MP3 - Spin-transfer and spin-orbit torques, current topics in magnetisation dynamics

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Brief review of concepts in spin-dependent transport

Spin-transfer torques (CPP, CIP) and spin-orbit torques
Slonczewski model, Zhang-Li model, spin Hall effect

Effects of current-driven torques on spin waves
Self-sustained oscillations, Doppler effect

Effect of current-driven torques on soliton dynamics
Domain wall propagation, vortex gyration
Magnetism affects transport: GMR

- Giant magnetoresistance (GMR): Electrical resistance of a metallic magnetic multilayer that depends on the relative orientation of the constituent layer magnetisations.

![Diagram showing GMR effect with two types of coupled layers: Antiferromagnetically coupled layers and Current in-plane (CIP) GMR.]

**Current perpendicular-to-plane (CPP)**

**Current in-plane (CIP)**

**FIG. 3** Magnetoresistance of three Fe/Cr superlattices at 4.2 K. The current and the applied field are along the same [110] axis in the plane of the layers.


2007 Nobel Prize in Physics
Two-channel model

- In metals, conduction processes occur at the Fermi surface.

- Assume spin-up and spin-down electrons propagate independently (OK if spin-flip scattering is weak).

- Assign a resistance to each spin channel (Mott).

- In normal metals, spin-up and spin-down channels are equivalent.

Fermi surfaces of some nonmagnetic metals

- K: 4s
- Cu: 3d\(^{10}\) 4s
- Al: 3s\(^{2}\) 3p

\[ R_{\uparrow} = R_{\downarrow} \]
Two-channel model

- In ferromagnetic metals, this degeneracy is lifted due to exchange splitting
- Spin-up and spin-down (majority/minority) resistances are different

Fermi surfaces of some ferromagnetic metals

http://www.phys.ufl.edu/fermisurface/
GMR with two-channel model

- Simple picture of giant magnetoresistance in terms of two-resistance model

\[ R_P \neq R_{AP} \]
... But can transport affect magnetism?

- **sd model (Vonsovsky-Zener):**
  Exchange interaction between local magnetisation ($\mathbf{M}$) and conduction electron spin ($\mathbf{s}$)

$$\mathcal{E}_{sd} = - J_{sd} \mathbf{M} \cdot \mathbf{s}$$

- Torques on the magnetisation can arise from this coupling
**Single electron at N/F interface**

- **Exercise:** Consider a free electron in the normal metal arriving at the normal metal (N)/ferromagnet (F) interface. Solve 1D Schrödinger equation

\[
\epsilon_F = \frac{\hbar^2 k_F^2}{2m} \\
\epsilon_F = \frac{\hbar^2 (k_F^{\uparrow,\downarrow})^2}{2m} \mp \frac{J_{sd}}{2}
\]

- Because the bands in the ferromagnet are spin-split, there is a spin-dependent step potential at the interface

\[
k_F^{\downarrow} < k_F^{\uparrow}
\]
Spin currents

- Exercise: Calculate spin current through this interface. What is conserved?

\[ \mathbf{Q}(\mathbf{r}) = Re \sum_{i\sigma\sigma'} \psi_{i\sigma}^{\ast}(\mathbf{r}) \hat{s} \otimes \hat{v} \psi_{i\sigma'}(\mathbf{r}) \]

Conserved

\[ Q_{xx}^{\text{in}} + Q_{xx}^{\text{ref}} = Q_{xx}^{\text{tr}} \]

longitudinal spin current

\[ Q_{zx}^{\text{in}} + Q_{zx}^{\text{ref}} = Q_{zx}^{\text{tr}} \]

transverse spin current

Not conserved

\[ Q_{\perp x}^{\text{in}} + Q_{\perp x}^{\text{ref}} \neq Q_{\perp x}^{\text{tr}} \]

- From conservation of spin angular momentum, argue that missing transverse spin current is transferred to ferromagnet \( M \)

\[
\left[ \frac{\partial \mathbf{m}}{\partial t} \right]_{\text{STT}} \propto \mathbf{s}_\perp
\]
Spin-transfer torques

- Express transverse spin component in terms of vector products

\[ s_\perp \propto (m \times s) \times m \]

- Typical realisations involve the CPP geometry where \( s \) is related to the magnetisation of a second (reference) layer

\[ \left[ \frac{\partial m}{\partial t} \right]_{\text{STT}} \propto (m \times s) \times m \]
Slonczewski model of CPP torques

- Accounting for transport properties, obtain Slonczewski term for spin-transfer torques

\[
\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} + \sigma j_e \mathbf{M} \times (\mathbf{p} \times \mathbf{M})
\]

Current density \(j_e\) with spin polarisation \(P\)

- Current density matters, not currents. We did not observe STT before the advent of nanofabrication

- Need typical densities of \(10^{12} \text{ A/m}^2\): 1 mA for 1000 nm², 1 000 000 A for 1 mm²

\[
\sigma = \frac{g\mu_B}{2e} \frac{1}{M_s^2 d} P
\]

efficiency factor

Consequences on precessional dynamics

- Spin-transfer torques can reverse magnetisation reversal without magnetic fields


Nanopillar structure

Cross-section $60 \times 180$ nm$^2$

- Basis of spin-torque magnetic random access memories STT-(M)RAM

Spin-transfer torques can reverse magnetisation reversal without magnetic fields.
Current-in-plane (CIP) torques

- Spin-transfer torques also occur in continuous systems in which there are *gradients* in the magnetisation.

- Important for micromagnetic states like domain walls, vortices.

- Torques are governed by how well the conduction electron spin tracks the local magnetisation.

- Like CPP case, spin transfer involves the absorption of transverse component of spin current.

**Adiabatic**

Conduction electron spin precesses about *sd* field.

**Nonadiabatic**

Conduction electron spin relaxes toward *sd* field.
Zhang-Li model of CIP torques

- In the drift-diffusion limit (not detailed here), Zhang and Li derived

\[
\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} + \mathbf{T}_{\text{CIP}}
\]

\[
\mathbf{T}_{\text{CIP}} = -\frac{b_J}{\mu_0 M_s^2} \mathbf{M} \times \left[ \mathbf{M} \times (\mathbf{j}_e \cdot \nabla) \mathbf{M} \right] - \frac{c_J}{\mu_0 M_s} \mathbf{M} \times (\mathbf{j}_e \cdot \nabla) \mathbf{M}
\]

- In this model, nonadiabaticity is a ratio between sd-exchange and spin flip time scales

\[
b_J = \frac{P\mu_B}{eM_s(1 + \xi^2)} \quad c_J = \frac{P\mu_B\xi}{eM_s(1 + \xi^2)}
\]

P: spin polarisation

- Many other theories have been proposed to describe this parameter
Re-interpreting Zhang-Li

- By recognising that the pre-factors in the CIP torques and the current density $j_e$ can be expressed in terms of an effective spin-drift velocity $u$

$$u = \frac{P g \mu_B}{2e} \frac{1}{M_s} j_e = \frac{\hbar}{2e} \frac{1}{M_s} j_e$$

$$[u] = \text{m/s}$$

the equations of motion for the magnetisation $\mathbf{M}$ can be written as

$$\frac{d\mathbf{M}}{dt} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{d\mathbf{M}}{dt} - (\mathbf{u} \cdot \nabla) \mathbf{M} + \frac{\beta}{M_s} \mathbf{M} \times [(\mathbf{u} \cdot \nabla) \mathbf{M}]$$

- Rearranging into a more suggestive form:

$$\left( \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{M} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \left( \frac{\partial}{\partial t} + \frac{\beta}{\alpha} \mathbf{u} \cdot \nabla \right) \mathbf{M}$$

**Convective derivative**
Convective derivatives

- Consider time evolution of an element $dV$ of a fluid
- Convective derivative $D$ accounts for local variations and particle flow

\[
\frac{D}{Dt} = \frac{\partial}{\partial t} + (\mathbf{u} \cdot \nabla)
\]

Consider time evolution of an element $dV$ of a fluid. Convective derivative $D$ accounts for local variations and particle flow.
Analogy with fluid dynamics?

\[
\left( \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{M} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \left( \frac{\partial}{\partial t} + \frac{\beta}{\alpha} \mathbf{u} \cdot \nabla \right) \mathbf{M}
\]

- This form can *almost* be obtained by replacing the time derivative of the usual Landau-Lifshitz equation

\[
\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}
\]

with the *convective derivative*

\[
\frac{\partial}{\partial t} \rightarrow \left( \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right)
\]

It almost works *except* for the $\beta/\alpha$ term. $\mathbf{u}$ therefore represents the average drift velocity of the magnetisation (under applied currents), which for ferromagnetic metals makes some sense.

- No consensus (theoretically and experimentally) over the ratio $\beta/\alpha$, which can vary between 0.1 and 10
Spin-orbit coupling

- In magnetic multilayered structures, metallic ferromagnets in contact with 5d transition metals ("heavy metals") exhibit strong effects due to spin-orbit coupling

\[ E_{SO} \sim \mathbf{L} \cdot \mathbf{S} \]
Spin-orbit coupling

- Examples:
  - Pt/Co (0.4 - 1 nm) /AlOx
  - Ta/CoFeB (1 nm)/MgO
  - Pt/[Co (0.4 nm)/Ni (0.6 nm)]\(_n\)

- Such multilayers are interesting for applications because they possess a strong anisotropy perpendicular to the film plane.

- Such multilayers also lack inversion symmetry, which gives rise to a class of spin-orbit interactions seen in two-dimensional systems, e.g. *Rashba interaction*.

\[ H_R = \alpha_R (\sigma \times \mathbf{p}) \cdot \hat{z} \]

*Rashba Hamiltonian*
Spin-orbit torques

- Such spin-orbit effects due to the heavy metal (HM) give rise to spin-orbit torques on the ferromagnet (FM)
**Spin-orbit torques**

- Torques due to the spin Hall effect can be described using the Slonczewski form
  \[
  \mathbf{T}_{\text{SH}} = \sigma_{\text{SH}} \mathbf{j}_e \mathbf{M} \times (\hat{\mathbf{y}} \times \mathbf{M})
  \]
  where
  \[
  \sigma_{\text{SH}} = \frac{g\mu_B}{2e} \frac{1}{M_s^2 d} \theta_{\text{SH}}
  \]
  - \(\theta_{\text{SH}}\) is the efficiency
  - \(\gamma_0\) is the spin Hall angle

- Torques due to the Rashba effect can be assimilated to an effective field
  \[
  \mathbf{T}_R = -\gamma_0 \mathbf{M} \times (H_R \hat{\mathbf{y}})
  \]
Spin-orbit torques with topological insulators?

- Another class of materials exhibiting strong spin-orbit coupling are topological insulators
- Unique materials in which bulk is insulating but surfaces have momentum-locked spin currents

LETTER

Spin-transfer torque generated by a topological insulator

A. R. Mellnik¹, J. S. Lee², A. Richardella², J. L. Grab¹, P. J. Mintun¹, M. H. Fischer¹,³, A. Vaezi¹, A. Manchon⁴, E.-A. Kim¹, N. Samarth² & D. C. Ralph¹,³

Many open questions!

Table 1 | Comparison of room-temperature $\sigma_{S,\parallel}$ and $\theta_{S,\parallel}$ for Bi$_2$Se$_3$ with other materials

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bi$_2$Se$_3$ (this work)</th>
<th>Pt (ref. 4)</th>
<th>$\beta$-Ta (ref. 6)</th>
<th>Cu(Bi) (ref. 23)</th>
<th>$\beta$-W (ref. 24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{\parallel}$</td>
<td>2.0–3.5</td>
<td>0.08</td>
<td>0.15</td>
<td>0.24</td>
<td>0.3</td>
</tr>
<tr>
<td>$\sigma_{S,\parallel}$</td>
<td>1.1–2.0</td>
<td>3.4</td>
<td>0.8</td>
<td>—</td>
<td>1.8</td>
</tr>
</tbody>
</table>

$\theta_{\parallel}$ is dimensionless and the units for $\sigma_{S,\parallel}$ are $10^5 \hbar/2e \Omega^{-1} m^{-1}$. 

Image 1: Depiction of the circuit used for the ST-FMR measurement and the sample orientation of the spin and the momentum in the surface state, this necessitates some proposals.

Image 2: The circuit shown in Fig. 1c, we apply a current of fixed microwave frequency and sweep an in-plane magnetic field to probe the torque from the Bi$_2$Se$_3$ magnetization using the least possible current and power.

Image 3: Depiction of the mechanism by which an in-plane current in a topological insulating Al$_2$O$_3$ pumps of spins from the precessing ferromagnet into the Bi$_2$Se$_3$ and couples to an adjacent magnetic film, the resulting flow of spin angular momentum will exert a spin-transfer torque.

Image 4: Illustration of the mechanism by which an in-plane current in a topological insulator surface spin accumulation with the spin moment in the precessing direction and wavevector for electrons is driven by the topological insulator surface magnet. We note that the oscillating current-density $J=\sigma_i E$ is not a linear function of frequency $f$. 

Image 5: Illustration of the circuit used for the ST-FMR measurement and the sample contact geometry.

Image 6: Depiction of the circuit used for the ST-FMR measurement and the sample contact geometry.
Spin waves: Effects of CPP torques

- Q: How do spin torques influence spin waves?
  A: Depends very much on the spin polarisation vector $p$

\[
\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} + \sigma j_e \mathbf{M} \times (\mathbf{p} \times \mathbf{M})
\]

- One possibility is the excitation of incoherent spin waves

Excitations of incoherent spin-waves due to spin-transfer torque

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Compensating relaxation processes

- Certain spin polarisation orientations can lead to self-sustained oscillations.
- Consider alternate form of Landau-Lifshitz equation with spin torques:

\[
\frac{d\mathbf{M}}{dt} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\alpha \gamma_0}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}}) + \sigma j_e \mathbf{M} \times (\mathbf{M} \times \mathbf{p})
\]

\text{Precession} \quad \text{Damping} \quad \text{Spin torques}

- If \( \mathbf{p} \) is collinear (on average) with \( \mathbf{H}_{\text{eff}} \), spin torques can either increase or decrease the damping depending on the sign of \( j_e \).
Compensating relaxation processes

- Certain spin polarisation orientations can lead to self-sustained oscillations.

- Consider alternate form of Landau-Lifshitz equation with spin torques:

\[
\frac{d\mathbf{M}}{dt} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\alpha \gamma_0}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}}) + \sigma j_e \mathbf{M} \times (\mathbf{M} \times \mathbf{p})
\]

- For sufficiently large currents, the spin torques can overcome the damping entirely.

\[\text{Precession} \quad \text{Damping} \quad \text{Spin torques}\]

\[\text{Relaxation} \quad \text{Spin transfer}\]
Self-sustained oscillations

- From spin wave theory, we can derive an oscillator model with spin torque dynamics.

- Let $c(t)$ represent a complex spin wave (oscillator) amplitude.

$$ \frac{dc}{dt} = -i\omega c - \Gamma c + \sigma j_e (1 - |c|^2) c $$

$$ c \simeq m_x + im_y $$

### Diagram:

- **Precession**
- **Damping**
- **Spin torques**

#### Threshold (Hopf bifurcation):

- $\Gamma > \sigma j_e$
- $\Gamma = \sigma j_e$
- $\Gamma < \sigma j_e$

Increasing current:

- Damped precession
- Self-sustained precession
Spin-torque oscillators

- Self-sustained magnetisation oscillations observed in nanopillar and nanocontact geometries
- Oscillation frequencies are tunable with field and current

Spin waves: Effects of CIP torques

- In-plane currents can also lead to interesting effects involving spin waves.
- Recall that spin torques due to CIP currents can be described by

\[
\left( \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{M} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \left( \frac{\partial}{\partial t} + \frac{\beta}{\alpha} \mathbf{u} \cdot \nabla \right) \mathbf{M}
\]

- From our plane wave solution for spin waves,

\[
m_{x,y}(\mathbf{r}, t) = m_{x0,y0} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)}
\]

we can immediately deduce the effect of CIP spin torques on the spin wave frequency,

\[
\omega + \mathbf{u} \cdot \mathbf{k} = \omega_k \quad \omega = \omega_k - \mathbf{u} \cdot \mathbf{k}
\]

- The CIP torques appear as a *Doppler shift* in the spin wave frequency.
Current-Induced Spin-Wave Doppler Shift

Vincent Vlaminck and Matthieu Bailleul

\[ \omega = \omega_k - \mathbf{u} \cdot \mathbf{k} \]
Current-induced spin wave instabilities

- The current-induced Doppler effect leads to a frequency shift that is linear in the wave vector
  \[ \omega = \omega_k - u \cdot k \]
  \[ u = P \frac{g \mu_B}{2e} \frac{1}{M_s} j_e = P \frac{\hbar}{2e} \frac{1}{M_s} j_e \]

- For sufficiently large currents, the mode frequency can decrease to zero. At this point, the ferromagnetic state becomes unstable (why?)

![Graph showing mode frequency as a function of wave vector](image)

nominal temperature 100 K

\[ j = 4.3 \times 10^5 \text{ A/cm}^2 \]

\[ j = 1.1 \times 10^6 \text{ A/cm}^2 \]

Magnonic Black Holes

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(Received 19 October 2016; published 8 February 2017)

We show that the interaction between the spin-polarized current and the magnetization dynamics can be used to implement black-hole and white-hole horizons for magnons—the quanta of oscillations in the magnetization direction in magnets. We consider three different systems: easy-plane ferromagnetic metals, isotropic antiferromagnetic metals, and easy-plane magnetic insulators. Based on available experimental data, we estimate that the Hawking temperature can be as large as 1 K. We comment on the implications of magnonic horizons for spin-wave scattering and transport experiments, and for magnon entanglement.

Spatial gradients in current densities result in different Doppler shifts
CIP torques for domain walls, vortices …

- In MP2, we saw that soliton dynamics can be described with method of collective coordinates

- CIP torques can be included in Lagrangian and dissipation function using convective derivative analogy

\[ L_B = \frac{M_s}{\gamma} \frac{\partial \phi}{\partial t} (1 - \cos \theta) \rightarrow \frac{M_s}{\gamma} \left( \frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \right) (1 - \cos \theta) \]

Berry phase term

\[ \mathcal{F} = \frac{\alpha M_s}{2\gamma} \left[ \left( \frac{\partial \theta}{\partial t} \right)^2 + \sin^2 \theta \left( \frac{\partial \phi}{\partial t} \right)^2 \right] \]

Dissipation function

\[ \left( \frac{\partial \theta}{\partial t} \right)^2 \rightarrow \left[ \left( \frac{\partial}{\partial t} + \frac{\beta}{\alpha} \mathbf{u} \cdot \nabla \right) \theta \right]^2 \]

nonadiabatic torques

adiabatic torques
Domain walls: CIP torques

- Similar equations of motion for domain walls in the presence of CIP spin torques:

\[
\dot{\phi}_0(t) + \frac{\alpha \dot{X}_0(t)}{\Delta} - \frac{\beta u}{\Delta} = -\frac{\gamma}{2M_s} \frac{\partial E}{\partial X_0} \\
-\frac{\dot{X}_0(t)}{\Delta} + \alpha \phi_0(t) + \frac{u}{\Delta} = -\frac{\gamma}{2M_s \Delta} \frac{\partial E}{\partial \phi_0}
\]

\[
u = P \frac{g \mu_B}{2e} \frac{1}{M_s} j_e = \frac{\hbar}{2e} \frac{1}{M_s} j_e
\]

adiabatic torque

nonadiabatic torque
Current-driven domain wall motion

- Field and current-driven motion result in very similar torque profiles on a single domain wall.

- However, for a sequence of domain walls, the overall effect is very different.
Current-driven domain wall motion

- Back and forth motion of domain wall driven by bipolar current pulses

A Yamaguchi et al, 
Magnetic Domain-Wall Racetrack Memory

Stuart S. P. Parkin,* Masamitsu Hayashi, Luc Thomas

Recent developments in the controlled movement of domain walls in magnetic nanowires by short pulses of spin-polarized current give promise of a nonvolatile memory device with the high performance and reliability of conventional solid-state memory but at the low cost of conventional magnetic disk drive storage. The racetrack memory described in this review comprises an array of magnetic nanowires arranged horizontally or vertically on a silicon chip. Individual spintronic reading and writing nanodevices are used to modify or read a train of ~10 to 100 domain walls, which store a series of data bits in each nanowire. This racetrack memory is an example of the move toward innately three-dimensional microelectronic devices.

There are two main means of storing digital information for computing applications: solid-state random access memories (RAMs) and magnetic hard disk drives (HDDs). Even though both classes of devices are evolving at a very rapid pace, the cost of storing a single data bit in an HDD remains approximately 100 times cheaper than in a solid-state RAM. Although the low cost of HDDs is very attractive, these devices are intrinsically slow, with typical access times of several milliseconds because of the large mass of the rotating disk. RAM, on the other hand can be very fast and highly reliable, as in static RAM and dynamic RAM technologies. The architecture of computing systems would be greatly simplified if there were a single memory storage device with the low cost of the HDD but the high performance and reliability of solid-state memory.

Racetrack Memory

Because both silicon-based microelectronic devices and HDDs are essentially two-dimensional (2D) arrays of transistors and magnetic bits, respectively, the conventional means of develop...
CPP torques for vortices, etc.

- CPP (Slonczewski) torques can be described with a dissipation function

\[
\mathcal{F}_{\text{CPP}} = -\frac{\sigma j_e}{\gamma} \mathbf{p} \cdot \left( \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right)
\]

- For vortices in dots, CPP torques can compensate damping

\[
\partial F_{\text{CPP}} \propto \sigma I p_z (\hat{z} \times \mathbf{X}_0)
\]

Current density \( j_e \) with spin polarisation \( P \)

\( \mathbf{p} \)

\( \mathbf{M} \)

\( \mathbf{G} \times \mathbf{X}_0 \)

\( \alpha D \mathbf{X}_0 \)

\( \frac{\partial F_{\text{CPP}}}{\partial \mathbf{X}_0} \)

\( \frac{\partial U}{\partial \mathbf{X}_0} \)

Gyrotropic

Damping

STT

Restoring

Core trajectory

Restoring force

Gyrotropic force

Damping force

Spin transfer force

Velocity
Vortex oscillators

- Self-sustained gyration of vortices with CPP torques in spin valves (GMR) and magnetic tunnel junctions (TMR)
- Gyration frequencies determined by confinement potential, GHz range

Summary

- Magnetism affects transport and vice versa

- Spin torques involve the absorption of transverse spin currents
  
  \textit{sd model, current-driven magnetisation reversal}

- Spin torques can compensate spin wave damping in certain geometries, modify frequencies in others
  
  \textit{Self-sustained oscillations, Doppler effect}

- Spin torques can displace magnetic solitons such as domain walls and vortices
  
  \textit{Back and forth wall propagation in wires, vortex oscillators}