Magnetic dynamics driven by spin current

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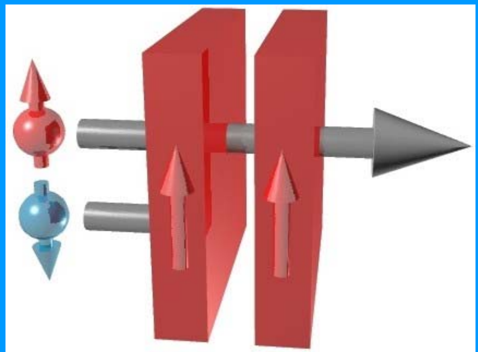
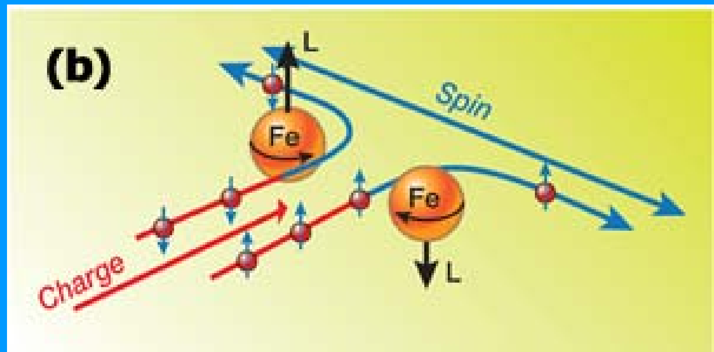


Giant magnetoresistance



Spin current

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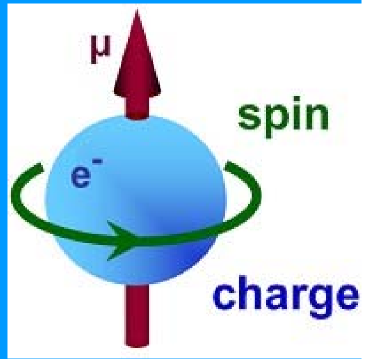
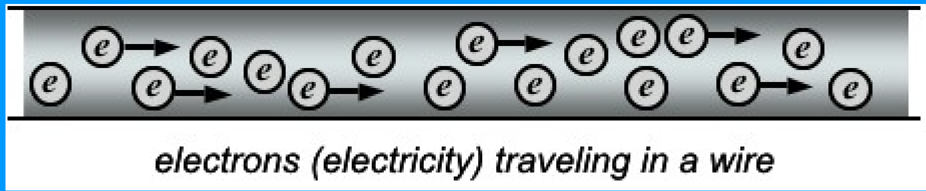
Group of NonLinear Magnetic Dynamics

Charge current vs spin current

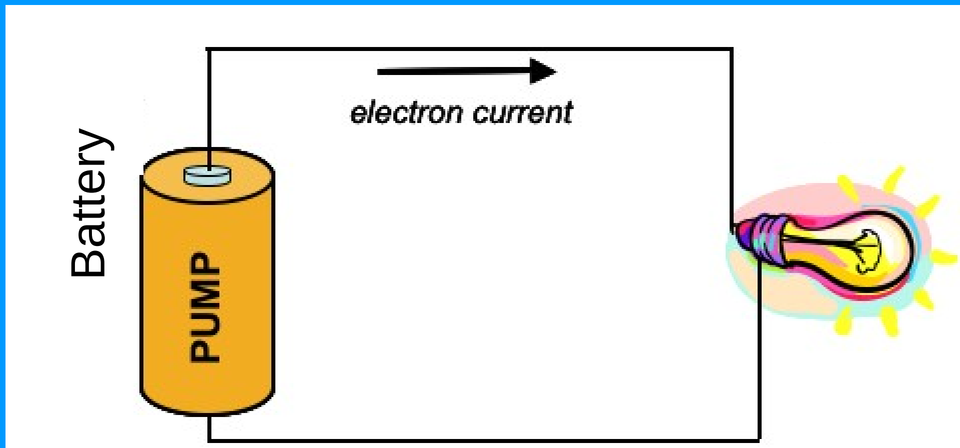
Electron: possesses both electric charge and spin (angular momentum)



Electronics is based on the flow of charge of electrons.



For an electric circuit we need sources of electric current (battery), conductors for electron flow (metallic wire), detectors of the current (lamp)

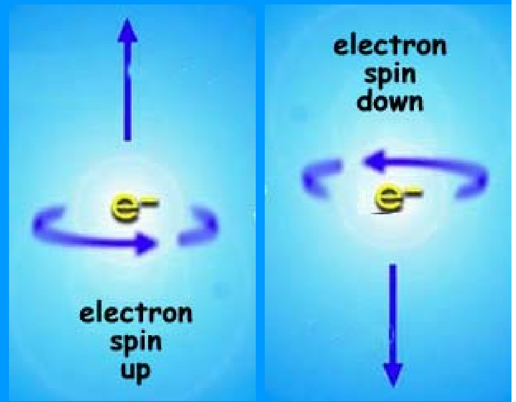


Charge is a scalar. It is conserved.

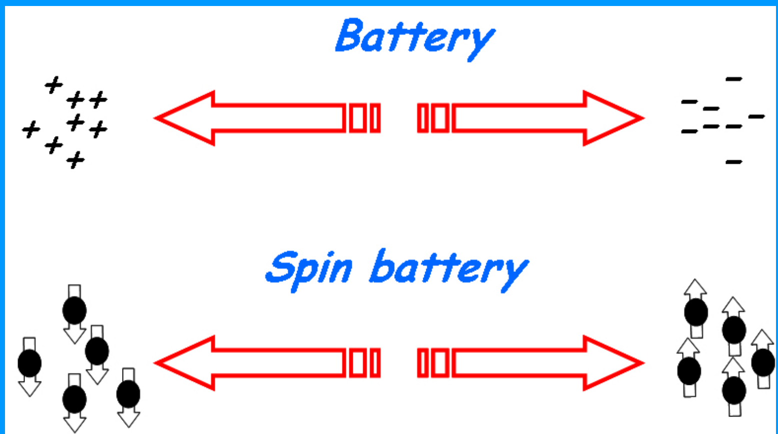
Charge current vs spin current

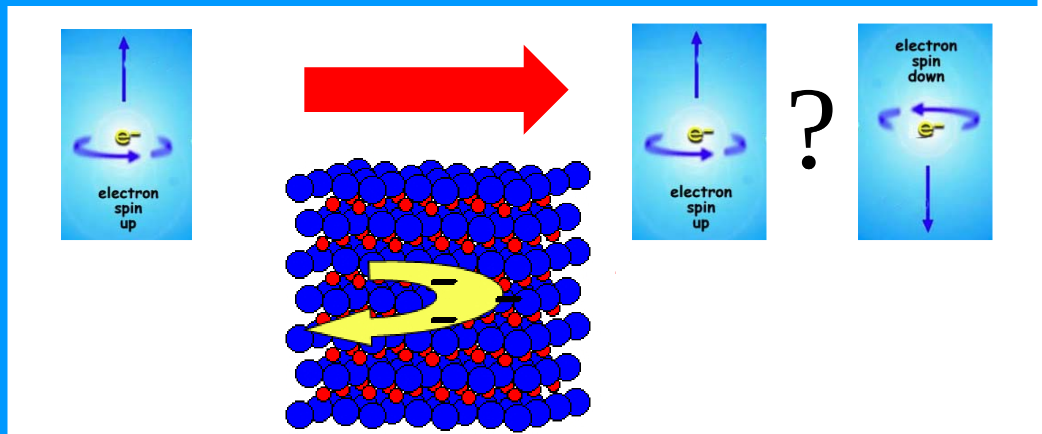
Electron: possesses both electric charge and spin

Spintronics is based on the flow of spin of electrons.



Do we have sources of spin current (battery), conductors for spin flow, detectors of the spin current (spin-lamp)?





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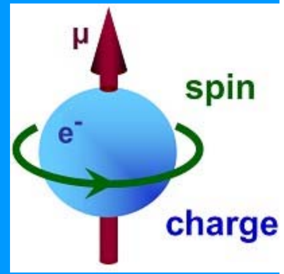
Spin-polarized vs pure spin current



Electron: possesses both electric charge and spin.

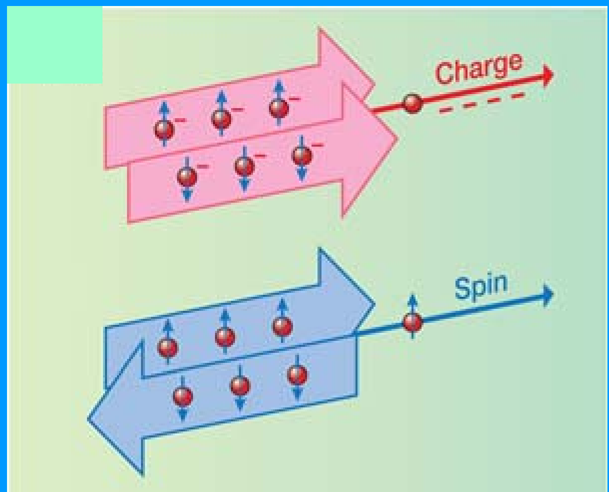
Since spin is a vector, we can separate electric and spin currents.

Electric current: motion of electrons with disordered spins

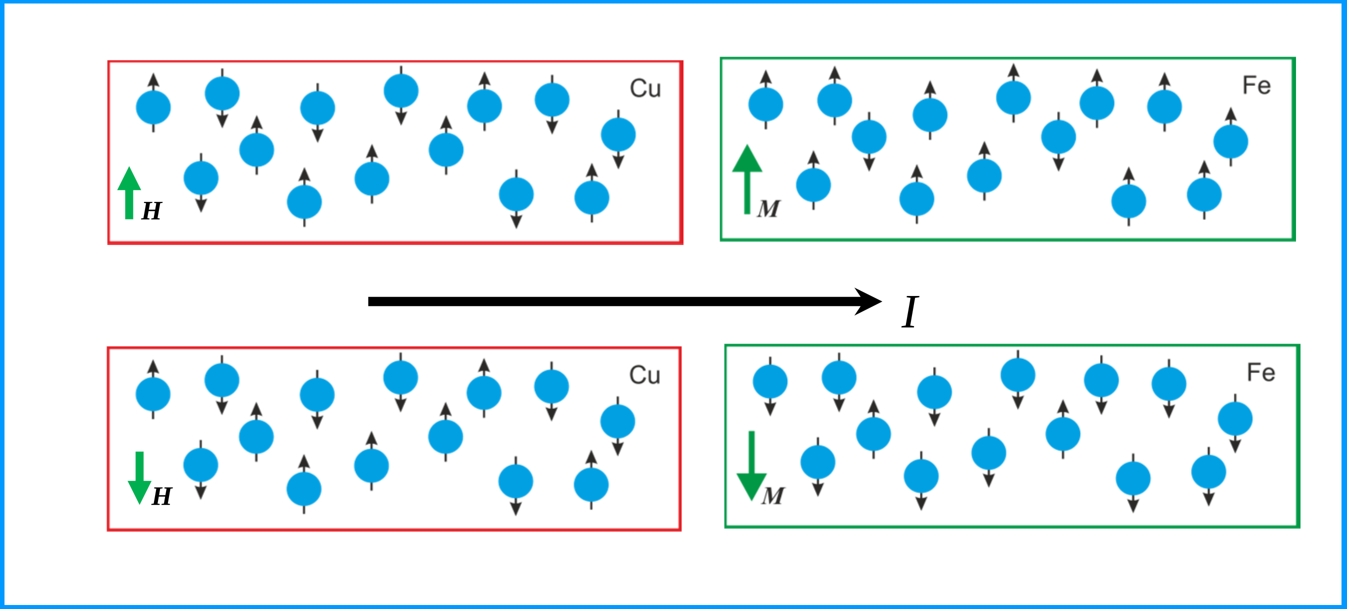
Spin-polarized current: motion of electrons with ordered spins.

Pure spin current: motion of ordered spin without motion of charge.

	Charge current	Spin current
Unpolarized current		0
Spin-polarized current		
Fully spin-polarized current		
Pure spincurrent	0	



Spin-polarized electric current



Spin-up and spin-down electrons equally contribute to the current

Non-polarized electric current

Symmetry with respect to spin-up and spin-down is broken

Spin-polarized electric current

Spin-polarized electric current

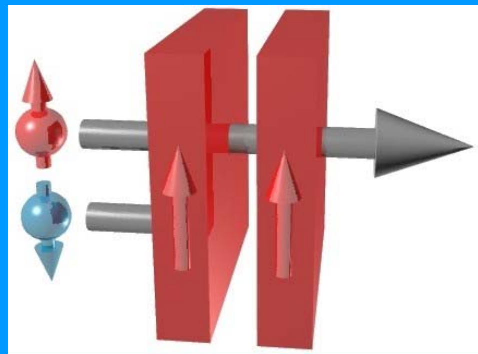
Does spin-polarized electric current have advantages?

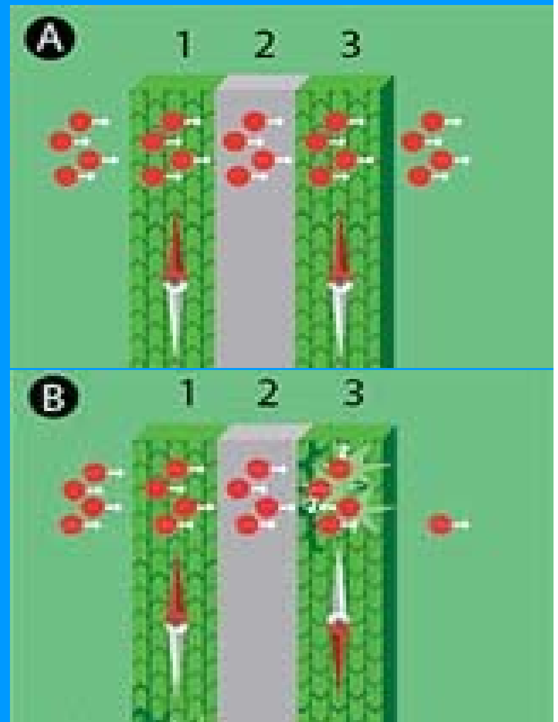
Spin-polarized electric current

Does spin-polarized electric current have advantages? YES!!!

Giant Magnetoresistance (GMR) effect.

If electrons are injected in a ferromagnet they can freely move or will be strongly scattered depending on the orientation of their spins with respect to the magnetization





Spin-polarized electric current

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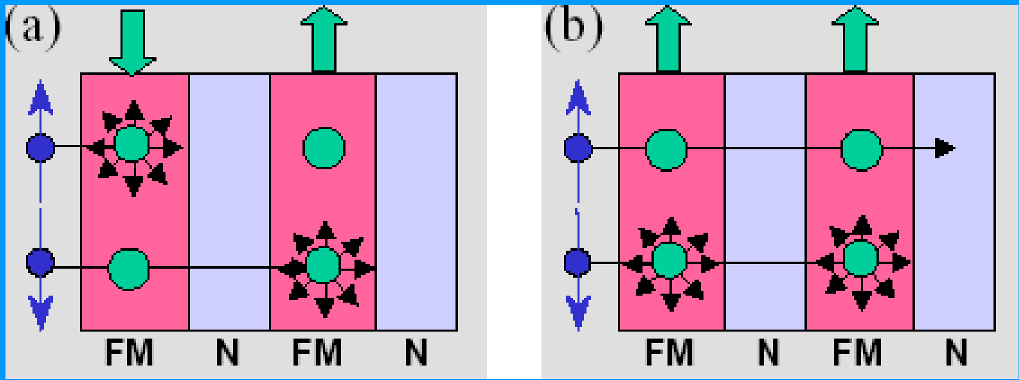
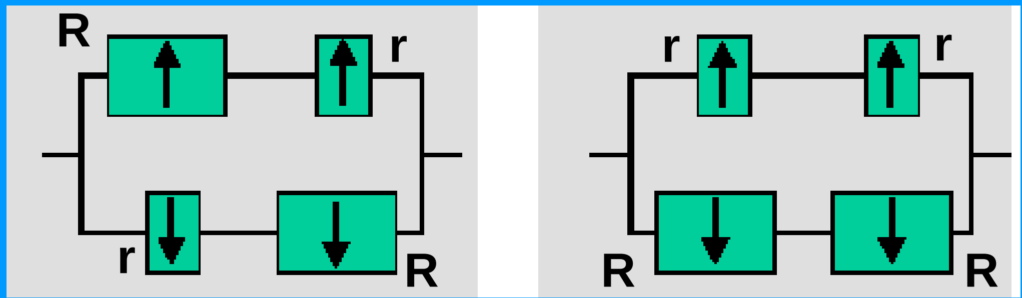


$$R^{AP} = \frac{R+r}{2} \approx \frac{R}{2} \quad R >> r$$

$$R^{P} = \frac{2r \times 2R}{2r+2R} = \frac{2rR}{r+R} \approx 2r \quad R >> r$$

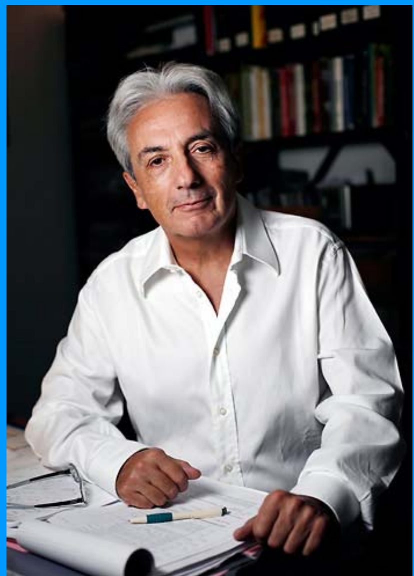


Spin-polarized electric current

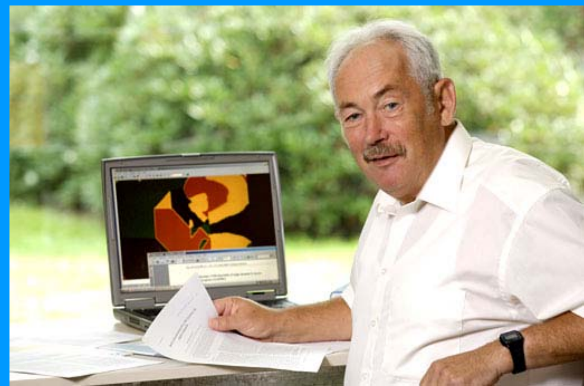
Does spin-polarized electric current have advantages? YES!!!

Giant Magnetoresistance (GMR) effect.

Application: computer hard drives



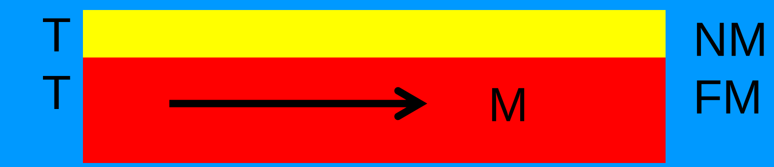
Albert Fert



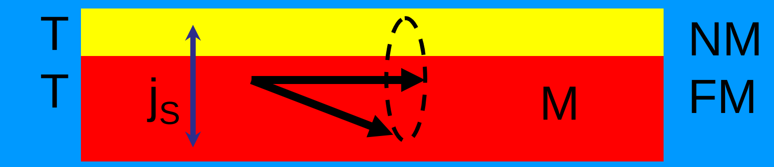
Peter Grünberg

The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg "for the discovery of Giant Magnetoresistance"

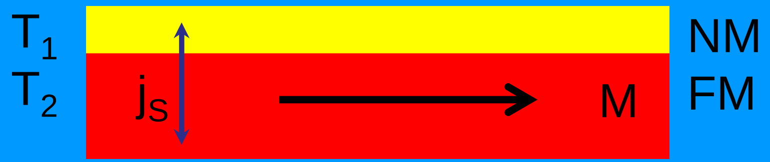
Spin current between FM and non-magnetic metal



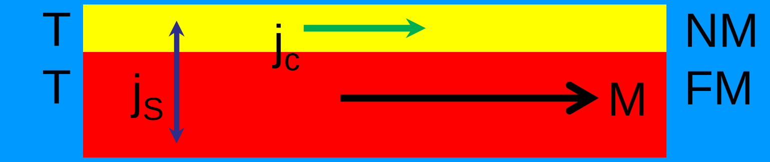
No spin current at the equilibrium



Spin current due to magnetization dynamics (spin-pumping)

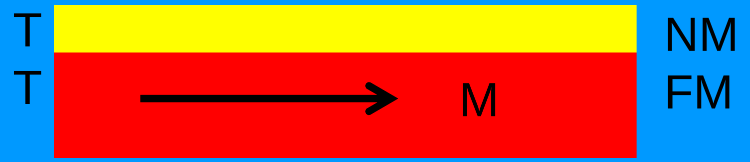


Spin current due to temperature gradient (spin Seebeck effect)

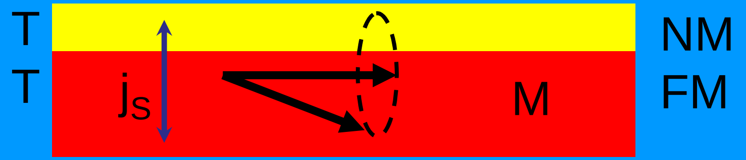


Spin current caused by charge current (spin Hall effect)

Spin current between FM and non-magnetic metal



No spin current at the equilibrium



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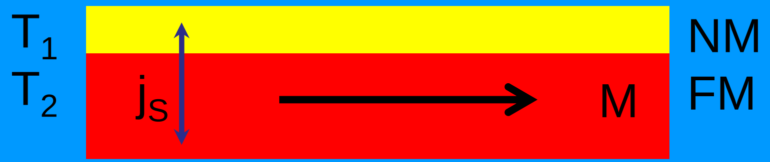

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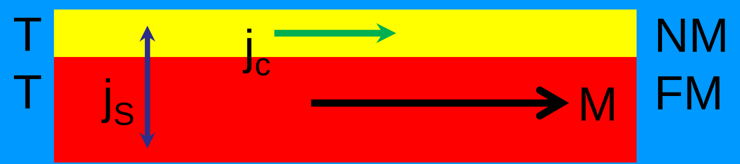
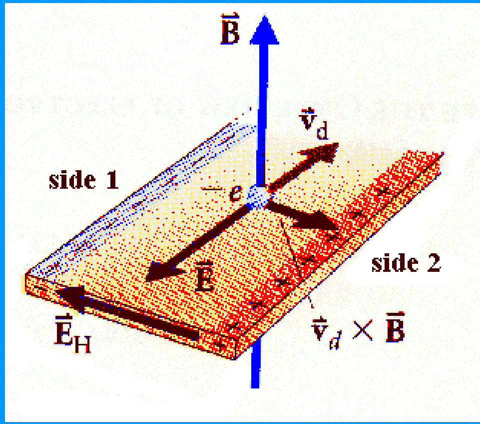


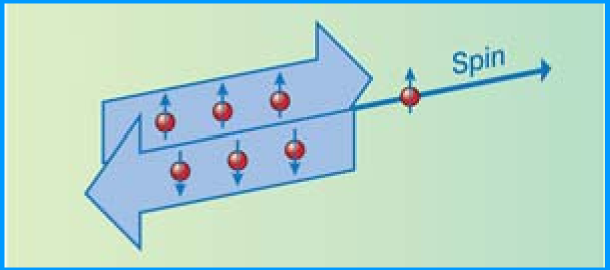
Spin current caused by charge current (spin Hall effect)

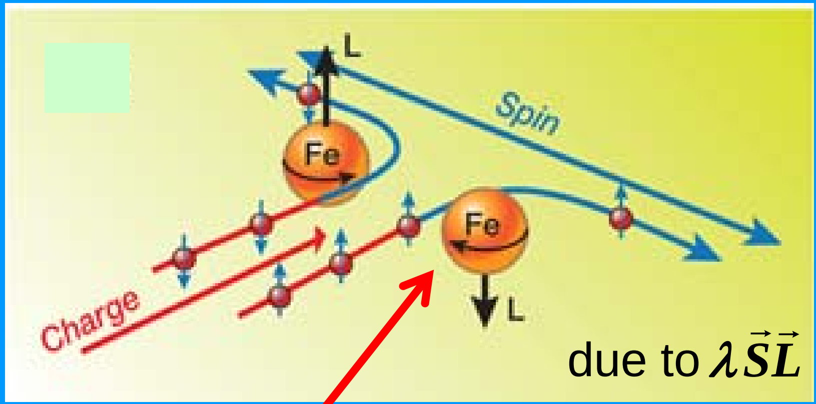
Spin-battery: Spin Hall effect

Ordinary Hall effect: separation of particles with positive and negative charges.



Spin Hall effect: separation of particles with spin up and down.

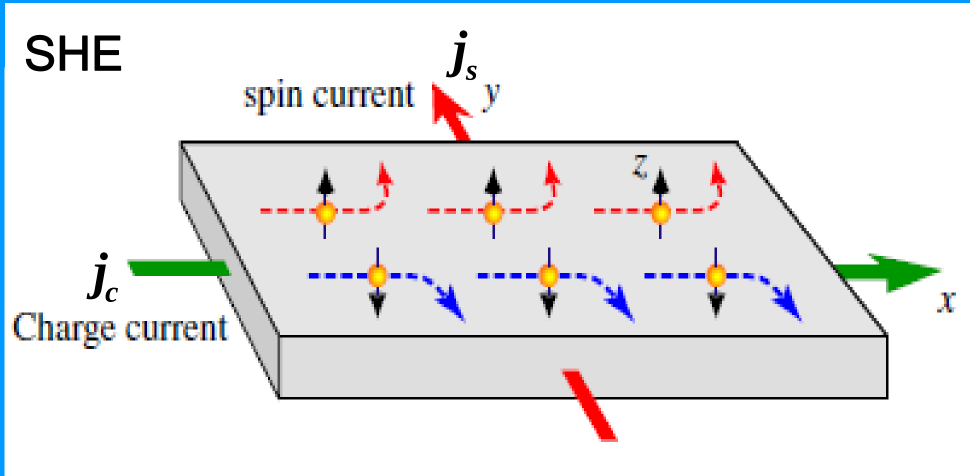




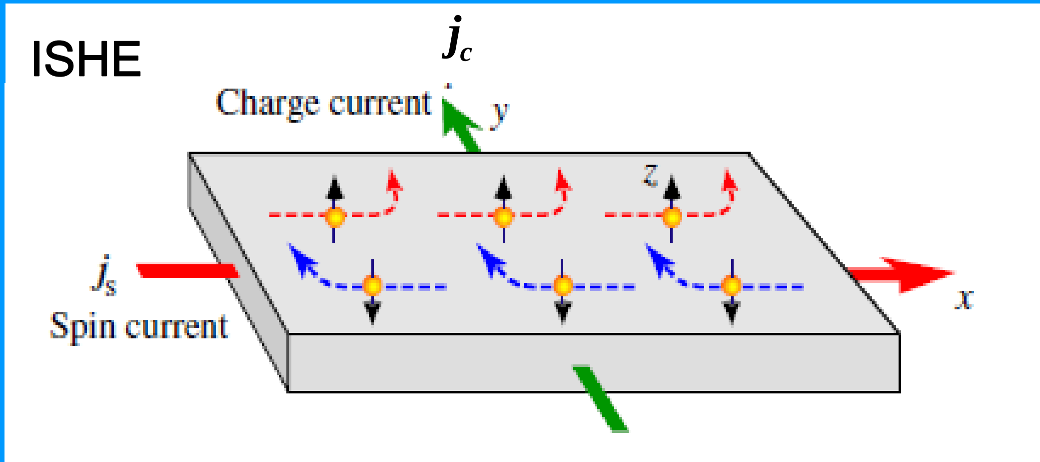
Magnetic impurities in normal metal

Spin Hall vs inverse spin Hall

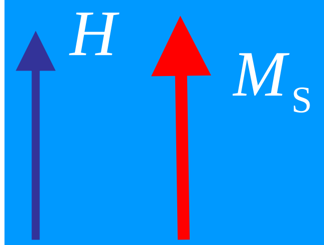
Spin Hall Effect
spin current battery



Spin Hall Effect
spin current detector

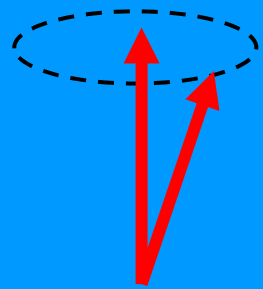


Magnetic dynamics of ferromagnets



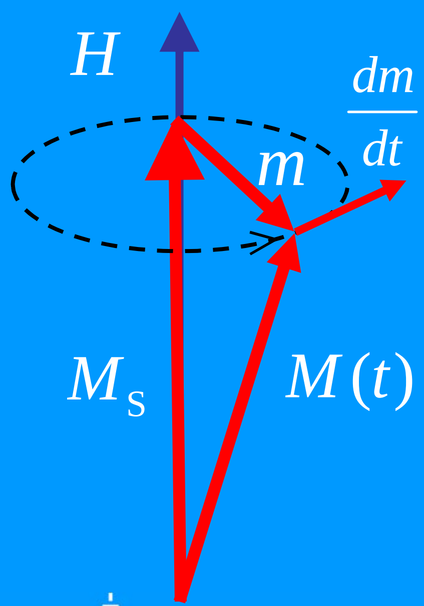
Static: magnetization is aligned along the magnetic field

The dynamic of a ferromagnet: precession
of the magnetization around the field.
Reduction of the static magnetization.



It is described by the Landau-Lifshitz-Gilbert equation

$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H} + \alpha_0 \mathbf{m} \times \frac{d\mathbf{m}}{dt}$$

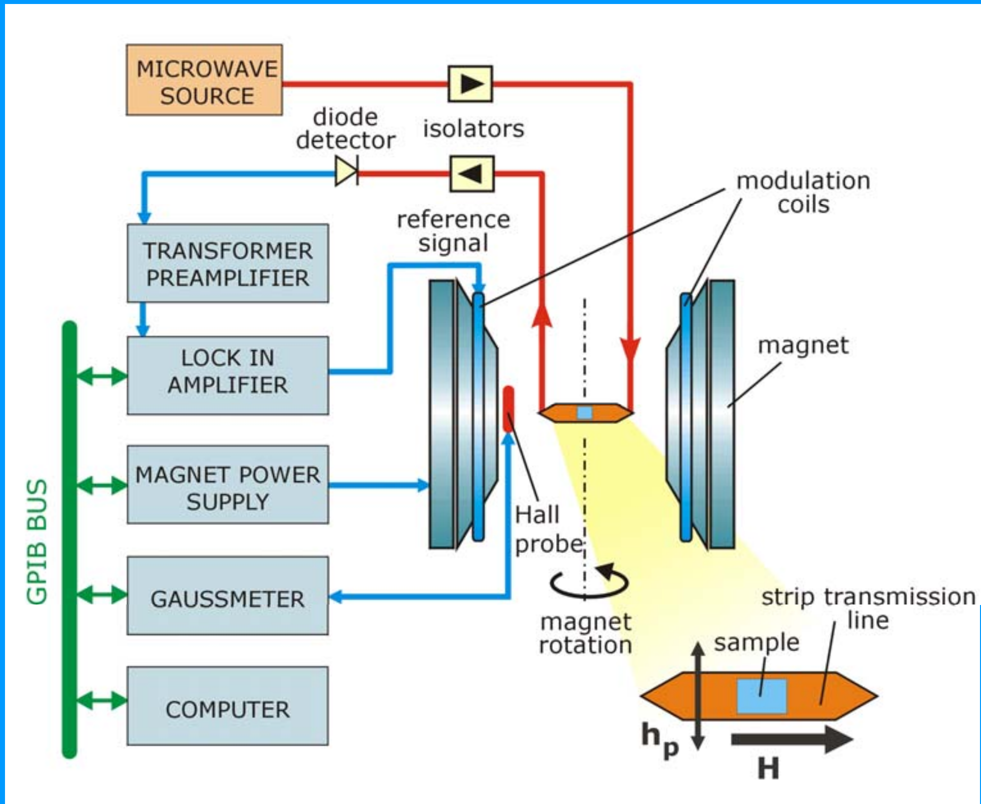


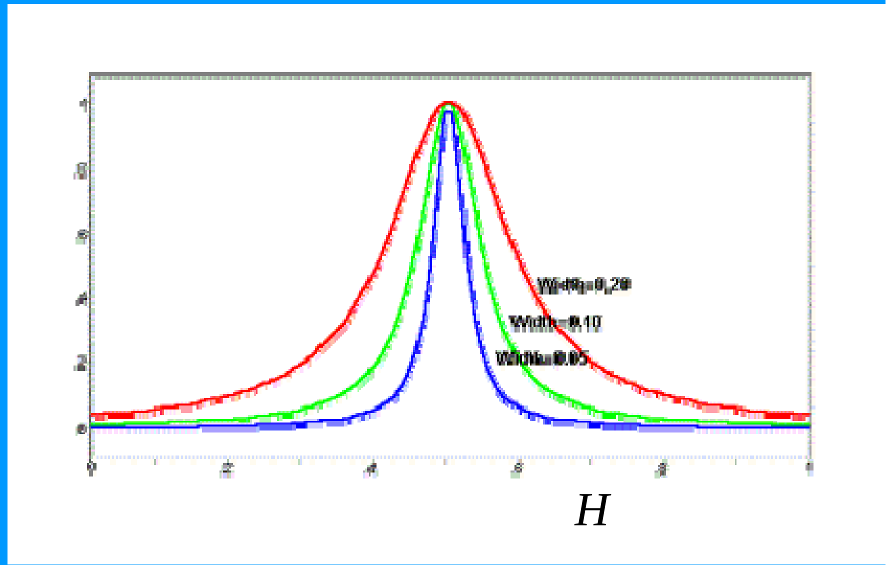
where α_0 is the Gilbert damping constant (spin-lattice relaxation)

Damping is due to transfer of the angular momentum from magnetic system to the lattice.

If one applies a dynamic magnetic field with a correct frequency, a persistent precession can be achieved.
Relaxation of magnetic moment to the lattice is compensated by the torque of the dynamic field

Ferromagnetic resonance (FMR)

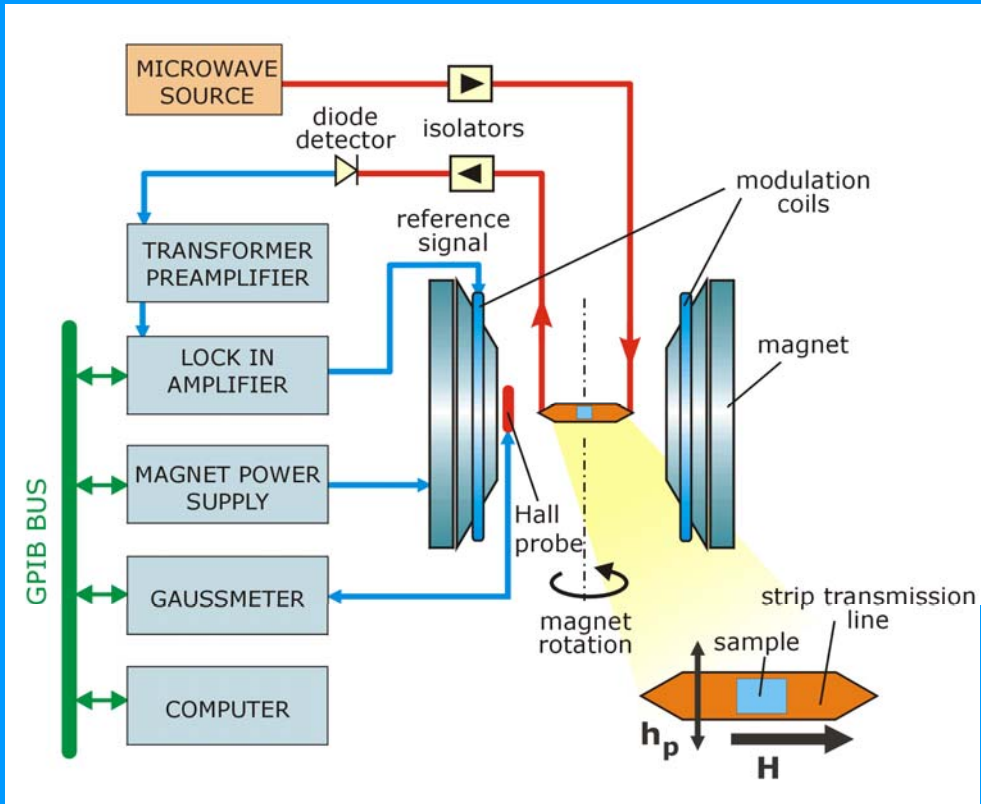


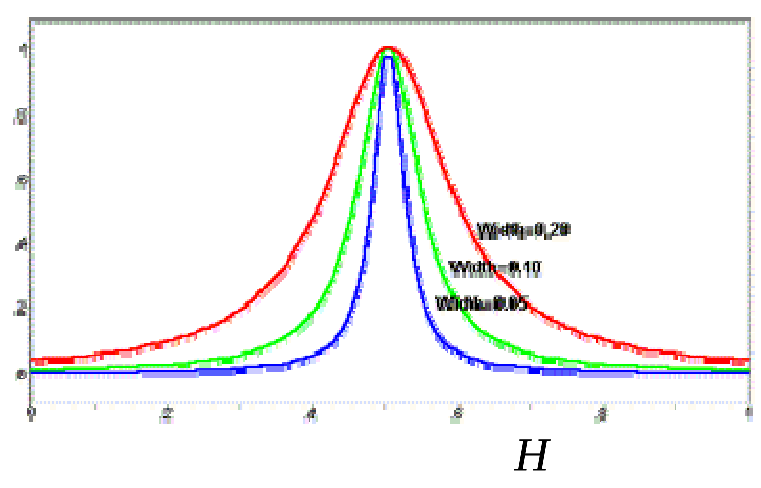


By sweeping the magnetic field (frequency of the precession) one can recoird the FMR-line.

Can we control the FMR-line by spin current?

Ferromagnetic resonance (FMR)



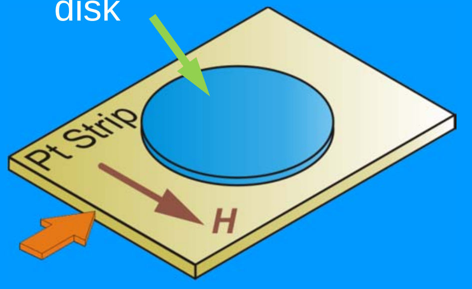


By sweeping the magnetic field (frequency of the precession) one can recoird the FMR-line.

Can we control the FMR-line by spin current? YES!!!

Test devices

Permalloy (Py) disk



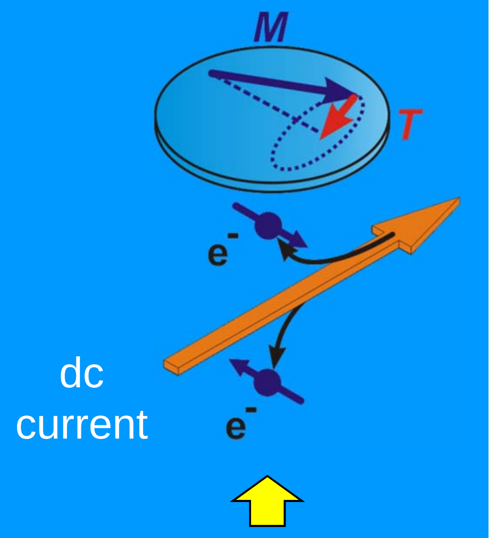
dc current
[+ microwave current]

Disk: Permalloy (Py), ∅2 μm, 5 nm thick

Microstrip: Pt, 2.5 μm wide, 10 nm thick

dc current is applied through the Pt strip.

The operation of the device relies on the spin Hall effect (SHE) induced by electrical current in the Pt strip.



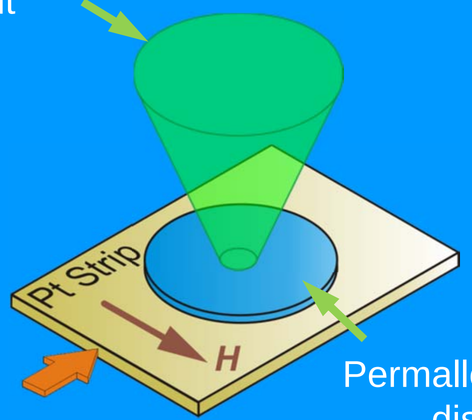
SHE produces a spin current at the interface with the Py dot, exerting spin transfer torque (STT) on its magnetization.

Depending on the direction of the current, spin current either stabilizes or destabilizes the magnetization.

SHE originates from spin-orbit scattering resulting in a deflection of conduction electrons with opposite spin orientations in opposite directions.

Measurement technique

To detect the magnetization dynamics we use
micro-focus Brillouin Light Scattering (BLS) spectroscopy.



1. Probing laser light is focused onto the surface of the magnetic film into a diffraction-limited spot.
2. Light scattered from magnetic excitations is analyzed.

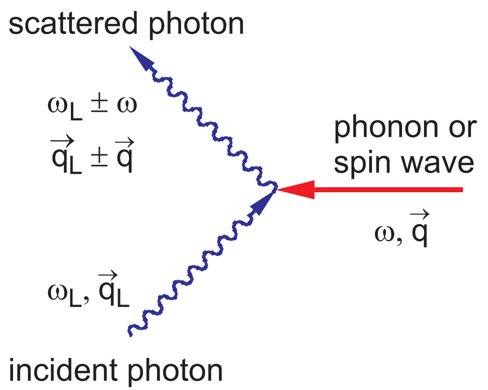
BLS signal is proportional to the
square of the dynamic magnetization
at the position of the probing light spot.

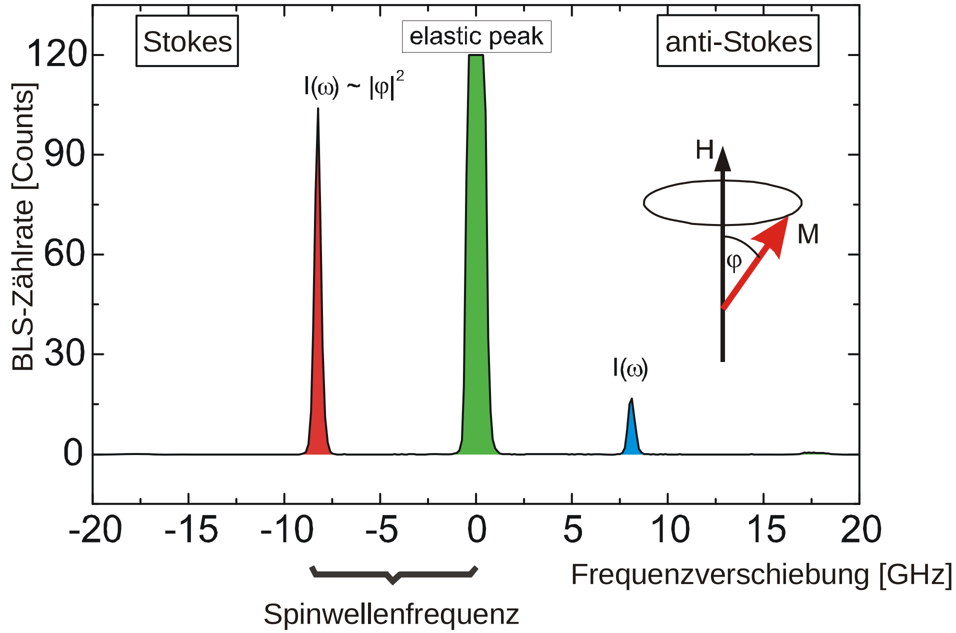
Available resolutions:

1. Frequency resolution 0.05-1000 GHz
2. Temporal resolution < 400 ps
3. Spatial resolution < 250/50 nm
4. Wavevector resolution < 10^6 cm^{-1}
5. Phase resolution

Brillouin light scattering process

= inelastic scattering of photons from spin waves



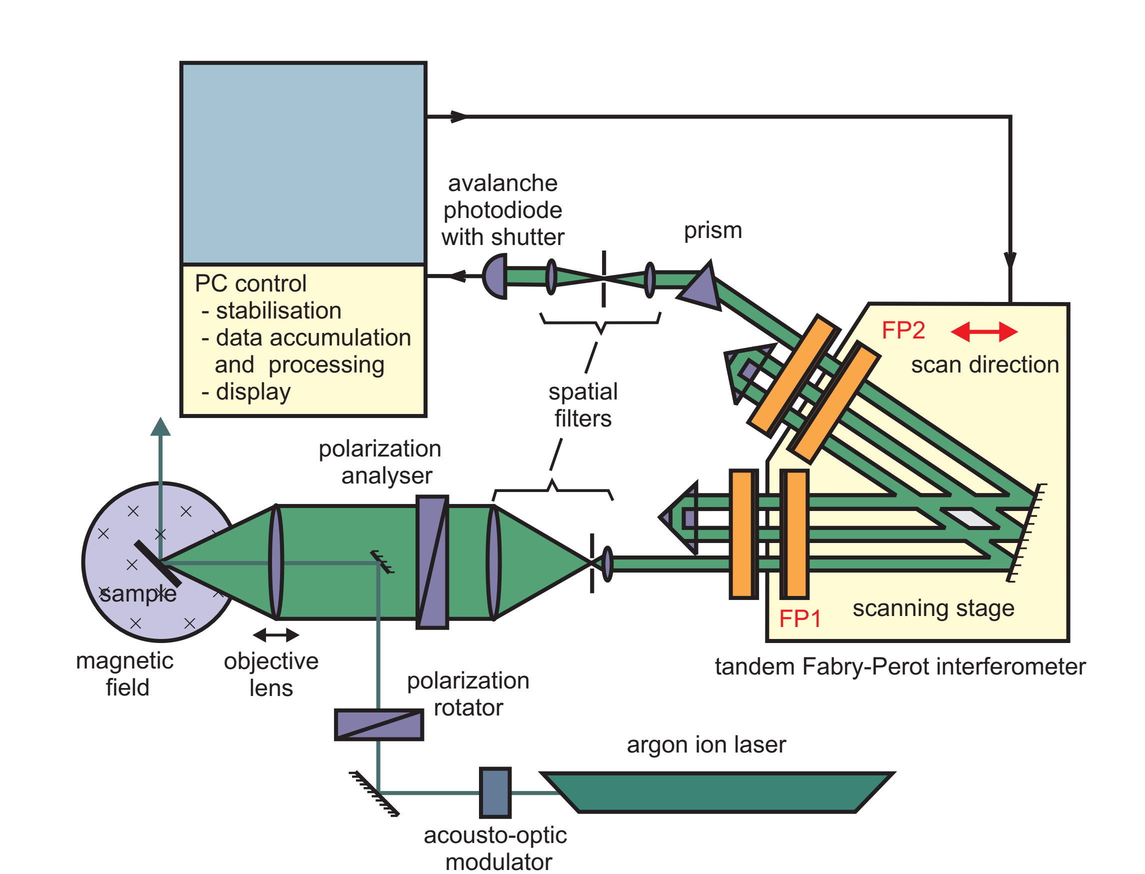


Conservation laws:

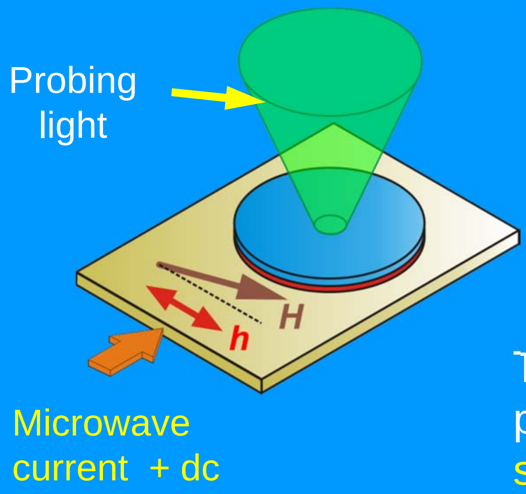
- Time invariance ⇒ $\omega_{sc} = \omega_L \pm \omega$
- In-plane translational invariance ⇒ $\vec{q}_{SC} = \vec{q}_L \pm \vec{q}$

Brillouin spectrometer

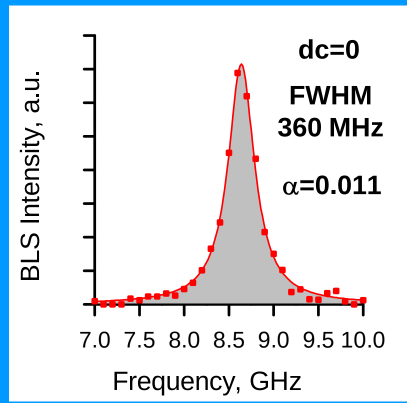
high resolution and contrast



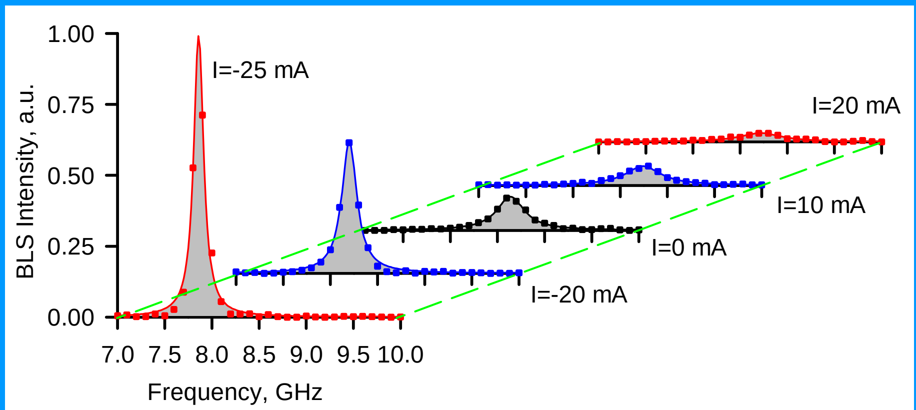
Control of effective damping in FMR



The FMR curve recorded without the dc current shows a linewidth of 360 MHz at H=900 Oe.



This corresponds to Gilbert damping parameter α=0.011, which is close to the standard value α=0.008 for Permalloy.

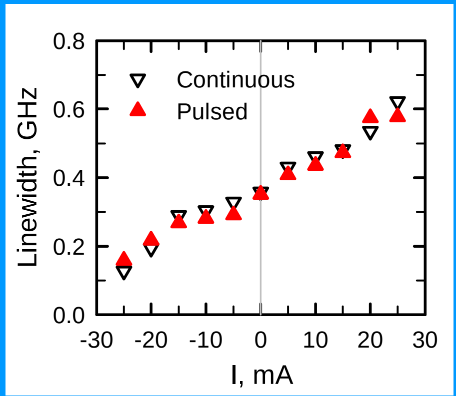


Effect of the current

Positive current: broadening of the FMR peak and reduction of its amplitude.

Negative current: increase of the amplitude and narrowing of the peak.

Control of effective damping in FMR

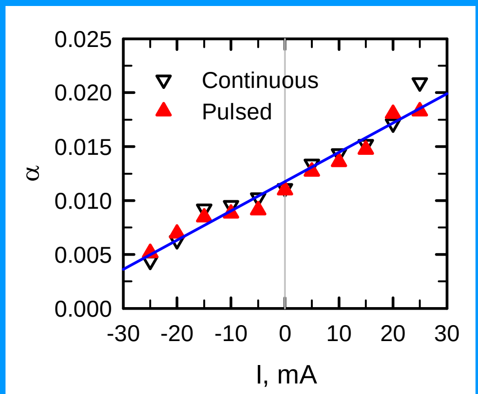


FMR Linewidth

The linewidth practically does not depend on whether the current is constant or pulsed (influence of the heating is negligible). ⇒

Dependence of the linewidth on *I* can be attributed entirely to the effect of the spin current.

Linewidth shows strong variation with current. ⇒ The effect of the spin current on the damping is not significantly reduced by the presence of the Cu spacer.



Effective Gilbert damping parameter α

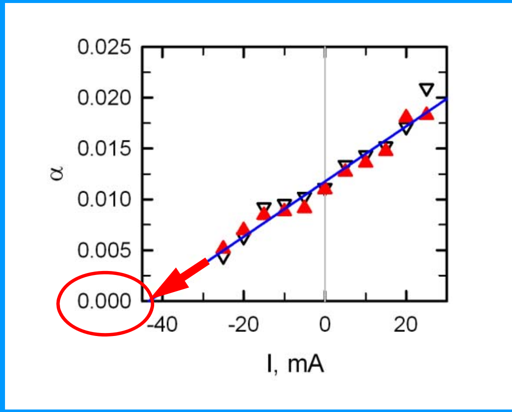
$$\alpha = \frac{\Delta f}{2\gamma(H + 2\pi M_e)}$$

The achieved variation of α is more than by a factor of 4.

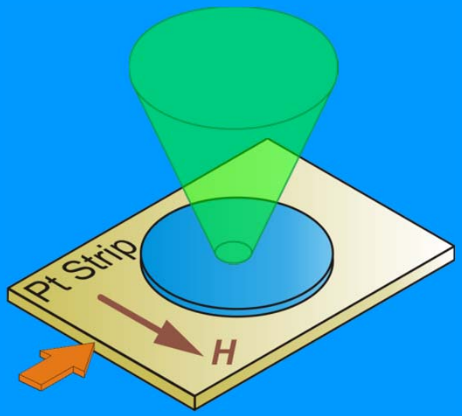
The smallest achieved α=0.004 is by a factor of 2 smaller than the standard value for Permalloy.

Our ultimate goal:

To compensate completely the dynamic damping and to achieve excitation of coherent magnetization dynamics by spin current without application of microwaves



Control of magnetic fluctuations

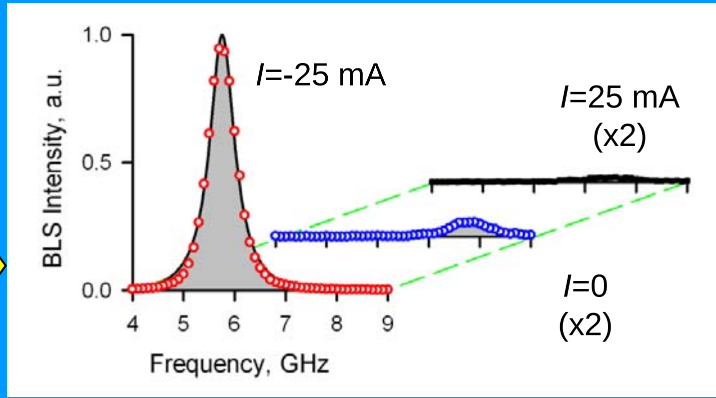


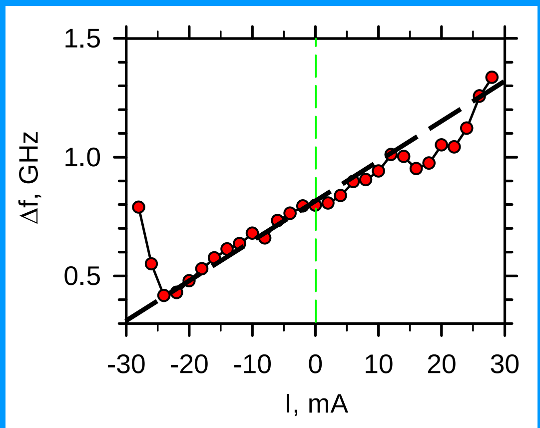
dc current
~~+ microwave current~~

Thermally-excited unifrom fluctuations are detected by BLS.

BLS spectra exhibit a peak with a Lorentzian shape.

The amplitude of the peak decreases at *I*>0 and increases at *I*<0.



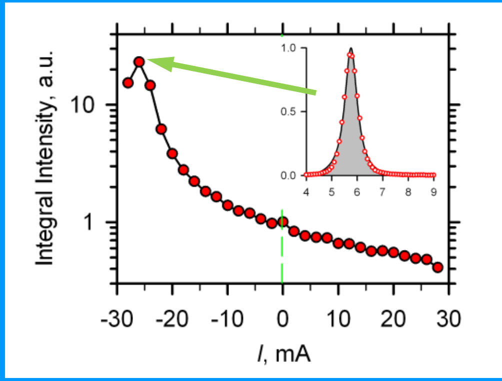


The linewidth varies linearly with current at small *I*.

These behaviors are typical for modification of the effective damping by STT.

Control of magnetic fluctuations

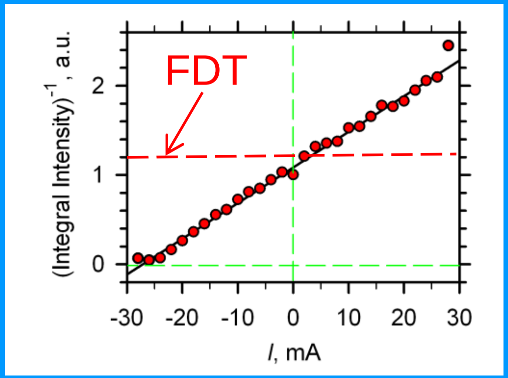
The integral under the measured peak is proportional to the average fluctuation energy in the mode.



At I=-28 mA, the integral intensity increases by more than a factor of 30, and at I=28 mA it decreases by more than a factor of 2.

Besides modifying the damping, STT changes the energy of magnetic fluctuations.

This phenomenon can be used for effective "cooling" of a magnetic system and provides practical ways for reduction of thermal noise in magnetic nano-devices.



In agreement with the non-equilibrium theory, the inverse integral intensity shows linear dependence on the current.

At I=I_c=-28 mA the integral intensity is expected to diverge (onset of auto-oscillations).

Instead, it saturates and starts to decrease at I<-26 mA.

Time-resolved measurements

Close to the auto-oscillation onset, the flow of energy into the uniform mode saturates, whereas short-wavelength modes are further enhanced.

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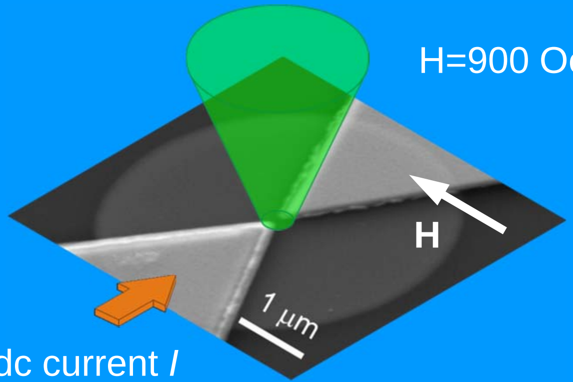
Auto-oscillations due to spin current

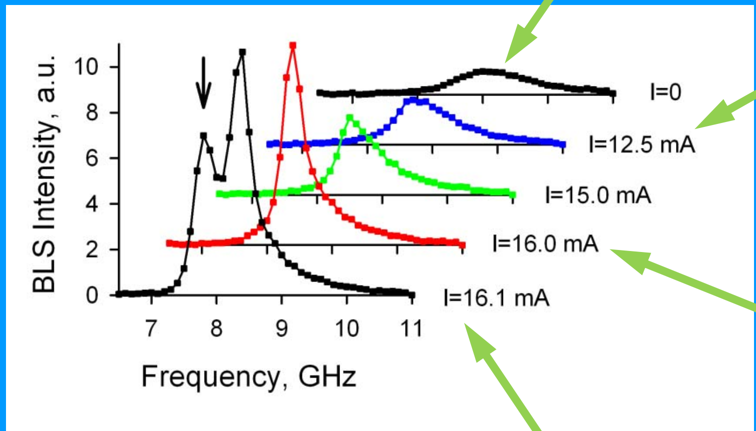


Probing spot is positioned in the gap.

Spectral BLS intensity is measured for different *I*.

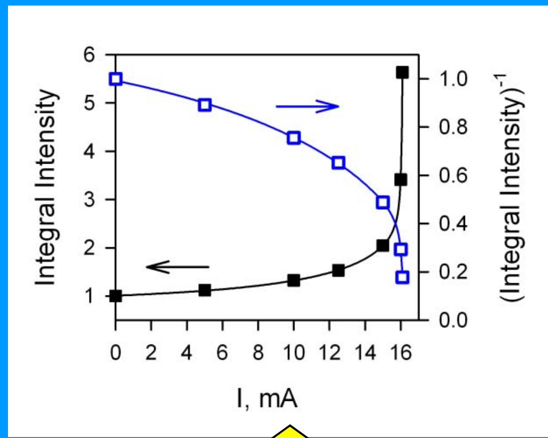
Before the onset of auto-oscillations

Spectrum of thermal magnetic fluctuations.



With increasing *I* the fluctuations are enhanced.

Low-frequency modes are enhanced stronger (frequency-dependent radiation losses).



The intensity of fluctuations diverges as the current approaches a critical value I_c≈16.1 mA (no saturation).

At $I=I_c$, a new peak appears in the BLS spectrum.

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Nature Mater. **11**, 1028 (2012).

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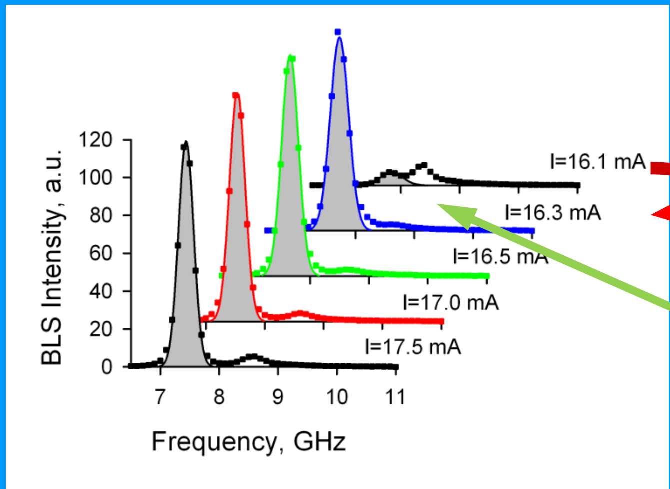
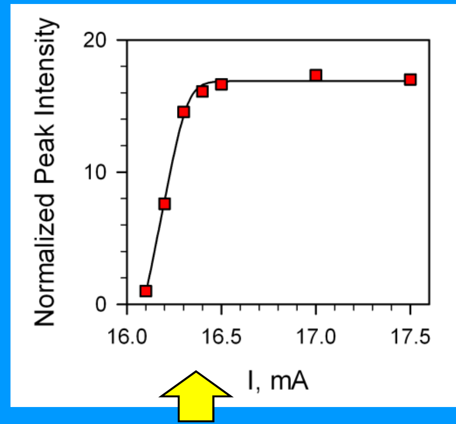
Spin-Hall nano-oscillator

After the onset of auto-oscillations



Increase of *I* by 1.3% results in dramatic increase of the intensity of the new peak – onset of auto-oscillations

Onset of auto-oscillations is accompanied by a decrease in the intensity of thermal fluctuations.

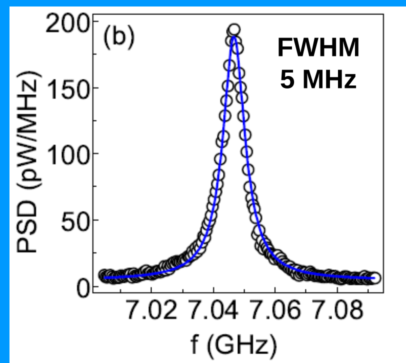


The peak rapidly grows and then saturates above 16.3 mA.

Electronic measurements with similar devices, PRL **110** 147601 (2013):

Microwave emission by a spin Hall nano-oscillator

R. H. Liu, W. L. Lim, and S. Urazhdin
Department of Physics, Emory University, Atlanta, GA 30322



Oscillation Linewidth is 5 MHz at 7 GHz (T=50 K)
– proof of high coherence degree

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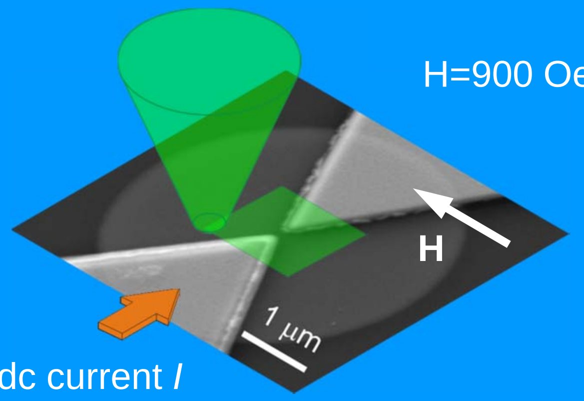
Nature Mater. **11**, 1028 (2012).

Self-localization of the oscillations



Auto-oscillation mode

To characterize the auto-oscillation mode, we performed two-dimensional mapping of the dynamic magnetization at the frequency of auto-oscillations.

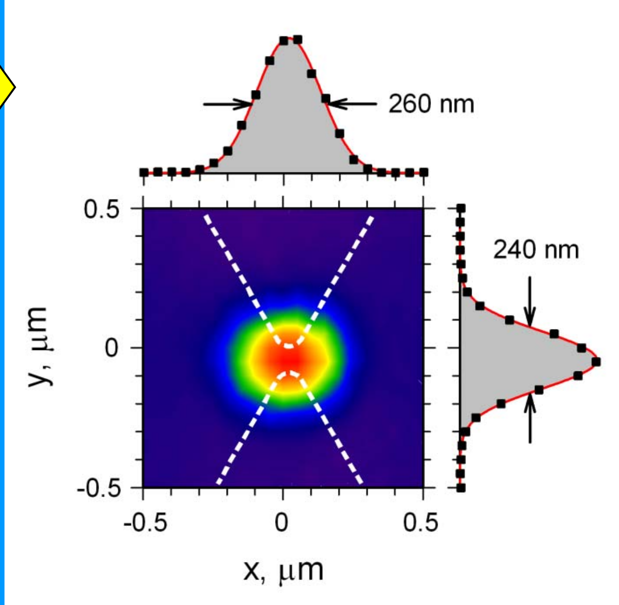
We rastered the probing laser spot in the two lateral directions and simultaneously recorded the BLS intensity.

Auto-oscillations are localized in a very small area in the gap between the electrodes.

The measured spatial distribution is a result of convolution with the instrumental function determined by the shape of the laser spot (∅≅250 nm).

The real size of the auto-oscillation area is less than 100 nm, significantly smaller than the characteristic size of the current localization.

The auto-oscillation mode is the nonlinear self-localized spin-wave “bullet”.



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Nature Mater. **11**, 1028 (2012).

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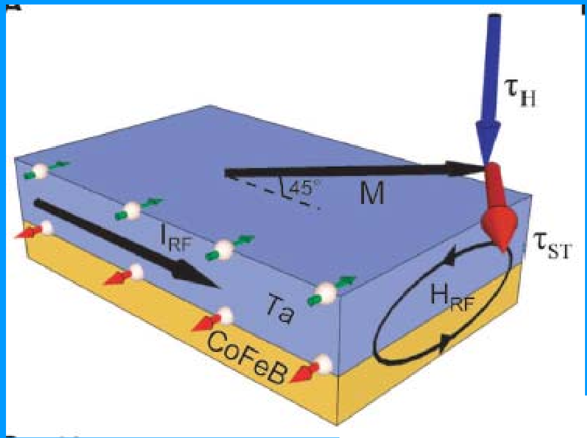
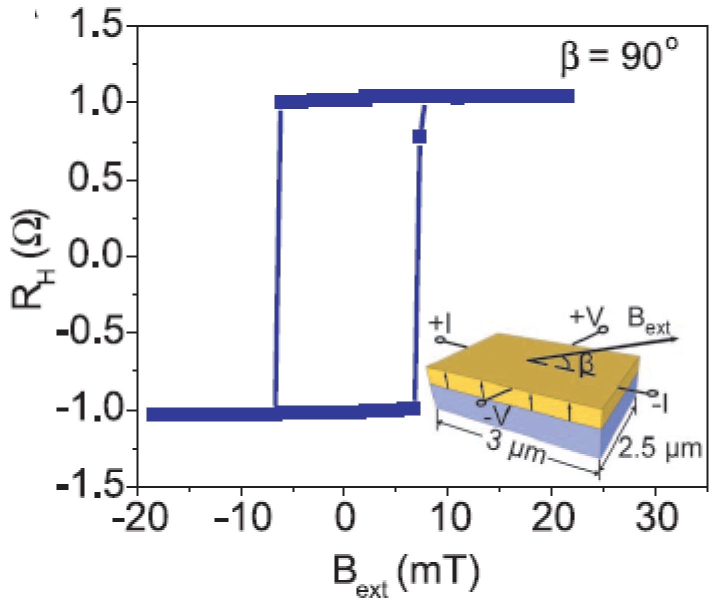
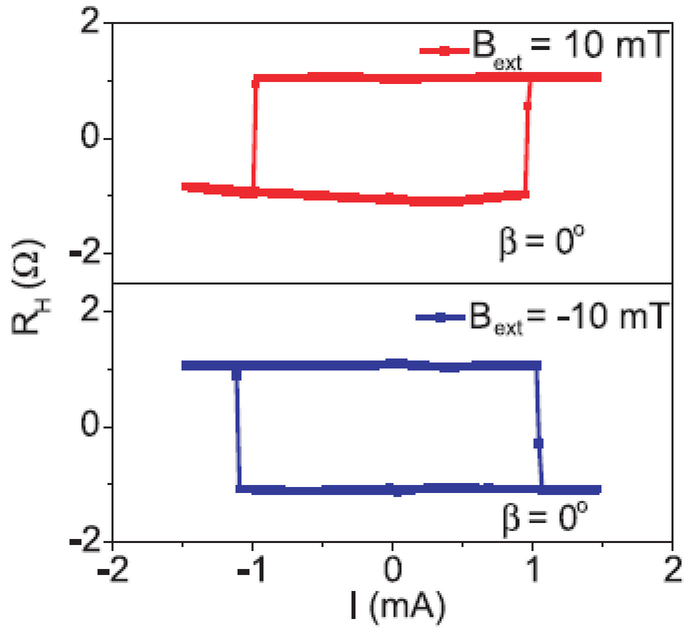
Switching using spin current



Using spin current one can switch the magnetization

Liu et al., *Science* **336, 555 (2012)**





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SEVENTH FRAMEWORK PROGRAMME

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