

Magnetic X-ray microscopy:

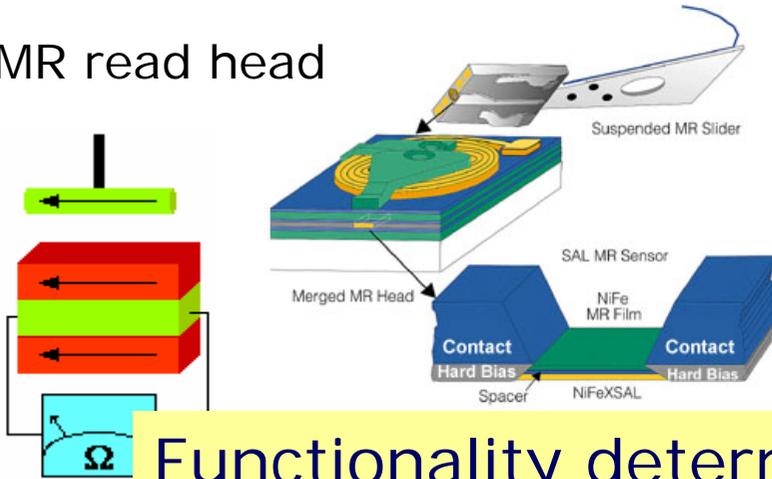
Real space imaging of nanomagnetism with high resolution

Peter Fischer
CXRO/LBNL, Berkeley CA
PJFischer@lbl.gov

- ❖ challenges
 - ❖ recent results
 - ❖ perspectives

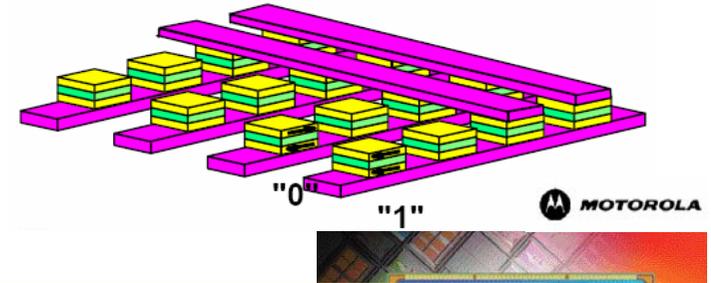
Application of magnetic materials

GMR read head



Cu 30nm
Ta 3,5nm
Ni ₈₀ Fe ₂₀ 4nm
AlO _x 1..2 nm
Co ₇₀ Fe ₃₀ 3nm
Ir ₁₇ Mn ₈₃ 12nm
Cu 30nm

Magnetic Tunnel Junction for MRAM
(Magnetic Random Access Memory)



Functionality determined by

- magnetic properties of the individual layers
→ layer-resolved magnetisation reversal
- surfaces/interfaces
- magnetic microstructure
→ magnetic domains
- magnetisation dynamics

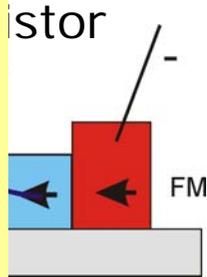
ultra fast



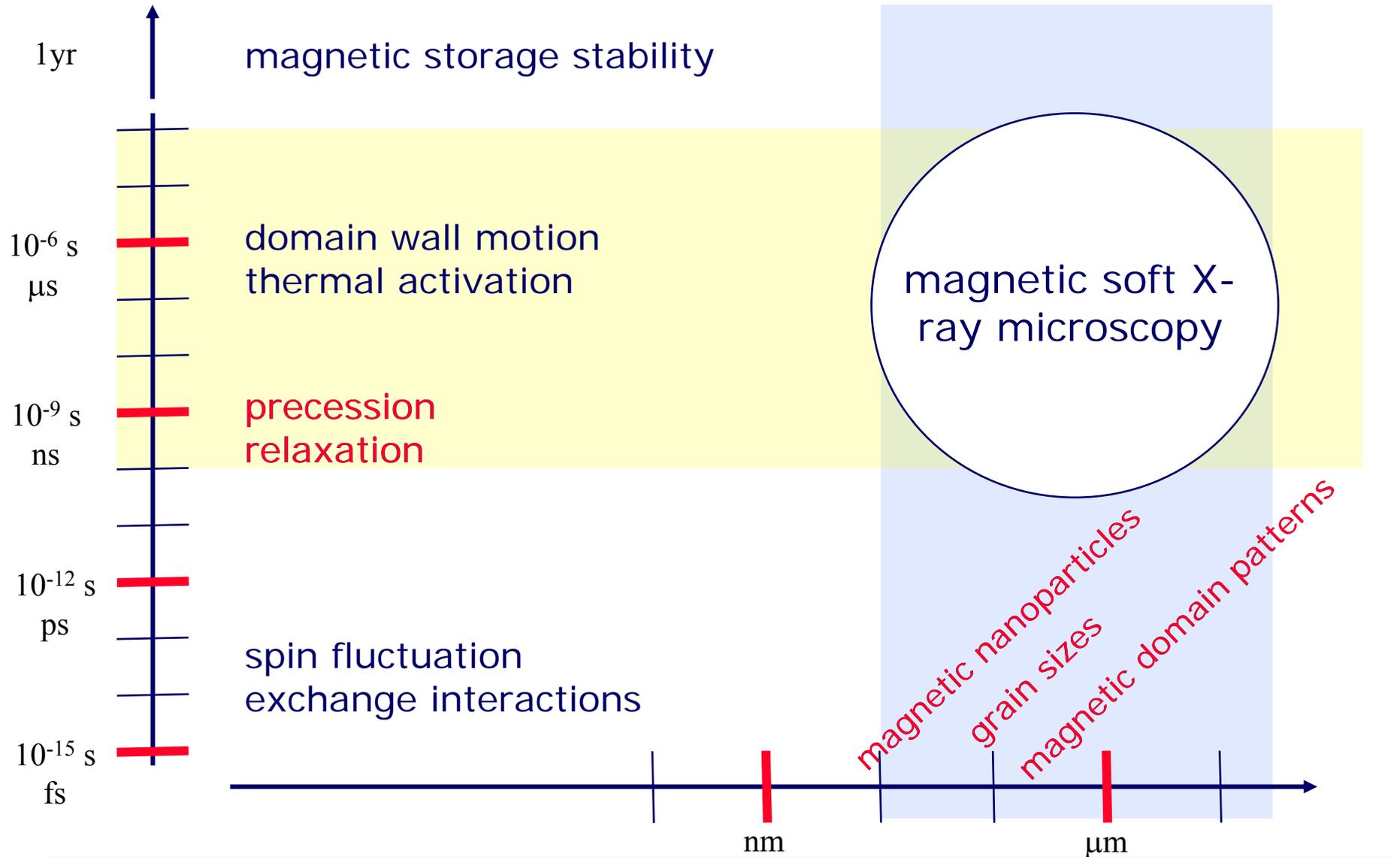
150 μm

C. H. Back et al Science (1999)

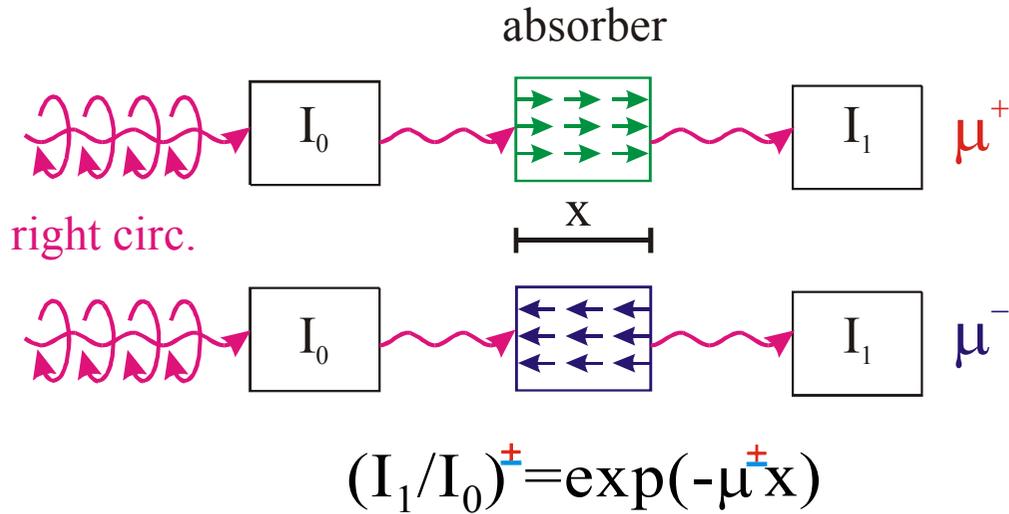
D.H. Allwood et al Science (2003)



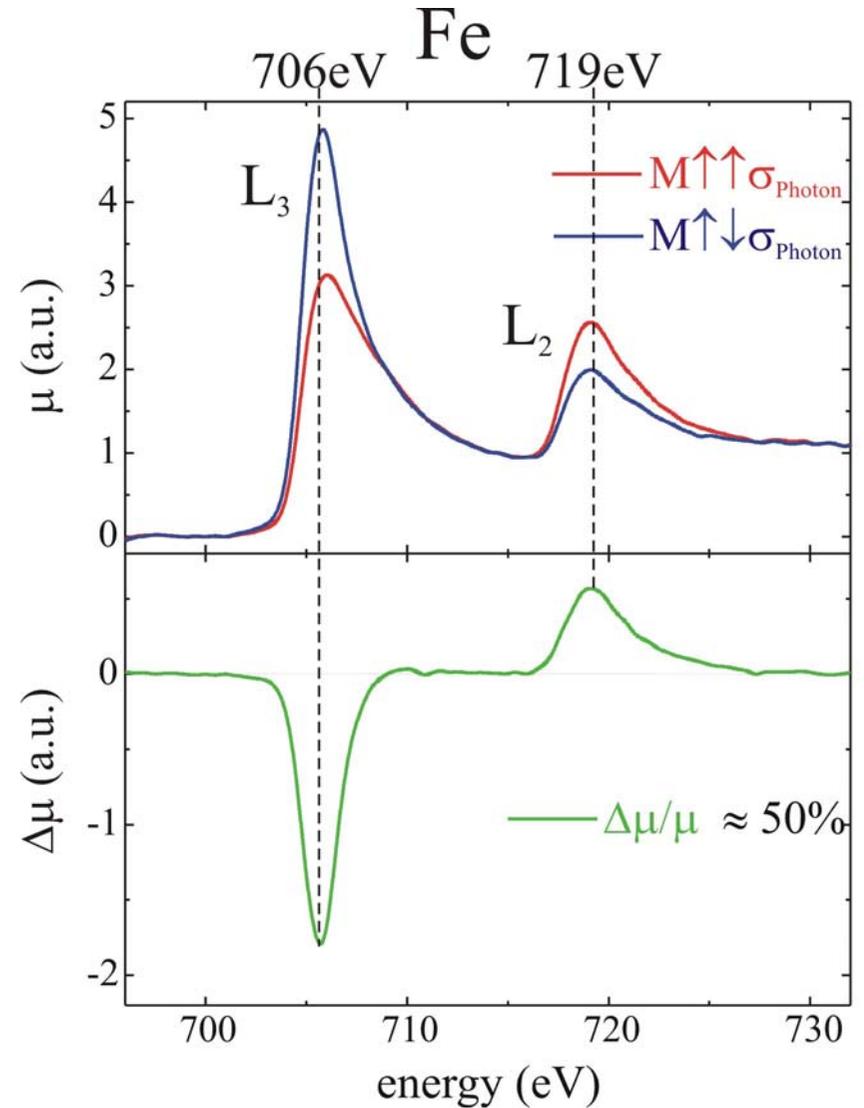
(Nano)-Magnetism



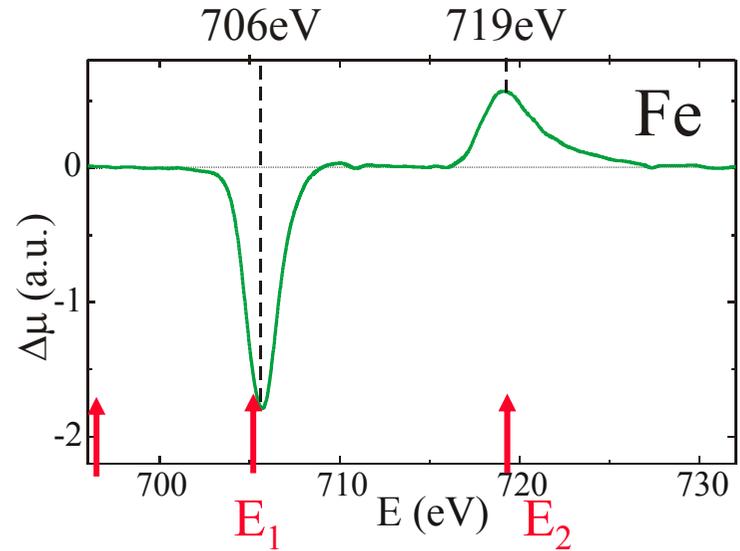
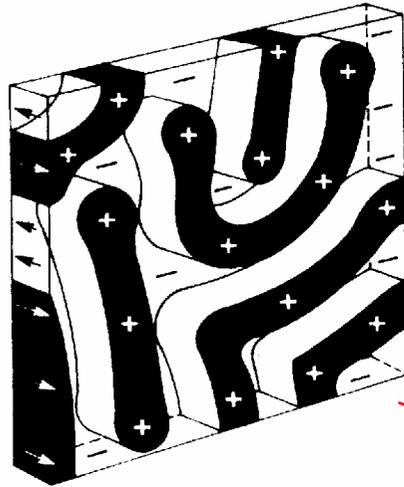
X-ray magnetic circular dichroism



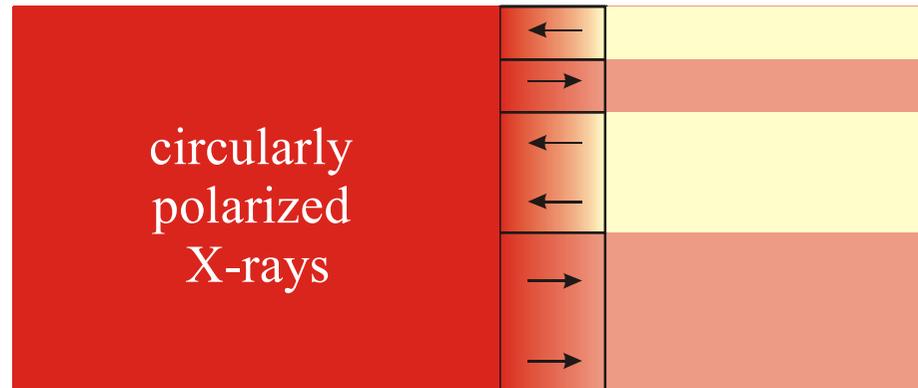
- ⊗ element-specific
- ⊗ huge magnetic contrast
- ⊗ $\underline{M} \cdot \underline{\sigma}_{\text{Photon}}$
- ⊗ Spin-orbit information



Magnetic Transmission X-ray Microscopy

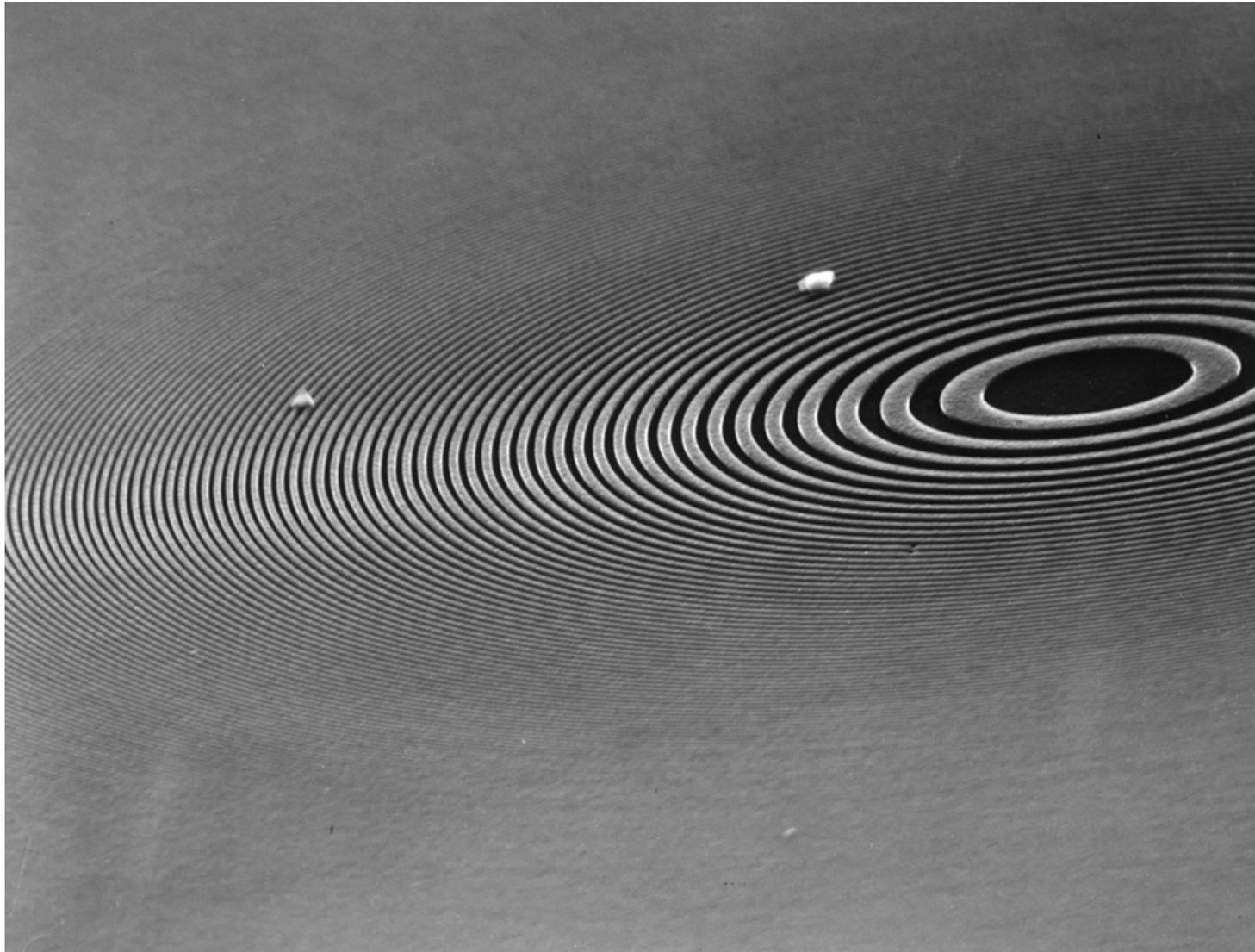


E_2
 E_1



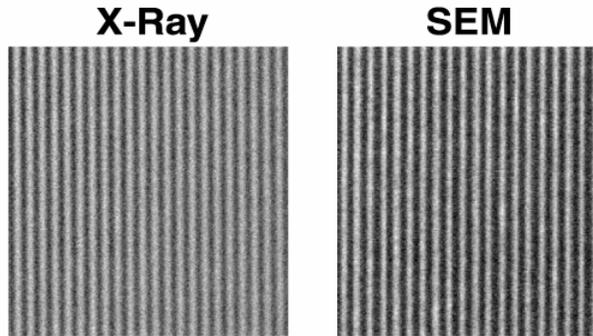
contrast reversal

Fresnel zone plates

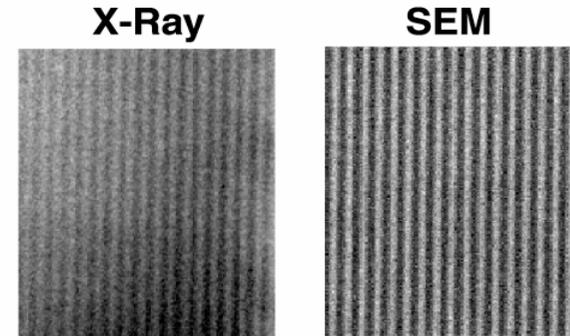




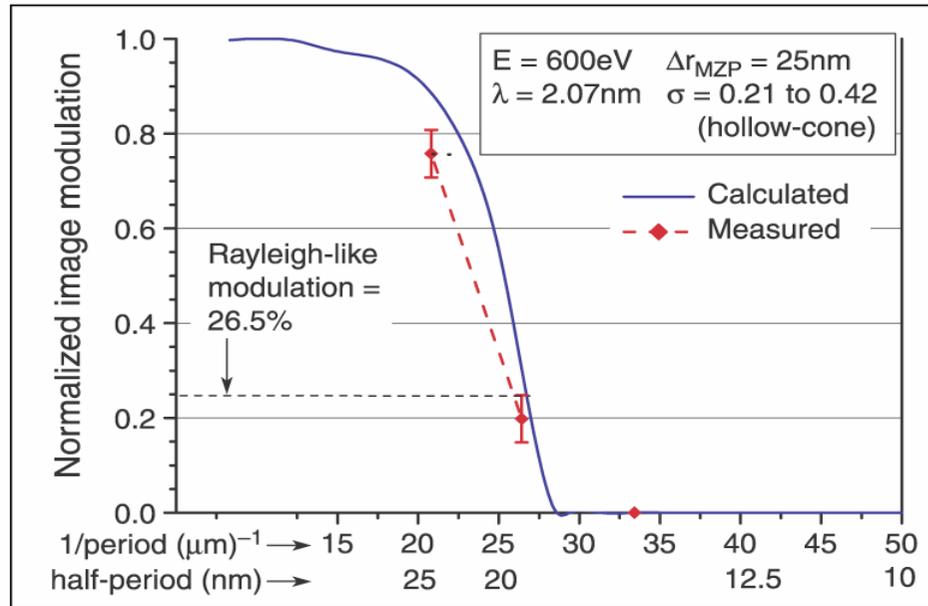
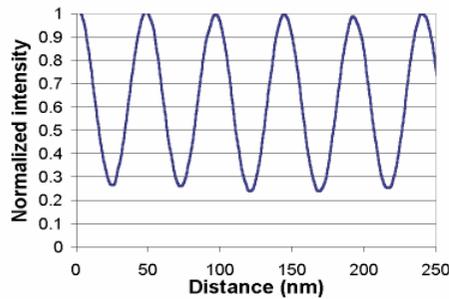
Near Diffraction Limited Soft X-Ray Microscopy: 20 nm Spatial Resolution at 2.07 nm Wavelength



24 nm lines and spaces (Cr/Si)
75% modulation
600 eV (2.07 nm)



19 nm lines and spaces (Cr/Si)
20% modulation



W. Chao et al.,
Opt. Lett. 28, 2019 (2003)

(Courtesy of Weilun Chao, UC Berkeley and CXRO/LBNL)



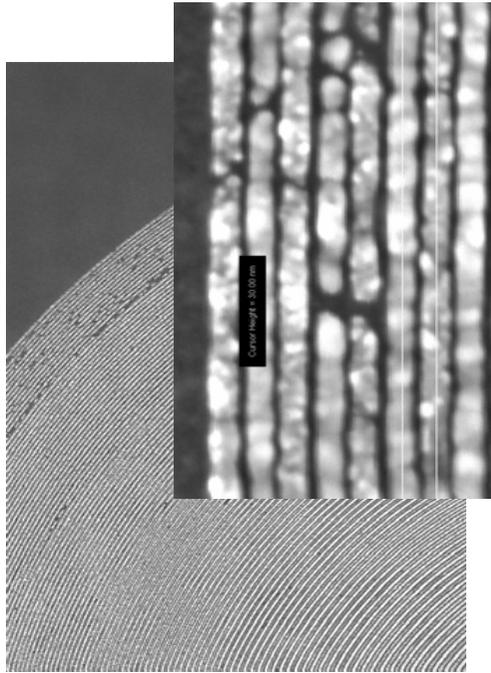
courtesy: D. T. Attwood



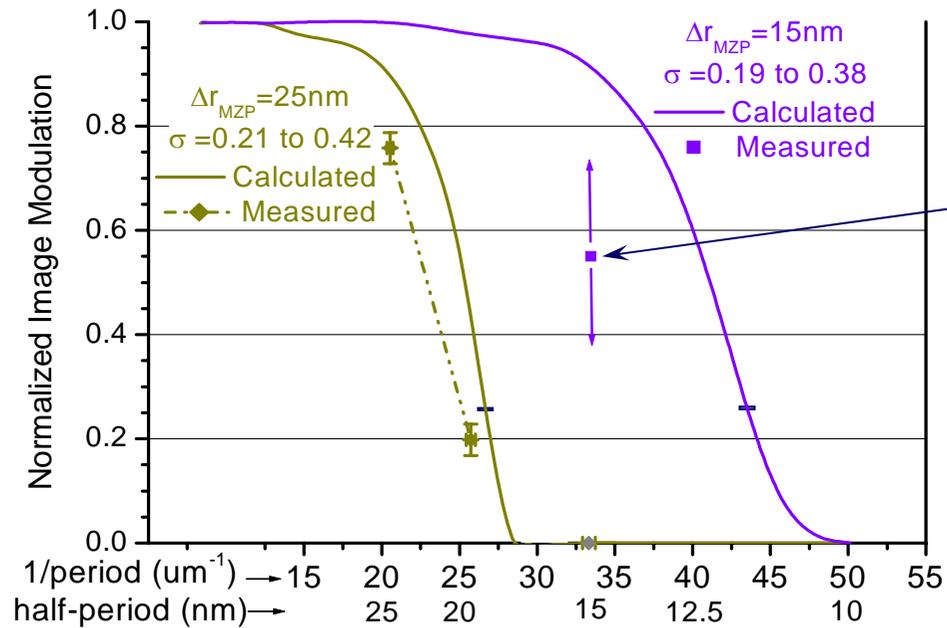
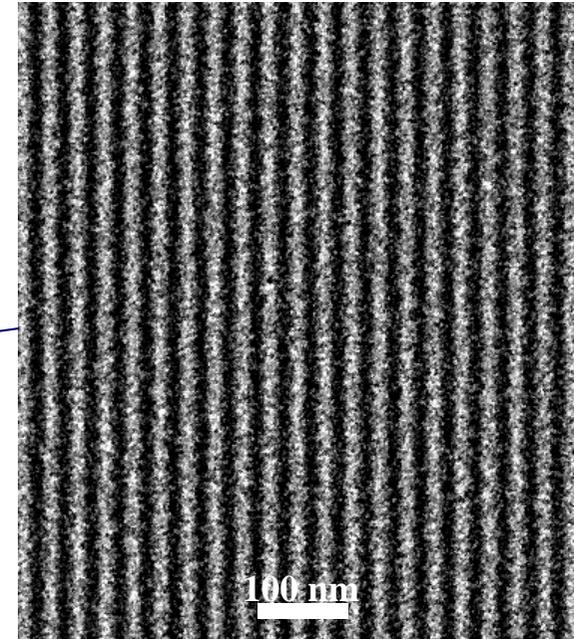
New Results Using Interleave Nanofabrication: Outer Zone Width of 15 nm



New zone plate lens with
15 nm outer zone width



Soft x-ray image of
15 nm Cr/Si lines & spaces

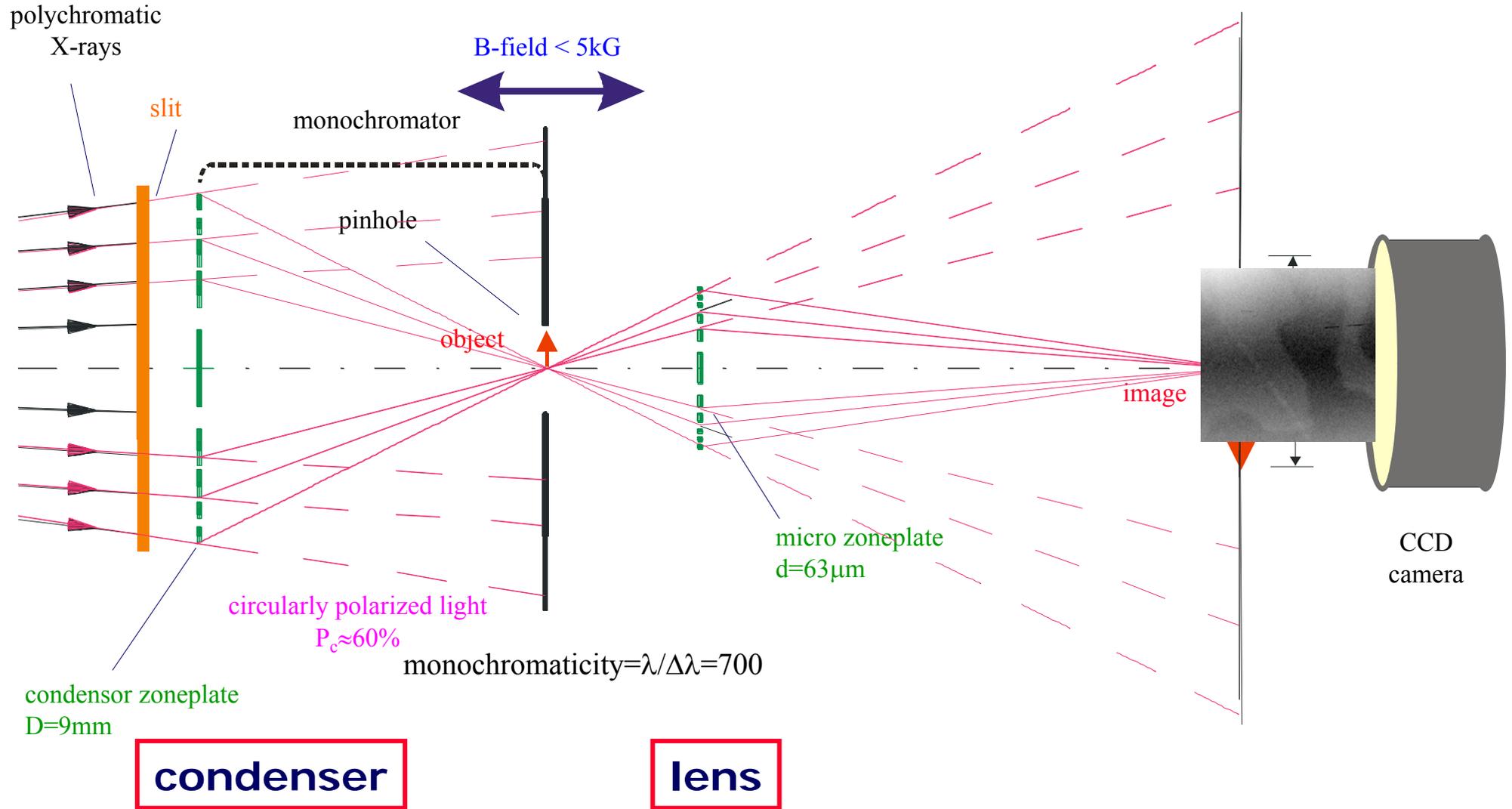


(Unpublished)

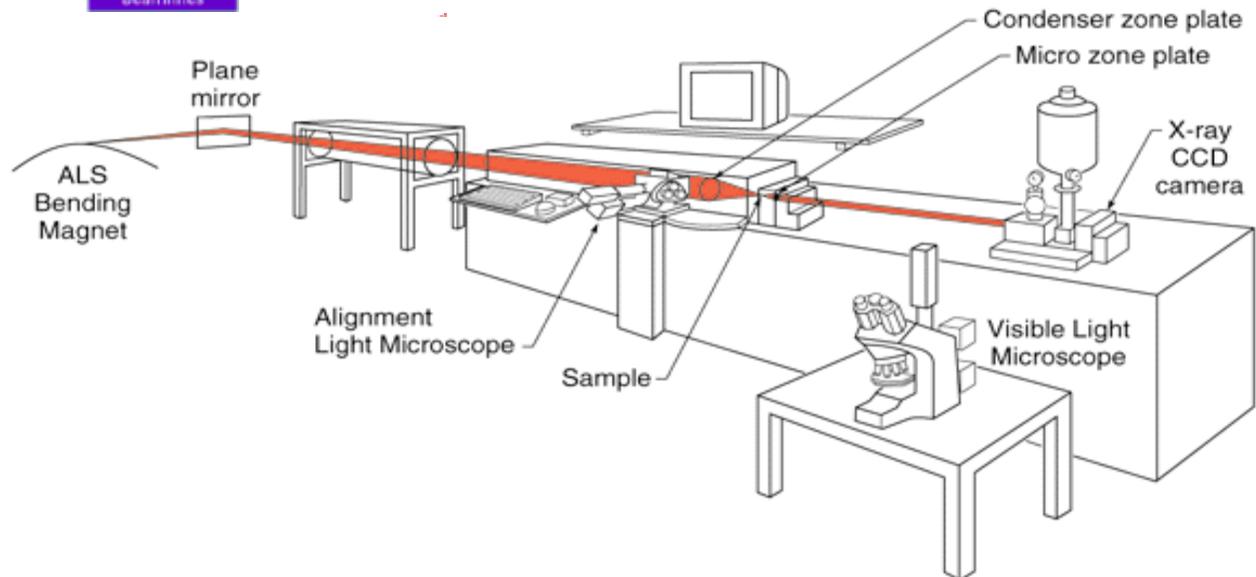
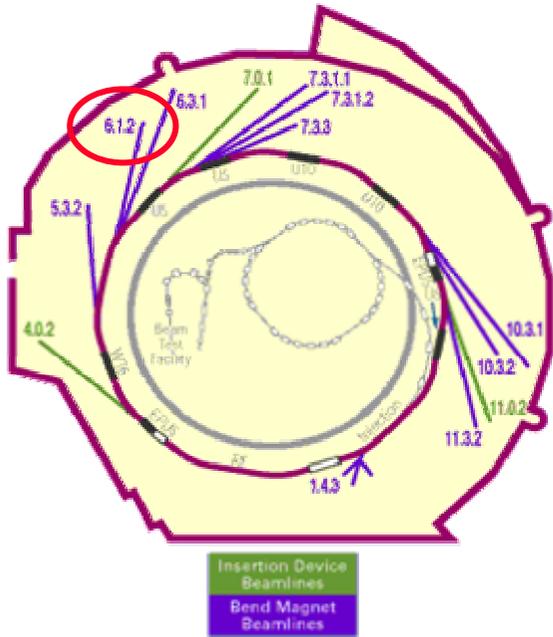
Courtesy of W. Chao, A. Liddle, E. Anderson, and B. Harteneck (CXRO/LBNL)



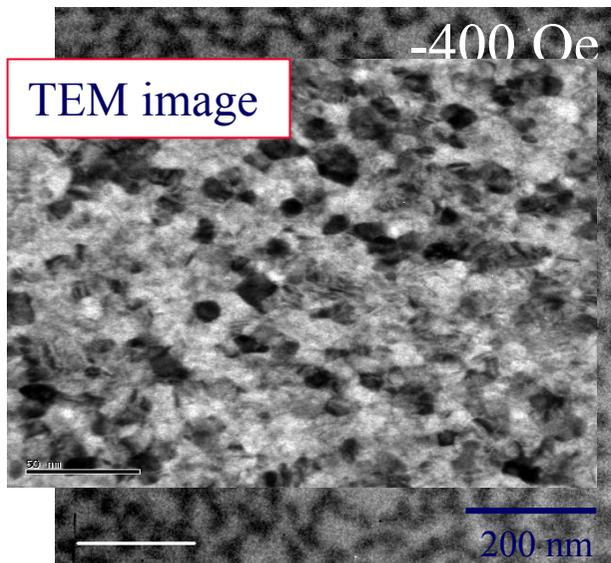
Magnetic Transmission X-ray-Microscopy



The XM-1 at the ALS in Berkeley/CA



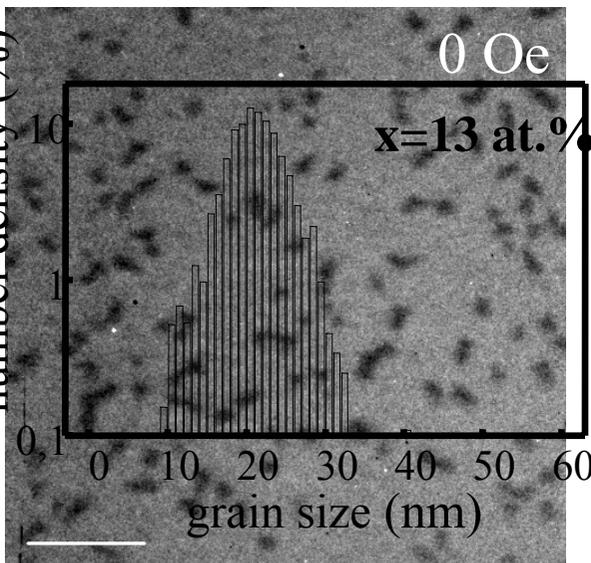
Magnetisation reversal in nanogranular media



TEM image

-400 Oe

1 μm

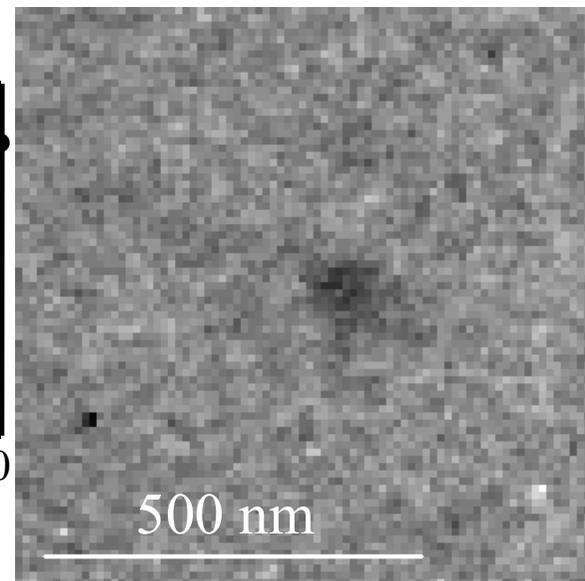


0 Oe

x=13 at.%

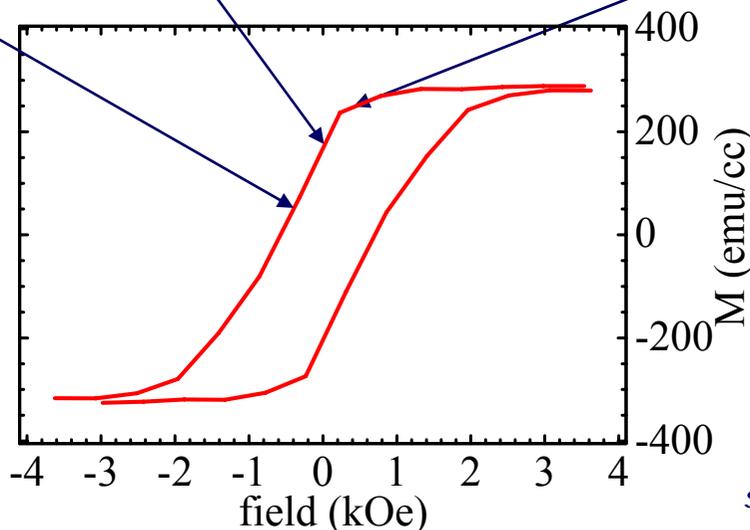
number density (%)

grain size (nm)



500 nm

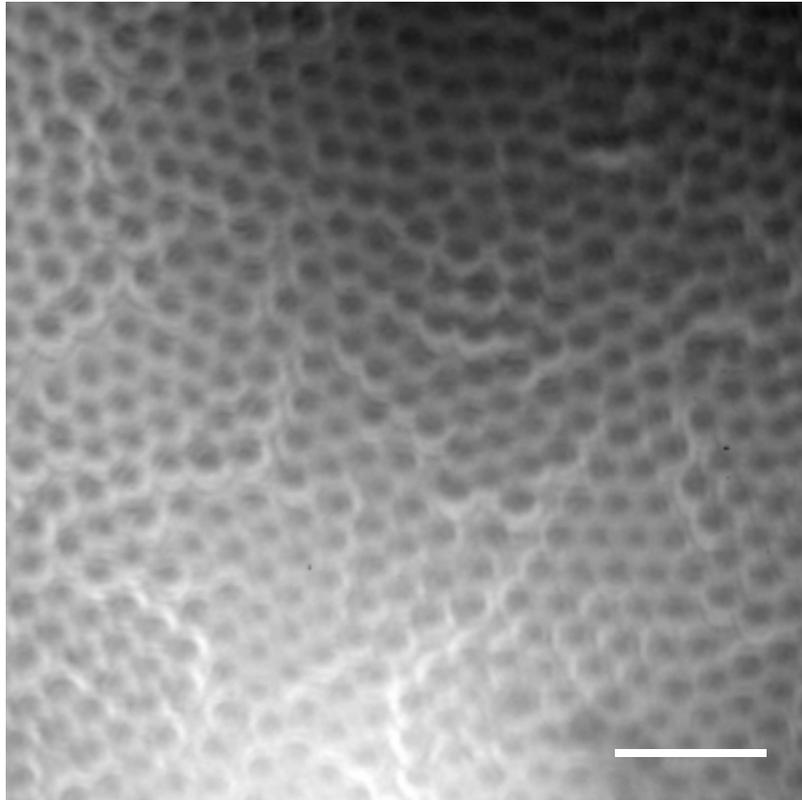
sample:
 $(\text{Co}_{84}\text{Cr}_{16})_{87}\text{Pt}_{13}$ (50nm)
 Ti buffer (40nm)
 Si_3N_4 (200nm)



\Rightarrow stochastically distributed nucleation sites

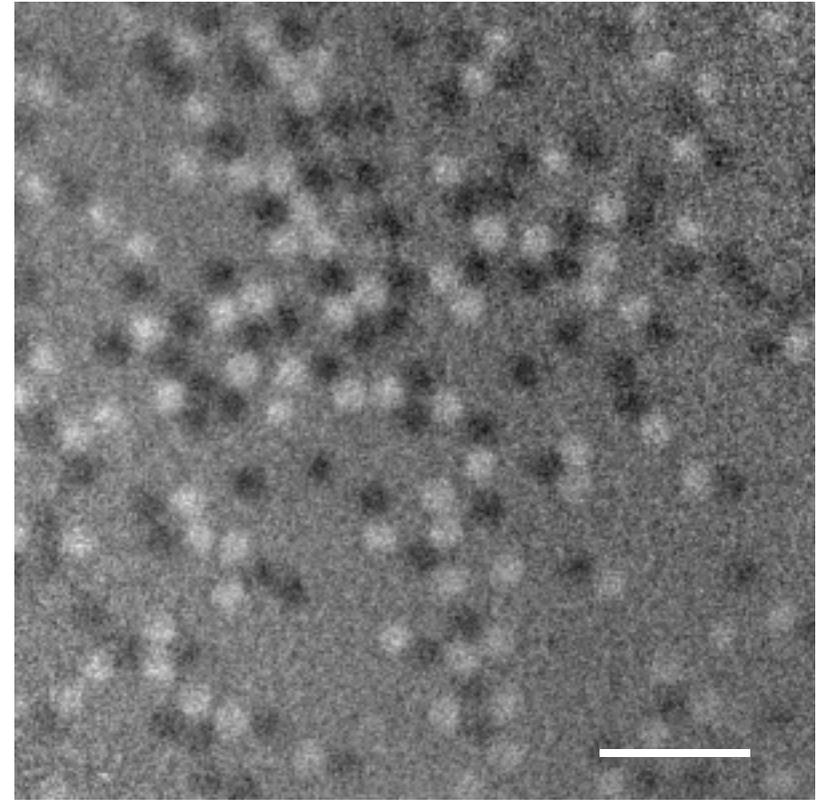
sample: M.-Y. Im (KAIST Korea)

Magnetisation reversal in nanoparticles



1 μm

X-ray microscopy
of CoPt nanoparticles

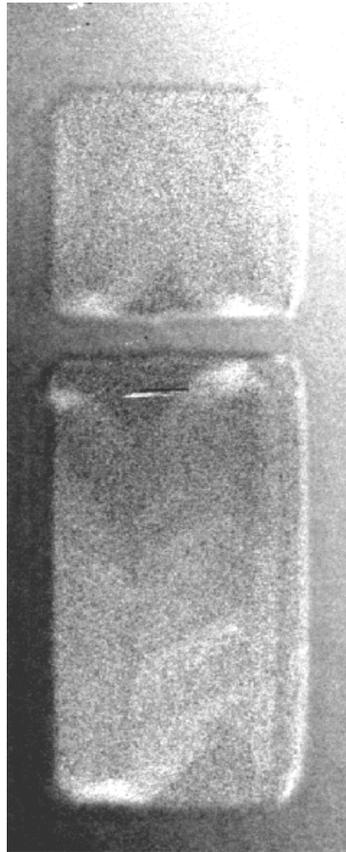


magnetic contrast
sensitive to 2.4nm Co

sample: M. Albrecht (U Konstanz)

Stray-field coupled microcontacts

MTXM@Fe L₃ OOMMF

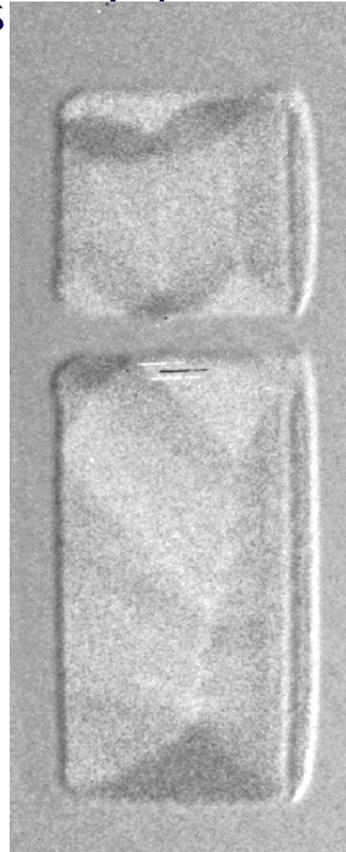


1 μm

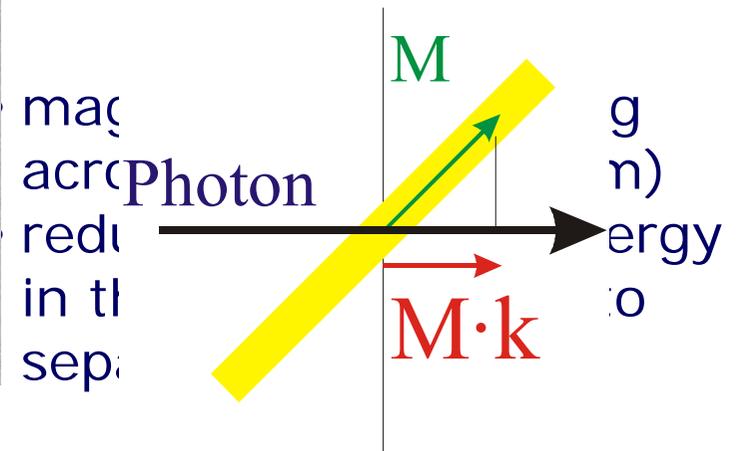
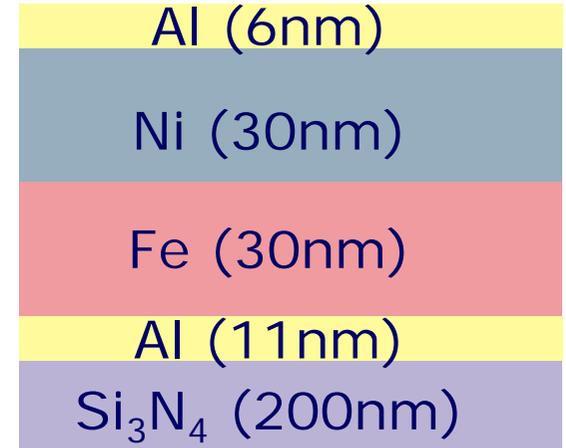
H = -8 mT



H = 0 mT



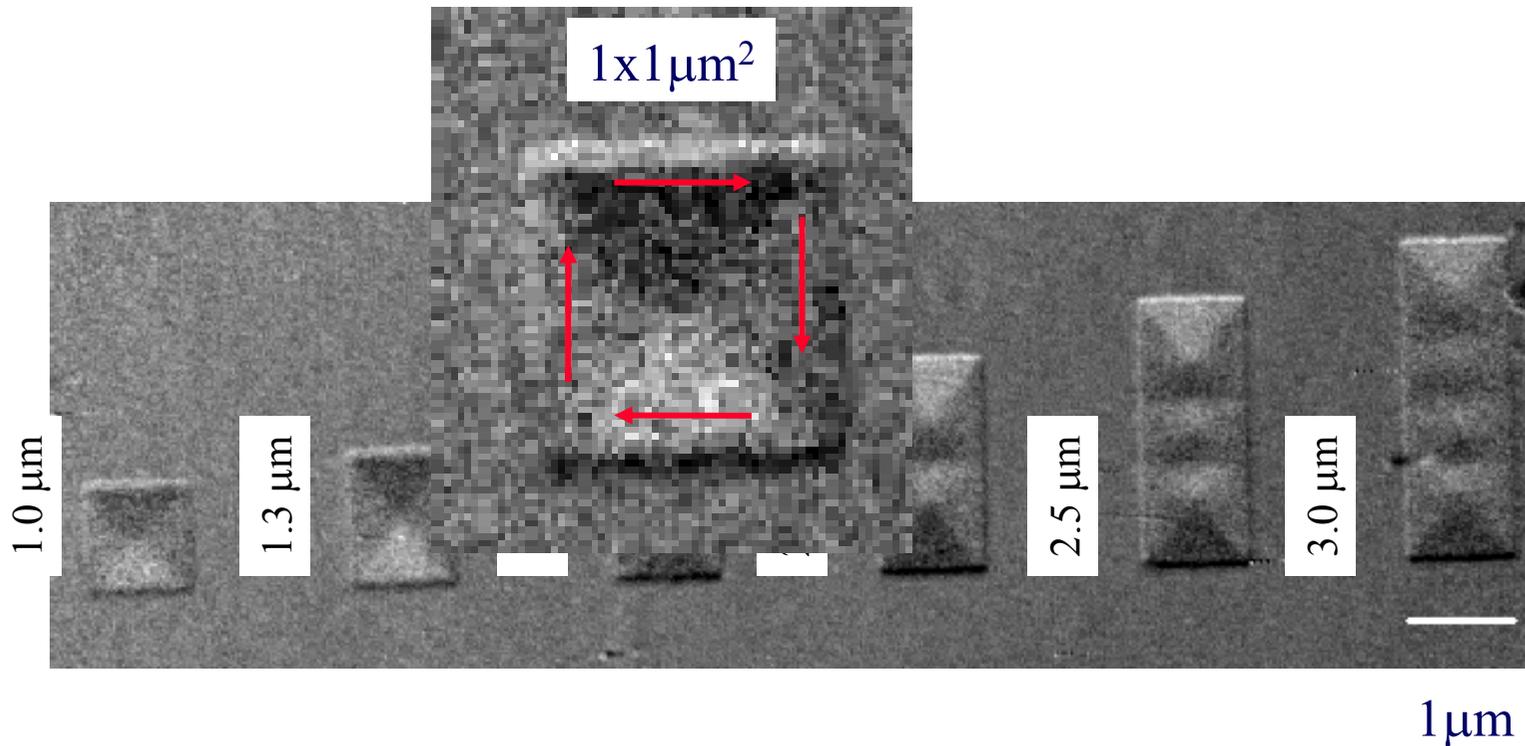
H = 3.8 mT



sample: G. Meier (U Hamburg)

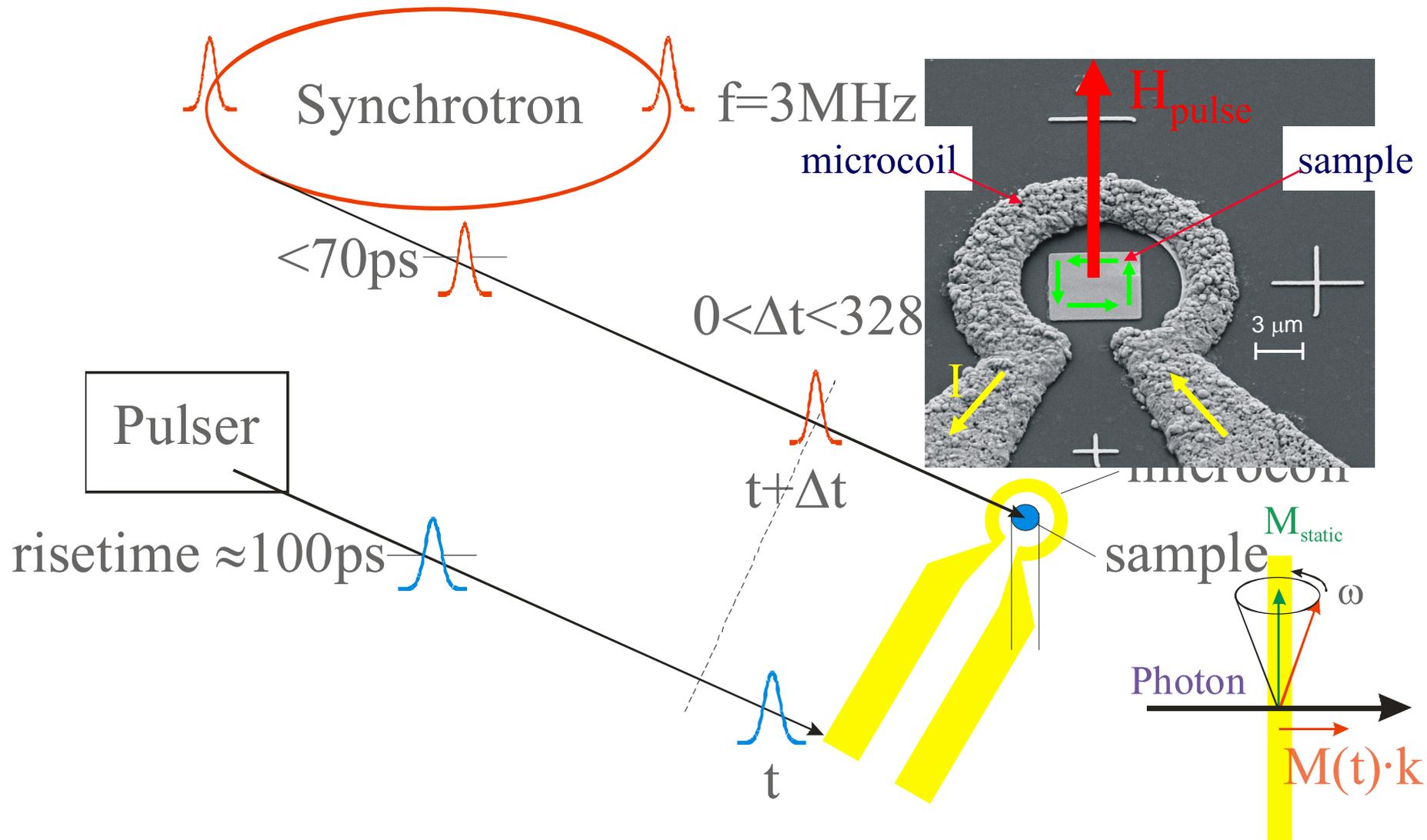
Landau patterns in PY elements

PY: $\text{Ni}_{80}\text{Fe}_{20}$ (50 nm) @ Ni L_3 edge



sample: T. Ono (U Kyoto Japan)

Stroboscopic pump-and-probe technique

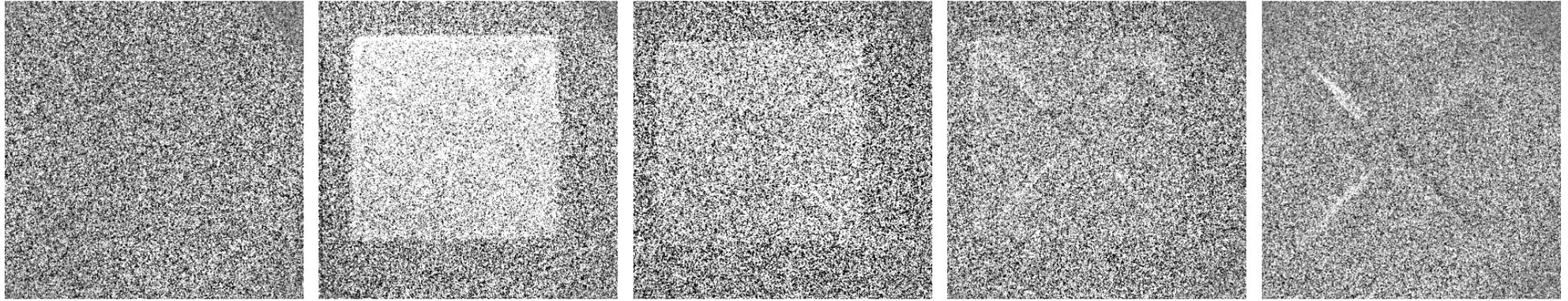


local spin dynamics

sample: J. Raabe / simul: R. Höllinger (U Regensburg)

experiment

sample: $(4 \times 4) \mu\text{m}^2 \times 50\text{nm}$ PY



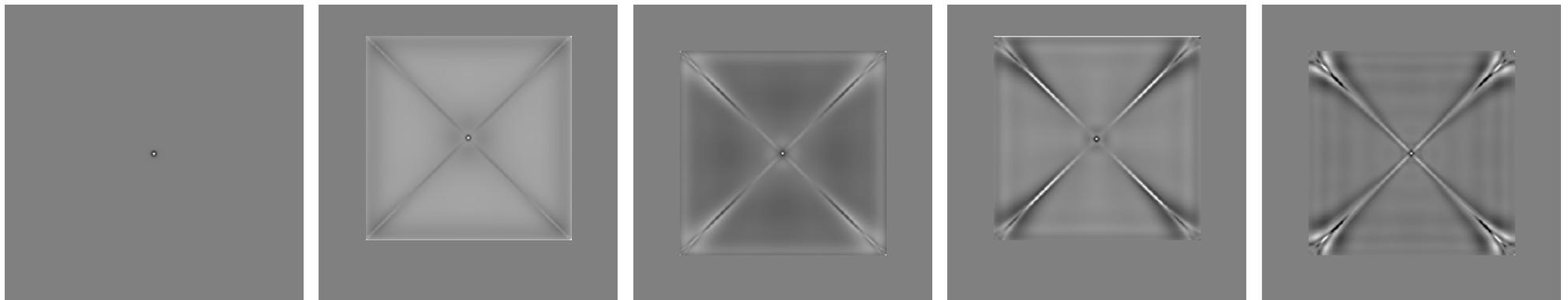
$\Delta t = -400\text{ps}$

$\Delta t = +400\text{ps}$

$\Delta t = +500\text{ps}$

$\Delta t = +600\text{ps}$

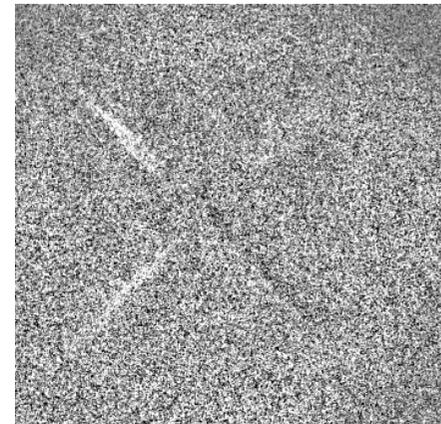
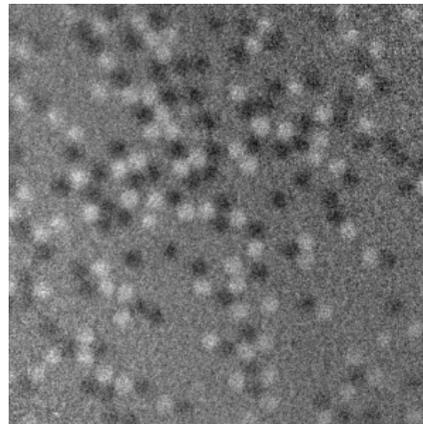
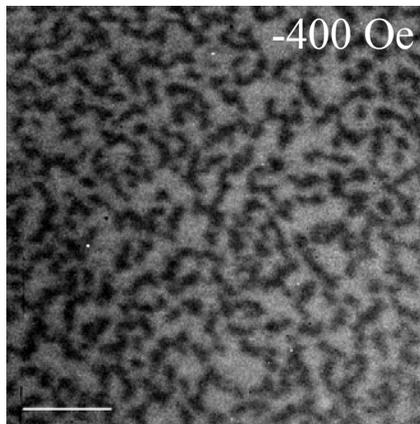
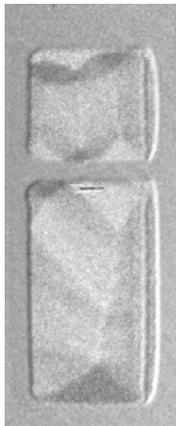
$\Delta t = +800\text{ps}$



simulation

Magnetic Soft X-ray Microscopy

- ✓ **element-specific (=layer sensitive)** contrast
- ✓ reversal studies in **external magnetic fields**
- ✓ **lateral** resolution (X-ray optics) ($\rightarrow 15\text{nm}$), large FOV
- ✓ **time dependent** studies in the sub-ns regime



Outlook



- accessing the microstructure at interfaces
 - ❖ microscopy in reflection mode
- dynamical studies
 - ❖ impurities, defects, impact of geometry, coupled systems
- distribution of local spin and orbital moments
 - ❖ magnetic microspectroscopy

The ALS is a unique place to study nanomagnetism!



Acknowledgement

- W. Chao, B. Kang, D.-H. Kim, B. Gunion, S. Rekawa, R. Oort, K. Bradley, P. Denham, D. Kemp, A. Sakdinawat, J. Gamsby, R. Tackaberry, D. Attwood, E. Anderson (*CXRO Berkeley CA, USA*)
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