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# Coupling of heat and spin currents in metallic multilayers

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Choi *et al.*, *Nature Communications* (2014)

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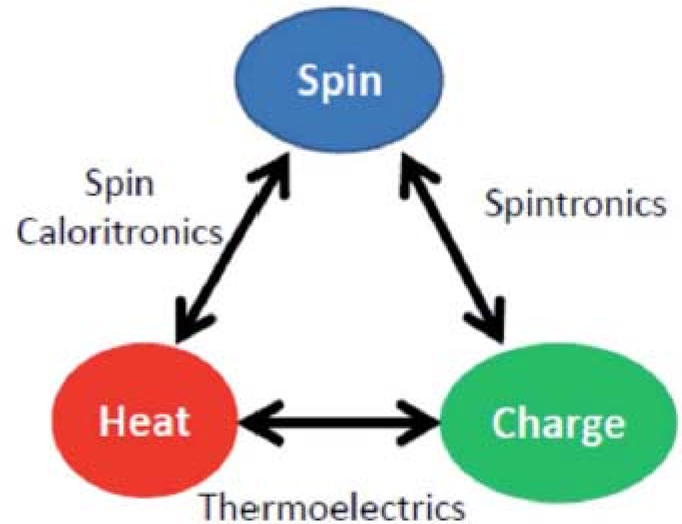
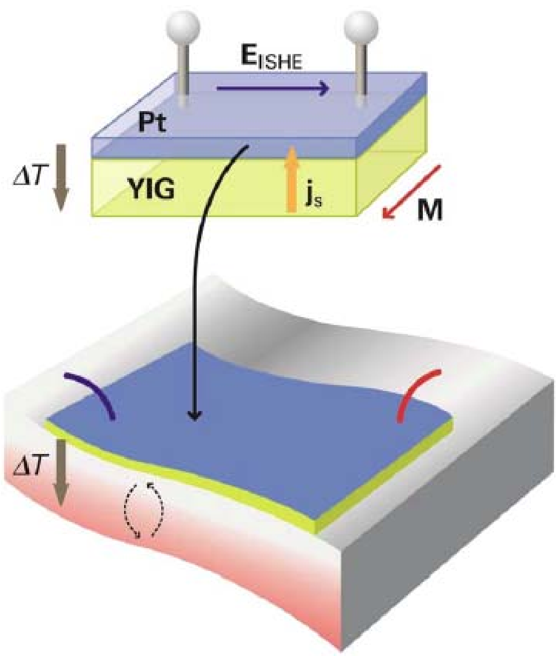
# Motivation I: Can we make use of spin in heat engines?

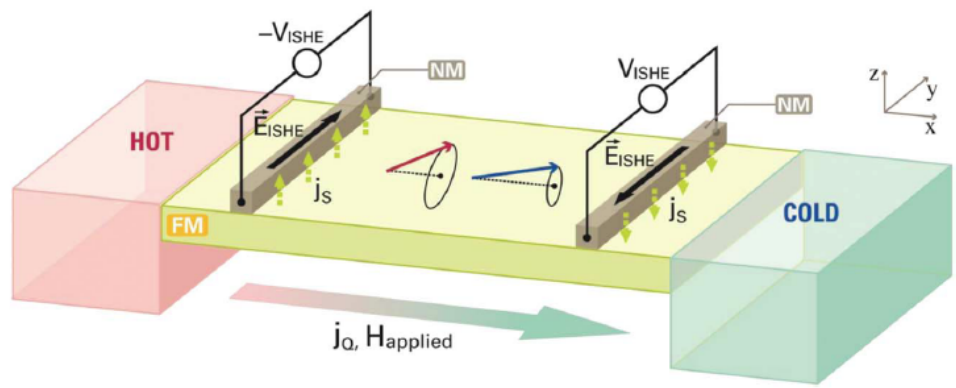
- Electronic states enumerated by energy, wave-vector, spin
- Possible advantages in geometrical scaling, $\nabla E \perp \nabla T$.




Boona, Myers, Heremans, *Energy and Env. Sci*. (2014)




Kirihara *et al*., *Nat. Mat.* (2013)

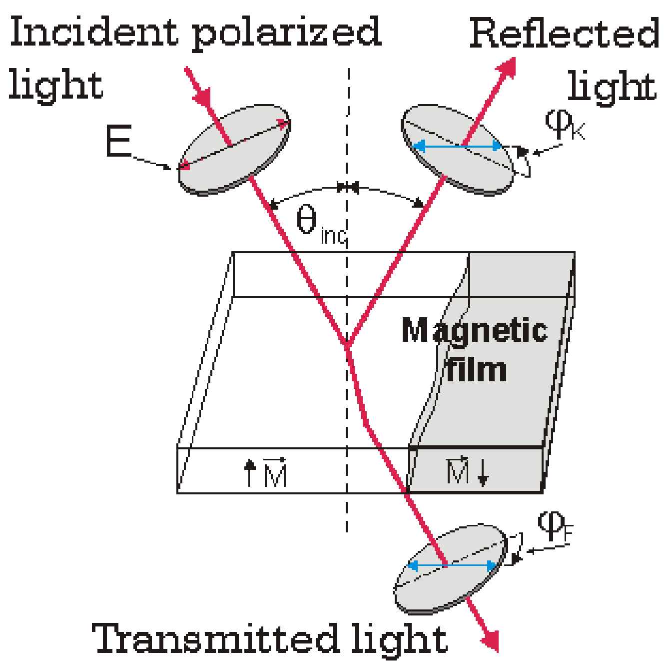


# Motivation II: Can we make use of heat currents in information technology?

- Big picture problem: “How can we write magnetic information without resorting to magnetic fields, e.g., with spin currents?”
  - Rapid changes in magnetization and strong temperature gradients in magnetic materials should produce spin currents.
  - Magnitudes of the effects are only beginning to be understood.
- Why now and why pump-probe?
  - Leveraging rapidly advancing tools and growing knowledge base for heat transport in nanoscale metallic structures.
  - Create huge heat fluxes 100 GW $m^{-2}$ $K^{-1}$ and detect spin current in real time with 1 ps time resolution.

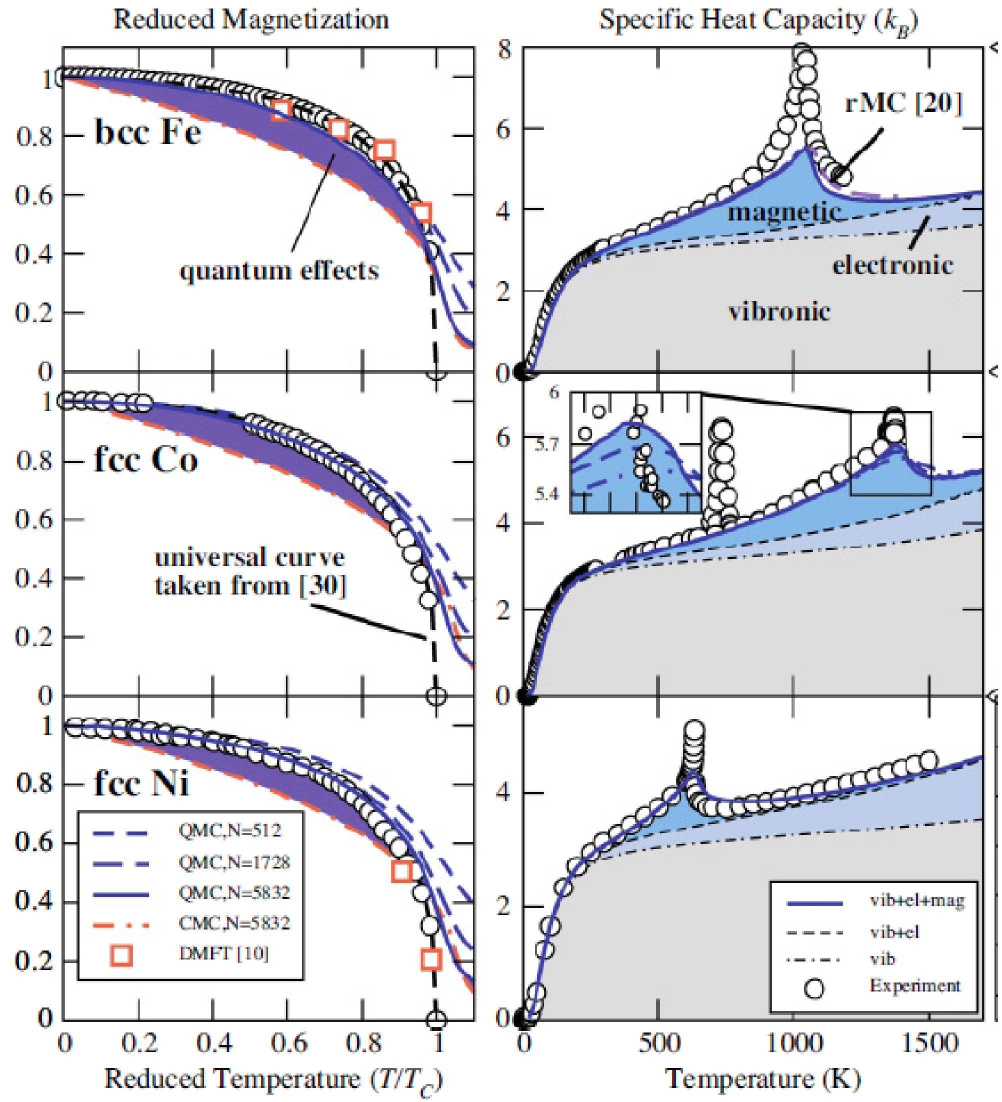
# Time-resolved magneto-optic Kerr effect (TR-MOKE) to measure magnetization and spin accumulation

Kerr rotation



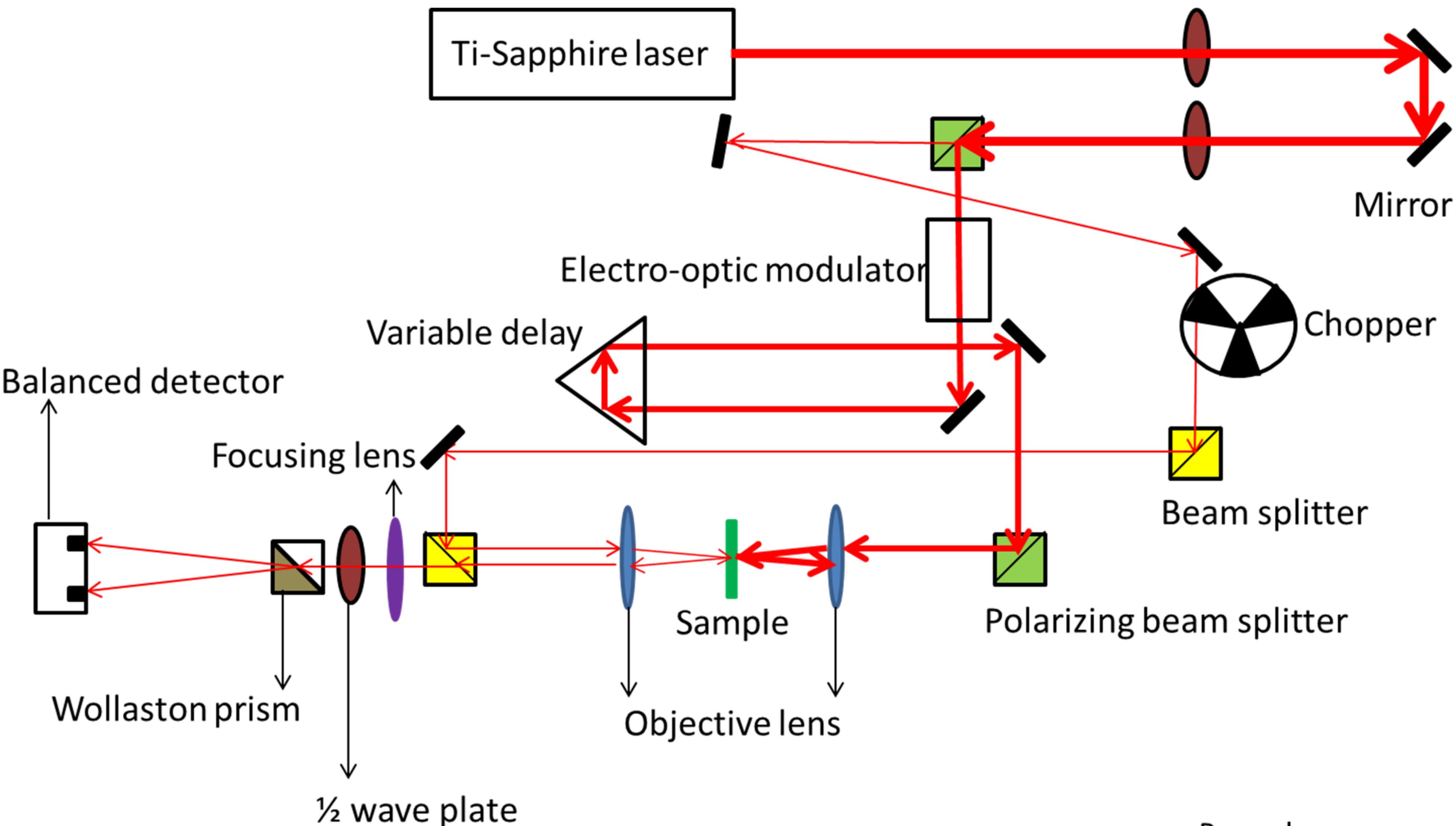

Faraday rotation

http://labfiz.uwb.edu.pl



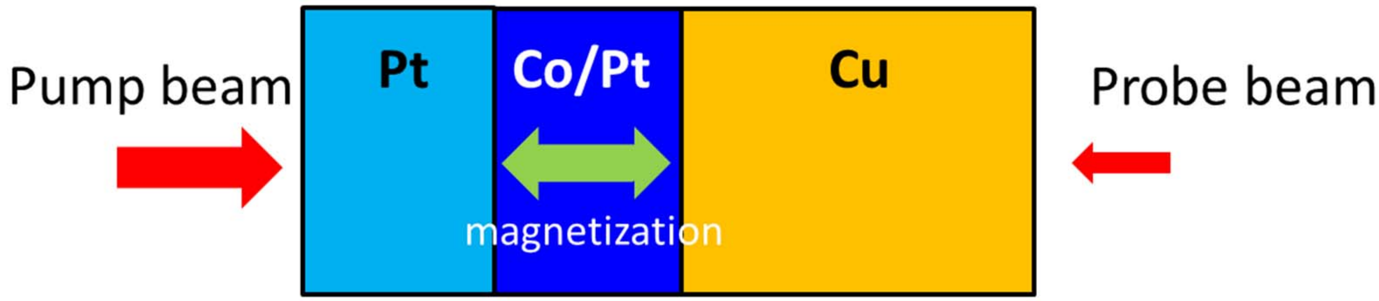

Körmann *et al.*, PRB (2011)

# Time-resolved magneto-optic Kerr effect (TR-MOKE) to measure magnetization and spin accumulation

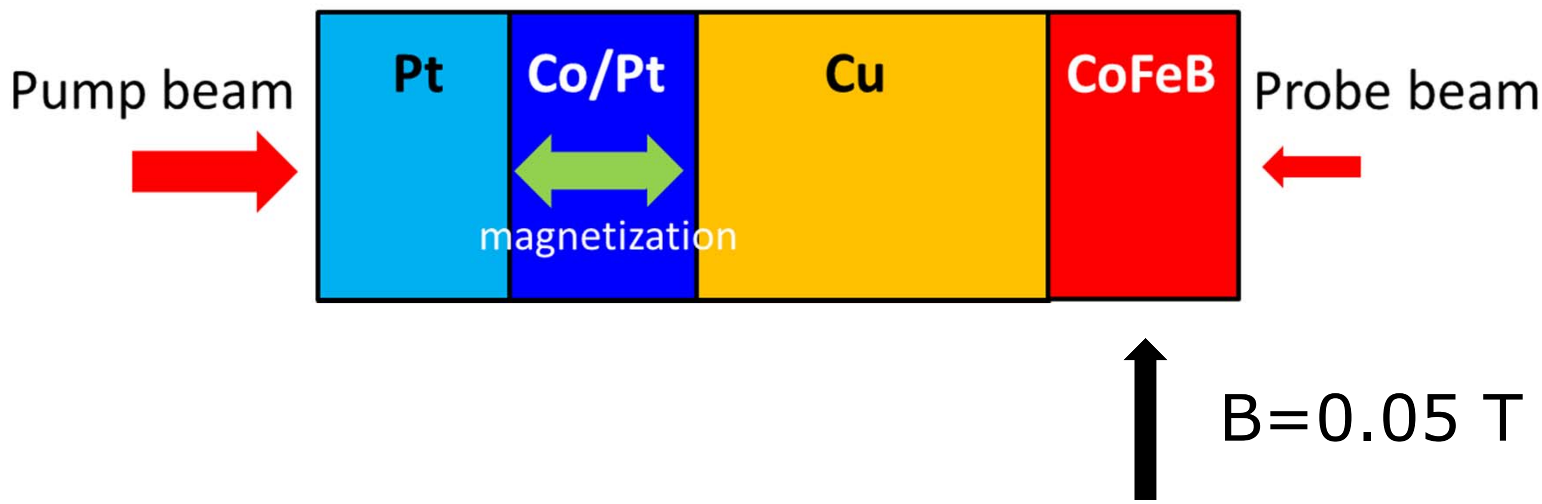


# Two types of samples: i) for spin accumulation; and ii) for spin-transfer torque

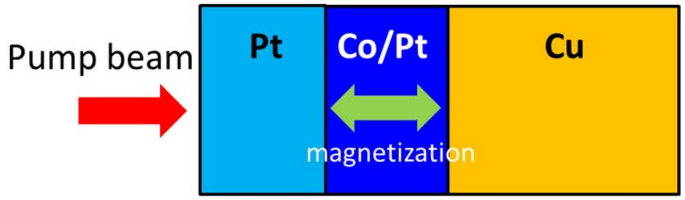
Sapphire/Pt(30)/[Co/Pt]$_{xn}$(6)/Cu(80)/MgO(10)/AlOx(5) (in nm)




Sapphire/Pt(30)/[Co/Pt]$_{xn}$(6)/Cu(10)/CoFeB(2)/MgO(10)/AlOx(5) (in nm)

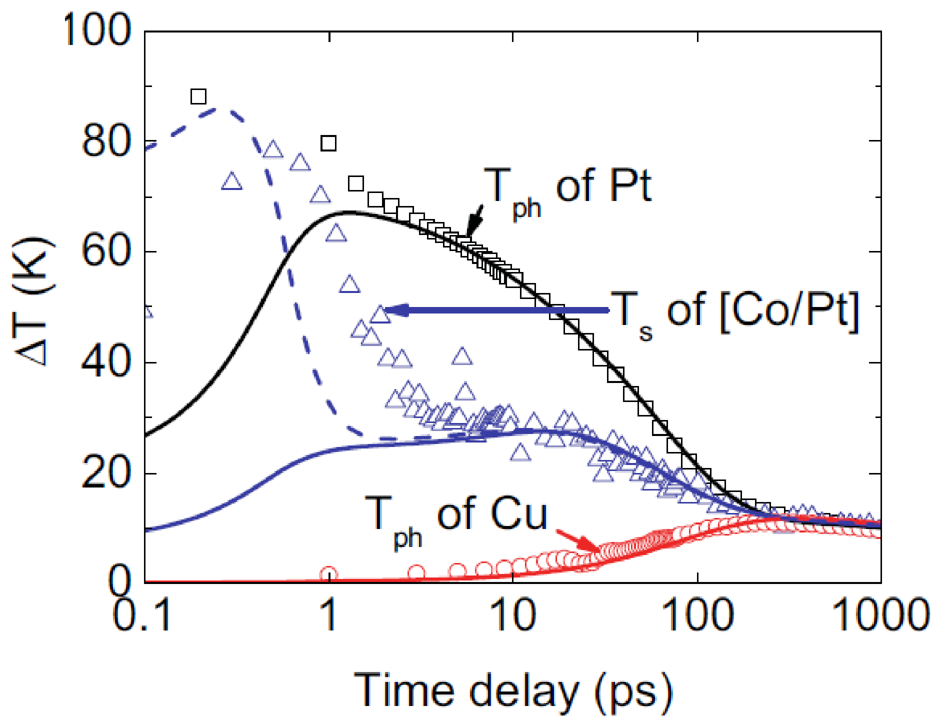


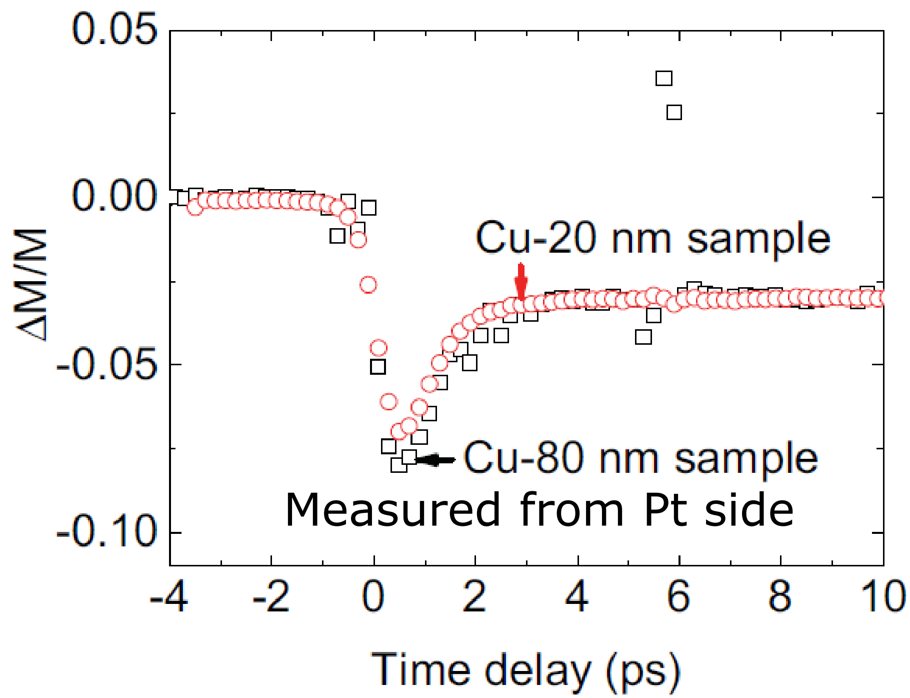
# Pump Pt-side, probe either Pt-side or Cu side by either TDTR or TR-MOKE



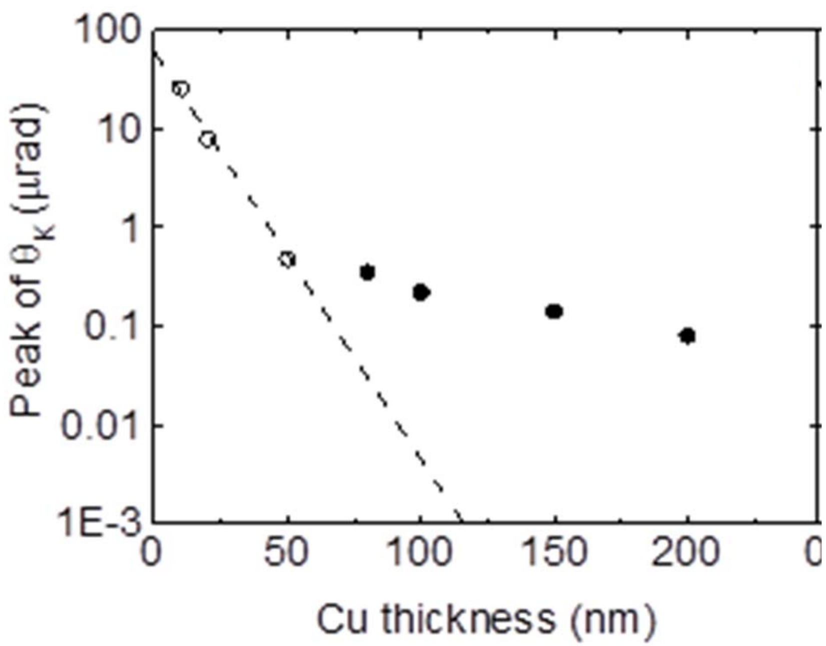

Normalized Kerr signal from Co/Pt is independent of Cu thickness

$$\left.\frac{\Delta M}{M}\right|_{\max} = -0.08 \pm 0.02 \text{ at } 0.5 \text{ ps}$$

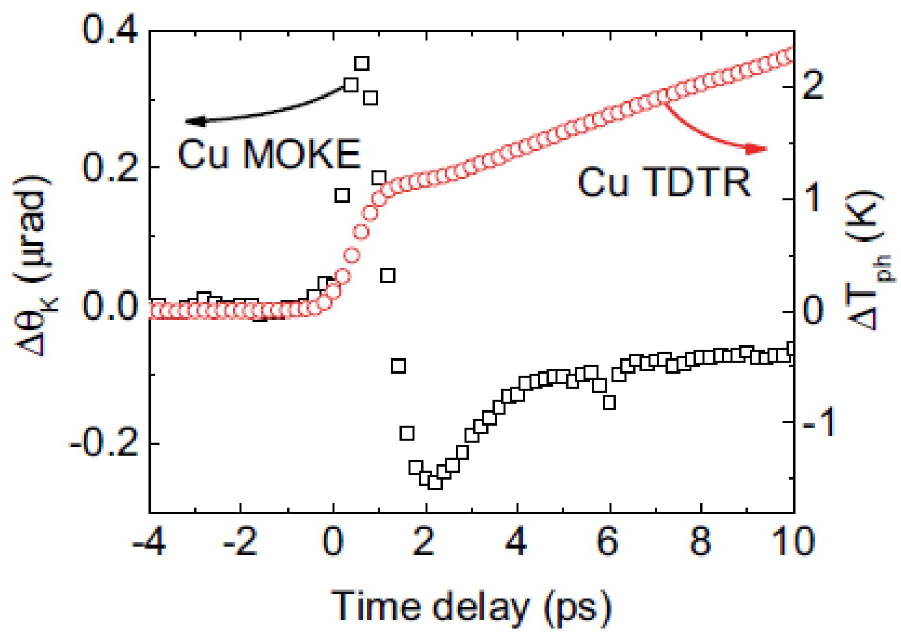


# Use thicker Cu layers to isolate contribution from spin-polarization in Cu

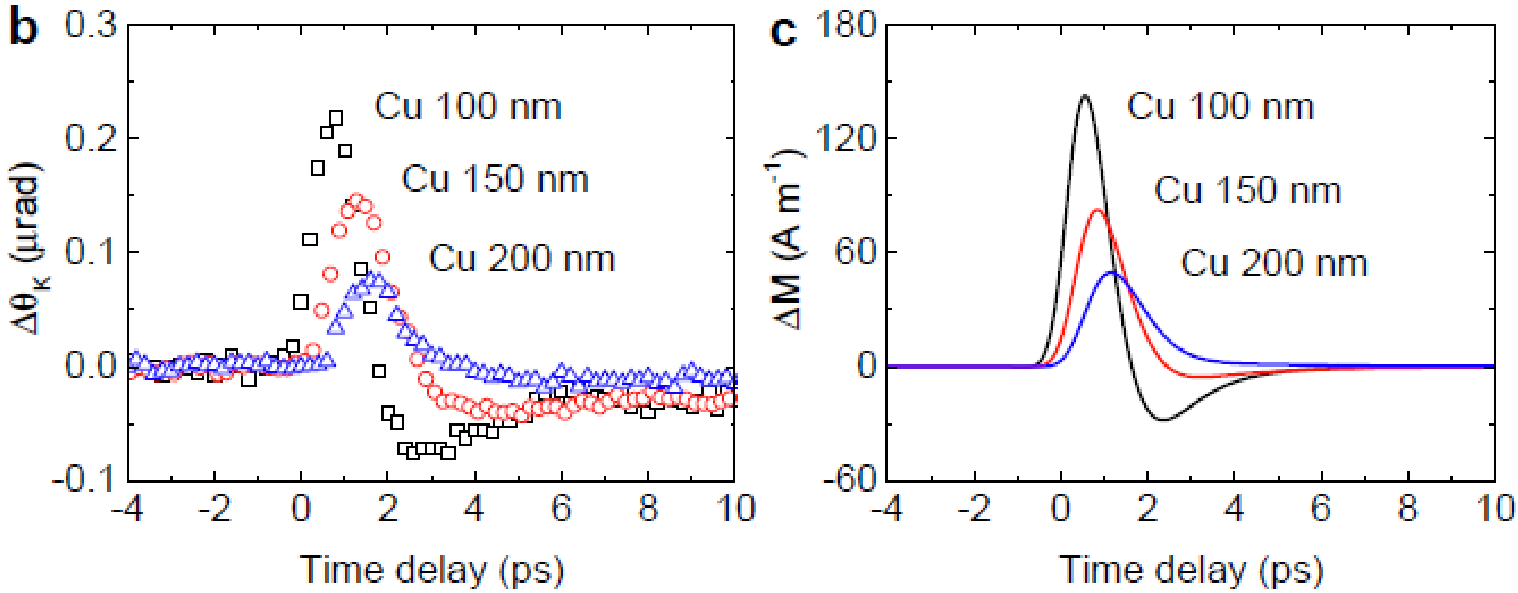



100 nm Cu



# Comparison between experiment and spin diffusion model using spin generation = *dM/dt*

Measured Kerr signal on Cu side　　　　Spin diffusion model



# Spin diffusion model

$$\frac{\partial \mu_S}{\partial t} = D\frac{\partial^2 \mu_S}{\partial^2 z} - \frac{\mu_S}{\tau_S}$$

spin generation rate per unit volume

$$G_S = -\frac{dM}{dt}$$

$\mu_S = \mu_\uparrow - \mu_\downarrow$ is the spin chemical potential

$D$ is the spin diffusion constant

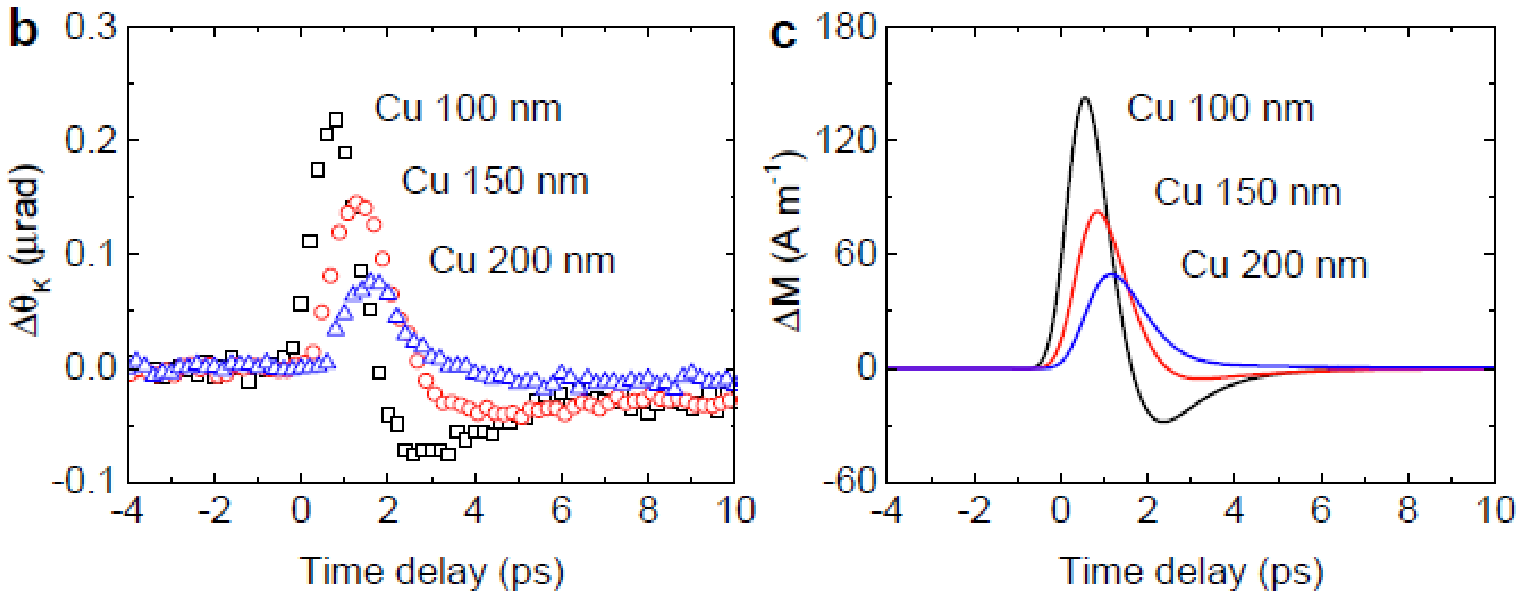
$\tau_S$ is the spin relaxation time

| | Pt | [Co/Pt] | Cu |
|---|---|---|---|
| D ($nm^2/ps$) | 200 | 100 | 6500 |
| $\tau_s$ (ps) | 0.5 | 0.05 | 25 |
| $(D\tau_s)^{1/2}$ (nm) | 10 | 2.2 | 400 |

# Comparison between experiment and spin diffusion model using spin generation = *dM/dt*

Measured Kerr signal on Cu side
$E$=36 J m$^{-2}$

Spin diffusion model
$E$=17 J m$^{-2}$



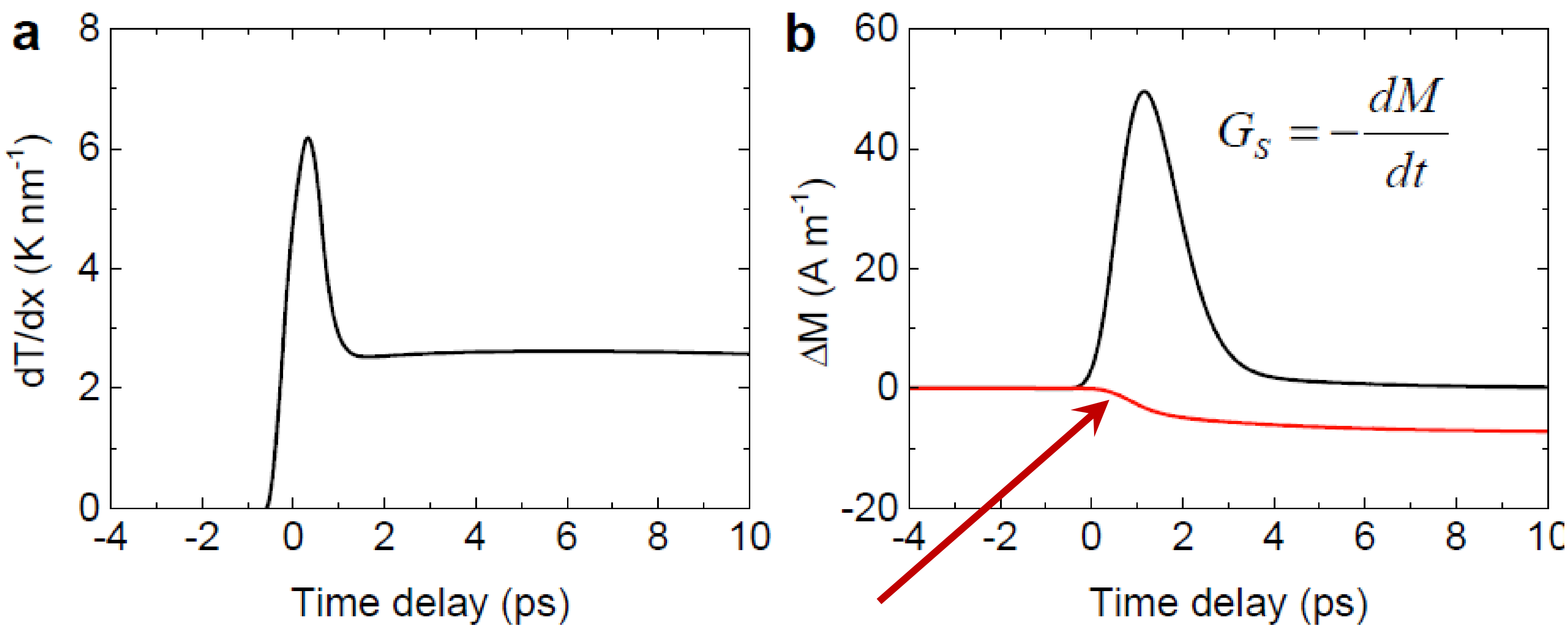

- No prior studies of how to convert Kerr rotation to spin accumulation.
- Working in progress to relate Kerr rotation quantitatively to spin accumulation in Cu and Au.

# Temperature gradient also contributes to spin accumulation

$$J_S = -\frac{\mu_B}{e}\left(\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow\right)\nabla T = -\frac{\mu_B}{e}\frac{\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}\sigma\nabla T$$

Temperature gradient in the Pt/Co layer from thermal modeling

Calculated spin accumulations




$$\frac{\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \approx 5\ \mu\mathrm{V\ K}^{-1}$$

# Spin diffusion modeling including spin-dependent Seebeck effect

- Spin chemical potential

$$\mu_S = \mu_\uparrow - \mu_\downarrow = A\exp\left(\frac{x}{l_S}\right) - A\exp\left(-\frac{x}{l_S}\right)$$

- Spin current for

$$|x| > l_s$$

$$\frac{d\mu_S}{dx} = \frac{A}{l_S}\exp\left(\frac{x}{l_S}\right) + \frac{A}{l_S}\exp\left(-\frac{x}{l_S}\right) \approx \frac{1}{l_S}\mu_S$$

$$J_S = J_\uparrow - J_\downarrow = \Lambda_S \frac{d\mu_S}{dx}$$ $\Lambda_s =$ spin conductivity

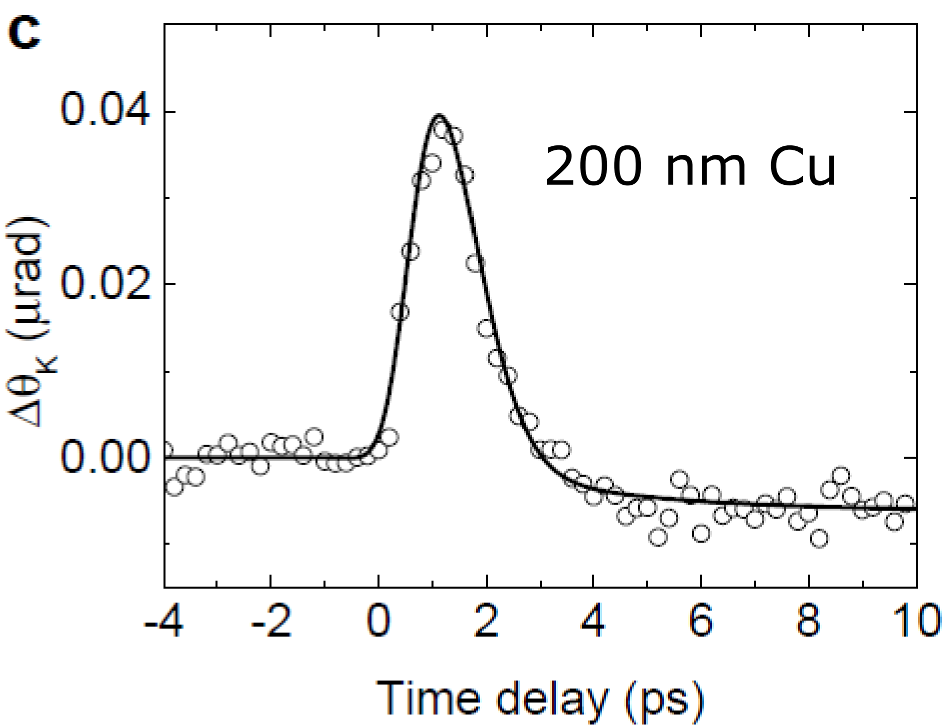
- Simple relationship between chemical potential and current

$$\mu_S = \frac{l_S}{\Lambda_S} J_S$$

# Temperature gradient also contributes to spin accumulation

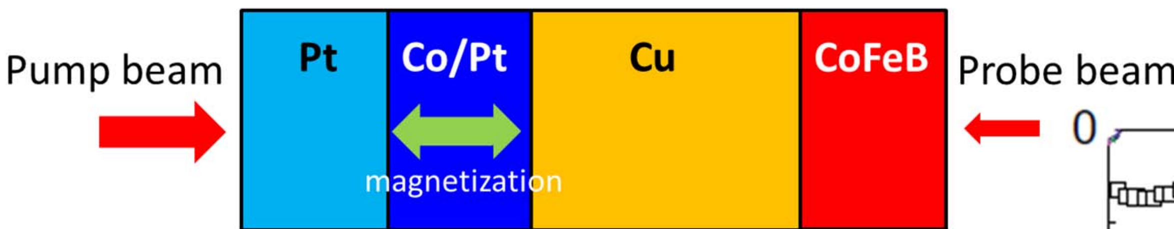
- More refined data with comparison to spin diffusion model including the spin-dependent Seebeck effect
- Comparison between model and data gives

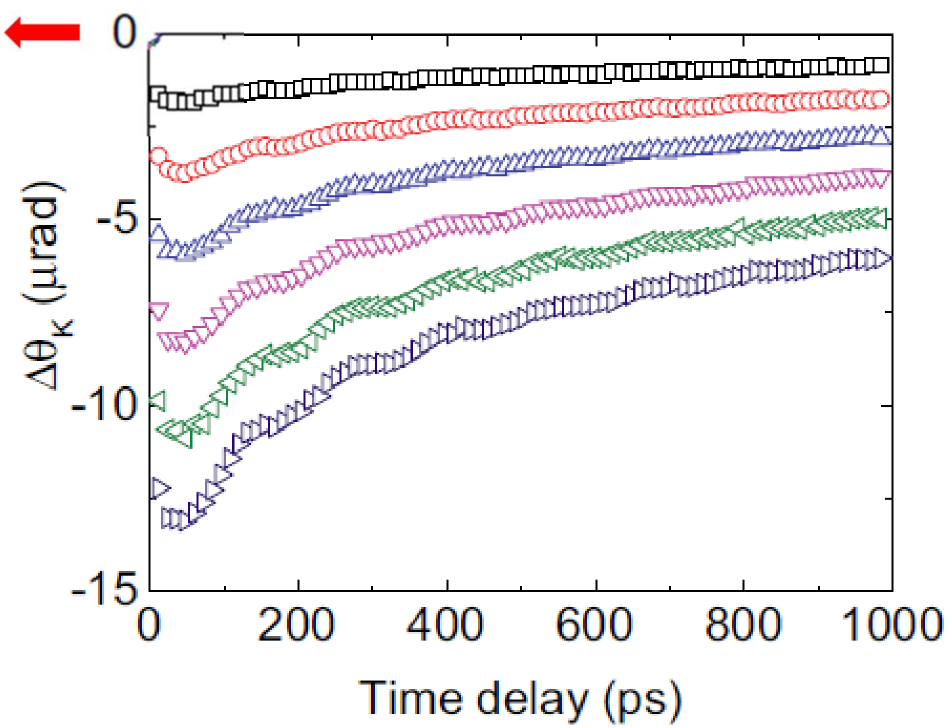
$$\left.\frac{\Delta\theta_K}{\Delta M}\right|_{Cu} \approx 8.5\times10^{-10}\ \text{rad m A}^{-1}$$



# Use an in-plane magnetic layer of CoFeB as a "ballistic pendulum" for the spin current

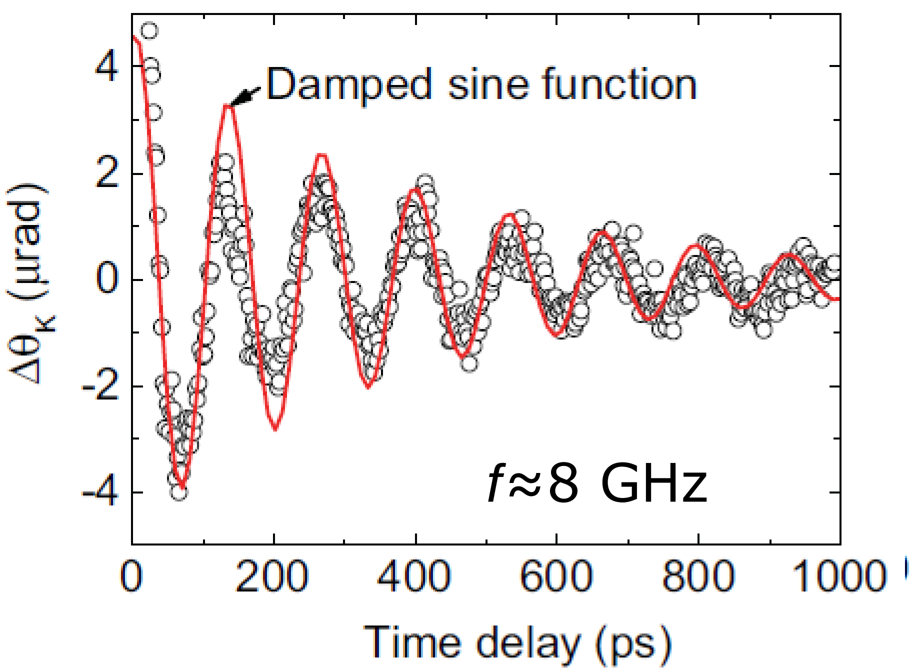
- Spin current kicks magnetization of CoFeB out-of-plane (spin torque) and induces precession.
- Amplitude of the precession can be calibrated using Kerr rotation in a static field perpendicular field.



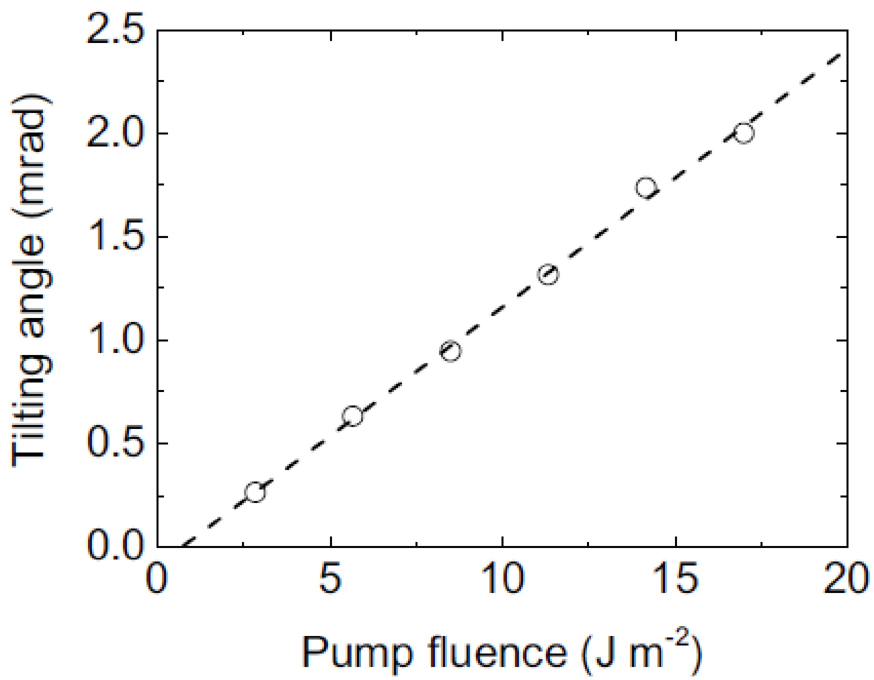



# Precession frequency is well-described by Kittel equation

$$f = \frac{\gamma}{2\pi}\sqrt{\mu_0 H_x\left(\mu_0 H_x + \mu_0 M_S - \frac{2K_Z}{M_S}\right)},$$




Linear response



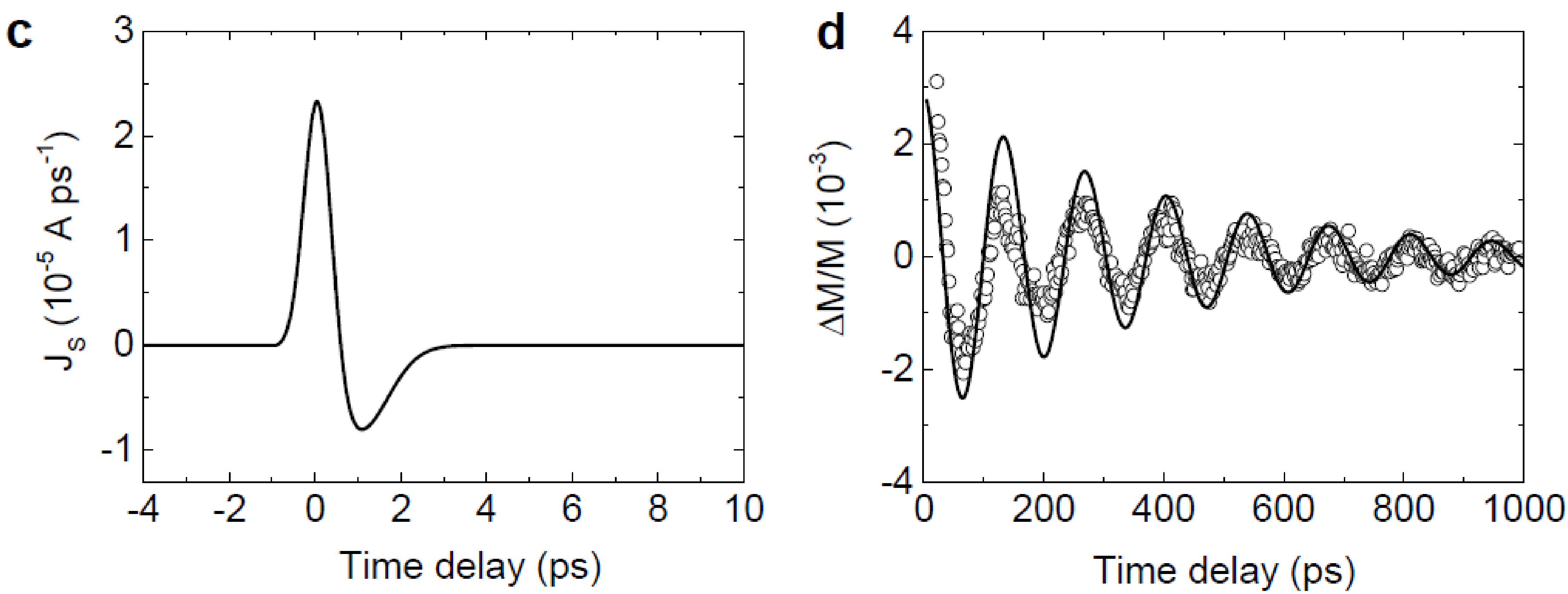
# Combine spin diffusion model with magnetization dynamics

- Spin current has transverse polarization with respect to CoFeB magnetization, therefore, CoFeB is a perfect sink for spin (spin chemical potential is zero at Cu/CoFeB interface)
- Cu layer is thin, therefore, we need to include finite spin conductance at the [Co/Pt]/Cu and Cu/CoFeB interfaces
  - longitudinal spin conductance $\frac{G_\uparrow + G_\downarrow}{2e^2} \approx 0.4\text{x}10^{15}\ \Omega^{-1}\ \text{m}^{-2}$
  - transverse spin conductance $\frac{\text{Re}\{G_{\uparrow\downarrow}\}}{e^2} \approx 0.6\text{x}10^{15}\ \Omega^{-1}\ \text{m}^{-2}$

# Good agreement between predicted and measured amplitude of spin precession

Landau-Lifshitz-Gilbert equation

$$\dot{m} = -\gamma\, m \times H_{eff} + \alpha\, m \times \dot{m} + \frac{J_S}{M_S h} m \times \left( m \times m_{fixed} \right)$$



# Summary

- Picosecond demagnetization of [Co/Pt] multilayer produces spin-currents that can exert a spin-transfer torque on a in-plane magnetic layer or produce spin accumulation in Cu
  - 6% of loss of demagnetization of [Co/Pt] magnetization is transferred to CoFeB layer
  - Increase efficiency with [Co/Pd] or [Co/Ni] with longer spin diffusion length?
- Coefficient for converting Kerr rotation to spin accumulation in Cu is 0.85 nm $A^{-1}$
  - Initial experiments on Au suggest that the detection sensitivity t is a factor of 5 larger than Cu
- Experiments and modeling give a spin-dependent Seebeck effect in [Co/Pt] of ≈5 μV $K^{-1}$
  - Will a tunnel barrier produce a larger effect?