Aalto University
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Step-pulse excitaiton of ferromagnetic resonance

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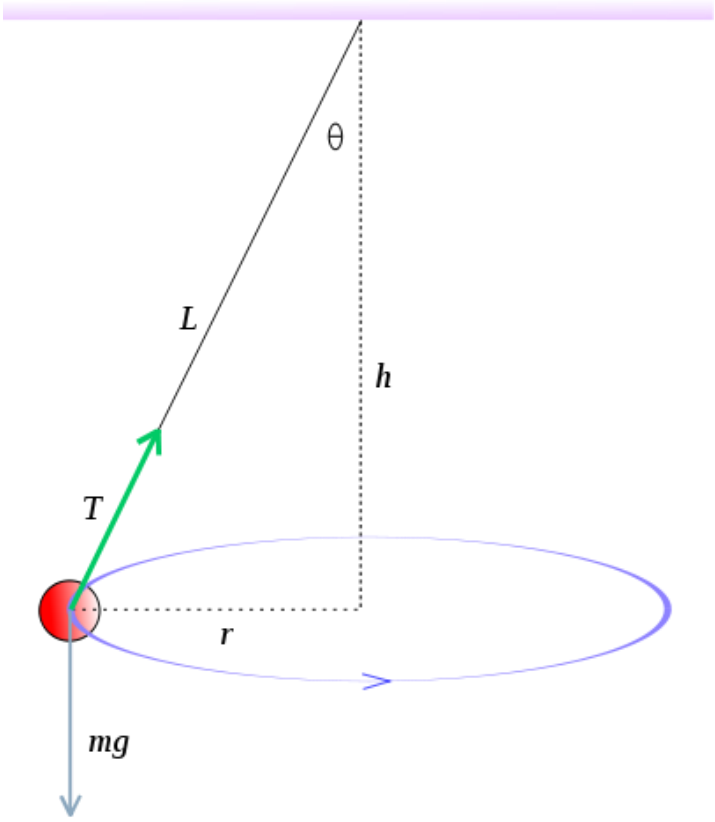
Bachelors thesis seminar

Outline

1. What is ferromagnetic resonance?
2. Theoretical model for ferromagnetic resonance
3. How to excite ferromagnetic resonance?
4. Pulse inductive microwave magnetometry
   - Theoretical predictions and measurements

What is ferromagnetic resonance?

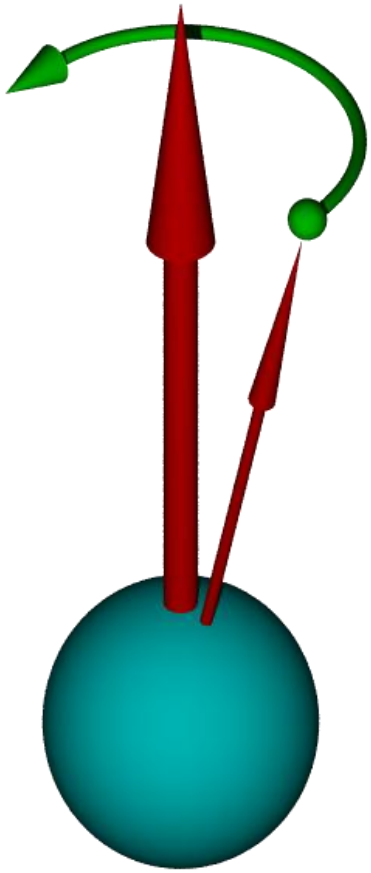


- Precession of magnetization at high frequency (~2 GHz+)
- Member of magnetic resonance family
  - Electron paramagnetic resonance
  - Nuclear magnetic resonance
- Very sensitive to magnetic environment

Why?

- FMR measures the dynamic response of magnetization
- Scans local magnetic environment
- Frequency and damping is essential
  - Limits magnetic switching speed
  - Spin torque switching

“Simple model” for precessional motion



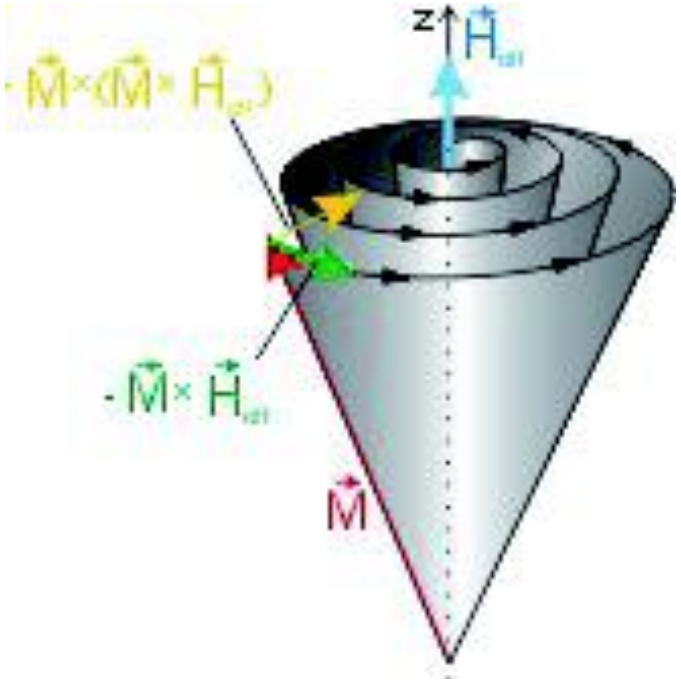
- Larmor precession

$$\frac{dM}{dt} = \mu \times B = -\gamma \mu_0 M \times H$$

- Solution:
  - Circular motion around equilibrium direction *H*
- Unphysical: no damping mechanisms

Landau-Lifshitz equation of motion

$$\frac{\partial \vec{M}}{\partial t} = -\gamma\mu_0 \vec{M} \times \vec{H} - \frac{\lambda}{M_s^2} \vec{M} \times (\vec{M} \times \vec{H})$$

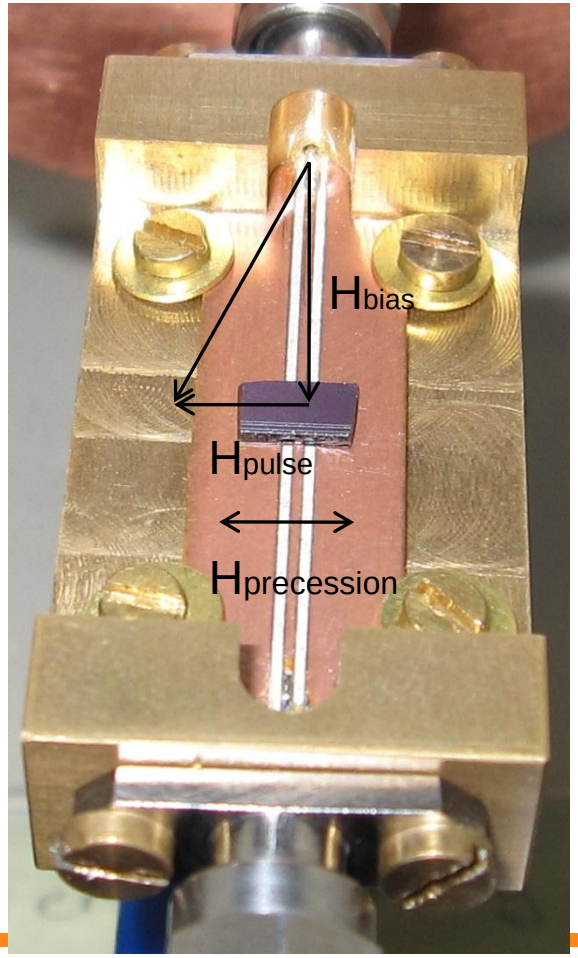


- Introduce damping term
  - Larmor precession + damping
- Important: |M(t)| = constant
- Difficult to solve
- Unphysical in high damping region

Excitation of ferromagnetic resonance

- Multiple excitation methods:
  - Forced oscillator
    - Force oscillatory motion at constant frequency
    - Measure absorption vs. frequency
  - Free oscillation decay
    - Push magnetization out of equilibrium
    - Measure the decay process

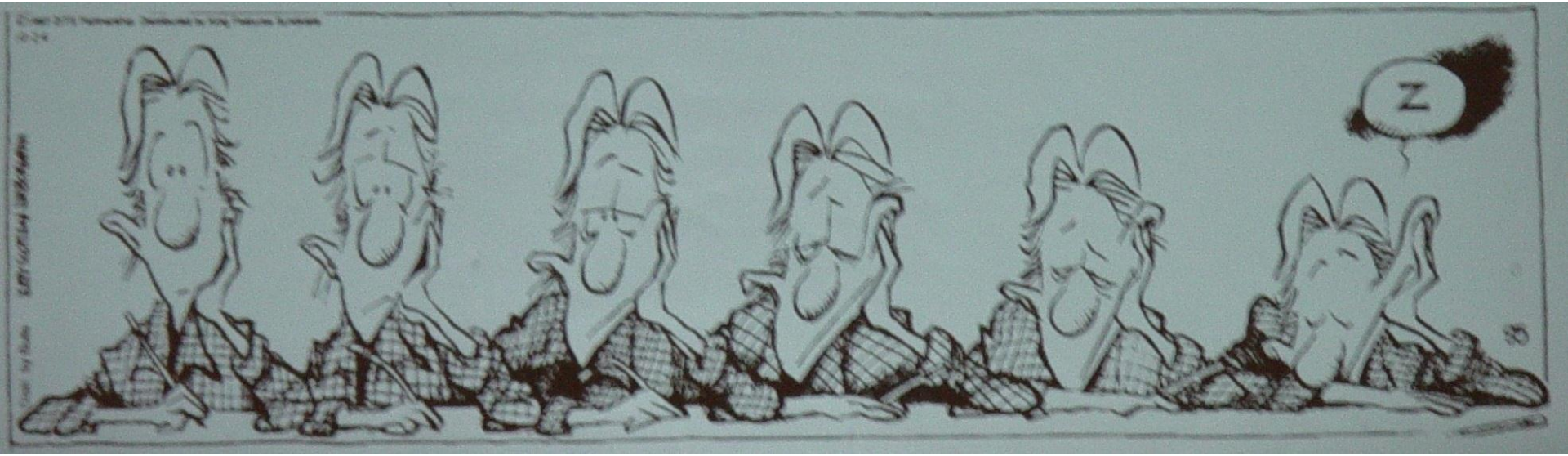
Pulse inductive microwave magnetometry



- Free oscillatory decay
- Bias magnetization parallel to the signal line
- Apply fast rise time perpendicular magnetic field
- Measure perpendicular inducted component of magnetization

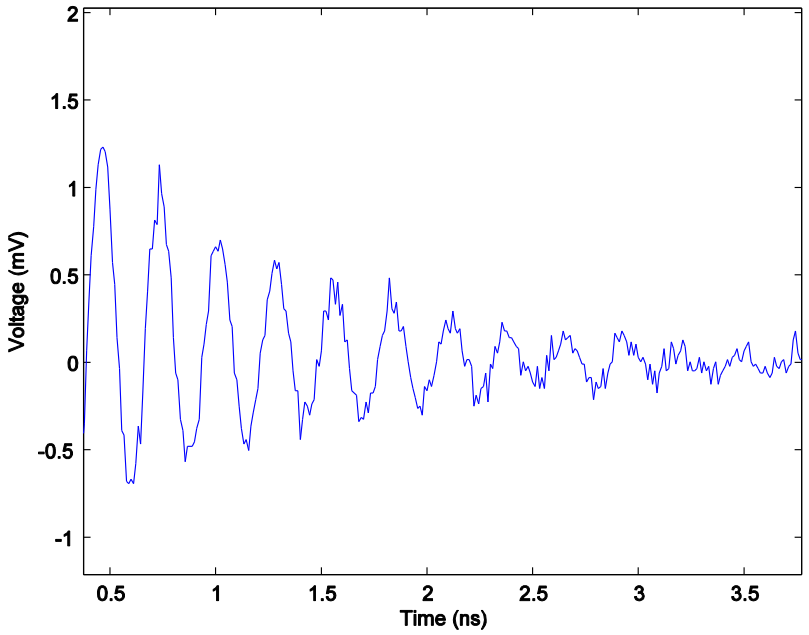
Solving Landau-Lifshitz equation: step pulse excitation…

- Bessel functions, trigonometry, 3D vector algebra, general spherical coordinate transformations…



… Solution!

$$\mathcal{E} \propto \frac{dM_y}{dt} = \omega_p M_s \cos(\omega_p t)\beta e^{-t/\tau}$$

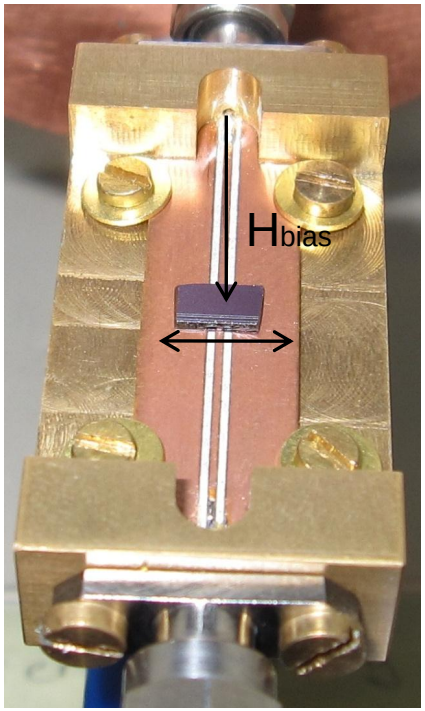


- Exponentially decaying sinusoid as expected
- Angular frequency:

$$\omega_p^2 = \gamma^2 \mu_0^2 \left(\frac{\partial^2 U}{\partial \phi^2} \right)_{\phi=\phi_0}$$

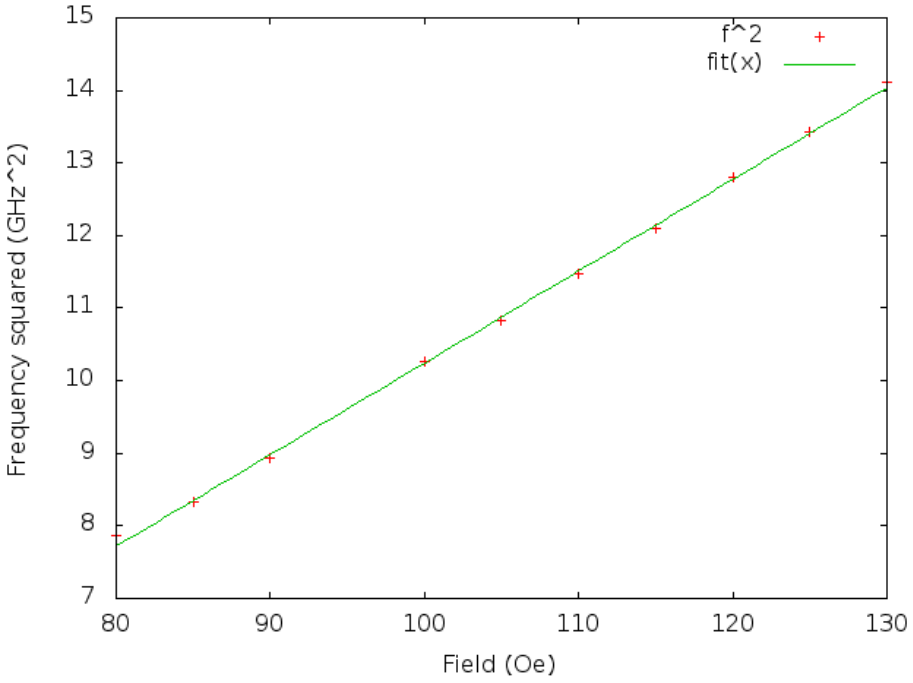
Solution for uniaxial anisotropy

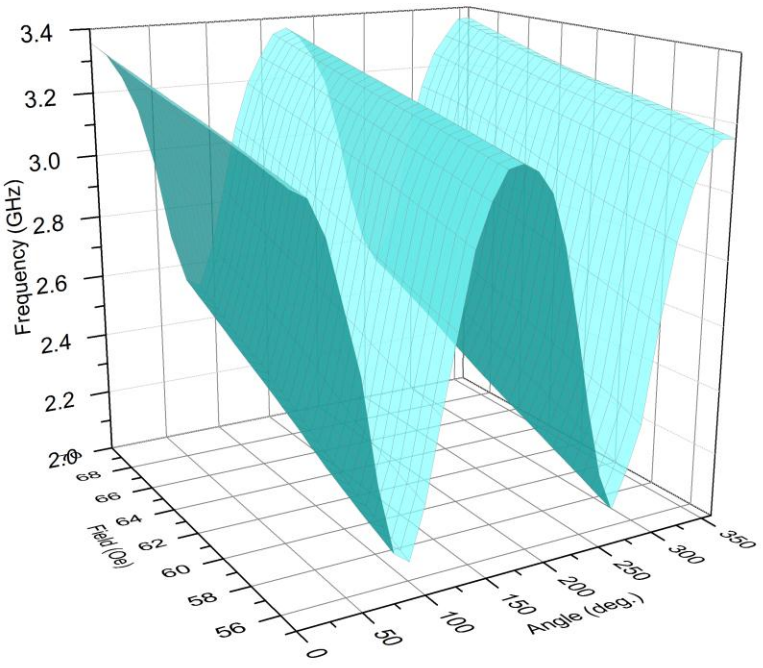
$$f_0^2 = \mu_0^2 \left(\frac{\gamma}{2\pi}\right)^2 M_s(H_k \cos 2(\phi - \alpha) + H_p \sin\phi + H_b \cos\phi)$$



- Resonance frequency depends
  - Anisotropy
  - Angle
  - Biasing field
- If saturation magnetization is known, gyroscopic splitting factor can be extracted

Experimental results





Conclusion

- Ferromagnetic resonance is important in the study of dynamic properties of magnetic thin films
- Solutions to Landau-Lifshitz agrees with experimental measurements
- Future: Measure more interesting samples
  - Stripe domains

Questions?