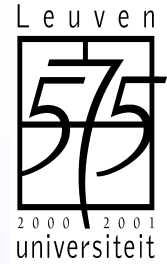




KATHOLIEKE  
UNIVERSITEIT  
LEUVEN



# Structural and magnetic properties of periodic dot lattices studied by off-specular x-ray and neutron reflectivity

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# MOTIVATION and OUTLINE

*Aim: - study magnetic properties of dots*

*- study diffuse reflectivity of structured surfaces*

*Domain structure and magnetization directions ?*

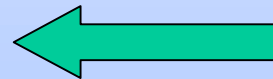
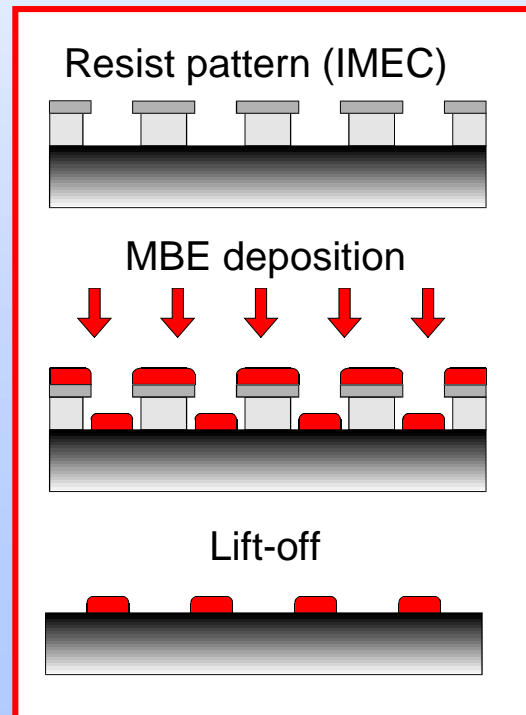
- ❖ Preparation of structured surfaces
- ❖ Magnetic dot arrays :
  - force microscopy and X-ray reflectivity
- ❖ Dots probed by polarized neutron reflectometry
- ❖ Conclusions



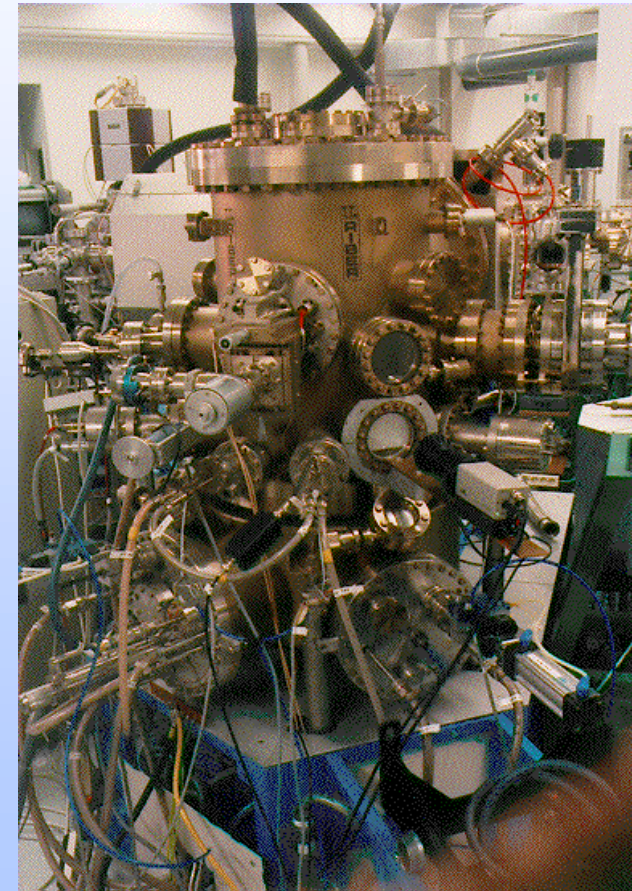


# Preparation by Molecular Beam Epitaxy

- ☞ **Substrate:**  $\text{SiO}_2$
- ☞ **Electron beam evaporation**  
Co  $0.45 \text{ \AA/s}$ ,  $10^{-10}$  Torr, 300 K  
**Knudsen effusion cell**  
Au  $0.25 \text{ \AA/s}$ ,  $10^{-10}$  Torr, 300 K



Riber MBE facility





# Characterization by Atomic Force Microscopy

## Tapping Mode Atomic Force Microscopy

**Period:**  $d = 1.5 \mu\text{m}$

**Dot dimensions:**

$L_l \times L_s = 0.54 \mu\text{m} \times 0.36 \mu\text{m}$

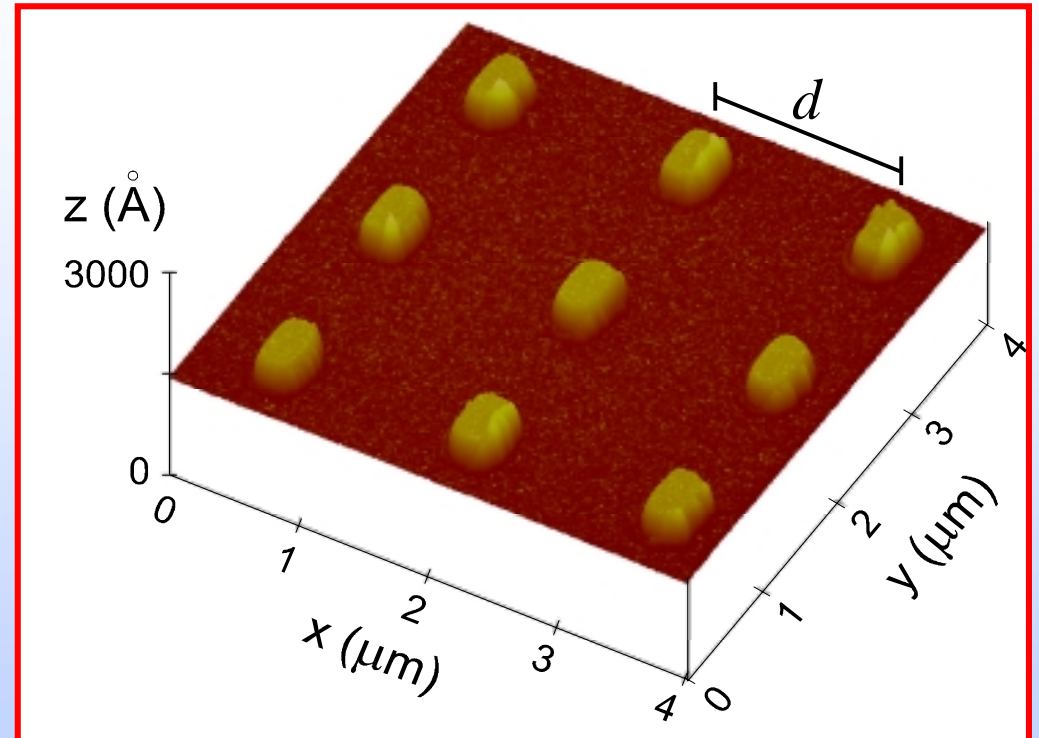
thickness:  $380 \text{ \AA}$

$L_l/L_s = 3/2$

**rms roughness of dot surface:**

$\sigma_{\text{RMS}} = 9 \text{ \AA}$

**Polycrystalline dots**



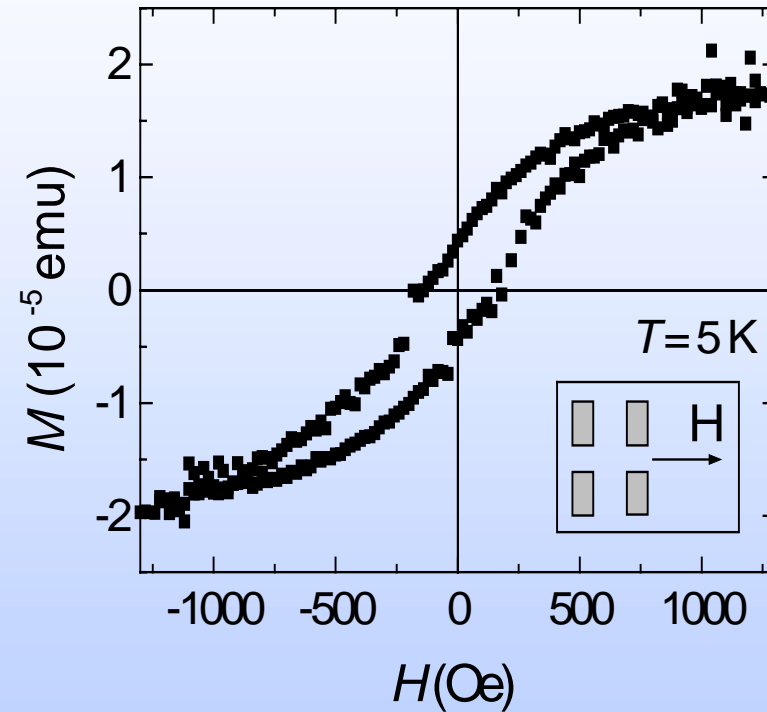
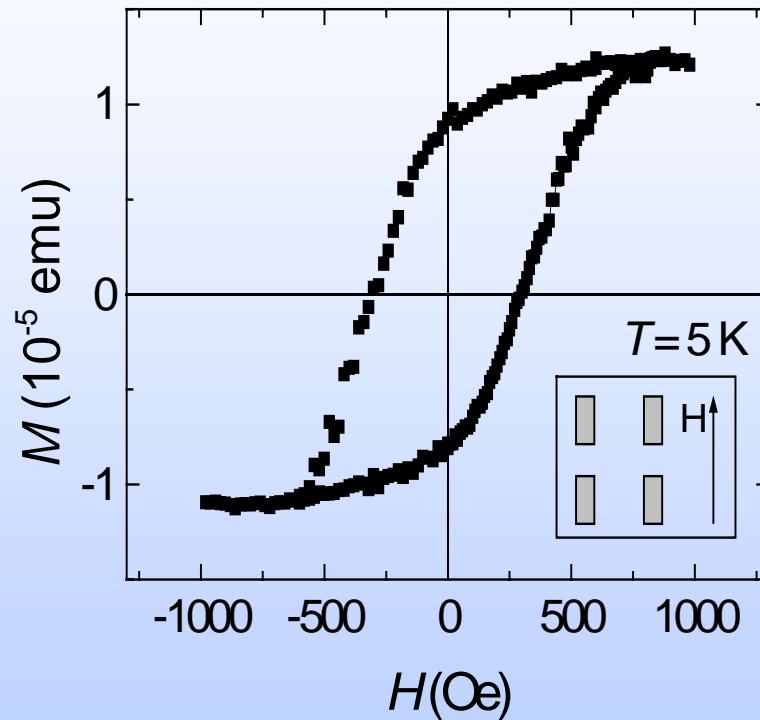
**Well defined periodicity, shape, and dimensions of dot lattice**





# SQUID magnetization experiments

## Determination of anisotropy and hysteresis



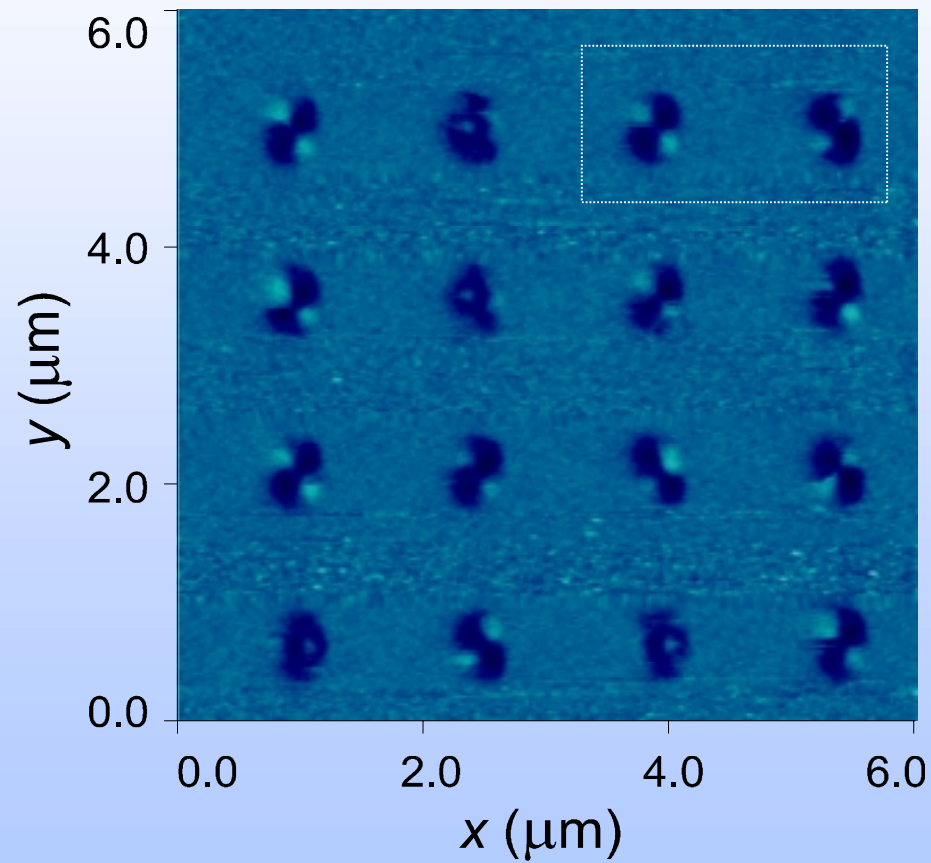
- Magnetization parallel to plane of the dots
- Easy axis determined by shape anisotropy



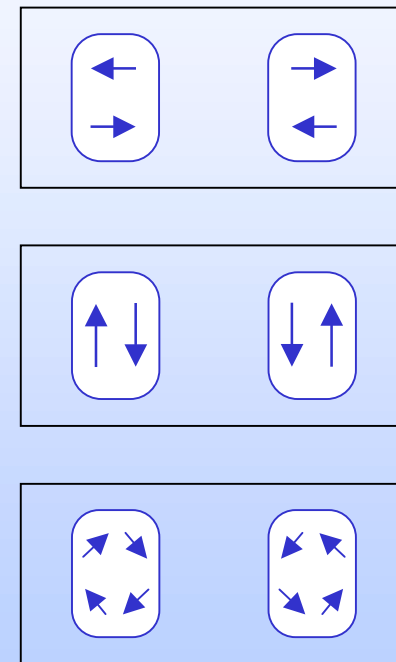


# Magnetic force microscopy on Co dots (virgin state)

as-grown



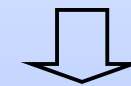
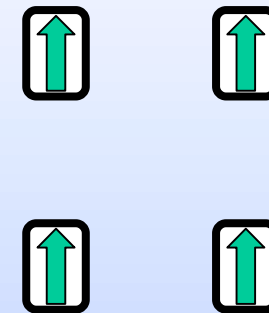
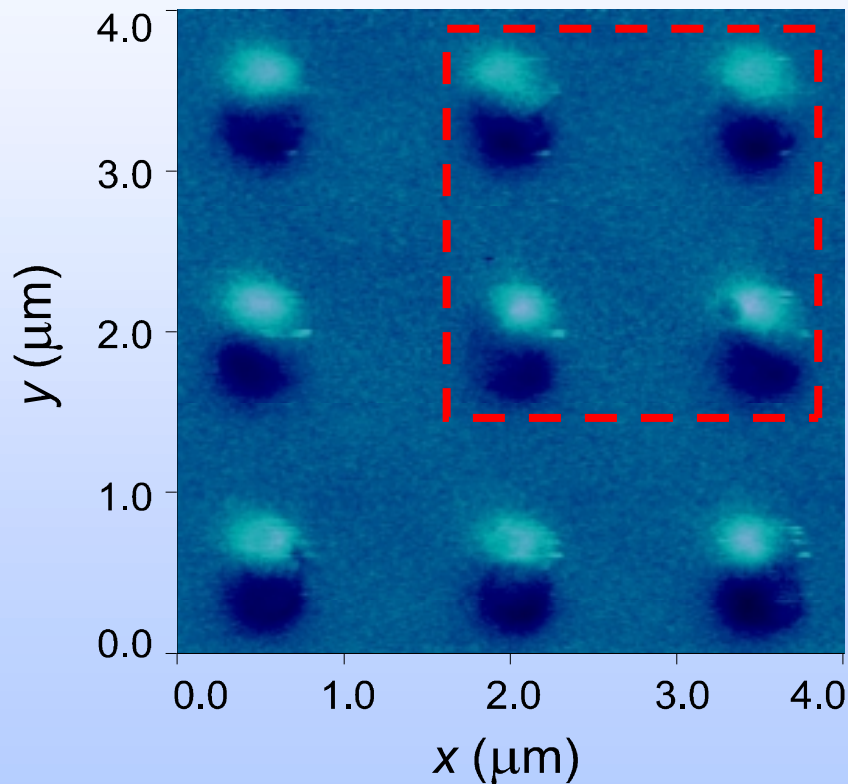
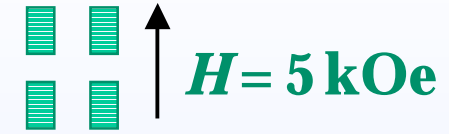
Multi-domain dots





# Magnetic force microscopy on Co dots (after saturation)

Remanent state ( $H = 0$ ) after saturation

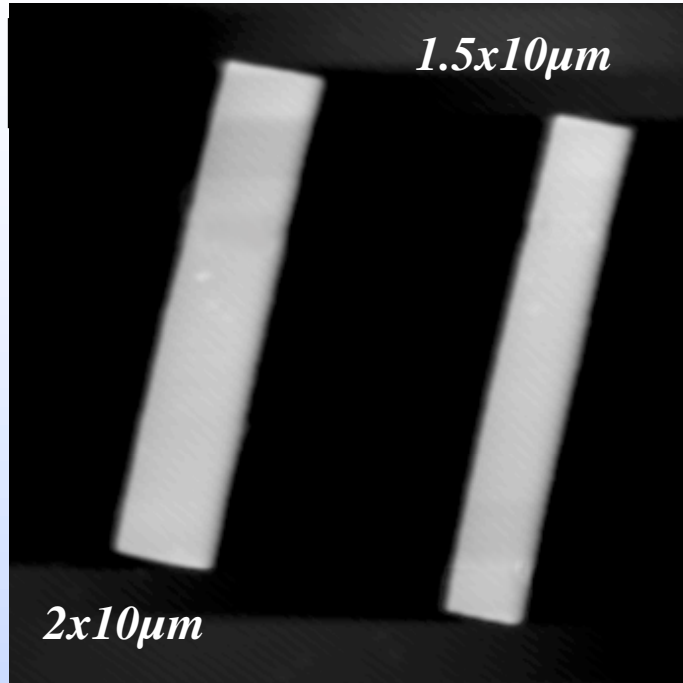


**single domain dots**  
**magnetisation //**  
**direction of saturating**  
**field**

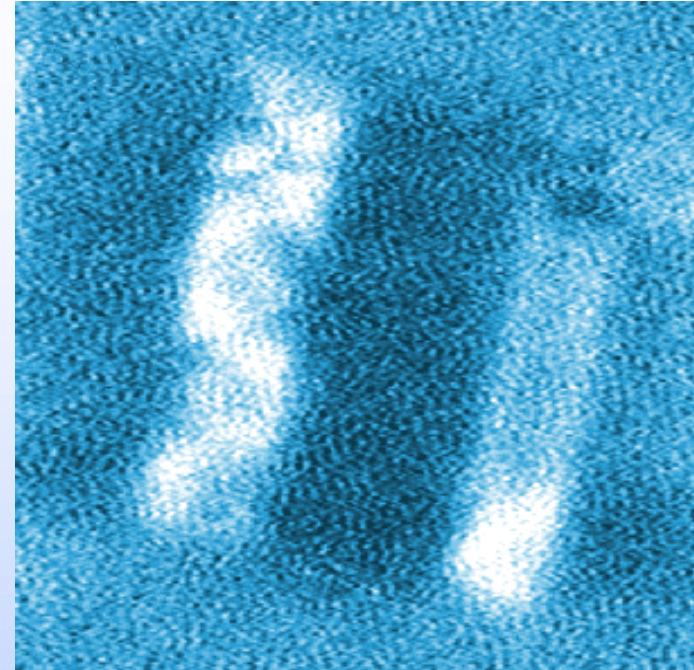




## MFM on Co dots: influence of aspect ratio



*Topography*



*MFM*

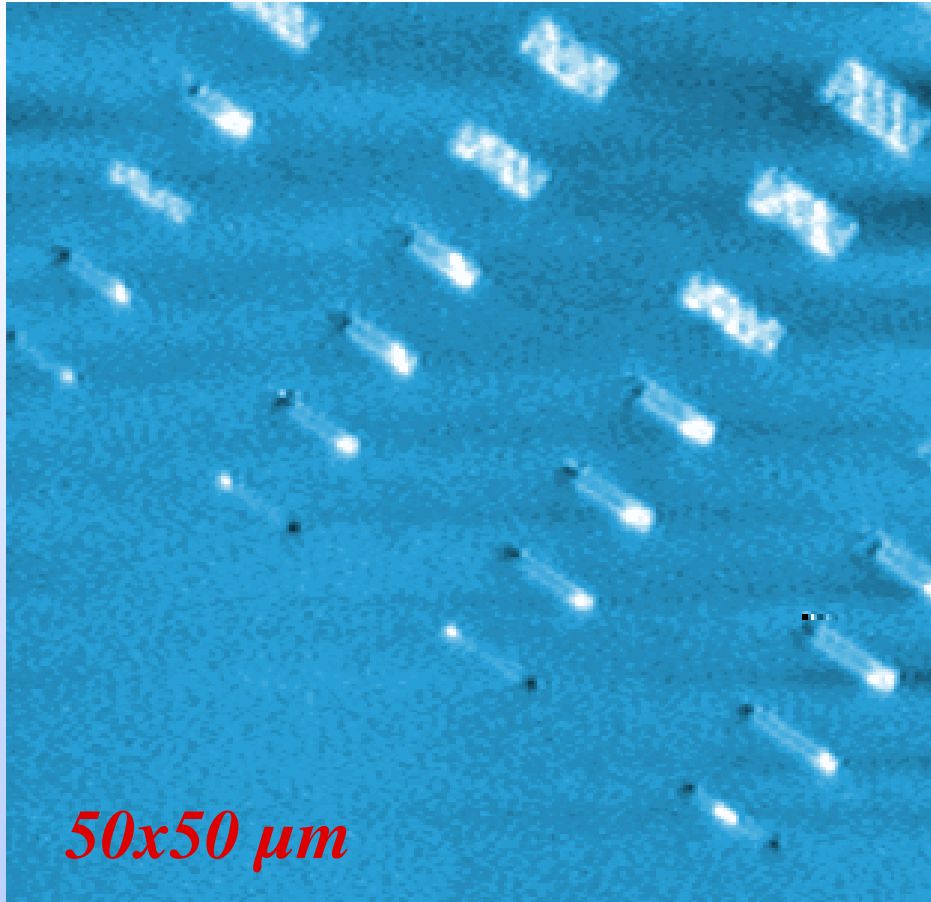
***Transition from single domain to multidomain  
by varying the 'aspect ratio'***

***Not always evident to extract magnetization directions***





## MFM on Co dots: influence of aspect ratio



*MFM image of Co (35 nm) structures with different aspect ratio*

*Length between 0.25 - 10  $\mu\text{m}$*

*Width between 0.25 - 5.5  $\mu\text{m}$*

*Aspect ratio 1 - 40*

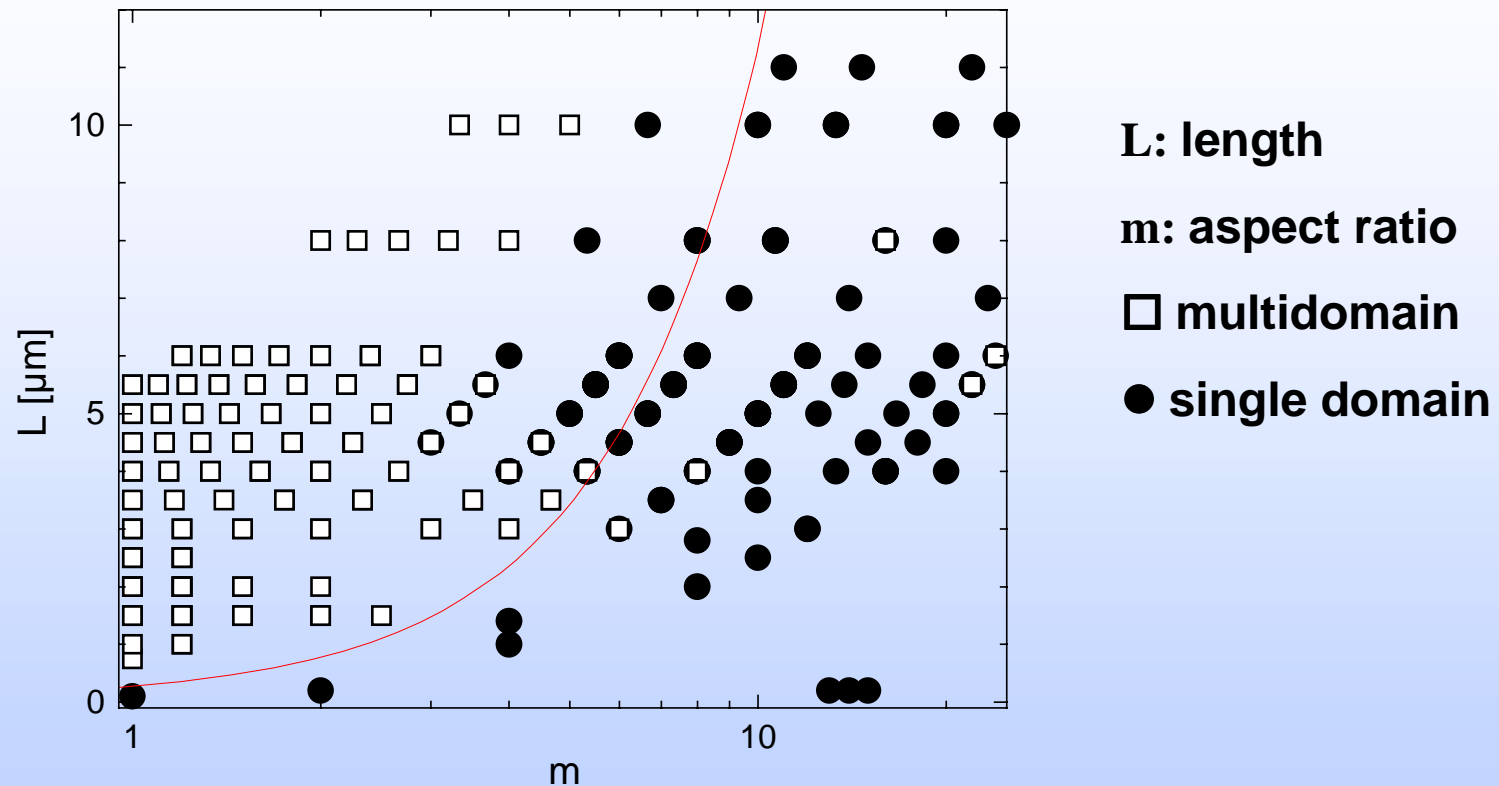
E. Seynaeve et al., J. Appl. Phys. 89, 531 (2001)

***'Statistics' of the experiment are enhanced by looking at many dots, all on the same wafer. Systematic behaviour ?***





# MFM on Co dots: influence of aspect ratio



## *Theory of Aharoni:*

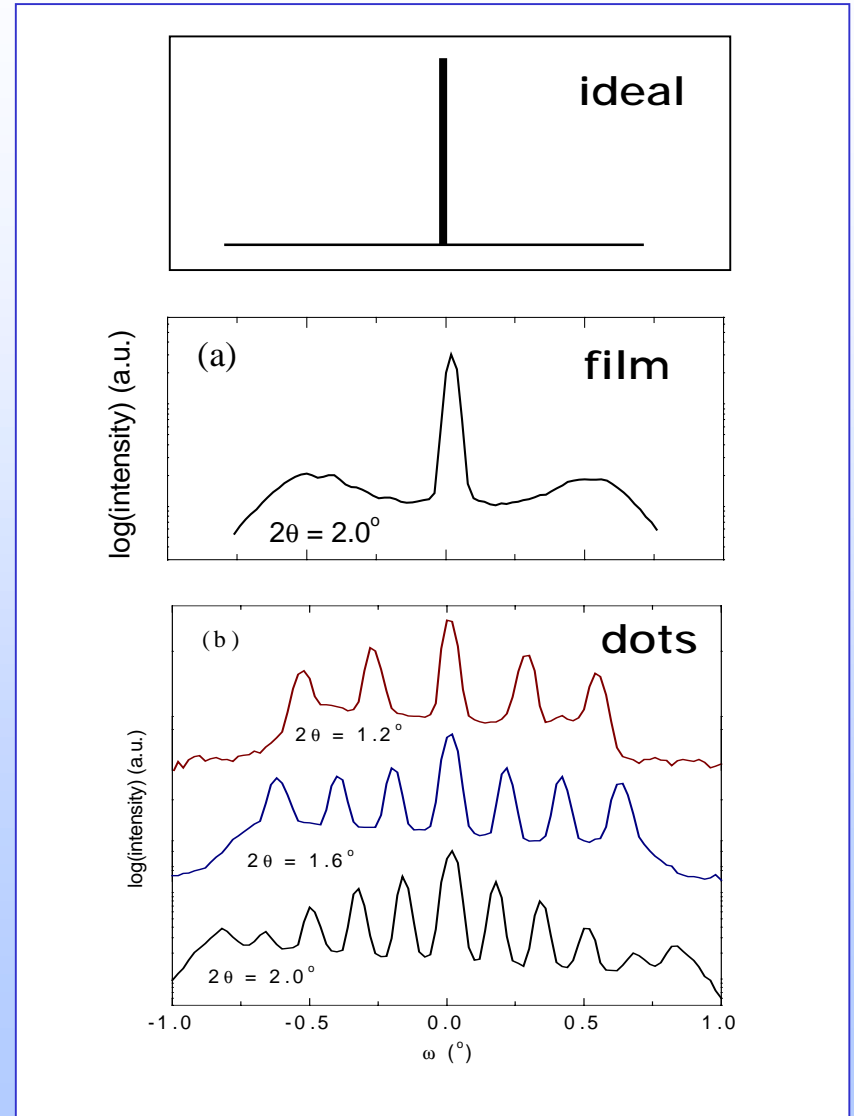
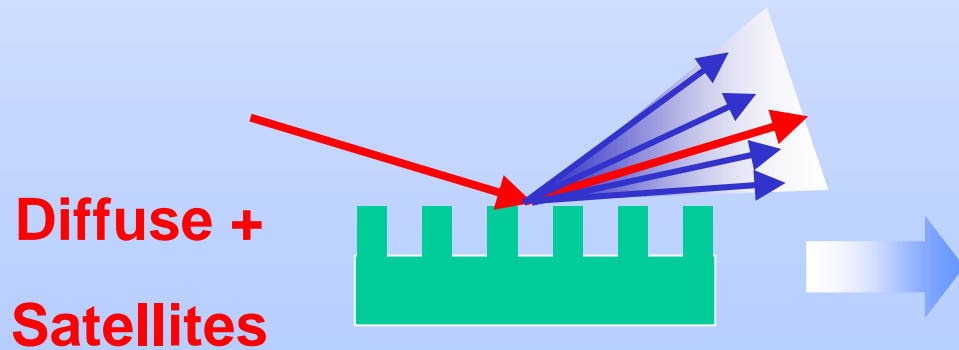
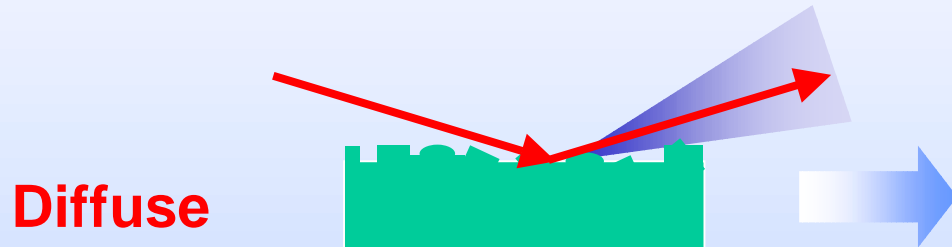
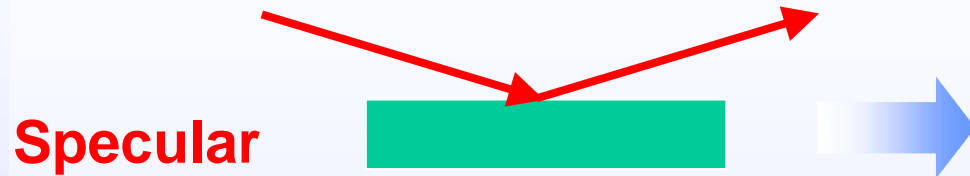
*existence of a critical length below which the islands become single-domain (J. Appl. Phys. 63, 5879 (1988))*



*'Road map' for the magnetic behaviour of Co dots*

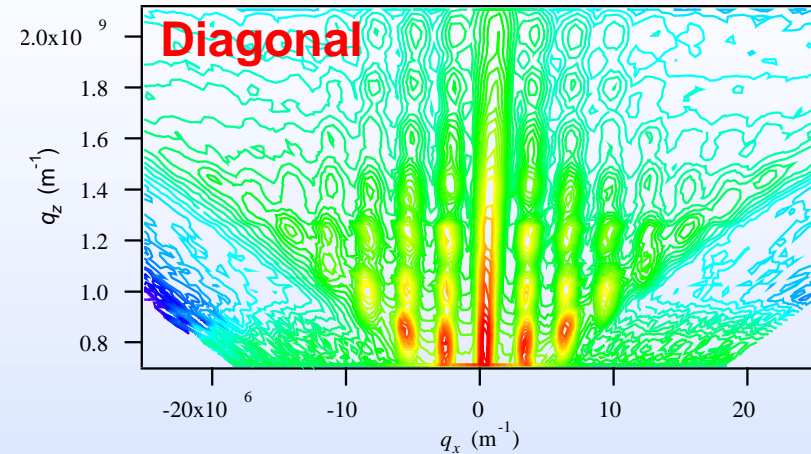
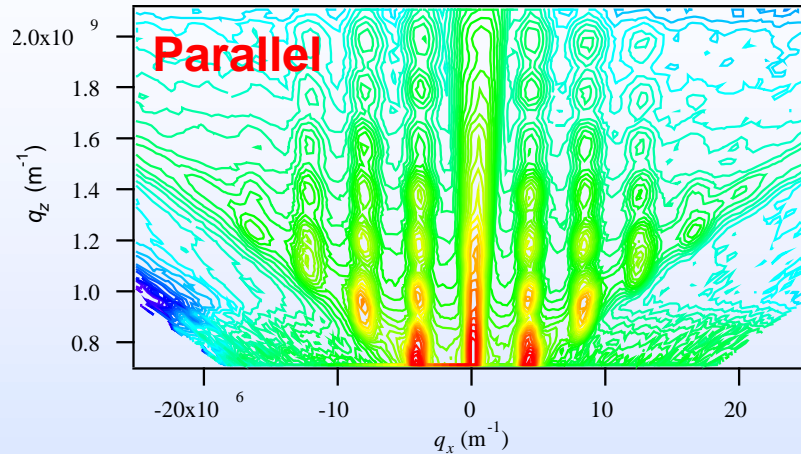


# Reflectivity of a film surface





# Reflectivity of a structured film surface

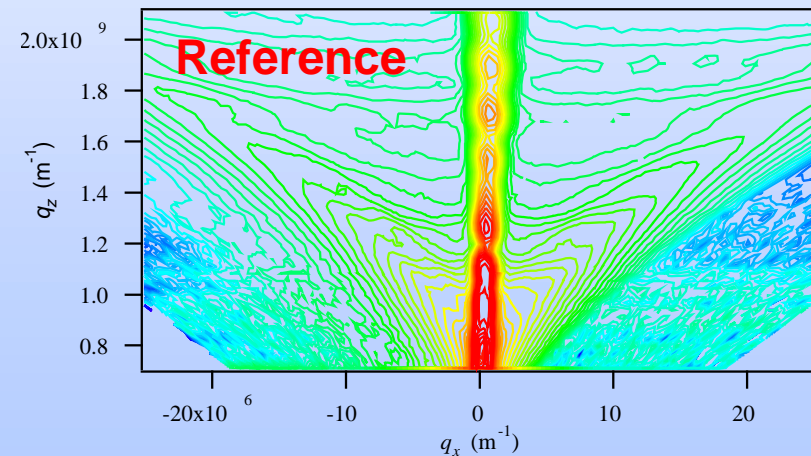


## Interpretation:

$q_z$ : vertical layering Au/Co/Au

$q_x$ : lateral dot periodicity

**Periodicity and shape uniform over large area of dot lattice.**

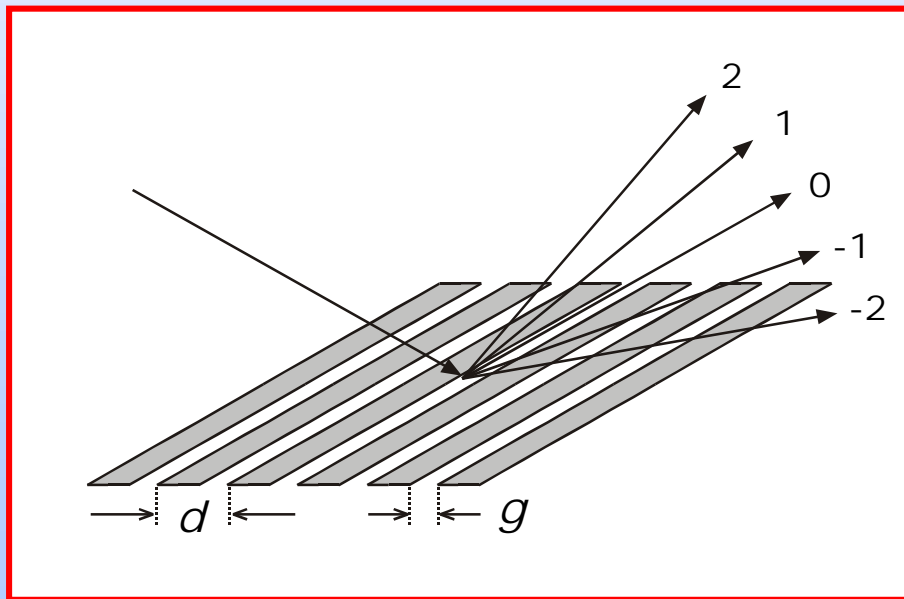




# Reflectivity of a structured film surface: simulations

Use kinematical diffraction model (Morrison, 1993)

$$I = I_{Au/Co/Au} \times \left( \frac{\sin(gq_x / 2)}{gq_x / 2} \right)^2 \times \left( \frac{\sin(Ndq_x / 2)}{\sin(dq_x / 2)} \right)^2$$

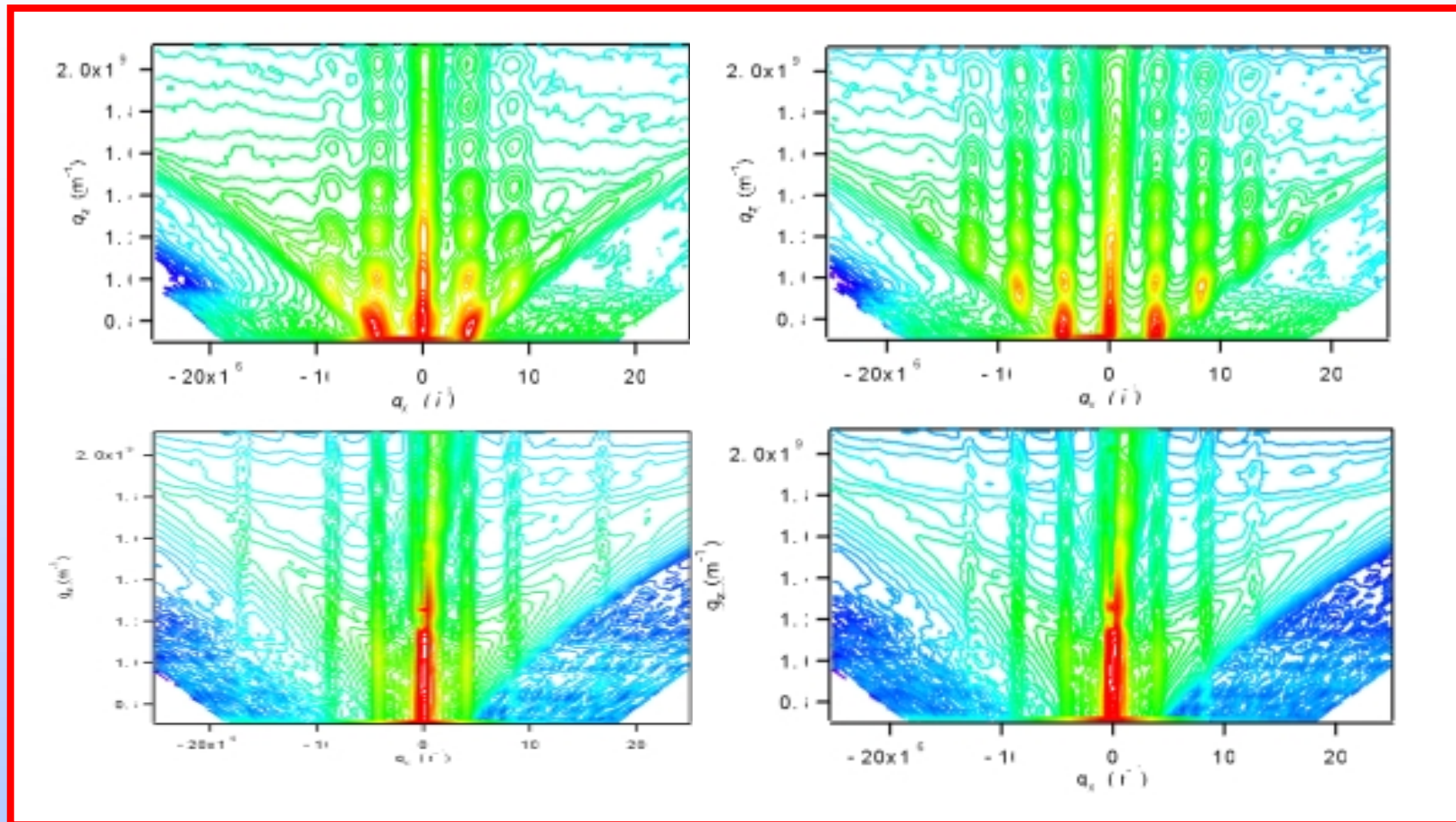


Diffraction envelope:  
reflects intensity  
distribution from single  
grating element



# Reflectivity of a structured film surface: simulations

Use kinematical diffraction model



Detailed characterization of vertical and lateral structure



# POLARIZED NEUTRON REFLECTOMETRY (PNR)

*Aim: - study neutron reflectivity of structured surfaces*

*- study magnetic properties of dots (dimensions ~ domain size)*

*Challenge: off-specular neutron scattering on dots + interpretation*

**Polarized neutron reflectometry:**

- provides information about structure and magnetism
- allows determination of magnetization direction
- provides a magnetic 'depth profile'

**This is complementary to:**

- MFM (no depth resolution, no magnetization direction)
- SQUID (substrate contribution, no depth information)



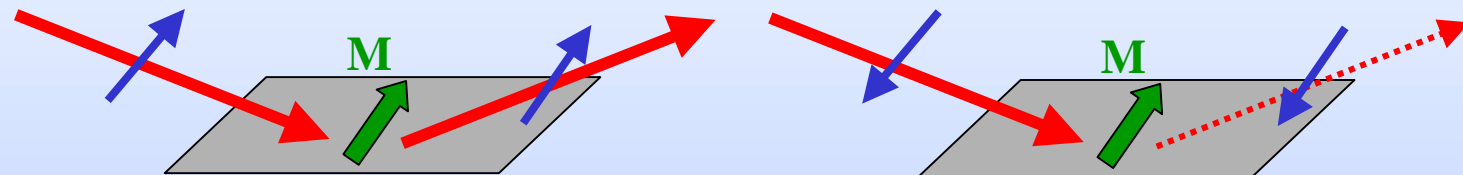


# NEUTRON REFLECTIVITY

Neutron beam can be polarized, i.e. spin up or down

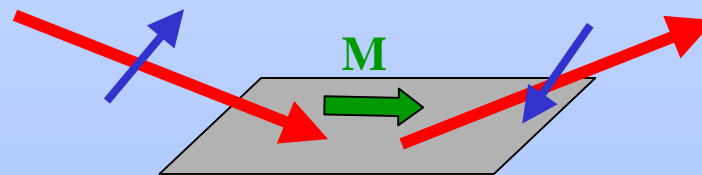
If neutron spin parallel to sample magnetization:

spin is conserved (NSF, non-spin-flip process)



If neutron spin perpendicular to sample magnetization

spin is reversed (SF, spin-flip process)



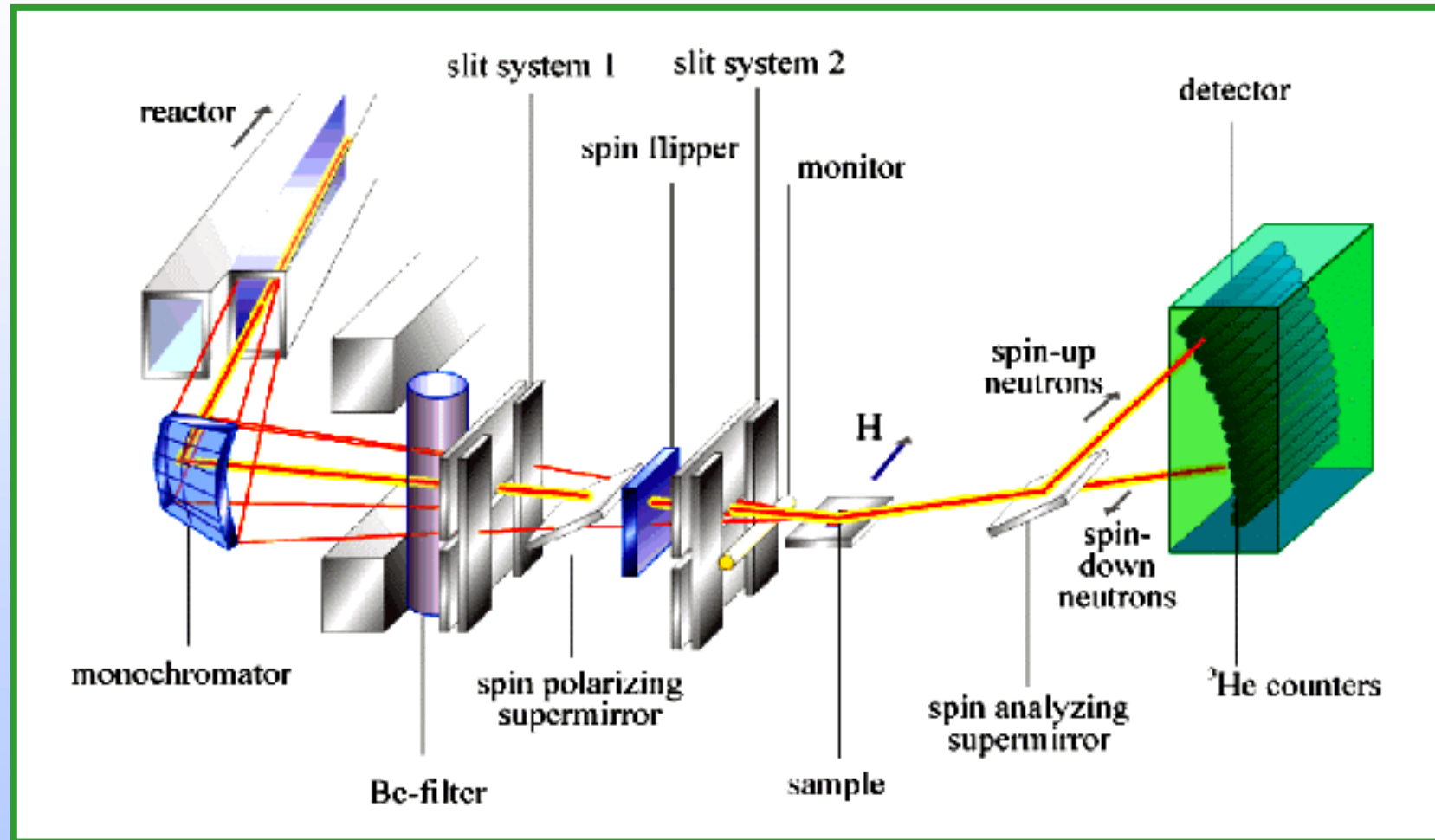
Spin analysis: magnetization directions.





# NEUTRON REFLECTIVITY: experimental

## V6 reflectometer, HMI Berlin, cold neutrons



**Polarization**

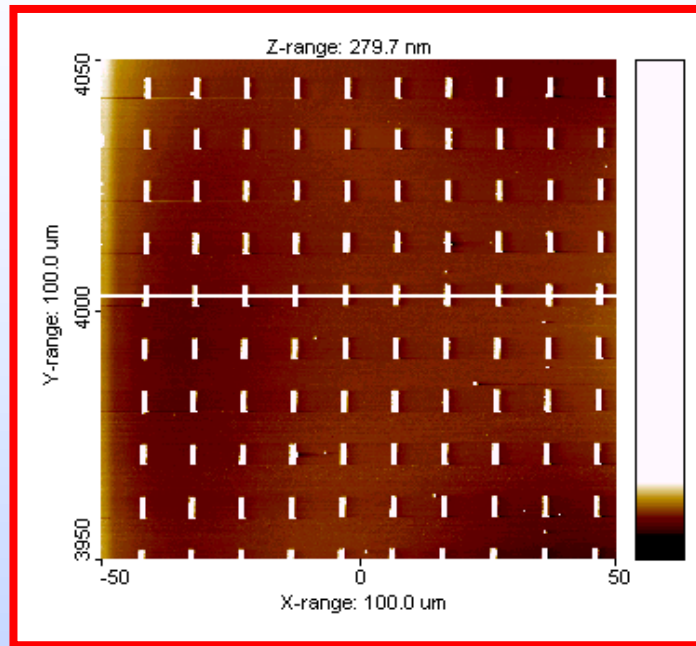
**Analysis**

**Interaction**



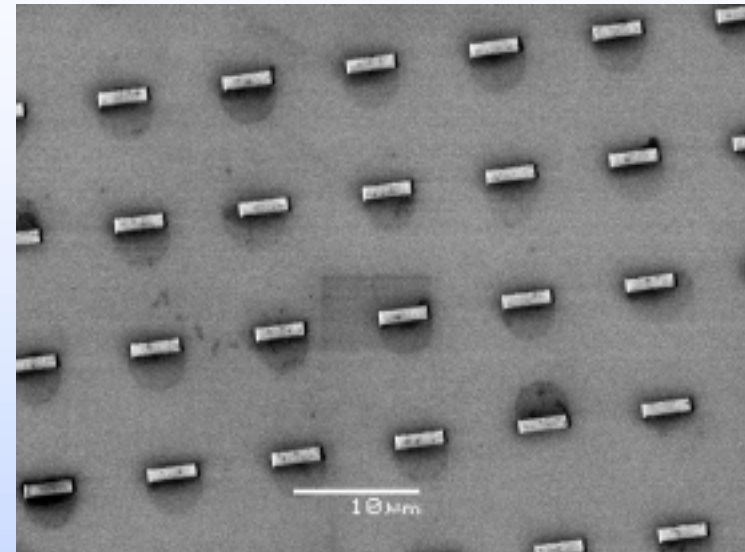


# NON-SPECULAR REFLECTIVITY: shape anisotropy



## AFM results

- electron beam lithography in Leica machine (IMEC)
- deposition of Au/Co/Au trilayer in MBE
- patterned area 4 cm<sup>2</sup>

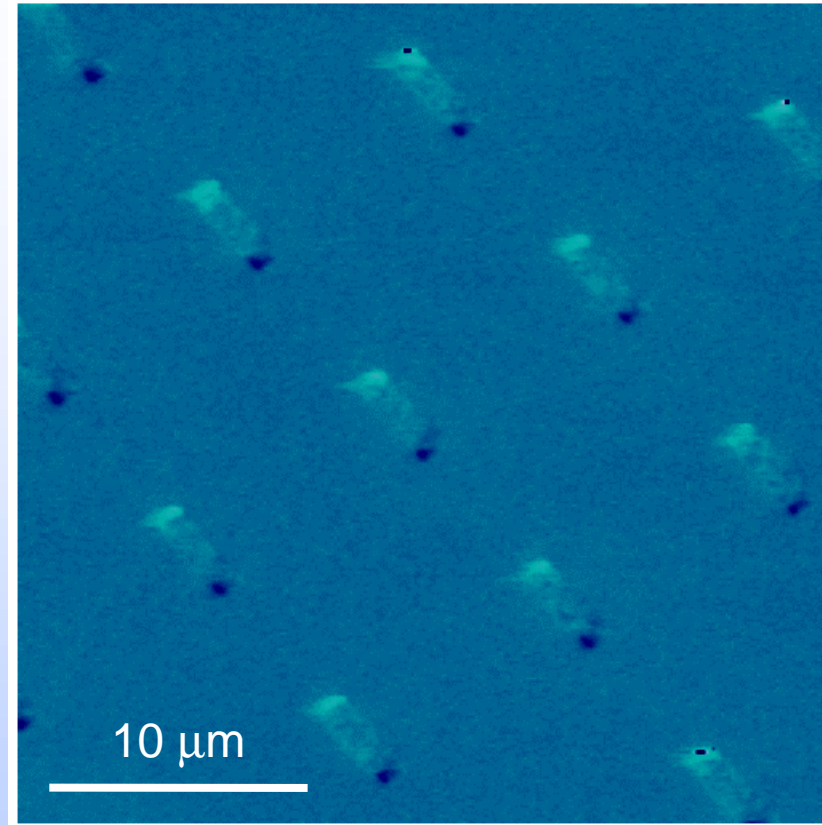


## SEM results





## Shape anisotropy: MFM results



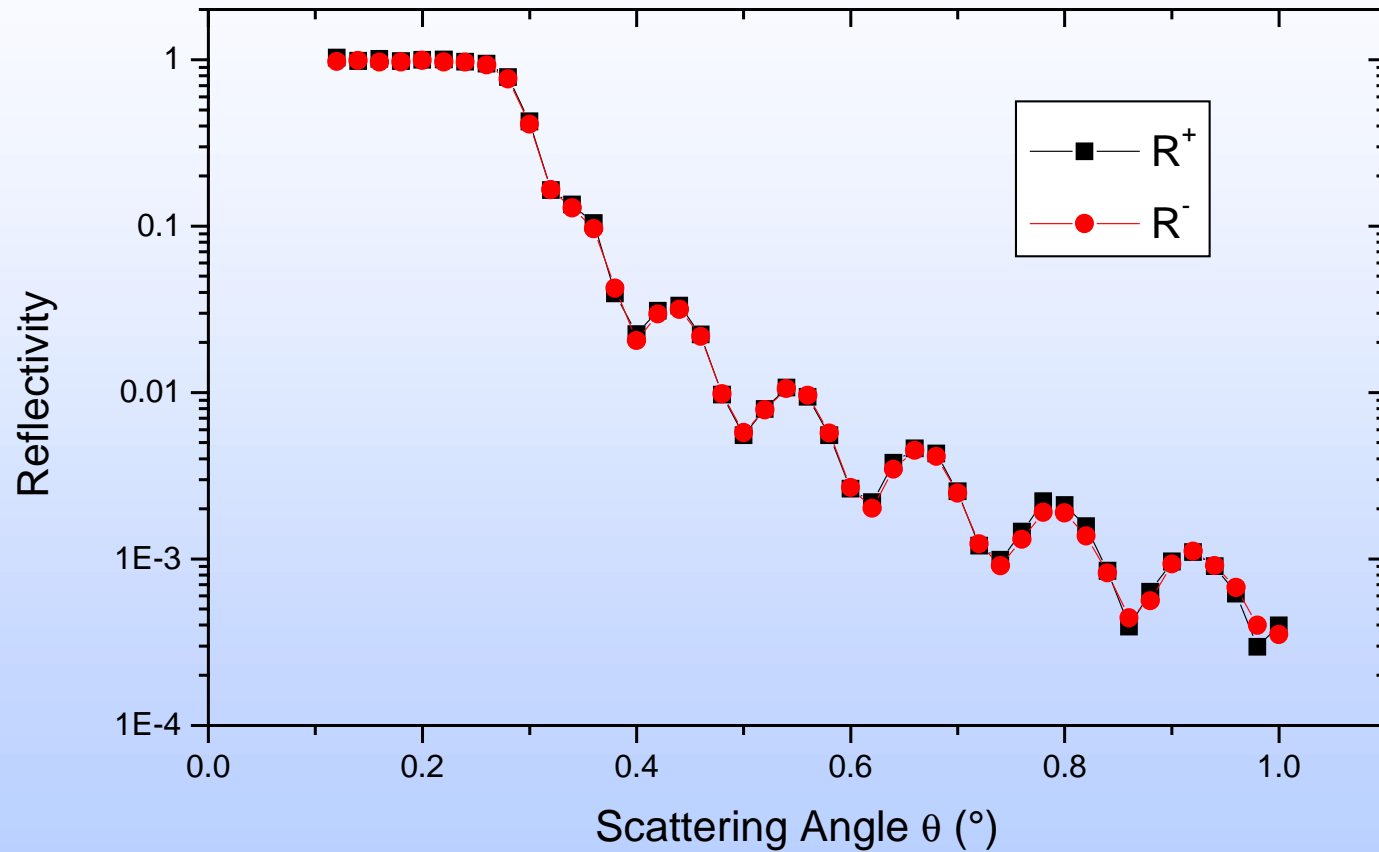
- clear dark/bright contrast in MFM image
- indicates a single-domain state after saturation
- same result over macroscopically large area





# SPECULAR REFLECTIVITY

Sample in saturated state ( $H=2400$  G)



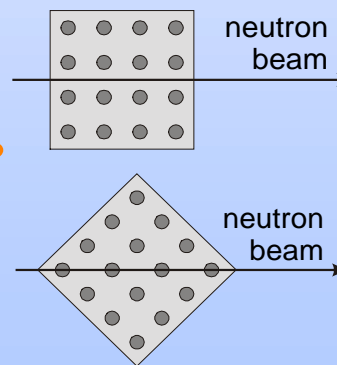
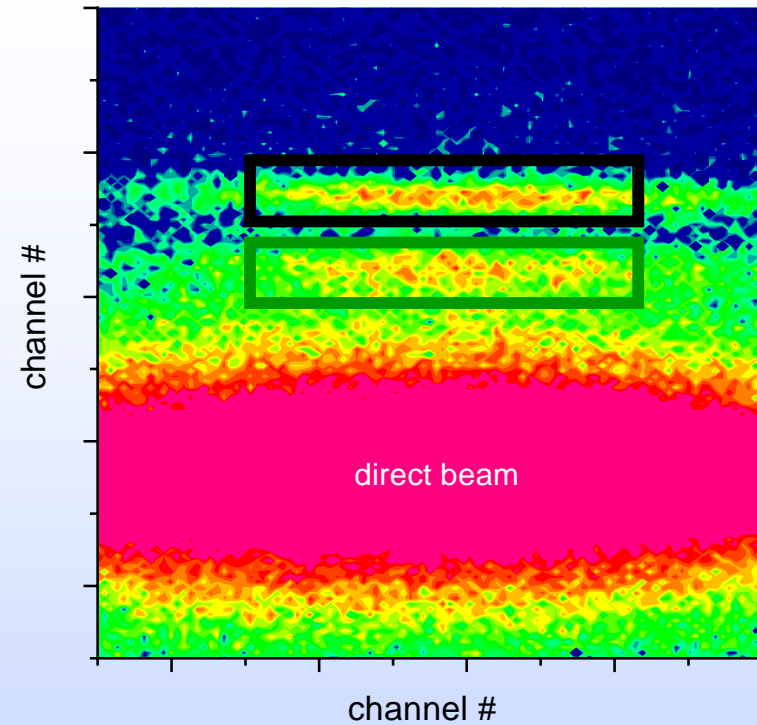
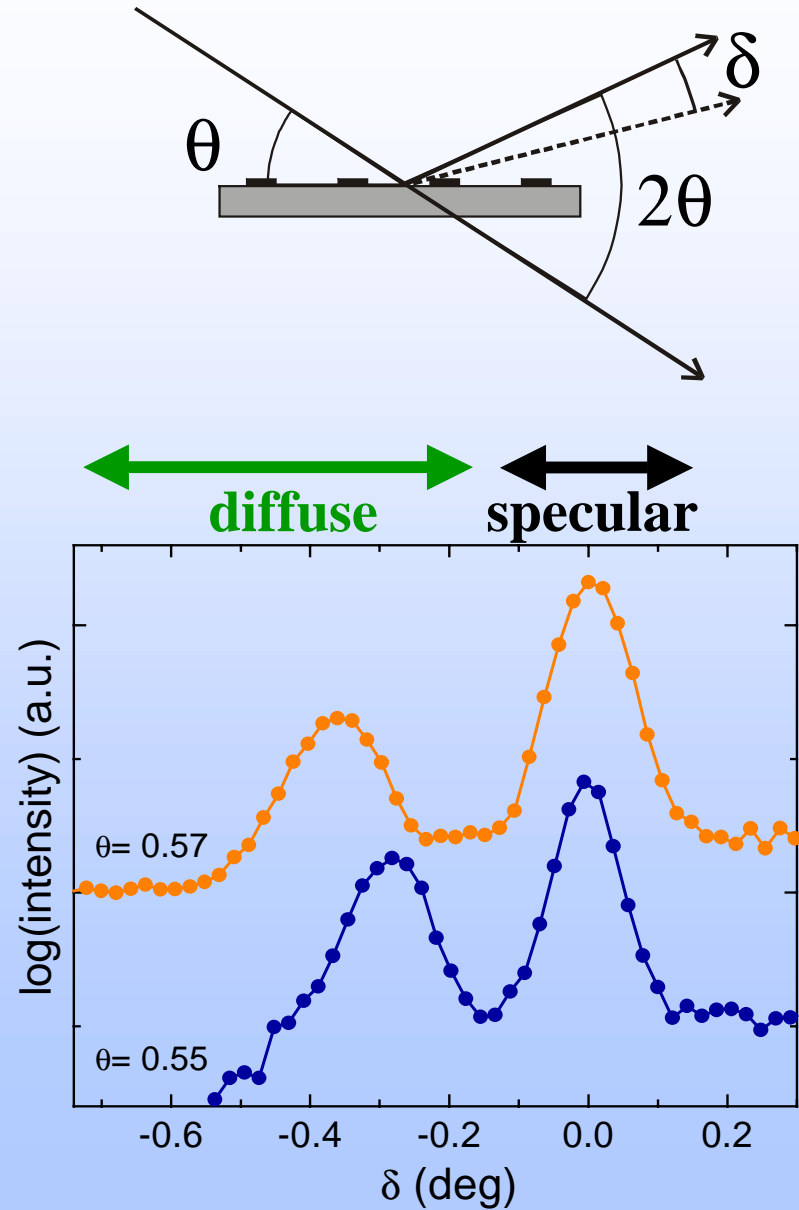
No clear splitting between  $R^+$  and  $R^-$

Specular reflectivity dominated by non-magnetic substrate





# 2-D NEUTRON DETECTION



**Observation of lateral periodic dot structure using neutron reflectivity**

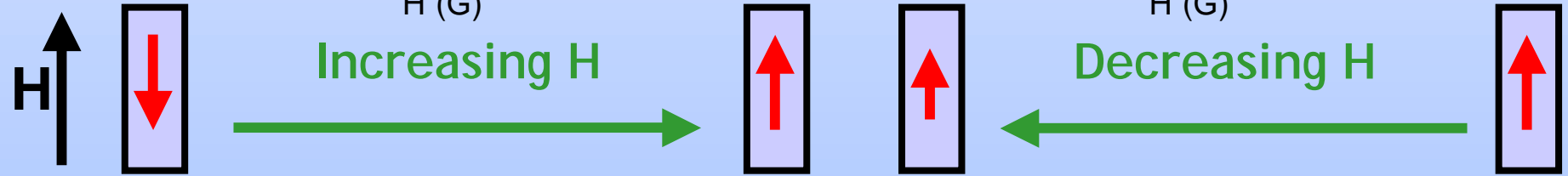
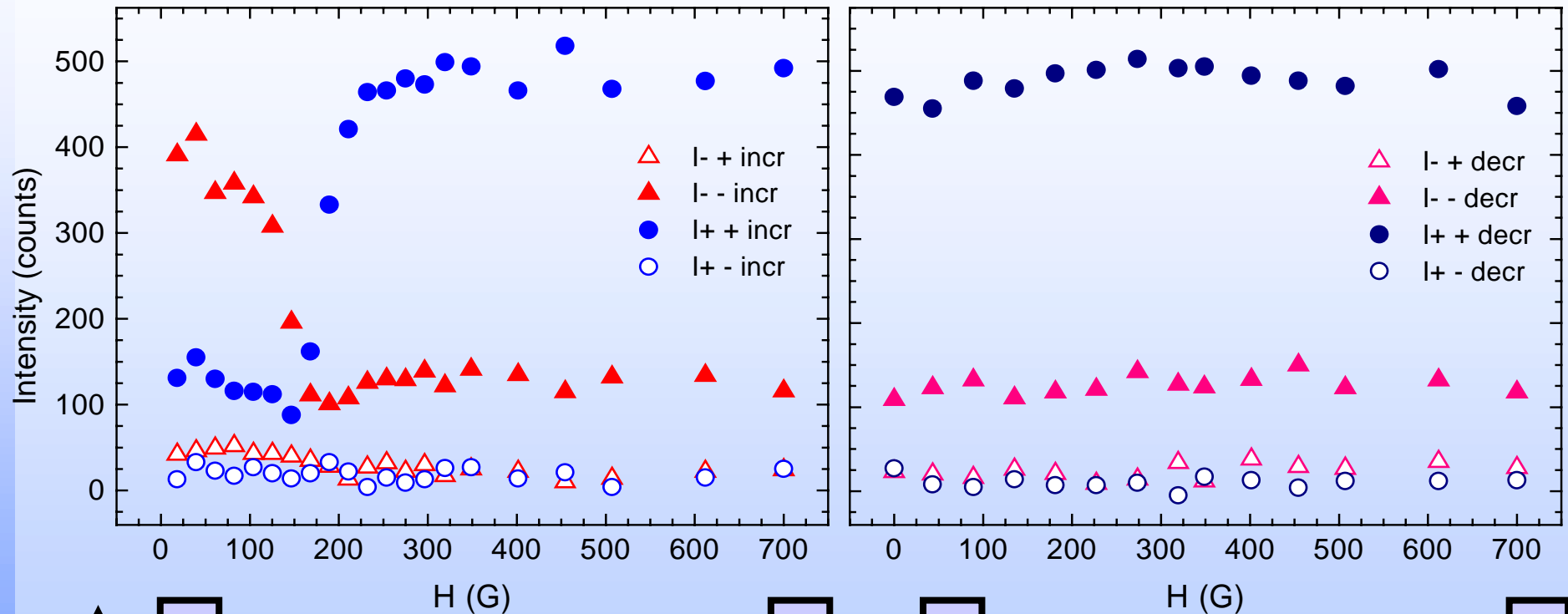
*K. Temst et al., Appl. Phys. Lett. 79, 991(2001)*  
*Fermon et al. (1999); Toperverg et al. (2000)*





# NON-SPECULAR REFLECTIVITY: shape anisotropy

Sample in remanent state after saturation in negative field



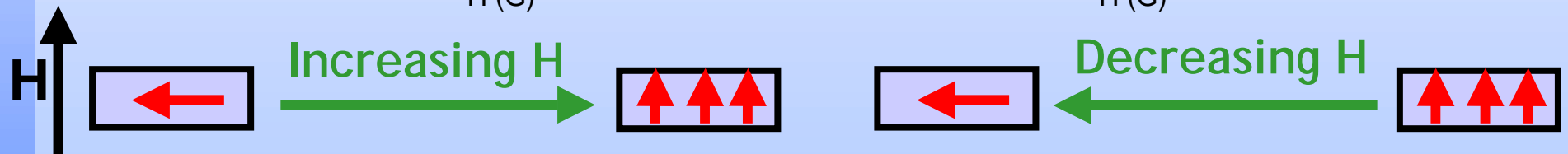
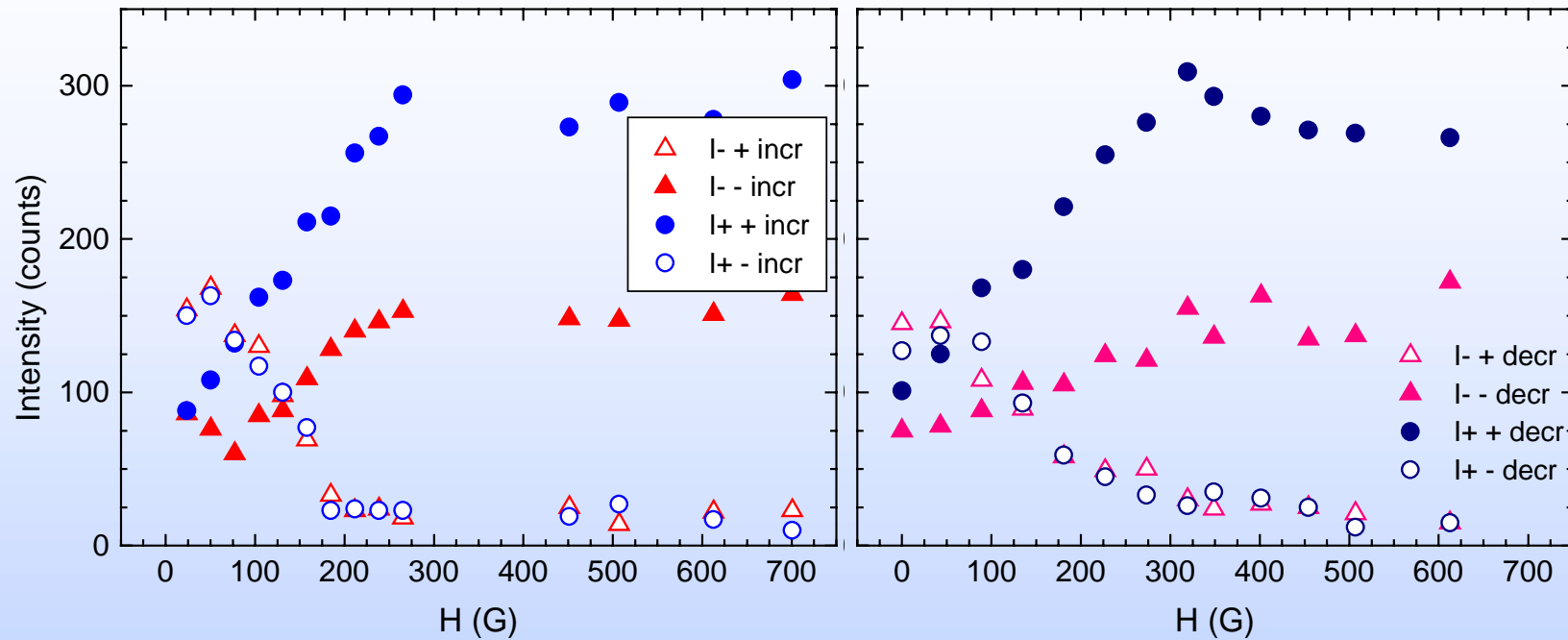
Little SF scattering: magnetizations (anti)parallel to neutron spin.

Splitting between  $I^{++}$  and  $I^{-}$  maximal in saturation.





# NON-SPECULAR REFLECTIVITY: shape anisotropy



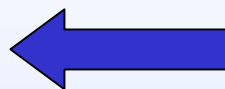
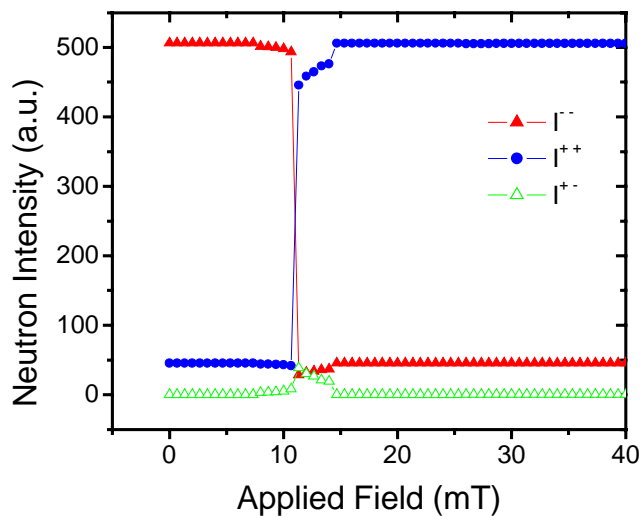
SF scattering: magnetization perpendicular to neutron spin.

I<sup>+</sup> + increases: magnetization gets parallel to neutron spin.





# NON-SPECULAR REFLECTIVITY: simulation



kinematic intensity calculation



6 mT



11.3 mT

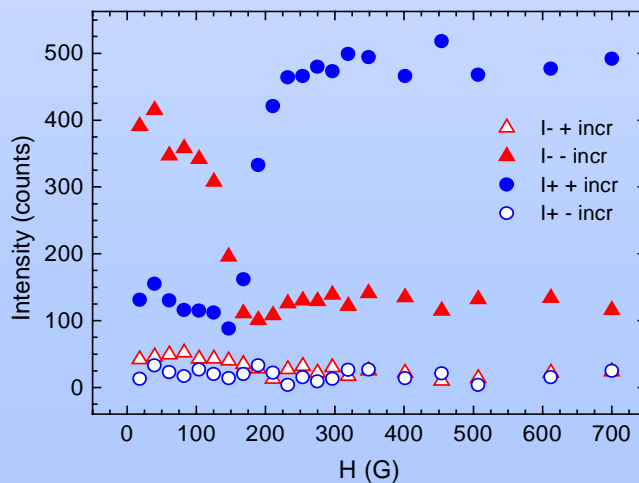


12 mT



18 mT

Micromagnetics simulation of reversal in single dot  
OOMMF Framework, NIST, Gaithersburg, USA



Qualitative agreement OK

*K. Temst et al., Appl. Physics A (2001), in press*

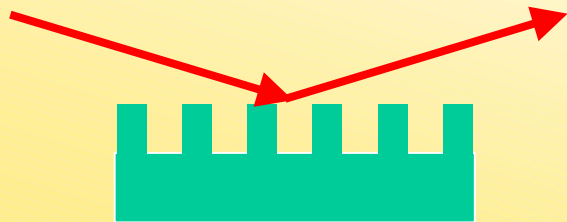




## CONCLUSIONS

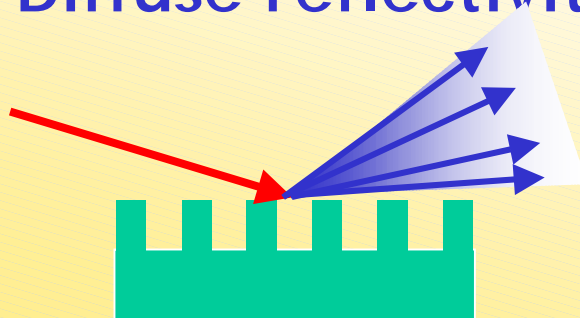
### Array of magnetic Co dots studied by Polarized Neutron Reflectivity

#### Specular reflectivity



*Dominated by substrate.  
No magnetic information.*

#### Diffuse reflectivity



*Selective information from dots.  
Field dependence shows  
magnetization reversal.*

