Spin waves in magnetic rings:

linear and nonlinear properties, non-local damping

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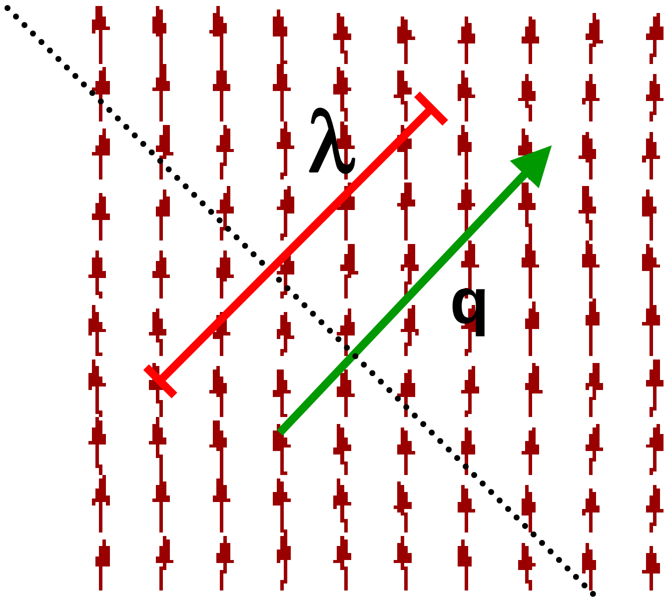
SPINSWITCH workshop on spin momentum transfer
Kraków, Poland, 3-5 September 2008

Coherent dynamics: spin waves

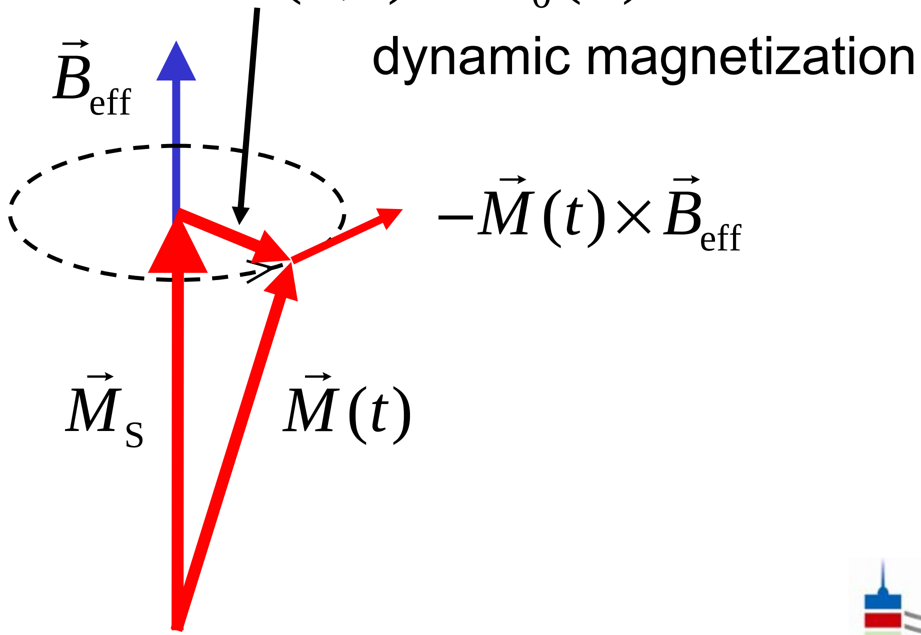


Landau-Lifshitz torque equation

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

Is intrinsically nonlinear equation !

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



Content

BACKGROUND

- linear: spin waves in small magnetic stripe with domain wall
- linear: spin waves in rings - partial coherence effects
- damping properties of spin waves
- nonlinear: mode coupling of spin waves in rings

OUTLOOK & SUMMARY

Coworkers

S. Hermsdörfer, B. Leven, B. Obry, C. Sandweg, S. Schäfer, H. Schultheiss	TU Kaiserslautern
A.N. Slavin	Dept. of Physics, Oakland University, Rochester, Michigan
J. Chapman	University of Glasgow

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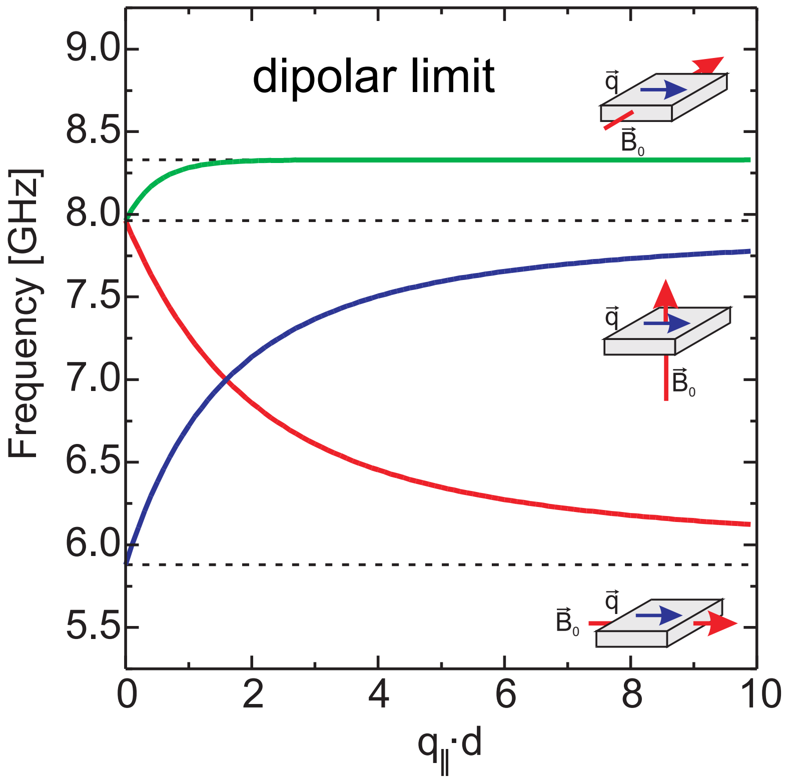
Spin waves

Two types of energy contributions

- exchange energy:
  - generated by twist of neighbored spins
- dipolar energy:
  - generated by magnetic poles in long-wavelength spin waves

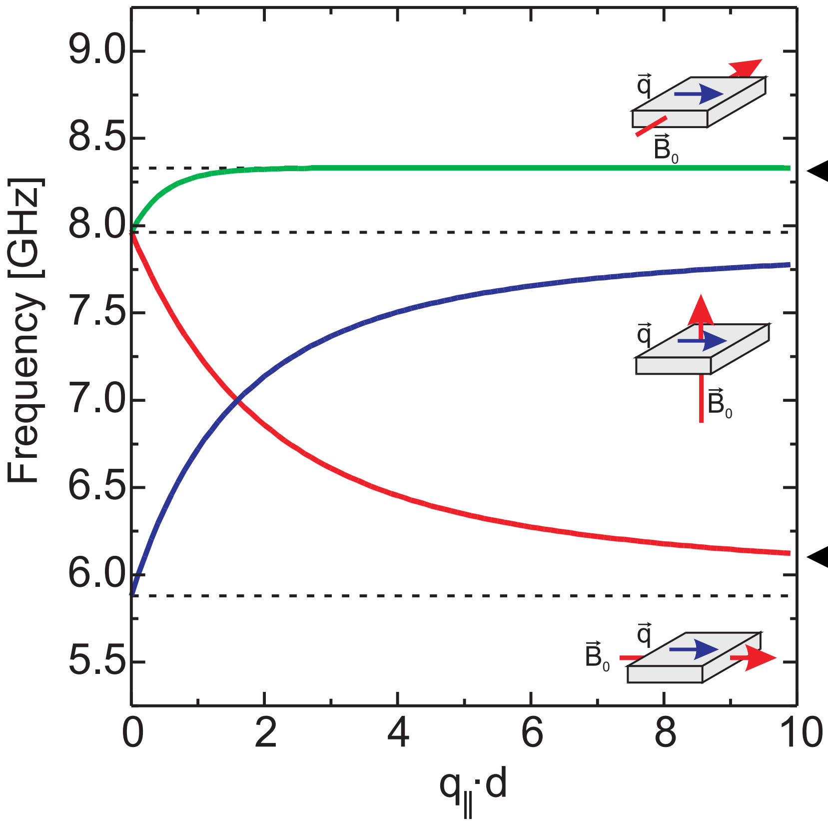


magnetostatic surface wave (MSSW)

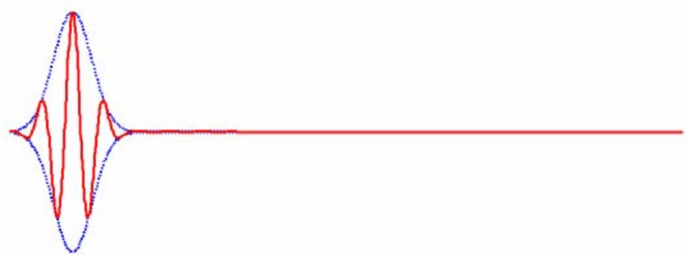
magnetostatic forward volume wave (MSFVW)

magnetostatic backward volume wave (MSBVW)

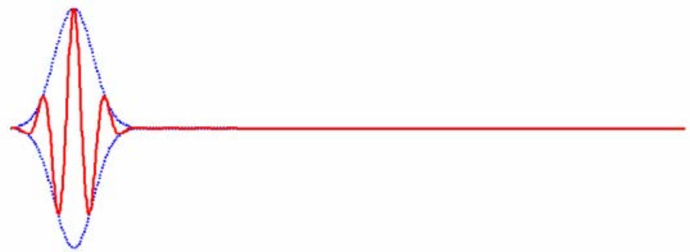
Dipolar spin waves: pulse propagation



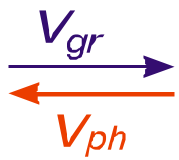
electromagnetic wave in vacuum ($v_{gr} = v_{ph}$)



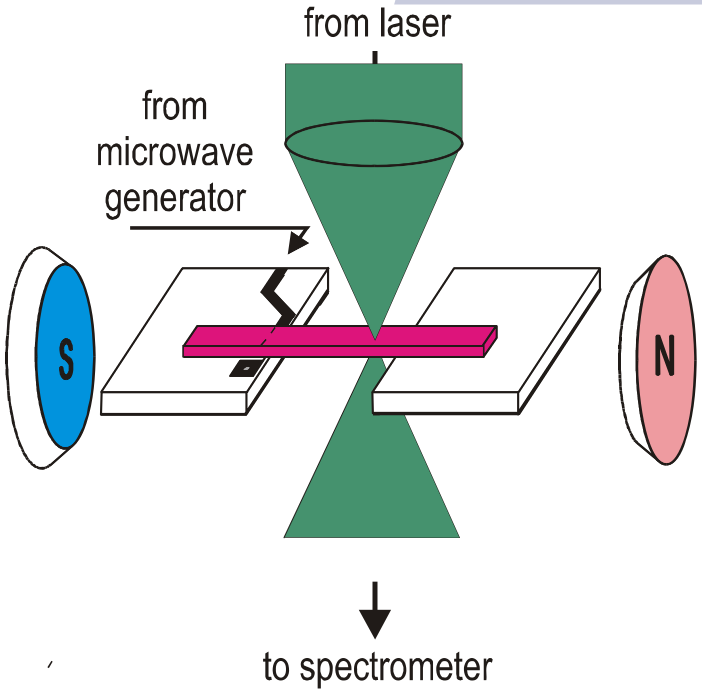
magnetostatic surface wave ($v_{gr} < v_{ph}$)

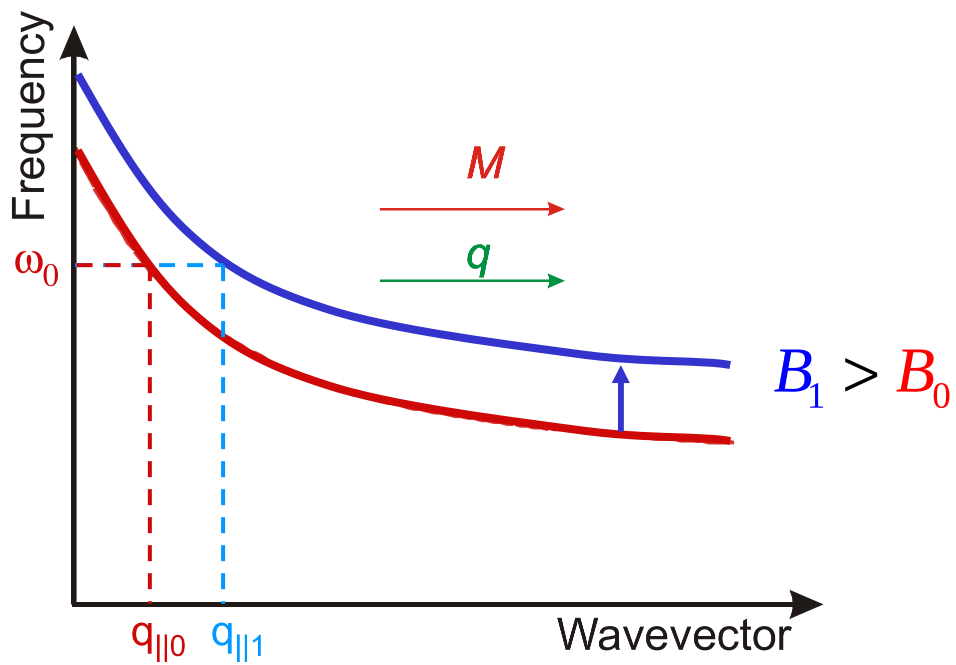


magnetostatic backward volume wave ($v_{ph} < 0$)



Spin wave propagation



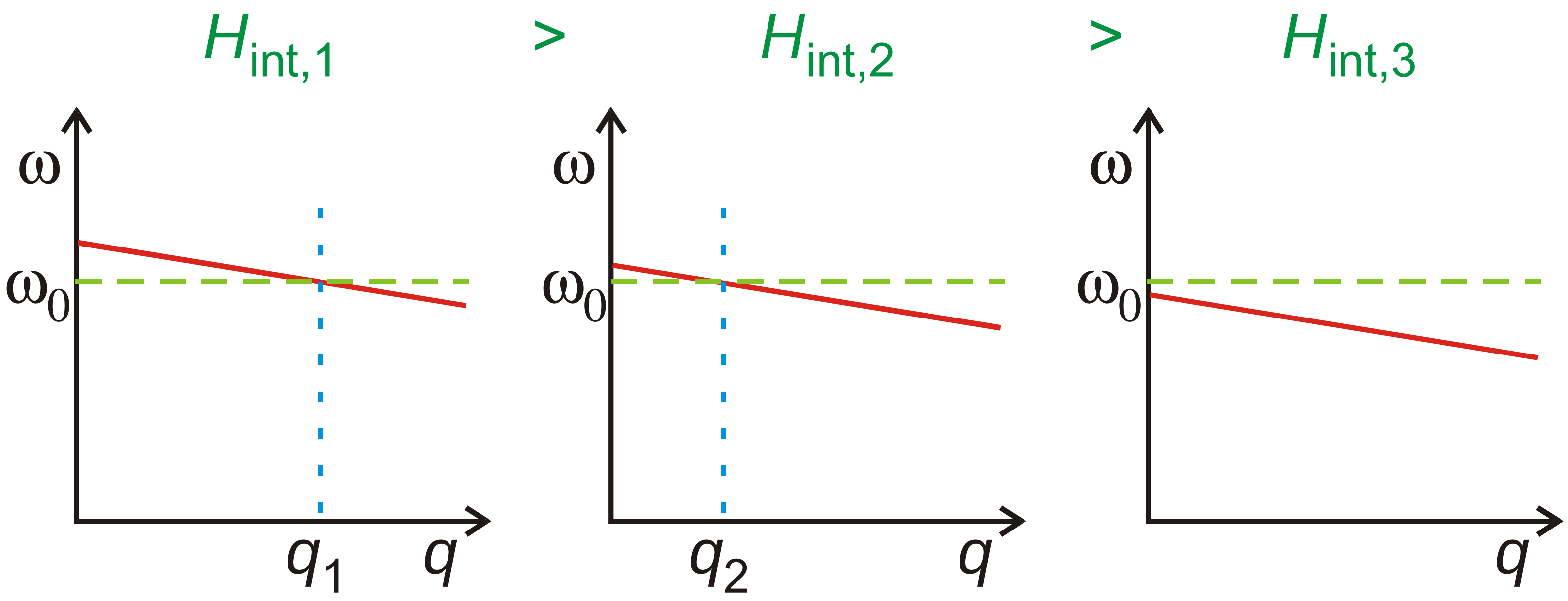


Wavevector **q**:

$q_{parallel}$ defined by input frequency and dispersion

Dispersion shifted vertically by change in magnetic field

Motion of a spin wave packet in varying field

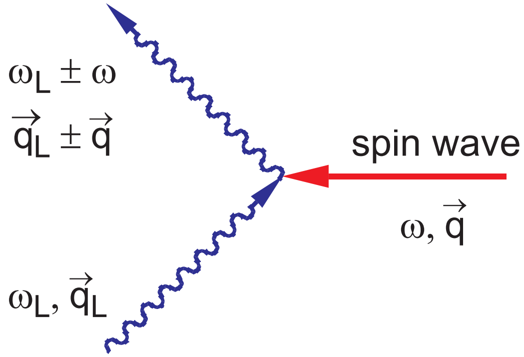


propagation **propagation (q_2<q_1)** **reflection**

Brillouin light scattering (BLS) process

= inelastic scattering of photons from spin waves

scattered photon

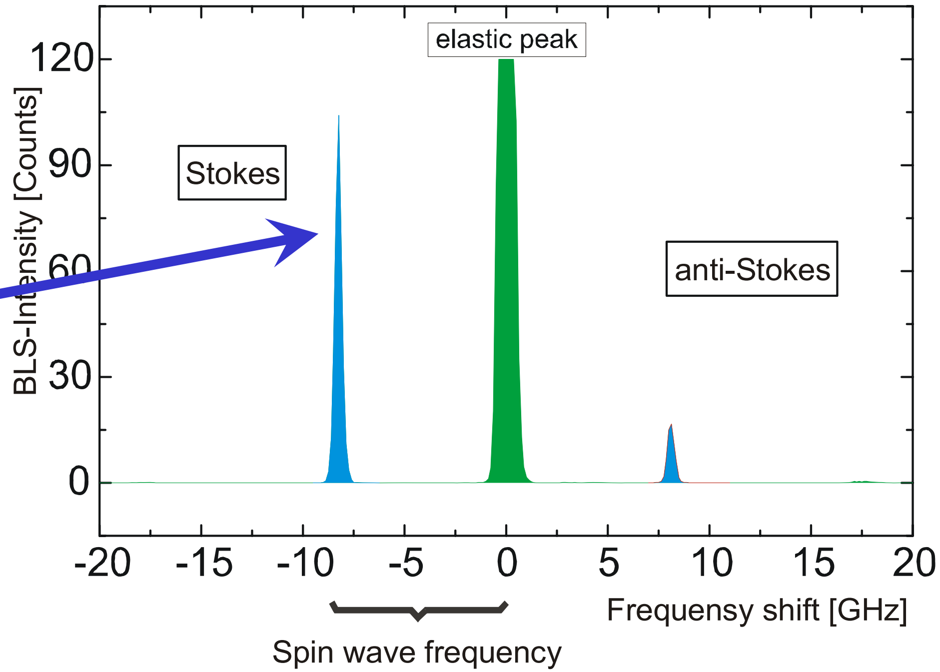


incident photon

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

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

spectrum of scattered light



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

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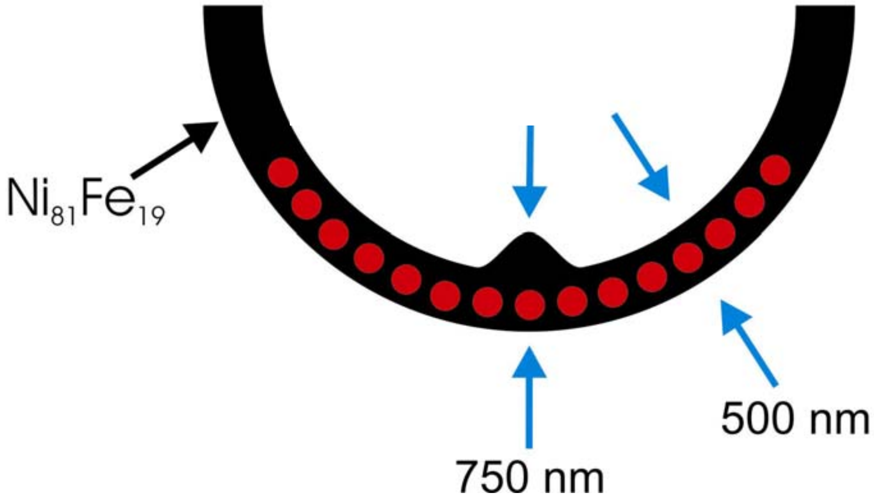
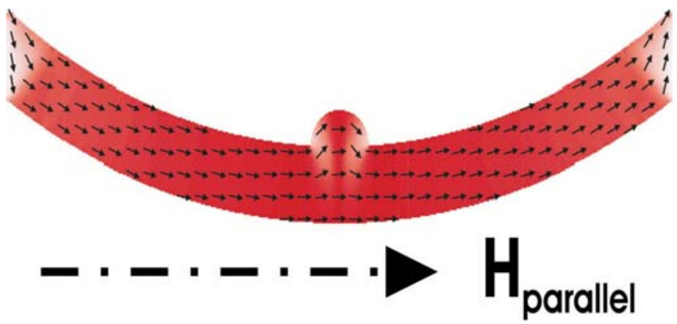
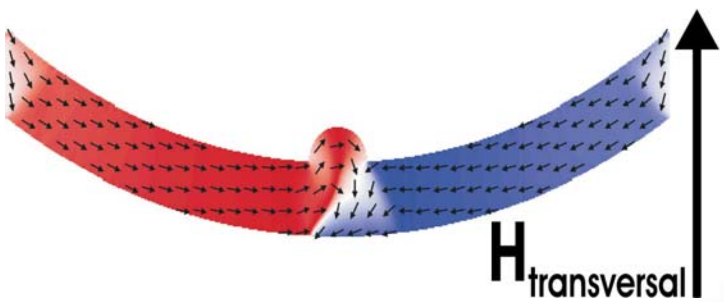
$Ni_{81}Fe_{19}$ nanostripes



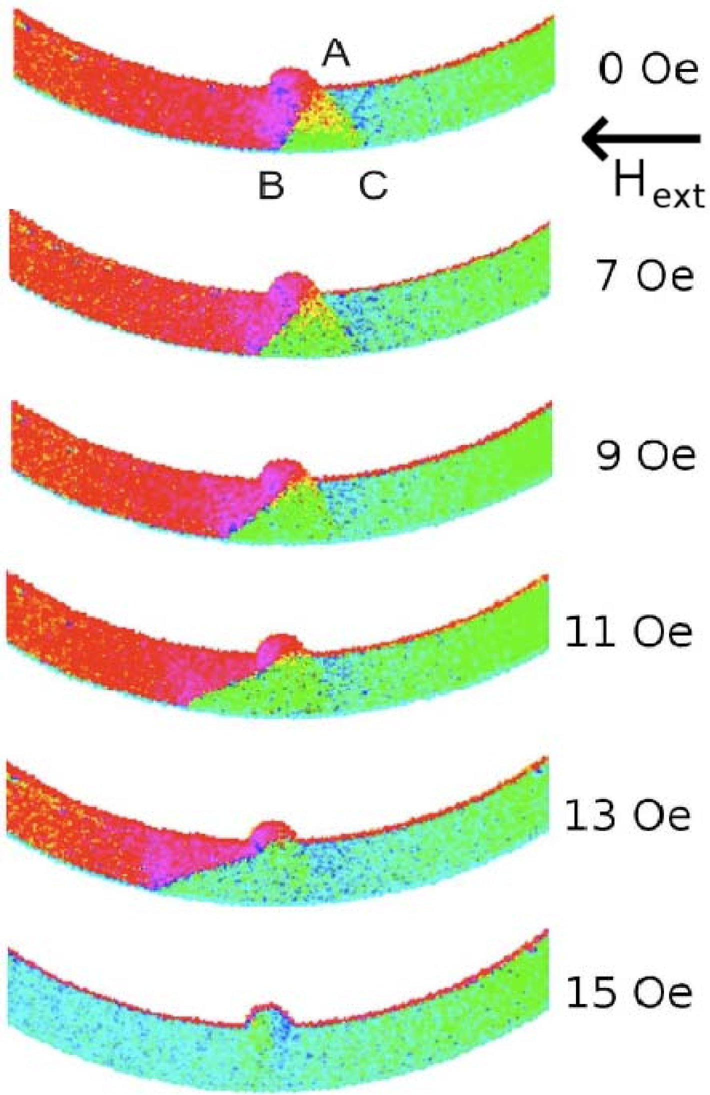
- Nucleation of a domain at protuberance applying a field sequence
- Observation of thermal spin waves
- Experiment: BLS spectra measured along a line indicated by the red dots, focus diameter 250 nm

OOMMF simulations:

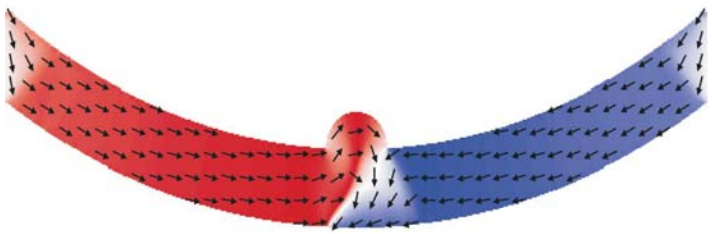




Lorenz microscopy

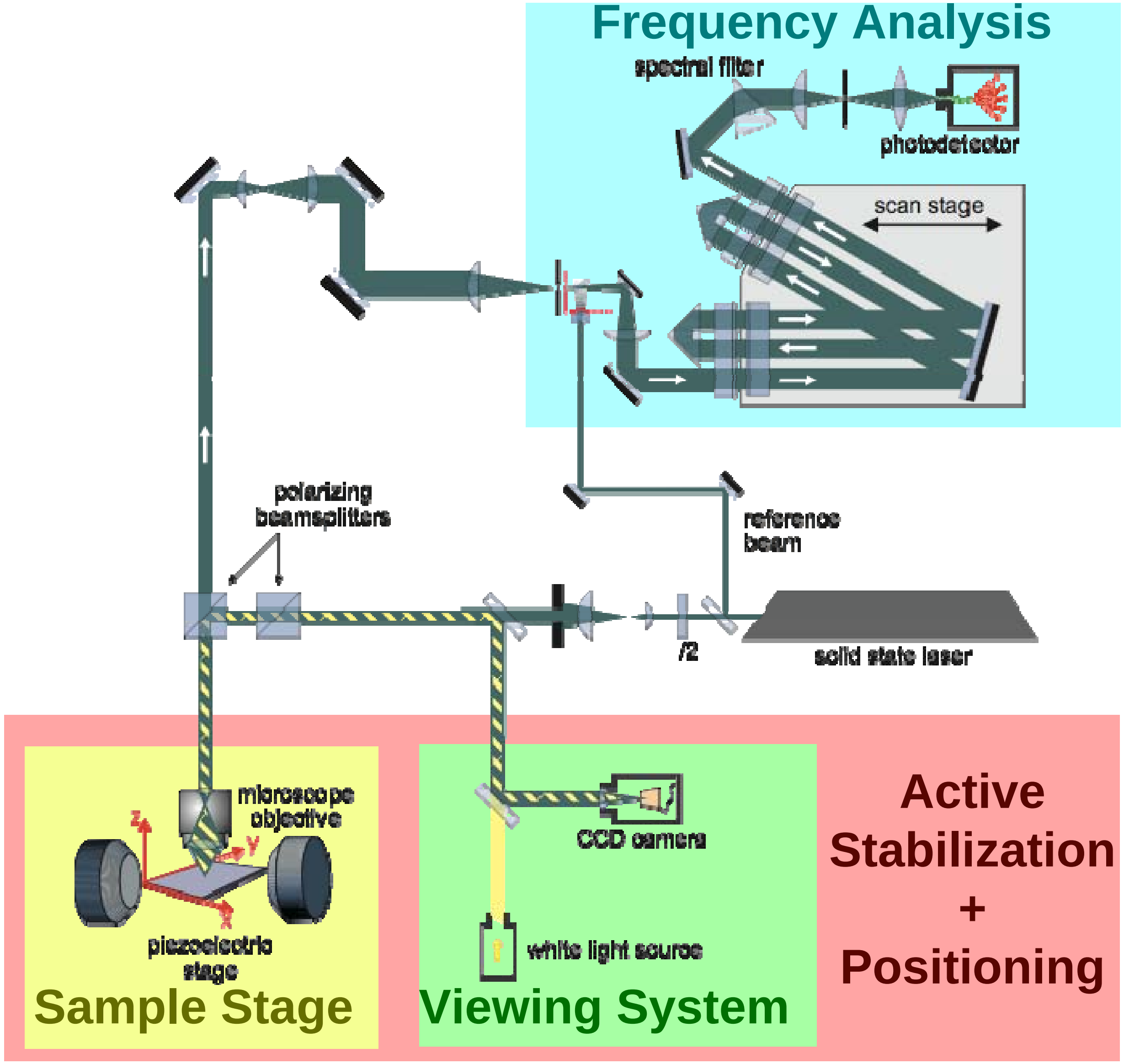


Comparison to OOMMF simulation:



in cooperation with
J. Chapman group, Glasgow

Technique: BLS Microscopy



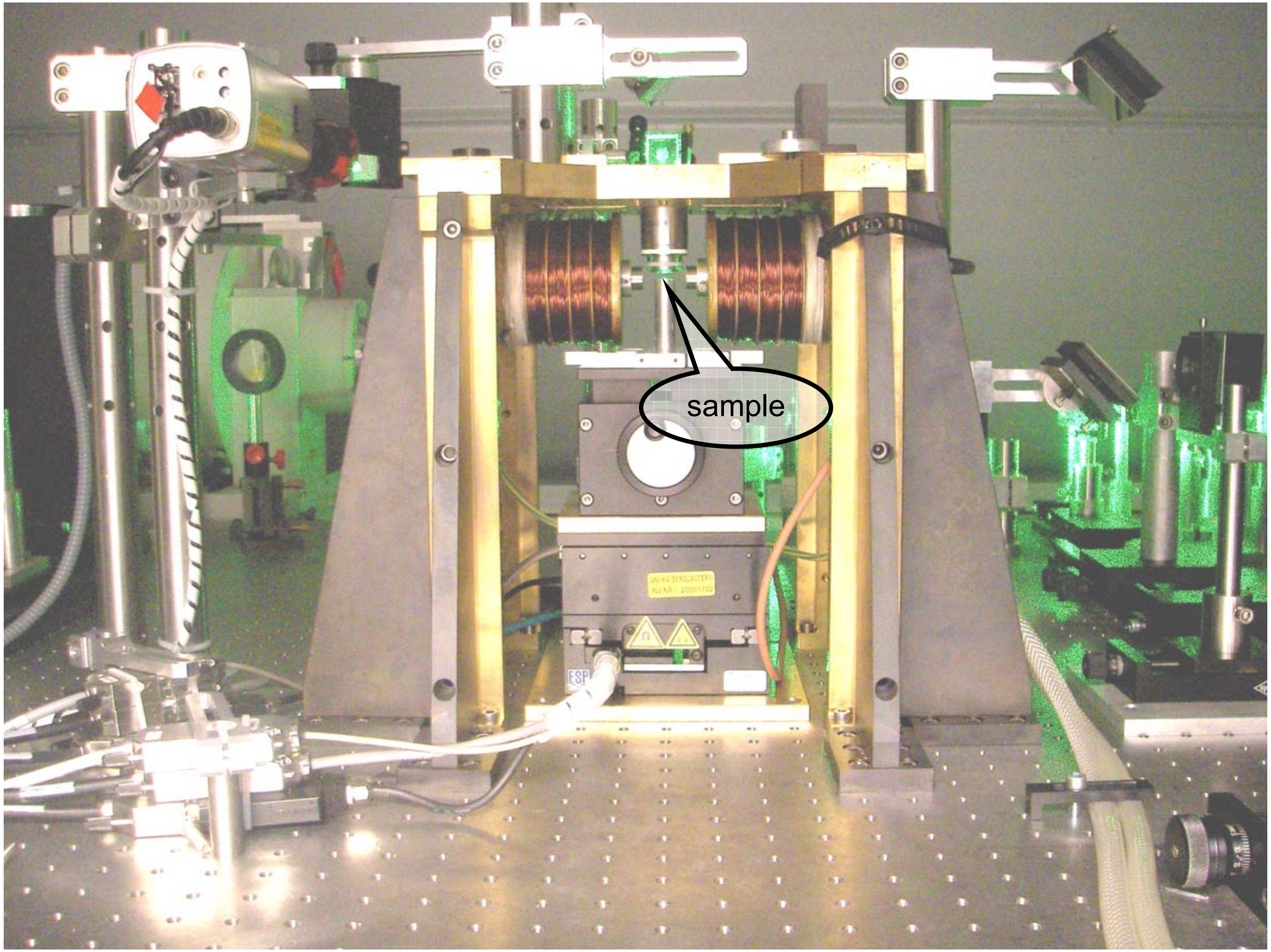
- optical resolution: 250nm
- 2D piezo stage

- controlling sample while measuring

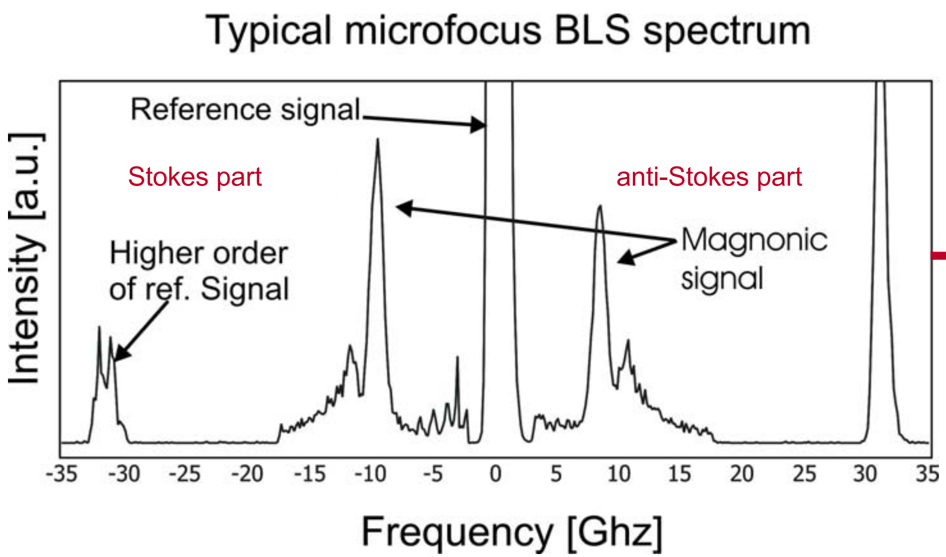
- frequency range: 1GHz – 1THz
- spectral resolution: 200MHz

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

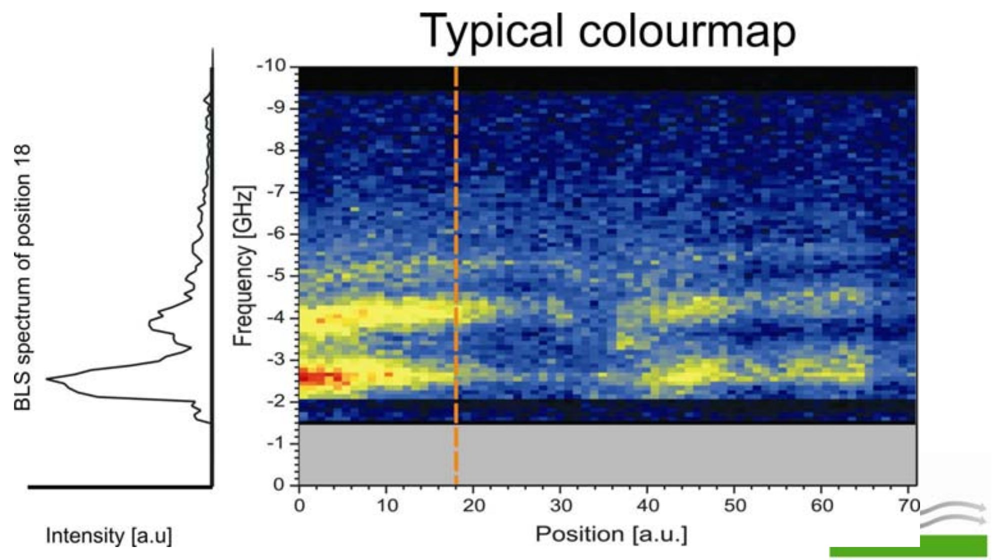
BLS Microscopy - experimental setup



Measurement procedure



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

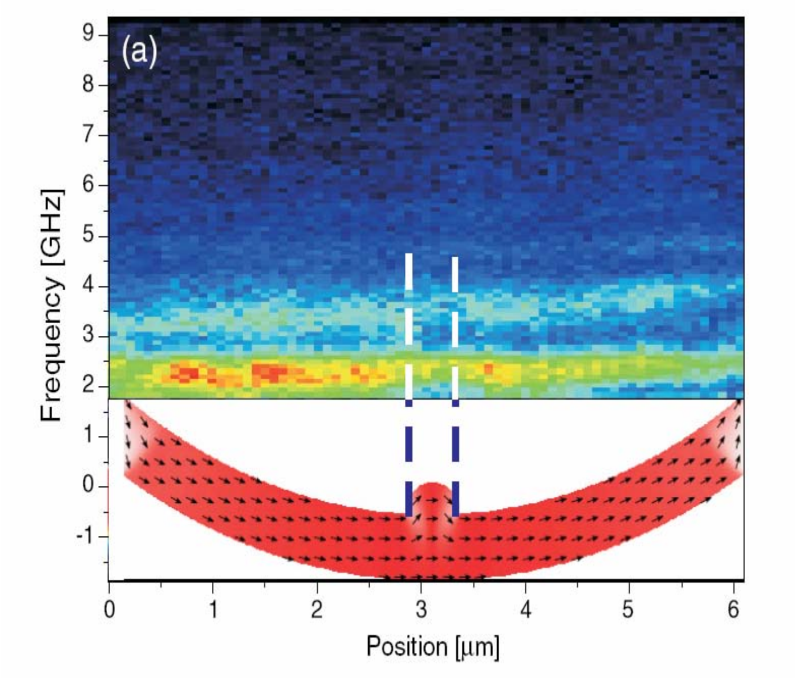


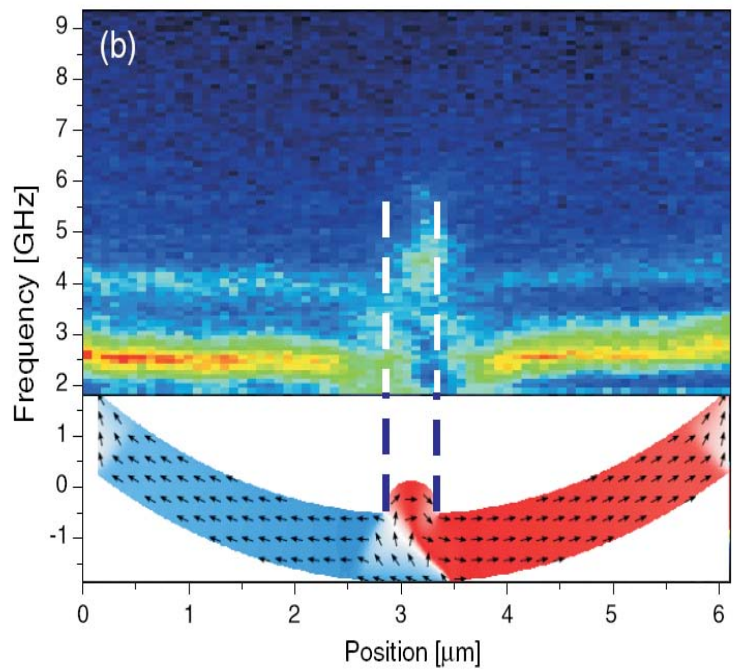
$Ni_{81}Fe_{19}$ nanostripes: thermal spectrum

Thermal spin wave spectrum…

…without domain wall

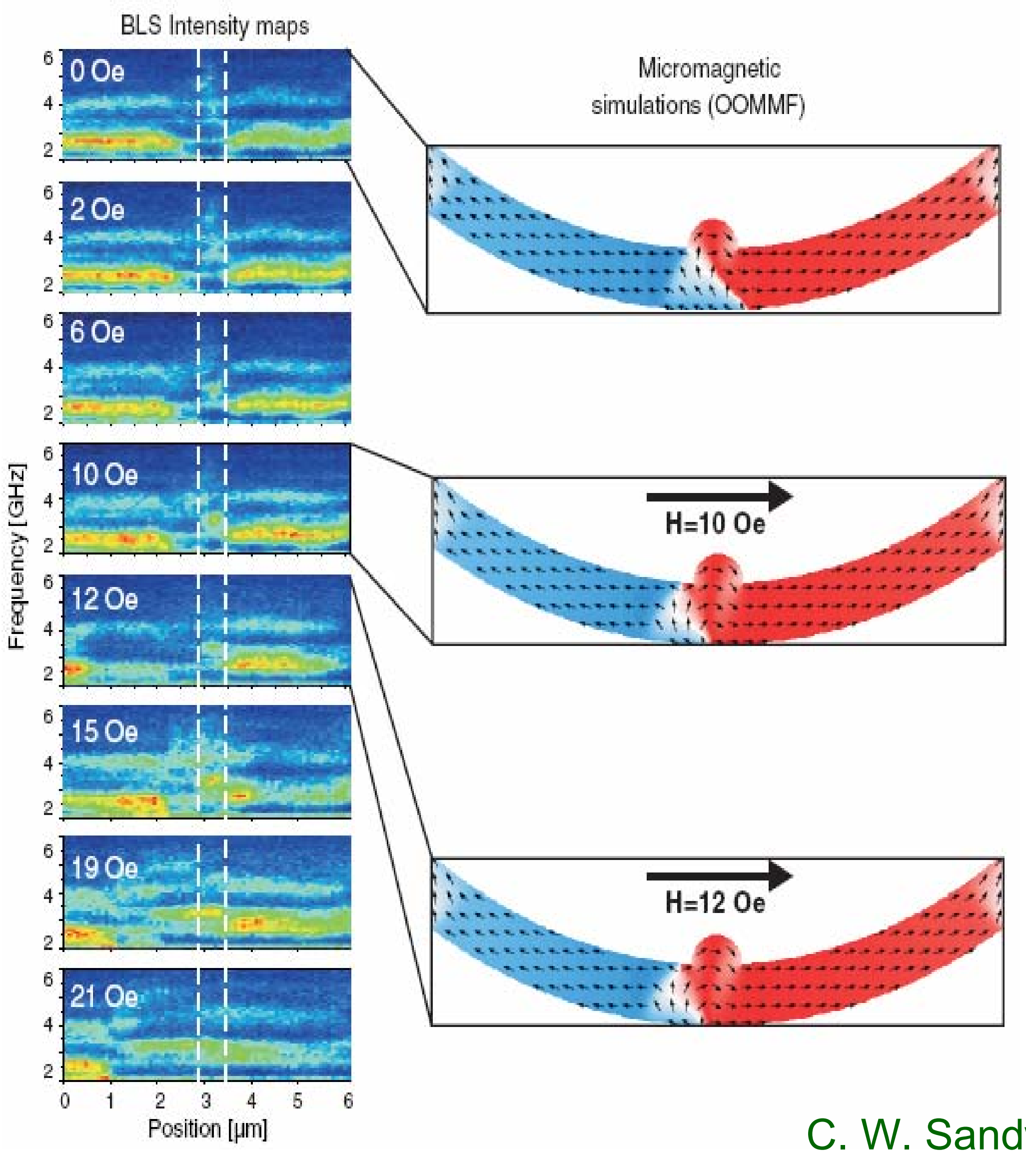
…with domain wall at protuberance





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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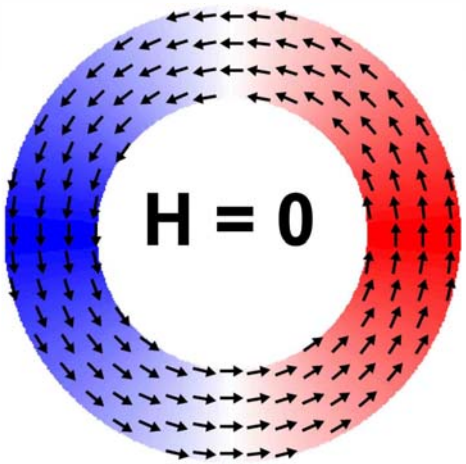
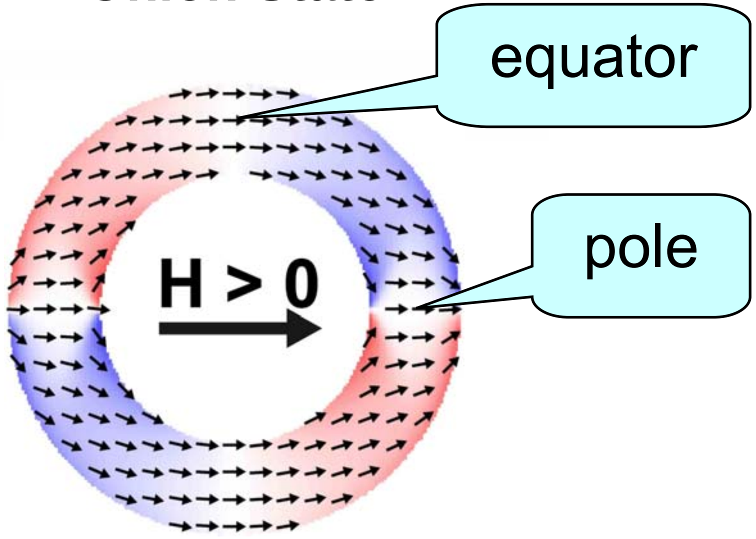
Magnetization configurations in ring

Vortex State



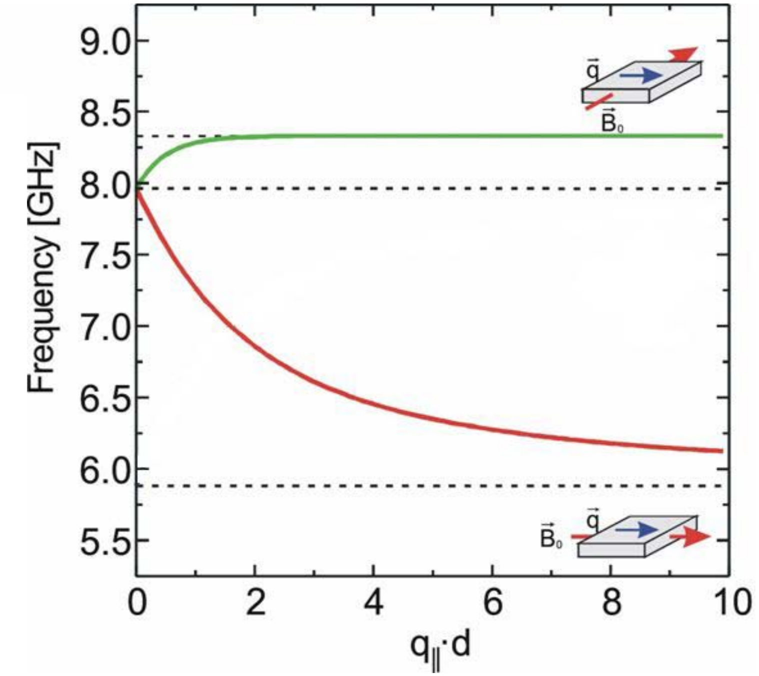
- rotational symmetry
- flux closure state
- no dipolar stray fields

Onion State

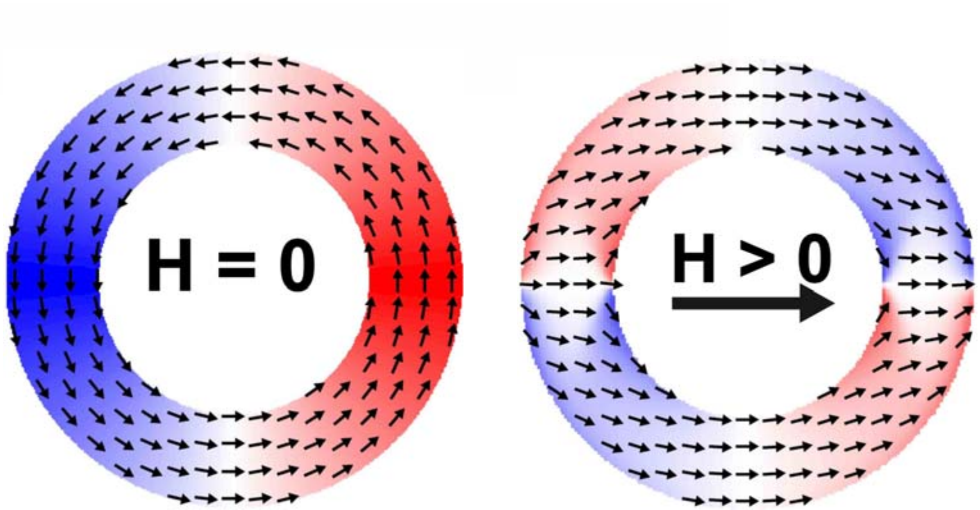


- broken symmetry
- effective surface charges at the poles
- strongly inhomogeneous internal field distribution

Magnetization configurations in ring



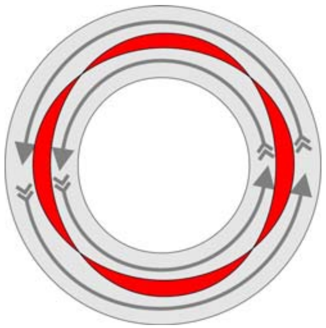
Vortex State **Onion State**



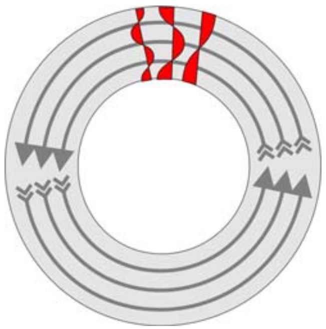
For spin wave propagation important:

- relative direction of wavevector and local field

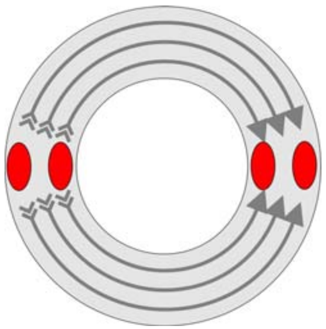
Spin wave quantization effects



- longitudinal/azimuthal quantization
- long wavelength
- **negative** frequency dispersion
  (local wavevector parallel to internal field)



- axial/radial quantization
- short wavelength
- **positive** frequency dispersion
  (local wavevector perpendicular to internal field)

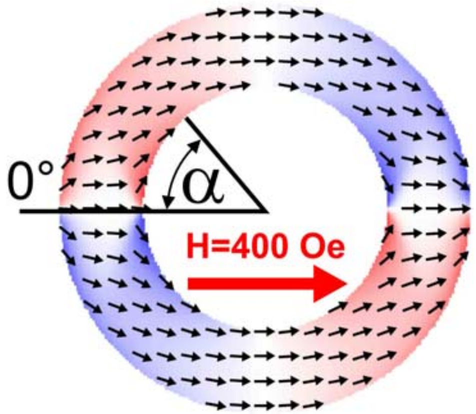


- localization in spin-wave wells or domain walls
- exchange dominated

Onion State: magnetic field distribution

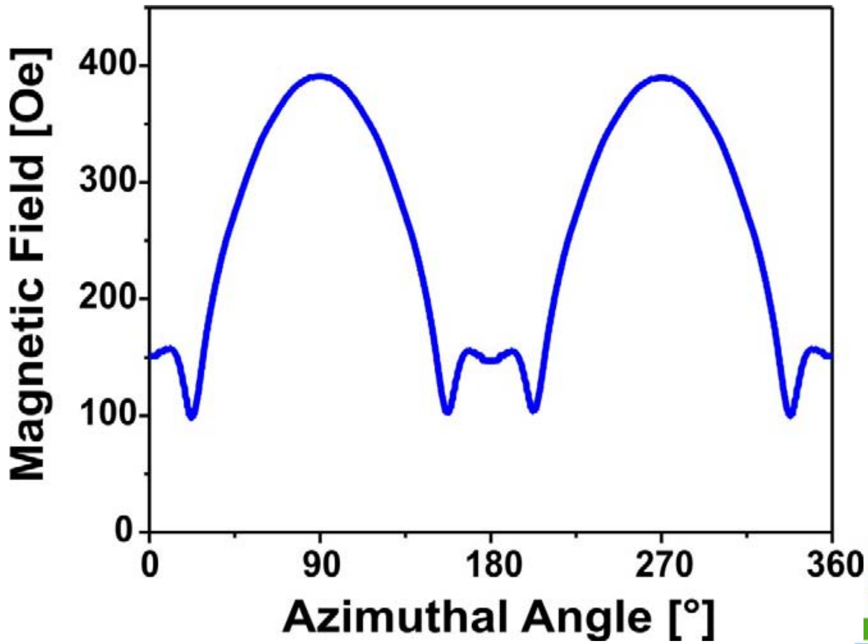
Inhomogeneity and gradient of internal field distribution can be controlled by

- geometry (diameter, width)
- external applied field



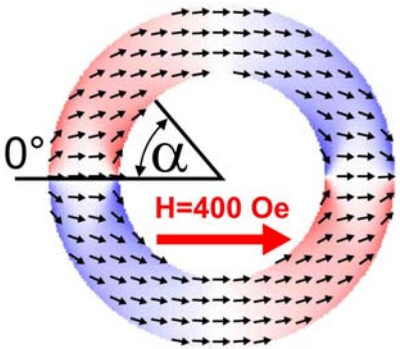
Calculated distribution of the internal field (OOMMF)

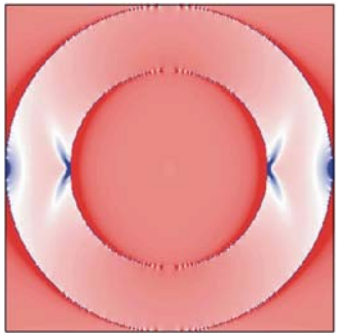
- $Ni_{81}Fe_{19}$ 15 nm
- diameter = 2 μm
- width = 400 nm
- H_{ext} = 400 Oe

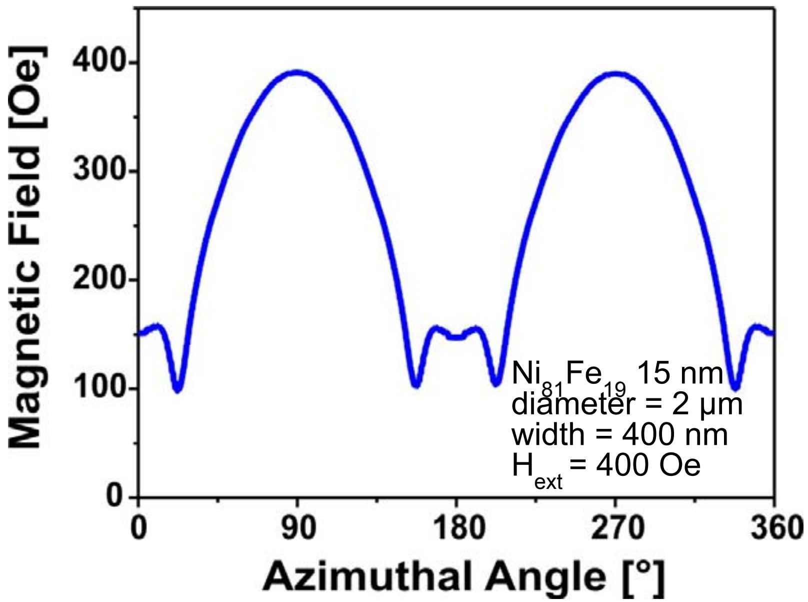


Dynamics in the onion state

OOMMF







Fully coherent spin-wave eigenmode:

- frequency must be identical across structure

$$\nu_0(k) = \frac{\gamma}{2\pi}\sqrt{\left(H+\lambda_{ex}k^2\right)\left(H+\lambda_{ex}k^2+4\pi M_S F_{00}\left(k_\parallel d\right)\right)}$$

constant for eigenmodes
changing with position
free parameter

- quantization condition (phase quantization):

$$\Delta\Phi = \int_0^{2\pi} k[H(\alpha),\nu]\, d\alpha = 2n\pi$$

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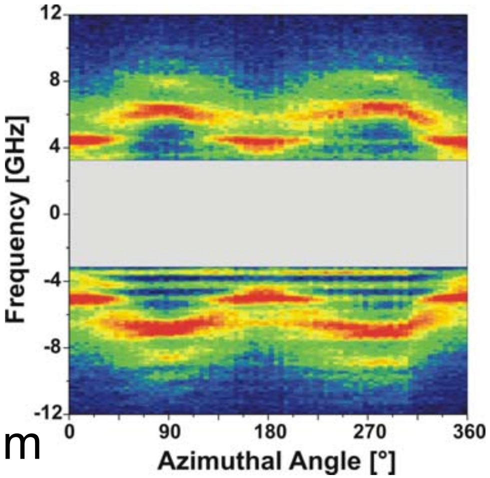
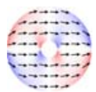
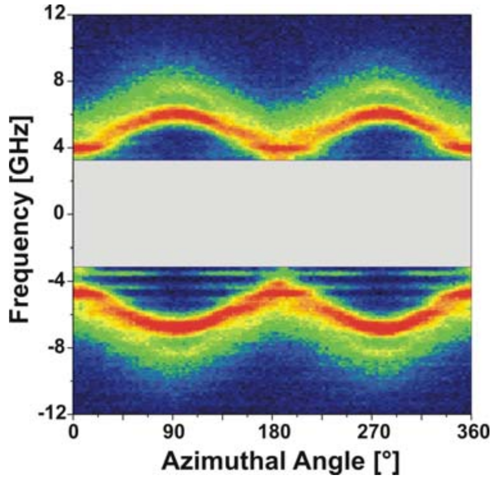
Spin waves in onion state

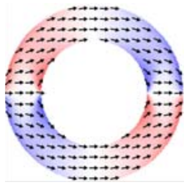
- Plot of spin wave intensity in false color scheme
- Quantization in radial direction maintained
- Loss of coherence when diameter increases



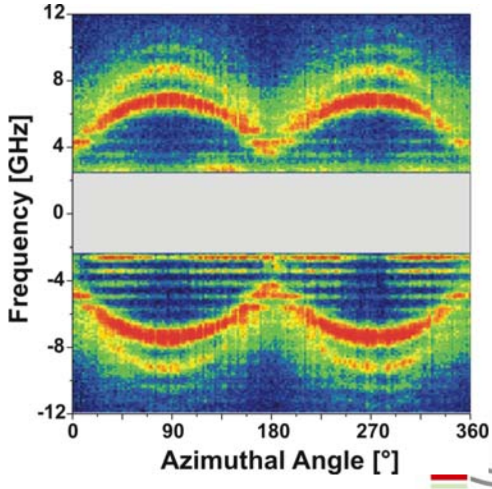


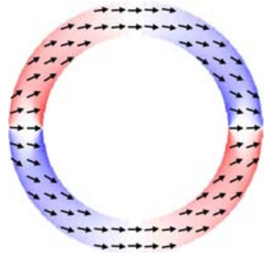
Diameter 1 µm





Diameter 2 µm





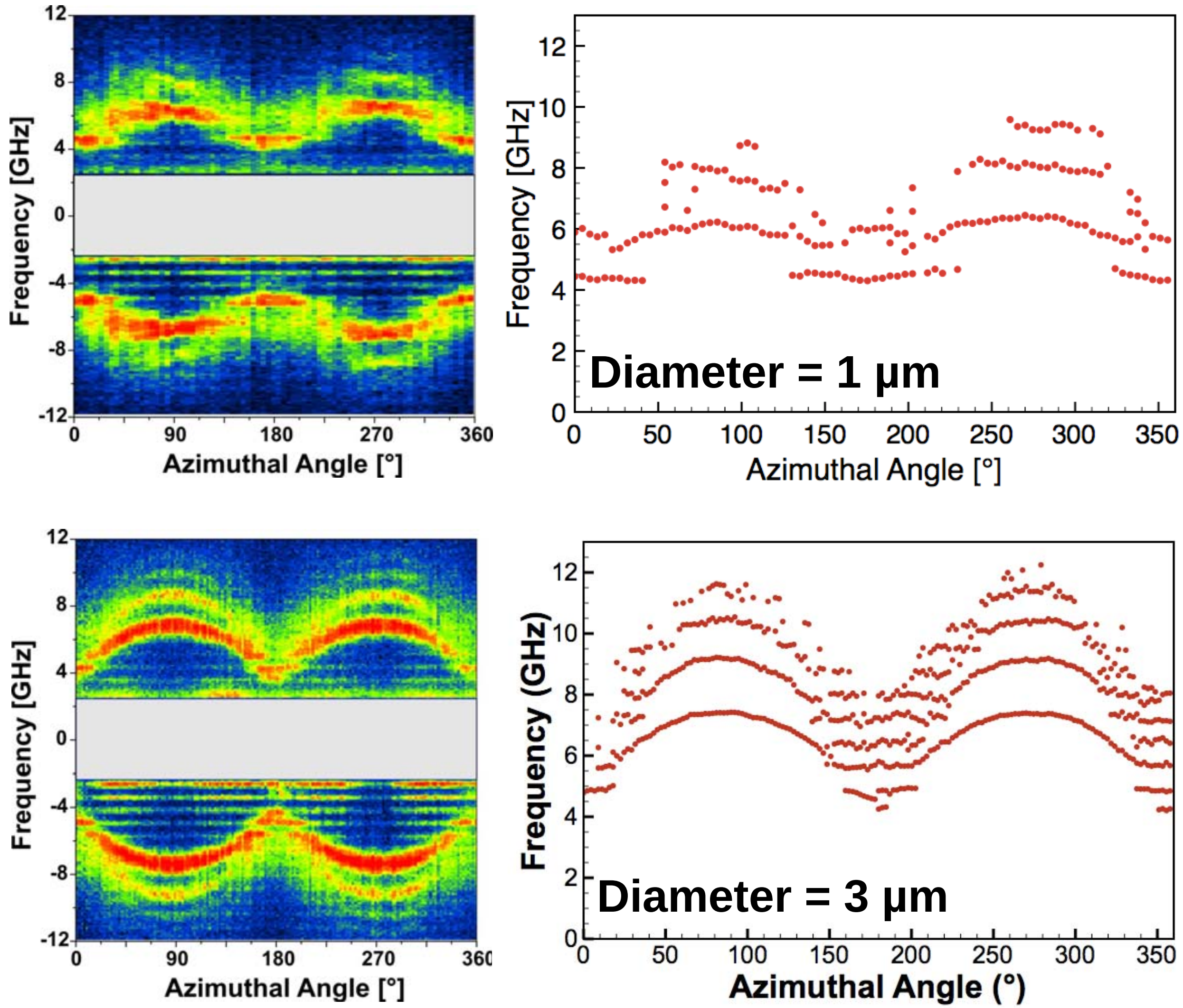
Diameter 3 µm

Width = 400 nm

H_{ext} = 400 Oe

H. Schultheiss et al, PRL **100**, 047204 (2008)

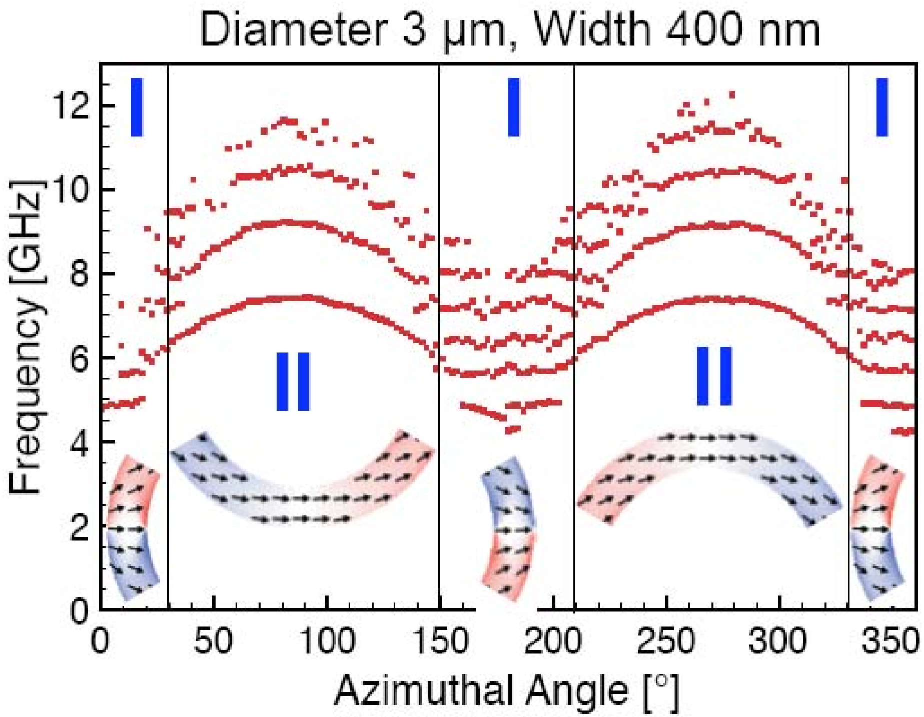
Spin waves in onion state: diameter variation



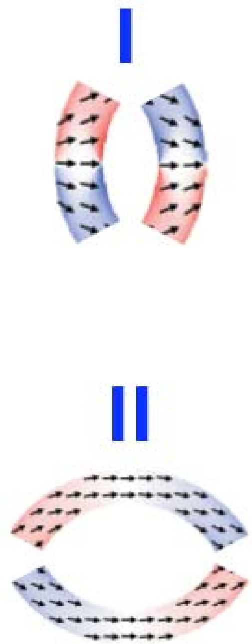
H. Schultheiss et al, PRL **100**, 047204 (2008)

Partial decoherence of spin waves in onion state

2 regions with characteristic behavior of spin-wave frequencies



- narrow region with ***constant frequencies*** in azimuthal direction and small frequency gaps
- clear resonances for each position – but ***continuous variation of frequencies*** in azimuthal direction



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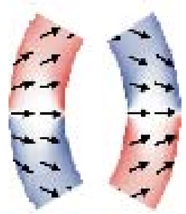
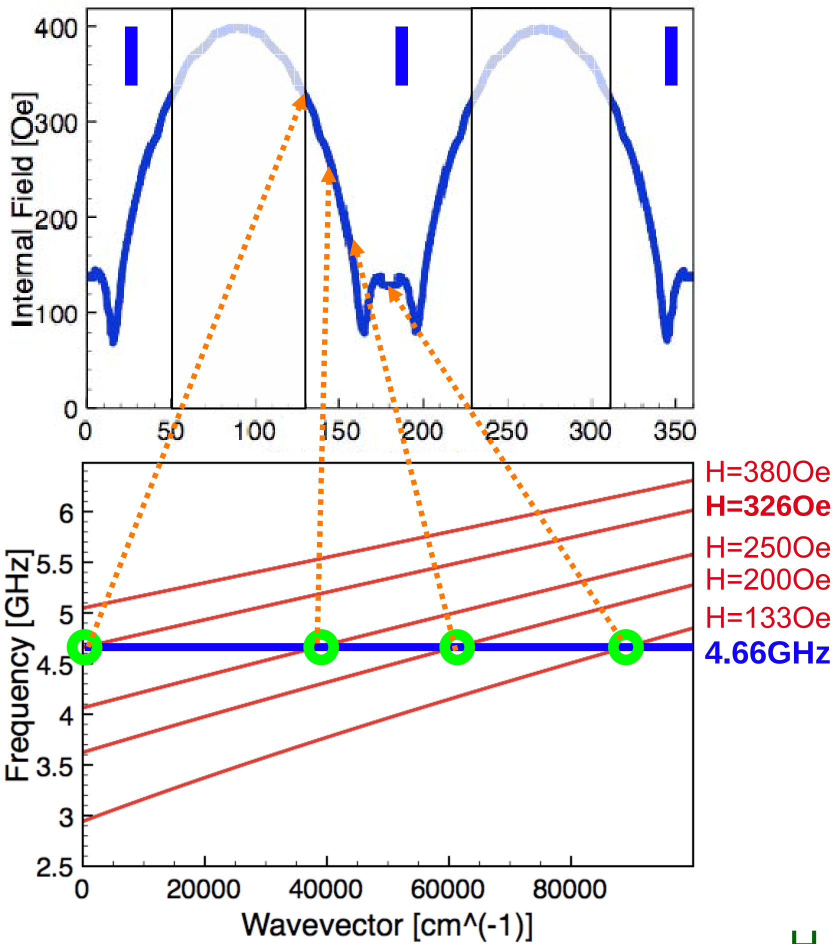
Spin waves trapped in the pole regions of the onion state

Spin-wave wells in the pole regions (0° and 180°) due to the inhomogeneity of internal field



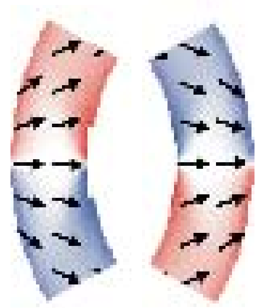


- for increasing field the spin-wave dispersion is lifted to higher frequencies
- e.g. for the lowest observed spin wave mode at **4.66 GHz** there is no possible wavevector for fields over **326 Oe**

→ **spin wave trapped in a spin wave well**

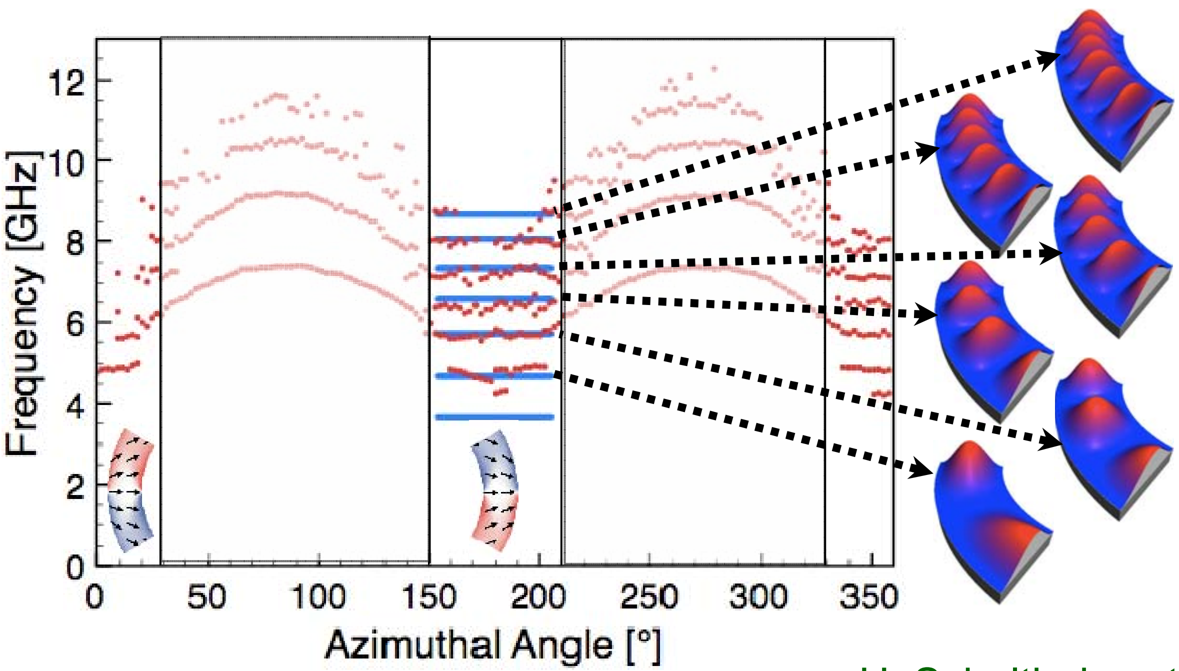
H. Schultheiss et al, PRL **100**, 047204 (2008)

Spin waves trapped in the pole regions of the onion state



Applying this model yields correct frequencies for spin waves...

- pinned at ring boundaries
- quantized in azimuthal direction perpendicular to magnetization



- spin waves coherent over the width of the spin wave well
- eigenmode system with constant frequencies as a function of position

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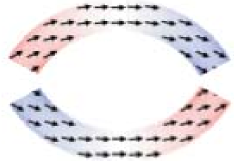
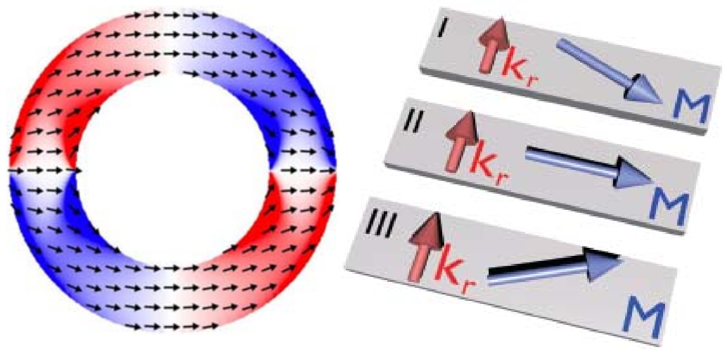
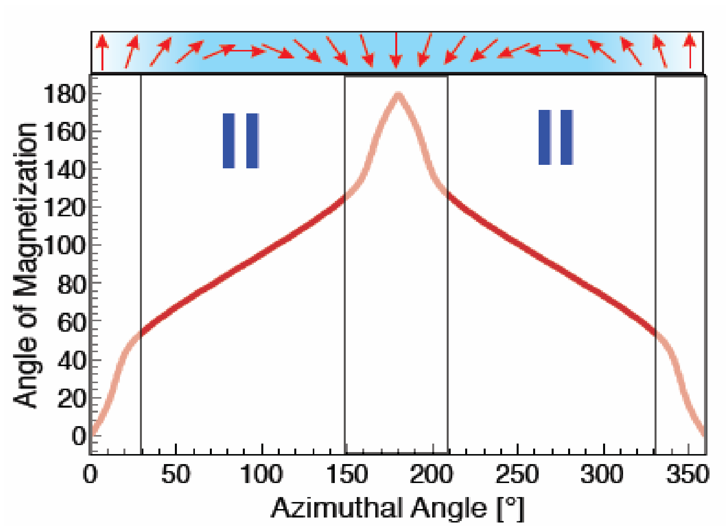
Partial decoherence of spin waves in onion state

Continuous frequency variation as a function of position only possible for partial decoherence in azimuthal direction







Model: Approximation of each ring element with an infinite extended stripe

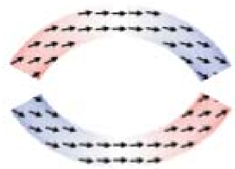
- only quantization in radial direction
- taking into account the continuous change of magnetization direction with respect to the radius
- using the corresponding value for the internal magnetic field at each position of the ring structure
- zero wavevector in azimuthal direction

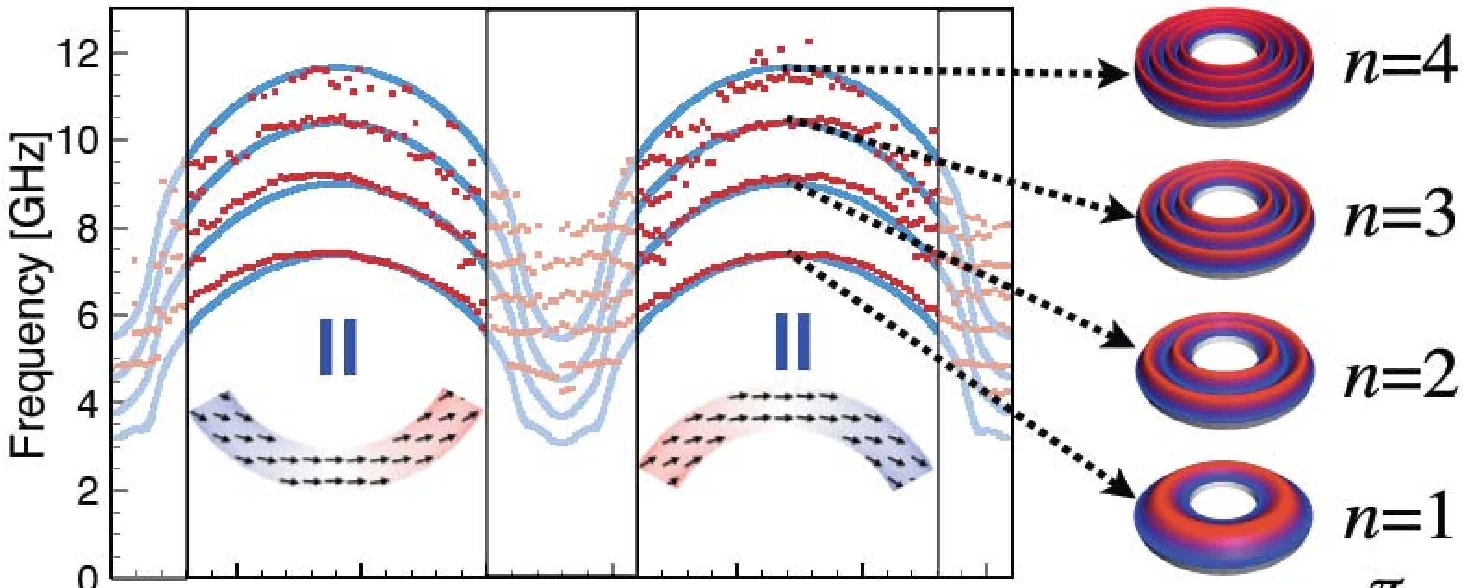
H. Schultheiss et al, PRL **100**, 047204 (2008)

Partial decoherence of spin waves in onion state

The model describes quantitatively

- frequency variation in azimuthal direction
- frequency separation of all modes





$$k_r = n\frac{\pi}{w_{eff}}$$

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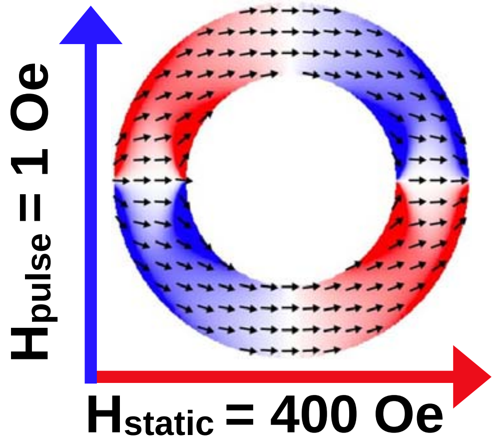
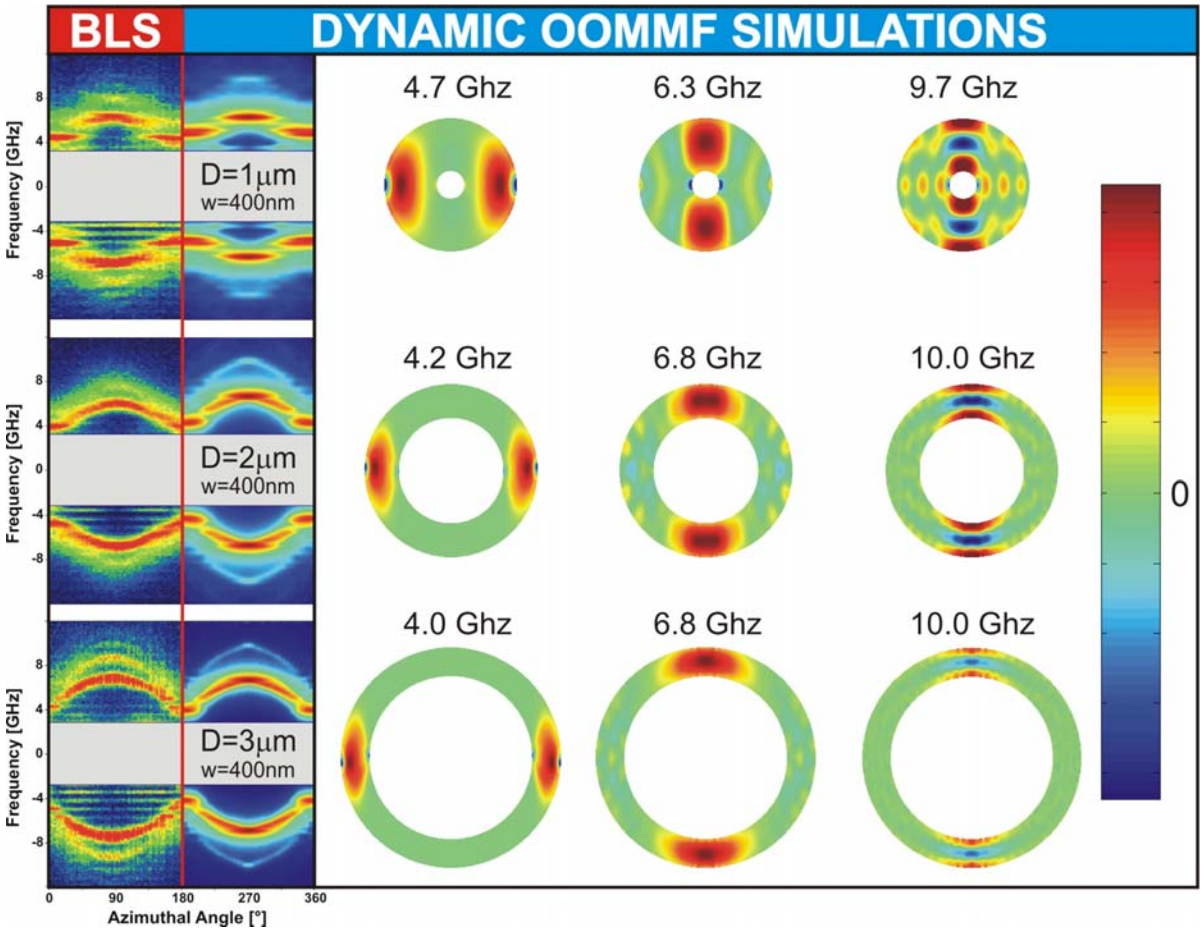
Spin waves in onion state: Comparison with OOMMF simulations





Duration of the pulse:

Δt_{pulse} = 10 ps

Material parameters:

M_s = 650 G

A = $1.60 \cdot 10^{-6}$ erg·cm^2

g = $1.76 \cdot 10^{-2}$ GHz/Oe

H. Schultheiss et al, PRL **100**, 047204 (2008)

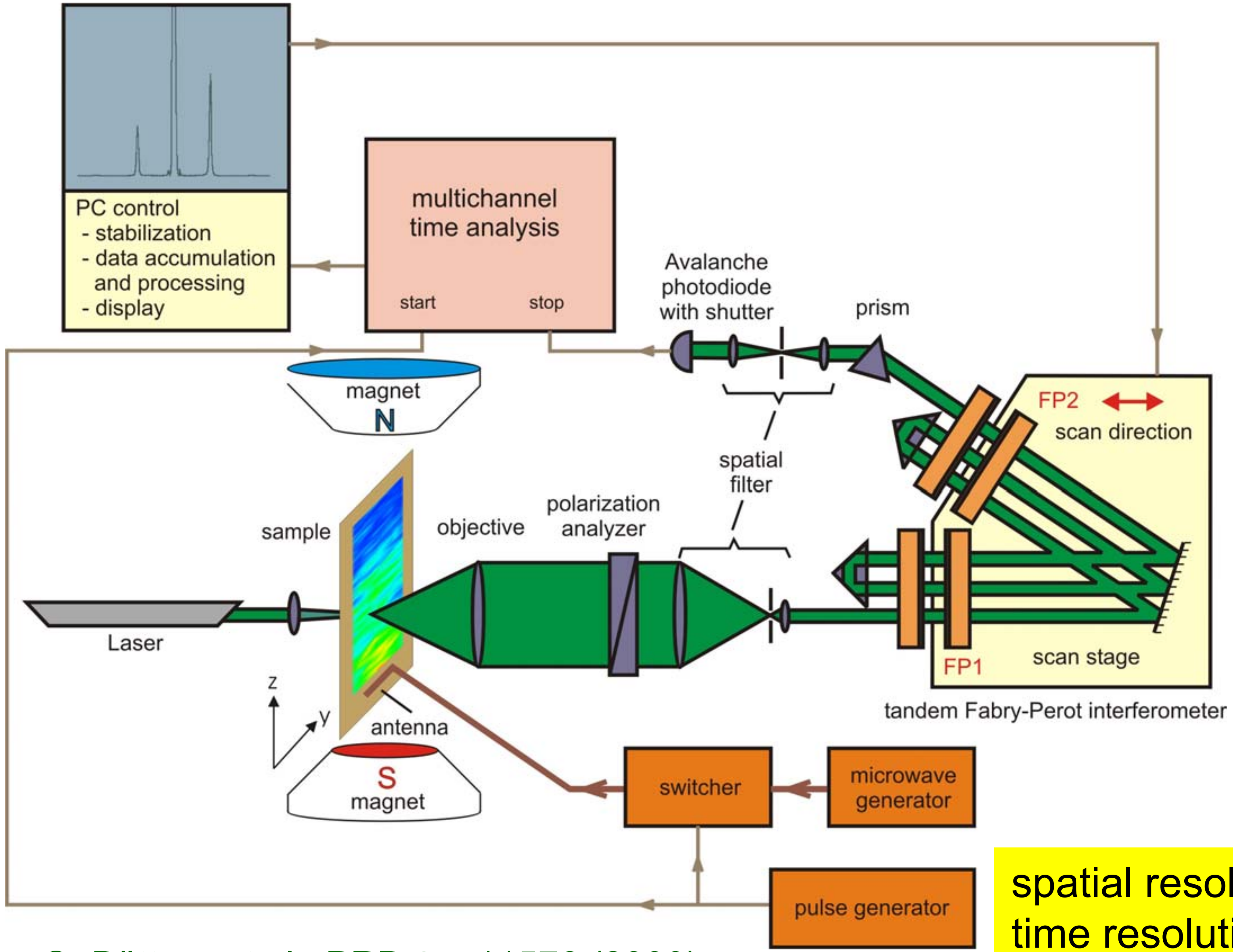
Content

BACKGROUND

- linear: spin waves in small magnetic stripe with domain wall
- linear: spin waves in rings - partial coherence effects
- damping properties of spin waves
- nonlinear: mode coupling of spin waves in rings

OUTLOOK & SUMMARY

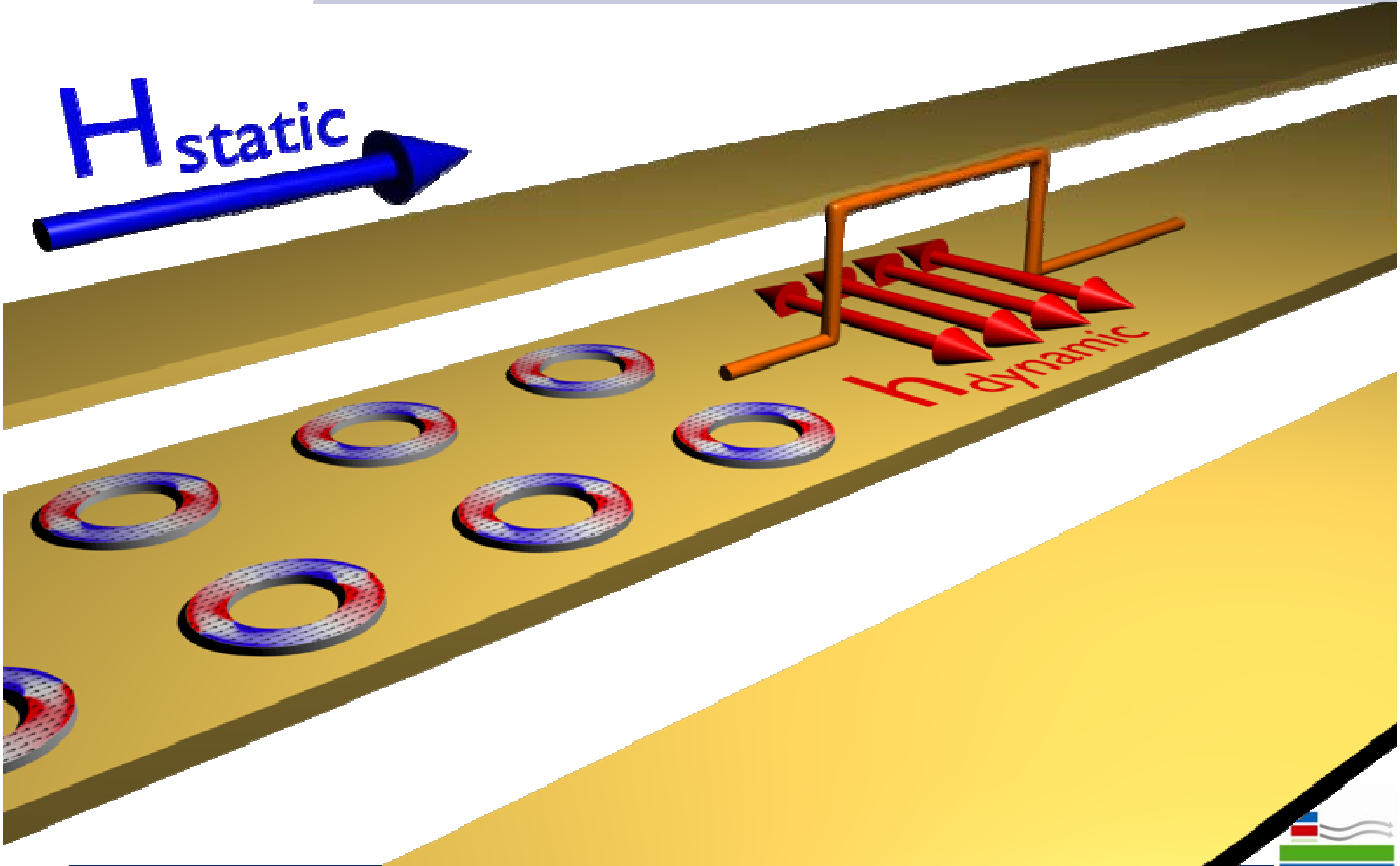
Space and time resolved BLS



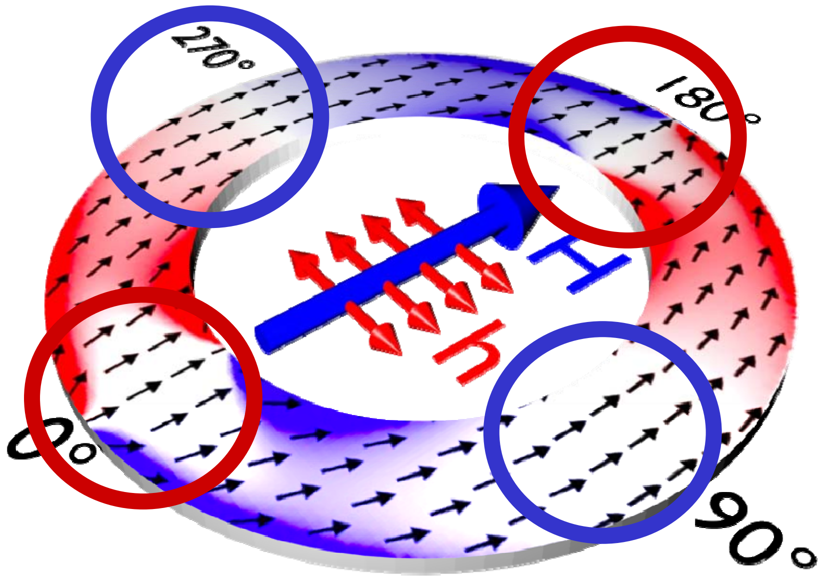
O. Büttner et al., PRB **61**, 11576 (2000)

spatial resolution: 40 µm
time resolution: 1 ns
dynamic range: >60 dB

Spin waves in magnetic rings: sample geometry



Spin waves in magnetic rings
Magnetic rings in the onion state



Pole regions

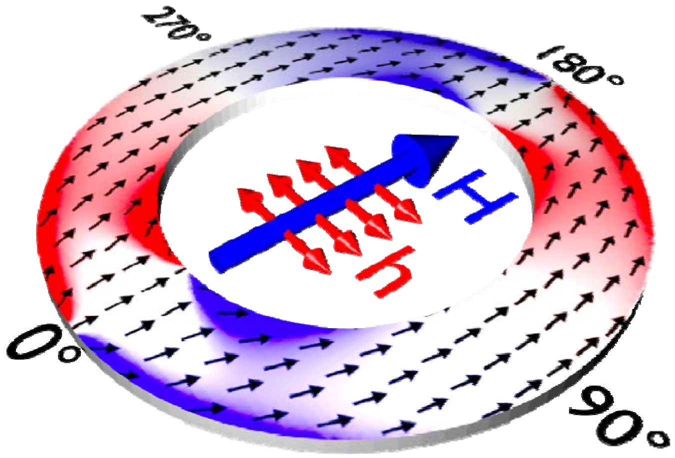
0°, 180°

Equator regions

90°, 270°

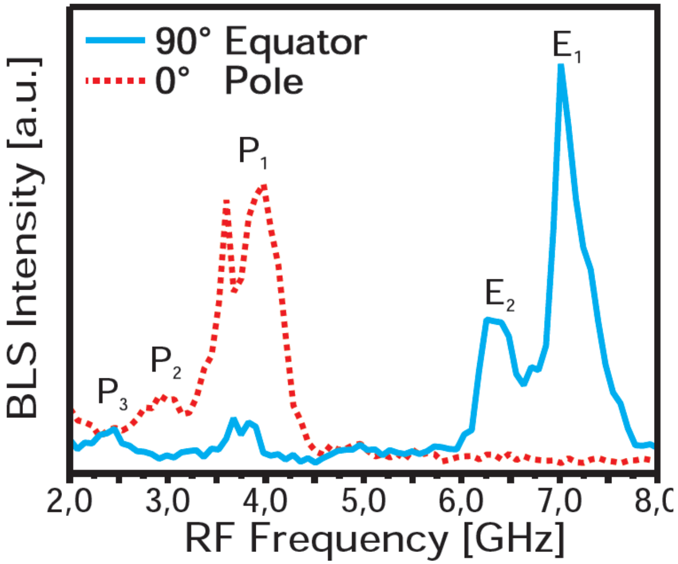
- Easy initialization of the onion state with H_{static}
- Pure in-plane RF excitation field
- Most efficient excitation in the pole and equator regions

Coupling of "quasi-eigenmodes" in rings



„FMR"-type BLS

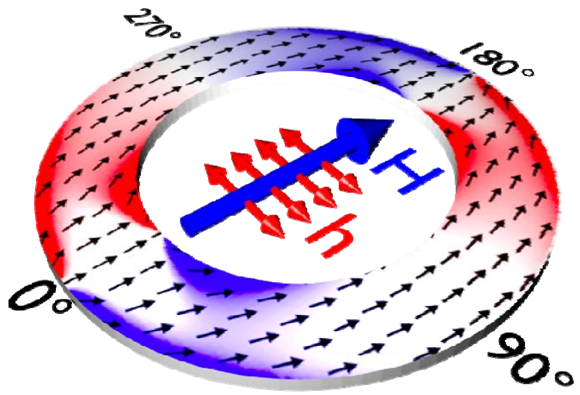
spin wave amplitude (BLS intensity) as a function of applied RF-frequency

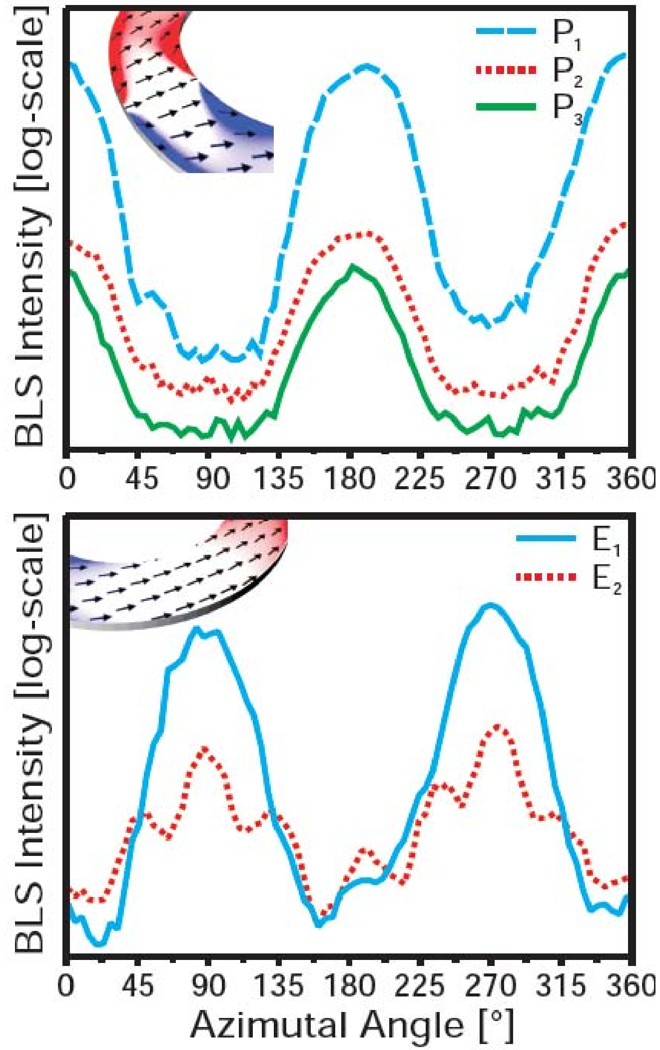


- Low frequency excitations at the pole **P_1, P_2** and **P_3**
- High frequency excitations at the equator **E_1** and **E_2**

H. Schultheiss et al, J. Phys. D 41, 164017 (2008)

Spin waves in magnetic rings

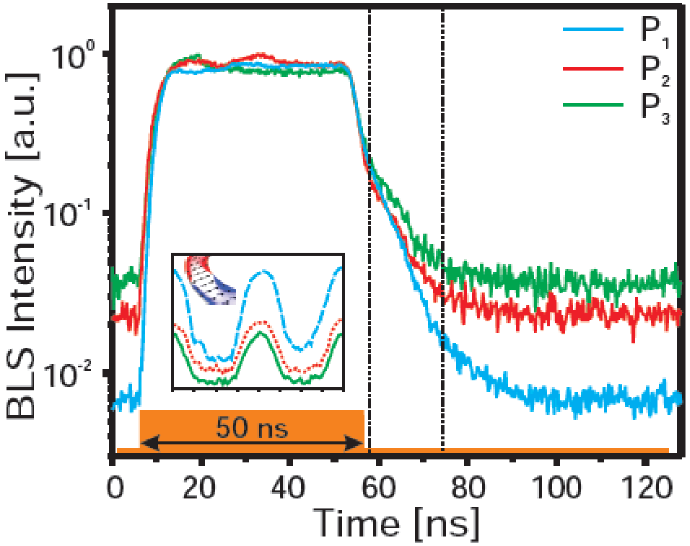


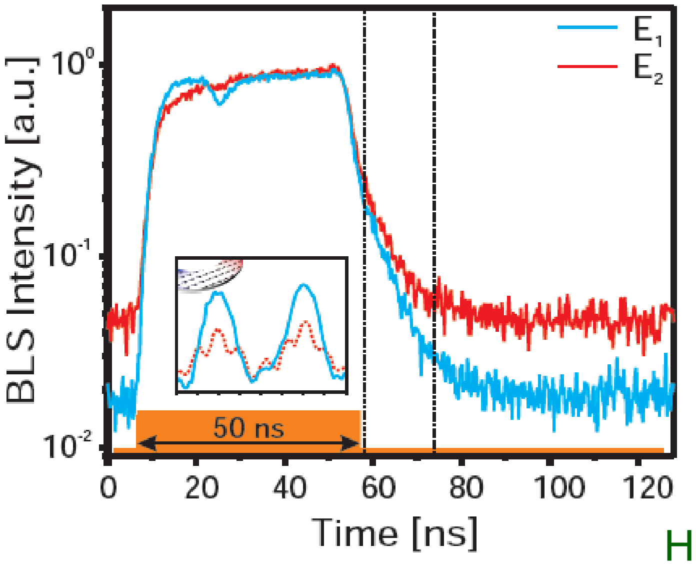


- P_1, P_2 and P_3 are strongly confined to the pole regions
- E_1 and E_2 are located at the equator and show maxima in azimuthal direction
- Decrease in frequency for higher-order mode numbers at the equator

H. Schultheiss et al, J. Phys. D 41, 164017 (2008)

Spin waves in magnetic rings: time-resolved BLS

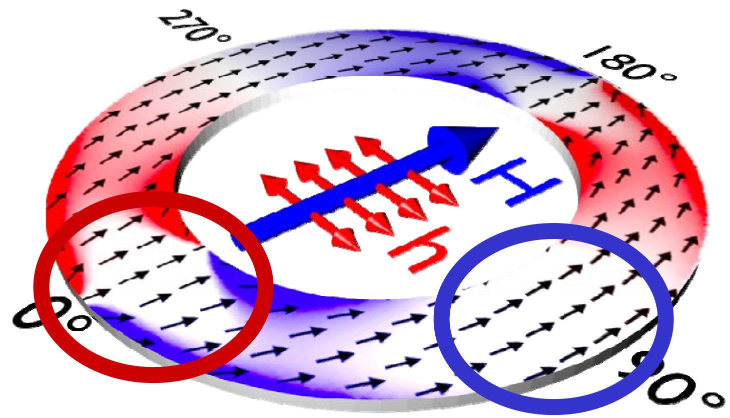




- Resonant excitation of the „quasi-eigenmodes“ **P_1, P_2** and **P_3**
- Exponential decay of the amplitudes after the RF-pulse

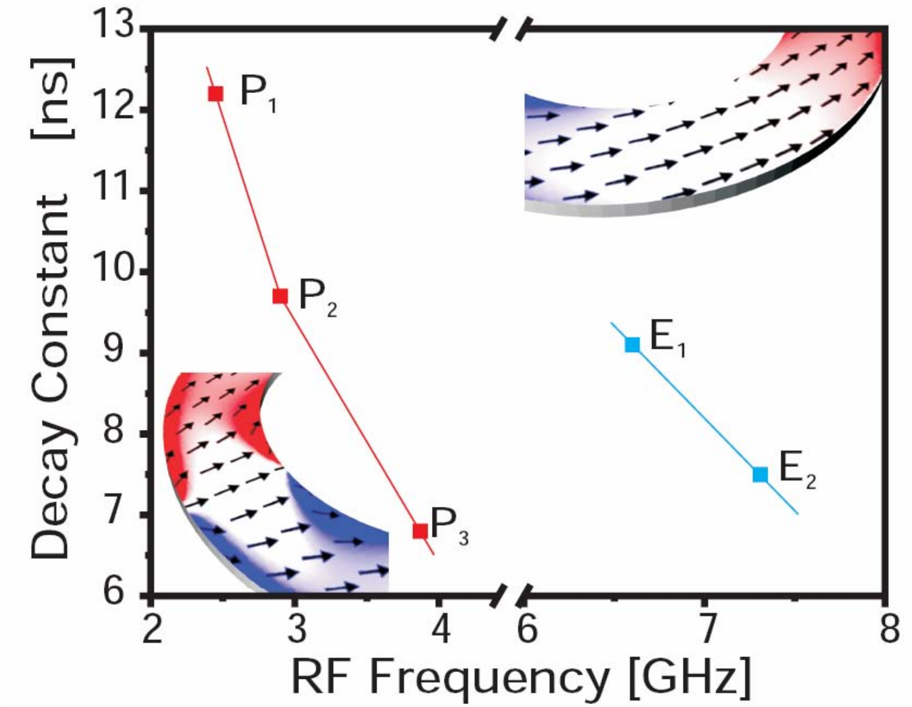
$$\sim e^{-\frac{t}{\tau}}$$

- Increased lifetime for smaller frequency



H. Schultheiss et al, J. Phys. D 41, 164017 (2008)

Spin waves in magnetic rings
Dissipation of „quasi-eigenmodes“



- Decay constant decreases for increasing frequency at a fixed position
- **BUT:** lifetime different for polar and equatorial region

Dissipation channels within the spin system are modified due to:

- modified internal magnetic field (magnitude and direction)
- quantization conditions

H. Schultheiss et al, J. Phys. D 41, 164017 (2008)

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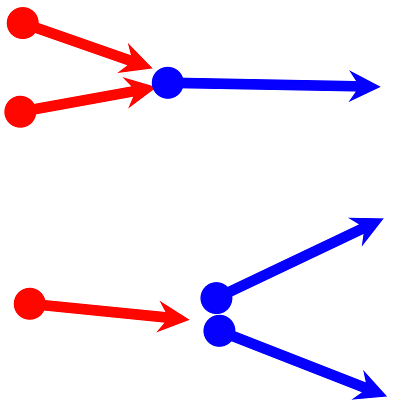
TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

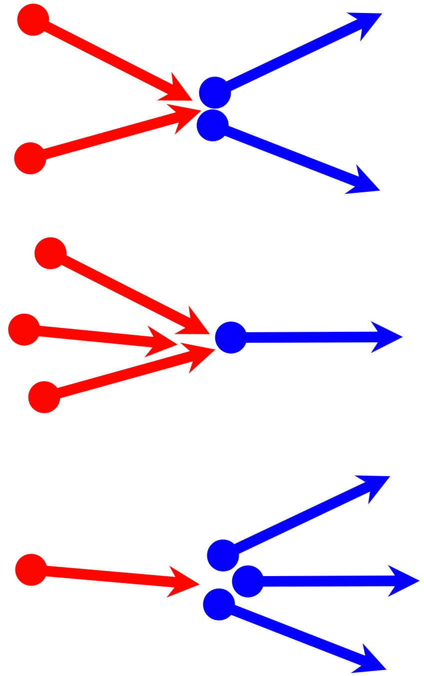
Coupling mechanisms of “quasi-eigenmodes” in rings

What are the possible mechanisms of energy transfer?

MAGNON - MAGNON - SCATTERING



3 magnon scattering



4 magnon scattering

...and higher processes...

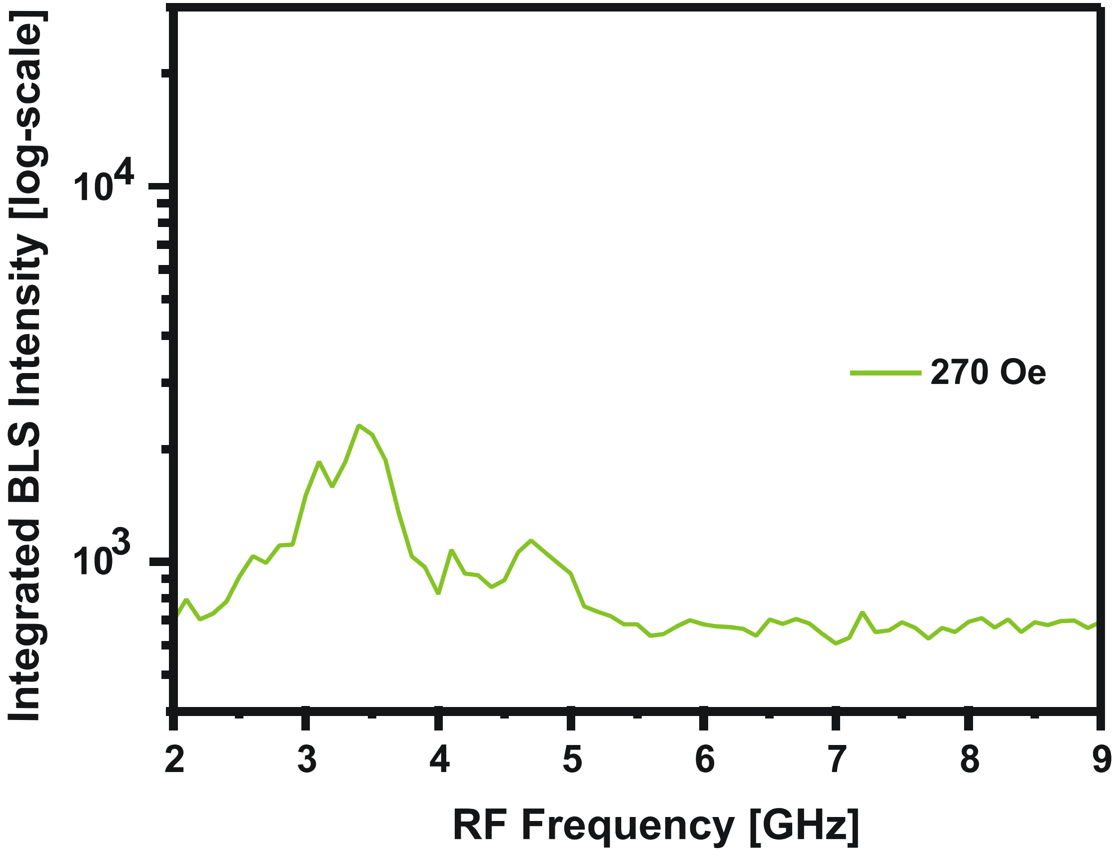
- Conservation of momentum

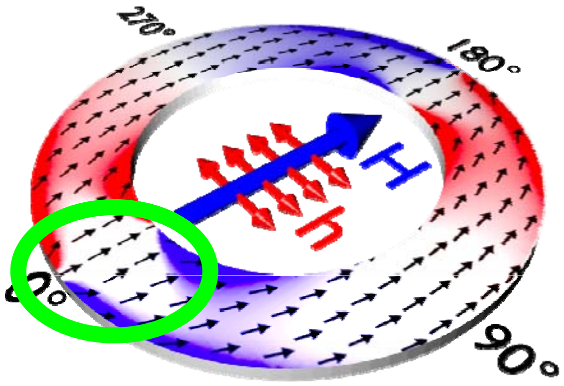
  ???

- Conservation of energy

  !!!

Coupling of "quasi-eigenmodes" in rings

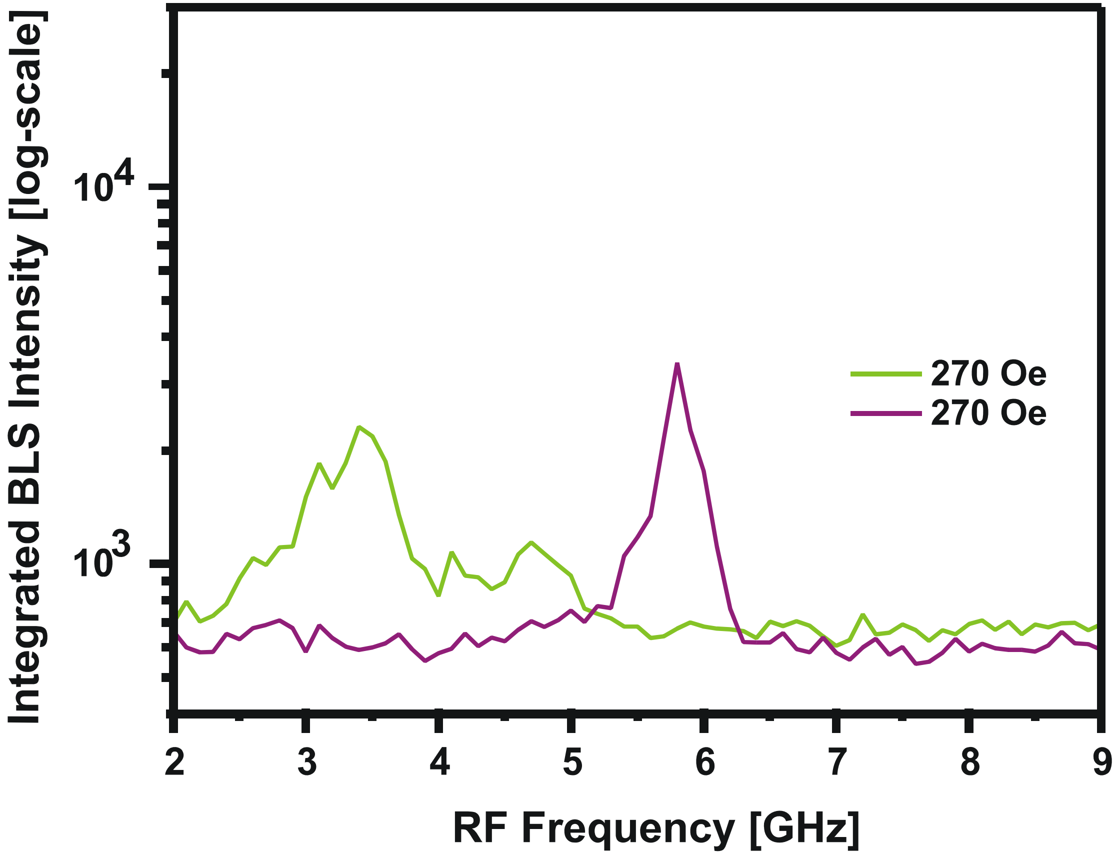


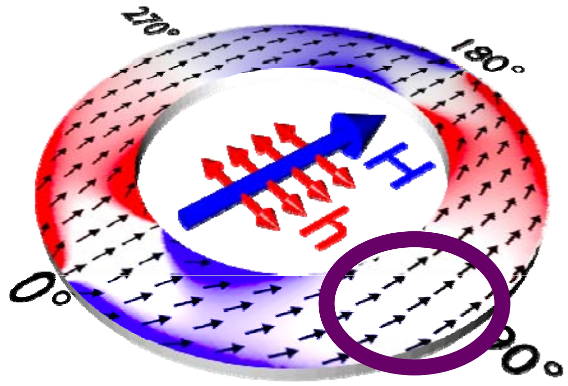


„FMR"-type BLS

frequency sweep to determine the resonance excitation

Coupling of "quasi-eigenmodes" in rings





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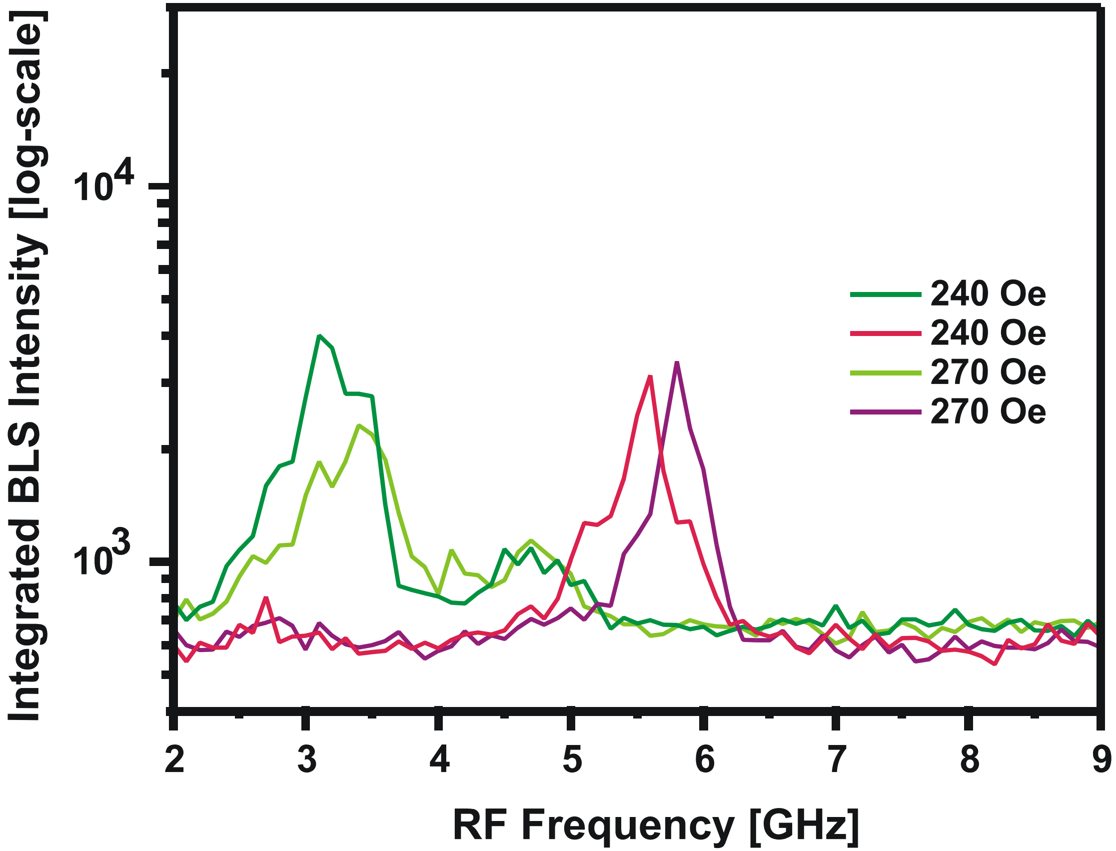
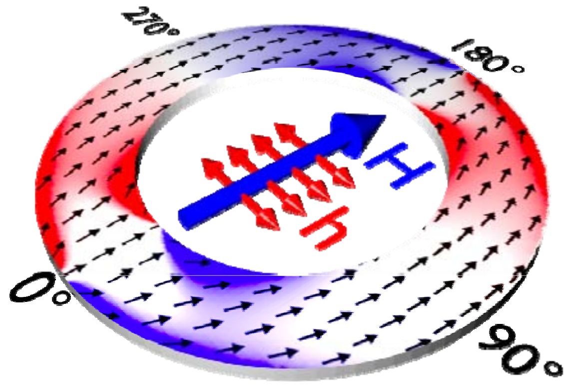
frequency sweep to determine the resonance excitation

Coupling of “quasi-eigenmodes” in rings





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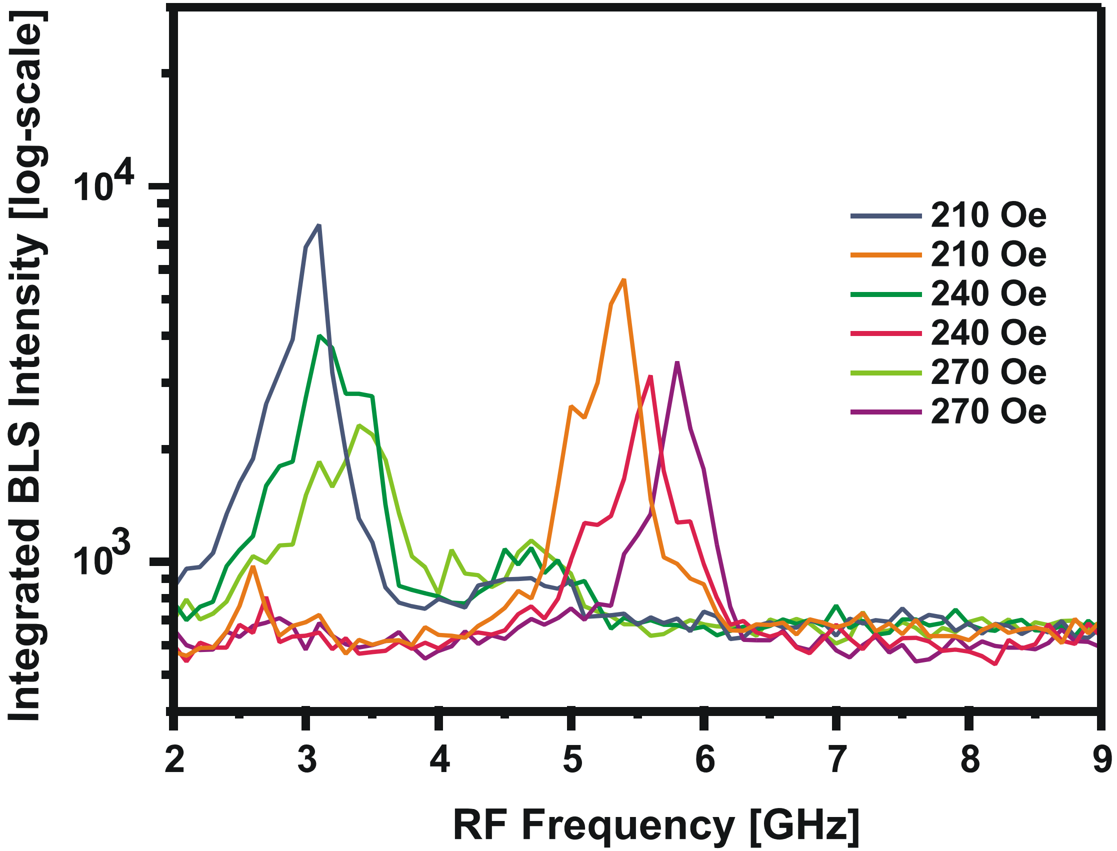

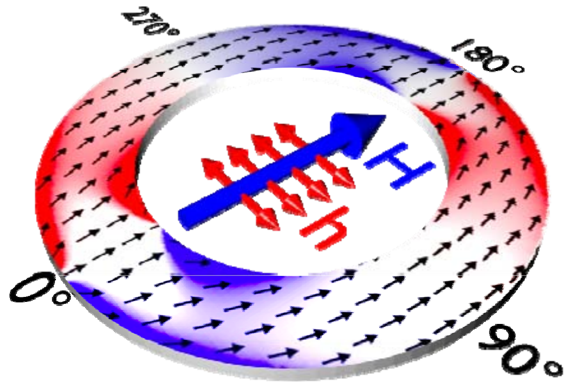

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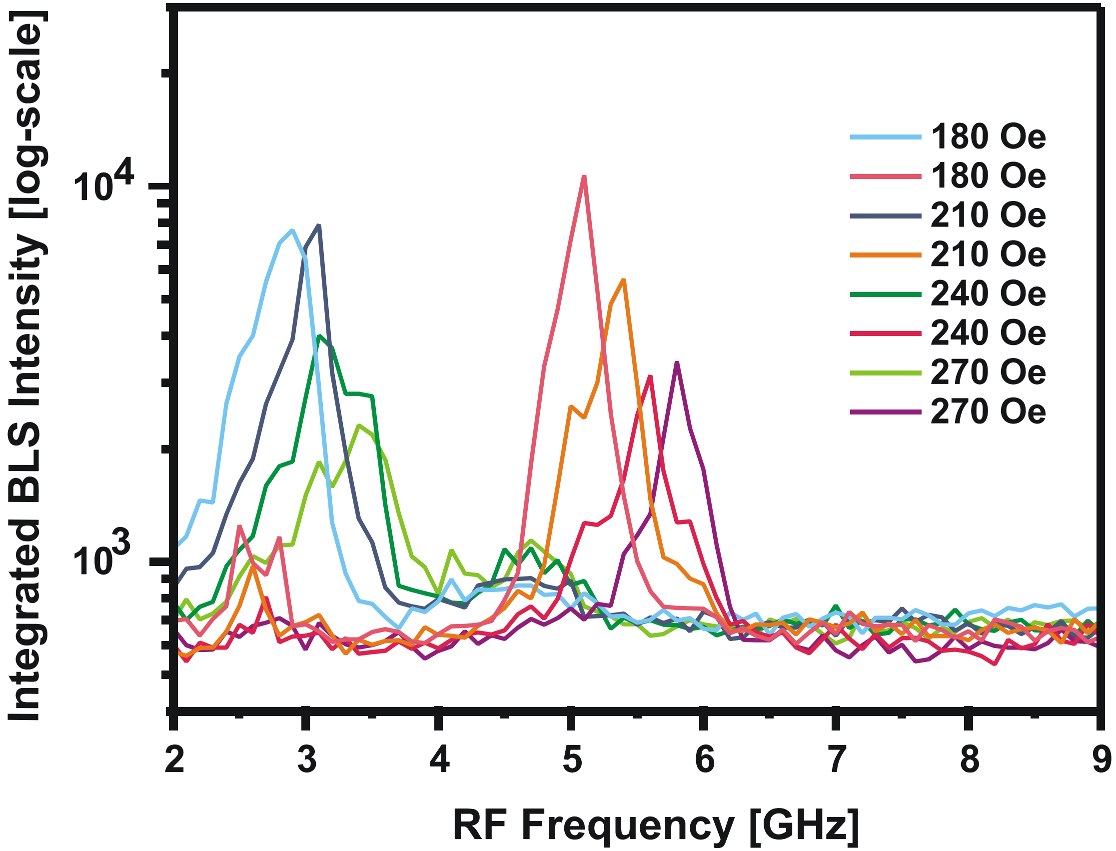

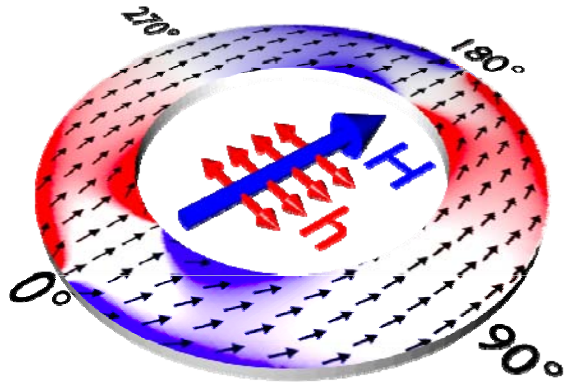

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frequency sweep to determine the resonance excitation

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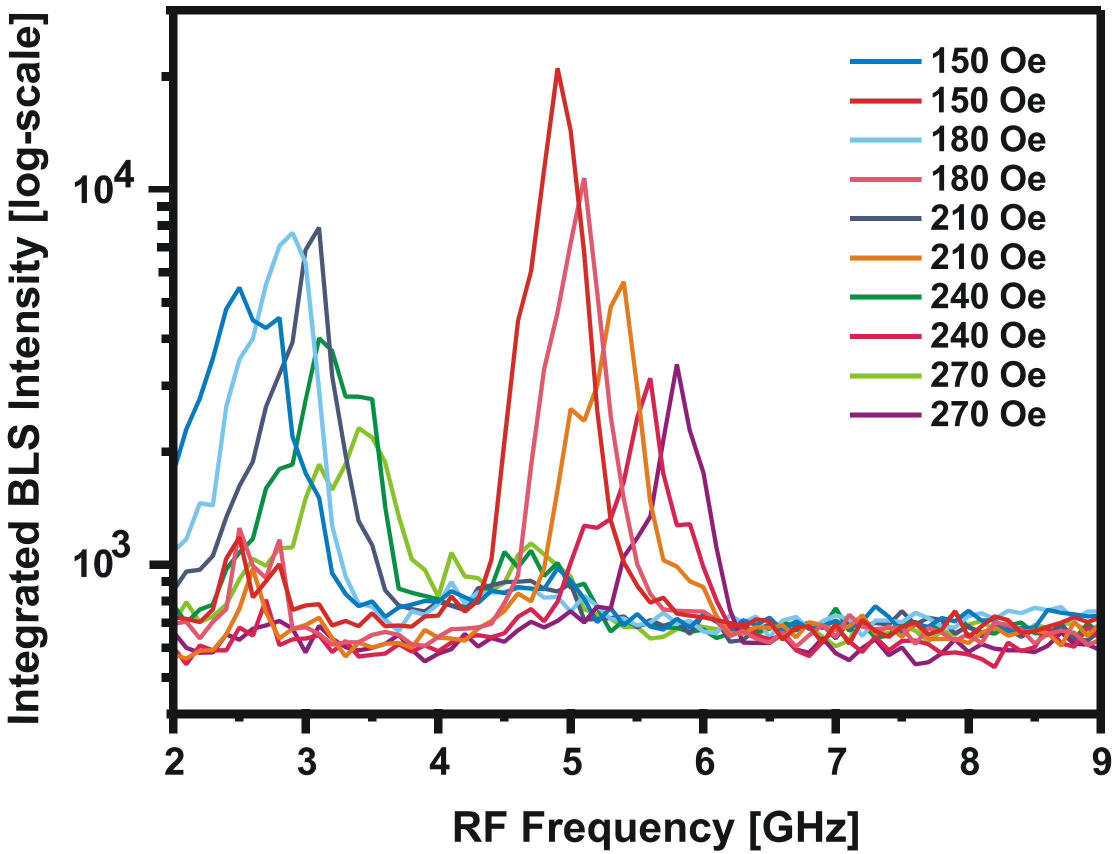

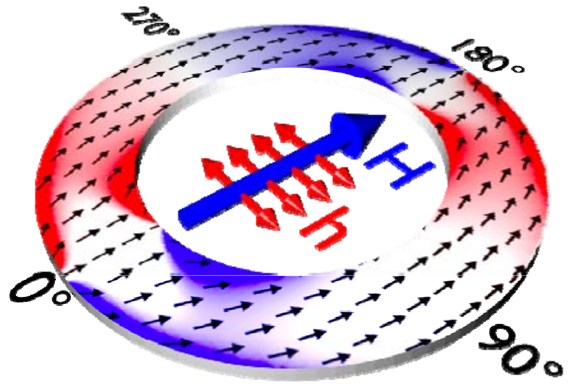

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frequency sweep to determine the resonance excitation

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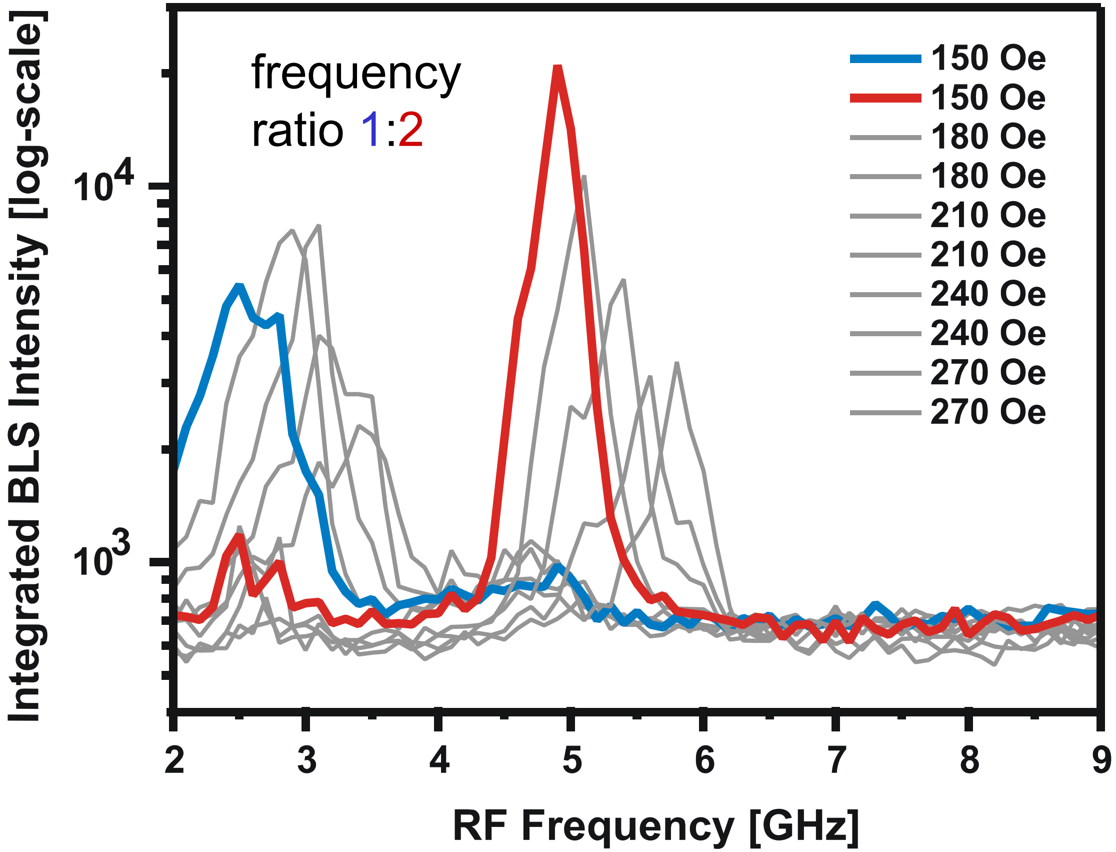
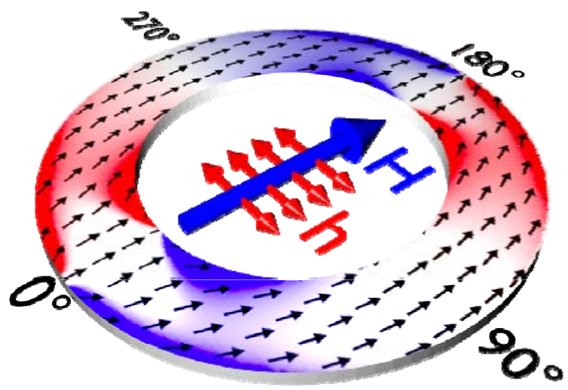
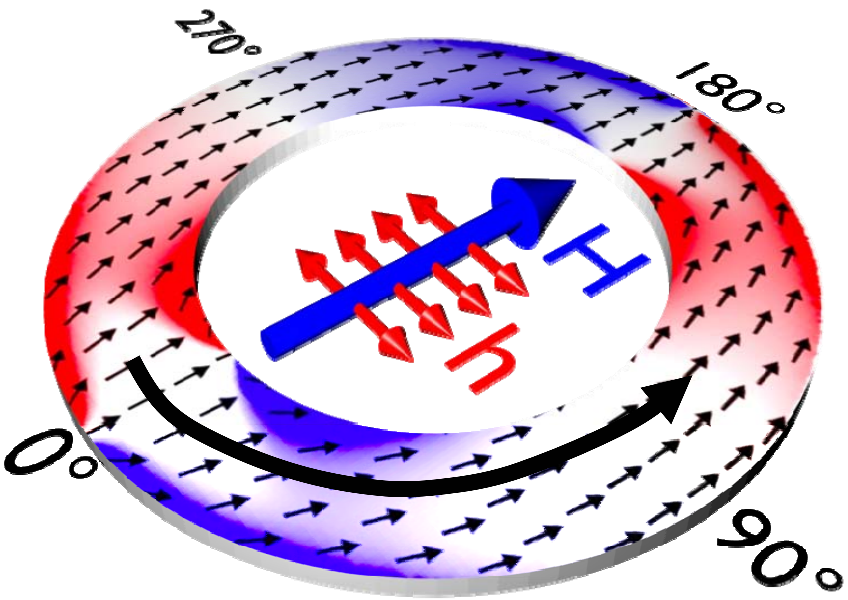


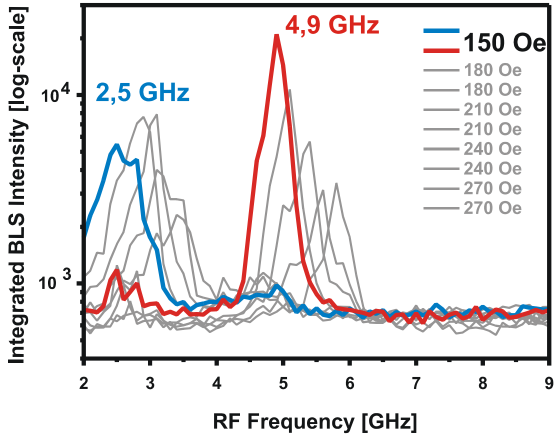


„FMR"-type BLS

frequency sweep to determine the resonance excitation

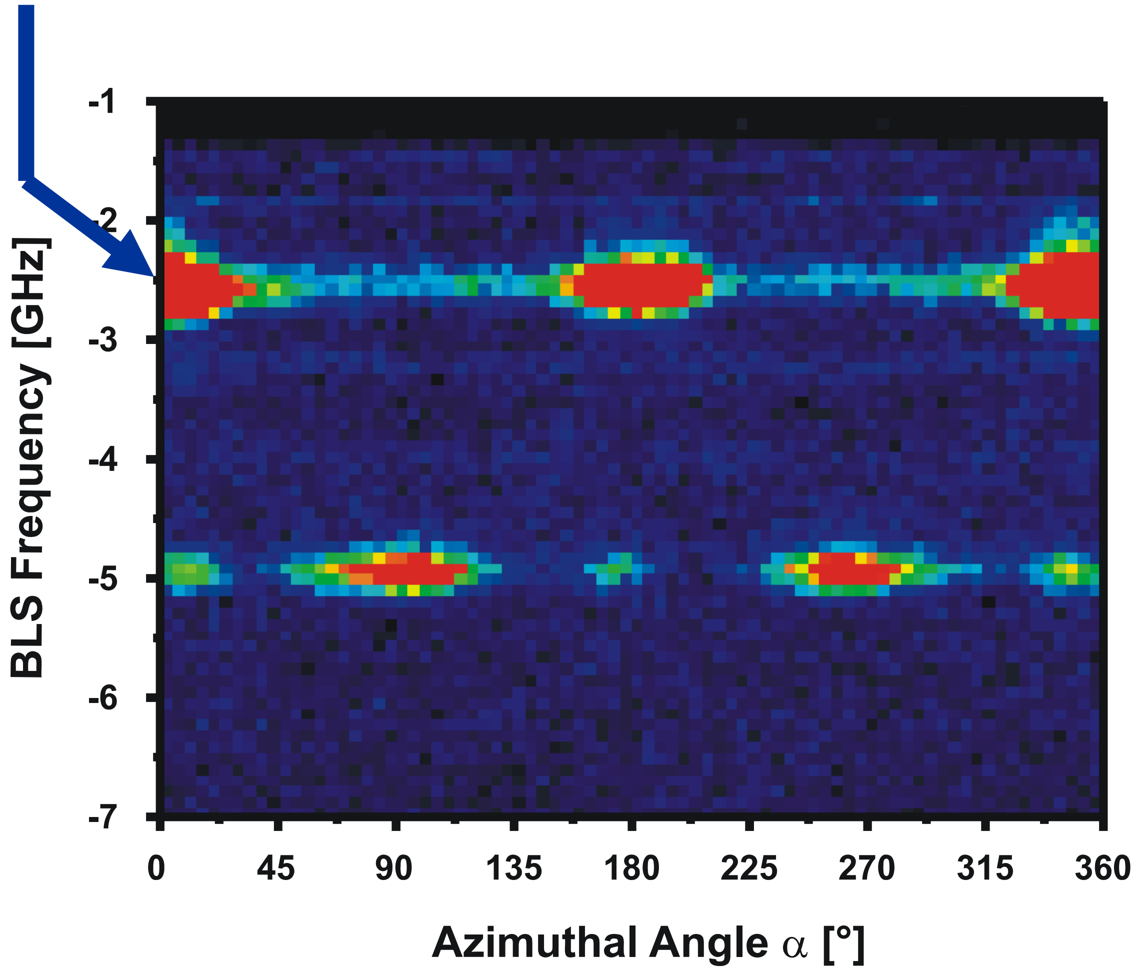
Coupling of "quasi-eigenmodes" in rings

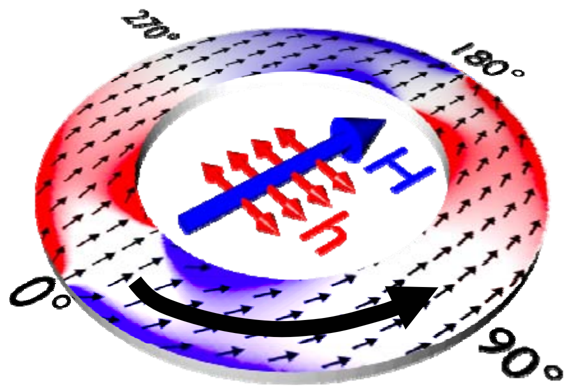


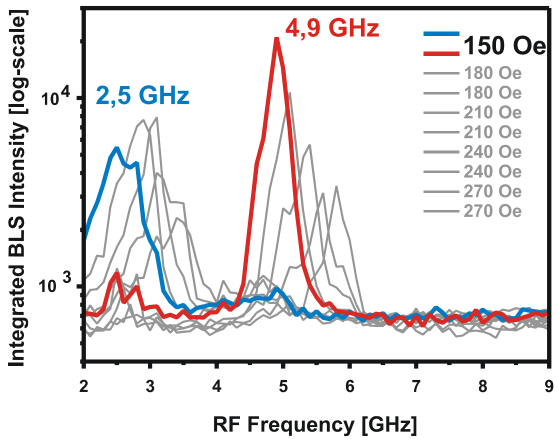


Coupling of “quasi-eigenmodes” in rings

excitation frequency: 2,5 GHz







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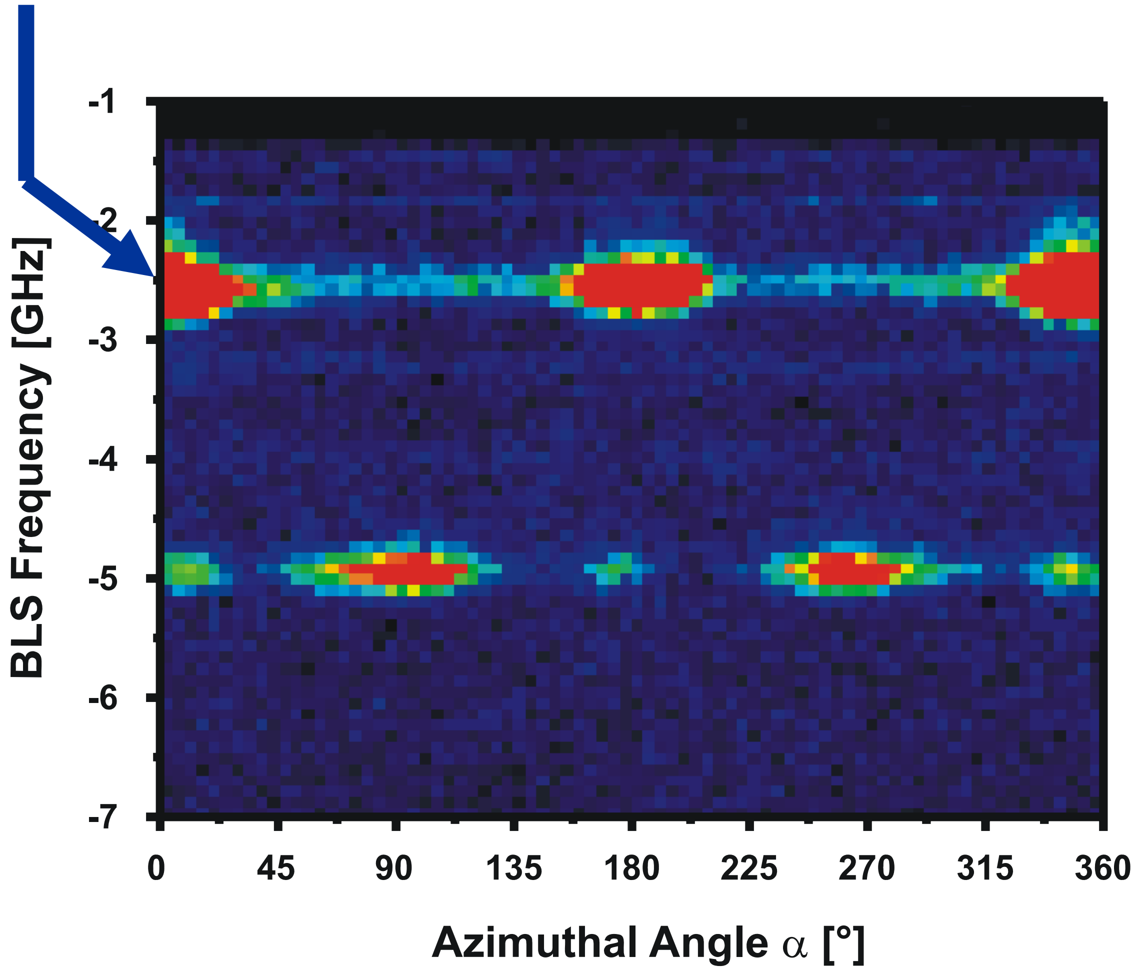
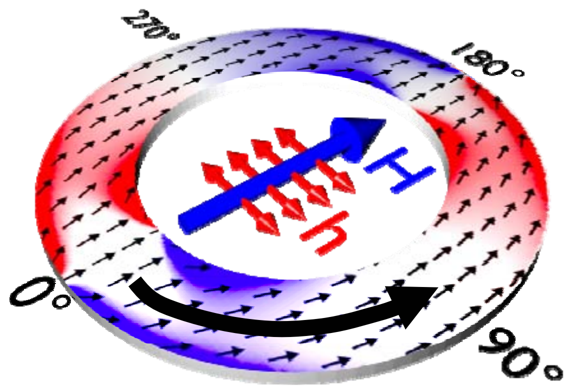
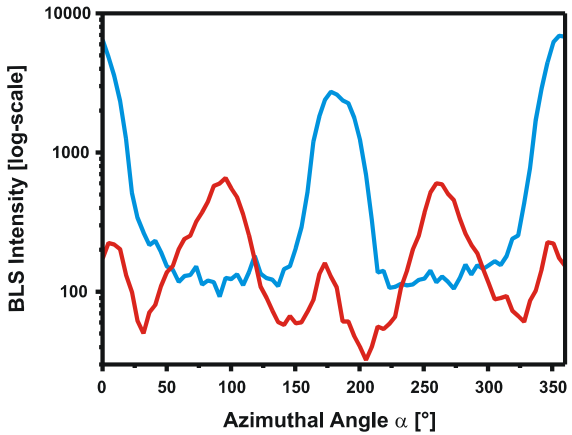




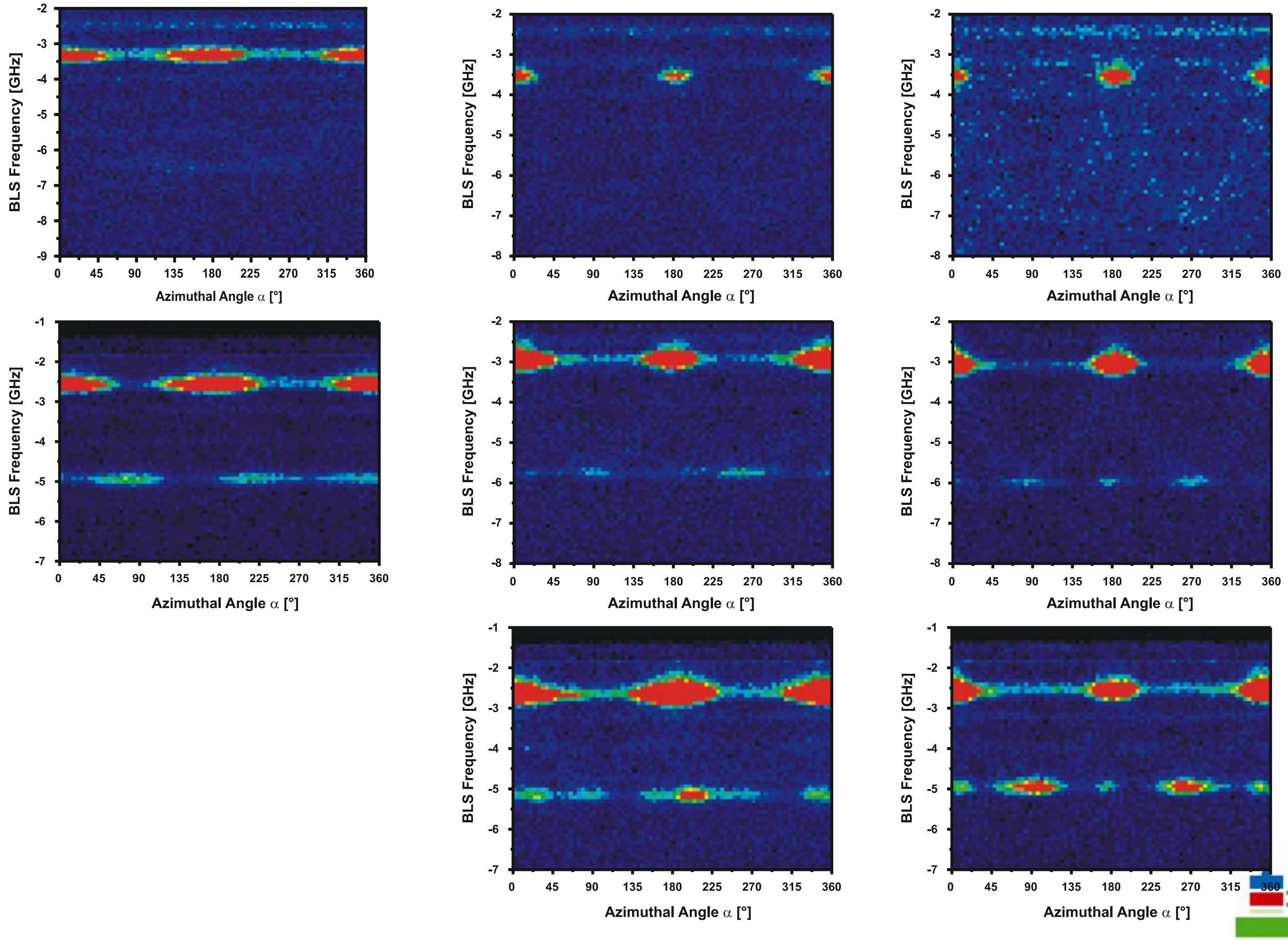


Coupling of “quasi-eigenmodes” in rings

diameter →

width ↓

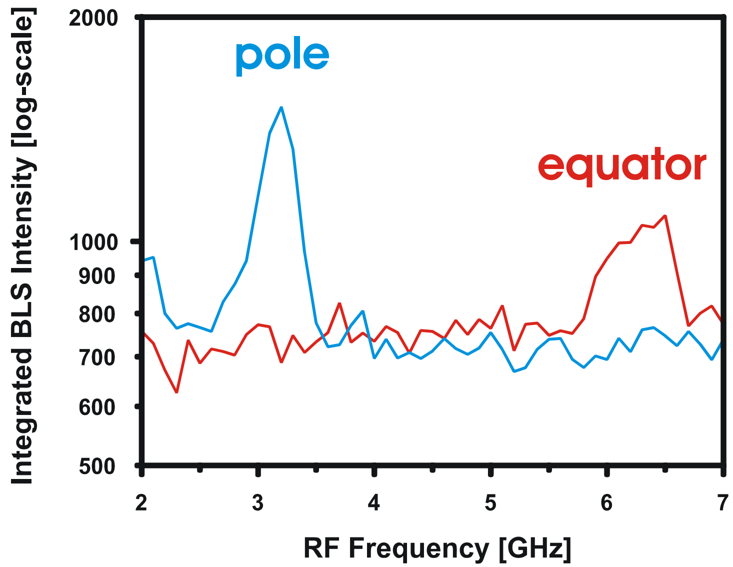
	1 µm	**2 µm**	**3 µm**
100 nm			
200 nm			
400 nm			

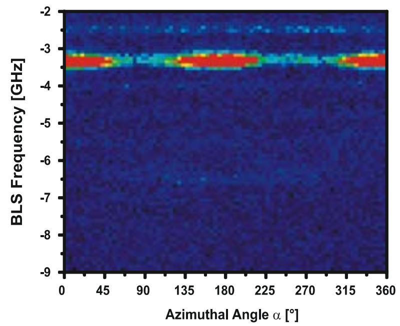


Coupling strength dependence on equator mode intensity

ring diameter 1 µm:

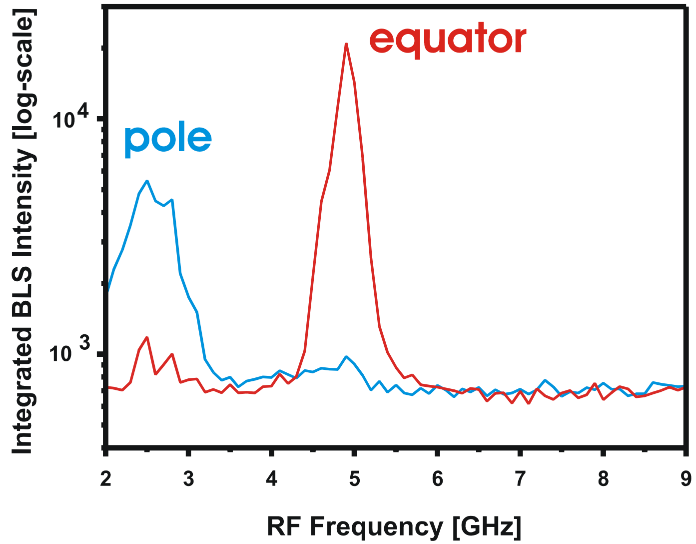
- small FMR-resonance signal at both pole and equator
- small equator to pole signal ratio

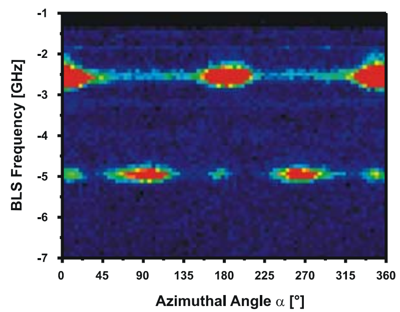




ring diameter 3 µm:

- large FMR-resonance signals
- large equator to pole signal ratio





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Outlook - where will we go ?

Magnon gases:

- Magnons: Quanta of spin waves
- Interaction can be tuned to four-magnon interaction only
  (2 magnons in $\Rightarrow$ 2 magnons out)

  ➔ magnons form gas of interacting quasiparticles
- Injection of magnons via parametric pumping

Issues:

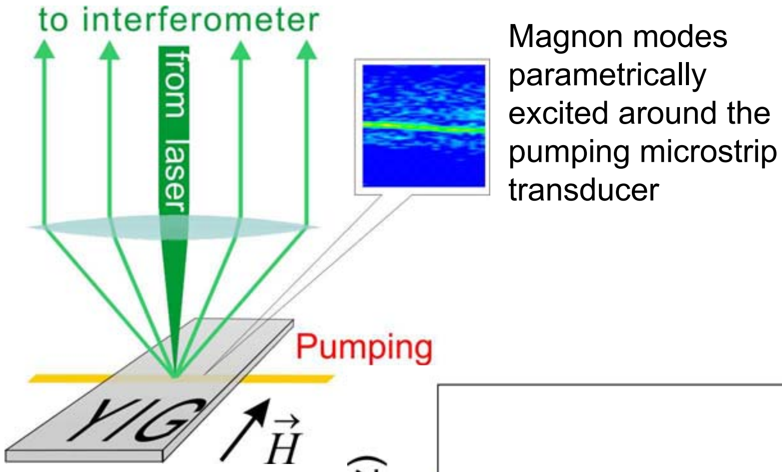
- Correlation effects and instabilities in magnon gases
- parametrically stimulated coherent interactions
- magnon condensates

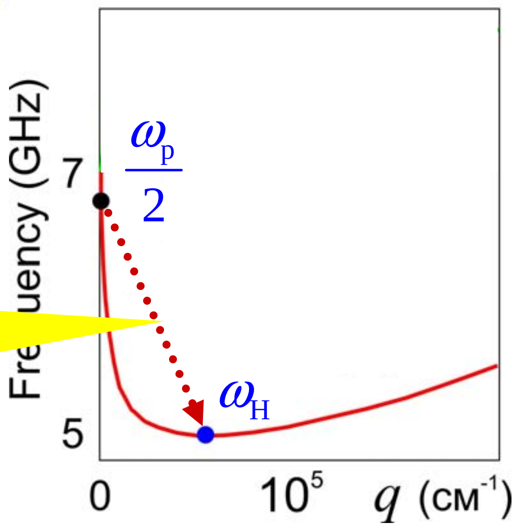
Outlook: dynamics of parametric amplification from thermal bath

Technische Universität Kaiserslautern

Scheme of experiment:

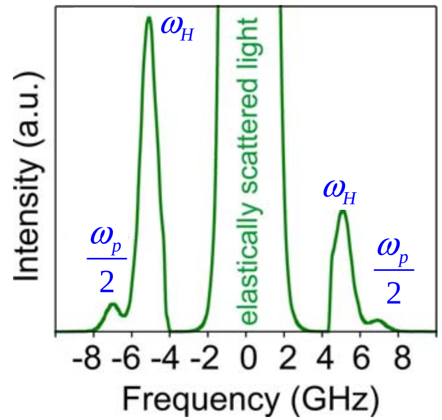
Light elastically scattered by the pumping transducer plays the role of an optic probe.



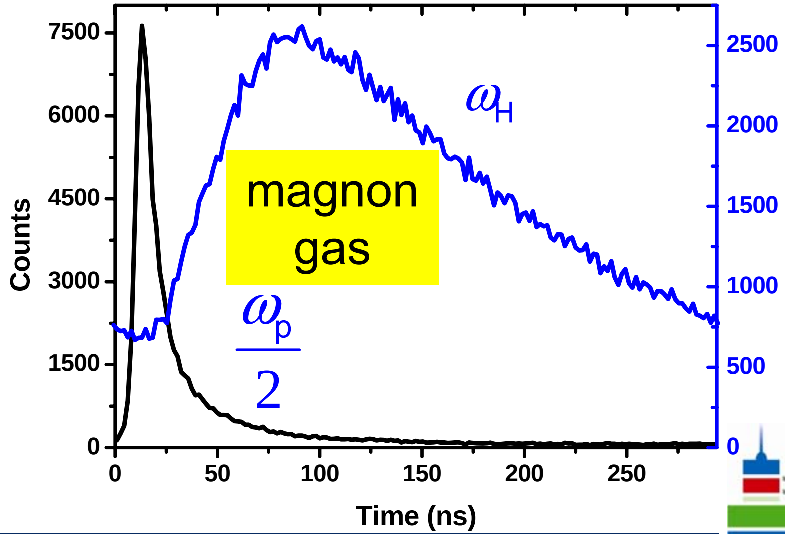


decay via four magnon scattering

BLS spectrum of magnon modes



Decay dynamics of magnon modes



SPINSWITCH