Magnetooptical microscopy

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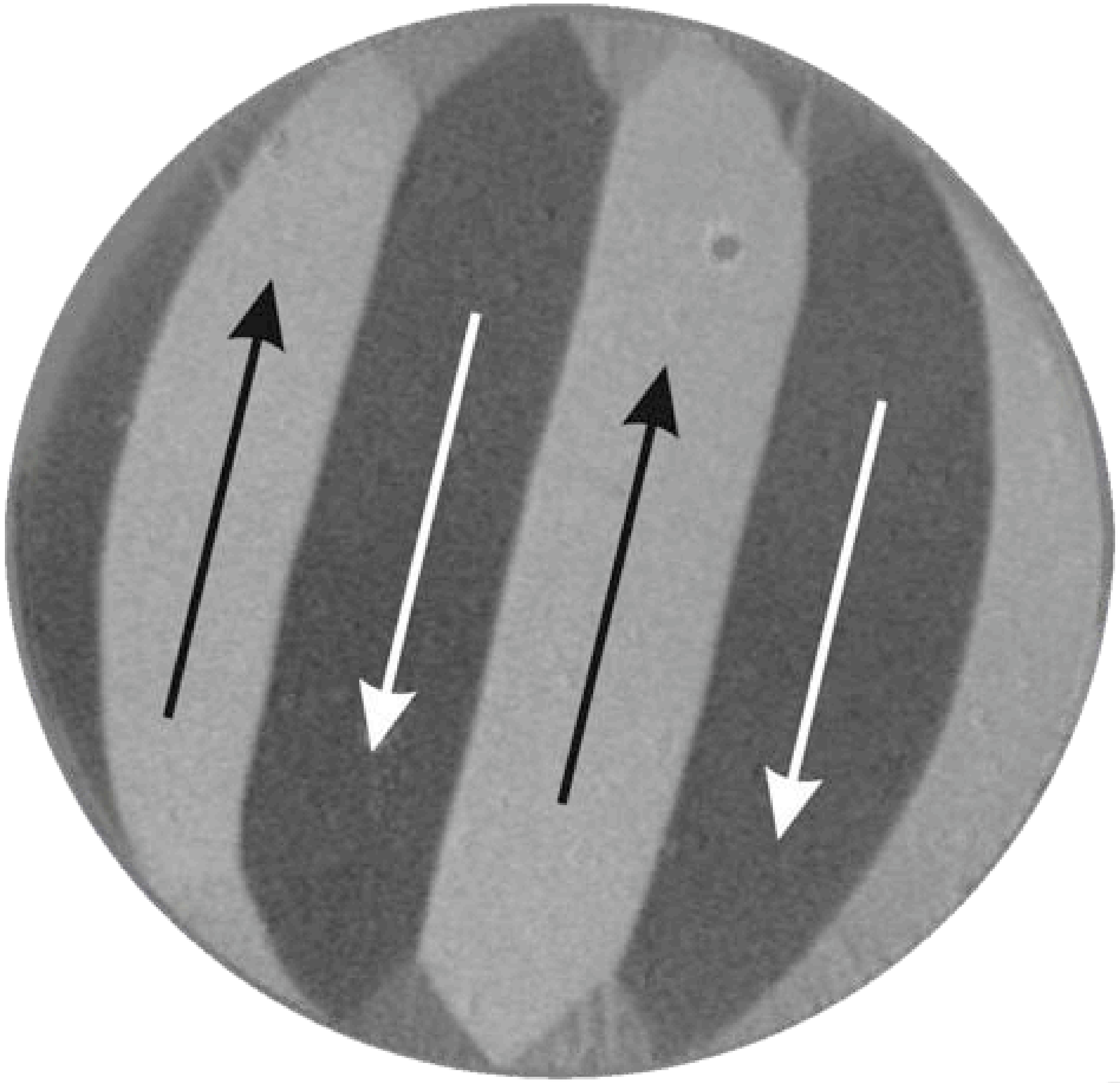
Dresden



Why domain observation?

- magnetic properties
  - hysteresis measurements
  - coercivity H_c, anisotropy field H_k
  - saturation magnetization B_s, remanent magnetization B_r
- but ...
  - local effects
  - domain walls
  - patterned samples
  - multilayers
  - ...

magnetic microstructure

Domain observation - wish list

- image magnetic microstructure with lateral resolution in the range from nanometer up to millimeter
- directly image magnetization
- element specific
- image depth sensitive
- imaging of working devices - through non-magnetic covering layers or substrate
- image while applying arbitrary magnetic fields
- allow sample manipulation (heating, cooling, stressing etc.)
- follow magnetization dynamics
- minimal interaction with magnetization

Magneto-optical microscopy

- image magnetic microstructure with lateral resolution in the range from ~~nanometer~~ up to millimeter
- ✓ directly image magnetization
- ✦ ~~element specific~~
- ✓ image depth sensitive
- ✓ imaging of working devices - through non-magnetic covering layers or substrate
- ✓ image while applying arbitrary magnetic fields
- ✓ allow sample manipulation (heating, cooling, stressing etc.)
- ✓ follow magnetization dynamics
- ✓ minimal interaction with magnetization

What is this about?

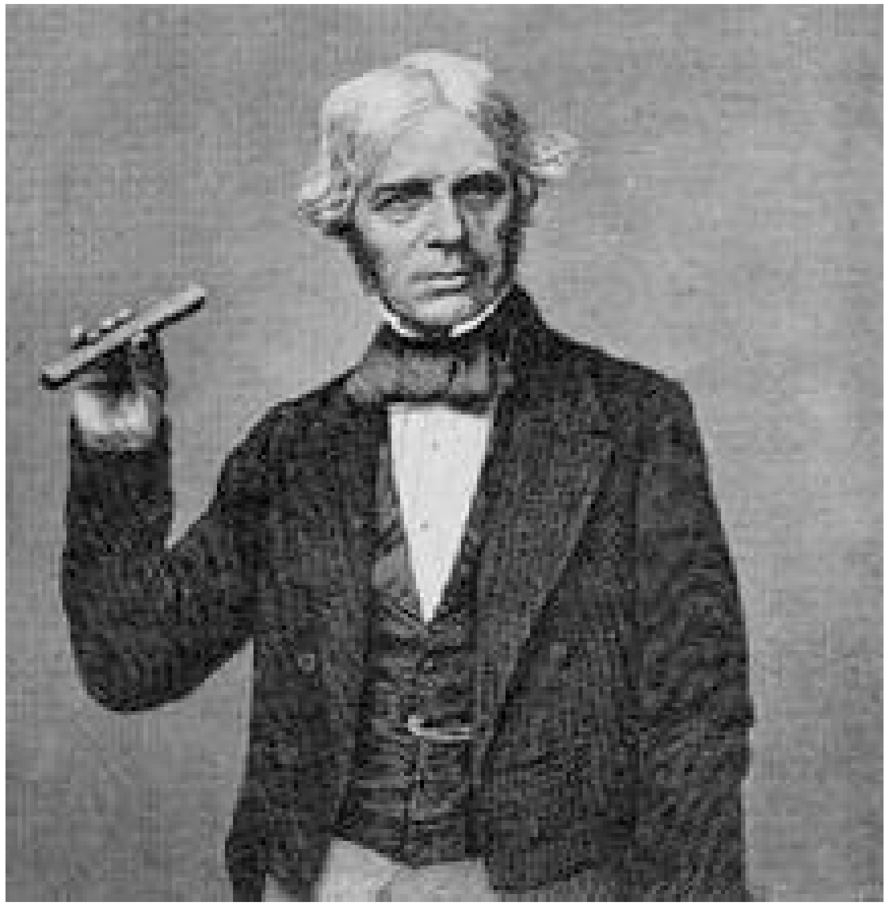
- optical microscopy
- magneto-optics

- magneto-optical microscopy (incl. time-resolved)
  - transmission microscopy - Faraday effect
  - wide-field and scanning Kerr microscopy
  - Voigt-effect microscopy
  - MOIF microscopy (indirect)

Magneto-optical effects

... change of polarization of light due to magnetism ...

Magneto-optical effects - history



- Michael Faraday (1791-1867)
- “Today worked with lines of magnetic force, passing them across different bodies (transparent in different directions) and at the same time passing a polarized ray of light through them and afterwards examining the ray by a Nichol’s Eyepiece or other means.”
- small change of polarization plane due to magnetic interaction in transmission. - ~ M

Magneto-optical effects - history

John Kerr

- J. Kerr (1824-1907)
- small change of polarization plane due to magnetic interaction in reflection
- "Circular birefringence" ~ M

W. Voigt (1850 - 1919)

even smaller change of polarization plane due to magnetic interaction.

"Linear birefringence" - ~ M^2

Dielectric law (cubic)

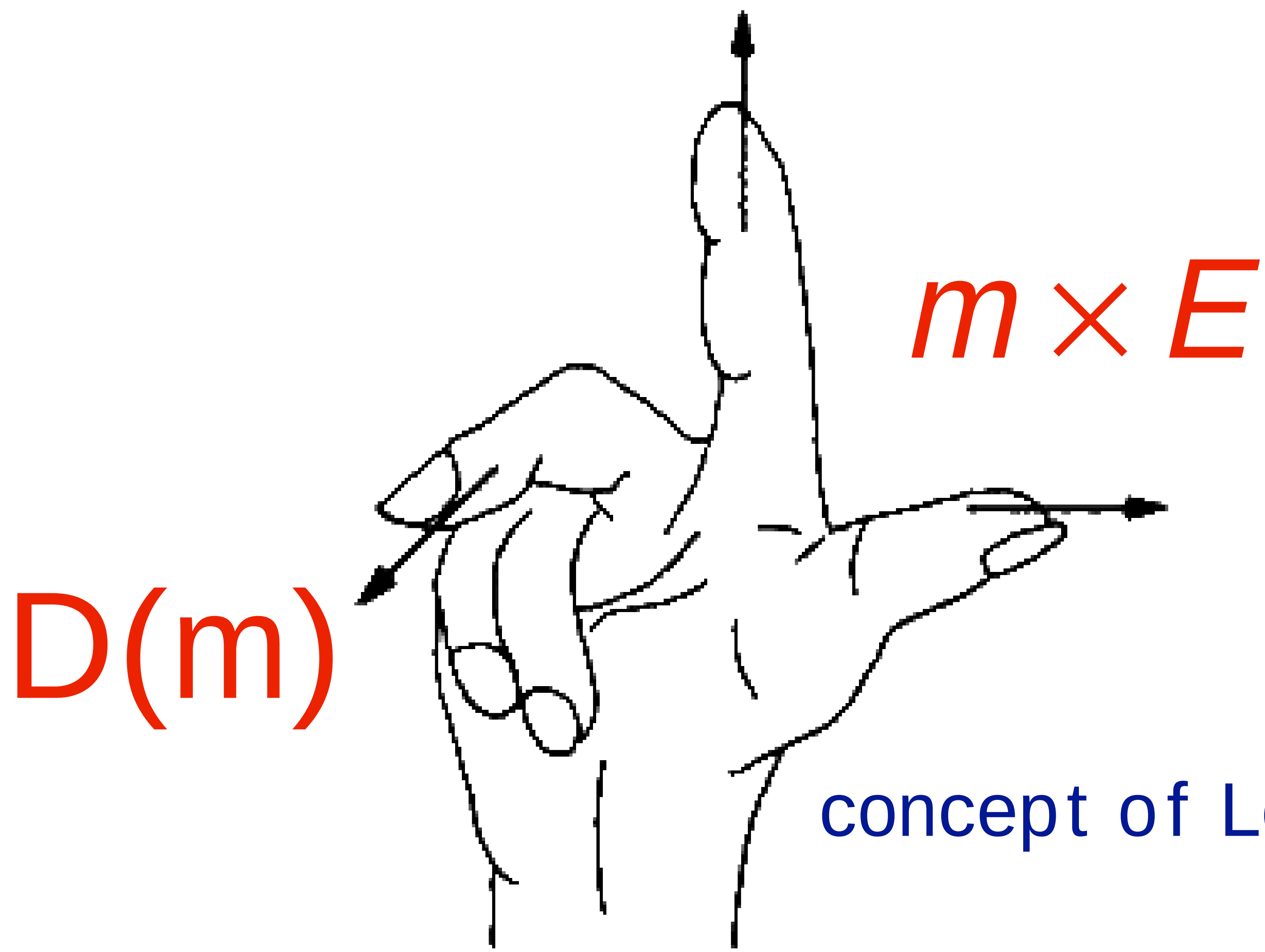
$$D = \varepsilon_{total} E$$

$$\varepsilon_{total} = \varepsilon \underbrace{\begin{pmatrix} 1 & -iQm_3 & iQm_2 \\ iQm_3 & 1 & -iQm_1 \\ -iQm_2 & iQm_1 & 1 \end{pmatrix}}_{\text{Kerr and Faraday}} + \underbrace{\begin{pmatrix} B_1 m_1^2 & B_2 m_1 m_2 & B_2 m_1 m_3 \\ B_2 m_1 m_2 & B_1 m_2^2 & B_2 m_2 m_3 \\ B_2 m_1 m_3 & B_1 m_2 m_3 & B_1 m_3^2 \end{pmatrix}}_{\text{Voigt}}$$

- E: electric vector of light wave
- e: dielectric tensor
- D: dielectric displacement vector
- m: magnetization vector components (cubic crystal, isotr.)
- Q, B_1, B_2: complex material constants

Dielectric law (II) - isotropic case

$$D = \varepsilon (E + i\,Q\; m \times E) = f\,(m \times E)$$

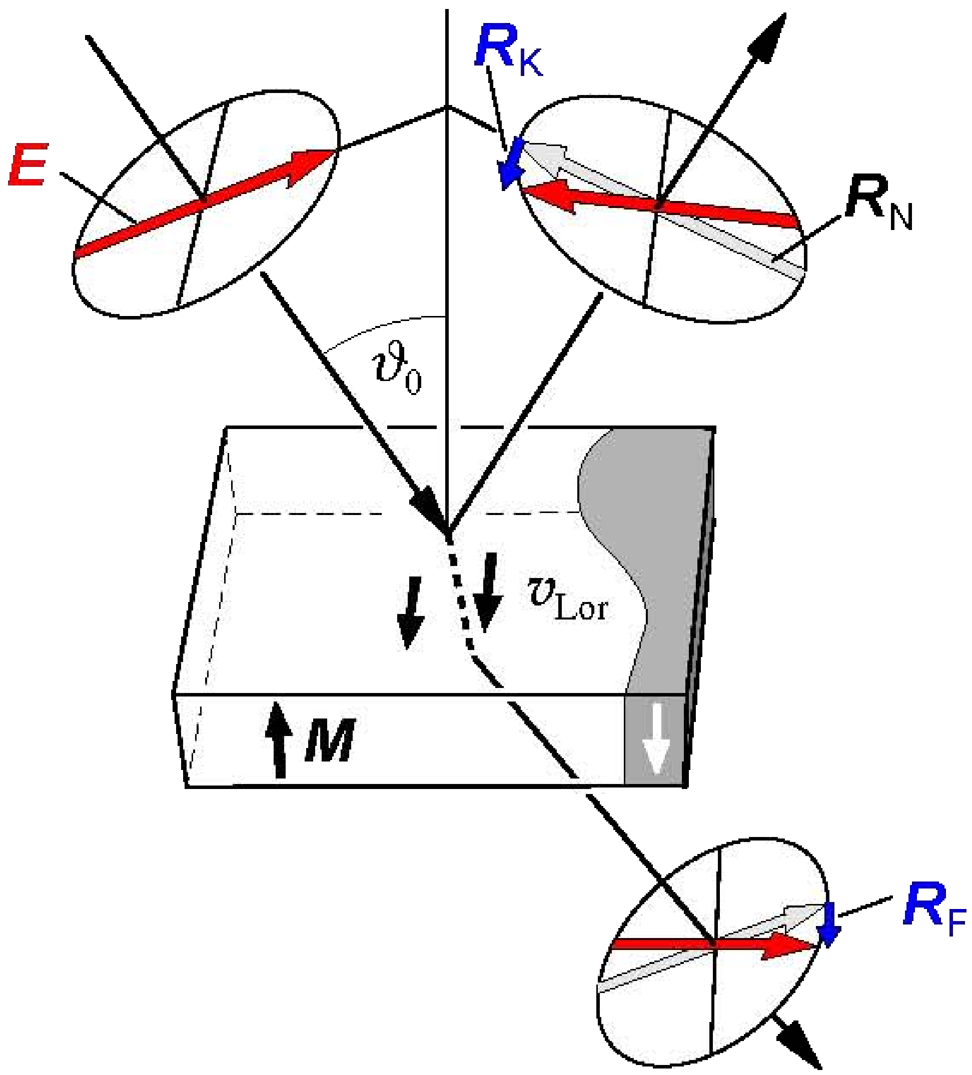


concept of Lorentz force

Overview - Kerr and Faraday

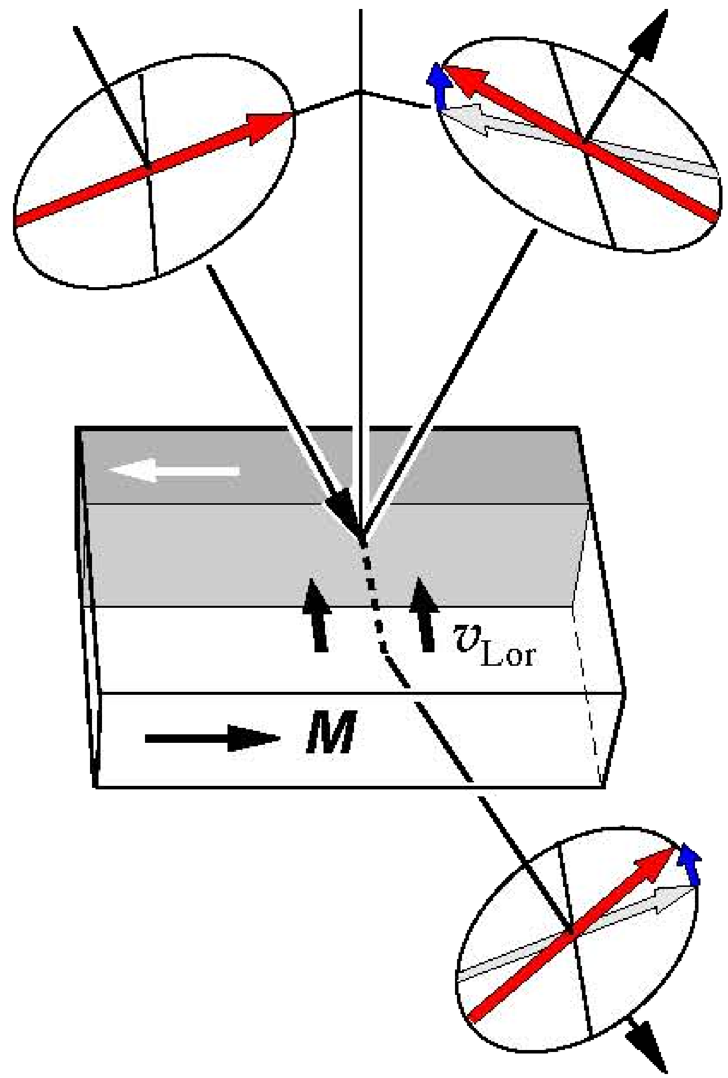
from A. Hubert, R. Schäfer; Magnetic domains ...

polar ||



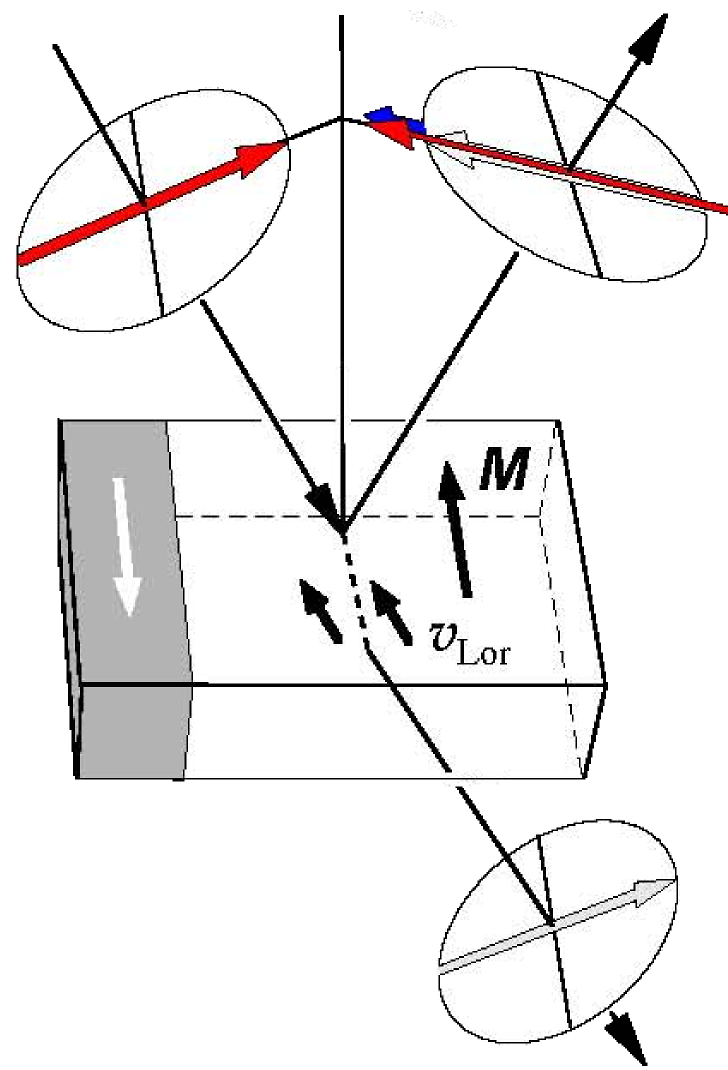
out-of plane sensitivity

longitudinal ||



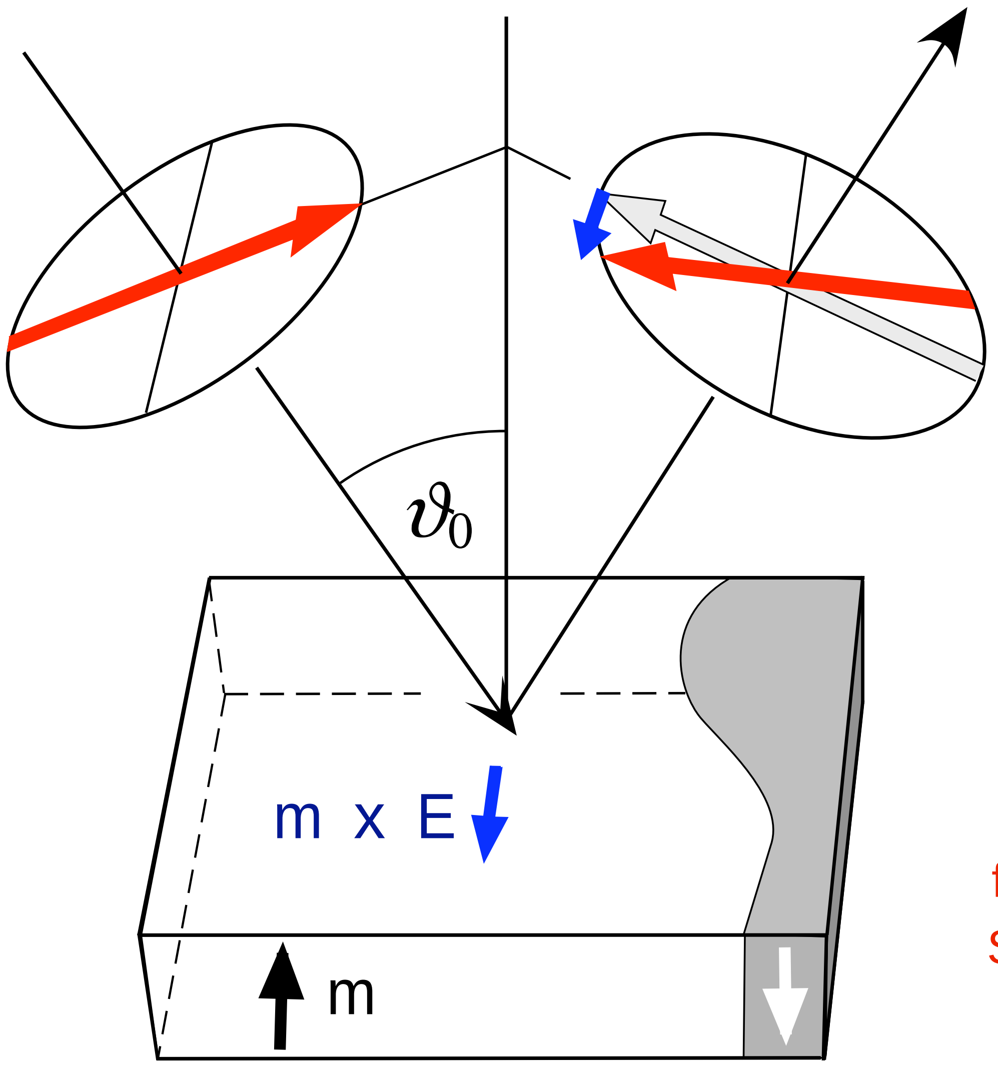
out-of plane sensitivity +
in-plane sensitivity

transverse



in-plane sensitivity

Polar Kerr effect

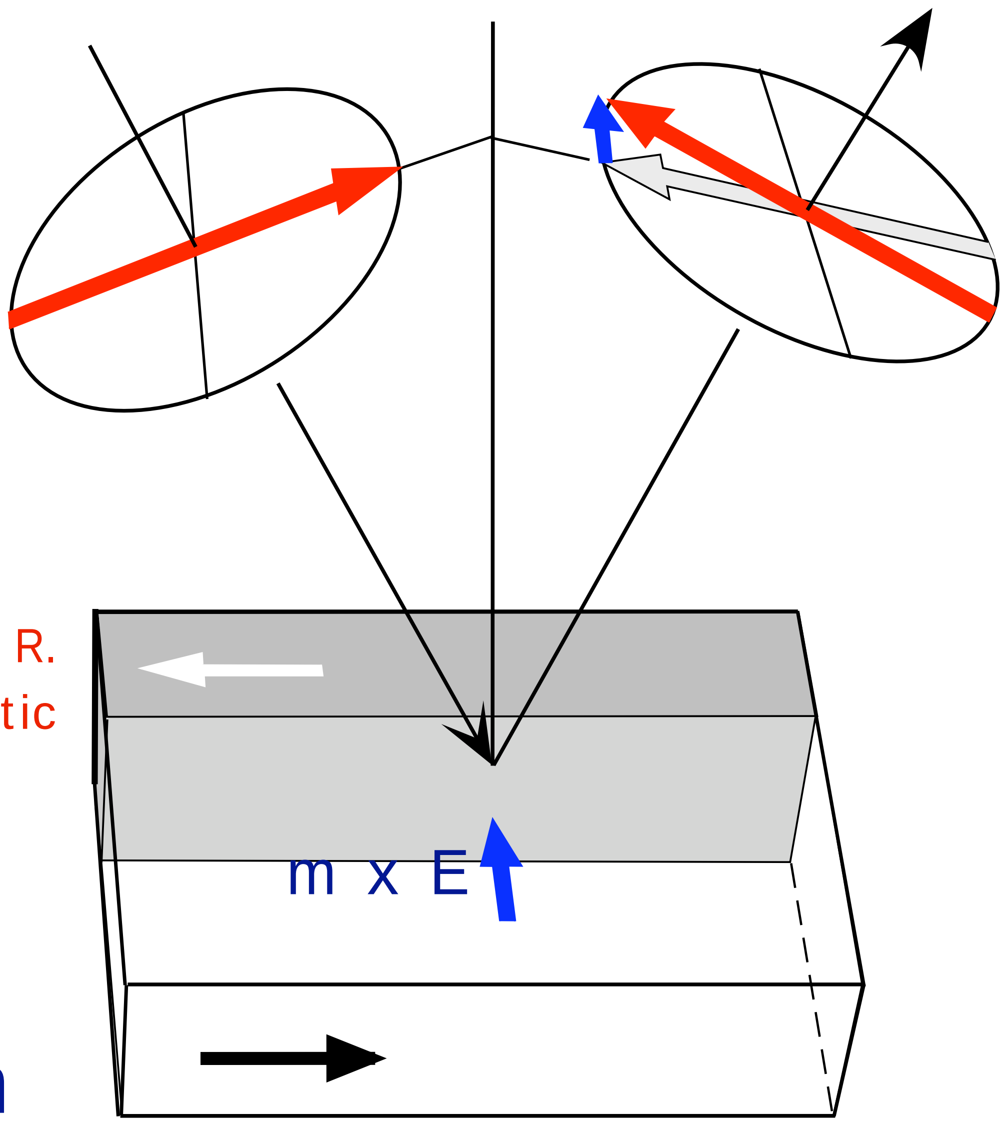


from A. Hubert, R. Schäfer; Magnetic domains ...

- perpendicular illumination
- sensitive to polar or out-of-plane magnetization component m

Longitudinal Kerr effect

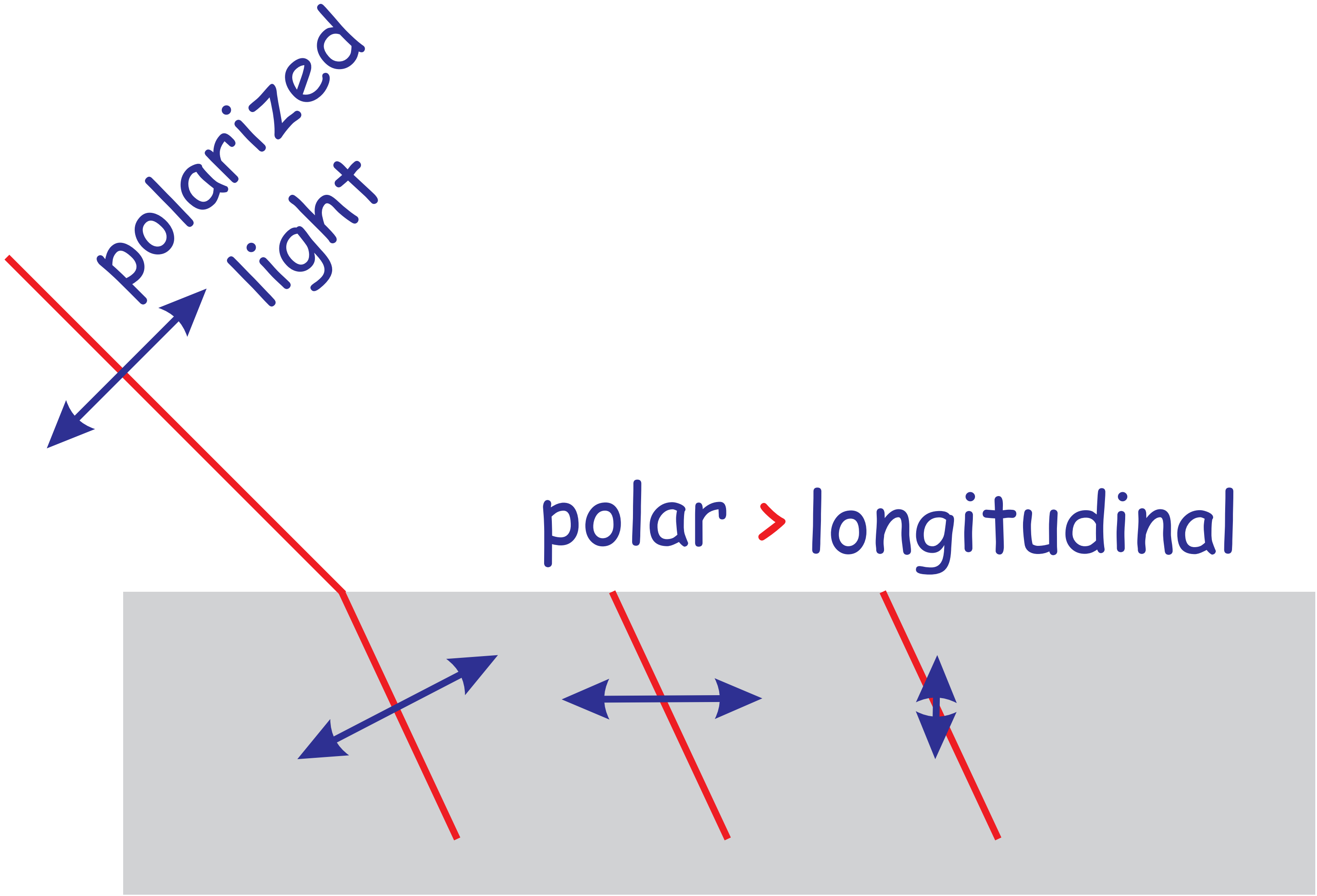
note:
still polar
effect
included



from A. Hubert, R. Schäfer; Magnetic domains ...

- non-perpendicular illumination
- oblique plane of incidence
- sensitive to magnetization component m parallel plane of incidence

Out-of-plane vs. in-plane sensitivity

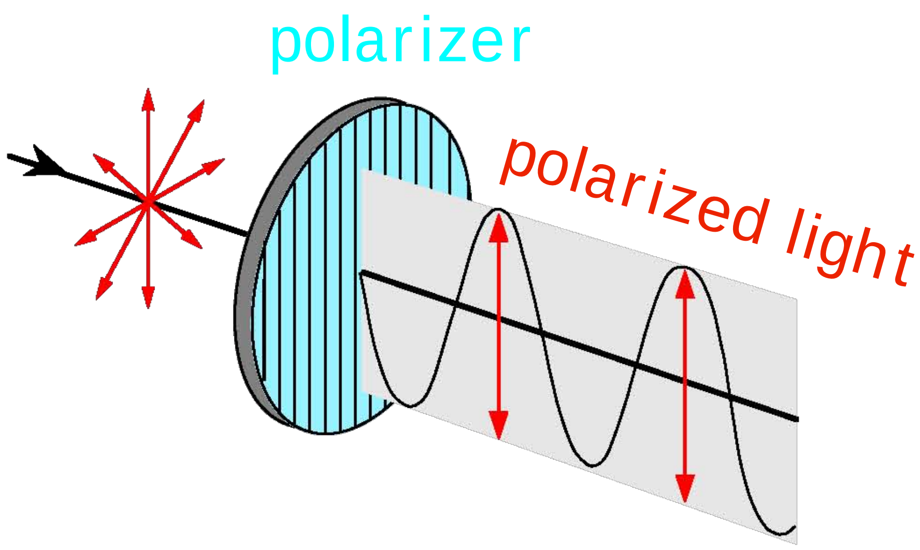


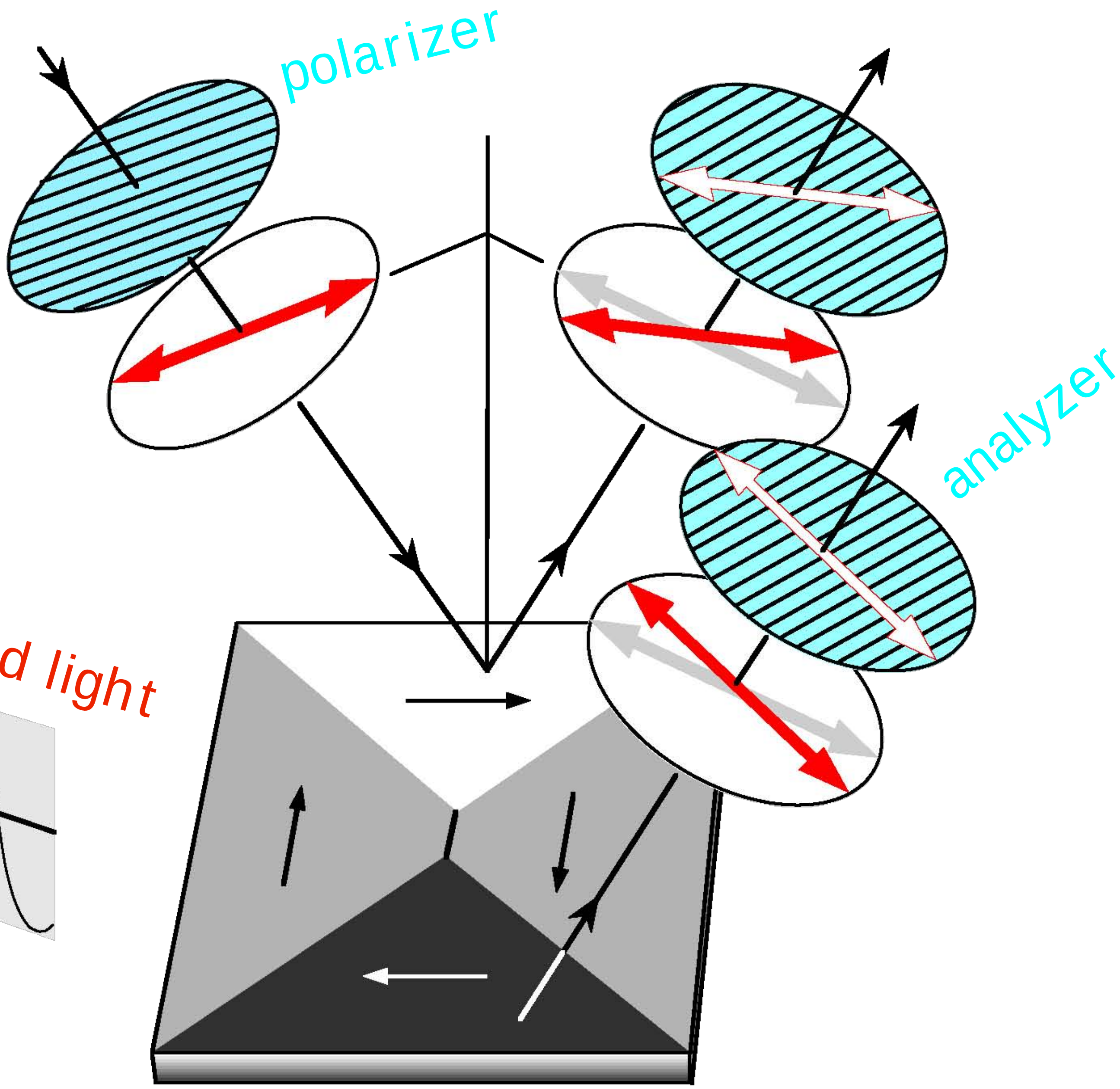
- $M_{polar} \times E > M_{longitudinal} \times E$
- diffraction index $n_{Metal} \approx 3$ (Fe)

➡ polar magnetization much easier to measure

Practical MOKE (longitudinal Kerr effect)

- detection of change of polarization

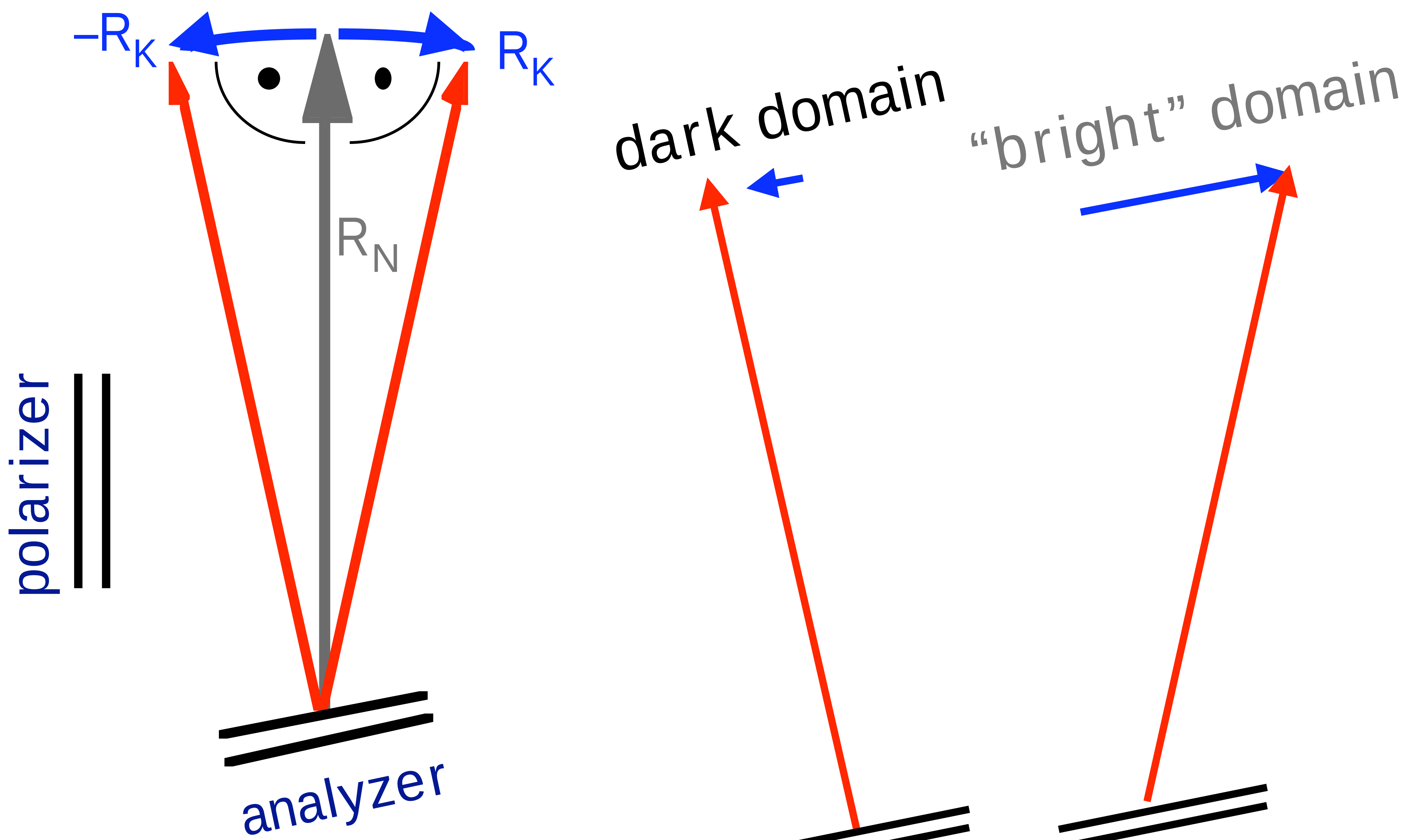




adapted from R. Schäfer

- goal...
  - domain contrast
  - ➡ f(analyzer setting)

Detection (wide-field microscopy)



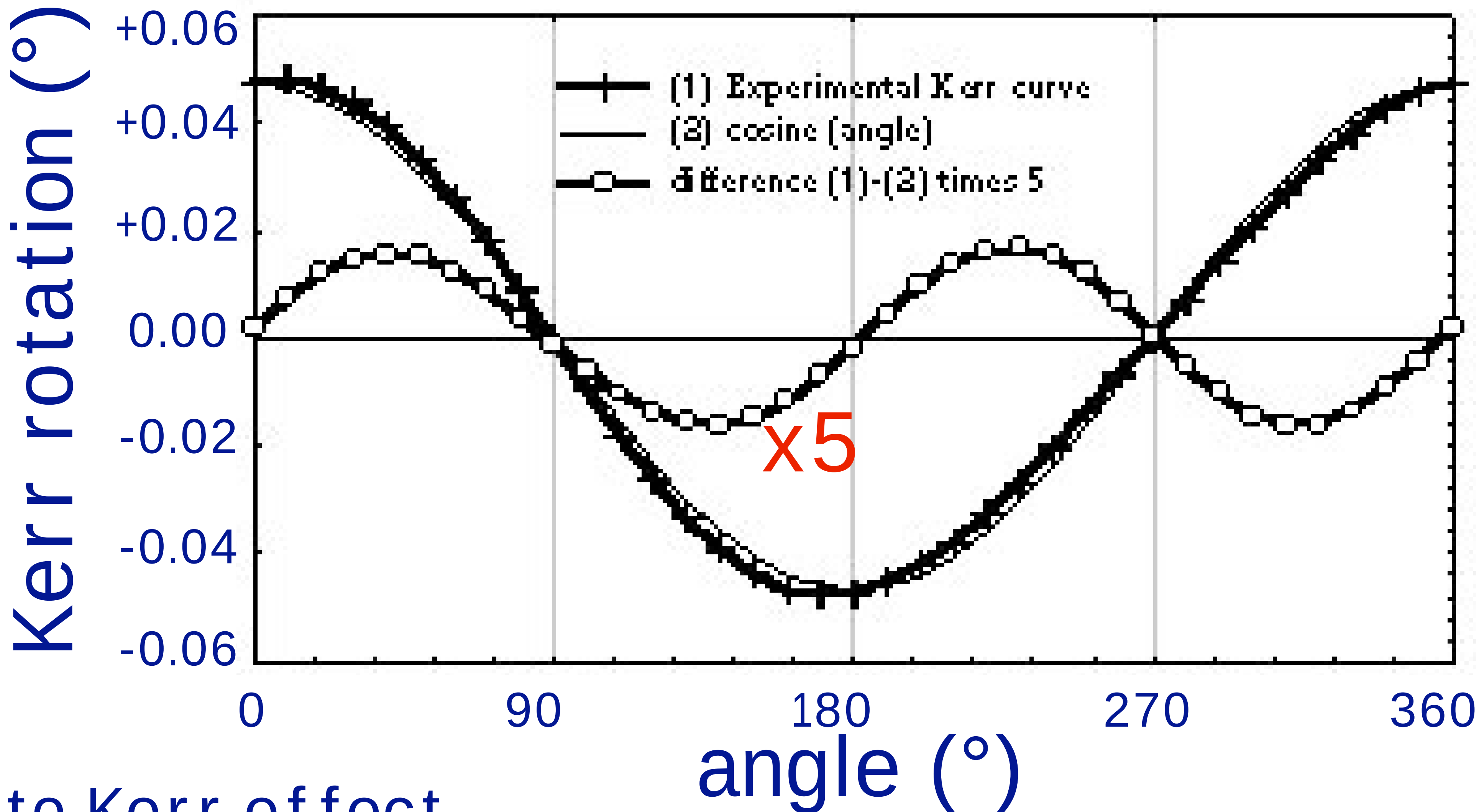
f(analyzer setting)

- analyzer not perpendicular to polarizer

➡ domain contrast

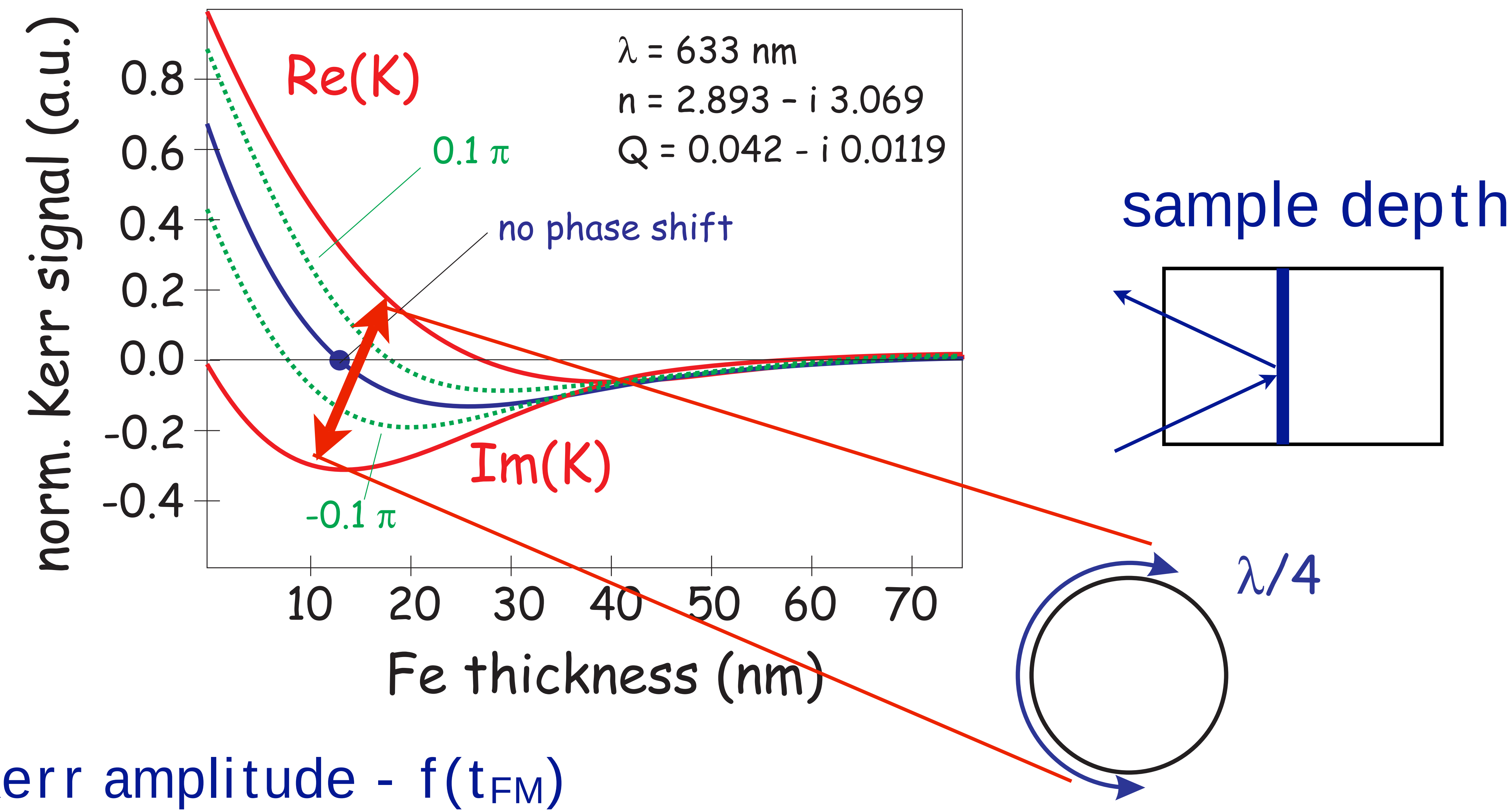
Voigt effect vs. Kerr effect

R. Mattheis, G. Quednau, phys. stat. sol. (a) 172 (1999) r7



- "Add-on" to Kerr effect
  - not easy to separate
  - Voigt signal small relative to Kerr signal (6% from FFT)
- complementary additional information possible

Penetration of light - depth sensitivity



- Kerr amplitude - $f(t_{FM})$
  - depth sensitivity adjustable through phase shift

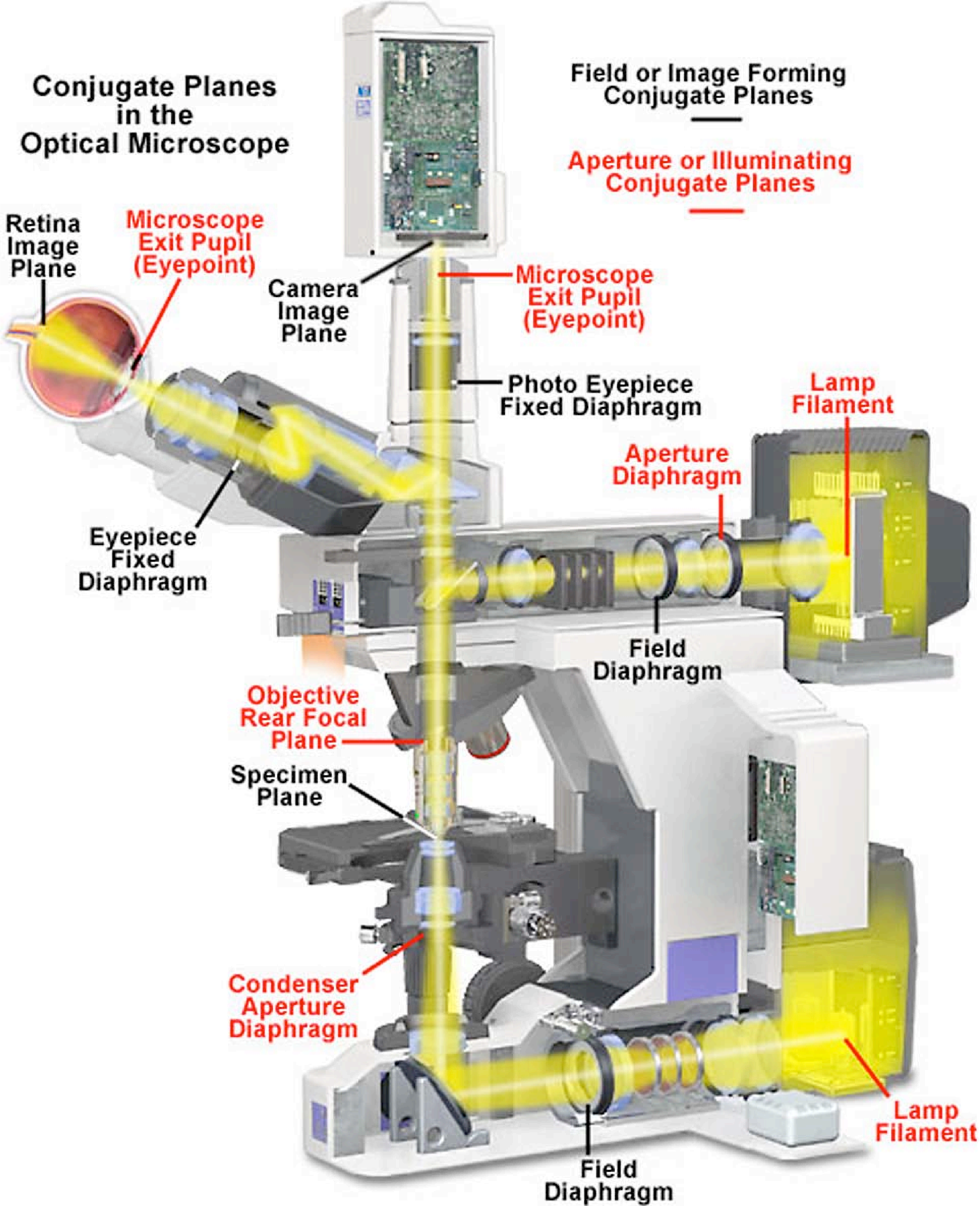
➡ layer sensitive imaging (?)

Summary on magneto-optical effects

- Faraday effect
- magneto-optical Kerr effect - MOKE
  - proportional to (projection of) magnetization
  - in-plane and out-of-plane sensitivity
  - “surface” sensitive (adjustable)
- Voigt effect

Optical microscopy

... microscope schemes and resolution ...



Wide-field microscope

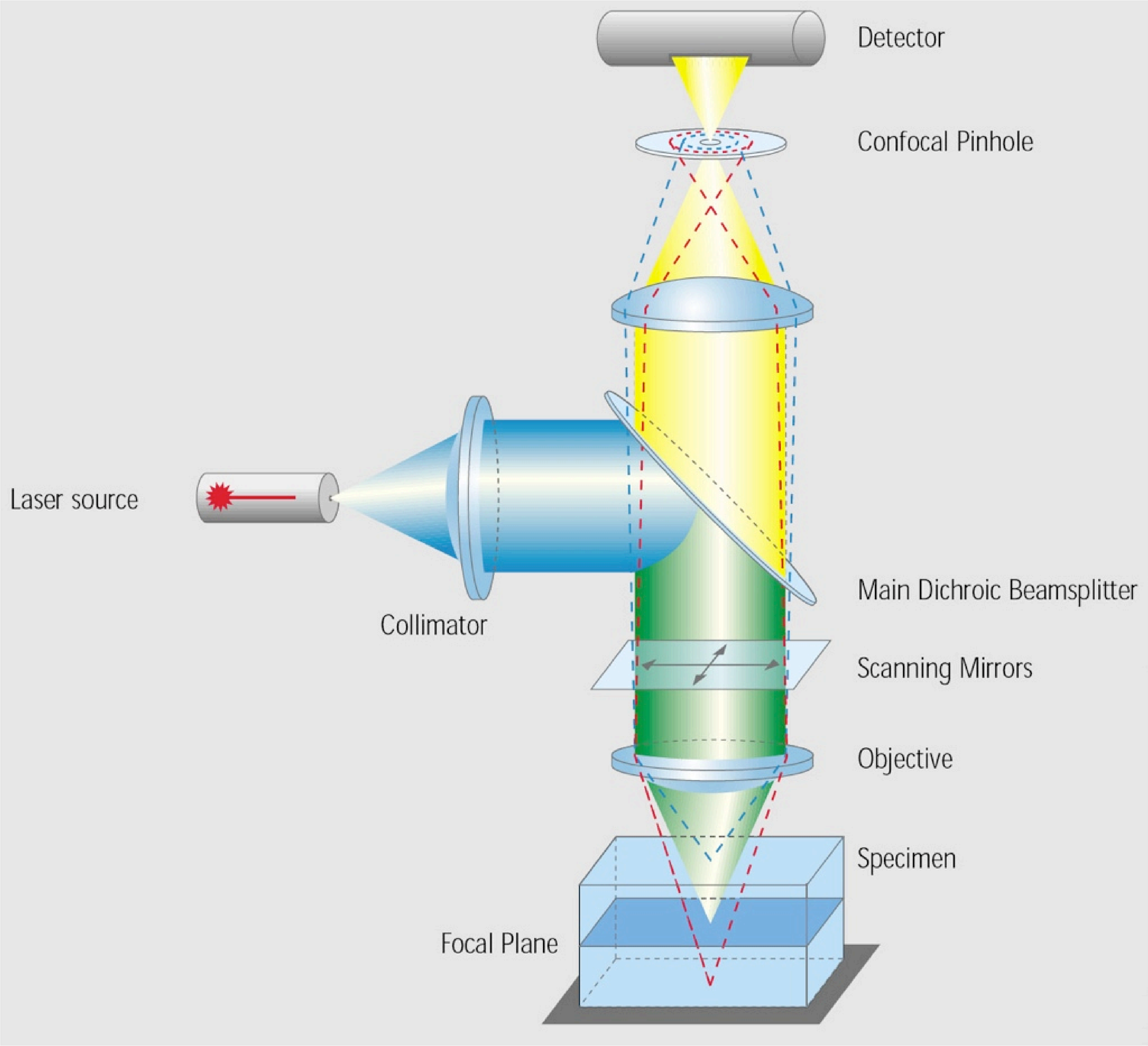
polarization elements missing

- 1-step image acquisition
- camera based

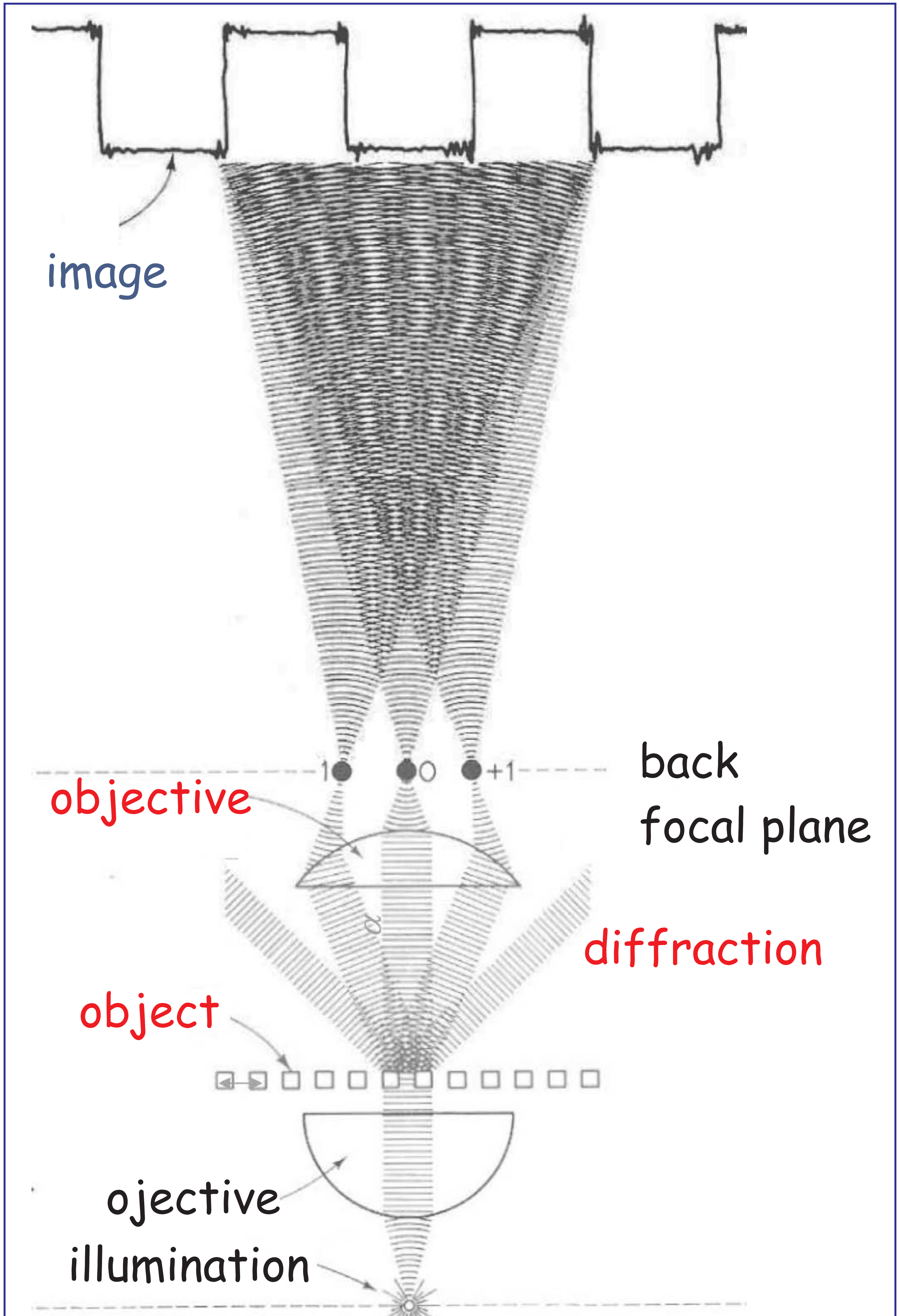
www.nikon.com

Scanning microscopy

- “step-by step” image acquisition
- resolution determined also by scanning procedure
- wide range of detectors possible



www.zeiss.com

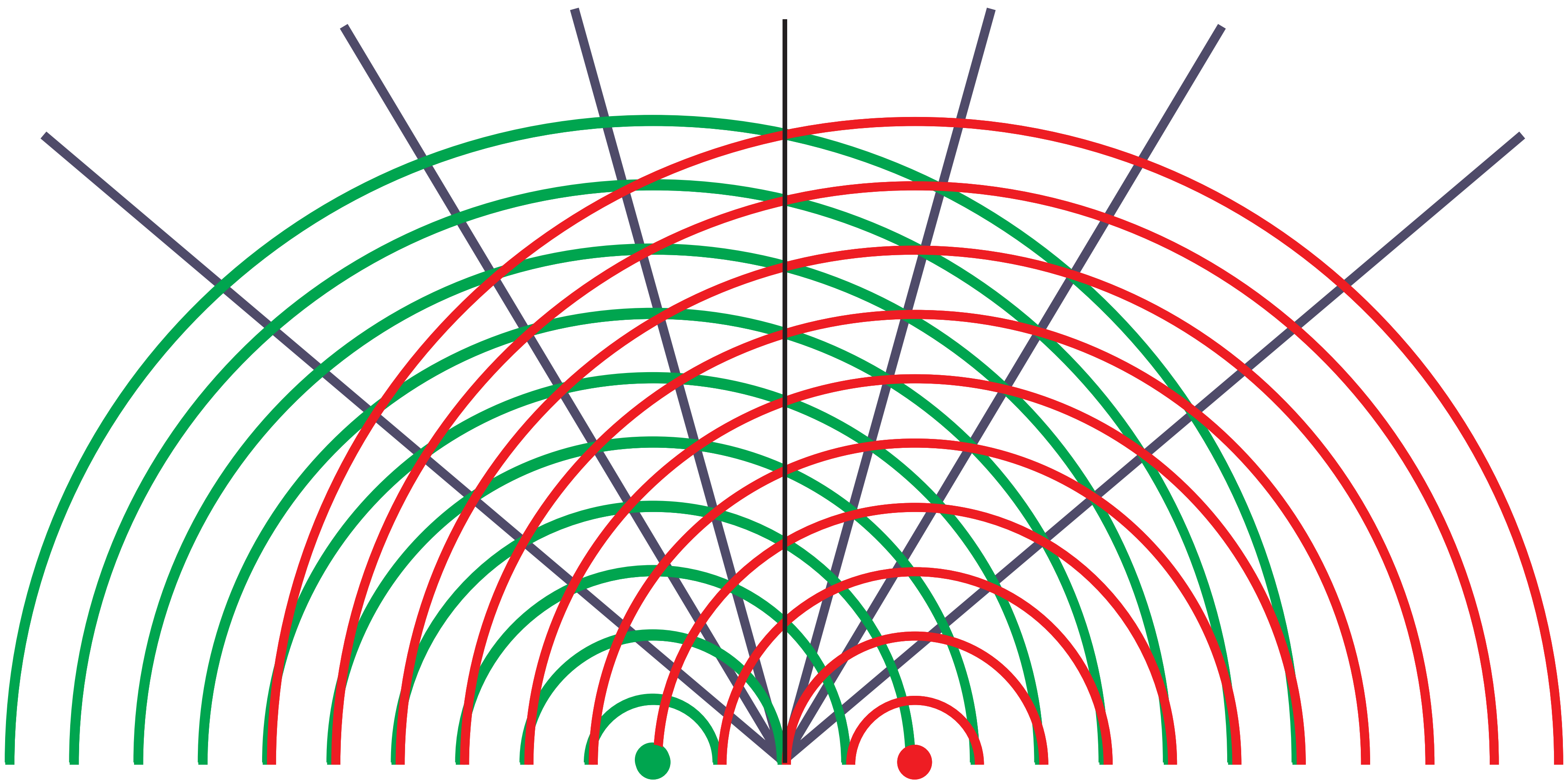


On the resolution of optical microscopy

(E. Abbe, 1840-1905)

- diffraction limited image formation
- resolution determent by the constructive interference
- diffraction limited
  - f(λ)
  - f(opening of objective)

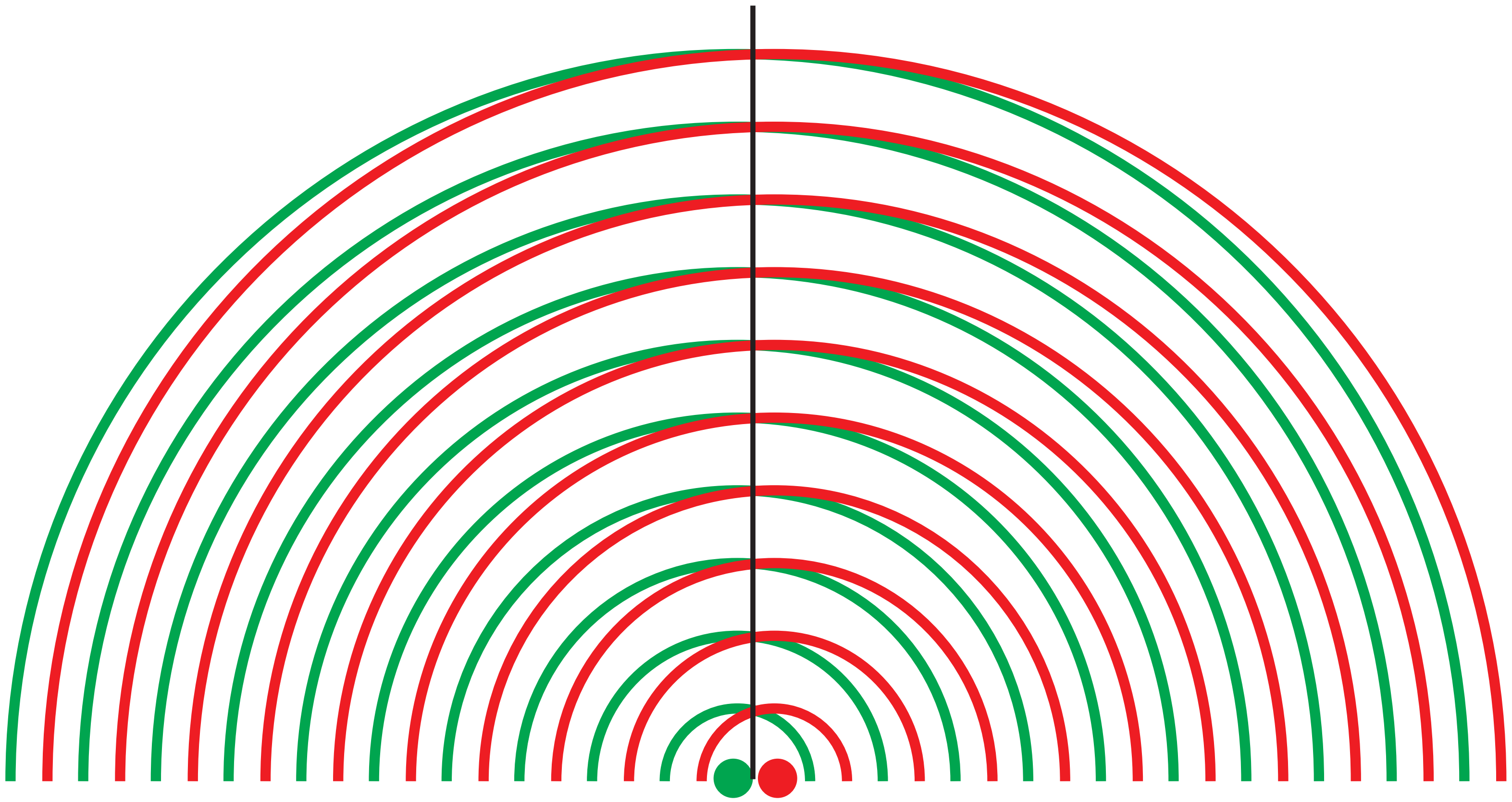
Lateral resolution - diffraction limited



object 1 + object 2

- distance > λ
- constructive interference

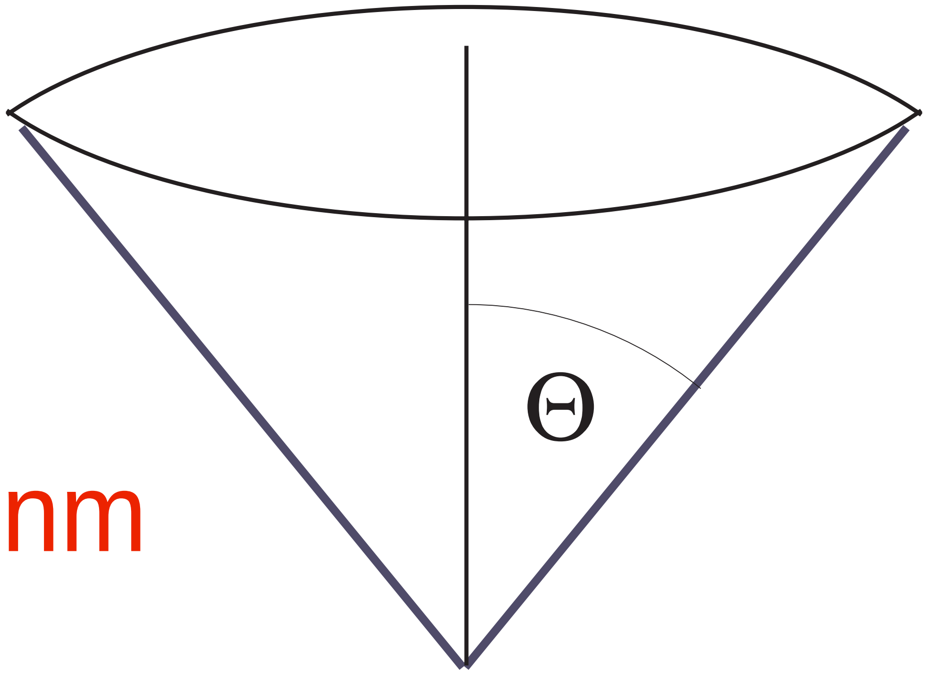
Lateral resolution - diffraction limited



- narrowing of object 1 + object 2
- reduction of diffraction maxima
- limited through λ and opening

Lateral resolution of a microscope

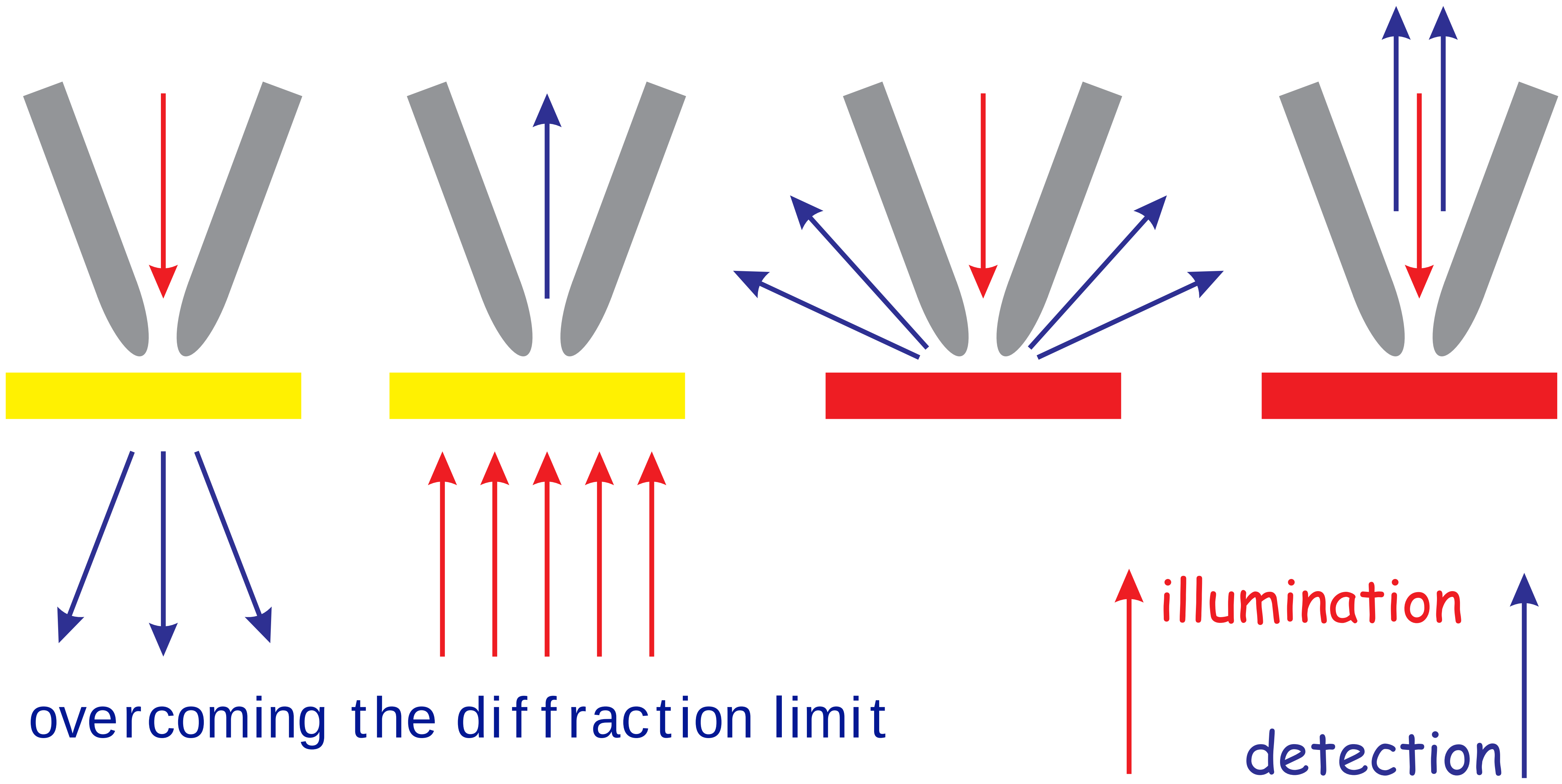
$$D \approx \frac{\lambda}{2 \cdot n \cdot \sin\Theta} = \frac{\lambda}{2 \cdot NA}$$



D ≈ 200 nm

- D: lateral resolution
- λ: wavelength of imaging radiation
- n: index of refraction of medium between point source and lens, relative to free space
- Θ: half the angle of the cone of light from specimen plane accepted by the objective
- n sin Θ is expressed as NA (numerical aperture)

Near field imaging (SNOM)



- overcoming the diffraction limit
  - e.g. aperture-type SNOM
  - resolution ≈ nm (demonstrated 100 nm)

(will not be further treated in this talk)

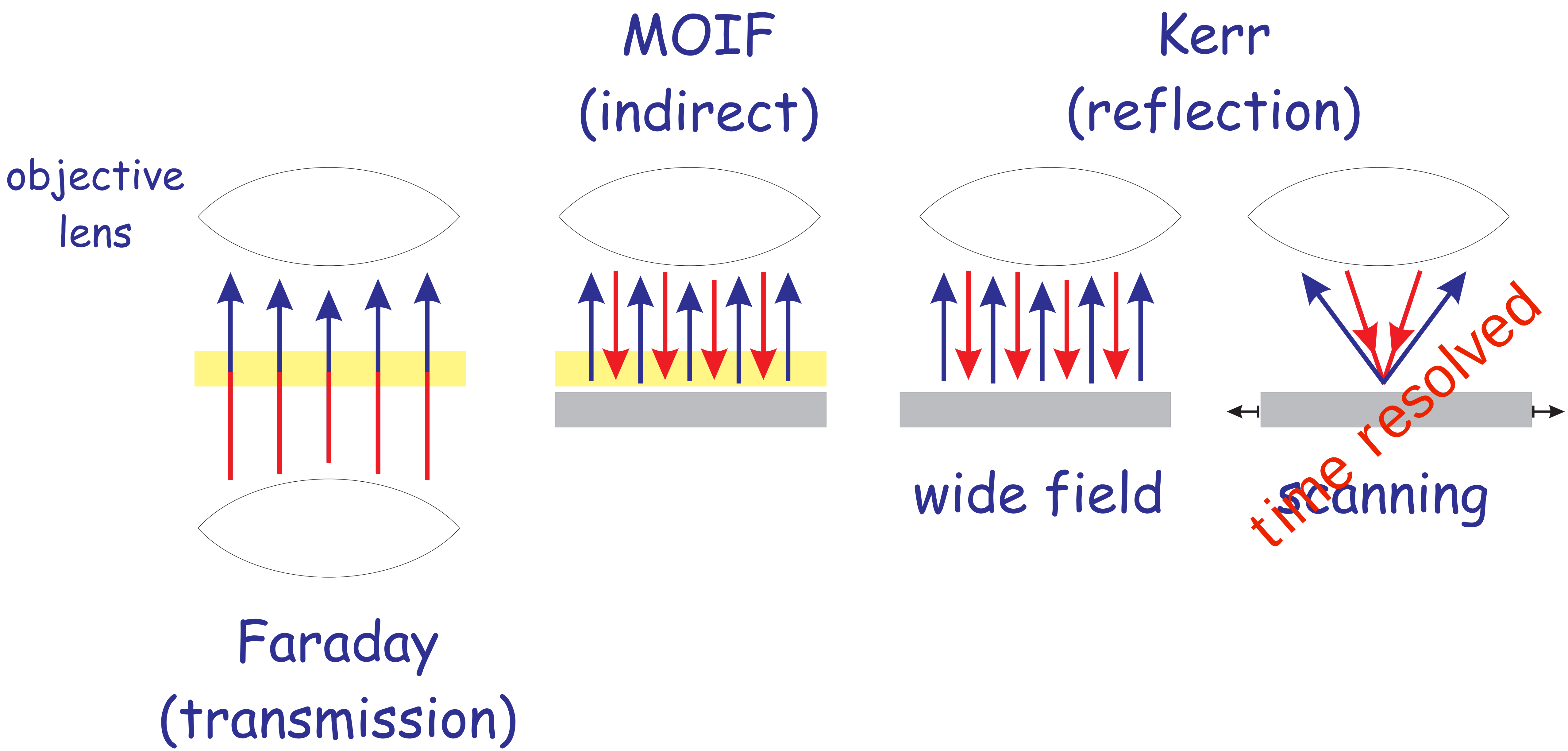
Summary on optical microscopy

- 2 types
  - wide-field microscope
  - scanning microscope
- resolution limited through (magnification not important)
  - wavelength λ
  - NA of objective
  - n (1.5 for immersion objectives)
  - best around 200 nm

Practical magneto-optical microscopy

... wide (bright) field imaging ...

Overview

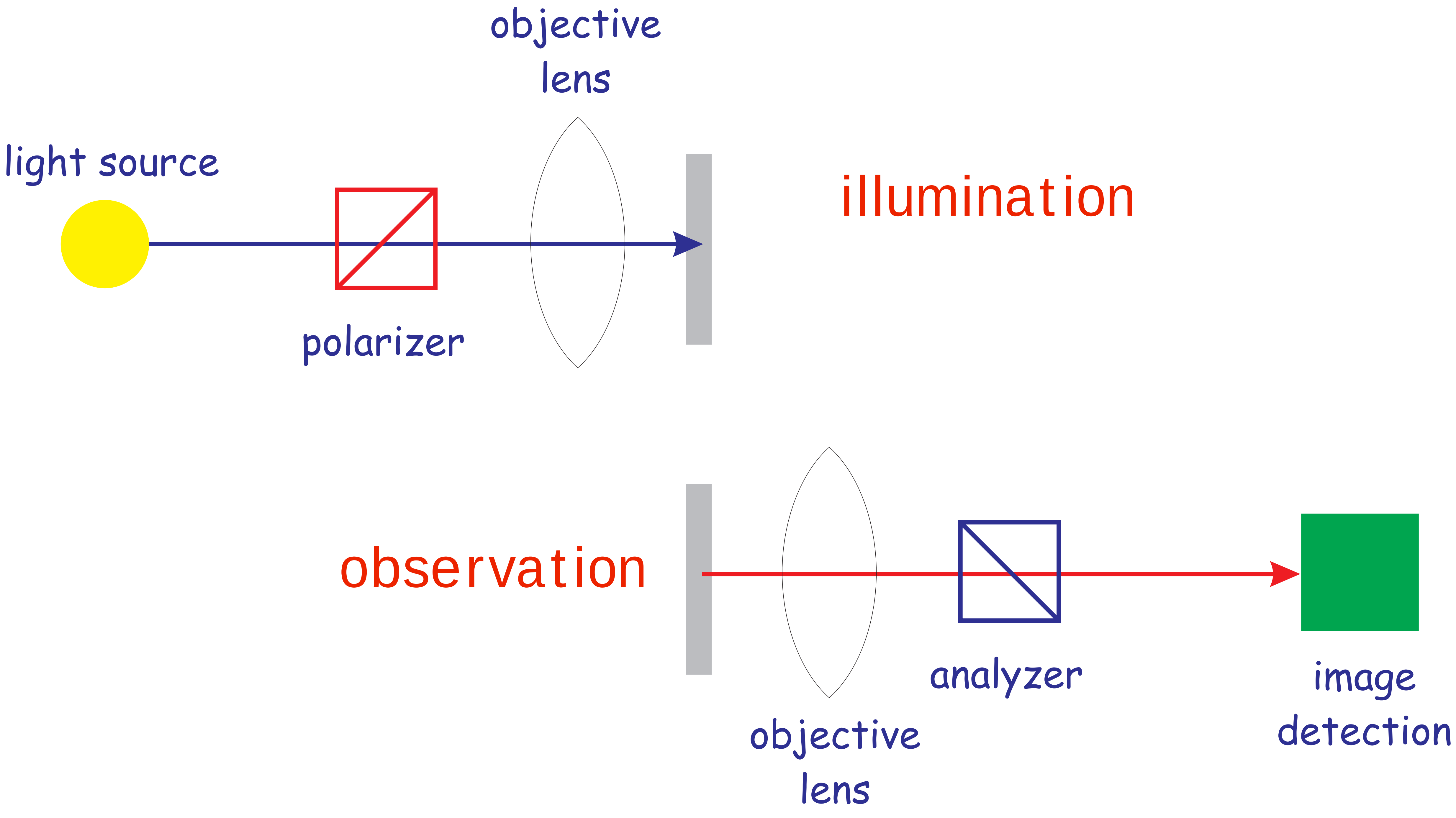


- different types of magneto-optical microscopy

“Ingredients”

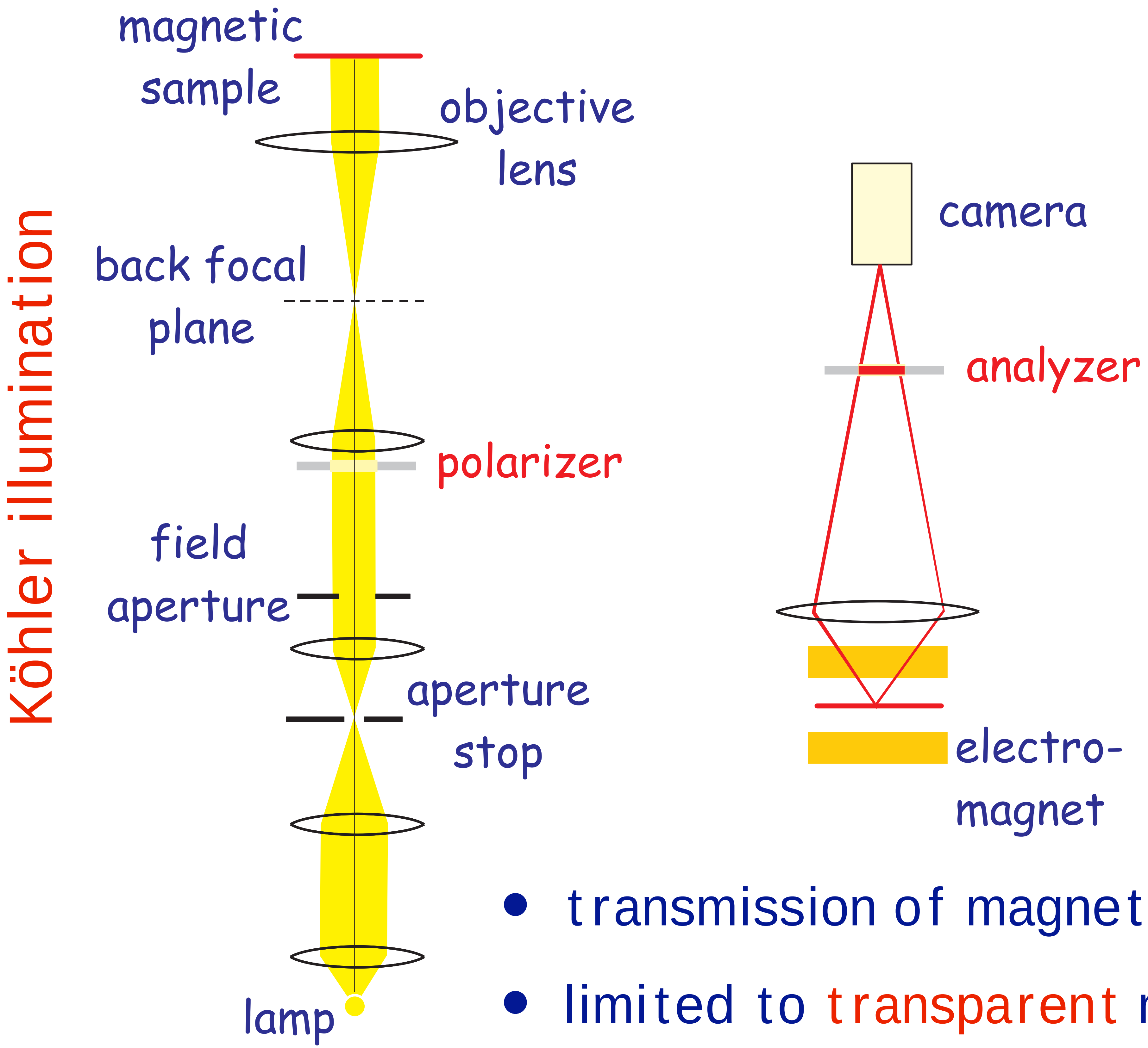
- (high intensity) light source
- polarized light
  - polarizer or polarized light source
  - analyzer
- imaging optics
  - objective lens
  - polarization microscope
- image detection
  - photo diode (scanning)
  - camera system

Common elements - wide field imaging



(very simple) - polarization optics

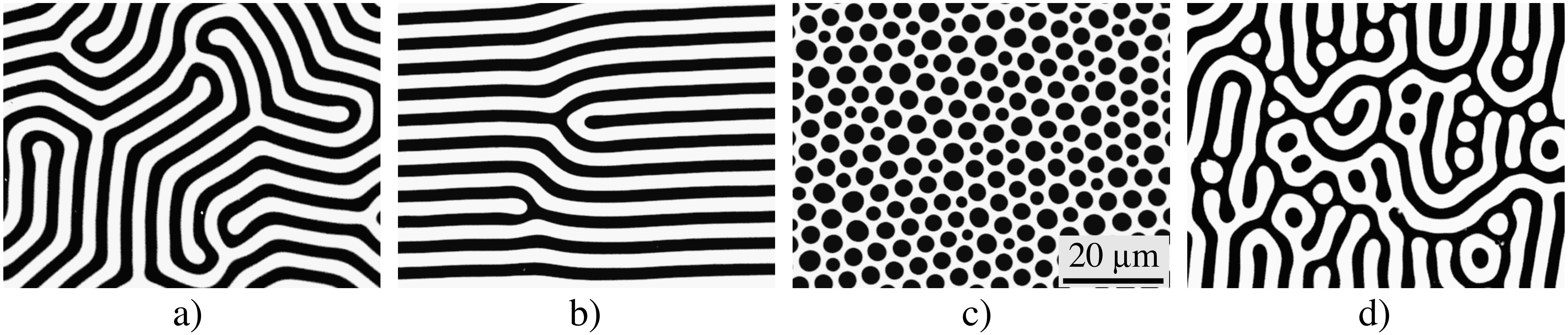
Faraday microscopy



- transmission of magnetic sample
- limited to transparent magnetic materials

Faraday example - garnet film

from A. Hubert, R. Schäfer; Magnetic domains ...



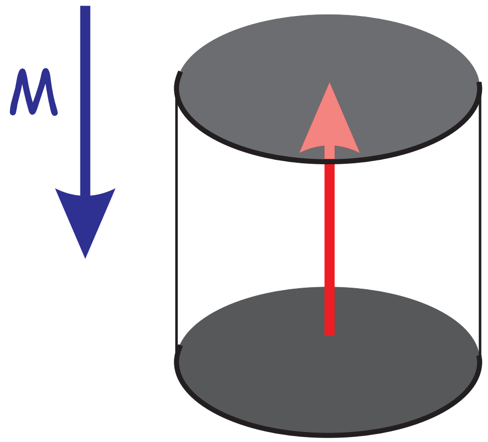
- polar sensitivity, perpendicular anisotropy
- meta-stable domain structure dependent on magnetic history

a) 90° (in-plane) - maze pattern

b) 20° - band domains

c) 1° - bubble lattice

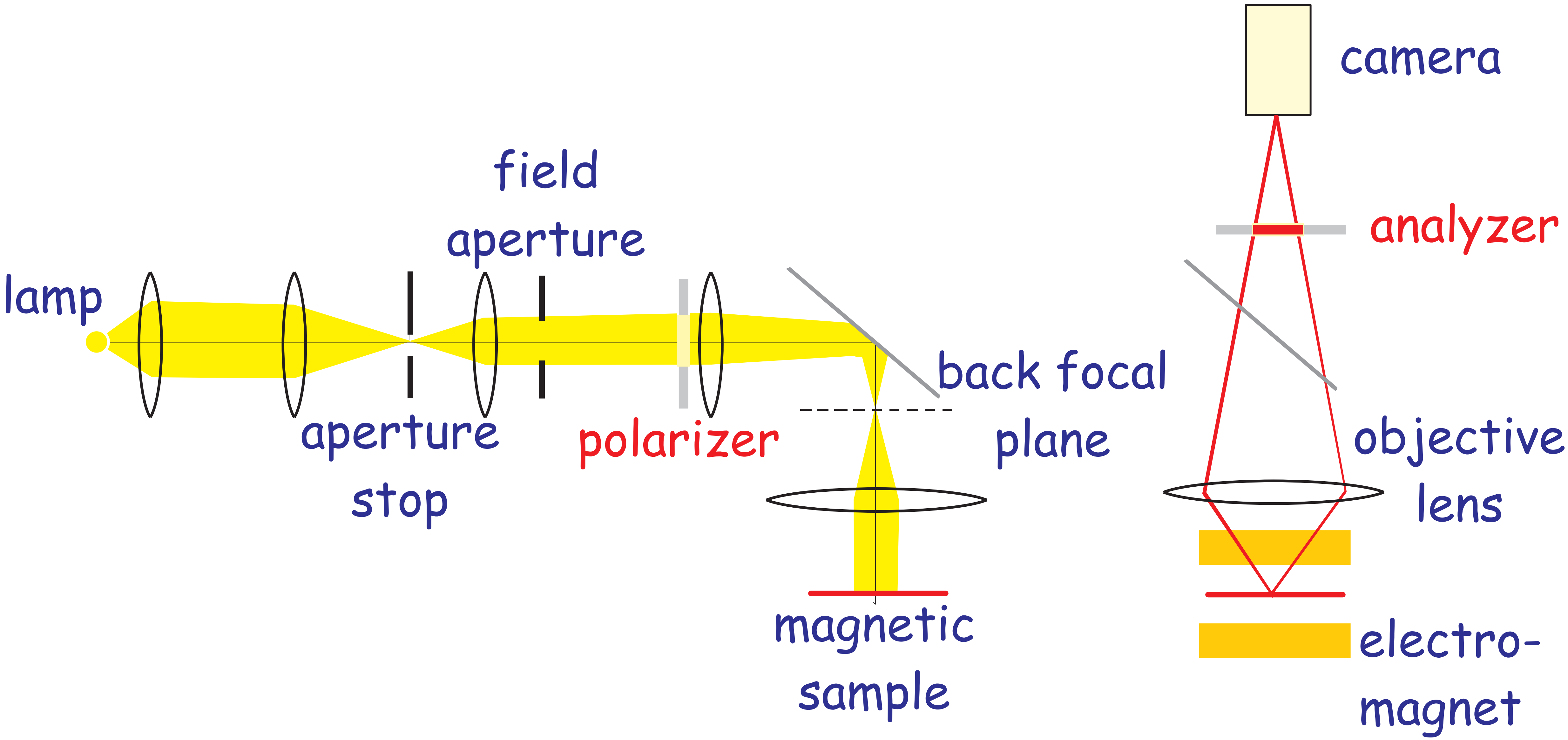
d) 0° - mixed pattern



Summary on Faraday microscopy

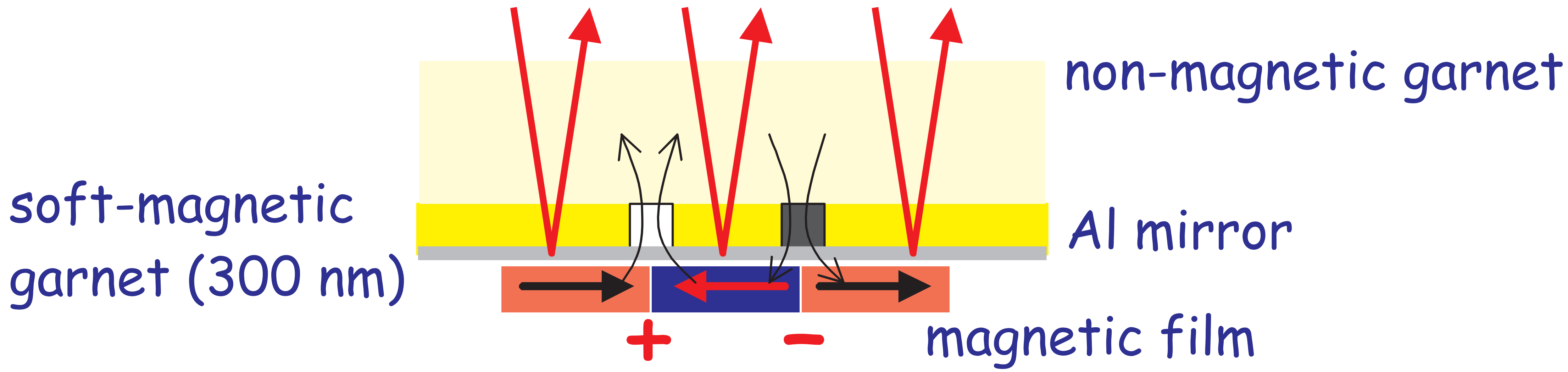
- direct method
  - limited to optical transparent materials (transmission)
  - averages over sample thickness
    - low lateral resolution
  - used as indicator film (next...)

Magneto-optical indicator film (MOIF)



- reflection - non-transparent samples (magnetic thin films)
- indirect method - use of garnet film as an indicator of magnetic stray fields

Magneto-optical indicator film (MOIF)

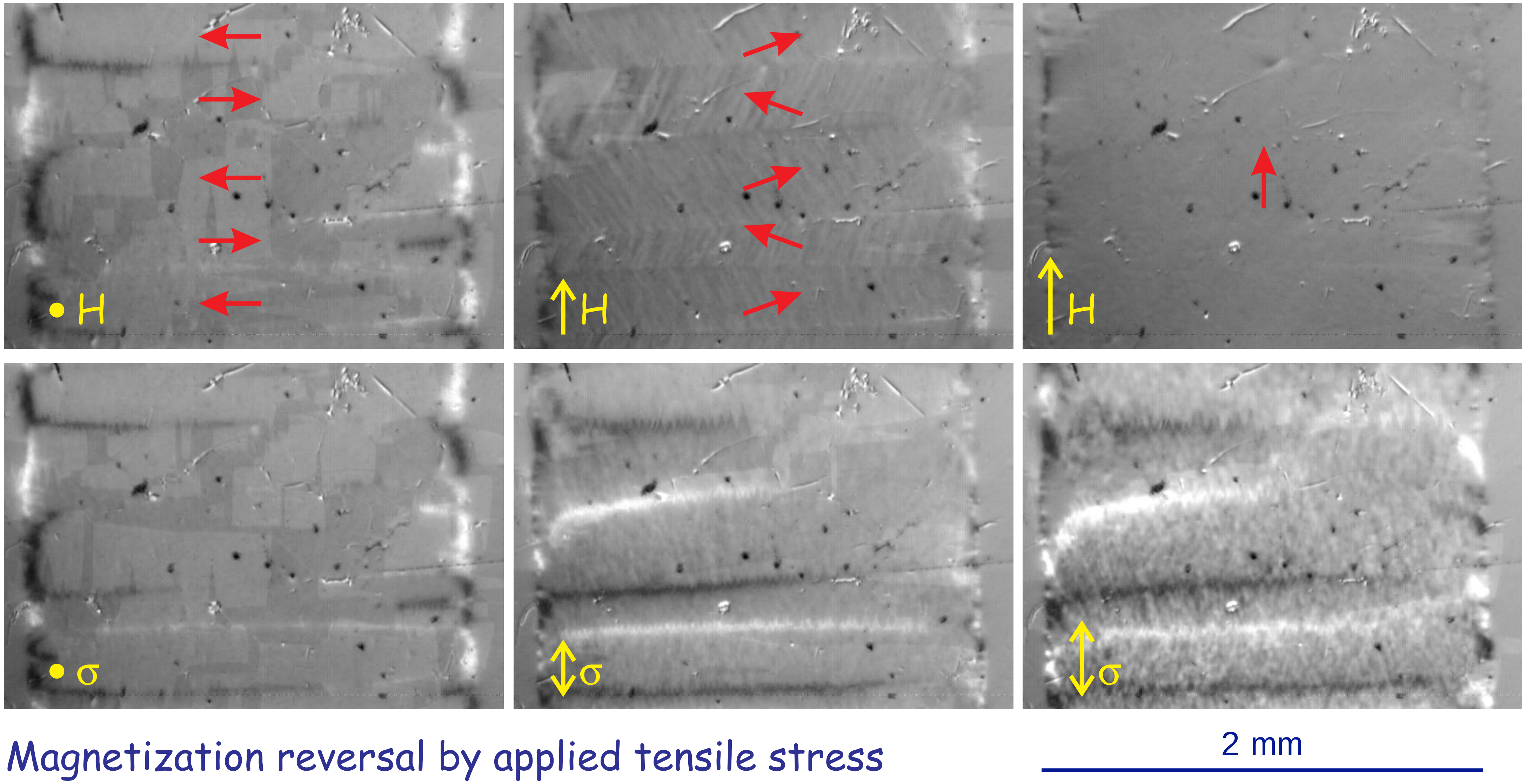


- transparent magnetic garnet film (thick, epitaxial grown on non-magnetic garnet film)
- Al mirror due to reflection mode
- imaging of magnetic charges
  - domain walls or “ripple” in thin films
  - patterned magnetic samples

MOIF - imaging of magneto-elastic films

images courtesy E. Quandt, CAESAR

Magnetization reversal by magnetic field

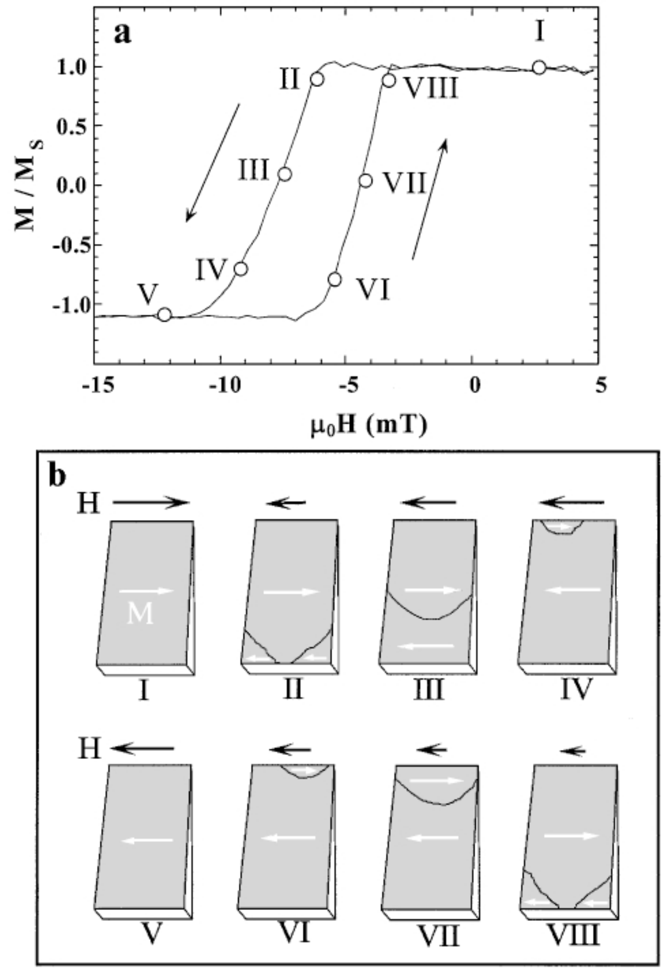


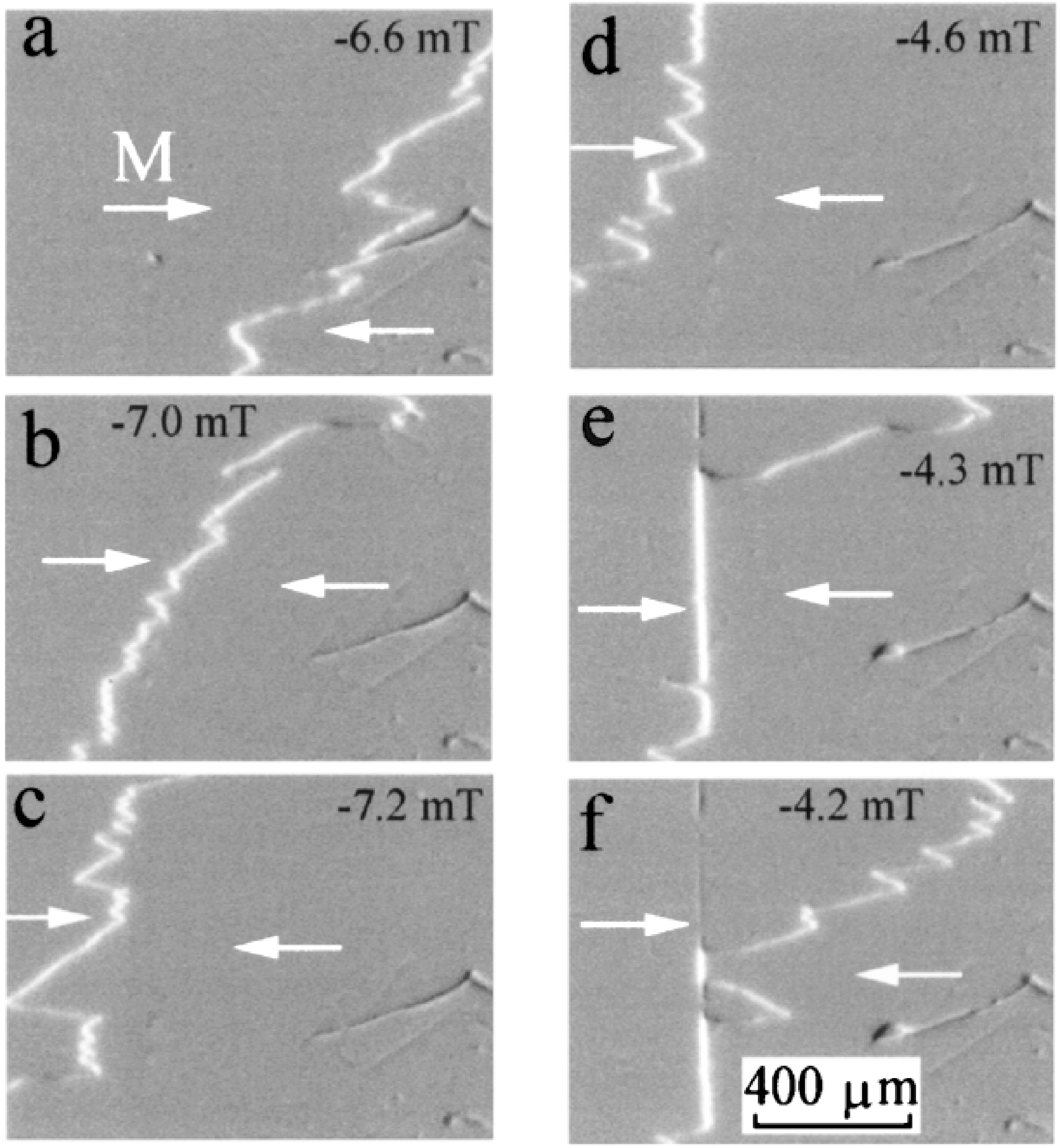
Magnetization reversal by applied tensile stress

- magnetization reversal of TbFe/FeCo multilayers by magnetic field H and applied tensile stress σ
  - ripple and domain wall visible

MOIF - exchange biased films

V. Nikitenko et al., Phys Rev. Lett. 84 (4), 765-768 (2000)





III (a) – (c)

VII (d) – (f)

- $Ni_{81}Fe_{19}$-$Fe_{50}Mn_{50}$ (11 nm ... 18 nm/ 30 nm)
- asymmetric domain nucleation and movement for forward and backward loop branch

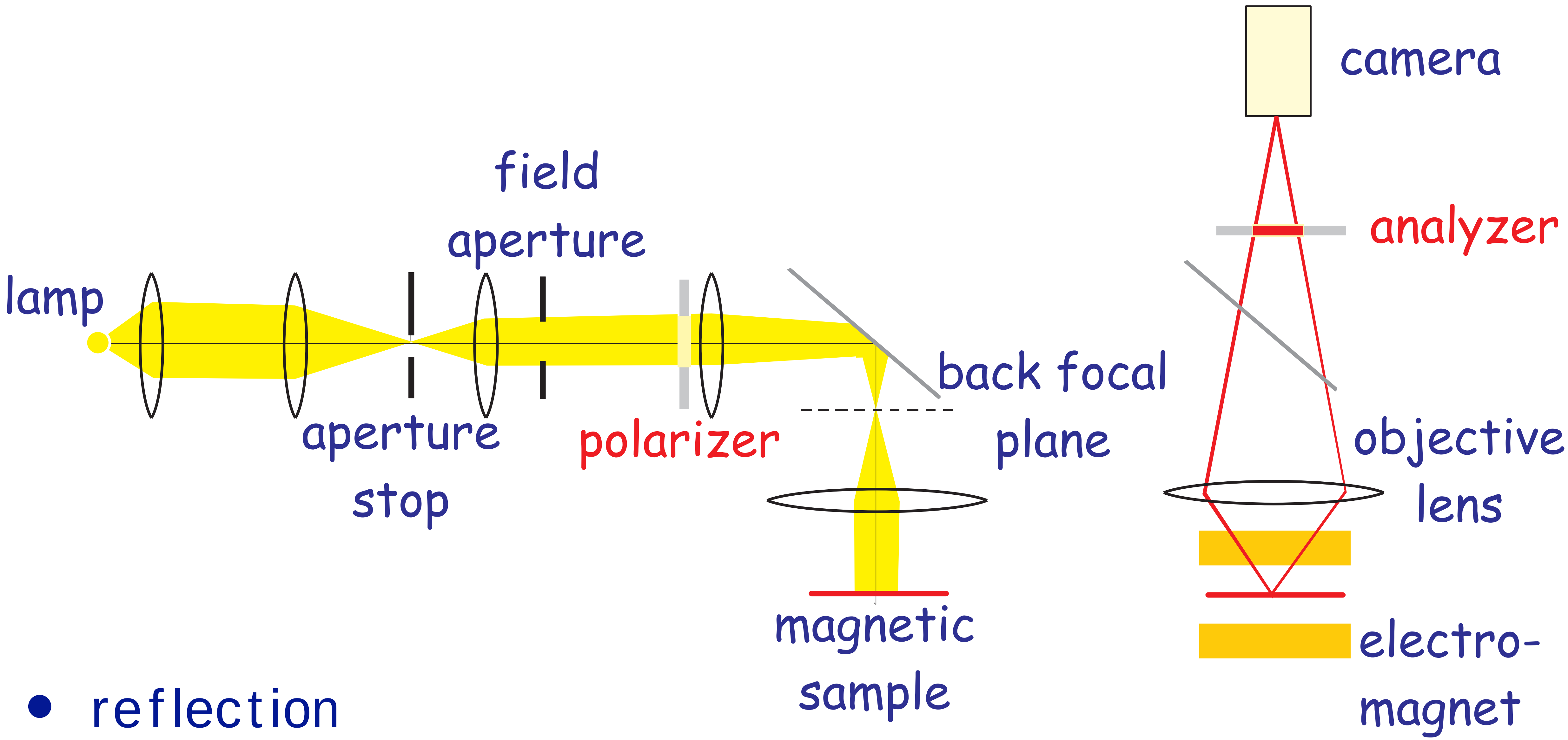
Summary on MOIF

- indirect method
  - detection of magnetic charges of ferromagnetic material's surface
  - metalized transparent epitaxial garnet layer as detection film
  - low resolution due to thickness of garnet film and "micromagnetic" feature size in garnet

Practical wide-field Kerr microscopy

... shining light on magnetic metals ...

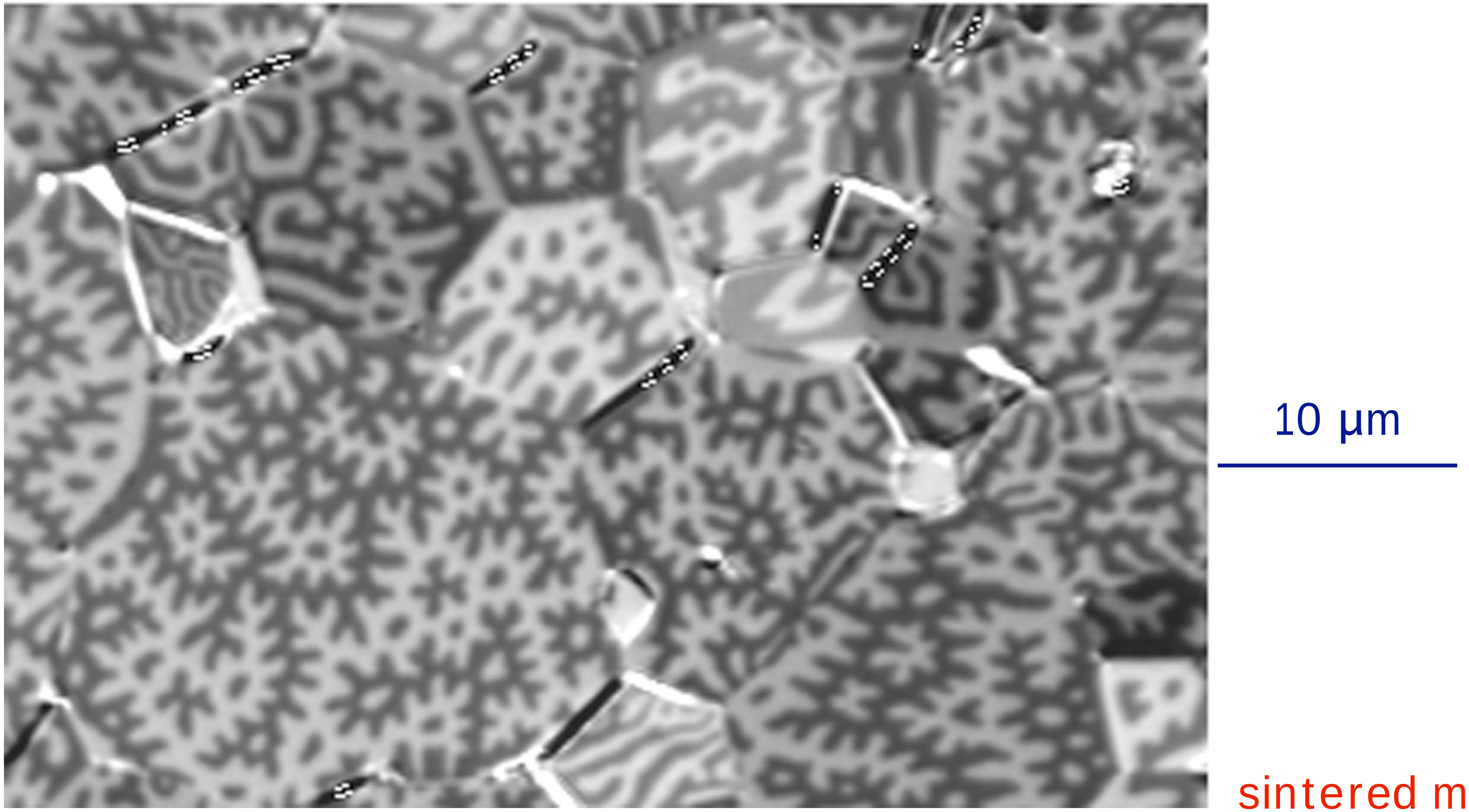
Illumination path (polar)



- reflection
  - non-transparent samples from bulk to thin films
- perpendicular incidence of light
- direct method - surface imaging

Example polar image (textured $Nd_2Fe_{14}B$)

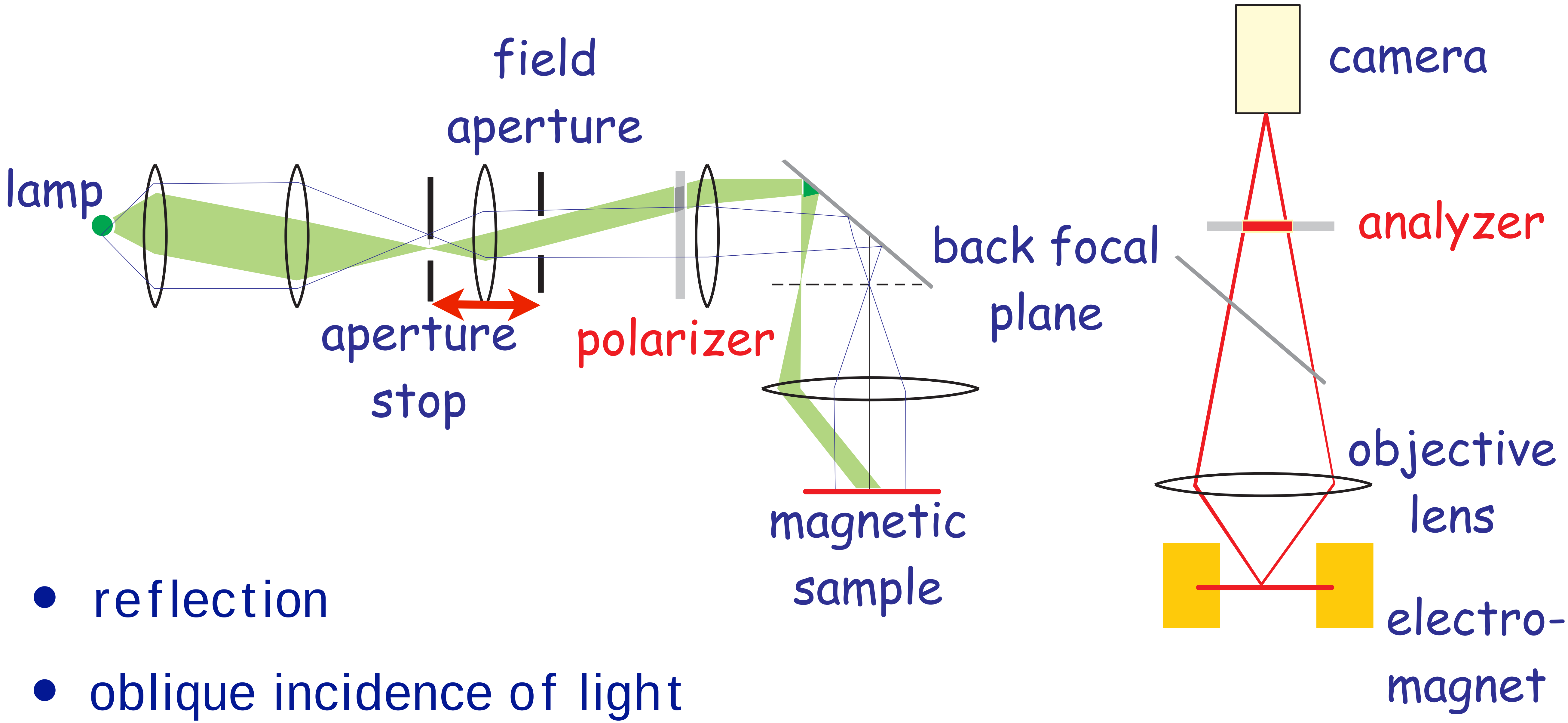
images courtesy O. Gutfleisch, IFW Dresden



sintered magnet

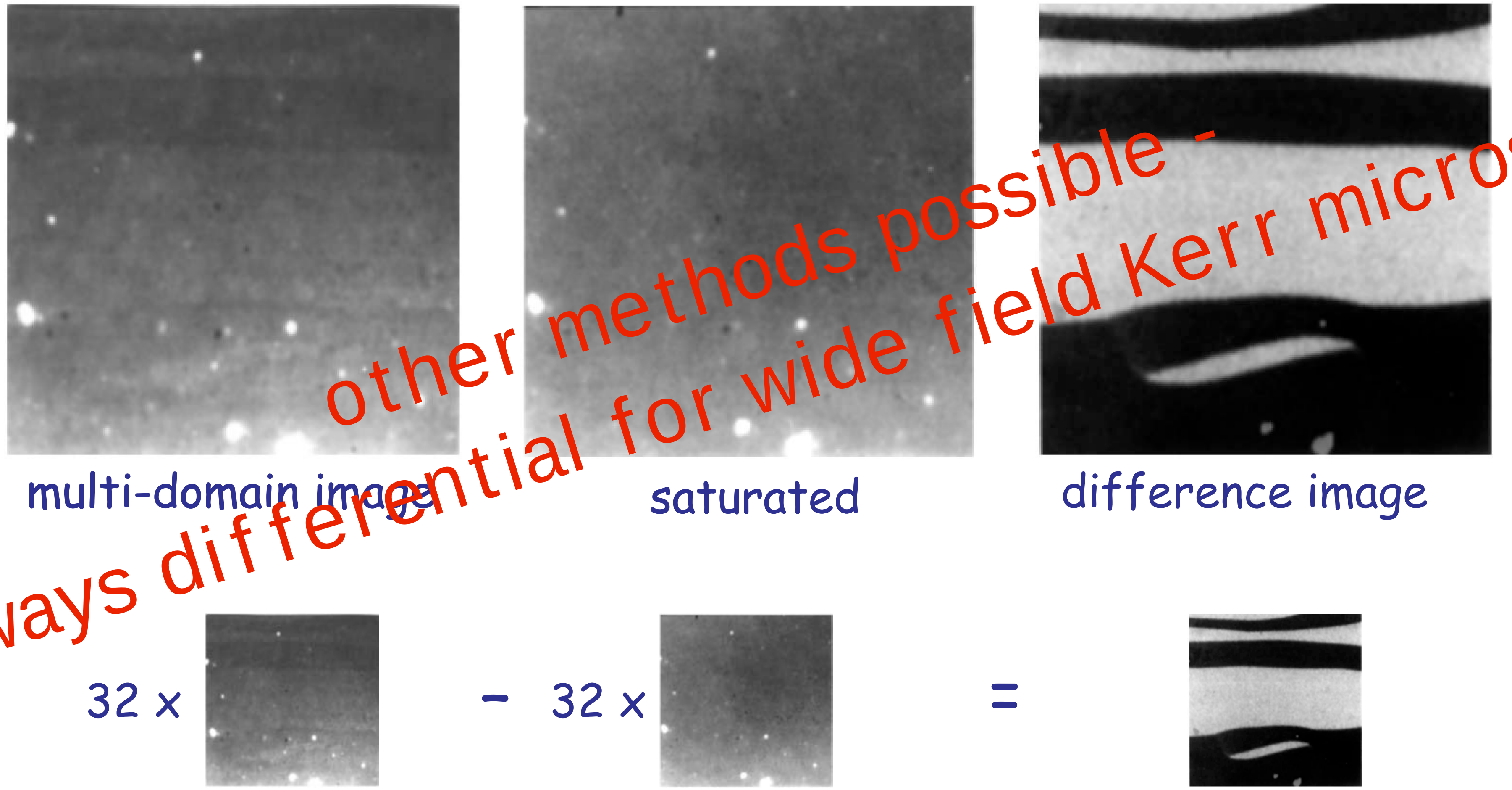
- permanent magnet
- thermally demagnetized magnetic state
- nominal c-axis perpendicular to imaging plane
  - small variations in domain structure

Illumination path (longitudinal+polar)



- reflection
- oblique incidence of light
  - in- and out-of-plane sensitivity (!)
- direct method - surface imaging

Contrast enhancement - $Ni_{81}Fe_{19}$ (8 nm)



other methods possible -
always differential for wide field Kerr microscopy

- magnetic contrast enhancement (low longitudinal contrast)
  - difference image - background subtraction
    - eliminate non-magnetic contrast
    - enhance domain contrast
  - averaging - improvement of signal-to-noise ratio

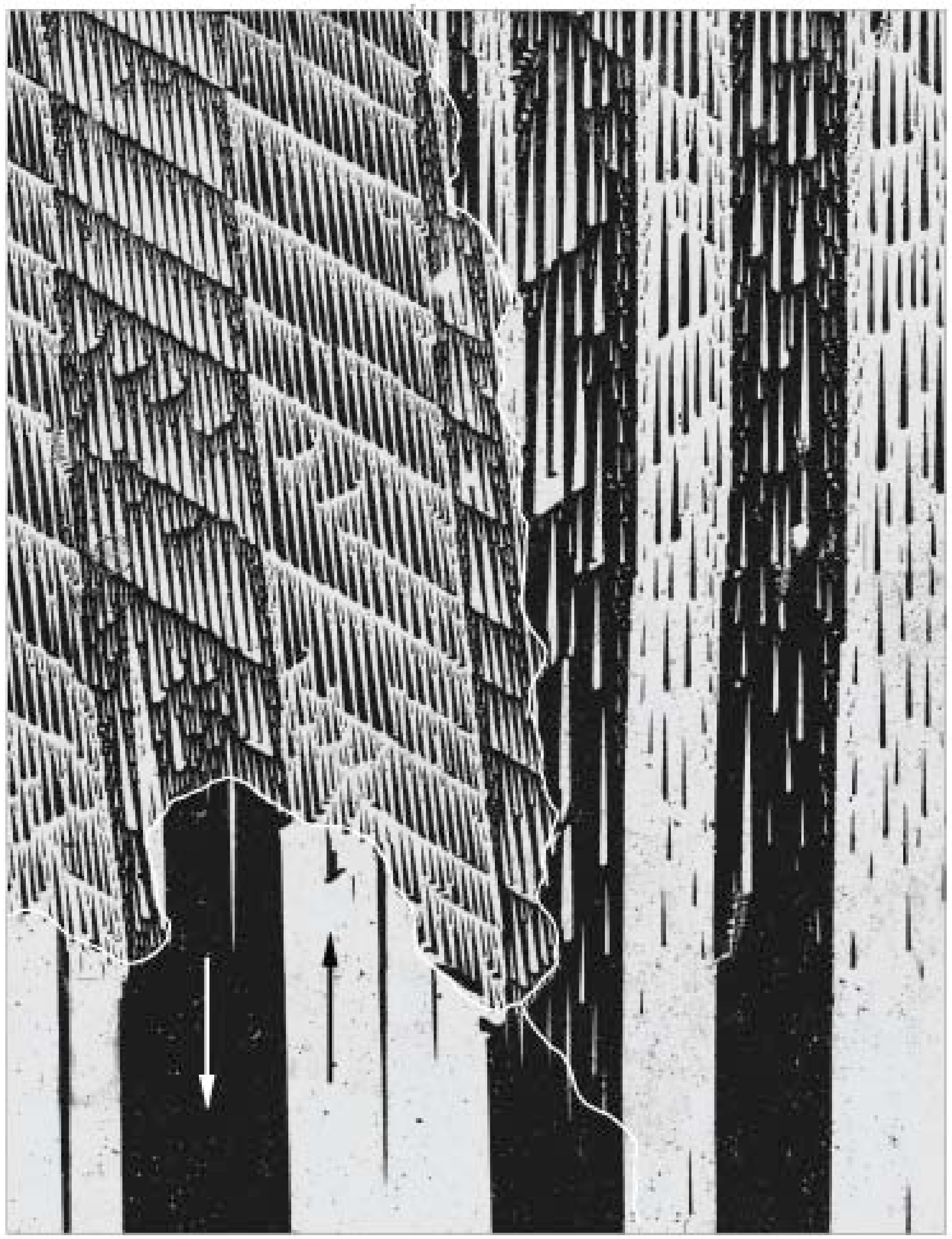
On magnification - field of view

… from mm to μm …

Longitudinal Kerr from mm ...

image courtesy R. Schäfer, IFW Dresden

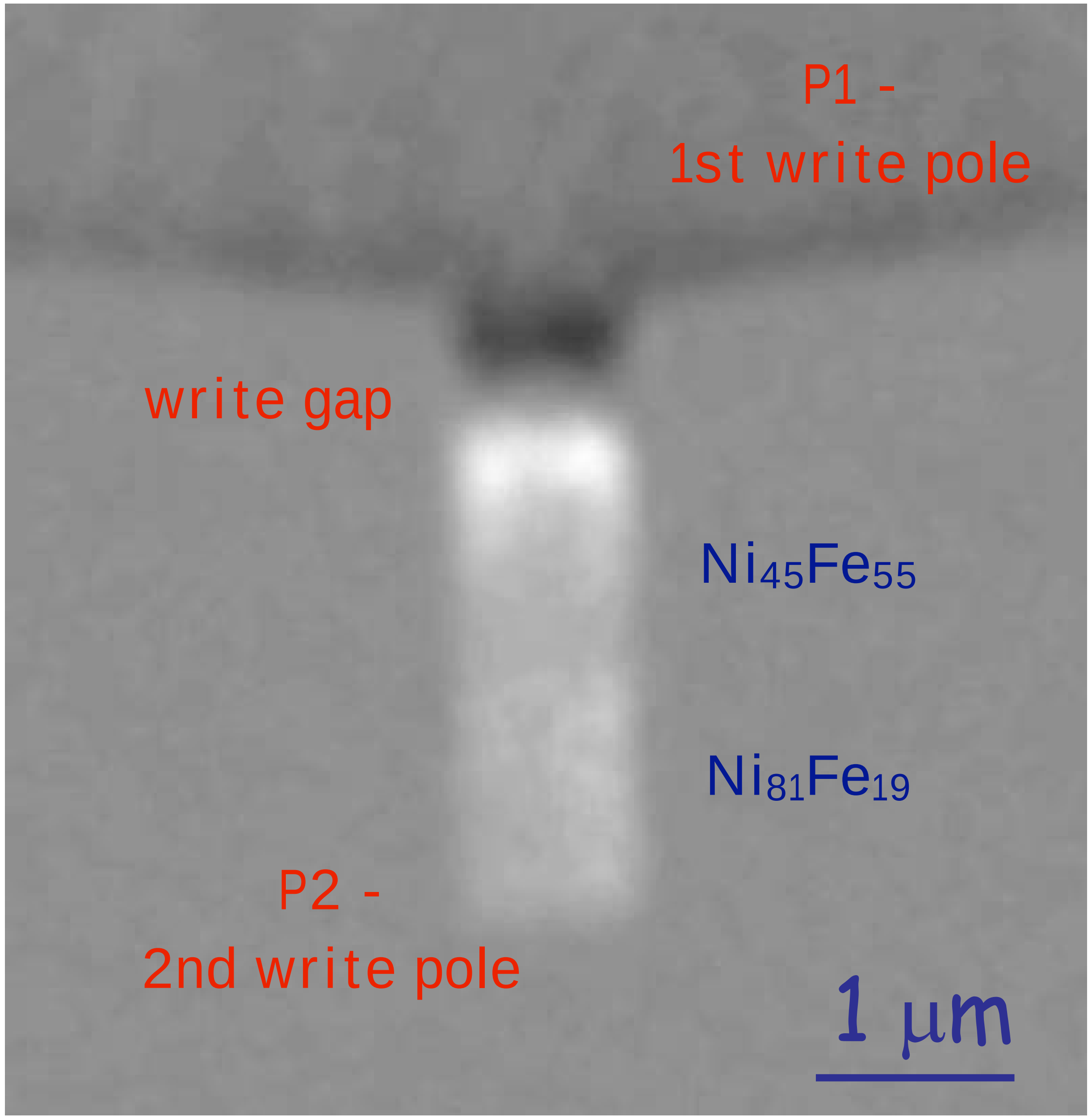
1 mm



- Fe-Si3% transformer steel
- nominal in-plane easy axis of magnetization aligned vertically
- 3 grains with different degree of disorientation

... polar Kerr down to μm (I)

B. Argyle, J. McCord,
Magnetic Storage Systems Beyond 2000/ Nato Science Series: II: Mathematics, Physics and Chemistry, vol. 41 ed. G.C. Hadjipanayis (2001)



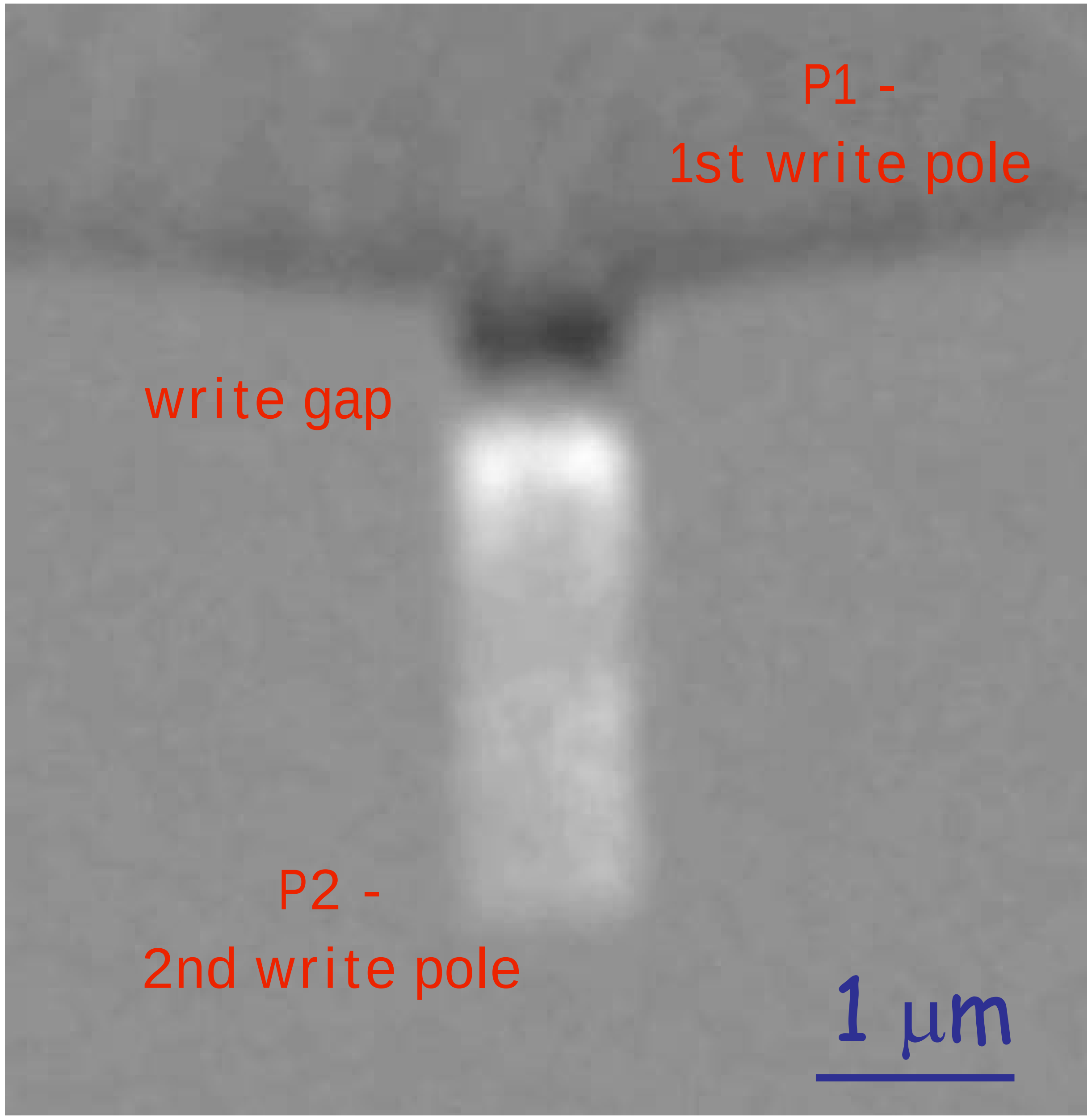
real device!

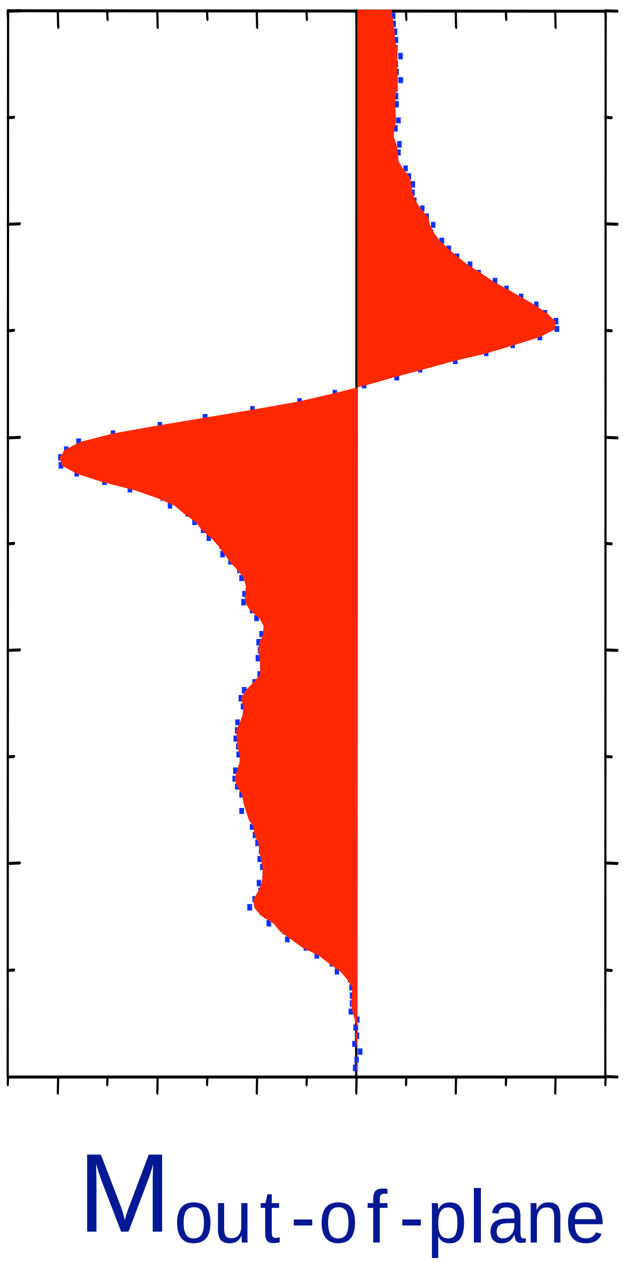
- longitudinal recording head pole-tip during write excitation
- enhanced polar magnetization at write gap between P1 and P2

On resolution . . .

... down to the sub-μm ...

High resolution - gap distance 200 nm

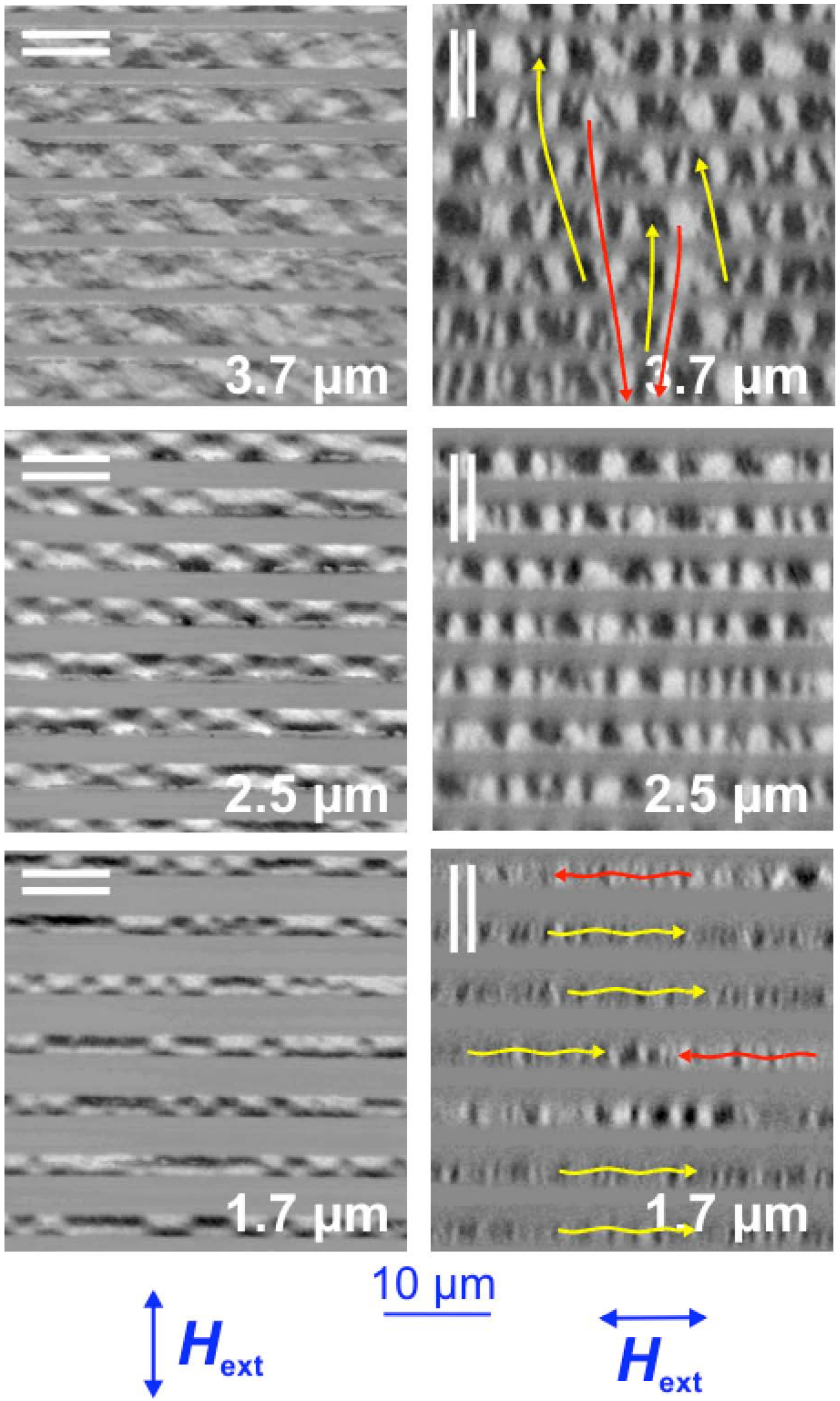




- imaging of micron sized pole-tip (again)
- determination of $M_{out\text{-}of\text{-}plane}$ (@30 mA write current)

… more on lateral resolution…

J. McCord, T. Schmitte, et al., IEEE Transactions on Magnetics 39, 2687-2689 (2003)
K. Theis-Bröhl, B. P. Toperverg, et al., Phys. Rev. B 72, 020403(R) (2005)

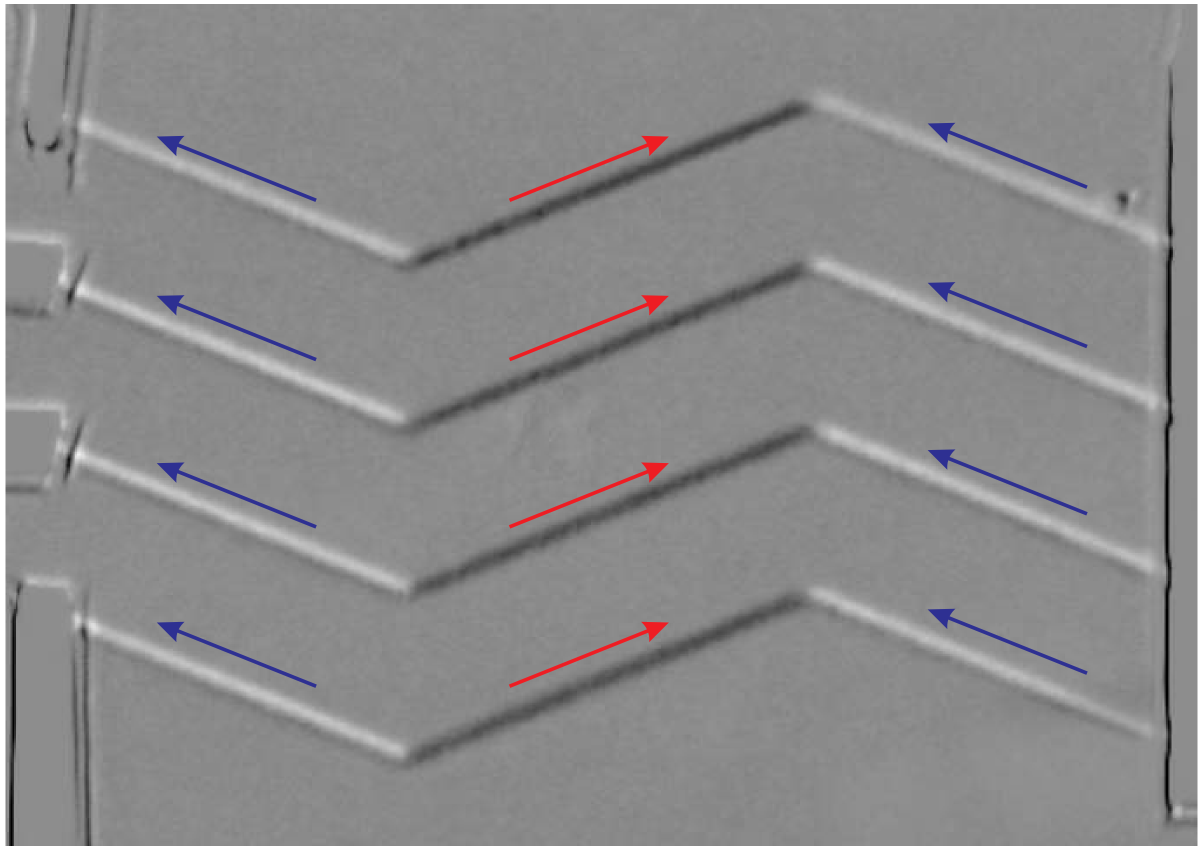


(comparison with polarized neutron scattering)

- $Fe_{50}Co_{50}$ stripes
  - varying width down to 1.7 μm
  - sub-μm ripple domains
- interacting domains across stripe border due to magneto-static interaction
- strong dependence on magnetic field history

… sub-μm imaging.

together with M. Kläui, University Konstanz



“2D-structure”

after H_{ext}

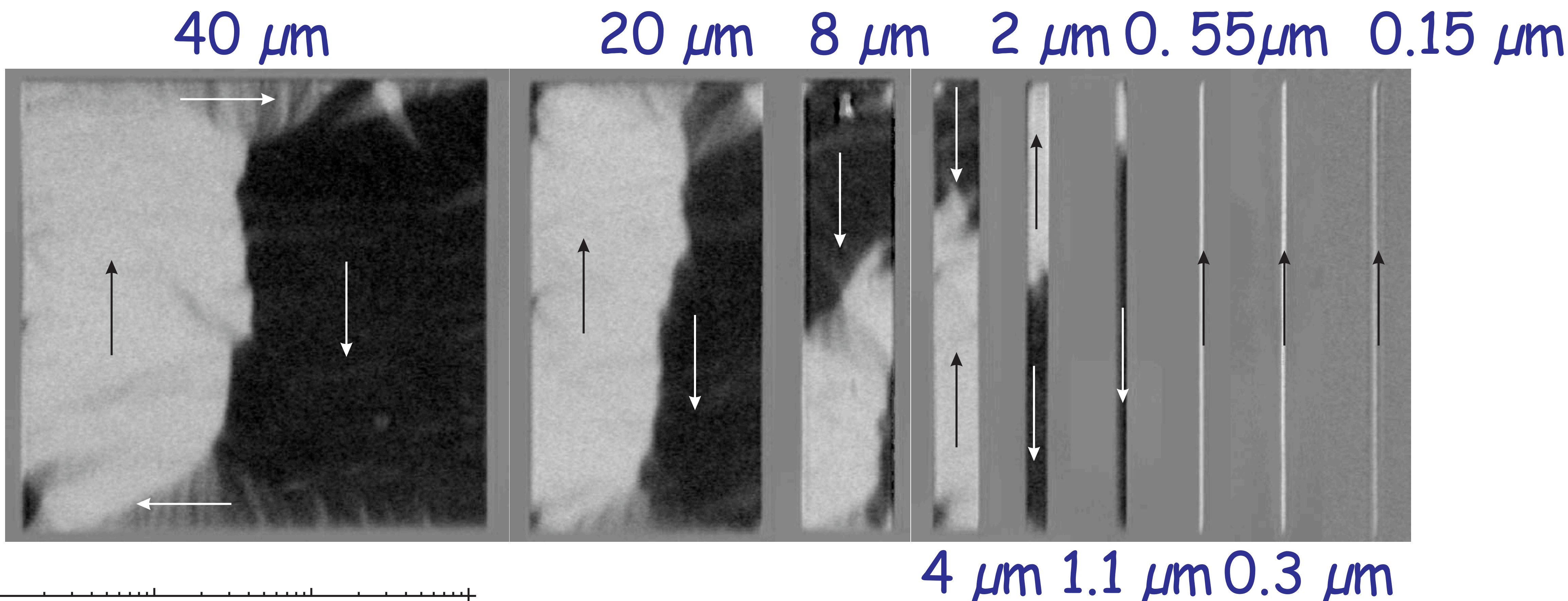
0.5 µm wide NiFe stripes

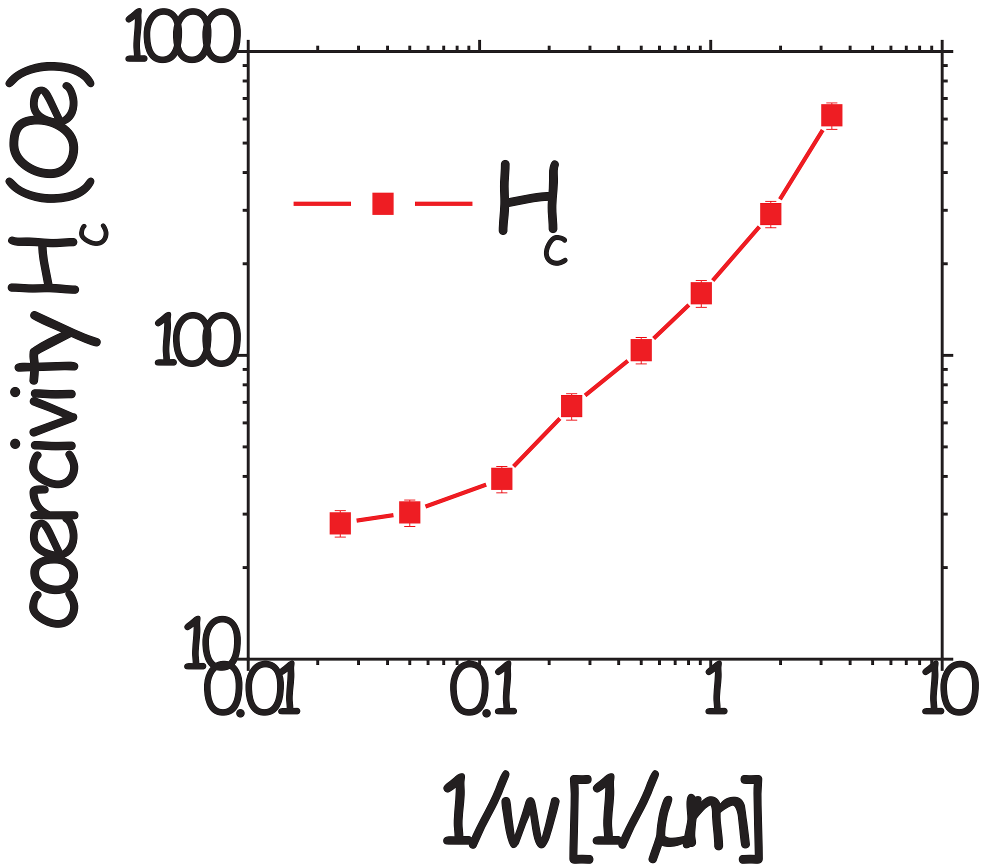
- head-on-domains in NiFe wires (20 nm x 500 nm)
  - aligned in vertical field

  (current induced domain wall motion)

Magnetization reversal in Co-wires

together with B. Hausmanns, University Duisburg





- measurement of magnetic properties (H_c)
- head-on domain wall motion through stripes (small width w)
- domain buckling (not shown)

Summary on practical resolution

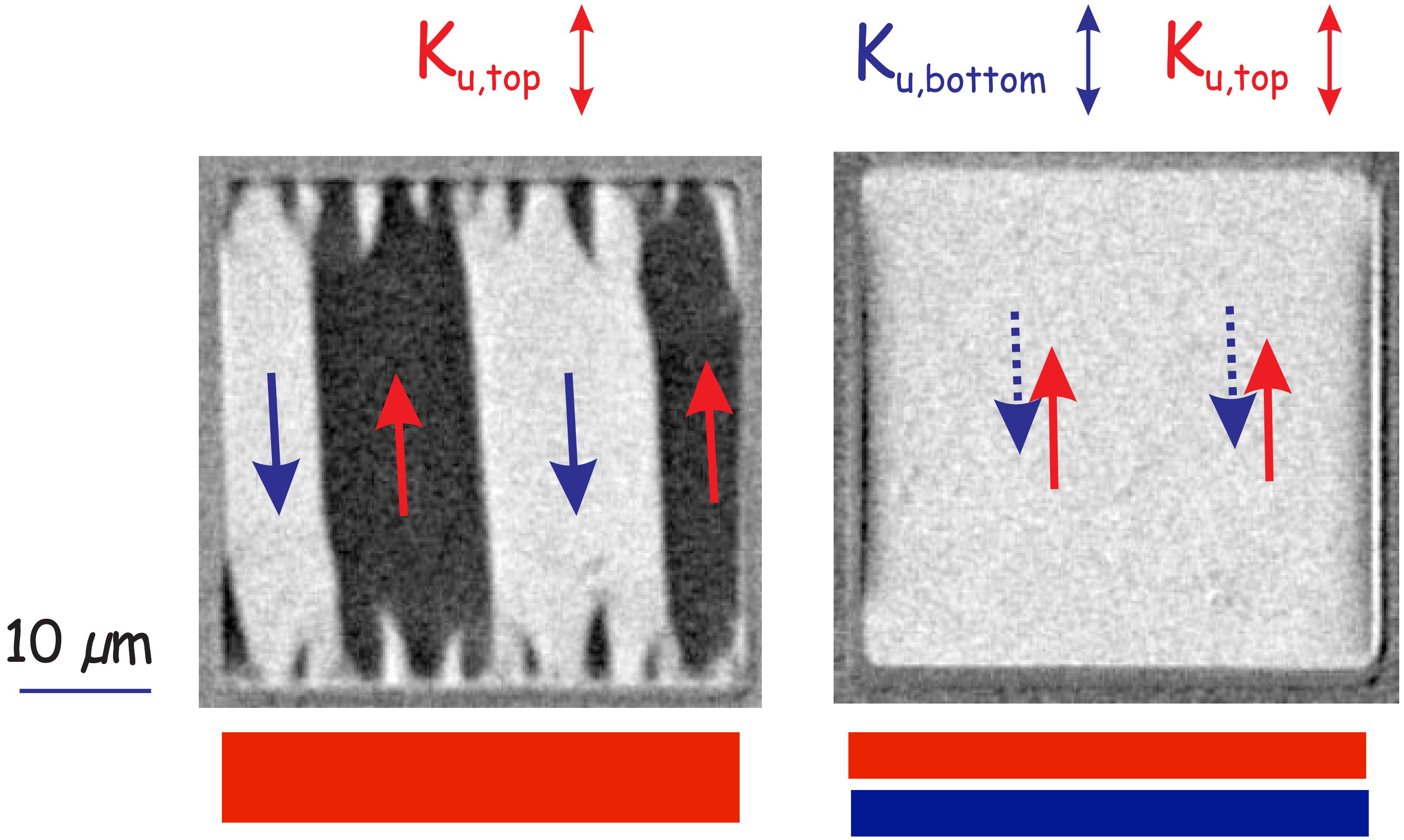
- demonstrated resolution close to theoretical resolution
- sub μm imaging “easily” achievable

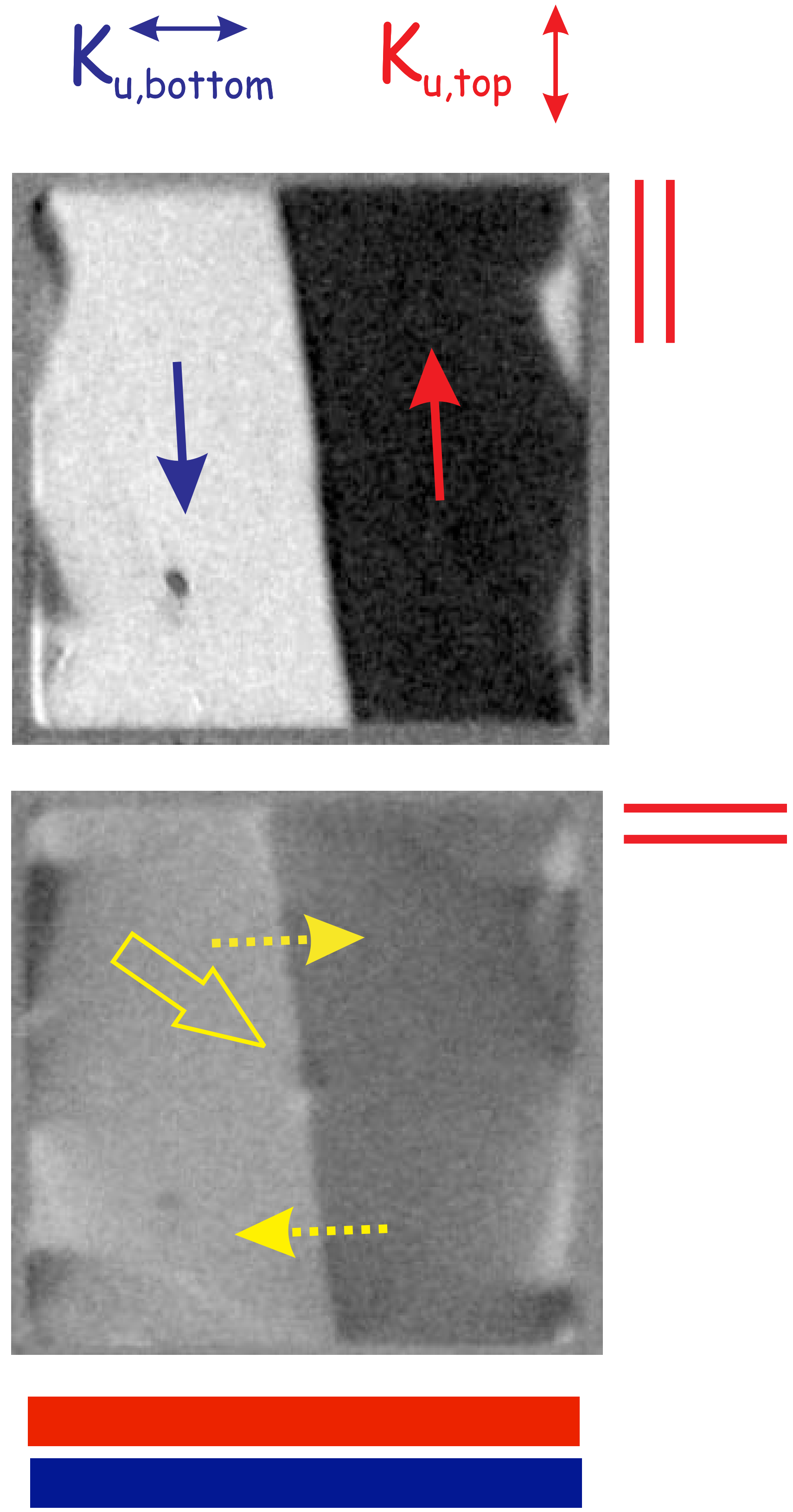
Magnetic multilayers ...

... from thick to thin, from non-transparent to transparent ...

Thick films - $CoFeSiB/SiO_2/CoFeSiB$

together with M. Frommberger, CAESAR





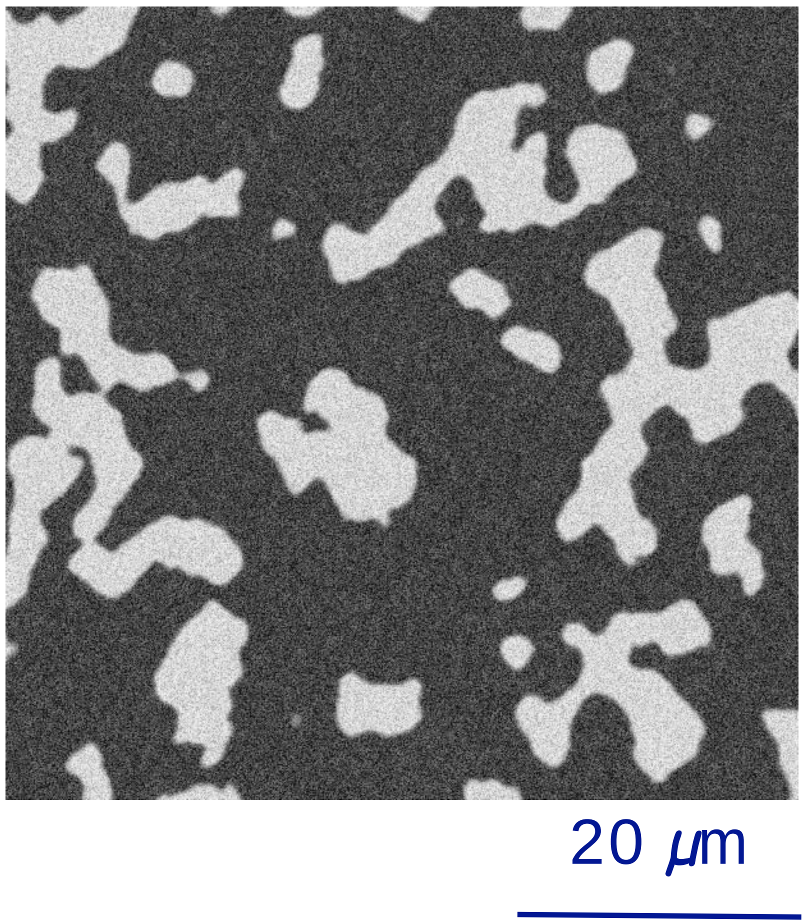
- determination of magnetic states in hidden layer from "micromagnetics"

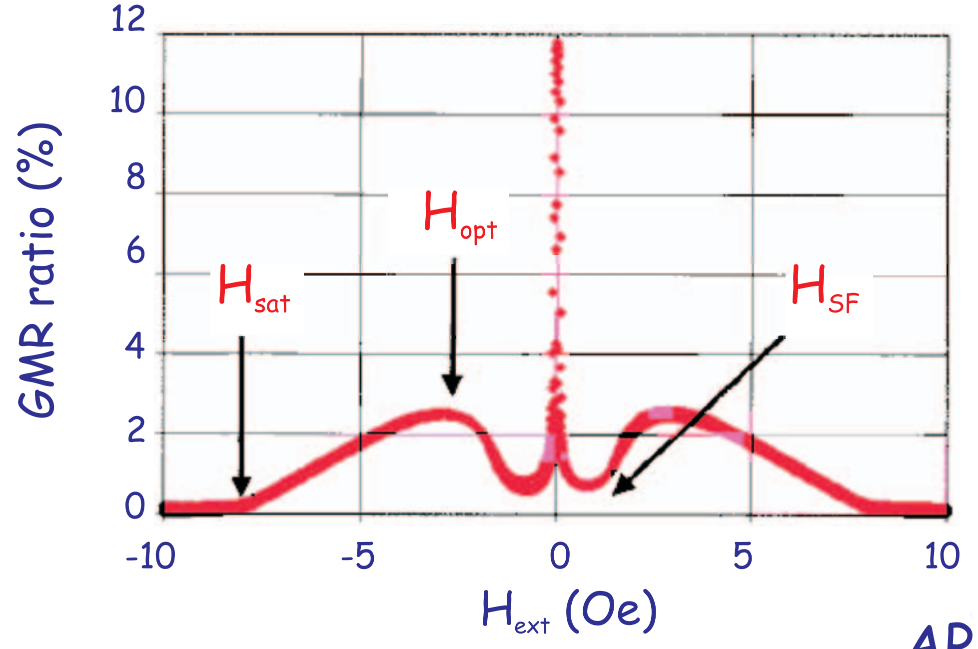
➡ known anisotropy axis

(microinductors)

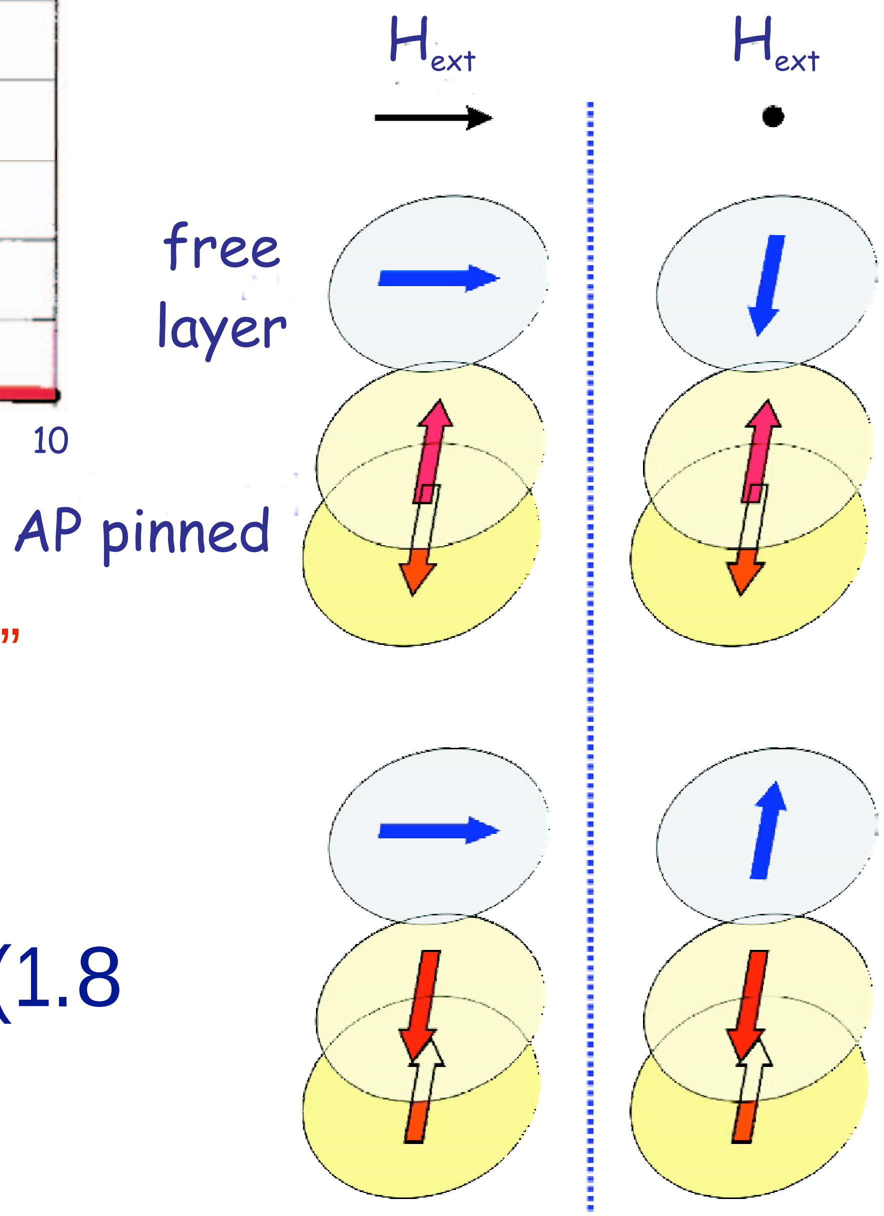
Domain structure in buried layers

R.S. Beach, J. McCord, et al., APL 80 (24), 4576-4578 (2002)





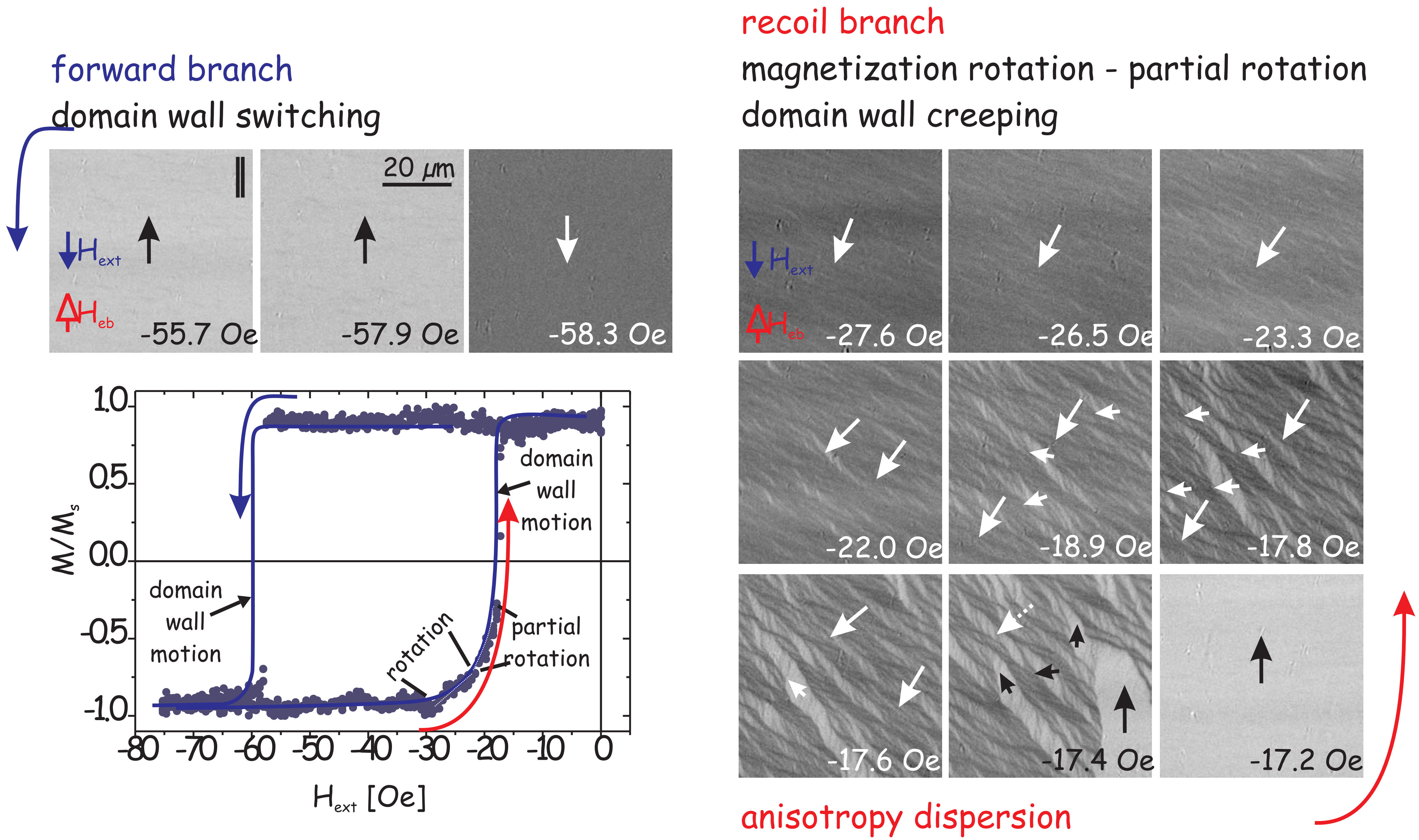
perpendicular "spin-flop" field anneal @ H_{opt}



- PtMn/CoFe (1.4 nm)/Ru (0.8 nm)/ CoFe (1.8 nm)/Cu/CoFe-NiFe (3 nm)
- coupled "free layer" acting as a detection layer
- two domain types evident

Asymmetric reversal - exchange bias

J. McCord, R. Mattheis, et al.. JAP 93 (9), 5491-5497 (2003)

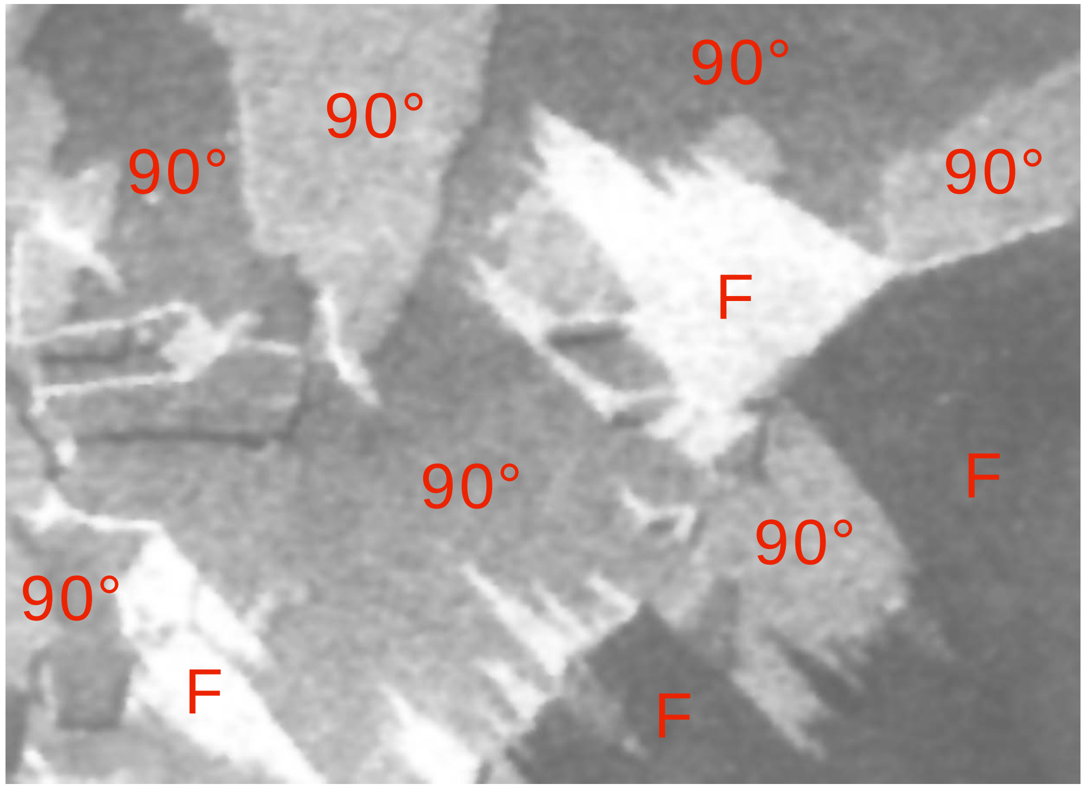


- exchange biased $Co_{90}Fe_{10}$ (20 nm) / $Ir_{23}Mn_{77}$ (10 nm)
- imaging through IrMn layer
- observation of loop and domain asymmetry

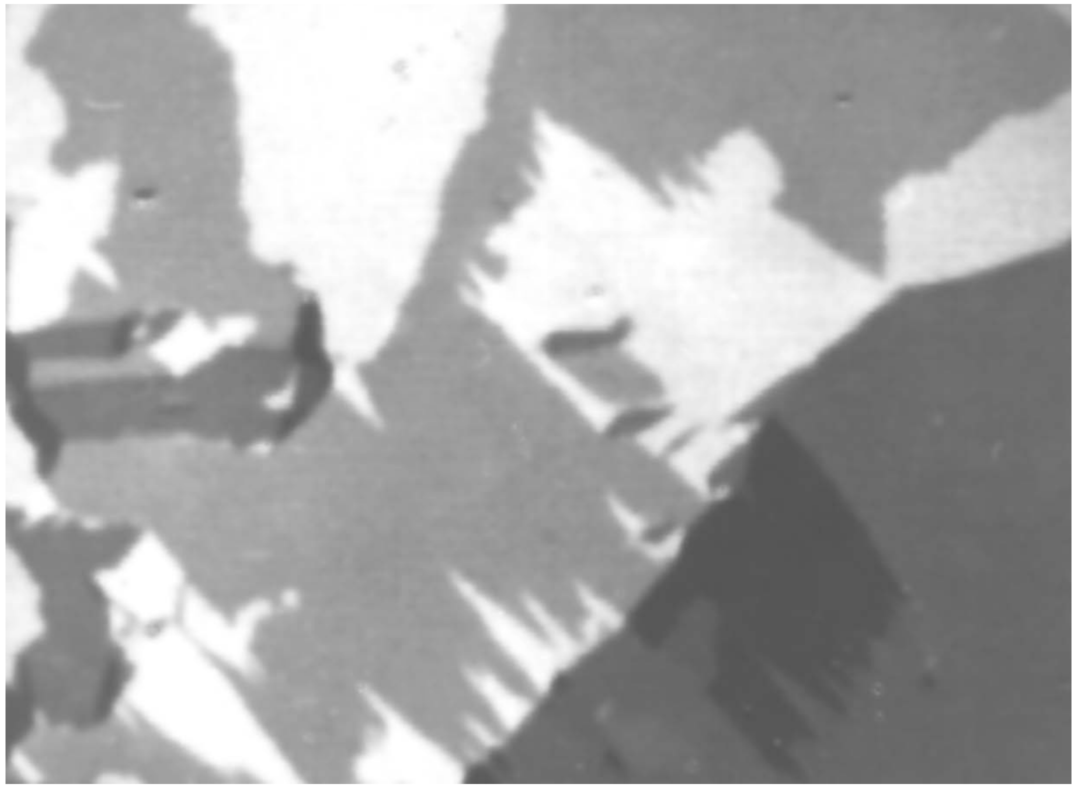
Complementary Voigt and Kerr imaging

J. McCord, A. Hubert et al., IEEE Transaction on Magnetics 29, 2735-2737 (1993)

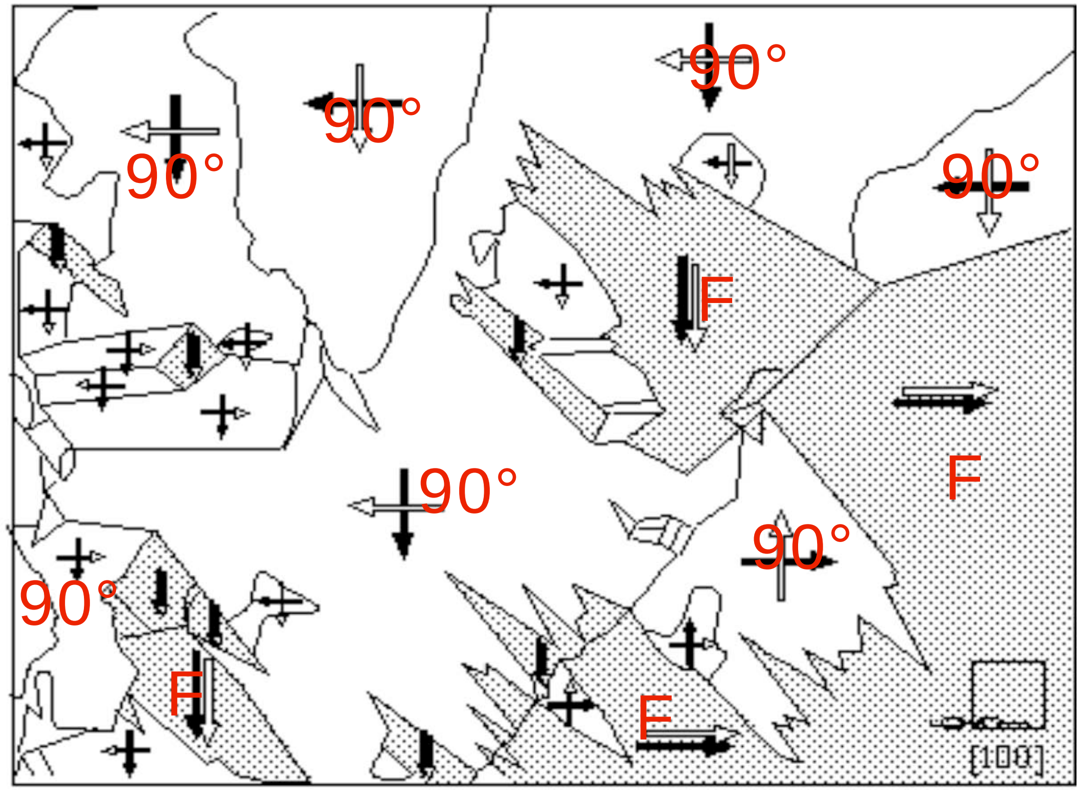
Voigt effect ~M^2



Kerr effect ~M

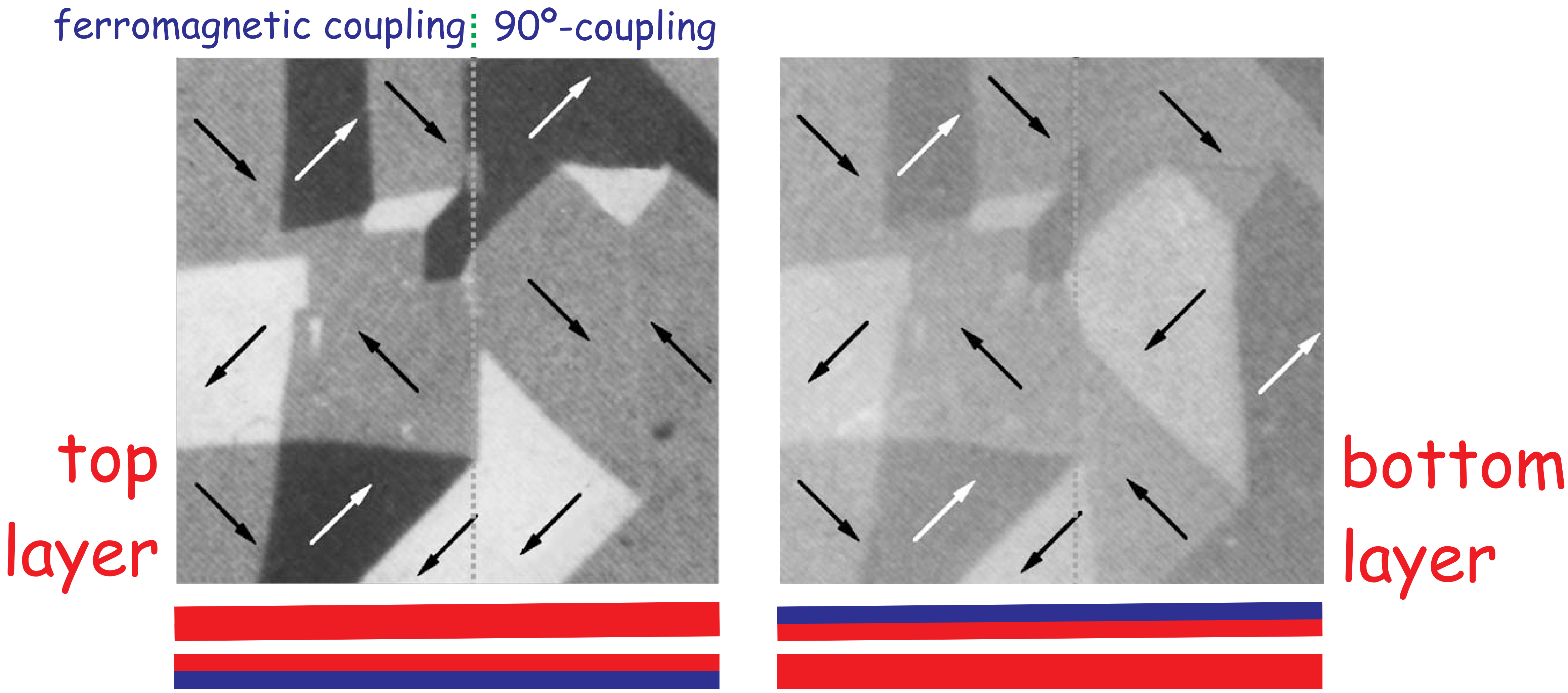


- Fe/Al/Fe (10 nm/3 nm/10 nm) magnetic bi-layer structure
- mixed alignment of magnetization - low coupling
- determination of parallel and orthogonal alignment of M



Layer sensitive imaging in Fe bi-layers

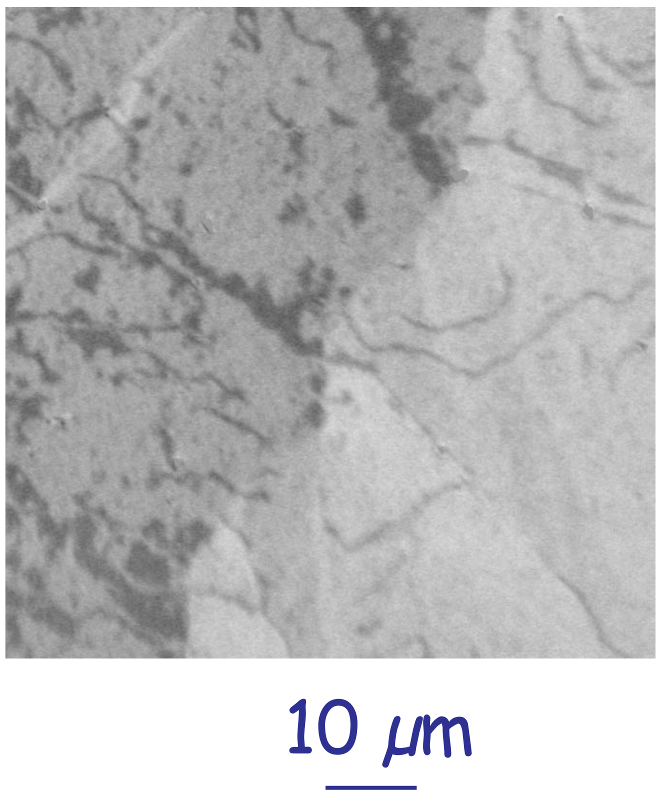
R. Schäfer, J. Magn. Magn. Mat., 148, 226-231 (1995)

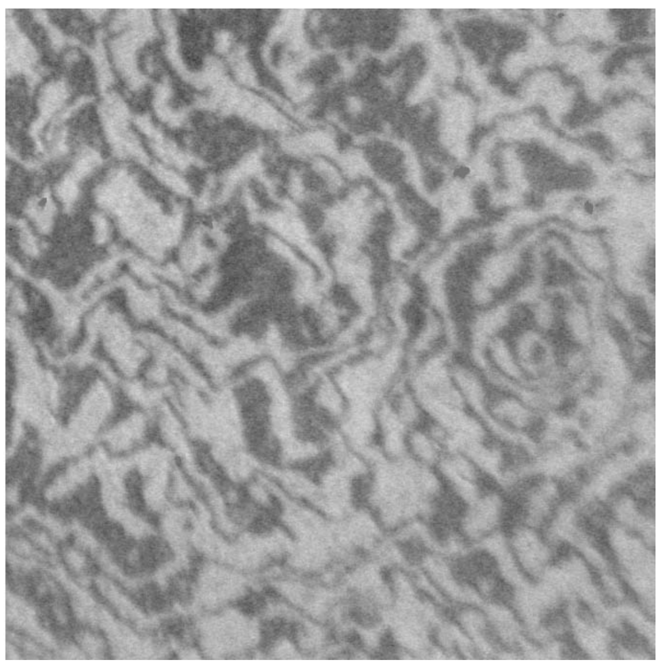


- Fe/Cr/Fe (15 nm/x/15 nm)
- identification of
  - ferromagnetic coupling (left)
  - 90°-degree or biquadratic coupling (right)

Bi-layer magnetization reversal

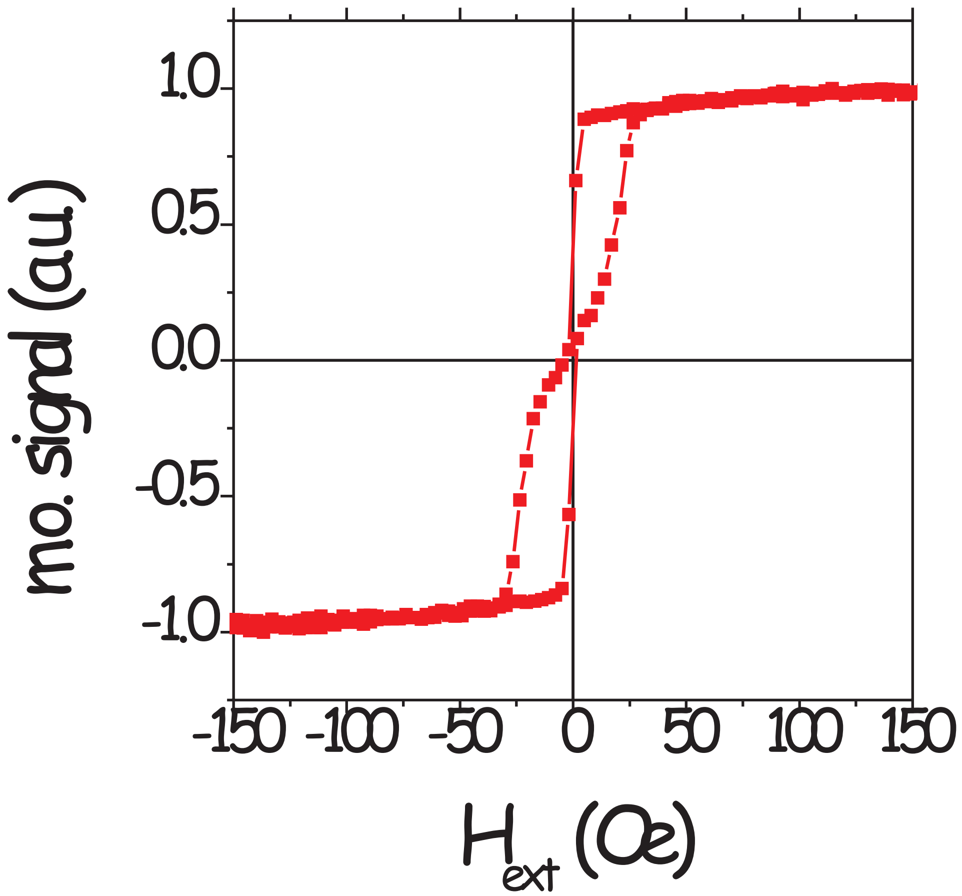
NiFe domain switching





degaussed

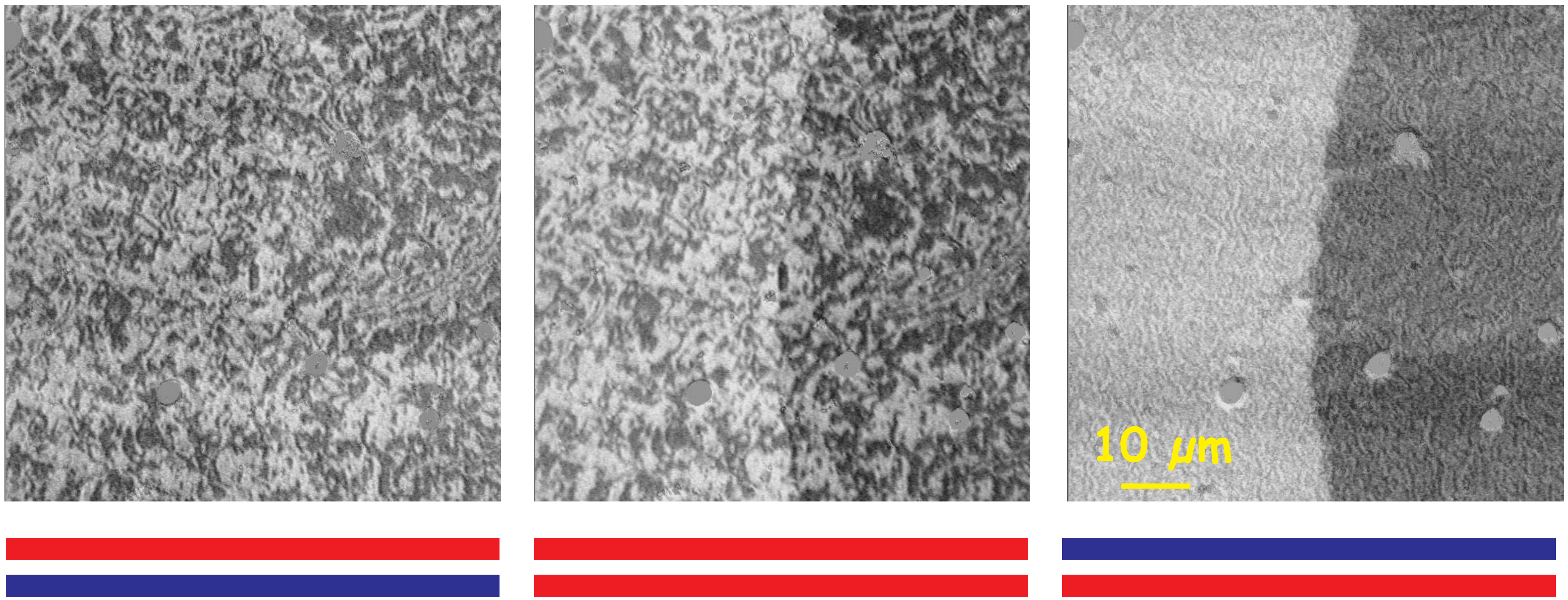
MOKE curve



- Co/Cu/$Ni_{81}Fe_{19}$ (5 nm/5 nm/50 nm)
  - top Co layer - both layers visible
  - magneto-static Néel wall interaction - charge compensation
  - regular and irregular domain walls

Layer-by-layer imaging (degaussed)

top layer | mixed Kerr signal | bottom layer



Co/Cu/$Ni_{81}Fe_{19}$ (5 nm/5 nm/50 nm)

- top Co layer
  - complicated domain structure and 360° walls
- bottom Permalloy layer
  - “modulated” 180° wall
  - magneto-statically induced variation inside the domains

Summary on multilayers

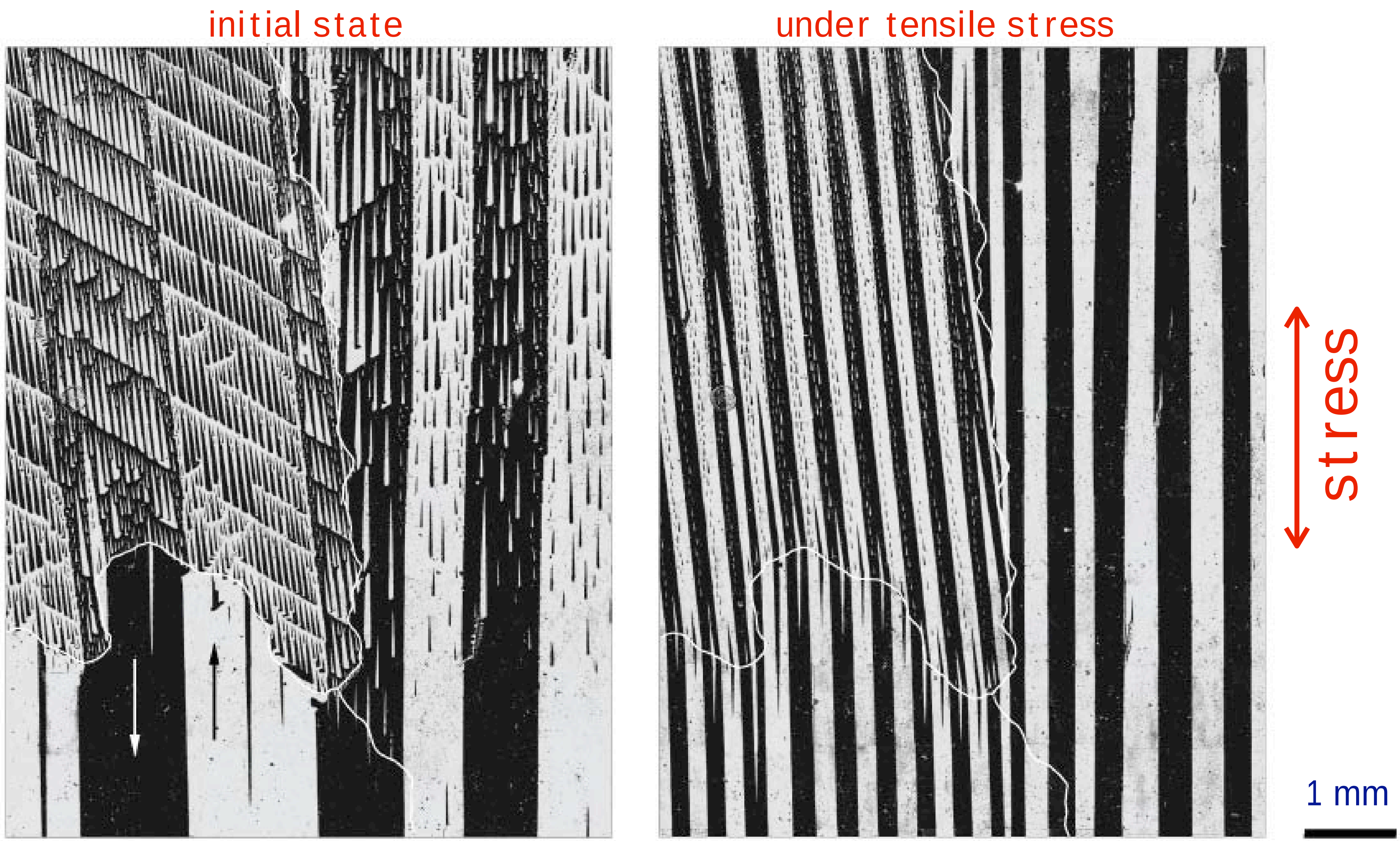
- magnetization in thin film multi-layers resolvable
  - imaging of buried layers
  - imaging through non-transparent covering layers
  - layer-by-layer imaging (thin films - bi-layer)

Effects of stress ...

... magnetostrictive materials, stress induced reversal ...

Alignment of magnetization in FeSi

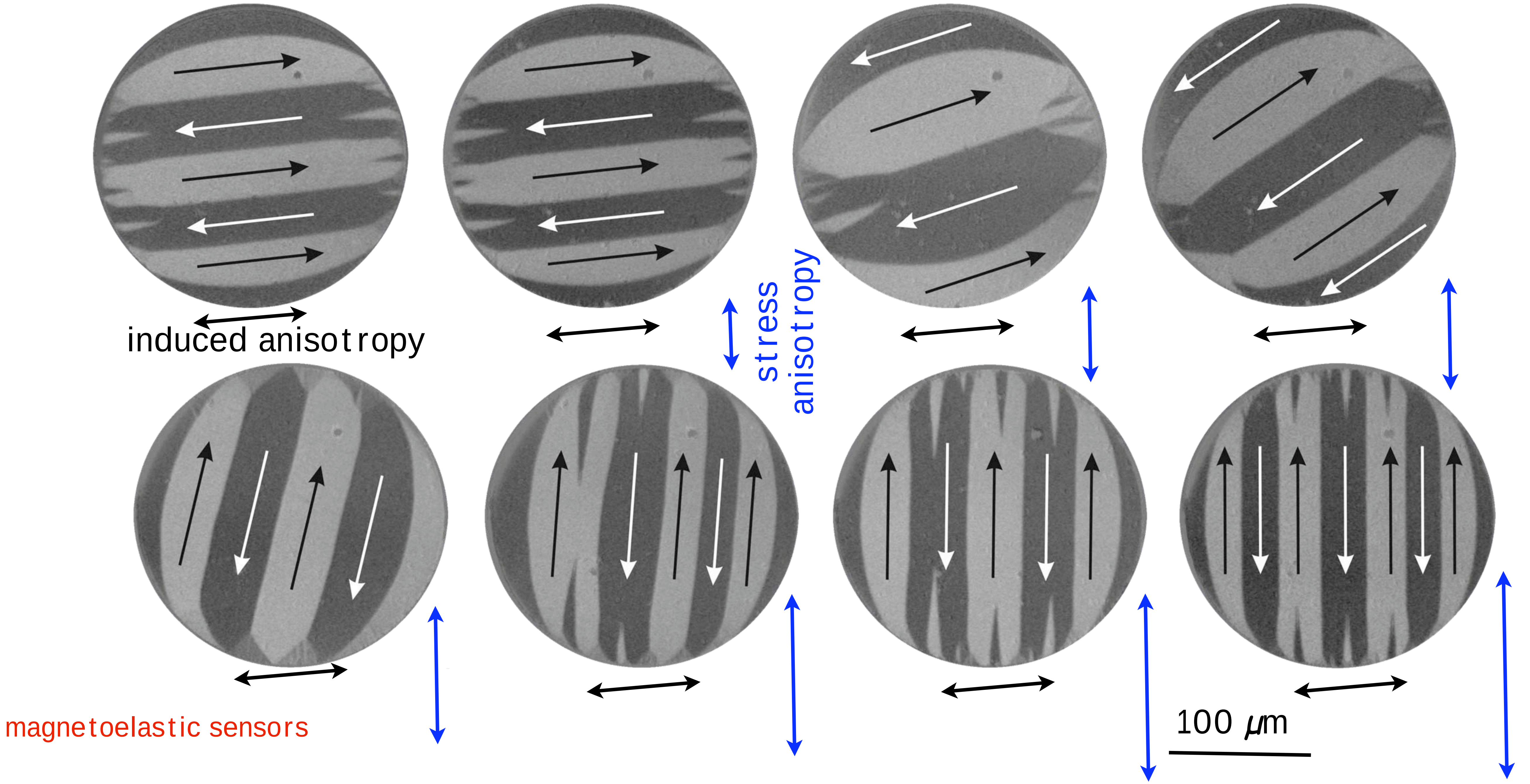
images courtesy R. Schäfer, IFW Dresden



- transformer steel $\lambda_{100} > 0$
- domain alignment through application of stress

Patterned FeCoSiB discs (0.5 μm)

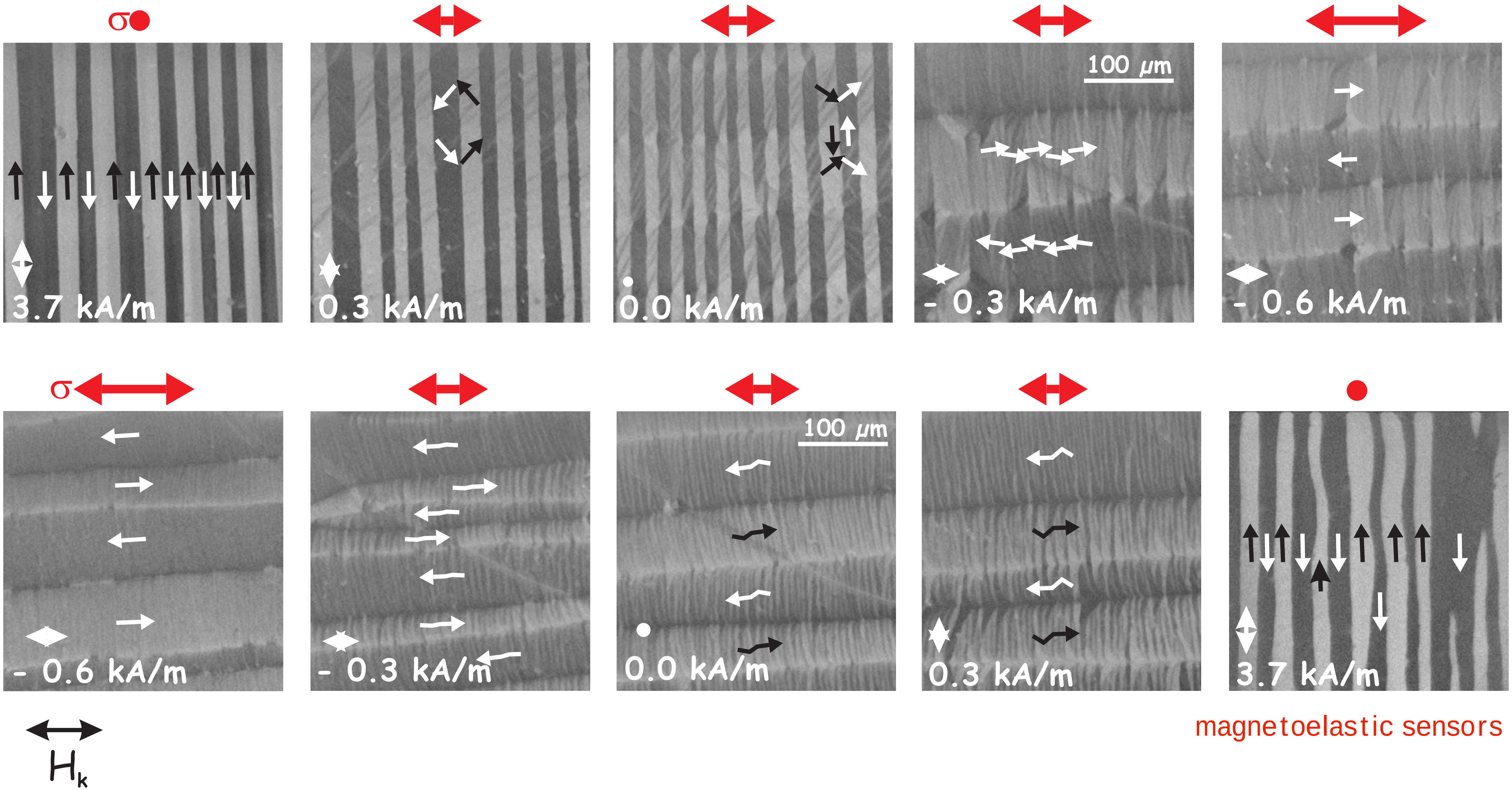
S. Glasmachers, M. Frommberger, J. McCord, E. Quandt, phys. stat. sol. (a) 201, 15, 3319-3324 (2004)



- stress induced K_u alignment in magnetoelastic sensor elements
- switch from branched to regular closure domains ($f(H_k)$)

Stress induced magnetization reversal

J. McCord, M. Frommberger et al., JAP 95, 6861-6863 (2004)



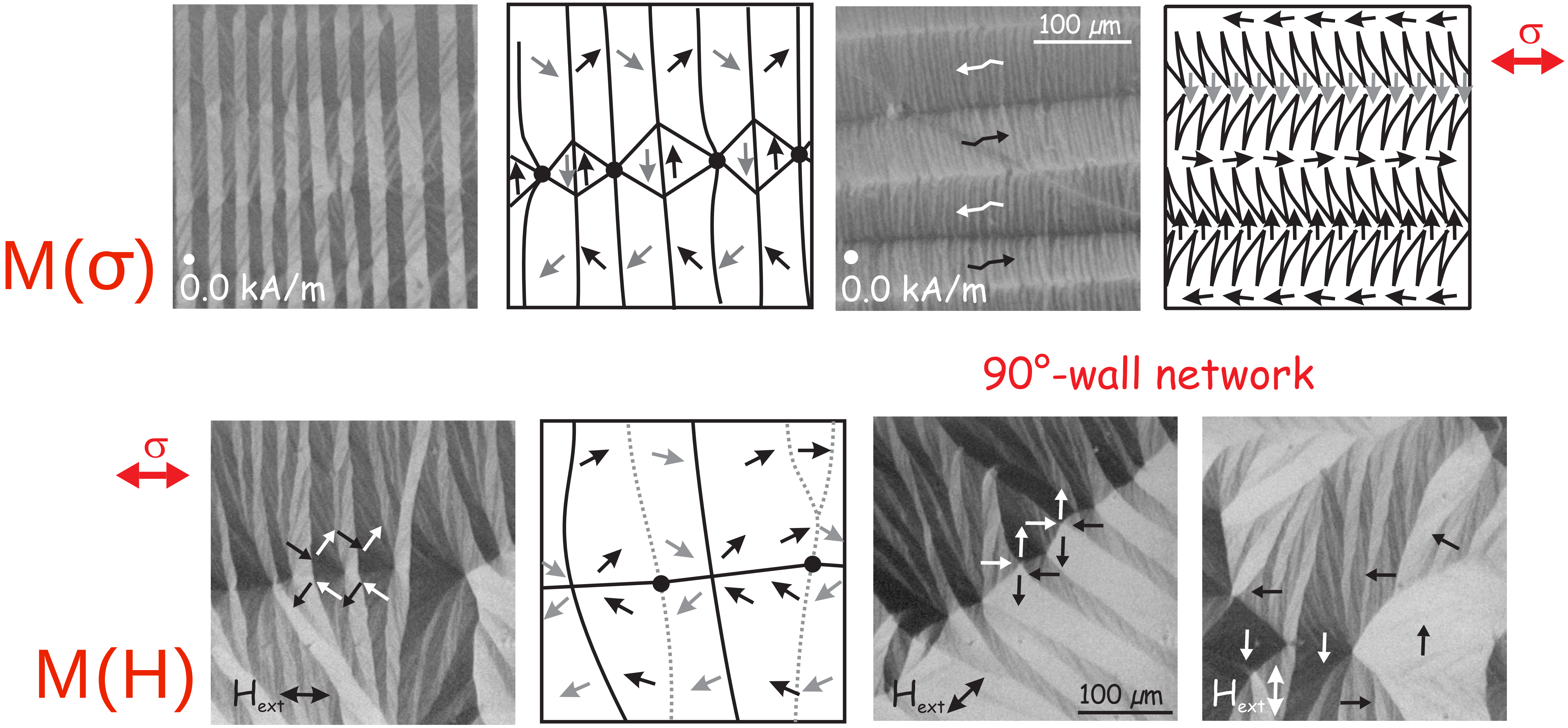
magnetoelastic sensors

- CoFe/CoB (7.7 nm/2.3 nm)$_{200}$ multilayers
- completely different domain (wall) behavior

no field applied!

Domain analysis - stress induced reversal

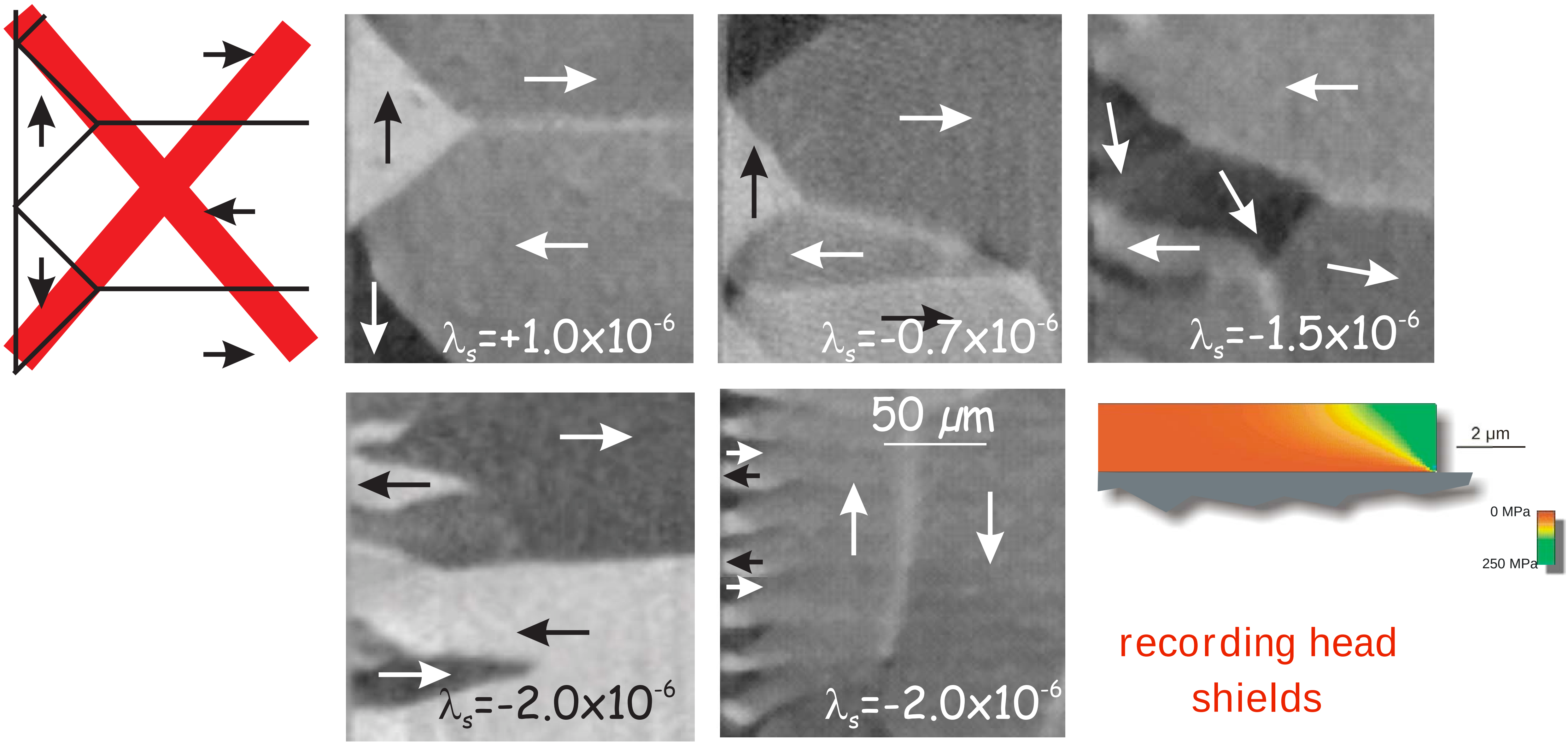
J. McCord, M. Frommberger et al., JAP 95, 6861-6863 (2004)



- similar to cross-tie walls
- preferred 90°-wall alignment
- stress energy minimization - film substrate interaction

Stress relaxation in magn. films - low λ_s

J. McCord., JAP 95, 6855-6857 (2004)

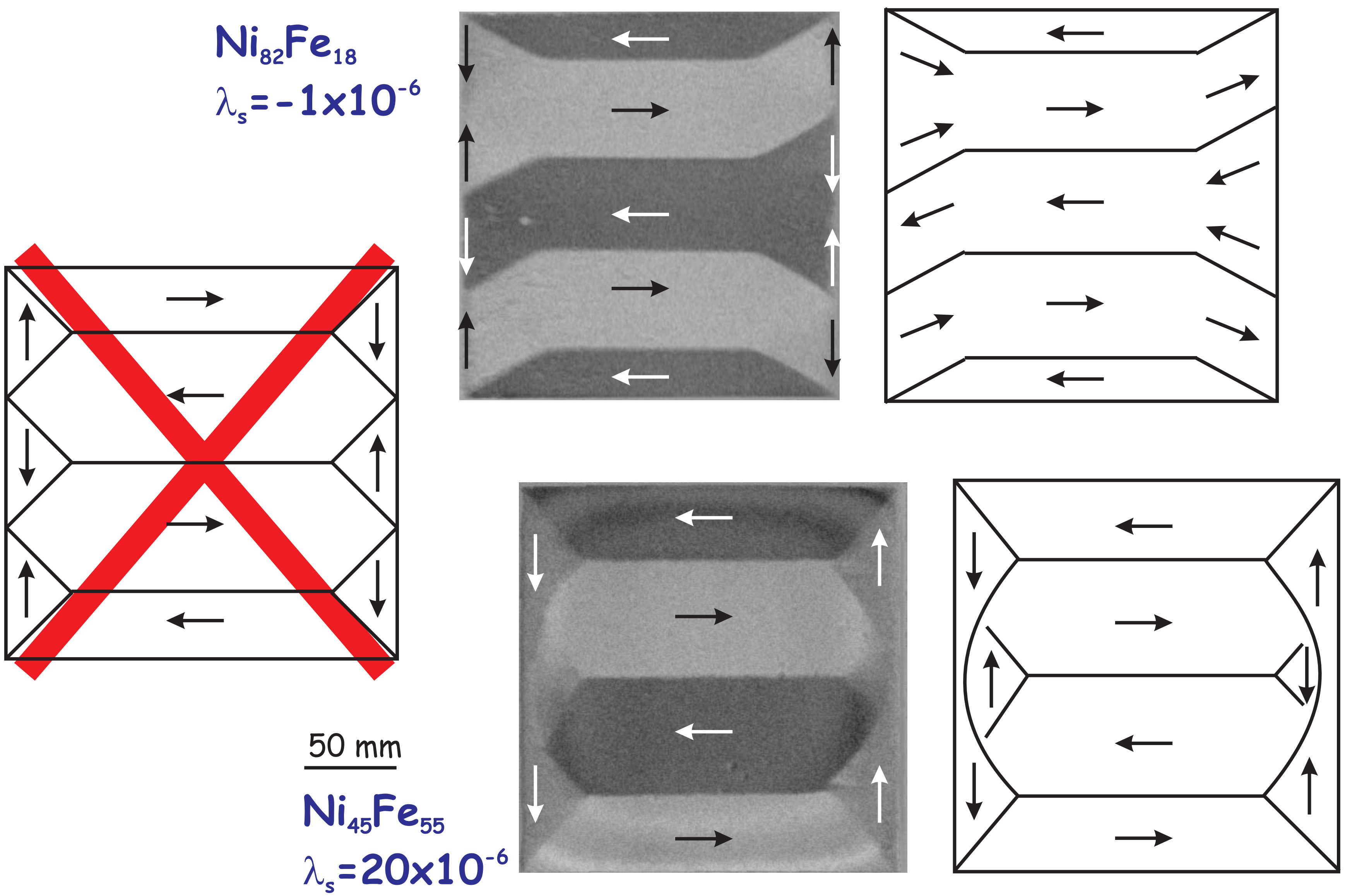


recording head shields

- edge domain structures in $Ni_{80.0}Fe_{20.0}$ ... $Ni_{82.5}Fe_{17.5}$ patterns
- thickness 2 μm
- domain structure determined by stress relaxation effects

Relaxation - comparison high vs. low λ_s

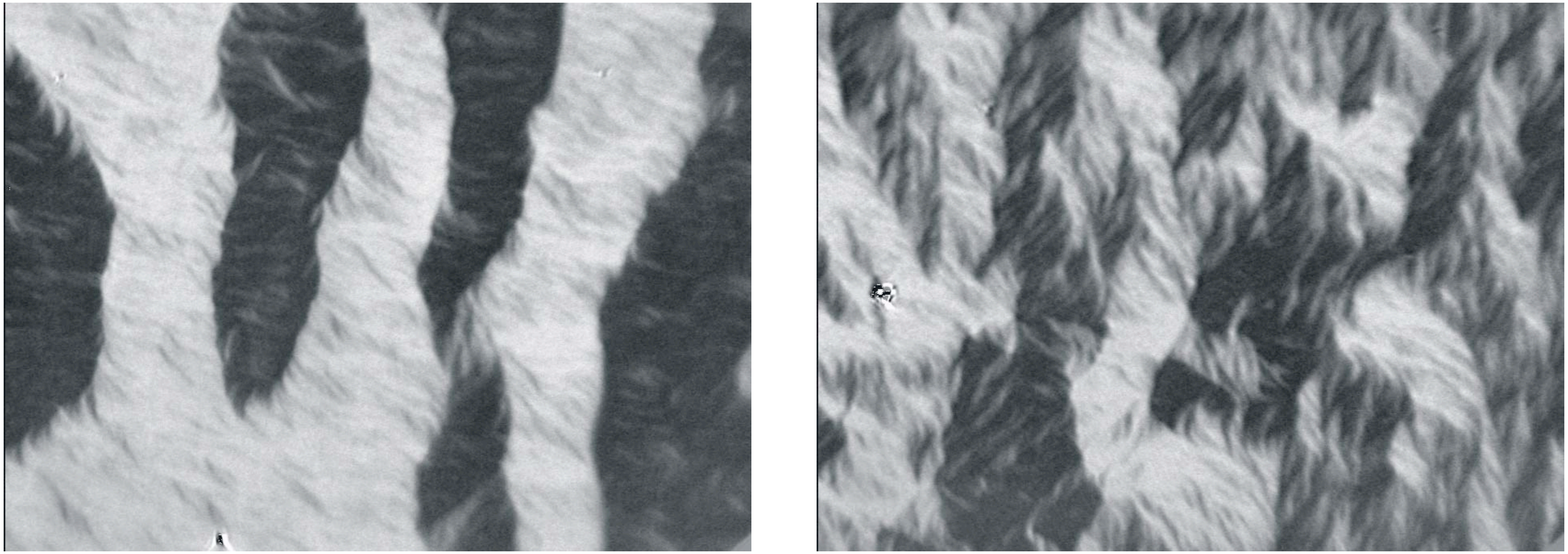
J. McCord., JAP 95, 6855-6857 (2004)



- no regular closure domain structures in square elements
- $Ni_{82}Fe_{18}$ - edge curling walls
- $Ni_{45}Fe_{55}$ - anisotropy patterning

Stress and domains in magnetic thin films

internal compressive film stress, $\lambda_s > 0$



σ = –70 MPa

H_c = 17 Oe

H_{ext} ⟷

σ = –860 MPa

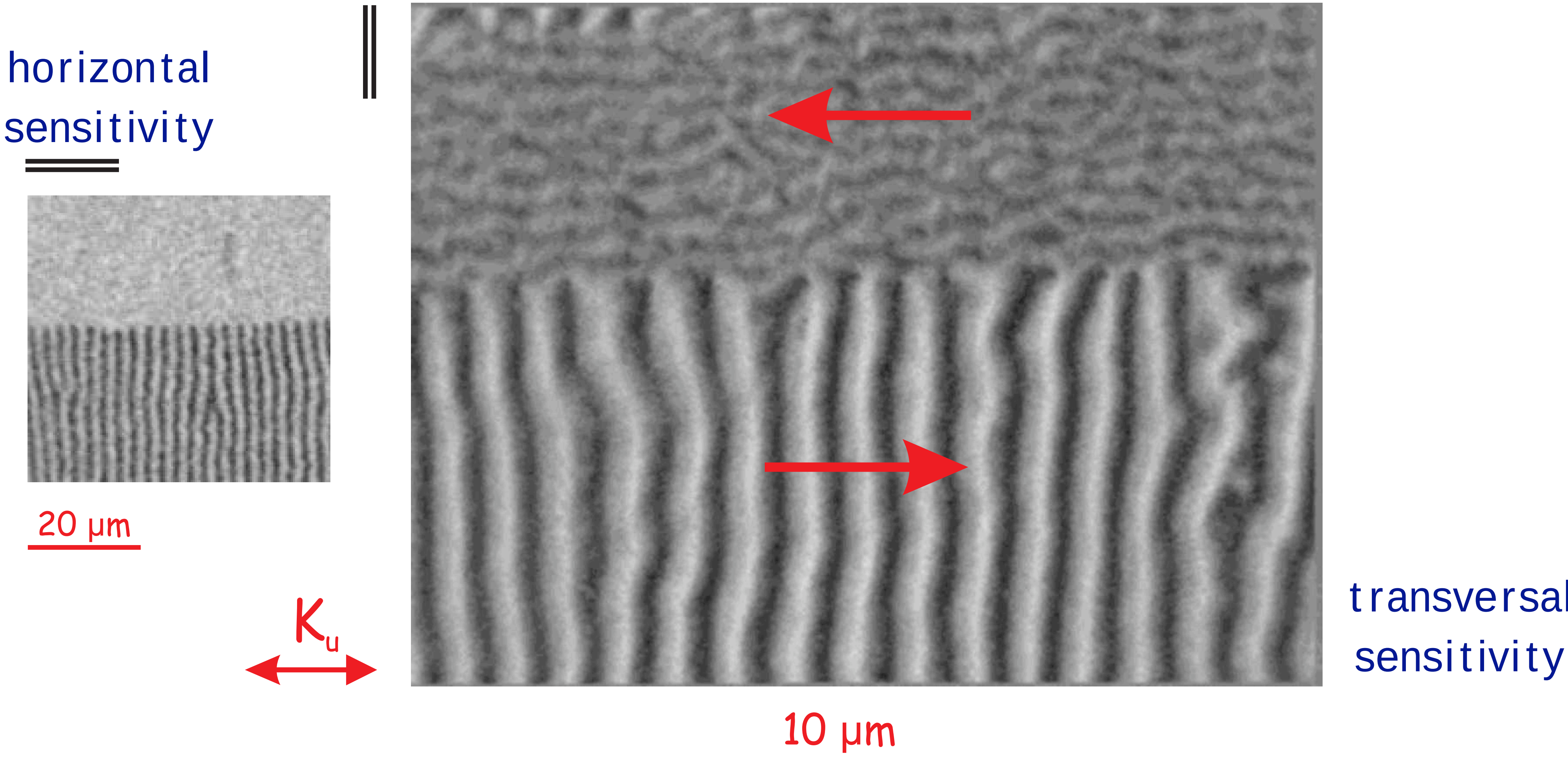
H_c = 35 Oe

20 μm

- $(Co_{50}Fe_{50}/SiO_2)_5$ multilayer, magnetic thickness 500 nm
- compressive stress induced magnetization ripple

Stress and domains in magnetic thick films

J. McCord, J. Westwood, IEEE Transactions on Magnetics 37, 1755-1757 (2001)



- stripe domain development in sputtered $Ni_{82}Fe_{18}$ films (2 μm)
  - simultaneous occurrence of weak and strong stripe domains during reversal
  - weak stripe domains not visible in longitudinal image

Summary on “stress”

application of stress

- observation of stress induced reversal (stress jig - sample holder)

- observation of stress effects
  - general and lateral

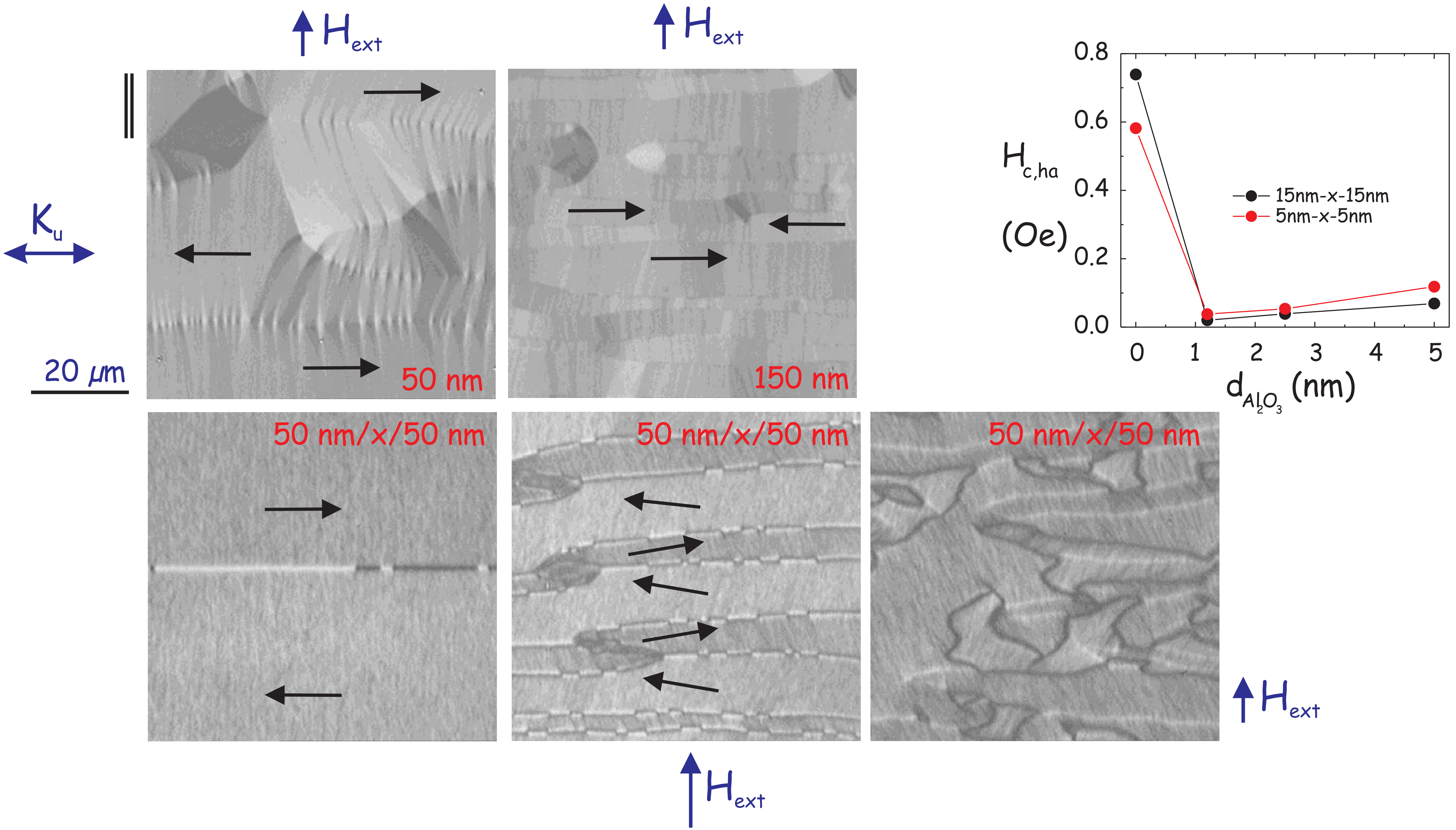
intrinsic stress

Domain walls

... examples from thin films ...

Domain walls in thin films

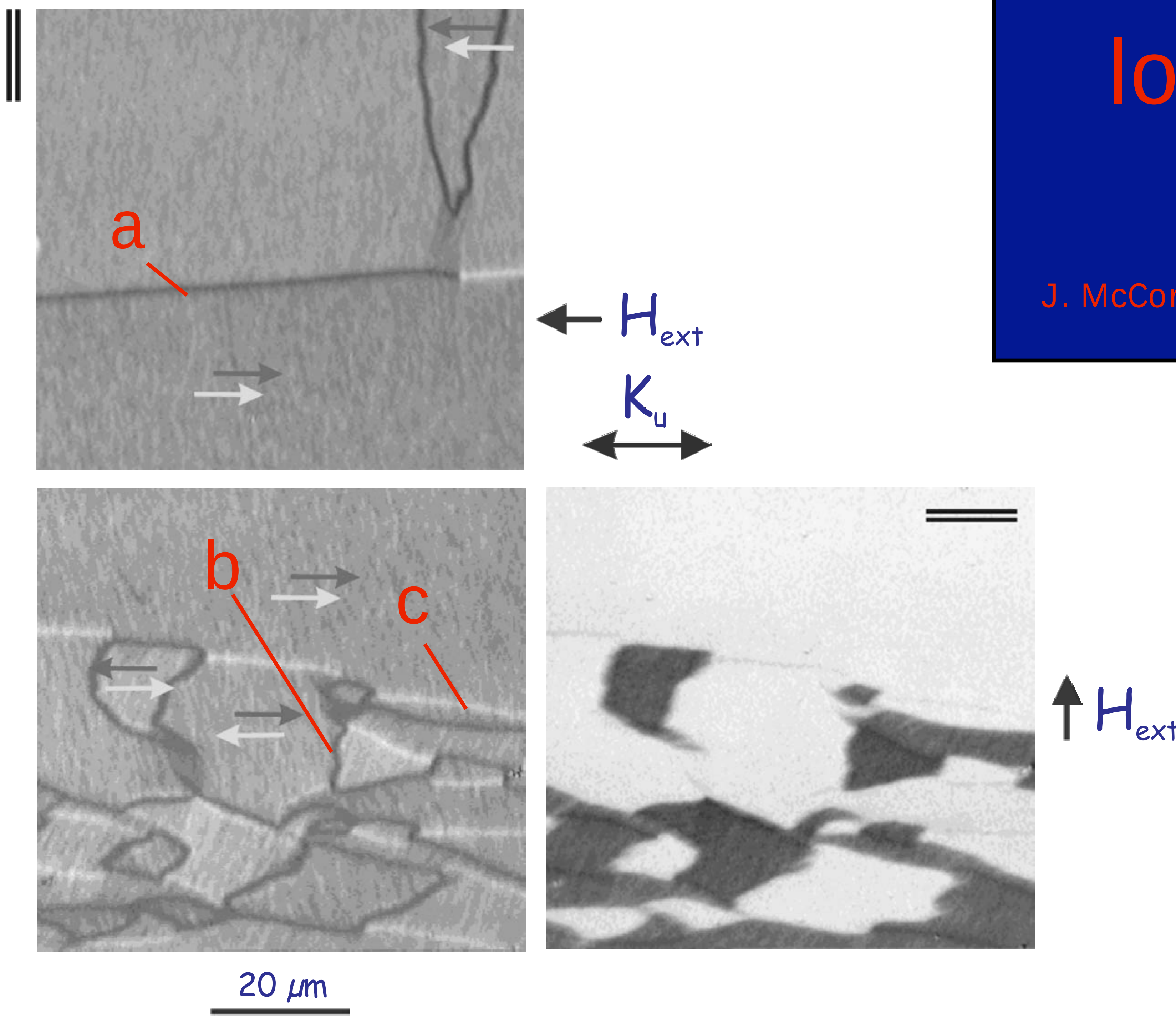
J. McCord, J. Westwood, Journal of Applied Physics 87, 6502-6504 (2000)



- different kind of domain walls in thin films (FeN)
- domain wall transformations with thickness, stack, and field

Domain walls in low coupled bi-layer films

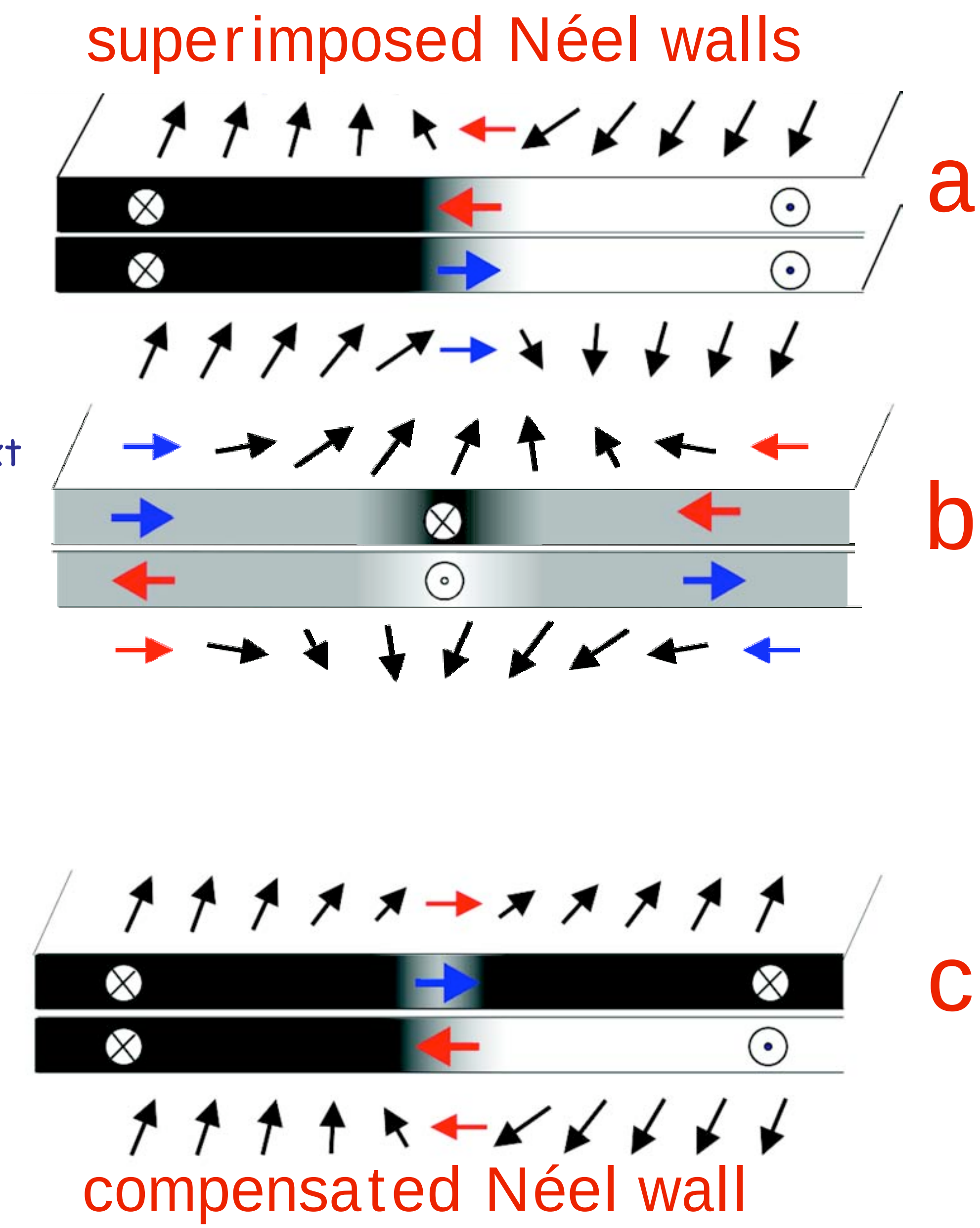
J. McCord, J. Westwood, JAP 87, 6502-6504 (2000)



top layer magnetization

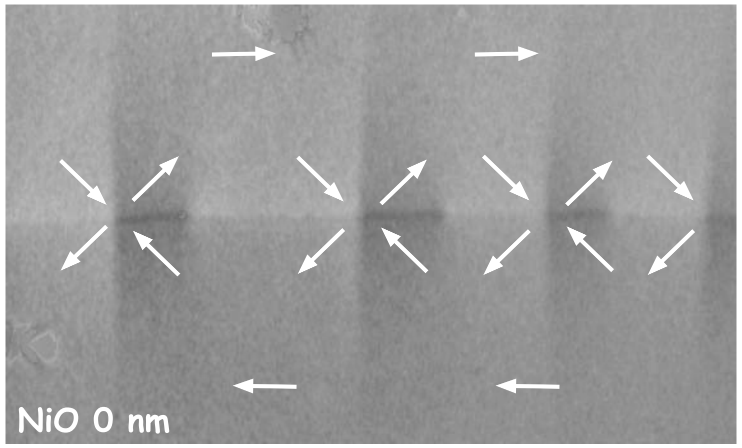
bottom layer magnetization

FeN (50 nm)/ Al_2O_3 (5 nm) / FeN (50 nm)

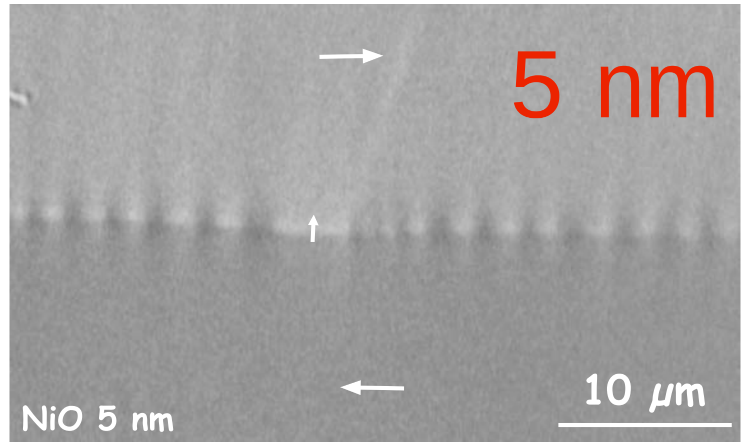


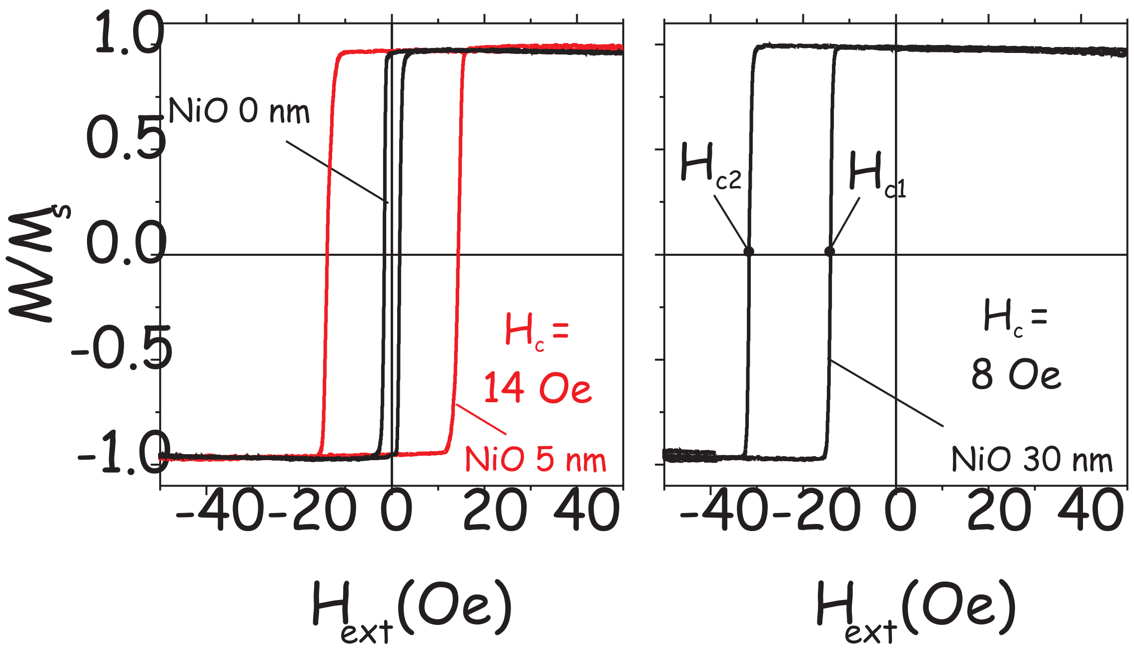
Domain walls asymmetry in EB bi-layers

J. McCord, submitted

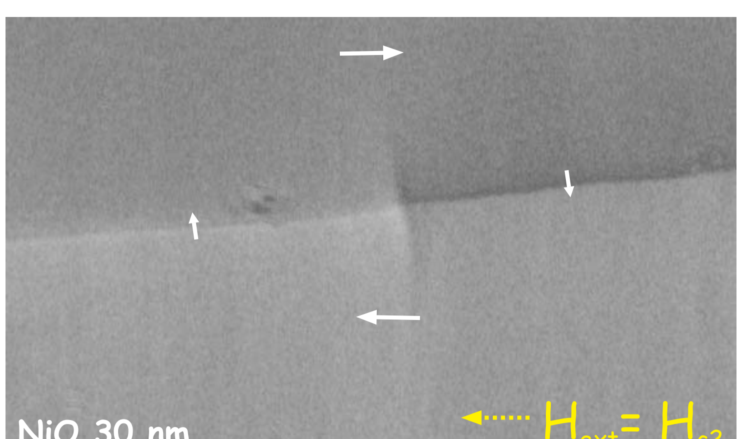


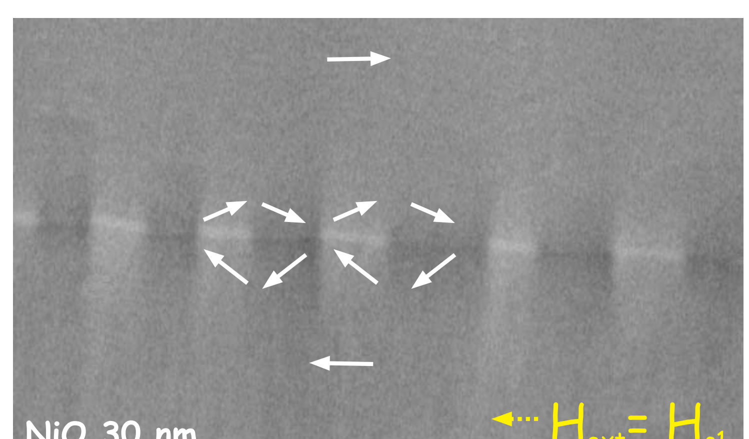
0 nm





30 nm





30 nm

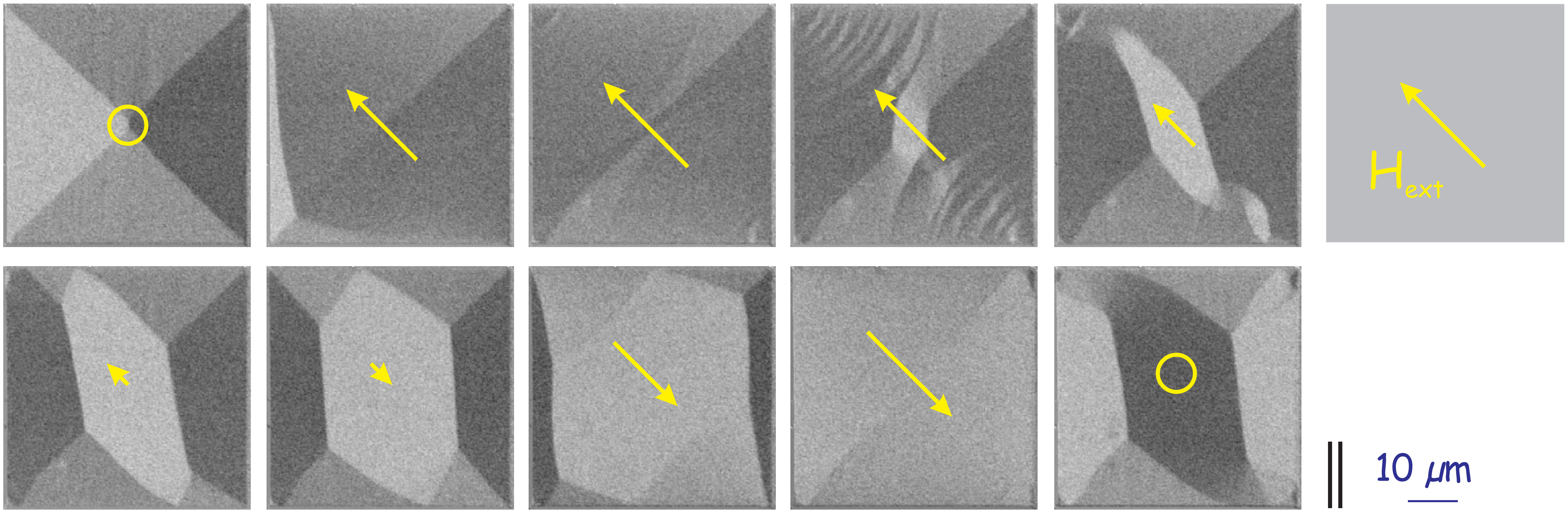
- NiFe(30 nm)/NiO (0 nm, 5 nm, 50 nm)
- change in cross-tie period ~ effective anisotropy
- asymmetric domain wall structure

Patterned samples ...

... including magnetically patterned samples ...

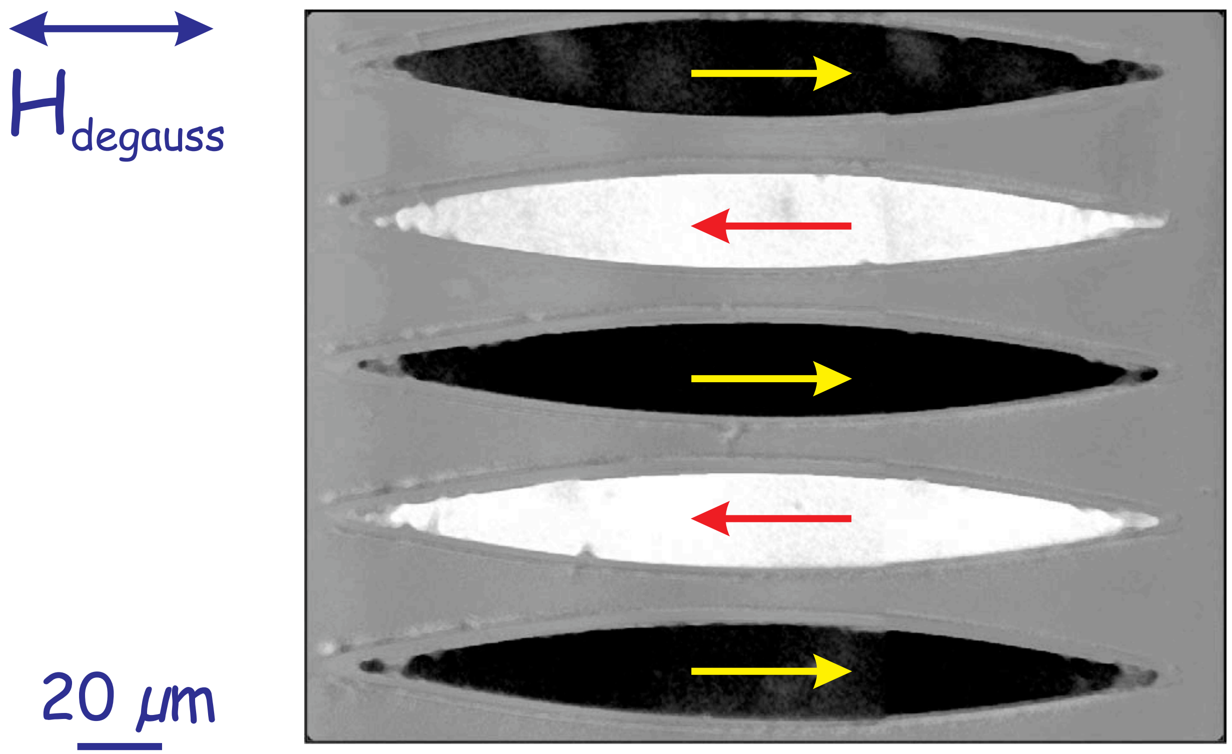
Reversal in patterned elements

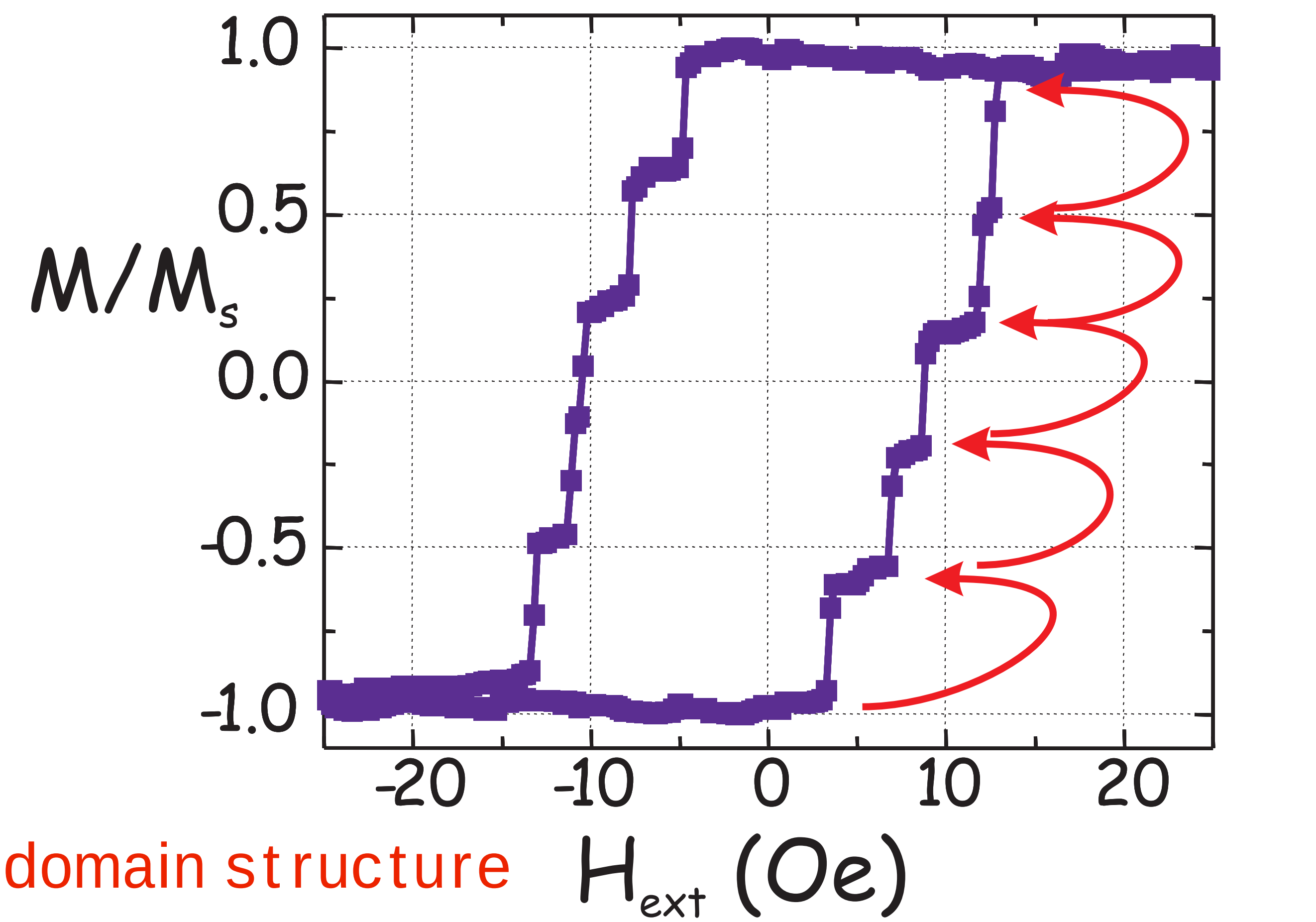
$Ni_{81}Fe_{19}$ 200 nm



- residual vertical anisotropy
  - domain wall motion with increasing field
  - concertina development and breakdown with again decreasing field

Multi-step reversal in pointed elements



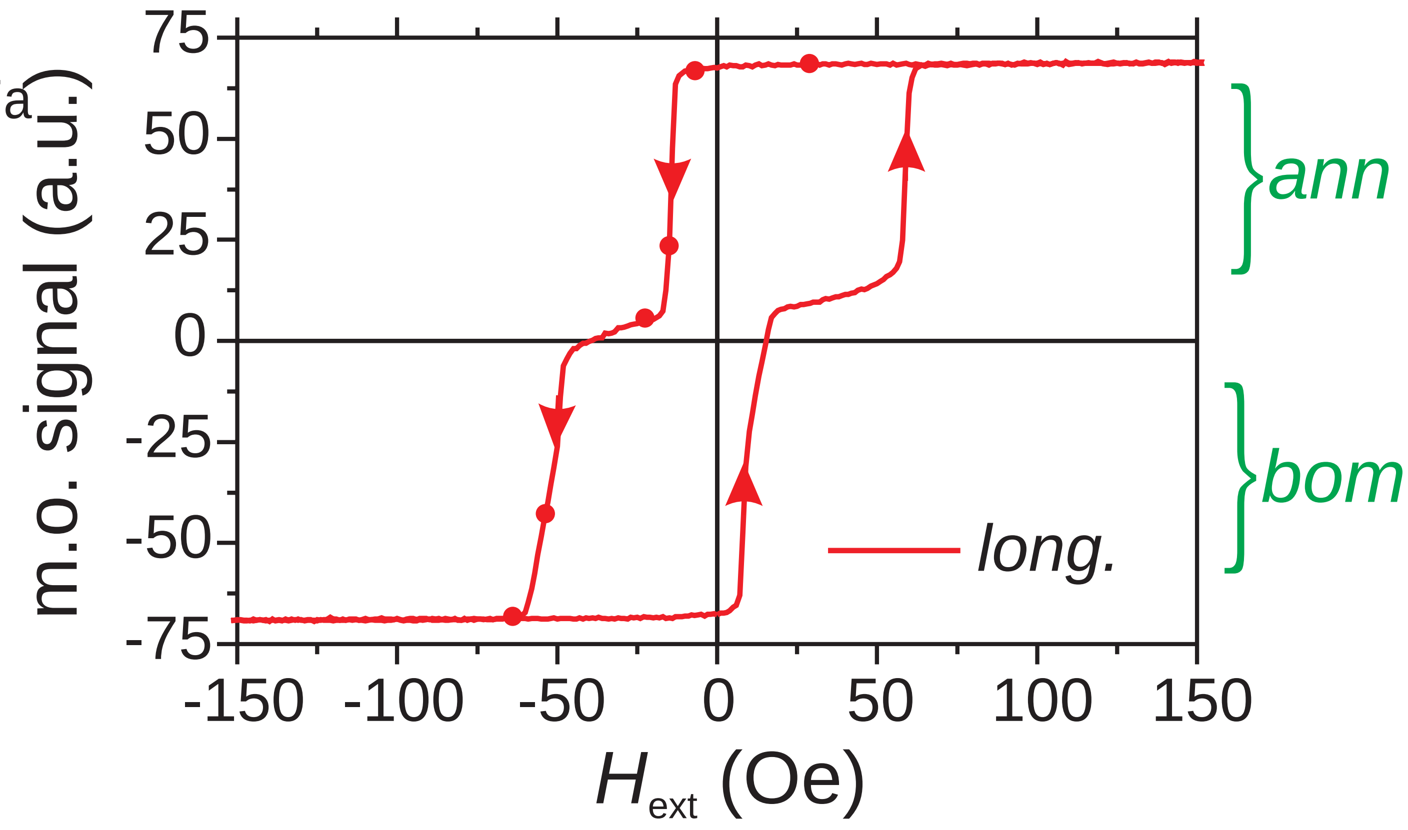


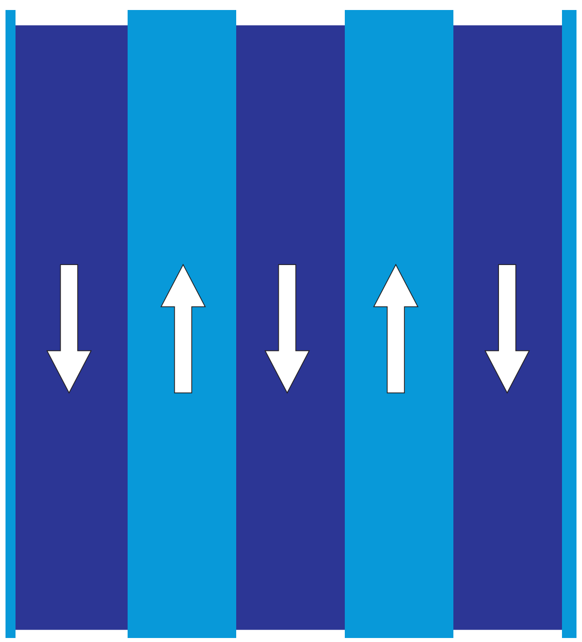
simultaneous measurement of hysteresis and domain structure

- $Ni_{81}Fe_{19}$ elements (160 nm)
- “single domain” behavior (large size!)
- element by element switching

Opposite exchange bias

J. McCord, K. Theis-Bröhl, et al., JAP 97, 10K102 (2005)

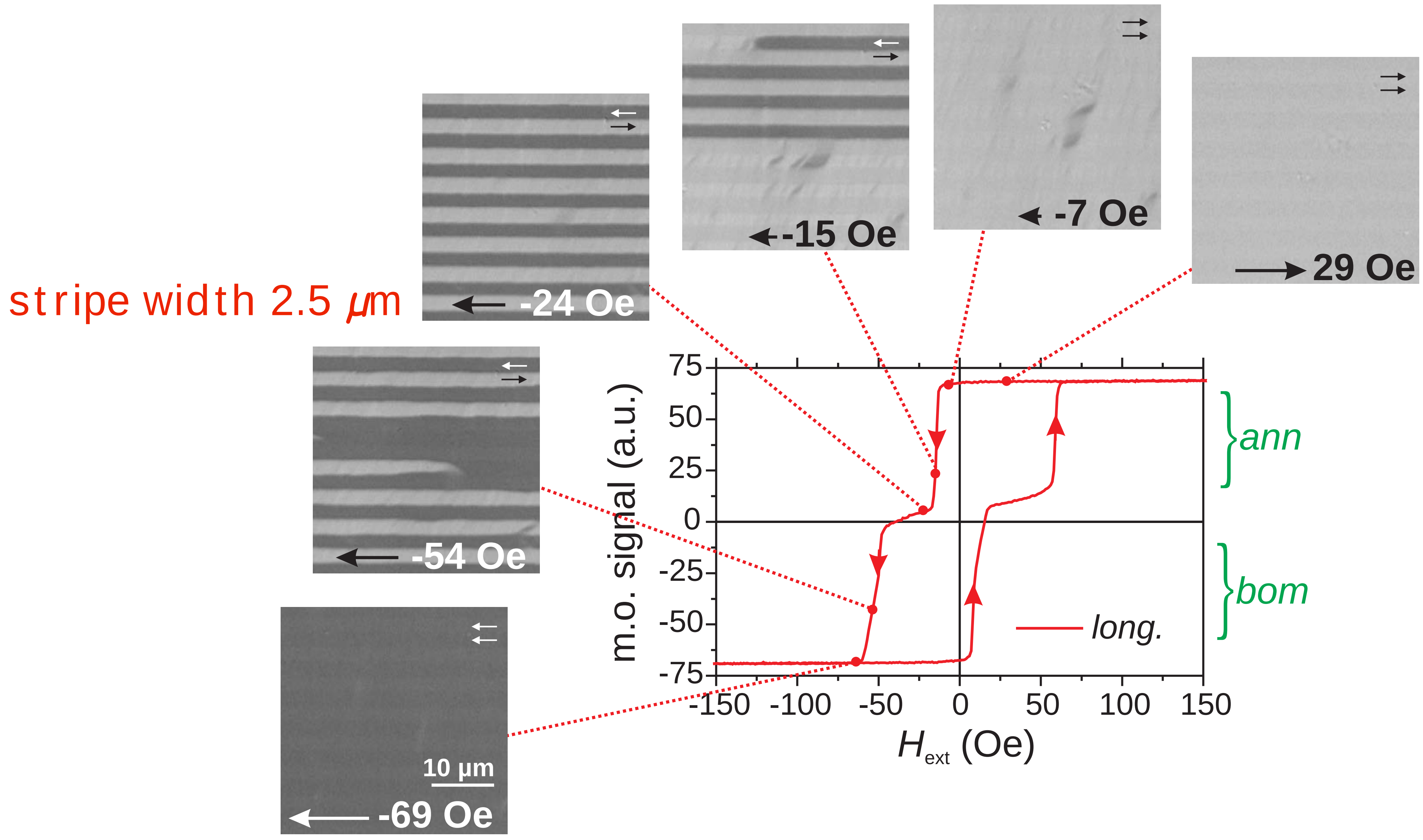




- Si/SiO_2/Cu(30nm)/$Ir_{17}Mn_{83}$(15nm)/$Co_{70}Fe_{30}$(30nm)/Ta(5nm)
- two step reversal - anti-parallel loop shift

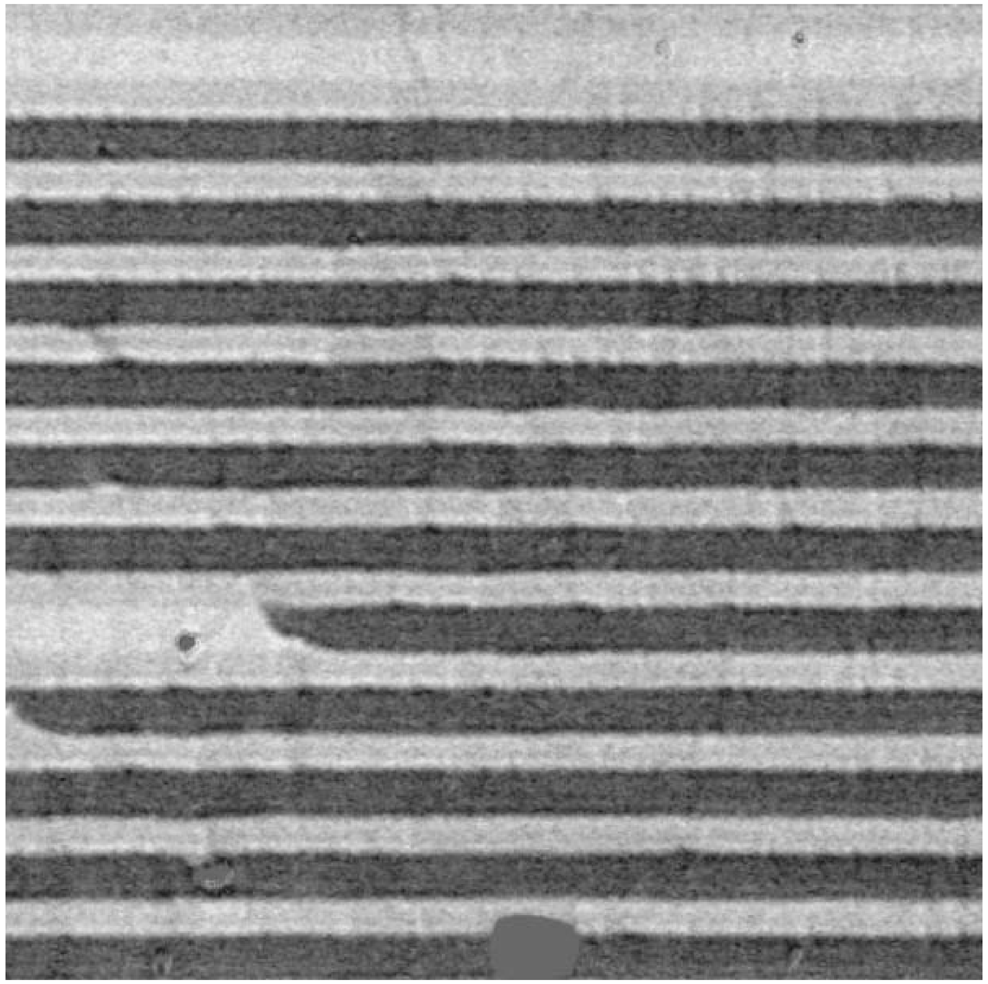
Longitudinal reversal

J. McCord, K. Theis-Bröhl, et al., JAP 97, 10K102 (2005)

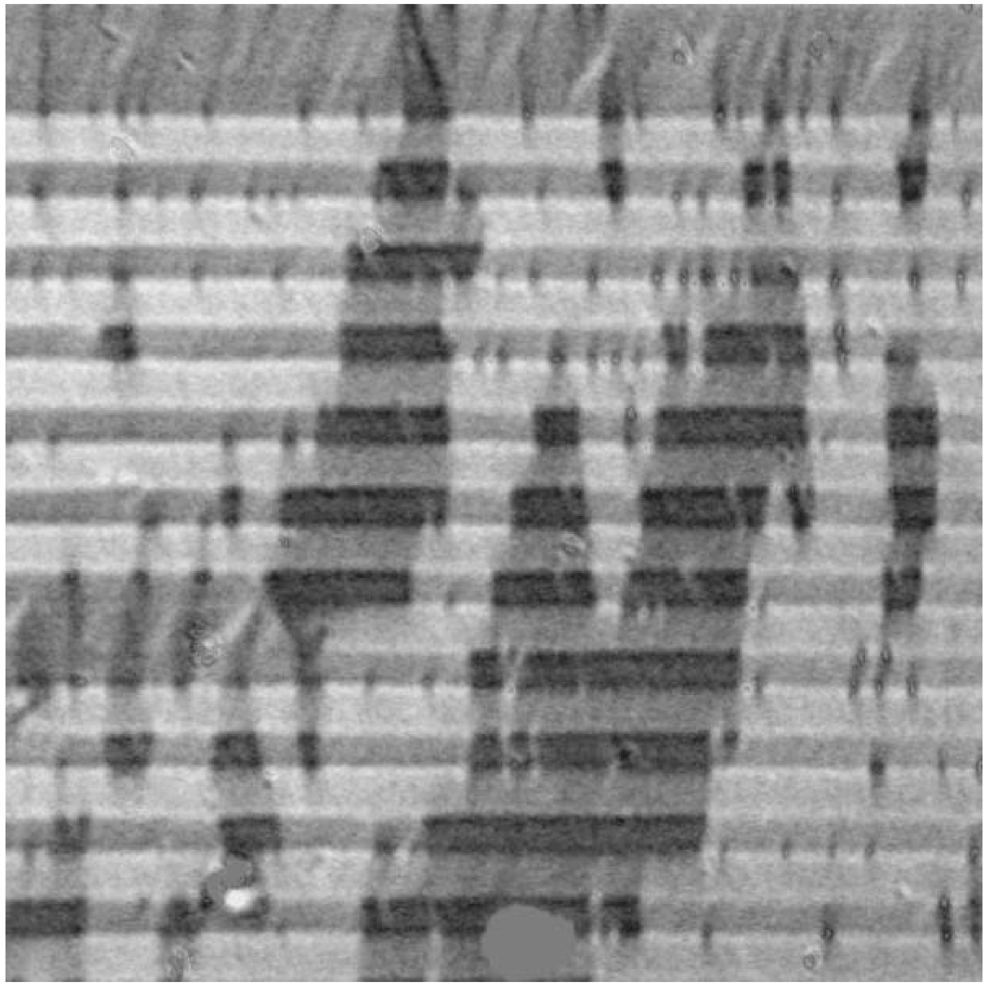


- nearly independent switching in stripes
- head-on domain wall motion
- slight modulation of magnetization at borders

Low angle domains - Néel wall tail influence



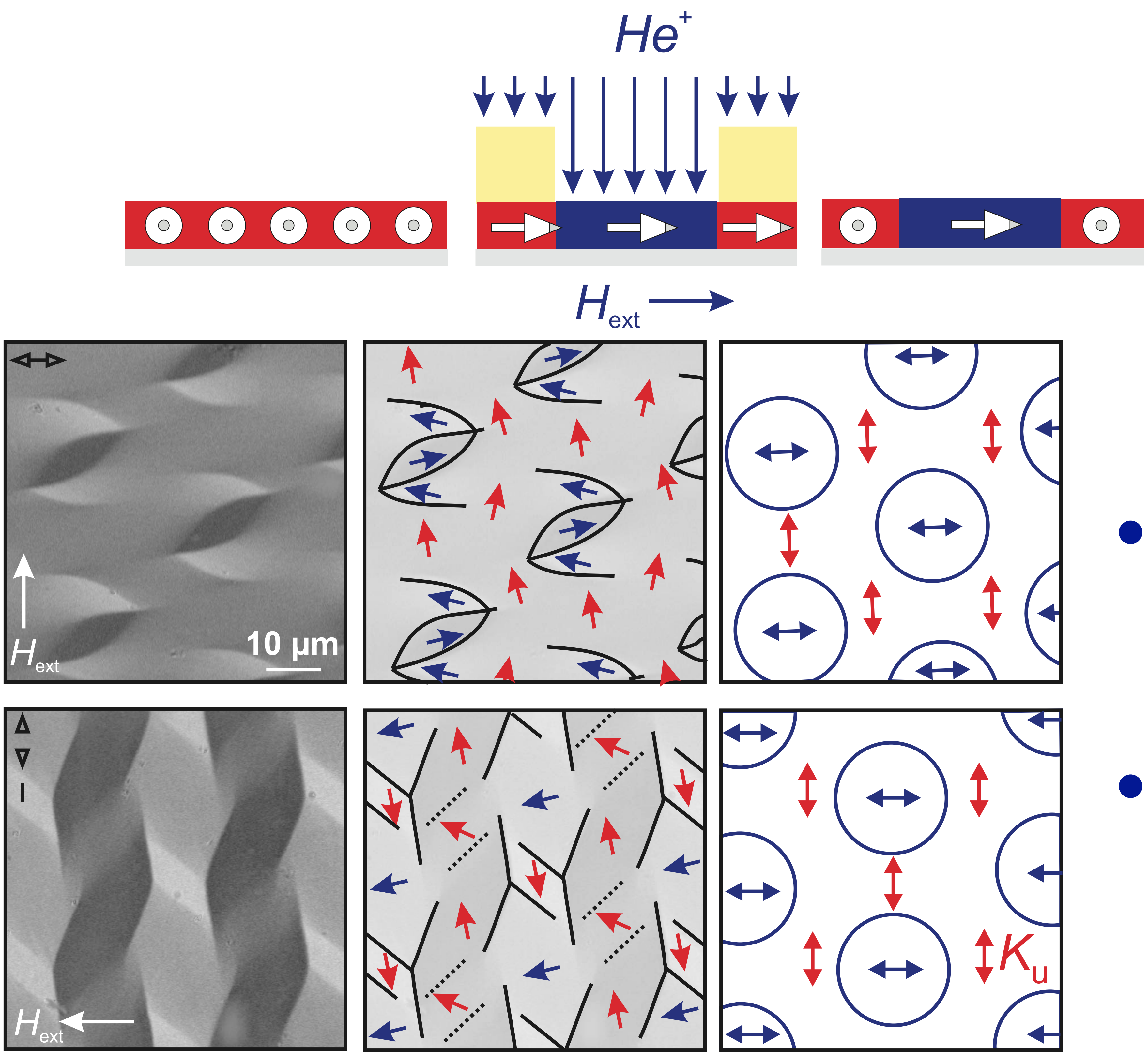
stripe width 2.5 μm



- Néel wall ensemble
- generation of low angle perpendicular domains through Néel wall tails

Anisotropy patterned samples

J. McCord, J. Fassbender, APL 86, 162505 (2005)



amorphous FeCoBSi film, 30 nm thick

- He-ion implantation assisted writing of anisotropy
- lateral modulation of domain structure

Summary on patterned samples

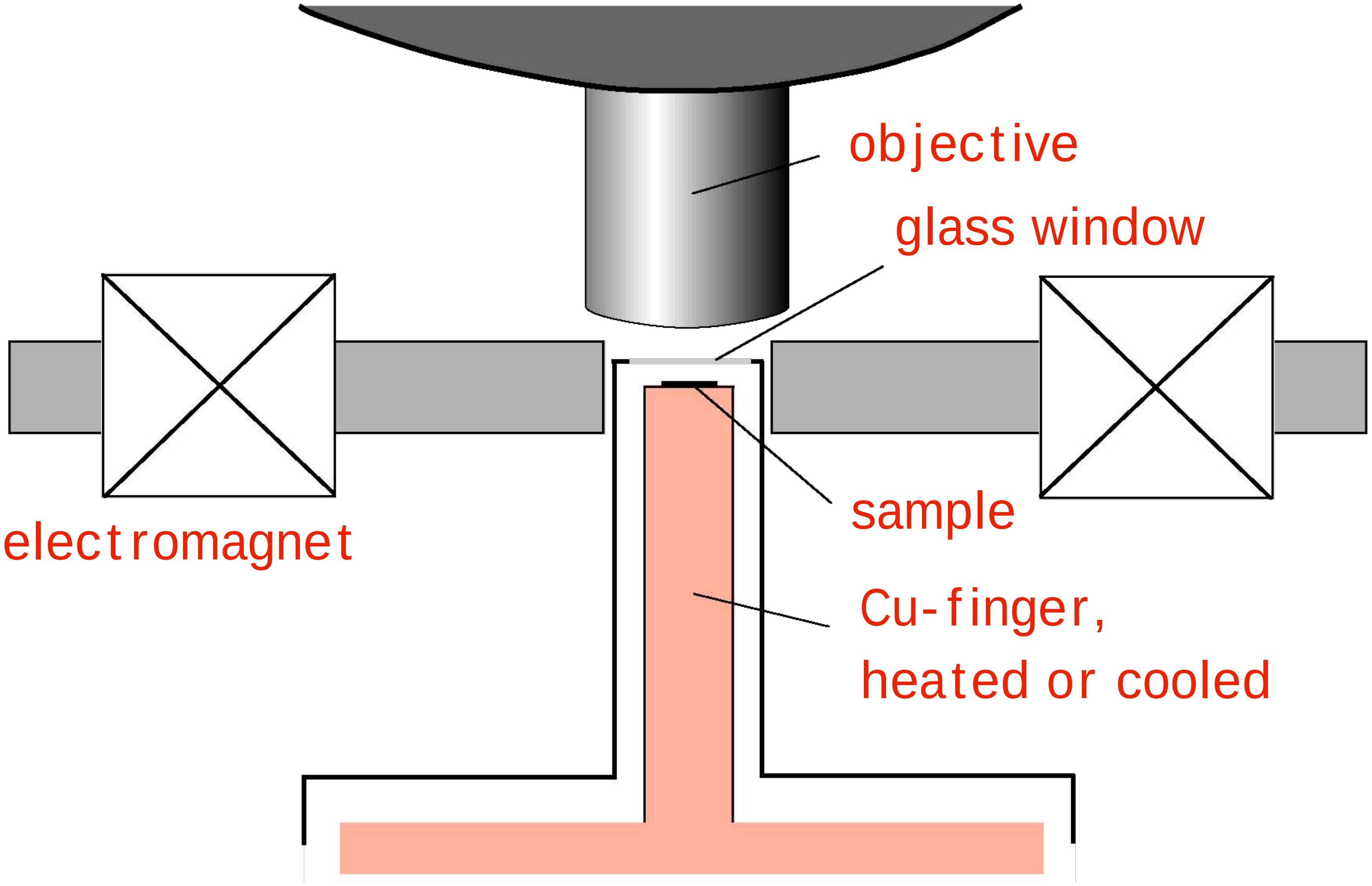
- clearly resolve domain features in
  - lithographically patterned samples
  - influence of magnetostatics (see also smaller stripes shown before)
  - local domain and domain wall features in anisotropy patterned samples

Low temperature imaging

... just two examples ...

Schematics - T dependent microscopy

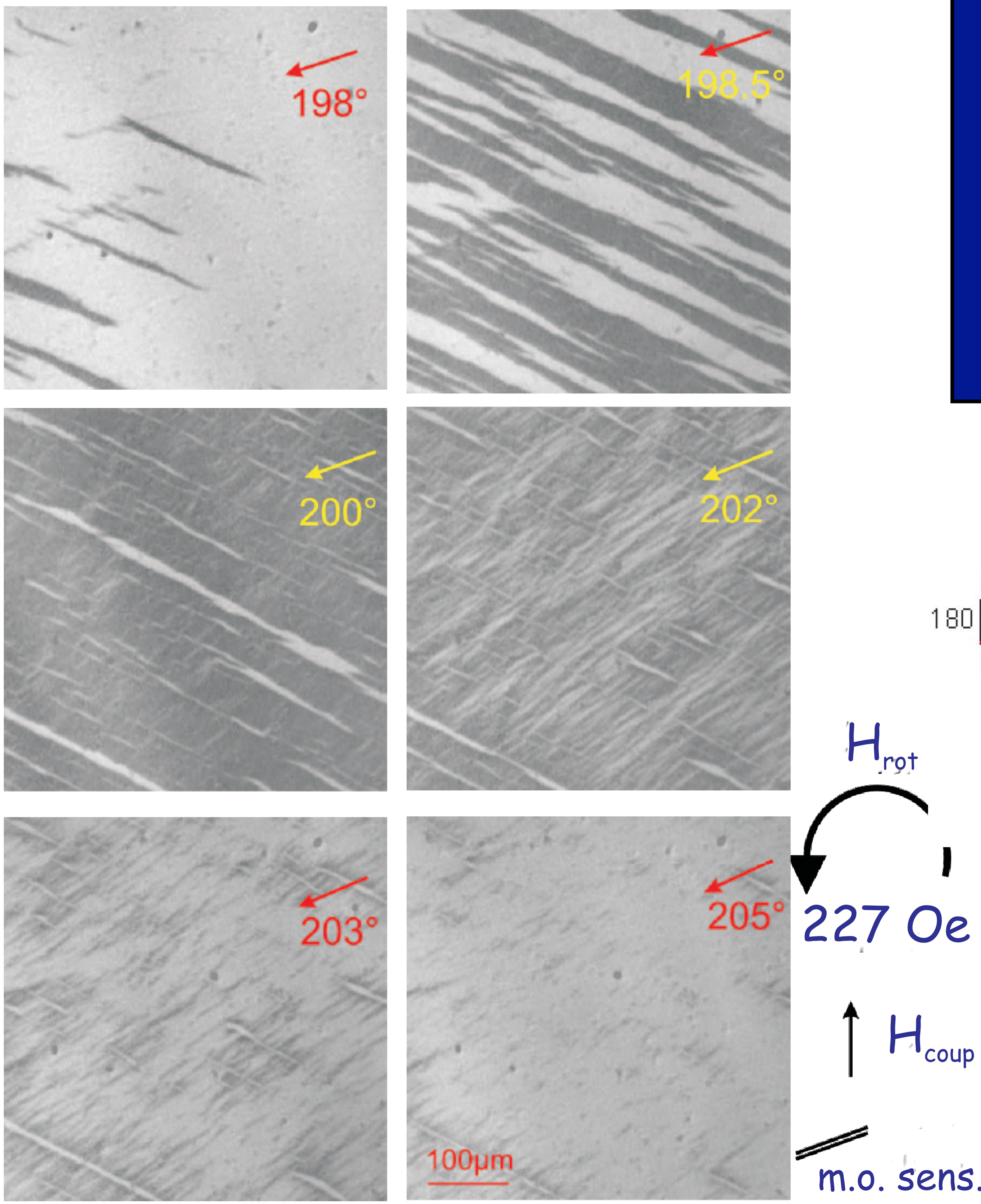
sketch, stolen from R. Schäfer, IFW Dresden



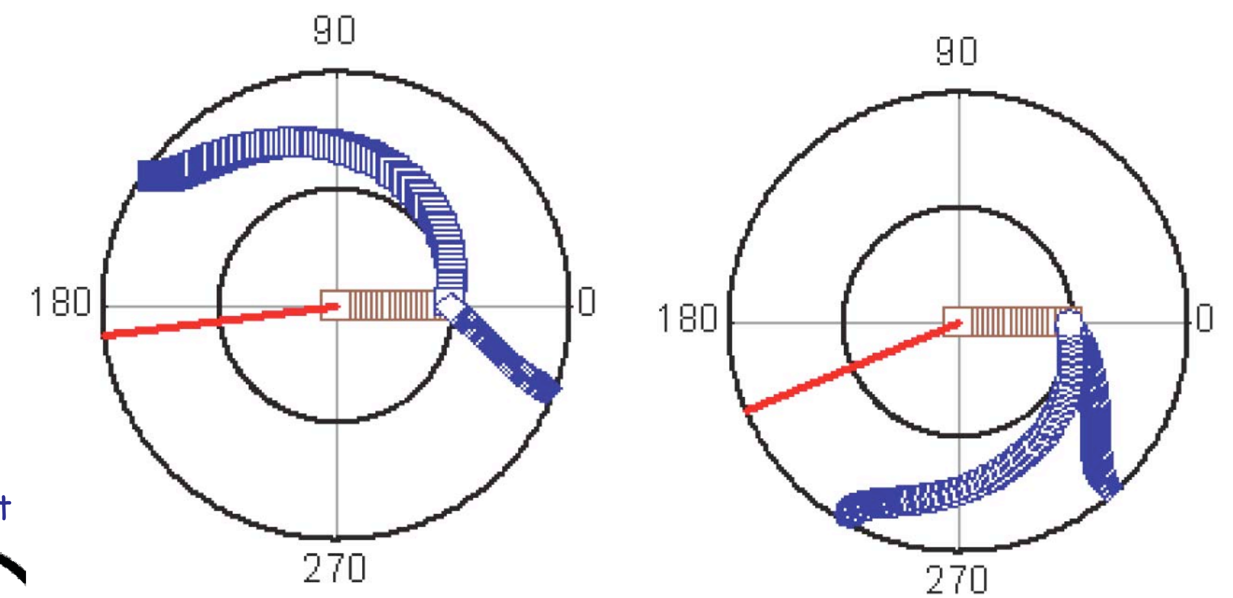
- domain observation from 10 K to 700 K
- lateral resolution (1 μm) limited due to sample-objective spacing
- additional application of magnetic field

Rotational reversal in spring magnets (@77 K)

together with S. Mangin, Uni Nancy
and Y. Henry, CNRS Strasbourg



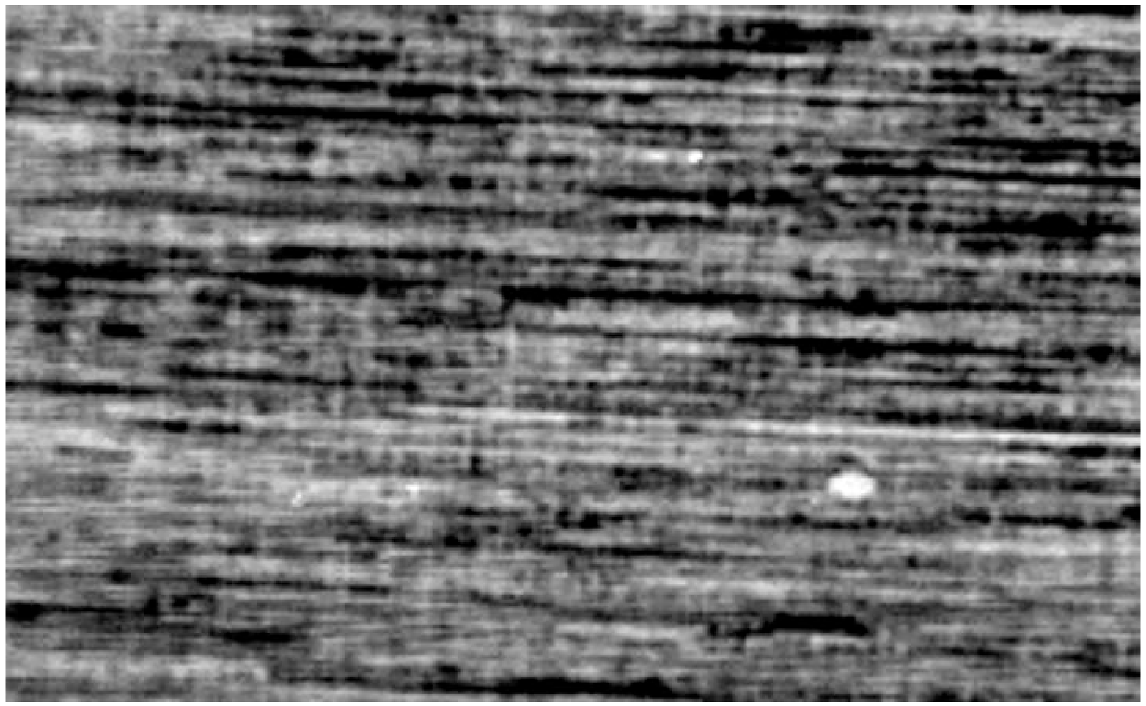
$Tb_{45}Fe_{55}$ (25 nm)/$Gd_{40}Fe_{60}$ (50 nm) @77K

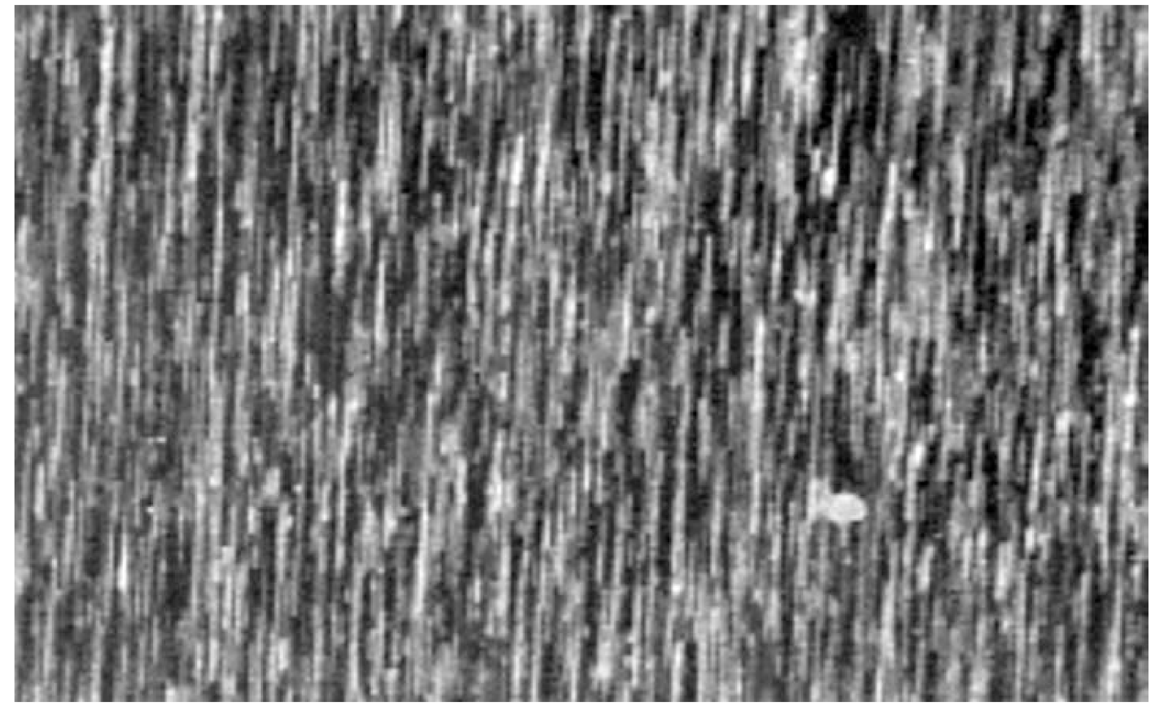


- winding and unwinding of planar domain wall
- three phases
- domain wall angles agree with net magnetization

Stripe domains in $(Ga_{0.95}Mn_{0.05})As$

sample courtesy H. Ohno, Japan





after H_{ext}

[-110]

[110]

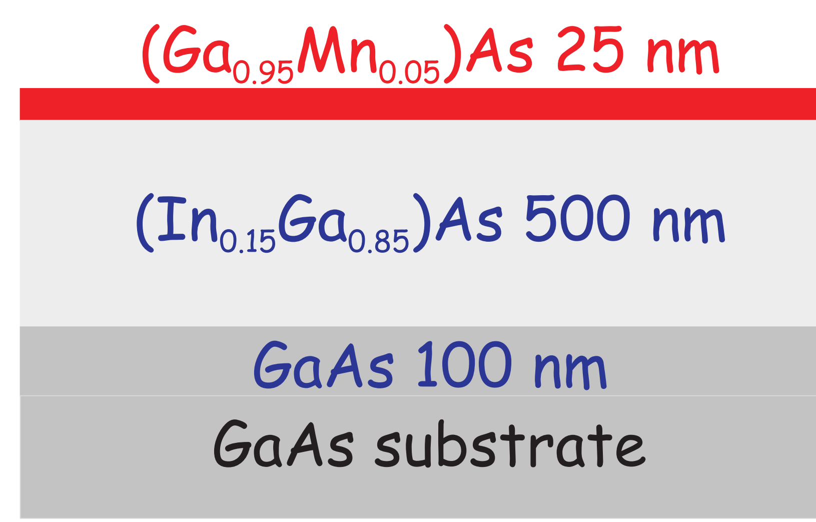
100 μm

after H_{ext}

@20 K

- dominating out-of-plane anisotropy
- additional in-plane anisotropy effects

(not investigated in detail)



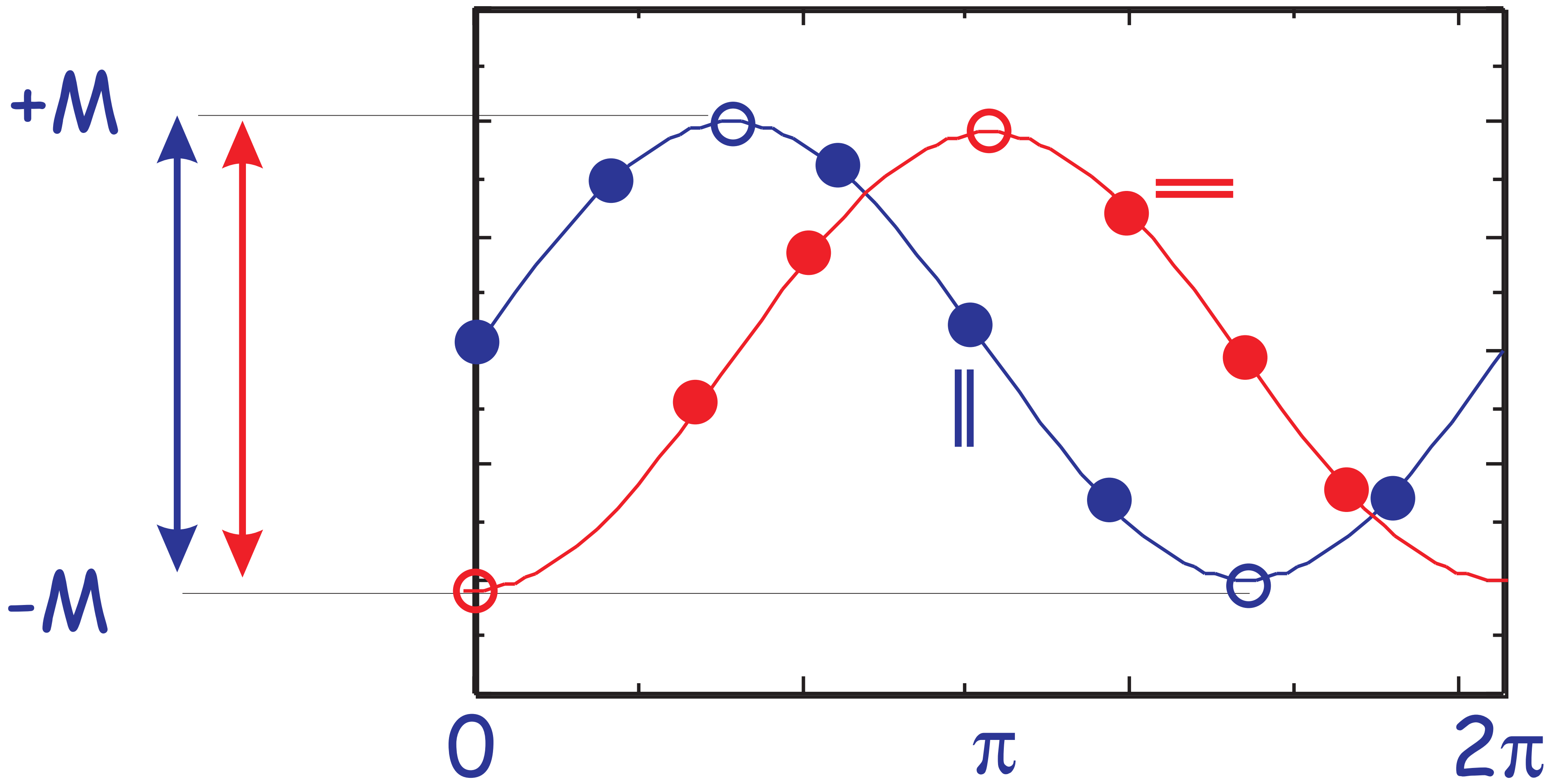
Summary on T-observations

- observations over the whole temperature range possible
- “hit” on resolution

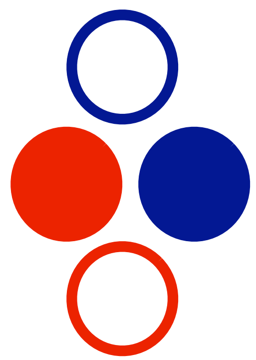
Advanced techniques (not mentioned so far) ...

... quantitative techniques, frequency analysis ...

Image calibration - M(Θ)

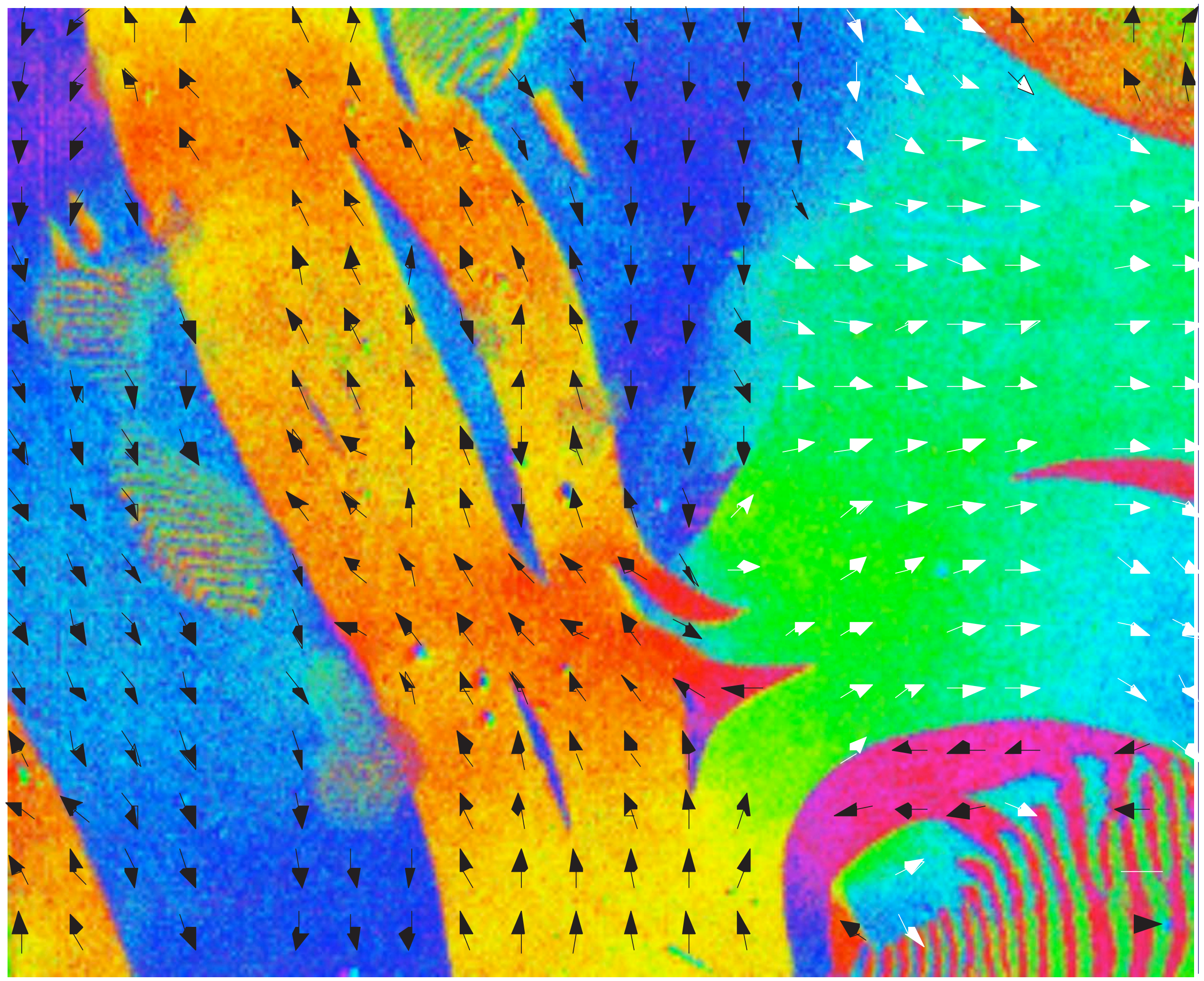


- image normalization
- determining the sensitivity function (better)
  - additional images necessary



Norm. Kerr microscopy (semi-quantitative)

J. McCord, A. Hubert, Physica Status Solidi (A) 171(2), 555-562 (1999)

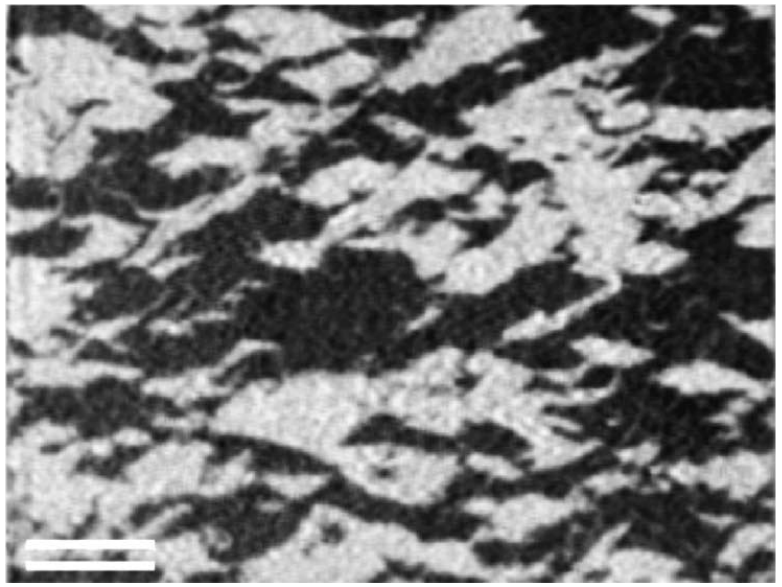


100 μm

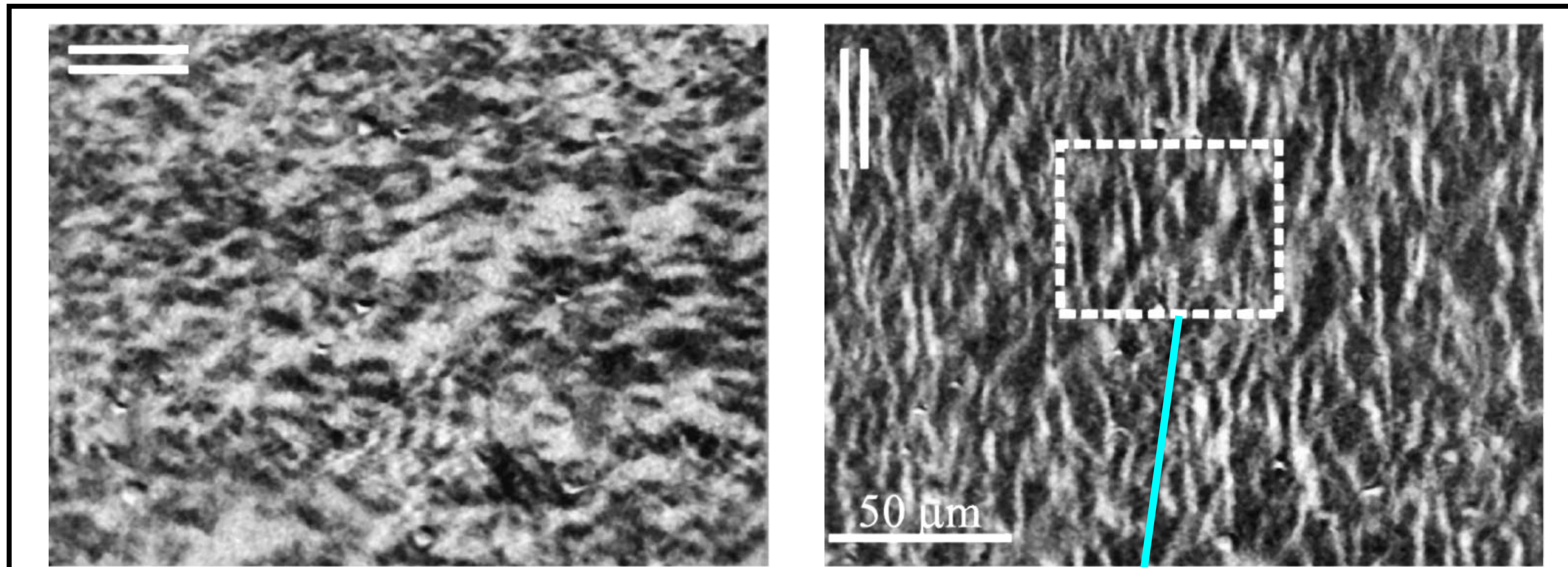
- analysis of two magnetization components
- quantitative magnetization vector representation in a metallic Fe-rich glass
  - stress dominated magnetization distribution

Thermal stability in GMR stacks

L. Baril, J. McCord et al., JAP 89, 1320-1324 (2001)

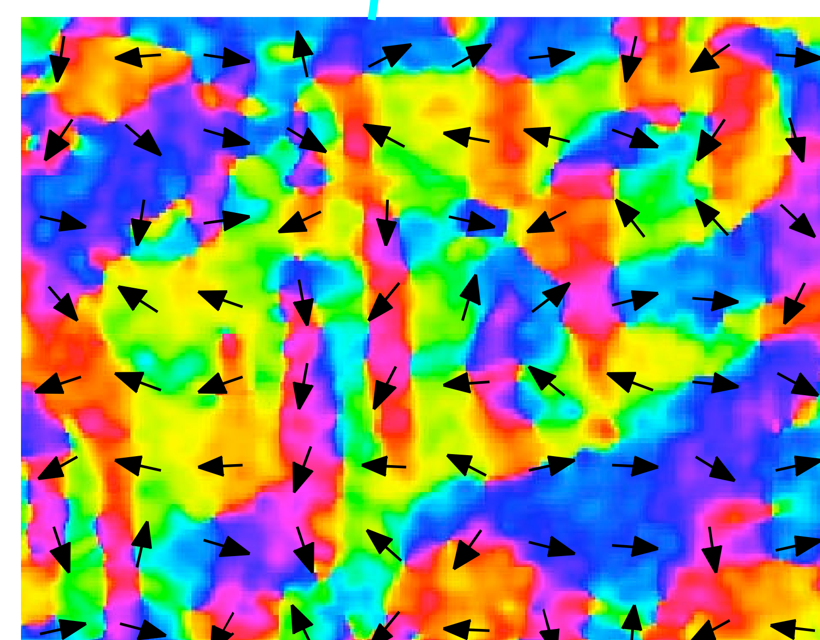


before annealing



after annealing at 200°C

↑ H_{anneal}



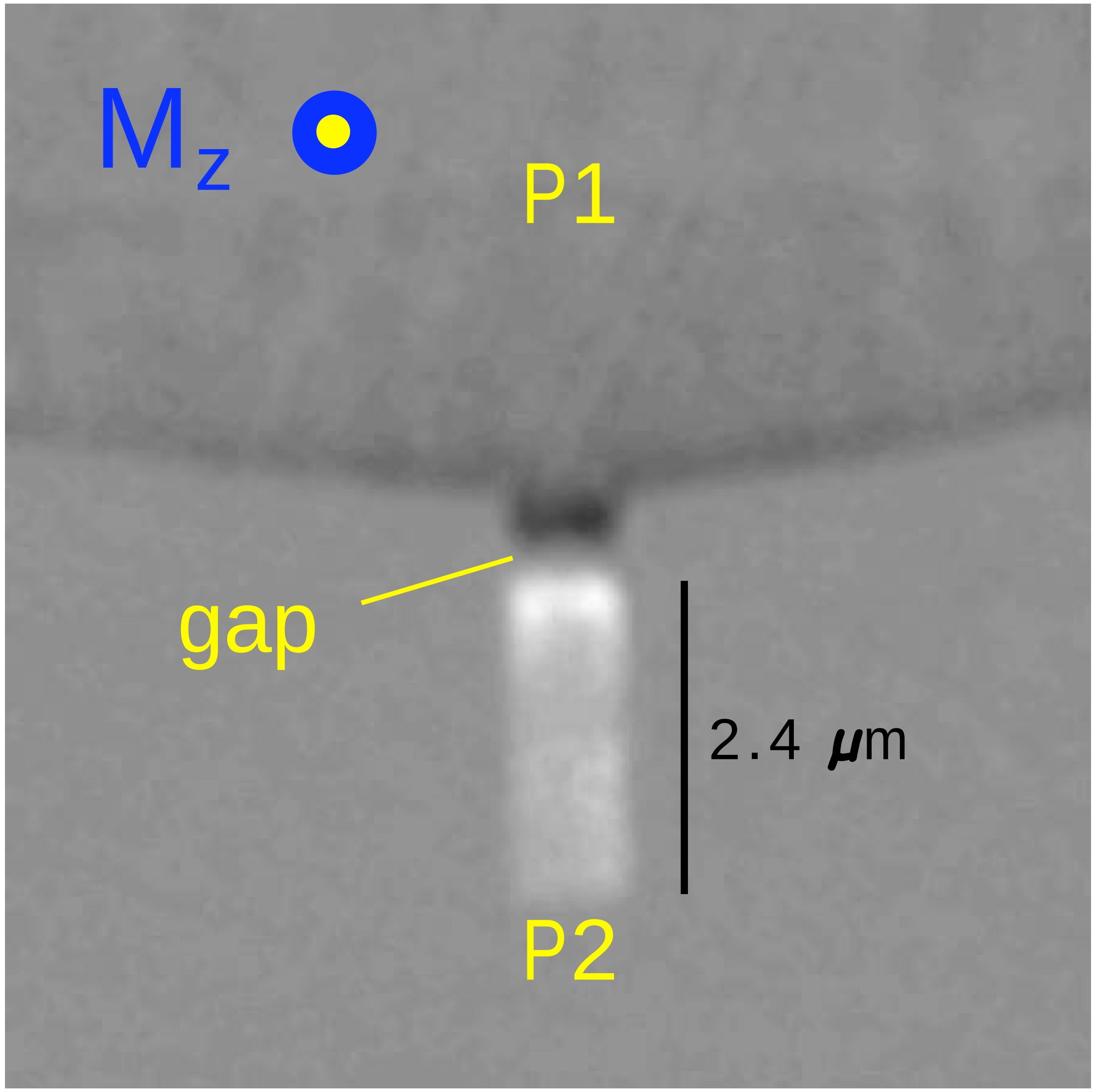
10 µm

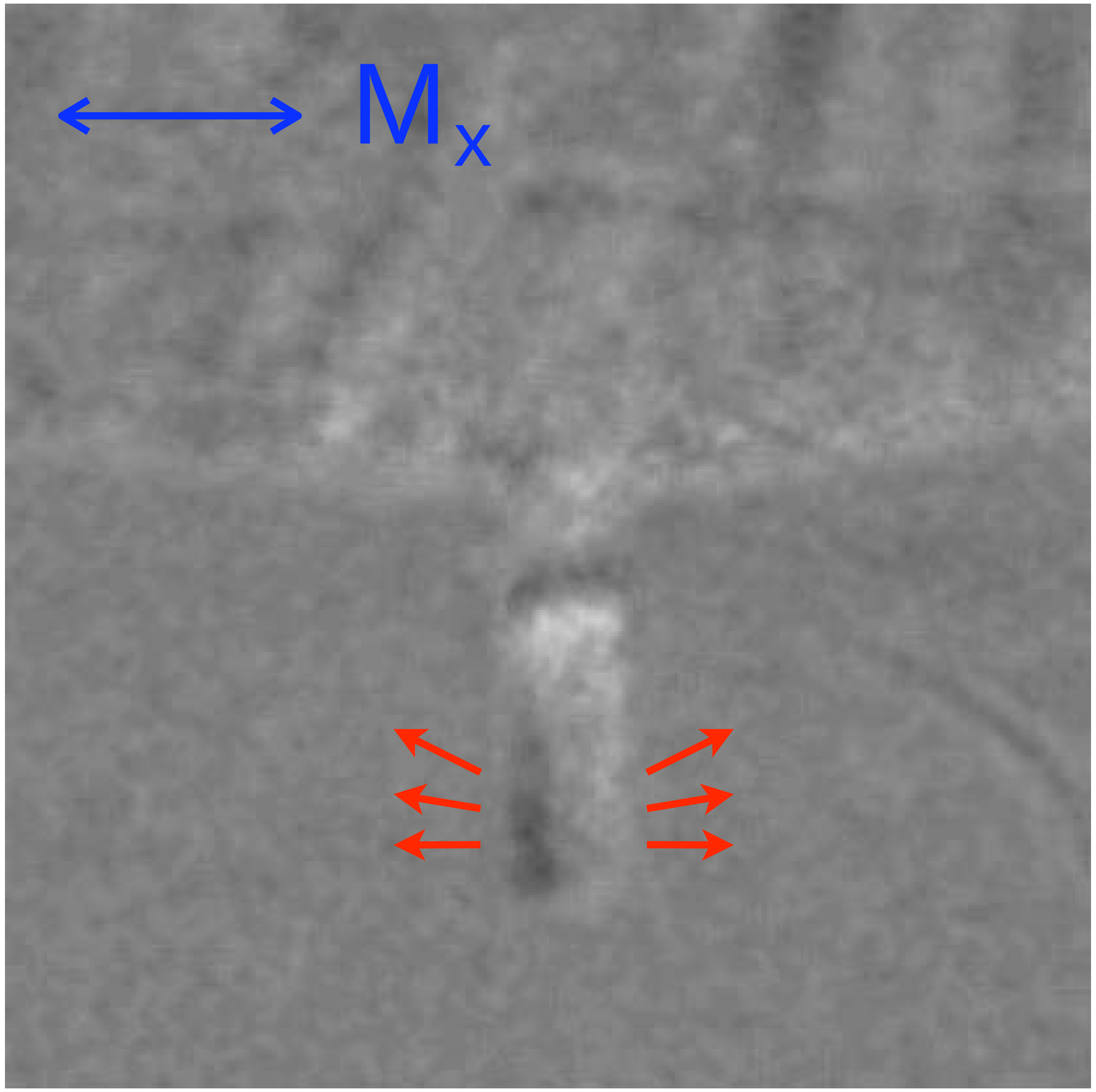
glass/NiFe(5nm)CoFe(0.6nm)/Cu (2.4nm)/CoFe(3nm)/NiMn(28nm)

- quantitative imaging
  - rotation of anisotropy and exchange bias after perpendicular field anneal below blocking temperature

Separation of longitudinal and polar signals

B. Argyle, J. McCord,
Magnetic Storage Systems Beyond 2000/ Nato Science Series: II: Mathematics, Physics and Chemistry, vol. 41 ed. G.C. Hadjipanayis (2001)

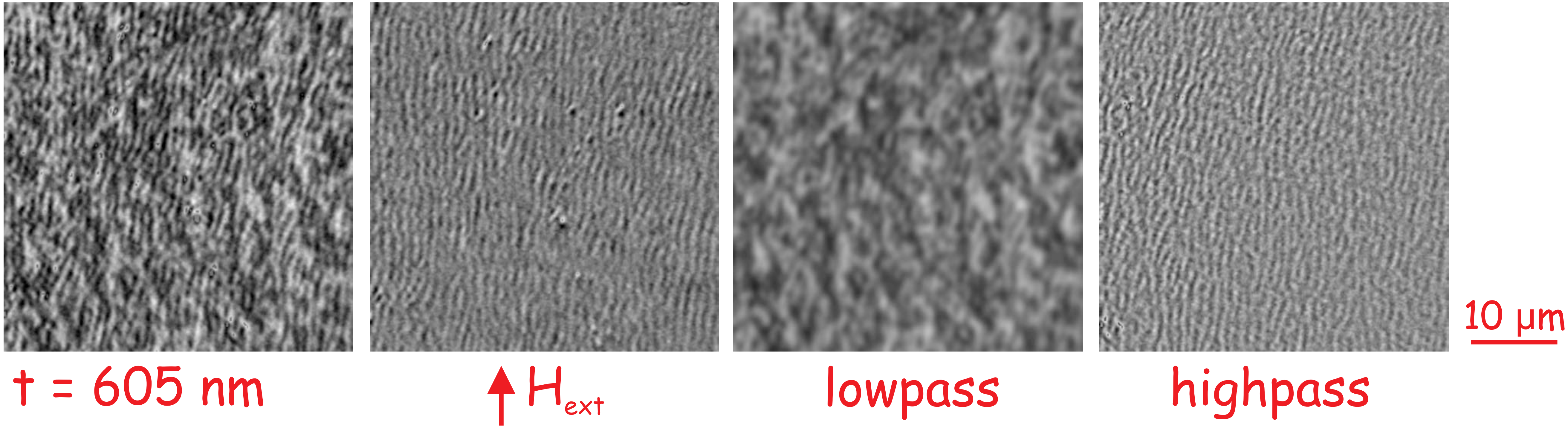




- fringing field generation in recording heads
  - adjacent track interference

Separation of mixed domain states

J. McCord, S. Dieter, et al., Journal of Magnetism and Magnetic Materials 271, 46-52 (2004)



- separation of mixed domain states by frequency filtering (FFT)
  - stress induced stripe domains
  - microstructure induced patch domains

Image processing

- more than one image of the same configuration needed
  - image normalization
  - quantitative imaging
  - separation of in-plane and out-of-plane components
- frequency analysis

Time resolved microscopy

... from minutes to picoseconds ...

Why/where is time resolution needed ...

- relaxation processes - up to minutes
- eddy-current limited switching - μsec for “bulk” samples
- magnetic precession - 10^{-9} sec

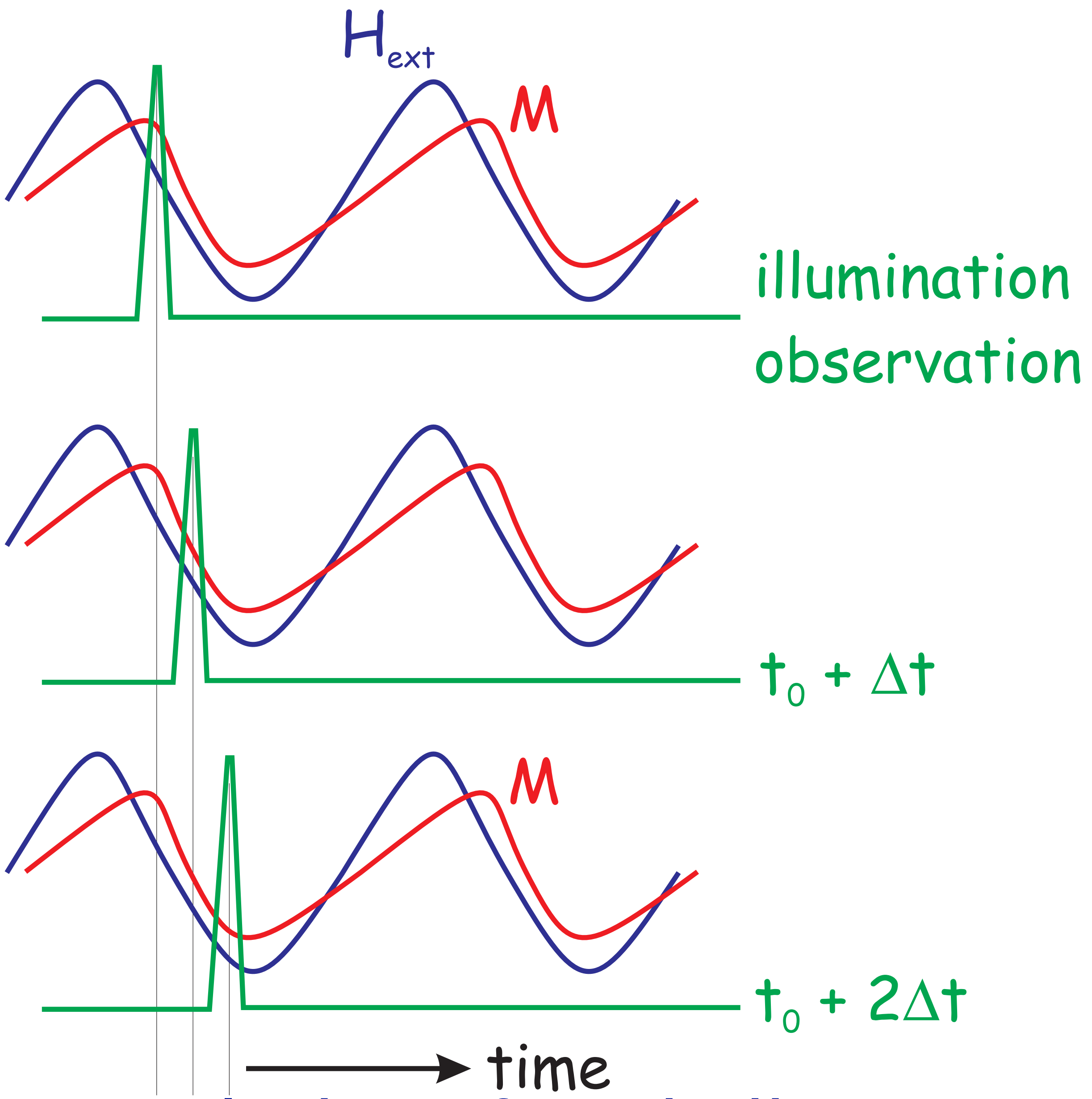
$$\frac{d}{dt}\vec{M} = -\gamma \vec{M} \times \vec{H}_{eff} + \frac{\alpha}{M_s}\left(\vec{M} \times \frac{d}{dt}\vec{M}\right)$$ LLG

Additional ingredients needed ...

- observation - camera
  - regular CCD camera @ 25 Hz - slow dynamics
  - gated intensified CCD camera - sub nsec resolution
- illumination
  - arc flash lamp - μsec
  - pulsed LED - approx. 50 psec (scanning mode)
  - mode-locked Laser based imaging - down to 10 psec
    - Laser scanning microscopy
    - Laser based wide-field imaging
- fast field excitation
- control of timing (!)

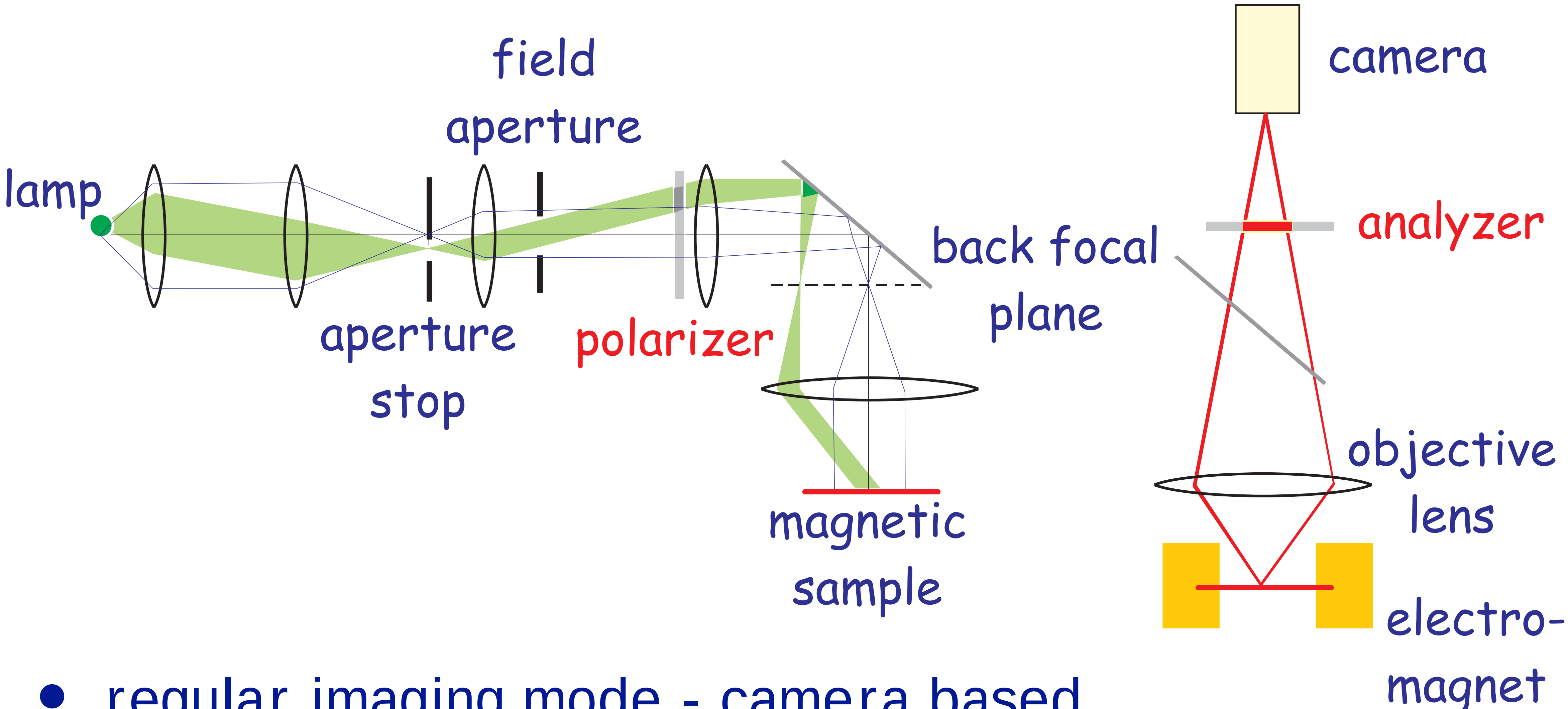
Stroboscopic imaging - high speed reversal

pump-probe approach



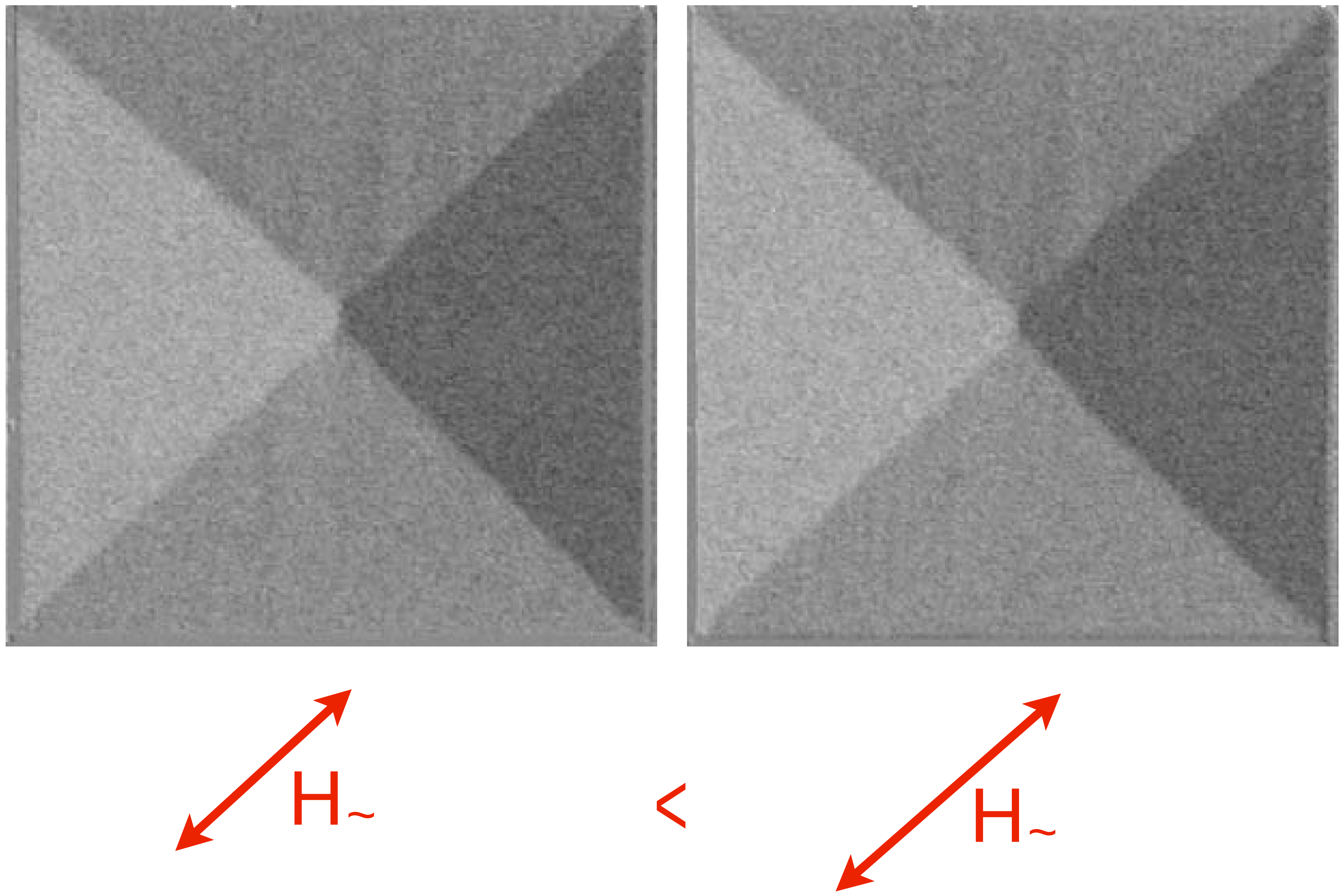
- continuous accumulation of periodic events
- time-slice through changing delay Δt
  - repetitive events needed

Time resolved wide-field imaging (I)



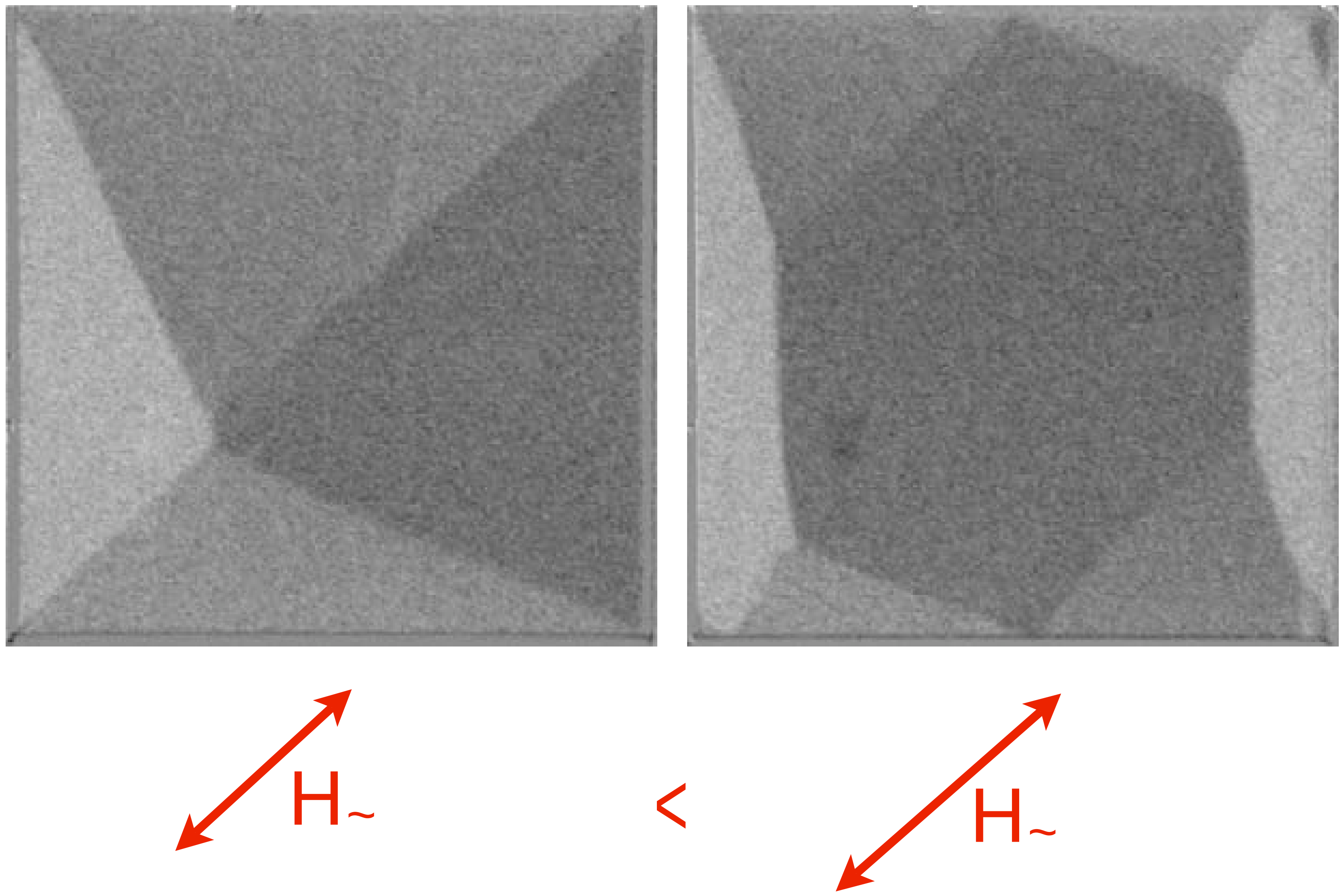
- regular imaging mode - camera based
- time-resolution variable from sec down to approx. 1/25 sec
- time-resolution down to approx. 1/1000 sec in stroboscopic imaging technique

Low speed reversal ($Ni_{81}Fe_{19}$, 240 nm)



- “Textbook” example
- “single shot” experiment
- direct observation of magnetization reversal

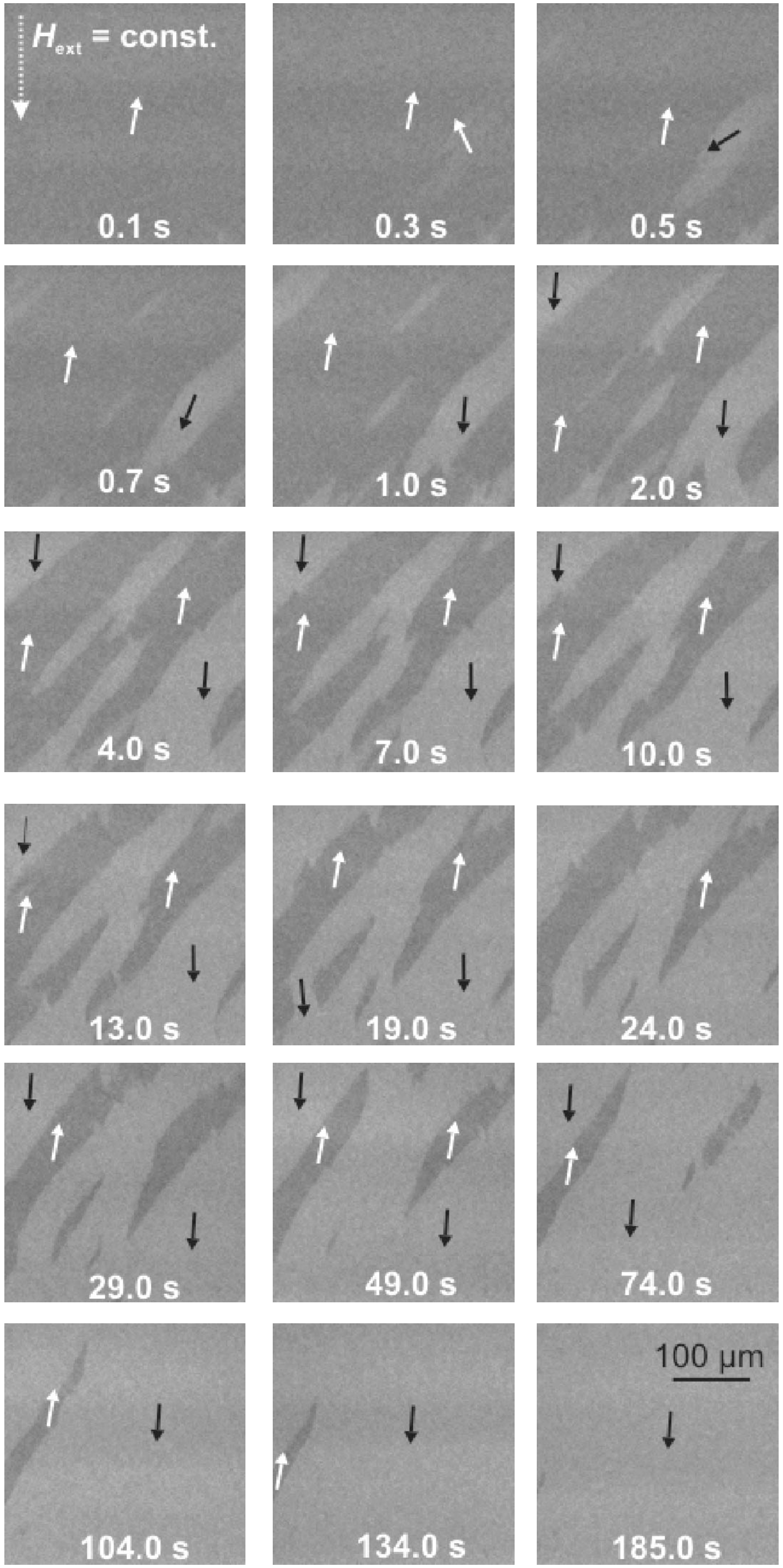
Low speed reversal ($Ni_{81}Fe_{19}$, 240 nm)

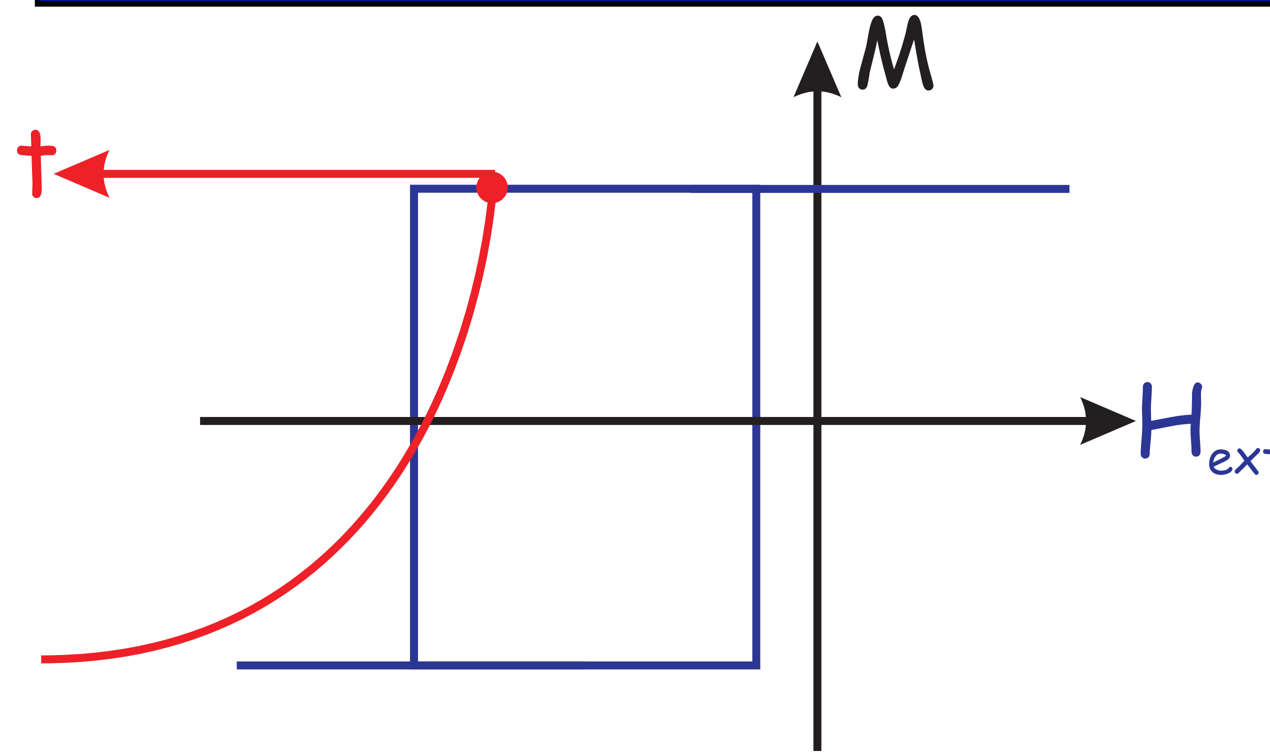


- “Textbook” example
- “single shot” experiment
- direct observation of magnetization reversal

Domain creeping in EB IrMn/NiFe

J. McCord, R. Mattheis, et al., Physical Review B 70, 094420 (2004)

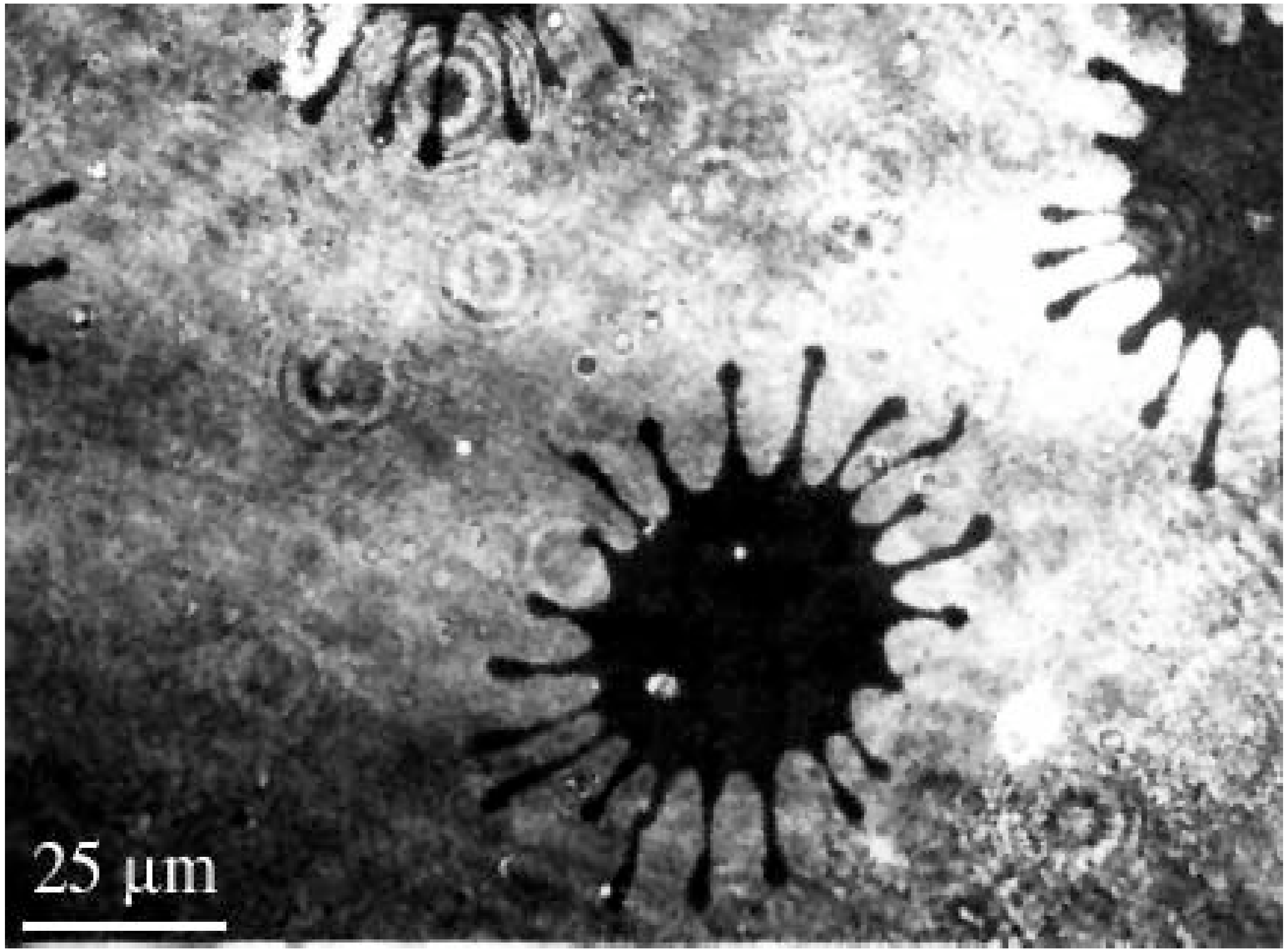




- IrMn/$Ni_{81}Fe_{19}$ (3 nm/40 nm)
- H_{ext} = const.; M(t)
- AF induced relaxation processes

History of high speed observation (I)

M. Kryder, F. Humphrey, J. Appl. Phys. 38, 829, 1969; L. Gal, G. Zimmer, et al., phys. stat. sol. A30, 561-569, 1975



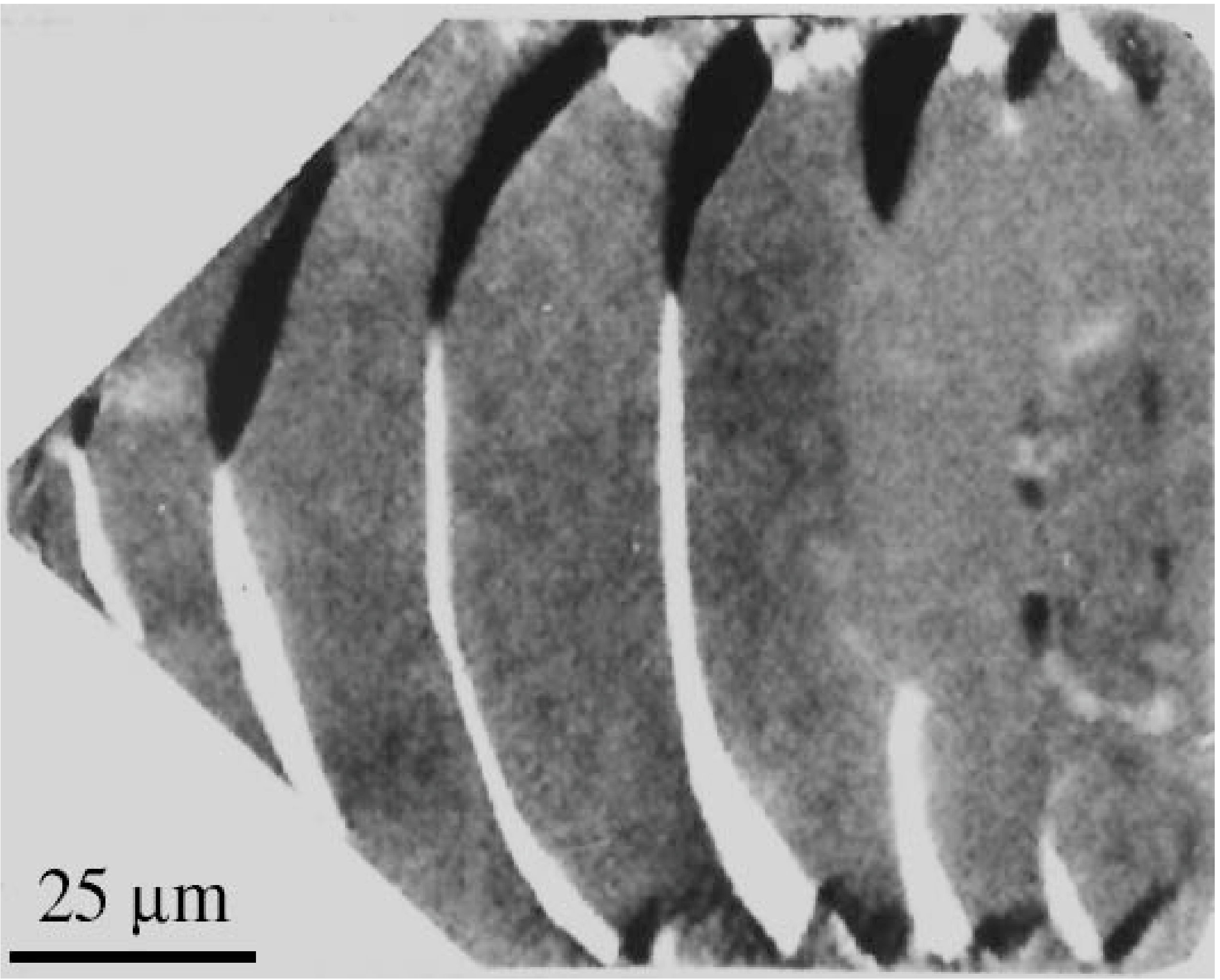
from A. Hubert, R. Schäfer, Magnetic domains (1998)

- q-switched ruby laser, dye laser
- ≈ 10 ns laser pulse-width
- magnetic bubble “explosion” in YEuTmGa-FeO garnet films

single shot image

History of high speed observation (II)

B. Petek, P.L. Trouilloud, et al., IEEE Trans. Magn. 24, 1722, 1990, Carnegie Mellon University



from A. Hubert, R. Schäfer, Magnetic domains (1998)

- Laser magneto-optical microscope "LAMOM"
- inductive recording head - $Ni_{81}Fe_{19}$ yoke
- Q-switched Nd-YAG laser ≈ 5 nsec
- "differential" imaging

Time resolved wide-field imaging (II)

camera based - intensified CCD

- time-resolution down to approx. 250 psec in stroboscopic imaging technique
- exact synchronization between magnetic field excitation and camera opening
- key element - gated image intensifier

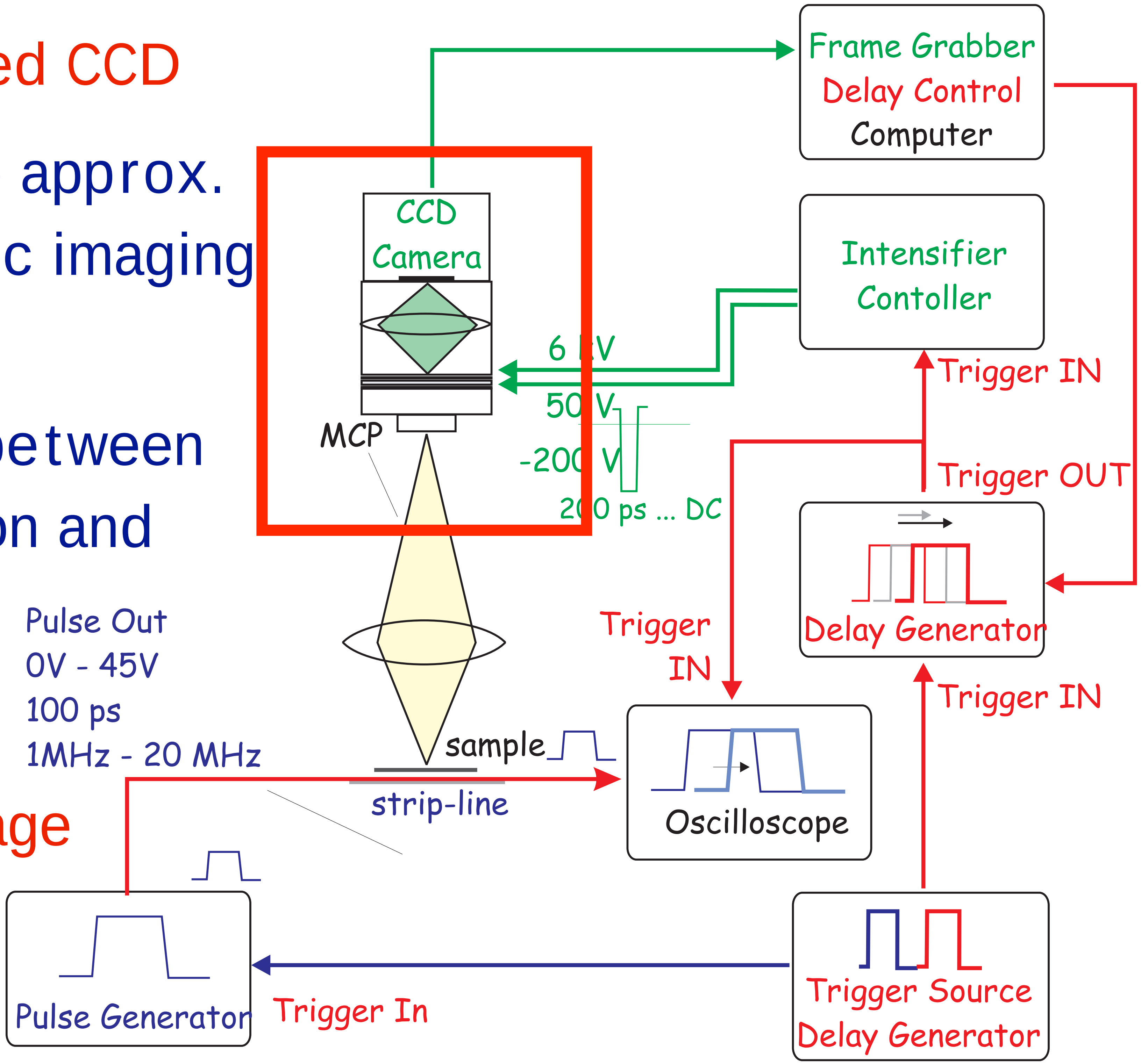
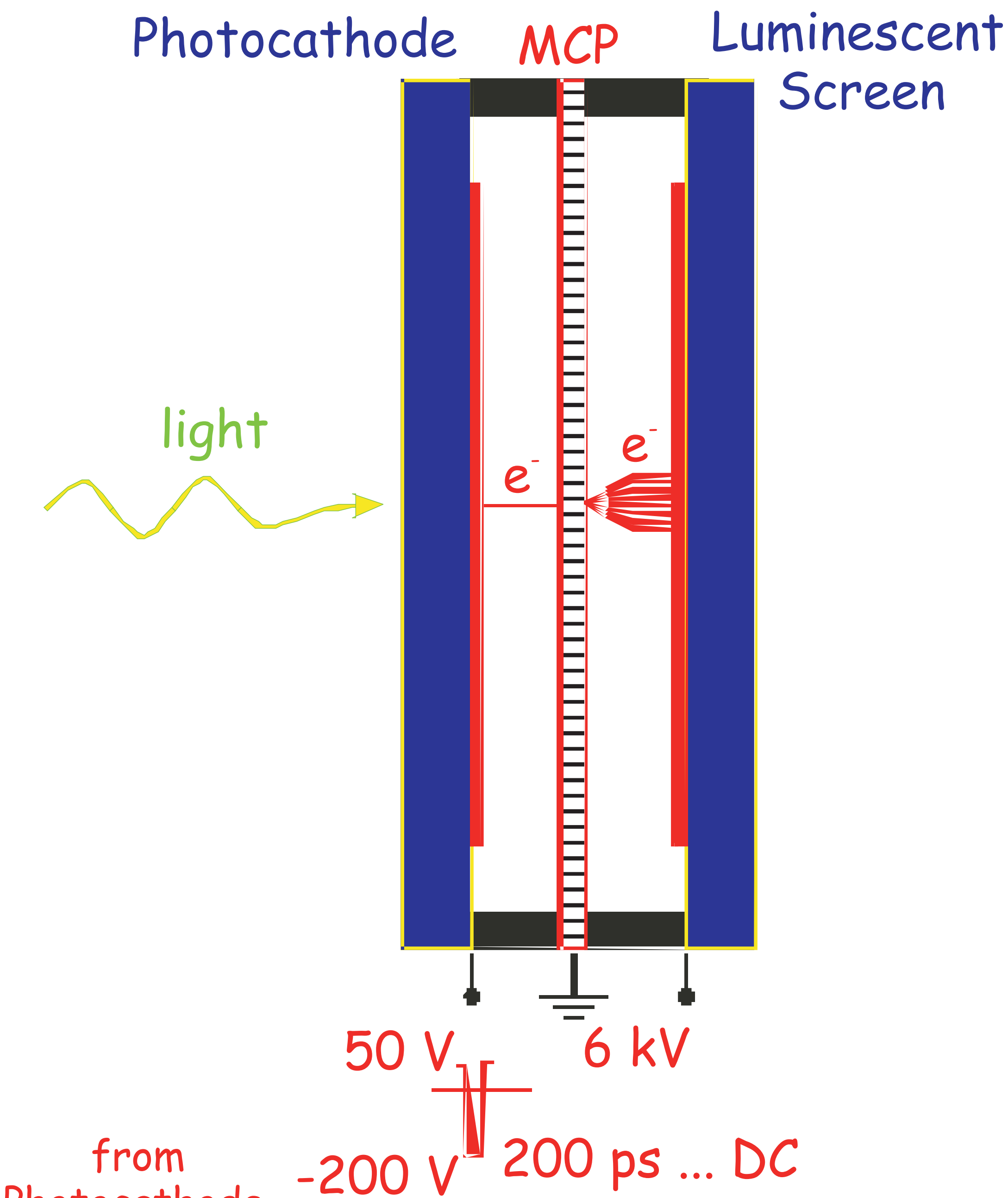
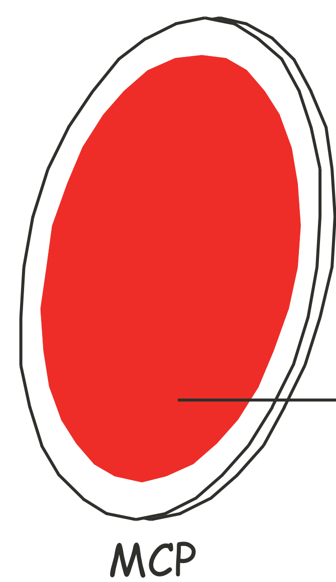


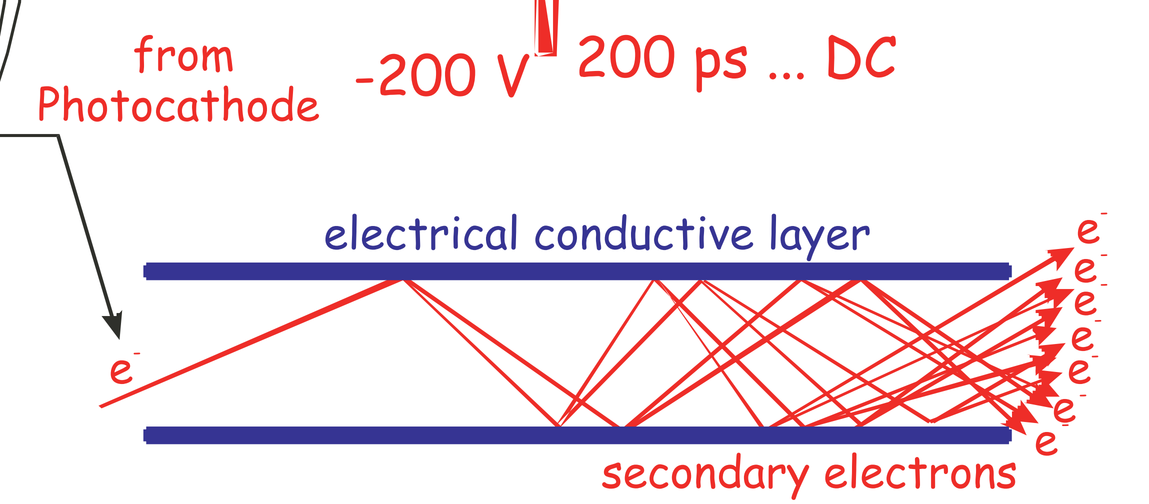
Image intensifier

gated image intensifier

- repetition rate DC ... 80 MHz
- gating time down to 200 ps
- adjusted by voltage between photo-cathode and micro-channel plate (MCP)
- micro-channel plate image intensifier



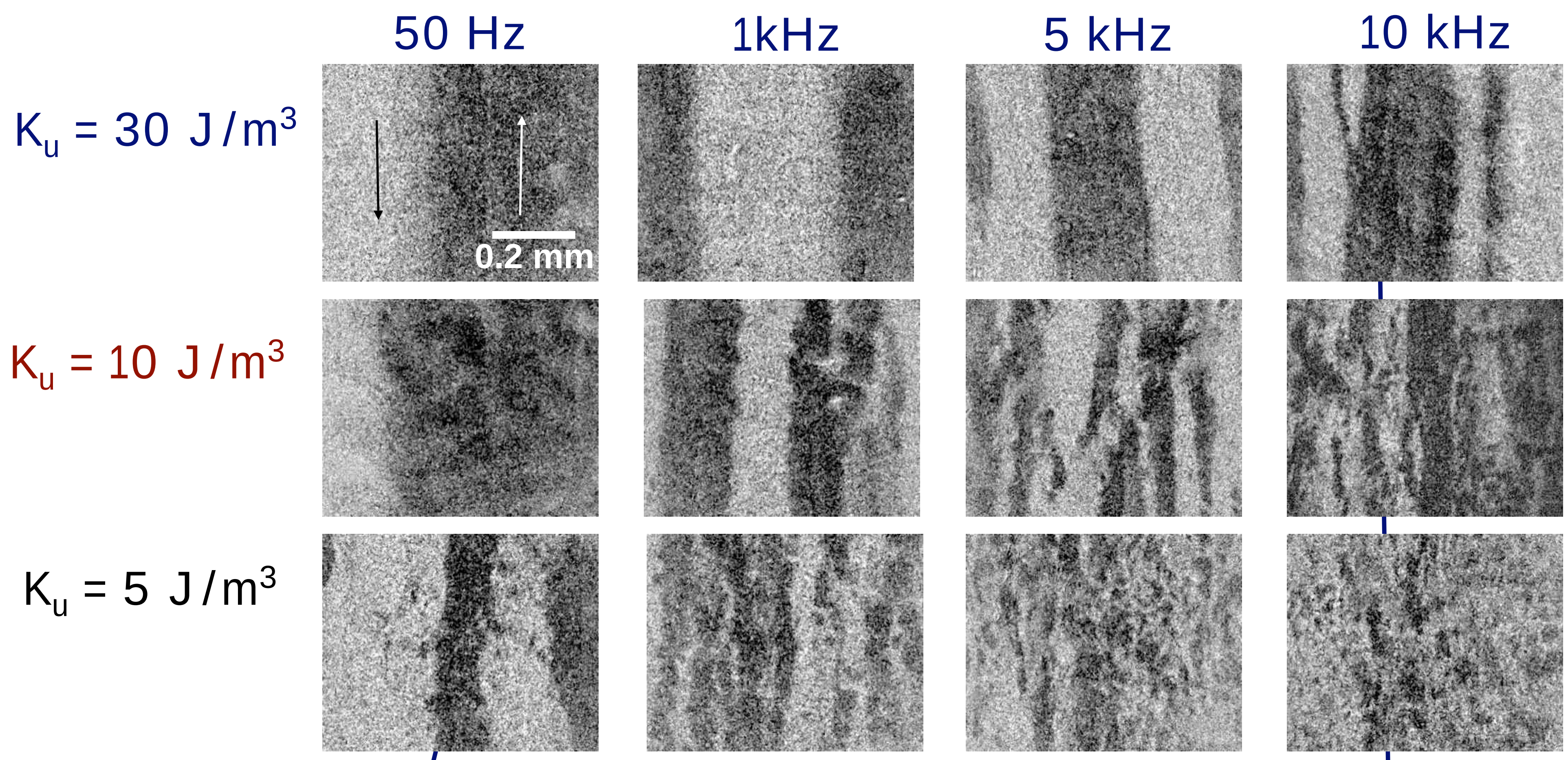


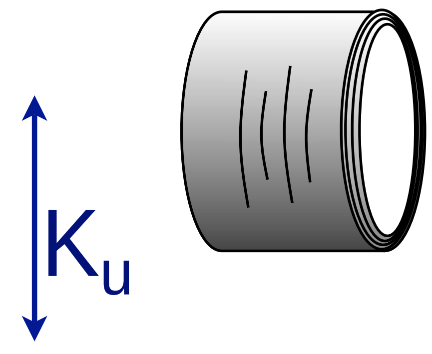


- exposure times 200 ps - 1000 sec

Dynamic losses and domain multiplication

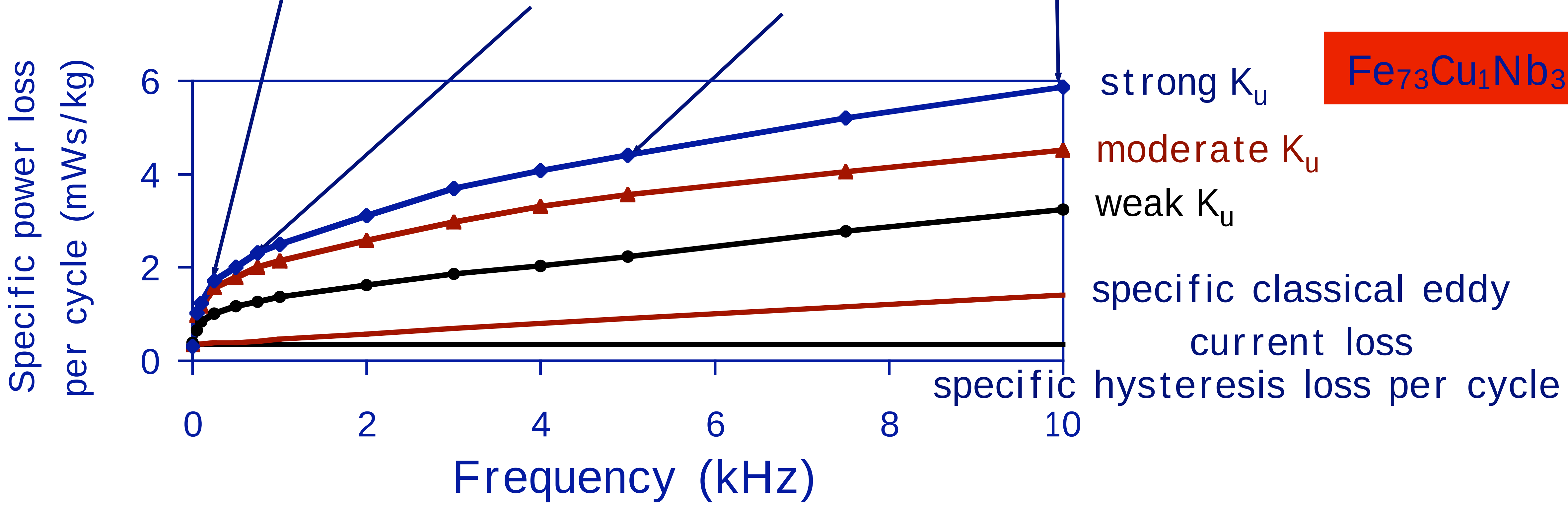
S. Flohrer, R. Schäfer, et al., submitted





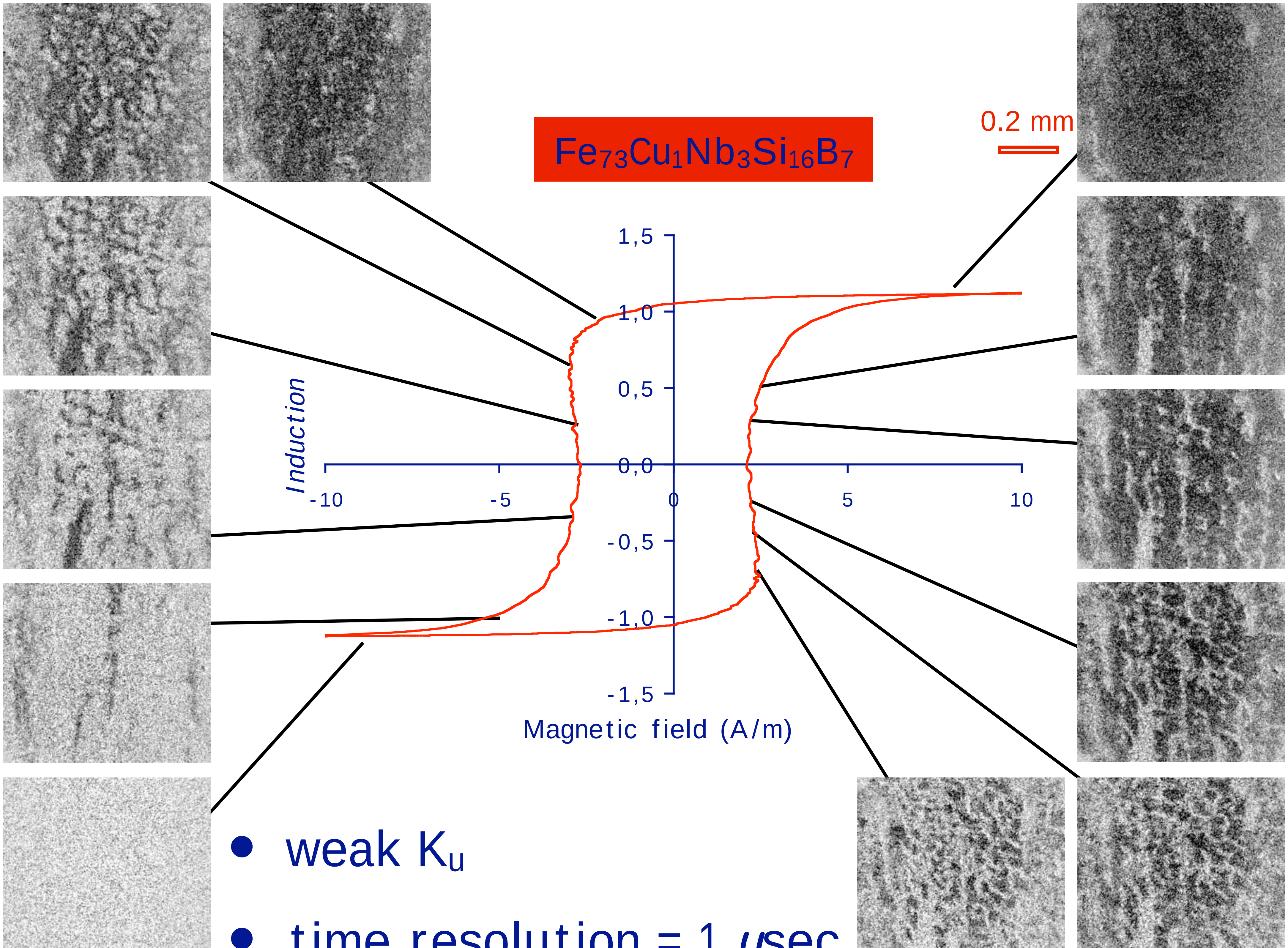
- nanocrystalline Fe-based wound core

$Fe_{73}Cu_1Nb_3Si_{16}B_7$



Domain nucleation of domains @ 1 kHz

S. Flohrer, R. Schäfer, et al., submitted

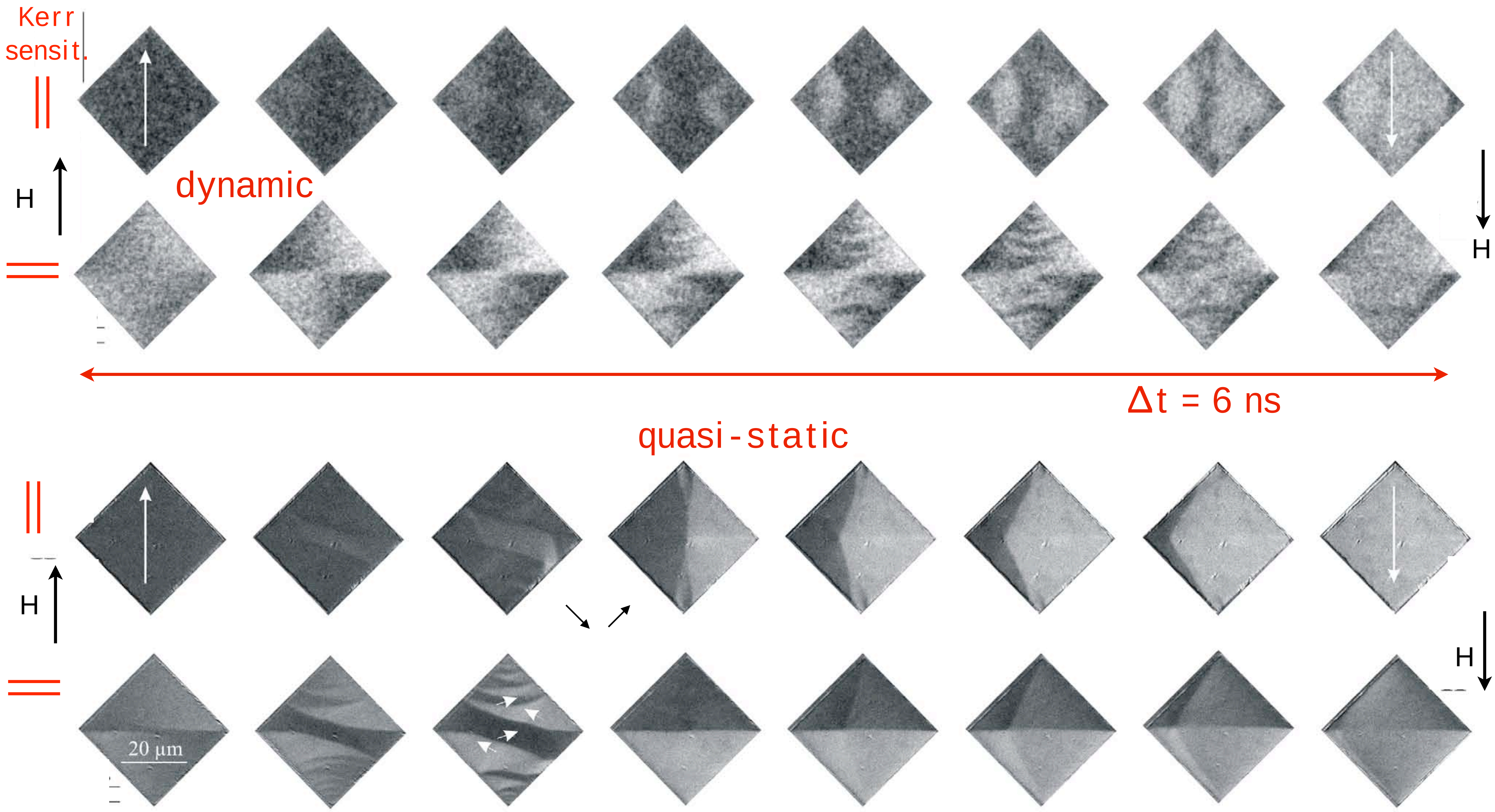


- weak K_u
- time resolution = 1 μsec

Comparison of quasi-static and dynamics

D. Chumakov, J. McCord et al., Phys. Rev. B 71, 014410 (2005)

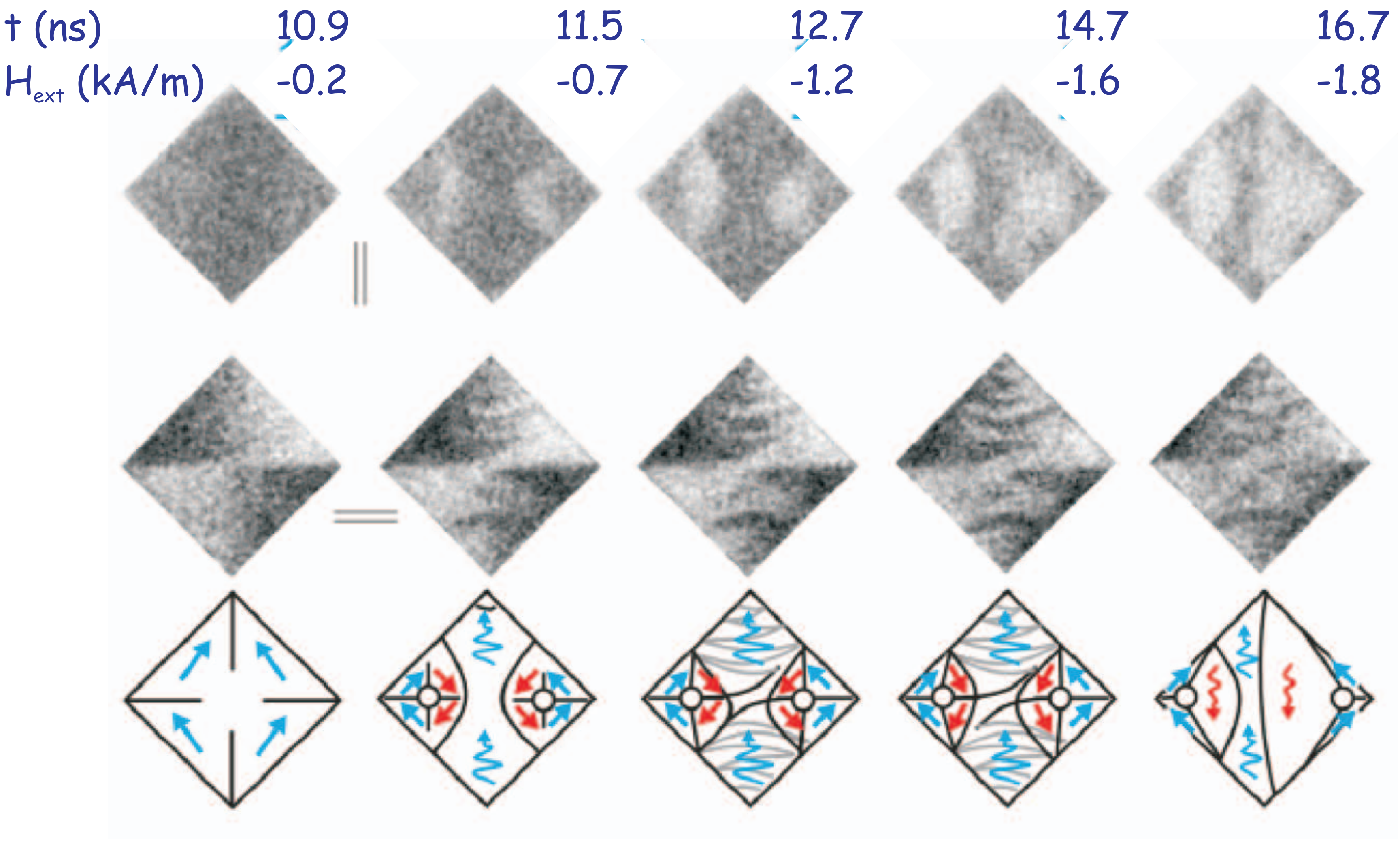
high field reversal of Permalloy element

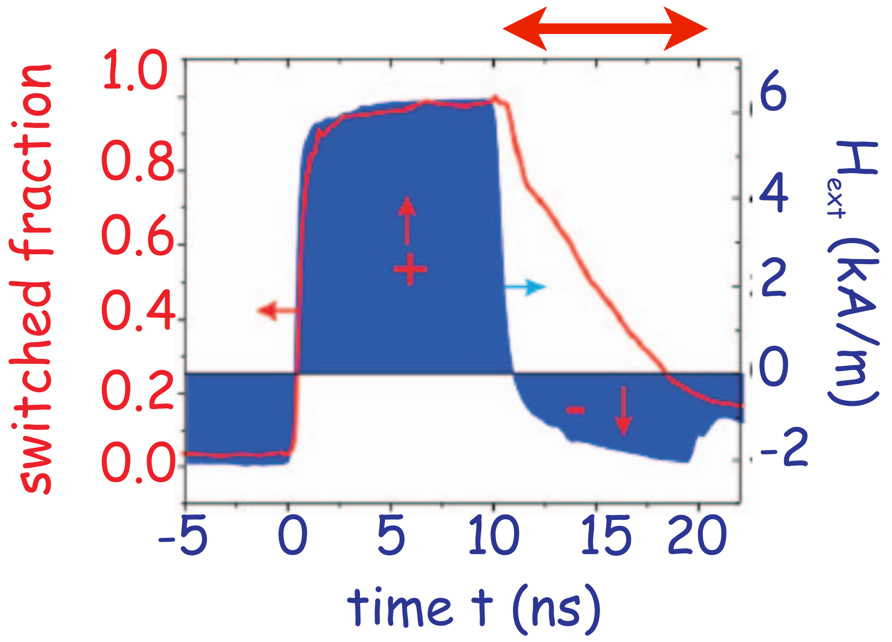


$Ni_{81}Fe_{19}$ 28 x 28 μm^2, 50 nm

Dynamic relaxation

D. Chumakov, J. McCord et al., Phys. Rev. B 71, 014410 (2005)





- small driving field (1.5·H_{sat}) - slow reversal
- concertina development
- vortices at the left-right corners
- domain wall generation

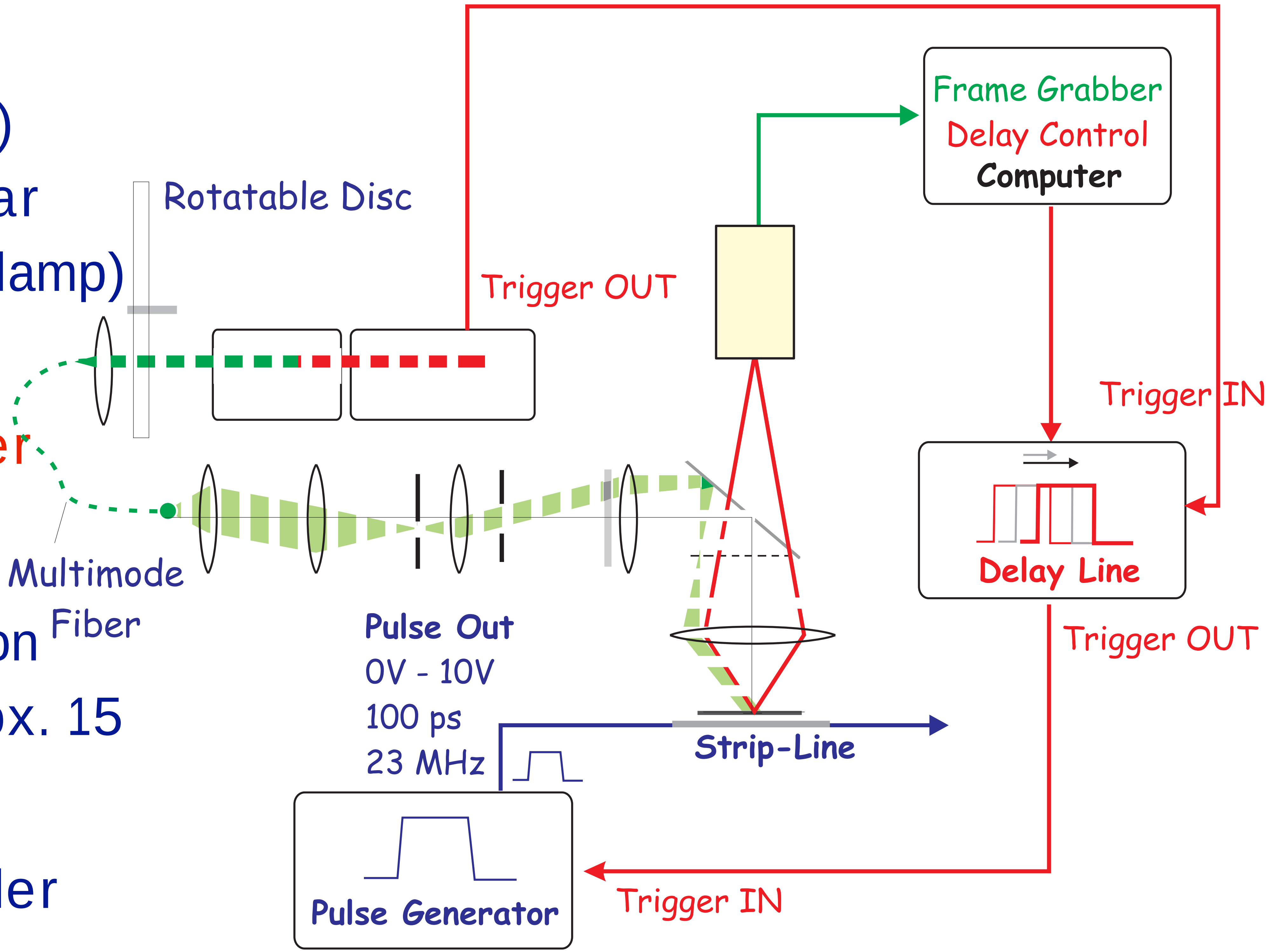
Summary - gated image intensifier

- variable gating time DC to 200 psec
- variable repetition rate DC to 80 MHz
- combination with quasi-static observation
- very flexible
- low efficiency 0.00025 (e.g. 1 MHz, 250 ps)
- low SNR

Time resolved wide-field imaging (III)

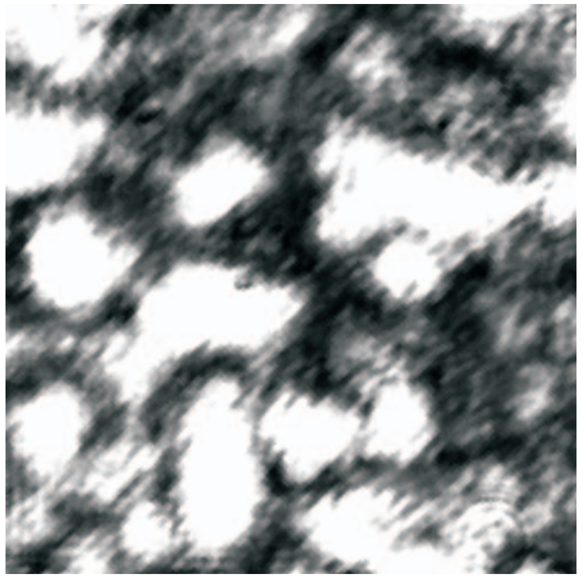
A. Neudert, J. McCord, et al., Phys. Rev. B 71, 134405 (2005)

- Laser based (stroboscopic) imaging (similar for arc flash lamp)
- mode-locked Nd:YVO_4 Laser
- time-resolution down to approx. 15 psec
- Laser scrambler needed

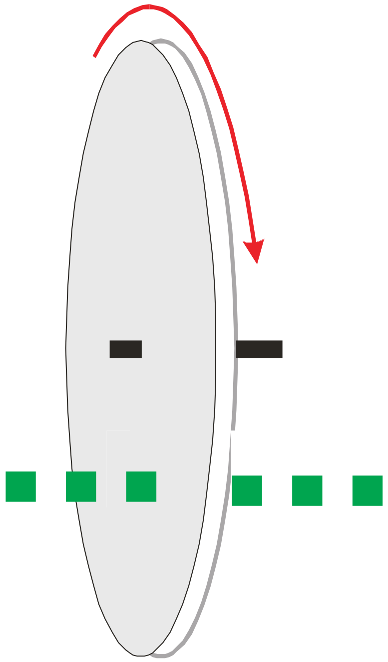


Speckle removal

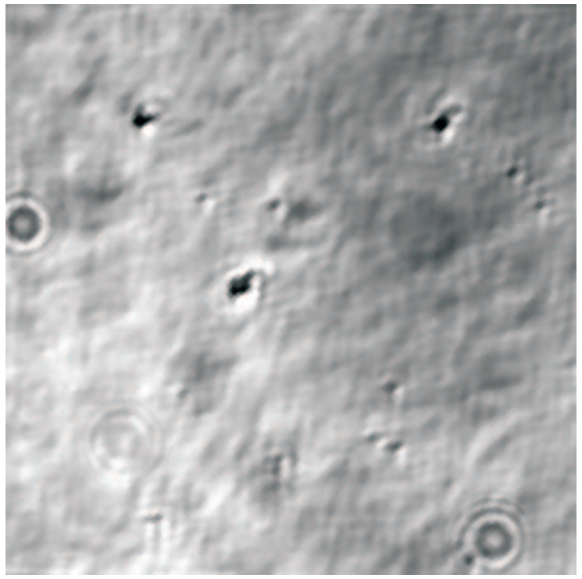
B.E. Argyle, J. McCord; JAP 87, 6487-6489 (2000)



laser speckle
interference pattern
no observation possible



Rotating Glass Disc

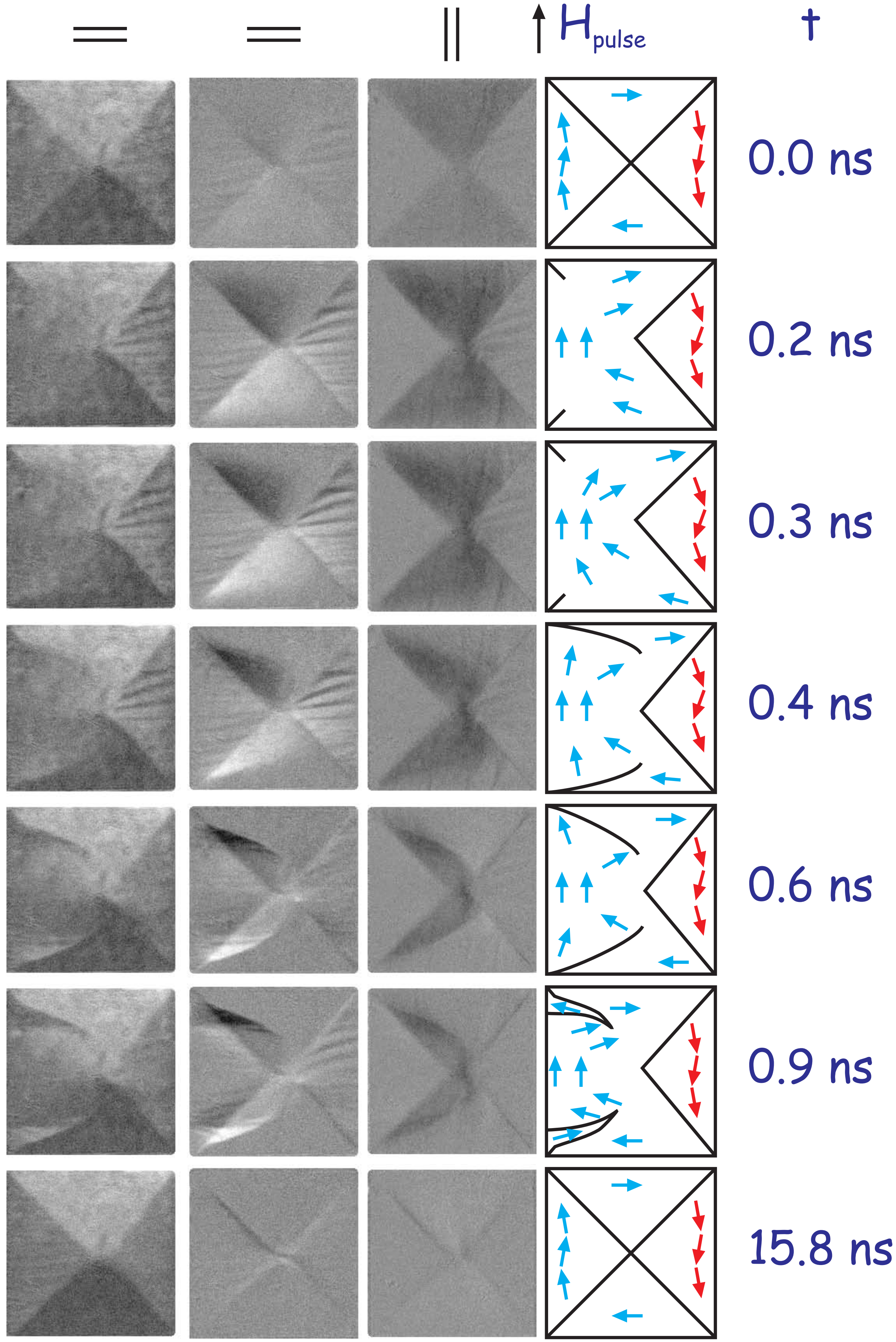


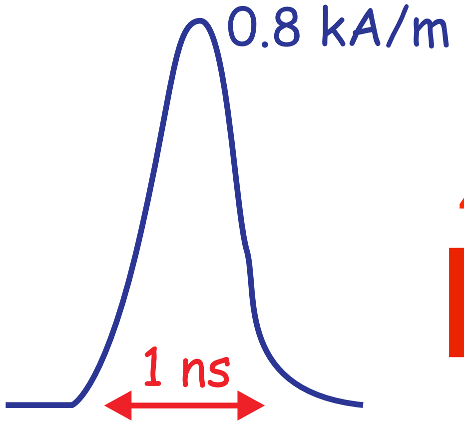
rotating "rough" glass disc
strongly reduced laser speckle
Kerr microscopy possible

- removal of coherence effects – laser scrambler
- averaging over moving speckle pattern

In plane excitation - square elements

A. Neudert, J. McCord, et al.,
Phys. Rev. B 71, 134405 (2005)





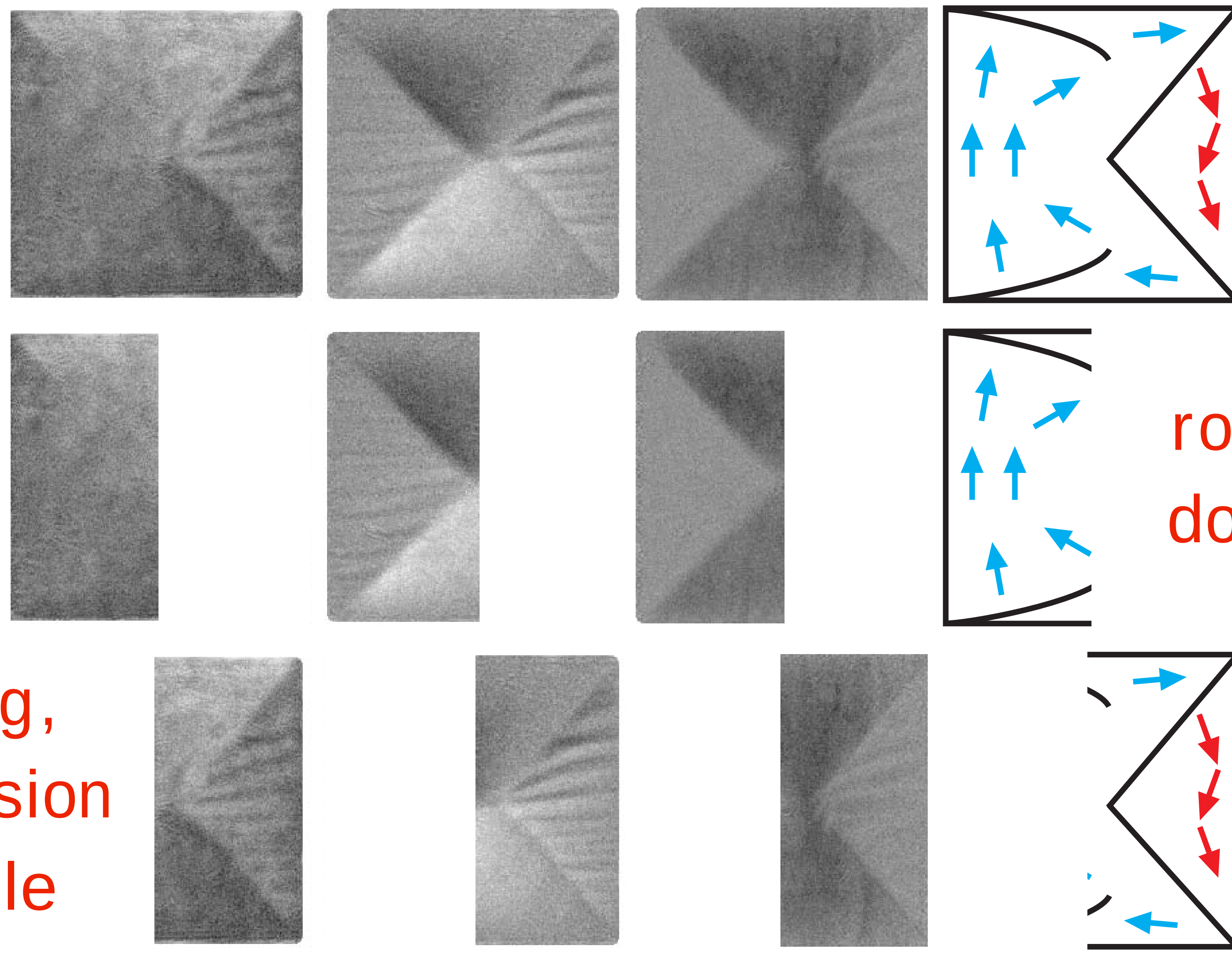
40 x 40 μm^2, 50 nm

$Ni_{81}Fe_{19}$

- rotation of M (MxH, top-b.)
- buckling of M (right)
- stretching of M (left)
- spike domains
- slow relaxation

Bi-modal reversal (Py 50 nm, □ 40 μm)

A. Neudert, J. McCord, et al., Phys. Rev. B 71, 134405 (2005)



0.4 ns

M par H

rotation of closure domains

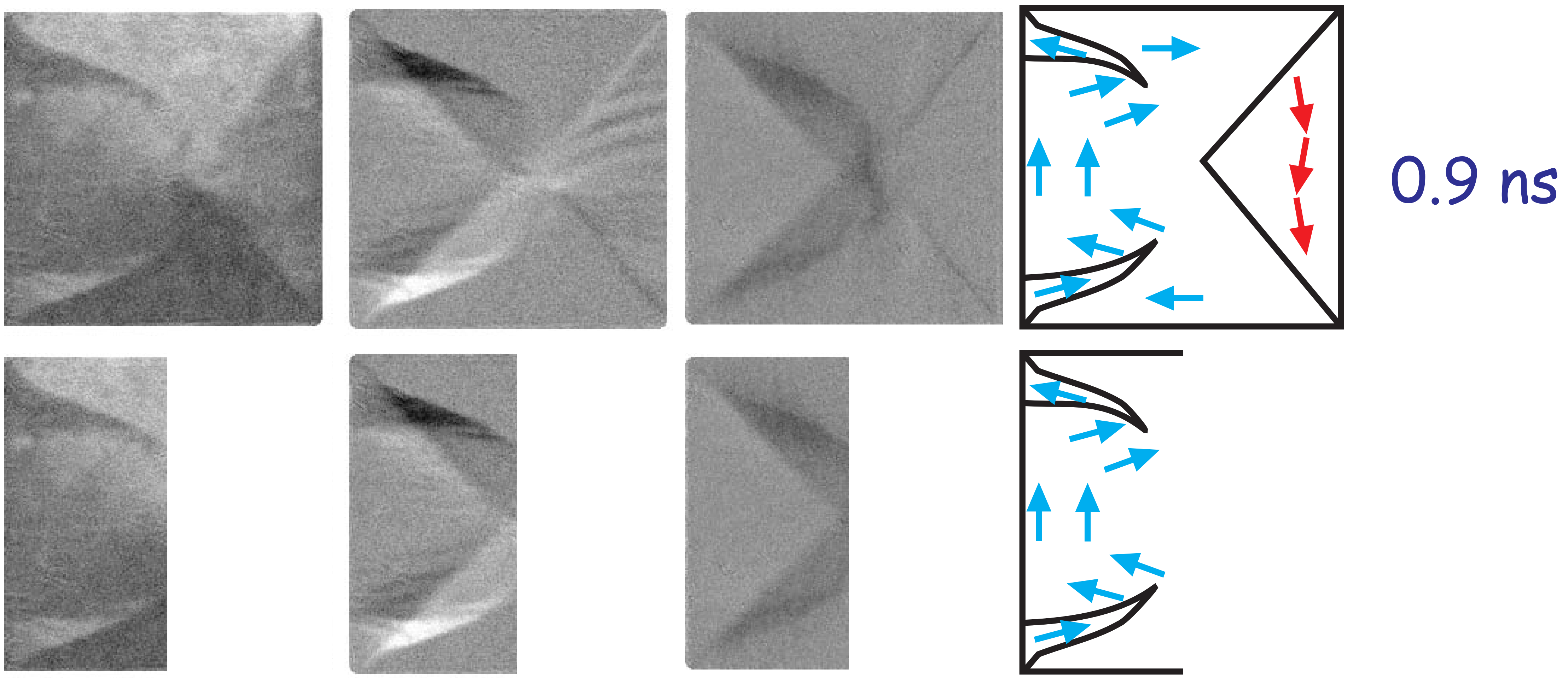
buckling, precession of ripple domains

M perp. H

2 element behavior

Spike domains (50 nm, □ 40 μm)

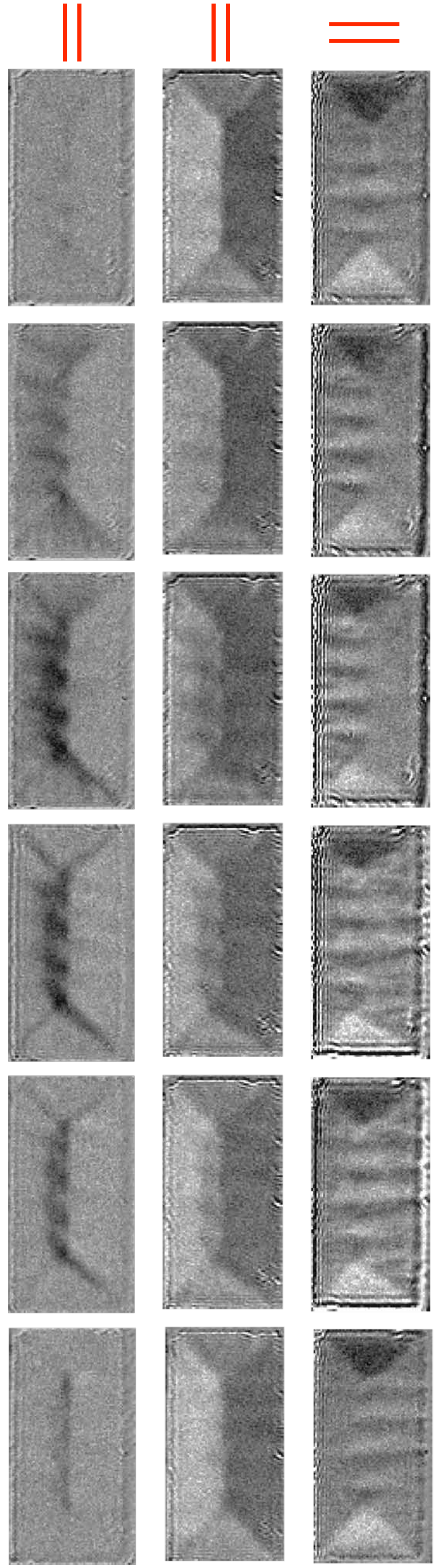
A. Neudert, J. McCord, et al., Phys. Rev. B 71, 134405 (2005)



- development of spike domains (after 1 ns)
- similar to quasi-static elements
- similar to concertina development

Quantitative time-resolved imaging

A. Neudert, submitted to JAP



0.9 ns

1.3 ns

1.7 ns

2.7 ns

5.2 ns

13.2 ns

pulse on

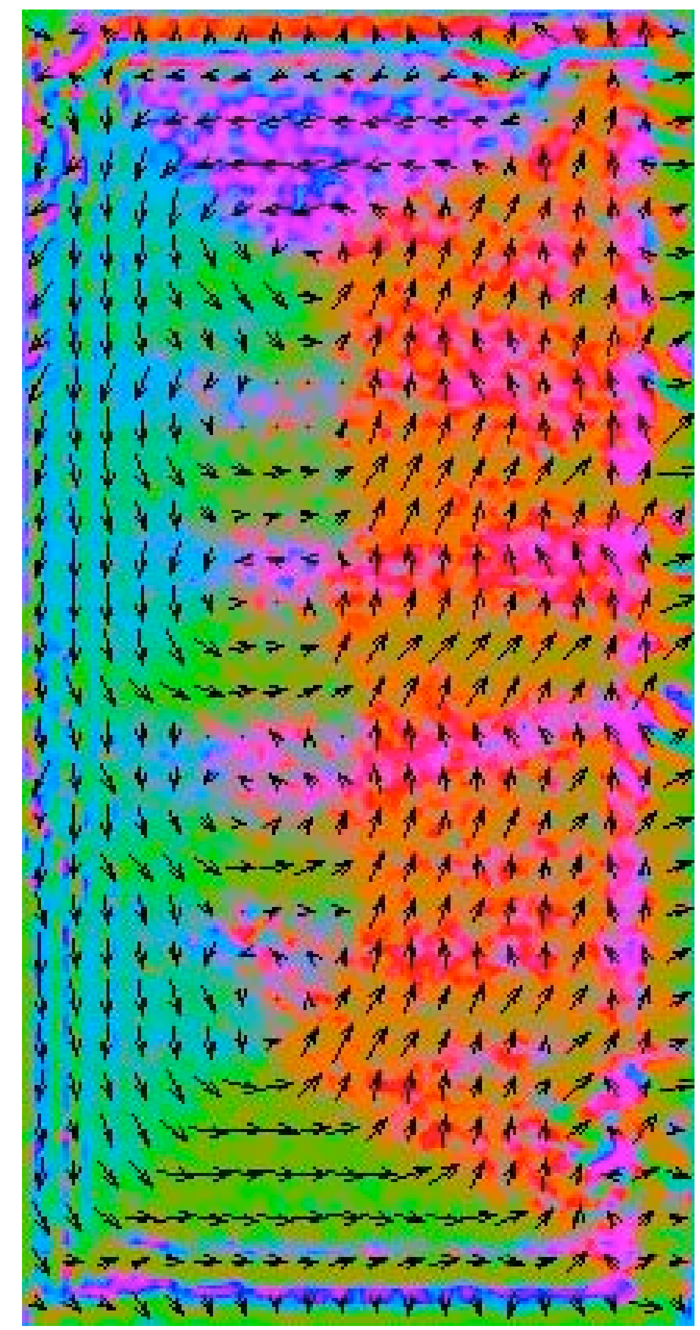
H_{pulse}

pulse off

precessional Bloch line generation

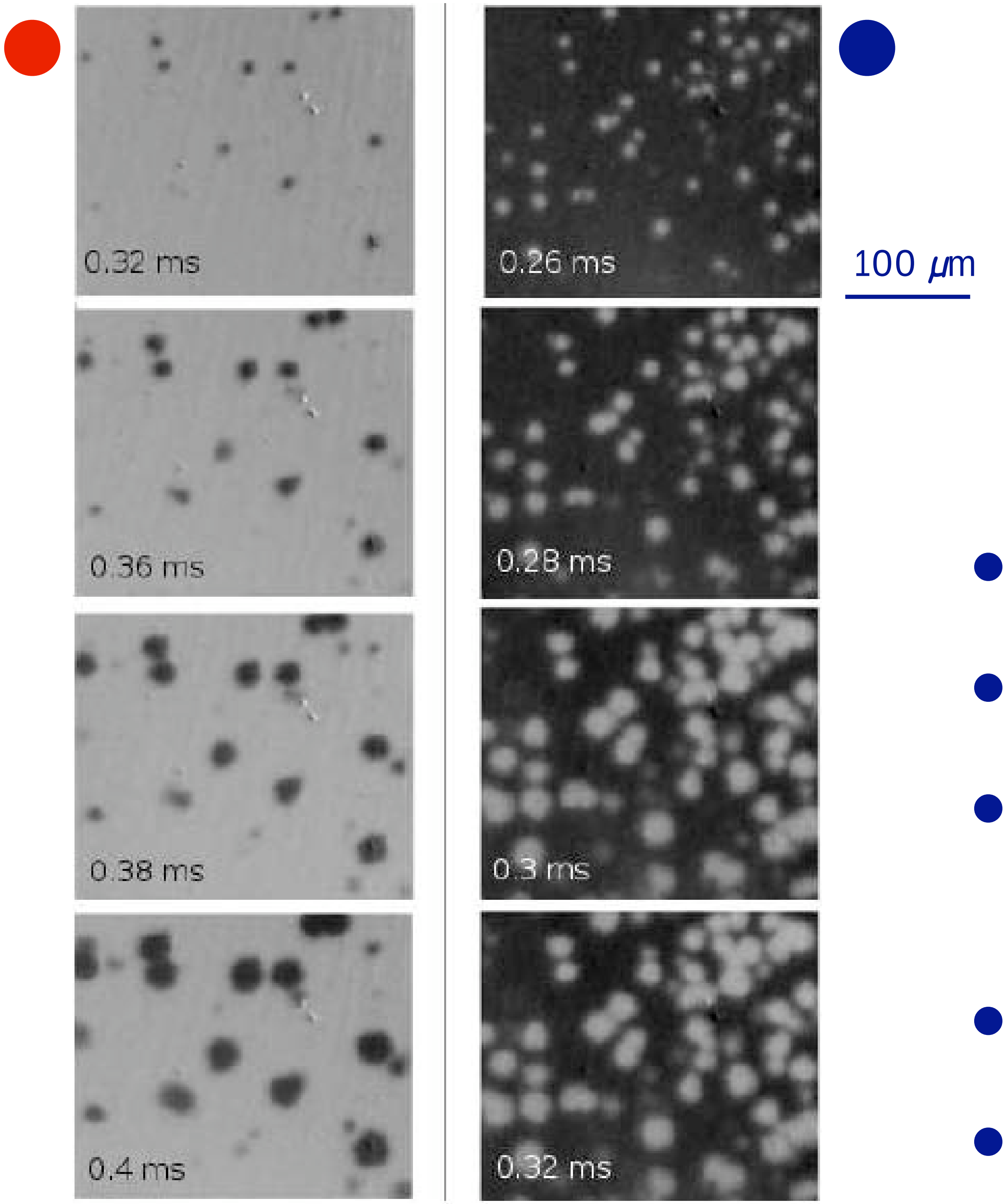
8 x 16 μm^2, 160 nm

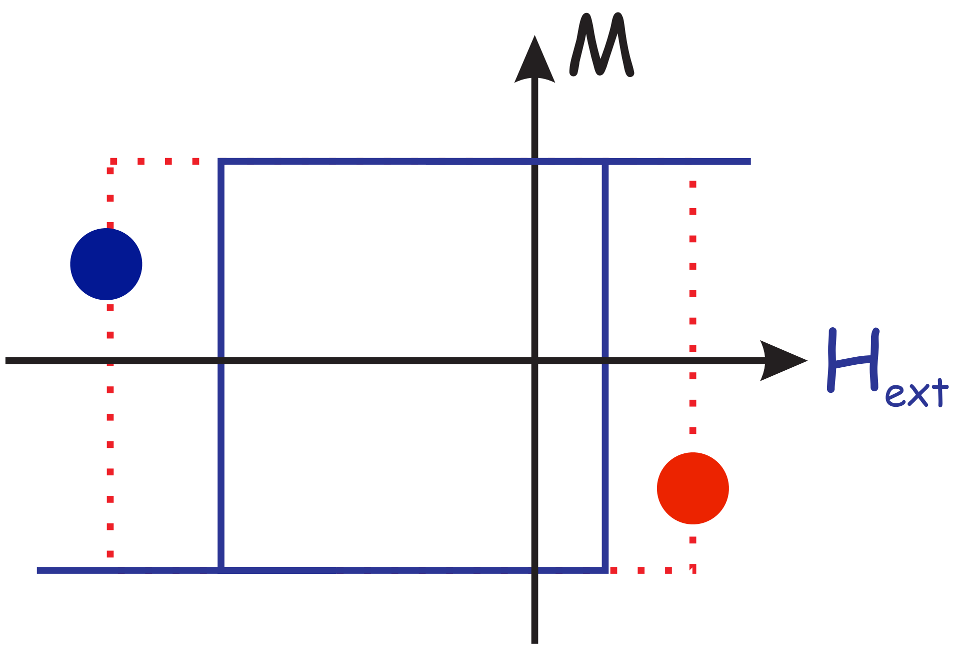
$Ni_{81}Fe_{19}$



Relaxation in perp. EB - arc flash lamp

F. Romanens, S. Pizzini, et al.; accepted for PRB





- low rep. rate arc flash lamp
- approx. 10 μsec time resolution
- stroboscopic observation of domain nucleation in EB systems
- (single-shot possible)
- asymmetry in nucleation density

$(Pt(2\ nm)/Co(0.4\ nm))_5/Pt(0.4\ nm)/IrMn\ (5\ nm)$

➡ wider distribution of EB field

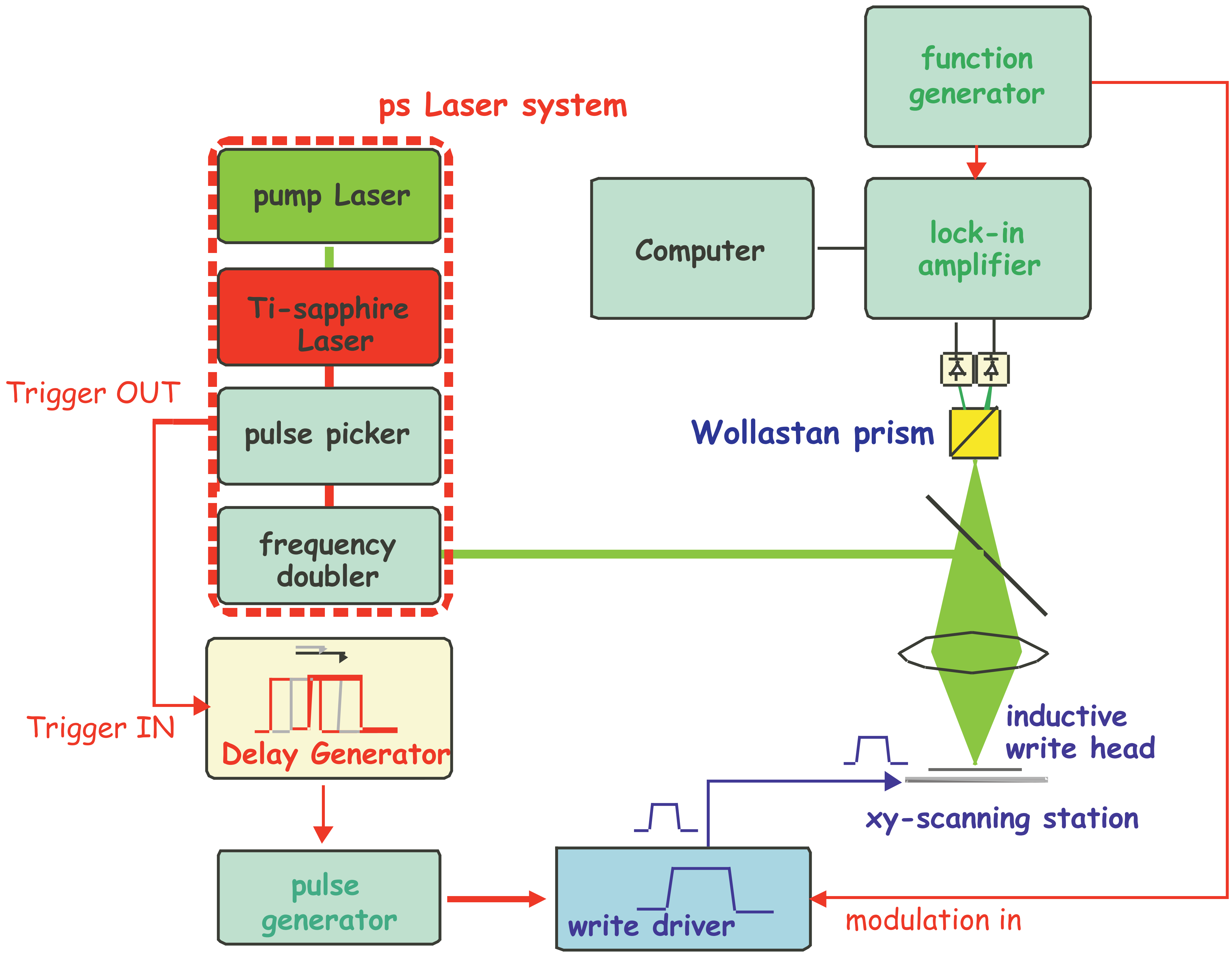
Stroboscopic wide-field illumination

- time resolution determined by illumination source (fixed)
  - from μsec to psec
- usually fixed repetition rate
- no sample movement - fast

- high efficiency
- good SNR

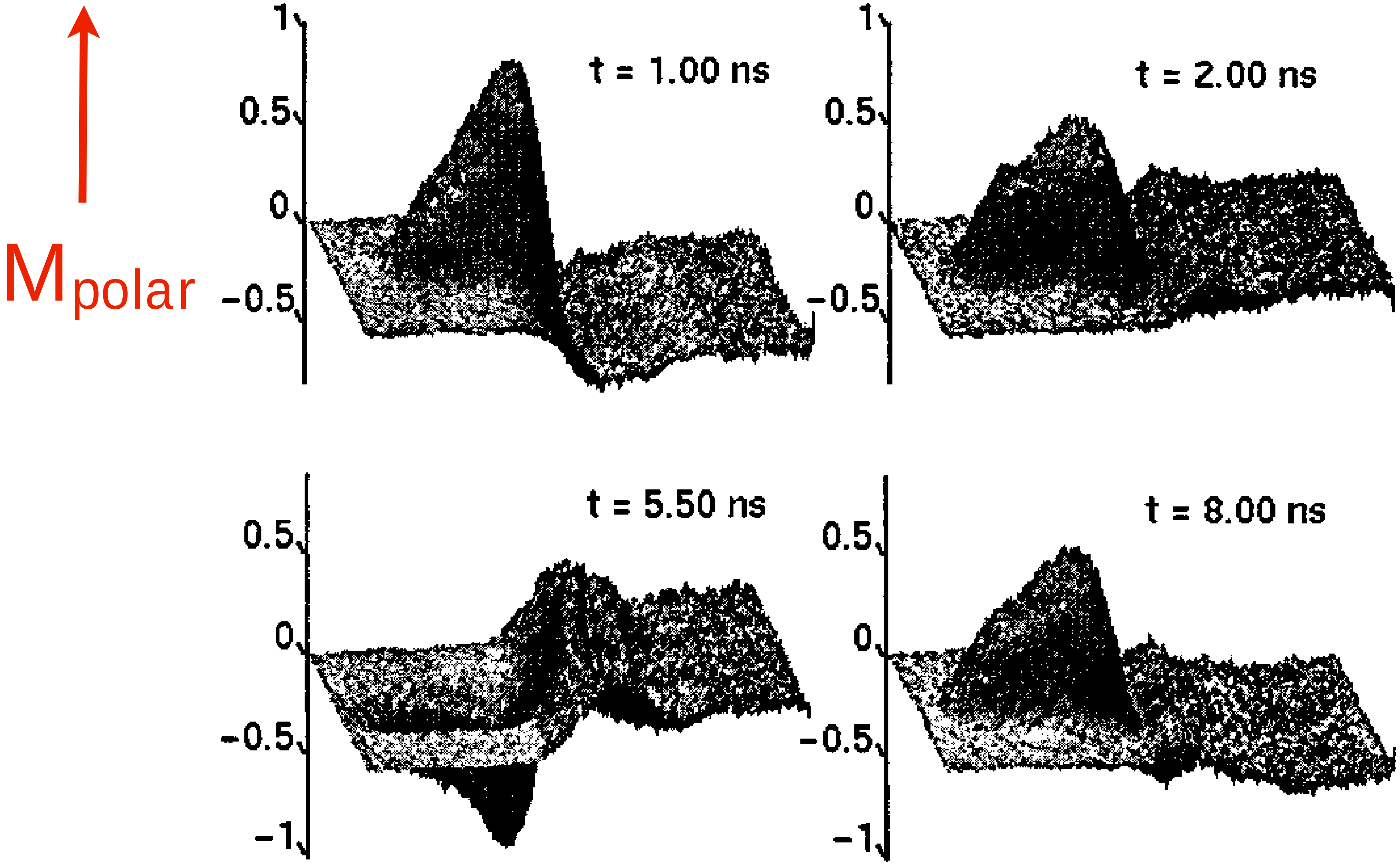
Time-res. Laser scanning microscopy (IV)

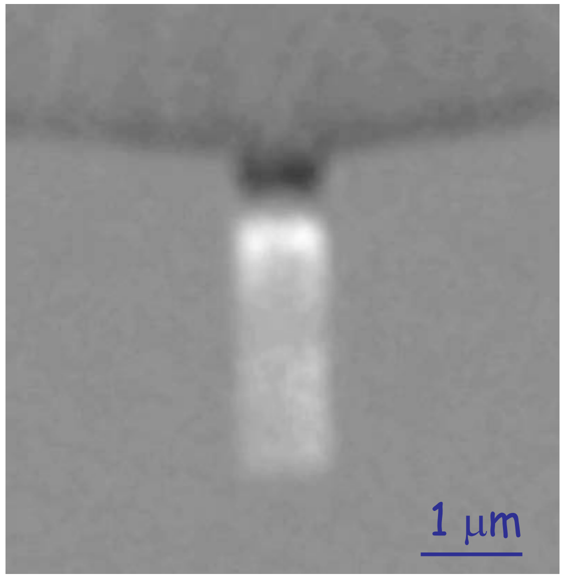
C. Back, J. Heidmann, J. McCord, IEEE Transactions on Magnetics 35, 637-642 (1999)



Magnetization dynamics in recording heads

M. Freeman, J. Smyth, JAP 79, 5898-5900 (1996)

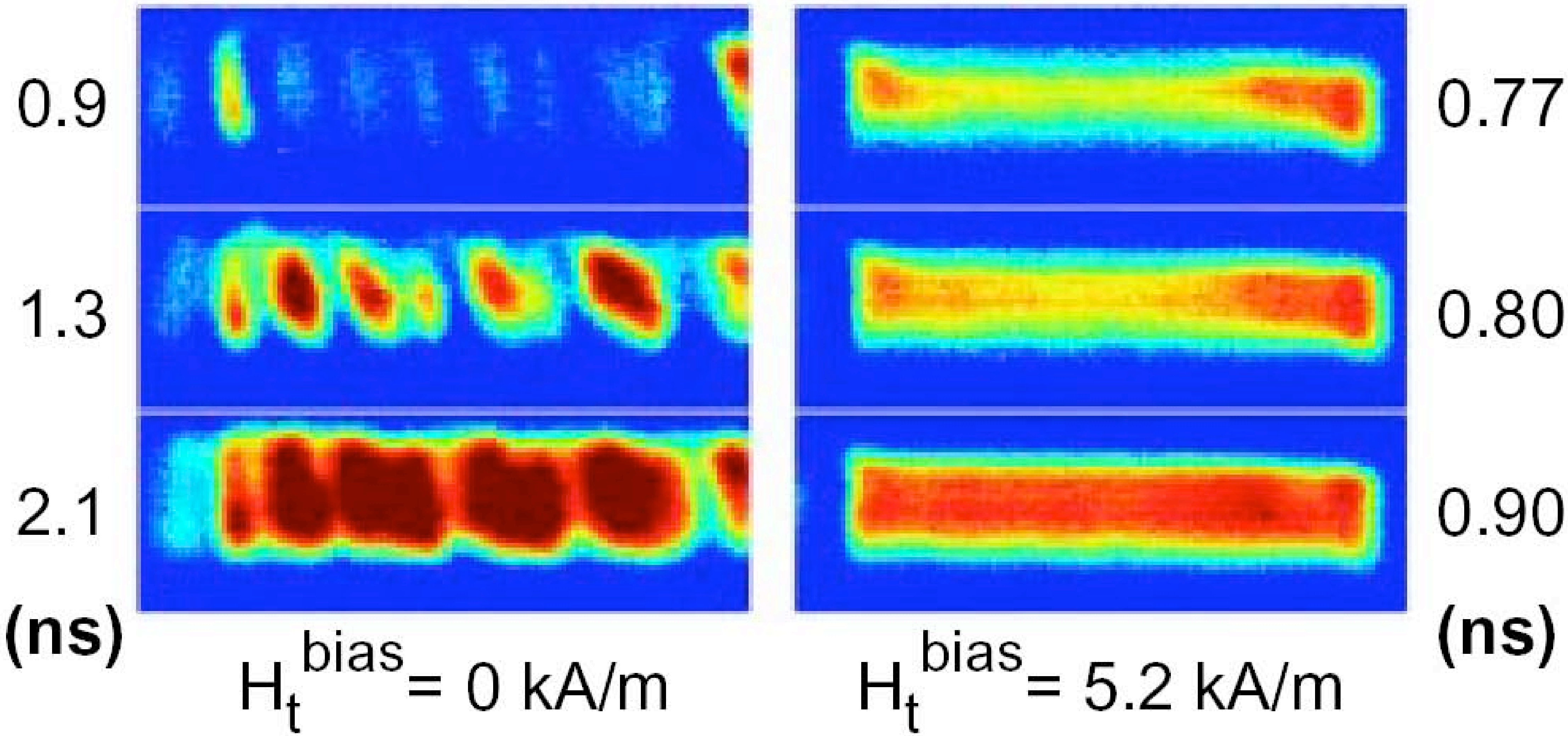




- out-of plane M(t) in pole-tips of recording head
- characterization of write head dynamics

Magnetization dynamics in NiFe elements

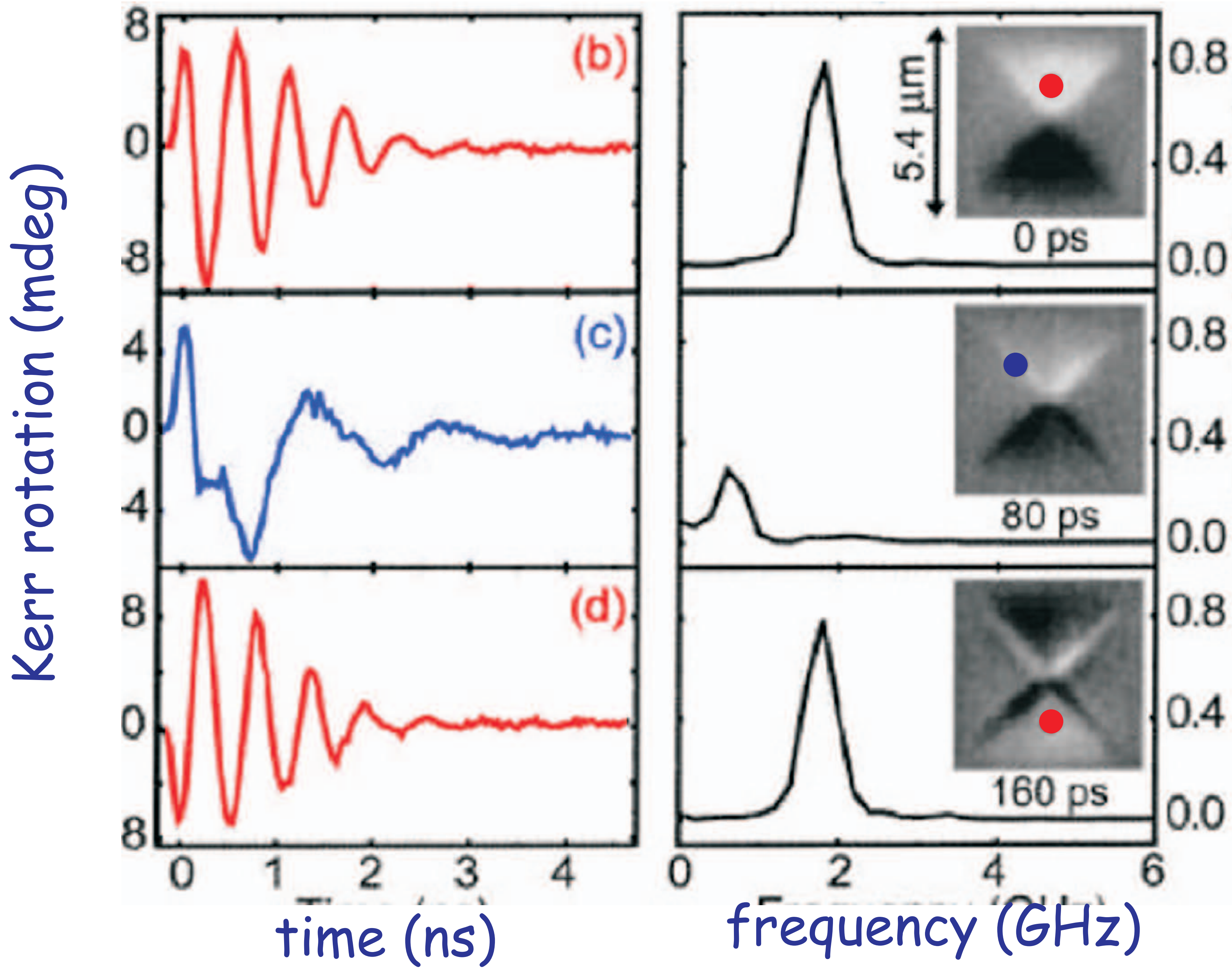
B. C. Choi, M. Belov, W. K. Hiebert, G. E. Ballentine, M. R. Freeman, Phys. Rev. Lett. 86, 728, 2001



- 15 nm $Ni_{80}Fe_{20}$ element, element size 10 μm x 2 μm
  - change of reversal modes with orthogonal bias field
  - domain walls decrease switching time

Precession of magnetic ground states

J. Park et al., PRB 67, 020403(R) (2003)



H_{pulse}

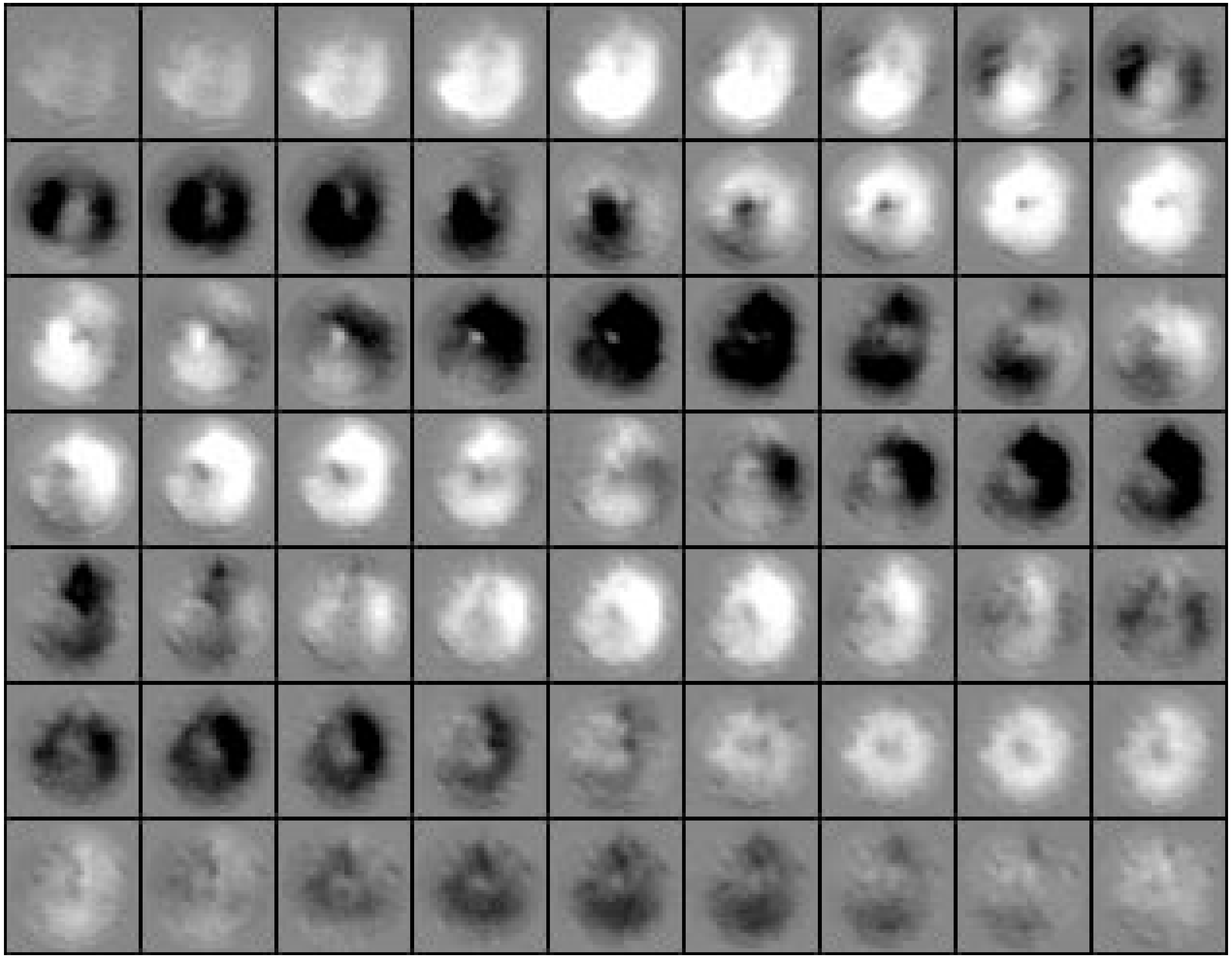
- spin dynamics in closure domains
- confirmed by micromagnetic calculations

5 x 5 μm^2, 50 nm

$Ni_{81}Fe_{19}$

Imaging of vortex eigenmodes

M. Buess, C. Back et al., Phys. Rev. Lett. 93, 077207 (2004)



diameter 6 μm

H_{pulse}

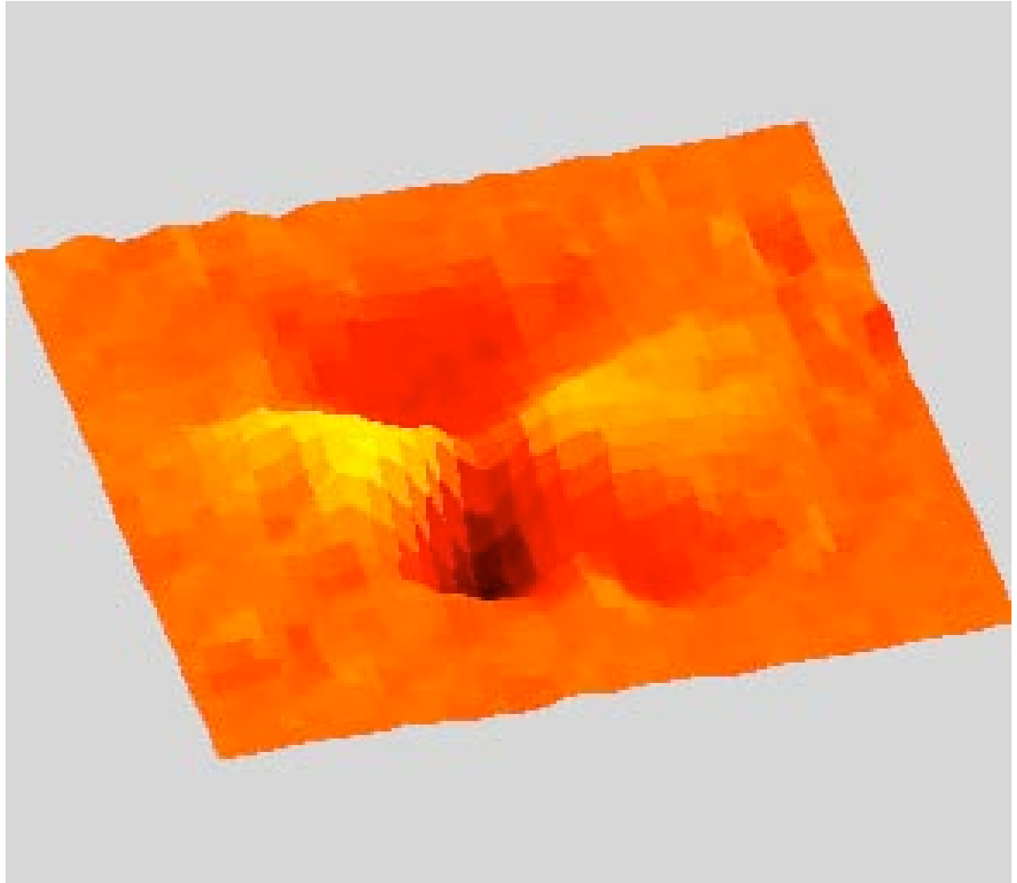
- multiple spin wave modes
- inversion in vortex contrast
  - switching of vortex core

6 x 6 μm^2, 15 nm

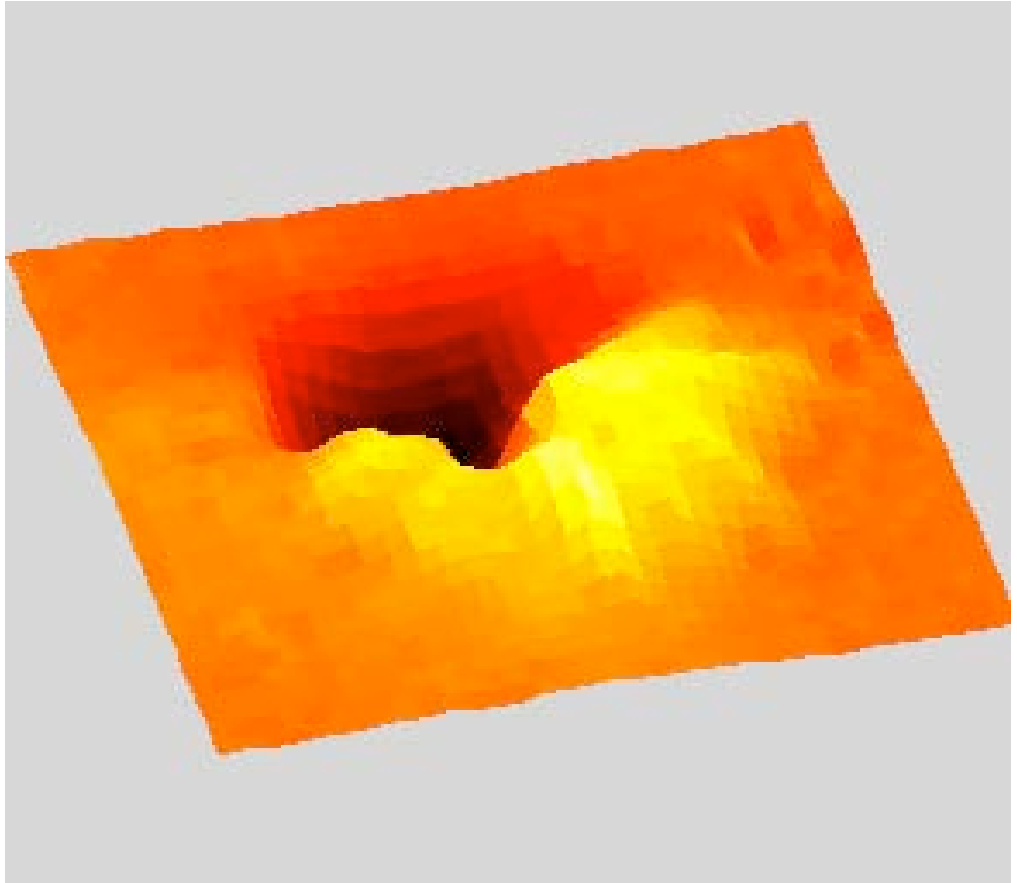
$Ni_{81}Fe_{19}$

Eigenmodes - Fourier imaging

M. Buess, C. Back et al., Phys. Rev. Lett. 93, 077207 (2004)



1.56 GHz mode



1.95 GHz mode

- extraction of non axially symmetric (shape induced) excitation modes by FFT processing

Summary on scanning dynamics

- time resolution to psec
- fixed repetition rate
- sample movement - slow

- high efficiency
- best SNR (magnetometer-like)

Overall summary - good ...

- sample manipulation easy: arbitrary sample shape and size, arbitrary magnetic fields, cooling, heating, fast

- simultaneous measurement of hysteresis curves
- imaging of magnetization vector

  ➡ quantitative microscopy

- information depth 20 nm

  ➡ depth-selective imaging possible in multilayers

laboratory tool

- imaging of dynamic processes at high speed

Overall summary - ... but ...

- optical resolution limited to approx. 250 nm
- only surface domains can be seen
- not element specific
- ...

Where to go from here …

- improve resolution
  - UV → x2 in resolution
  - optical near field microscopy?
- single shot psec imaging
  - high power laser + ultra sensitive camera system

- Introduction - overview (pre 2002)
  - A. Hubert & R. Schäfer, “Magnetic Domains”, Springer (1998)
  - M. Freeman & W. Hiebert, “Stroboscopic microscopy of magnetic domains”, in “Spin dynamics in confined magnetic structures I”, B. Hillebrands, K. Ounadjela (Eds.) (2002)