Driving Exchange Mode Resonance as Adiabatic Quantum Motor with 100% Mechanical Efficiency

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Reference:

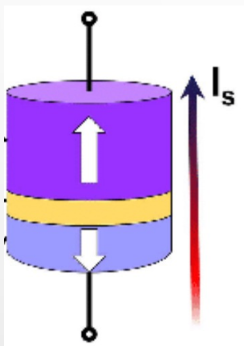
J. Tang and R. Cheng, Phys. Rev. B **106**, 054418 (2022)

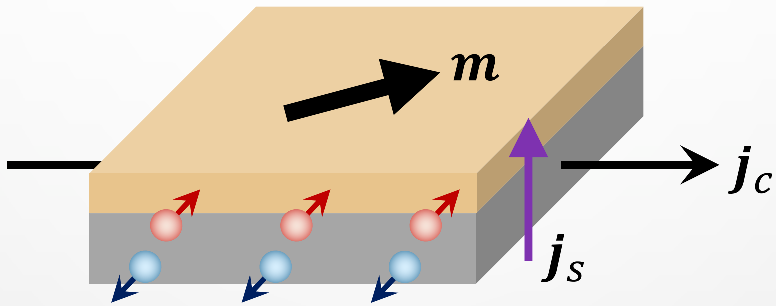
Funding

Current-Induced Torque

From spin valve to spin Hall device

$$P_M \sim \frac{\alpha M_s}{\gamma}\overline{|\dot{\boldsymbol{m}}^2|} \qquad P_J \sim \overline{j_c^2}/\sigma \text{ with } \sigma = \sigma_0 + \sigma_{SMR}$$





$$\eta = \frac{P_M}{P_J} \ll 1$$

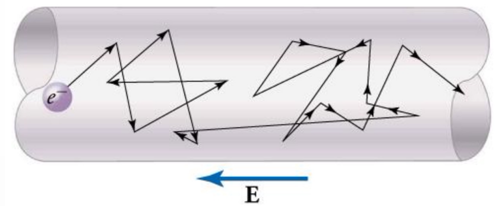
1. **Joule heating**
2. Spin Hall angle: $\theta_{SH} = j_s/j_c$
3. Spin diffusion & Backflow

$$g_r' = \frac{g_r}{1 + \frac{2\lambda e^2}{h\sigma} g_r \coth\frac{d_N}{\lambda}}$$

renormalized
spin-mixing conductance

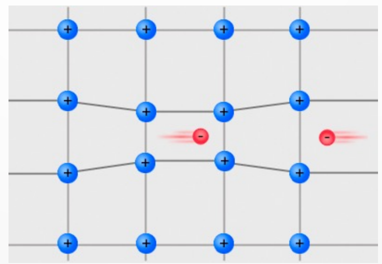
Physical Currents

- Dissipative Current



$\boldsymbol{j}_c = \sigma \boldsymbol{E}$

- Superconducting Current



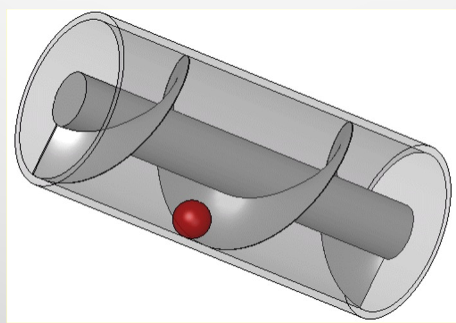
persistent current

($T<T_c$)

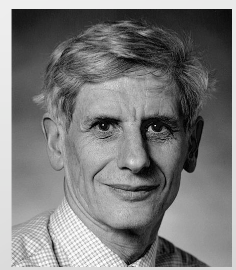
- Adiabatic Current

$$\boldsymbol{j} = \int dk \, \overleftrightarrow{\Omega}_{kt}$$

$$\rightarrow \quad \boldsymbol{j} \sim \dot{\boldsymbol{m}}$$



One cycle: $Q = \int dt \int dk \, \overleftrightarrow{\Omega}_{kt}$



David J. Thouless
(1934 - 2019)

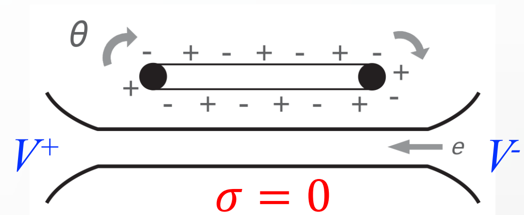
Nobel Prize in
Physics **2016**
(1/2 Share)

Adiabatic Quantum Motor

- Reversed operation of a Thouless pump

$\sigma \boldsymbol{E} = \mathbf{0}$

$\boldsymbol{E} \xrightarrow{\text{Voltage-induced torque}} \dot{\boldsymbol{m}} \xrightarrow{\text{Thouless pump}} \boldsymbol{j}$

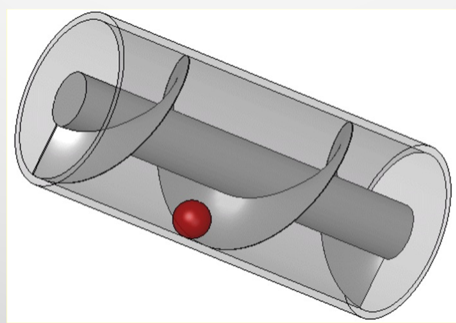


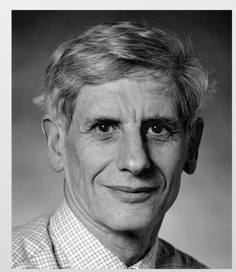
Bustos-Marún, Refael & von Oppen,
Phys. Rev. Lett. **111**, 060802 (2013)

$P_J = \langle \boldsymbol{E} \cdot \boldsymbol{j} \rangle$ all converted to $P_J = \alpha \langle \dot{\boldsymbol{m}}^2 \rangle$

$$\boldsymbol{j} = \int dk\, \overleftrightarrow{\Omega}_{kt}$$

$$\rightarrow \quad \boldsymbol{j} \sim \dot{\boldsymbol{m}}$$





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One cycle: $Q = \int dt \int dk\, \overleftrightarrow{\Omega}_{kt}$

Adiabatic Quantum Motor

- Voltage-induced torque

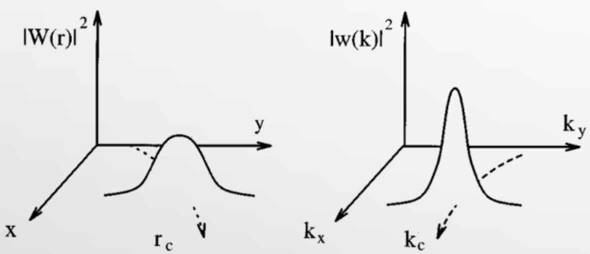
Sundaram-Niu equation [PRB **59**, 14915 (1999)]

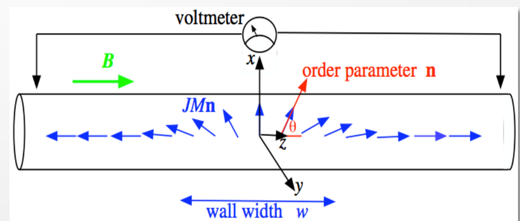
$$\dot{\boldsymbol{r}} = \frac{\partial \varepsilon}{\partial \boldsymbol{k}} + \dot{\boldsymbol{k}} \cdot \overleftrightarrow{\Omega}_{kk} + \dot{\boldsymbol{r}} \cdot \overleftrightarrow{\Omega}_{rk} - \Omega_{kt}$$

$$\dot{\boldsymbol{k}} = -e\boldsymbol{E} - \dot{\boldsymbol{k}} \cdot \overleftrightarrow{\Omega}_{kr} - \dot{\boldsymbol{r}} \cdot \overleftrightarrow{\Omega}_{rr} + \Omega_{rt}$$

Ganesh Sundaram Qian Niu

Semiclassical wavepacket

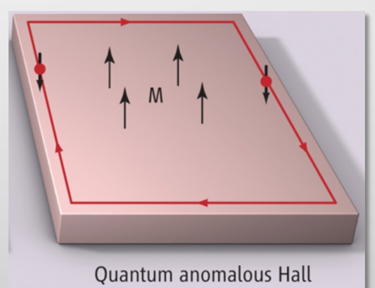


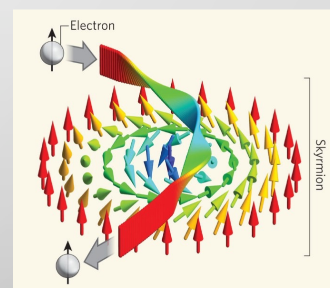


Spin-motive force

$$\overleftrightarrow{\Omega} = \begin{bmatrix} \boxed{\Omega_{kk}} & \Omega_{kt} & \Omega_{kr} \\ \Omega_{tk} & \Omega_{tt} & \boxed{\Omega_{tr}} \\ \Omega_{rk} & \boxed{\Omega_{rt}} & \boxed{\Omega_{rr}} \end{bmatrix}$$

uniform magnetic order





Topological Hall effect

Adiabatic Quantum Motor

- Voltage-induced torque

Coupled ***Sundaram-Niu*** & ***LLG*** equations

$$\dot{\boldsymbol{k}} = -e\boldsymbol{E} \qquad\qquad (\hbar = 1)$$

$$\dot{\boldsymbol{r}} = \frac{\partial \varepsilon}{\partial \boldsymbol{k}} + \dot{\boldsymbol{k}} \cdot \overleftrightarrow{\Omega}_{kk} + \dot{\boldsymbol{m}} \cdot \boxed{\overleftrightarrow{\Omega}_{mk}}$$

$$\boldsymbol{m} \times \dot{\boldsymbol{m}} = \frac{\partial \varepsilon}{\partial \boldsymbol{m}} + \dot{\boldsymbol{k}} \cdot \boxed{\overleftrightarrow{\Omega}_{km}} + \dot{\boldsymbol{m}} \cdot \boxed{\overleftrightarrow{\Omega}_{mm}}$$

Ganesh Sundaram

Qian Niu

Voltage-induced torque

Renormalization of Damping

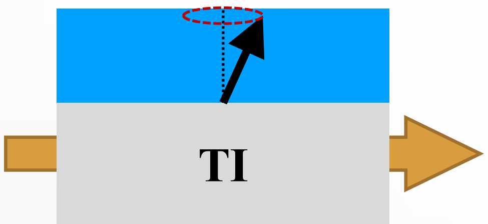
$$\boxed{\dot{\boldsymbol{m}} = \gamma\left(e\boldsymbol{E} \cdot \int \overleftrightarrow{\boldsymbol{\Omega}}_{km}[\mathrm{d}k] - \dot{\boldsymbol{m}} \cdot \int \overleftrightarrow{\boldsymbol{\Omega}}_{mm}[\mathrm{d}k]\right) \times \boldsymbol{m}_i + \cdots}$$

$$\overleftrightarrow{\Omega} = \begin{bmatrix} \Omega_{kk} & \boxed{\Omega_{km}} & \mathbf{0} \\ \boxed{\Omega_{mk}} & \boxed{\Omega_{mm}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}$$

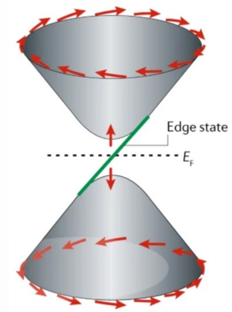
$$\boxed{\boldsymbol{j} = -e\dot{\boldsymbol{m}} \cdot \int \overleftrightarrow{\boldsymbol{\Omega}}_{mk}\,[\mathrm{d}k]}$$

Thouless pumping
(*adiabatic current*)

Voltage-Induced Torque



$\boldsymbol{E}$



$$\boldsymbol{H}^{\mathrm{SOT}} \sim \mathrm{sng}(m_z)\boldsymbol{E}$$

Not from edge state

Xiao, Xiong & Niu, PRB **104**, 064433 (2021)
Xiong & Niu, PRB **98**, 035123 (2018)
Arrachea & von Oppen, Phys. E **74**, 596 (2015)

Voltage-induced torque   Renormalization of Damping

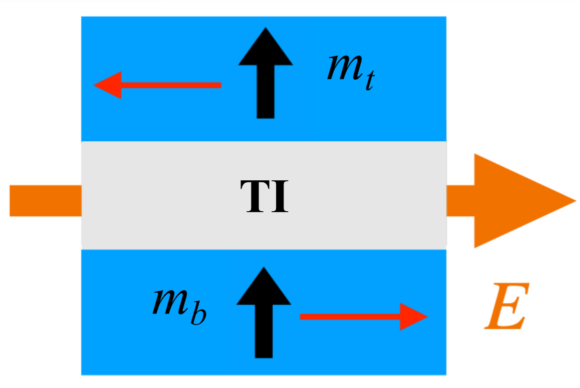
$$\boxed{\dot{\boldsymbol{m}} = \gamma\left(e\boldsymbol{E}\cdot\int \overleftrightarrow{\boldsymbol{\Omega}}_{km}[\mathrm{d}k] - \dot{\boldsymbol{m}}\cdot\int \overleftrightarrow{\boldsymbol{\Omega}}_{mm}[\mathrm{d}k]\right)\times \boldsymbol{m}_i + \cdots}$$

$$\overleftrightarrow{\Omega} = \begin{bmatrix} \Omega_{kk} & \boxed{\Omega_{km}} & \mathbf{0} \\ \boxed{\Omega_{mk}} & \boxed{\Omega_{mm}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}$$

$$\boxed{\boldsymbol{j} = -e\dot{\boldsymbol{m}}\cdot\int \overleftrightarrow{\boldsymbol{\Omega}}_{mk}\,[\mathrm{d}k]}$$

Thouless pumping
(*adiabatic current*)

Voltage-Induced Torque



$$\boxed{\begin{aligned} H_0 = &\hbar v_f (k_x \tau_z \otimes \boldsymbol{\sigma}_y - k_y \tau_z \otimes \boldsymbol{\sigma}_x) + A(\boldsymbol{k}) \tau_x \otimes \boldsymbol{I} \\ &+ J_{sd} (\boldsymbol{m}^t \cdot \boldsymbol{\sigma}) \oplus (\boldsymbol{m}^b \cdot \boldsymbol{\sigma}), \end{aligned}}$$

$$\boxed{A(\boldsymbol{k}) = b_0 + b_1 (k_x^2 + k_y^2)}$$

$$\boldsymbol{H}_t^{\mathrm{SOT}} = -\boldsymbol{H}_b^{\mathrm{SOT}}$$

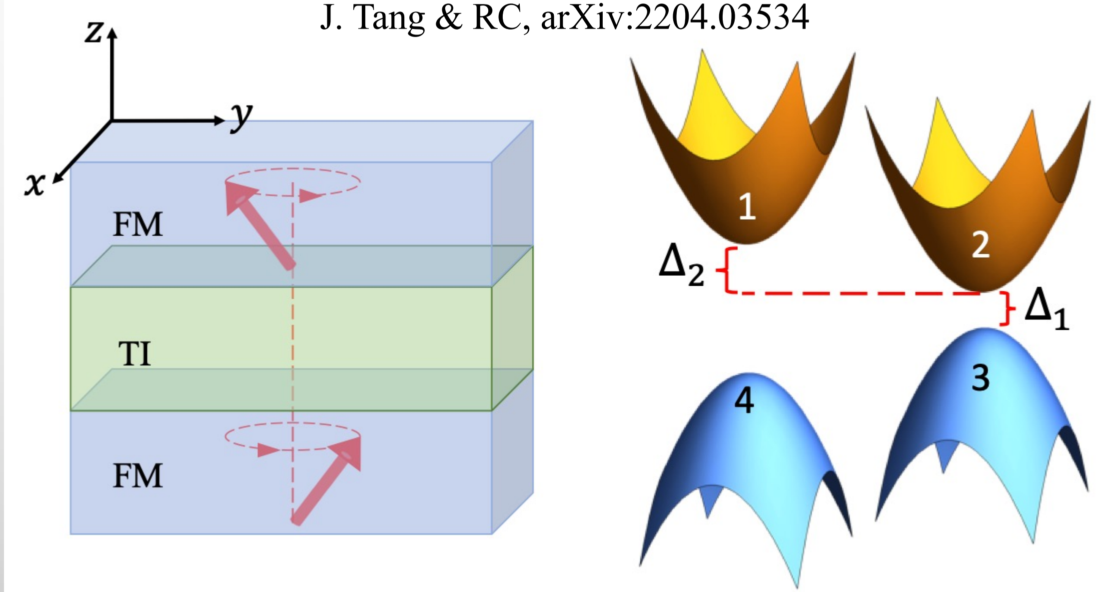
Exchange mode

$$f_r = f_{\mathrm{A}} + f_{\mathrm{E}}$$

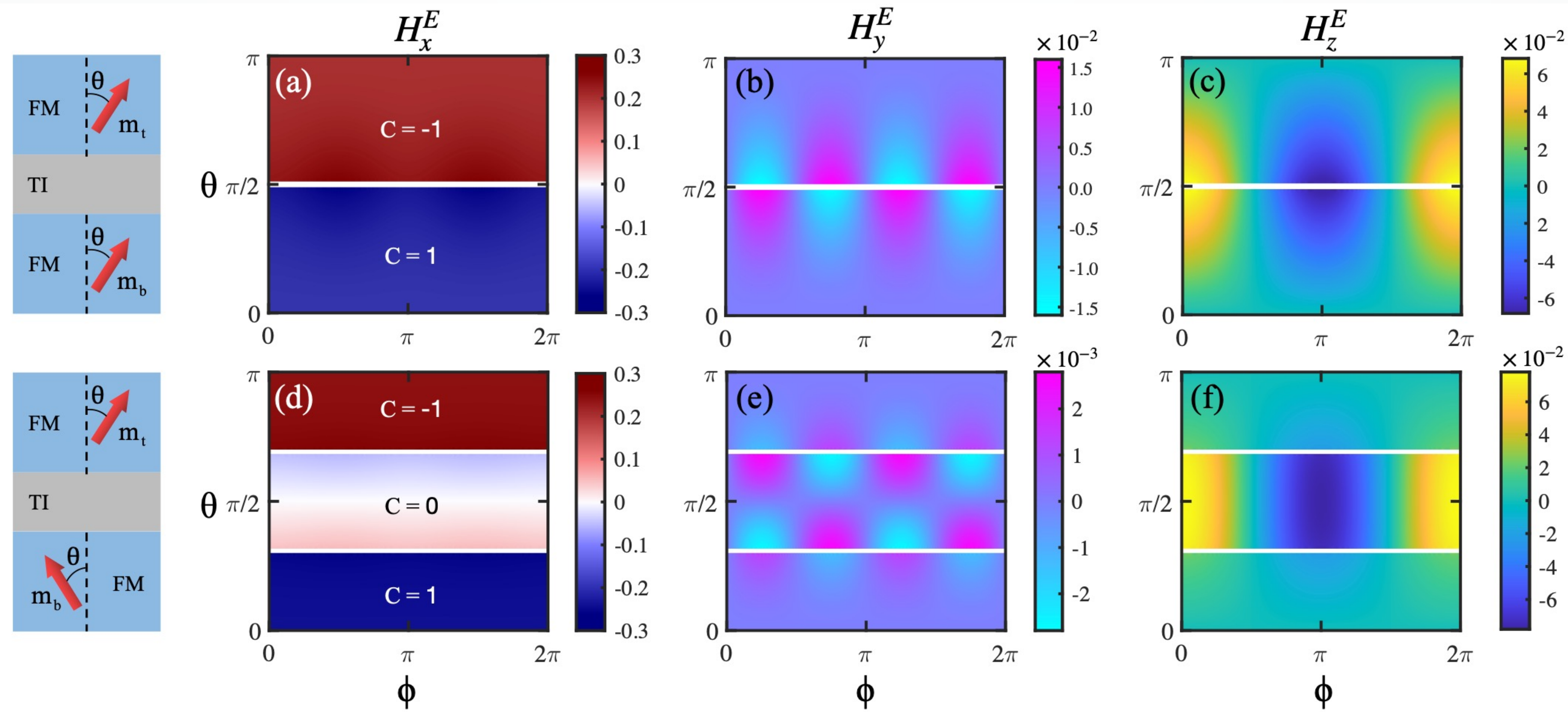
can be 100 GHz

Li *et al*., PRB **91**, 014427 (2015);
Son Ho & Jalil, AIP Adv. **7**, 055926 (2017)

J. Tang & RC, arXiv:2204.03534

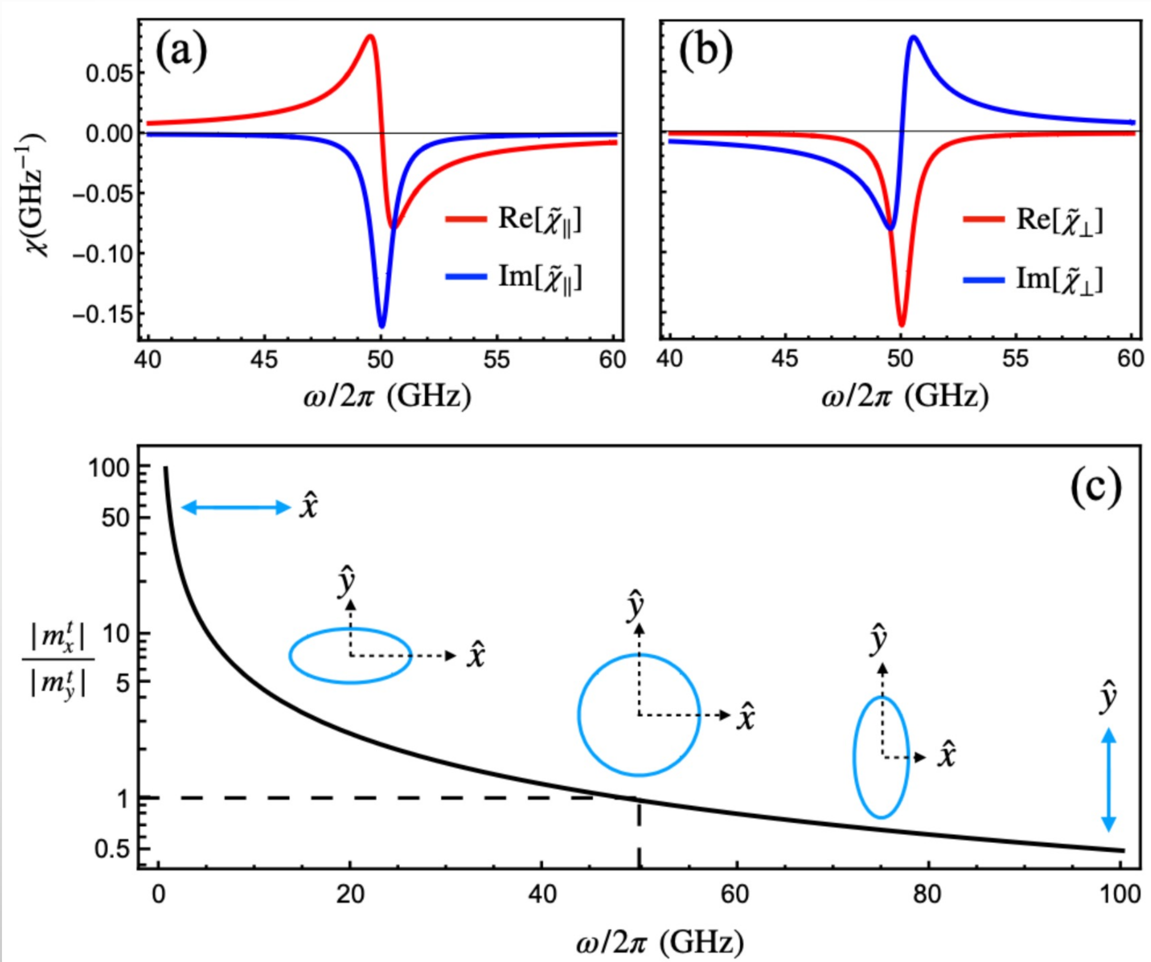


Exchange Mode Resonance



Exchange Mode Resonance

$$\tilde{m}_x^{t/b} = \pm\tilde{\chi}_{\parallel}\tilde{H}_x^{\mathrm{SOT}} \text{ and } \tilde{m}_y^{t/b} = \pm\tilde{\chi}_{\perp}\tilde{H}_x^{\mathrm{SOT}}$$



Effective Admittance

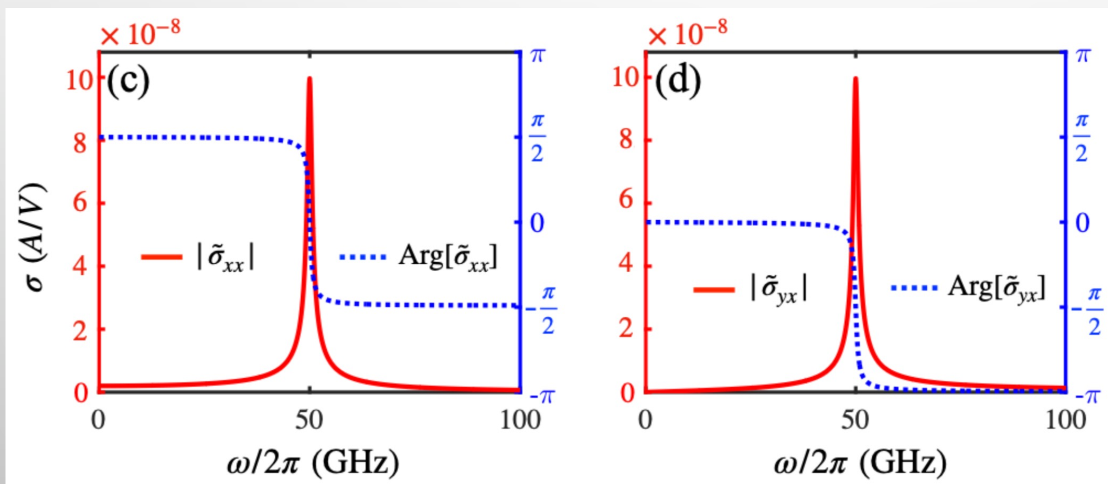
For AC drive: $\boldsymbol{E}(t) = \hat{\boldsymbol{x}} E_0 e^{i\omega t}$

Insert LLG $\dot{\boldsymbol{m}}_i = -\gamma \boldsymbol{m}_i \times \overleftrightarrow{\boldsymbol{\Omega}}_{k m_i} \cdot \frac{e\boldsymbol{E}}{\hbar} + \cdots$

into $\boldsymbol{J} = -\frac{e}{(2\pi)^2} \sum_{i=t,b} \int \dot{\boldsymbol{m}}_i \cdot \overleftrightarrow{\boldsymbol{\Omega}}_{m_i k}\, d^2k$

$\boldsymbol{E} \xrightarrow{\text{Voltage-induced torque}} \dot{\boldsymbol{m}} \xrightarrow{\text{Thouless pump}} \boldsymbol{j}$

$J_\mu(\omega) = \sigma_{\mu\nu}(\omega) E_\nu(\omega)$



- Transverse:

  $\sigma_{xy}(\omega_r) \ll \sigma_{\mathrm{QAH}}$

- Longitudinal:

  $\sigma_{xx}^0 \approx 0$

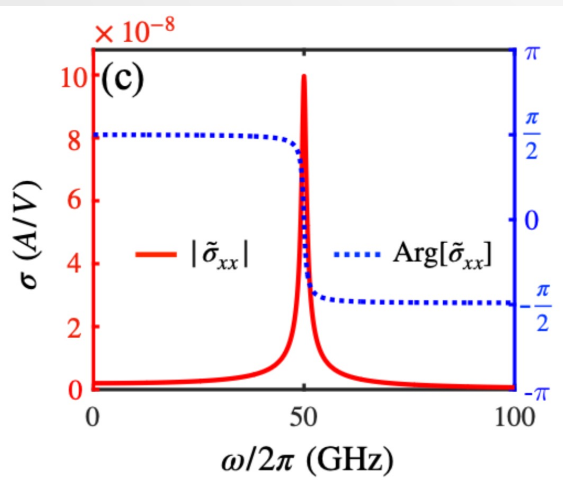
  $\sigma_{xx}(\omega)$ significant

Effective Admittance

Impedance $Z_{\mathrm{sys}} = 1/\sigma_{xx}$

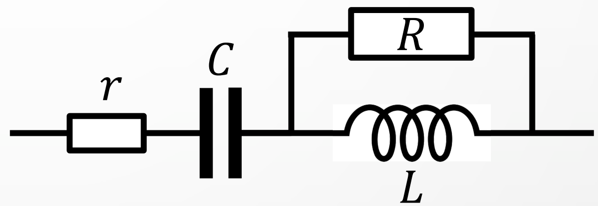
$$Z_{\mathrm{sys}} = Z_m \frac{(\alpha\omega - i\omega_r)^2 + \omega^2}{\omega(\alpha\omega - i\omega_r)}$$
$$= \boxed{Z_m \left(\alpha + \frac{\omega_r}{i\omega}\right)} + \boxed{\frac{Z_m}{\left(\alpha + \frac{\omega_r}{i\omega}\right)}}$$

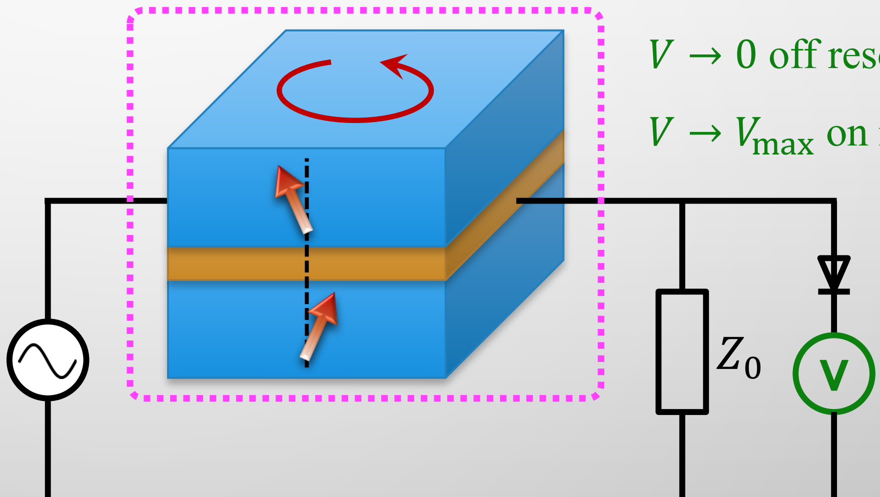
$Z_m^{-1} = \overline{\Omega}^2_{k_x m_x^t} \zeta w/l$ about $5 \times 10^8 \Omega$



Setting $Z_{\mathrm{eff}}(\omega) = Z_{\mathrm{sys}}(\omega)$ solves

$$R = \frac{Z_m}{\alpha}, \quad r = Z_m \alpha, \quad L = \frac{Z_m}{\omega_r}, \quad C = \frac{1}{Z_m \omega_r},$$





$V \to 0$ off resonance

$V \to V_{\max}$ on resonance

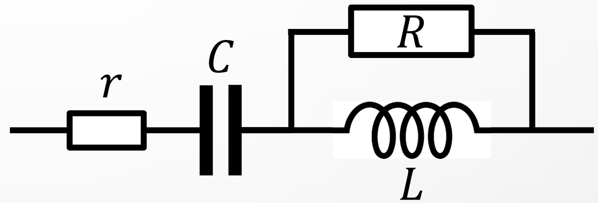
Mechanical Efficiency

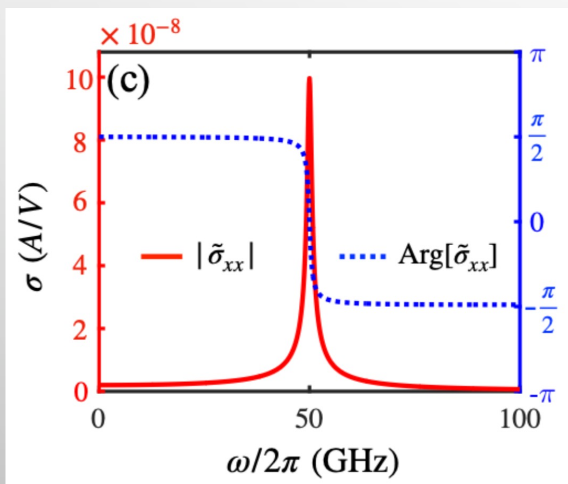
$$P_M = \alpha \frac{E_x^2 w l \zeta}{2} \overline{\Omega}^2_{k_x m_x^t} \omega^2 \left[|\tilde{\chi}_\parallel(\omega)|^2 + |\tilde{\chi}_\perp(\omega)|^2 \right],$$

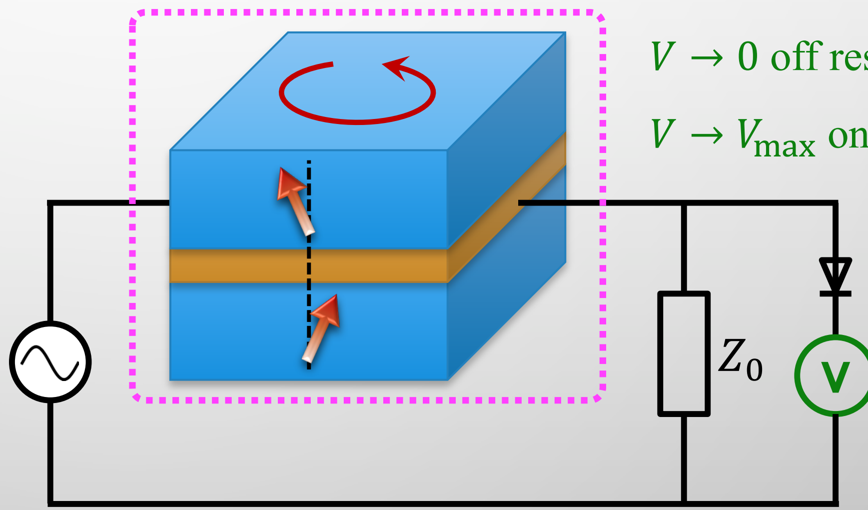
$$P_J = \frac{E_x^2 w l \zeta}{2} \overline{\Omega}^2_{k_x m_x^t} \omega \left| \mathrm{Im}\left[\tilde{\chi}_\parallel(\omega) \right] \right|,$$

$$\boxed{\eta = \frac{P_M}{P_J} = 1,}$$

$$\zeta = \frac{2e^2}{N_z \hbar S a_0^2}$$







$V \to 0$ off resonance

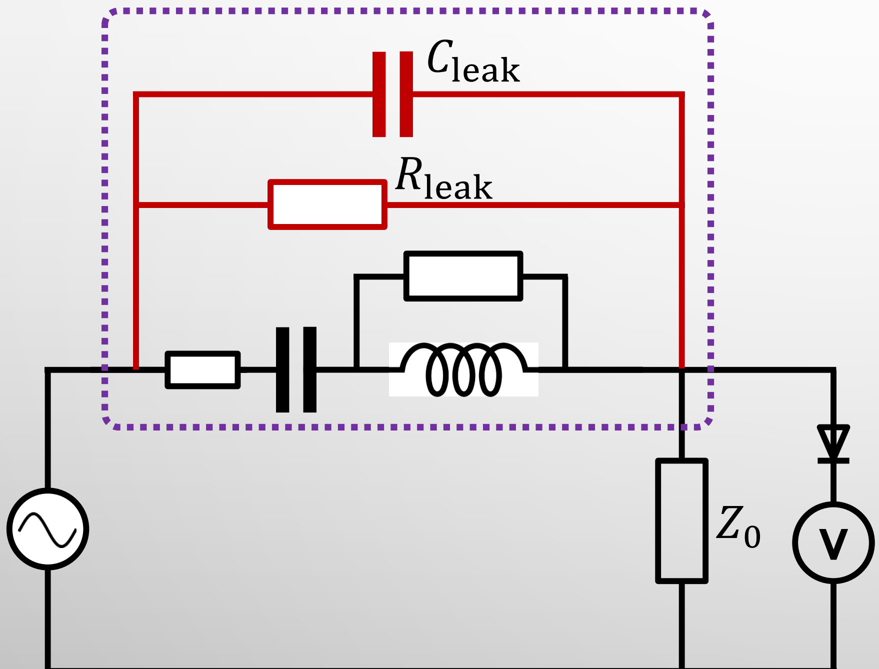
$V \to V_{\max}$ on resonance

Mechanical Efficiency

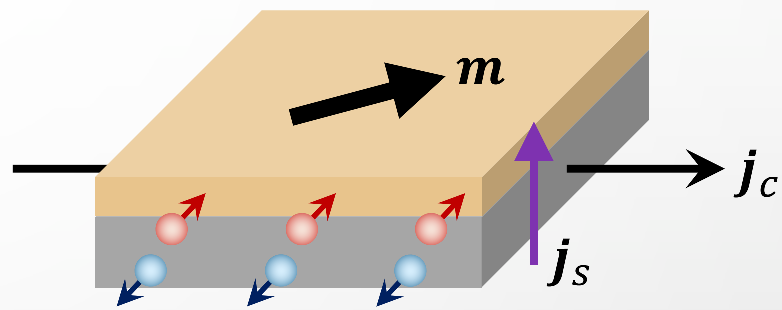
$$\boxed{\eta = \frac{P_M}{P_M + P_{\text{leak}}}}$$

Still above 50% for imperfect TI

$$P_{\text{leak}} = E_x^2 l^2 / 2R_{\text{leak}}$$



- Comparing with current-driven systems



$$\eta = \frac{P_M}{P_J} = \frac{\alpha\sigma\hbar\theta_s^2\xi^2}{Se^2}\left(\frac{a_0^3}{d_n d_m}\right)\omega^2\left(|\tilde{\chi}_\perp|^2 + |\tilde{\chi}_\parallel|^2\right)$$

$$\xi = \frac{\lambda G_r \tanh\frac{d_n}{2\lambda}}{\sigma + 2\lambda G_r \coth\frac{d_n}{2\lambda}}$$

η on the order of 1%

Oersted Field

Current-driven system

Metal
$\boldsymbol{J}_c = \sigma \boldsymbol{E}$

charge-spin conversion

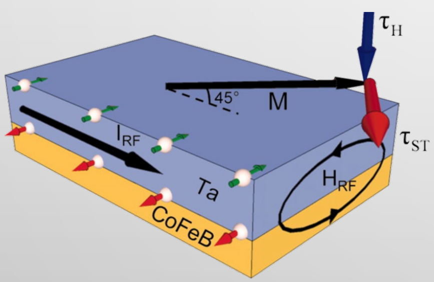
$\boldsymbol{J}_c \rightarrow \boldsymbol{J}_s$

$\boldsymbol{\tau}_{\mathrm{ST}} = \boldsymbol{\nabla} \cdot \boldsymbol{J}_s$

current-induced torque

Oersted field

$\boldsymbol{\nabla} \times \boldsymbol{H} = \boldsymbol{J}_c$



$\tau_{\mathrm{H}} \sim \tau_{\mathrm{ST}}$

Liu *et al.*, Science 2012

Voltage-driven system

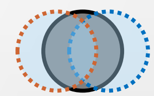
Insulator
$\boldsymbol{J}_c = 0$ but $\boldsymbol{J}_D = \varepsilon_0 \varepsilon_r \dot{\boldsymbol{E}}$

Oersted field

$\boldsymbol{\nabla} \times \boldsymbol{H} = \boldsymbol{J}_D$

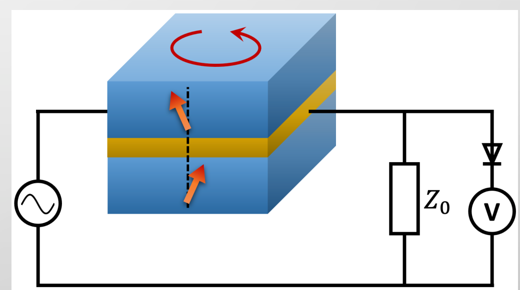
bound charge vibration

$\boldsymbol{E} e^{i\omega t}$



voltage-induced torque

$\tau_{\mathrm{H}} \ll \tau_{\mathrm{ST}}$



J. Tang & RC, arXiv:2204.03534

Conclusions & Outlook

- Operating F/TI/F as adiabatic quantum motor can achieve 100% mechanical efficiency
- Voltage-induced torque can drive the exchange mode resonance
- Effective circuit found for the proposed device
- Oersted field effect is negligible

- Under investigation: generalizing into intrinsic antiferromagnetic topological insulators