Paramagnetic spin pumping with microwave magnetic fields

Steven M. Watts

Physics of Nanodevices
Materials Science Centre
University of Groningen
the Netherlands

MSC plus
Materials Science Centre

http://nanodevices.fmns.rug.nl/
s.watts@rug.nl

RuG

Mesoscopic metal spintronics team

B. J. van Wees
C. H. van der Wal

Postdoc:
J. Grollier*
S. Watts

Ph.D. Student:
M. V. Costache

Students:
M. Sladkov

* Now at Unite Mixte de Physique CNRS/Thales

Techniques to obtain spin accumulation:

- **Spin injection into metals and semiconductors:**

  Optical (circularly polarized light)

  Not good for Si, metals or devices

  Electrical (injection from ferromagnets)

  Problems with mismatch & interfaces between FM and SC

- **New method: Spin pumping, the "spin battery"**

  No charge currents required!

  Spin currents generated by precessing magnetization in a ferromagnet

- **Our new approach: Spin pumping with rf magnetic fields**

  No ferromagnet required!

Outline

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Background 2: Spin battery device

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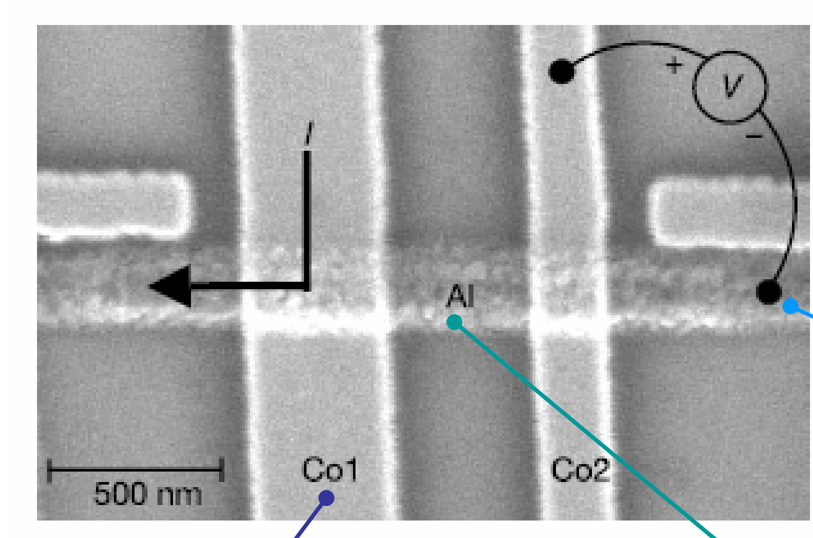
- Some realistic numbers

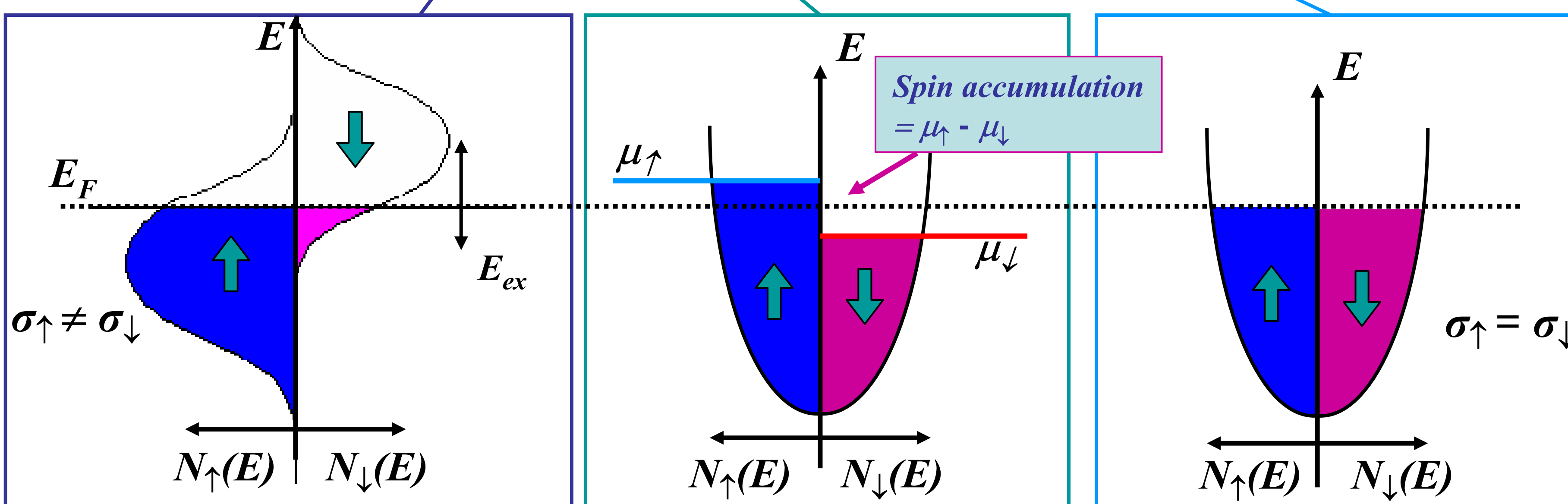
Interface-enhanced spin accumulation

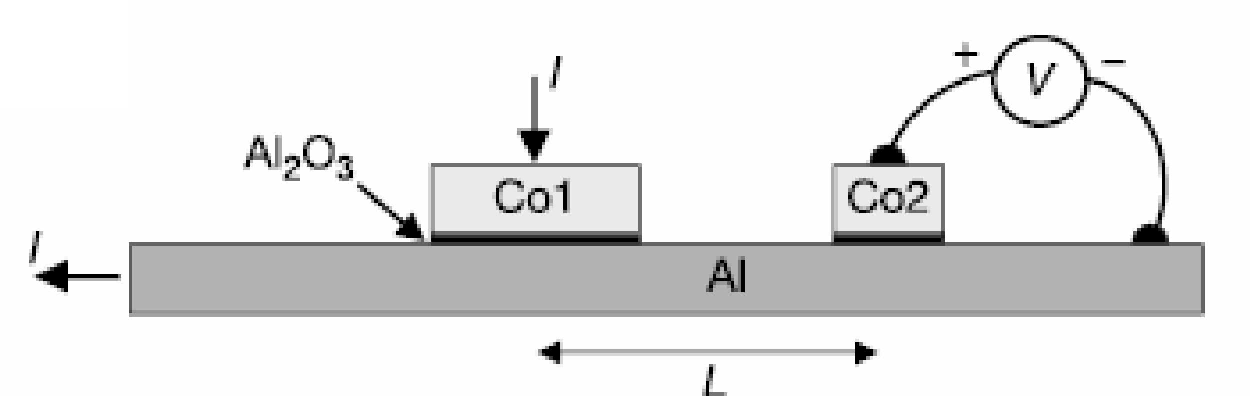
The spin-injection MASER

All-electrical spin injection by charge current



Cobalt-aluminum mesoscopic spin valve with tunnel junctions

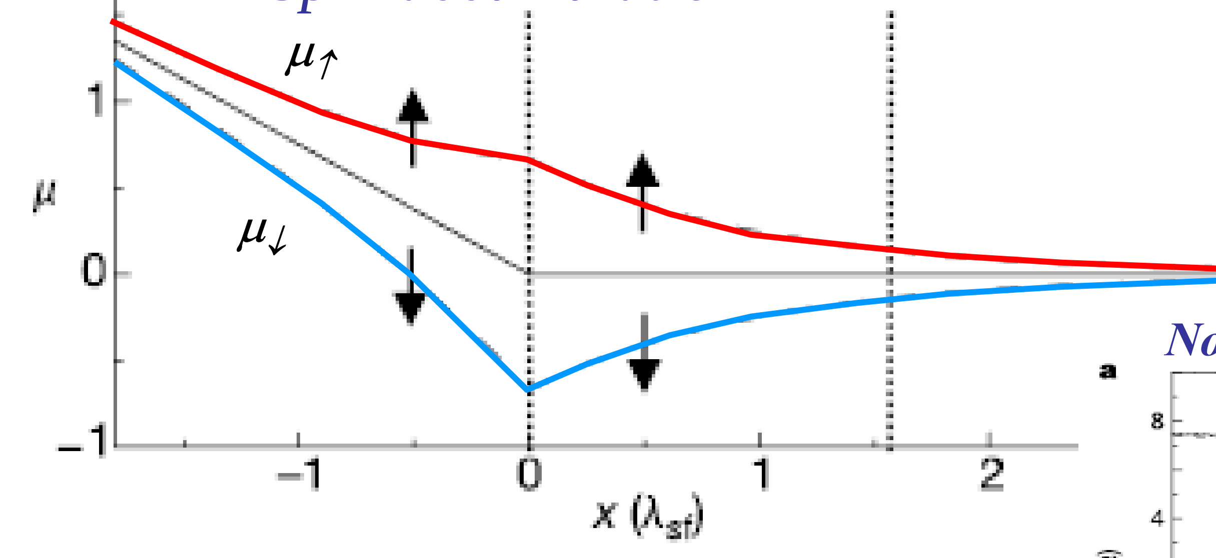




Spin diffusion length:

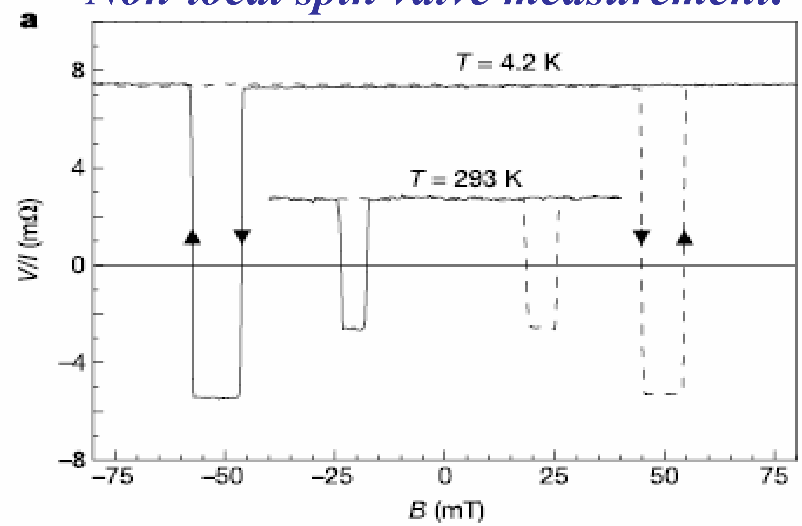
$$\lambda_{sf} = \sqrt{D\tau_{sf}}$$

Spin accumulation in Al



Spin relaxation time: τ_{sf}

Non-local spin valve measurement:

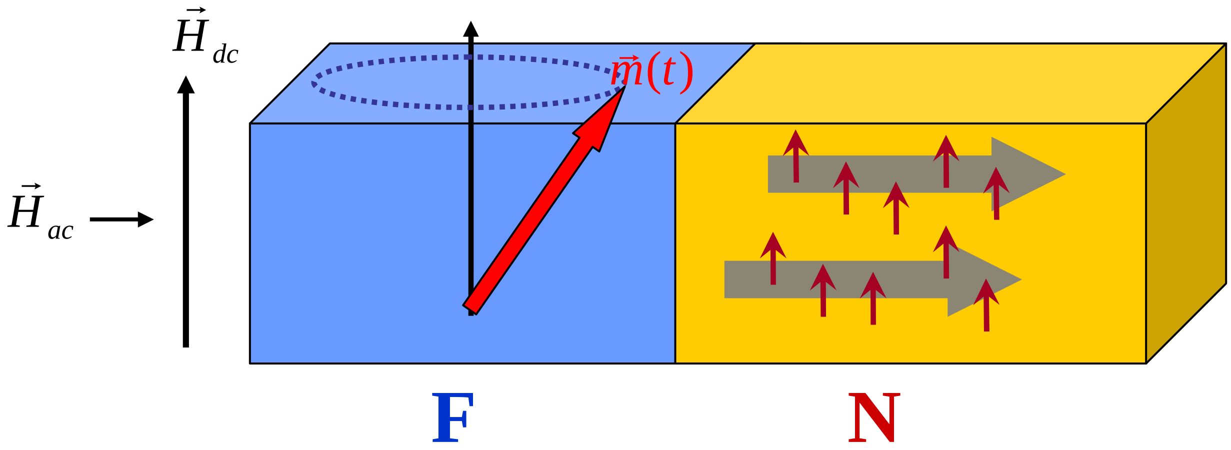


F. J. Jedema *et al.*, Nature **416** (2002)

Spin battery : interface scattering model

Spin transfer effect : spin polarized current ⇨ magnetization motion

Spin battery effect : magnetization motion ⇨ spin polarized current

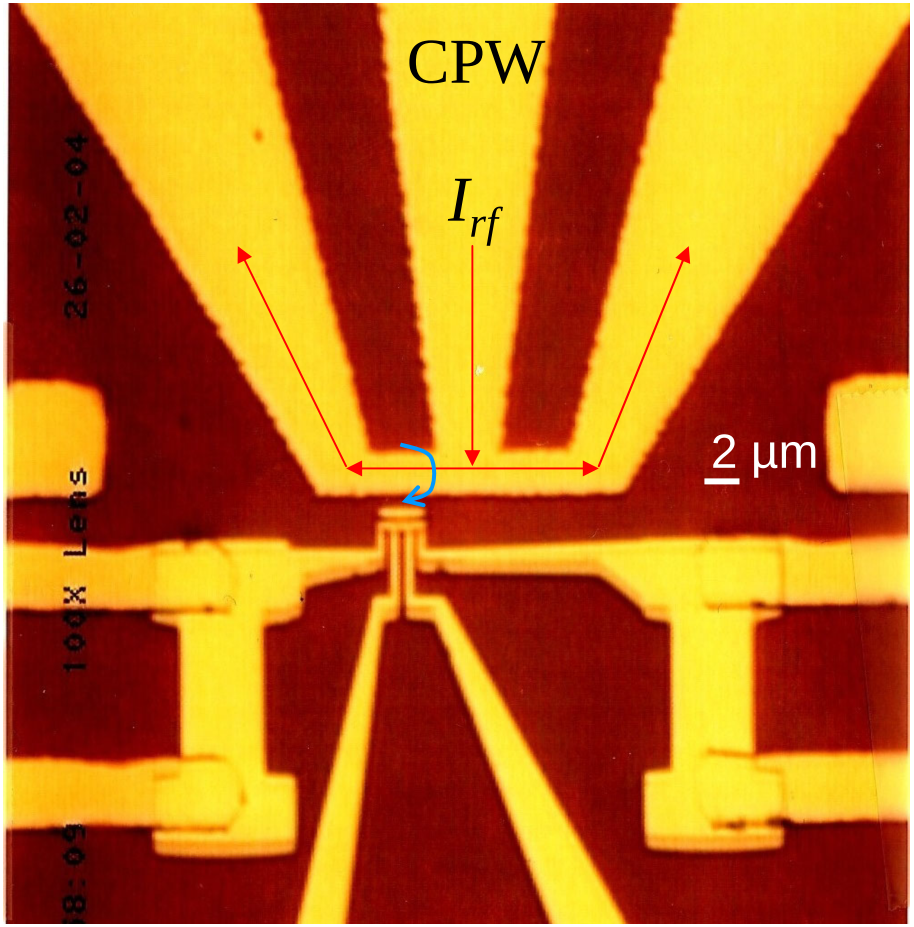


For long τ_{sf}, pumped spin accumulation has the universal value $\hbar\omega$

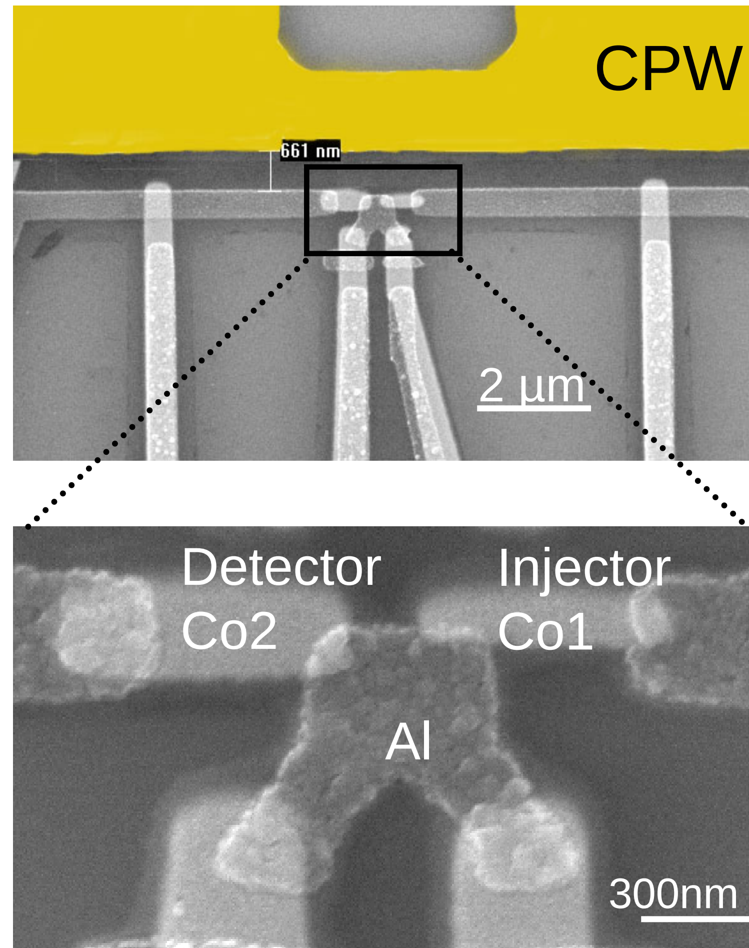
A. Brataas, Y. Tserkovnyak, G. E. W. Bauer, & B. I. Halperin, PRB **66** (2002)

Y. Tserkovnyak, A. Brataas and G. E. W. Bauer, PRL **11** (2002)

Coplanar wave guide to apply localized rf field:



Electrical detection: reference ferromagnet



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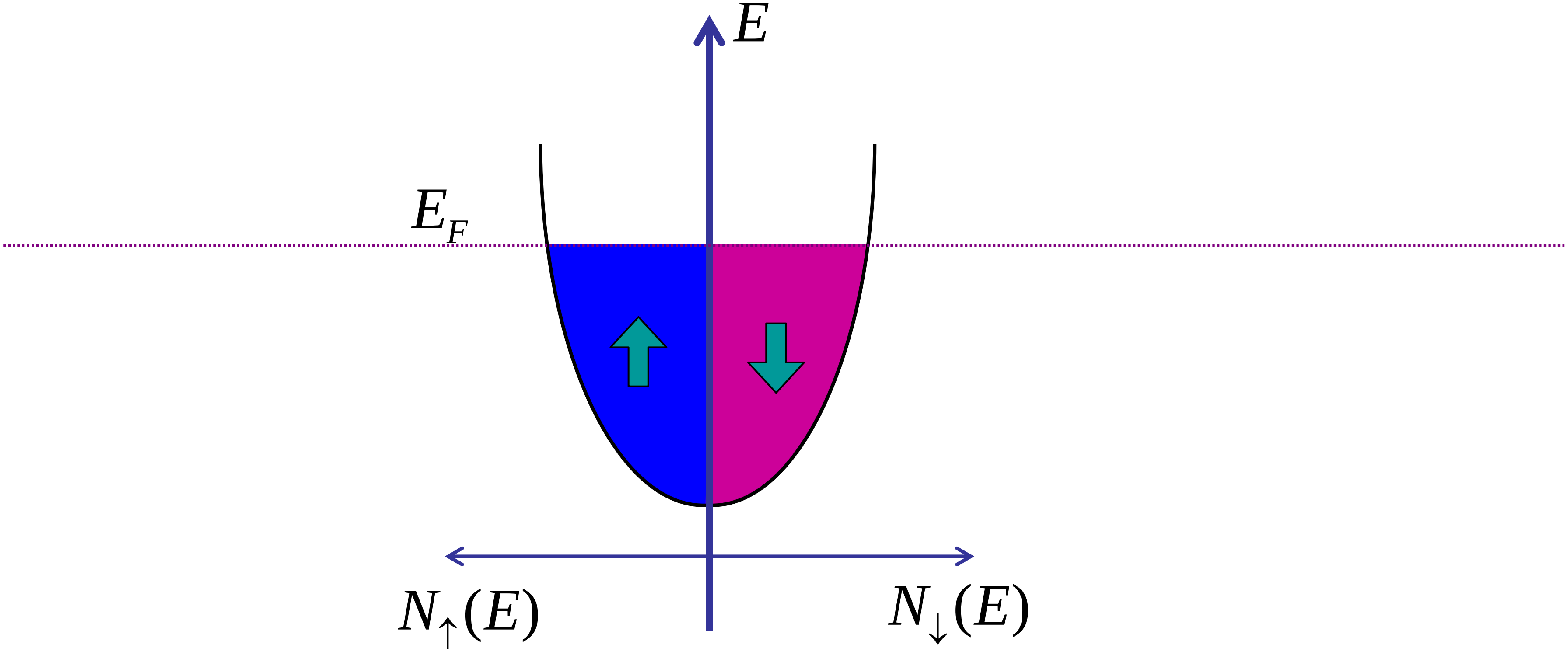
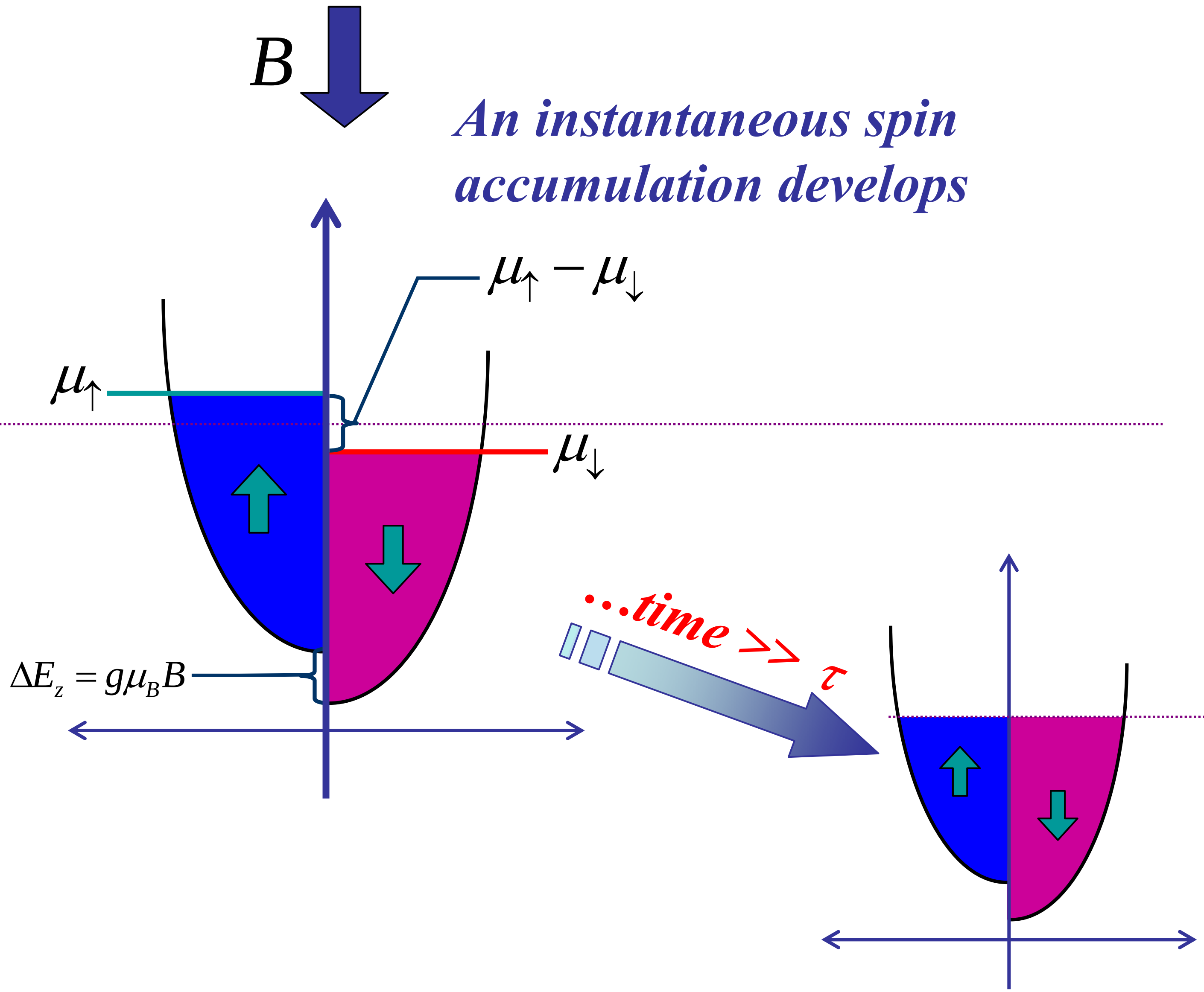
Spin accumulation in time-dependent magnetic fields

The spin-resolved density of states of nonmagnetic, conducting material in zero magnetic field:



Turn on a magnetic field, the states are Zeeman - split:

An instantaneous spin accumulation develops



after relaxation, we have magnetization with no spin accumulation

Rate equation for spin accumulation generated by an oscillating magnetic field: $B_z(t) = B_0 \sin \omega t$

$$-\frac{d\mu_z}{dt} + I_{source} = \frac{\mu_z}{\tau}$$

Source term for spin accumulation:

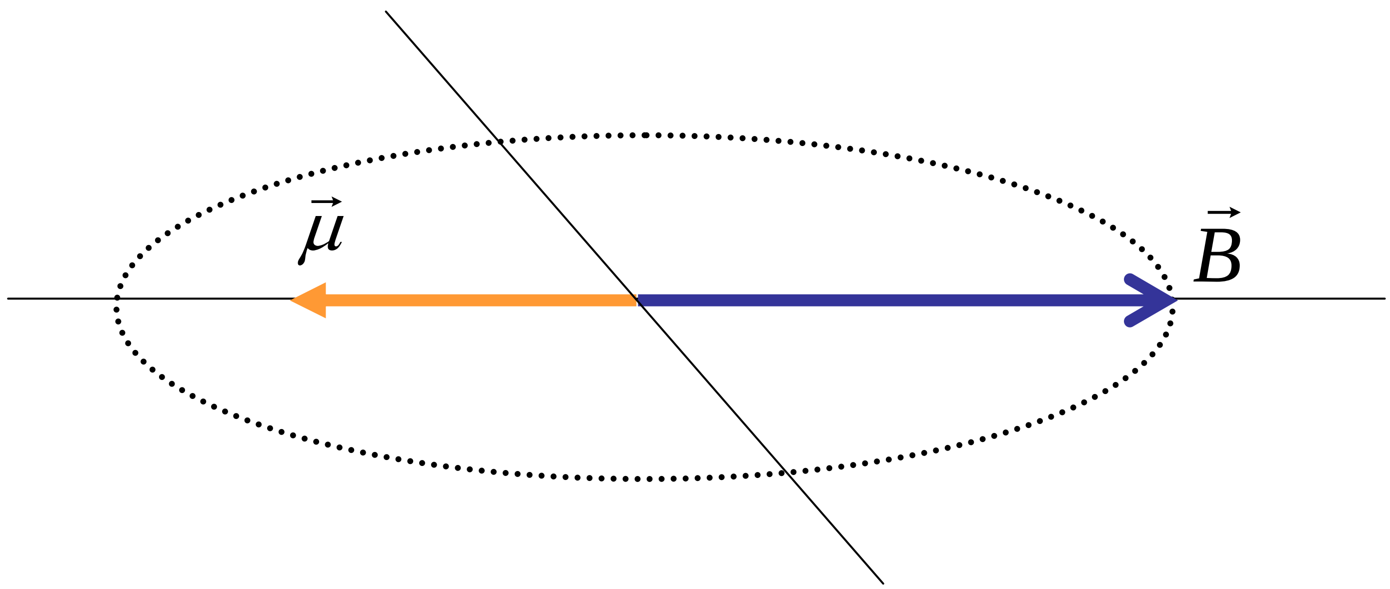
$$I_{source} = \frac{d}{dt} E_{Zeeman} = -g\mu_B \frac{dB_z}{dt}$$

Solution: μ_z ***oscillates with field but out-of-phase by***

$$\phi = \tan^{-1}\frac{1}{\omega\tau}$$

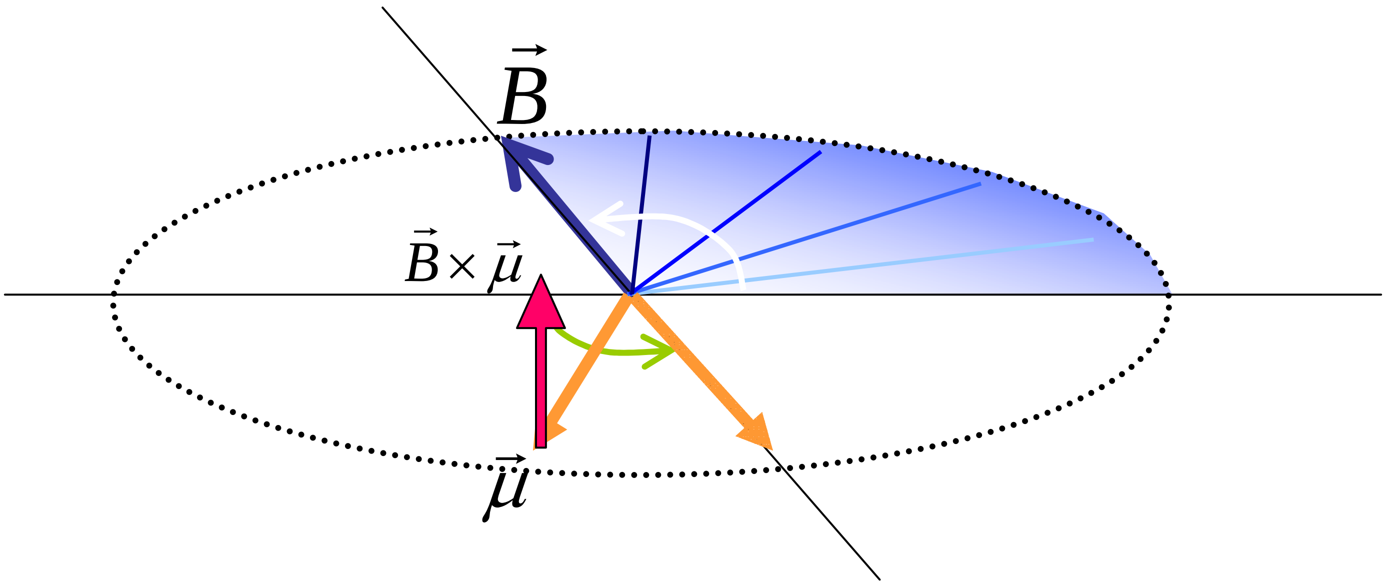
Now consider a rotating magnetic field: $\vec{B} = (B_{xy}\cos\omega t, B_{xy}\sin\omega t, 0)$

At t=0, field generates collinear spin accumulation $\vec{\mu}$



Now consider a rotating magnetic field: $\vec{B} = (B_{xy} \cos \omega t, B_{xy} \sin \omega t, 0)$

The spin relaxation time causes the spin accumulation vector $\vec{\mu}$ to lag behind the field



The accumulated spins will precess around $\vec{B}$ ***producing accumulation perpendicular to the plane of rotation***

(*See also* A. Abragam, *The Principles of Nuclear Magnetism*)

Spin pumping in a bulk conductor

Bloch-type equations for spin accumulation $\vec{\mu}(t)$

Source term

Spin precession

$$-\frac{d\vec{\mu}}{dt}+\vec{I}(t)=\frac{\vec{\mu}}{\tau}-\left(\frac{g\mu_B}{\hbar}\vec{B}\times\vec{\mu}\right)$$

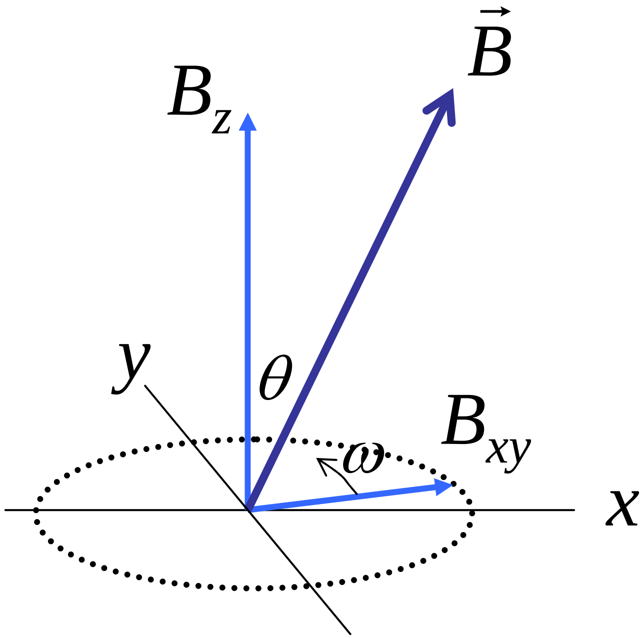
Spin relaxation

Key ingredient, the source term:

$$\vec{I}(t)=\frac{d}{dt}\vec{E}_{Zeeman}=-g\mu_B\frac{d\vec{B}}{dt}$$

$$-\frac{d\vec{\mu}}{dt}+\vec{I}(t)=\frac{\vec{\mu}}{\tau}-\left(\frac{g\mu_B}{\hbar}\vec{B}\times\vec{\mu}\right)$$

The field configuration:



$$\vec{B}=(B_{xy}\cos\omega t, B_{xy}\sin\omega t, B_z)$$

$$\hbar\omega_{xy}=g\mu_B B_{xy}$$

$$\hbar\omega_z=g\mu_B B_z$$

Steady-state solution in the rotating reference frame:

$$-\frac{d\vec{\mu}}{dt} = \frac{\vec{\mu}}{\tau} - (\vec{\omega}_B + \vec{\omega}) \times \vec{\mu} + \hbar\left(\vec{\omega} \times \vec{\omega}_B\right) = 0$$

$$\mu_{\parallel} = \frac{(\omega_z - \omega)\tau(\omega_{xy}\tau)}{1 + (\omega_{xy}\tau)^2 + ((\omega_z - \omega)\tau)^2}\hbar\omega$$

In-phase with field

$$\mu_{\perp} = -\frac{(\omega_{xy}\tau)}{1 + (\omega_{xy}\tau)^2 + ((\omega_z - \omega)\tau)^2}\hbar\omega$$

Out-of-phase

$$\mu_z = -\frac{(\omega_{xy}\tau)^2}{1 + (\omega_{xy}\tau)^2 + ((\omega_z - \omega)\tau)^2}\hbar\omega$$

dc component

Analytic solution for steady-state dc spin accumulation:

$$\mu_z = -\frac{(\omega_{xy}\tau)^2}{1+(\omega_{xy}\tau)^2+((\omega_z-\omega)\tau)^2}\hbar\omega$$

In general, we get only some small fraction of the universal result $\hbar\omega$

Special conditions to obtain the universal result:

Resonance, $\omega=\omega_z$**:** $\omega_{xy}\tau >> 1$

No dc field, $B_z=0$**:** $\omega_{xy}\tau, \omega\tau >> 1 \text{ and } \omega_{xy} >> \omega$

Some realistic numbers…

- ***Standard NMR/ESR techniques can be used***

  Near resonance, linear rf field = left + right rotating fields

Simulated signal for Al metal:

$$\tau = 0.1ns$$

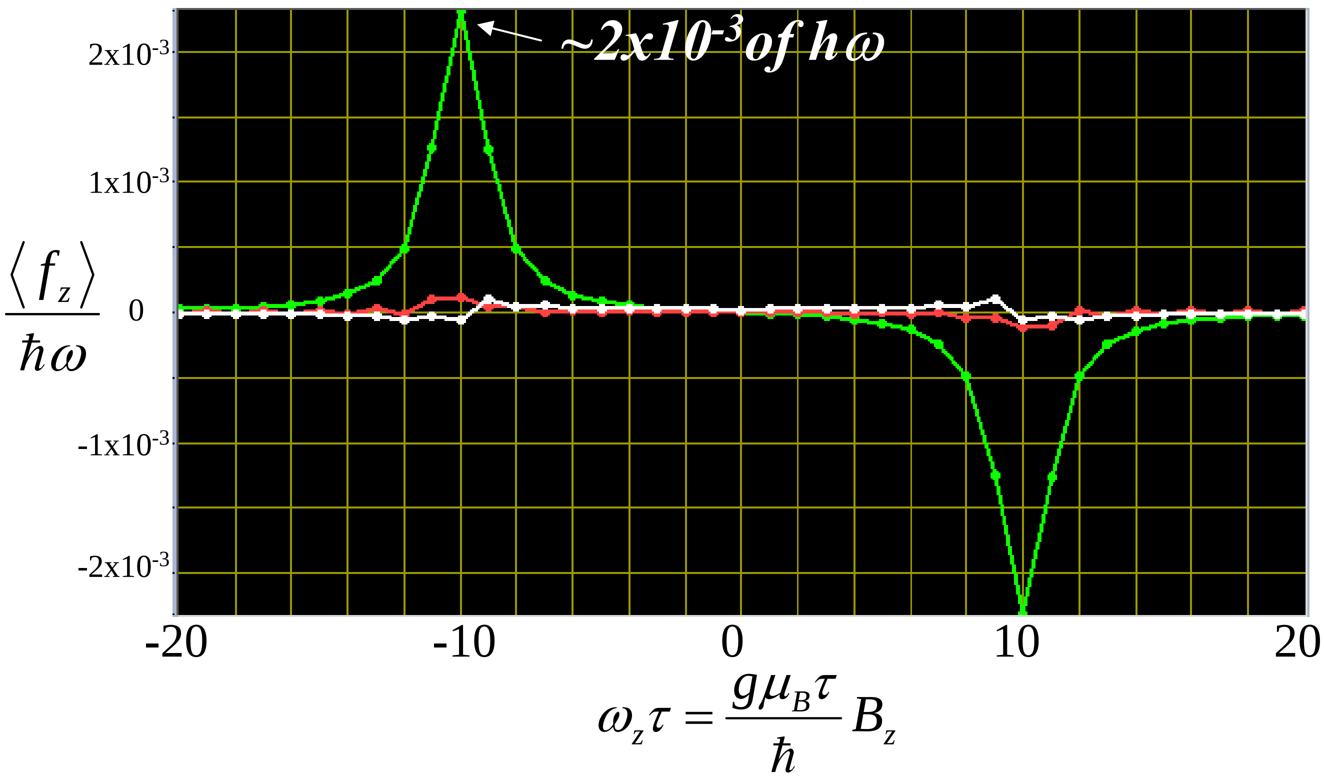
$$\omega_{xy}\tau = 0.1 \quad (B_{xy} = 6mT)$$

$$\omega\tau = 10 \quad (f = 16GHz)$$

$$\hbar\omega = 66\mu V$$

$$V_{exp} = 150nV$$

$$n_{spins} \sim 10^{15} cm^{-3}$$



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Interface-enhanced spin accumulation

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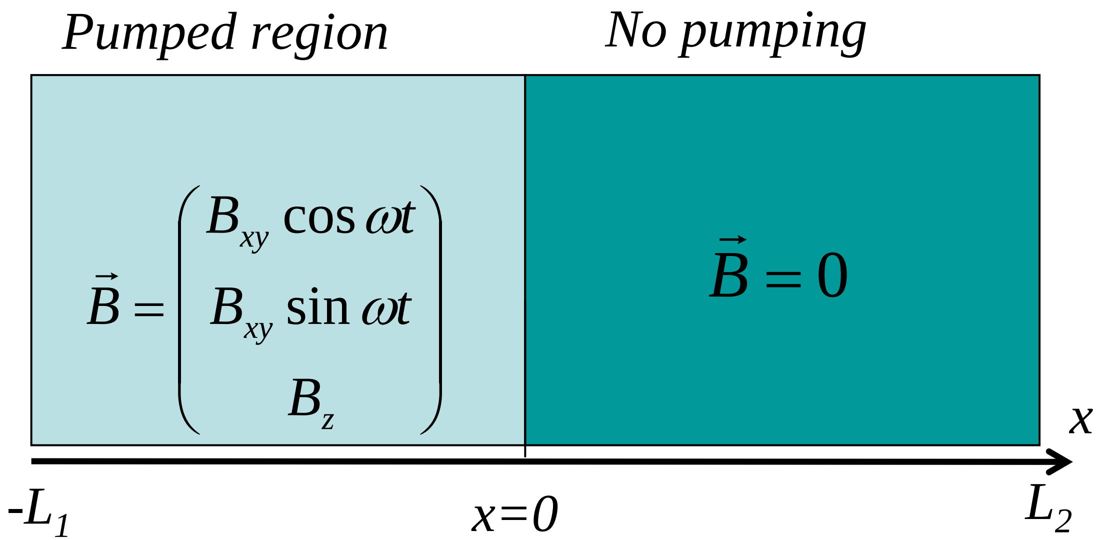
Now add interface, and diffusion across interface

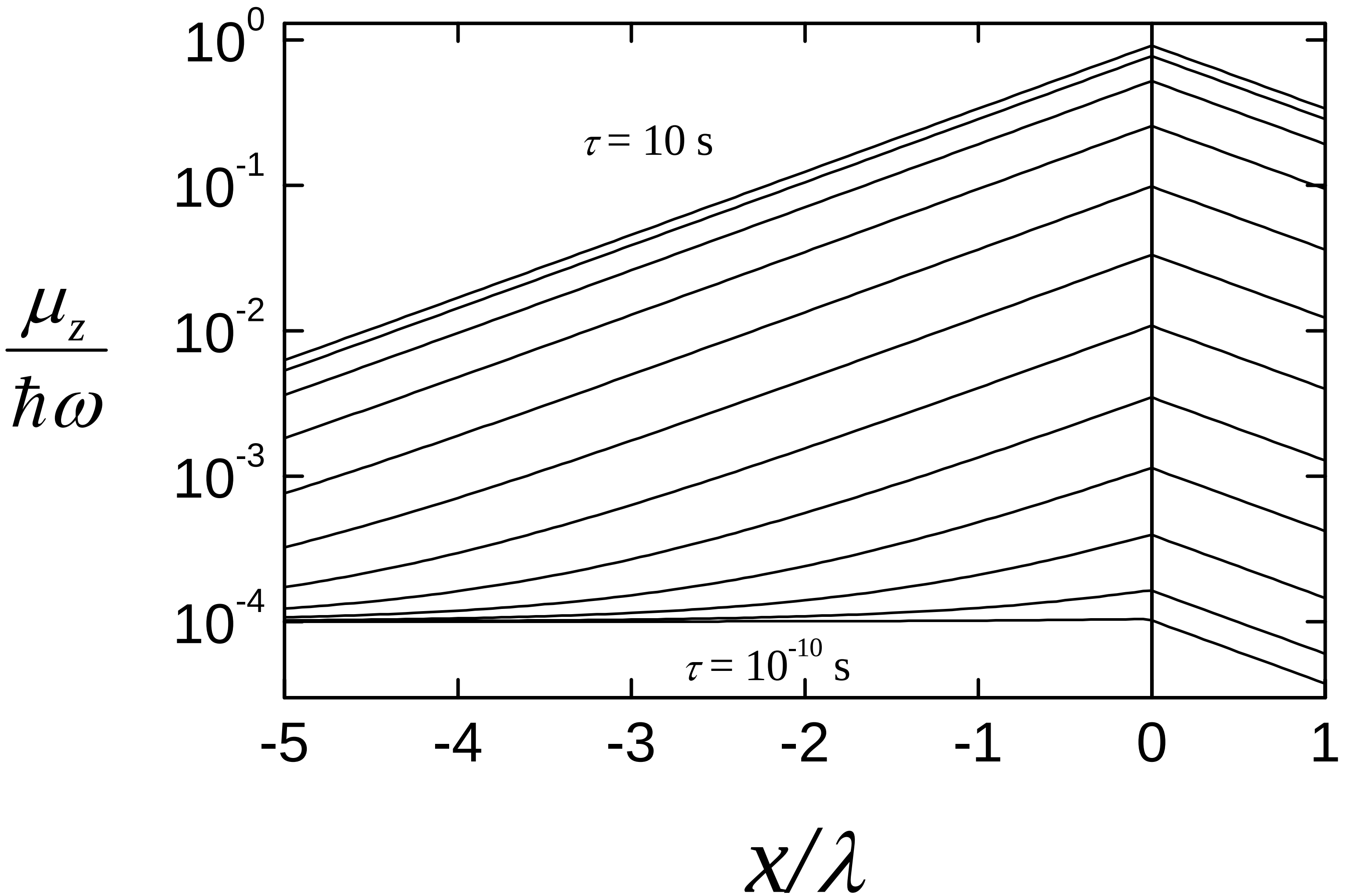
$$-\frac{\partial \vec{\mu}}{\partial t} + \vec{I}(x,t) = -D\nabla^2 \vec{\mu} + \frac{\vec{\mu}}{\tau} - \left(\frac{g\mu_B}{\hbar} \vec{B} \times \vec{\mu} \right)$$

Spin diffusion



…1-D system to be solved numerically

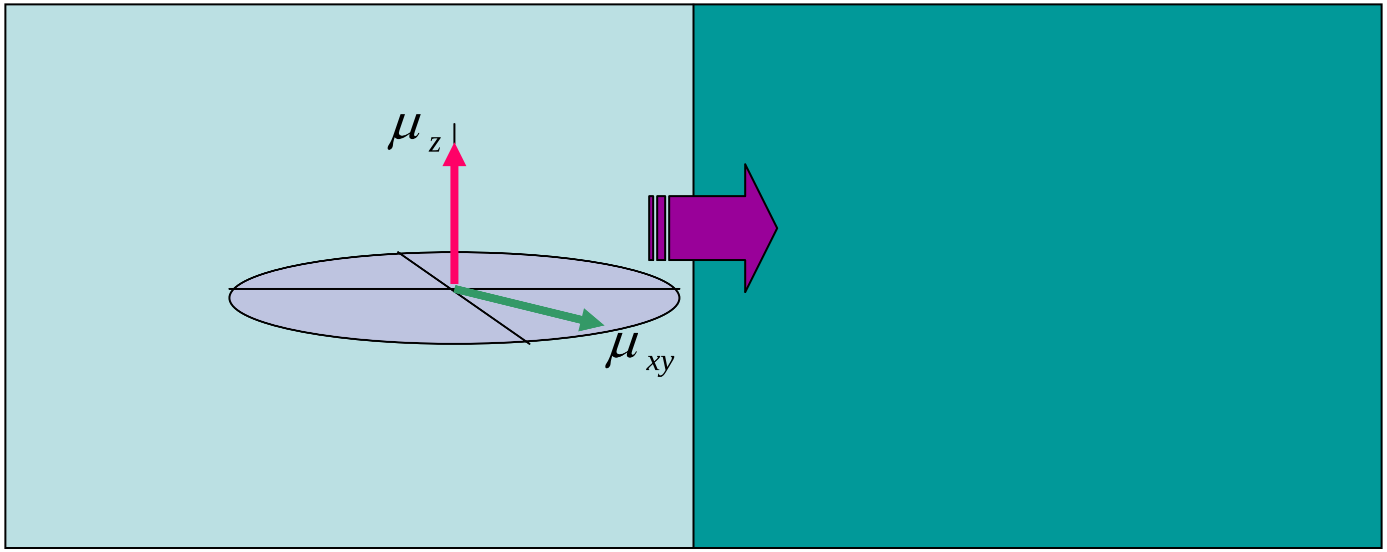
Unbounded system



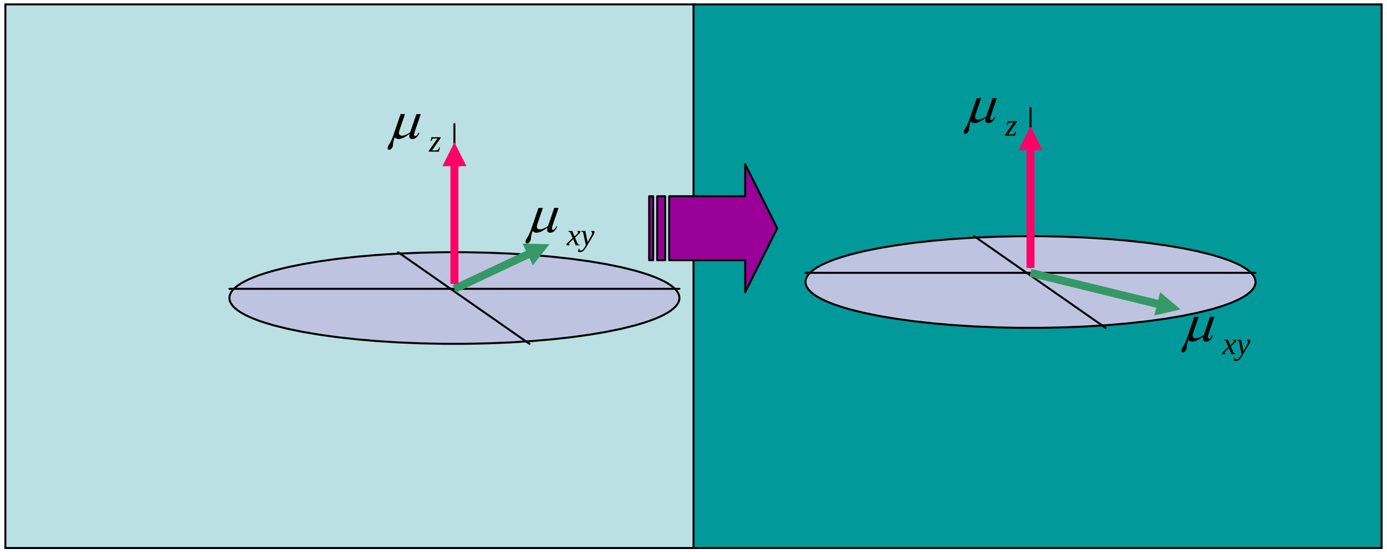
$\omega = 10$ GHz

Weak ferromagnet model: $B_{xy} = 1$ T, $B_z = 100$ T

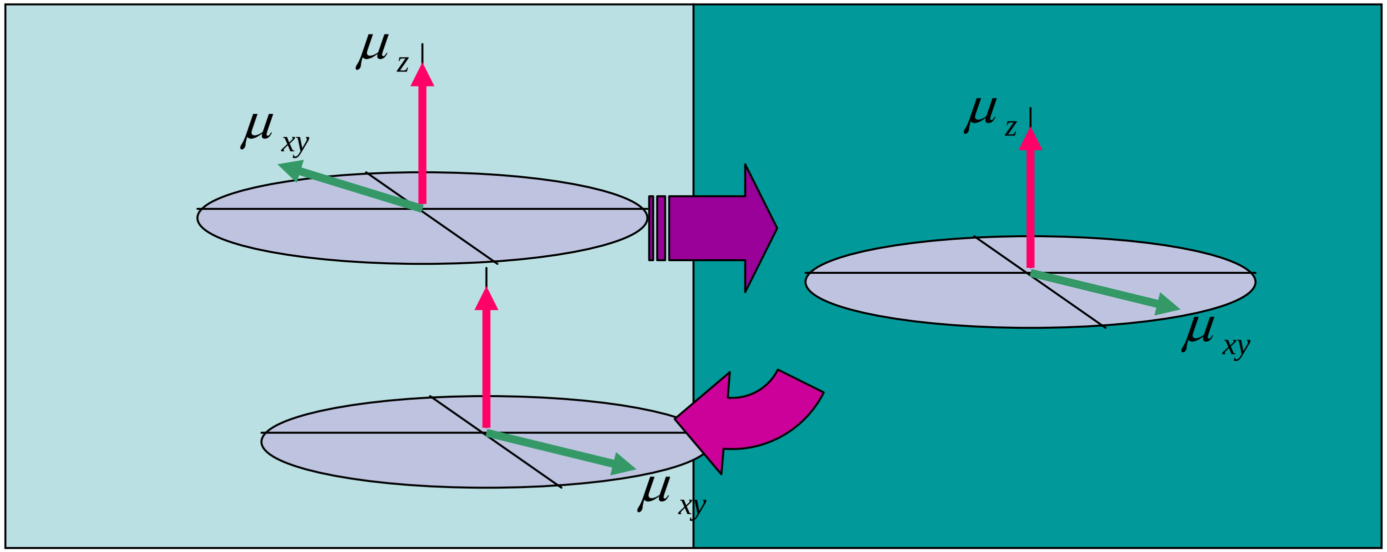
Pumped spin current *across the interface*



Dwell time, *μ_{xy} no longer precesses in region II*



Back-flow current *randomizes xy components near interface*



- The randomization leads to partial cancellation of the xy component near the interface
- This can be thought of as giving an effective *anisotropic relaxation time:*

τ_{xy} ***Reduced by back-flow current***

τ_z ***Not effected by back-flow current***

$$\tau_z >> \tau_{xy}$$

Analytical model with anisotropic relaxation

$$\frac{d\mu_{x,y}}{dt} = \left(\vec{\omega}_B \times \vec{\mu}\right)_{x,y} - \frac{\mu_{x,y}}{\tau_{xy}} - \hbar \frac{d\omega_{x,y}}{dt}$$

$$\frac{d\mu_z}{dt} = \left(\vec{\omega}_B \times \vec{\mu}\right)_z - \frac{\mu_z}{\tau_z}$$

$$\mu_z = -\frac{\omega_{xy}^2 \tau_{xy} \tau_z}{1 + \omega_{xy}^2 \tau_{xy} \tau_z + (\omega_z - \omega)^2 \tau_{xy}^2} \hbar \omega$$

Relevant regime: $\tau_{xy} << \tau_z$

Strongest effect off-resonance and for regions bounded at $L = \lambda_\omega = \sqrt{\frac{2\pi D}{\omega}}$

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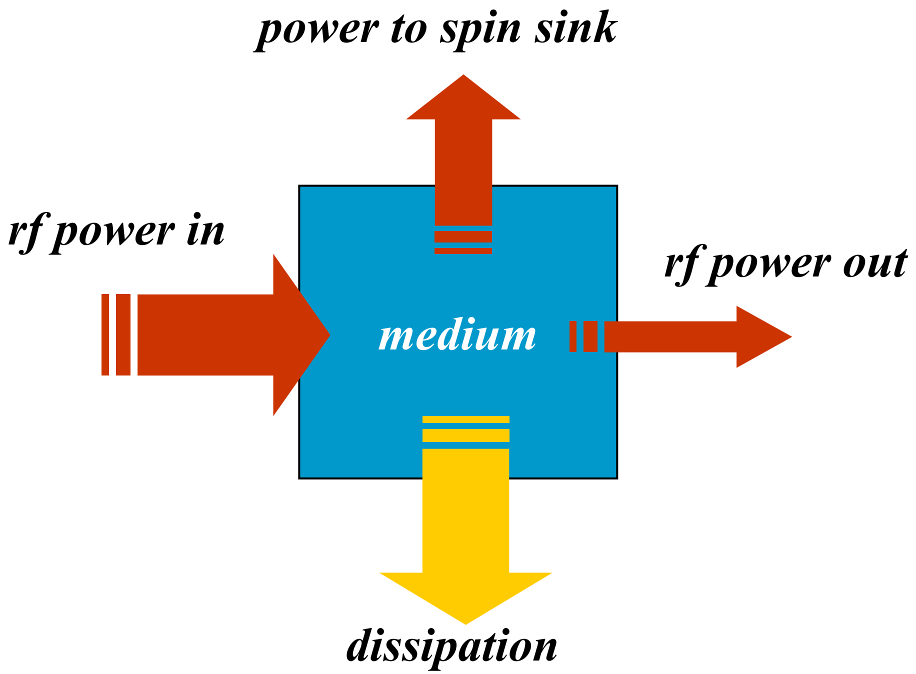
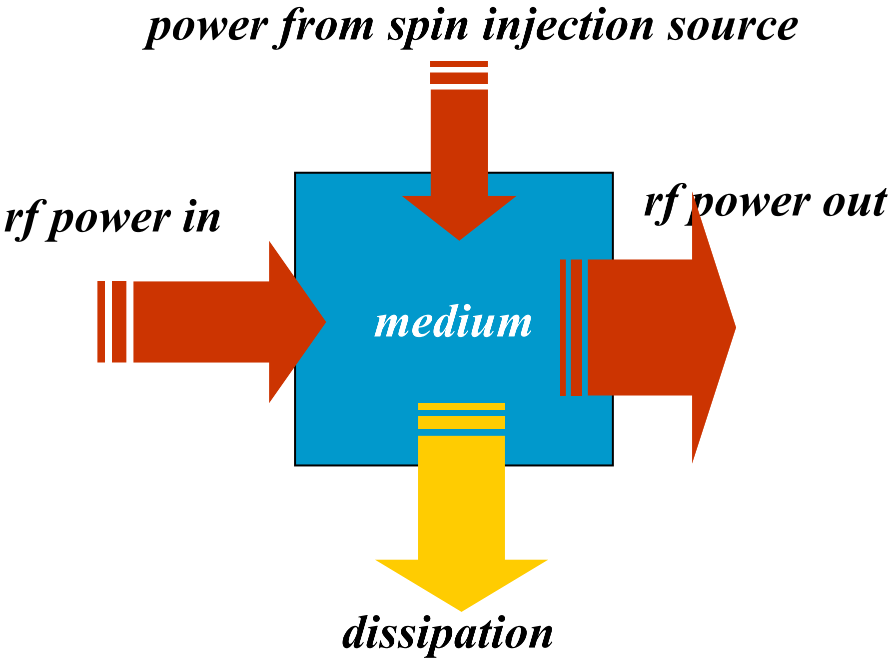
Energy flows…

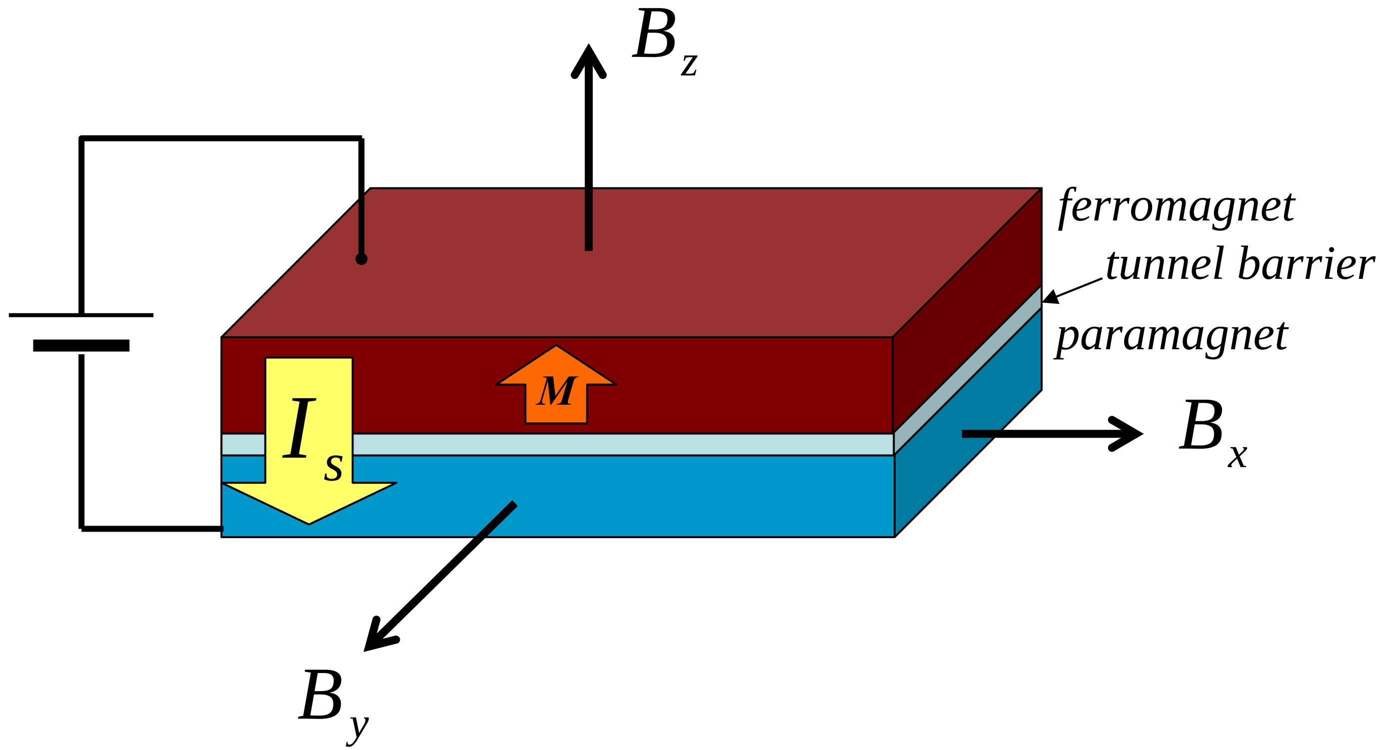
Energy is absorbed from the rf field to generate spin accumulation



Can we reverse the process?

An injected spin current drives the medium to produce gain:





$$\frac{d\vec{\mu}}{dt} = -\hbar\frac{d\vec{\omega}_B}{dt} - \frac{\vec{\mu}}{\tau} + \vec{\omega}_B \times \vec{\mu} + \vec{I}_s(t)$$

1 *2* *3* *4*

1. ***Pumping***
2. ***Relaxation***
3. ***Precession***
4. ***Injection***

Spin pumping with a spin injected current $\vec{I}_s = \frac{\mu_s}{\tau}\hat{z}$

Solutions:

$$\mu_{\parallel} = \frac{(\omega_z - \omega)\tau(\omega_{xy}\tau)}{1 + (\omega_{xy}\tau)^2 + ((\omega_z - \omega)\tau)^2}(\hbar\omega + \mu_s)$$

Dispersive component

$$\mu_{\perp} = -\frac{(\omega_{xy}\tau)}{1 + (\omega_{xy}\tau)^2 + ((\omega_z - \omega)\tau)^2}(\hbar\omega + \mu_s)$$

Absorptive component

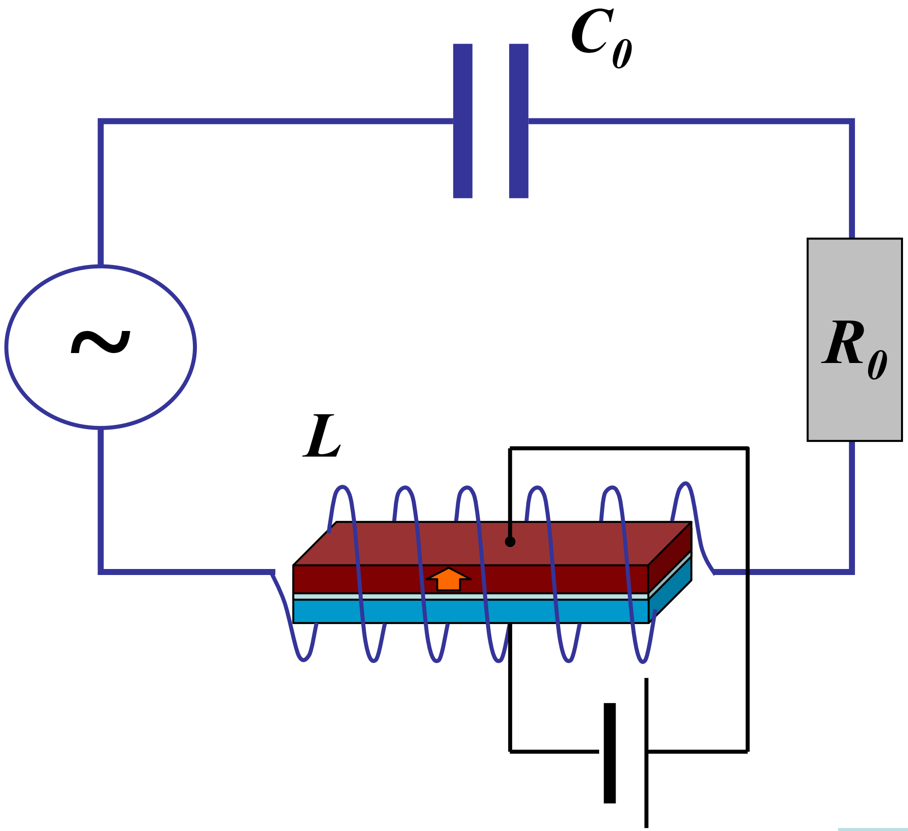
$$\mu_z = \mu_s - \frac{(\omega_{xy}\tau)^2}{1 + (\omega_{xy}\tau)^2 + ((\omega_z - \omega)\tau)^2}(\hbar\omega + \mu_s)$$

With $\mu_s = -\hbar\omega$ ***we can turn off effect of spin pumping!***

With $\mu_s < -\hbar\omega$ ***we can change the sign of the components***

Absorption ⇒ ***Emission***

An LRC circuit model:



The sample magnetization couples to the circuit via the inductance:

$$L = L_0(1+\eta\chi)$$

Define the complex susceptibility :

$$\chi = \chi' + i\chi''$$

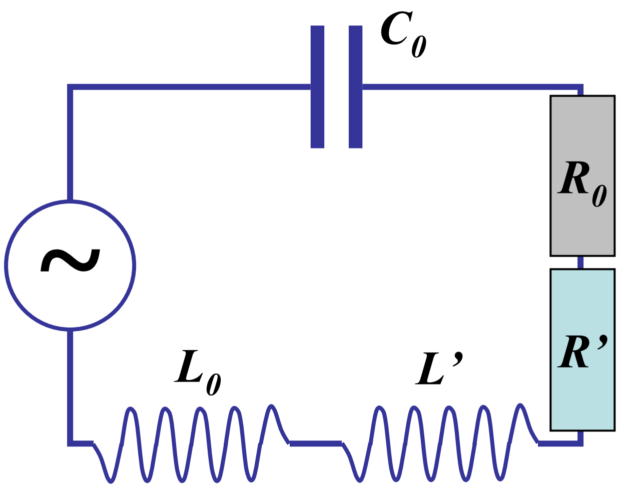
$$\chi' = \frac{\mu_0 m_{\parallel}}{B_{xy}} \approx \tfrac{1}{4} g N_F \mu_B^2 \mu_0 \equiv \chi_0$$

$$\chi'' = \frac{\mu_0 m_{\perp}}{B_{xy}} \approx -\chi_0 \frac{\tau}{\hbar}(\hbar\omega + \mu_s)$$

The total impedance:

$$Z = R_0 + i\omega L + (i\omega C_0)^{-1}$$
$$= R_0 - \omega L_0 \eta \chi'' + i\omega L_0 (1 + \eta \chi') + (i\omega C_0)^{-1}$$

R' ***L'***



The condition for MASER operation: $R_0 + R' < 0$

Expressed in terms of the quality factor:

$$Q = \frac{\omega L_0}{R_0} > \left(\eta \chi_0 \frac{\tau}{\hbar} (\hbar\omega + \mu_s) \right)^{-1}$$

For Al metal: $Q \gtrsim 1/\mu_s(eV) \sim 200$

Conclusions

- We describe a new way to produce dc spin accumulation in non-magnetic metals and semiconductors

- Spin pumping with a rotating magnetic field can produce dc spin accumulations as large as $\hbar\omega$

- Spin accumulation can be interface-enhanced by engineering *anisotropic relaxation*

  S. M. Watts, J. Grollier, C. H. van der Wal, and B. J. van Wees, PRL **96,** 077201 (2006)

- Spin injection + spin pumping $\Rightarrow$ ***spin-injection MASER***

  S. M. Watts and B. J. van Wees, submitted to Nature Physics.