5. Dynamics (if there is time, otherwise in the magnetism lecture course)

- So far, only static properties have been treated (magnetization configuration, etc.) and usually without the application of an external field B_0.

- But what is happening if a field is applied and how does the magnetization switch from one equilibrium to another? What happens during the switching process?

- Now investigation of nonequilibrium conditions, which change with time.

- Dynamically processes in ferromagnetic materials are of considerable interest because there are measurement methods that are based on this dynamics (ferromagnetic resonance, Brillouin scattering, nuclear magnetic spin resonance, etc.), but there are also important applications such as fast data storage, medical technology, etc., based on magnetization dynamics.

- A spin behaves as angular momentem (it follows the quantum mechanical commutation relations for an angular momentum):

- The magnetization is:

(with g the Landé Factor, approximately 2 for Fe, Ni, Co due to spin moment)

- An external field exerts a torque on the spin: (derivation see course on magnetism in the next semester):

- Quantum mechanics: Heisenberg equation of motion:
  (Heisenberg: time evolution of observables)
  (Schrödinger: time evolution of states)

(last term = 0 if operator $\hat{A}_H$ is not explicitly time dependent)

- For a spin:

($\hat{s}_i$ not explicitly time dependent)

- Now insert the Hamiltonian :

- This yields (derivation see magnetism lecture course):

- Transition to classical magnetization via Ehrenfest theorem:

  with $\gamma_H = \frac{q_e}{m_e}\frac{g}{2} = 175,8GHz/T$ for electrons (g = 2 for spin, g = 1 for orbit, g ≈ 2,2 realistically for 3d metals).

- This is the fundamental equation for the precessional motion of the magnetization in an external field.

- But this does not contain a change of the energy G, since **M**·**B** always stays constant, so this cannot describe a system on its way to equilibrium.

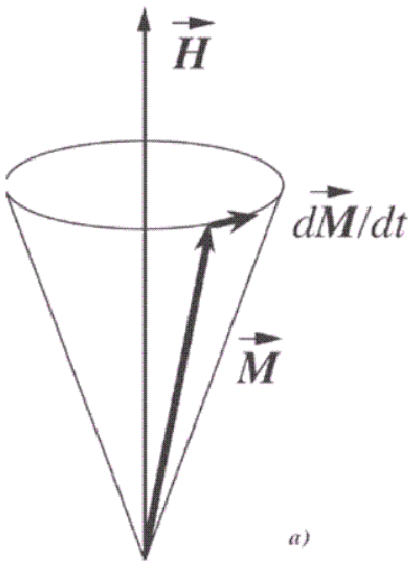


Figure: Precession of magnetic a moment in an applied field H

5.1 Dynamics - micromagnetics

- The effectively acting field B_{eff} contains different terms:

$$\mathbf{B}_{eff} = -\frac{dG}{dM}$$
$$G = -\mathbf{M} \cdot \mathbf{B}_{eff}$$

With:

$$\mathbf{B}_{eff} = 2\mu_0 A \Delta \mathbf{m} + \nabla_m E_{Aniso}(\mathbf{m}) + \mathbf{B}_0 + \mu_0 \mathbf{H}_d$$

- To introduce dissipation, and therefore a change of the energy analogous to mechanical friction, a damping term is introduced which is proportional to the generalized velocities dm/dt:

- In addition to precession this "Landau, Lifschitz and Gilbert equation (LLG)" also describes an alignment of the magnetization in the effective field, so the magnetization gradually moves on a spiral trajectory towards the direction of the effective field.

- The strength of this damping is described by the phenomenological parameter α (which includes, for instance, eddy currents).

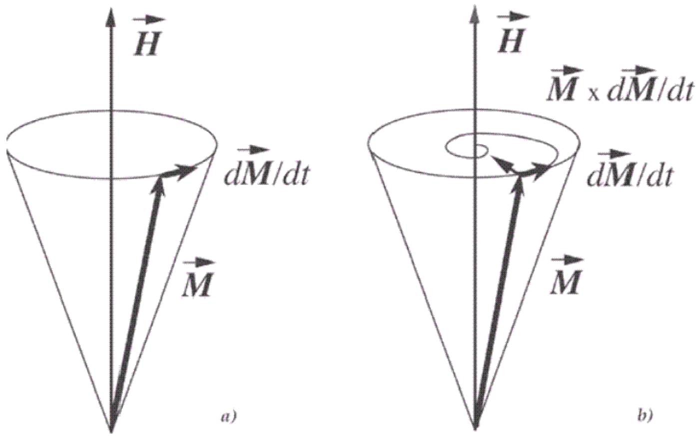


Figure: Precession of magnetic moment without (left) and with (right) damping

- This implicit LLG equation can be transformed into an explicit form with different constants (the Landau-Lifschitz (LL) equation, see derivation):

5.2 Dynamics - monodomain systems

- The LLG respectively the LL equation gives us a law for the time evolution of the magnetization. For instance we can now model the time evolution of a Stoner-Wohlfarth system (so called coherent or homogeneous rotation).

- The magnetization lies along the x-axis.

- A field is applied: B_x = -800Oe, B_z = -70Oe

- The magnetization first turns in the -y direction, and then in the +z direction and spirals into the field direction (animation).

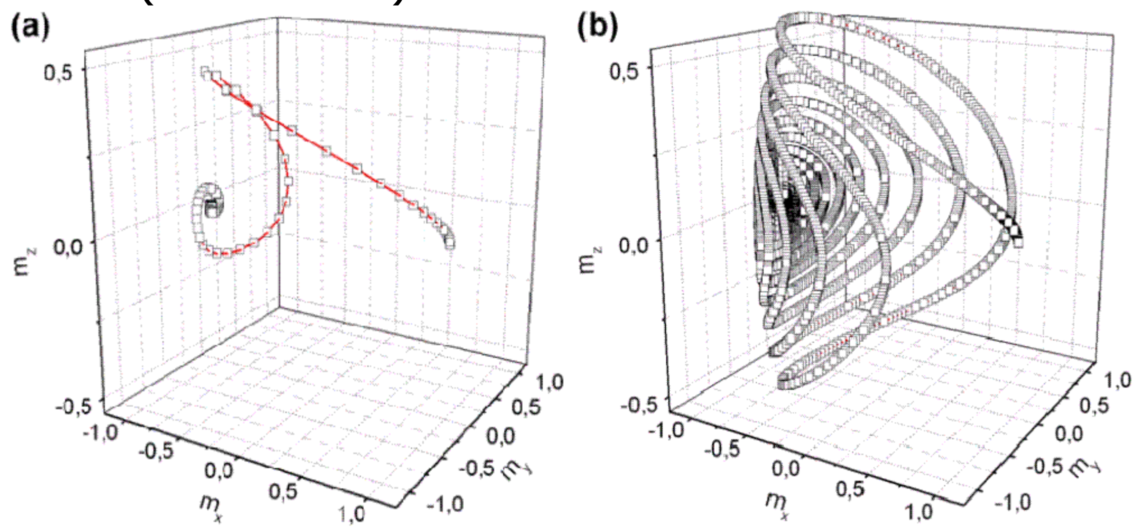


Figure: Simulated reversal of a macro spin (Stoner-Wohlfarth system) with different damping terms

- At lower (more realistic) damping (0.01 to 0.1) the precession becomes more important and therefore the magnetization direction rotates more often around the field direction before it eventually settles in that direction.

- The precession of a monodomain system can be visualized with OOMMF. One sees this in the x- and y-components, which are shifted 90° from the magnetization a damped precession.

- OOMMF examples for the precession of a monodomain system:

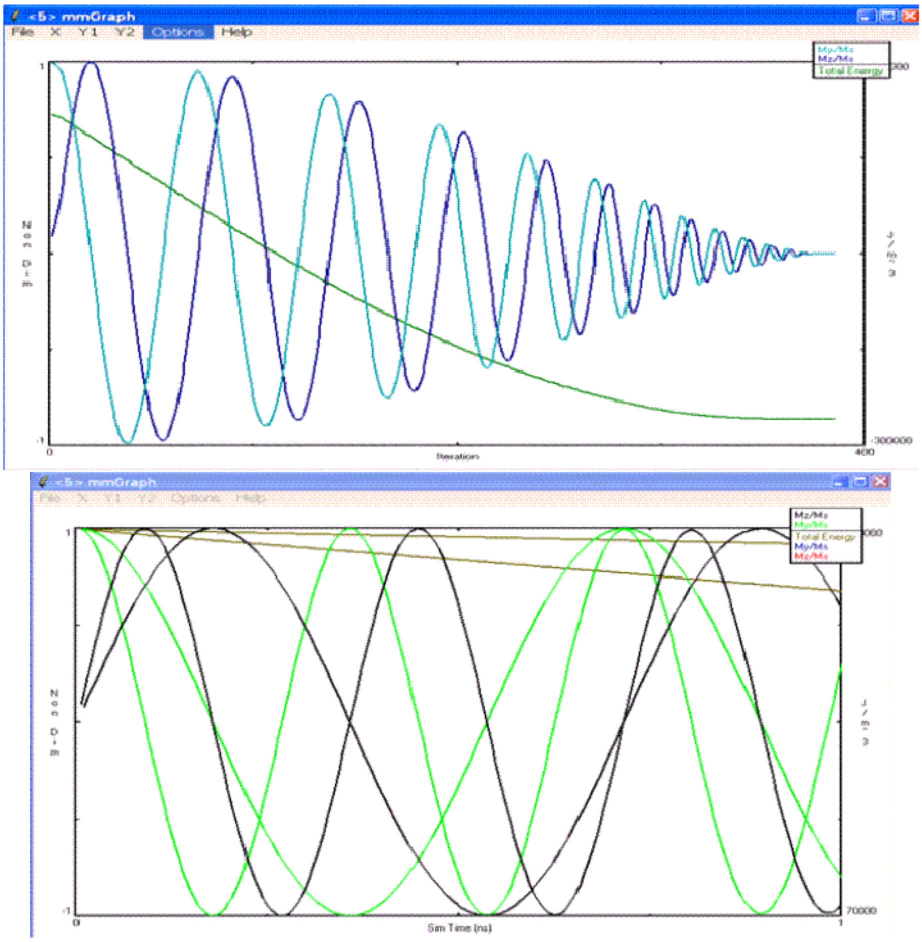


Figure: Precession of a monodomain systems described by macrospin dynamics

- Experimentally one can determine the precession frequency.
- The frequency is a function of the applied field in the plane of the sample which increases with increasing field 5.7.1 (continuous line shown as the fit).

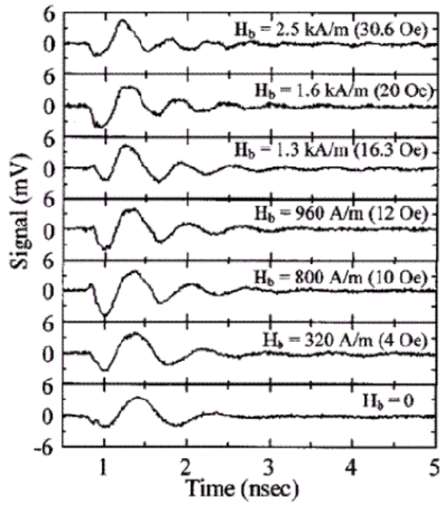


FIG. 2. Inductive wave forms obtained for impulse excitations with the 100 μm wide NiFe sample. Wave forms were acquired with different levels of dc bias field H_b applied along the easy axis of the sample.

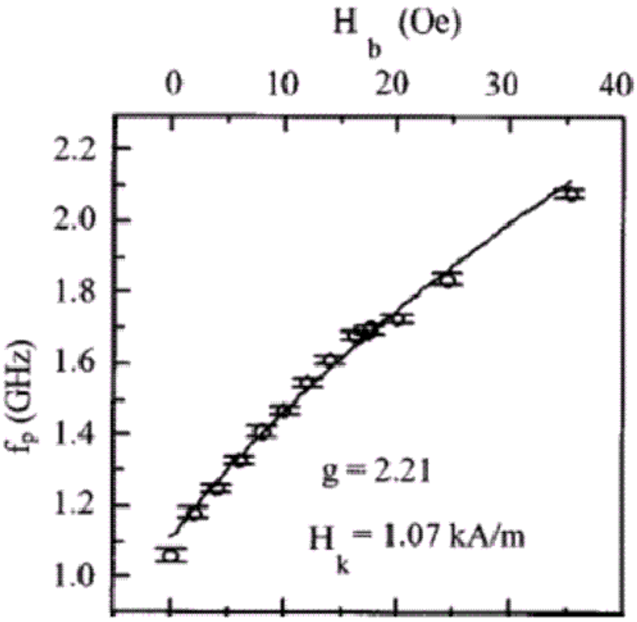
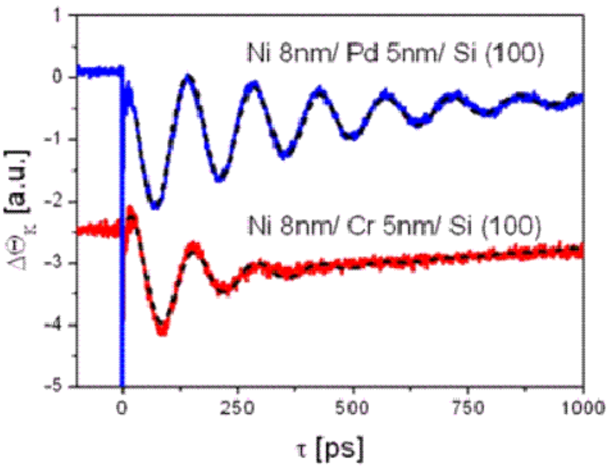


Figure: Experimentally measured precession and damping for various applied fields (left), resonance frequency as a function of an externally applied field (right) [T. Silva, J. Appl. Phys. 85, 7849 (1999)]

- Experimentally one can also determine the damping.
- Here we see that a Cr or Pd layer on top of the magnetic layer leads to a stronger damping.
- Reasons for this stronger damping are spin pumping (see references).
- The dip at t = 0 is not yet fully understood.



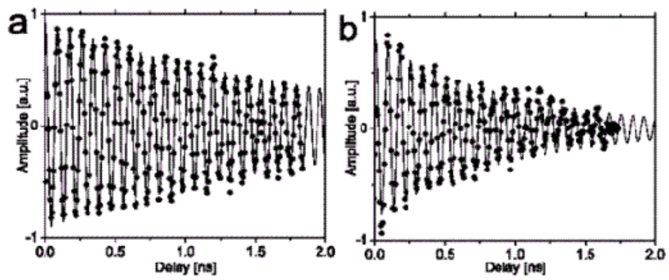


FIG. 2. Time-resolved magnetization data for (a) 20Au/16Fe/GaAs with the bias field $H_B = 500$ Oe $\|$ $[110]_{\mathrm{Fe}}$ leading to oscillations at $f = 11.8$ GHz with a decay time $\tau = 1.9$ ns and (b) 20Au/25Pd/16Fe/GaAs with $H_B = 500$ Oe $\|$ $[110]_{\mathrm{Fe}}$ ($f = 12.0$ GHz, $\tau = 1.1$ ns). The solid lines are fits obtained by using Eq. (2). The enhanced relaxation in the 20Au/25Pd/16Fe/GaAs sample is caused by spin pumping.

Figure: Experimental determination of precession and damping for Ni with Cr and Pd capping layers (left) [M. Muenzenberg, M. Kläui et al., (unpublished)], experimental determination of precession and damping for Fe with and without a Pd capping layer (right) [G. Woltersdorf et al., Phys. Rev. Lett. **95**, 37401 (2005)]