Nanomagnetism –

a perspective from the dynamic side

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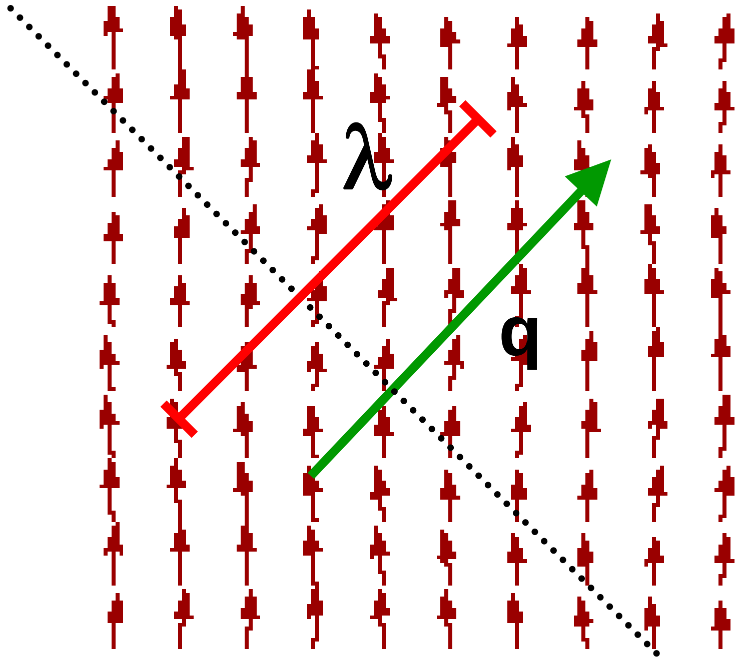
Coherent dynamics: spin waves

Landau-Lifshitz torque equation

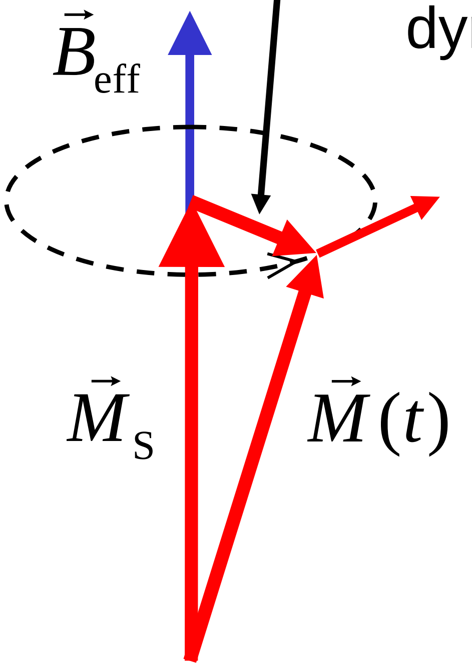


$$\frac{1}{|\gamma|}\frac{d\vec{M}(t)}{dt} = -\vec{M}(t)\times\vec{B}_{\text{eff}}(t)$$

Is intrinsically nonlinear equation !

$$\vec{m}(\vec{r},t) = \vec{m}_0(\vec{r})\times e^{i(\vec{q}\vec{r}\text{-}\omega t)}$$

dynamic magnetization



Content

Background

- spin waves in a small magnetic stripe with domain wall
- nanocontacts on spin-valve samples
- propagating spin waves in a small magnetic stripe

Summary

Coworkers

F. Ciubotaru, S. Hermsdörfer, A. Laraoui, B. Leven, B. Obry, C. Sandweg, S. Schäfer, H. Schultheiss, A. Serga, K. Vogt	TU Kaiserslautern
M. van Kampen, X. Janssens, L. Lagae	Interuniversitaire Micro-Electronica Centrum vzw (IMEC), Leuven, Belgium
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J. Chapman	University of Glasgow
J. Miltat	LPS, Université Paris-Sud

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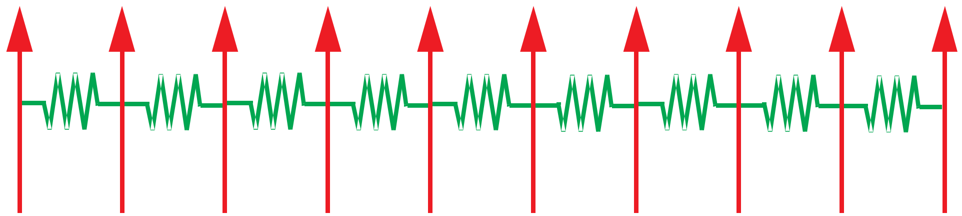
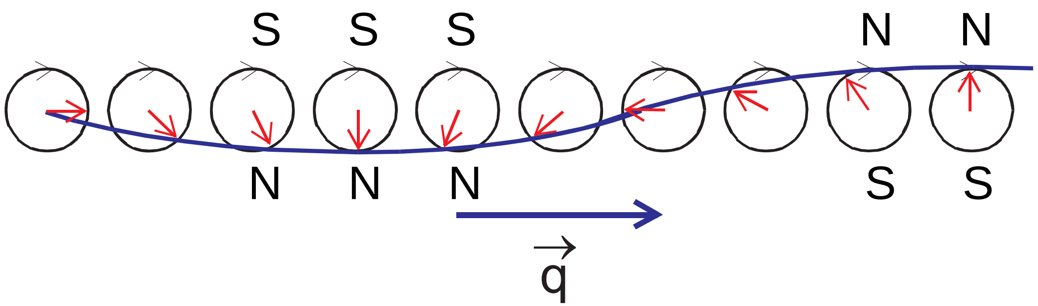
Spin waves

Two types of energy contributions

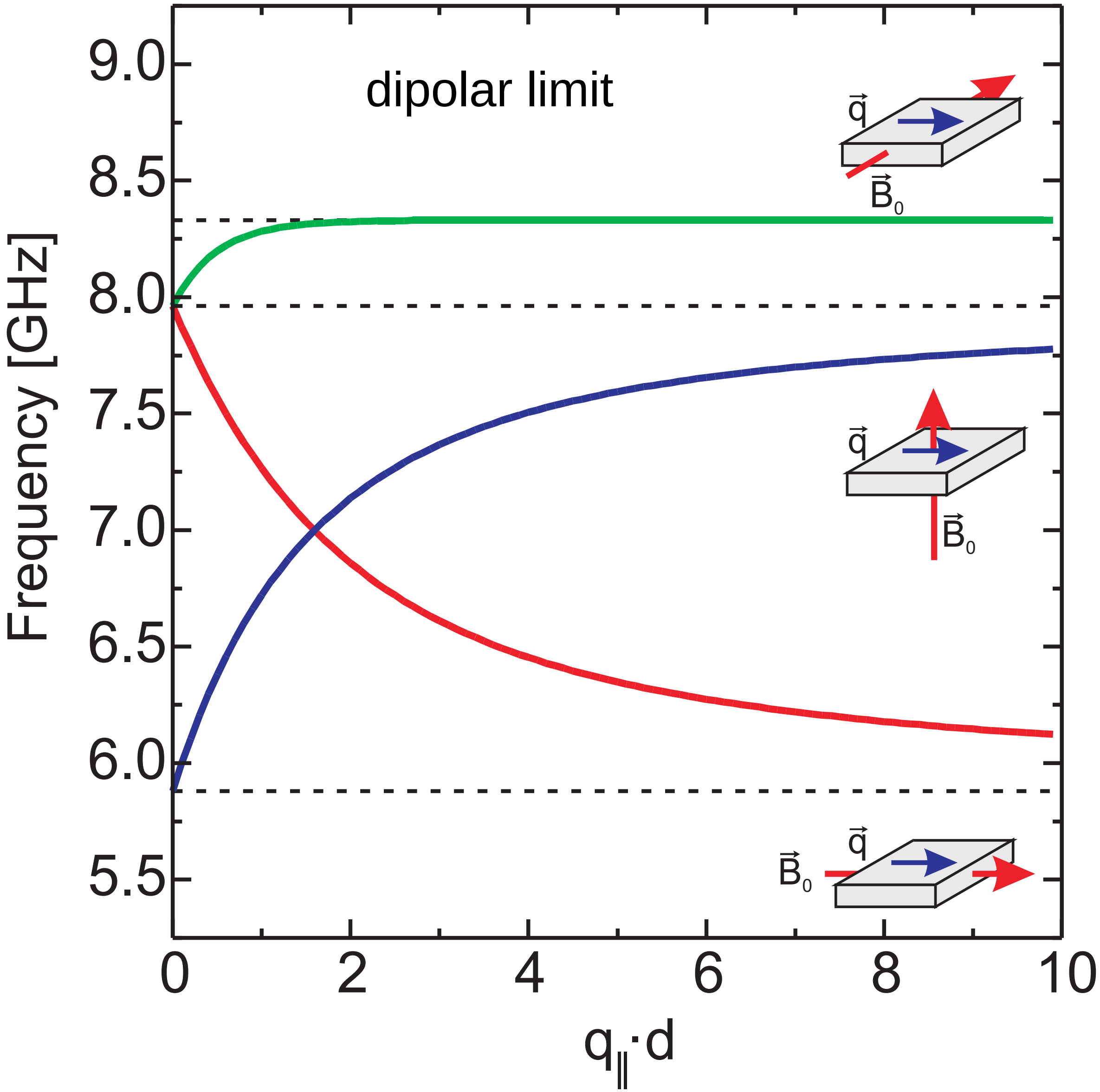
- exchange energy:
  generated by twist of neighbored spins



- dipolar energy:
  generated by magnetic poles in long-wavelength spin waves



Spin waves – dipolar limit



magnetostatic surface wave (MSSW)

magnetostatic forward volume wave (MSFVW)

magnetostatic backward volume wave (MSBVW)

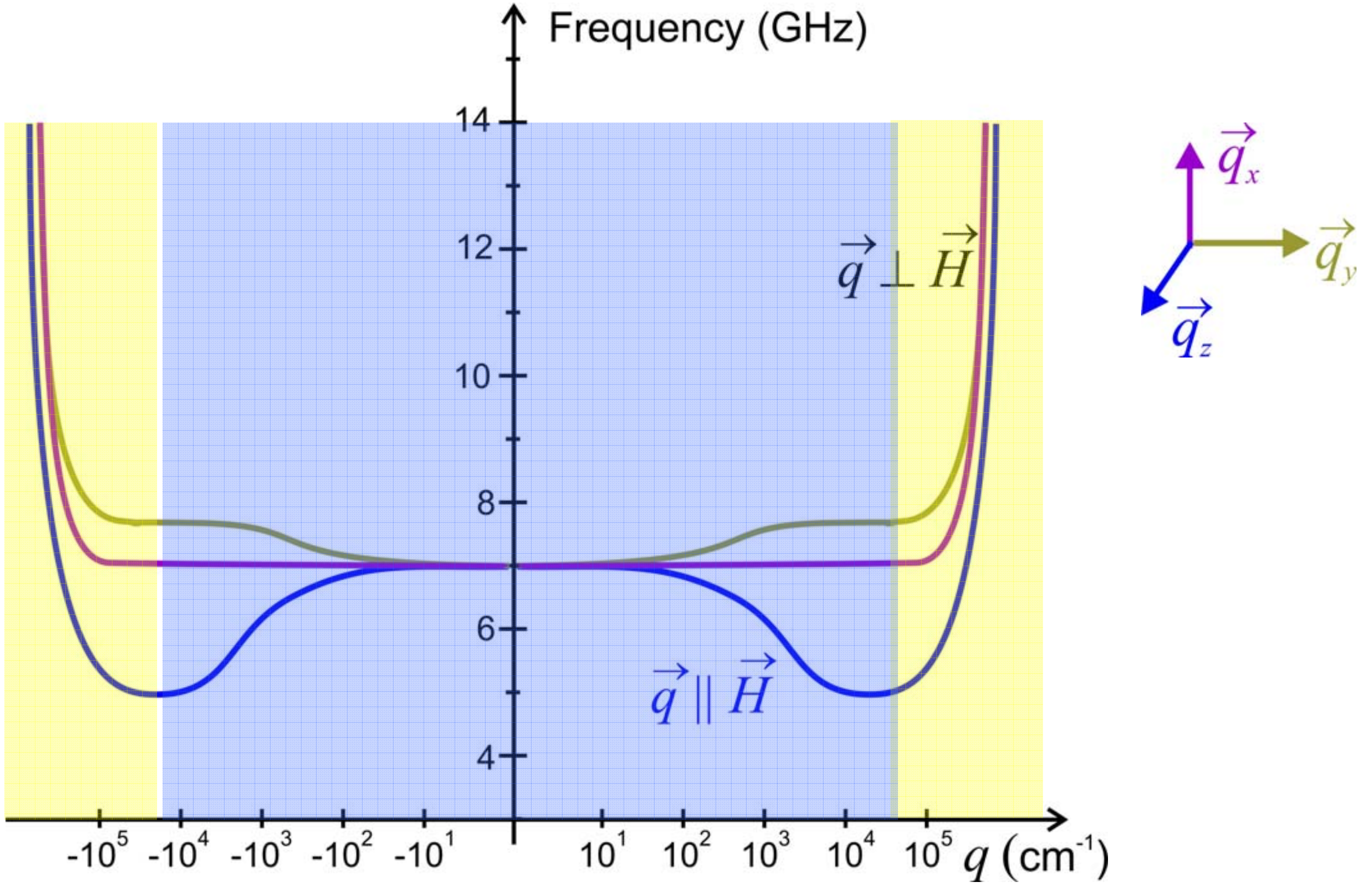
Spin waves - dipolar-exchange

Landau-Lifshitz equation: $\frac{\partial \vec{M}}{\partial t} = -|\gamma| \vec{M} \times \vec{H}_{\text{eff}}$

$$\vec{H}_{\text{eff}}(\vec{r}) = \vec{H}_{\text{appl}} + \int_V \tilde{G}(\vec{r},\vec{r}\,') \cdot \vec{M}(\vec{r}\,')\,dr'^3 + \frac{2A}{M_S^2}\nabla^2 \vec{M} + \ldots$$

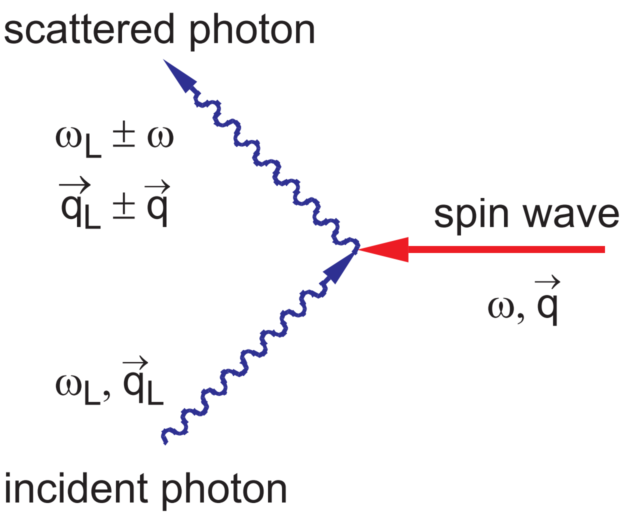
dipolar interaction

exchange interaction



Brillouin light scattering (BLS) process

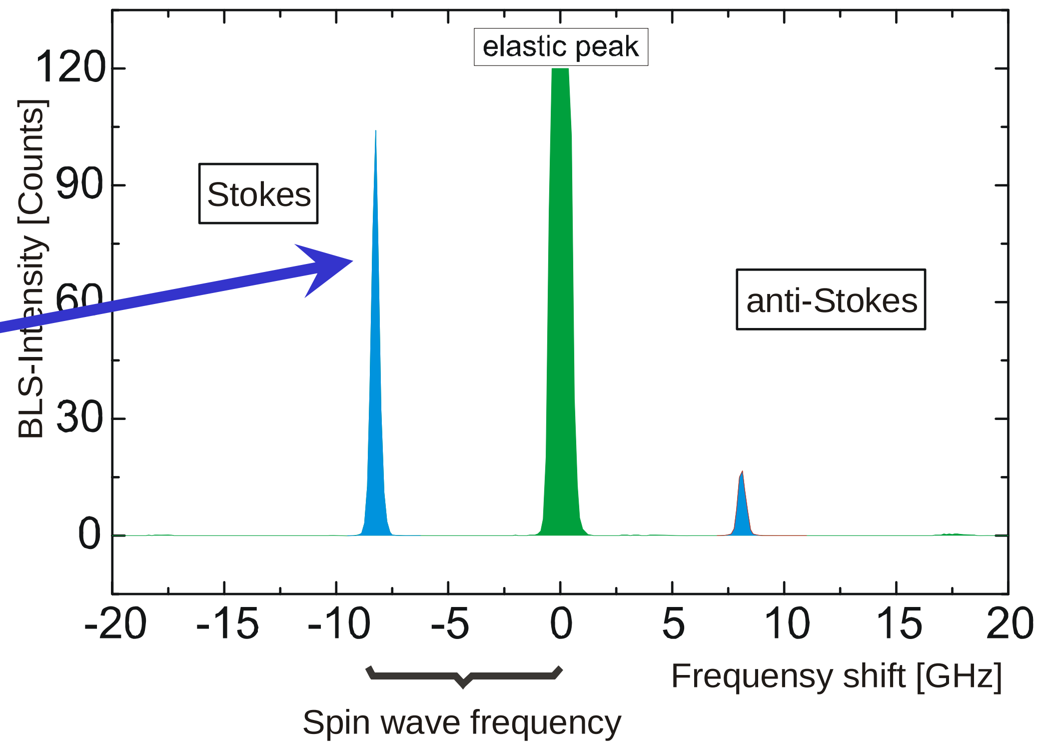
= inelastic scattering of photons from spin waves



$$\vec{q}_{SC} = \vec{q}_L \pm \vec{q}$$

$$\omega_{sc} = \omega_L \pm \omega$$

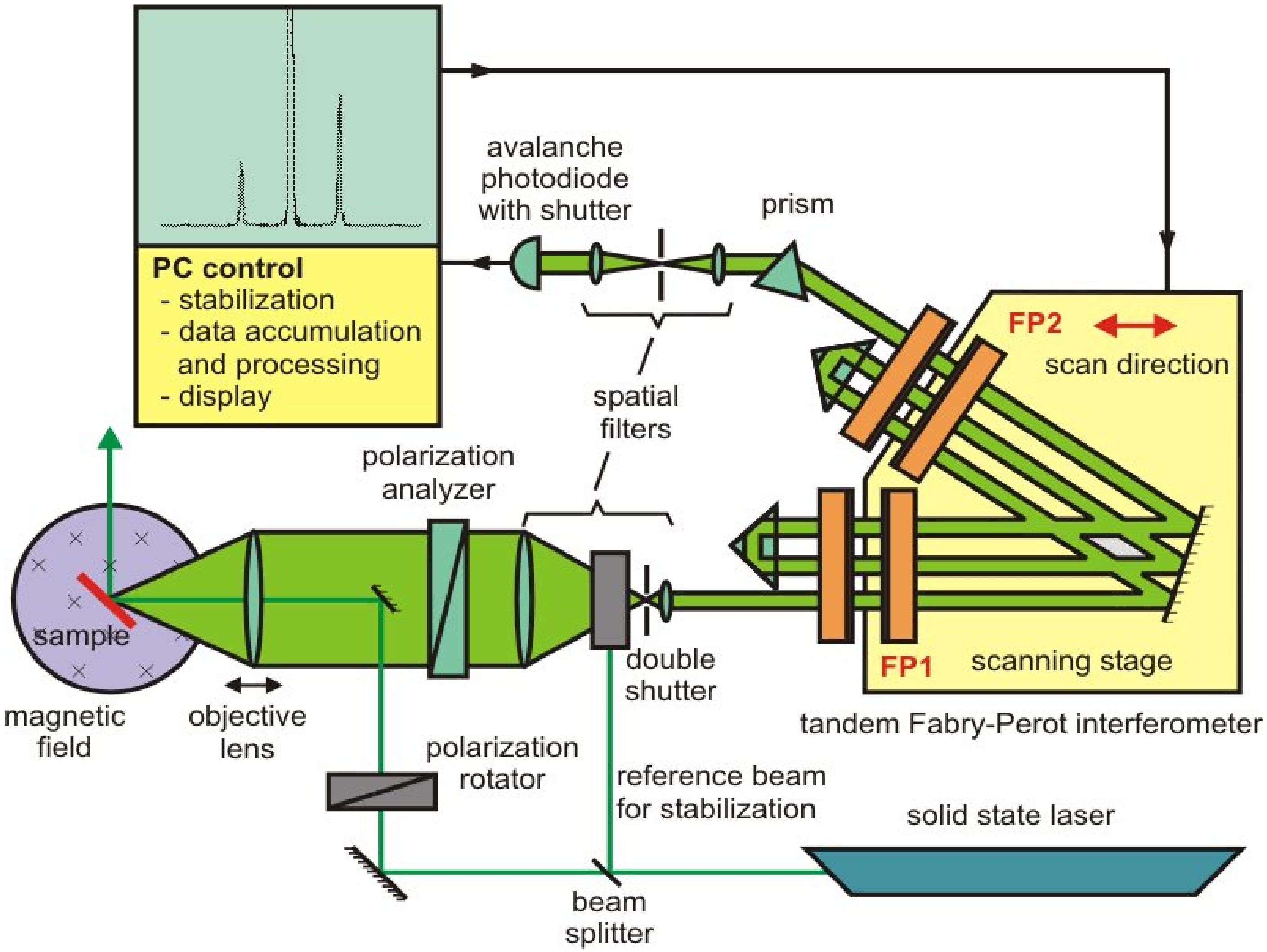
spectrum of scattered light



proportional to the
spin wave intensity $|\varphi|^2$

Brillouin light scattering spectrometer

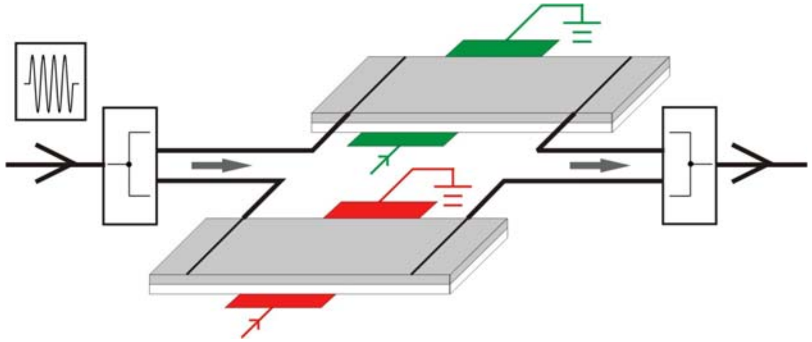
high-resolution interferometry with high contrast for measurements of acoustic phonons and spin waves

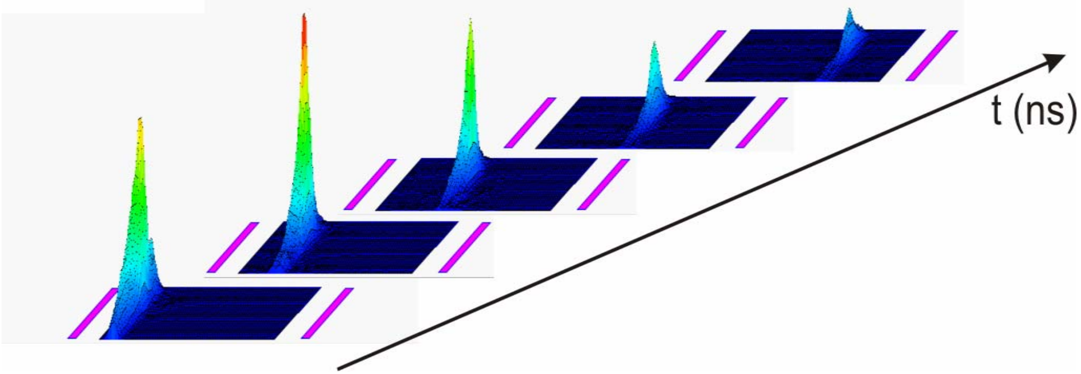


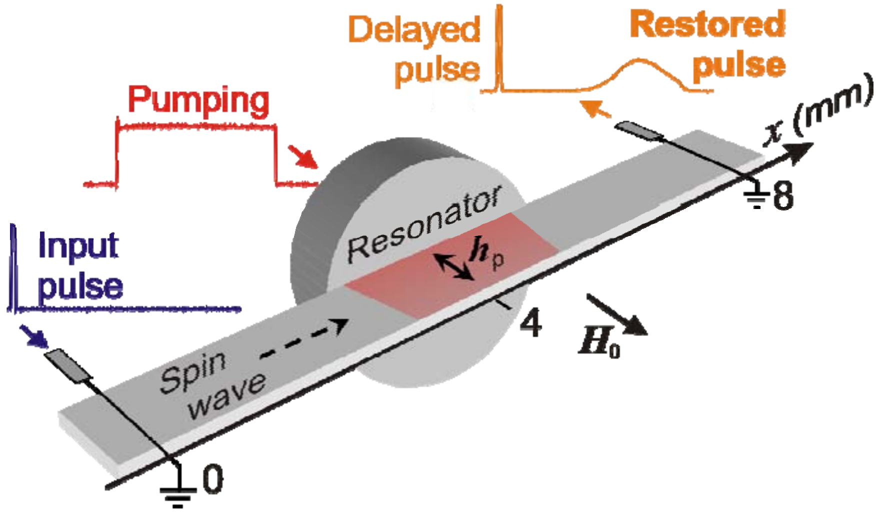
On macroscopic scale ...

... so far a lot of experience in development of spin-wave based concepts, such as:

- spin-wave logic
- nonlinear excitations (solitons, bullets)
- parametric amplification
- magnonic crystals
- ...







Realize these concepts on submicrometer scale

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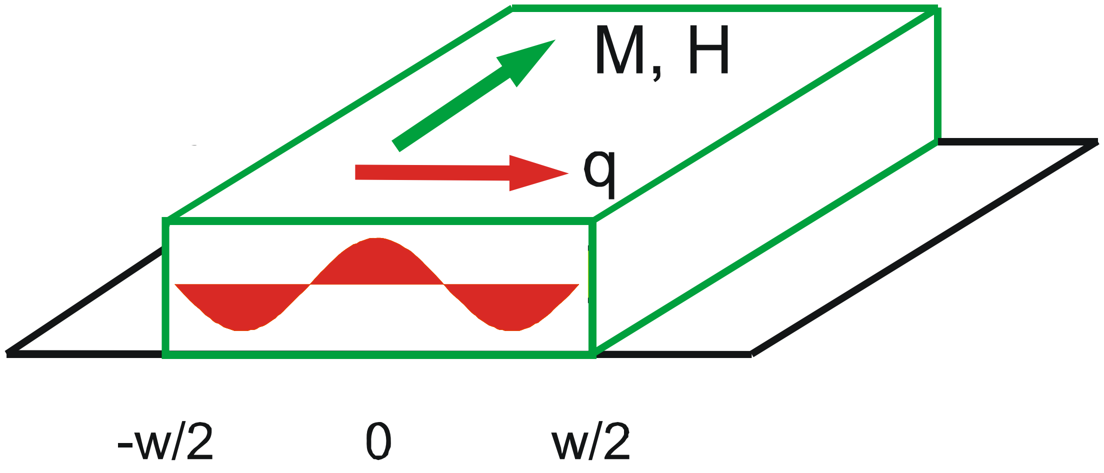
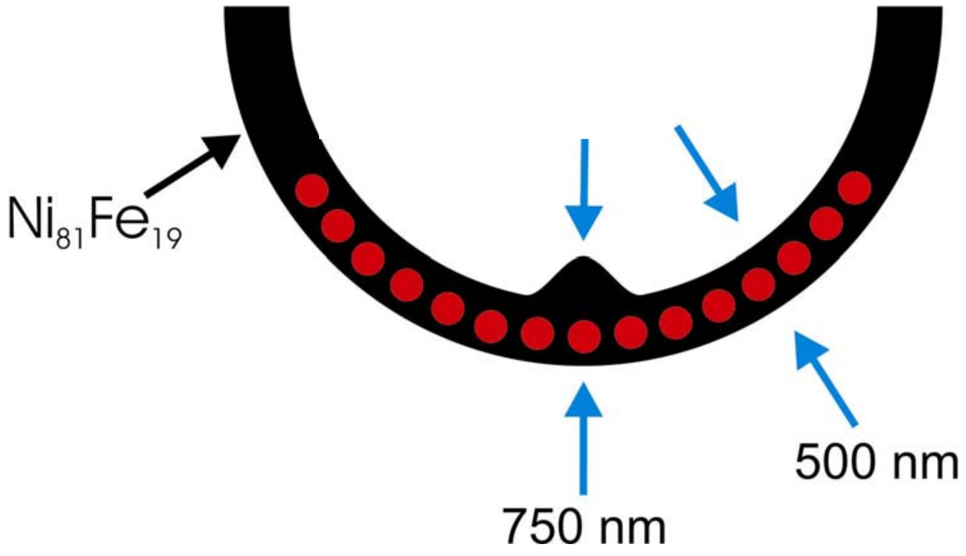
Lateral spin-wave quantum size effect



Standing lateral modes

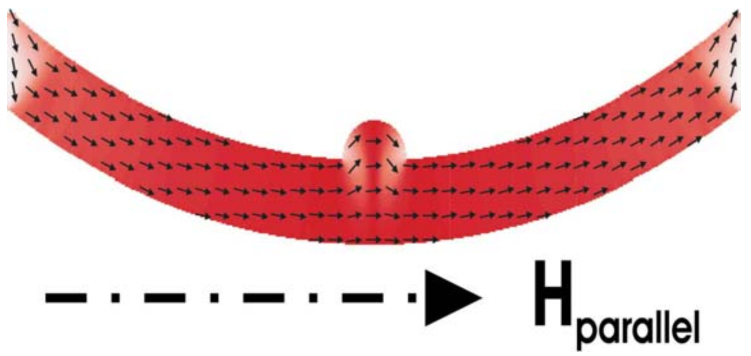
- propagating dipolar spin-wave modes
- quantization condition due to the lateral edges:
  $w = n\,\lambda_{\text{spin wave}}/2$;
  $q_n = 2\pi/\lambda_{\text{spin wave}} = \pi n/w$; $n = 1,2,3,...$
- boundary conditions (open – pinned)

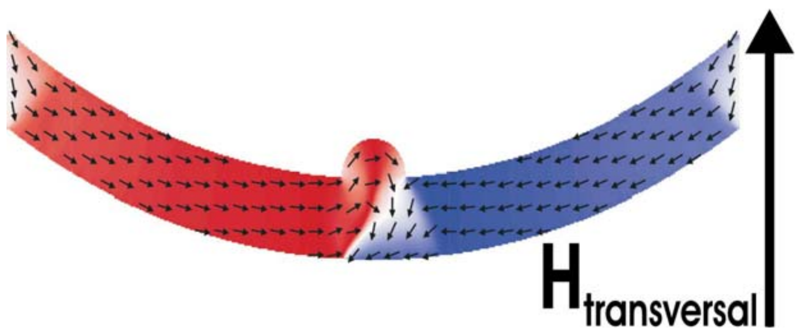
$Ni_{81}Fe_{19}$ nanostripes



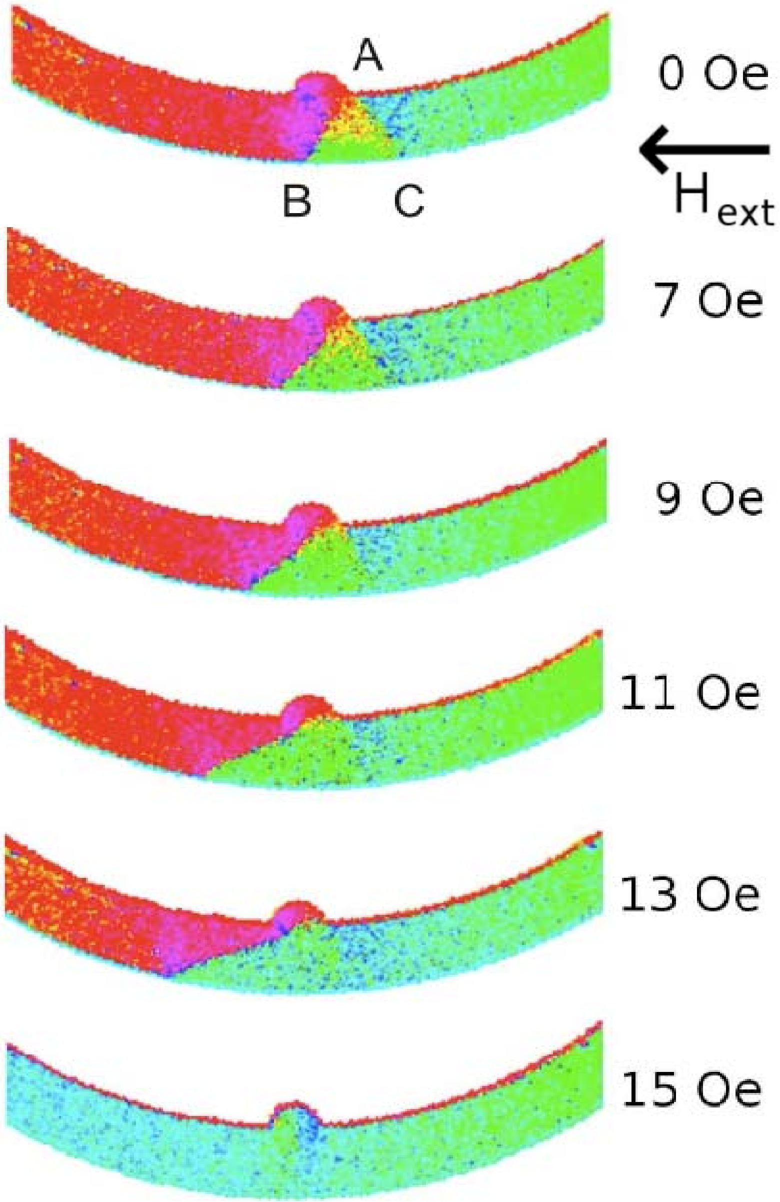
- Nucleation of a domain at protuberance applying a field sequence
- Observation of thermal spin waves
- Experiment: BLS spectra measured along a line indicated by the red dots, focus diameter 250 nm

OOMMF simulations:

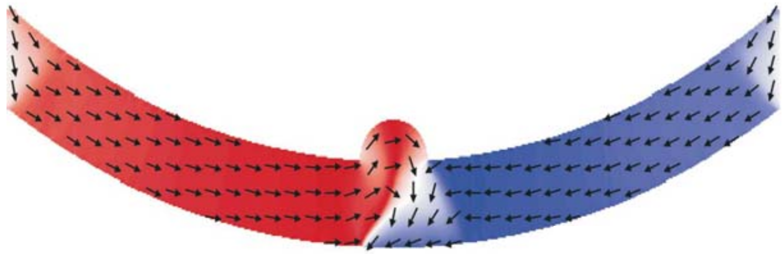




Lorenz microscopy

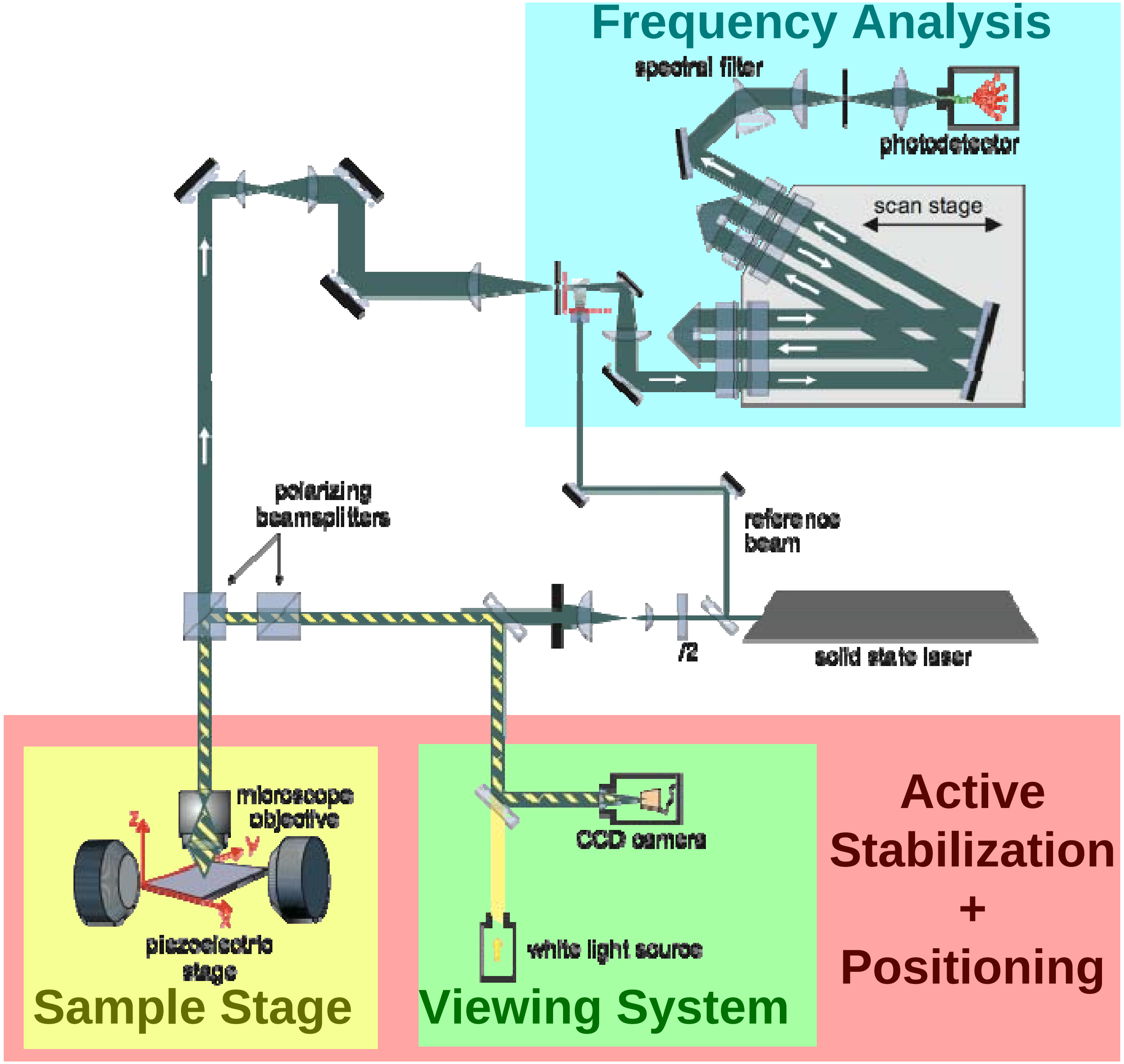


Comparison to OOMMF simulation:



in cooperation with
J. Chapman group, Glasgow

Technique: BLS Microscopy



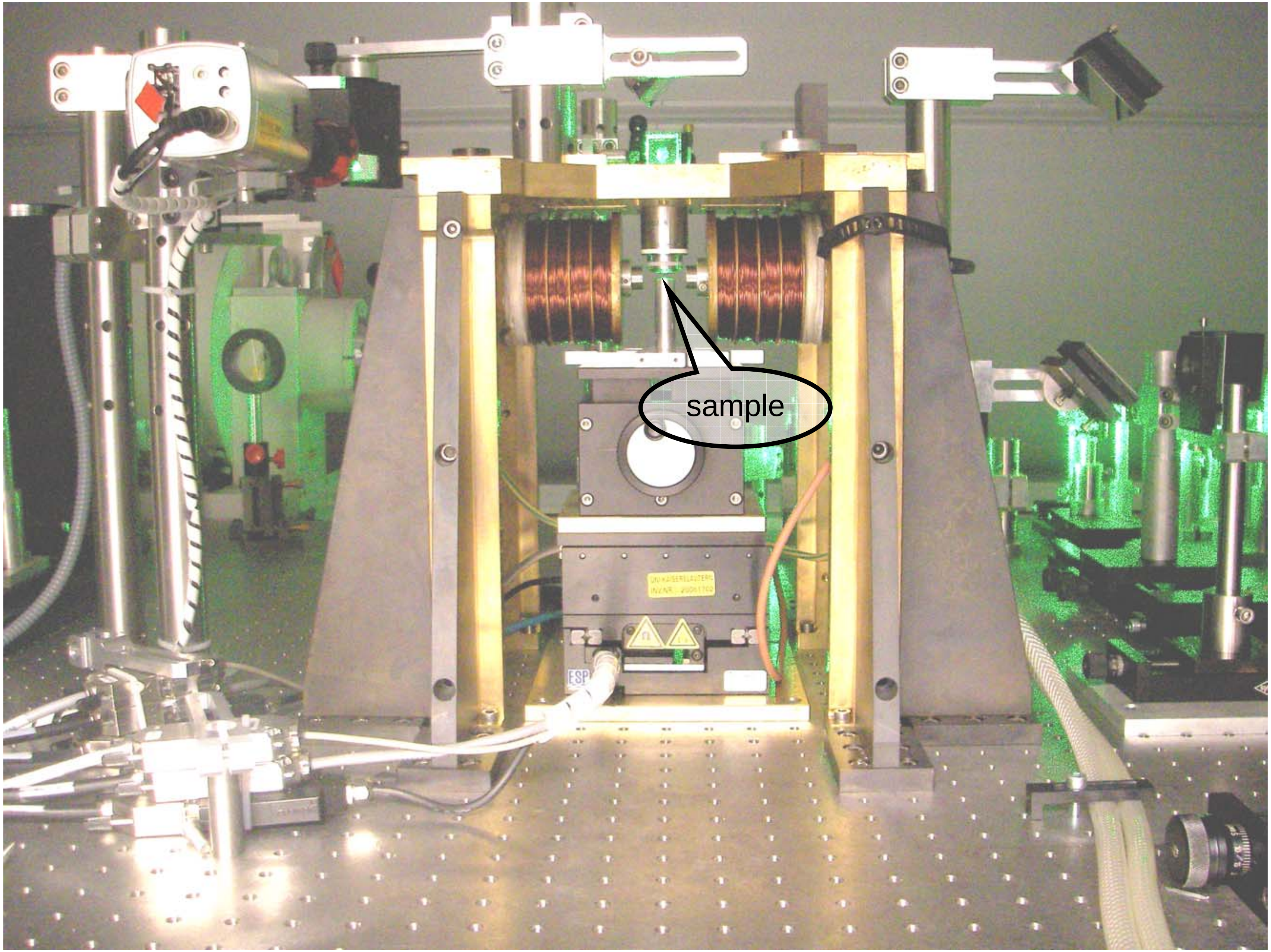
- optical resolution: 250nm
- 2D piezo stage

- controlling sample while measuring

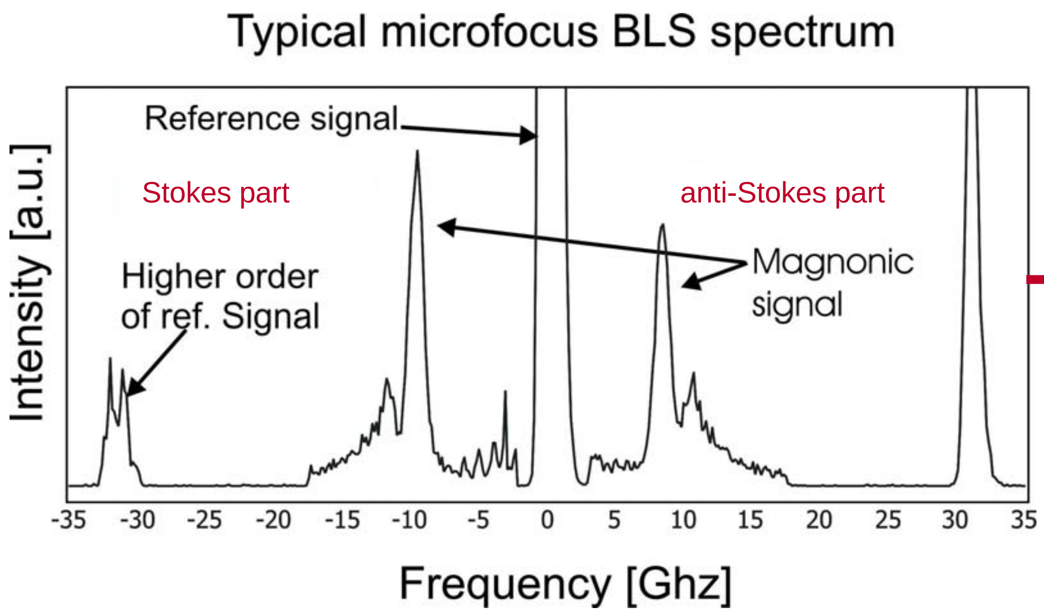
- frequency range: 1GHz – 1THz
- spectral resolution: 200MHz

- position stability: ***infinite***
- accuracy: ***better than 20nm***
- high reproducibility

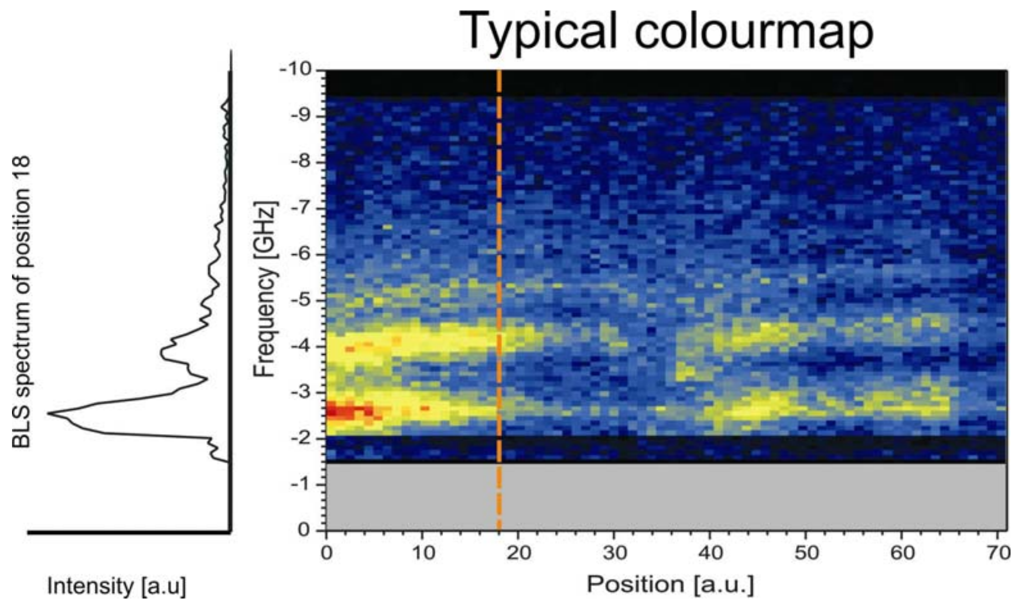
BLS Microscopy - experimental setup



Measurement procedure



- Colour maps are created by assembling the spectra of each scan point
- Only the Stokes part of the spectrum is used

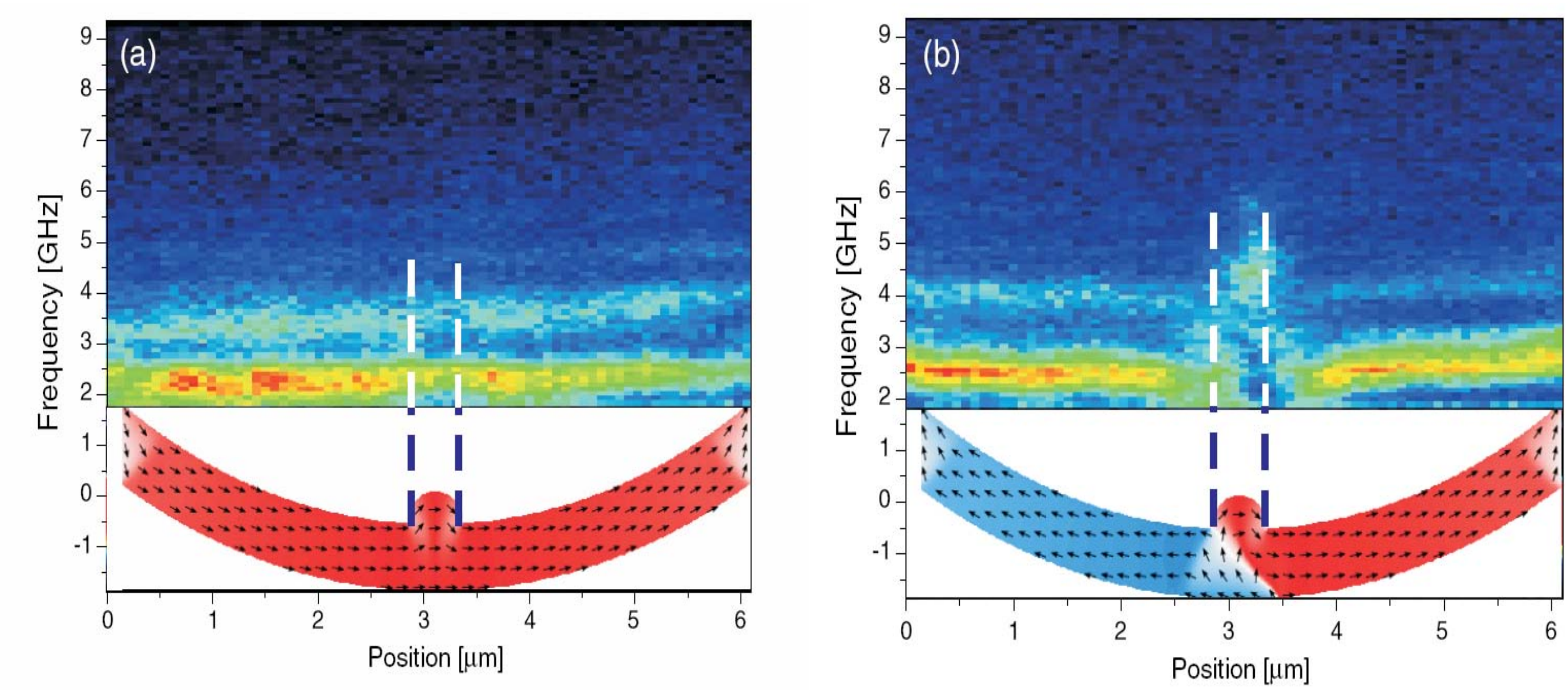


$Ni_{81}Fe_{19}$ nanostripes: thermal spectrum

Thermal spin wave spectrum…

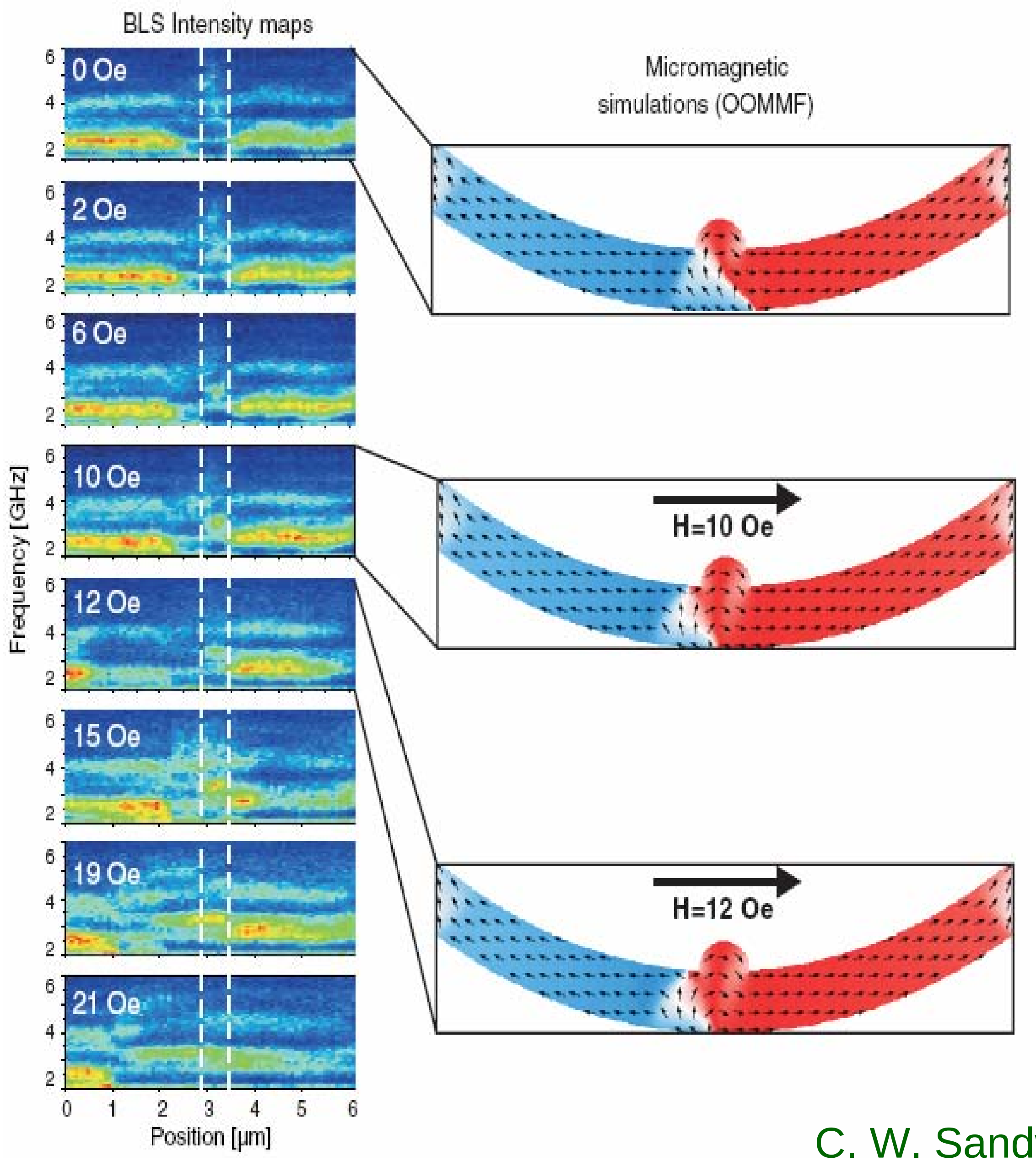
…without domain wall

…with domain wall at protuberance



C. W. Sandweg et al., J. Phys. D **41**, 164008 (2008)

$Ni_{81}Fe_{19}$ nanostripes: thermal spectrum



C. W. Sandweg et al., J. Phys. D **41**, 164008 (2008)

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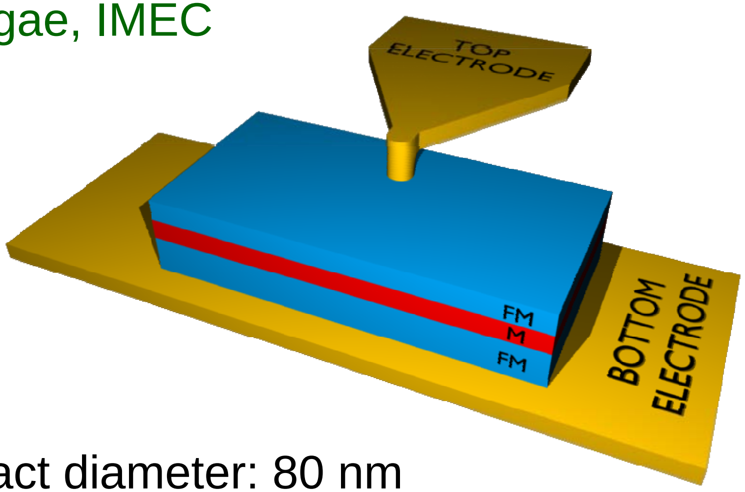
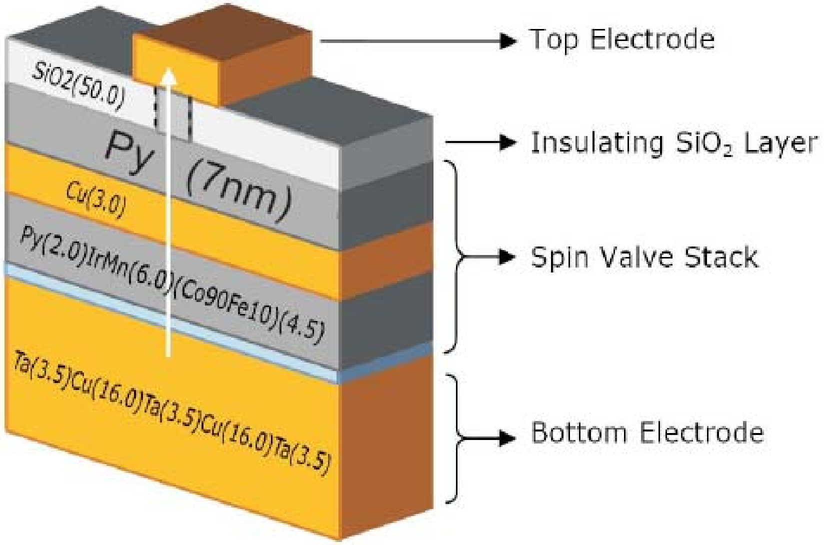
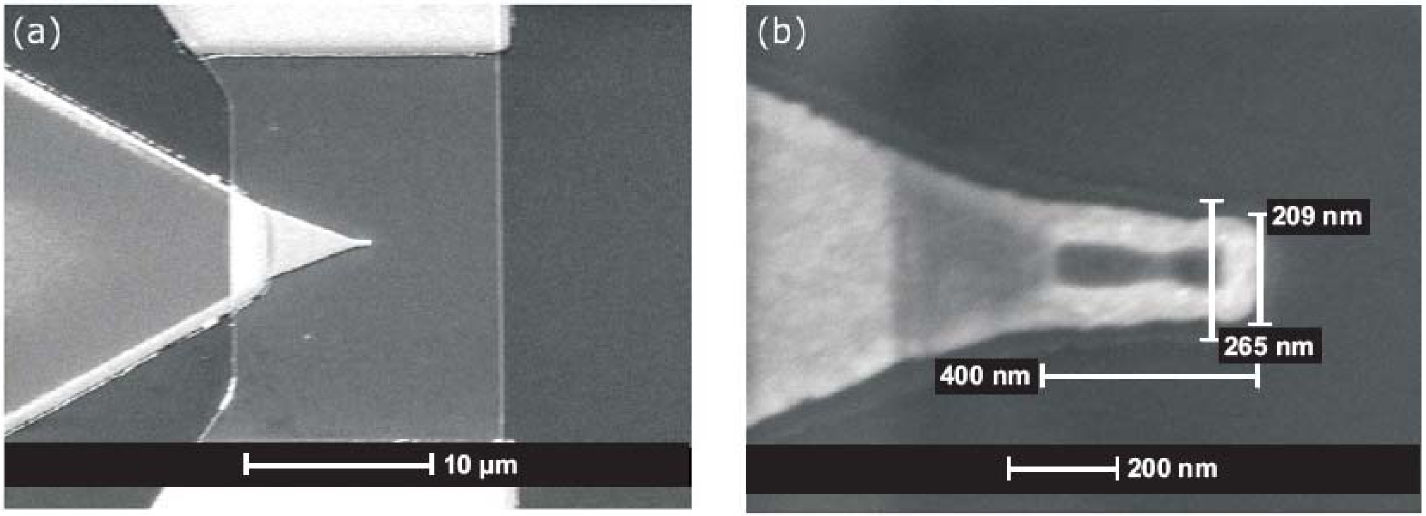
Nano-contact sample layout

Samples provided by
M. van Kampen, X. Janssens
and L. Lagae, IMEC





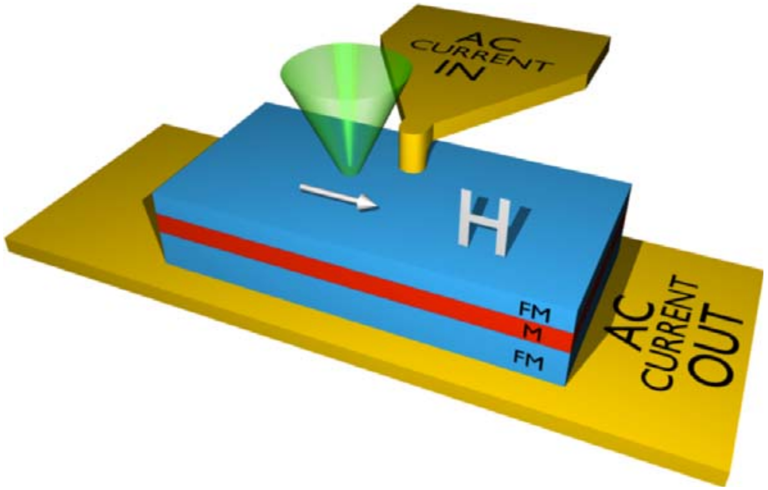
Point contact diameter: 80 nm

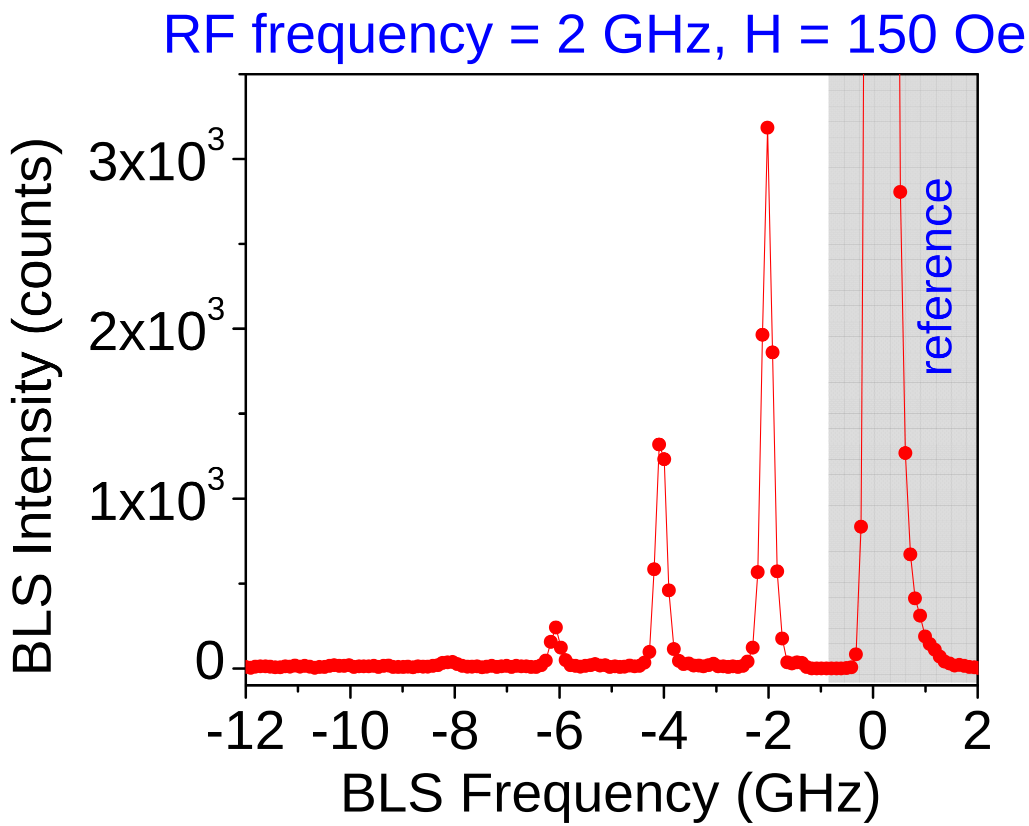


SEM images of the sample (top view)

AC induced magnetization dynamics

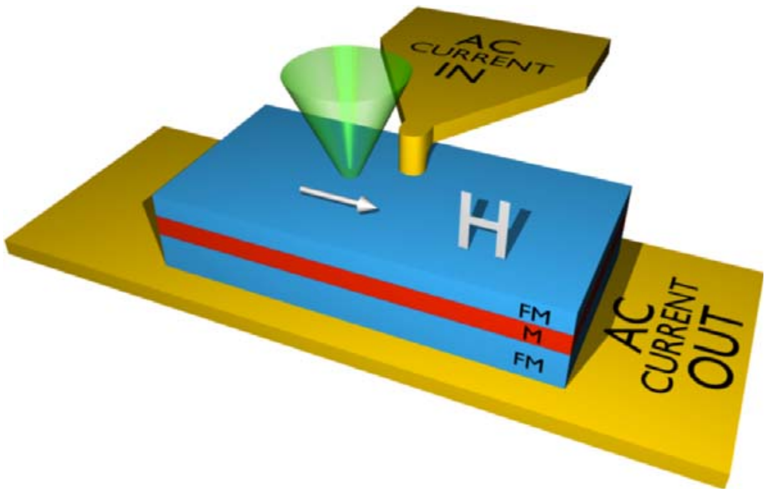
- Measuring at fixed position near the nanocontact

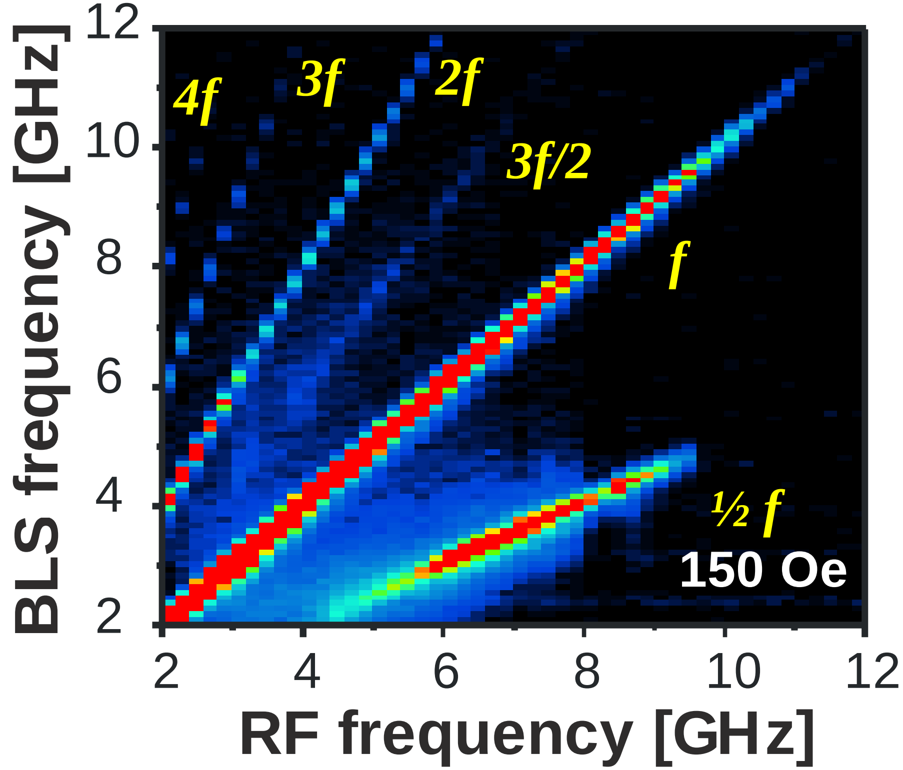




AC induced magnetization dynamics

- Measuring at fixed position near the nanocontact
- Sweeping the RF current frequency for a fixed applied power (= 20 mW)



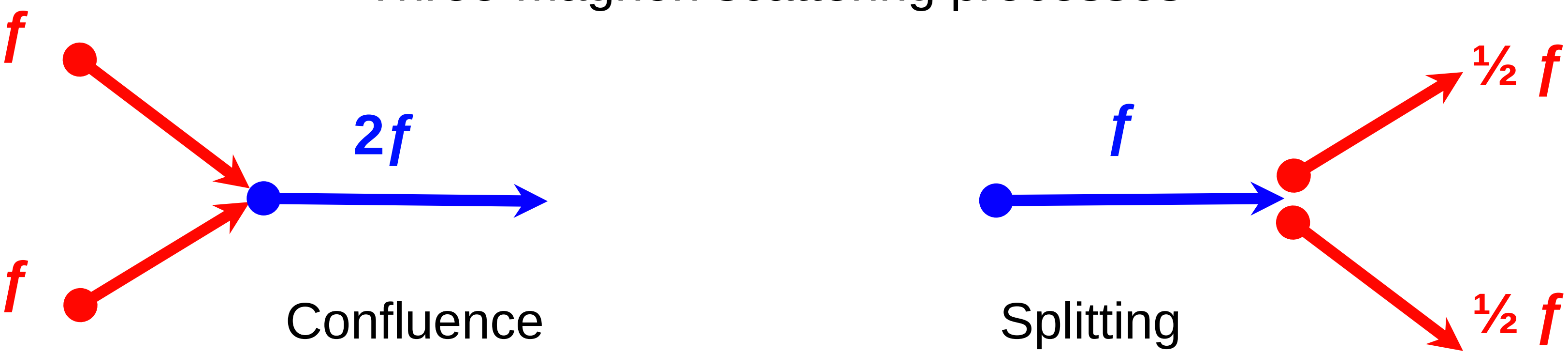


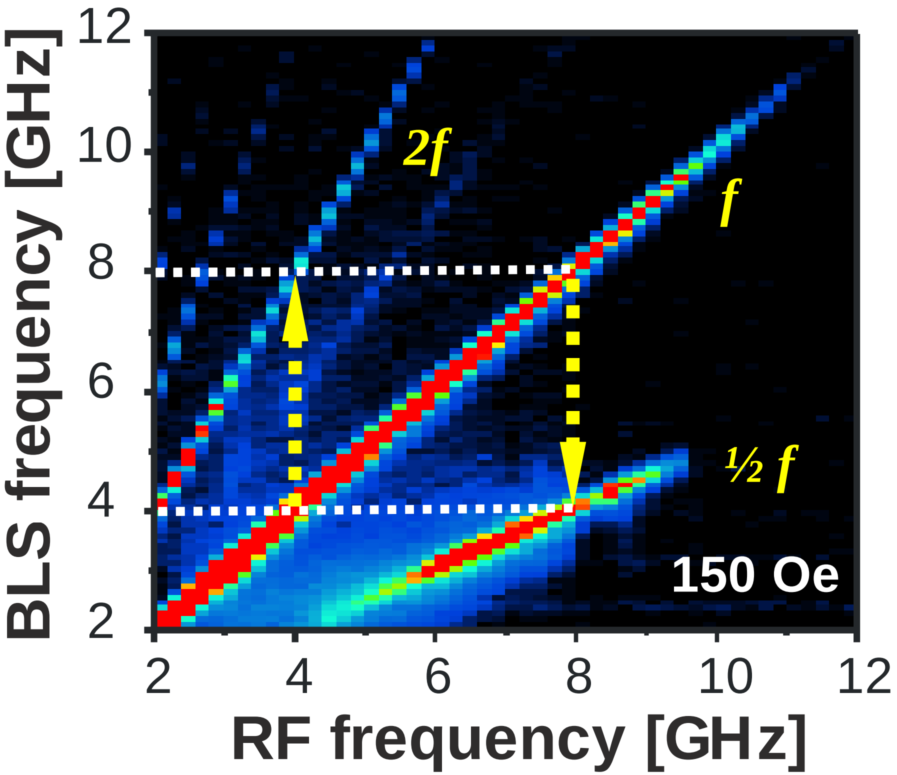
Higher frequency generation: 2*f*, 3*f*, 4*f*

Non-integer-half frequency generation: 1/2 *f*, 3/2 *f*

Nonlinear magnetic phenomena

Three-magnon scattering processes





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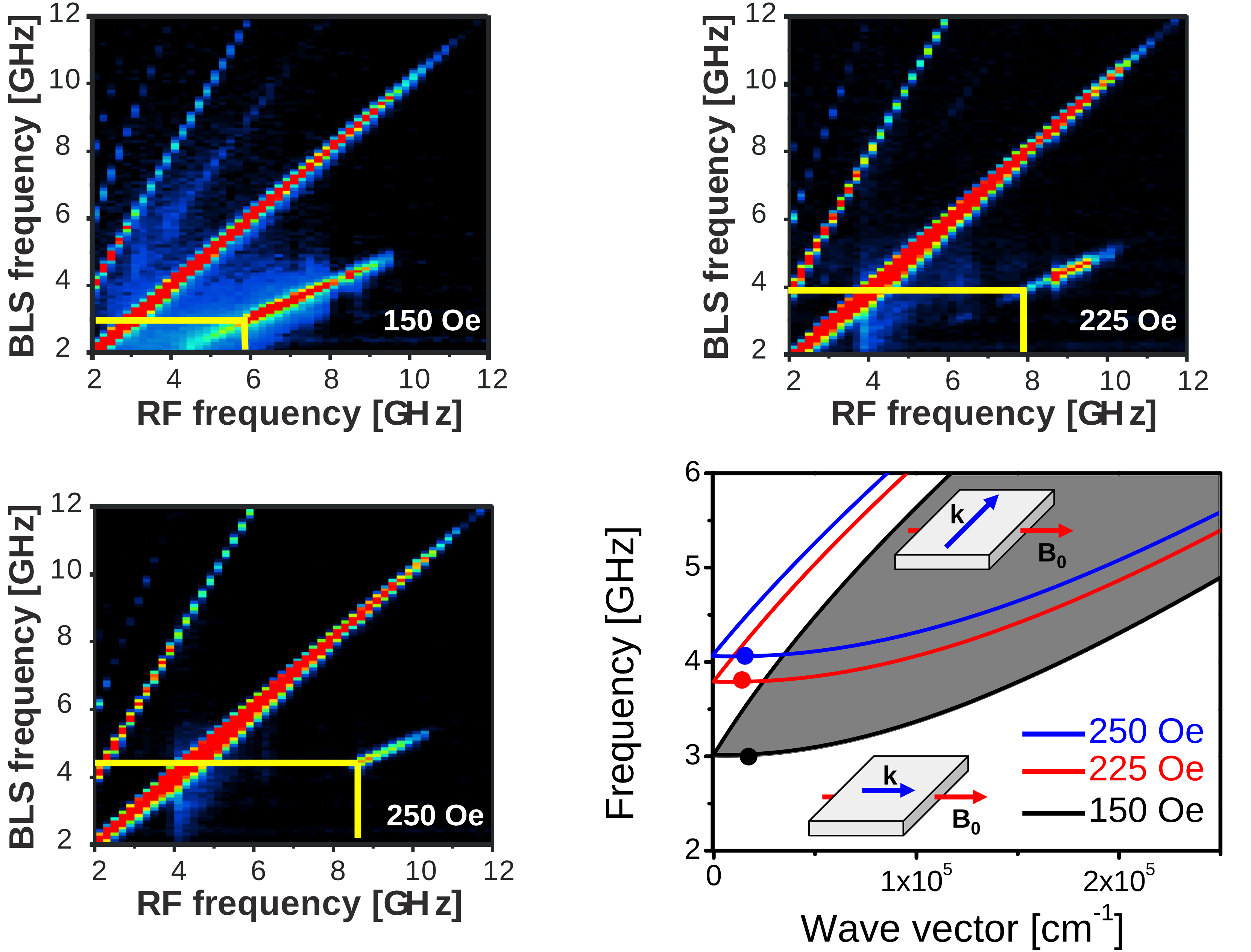
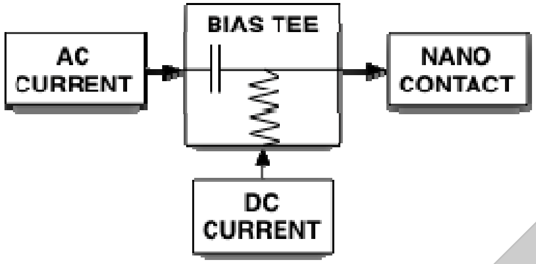
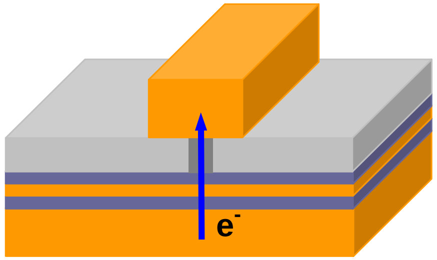
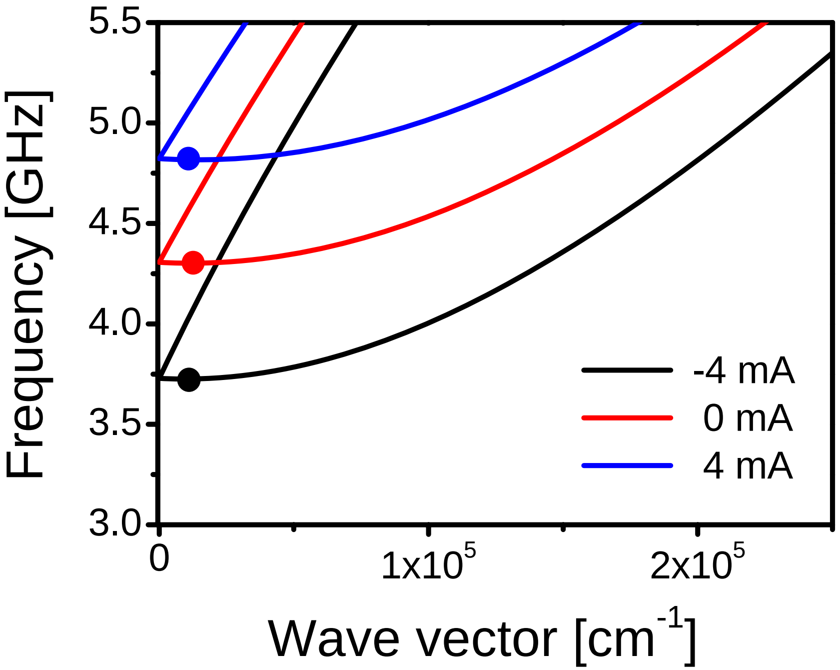
Field-dependent excitation spectra

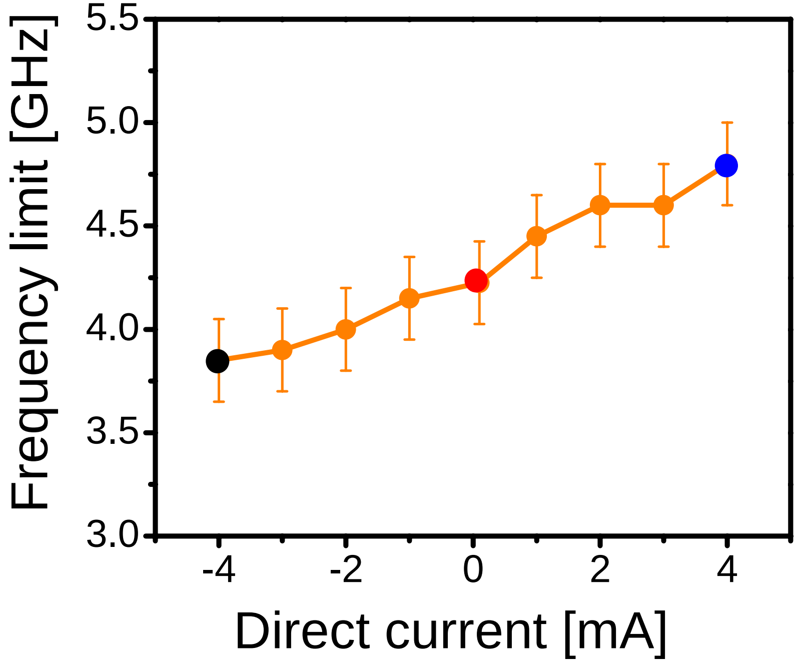


Splitting process – threshold frequency





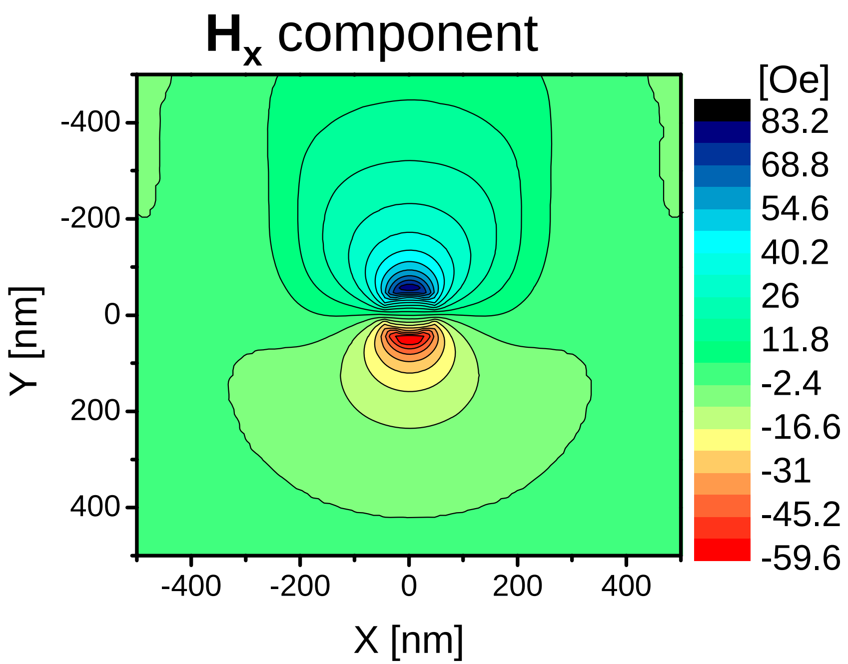


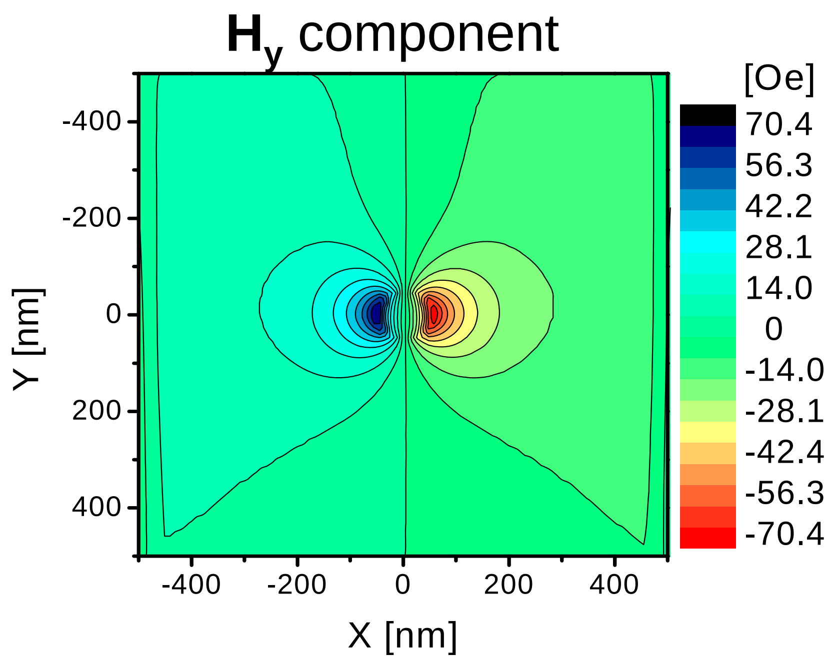


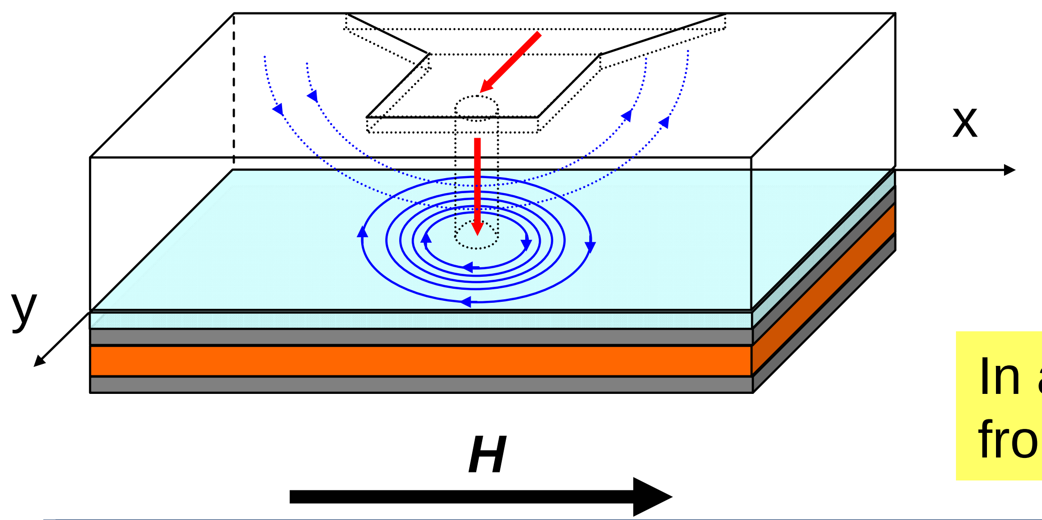
$$H_{total} = H_{external} + H_{Oe}$$

Oersted field contribution of 16 Oe/mA to the internal field

Origin of the Oersted field contribution



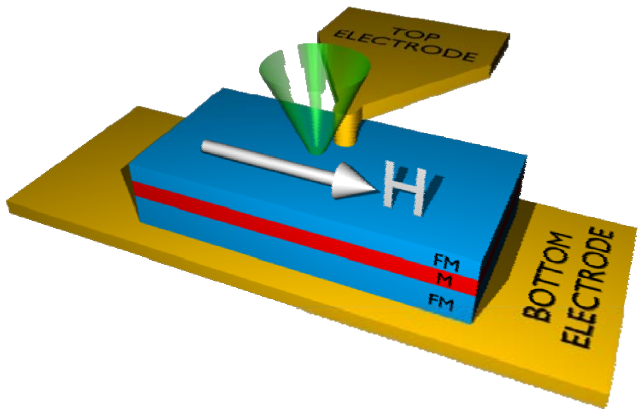


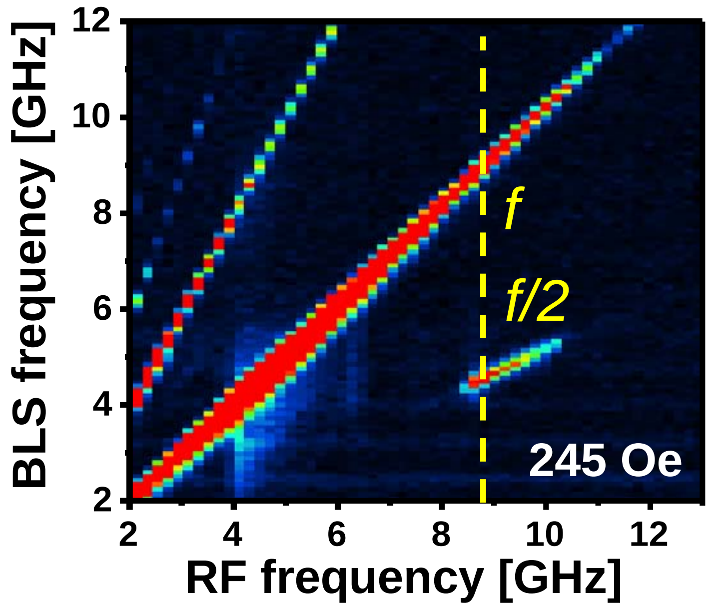


- Asymmetry for the component parallel to the applied field
- Contribution of top electrode to the free layer is ~ 13 Oe/mA

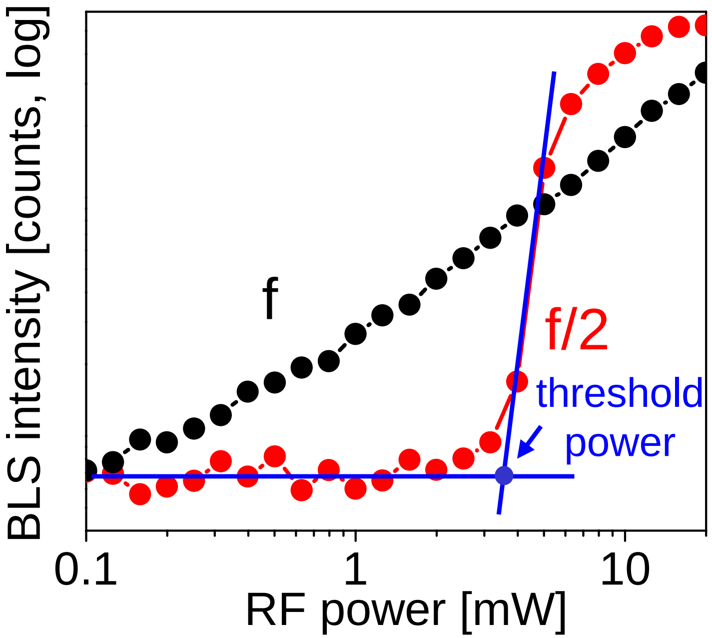
In agreement with experimental findings from *f* /2 mode frequency limit (~16 Oe/mA)

Splitting process – threshold power





RF Frequency = 8.9 GHz; H = 245 Oe



- The resonance mode increases linearly with the applied RF-power
- The *f*/2 mode shows clearly threshold behaviour

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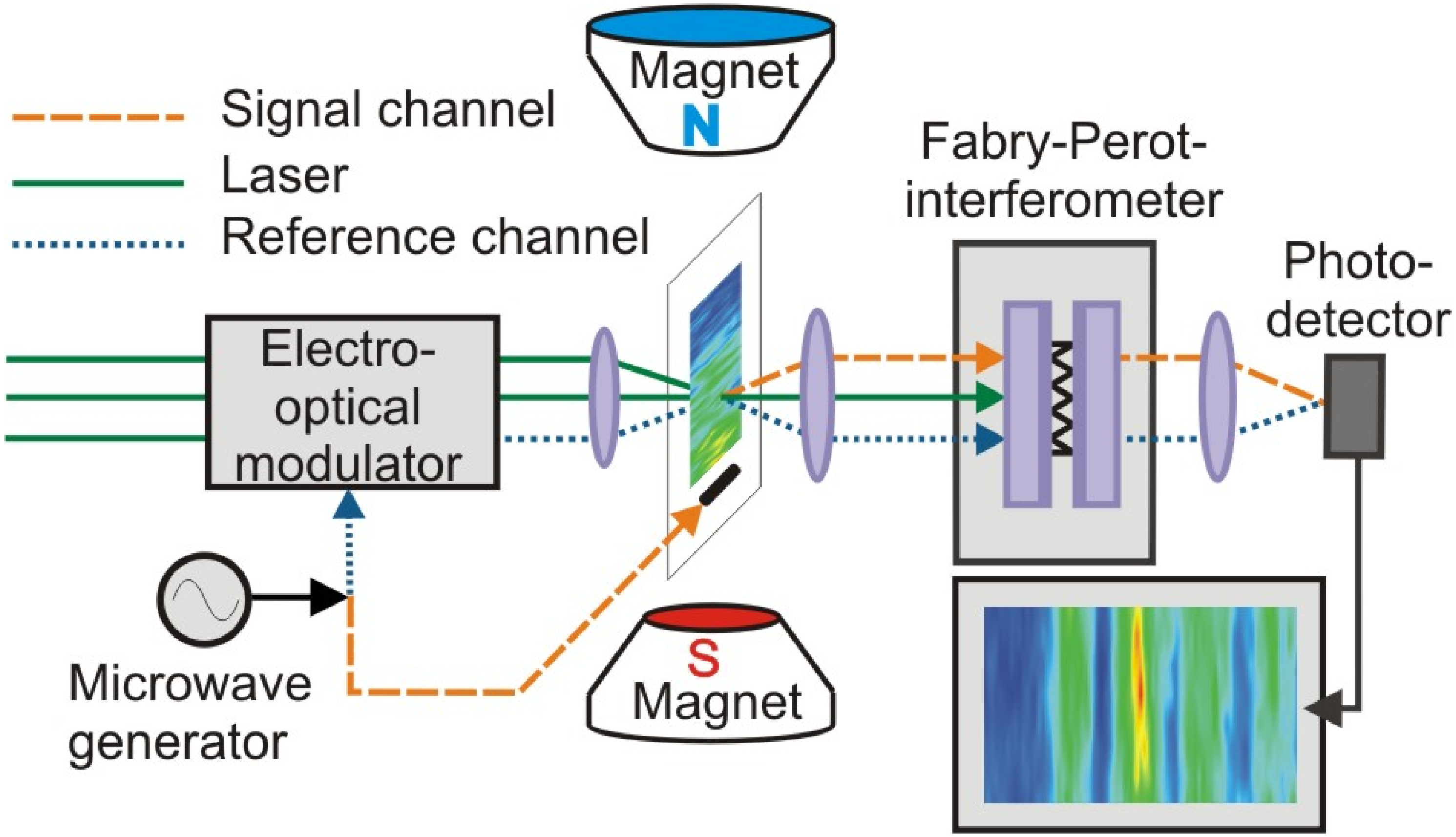
Summary

Phase-resolved BLS

Inelastically scattered light contains phase information

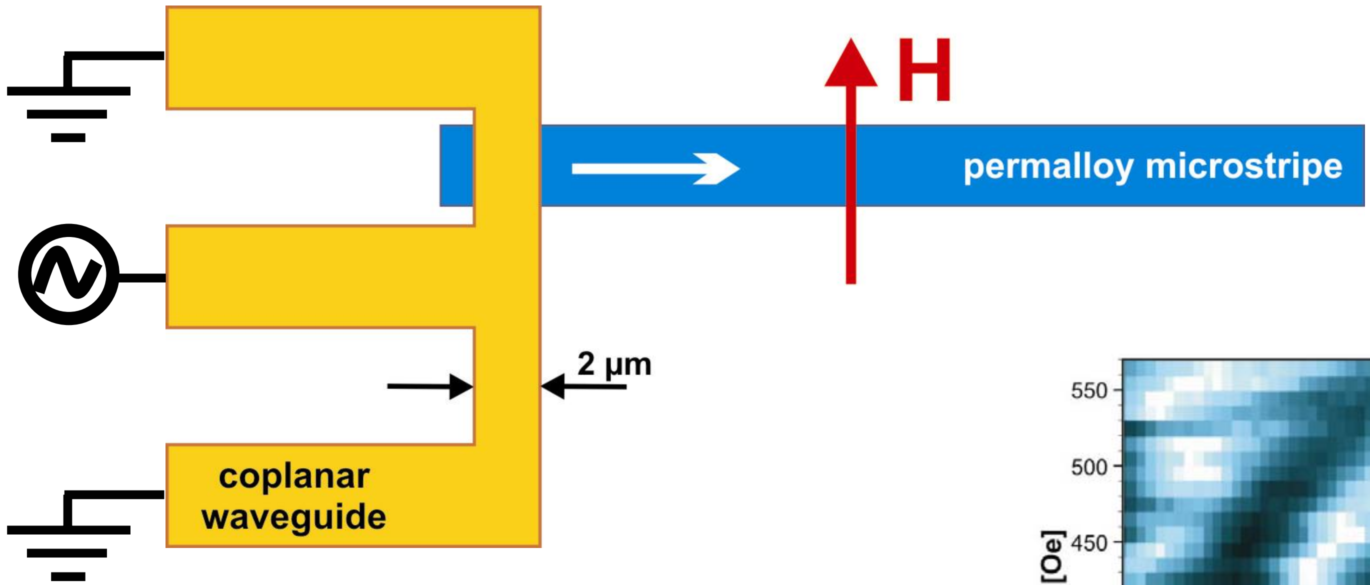
Interference between
sample beam and reference beam



A. A. Serga et al., APL **89**, 063506 (2006)

Phase-resolved BLS microscopy

Phase-resolved detection of propagating spin waves in small Py microstripe

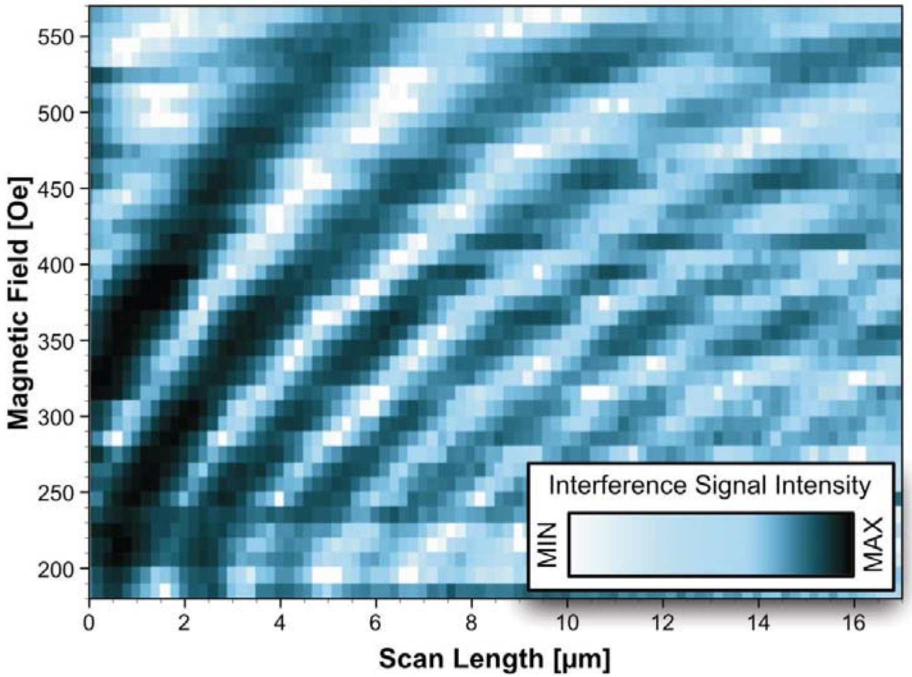


Permalloy stripe:

width: 2.5 µm
length: ~ 100 µm
thickness: 40 nm

Interference picture:

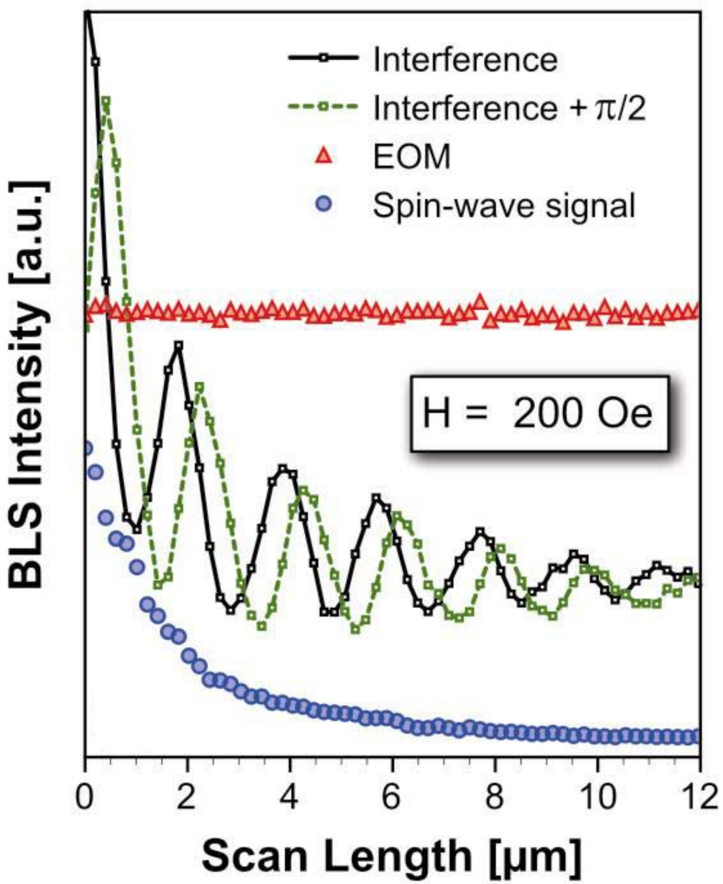
- proof of propagating spin-wave nature
- information on spin-wave wavelength

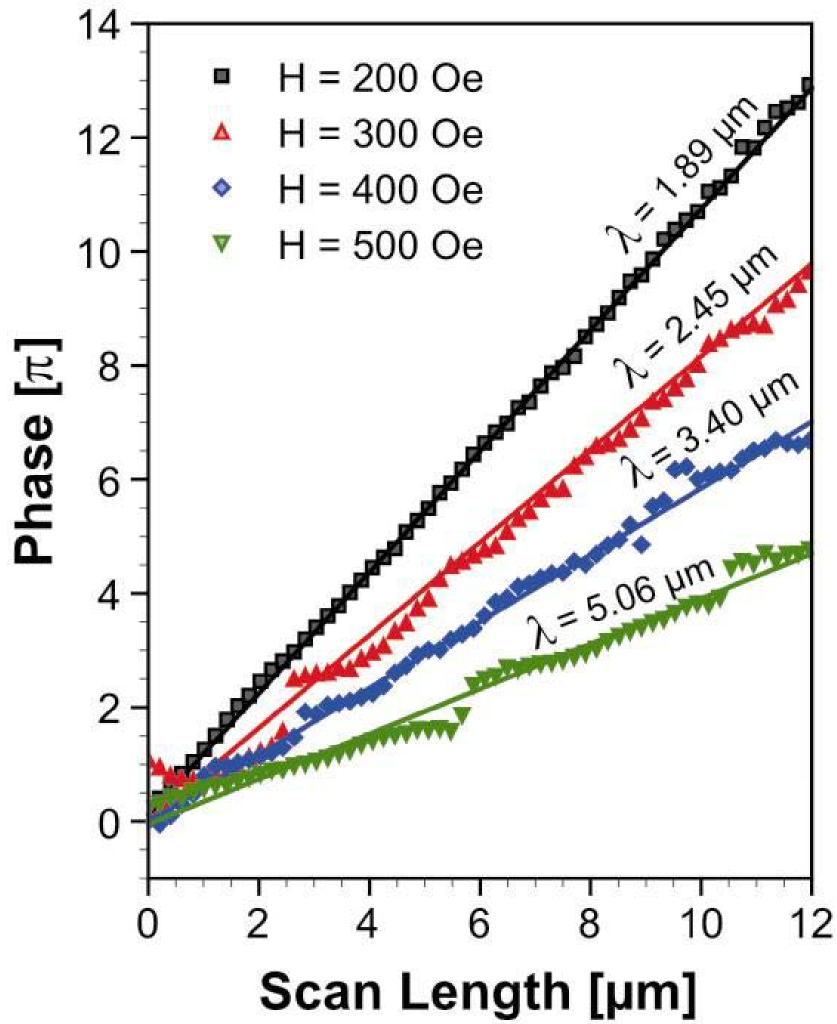


Phase profile of spin waves

Spin-wave phase profile:

- four measurements required [1]
- slope yields spin-wave wavelength

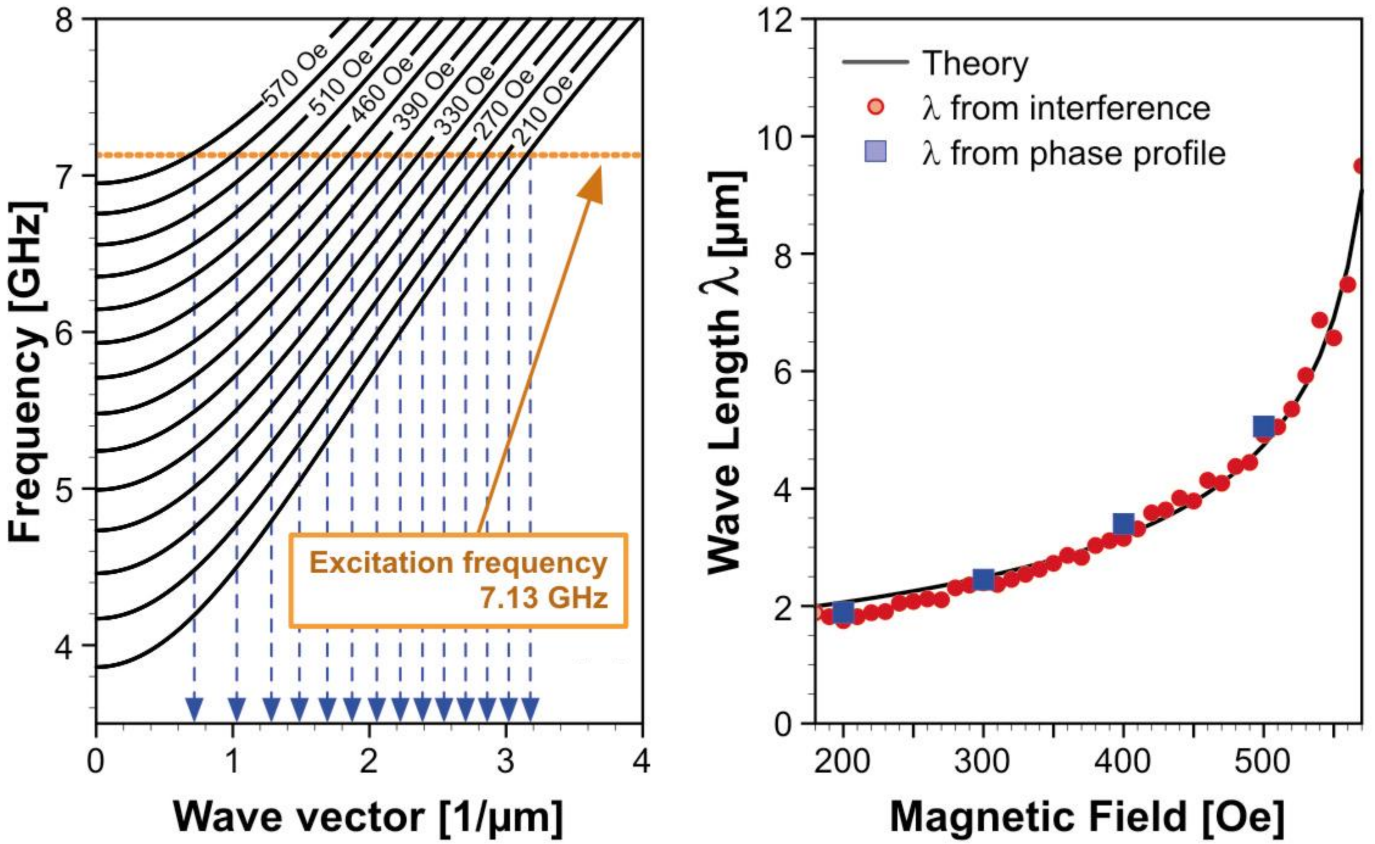




[1] A. A. Serga et al., APL **89**, 063506 (2006)

Propagating spin waves

Comparison with theory yields perfect agreement:



Material parameters:

M_S = 860 G

γ = 0.0176 GHz/Oe

A = 1.6 · 10^{-6} erg/cm

Phase-resolved BLS microscopy is a powerful tool
for the detection of propagating spin waves

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nano-magnonics:
spin dynamics on the nano-scale