Spin Transfer Torques in Interacting Wires

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Use of a spin polarized current for the manipulation of magnetic domain walls in ferro- magnetic nanowires has been the subject of intensive research for many years. While so far the theoretical investigation has been mostly concerned with the mean-field approximation of the electron-electron correlation, the electrons confined to a quasi-one-dimensional wire be- have fundamentally different from standard Fermi-liquid picture. Our goal is to delve into the full quantum investigation of the electron-electron interaction in low dimensions. To this end, first we establish a reference point by solving the scattering problem of a noninteracting tight-binding Hamiltonian including an s-d interaction that couples the domain wall and the itinerant electrons. With this approach the behaviour of the adiabatic spin transfer torque has been investigated and the existence of a topological torque has been established. Next, we make an inquiry into the full quantum effects of electron-electron correlation on spin densities and consequently on spin transport.

Motivation

One-dimensional (1D) systems (Nanowires):

- Fermi liquid theory breaks down
  $\rightarrow$ Luttinger liquid theory
- Dominance of e-e correlations
- Pronounced effect of impurities
- DWs are extended magnetic impurities

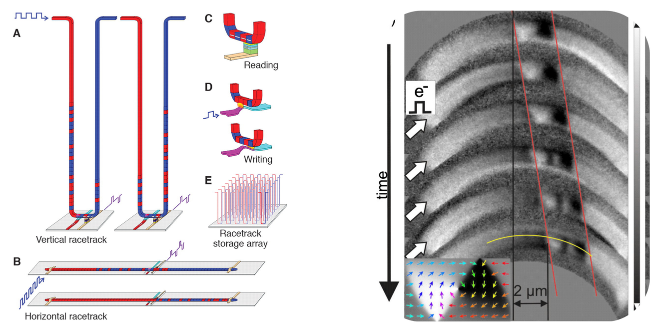
Relevance to applications:

- All electronic (without moving parts), faster, miniaturizable and more energy efficient DW based racetrack memories

Drawbacks?

- High polarized current density needed to move DWs.
- Better understanding of correlations and non-adiabatic spin-torque required

Current induced DW motion and DW based racetrack memories



Left: Proposed racetrack memory: a ferromagnetic nanowire, with data encoded as a pattern of magnetic domains [1].
Right: X-ray photoemission electron microscopy image series of a Py wire. Current pulses were injected. The DW is displaced about 400 nm on average per current pulse [2].

Model and Hamiltonian

Interplay between the electrons and the DW is described by spin-spin coupling in terms of s-d model [3].

$$\mathcal{H}=\sum_{j,\sigma}\left[-t\left(c^\dagger_{j,\sigma}c_{j+1,\sigma}+\text{h.c.}\right)+\mu c^\dagger_{j,\sigma}c_{j,\sigma}-\frac{J_{sd}}{2M_s}\sum_{\sigma'}\left(c^\dagger_{j,\sigma}\boldsymbol{\sigma}_{\sigma,\sigma'}\cdot\mathbf{M}(x_j)c_{j,\sigma'}\right)+Un_{j,\sigma}n_{j+1,\sigma}\right]$$

$c^\dagger_{j,\sigma}$ is the creation operator of a spin σ electron at site j; t is the hopping, J_{sd} is the s-d exchange interaction and U represents the electron-electron interaction. M_s is the saturation magnetization.

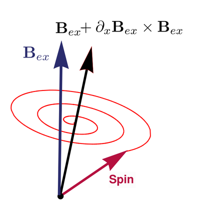
Spin Torques

Different types of torques in DWs and Multilayers (ML)			
Torque	Medium	Due to	Limit
Adiabatic STT [4, 5]	DW, ML	Gradual spin-flip	Adiabatic
Non-adiabatic (Mom. transfer) [6]	DW, ML	Reflection + exchange term	Sharp, interface
Non-adiabatic, due to spin flip relaxation (β term) [7]	Collinear structures	Spin-flip relaxation ($\delta m/\tau_{sf}$)	Interface
Gauge Torque [6, 8]	DW	DW width and misalignment from effective field	Sharp

Torque:

$$\boldsymbol{\tau}=\mathbf{B}_{\text{ex}}(x)\times\mathbf{m}(x)\quad \mathbf{B}_{\text{ex}}(x)=\frac{SJ_{sd}}{M_s}\mathbf{M}(x)$$

Procession of spin around the effective field, i.e. the sum of the exchange and gauge field.



Adiabatic STT: In the plane of incoming and outgoing electron's spin direction.
Gauge STT: Due to the procession of spins around the effective field[9]

$$\mathbf{B}_{\text{eff}}(x)=\mathbf{B}_{\text{ex}}(x)+\partial_x\mathbf{B}_{\text{ex}}(x)\times\mathbf{B}_{\text{ex}}(x)$$

Nonadiabatic STT due to relaxation: Perpendicular to the plane of incoming and outgoing electron's spin direction.

Collinear magnetization [7]
(Gradient STT: $c_1=const$; Zhang-Li STT: $c_1\propto$ current density):

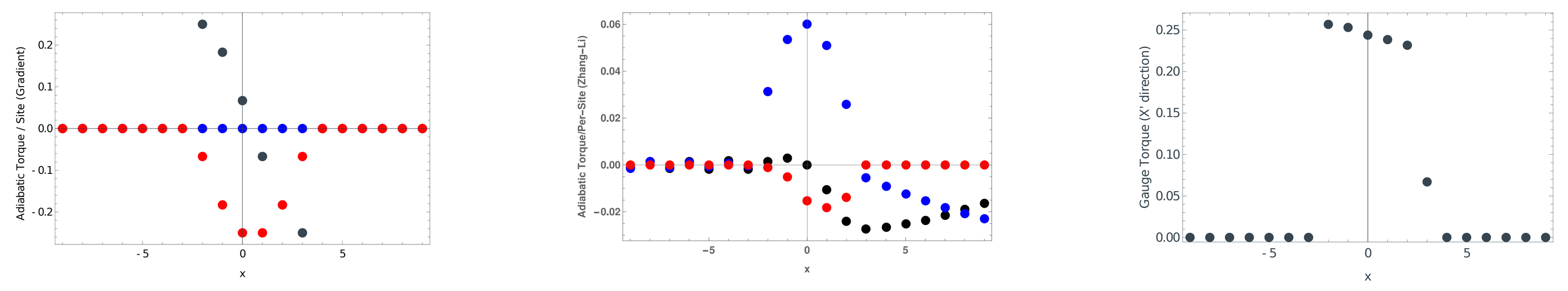
$$\tau(x)=\underline{c_1\partial_x\mathbf{M}(x)}+c_2\mathbf{M}(x)\times\partial_x\mathbf{M}(x)$$

Non-collinear magnetization [8]:

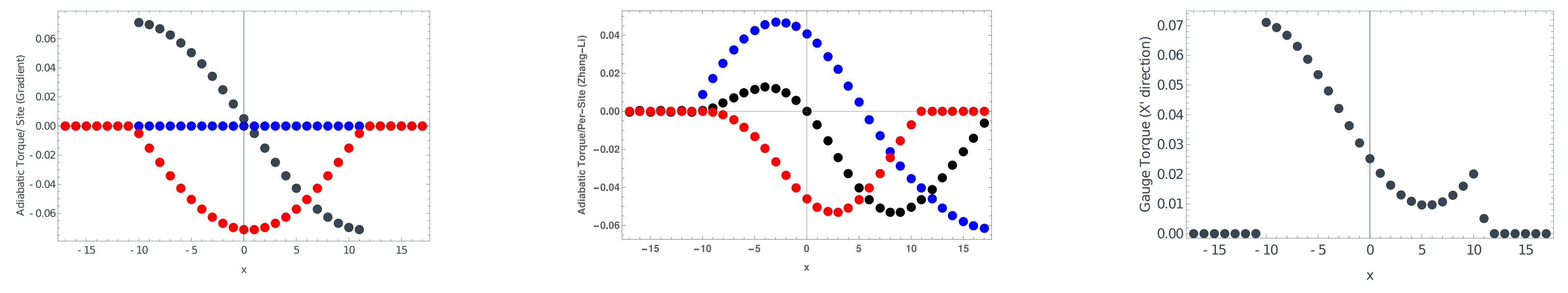
$$\boldsymbol{\tau}(x)=\underline{c_1\partial_x\mathbf{M}(x)+a(x)\hat{\mathbf{x}}'}+b(x)\hat{\mathbf{y}}$$

DW Torques in Non-Interacting Wires

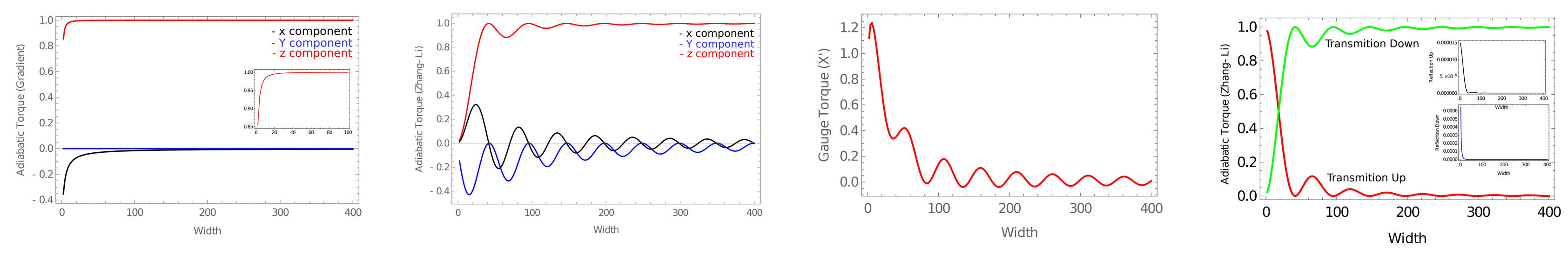
Diagonalizing the noninteracting Hamiltonian ($U=0$), we investigate the resulting torques on the local magnetic moments.



STT in a DW of width = 5 (sharp limit). Polarization of incoming electron: ↑ and wave vector of $\mathcal{O}$(lattice site).



STT in a DW of width = 21 (adiabatic limit). Polarization of incoming electron: ↑ and wave vector of $\mathcal{O}$(lattice site).



These results will be used as a reference point for our future studies into the interacting case.

Luttinger Liquid Theory

The model can be bosonized[10, 3]

$$H=H_q+H^f_{\text{Gsf}}+H^b_{\text{Gsf}}+H^b_{\text{Gp}}$$

Spin and charge modes are related to the diagonal modes by a transformation and we use the frame of the local magnetization direction

The diagonal Hamiltonian:

$$H=\frac{1}{2}\int \mathrm{d}x\sum_{\iota=1,2}\left(\frac{u_\iota}{g_\iota}(\partial_x\phi_\iota)^2+u_\iota g_\iota(\partial_x\tilde{\phi}_\iota)^2\right)$$

N.B. this is no longer spin-charge separated!

Scattering terms from the domain wall ($\Theta(x)$ controls the DW profile):

$$\begin{aligned}
H^f_{\text{Gsf}} &= -\int \mathrm{d}x\frac{k_{F+}t}{\pi a}\Theta'(x)\sin[\sqrt{2\pi}\tilde{\phi}_s(x)]\cos[k_{F-}x+\sqrt{2\pi}\phi_s(x)]\\
H^b_{\text{Gsf}} &= -\int \mathrm{d}x\frac{k_{F-}t}{\pi a}\Theta'(x)\cos[\sqrt{2\pi}\tilde{\phi}_s(x)]\sin[k_{F+}x+\sqrt{2\pi}\phi_c(x)]\\
H^b_{\text{Gp}} &= -\int \mathrm{d}x\frac{t}{4\pi a}\sum_\sigma[\Theta'(x)]^2\sin[2k_{F\sigma}x+\sqrt{4\pi}\phi_\sigma(x)]
\end{aligned}$$

We can calculate all spin densities, currents, etc., and the low energy phase diagram[3]:

Backscattering relevance for RG	$\lambda\lesssim\lambda_\pm$	$\lambda_+<\lambda<\lambda_-$	$\lambda_\pm<\lambda$
$2-\gamma_b>0$	Spin and charge insulator	C1S0	Adiabatic LL
$2-\gamma_b<0$	C1S0	C1S0	Adiabatic LL

Outlook

- Non-adiabatic STT due to relaxation can be calculated if we introduce a damping mechanism
- The electrons confined to a 1D wire behave fundamentally different from standard Fermi-liquid quasiparticle picture, so a characteristic change in the spin transfer torque is expected
- To take into account electron-electron correlations, DMRG and bosonization will be used
- DMRG is nearly exact at almost any temperature but is limited by system size
- Field theory provides almost exact analytical results for thermodynamic limit and low T
- Numerical studies will be complemented by bosonization and Luttinger liquid theory
- For more realistic DWs, geometry and system parameters from experimentalists is needed

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