Nano - Magnetism

What new physics emerges as you shrink a magnet to small sizes?

Some features - straightforward extrapolation from larger magnets.

- Smaller activation barriers for magnetic dynamics
  - → superparamagnetism, possibility of tunneling
- Large surface/volume ratio
  - → important effects of surface on magnetic anisotropy, moments

But also: qualitatively new physics as samples become smaller than important length scales.

- $L <$ domain-wall widths (2-100 nm range) → single domain structures
- $L < l_{sf}$ spin-flip diffusion length (100's of nm in metals like copper)
  - → spin-polarized transport
- $L < l_{in}$ inelastic scattering length (energy-dependent: can be 1000 nm near Fermi energy at low T → ~5 nm at $E = 30$ meV)
  - → hot electrons, can't assume Fermi distributions
- $L < l_\phi$ phase coherence length (5-1000 nm)
  - → weak localization, Aharonov-Bohm, quantized channels.
- $L < l_{ee}$ elastic mean free path → ballistic electron motion

Other new phenomena, too:

- Single-electron effects - Coulomb blockade
  small capacitances so $\frac{e^2}{2C} \gg k_B T$ and $R \gtrsim \frac{h}{e^2} \sim 25\,k\Omega$.
- Quantized electrons-in-a-box states
  $L \lesssim 5$ nm so $\Delta E \gg k_B T$.

- High current densities:
  10^9 A/cm^2 OK for channels with $L, w \ll l_{in}$
- Atom-by-atom manipulation of known structures
  → sensitivity to individual defects, impurities, bonding
  → can manipulate and contact single magnetic molecules
- New high speed techniques to measure magnetic dynamics
- New techniques for nm-scale magnetic imaging

My lectures: Will pick and choose a few of my favorite topics – not a comprehensive treatment.

I am an experimentalist – but will try to reveal opportunities for clever theory. Will try to emphasize what is understood theoretically and what is not.

Will concentrate on metal devices.

Nano-Magnetics Lecture Topics, Dan Ralph
(but I probably won't cover everything)

A. Torques on Magnets from Spin-Polarized Currents

(A new way to manipulate magnets without magnetic fields)
"Taking a spin with Newton's 3rd Law"

B. Magnetic Wires and Point Contacts

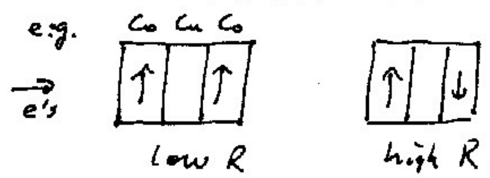
- Domain walls and resistance
- Spectroscopy with point contacts
- "Ballistic Magnetoresistance"?
- Manipulating single domain walls

C. Coulomb Blockade and Tunneling in Small Magnets

- The electrochemical potential can depend on magnetic field
- Effects of electron interactions
- Surface Effects
- Quantized States in Magnetic Quantum Dots
- Probing Individual Magnetic Molecules

Torques from Spin-Polarized Currents

Review: GMR – relative orientation of magnets affects resistance / current flow



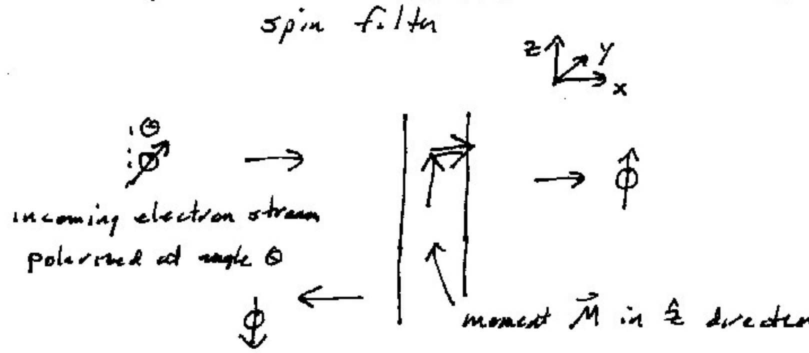
What about the reverse? Can spin-polarized currents affect the orientation of magnets?

one way – trivial – current-induced magnetic fields

More interesting (and much stronger in small devices) – direct transfer of angular momentum

Central Message: Magnets act like spin filters. Newton's 3rd Law says that the magnets can feel torques as a result.
(predicted by John Slonczewski, Luc Berger)

To get started: Cartoon, assume magnet is a 100% efficient spin filter



Summing over an ensemble of incoming spins, the consequence of spin filtering is a spin ↑ current transmitted, and a spin ↓ current reflected.

From conservation of angular momentum – x component of angular momentum absorbed so the magnet must feel a torque in that direction

All a consequence of filtering.

Now More Realistic Situation: Less than perfect filter.

Some notation: Ψ a spinor

charge density $\rho(r) = e \langle \sum_\alpha \Psi_\alpha^+(r)\, \Psi_\alpha(r) \rangle$ ← expectation value

current density: $\vec{J}(r) = \frac{-i\hbar e}{2m} \sum_\alpha \langle \Psi_\alpha^+(r)\, \vec{\nabla} \Psi_\alpha(r) - (\vec{\nabla} \Psi_\alpha^+(r))\, \Psi_\alpha(r) \rangle$

Can write similar expressions for spin density and spin current density

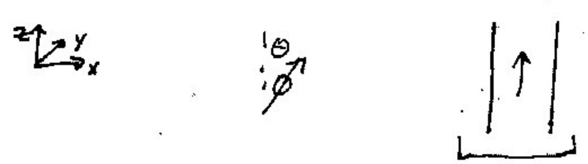
$\vec{\text{spin density}} = \frac{\hbar}{2} \langle \Psi^+(r)\, \vec{\sigma}\, \Psi(r) \rangle$ ← Pauli matrices

spin current density (tensor) $\vec{J}_s = -\frac{i\hbar^2}{4m} \langle \Psi^+ \vec{\nabla} \vec{\sigma} \Psi - \vec{\nabla} \Psi^+ \vec{\sigma} \Psi \rangle$

Example: If $\Psi = \begin{pmatrix} a \\ b \end{pmatrix} e^{i\vec{k}\cdot\vec{r}}$

$$\vec{J}_z = \frac{\hbar^2 k}{2m} (|a|^2 - |b|^2)\, \hat{k}$$
$$\vec{J}_x = \frac{\hbar^2 k}{2m} (ab^* + a^*b) = \frac{\hbar^2 k}{m} \mathrm{Re}[ab^*]$$
$$\vec{J}_y = \frac{\hbar^2 k i}{2m} (ab^* - a^*b) = -\frac{\hbar^2 k}{m} \mathrm{Im}[ab^*]$$

Think about the filtering geometry again, incident electrons in a single state.



$$\Psi_{inc.} = [\cos\tfrac{\theta}{2} |\uparrow\rangle + \sin(\tfrac{\theta}{2}) |\downarrow\rangle]\, e^{ikx}$$

Consider the scattering properties of the magnetic thin film
Assume no spin-flip scattering, just filtering

Transmission matrix: $\begin{pmatrix} t_\uparrow & 0 \\ 0 & t_\downarrow \end{pmatrix}$ $\quad t_\uparrow \neq t_\downarrow$ for magnetic film (it acts as a filter)

Reflection matrix $\begin{pmatrix} r_\uparrow & 0 \\ 0 & r_\downarrow \end{pmatrix}$ $\quad |t_\uparrow|^2 + |r_\uparrow|^2 = 1$, $\quad |t_\downarrow|^2 + |r_\downarrow|^2 = 1$

Transmitted wavefunction:

$$\Psi_T = [t_\uparrow \cos\tfrac{\theta}{2} |\uparrow\rangle + t_\downarrow \sin\tfrac{\theta}{2} |\downarrow\rangle] e^{ikx}$$

Reflected wavefunction:

$$\Psi_R = [r_\uparrow \cos\tfrac{\theta}{2} |\uparrow\rangle + r_\downarrow \sin\tfrac{\theta}{2} |\downarrow\rangle] e^{-ikx}$$

Compute Torque = [Ang. Momentum flow in] - [Ang. Momentum flow out]

$$= [J_{inc} - J_T - J_R]\ (\text{area})$$

Will leave the calculation as an easy exercise. Results:

$$\tau_z = 0$$
$$\tau_x \propto \sin\theta\, [1 - \mathrm{Re}(t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*)]$$
$$\tau_y \propto -\sin\theta\, \mathrm{Im}[t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*]$$

Notes: $\vec{\tau} = 0$ for $\theta = 0$ or π ⇒ No torques for collinear magnets

Check - torque should be zero for nonmagnetic film -

if $t_\uparrow = t_\downarrow$, $r_\uparrow = r_\downarrow$ then $t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^* = |t_\uparrow|^2 + |r_\uparrow|^2 = 1$

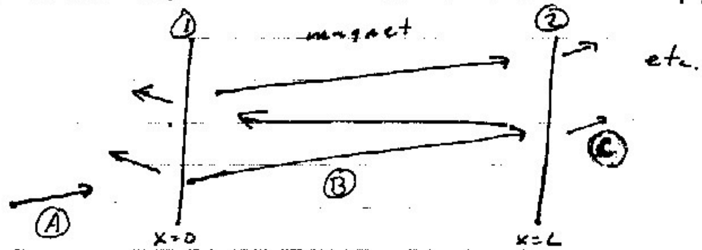
so $\vec{\tau} = 0$. ✓.

τ_x is in the same direction as for the perfect polarizer.

τ_y is new - it is like the torque from an "effective field" pointed in the direction of the spin polarization - causes the moment to precess out of the plane as I have drawn the picture.

<u>Now for a more microscopic view</u>

Think of a thin magnetic film like a Fabrey-Perot etalon – can calculate transmission and reflection as a sum of multiply-reflected waves.



Can get some insight even from the first path

Ⓐ $\Psi_{inc} = \left(\cos\frac{\theta}{2}\,|\uparrow\rangle + \sin\frac{\theta}{2}\,|\downarrow\rangle\right) e^{ikx}$

Ⓑ After transmission through interface ①

$$\Psi_B = t_{1\uparrow}\cos\left(\frac{\theta}{2}\right)|\uparrow\rangle\, e^{ik_\uparrow x} + t_{1\downarrow}\sin\left(\frac{\theta}{2}\right)|\downarrow\rangle\, e^{ik_\downarrow x}$$

important: $k_\uparrow$ and $k_\downarrow$ are different in a ferromagnet.
Strong exchange splitting $\gtrsim$ bandwidth, so electrons at the Fermi energy have very different wavelengths for spin ↑ and spin ↓ (think different kinetic energies)

Can write $\Psi_B \propto \left[\cos\left(\frac{\theta_F}{2}\right)|\uparrow\rangle + \sin\left(\frac{\theta_F}{2}\right) e^{i\phi_0} e^{i(k_\downarrow - k_\uparrow)x}\,|\downarrow\rangle\right] e^{ik_\uparrow x}$

phase factor – precession around z-axis as a function of position x : $\phi = (k_\downarrow - k_\uparrow)\,x$

In Co, Fe, Ni: $k_\downarrow - k_\uparrow \approx \frac{1}{\text{atomic distance}}$, so a spin will process many times in going through even a thin film.

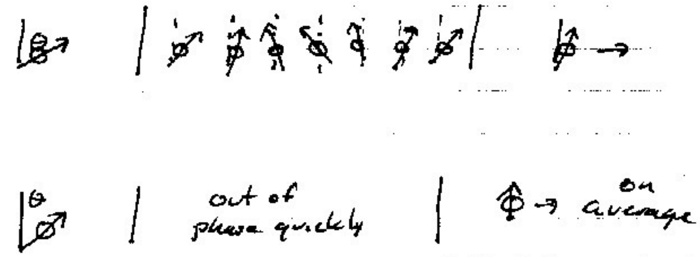
Ⓒ $\Psi_C \propto \left[t_{2\uparrow}\cos\left(\frac{\theta_F}{2}\right)|\uparrow\rangle + t_{2\downarrow}\sin\left(\frac{\theta_F}{2}\right) e^{i\phi_0} e^{i(k_\downarrow - k_\uparrow)L}\,|\downarrow\rangle\right] e^{ik(x-L)}$

In a real device, electrons are not incident in just one quantum state, but with a variety of different angles, wavelengths. To calculate torque, must sum over all electrons. Even if they all start polarized in the same direction, they will precess incoherently. For transmitted electrons, the average angular momentum in the x and y directions will be zero.

Semiclassical Picture:

one quantum state

sum over many incident wavevectors



From before

$$\tau_x \propto \sin\theta\,\left[1 - \mathrm{Re}\left(t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*\right)\right] \rightarrow \boxed{\sin\theta\left[1 - \mathrm{Re}\,\langle r_\uparrow r_\downarrow^*\rangle\right]}$$

↖ positive + negative cancel

$$\tau_y \propto -\sin\theta\,\mathrm{Im}\left[t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*\right] \rightarrow \boxed{-\sin\theta\,\mathrm{Im}\,\langle r_\uparrow r_\downarrow^*\rangle}$$

$\tau_z = 0$ obvious - electron just precesses around the exchange field.

At this point, need input from band structure calculations to work out what are the reflection coefficients. These indicate that $\mathrm{Im}(r_\uparrow r_\downarrow^*)$ is only 2–10% of $1 - \mathrm{Re}(r_\uparrow r_\downarrow^*)$

⇒ usually OK to consider only the τ_x term (as in perfect filter case) and ignore the τ_y "effective field" term.

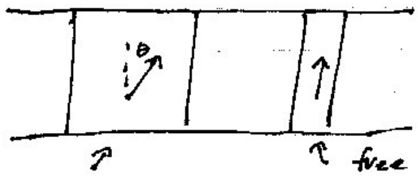
<u>Bottom Line</u>: To a good approximation, the transverse component of angular momentum is effectively absorbed (just as in the perfect filter case) in the first few monolayers of a magnet. (effectively a torque applied to the magnet's surface)

total $\tau_x \sim \sin\theta \times$ a good fraction of $\frac{\hbar}{2}$ per electron.

This can be a big torque.

Dynamical Consequences of Spin Transfer

For the simplest real device, need 2 magnetic layers, a polarizer and a "free layer"



polarizer ↑ free layer $\frac{d\vec{\mu}}{dt} = \vec{\tau}$, can respond to torque.

polarizer : thick enough not to respond to any torques

Consider a linear stability analysis - imagine a small fluctuation Θ angle between the two moment directions. Pass a current. Will the torque from the current amplify or suppress the deviation?

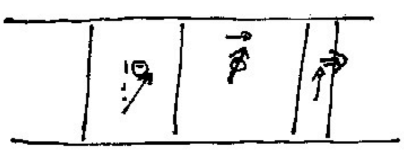
Lesson : Will depend on current direction

Could do a full calculation as for the single layers (Waintal et al., PRB 62, 12317 (2000))

but the cartoons are good enough for our purpose.

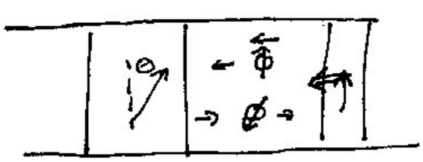
One direction of current :

incoming e's →



as before. This direction of current stabilizes the parallel orientation

Other direction of current



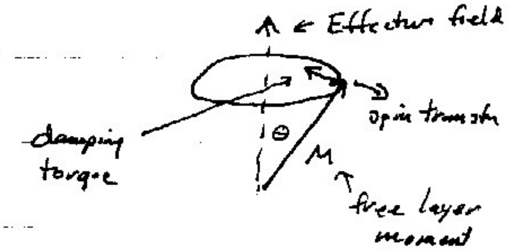
← incoming e's.

Here spin transfer twists the free layer away from the polarizer direction

Next: Can possibly destabilize parallel configuration with one sign of current.

To understand fully the resulting dynamics, one must consider all the torques acting on the free layer
→ Magnetic field and damping too

Picture first - will discuss Landau-Lifshitz-Gilbert equation later
Assume effective field and the polarizer point in the same direction



Torque due to effective field causes precession of free layer.
Damping - gives torque toward the field direction to lower energy

Spin transfer: If current is in the correct direction, gives a torque that points opposite to the damping

Can give effectively a negative damping - spiral away from the applied field direction.

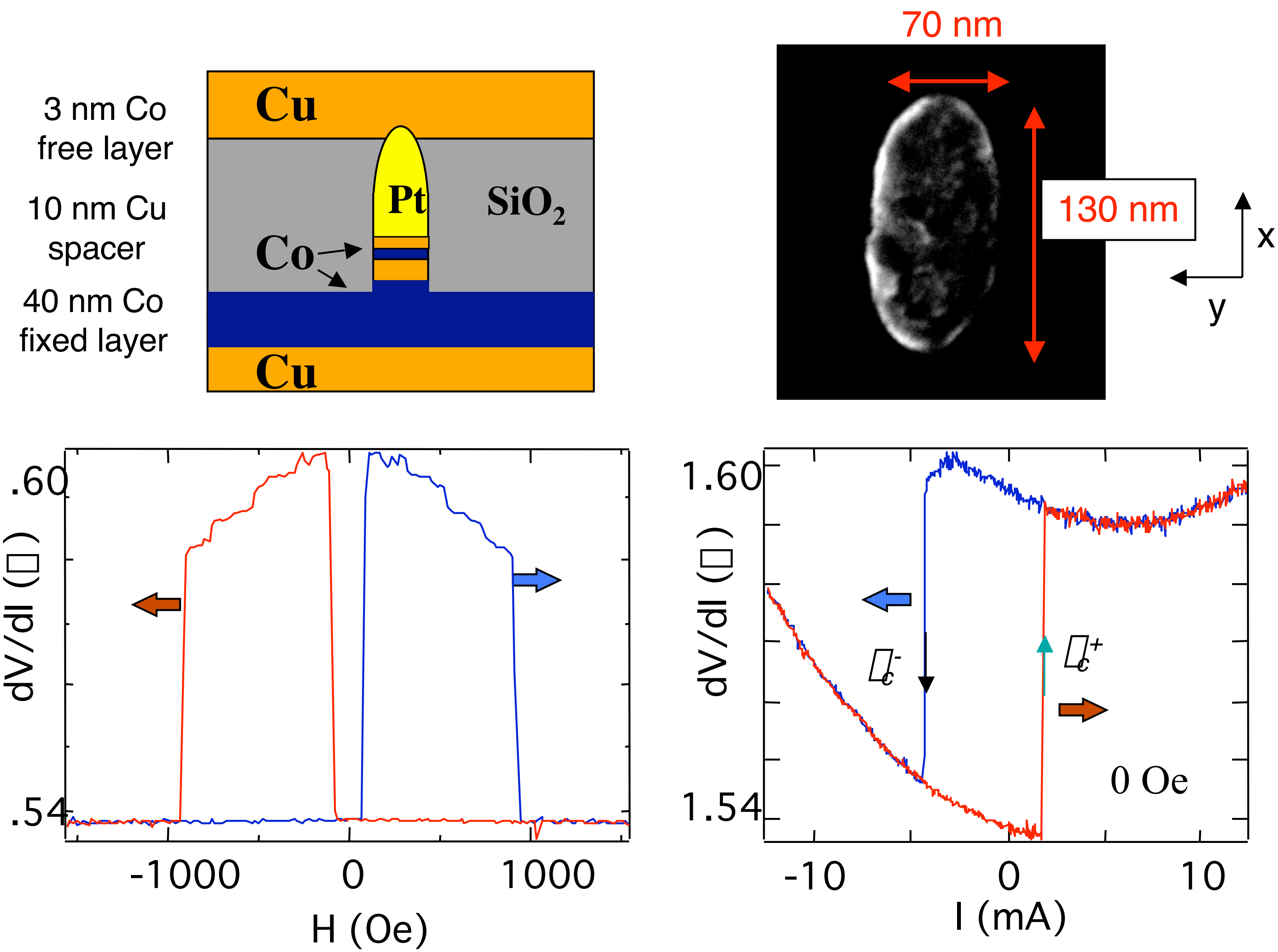
3 possible types of regimes

1. switching - free layer flips 180°, antiparallel to polarizer (reversed current can flip it back)
2. dynamical equilibrium - at some angle damping balances spin transfer torque. DC current drives steady-state precession
3. Single-domain approximation fails - spatiotemporal chaos?

experimental evidence for all 3 regimes

switching - low applied magnetic fields
steady-state precession - larger fields, current not too high
not single domain - probably for large fields, large currents.

Spin-Transfer-Driven Magnetic Reversal

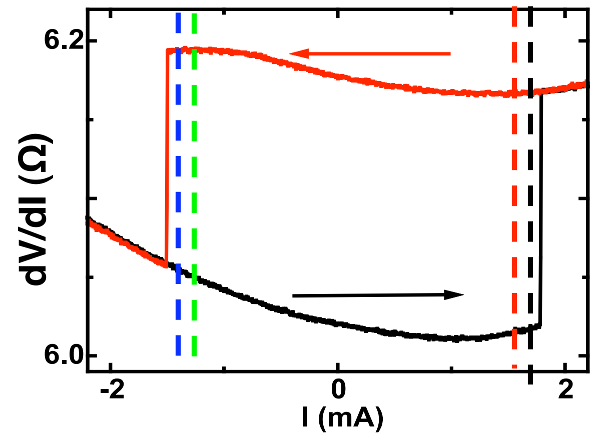


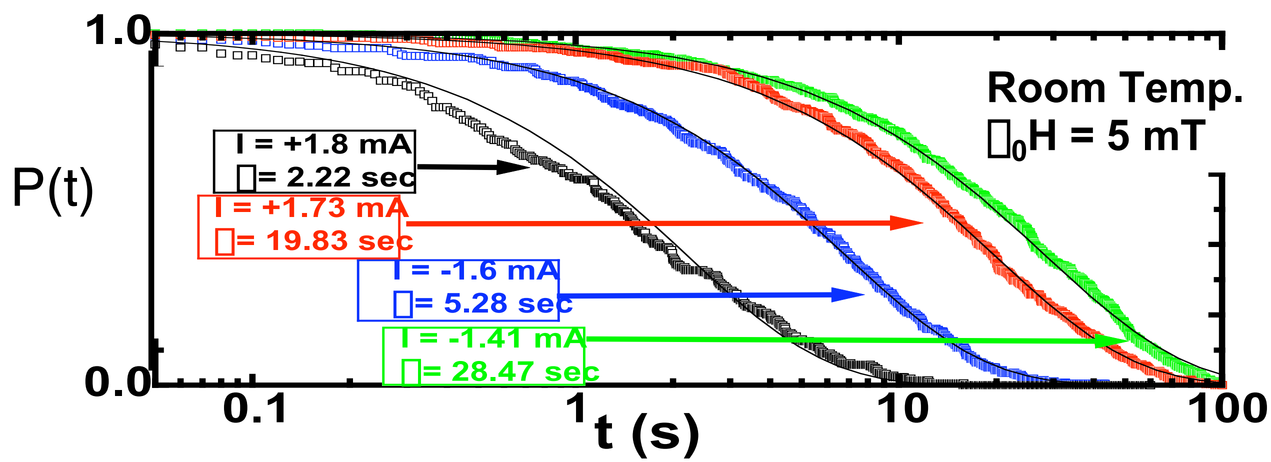
Switching at Room Temperature Displays Randomness

P(t) = distribution of switching times at a fixed current

-Distributions fit well to exponential decay P(t) = $e^{-t/□}$

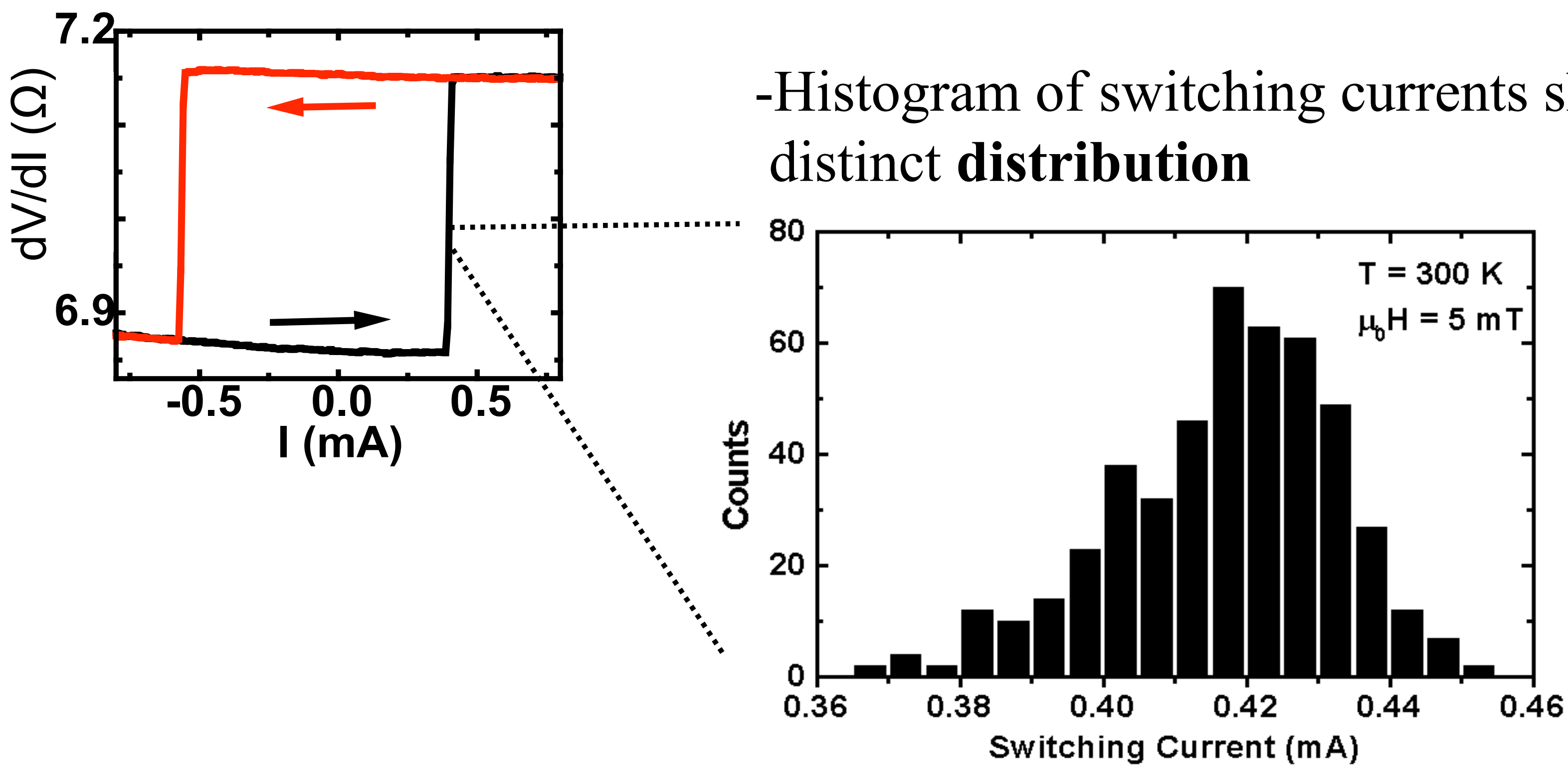
-Switching times strongly **current-dependent**

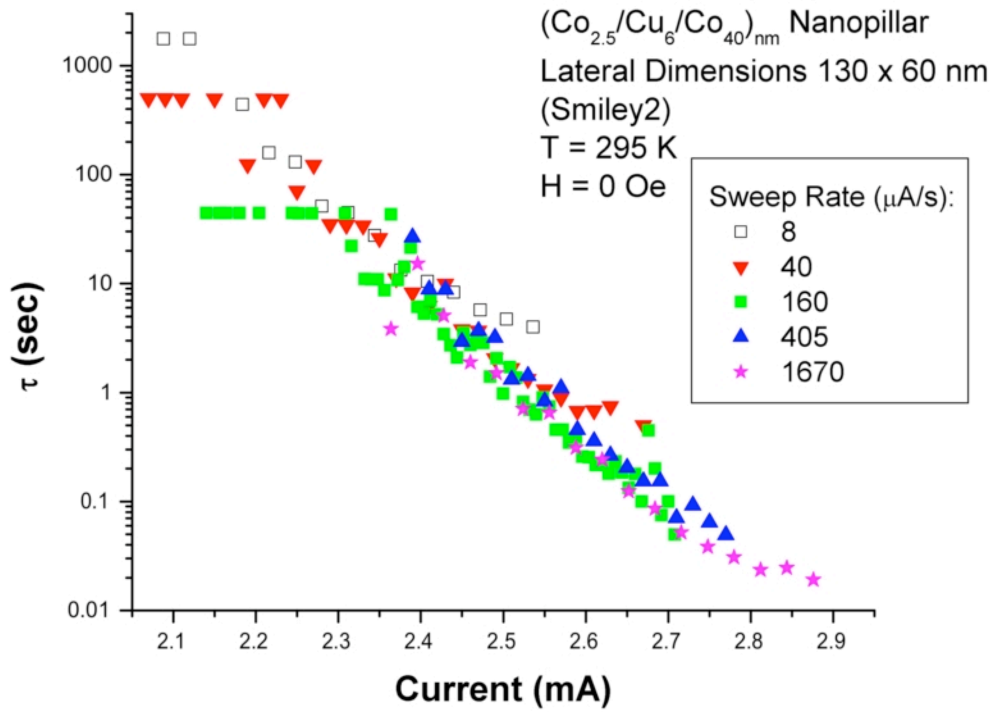




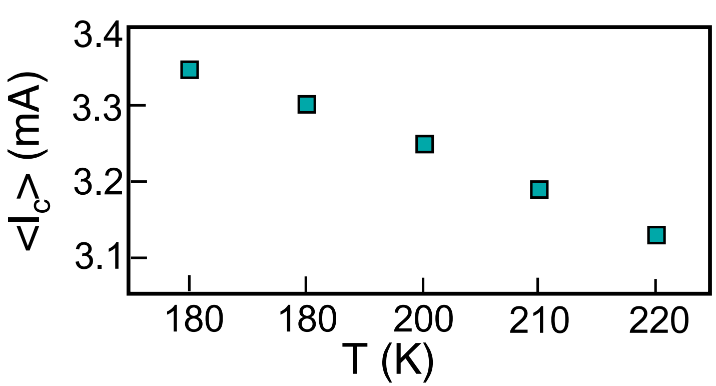
Distributions in Critical Currents

-Histogram of switching currents shows distinct **distribution**





Temperature dependence



$$\text{switching rate} = \tau_0^{-1} \exp\left(-\frac{U(I,B)}{kT}\right)$$

U(I,B) = **effective** activation barrier

<u>How can spin-transfer-driven switching be thermally activated?</u>

Argument I just gave: switching at $T=0$ occurs when the spin transfer torque overcomes the intrinsic damping – not about an energy barrier.
Also – the spin transfer torque is nonconservative – not expressible in terms of a potential energy function

[Simple explanation due to Roger Koch and Jonathan Sun (IBM)]

Start with Landau-Lifshitz-Gilbert equation with <u>no spin transfer term</u>.

$$\frac{d\vec{m}}{dt} = -\gamma \vec{m} \times \vec{H}_{eff} + \frac{\alpha}{M_s}\left(\vec{m} \times \frac{d\vec{m}}{dt}\right) - \gamma\sqrt{\alpha kT}\, \vec{m} \times \vec{A}(t)$$

precession — damping torque — thermal fluctuations modeled by a fluctuating field

(The $\sqrt{\alpha kT}$ term is necessary to obey fluctuation-dissipation theorem)

With the magnets anisotropy energy included in the effective field, the solution of this equation obeys a thermal activation form
Switching rate $\propto \exp[-U/kT]$.

Now add spin transfer. For currents less than the $T=0$ switching current, I have argued that the spin transfer torque can be understood as decreasing the damping
(Simple idea: less damping → bigger fluctuations → faster switching)
With spin transfer, decrease α to $\alpha_{eff}(I)$

$$\frac{d\vec{m}}{dt} = -\gamma \vec{m} \times \vec{H}_{eff} + \frac{\alpha_{eff}}{M_s}\left(\vec{m} \times \frac{d\vec{m}}{dt}\right) - \gamma\sqrt{\alpha kT}\, \vec{m} \times \vec{A}(t)$$

← fluctuation size unchanged.

Now rewrite final term by multiplying by $1 = \frac{\alpha_{eff}}{\alpha_{eff}}$

$$\frac{d\vec{m}}{dt} = -\gamma \vec{m} \times \vec{H}_{eff} + \frac{\alpha_{eff}}{M_s}\left(\vec{m} \times \frac{d\vec{m}}{dt}\right) - \gamma\sqrt{\alpha_{eff}\, k\left(\frac{\alpha T}{\alpha_{eff}}\right)}\, \vec{m} \times \vec{A}(t)$$

This is the same equation we had without the spin transfer term but with $T \to \frac{\alpha T}{\alpha_{eff}}$

$\Rightarrow$ Switching rate has the same form as before but now

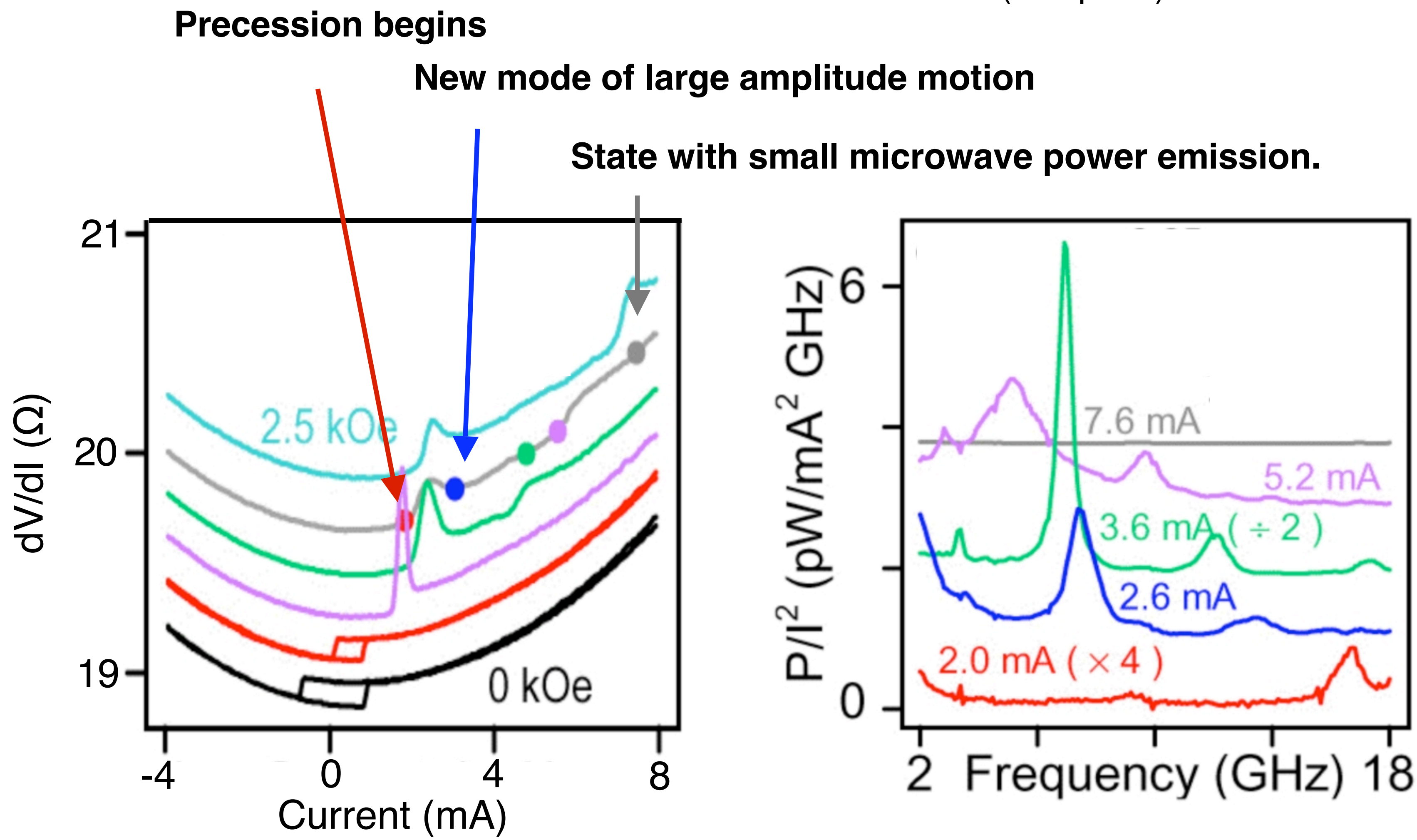
$$\text{switching rate} \propto \exp\left[-\frac{U\alpha_{eff}}{\alpha T}\right] .$$

This can be understood as thermal activation at an elevated temperature $T_{eff}(I) = \frac{\alpha T}{\alpha_{eff}(I)}$ or as ordinary thermal activation with a decreased effective activation energy $U_{eff} = \frac{U \alpha_{eff}(I)}{\alpha}$.

Note that this is not simple heating, because T_{eff} is still proportional to T. In simple heating, for large enough currents the true background temperature will not matter.

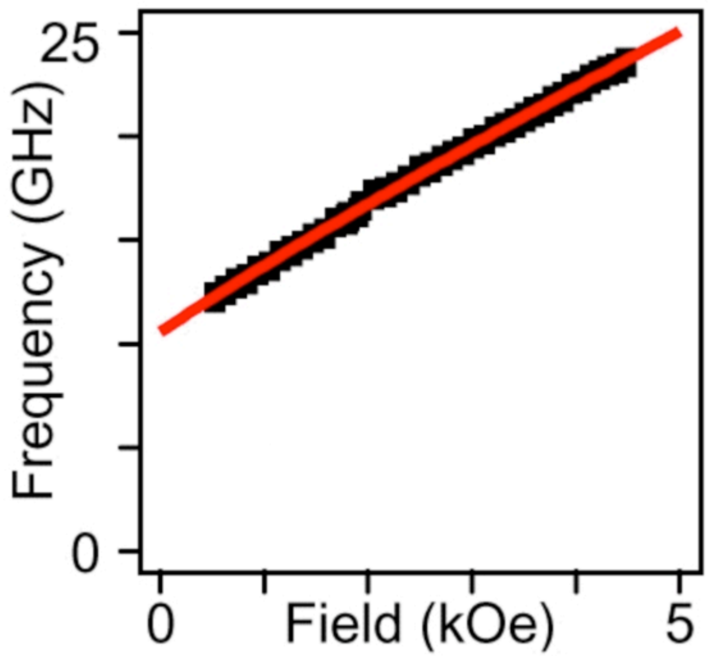
Dynamics at 2000 Gauss

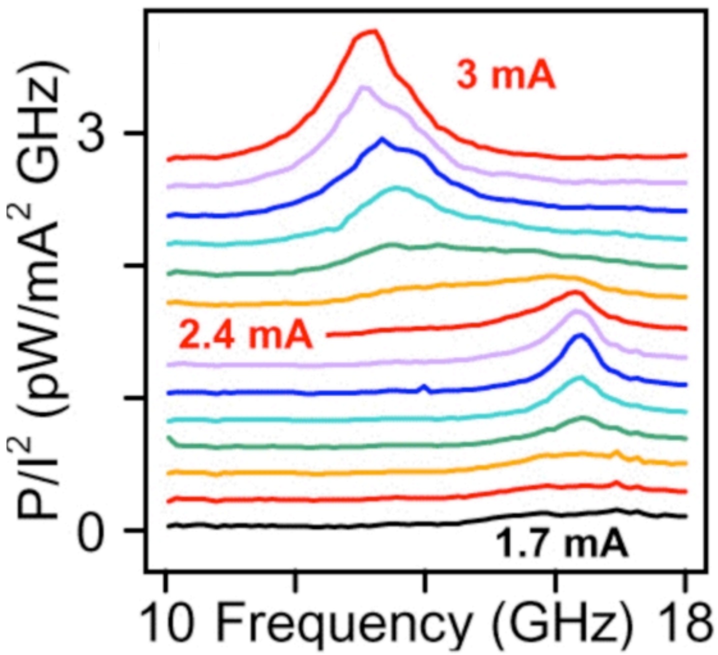
(sample 1)



Magnetic-Field and Current Dependence of Precessional Resonance

(sample 1)





Peak frequency is consistent with Kittel formula.

$$f = \frac{\gamma}{2\pi}\sqrt{(H + H_0)(H + H_0 + 4\pi M)}$$

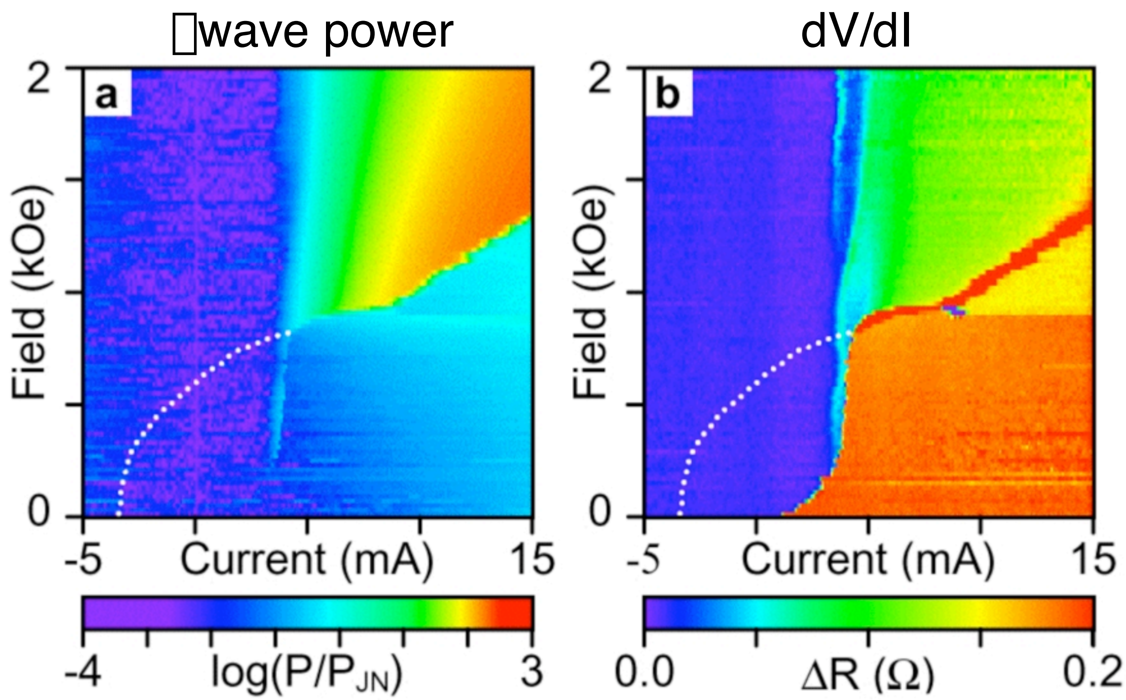
from preliminary fit: $4\pi M = 8.0 \pm 0.5$ kOe
$H_0 \sim 1.18 \pm 0.04$ Oe

Signal from precessional resonance grows with current, but then the dynamics switch to a different regime beyond 2.4 mA.

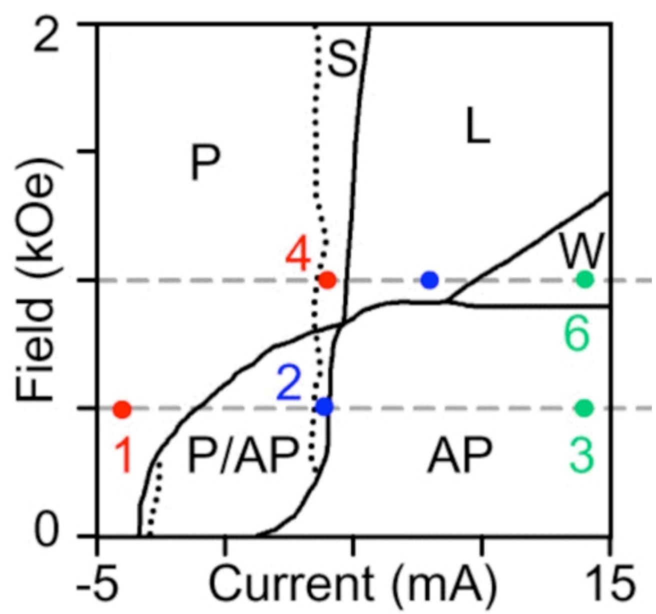
Minimum detectable precession angle is about 10 degrees.

Overall Phase Diagram

(sample 2)

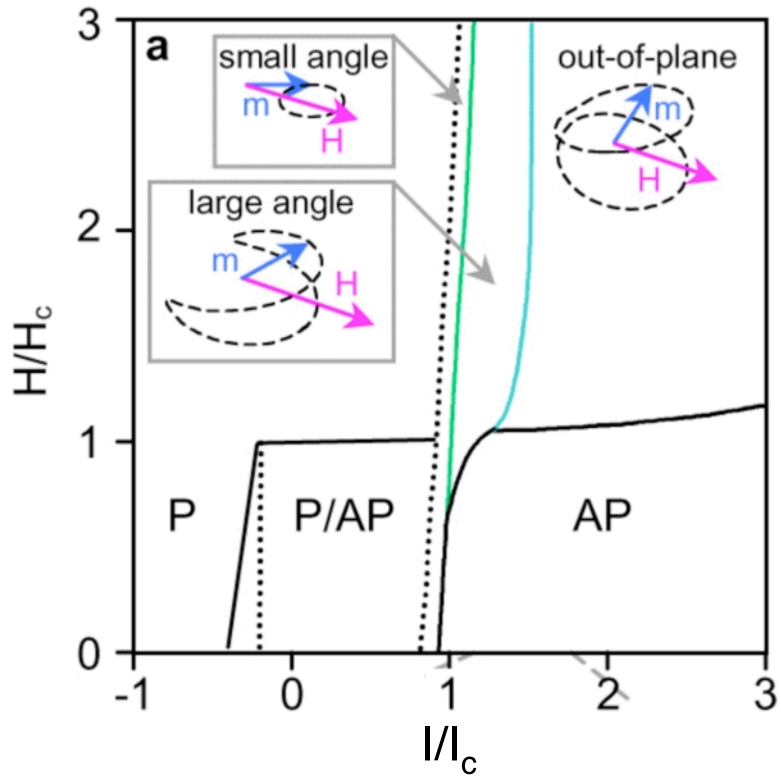


P = parallel
AP = antiparallel
S = small-angle precession
L = large amplitude signal
W = small microwave signal,
not P or AP

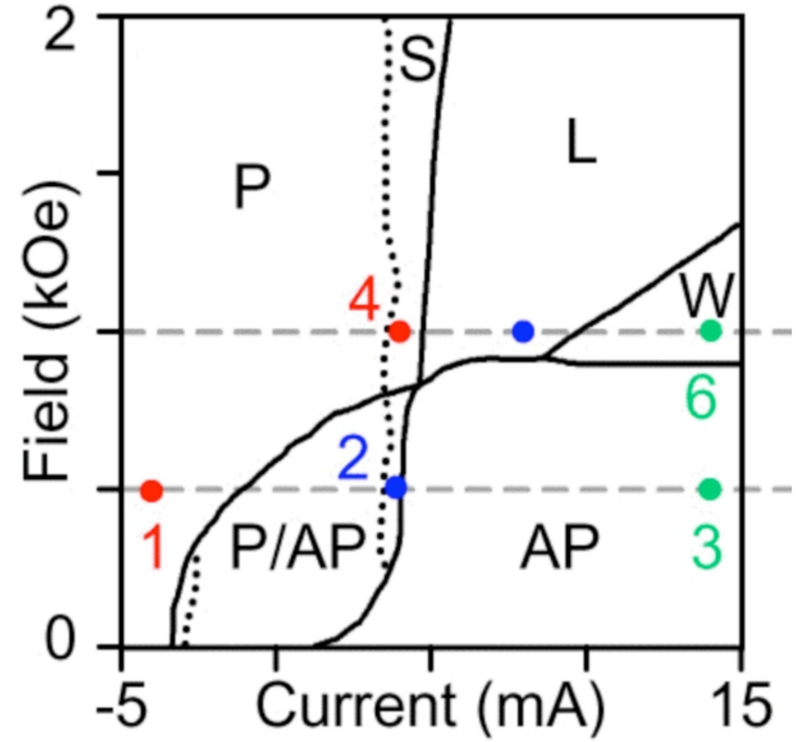


Comparing to Single-Domain LLG Simulations

simulated stability diagram (T=0)



from the experimental data (room T)



Signal size in the large-amplitude regime and the dependence of frequency on current are consistent with large-angle in-plane precession.

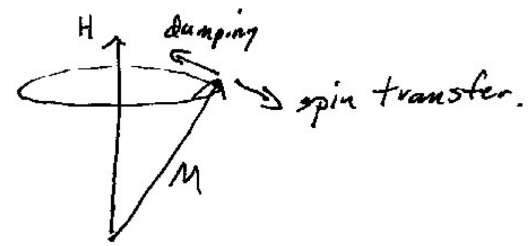
State W is not predicted by single-domain simulation. Dynamical instability to a non-uniform state?

Summary

Spin-polarized currents apply a torque to a magnetic thin film when that film acts as a spin filter.

At low applied magnetic fields, this torque can be used to switch 2 magnetic layers reversibly between parallel and antiparallel orientations.

At larger applied magnetic fields, a DC spin-polarized current can drive steady-state magnetic precession in a nanomagnet.



Unresolved Questions Regarding Spin Transfer

① Role of spin-flip scattering at magnetic interfaces, as distinct from simple spin filtering.

I had assumed $T = \begin{pmatrix} t_\uparrow & 0 \\ 0 & t_\downarrow \end{pmatrix}$ but really $T = \begin{pmatrix} t_{\uparrow\uparrow} & t_{\uparrow\downarrow} \\ t_{\downarrow\uparrow} & t_{\downarrow\downarrow} \end{pmatrix}$.

$t_{\uparrow\downarrow}$ is ordinarily assumed to be small, but I don't know of an honest calculation.

② Dynamics beyond the single-domain approximation.

③ Calculating the scattering coefficients for realistic interfaces.

④ How important are real heating effects in the small magnets in determining dynamics?

⑤ What materials / device geometries can optimize (lower) the needed currents?
- large polarization
- low moment (less angular momentum to turn)
- small damping
- small anisotropies

⑥ How to obtain the properties needed for memory or communications applications?
- larger resistance than 1-10 Ω (for signal/noise needs)
- minimizing critical currents while avoiding superparamagnetism
- high quality factor for spin-transfer-driven precession
- good control of precession frequencies.

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