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Magnetic North III

Angular dependence of FMR measurements in exchange coupled NiFe/NiO bilayers: Experiment and Theory

B.W. Southern*

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Outline

- Introduction
- Experimental results
- Theoretical Interpretation
- Summary

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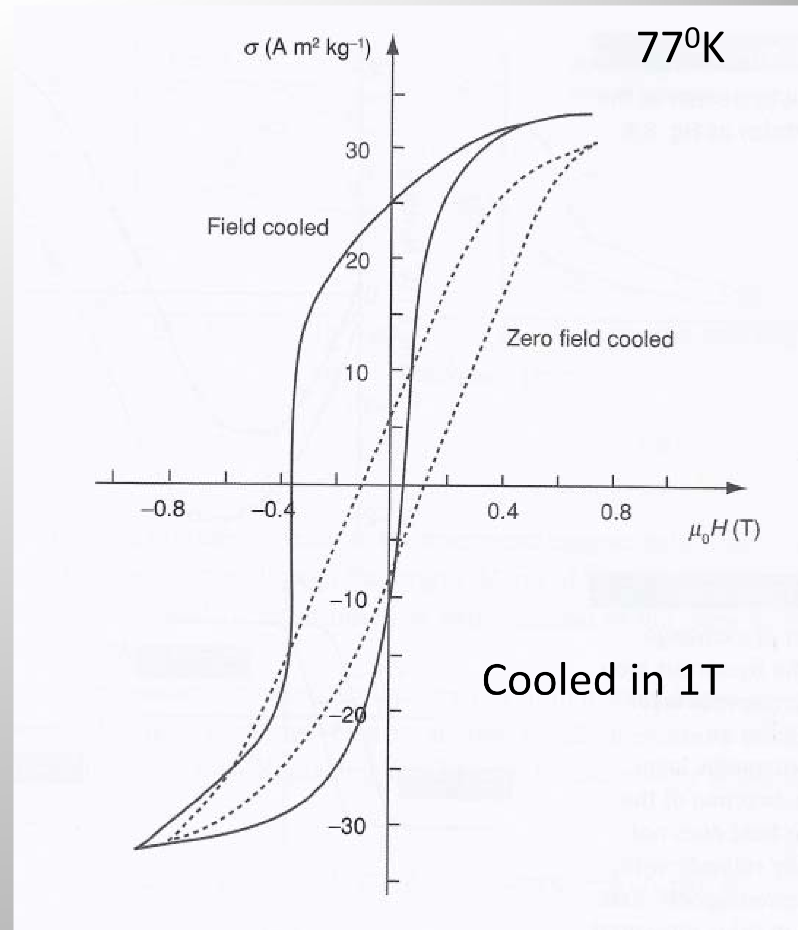
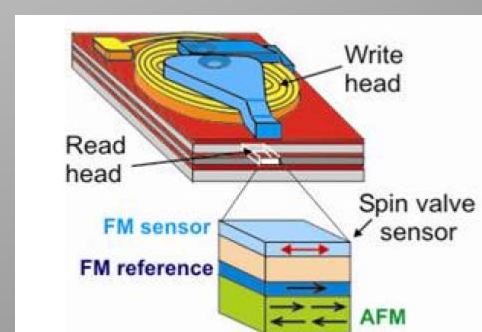
- Ferro (F) and Anti-ferro (AF) films in contact exhibit the phenomenon of exchange-bias first observed by Meiklejohn and Bean (1956) in CoO
- Usually characterized by a shifted hysteresis loop after field cooling.
- Attributed to a unidirectional anisotropy
- Applications in information storage technologies and was first practical application of AF in spin valves





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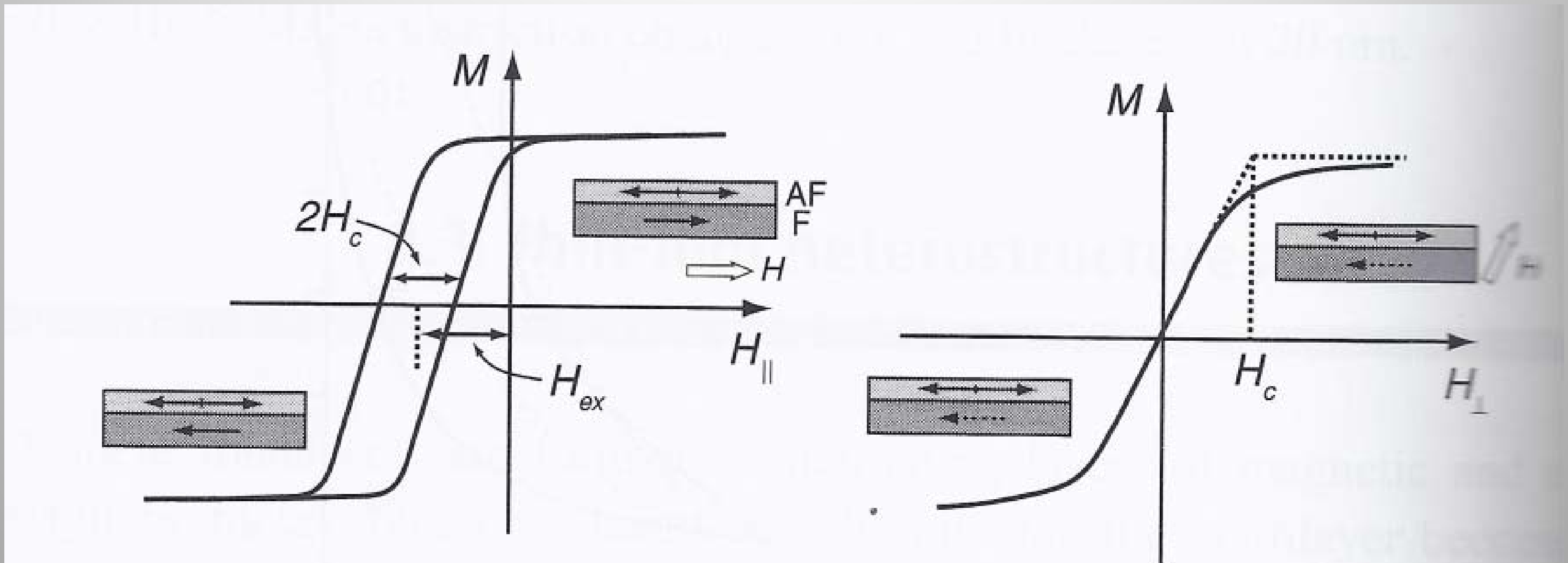

Easy ($0^{0)}$ Hard(90^0)

$H_c=(h_R-h_L)/2$
$H_{ex}=(h_R+h_L)/2$

See review articles by

- Nogues and Schuller JMMM 192,203(1999)
- Berkowitz and Takano JMMM 200,552 (1999)
- Stamps J. Phys. D. 33, 247 (2000)
- Kiwi JMMM 234,584 (2001)

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- Different experimental techniques yield different values for the coupling field H_{ex} at the interface
- Hysteresis loops involve irreversible switching of the magnetization
- FMR and BLS generally involve small pertubations of the magnetization about equilibrium and are reversible
- In this talk I will discuss a particular NiFe/NiO bilayer system where both magnetization and FMR measurements have been performed by research groups in Manitoba.

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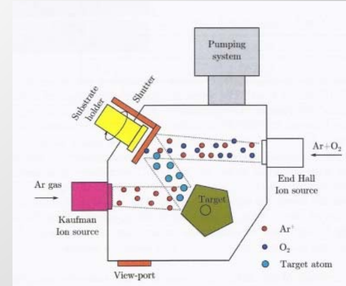
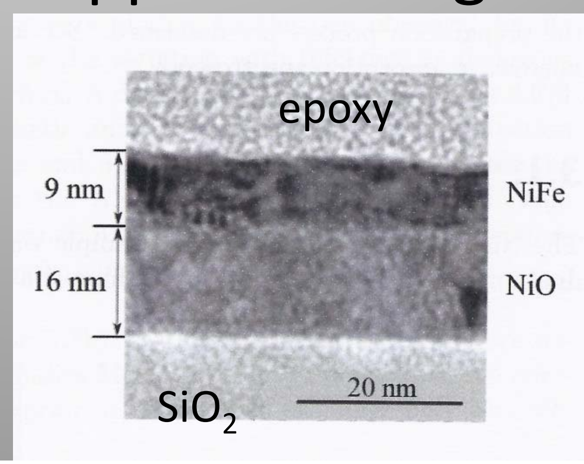
Fabrication

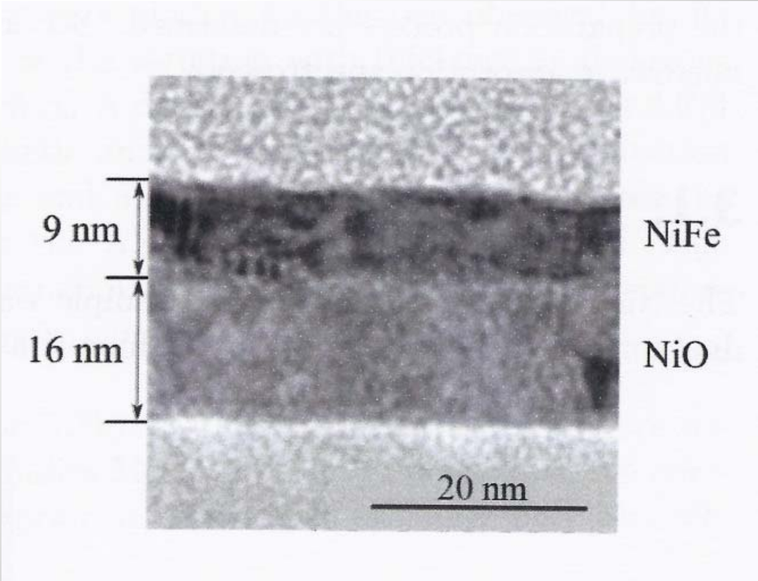


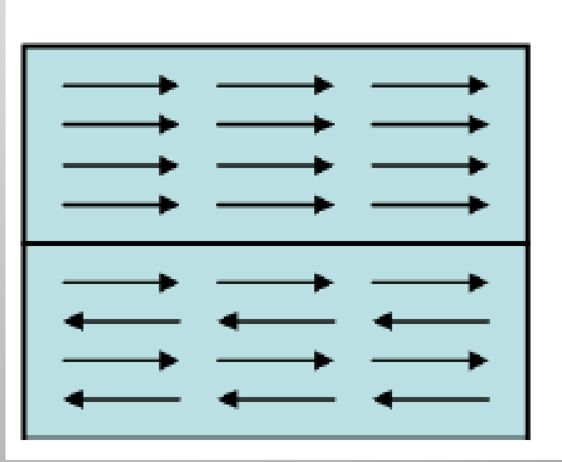
- The bilayer was prepared by the group of Ko-Wei Lin at the National Chung Hsing University in Taiwan using a dual ion-beam sputtering technique at room temperature.
  Lin et al Appl. Phys. Lett. 100, 122409(2012)
- The NiFe/NiO film was fabricated on a SiO_2 substrate and no external field was applied during any stage of the growth

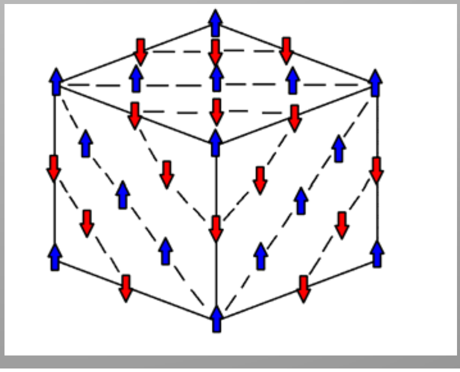


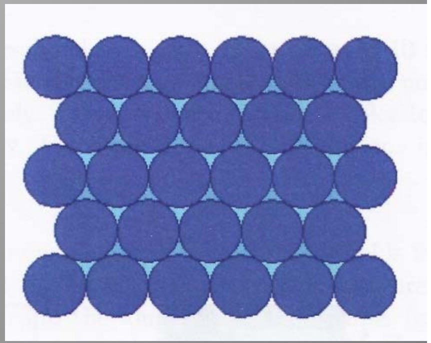
Analysis

- NiO film layers had crystallite sizes between 5 and 20 nm in diameter that penetrated the 16 nm thickness (XRD)
- ZFC and FC DC susceptibility measurements indicated a blocking temperature T_B=360K
- NiO has a cubic fcc structure with alternating ferromagnetic sheets along the [111] direction
- Since no field was applied during fabrication, many AF domain configurations could be present.(there 4 possible [111] directions as well as perhaps three in each plane)









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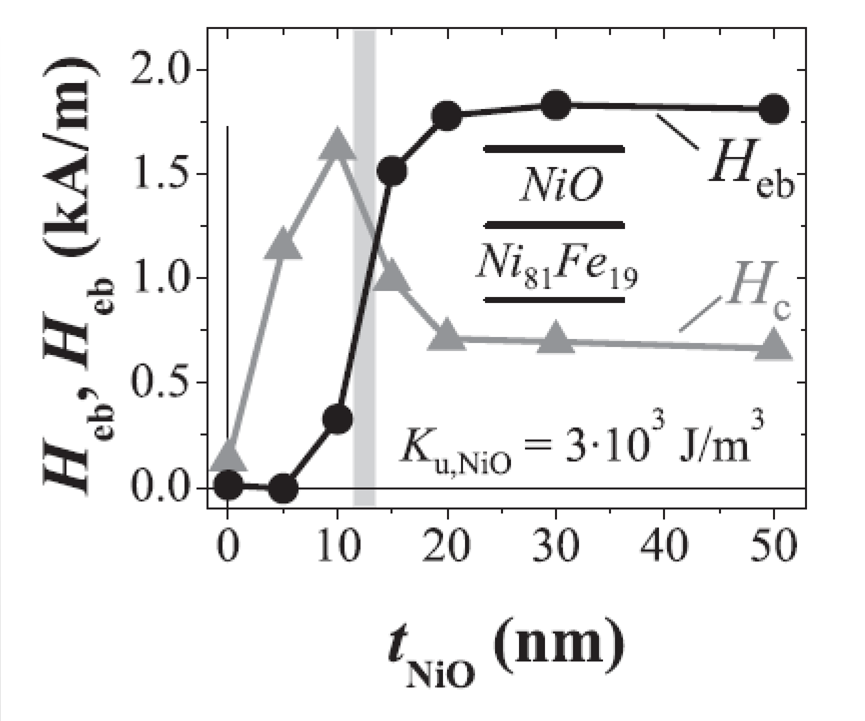

McCord: Adv in Solid State Physics 48, 157 (2009)

- The presence of exchange bias and coercivity depends on the thickness of the AF layer
- For 16 nm thickness, H_c and H_{ex} could be of the same order of magnitude with H_{ex} larger

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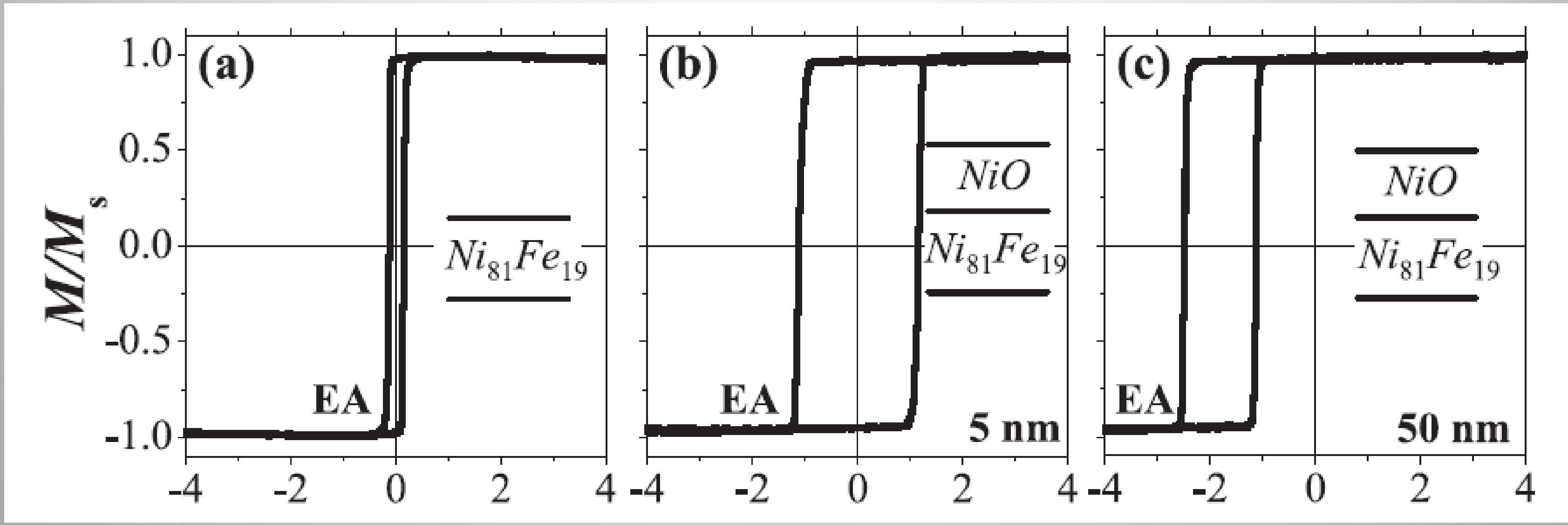
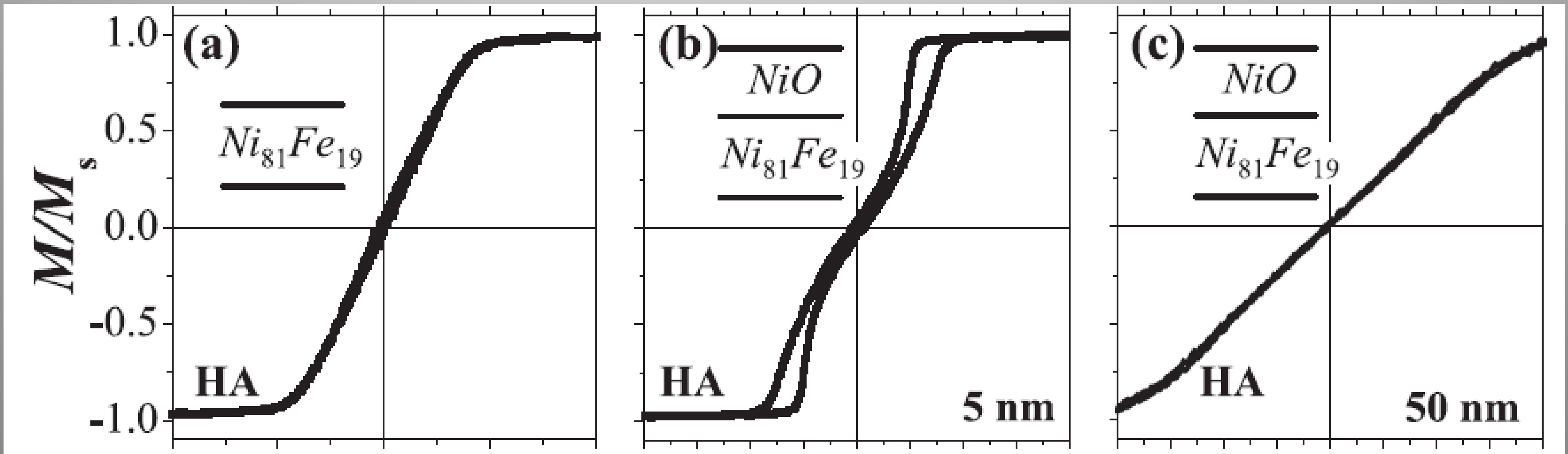
McCord: Adv in Solid State Physics 48, 157 (2009)

Easy





Hard

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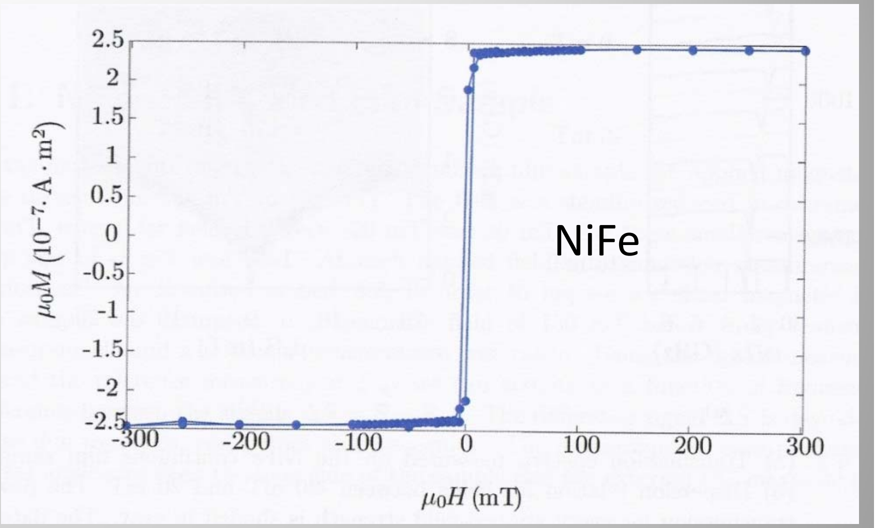
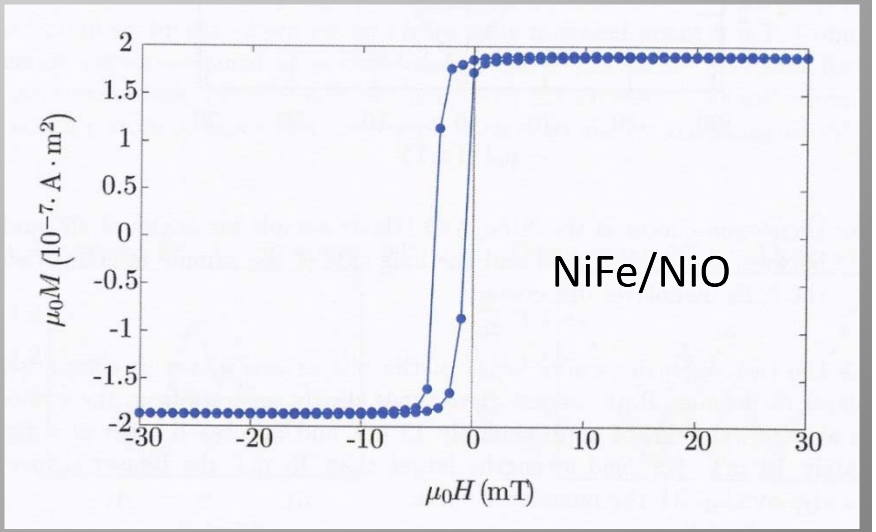
Magnetometry

- Magnetometry measurements by Van Lierop's group on a sample of length 6 mm and width 2 mm for both a single and bilayer were performed
- Films were heated to 400K and cooled in a field of 2T
- Single NiFe layer exhibited negligble coerciviity and no exchange bias
- Bilayer sample exhibited both coercivity and exchange bias shift H_{ex} ~ 2.0 mT along the cooling field direction
- H_c ~ 1.1 mT @ 300K





FMR Measurements

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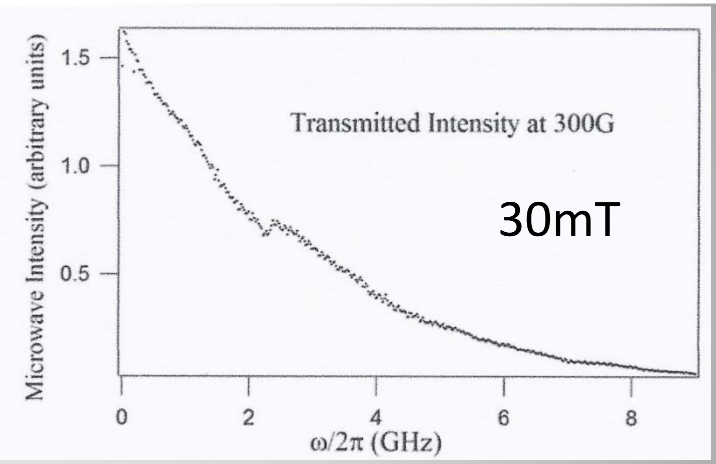
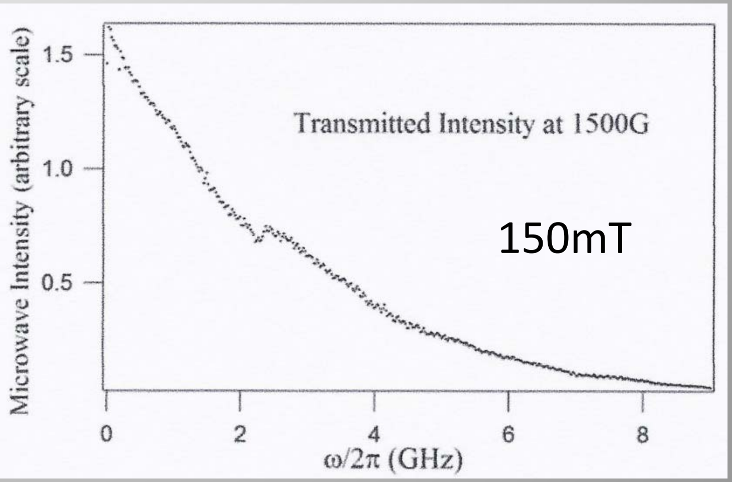
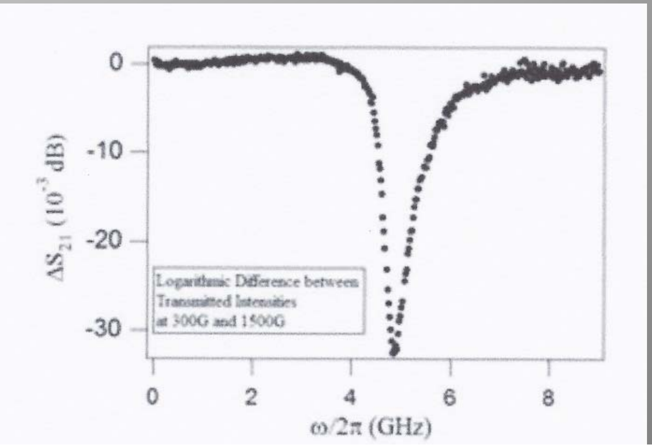
- FMR measurements on the same samples were performed by the group of Can-Ming Hu
  NiFe:
  L=21 mm W=20.0 mm T=9nm
  NiFe/NiO:
  L=16.3 mm W=13.8 mm T=9 nm
- Broadband microwave absorption spectroscopy was used to detect the FMR frequency as evidenced by a transmission minimum
- A reference measurement at 150 mT is used to perform a subtraction at lower fields







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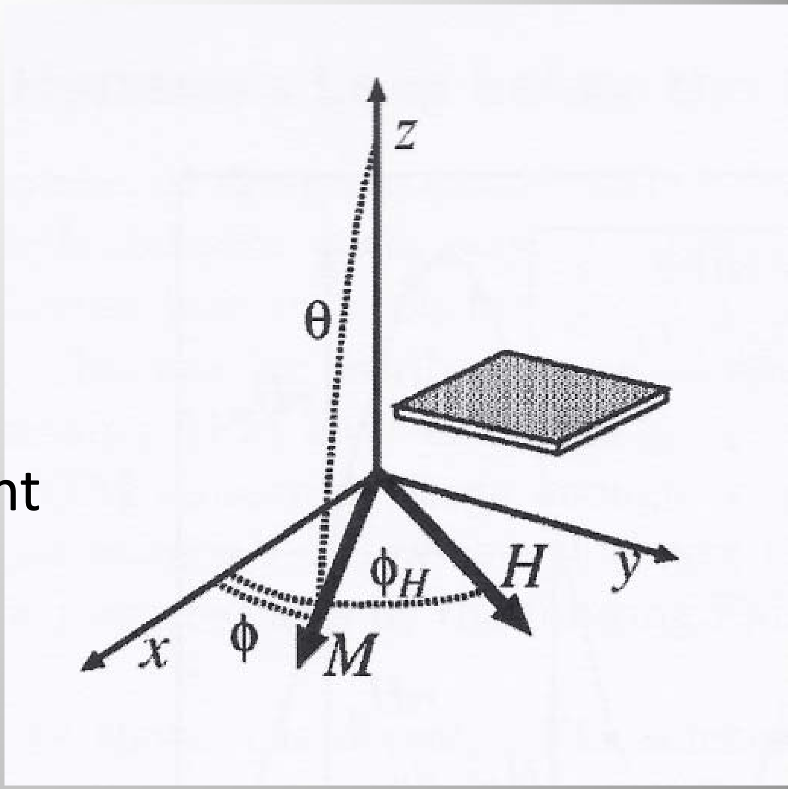
FMR

- External field is applied in-plane at various angles ϕ with respect to the long direction
- For each ϕ, a reference measurement is made at ± 150 mT and then either an up sweep or a down sweep is carried out between ±30 mT at intervals of 0.4 mT
- No heating or cooling in a field performed
- Two distinct types of behaviour are observed for the FMR frequency as a function of the field which depend upon the direction of the field.



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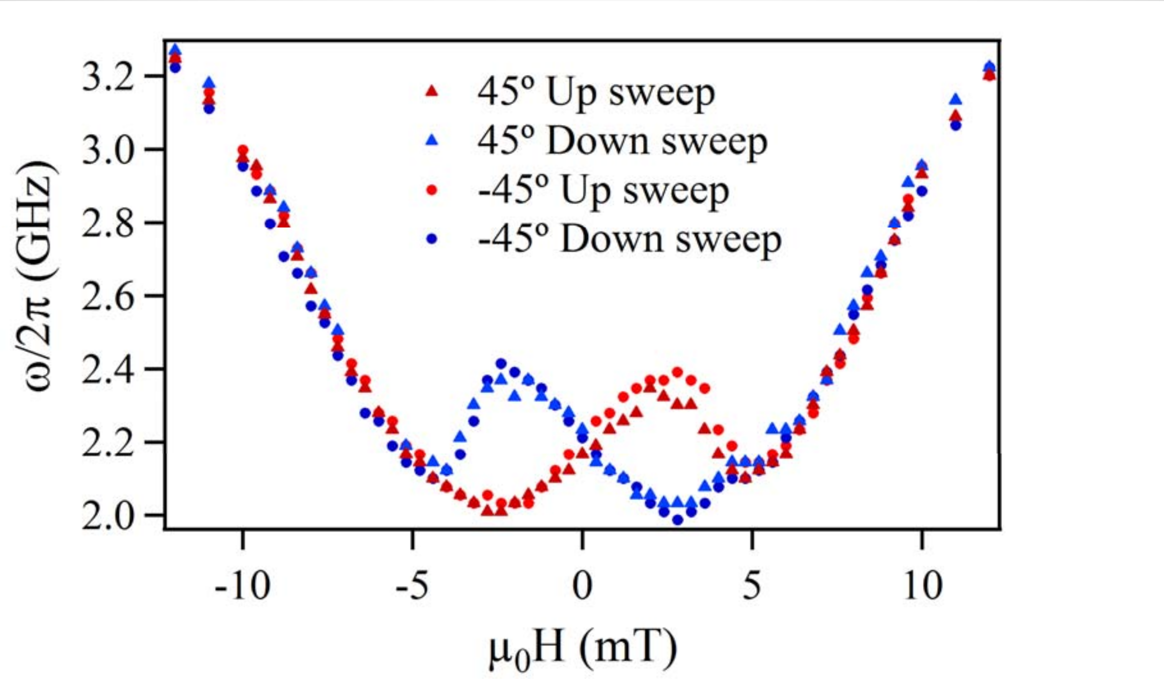

- Irreversible switching is observed in the range -6mT < H < 6mT
- For all angles < 45^0 a single peak is found
- Frequency range is 2.0 < f < 2.5 GHz

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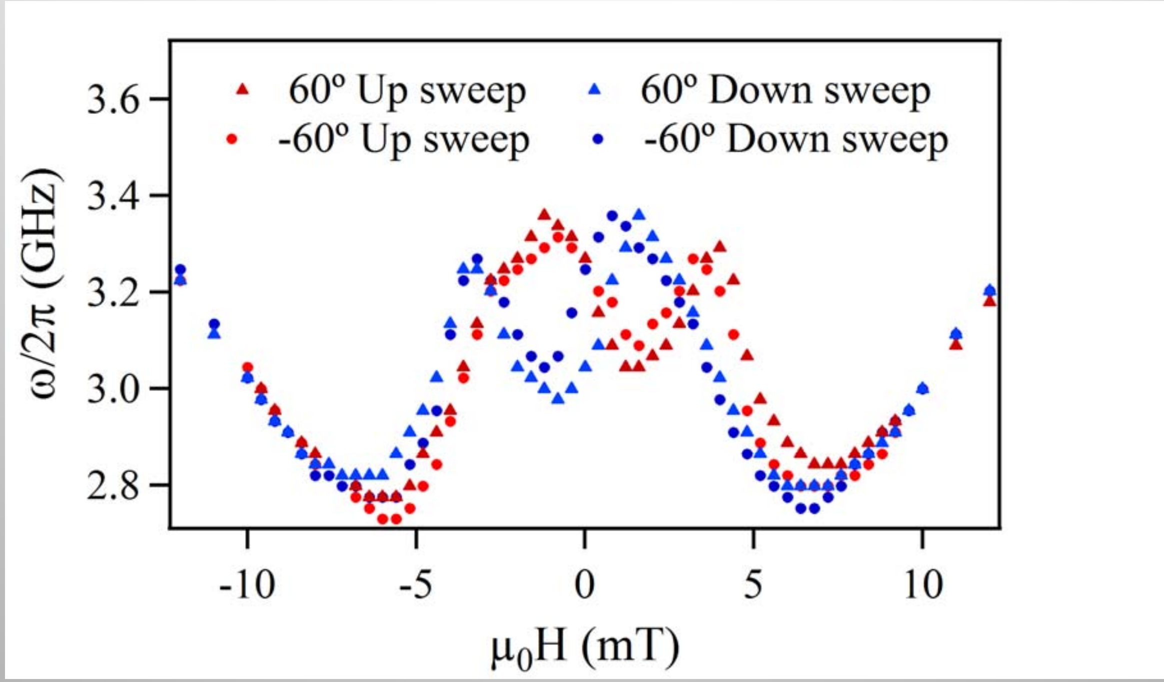
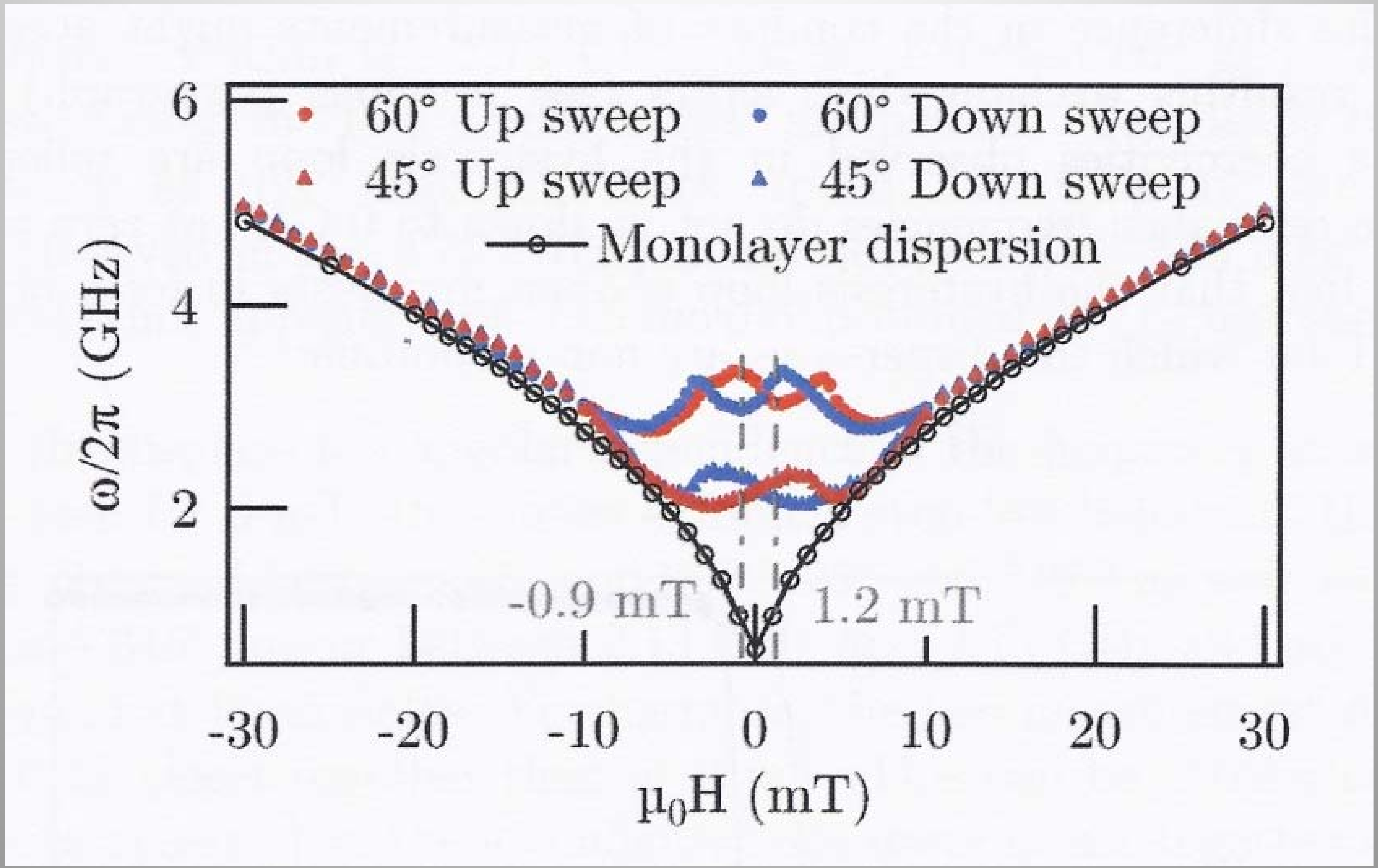


- Irreversible switching is observed in the range -8mT < H < 8mT
- For all angles >60^0 a two peaks are found
- Suggests a two step reversal process
- Frequency range is 2.7 < f < 3.4 GHz



$$f_r = \frac{\gamma \mu_0}{2\pi}\sqrt{\left(H + M_s\right)H}$$

$\mu_0 M_s$=963 mT, γ= 176 GHz/T

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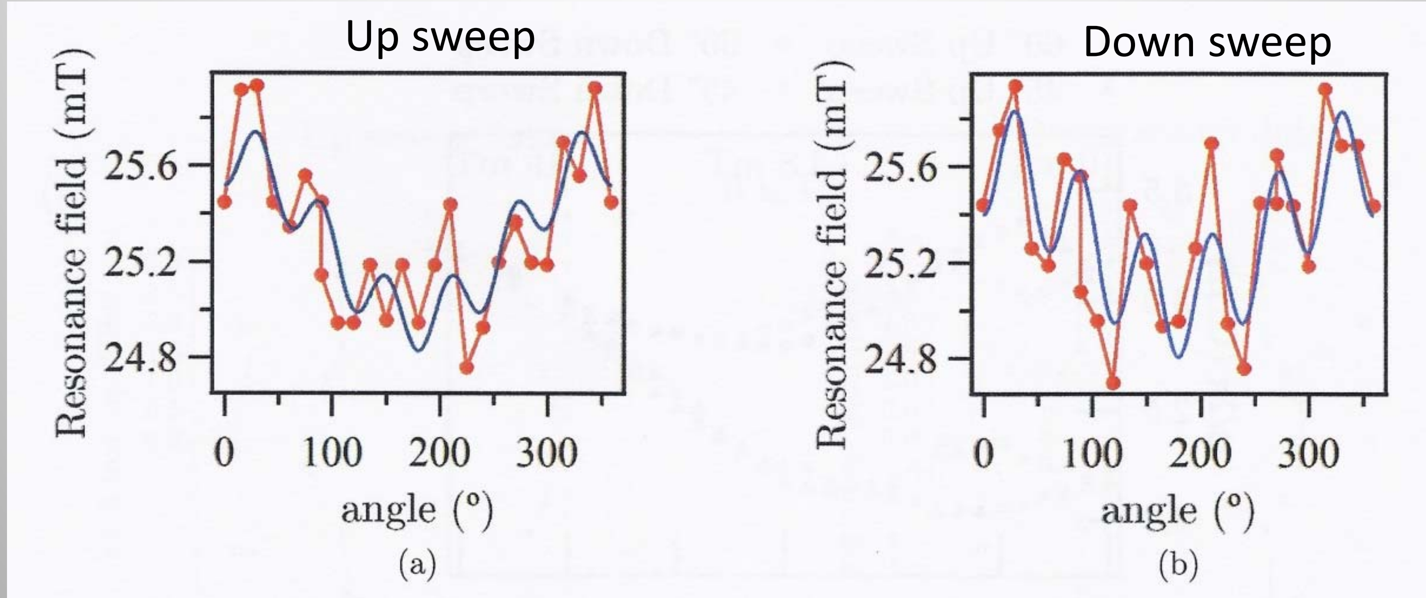

- For 4.5 GHz we can plot the resonant field H_r as a function of ϕ
- Can be fit to the form $H_r = a_0 + a_1 \cos(\phi) + a_6 \cos(6\phi)$
  a_0= 25.306 mT, a_1= .345 mT and a_6=-0.133 mT for up sweep (a)
  a_0= 25.338 mT, a_1= .296 mT and a_6=-0.237 mT for down sweep (b)
- Suggests that there may be a unidirectional anisotropy as well as a six-fold anisotropy

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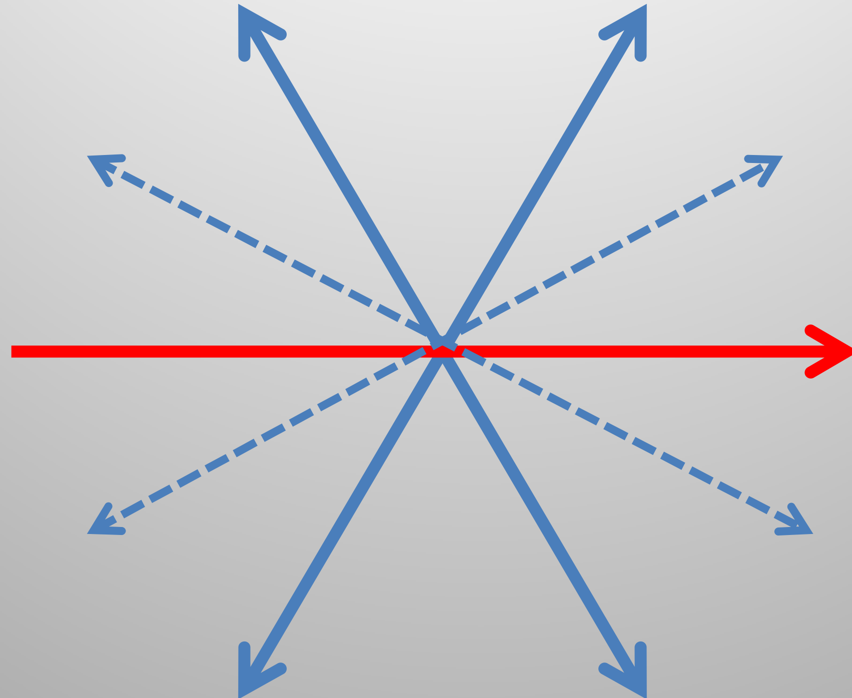

? Theory

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- In order to model this behaviour we treat the NiFe as a single domain and include the effect of the NiO as introducing anisotropies at the interface
- The energy of the system can be written as

$$E = -H.M + \frac{1}{2}M_z^2 - \frac{x_2}{2}S_x^2 + \frac{x_4}{4}\left(S_x^2 S_y^2 + S_y^2 S_z^2 + S_z^2 S_x^2\right) + x_6\left(S_x^6 - S_y^6 - 15S_x^4 S_y^2 + 15S_x^2 S_y^4\right) - jS_x$$

- Use spherical coordinates to find extrema of E as function of the field direction ϕ_H and magnitude
- Calculate FMR frequencies using Smit-Beljers formula (1955)

$$\frac{\omega}{\gamma} = \frac{1}{M_s \sin\theta}\sqrt{E_{\theta\theta}E_{\phi\phi} - E_{\theta\phi}^2}$$

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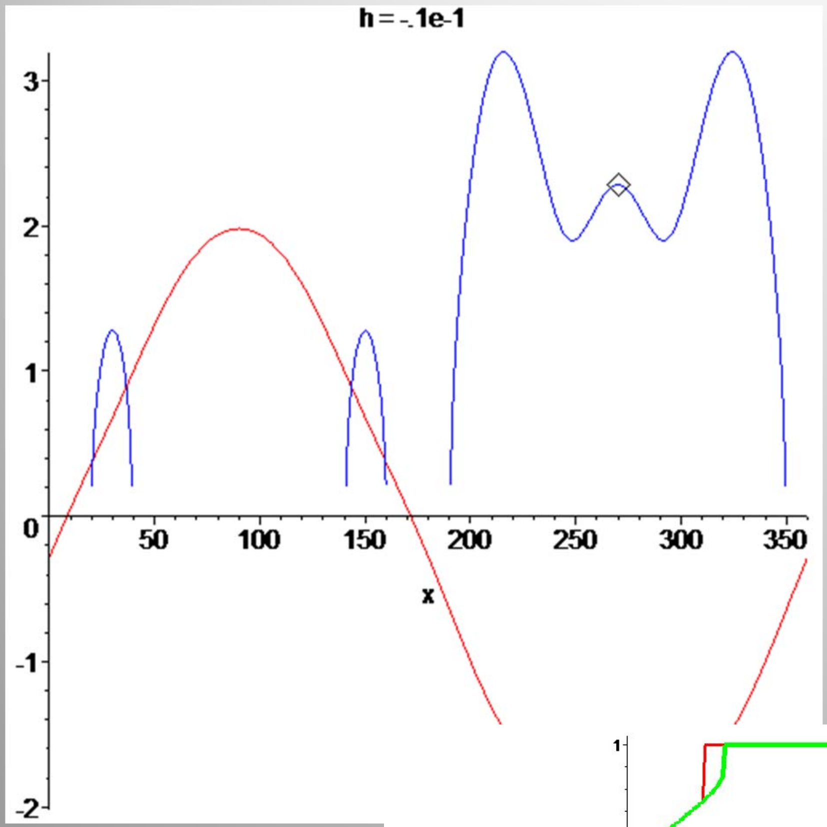
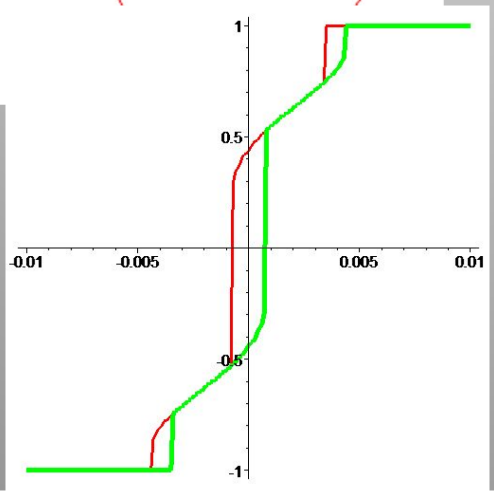
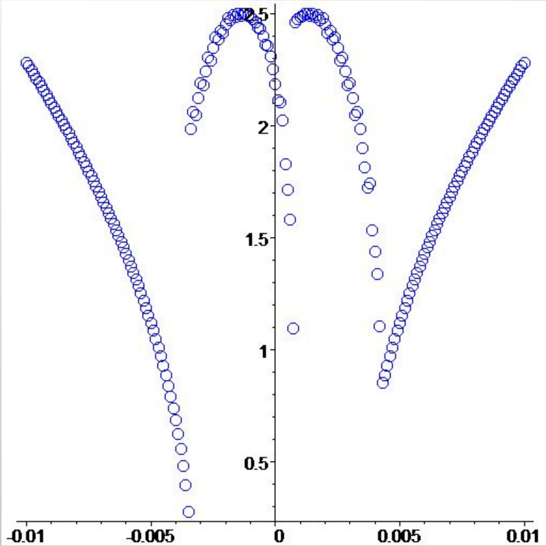
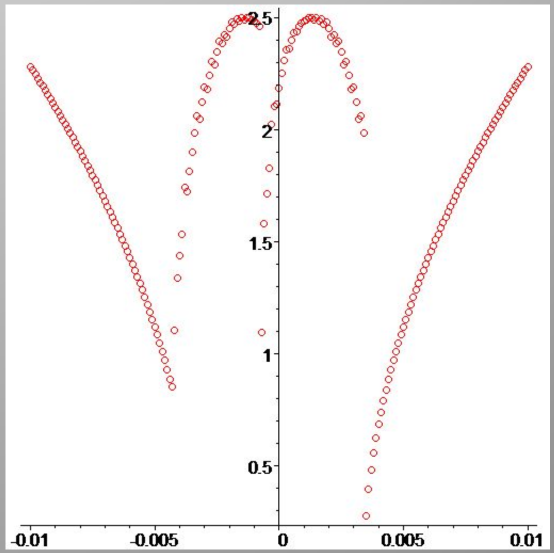
90 degrees x_2=3 mT x_4= -8mT x_6= 0.1 mT









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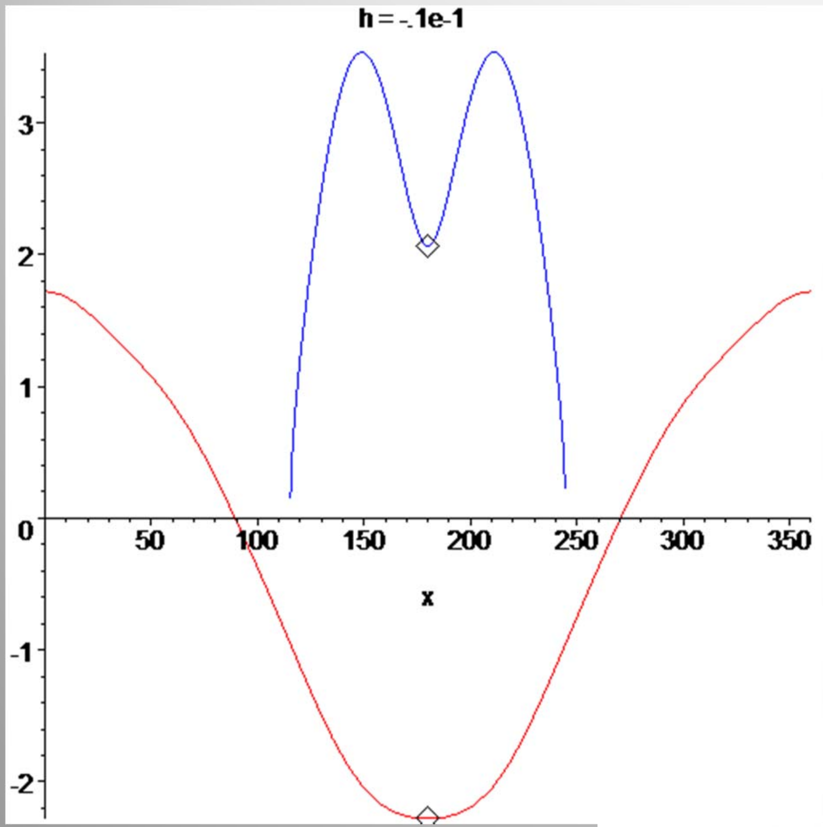
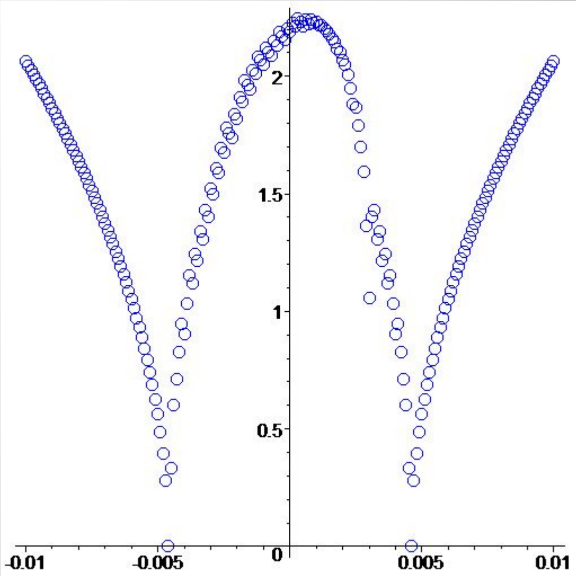
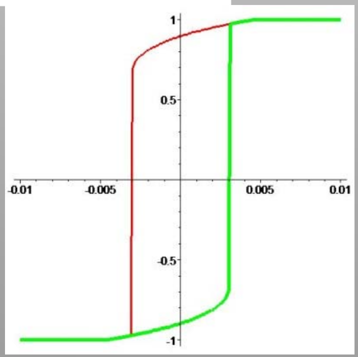
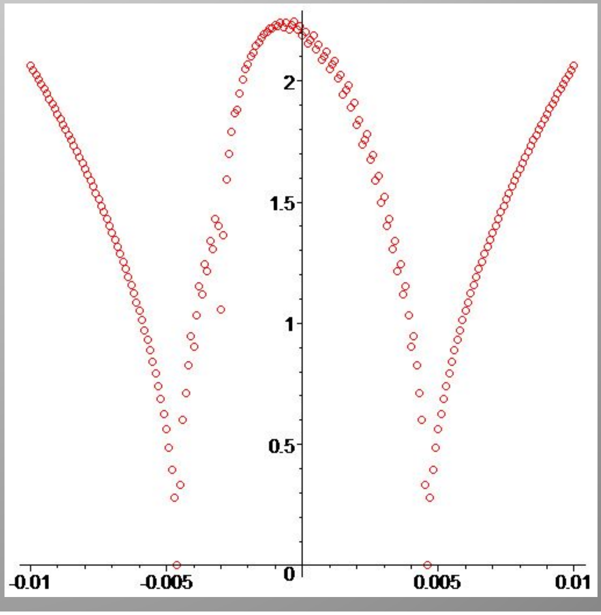
0 degrees x_2=3 mT x_4= -8mT x_6= 0.1 mT









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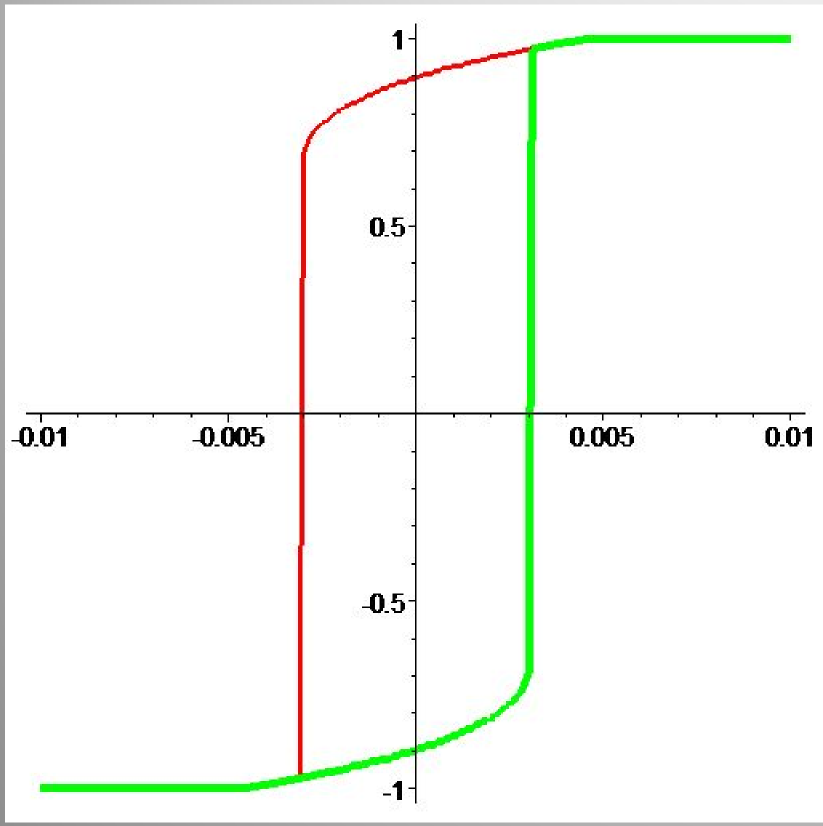
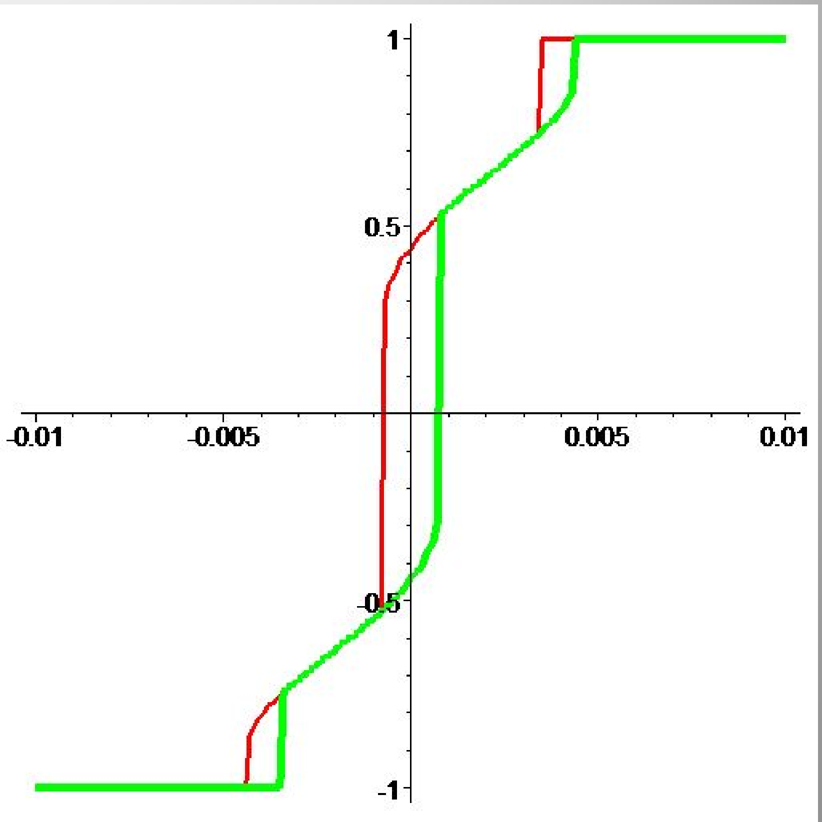


0 degrees



90 degrees

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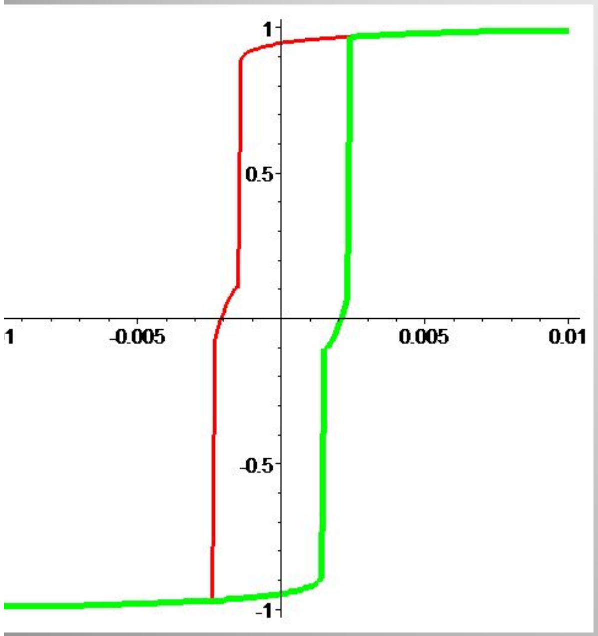

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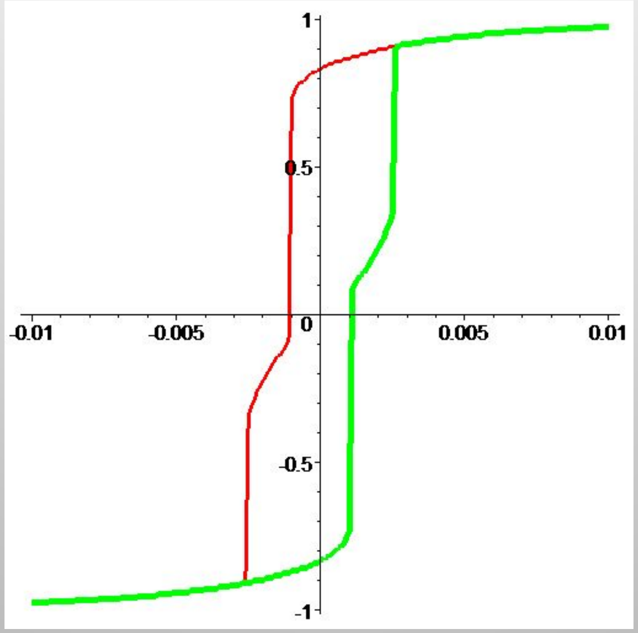
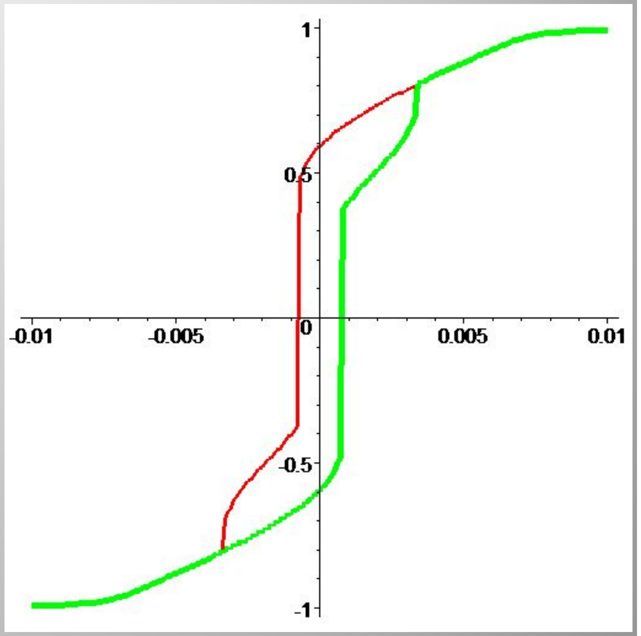


60



80

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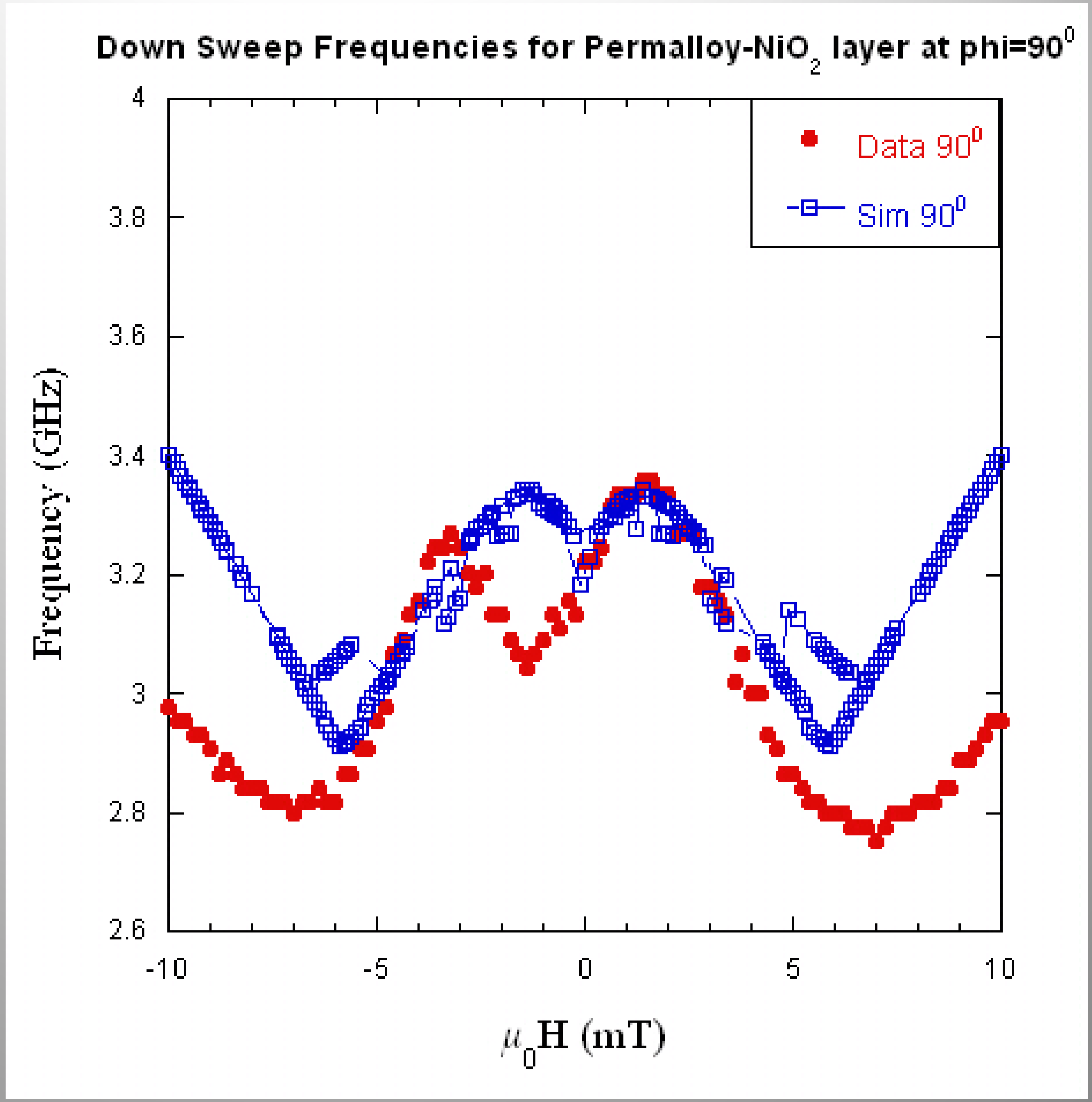
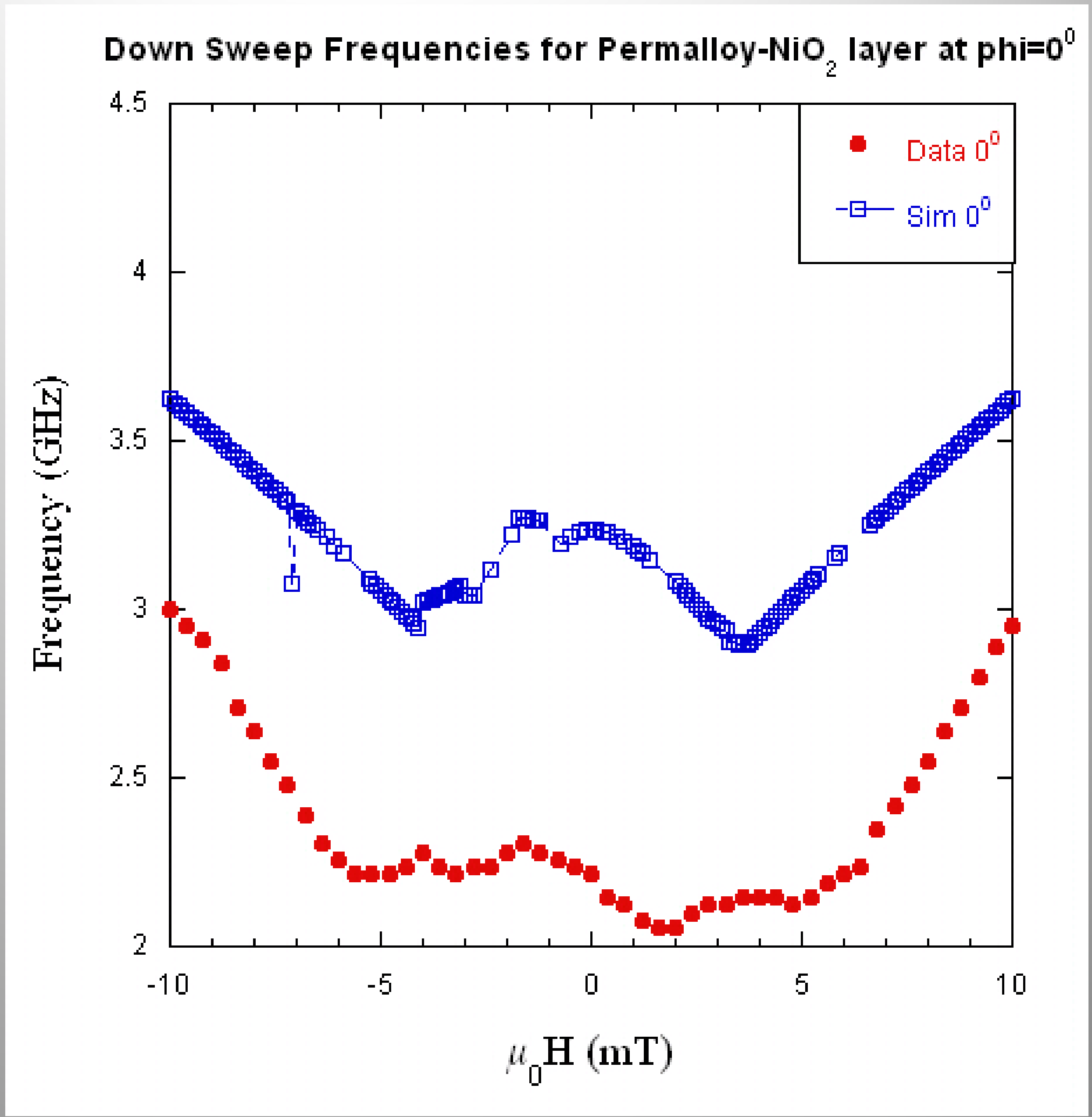
Downsweep
90 degrees



Downsweep
0 degrees



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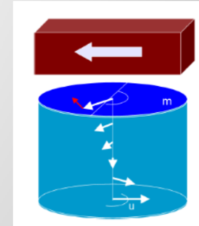
Summary



- Bilayers were fabricated in zero field and no field cooling was performed for the FMR measurements
- Minor hysteresis loops appear as the field direction is rotated from 0 to 90 degrees with respect to the longer sample side
- The single domain model is too simple to make detailed comparisons with experiment but does indicate that anisotropies contribute to the angular dependence of the resonant frequencies
- F layer may not be homogeneous at interface
- Micromagnetic results indicate that reversal is not single domain
- AF layer is treated as being static and providing an effective anisotropy
- The micromagnetic calculations need to be extended to multiple layers which would allow some dynamics in the AF

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The End