Light scattering from spin waves in quantum dots and wires

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Plan of the lectures:

Part 1: Basics of spin dynamics

Magnetic interactions
Dynamic of spins
Spin waves
Brillouin light scattering

Part 2: Spin wave confinement in dots&wires

Spin wave modes in dots& wires
Lateral quantization
Spin wave wells

Part 3: Staic and dynamic interaction between dots&wires

Collective static properties
Anisotropic interaction
Dynamic mode coupling

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Part I

Basics of spin dynamics

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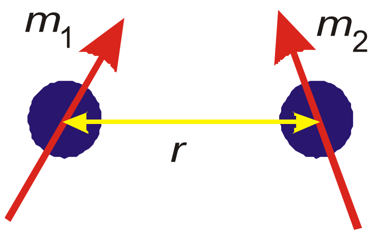
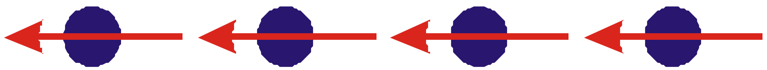
Magnetic interactions

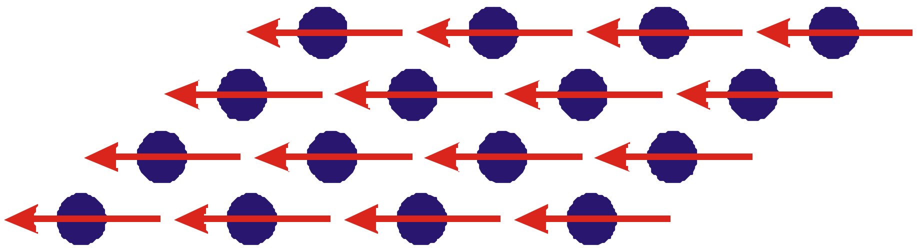


Exchange interaction : $E = -Jm_1 \cdot m_2$

Magnetic dipolar interaction: $E = \frac{m_1 \cdot m_2}{r^3} - \frac{3(m_1 \cdot r)(m_2 \cdot r)}{r^5}$



$J > 0$, ferromagnet



Shape anisotropy:

due to dipole interaction the spins in a film are „in-plane“

Zeeman energy : $E = -B \cdot m$

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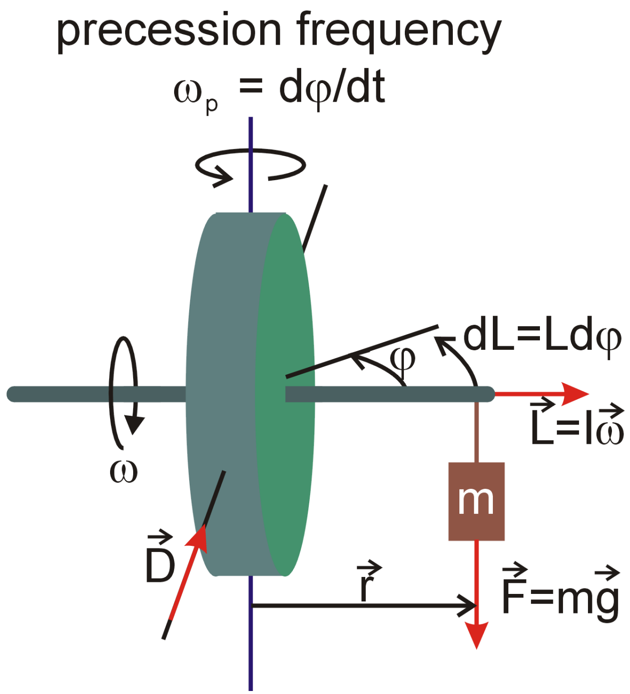
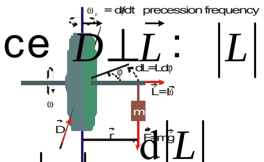
Precession of a spin



angular momentum $\vec{L} = I\,\vec{\omega}$

acting torque $\vec{D}$:

$$\vec{D} = \vec{r} \times \vec{F} = \vec{r} \times m\vec{g} \overset{!}{=} \frac{d\vec{L}}{dt} \quad \Rightarrow \quad d\vec{L} \parallel \vec{D}$$



since $\vec{D} \perp \vec{L}$: $\quad |L| = \text{const}$ and $|dL| = L\,d\varphi$

$$\Rightarrow \quad |D| = \frac{d|L|}{dt} = L\frac{d\varphi}{dt} = L\omega_p$$

$$\Rightarrow \quad \boxed{\omega_p = \frac{D}{L} = \frac{mrg}{I\omega}}$$

frequency of precession

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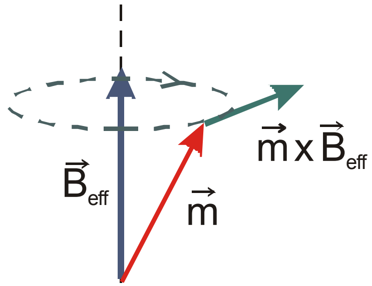
Precession of a magnetic moment in a field

Relation between magnetic moment $\vec{m}$ and

angular momentum $\vec{l}$:

$$\vec{m} = -\frac{g\,\mu_B}{\hbar}\vec{l} = \gamma \cdot \vec{l} \quad \text{with} \quad \gamma = \gamma_e \cdot g/2$$



γ_e = 175,8 GHz/T: gyromagnetic factor of a single electron

g : g-factor

Equation of motion (Landau-Lifshitz equation):

$$\vec{D} = \frac{d}{dt}\vec{l} = \frac{1}{\gamma}\frac{d\vec{m}}{dt} = \vec{m} \times \vec{B}_{eff}$$

or, using magnetization *M* (density of magnetic moments):

$$\frac{1}{\gamma}\frac{d\vec{M}}{dt} = \vec{M} \times \vec{B}_{eff}$$

$B_{eff} = B_e \quad \Rightarrow \quad \omega = \gamma B_e$

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Precession of a magnetic moment in a field (2)

$\vec{B}_{\mathrm{eff}}$: magnetic field acting on magnetic moment:

$$\vec{B}_{\mathrm{eff}} = \vec{B}_0 + \vec{B}(t) + \vec{B}_{\mathrm{exch}} + \vec{B}_{\mathrm{ani}}$$

$\vec{B}_0$: external magnetic field

$\vec{B}(t)$: time dependent field (caused by precession; plus microwave field, if applicable)

$\vec{B}_{\mathrm{exch}}$: exchange field between neighbored moments

$$\vec{B}_{\mathrm{exch}} = \frac{2A}{M_s^2}\nabla^2\vec{M} = \frac{D}{M_s}\nabla^2\vec{M}$$

$\vec{B}_{\mathrm{ani}}$: anisotropy field

$$\vec{B}_{\mathrm{ani}} = -\frac{1}{M}\nabla_{\vec{\alpha}} E_{\mathrm{ani}} \quad \text{with} \quad \vec{\alpha} = \vec{M}/|M|$$

E_{ani} : magnetic free anisotropy density

cubic anisotropy:

$$E_{\mathrm{ani}} = K_1(\alpha_x^2\alpha_y^2 + \alpha_y^2\alpha_z^2 + \alpha_z^2\alpha_x^2)$$

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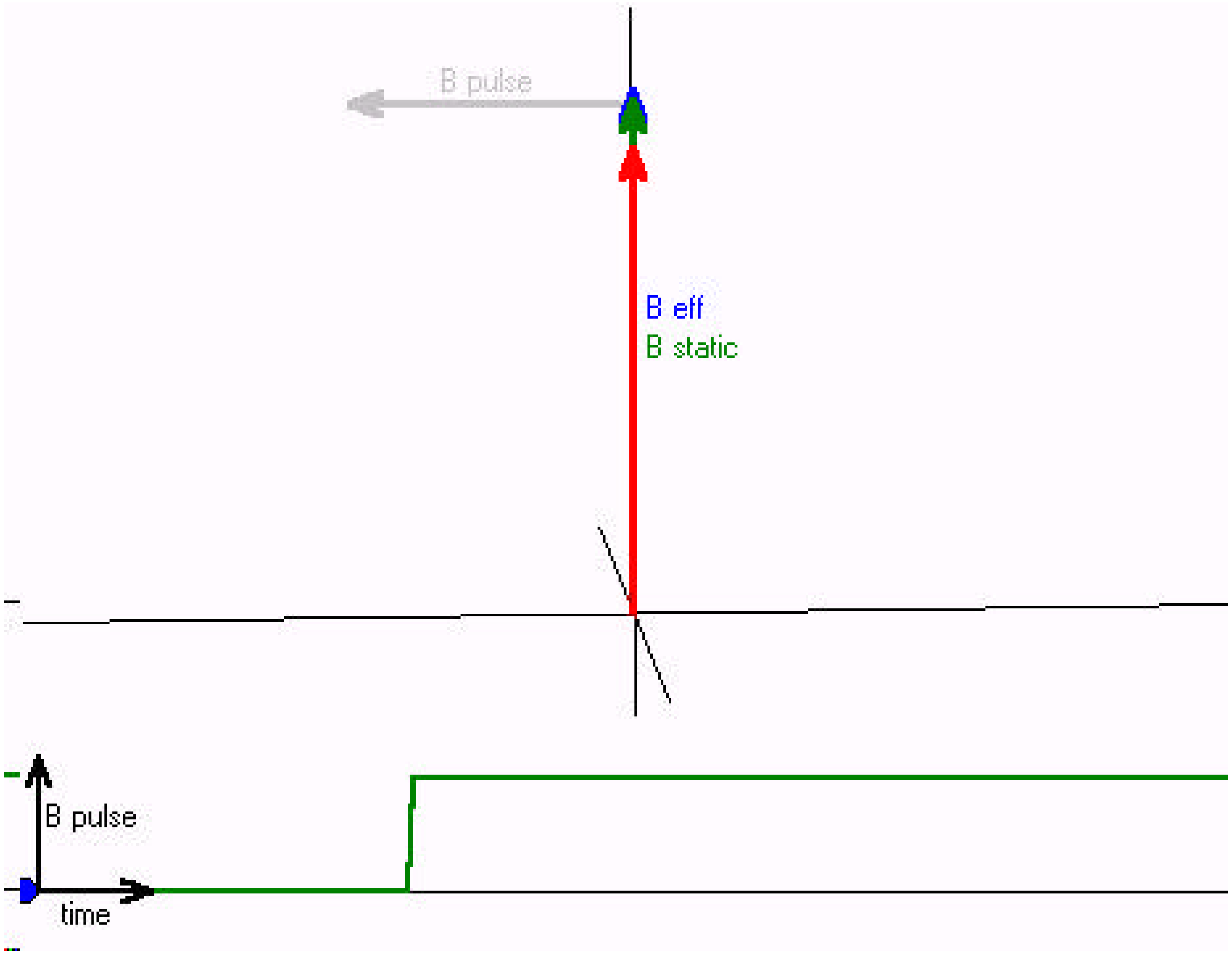
Precession of magnetization



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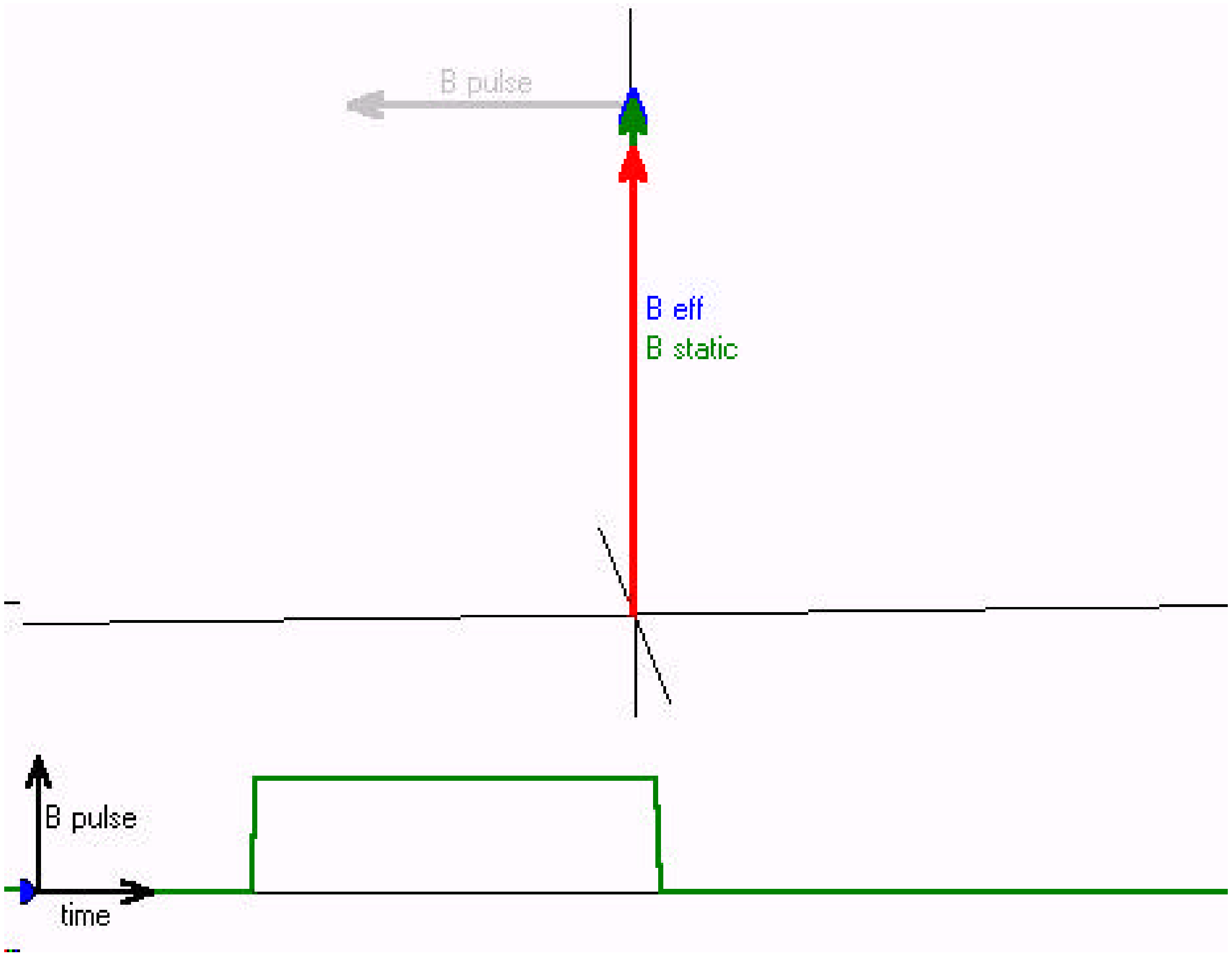
Precession of magnetization



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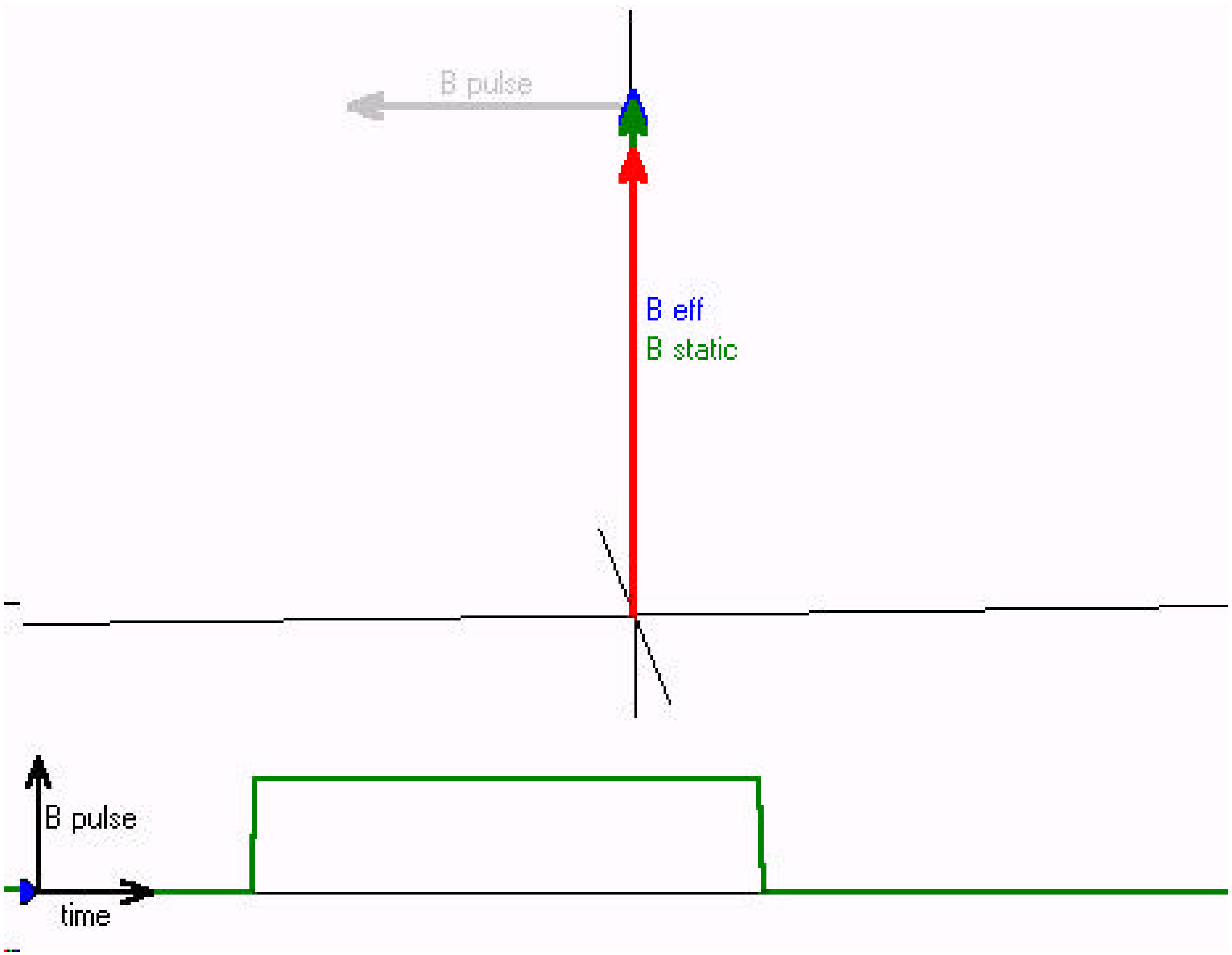
Precession of magnetization



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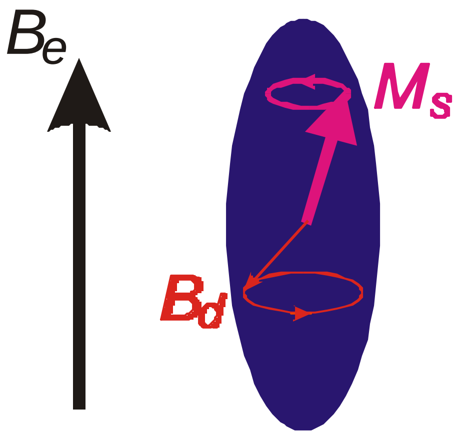
Dynamic of confined systems



Example: ellipsoid

Dipolar interaction can be characterized by a demagnetizing tensor N_x, N_y and N_z:

Uniform precession with frequency

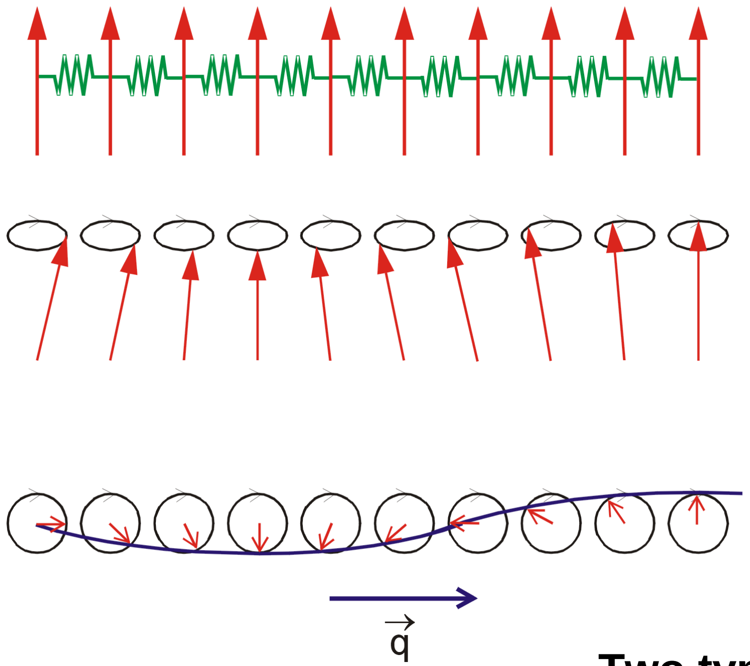
$$\left(\frac{\omega}{\gamma}\right)^2 = \left(B_e + (N_x - N_z)J_s\right)\cdot\left(B_e + (N_y - N_z)J_s\right)$$

with :

$J_s = \mu_0 M_s$ (magnetic saturation polarization) in *z*-direction

Uniform eigen-mode of the system (FMR)

Spin waves



Non-uniform eigen-modes of the magnetic system

Two types of energy contributions

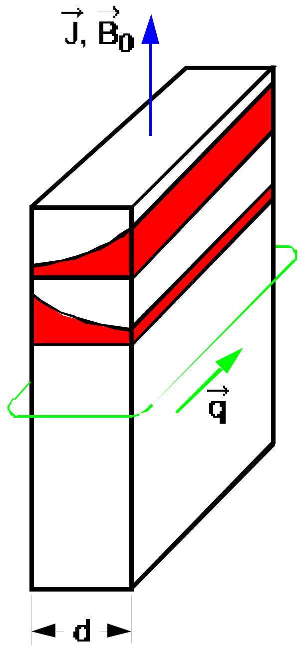
- exchange energy:
  generated by twist of neighbored spins
- dipolar energy:
  generated by magnetic poles in long-wavelength spin waves

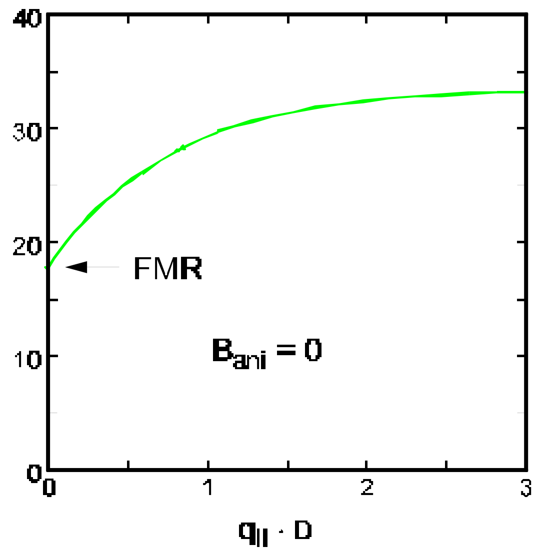
Spin waves in films

Solution to equation of motion (without anisotropies):

$$\left(\frac{\omega}{\gamma}\right)^2 = B_0\left(B_0 + J_s\right) + \left(\frac{J_s}{2}\right)^2\left(1 - e^{-2q_{||}d}\right)$$

with: $J_s = \mu_0 M_s$ (magnetic saturation polarization)





Mode is localized on the film surfaces

Surface (so-called Damon-Eshbach) modes

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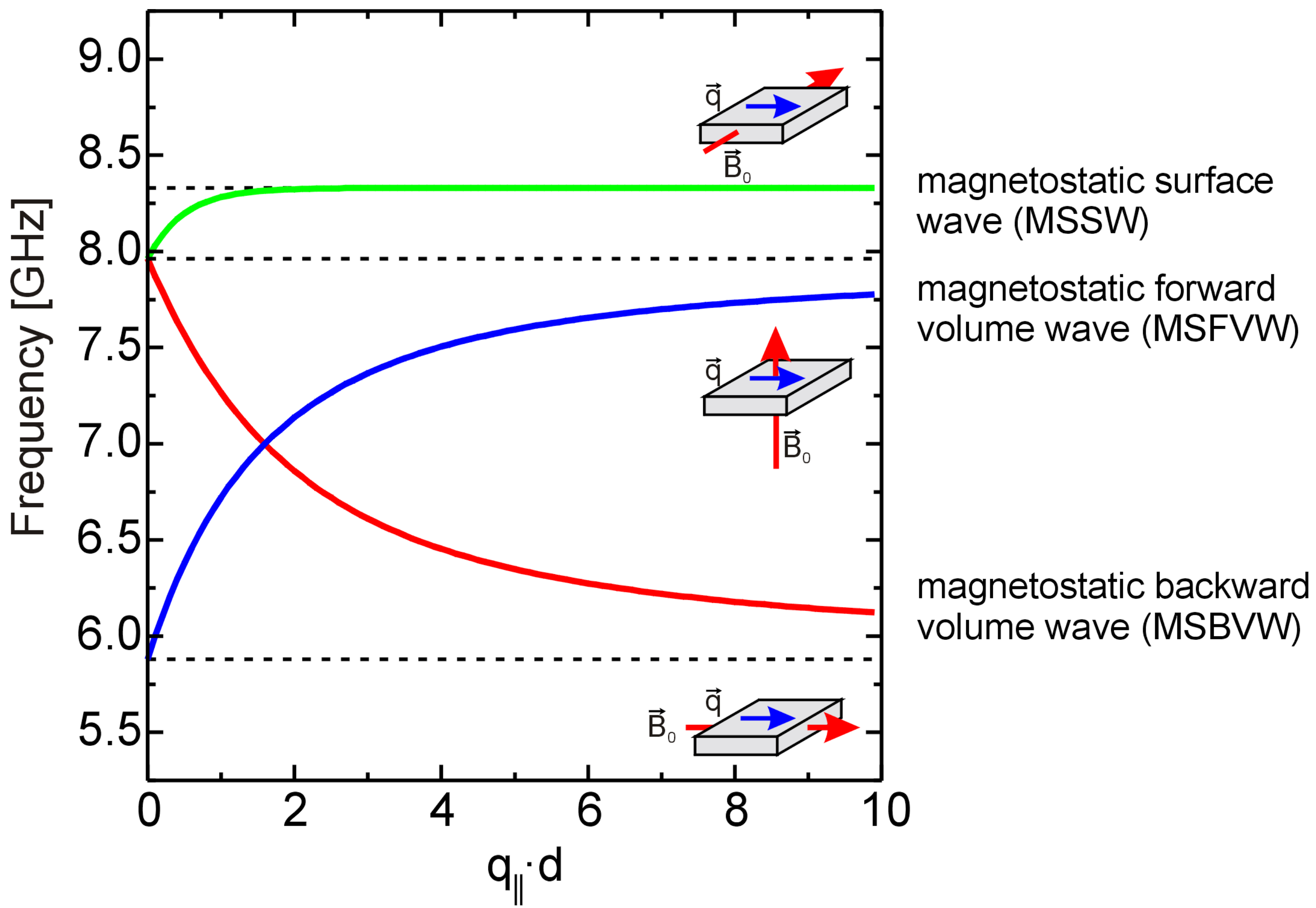
Spin waves in films: field geometry



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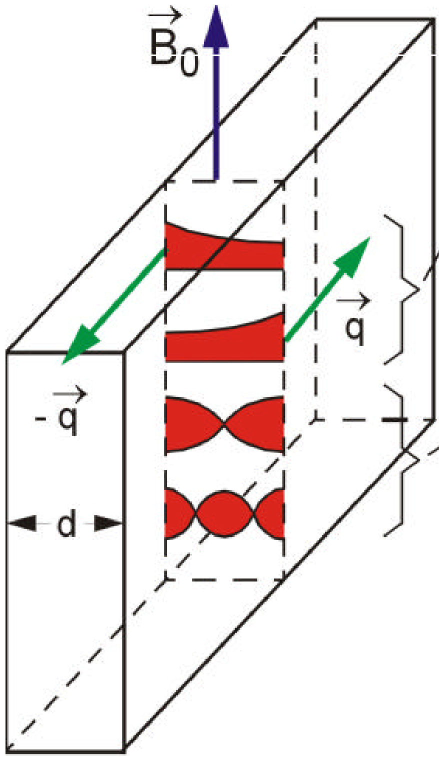
Dipolar and exchange spin waves



Dipolar Damon-Eshbach modes

$$\omega^2/\gamma^2 = [B_0(B_0 + J_s) + (J_s/2)^2\,(1- e^{-2qd})]$$

Standing spin waves

$$\frac{\omega}{\gamma} = \frac{2A}{M_s} \cdot q^2 = \frac{2A}{M_s}\left(\frac{n\pi}{d}\right)^2 \qquad n = 1,2,\ldots$$

A: exchange constant

M_s: magnetization

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Solving the Landau-Lifshitz equation

1st step:

solve LL equation of motion

$$\frac{1}{\gamma}\frac{d\vec{M}}{dt} = \vec{M} \times \vec{B}_{\text{eff}}$$

Þ 6 partial wave solutions

- non-linearity intrinsically built in due to $M_i \cdot B_{\text{eff},j}$ products

2nd step:

formulate boundary conditions

Þ coupled partial waves

a) boundary conditions from Maxwell equations

b) Rado-Weertman boundary condition (from LL-equation)

$$\vec{M} \times \left(A \frac{\partial}{\partial \vec{n}} \vec{M} - k_s \vec{n} (\vec{n} \cdot \vec{M}) \right) = 0$$

with:

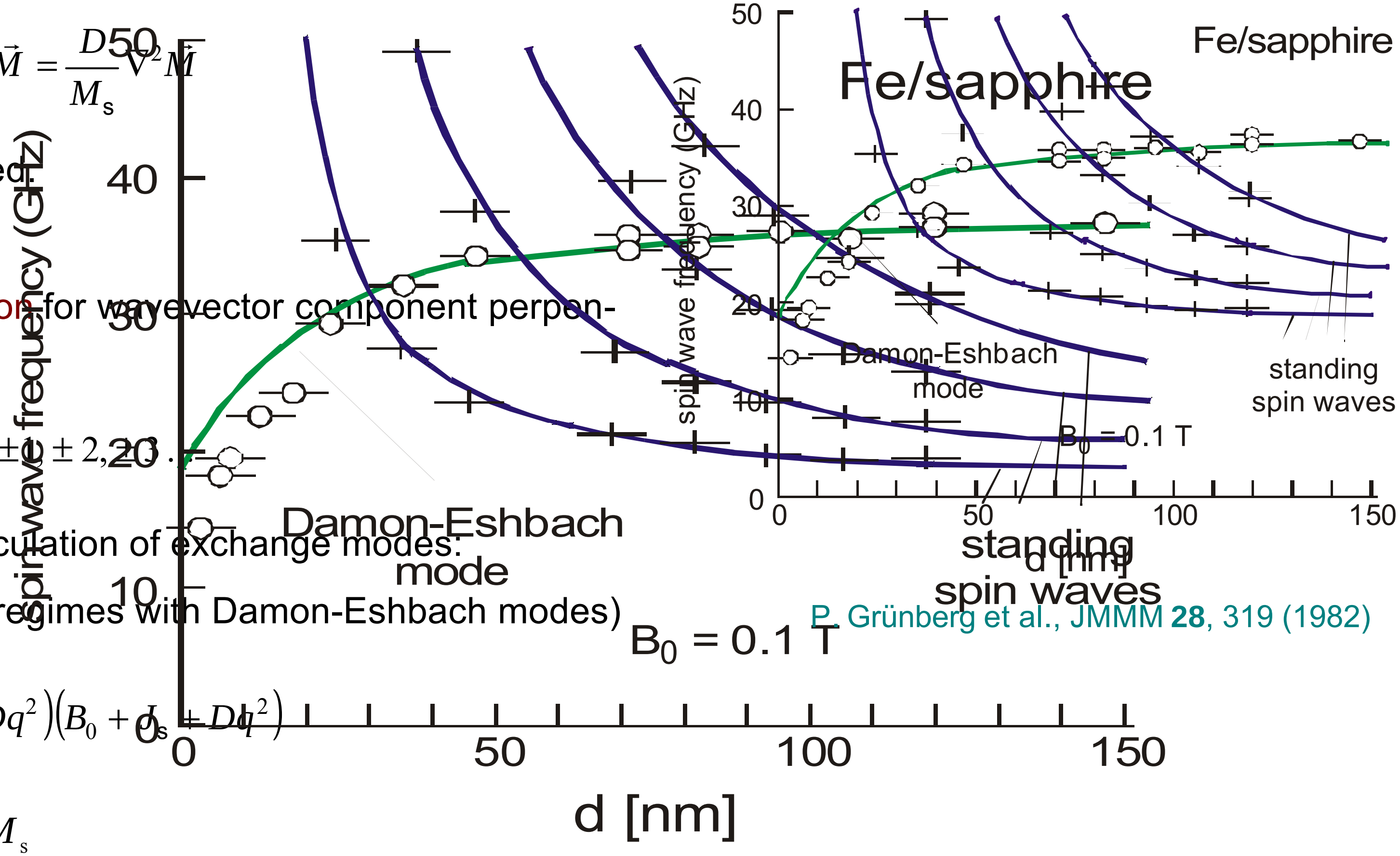
$\vec{n}$:	unit vector normal to surface
$\partial \vec{M} / \partial \vec{n}$:	derivative of $\vec{M}$ in direction of $\vec{n}$
k_s :	out-of-plane interface anisotropy constant

Exchange modes

small wavelength: exchange interaction

$$\vec{B}_{\text{exch}} = \frac{2A}{M_s^2}\nabla^2\vec{M} = \frac{D}{M_s}\nabla^2\vec{M}$$

must be considered.



resonance condition for wavevector component perpendicular to film:

$$q_\perp = n\frac{\pi}{d}; \quad n = \pm 1, \pm 2, \pm 3 \ldots$$

approximative calculation of exchange modes:

(outside crossing regimes with Damon-Eshbach modes)

$$\left(\frac{\omega}{\gamma}\right)^2 = \left(B_0 + Dq^2\right)\left(B_0 + J_s + Dq^2\right)$$

with: $D = 2A/M_s$

P. Grünberg et al., JMMM **28**, 319 (1982)

Experiments on spin dynamics

Experiments on the time scale:

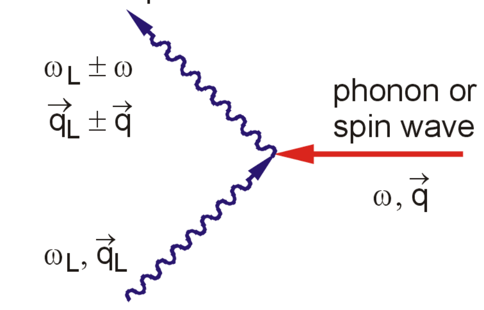
- **suppression of precession**
- **magnetic switching**

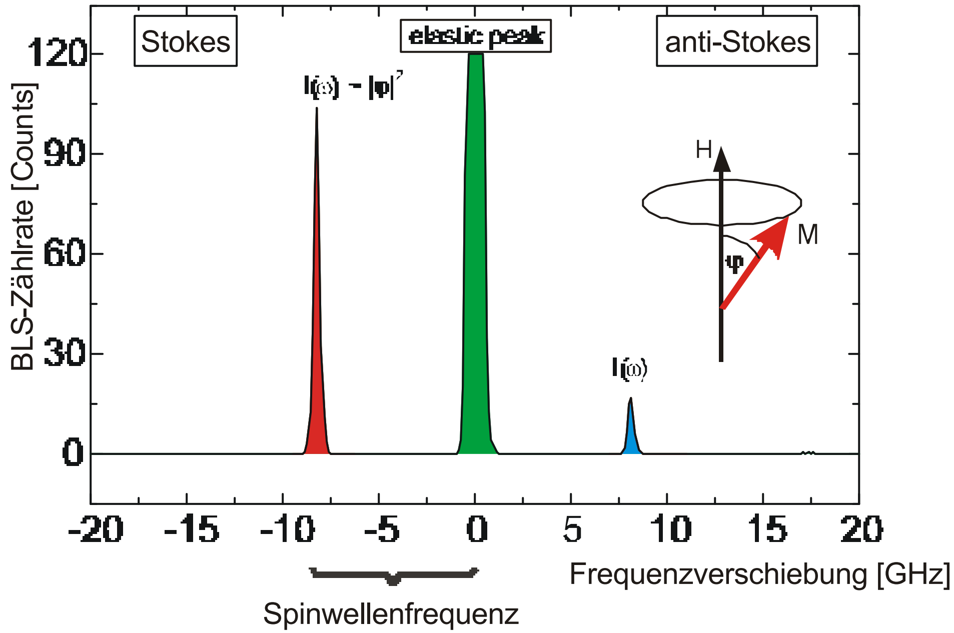
Experiments on the frequency scale:

- **dynamic eigen-excitations of islands**
- **excitations in inhomogeneous internal fields**

Brillouin light scattering (BLS) process

= inelastic scattering of photons from spin waves

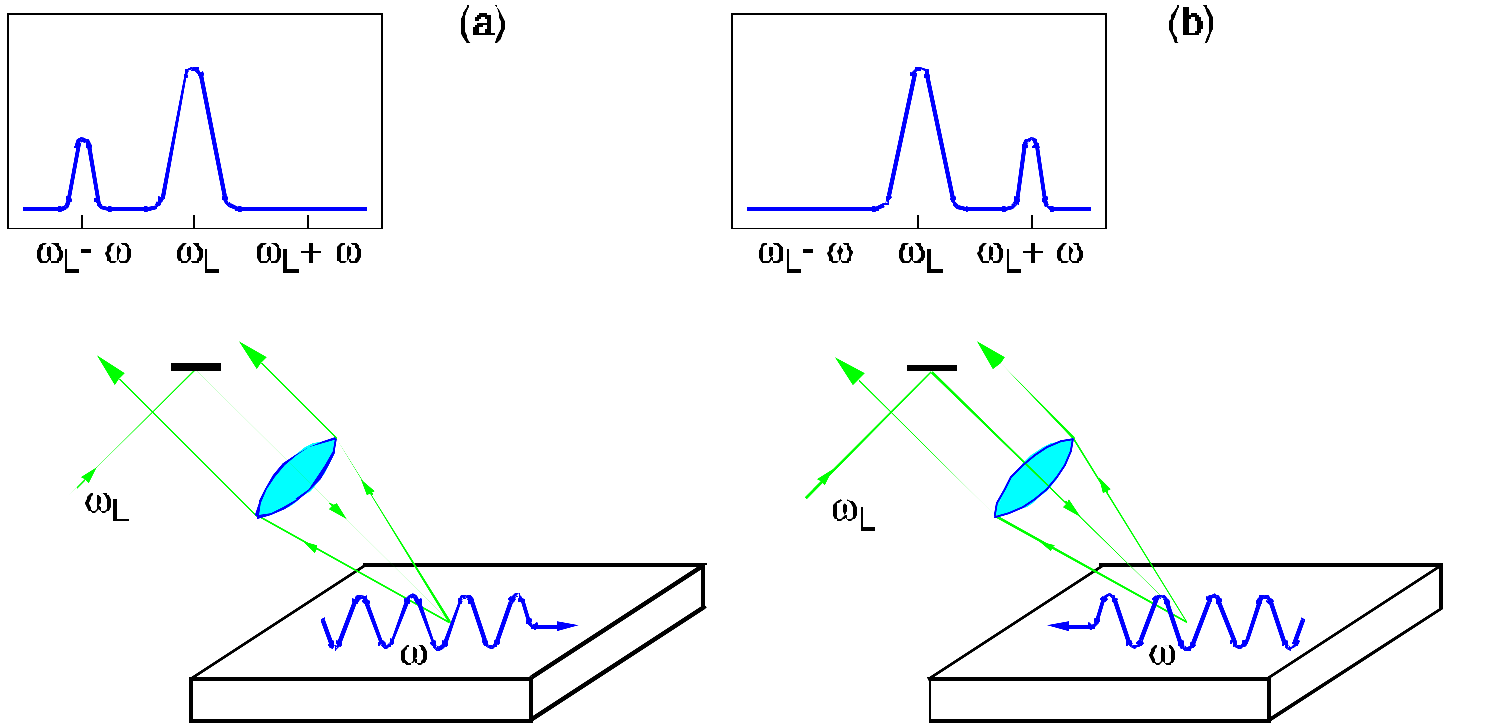




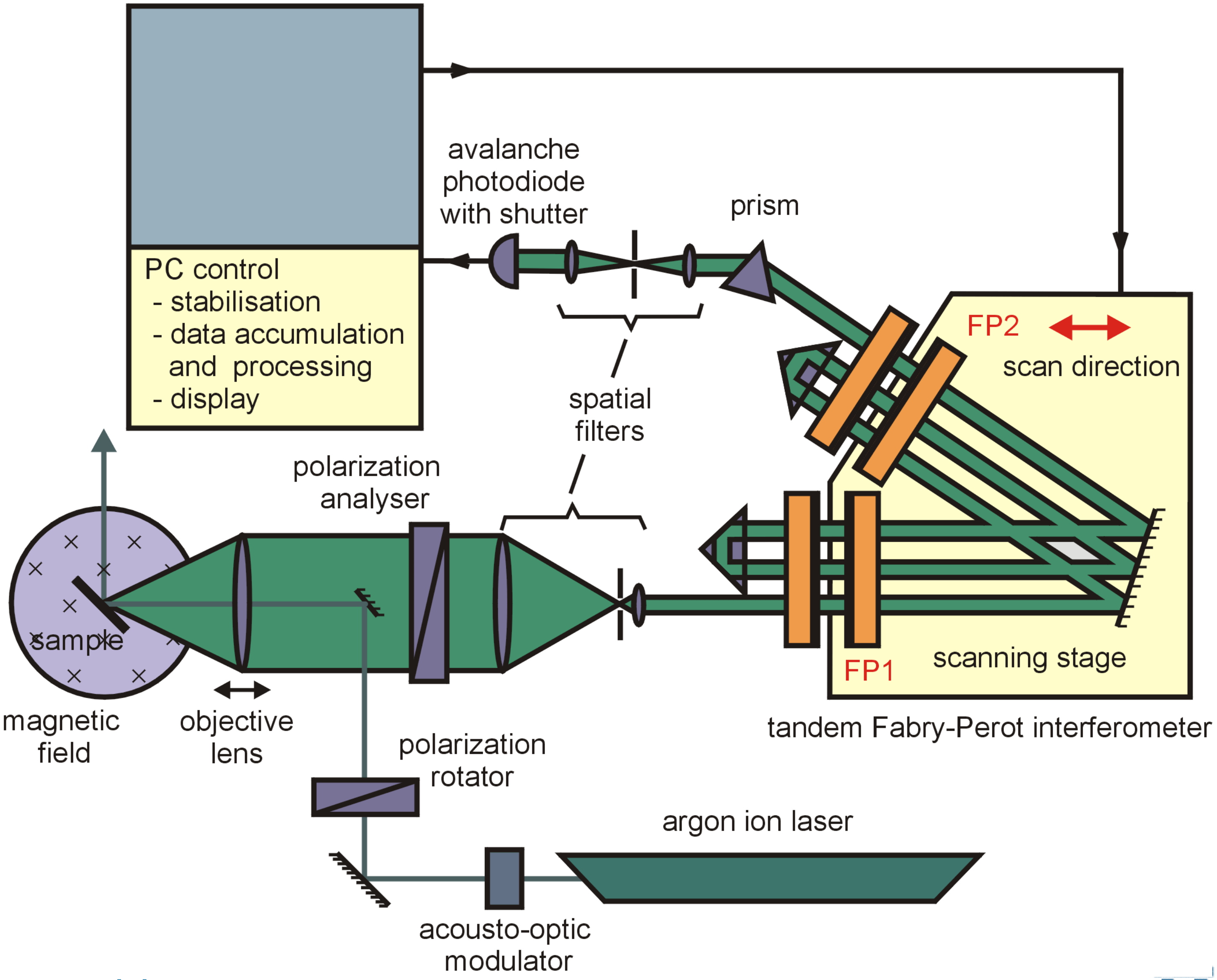
Conservation laws:

- Time invariance Þ $\omega_{sc} = \omega_L \pm \omega$
- In-plane translational invariance Þ $\vec{q}_{SC} = \vec{q}_L \pm \vec{q}$

Light scattering cross section



BLS spectrometer



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BLS spectrometer (2)

frequency range: 1–500 GHz
resolution: 0.1 GHz (or 1% of free spectral range)
contrast: > $1:10^{10}$ (multipass arrangement)
laser spot diameter: 40 µm
magnetic sensitivity: $7 \cdot 10^{10}$ Co atoms ($2 \cdot 10^{-9}$ emu) at 300 K
wavevector range: $0 – 2.4 \cdot 10^{5}$ cm^{-1}
determined quantities: dispersion of

- surface acoustic waves
- spin waves
- nonlinear spin wave phenomena

BLS spectroscopy

Observation of:

- dispersion of acoustic phonons in the volume, on surfaces and in films
  $\Rightarrow$ elastic properties

- dispersion of spin waves in magnetic materials
  $\Rightarrow$ anisotropies, magnetic moments, magnetic exchange constant

- nonlinear spin waves at large precession angles

Light scattering cross section

- spin orbit coupling generates phase grating in refractive index propagating with speed of spin wave

electric polarization *P* in medium:

$$\vec{P} = (\varepsilon_{11} - 1)\varepsilon_0 \vec{E} + K / M_s \ (\vec{E} \times \vec{M}_s)$$

with *K*: magneto-optic coefficient

- light is refracted at phase grating
- frequency is Doppler shifted

Conclusions (I)

exchange and dipole coupling are the most important interactions in spin systems

spin dynamics is determined by the Landau-Lifshitz-equation

spin waves are non-uniform eigenmodes of the system

properties of spin waves reflect the dimensionality of the system

Brillouin light scattering(BLS) is a powerful tool for studies of spin waves

different spin wave modes can be investigated separately

BLS sensitivity is high enough to allow experiments on ultra-thin films