SPINSWITCH workshop
Krakow, September 2008

Quantized Spin Wave Modes In Magnetic Tunnel Junctions

Annerose Helmer
Université Paris-Sud

Advanced Research Laboratory
Hitachi, Japan

J. Hayakawa
K. Ito
H. Takahashi

Laboratory for Nanoelectronics and Spintronics
Tohoku University, Japan

J. Hayakawa
S. Ikeda
H. Ohno

Institut d'Electronique Fondamentale
Université Paris-Sud, France

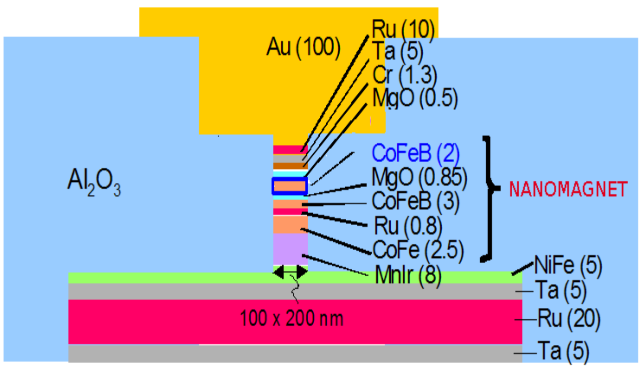
T. Devolder
J.-V. Kim
C. Chappert

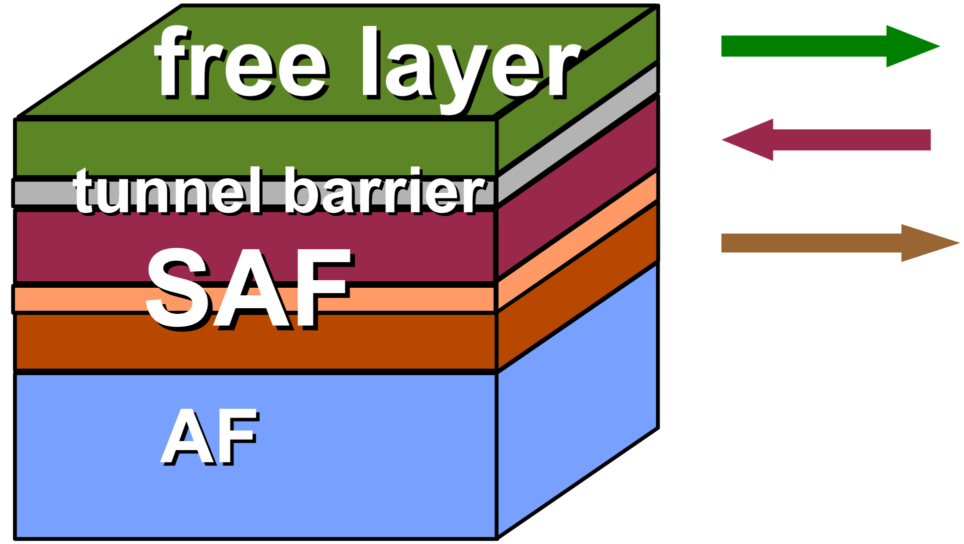
IMEC, Leuven, Belgium

S. Cornelissen
L. Lagae

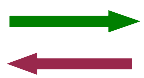
Thermally Excited Spin Waves in MTJ

why spin waves?





- Principle:
  magnetic configuration TMR → electrical signal



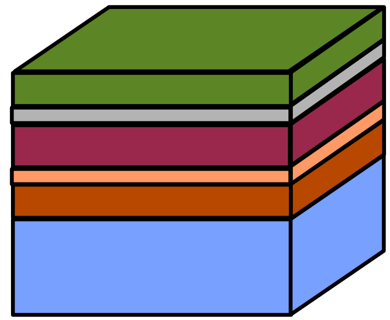
  static or dynamic devices: MRAM, STO

- omnipresent source of RF magnetization fluctuations:
  thermally excited spin waves =
  eigenexcitations of the magnetic system

samples

3 CoFeB
0.9 MgO
2 CoFeB
0.8 Ru
2 CoFe

20 PtMn
nm



2 CoFeB
0.85 MgO
3 CoFeB
0.8 Ru
2.5 CoFe

8 MnIr
nm

100 x 200 nm² (L)

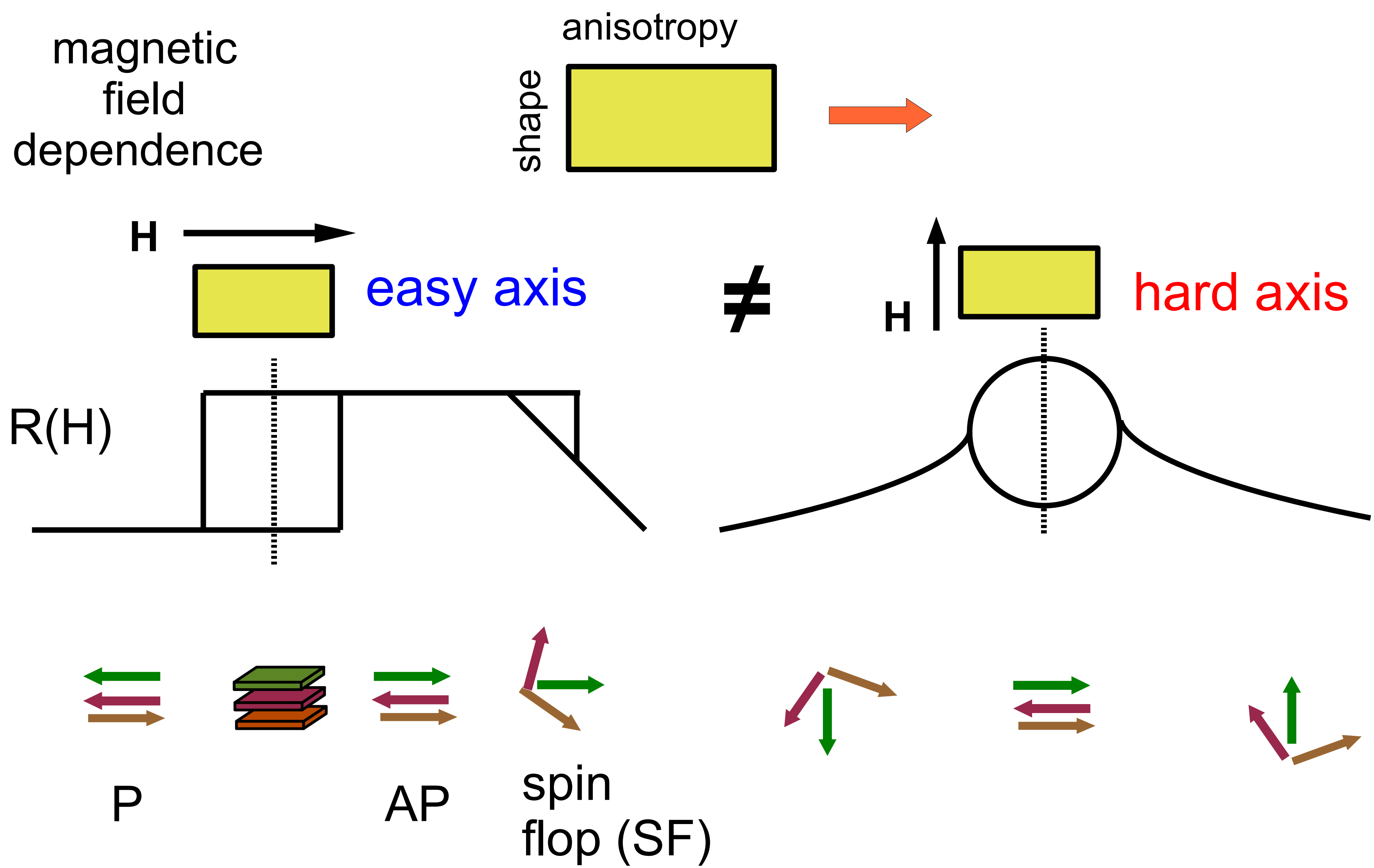
75 x 150 (M)

50 x 100 (S)

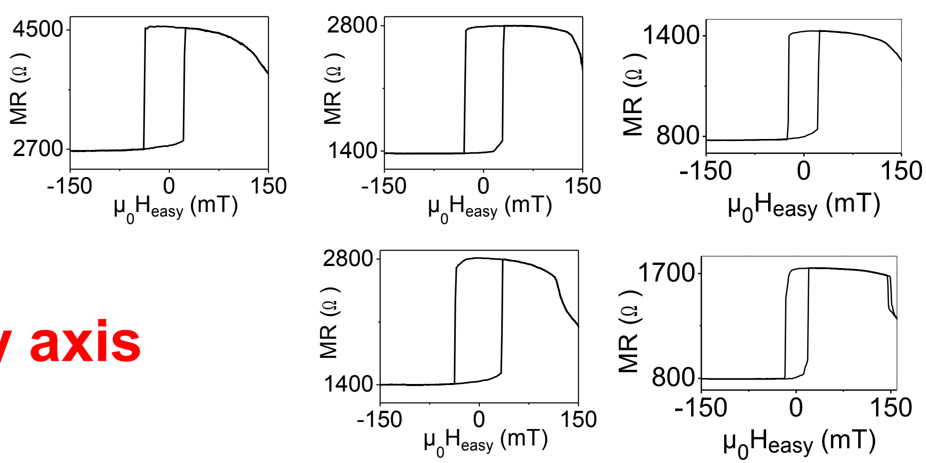
↔ 100 x 200 nm² (prototypes of working MRAM)

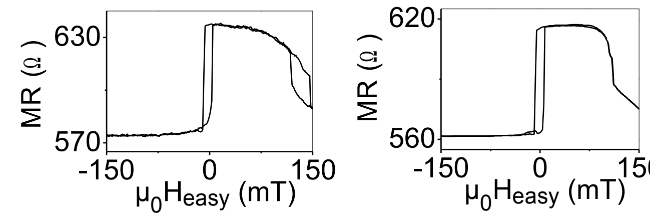
size effects + stack composition & fabrication effects

magneto-static properties



S M L





easy axis

MR	100 ... 150 %
H_{co}	20 ... 35 mT
M_S	1.0 ... 1.4 T

MR	5 ... 60 %
H_{co}	1 ... 7 mT
M_S	0.4 ... 0.6 T

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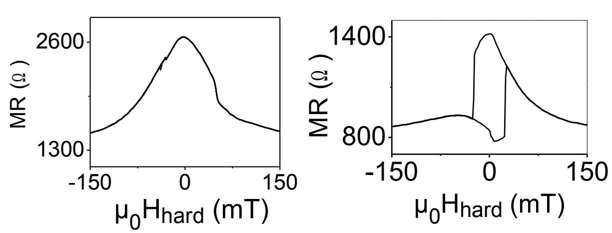
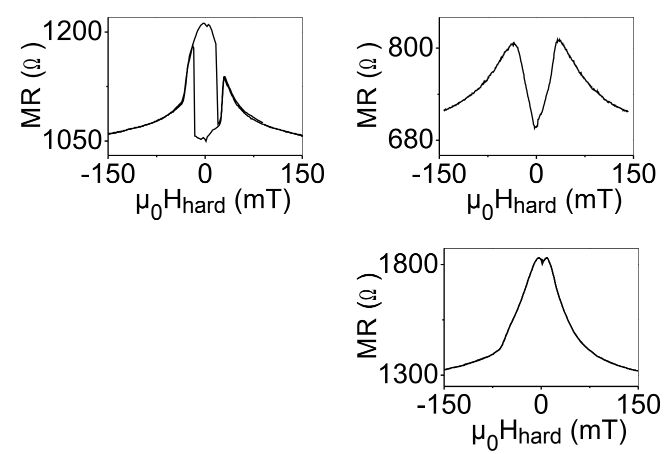
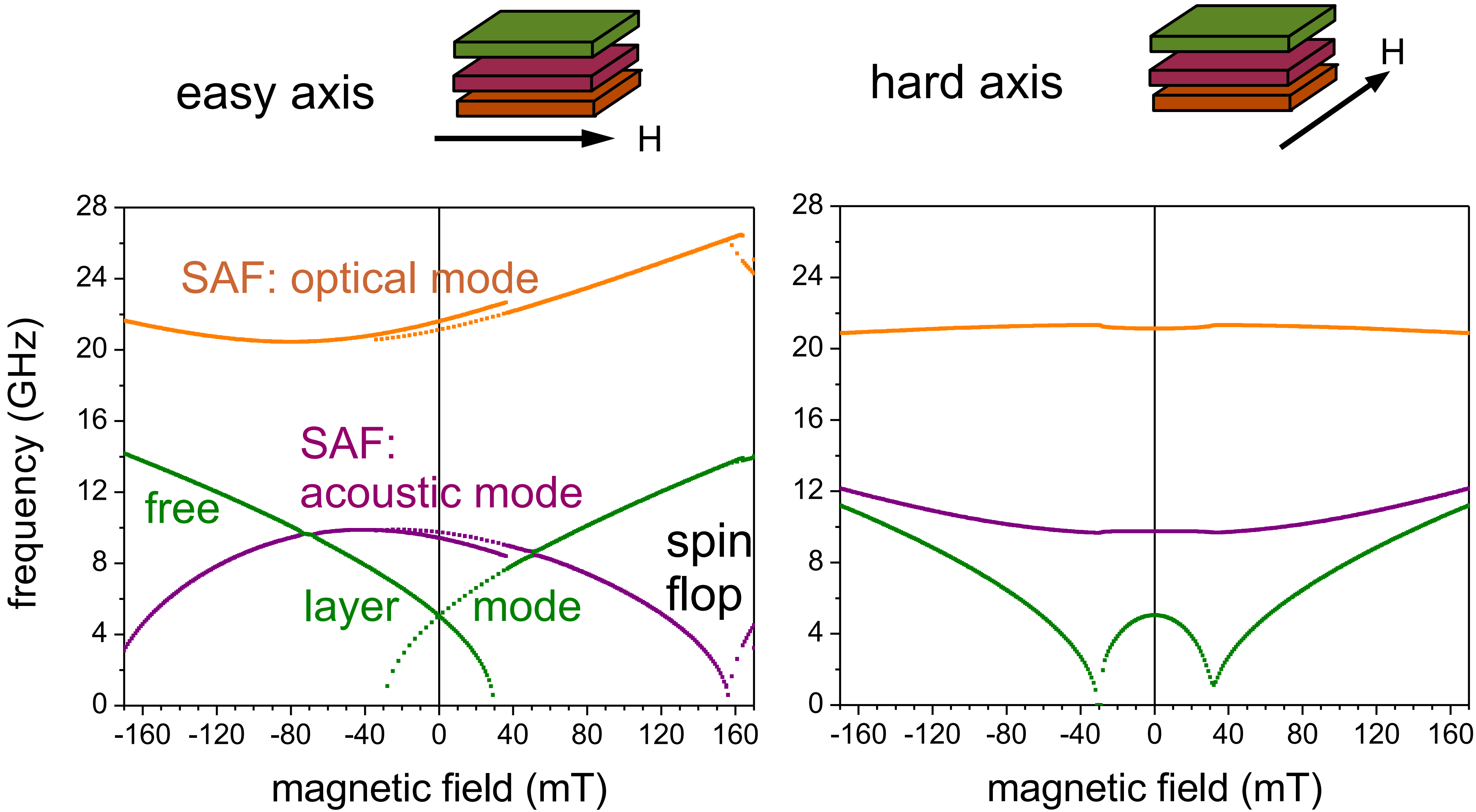
hard axis





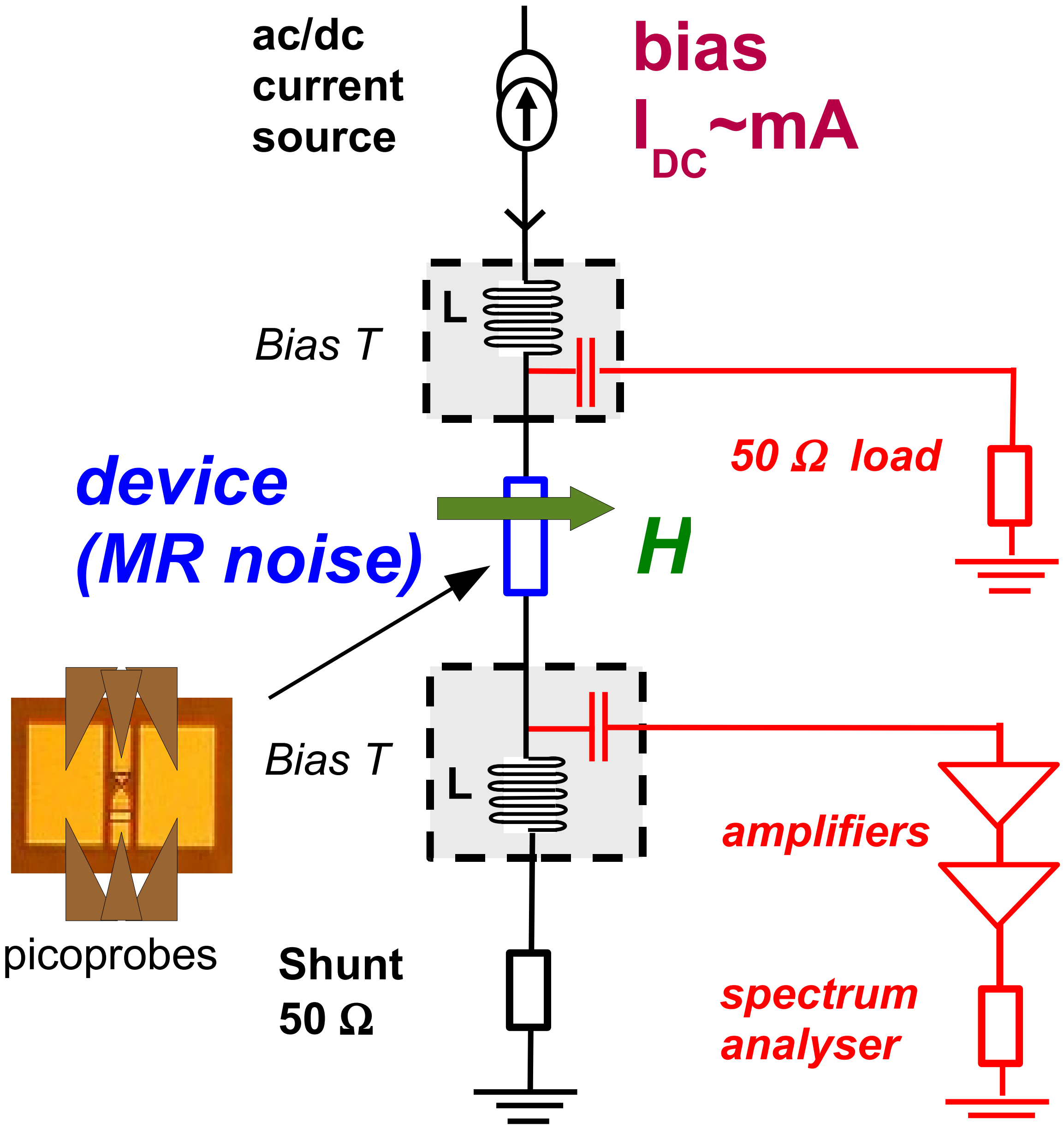
fundamental eigenexcitations of 3-layer system



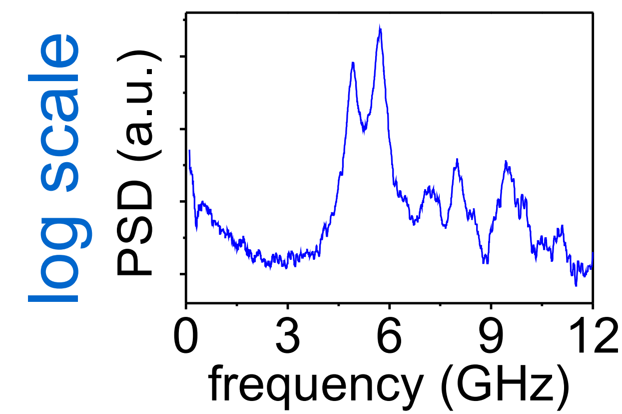
free layer mode (easy axis)

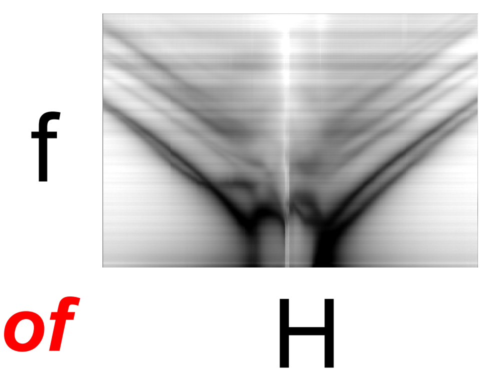
$$\omega^2 = (\gamma \mu_0)^2 \left[H_{appl} + H_k \right] \left[H_{appl} + M_S - H_k \right]$$

electrical measurement: set-up



averaged PSD ($I \neq 0$)
minus
averaged PSD ($I = 0$)



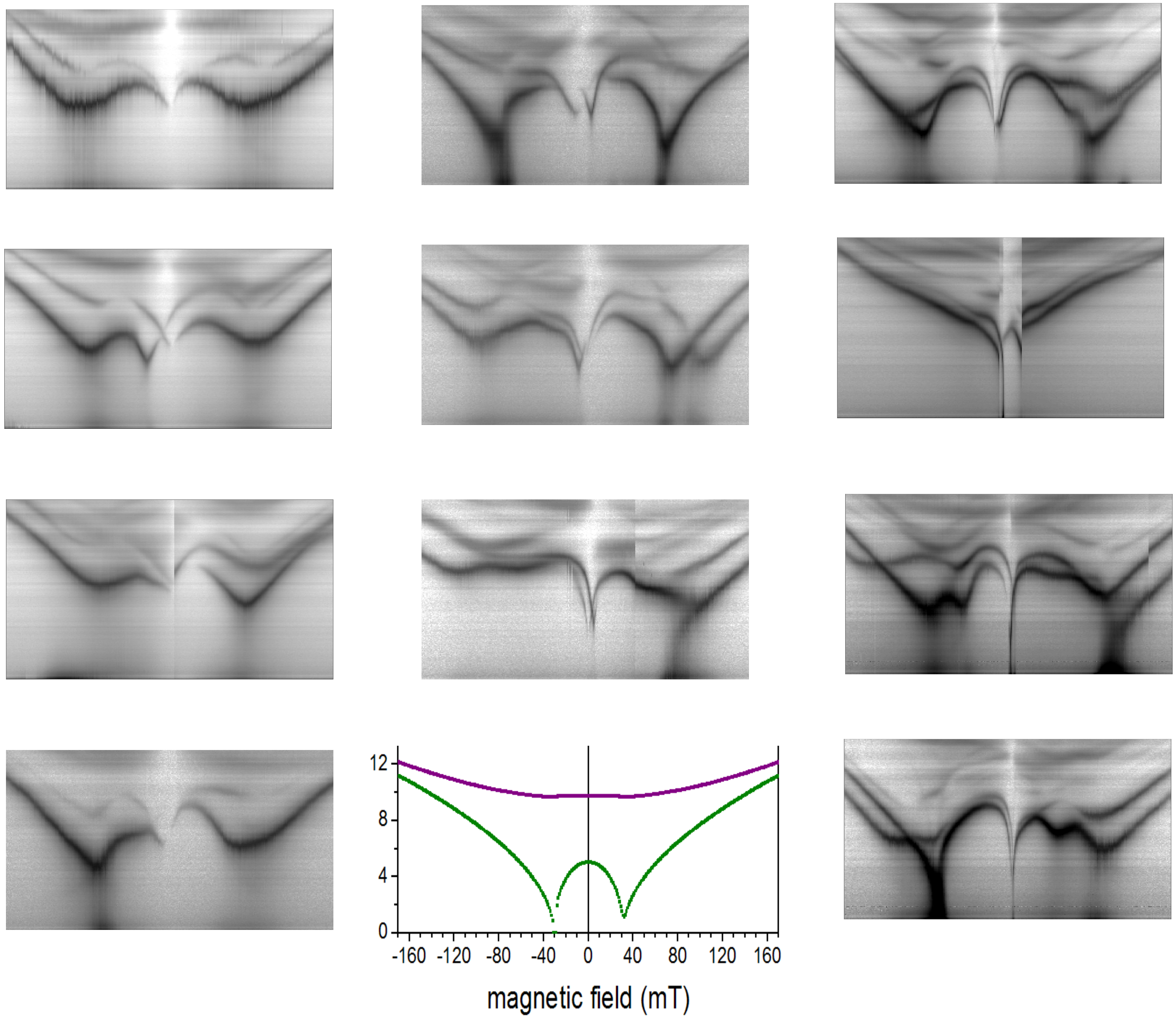


spectral analysis of voltage noise

S

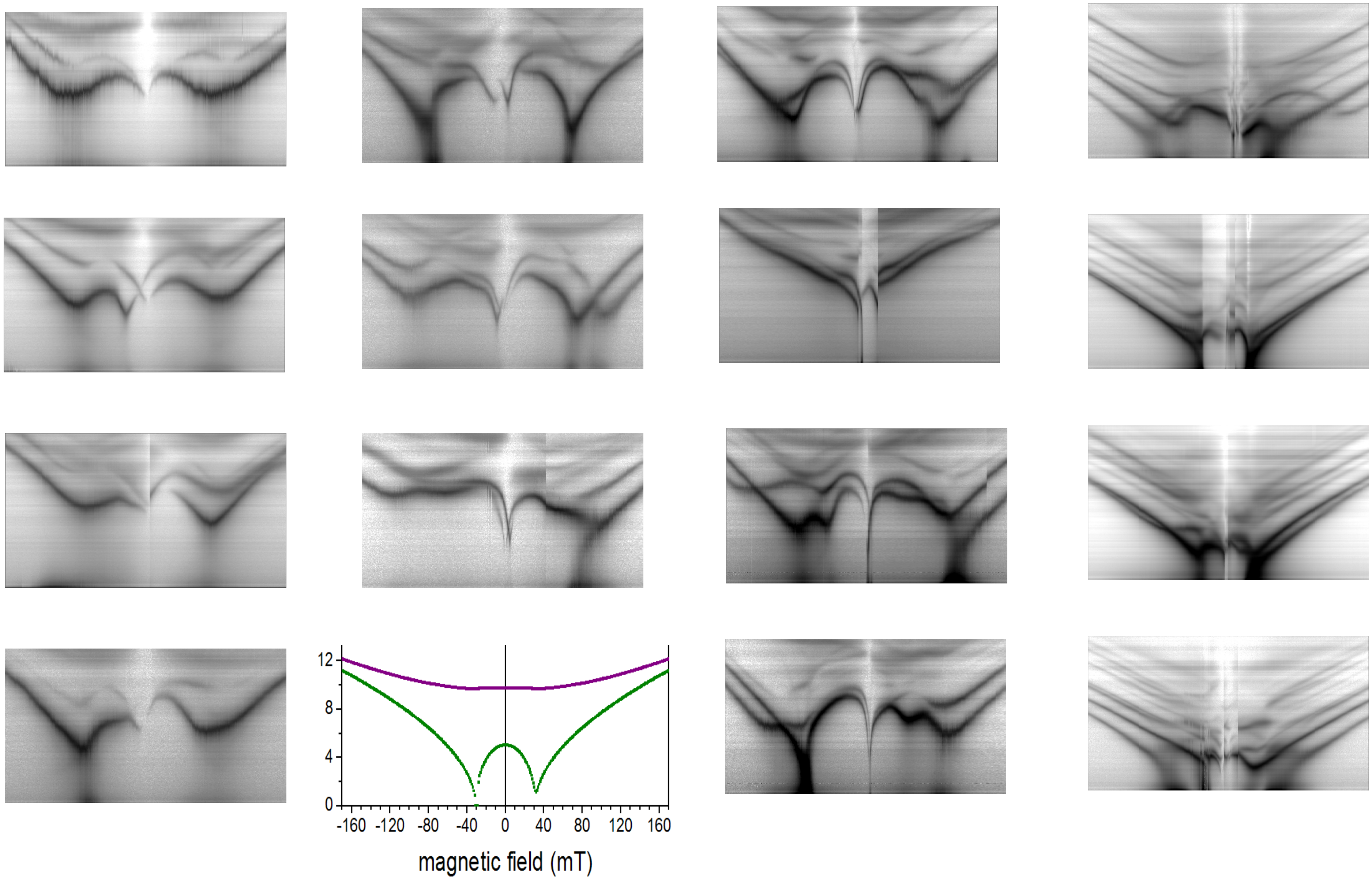
M

L



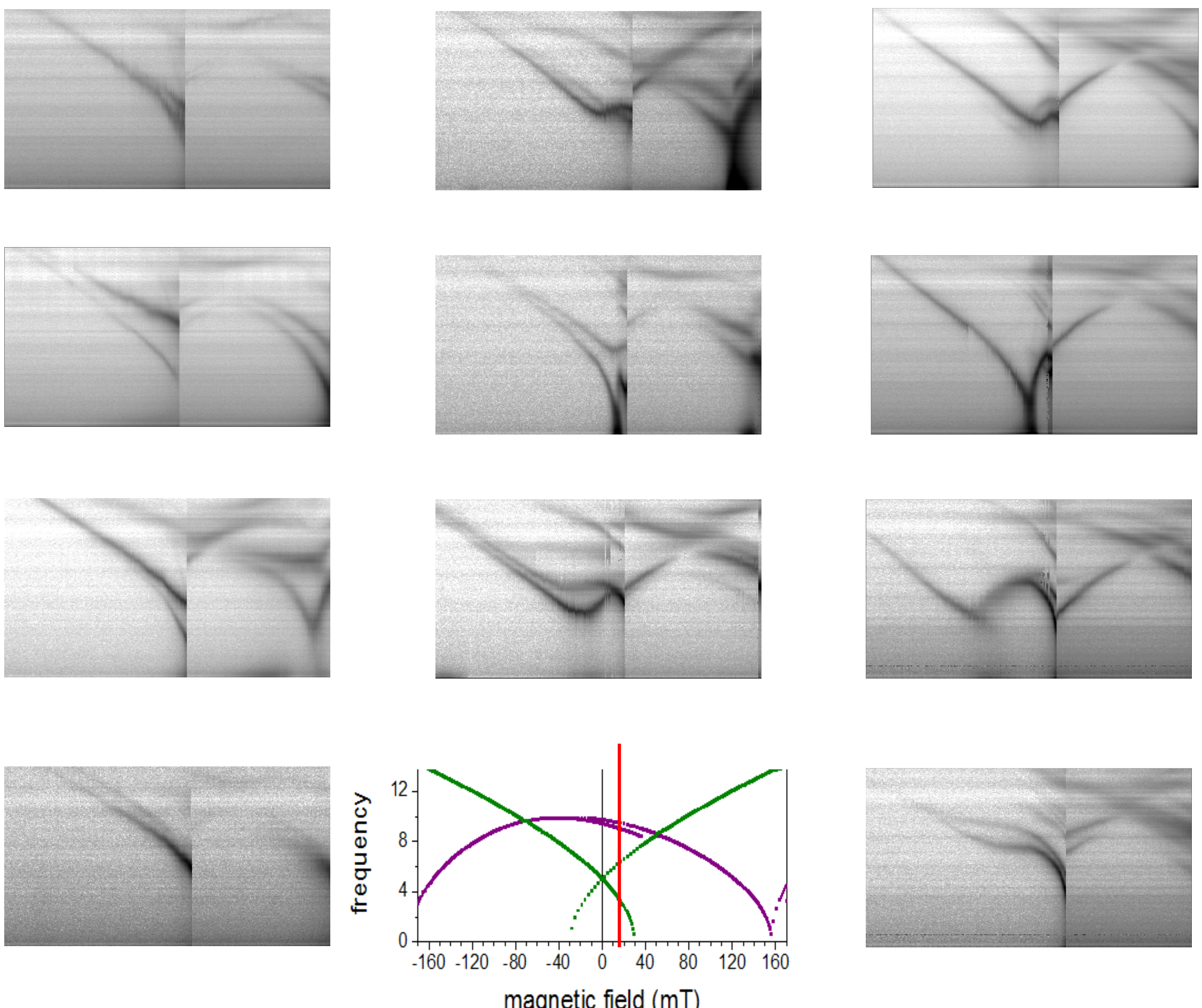
hard axis

S imec aspire invent achieve M imec aspire invent achieve L HITACHI Inspire the Next L



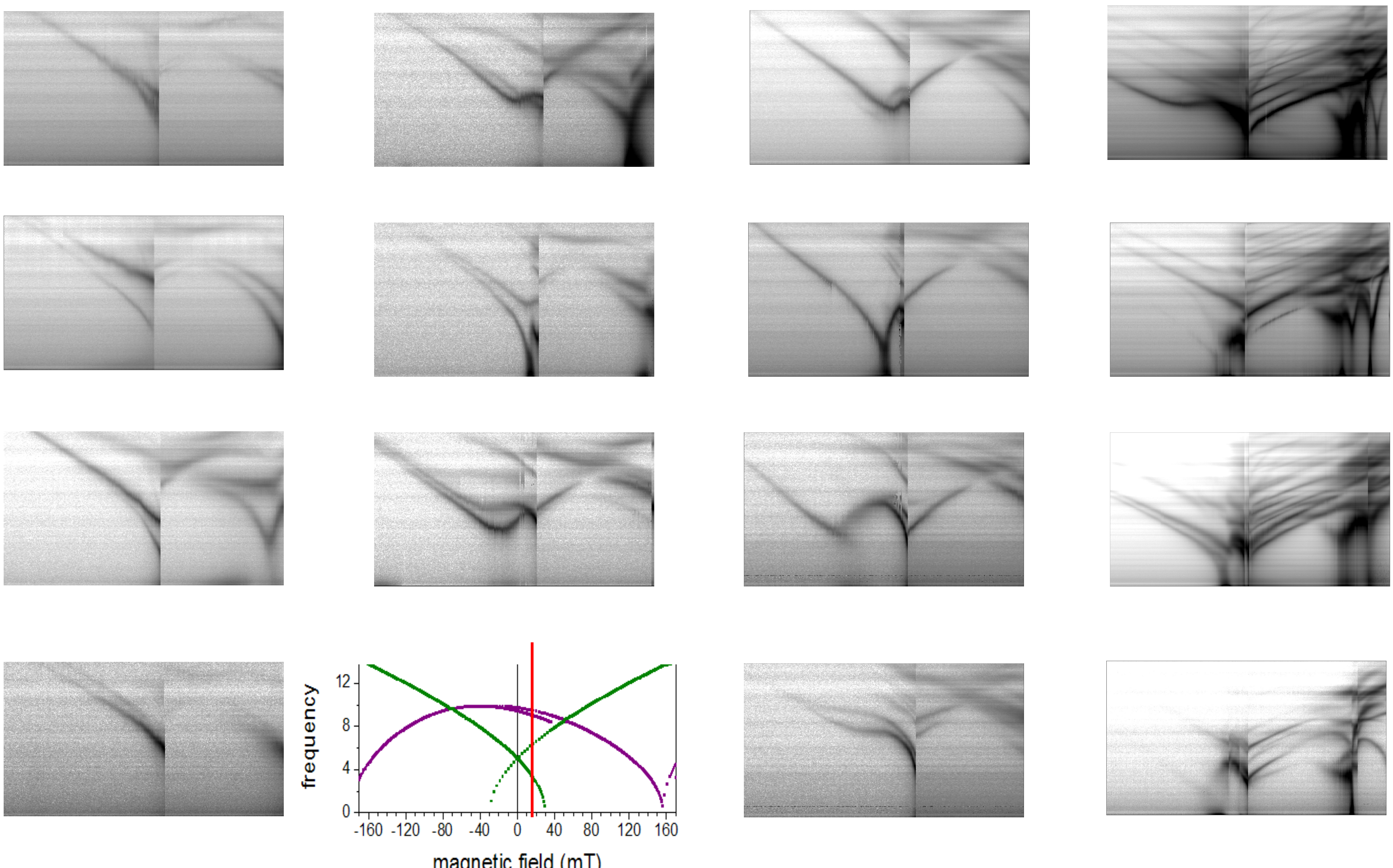
hard axis

S M L



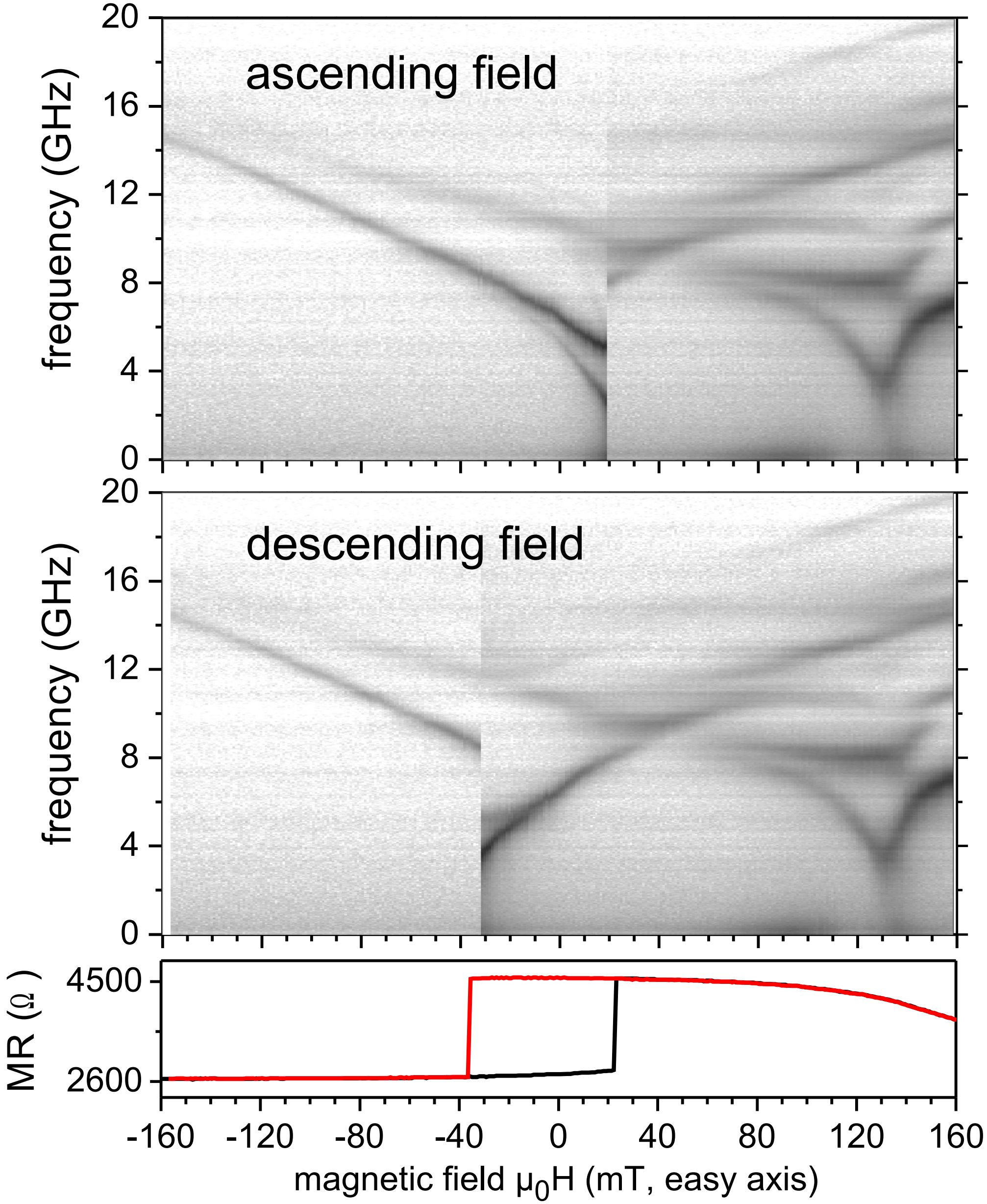
easy axis

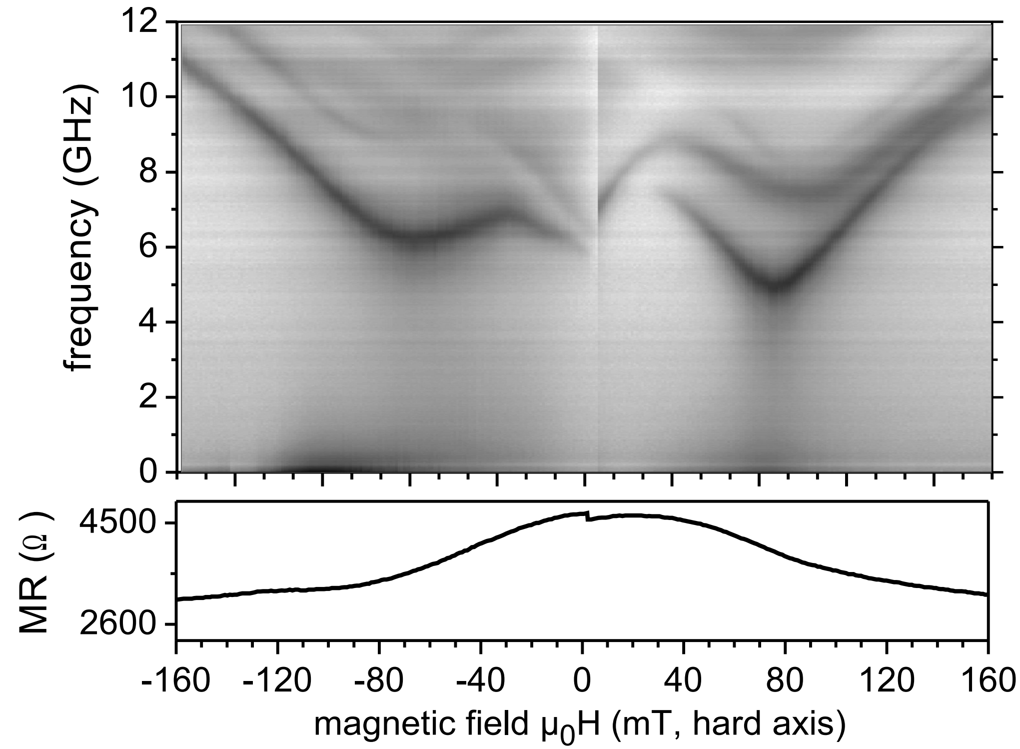
S imec aspire invent achieve M imec aspire invent achieve L HITACHI Inspire the Next L



easy axis

S easy axis I = 0.1 mA hard axis

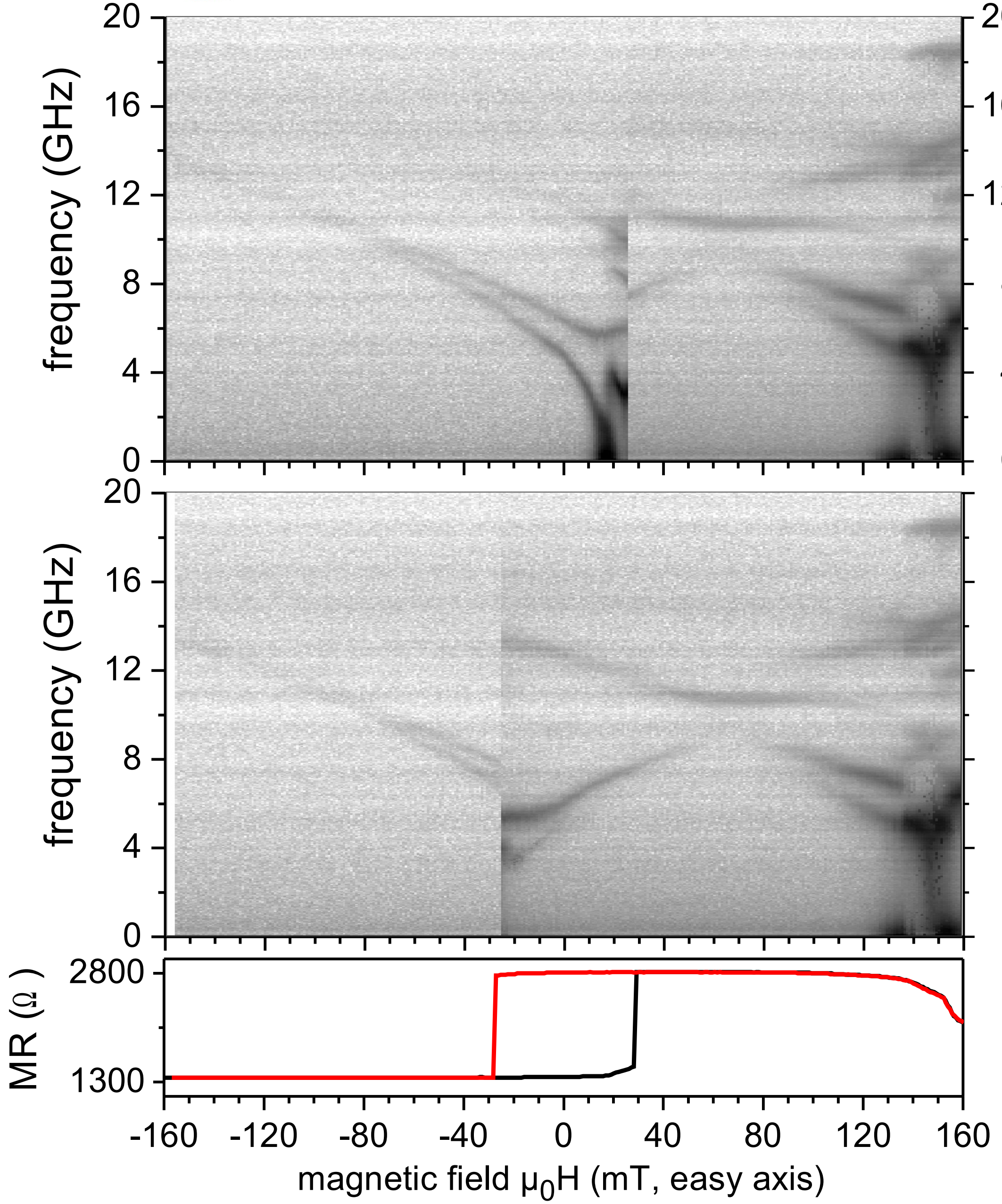


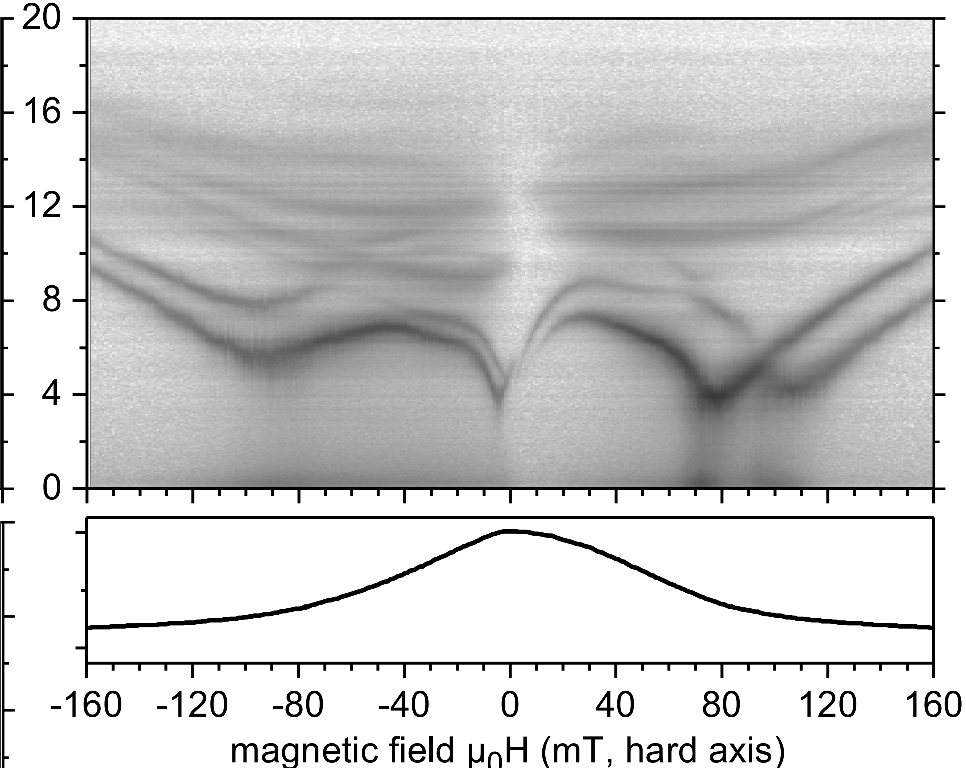


P mode: $M_S \sim 1.4T$

AP mode: $M_S \sim 1.3T$

M easy axis I = 0.1 mA hard axis





P mode: M_S ~ 1.1T

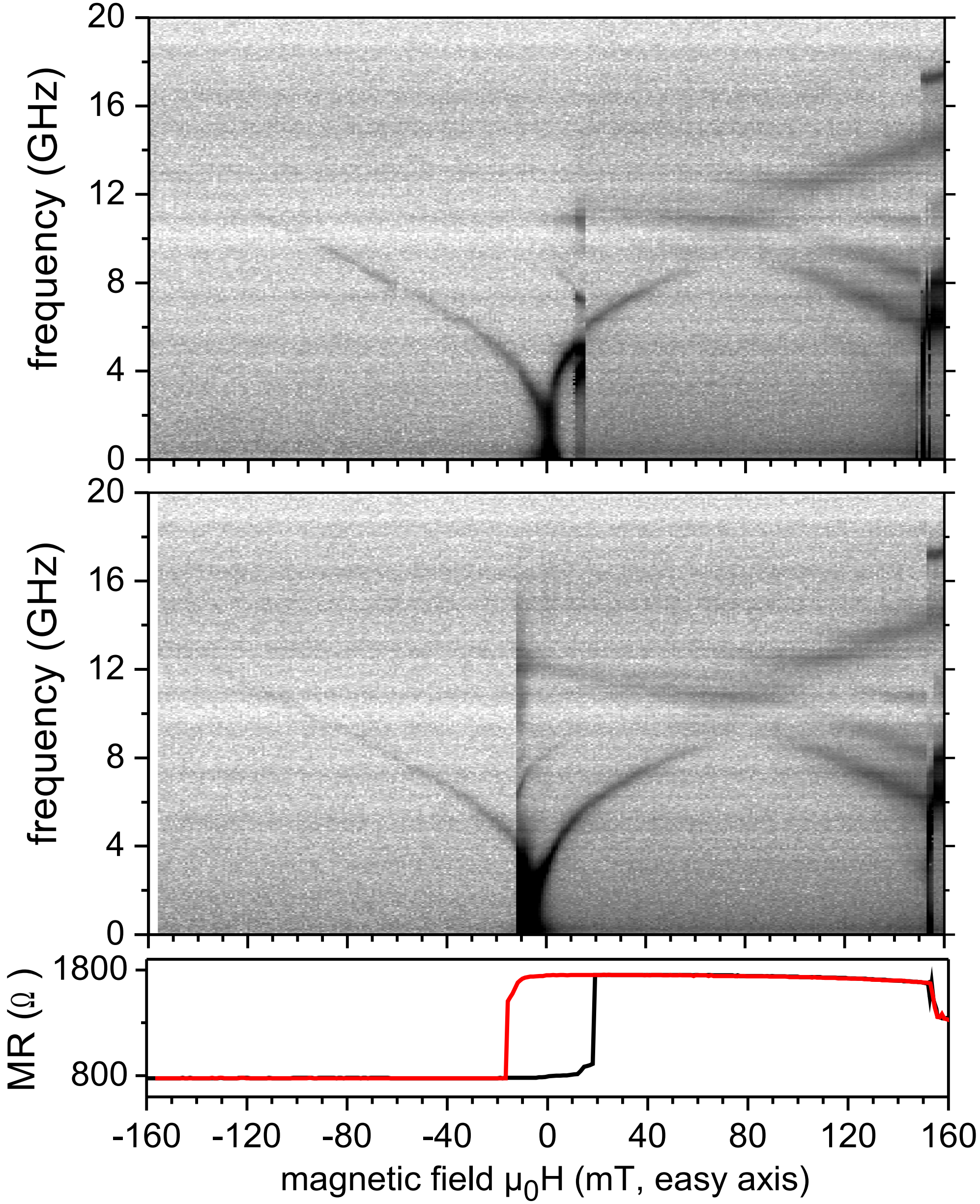
AP mode: M_S ~ 0.9T

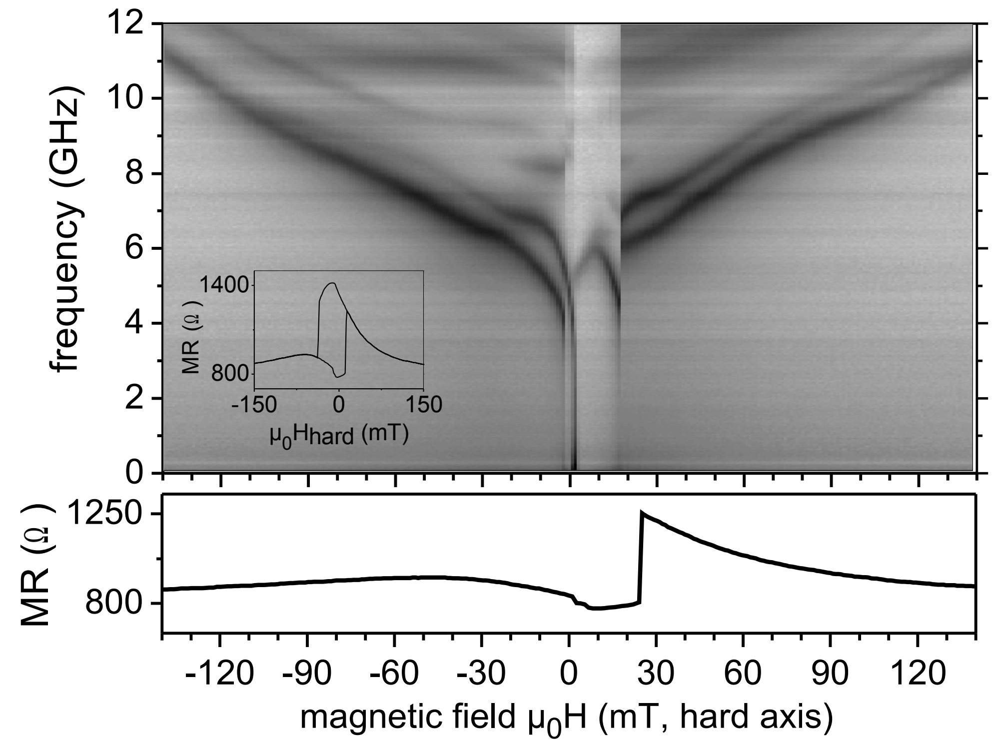
L

easy axis

I = 0.1 mA

hard axis





P mode: $M_S \sim 1.3T$

AP mode: $M_S \sim 1.4T$

1st sample

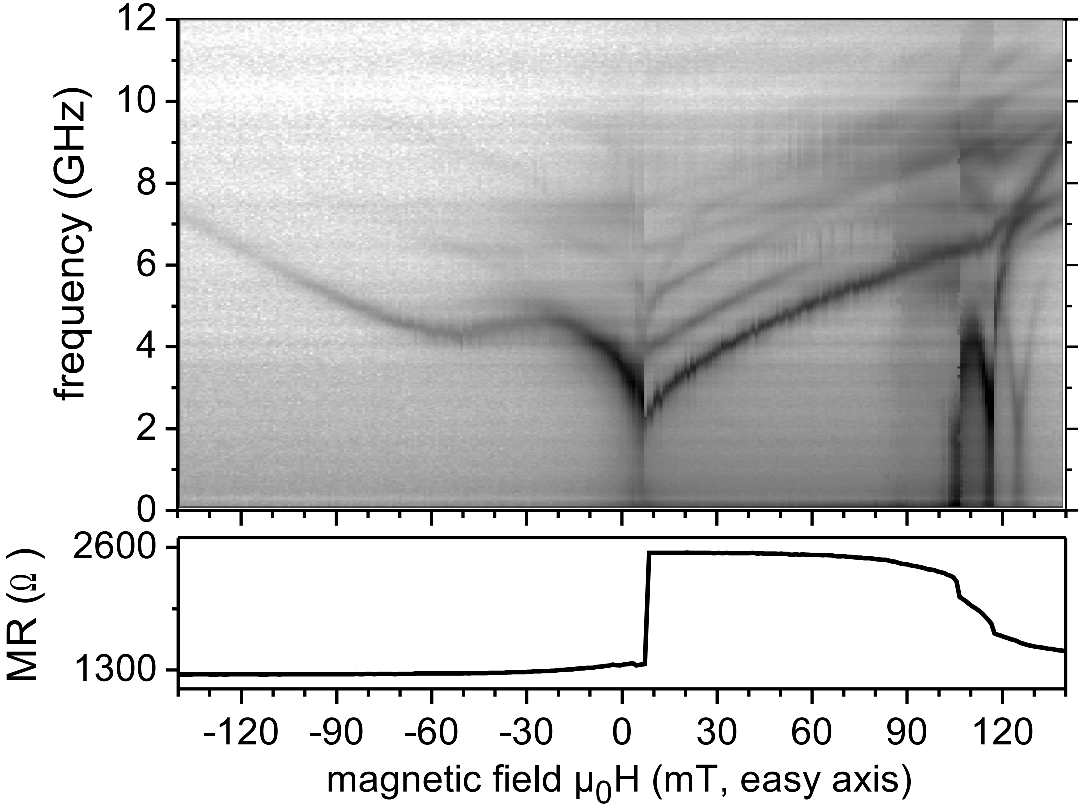
HITACHI
Inspire the Next

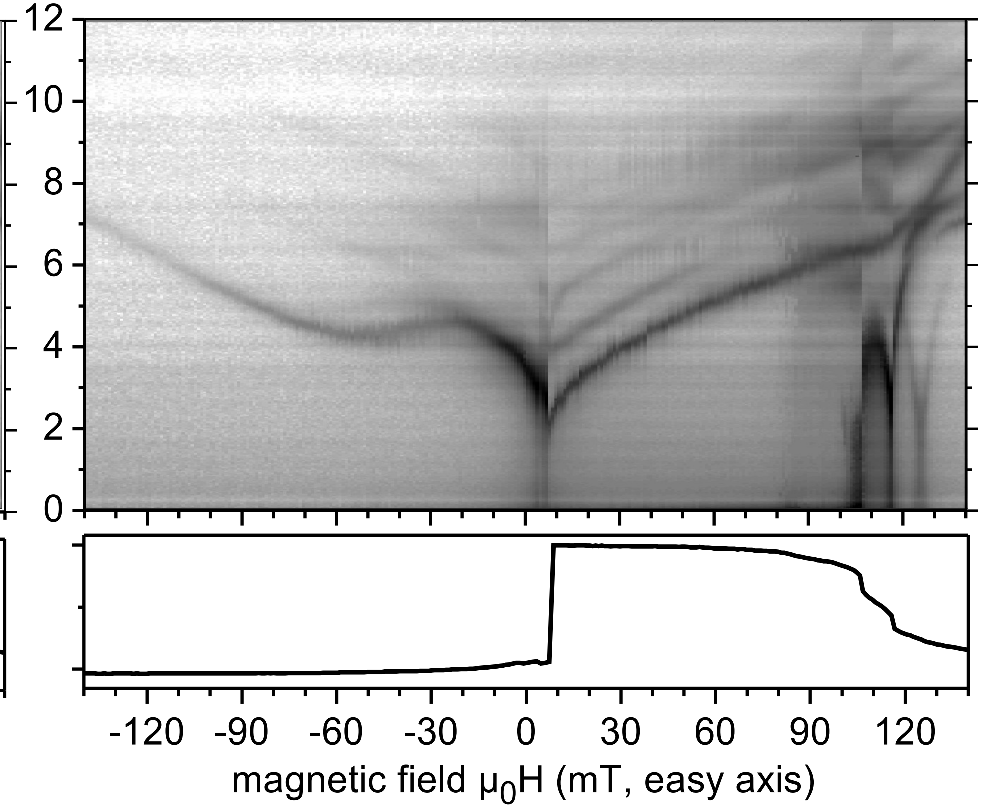
easy axis

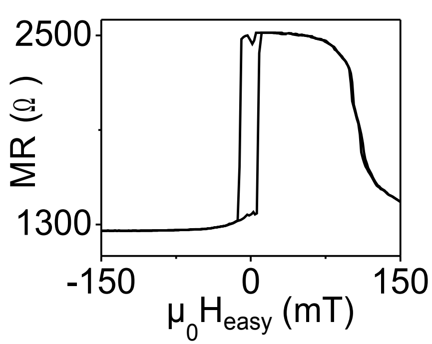
I = 0.1 mA

"3 spin flops"

I = - 0.1 mA







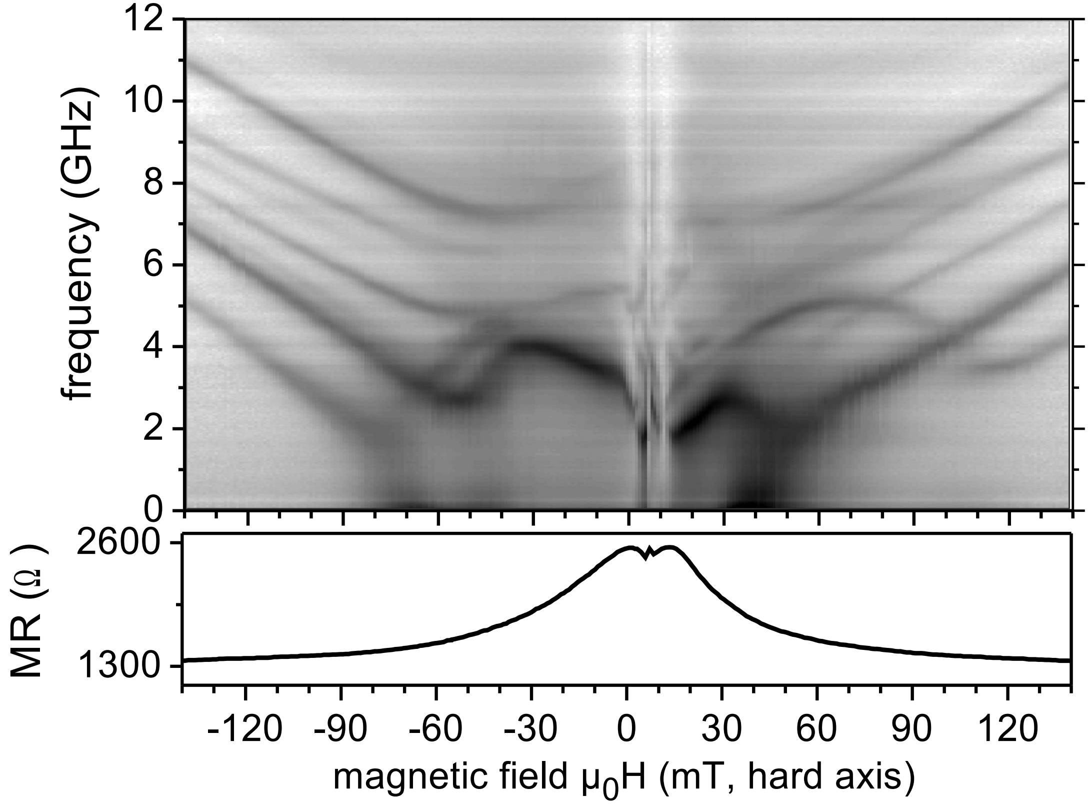
1st AP mode = uniform mode:

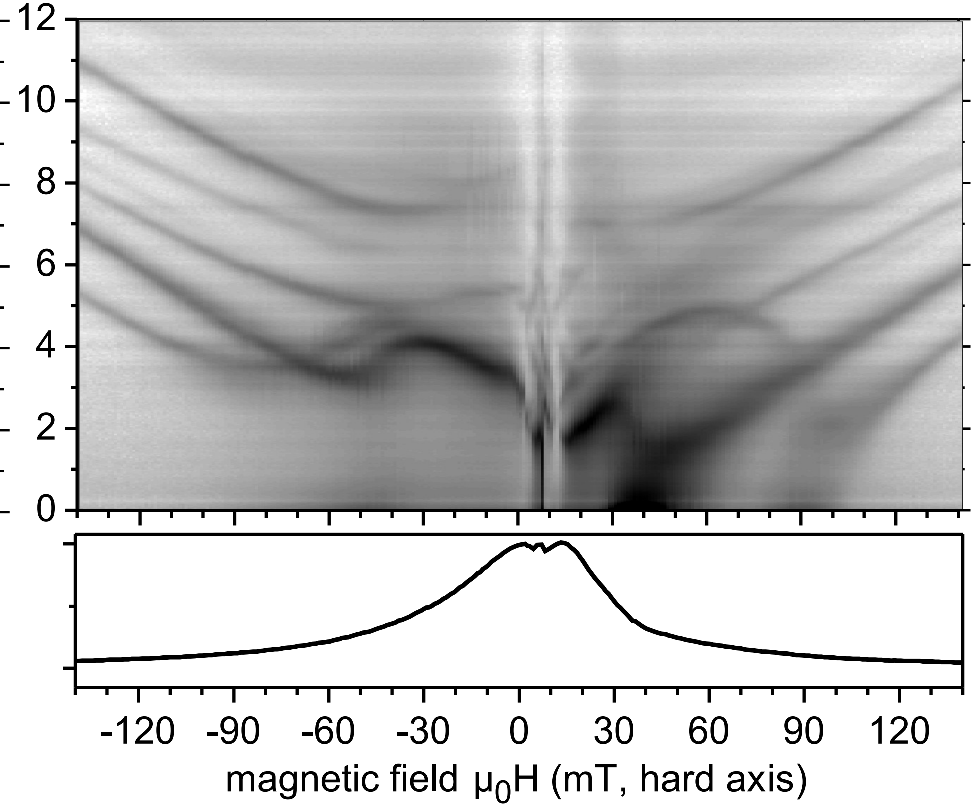
M_S ~ 0.4T

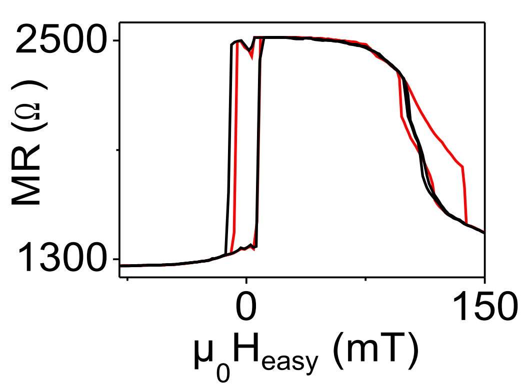
hard axis

I = 0.1 mA

H tilted by 2°

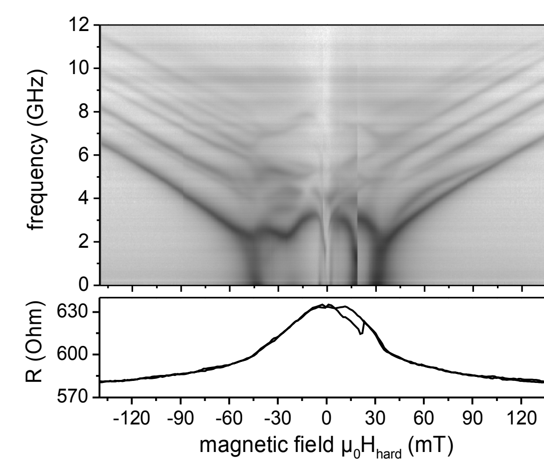




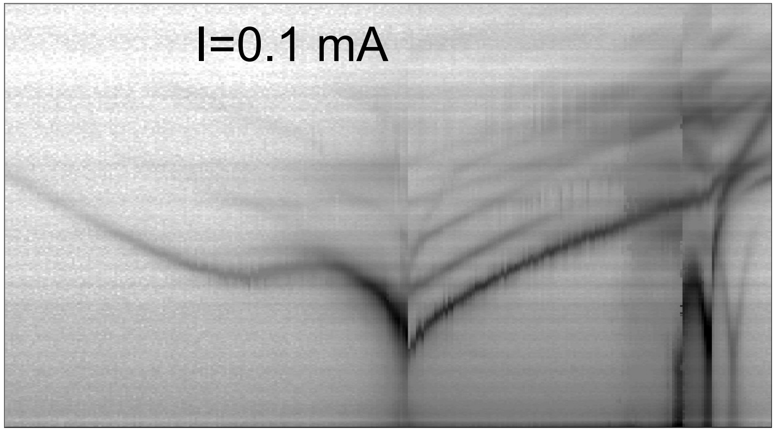


easy axes of free layer and SAF different ?

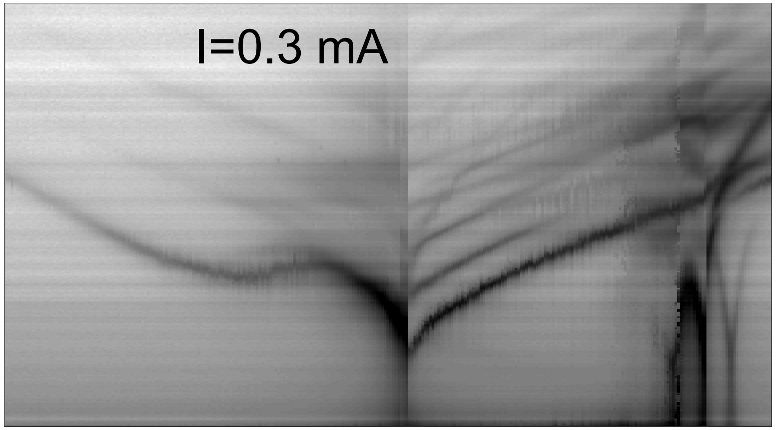
Reference other sample with similar RH-loop:

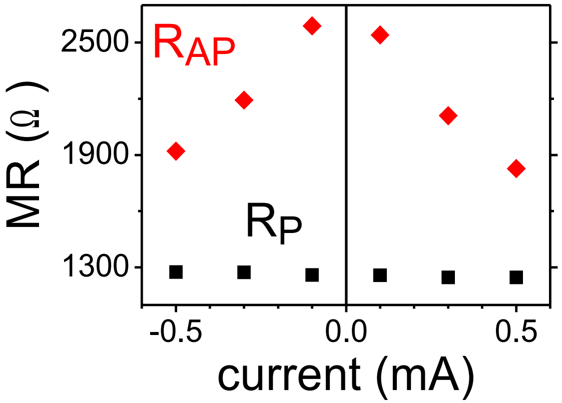


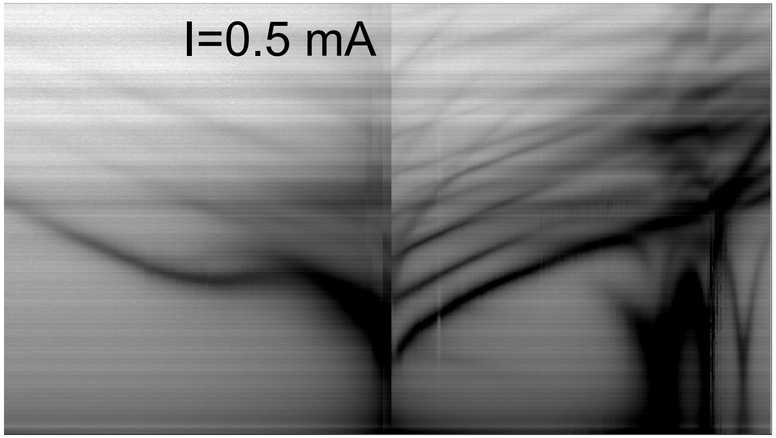
current dependence

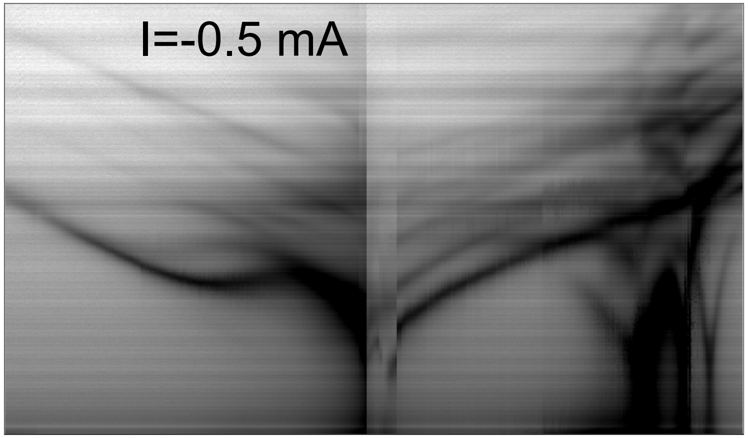


no additional modes
for higher current







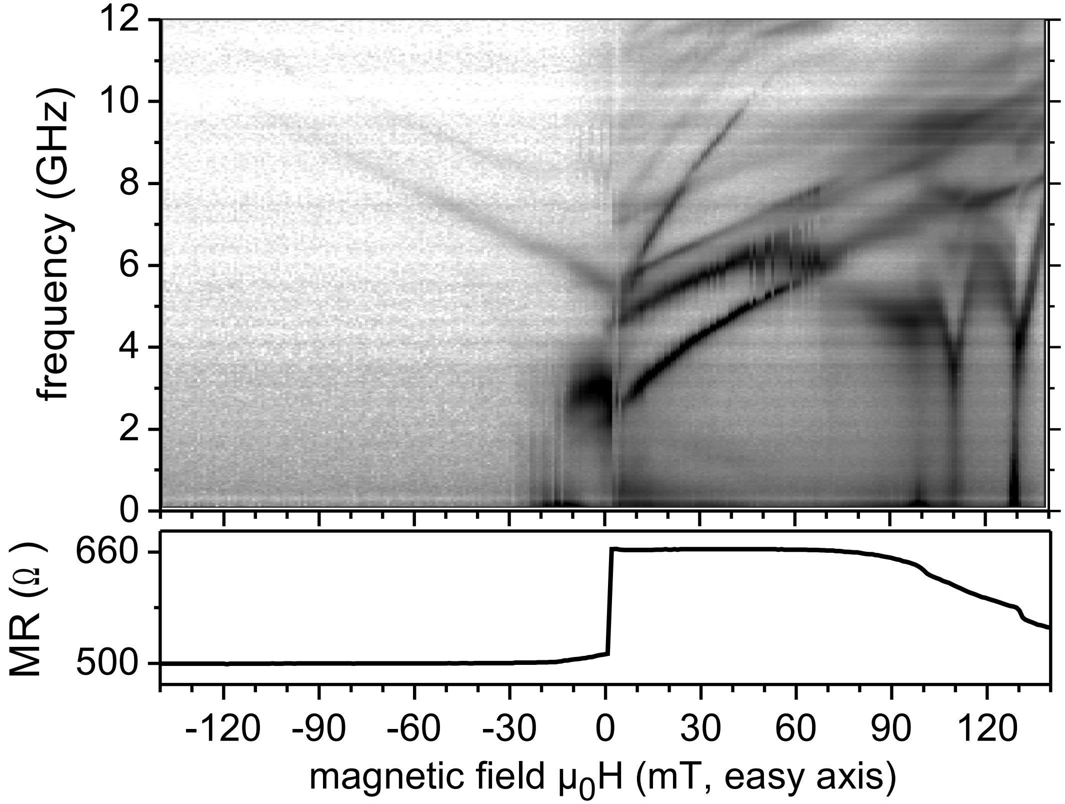


2^{nd} sample

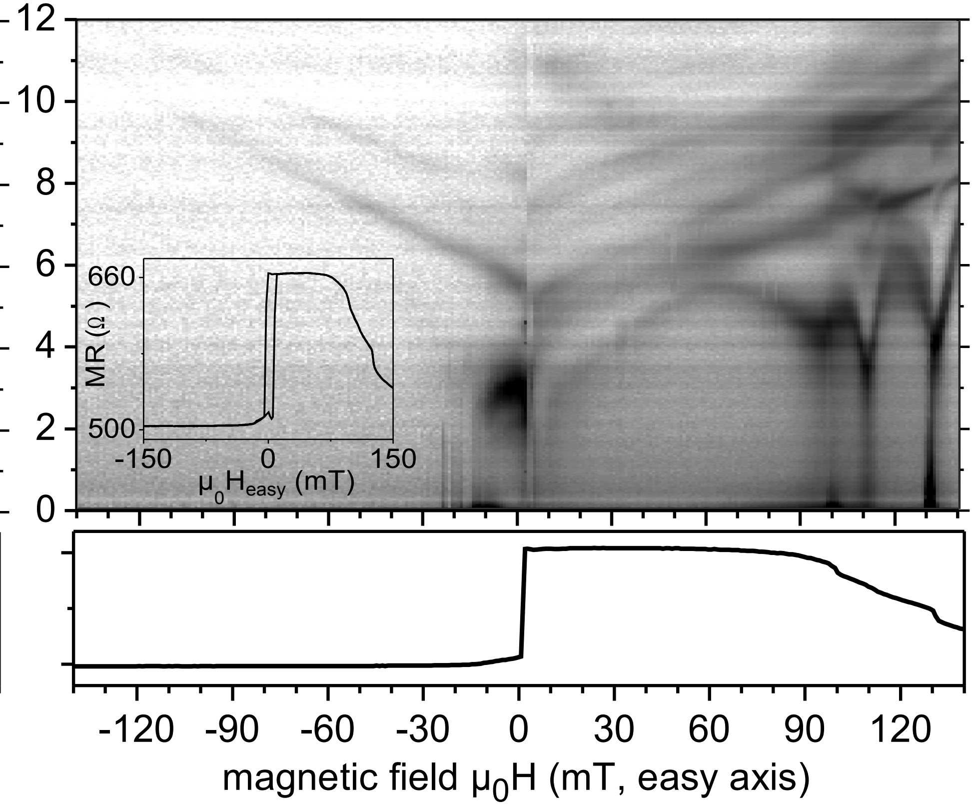
HITACHI Inspire the Next

easy axis

I = 0.2 mA

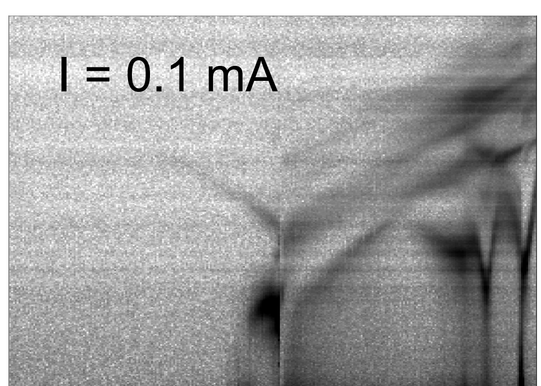


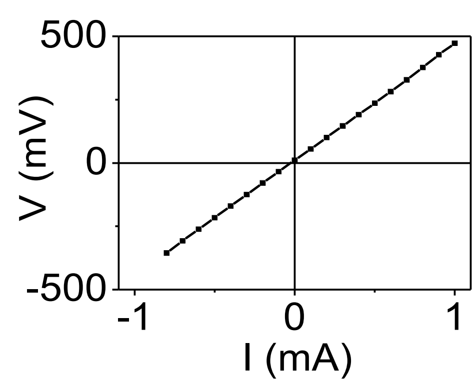
I = - 0.2 mA

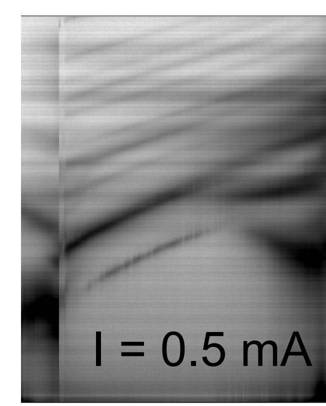


2^{nd} AP mode:
$M_S \sim 0.5T$

1^{st} P mode:
$M_S \sim 0.6T$

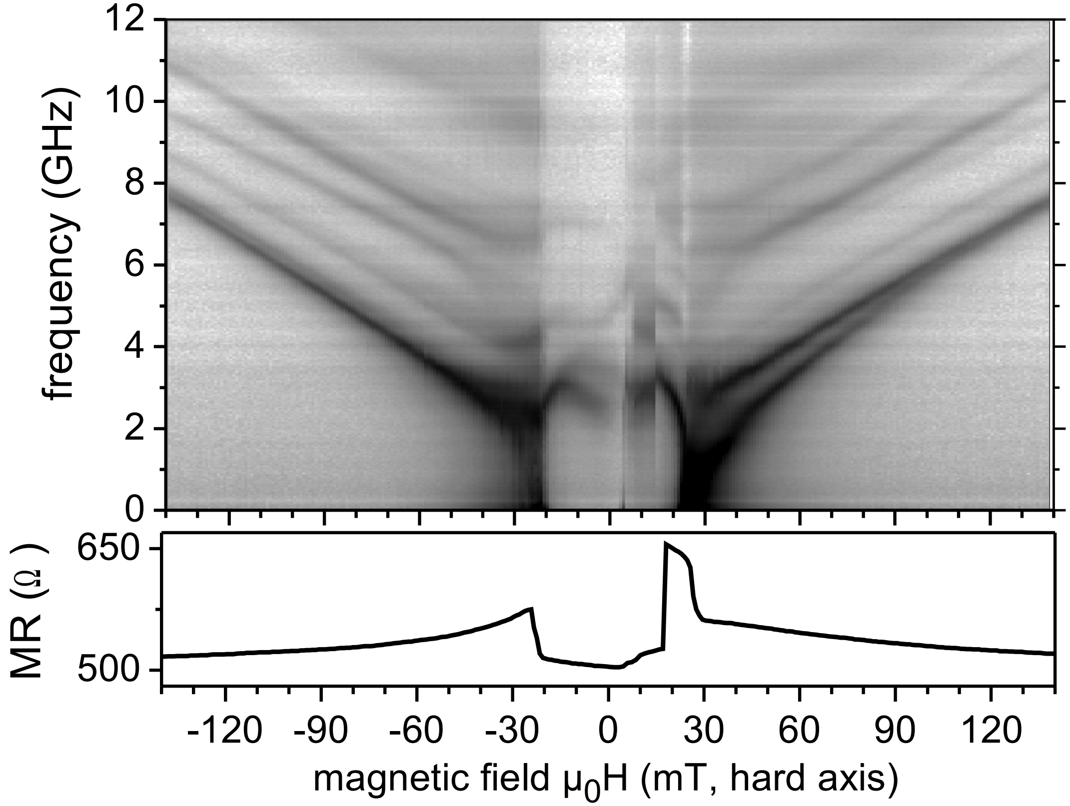




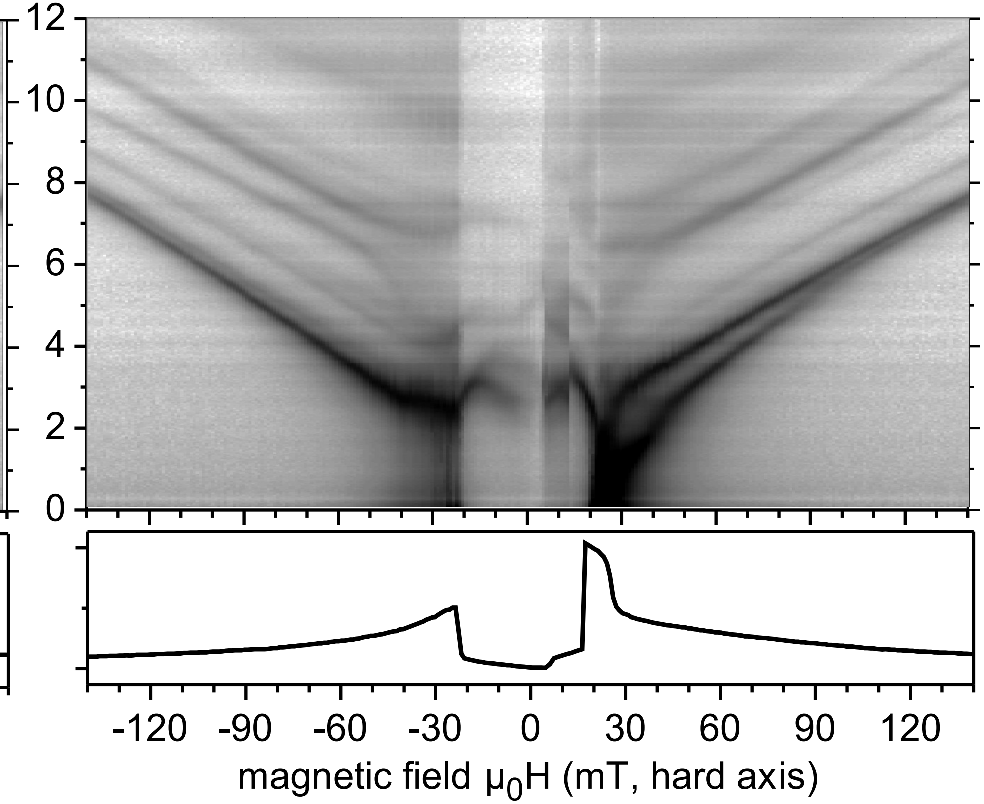


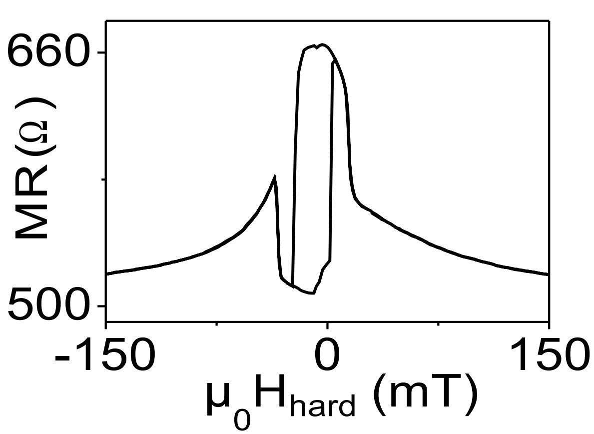
hard axis

I = 0.2 mA

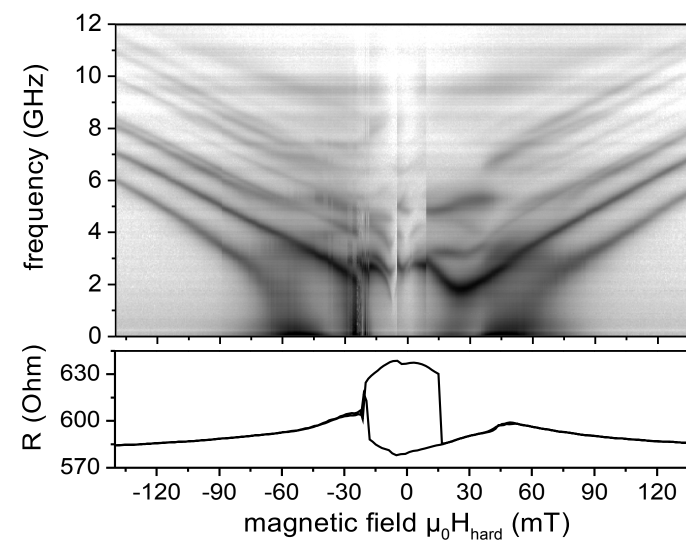


I = - 0.2 mA



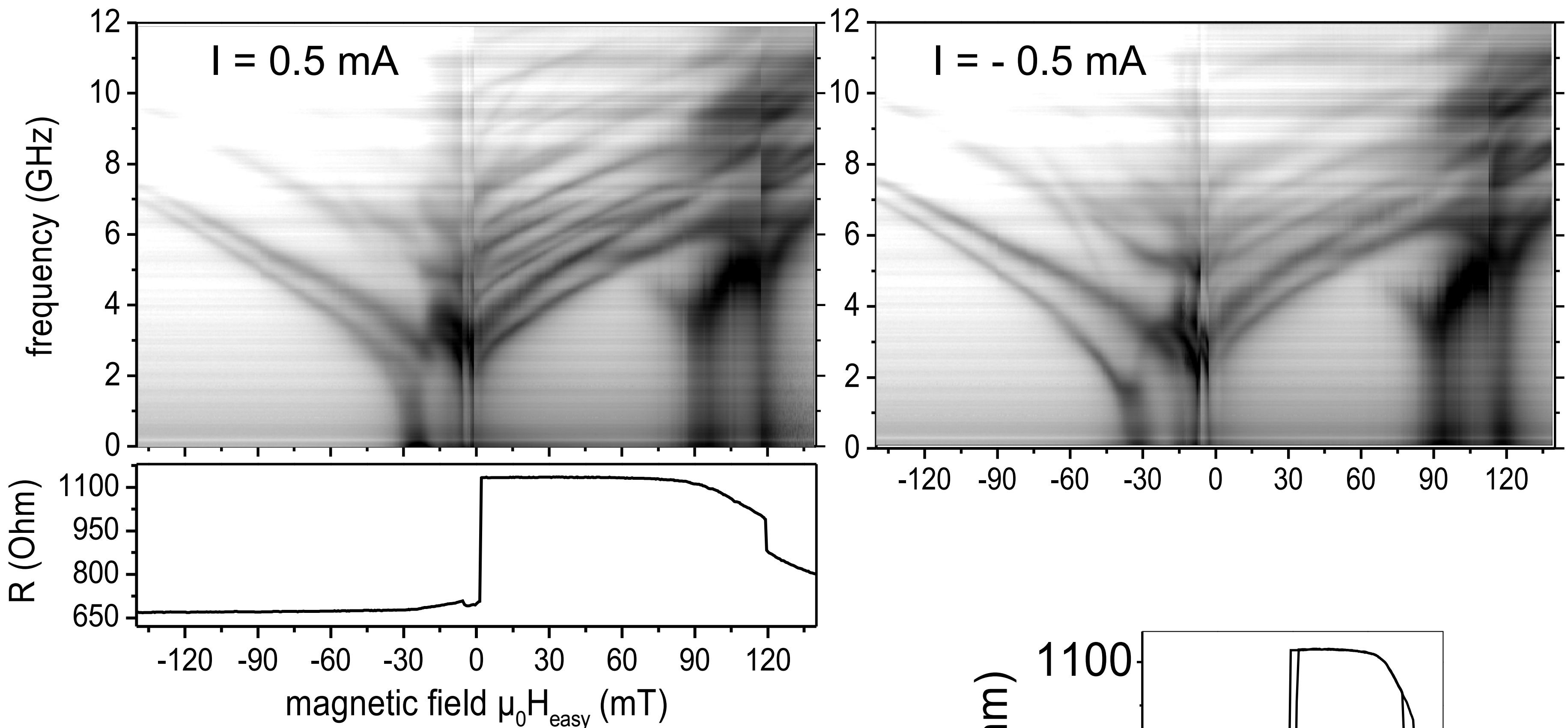


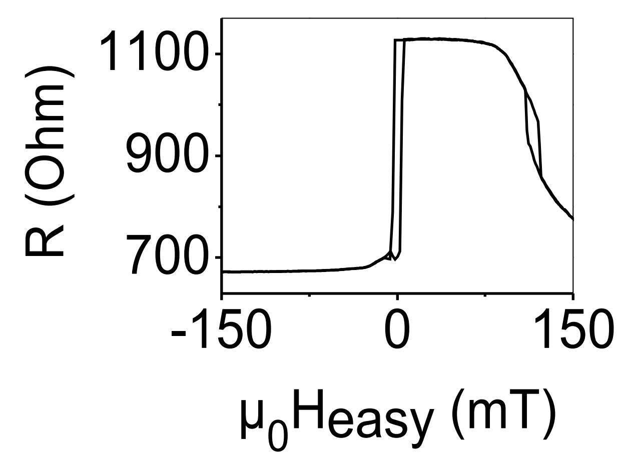
Reference
other sample with
similar RH-loop:



3rd sample

easy axis

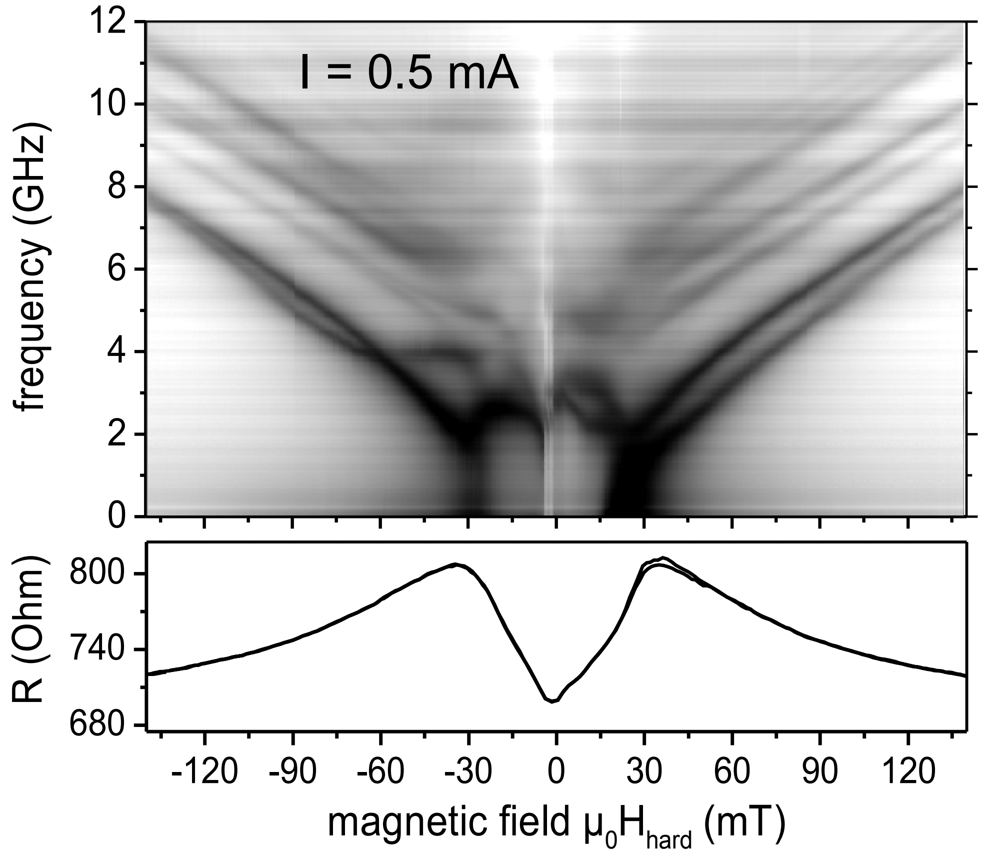


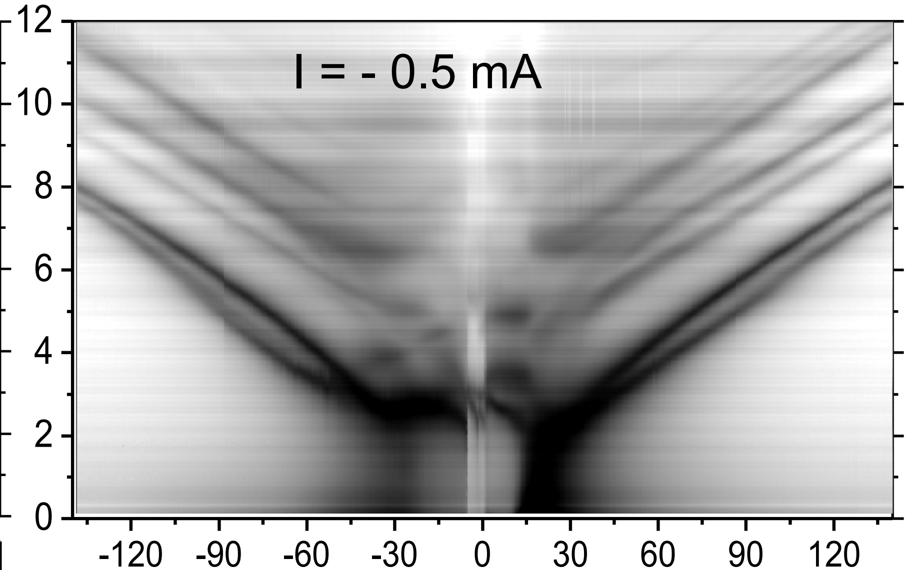


2nd AP mode:
$M_S \sim 0.45T$

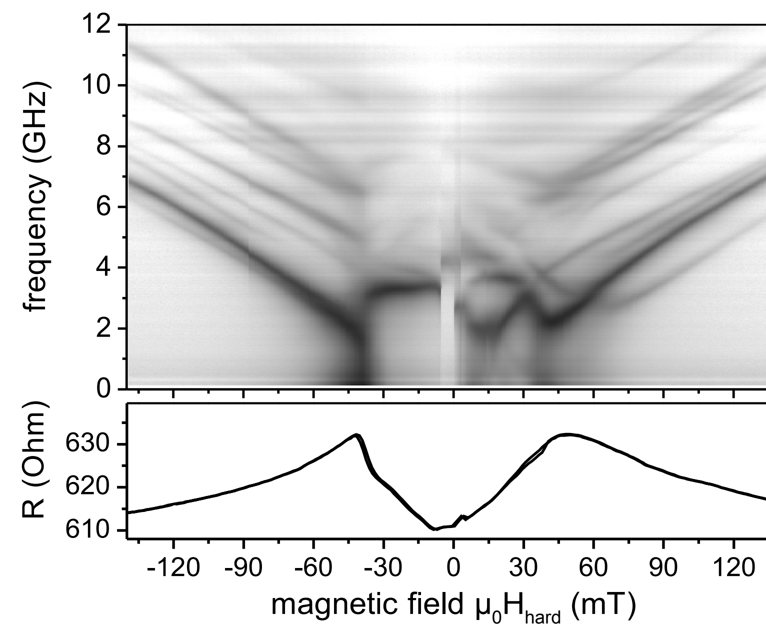
1st AP mode:
$M_S \sim 0.55T$

hard axis





Reference
other sample with
similar RH-loop:



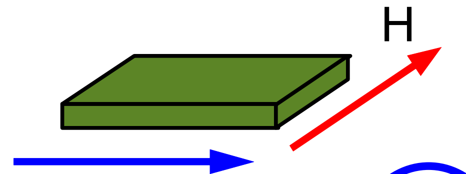
Conclusions

- comparative study of spin wave modes in 100 x 200 nm² MTJs on two sets of samples of slightly different stack composition:
  - for the Hitachi samples up to 12 quantized modes are observed, for IMEC samples not more than 3 (under equal conditions)
  - magnetization of CoFeB free layer extracted from easy axis spectra ~ 0.5 T for Hitachi and ~ 1.2 T for IMEC samples

- size effect: with increasing lateral size the spectra become more and more complex (saturation of edge domains)

Approximate Analytical Model for Free Layer Modes

single free rectangular element



K. Guslienko *et al.*
PR B **68**, 024422 (2003)

$$\omega_{mn}^2 = (\gamma \mu_0)^2 \left[H_{appl} + H_k + H_{exch}^{mn} \right] \left[H_{appl} + M_{eff} + H_k + H_{exch}^{mn} + H_{dem}^{dyn,mn} \right]$$

$$\omega_{mn}^2 = (\gamma \mu_0)^2 \left[H_{appl} - H_k + H_{exch}^{mn} \right] \left[H_{appl} + M_{eff} \quad + H_{exch}^{mn} + \tilde{H}_{dem}^{dyn,mn} \right]$$

quantized exchange field

$$H_{exch}^{mn} = \frac{2A}{\mu_0 M_S} \left(k_{xm}^2 + k_{yn}^2 \right)$$

dynamic demagnetizing field

$$H_{dem}^{dyn,mn} = M_S * F(k_{xm}, k_{yn}, H_{appl}, \ldots)$$

quantization of in-plane wavevectors

$$k_{xm} = m \frac{\pi}{l}$$

$$k_{yn} = n \frac{\pi}{w}$$

unpinned BC

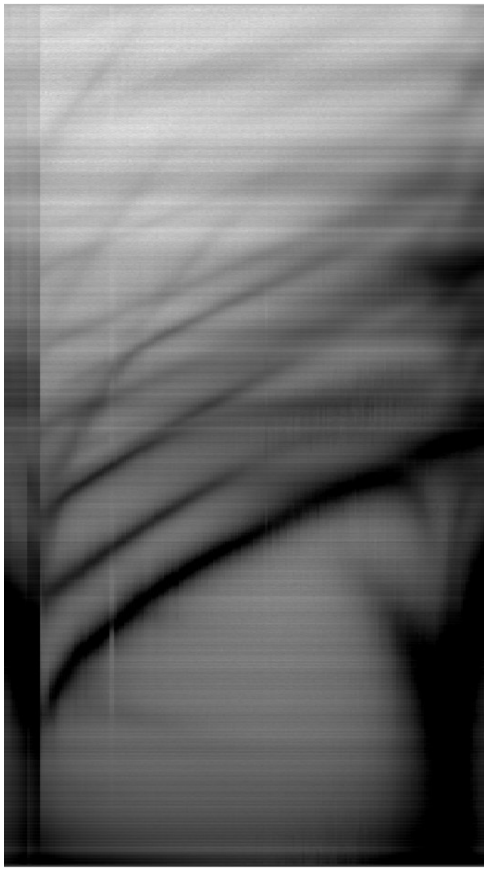
$$m = 0, \; 1, 2, 3, \ldots$$

$$n = 0, \; 1, 2, 3, \ldots$$

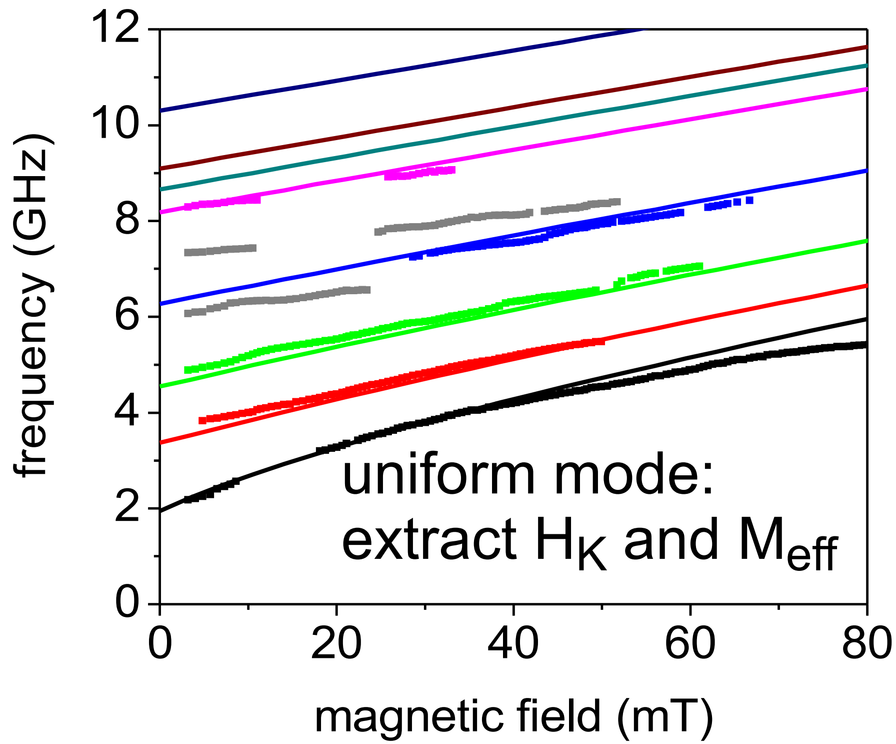
?

mixed boundary conditions:
effective k
non-integer m,n

Extraction of magnetic parameters



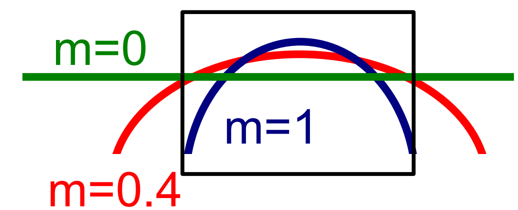
1[st] mode =
edge mode
or
uniform mode?



2 groups of modes with
distinct slope
(+ additional higher harmonics)

↓

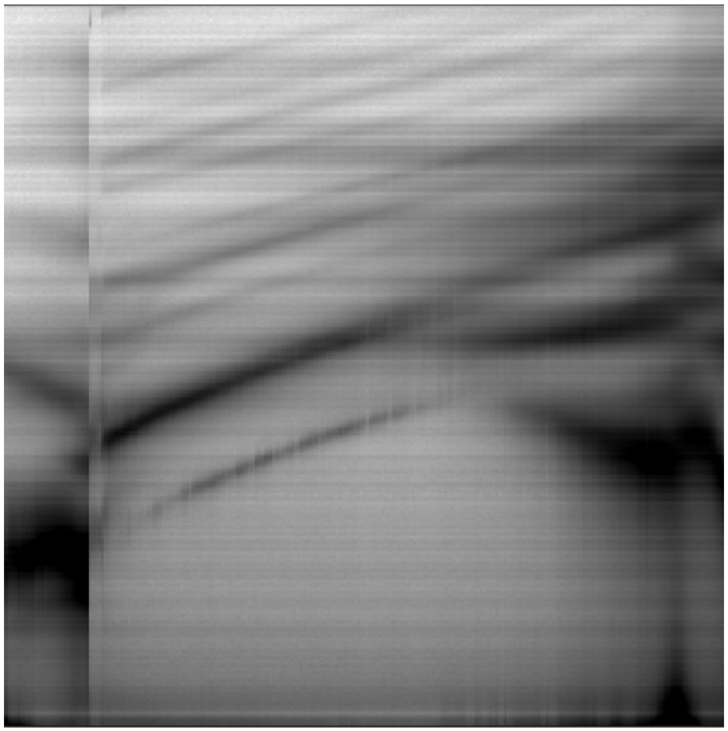
nature of modes with
lower slope?

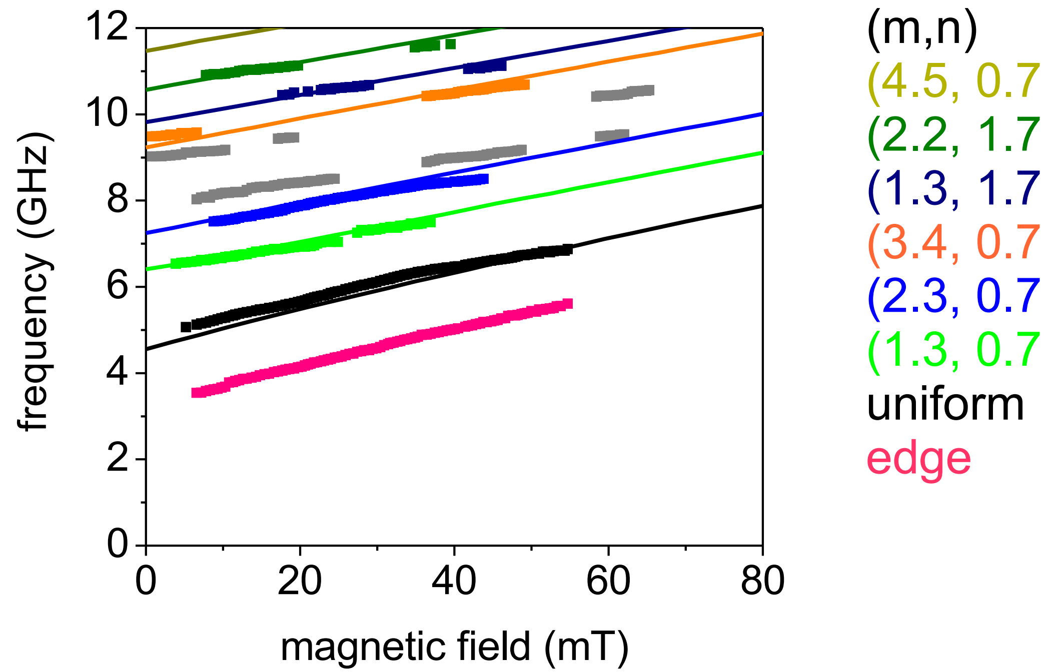


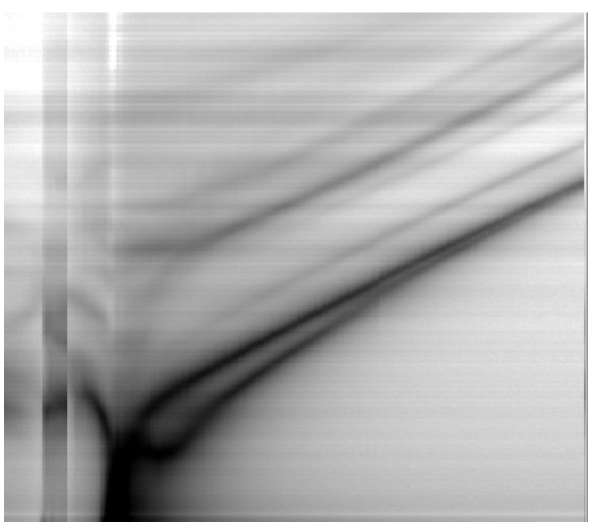
$$l = 180\,nm$$
$$w = 90\,nm$$
$$H_K = 12\,mT$$
$$M_{eff} = M_S = 0.4\,T$$
$$A = 5 \times 10^{-12}\,J/m$$

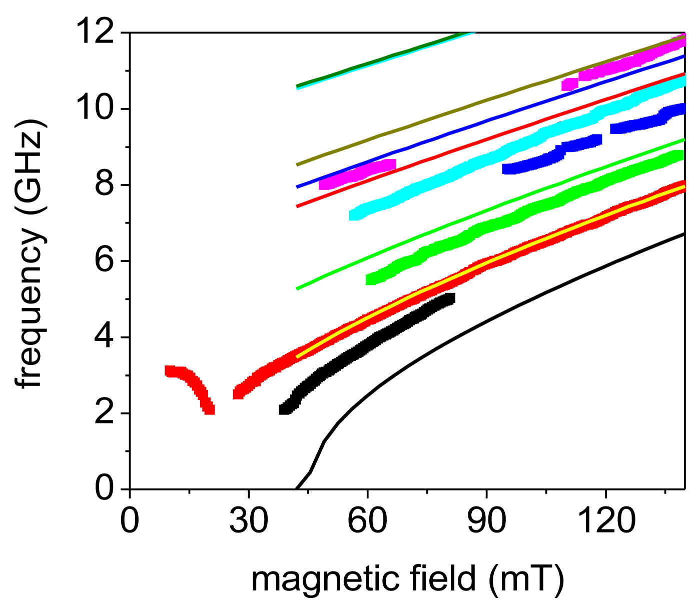
<< bulk values CoFeB
(1.9 T, 28×10^{-12} J/m)

Supposition: lowest mode = edge mode

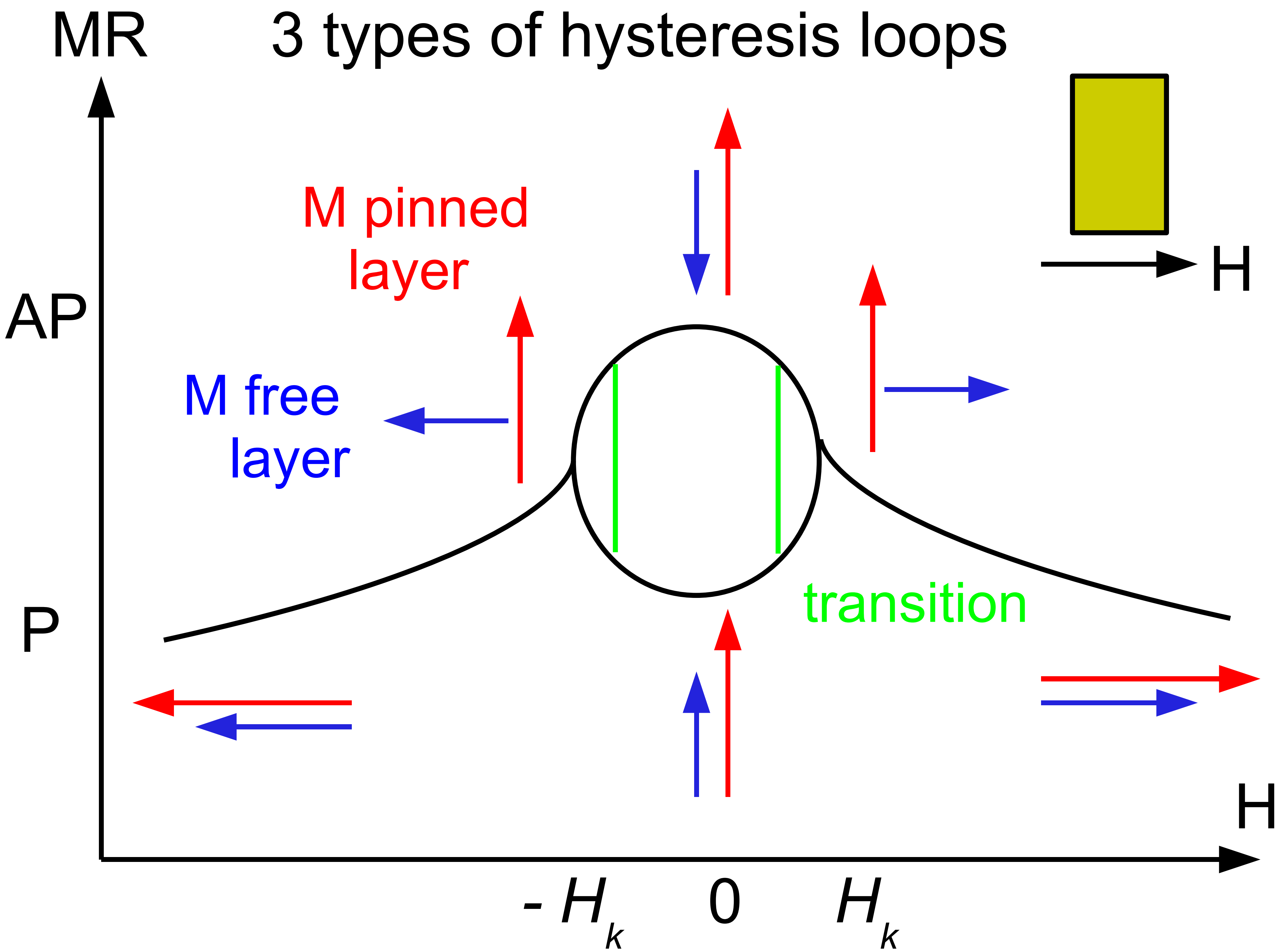








$$l = 180\,nm$$
$$w = 90\,nm$$
$$H_K = 45\,mT$$
$$M_{eff} = M_S = 0.5\,T$$
$$A = 5 \times 10^{-12}\,J/m$$
$$assump.: H_{SAF} = 0\,!!$$



MR
3 types of hysteresis loops
H
AP
M pinned
layer
M free
layer
P
transition
H
- H_k
0
H_k