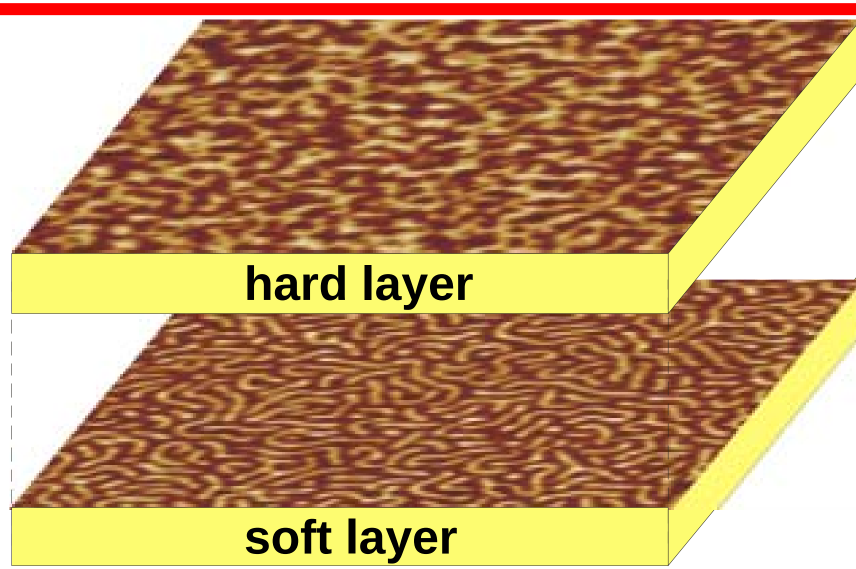


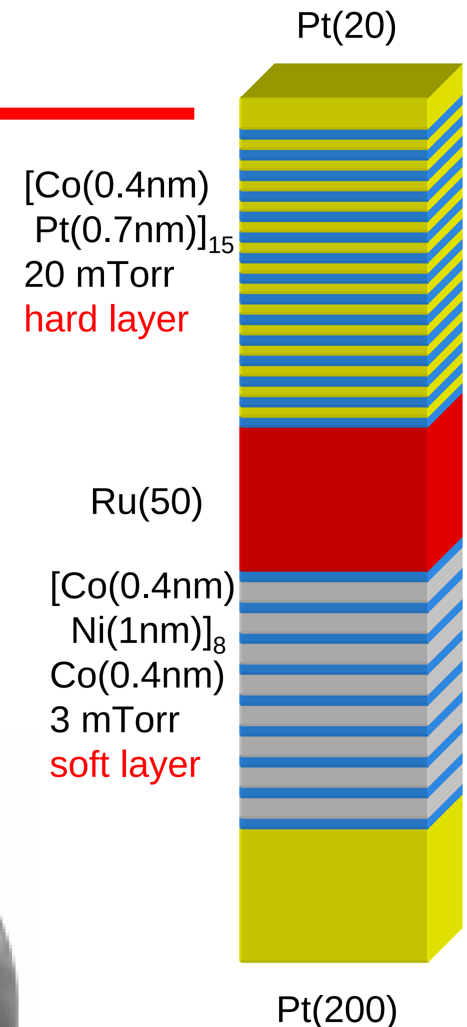
ALICE chamber
Univ. Bochum

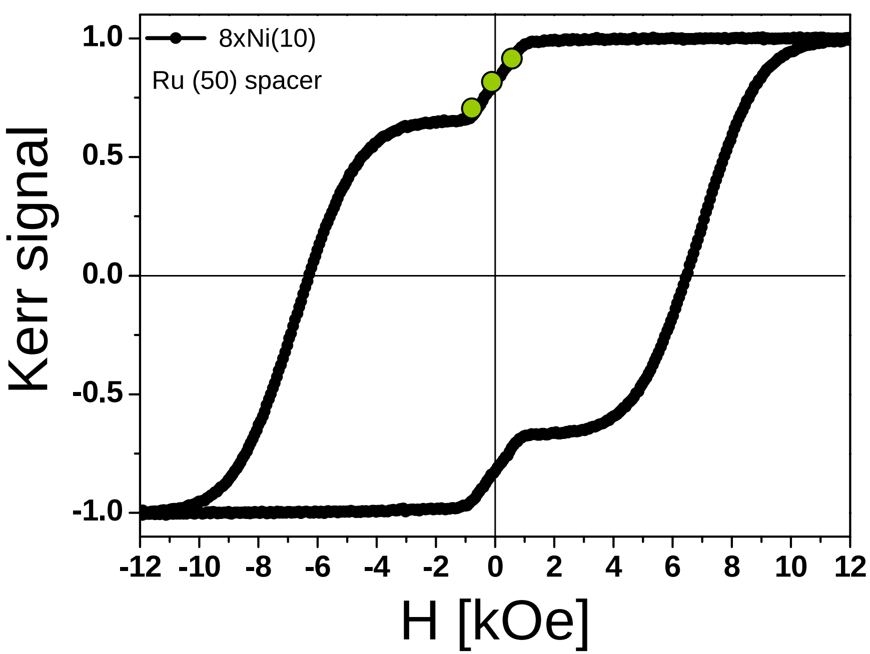
Perpendicular Hard/Soft Layer System

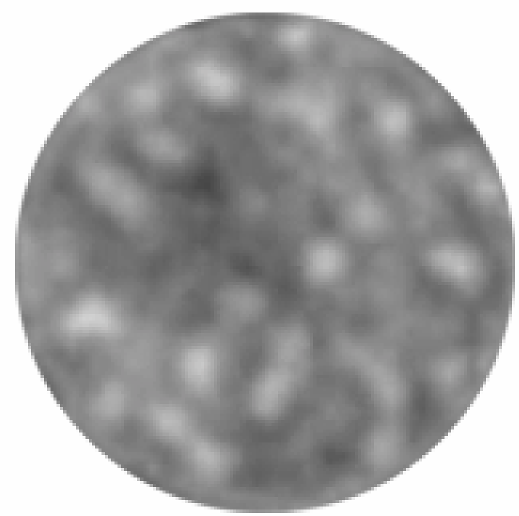
effect from the dipole fields of the hard layer

on the reversal of the soft layer







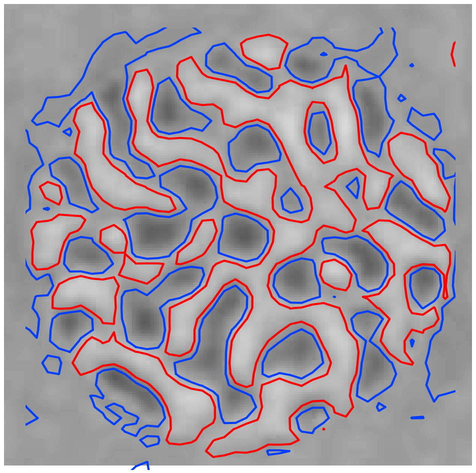


soft layer reversal, Ni edge

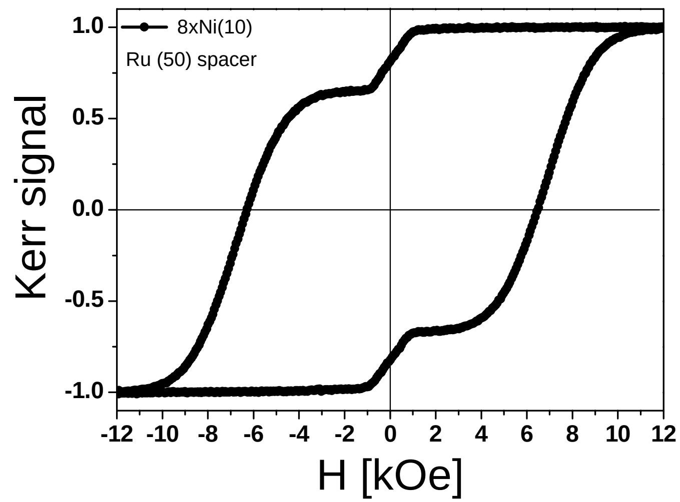
Induced Nucleation

Co

-2.5 kOe

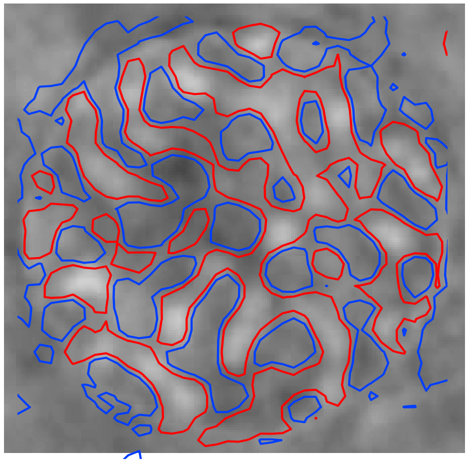


model system for: dipole coupled & perpendicular

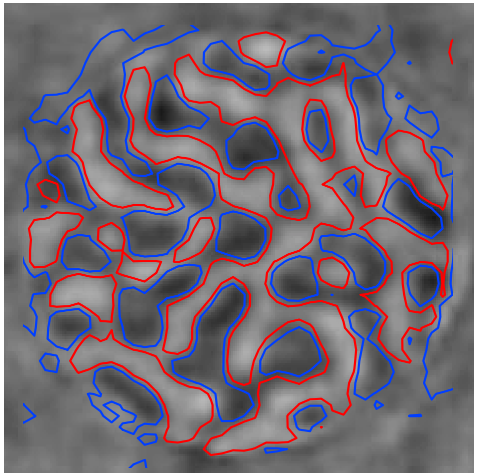


Ni

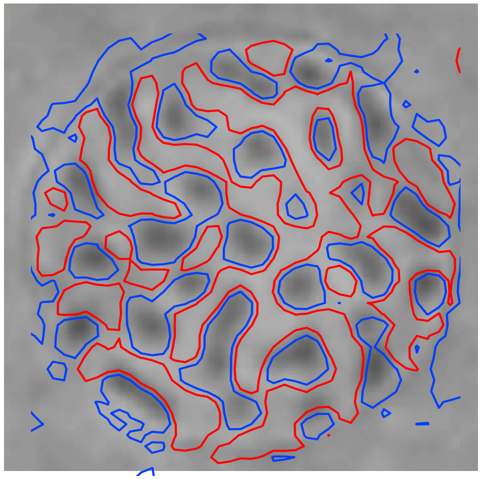
-1 kOe



0 kOe

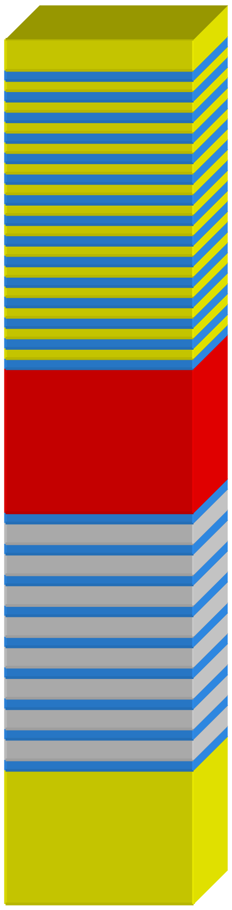


+1 kOe



8 nm Ni

Pt(20)



[Co(0.4nm) Pt(0.7nm)]$_{15}$
20 mTorr
hard layer

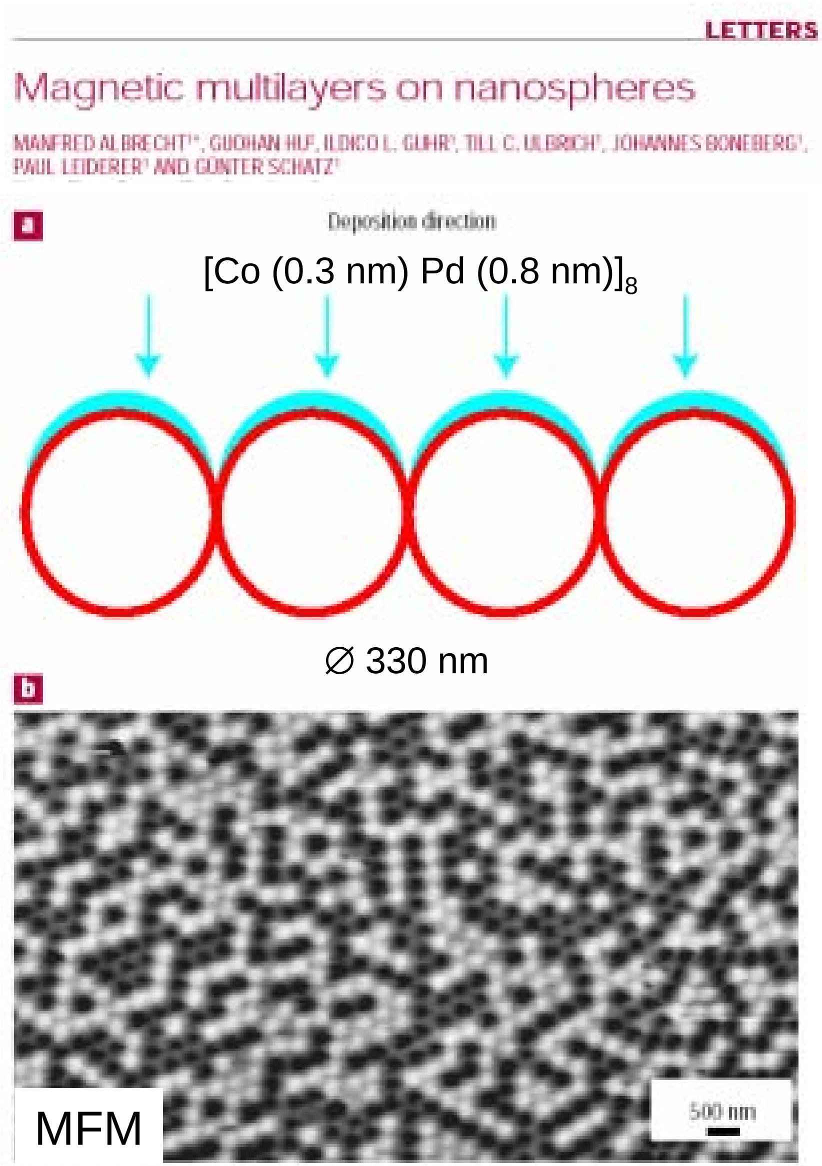
Ru(50)

[Co(0.4nm) Ni(1nm)]$_{8}$
Co(0.4nm)
3 mTorr
soft layer

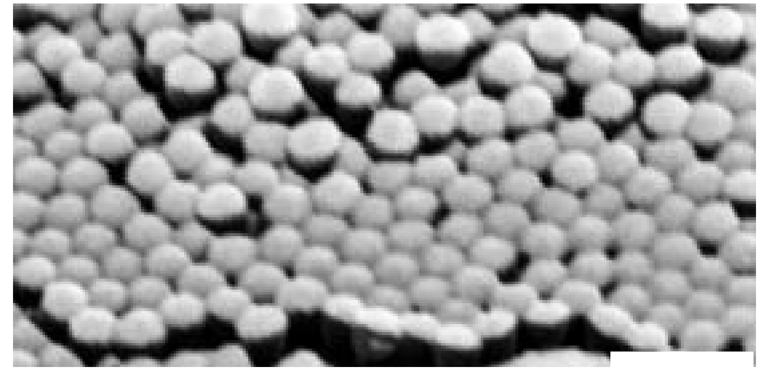
Pt(200)

S. Eisebitt, Coherence 2005, Porquerolles June '05

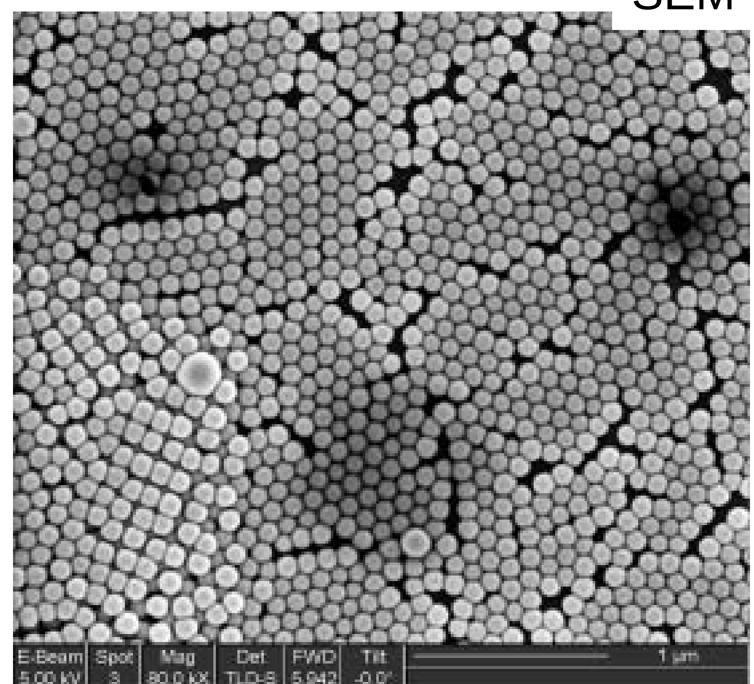
Future: Patterned Magnetic Media



∅ 110 nm

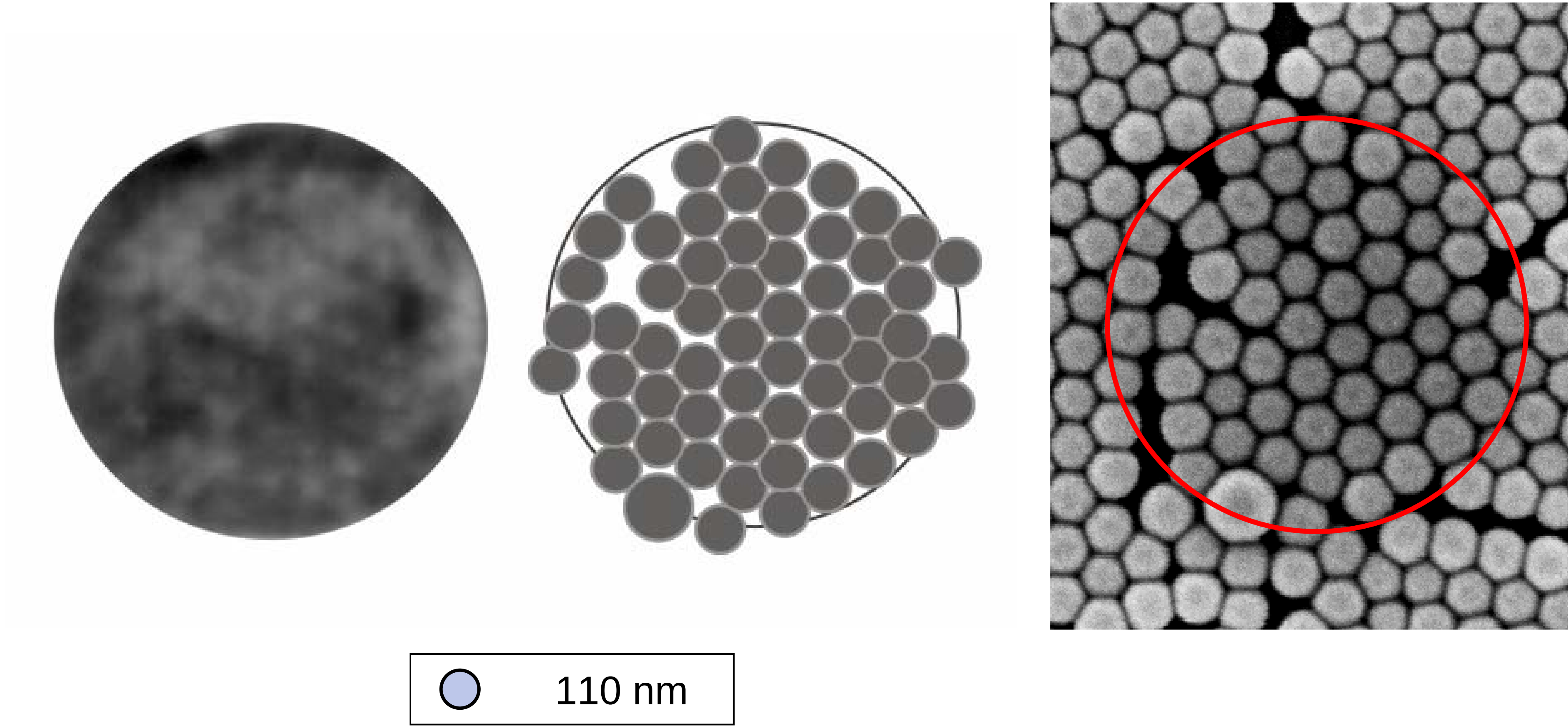


SEM



Nature Materials **4**, 203 (2005)

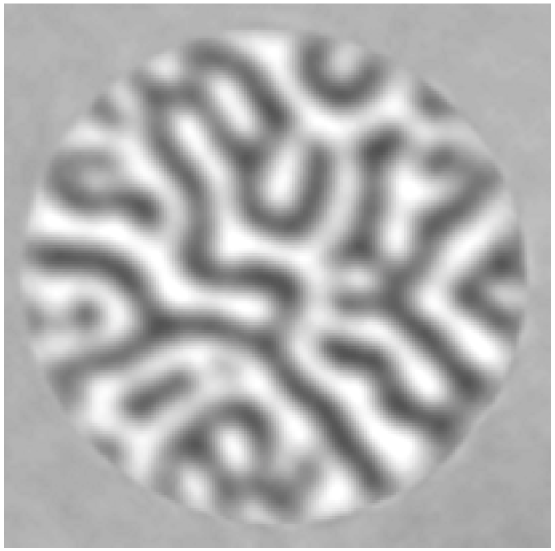
Flipping the bits in an applied field



O. Hellwig, S. Eisebitt, W.F. Schlotter, J. Lüning (unpublished)

Recent Progress in Spectro-Holography

february 2004

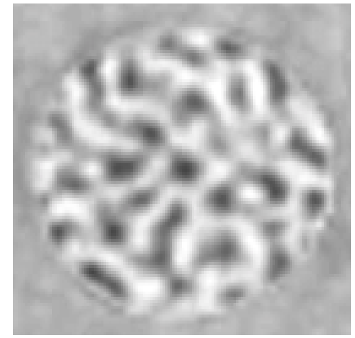


1500 nm

november 2004

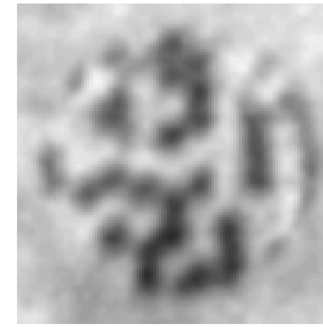
1300 nm

may 2005

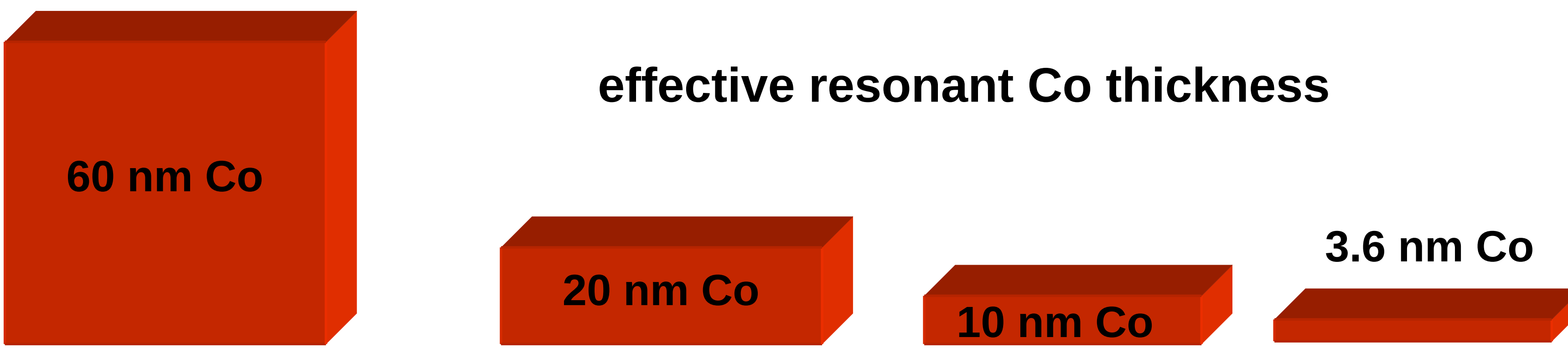


940 nm

may 2005



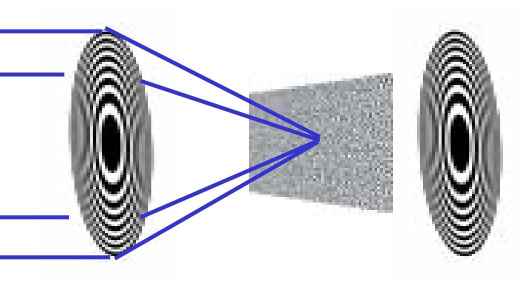
900 nm

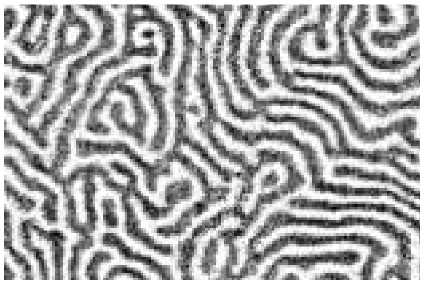


Optical Elements

TXM

zone plate

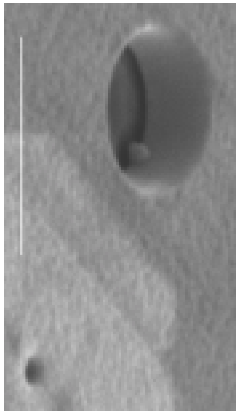


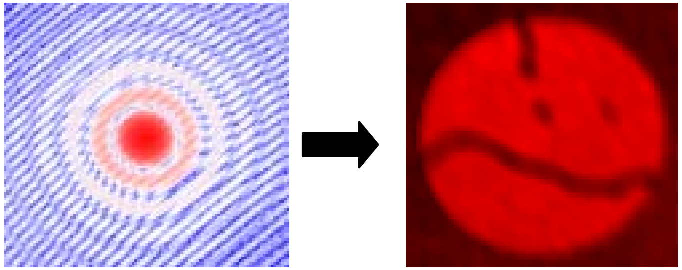


unambiguous

FT Holo

ref. hole



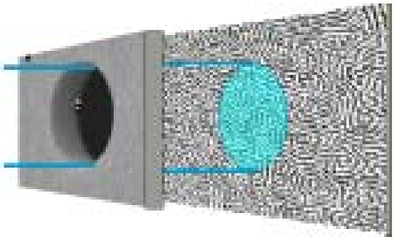


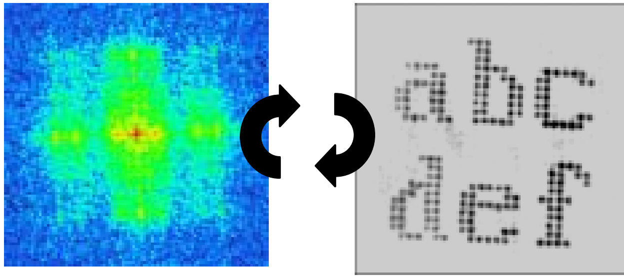
unambiguous

"a good initial guess helps…"

CDI

none

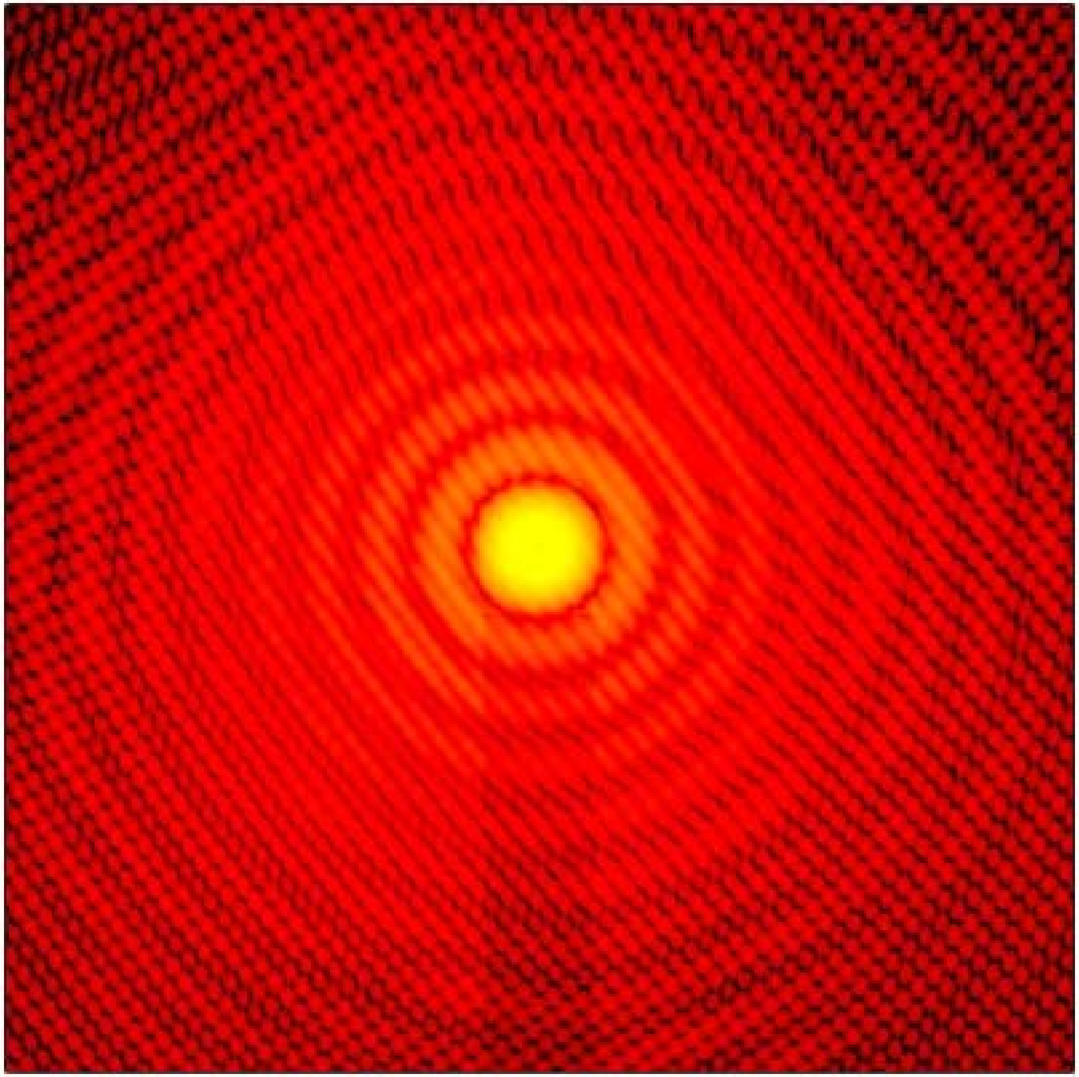




unique ?

high resolution
low dose

X-Ray Spectro-Holography



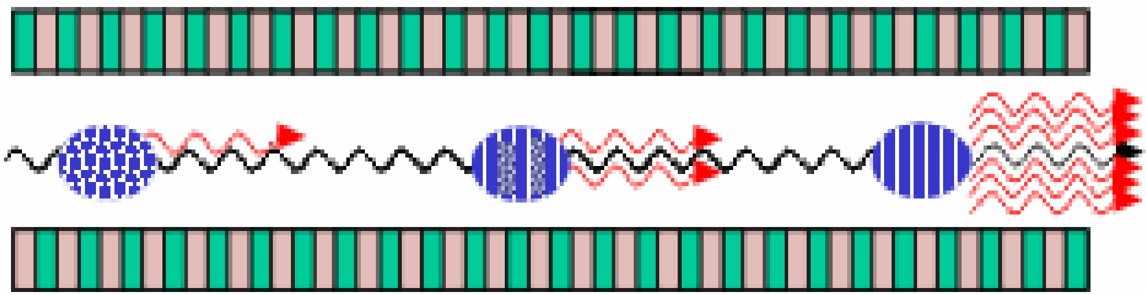
- Holographic Image
- Magnetic Profile
- 50 nm resolution
- Subsequent phase retrieval possible

- Mask approach
  - simple
  - stable
  - no focussing
  - characterize reference
  - sample environment

- Free Electron Laser

Vision: Femtosecond Snapshots

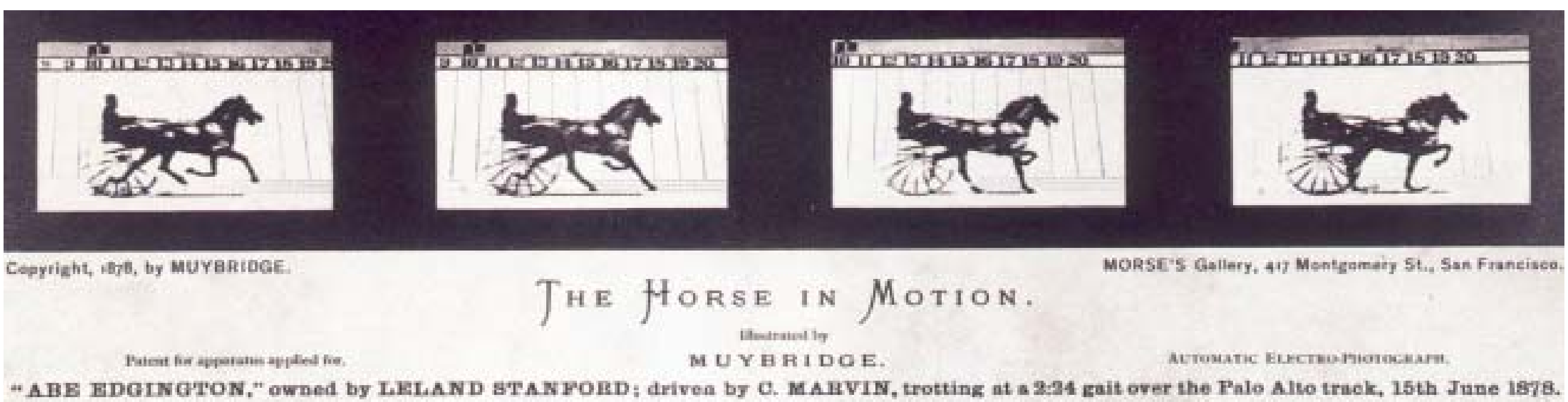
Free Electron X-Ray Laser



SLAC
DESY
BESSY
…

- coherent flux sufficient to image with a single pulse
- pulse duration 10-100 fs

- holography & oversampling phasing benefit from increased coherence



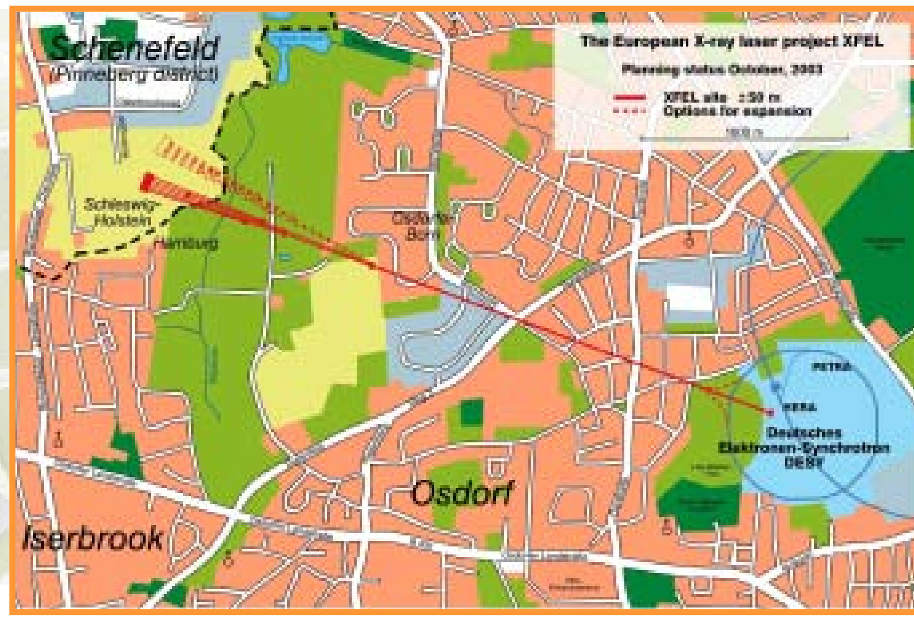
Germany: Complementary Free Electron Lasers

VUV and Soft X-Ray
BESSY FEL

Function

X-Ray
TESLA X-FEL

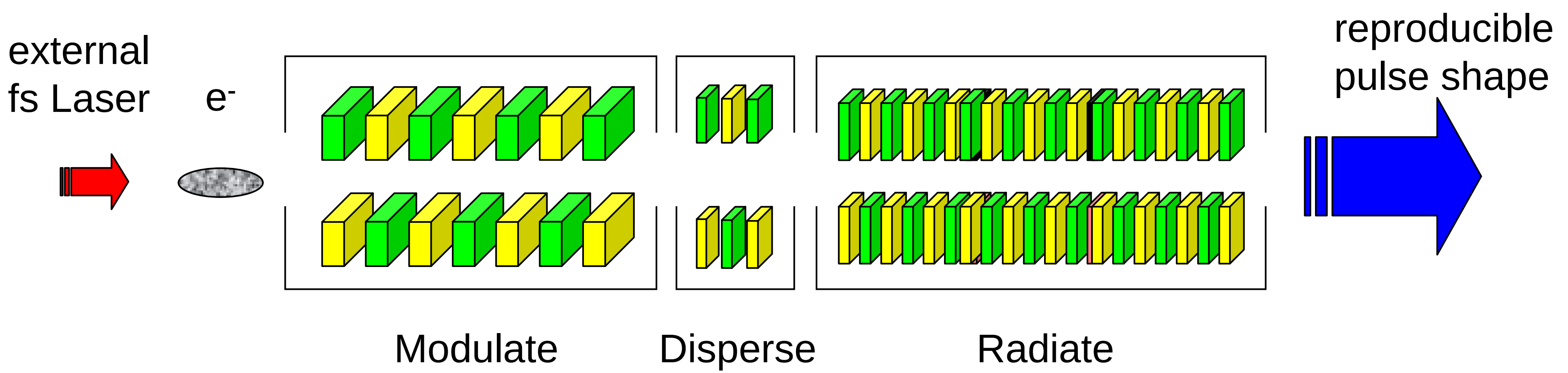
Structure



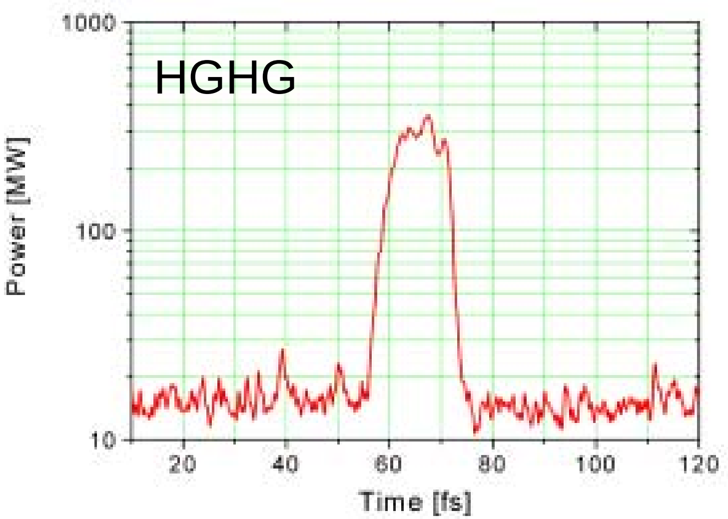
BESSY FEL		TESLA X-FEL
20 eV to 1 keV	Photon Energy	500 eV to 15 keV
<20 fs controlled	Pulse Length	<100 fs
1 kHz (1-25 pulses)	Repetition Rate	5 Hz (7200 pulses)

High Gain Harmonic Generation

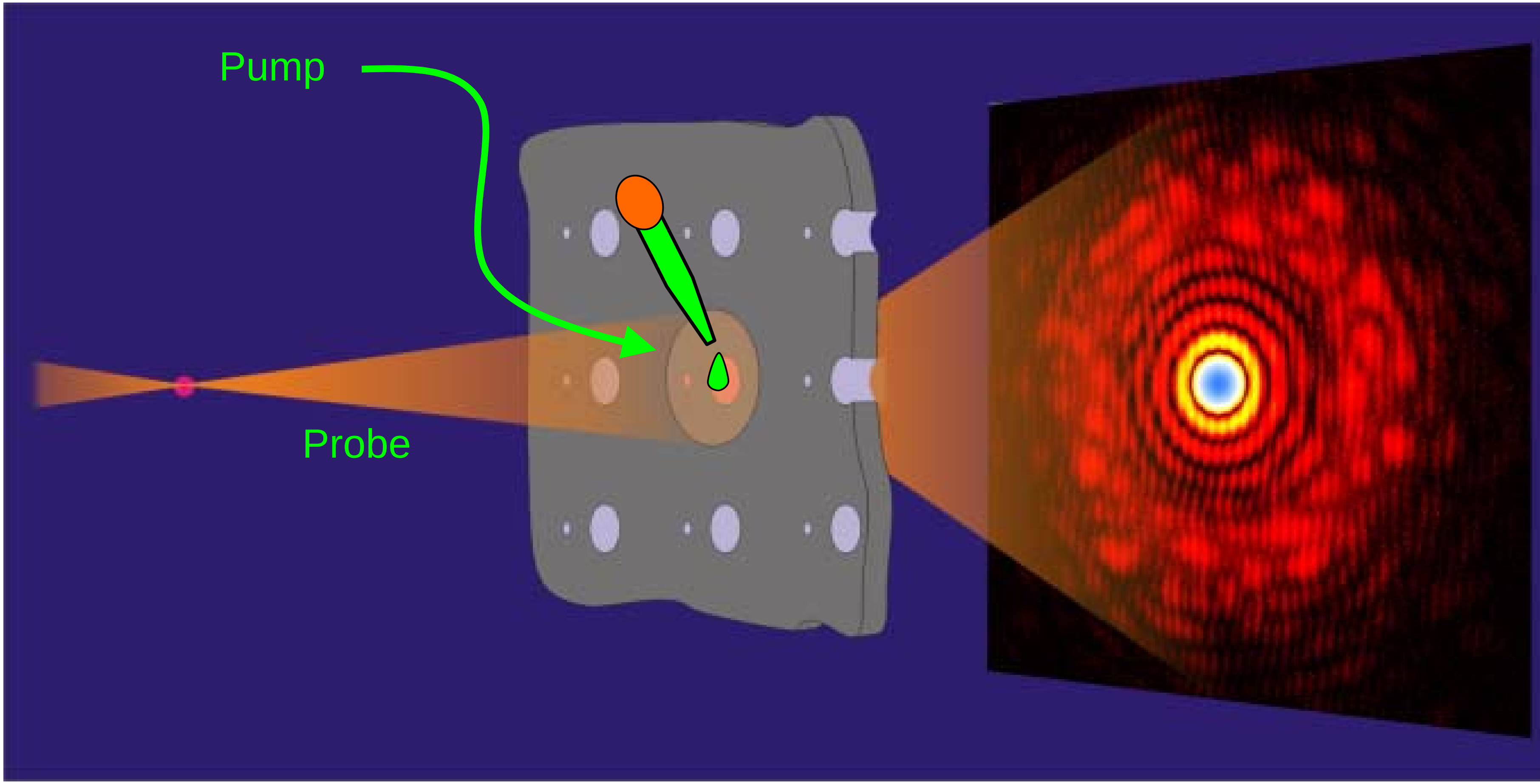
L.H. Yu et al., BNL, FEL Price 2003



- Fast pulses < 20 fs
- Reproducible
- Intrinsic synchronization
- Attosecond HHG option



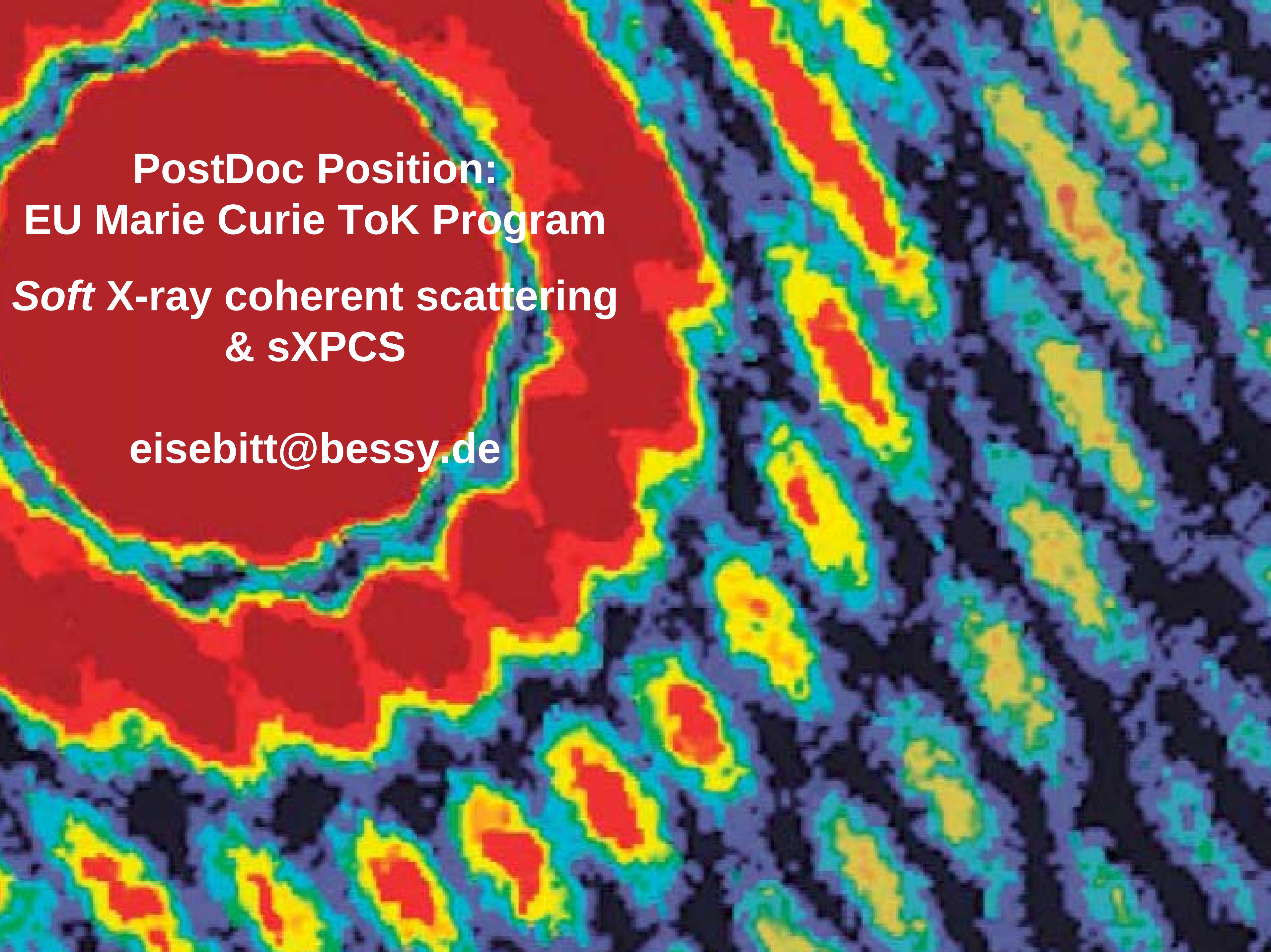
Single Shot Experiments



• Single Nano-objects • Pump-Probe • Non-repetitive Dynamics

X-Ray: spatial resolution, atomic / chemical / magnetic contrast

S. Eisebitt, Coherence 2005, Porquerolles June ‘05


PostDoc Position:
EU Marie Curie ToK Program
Soft X-ray coherent scattering
& sXPCS
eisebitt@bessy.de