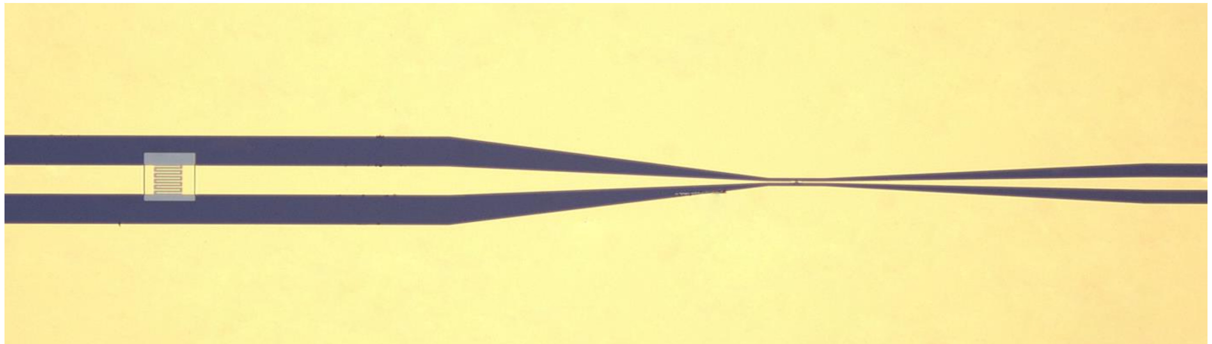
Spintronique *ultra*rapide

Jon Gorchon – chercheur CNRS



Journée Science et Progrès - F2S

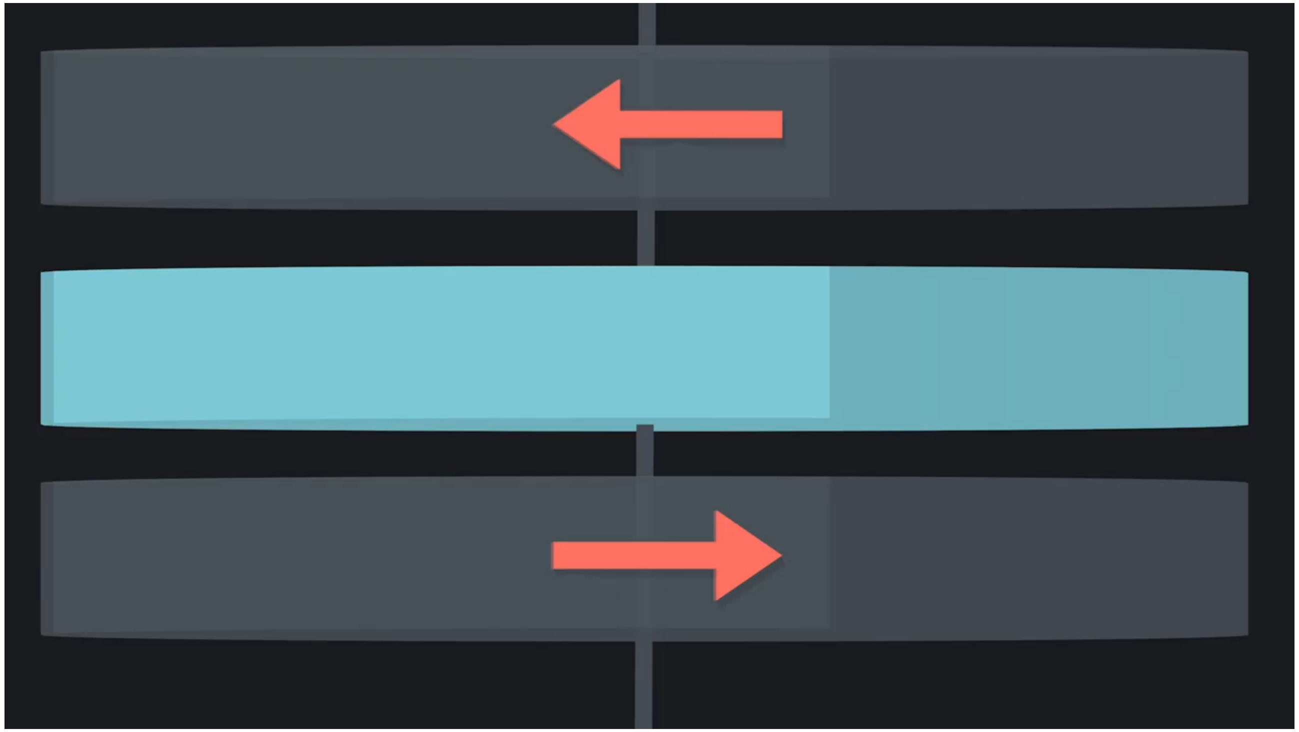
Paris – 24 Mar 2022

La *spin*-tronique

Animations: Scitoons, *What is spintronics and how is it useful?* – YouTube 2019

La *spin*-tronique

Vanne de spin



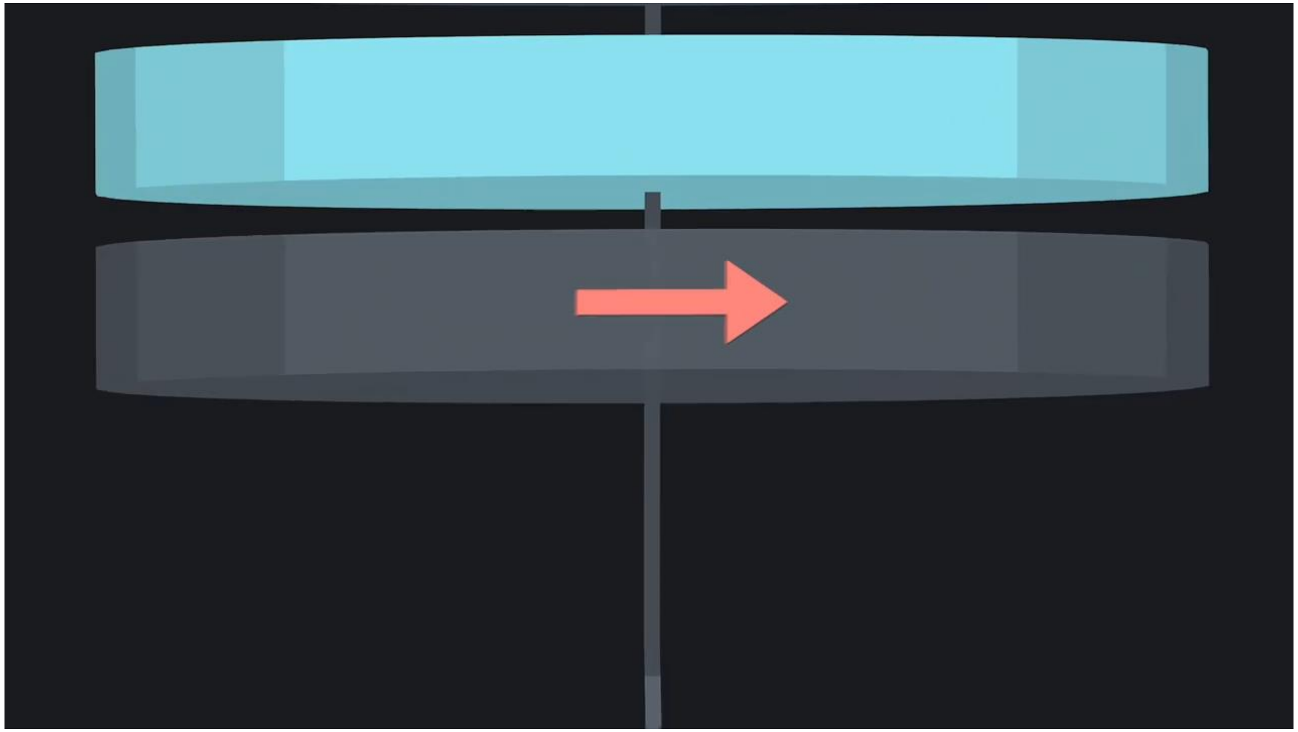
Libre

Fixe

detection (senseurs)

L'aimantation affecte le courant

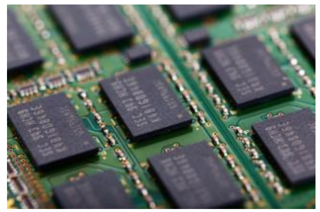
La *spin*-tronique



detection (senseurs)

L'aimantation affecte le courant

Le courant affecte l'aimantation



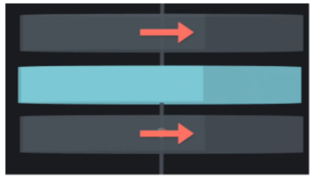
manipulation (memoire, calcul)

Spintronique 2022

courants

chaleur

lumière



champ électriques

contraintes mécaniques

→ Spintronique *ultrarapide*

Ce quoi *ultra*-rapide?

< 1 / 1 000 000 000 000 s $(10^{-12}$ s)

Comment explorer ces échelles de temps experimentalement?

Comment se comporte la matière (spins) à ces échelles de temps?

Option A)

détecteur rapide?
~10 000 fps

Option B)

detecteur lent + source rapide!

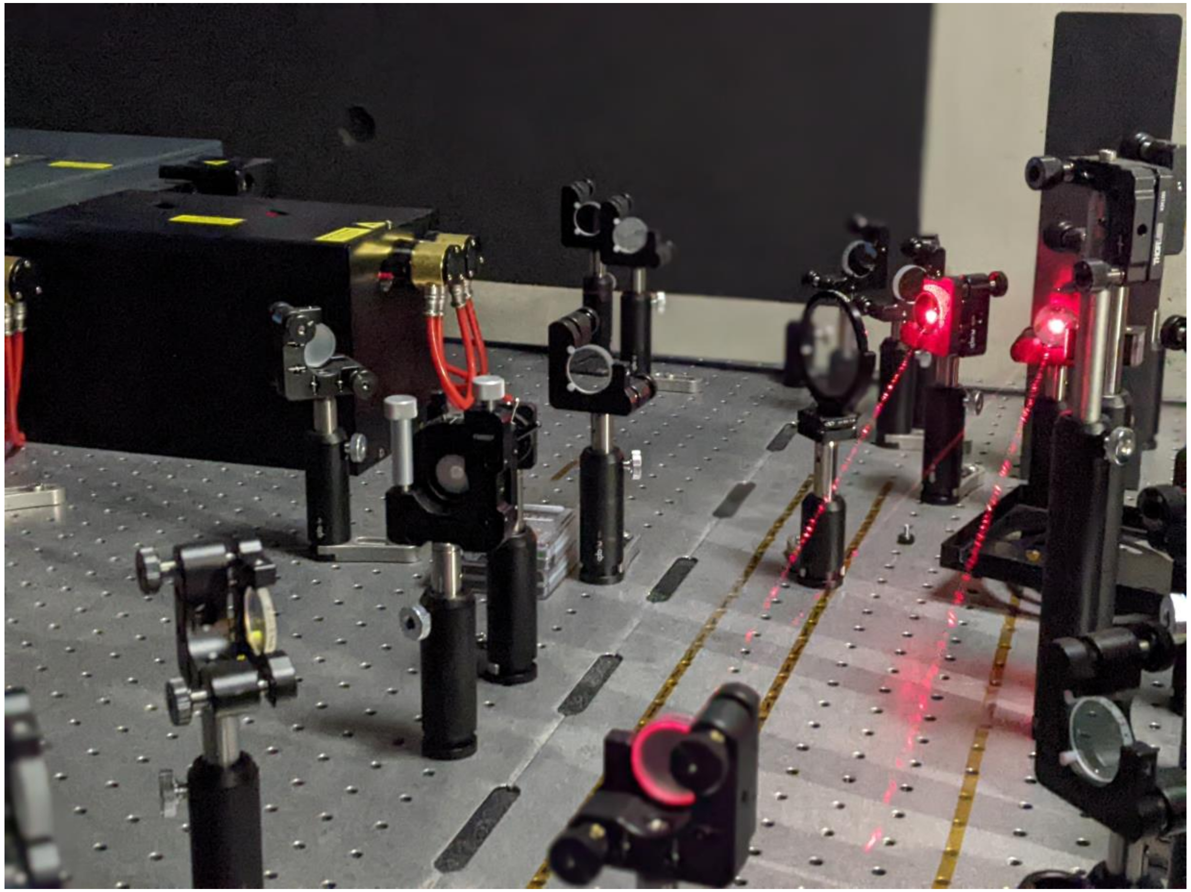
Il nous faut une source ultra-rapide!

Types de sources

1 s	10^{-9}s	10^{-15}s
seconde	nanoseconde	femtoseconde

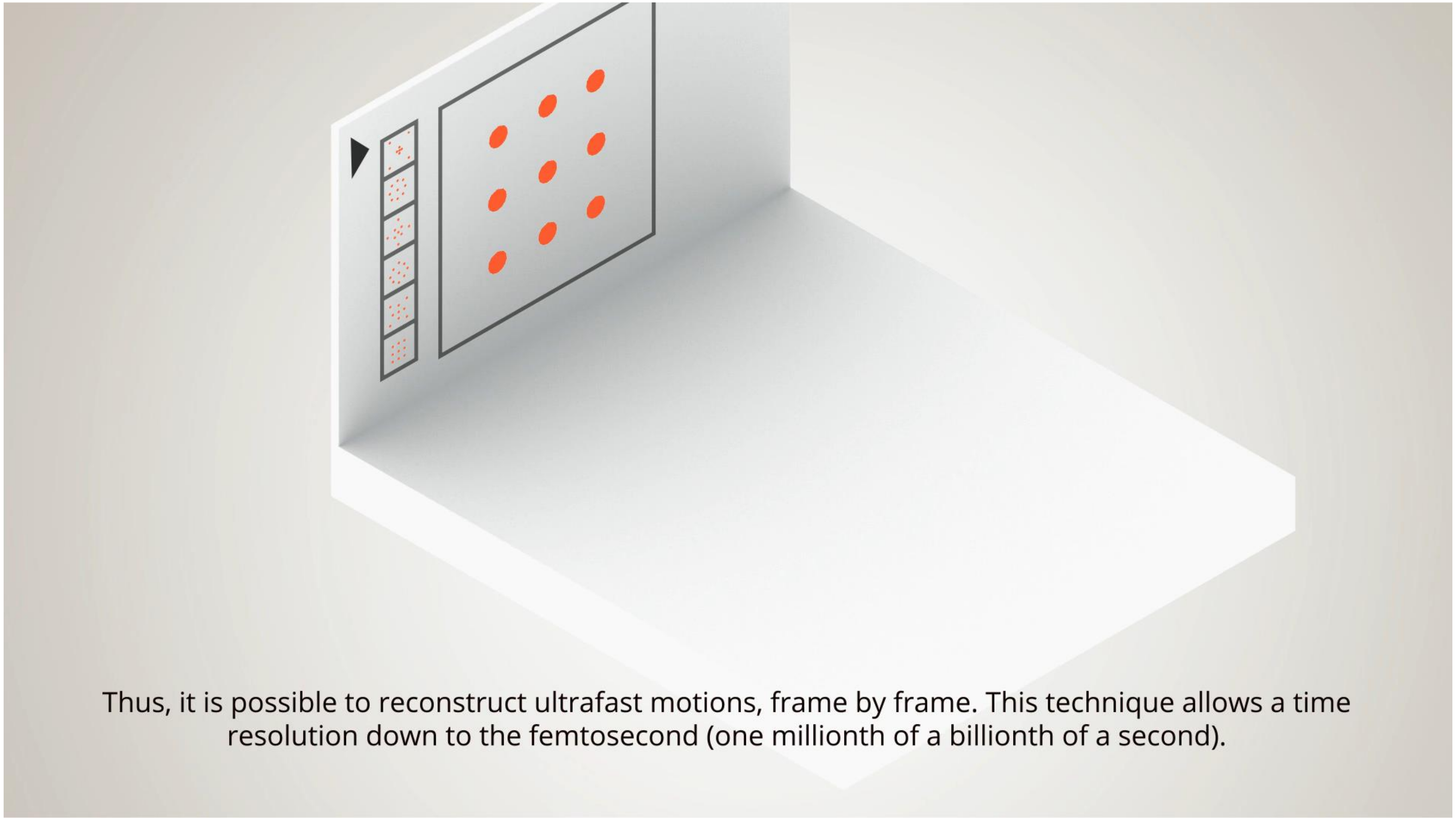
Interrupteurs mécanique

Interrupteurs électroniques (transisteurs)



***Lasers* impulsionnels femtoseconde**

Expériences pompe-sonde

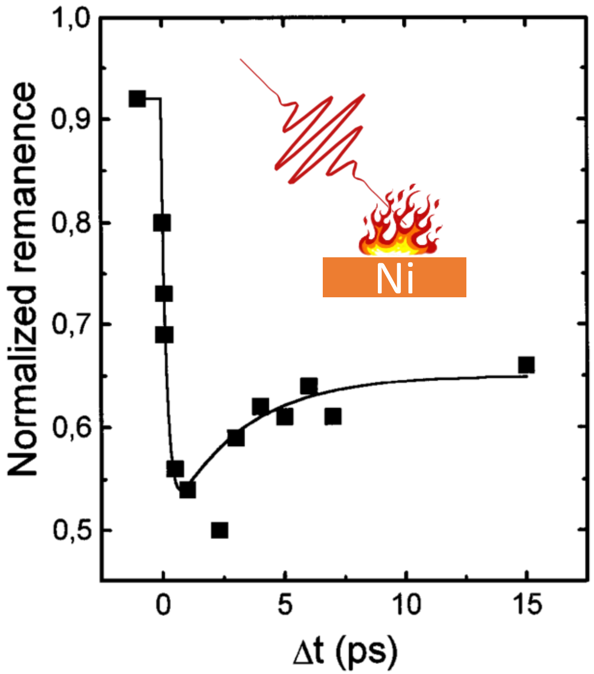


http://toutestquantique.fr/

Observation de la dynamique magnétique

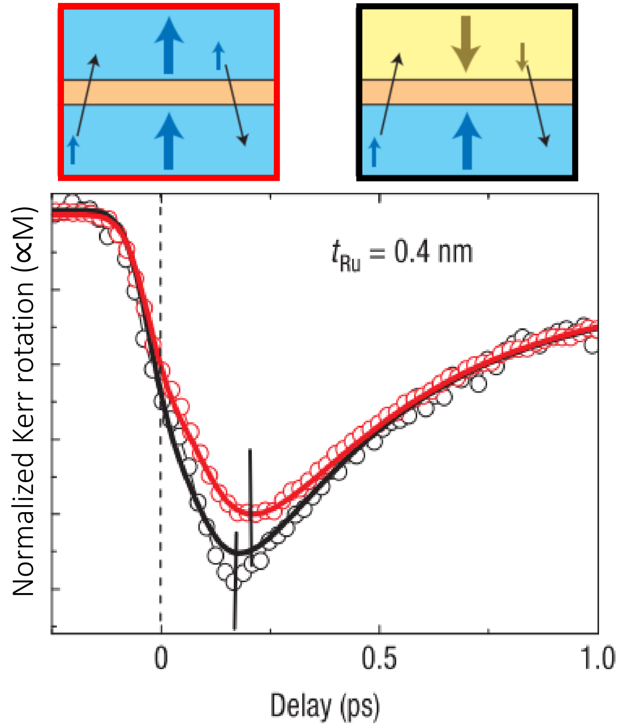
Comment réagi l'aimantation à ces échelles?

Desaimantation ultrarapide
d'un matériau ferromagnétique



Beaurepaire et al., PRL 1996

Desaimantation d'une vanne de spin



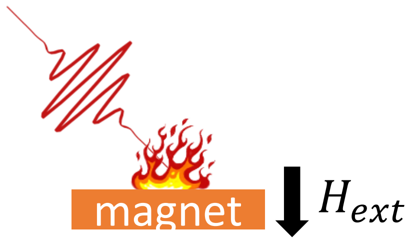
Malinowski et al., Nat. Phys. 2008

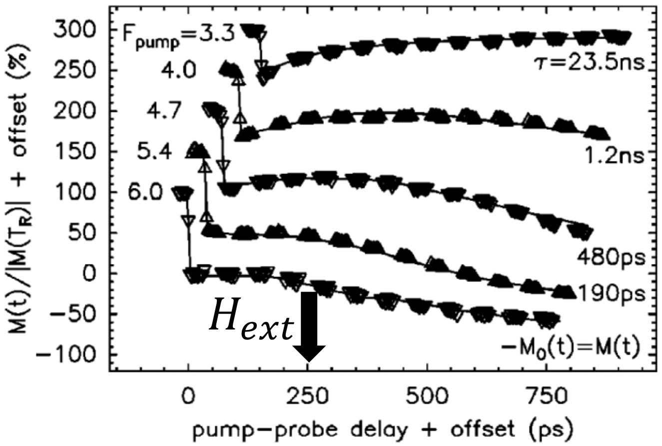
Le moment angulaire (spin) doit être conservé. Oú va t'il?

Des courants de spins sont générés

Peut-on retourner l’aimantation rapidement?

Chauffage + champ magnétique?

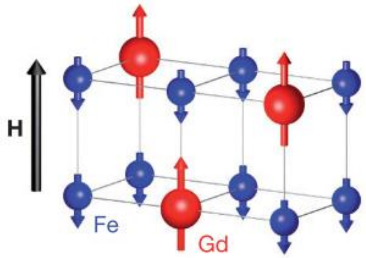


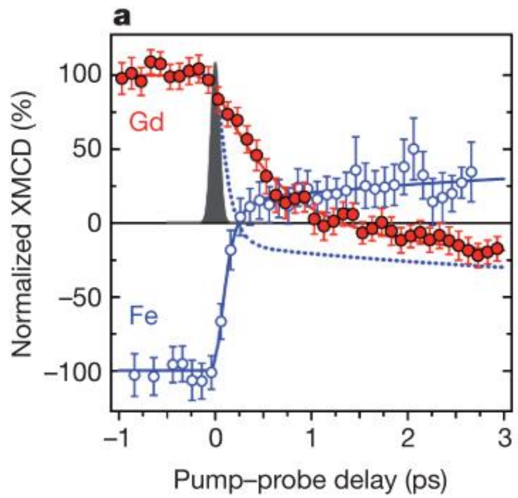


Hohlfeld et al., PRB 2001

Retournement pendant le refroidissement

Matériaux ferr-**i**-magnetiques

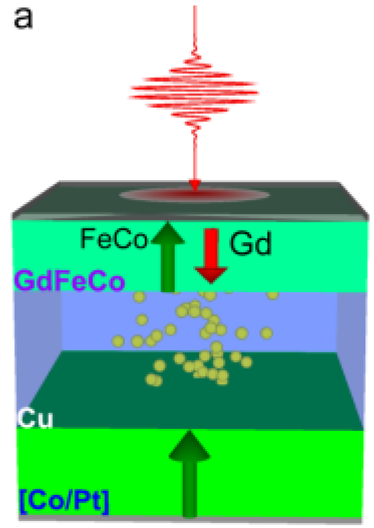




Radu et al., Nature 2011

Chaleur seule induit le retournement

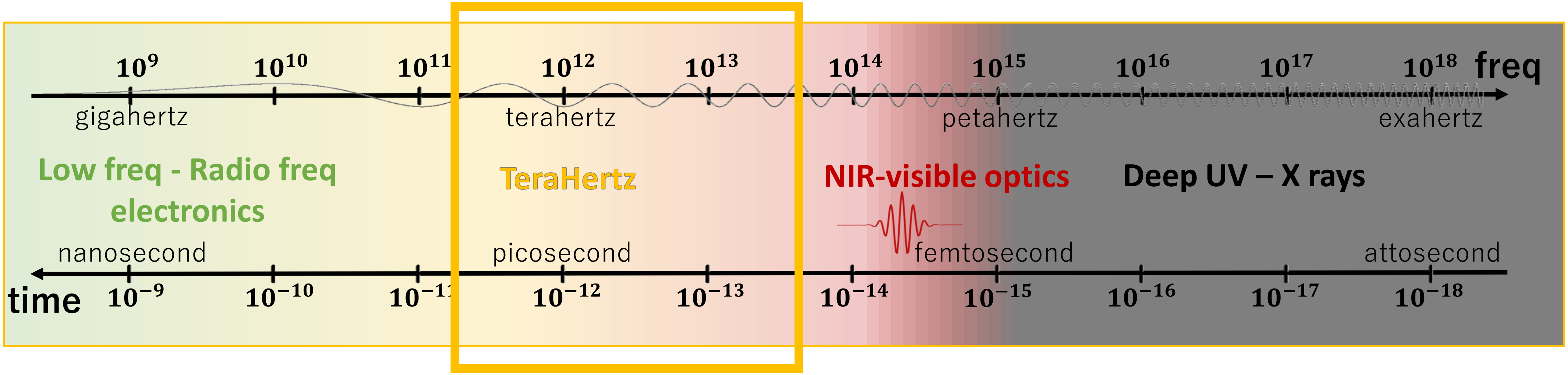
Combinaison ferr-**i** et ferr-**o**-magnetique



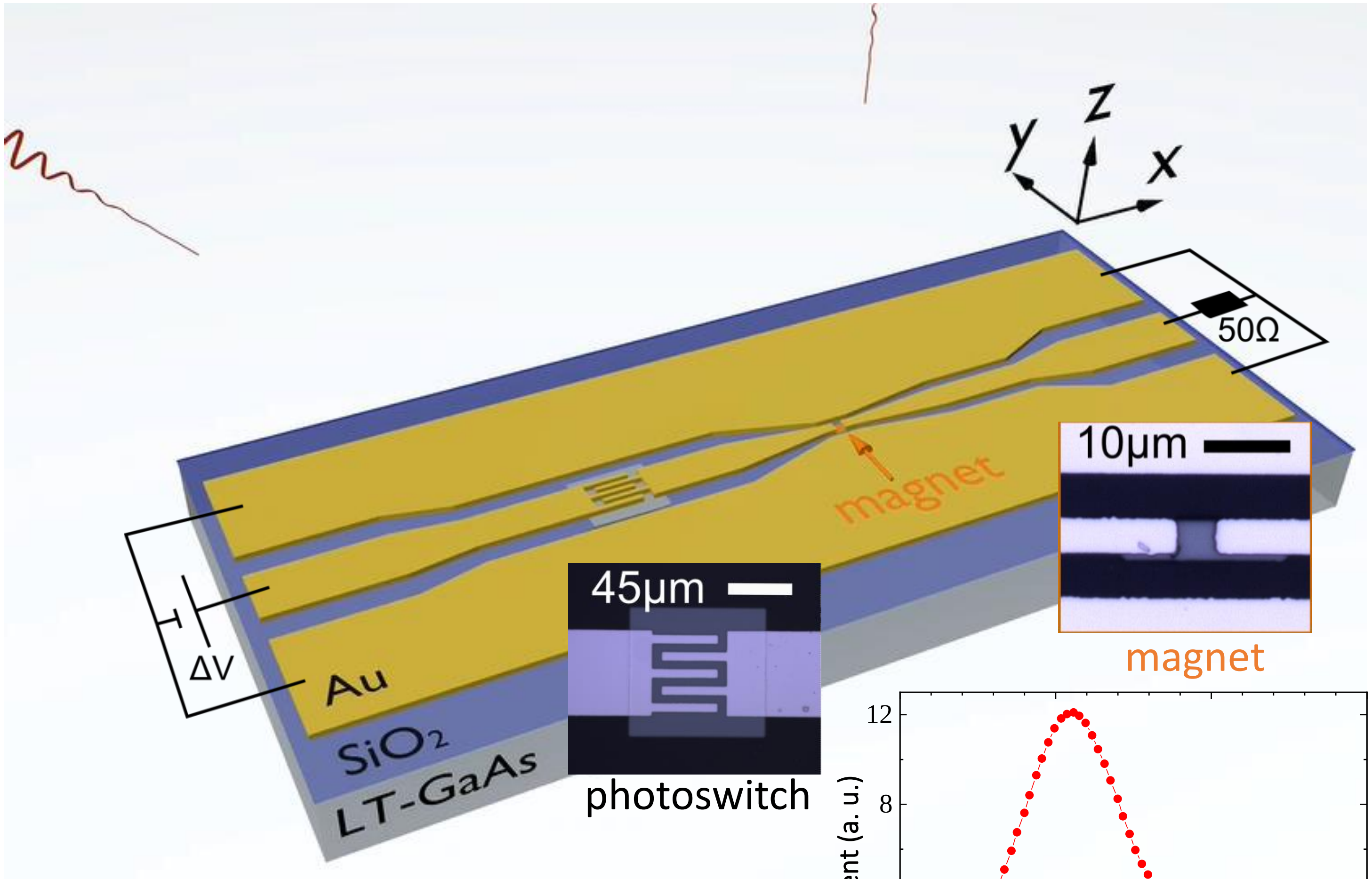
Iihama et al., Adv. Mat. 2018

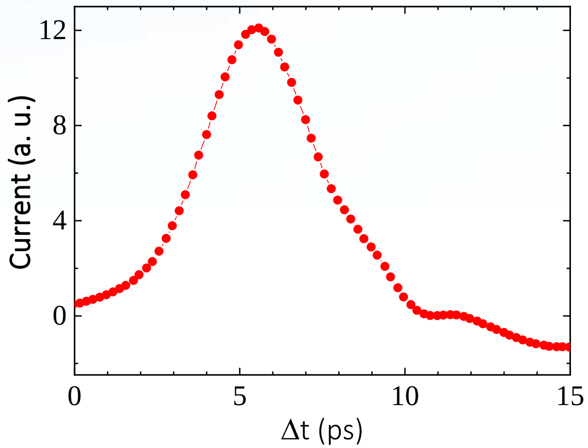
Les courants de spins retournent la couche ferromagnetique

Des impulsions de *courant électrique* rapides?

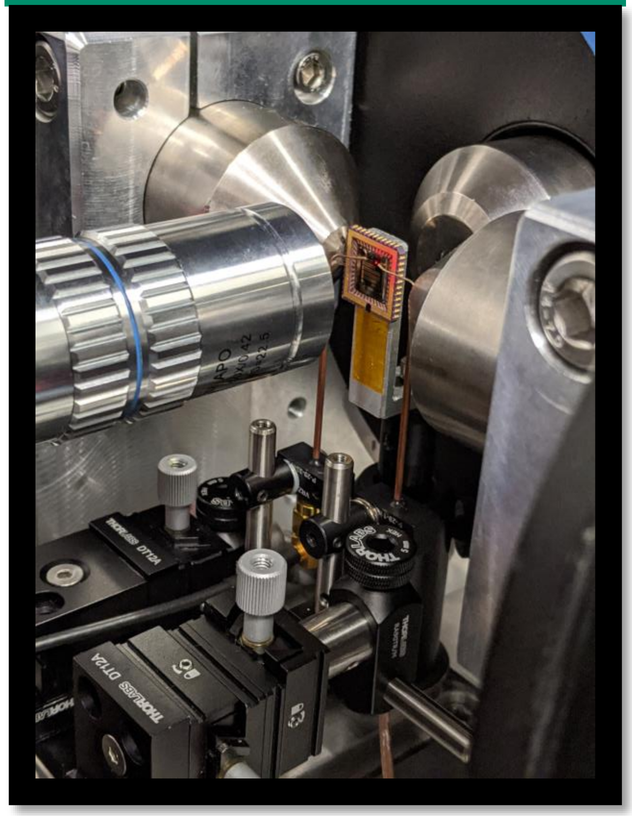


Generation de courants picoseconde

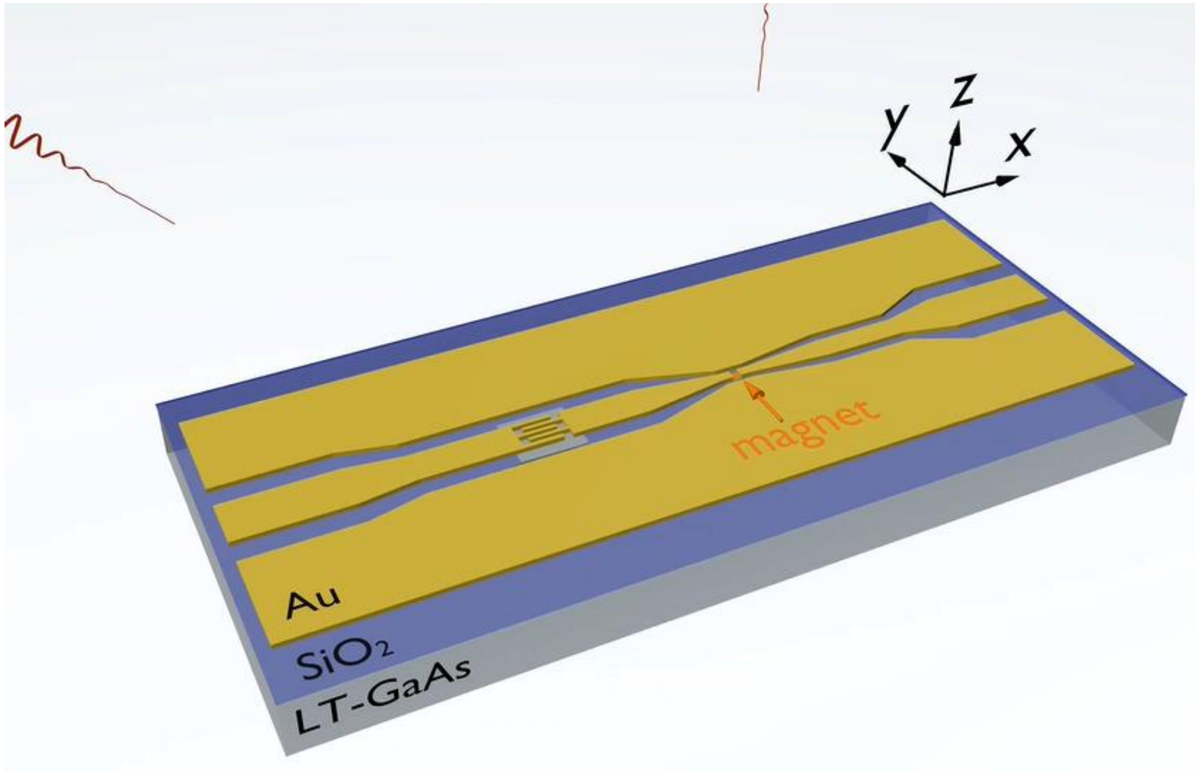


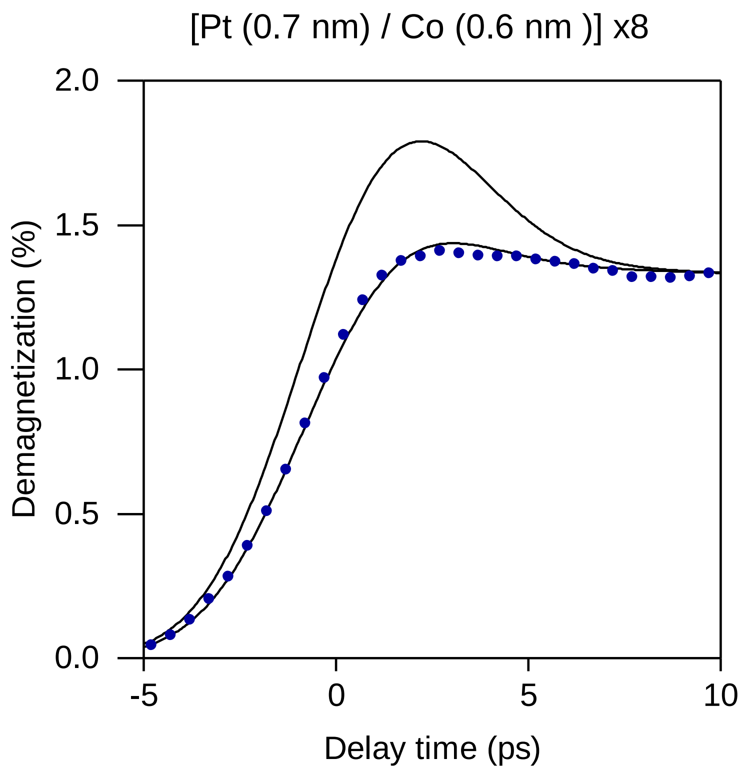


THz pump – optical probe



Chauffage rapide d'un aimant par le courant



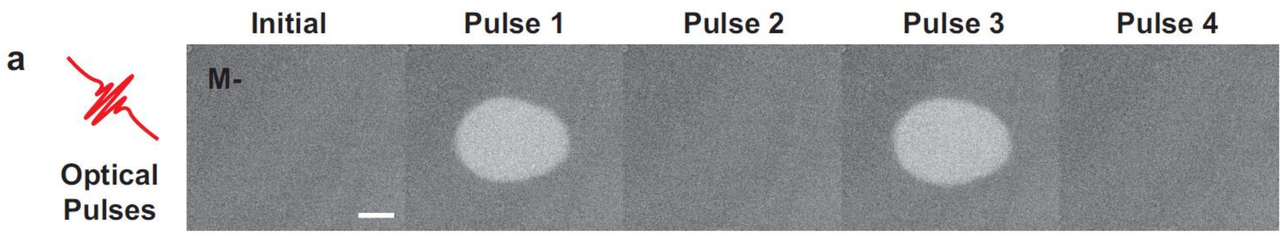


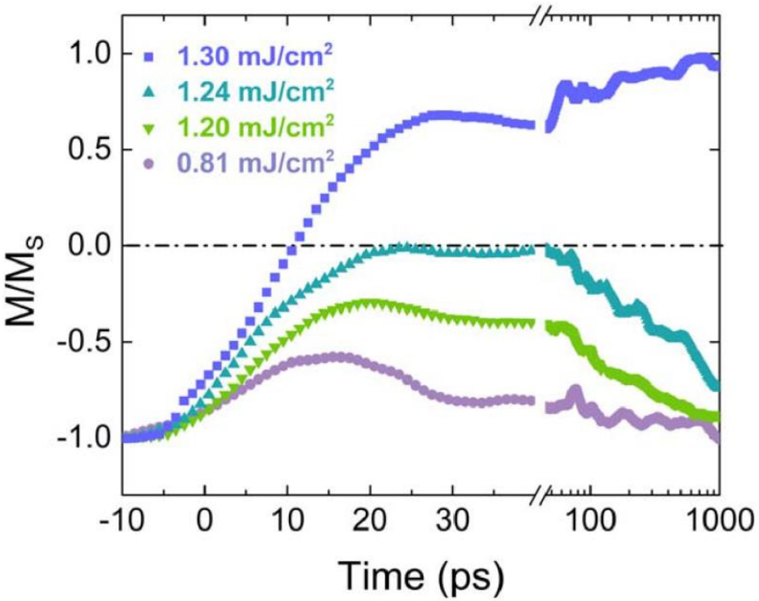
Analogue électrique de la desaimantation par impulsions optiques

Wilson, R. B. *et al. Phys. Rev. B* **96**, 045105 (2017).

Chauffage electrique pour retourner l'aimantation

Ta (5 nm) / $Gd_{30}Fe_{63}Co_{7}$ (20 nm) / Pt (5 nm)

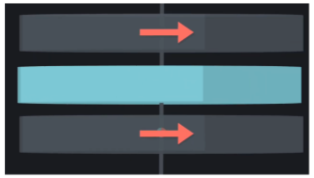


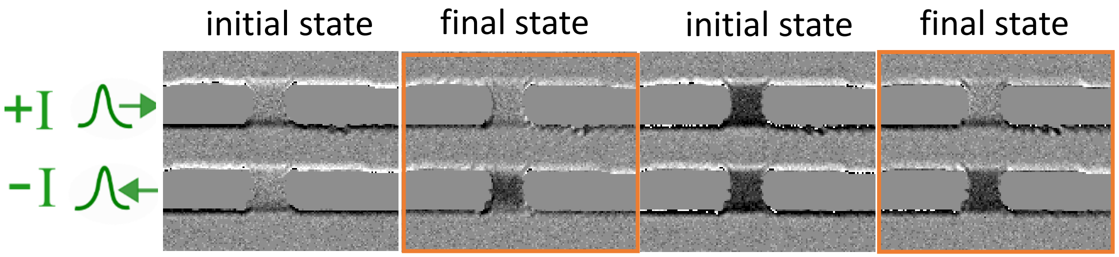


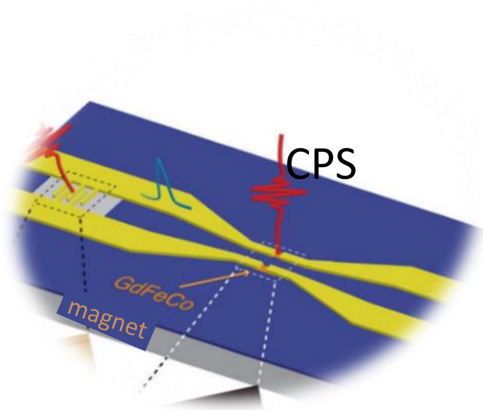
Analogue électrique du retournement par impulsions optiques

Y. Yang, et al., Sci. Adv. **03**, 11 (2017)

Injection de courants de spin ultra-rapides





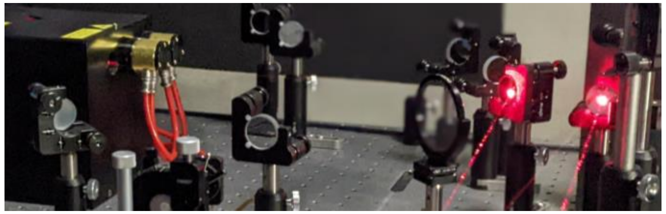


Des couples de spin ultra-rapides determinent l'état magnétique final!

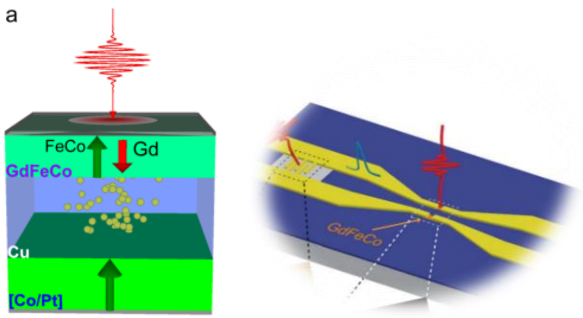
Jhuria K., et al. *Nature Electronics* **3**, 680-686 (2020)

Conclusion

Grand intérêt de la **spintronique**



Pompe-sonde pour **l'ultra-rapide**



Impulsions **optiques** ET **électriques** **ultra-courtes** pours le **contrôle de l'aimantation**

Pas encore très utile… mais extrêmement intéressant et prometteur!

Merci!

WE STAND WITH UKRAINE

INSTITUT JEAN LAMOUR

Jon Gorchon
Kaushalya Jhuria
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Sebastien Petit-Watelot
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AGENCE NATIONALE DE LA RECHERCHE ANR
LORRAINE Université d'Excellence – IMPACT N4S
UNION EUROPEENNE Fonds Européen de développement Régional
NSF
SRC JUMP
ARMY RESEARCH OFFICE

END

Outline

1. **Experimental setup**

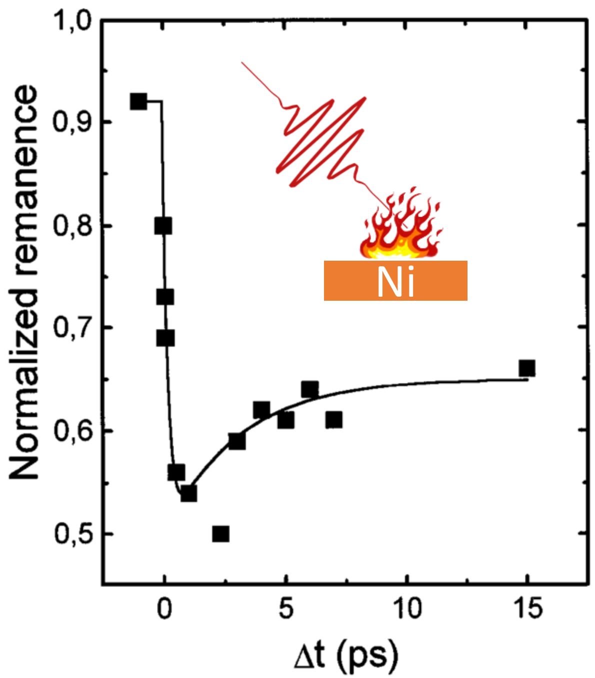
2. **SOT samples**

3. **Picosecond SOT switching & dynamics**

4. **Discussion**

Comment réagi l’aimantation à ces échelles?

Desaimantation ultrarapide
d’un matériau ferromagnétique



Beaurepaire et al., PRL 1996

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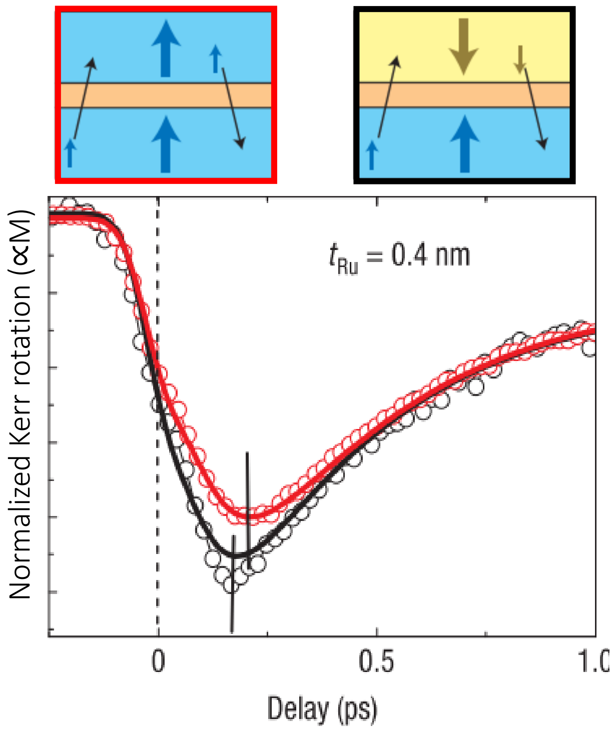
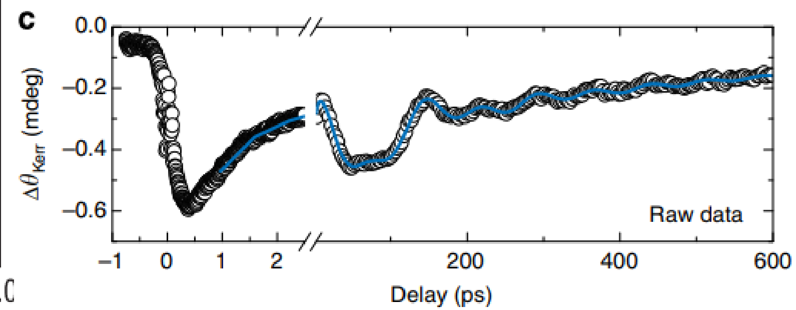


Malinowski et al., Nat. Phys. 2008

Des courants de spins sont générés

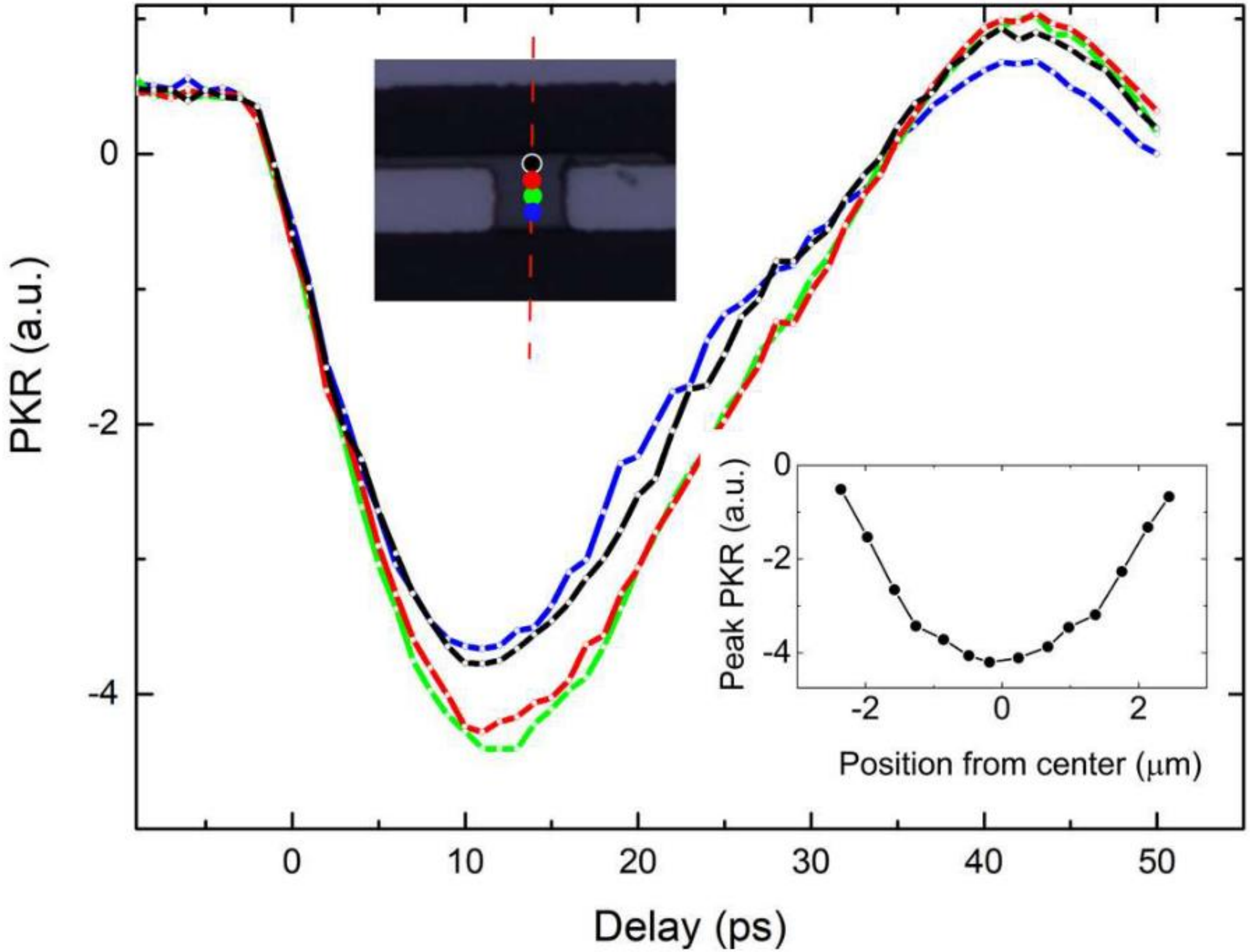
Injection de spins perpendiculaires



Schellekens et al., Nat. Comm. 2014

***Couples* de transfer de spin**

Spatial dependence of dynamics



Energy and current vs pulse duration

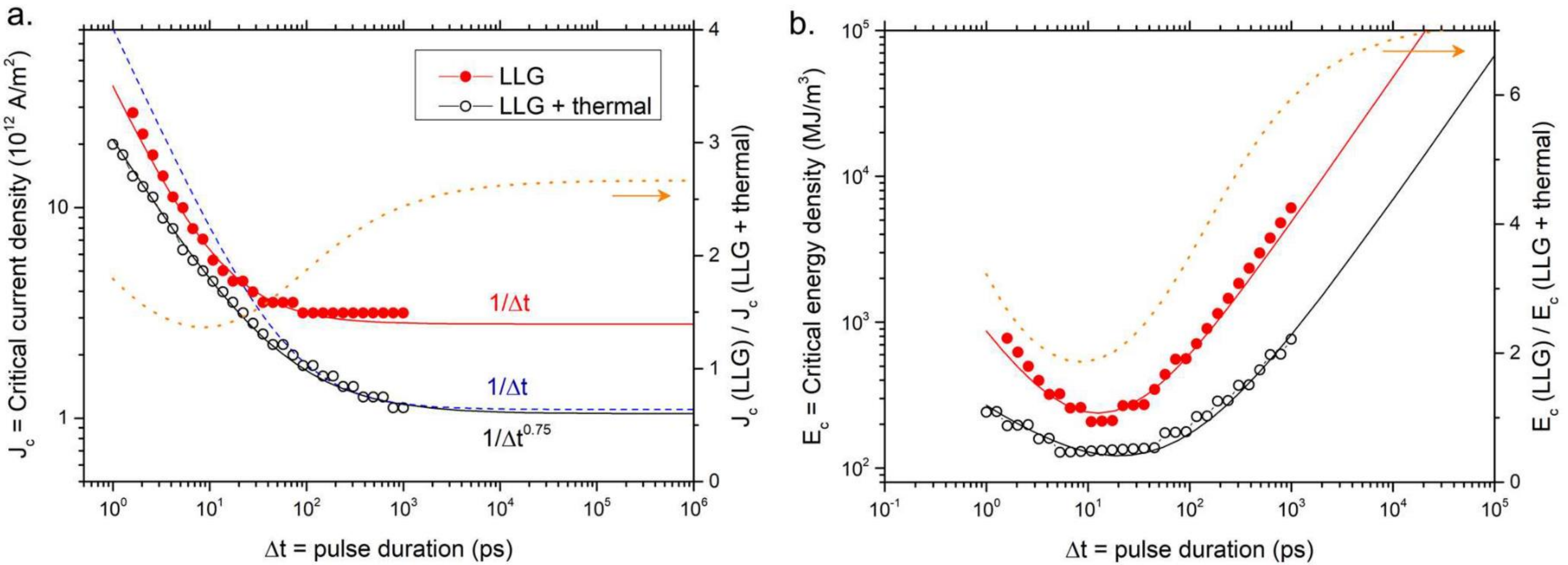
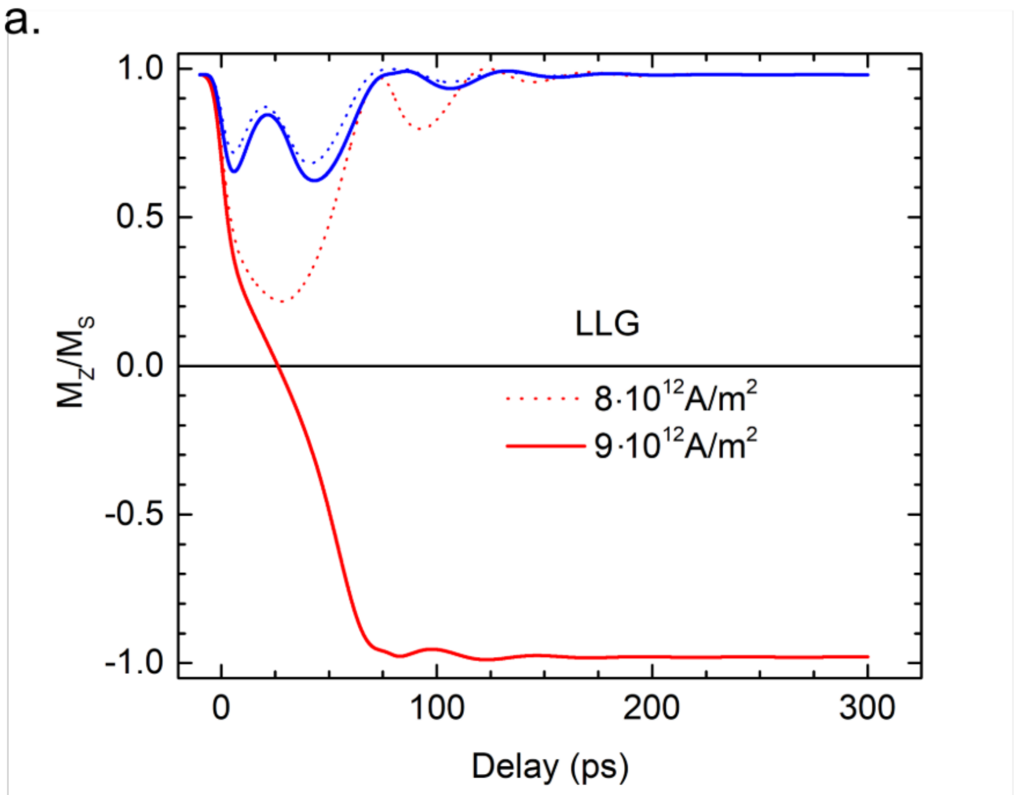
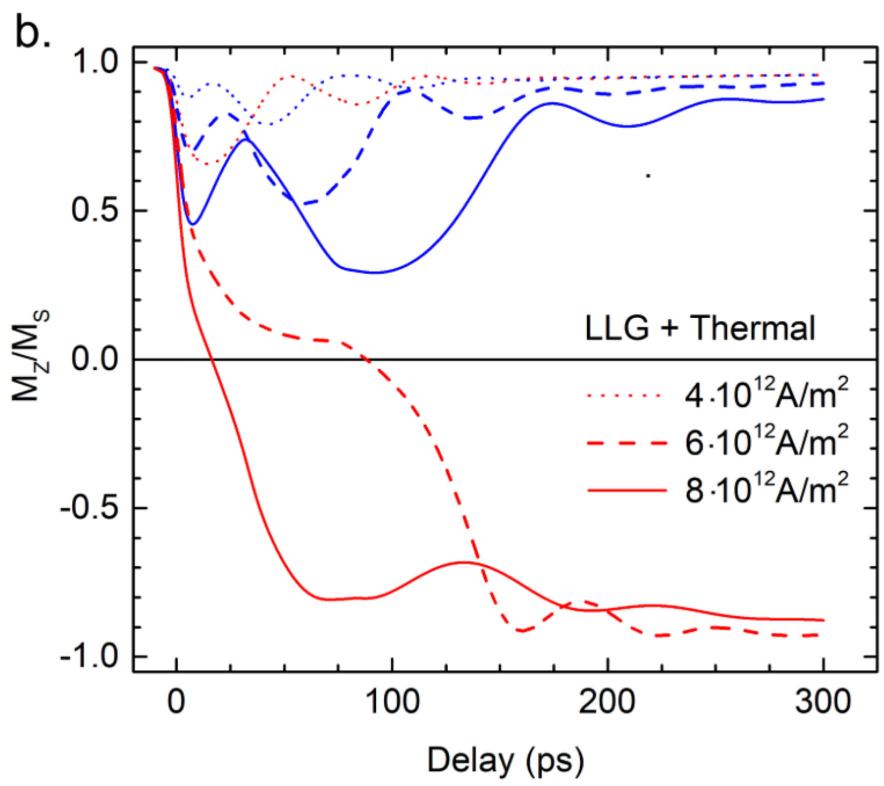


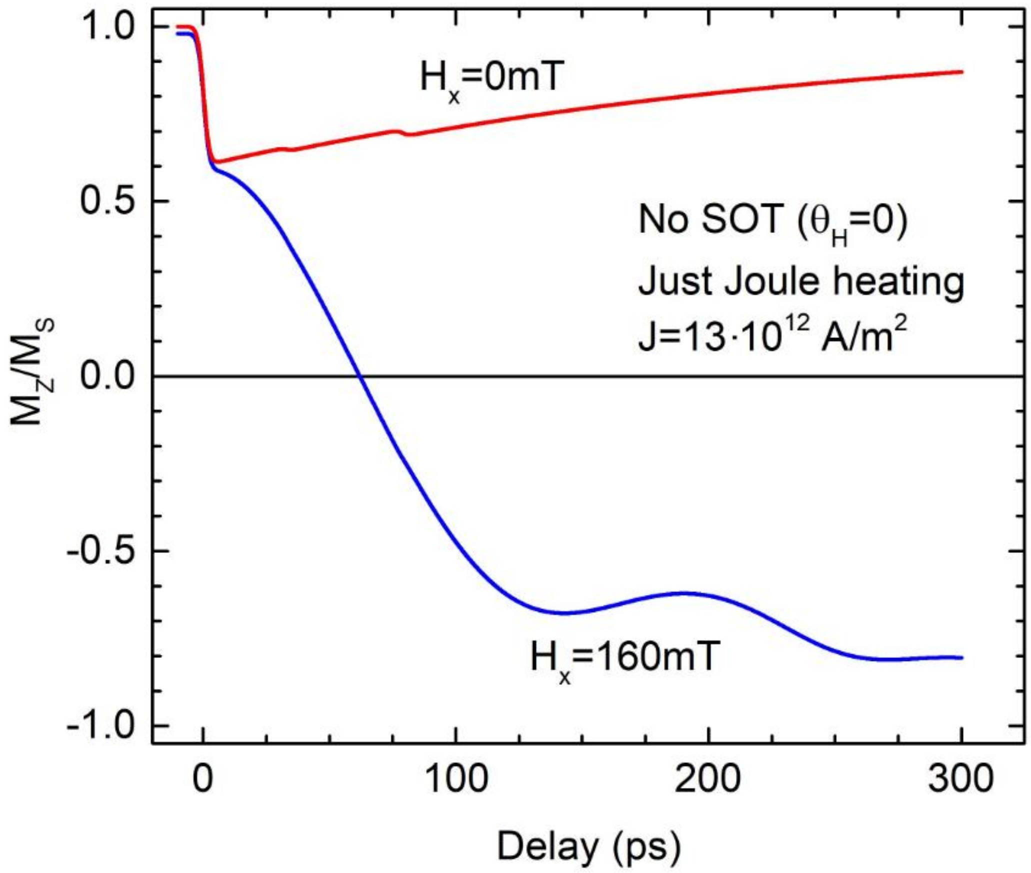
Figure S8. Simulated critical current densities as a function of current pulse duration. a. Critical current density and b. critical energy as a function of the pulse duration. Red filled circles are obtained using the LLG model and the black open circles are obtained when adding the thermal model. Lines are $\sim 1/\Delta t^{\beta} + J_{c0}$ fits, as discussed in the text, for comparison with previous work from Ref.14. The orange dot line in a. (b.) corresponds to the ratio of critical current densities (energies) between the LLG and the LLG + thermal model. In plane field is 0.16T and the rest of parameters are presented in table T1.

Switching dynamics





Switching via pure Joule heating



Cost of switching

$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{ext} - \gamma \boldsymbol{M} \times \left(\frac{\boldsymbol{M}}{M_s} \times \alpha \boldsymbol{H}_{total}\right)$$

Field Torque — *Damping*

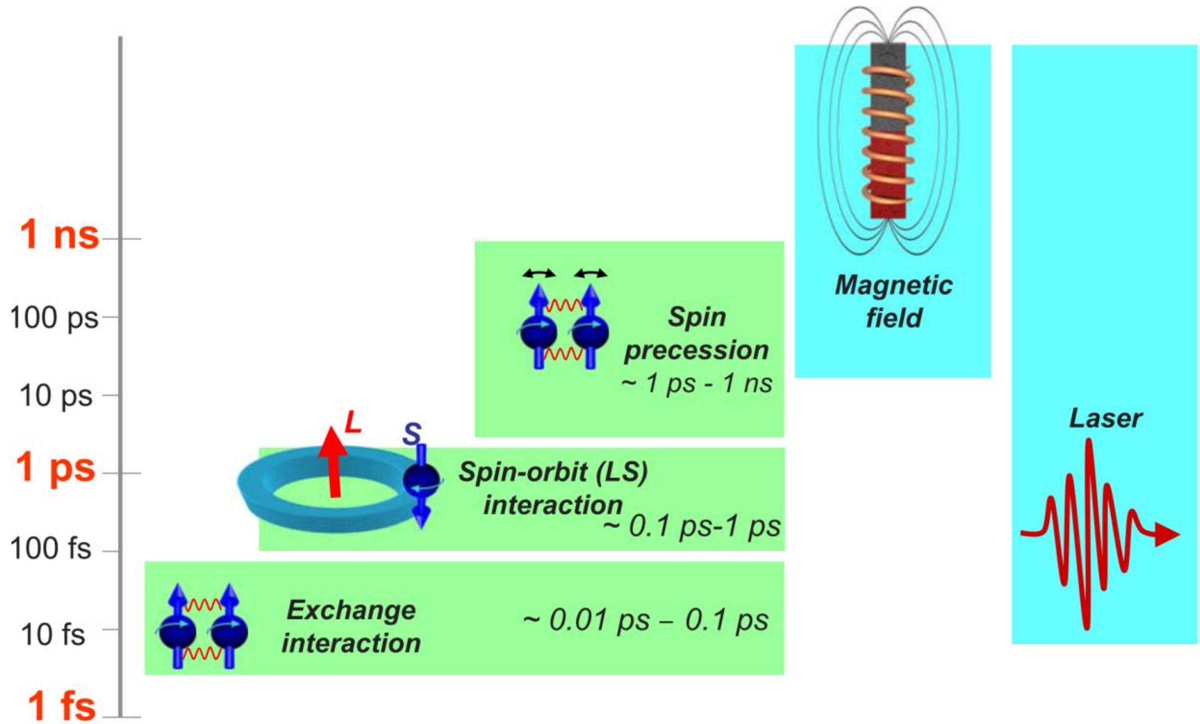
$$- \gamma \boldsymbol{M} \times \underbrace{\frac{\theta_{FL} J_x}{e M_s t} \boldsymbol{S_y}}_{\boldsymbol{H}_{FL}} - \gamma \boldsymbol{M} \times \underbrace{\left(\frac{\boldsymbol{M}}{M_s} \times \frac{\theta_{DL} J_x}{e M_s t} \boldsymbol{S_y}\right)}_{\boldsymbol{H}_{DL}}$$

Field-like — *Damping-like*

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$$

$$\Delta t \geq \frac{\hbar}{2\Delta E} \sim \frac{\hbar}{2\Delta E} \sim \frac{1.054 \cdot 10^{-34}}{2 \cdot 10^{-21}} \sim 10^{-13}$$

$$s.o: \; 5\; 10^{-5} eV = 10^{-23}$$

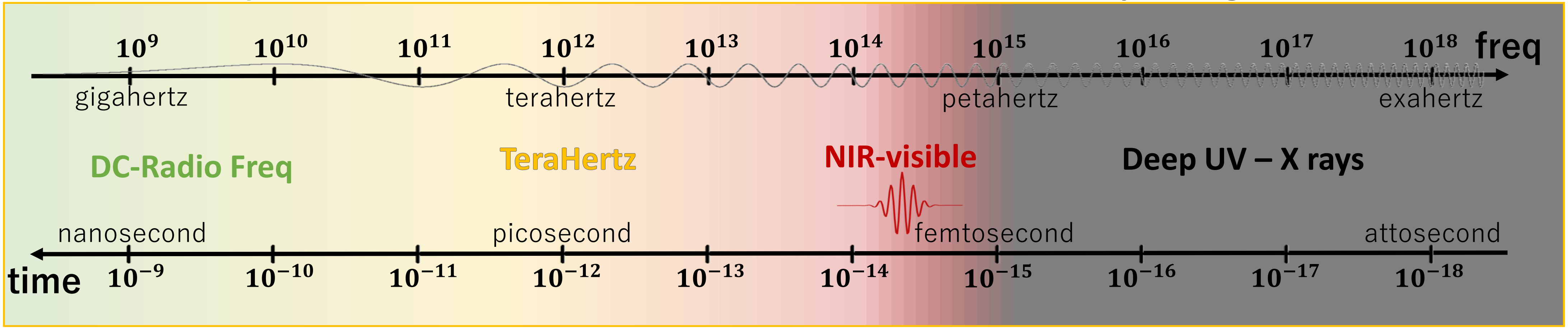


REVIEWS OF MODERN PHYSICS, VOLUME 82, JULY–SEPTEMBER 2010 Ultrafast optical manipulation of magnetic order

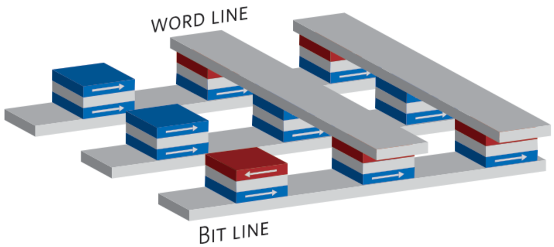
Andrei Kirilyuk,* Alexey V. Kimel, and Theo Rasing

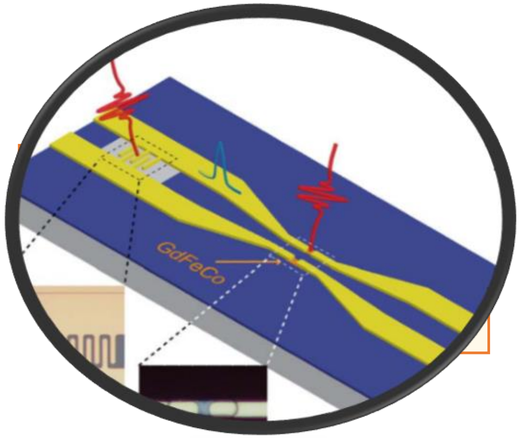
Platform for ultrafast spintronics studies

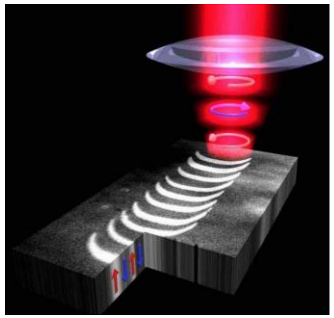
conventional spintronics | ultrafast spintronics | ultrafast optomagnetism



excitations: ~100ps – 100fs | ~20ps – 3fs | ~20fs – 40as

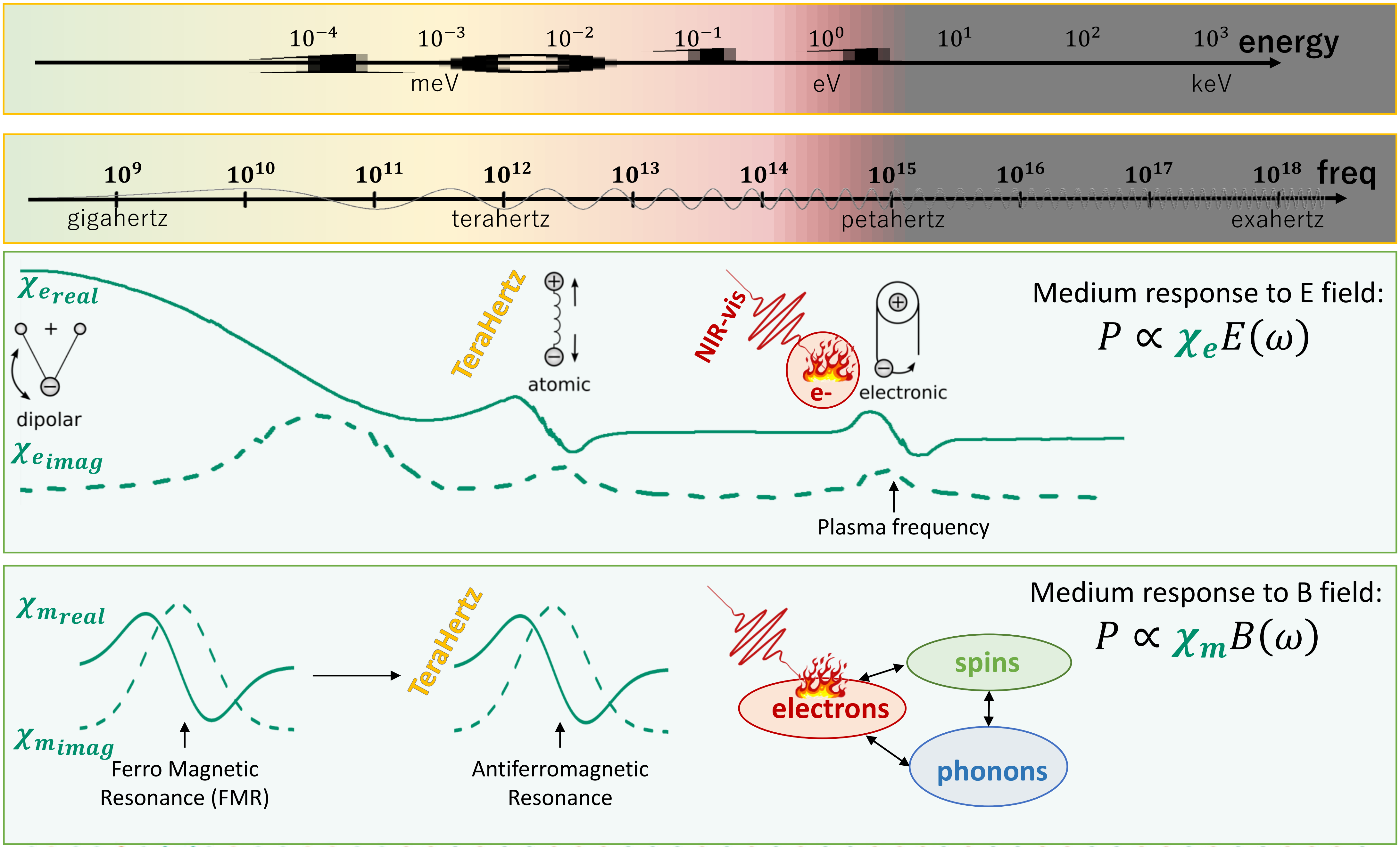






Yang Y.*, Wilson RB.*, Gorchon J.* et al.,
Science Advances, e1603117 (2017) *equal contribution

*Left figure extracted from Schellekens thesis
**Right figure extracted from Stanciu thesis

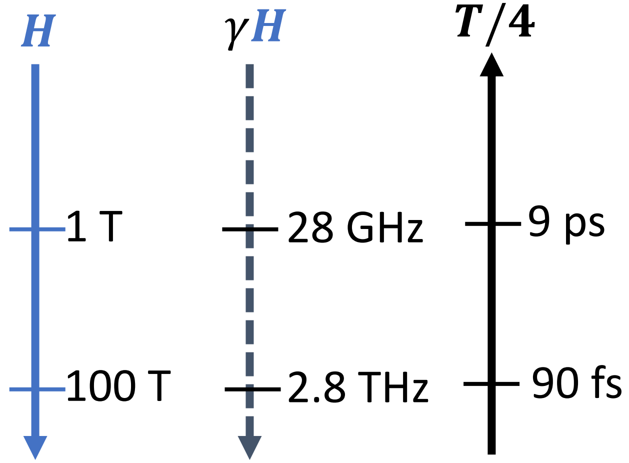


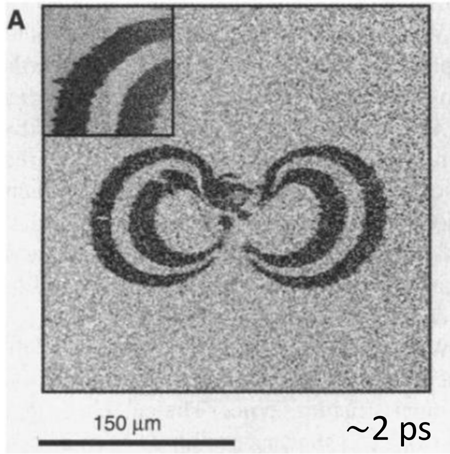
*Figures adapted from Wikipedia.org

Speed limits of magnetization dynamics

Landau-Lifshitz-Gilbert (LLG)

$$\frac{\partial \boldsymbol{m}}{\partial t} = -\gamma \boldsymbol{m} \times \boldsymbol{H} - \alpha \boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial t}$$

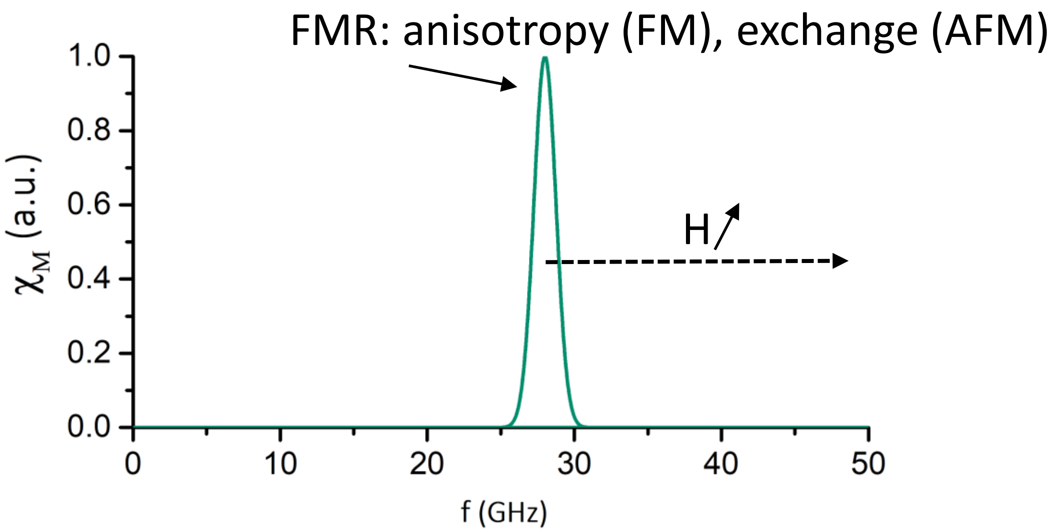




C. Back et al., *Science* **285** (1999)

External fields are ineficient

Internal fields?



Co/Pt: 1T → 9ps

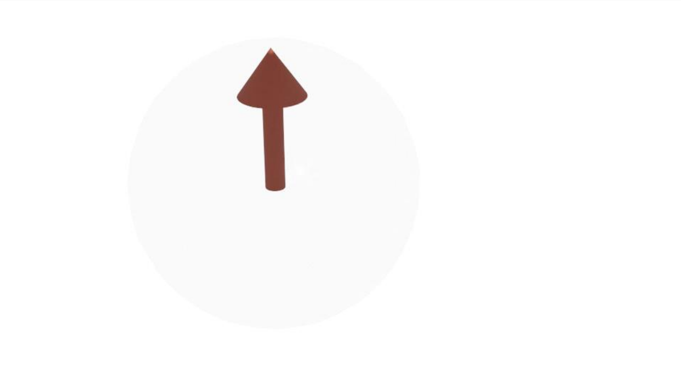
FePt: 5T → 2ps

Antiferromagnets:
10-100T → sub-ps

Exchange in ferromagnets?

Spin Torques

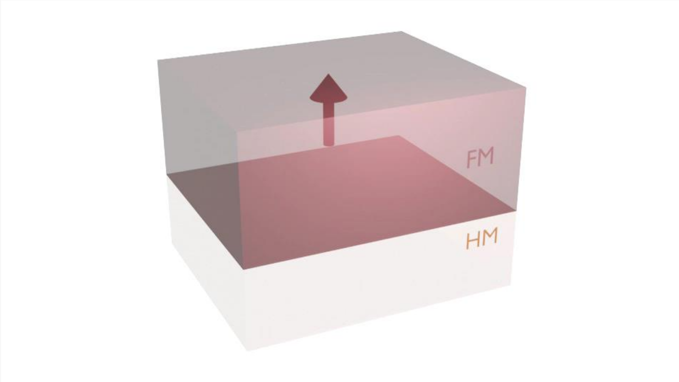
Spin-Transfer Torque (STT)



$\sim\gamma \boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{\sigma}_{DL})$
Damping-like

$\sim\gamma \boldsymbol{m} \times \boldsymbol{\sigma}_{FL}$
Field-like

Spin-Orbit Torque (SOT)



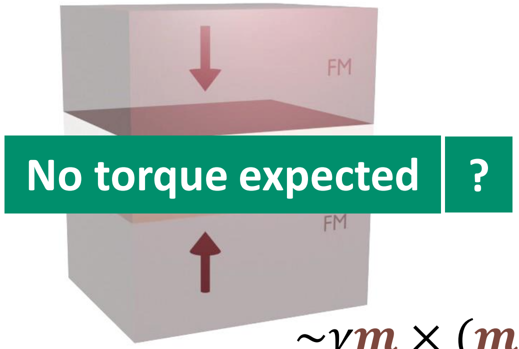
Spin Hall effect, Rashba effect… + STT

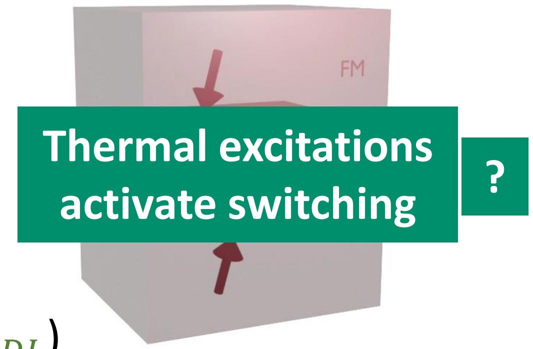
How fast (and energy-efficiently) can we switch a magnet?

Fast switching by STT

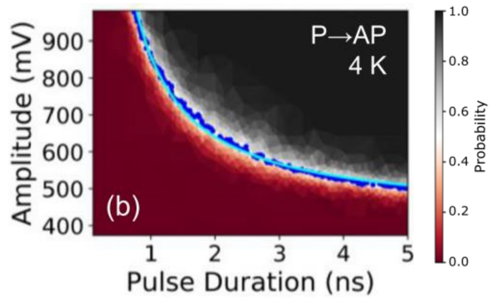
a) Collinear spin injection

$T = 0$ $\qquad\qquad$ $T > 0$





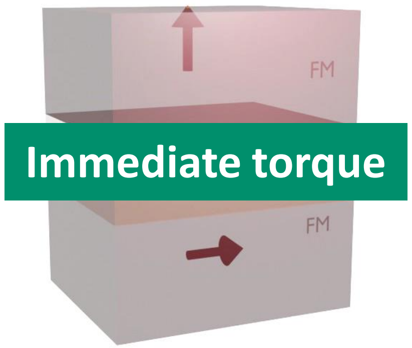
$$\sim\gamma \boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{\sigma}_{DL})$$

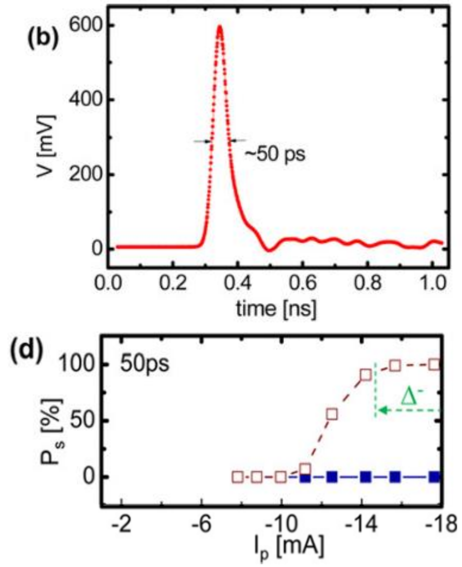


Rehm, L. et al. *Appl. Phys. Lett*. **115**, 182404 (2019)

b) Orthogonal spin injection [1]

$T = 0$





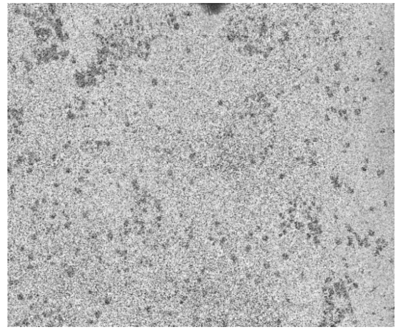
Lee, O.J. et al. *Appl. Phys. Lett*. **99**, 102507 (2011)

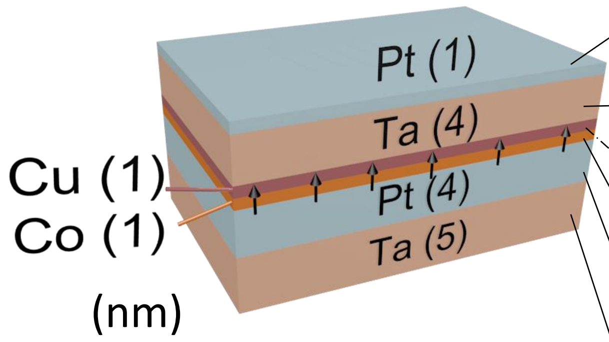
Ultrafast STT switching

- ✘ So far, limited to in-plane magnetization
- ✘ Current through tunnel-barrier

SOT samples

RT zero field skyrmions?





Pt: Capping layer

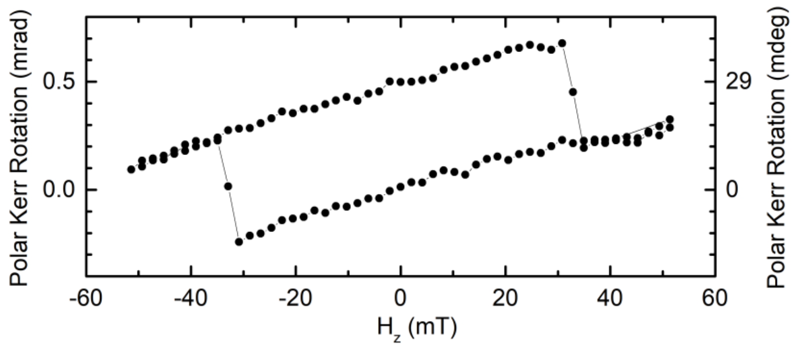
Ta: Heavy metal with high $\theta_H (< 0)$

Cu: Decouple Co & Ta (reduce DMI), allow spin flow

Co: Perpendicular magnetic anisotropy

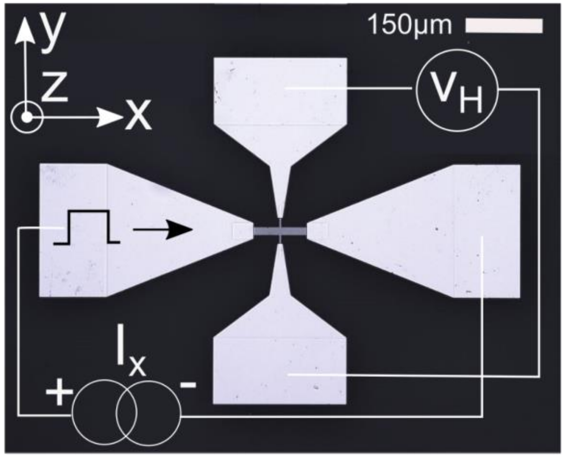
Pt: Heavy metal with high $\theta_H (> 0)$

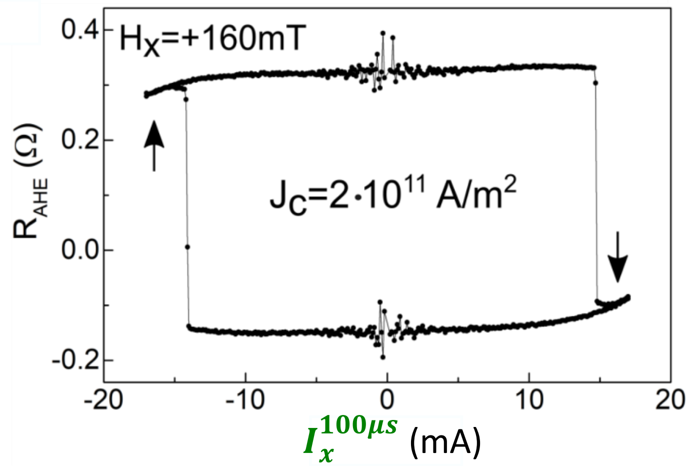
Ta: Buffer layer



✓ PMA, remanence

Quasi-static SOT Switching

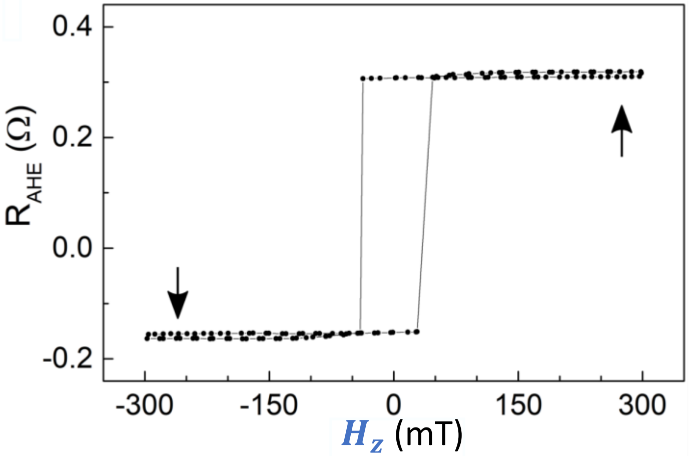


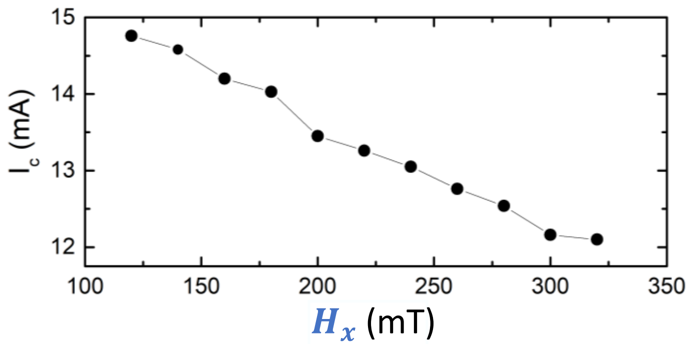


$\mathbf{I} \parallel H_x \rightarrow -M_z$

$\mathbf{I} \nparallel H_x \rightarrow +M_z$

✓ Pt/Co & Co/Ta SOT [1,2]

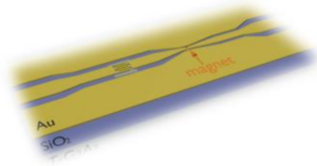


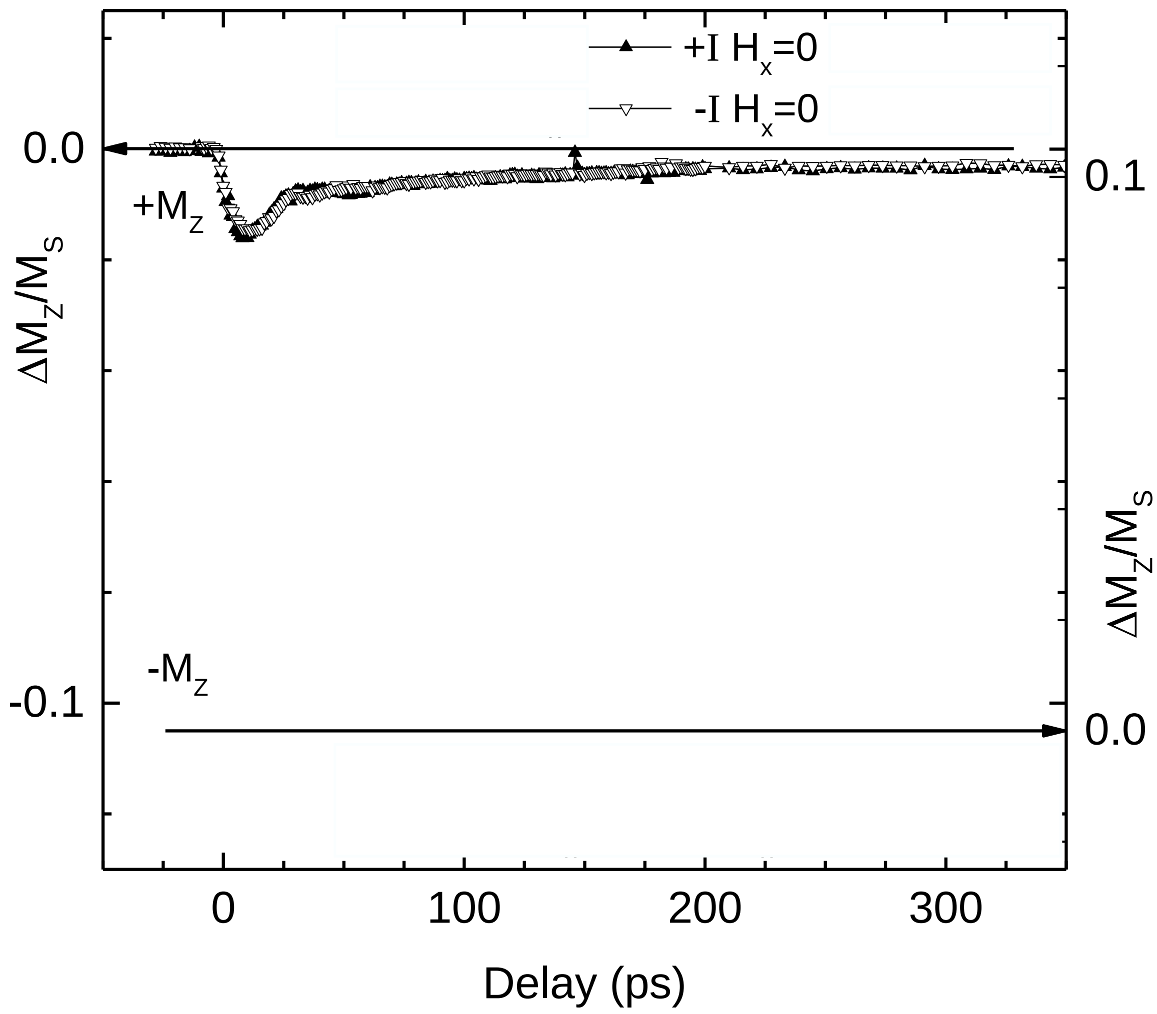


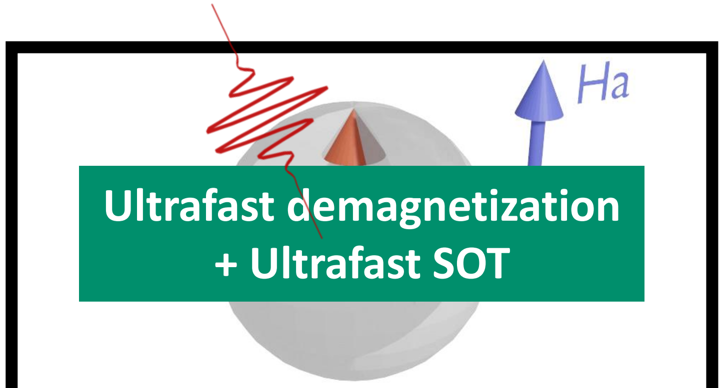
✓ In plane field assists SOT [1,2]

1. Liu, L. et al. *Phys. Rev. Lett.* **109**, 096602 (2012)
2. Baumgartner, M. et al. *Nat. Nano.* **12**, 980-986 (2017)

Picosecond SOT dynamics





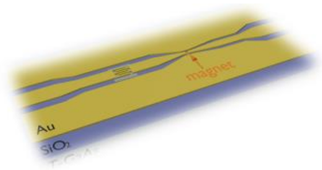


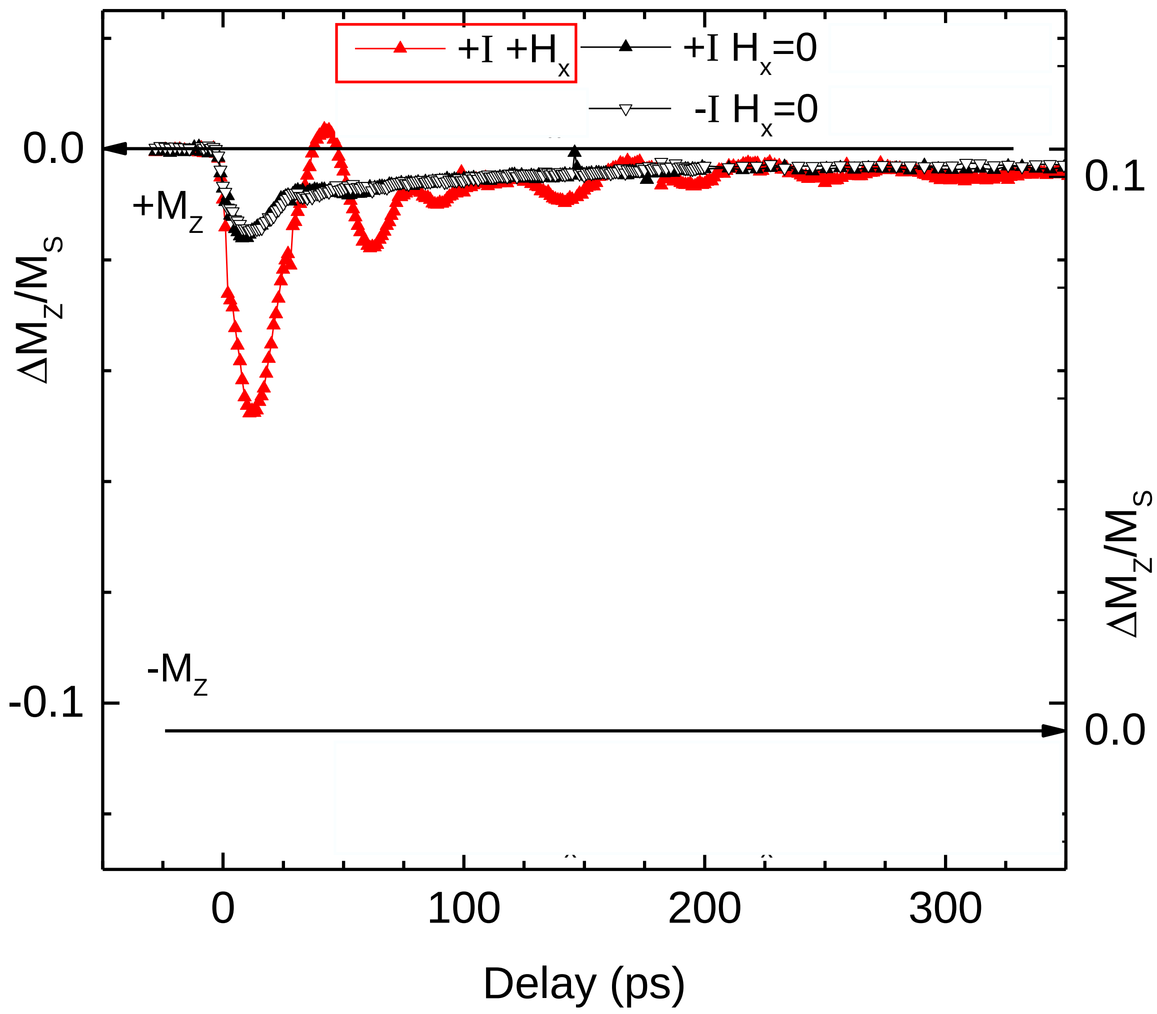
Wilson, RB. et al. *Phys. Rev. B* **96**, 045105 (2017)

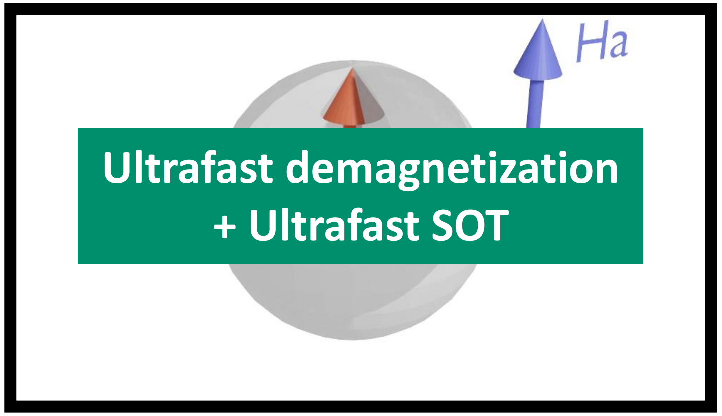
Jhuria K., et al. *Nature Electronics* **3**, 680-686 (2020)

Note: a data renormalization correction reduces the amplitudes by ~4

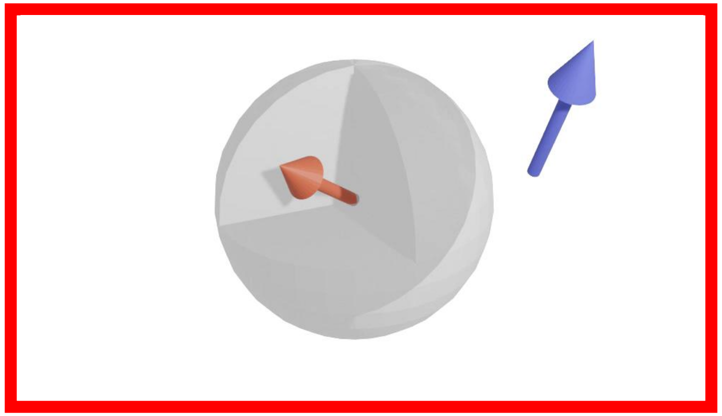
Picosecond SOT dynamics





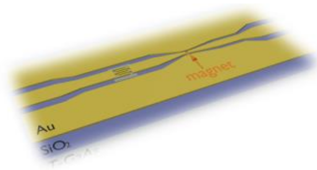


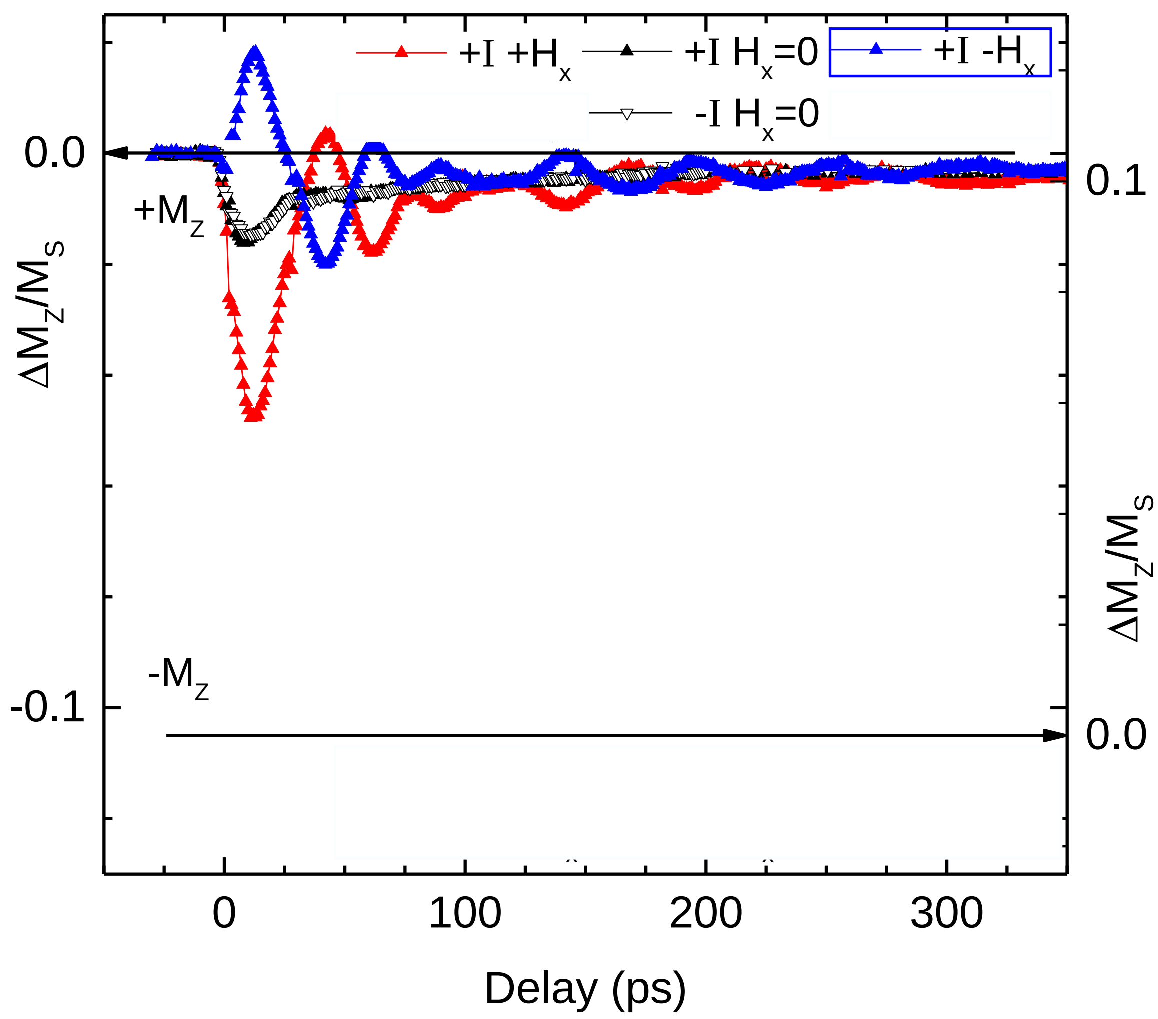
Ultrafast demagnetization + Ultrafast SOT

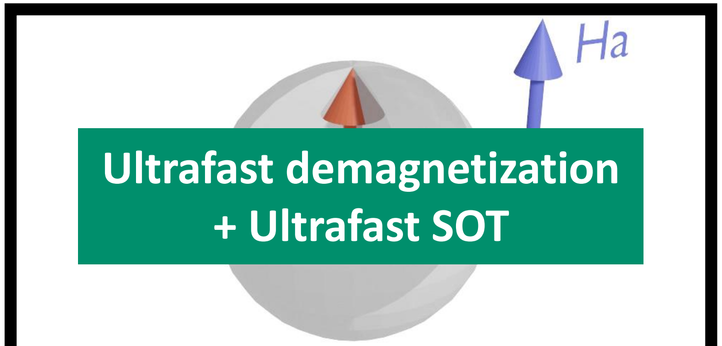


In plane field tilts precession plane

Picosecond SOT dynamics

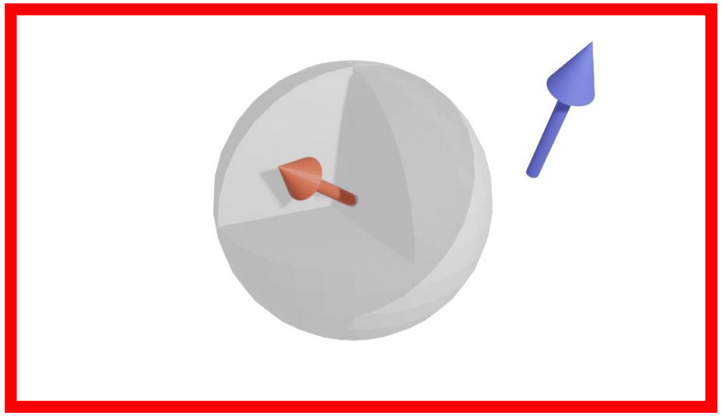






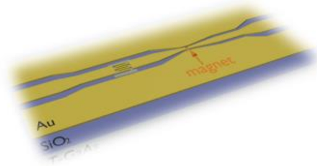
Ultrafast demagnetization + Ultrafast SOT

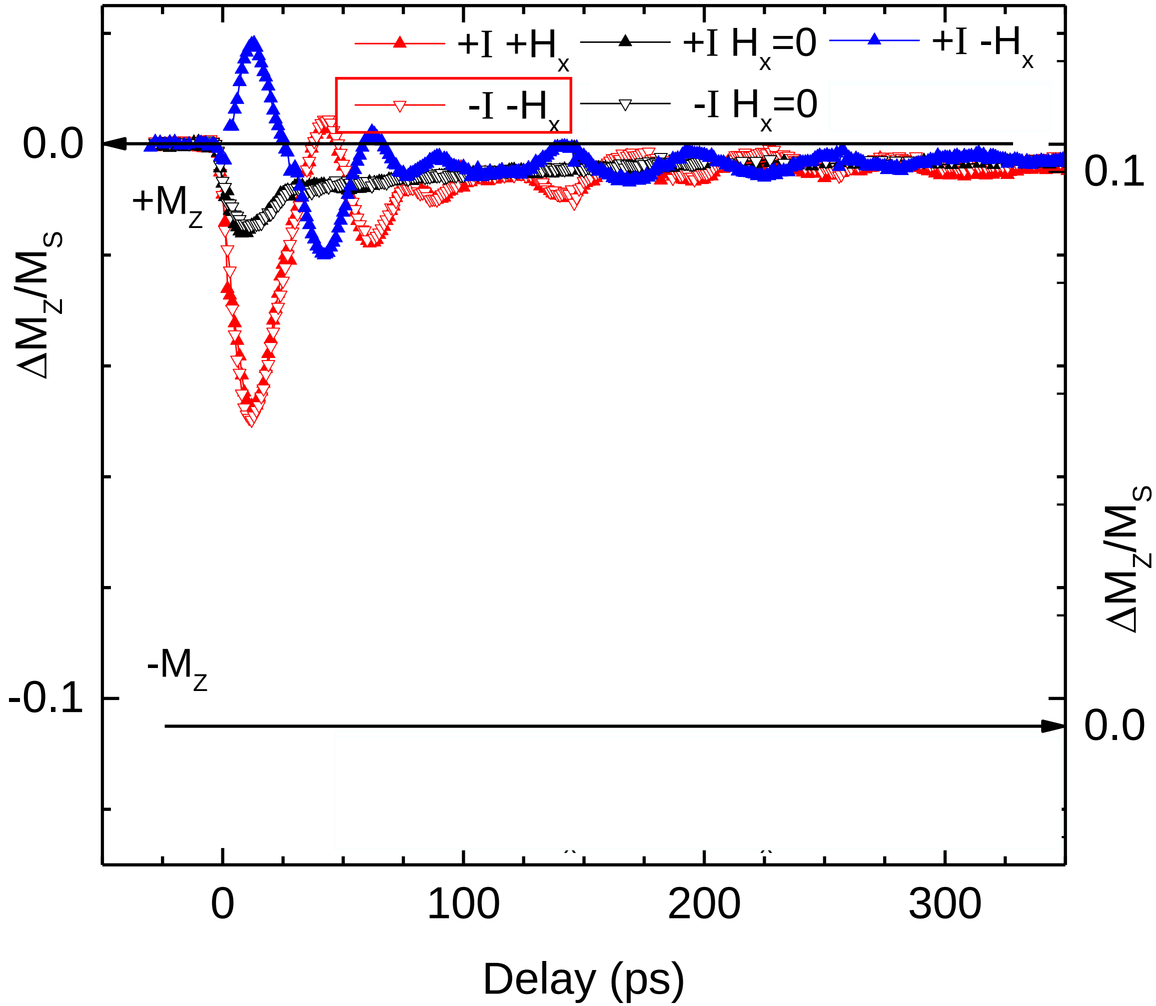
Wilson, RB. et al. *Phys. Rev. B* **96**, 045105 (2017)

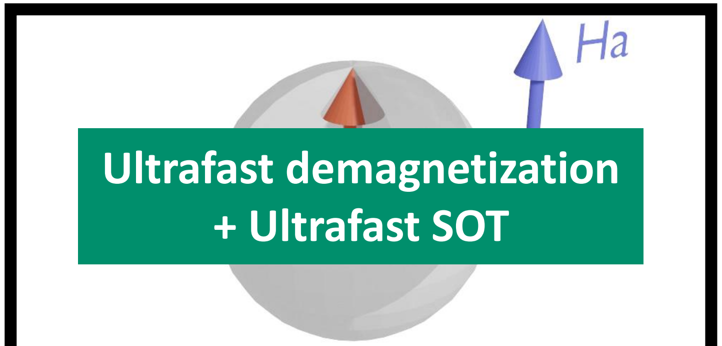


In plane field tilts precession plane

Picosecond SOT dynamics







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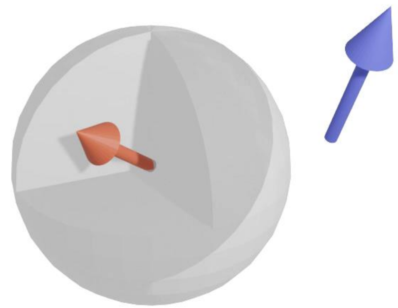
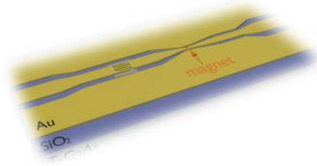
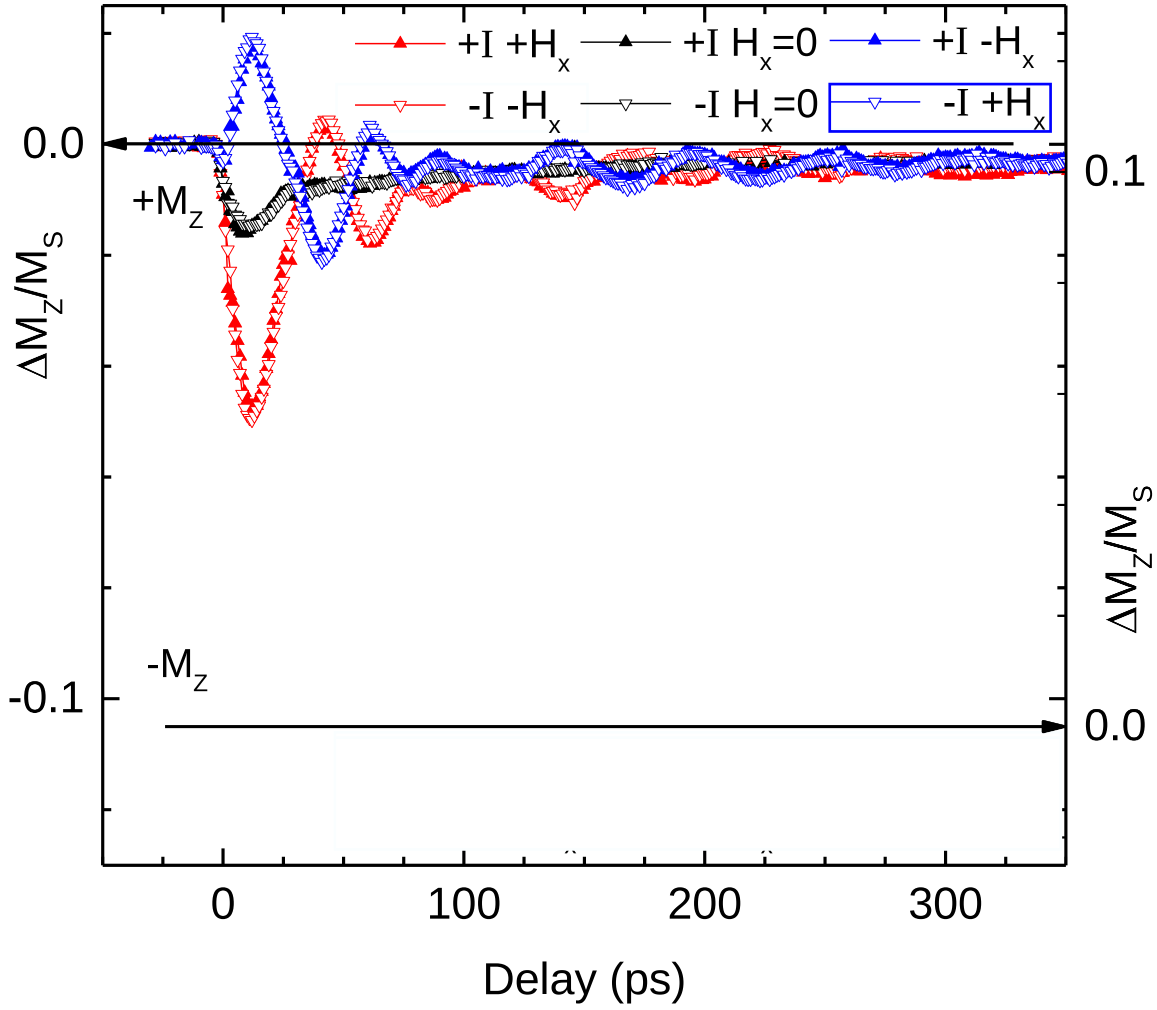
Wilson, RB. et al. *Phys. Rev. B* **96**, 045105 (2017)

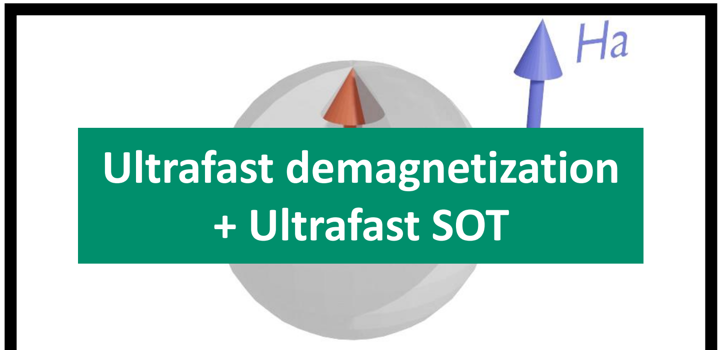


In plane field tilts precession plane

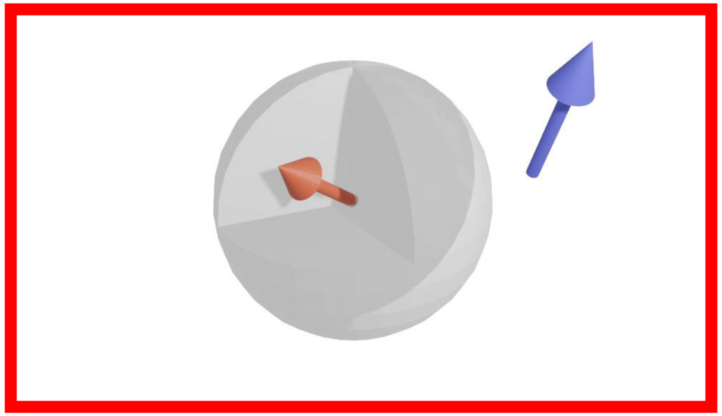
Picosecond SOT dynamics







Wilson, RB. et al. *Phys. Rev. B* **96**, 045105 (2017)



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Jhuria K., et al. *Nature Electronics* **3**, 680-686 (2020)

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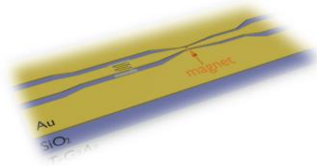
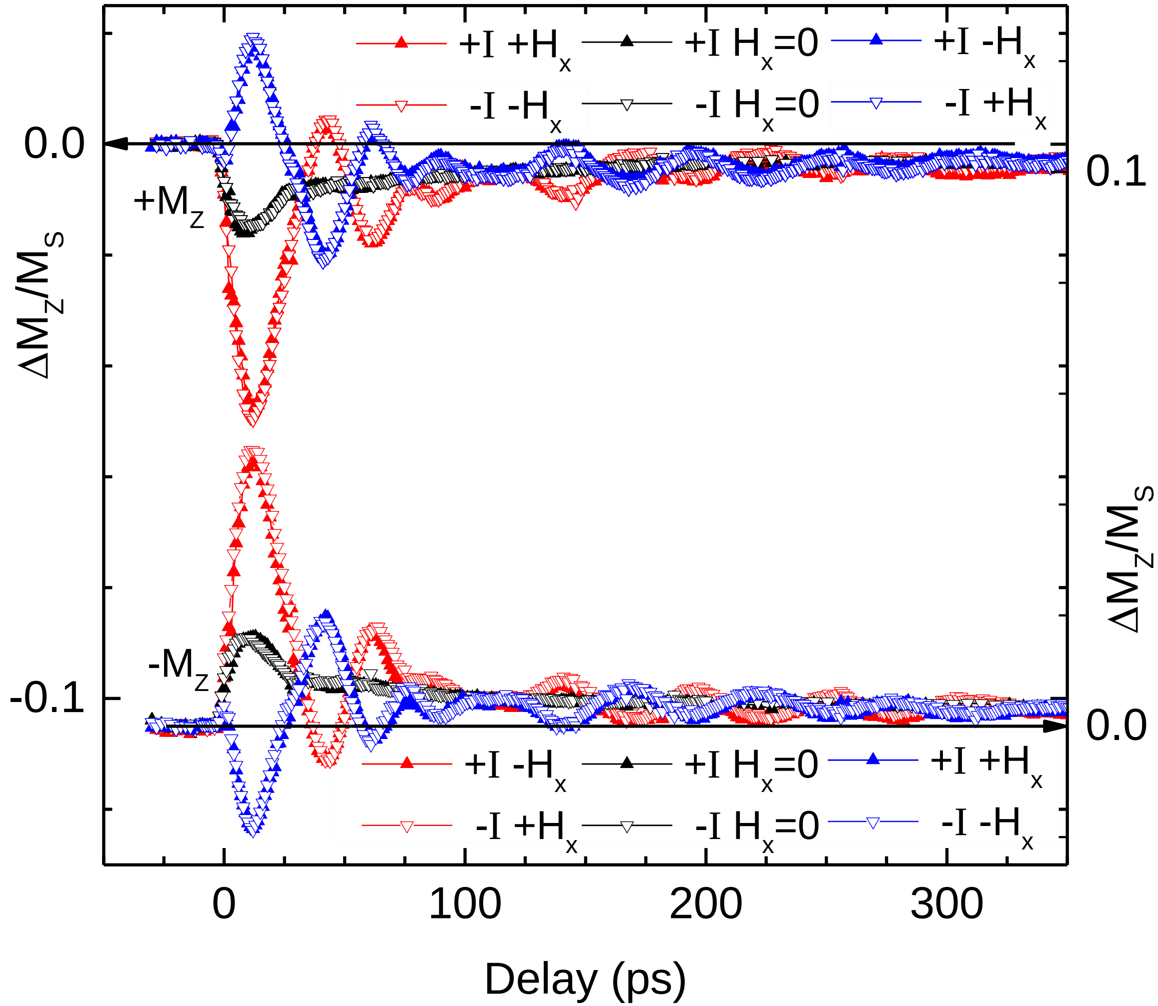
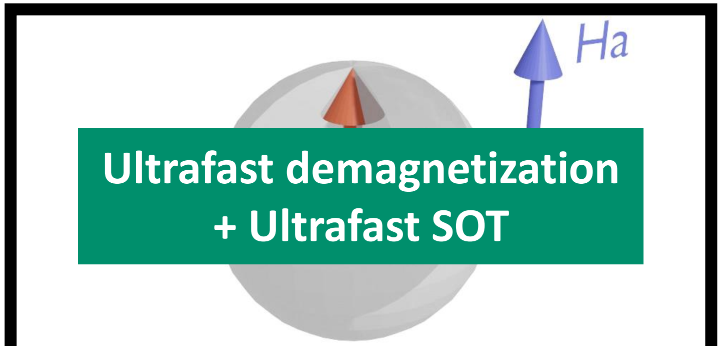
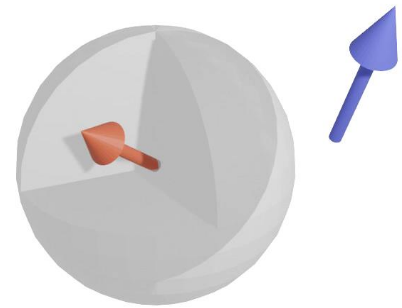






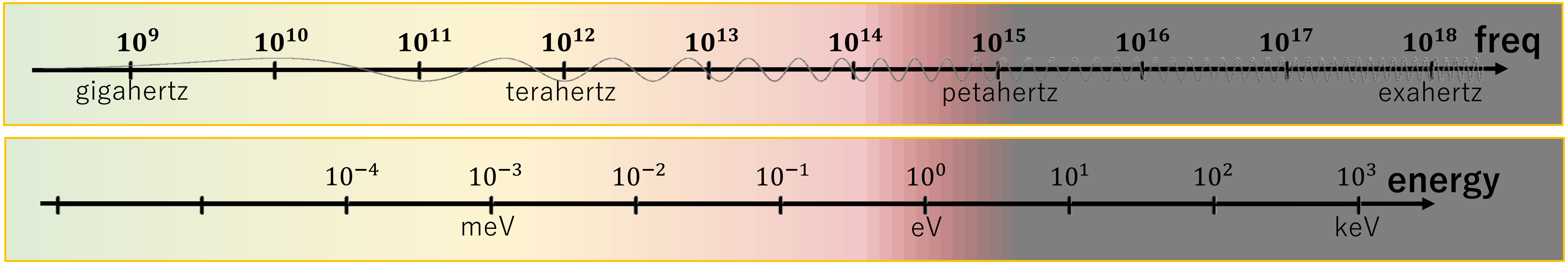
Ultrafast demagnetization + Ultrafast SOT

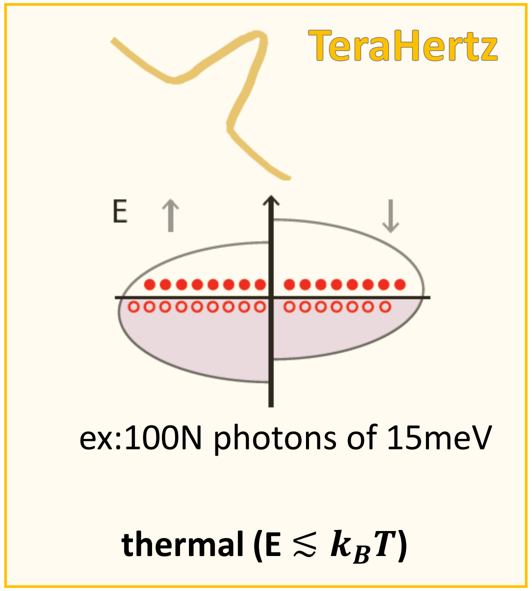
Wilson, RB. et al. *Phys. Rev. B* **96**, 045105 (2017)

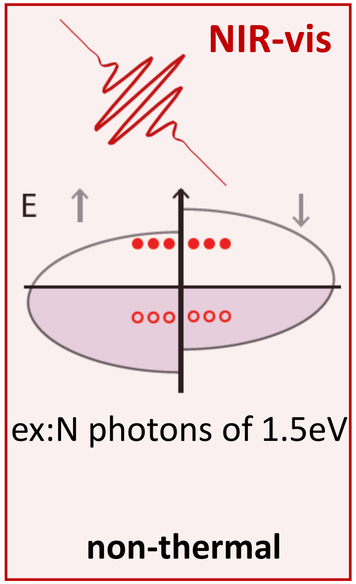


In plane field tilts precession plane

Optical vs THz heating

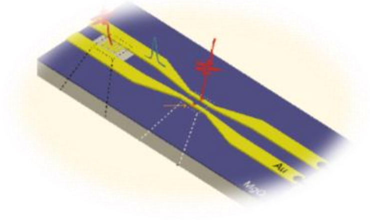




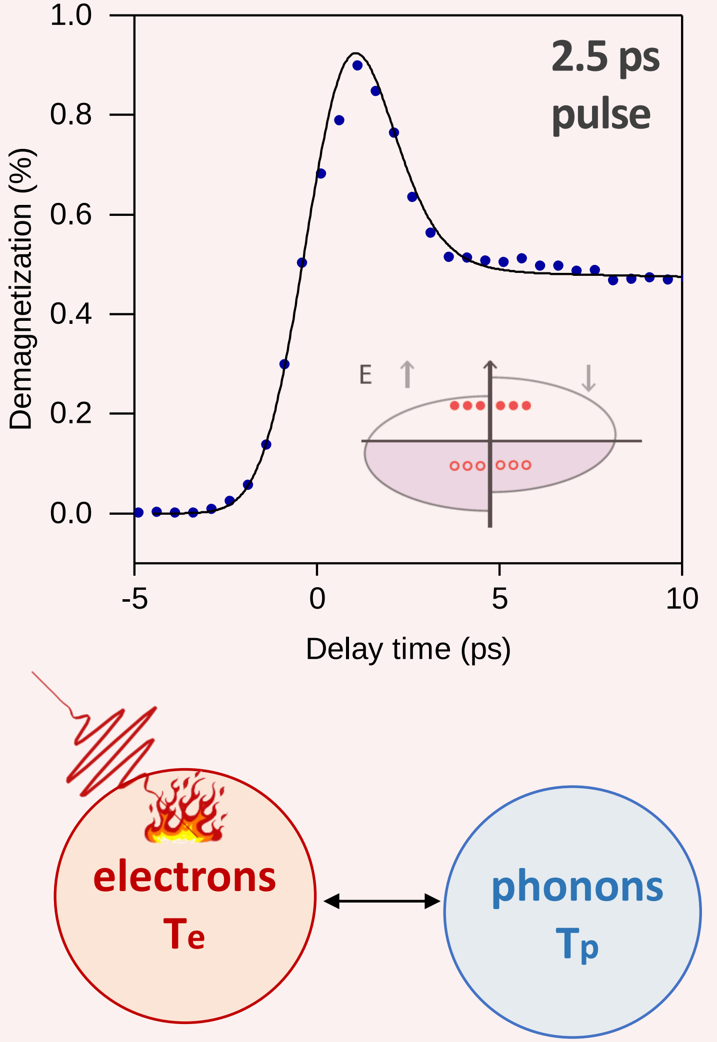


➔ Does the thermal character matter for ultrafast magnetic dynamics?

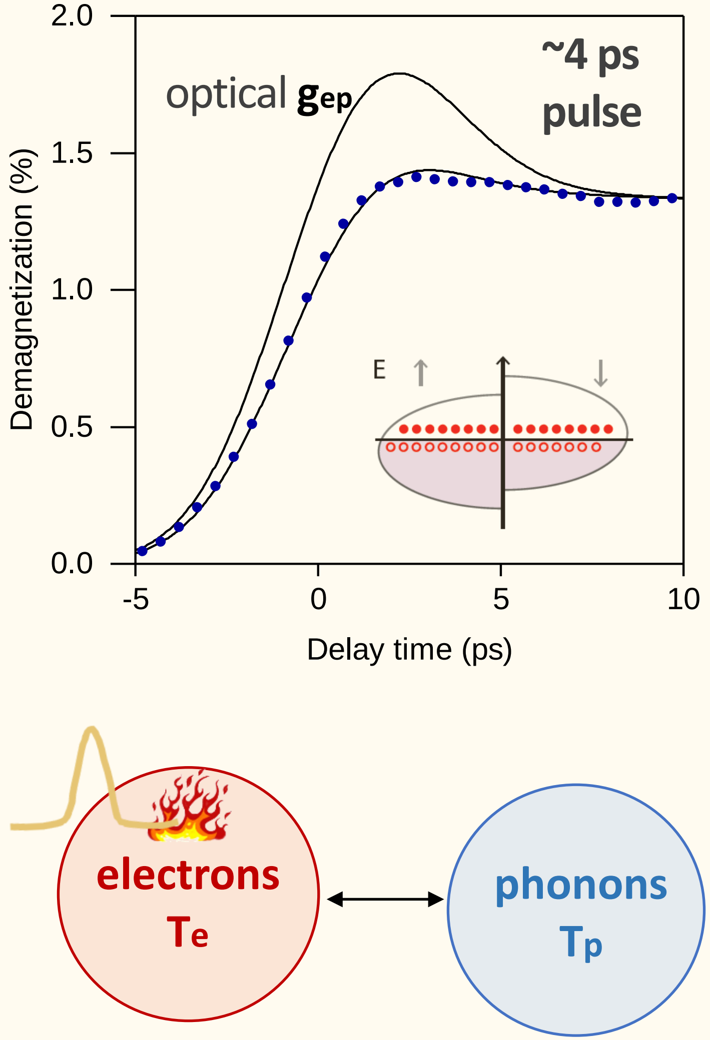
Ultrafast demag via picosecond Joule



Optical [Pt (0.7 nm) / Co (0.6 nm)] x8 Electrical (THz)



g_{ep} = 7 x 10^{17} W m^{-3} K^{-1}



g_{ep} = 15 x 10^{17} W m^{-3} K^{-1}

Thermal/non-thermal discussion:

Tas and Maris, *PRB* (1994)

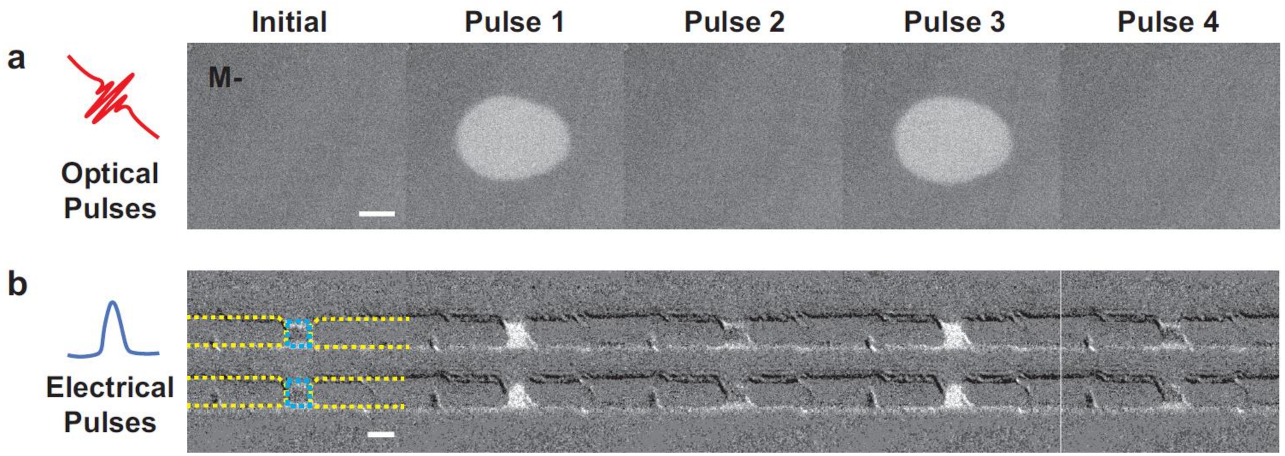
Rethfeld et al, *PRB* (2002)

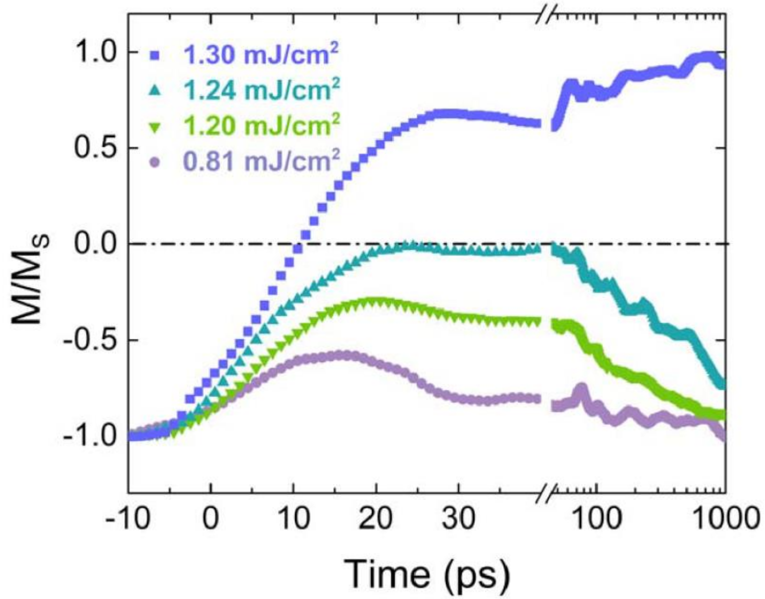
Electrical (thermal) pulses thermalize faster with phonons

Wilson et al., Phys. Rev. B **96**, 045105 (2017)

Ultrafast Joule Switching of GdFeCo

Ta (5 nm) / $Gd_{30}Fe_{63}Co_{7}$ (20 nm) / Pt (5 nm)





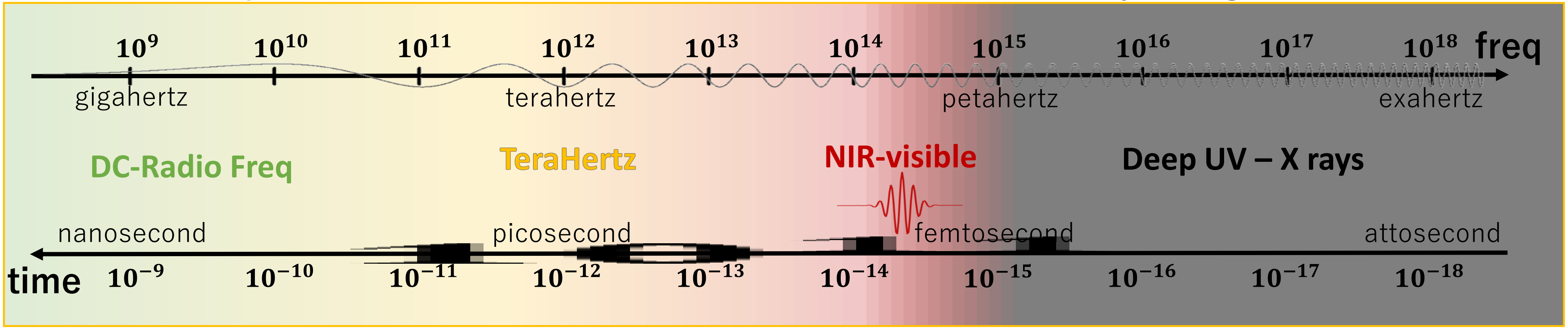
- **Peak current density ~ $7 \cdot 10^{8}$ A/cm²**
- **Scaled switching energy ~4 fJ for $(20\text{nm})^{3}$ cell**
- **Over 10^{10} switching cycles without failure**

- **Deterministic switching via Joule heating**
- **Fastest electrical switching with < 10 ps**

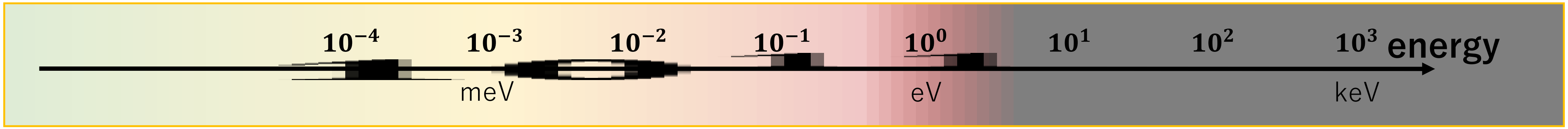
Y. Yang*, R. Wilson*, **J. Gorchon***., Sci. Adv. **03**, 11 (2017) *Equal contribution

Ultrafast spintronics?

conventional spintronics | ultrafast spintronics | ultrafast optomagnetism



excitations: ~100ps – 100fs | ~20ps – 3fs | ~20fs – 40as



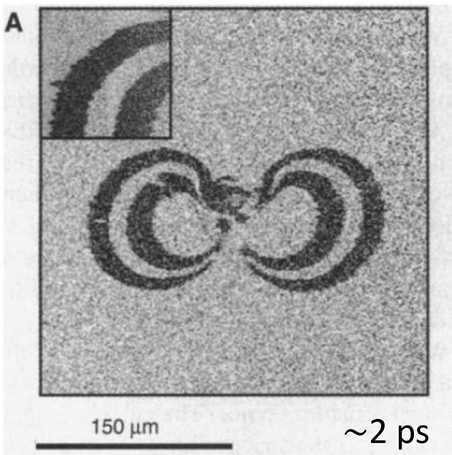
probe/excite: around Fermi level ($\lesssim k_B T$) | eV range transitions | interband transitions (element specificity)

The SPIN team

- Growth (MBE, Sputtering, PLD, ALD…)
- Magnetometry (MFM, Squid, VSM…)
- Ultrafast Magnetism
- Transport, FMR…
- Outreach

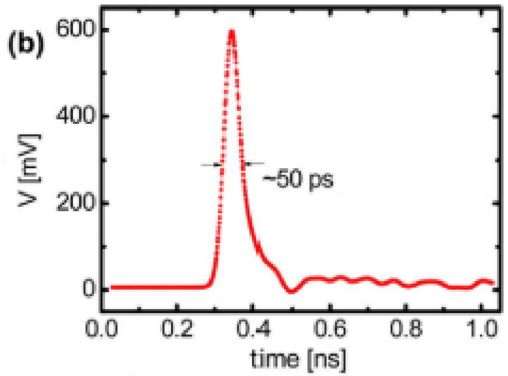
Can we switch a *magnet* using a single electrical current pulse shorter than 100 ps?

Oersted field



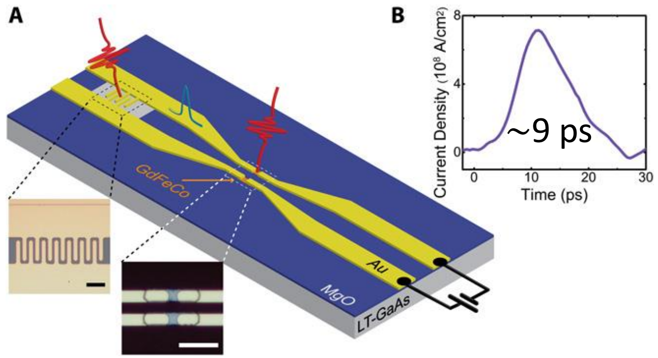
C. Back et al., *Science* **285** (1999)

Spin Transfer Torque



O. J. Lee et al., *APL* **99**, 102507 (2011)

Picosecond Joule heating



Y. Yang et al., *Sci. Adv.* **3**, e1603117 (2017)

Exchange in ferromagnets?