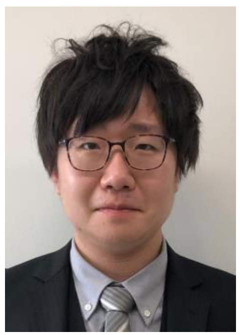
Spin-transport Mediated Single-shot All-optical Magnetization Switching of Metallic Films

INSTITUT JEAN LAMOUR

Q. Remy, J. Igarashi, S. Iihama, G. Malinowski, M. Hehn, J. Gorchon, J. Hohlfeld, S. Fukami, H. Ohno, S. Mangin

http://spin.ijl.cnrs.fr

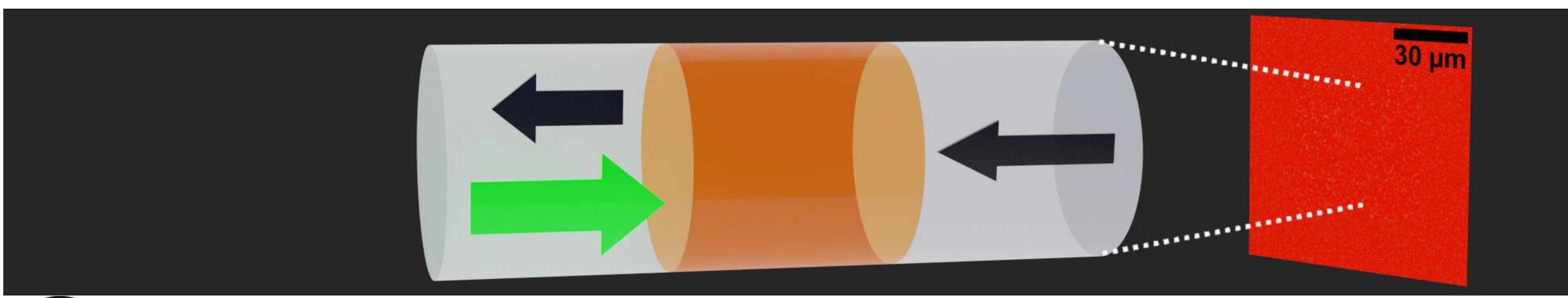
Quentin Remy



Junta Igarashi

Satoshi Iihama

TOHOKU UNIVERSITY



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INSTITUT JEAN LAMOUR

- 500 peoples

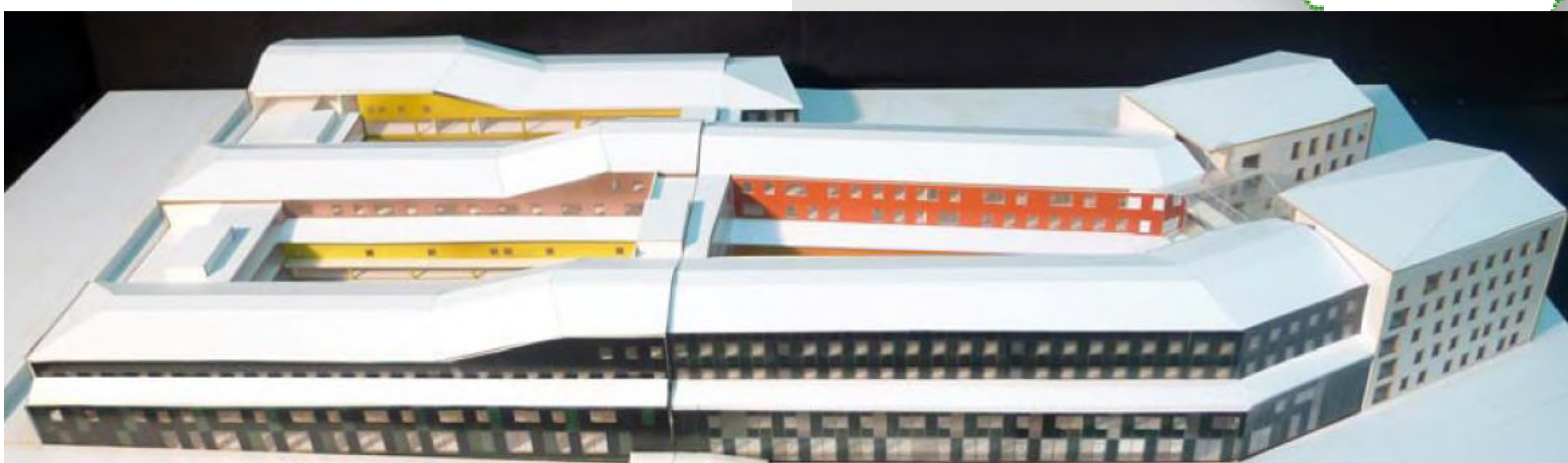
Nano-science

Surface science

Nuclear Fusion

Metallurgy

Groß / Grande REGION



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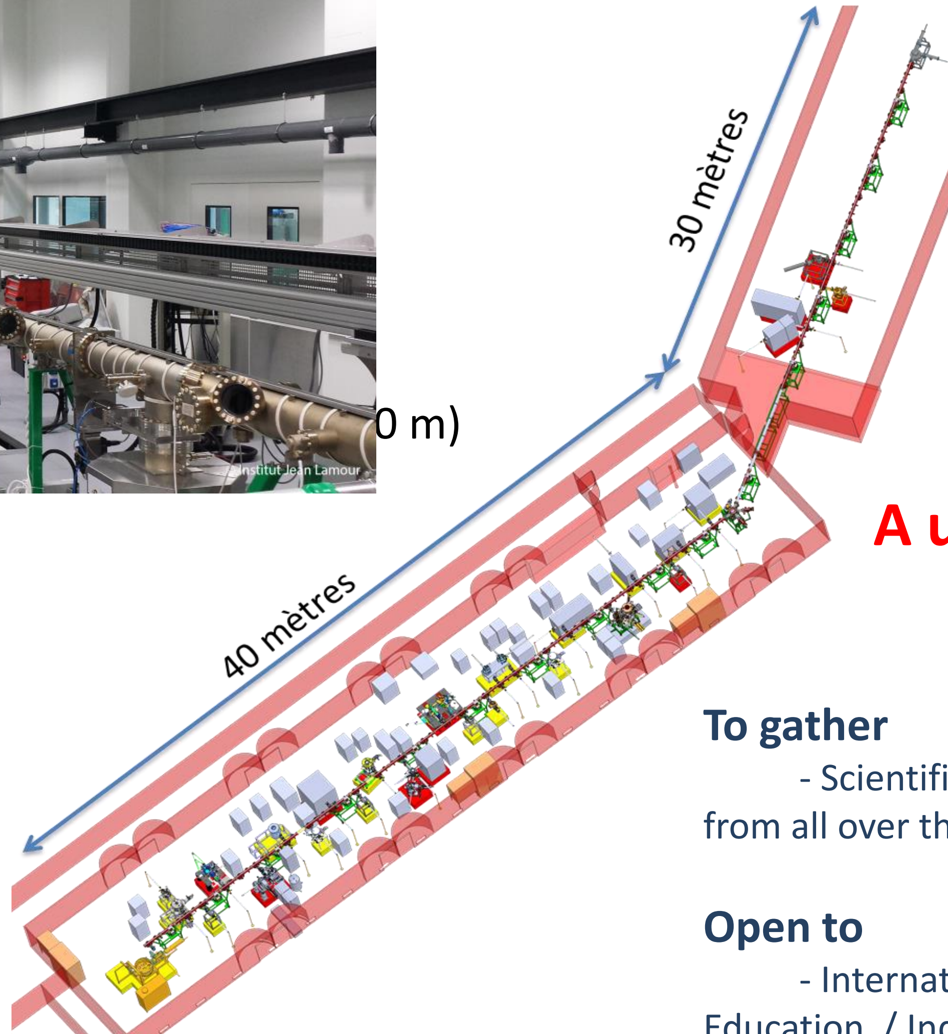
GrandNancy
COMMUNAUTÉ URBAINE à HUMAINE

l'Europe s'engage en Lorraine avec le FEDER

TUBE-Davm

0 m)

70 m under 10^{-10} mbar



A unique tool

To gather

- Scientific, industrial, students from all over the world

Open to

- International Research / Education / Industrial transfer

LEVERHULME TRUST

Visiting Professor (08/2021 -07/2022)

Maxwell Centre

Chiara Ciccarelli

UNIVERSITY OF CAMBRIDGE

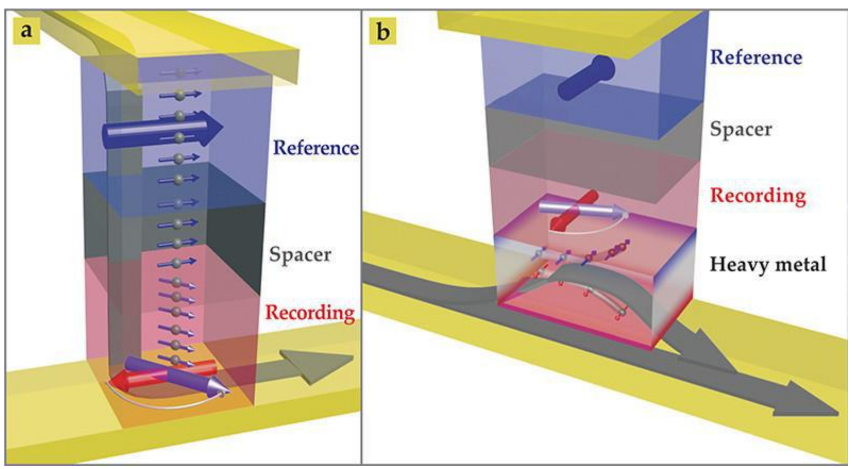
Cavendish Laboratory

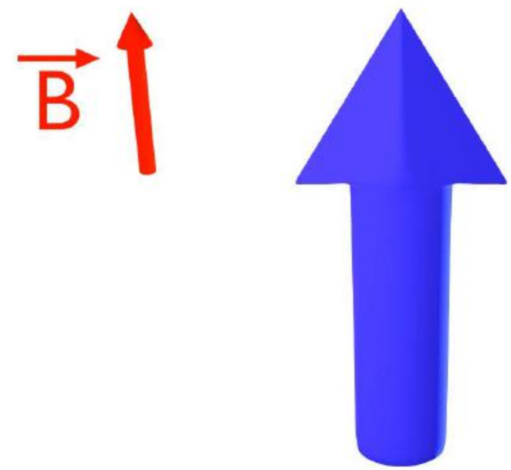
Standard magnetization dynamics

- Landau-Lifshitz-Gilbert equation:

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = -\gamma \boldsymbol{M} \times \left(\boldsymbol{H}_{\mathrm{eff}} - \frac{\alpha}{\gamma M} \left(\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} \right) \right) + \boldsymbol{\Gamma}$$

- Precession $\boldsymbol{H}_{\mathrm{eff}}$ +Damping
- Other possible torques in $\boldsymbol{\Gamma}$ **(STT , SOT)**

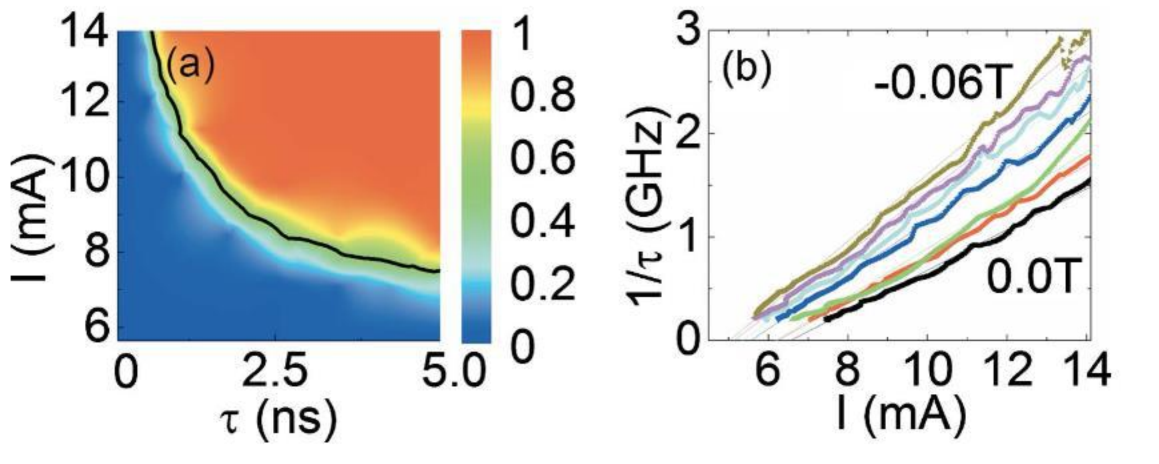




Jairo Sinova; Tomas Jungwirth; *Physics Today* **70,** 38-42 (2017)

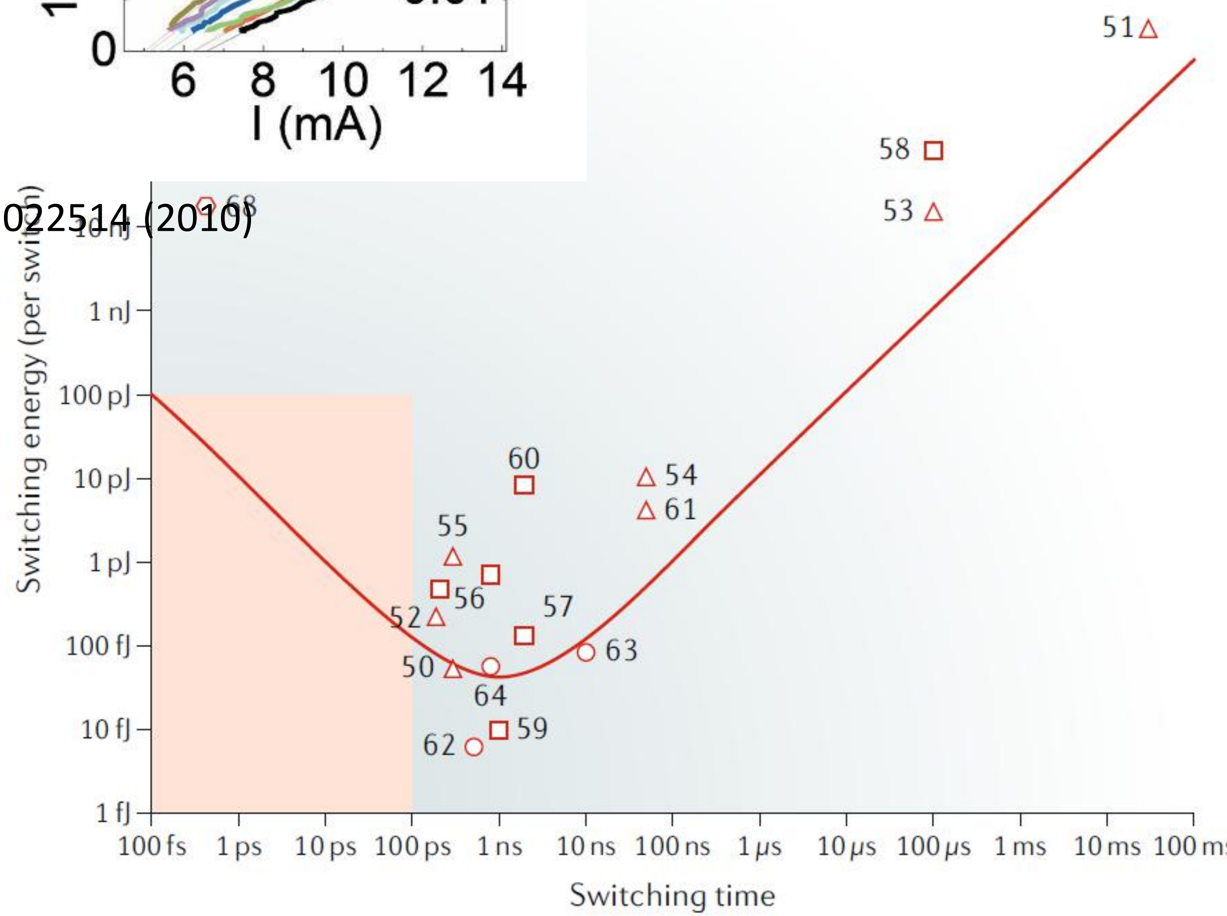
➔ Only for $M = |\boldsymbol{M}| = \text{cste}$!

Spin Transfer Torque



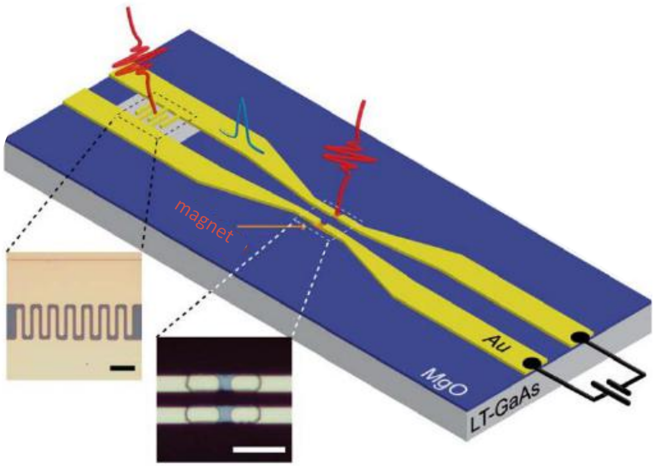
D. Bedau et al Appl. Phys. Lett. 96, 022514 (2010)

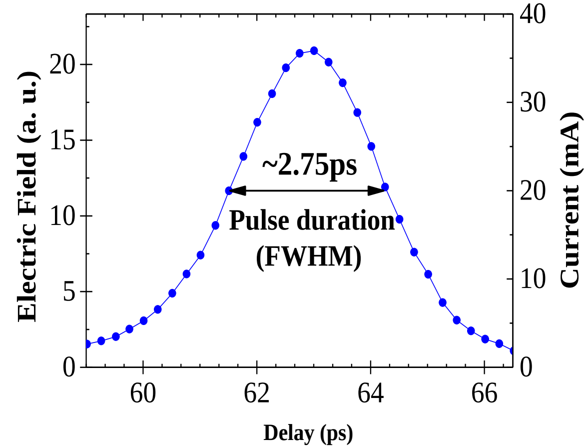
$$U = R\, I^2\, t$$

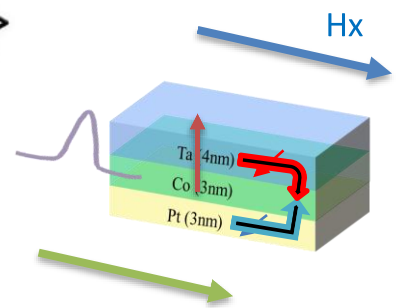


Kimel, A. V. & Li, M. *Nat. Rev. Mater.* **4**, 189–200 (2019).

Spin Orbit Torque







Kaushalya

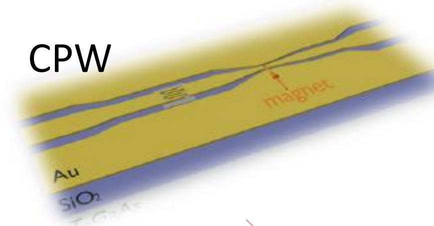
Berkeley
UNIVERSITY OF CALIFORNIA

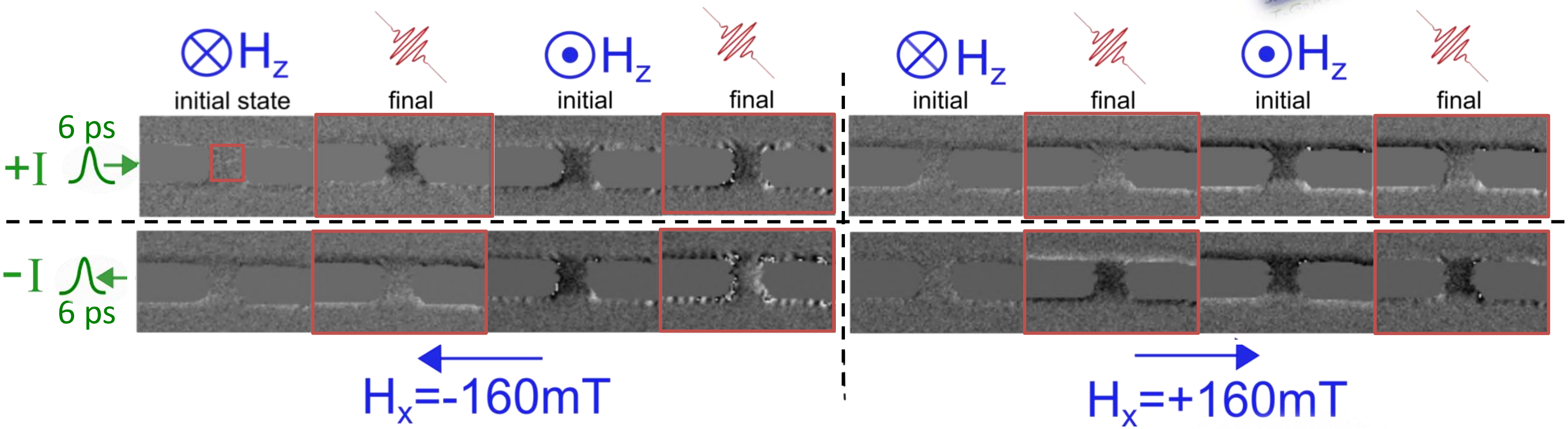
ijl INSTITUT JEAN LAMOUR

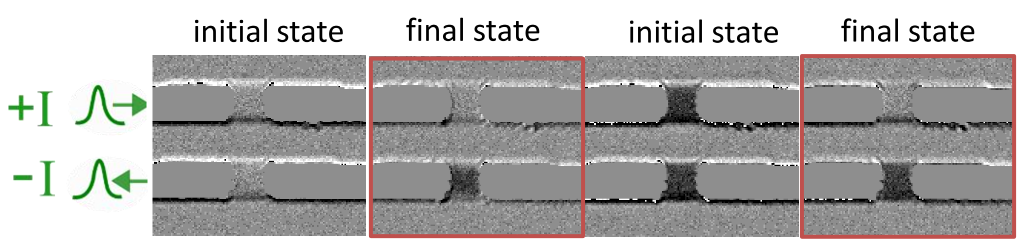
SPINTEAM

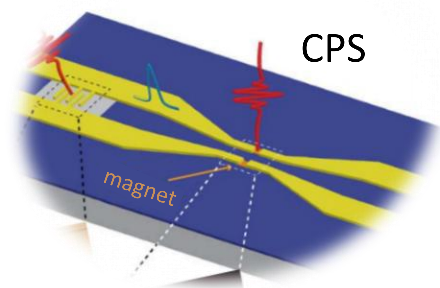
K. Jhuria et al Nature Electronic 3, 680–686 (2020)

Spin Transfer Torque







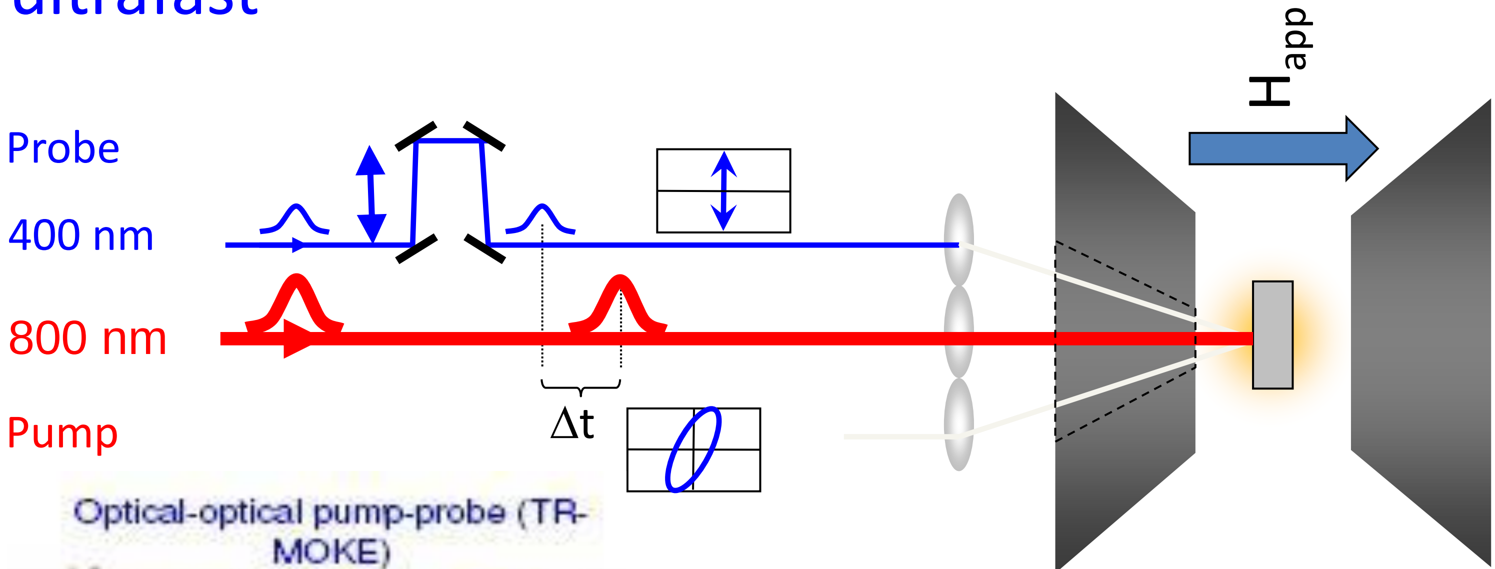


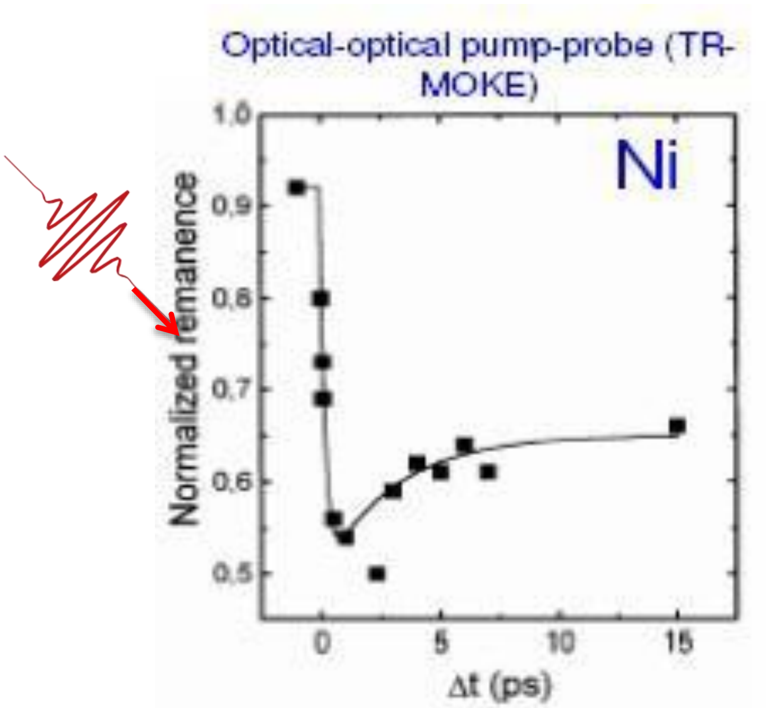
Switching via a single 6 ps SOT pulse

Energy estimates → < 50 pJ

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

Going ultrafast





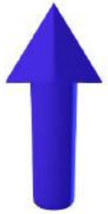
Jean Yves Bigot
1956-2018

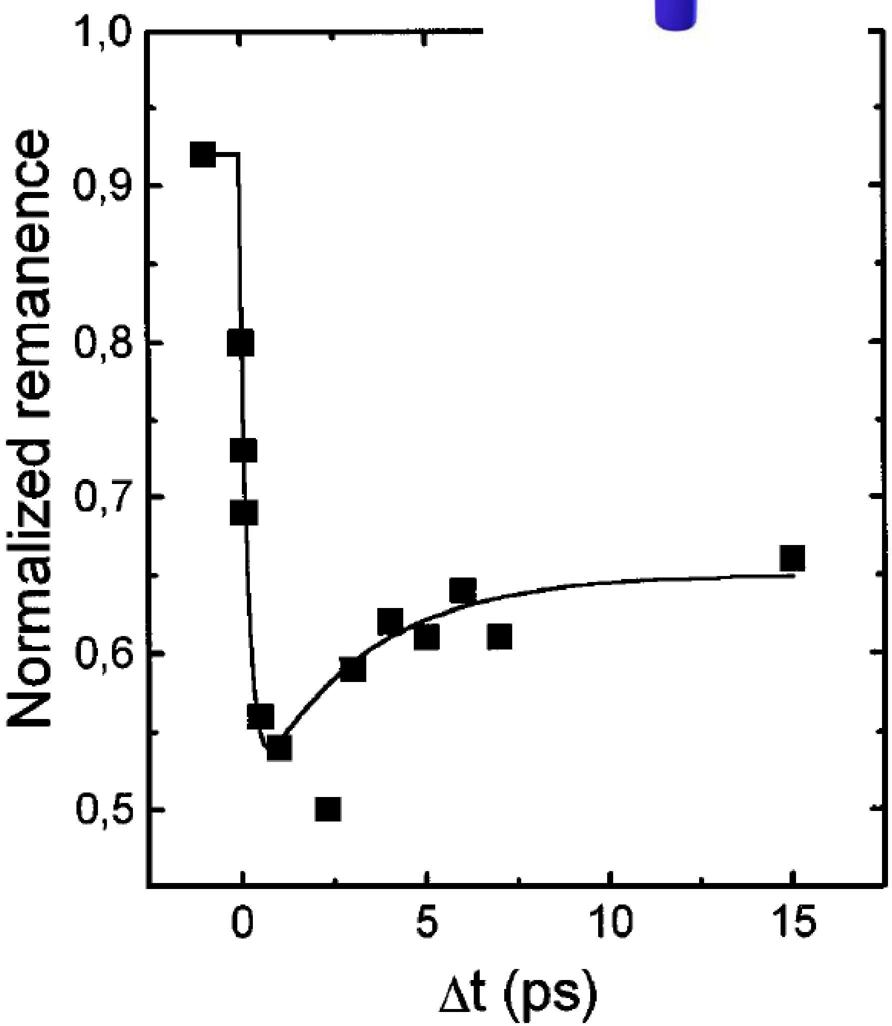
Eric Beaurepaire
1959-2018

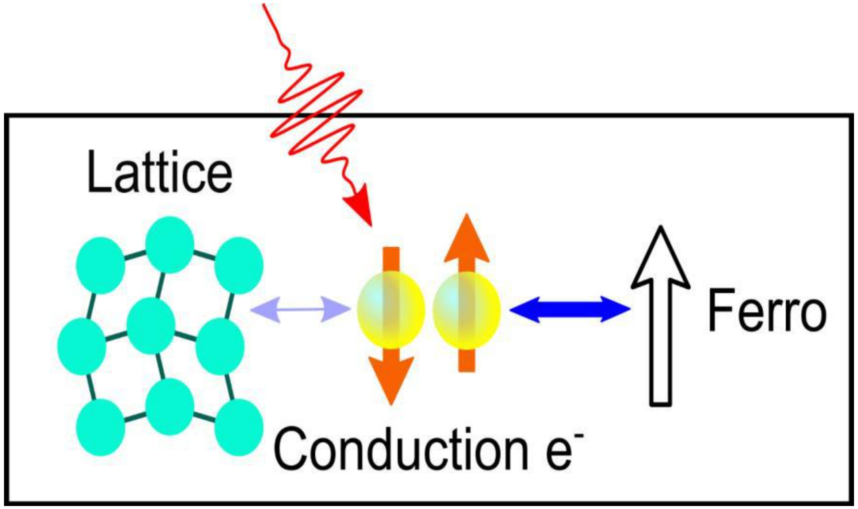
E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot
Phys. Rev. Lett. 76, 4250 (1996)

Going ultra-fast

Ultrashort stimuli bring the system into **a strongly out of equilibrium state** ➔ reduces the amplitude of the magnetization.

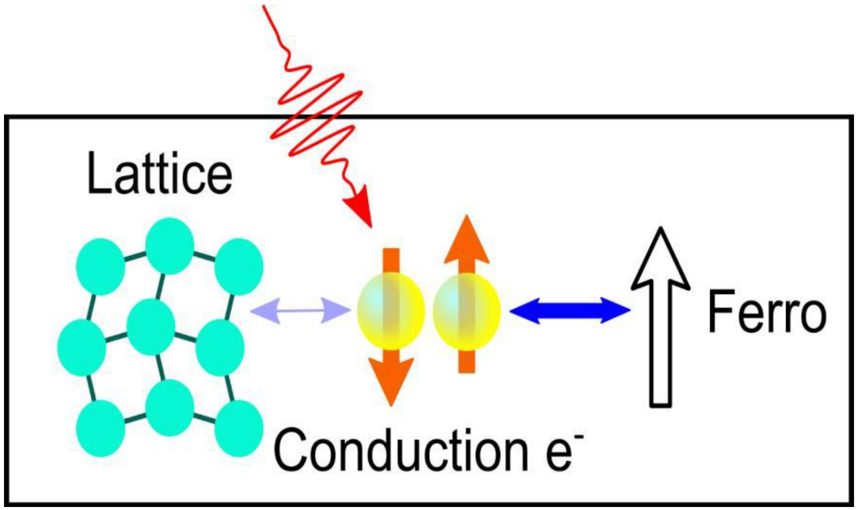


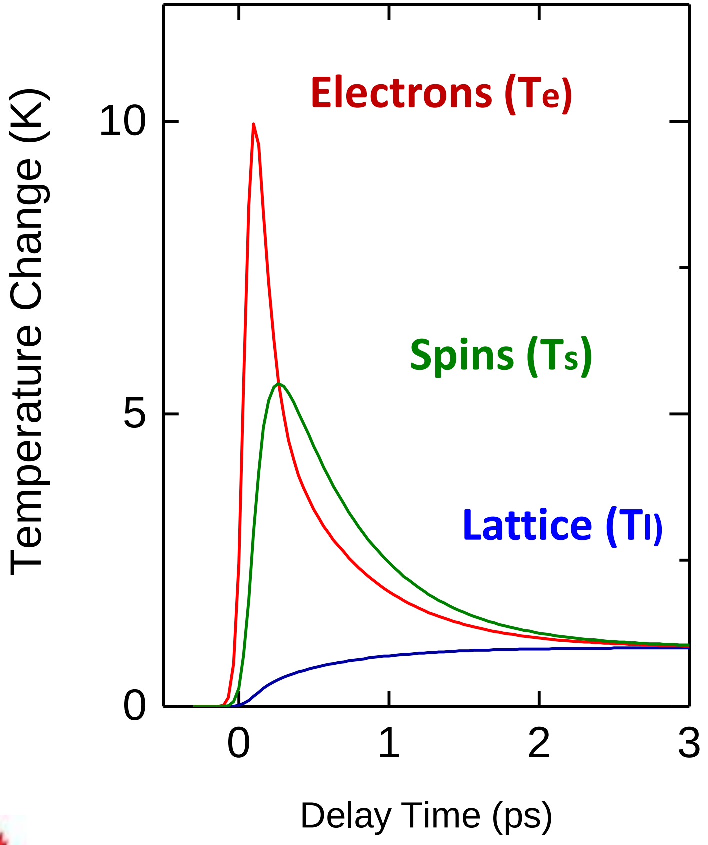




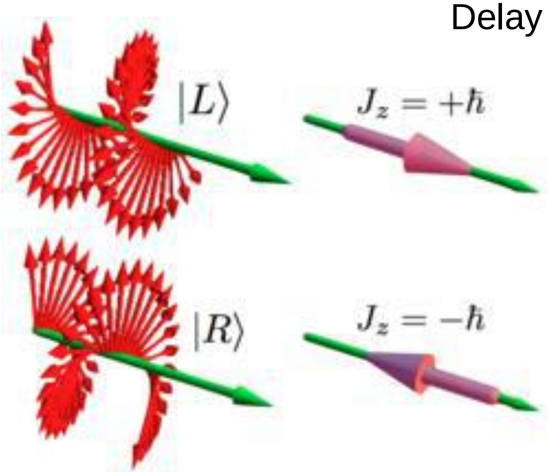
No external magnetic field !

Going Ultra-fast : Fundamental Interest

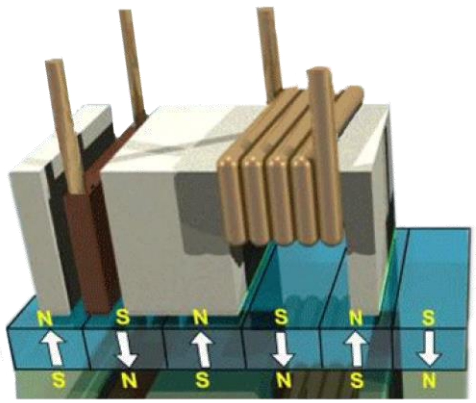




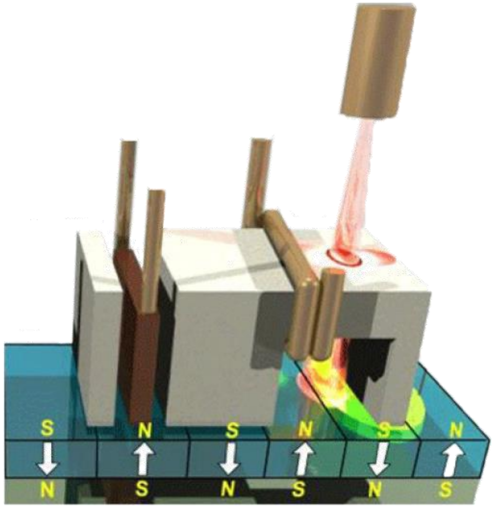
- Energy Transfer
- Angular Momentum Transfer
- Charge / Spin Current Transfer



Going Ultrafast:
Next generation of Magnetic Recording, Memories and logic ?

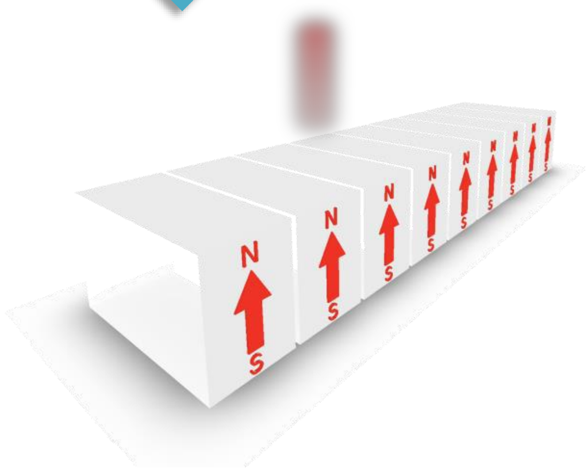


Magnetic field



HAMR (Seagate Inc.)

AOS



?

Can we combine ultra-fast and deterministic ?

Ultra-fast Magnetization Manipulation

- Femto second light pulse magnetisation manipulation
  - All Optical Helicity Dependent Switching (AO-HDS)
  - All Optical Helicity Independent Switching (AO-HIS)

- Femto second electron pulse magnetisation manipulation
  - Demagnetisation
  - Toggle switching (GdFeCo)
  - Deterministic ultra-fast switching of a ferromagnet

Ultra-fast Magnetization Manipulation

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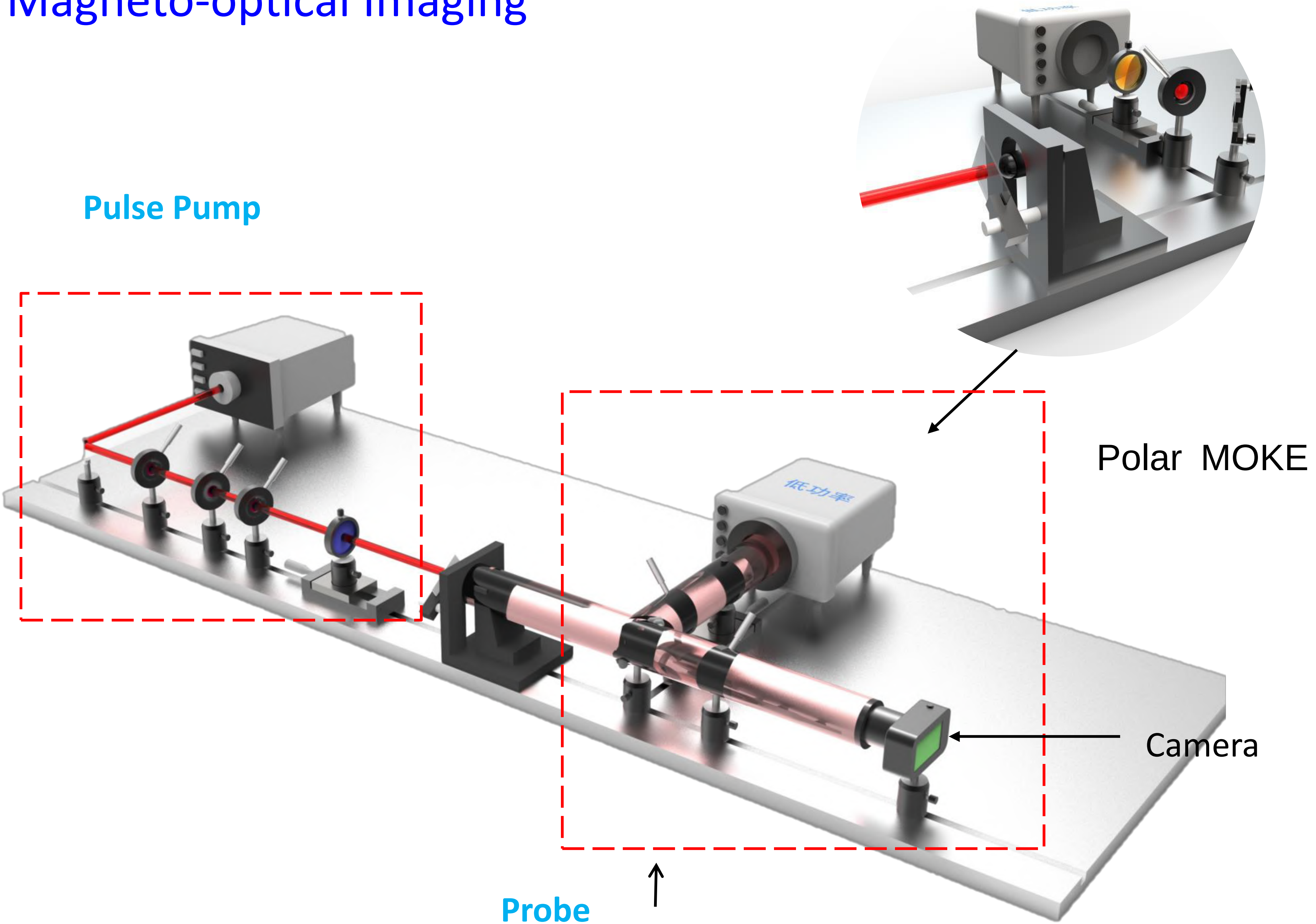
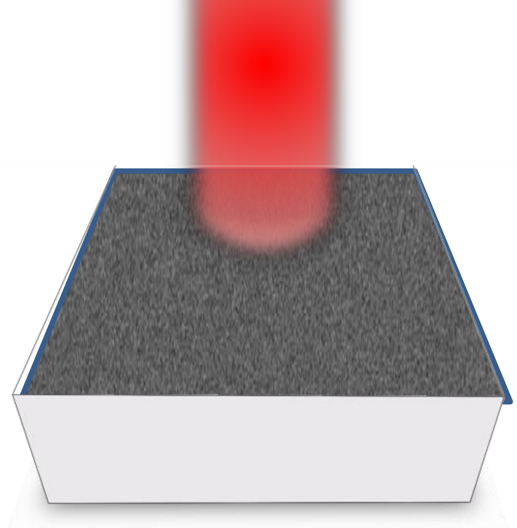
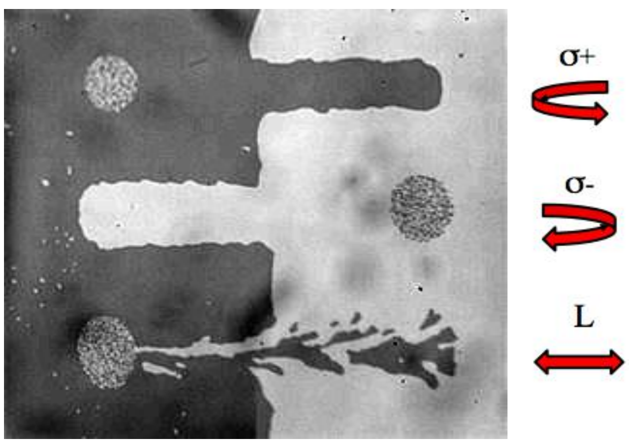
- Femto second electron pulse magnetisation manipulation
  - Demagnetisation
  - Toggle switching (GdFeCo)
  - Deterministic ultra-fast switching of a ferromagnet

Magneto-optical Imaging





All Optical – Helicity Depent Switching (AO-HDS)



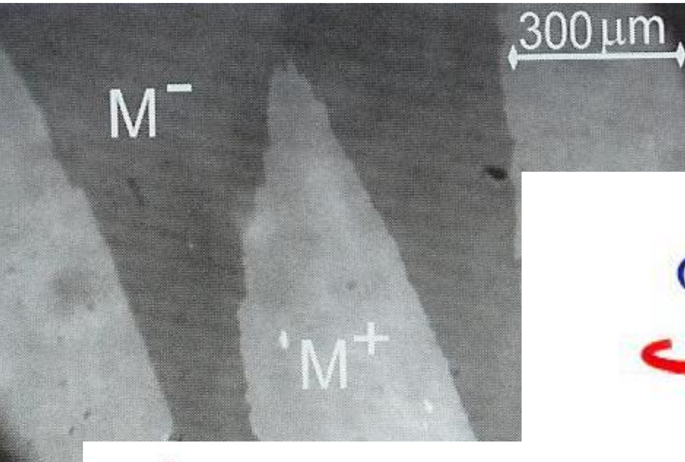
All Optical – Helicity Indepedent Switching (AO-HIS)

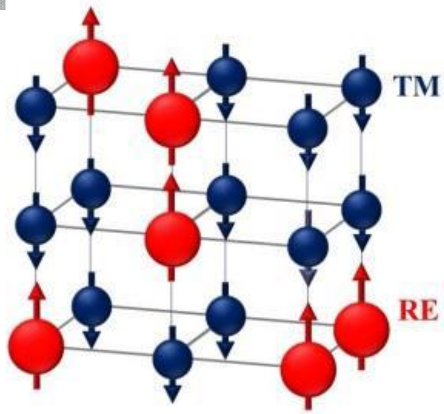
Pulse 1 Pulse 2

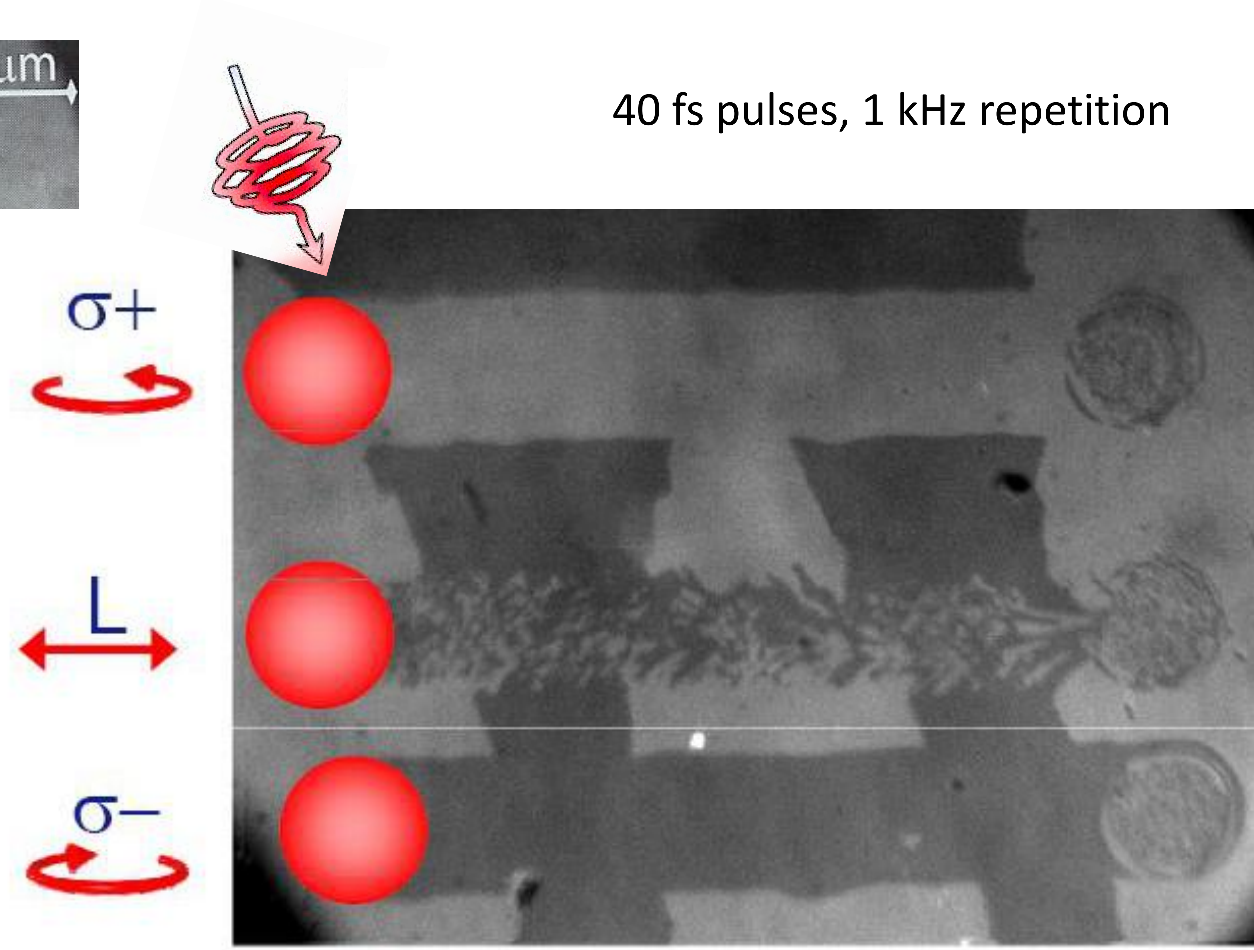
AO-HDS	AO-HIS
Many pulses needed	Single pulse switching
Any material	Very few Materials

All Optical – Helicity Depent Switching (AO-HDS)

40 fs pulses, 1 kHz repetition





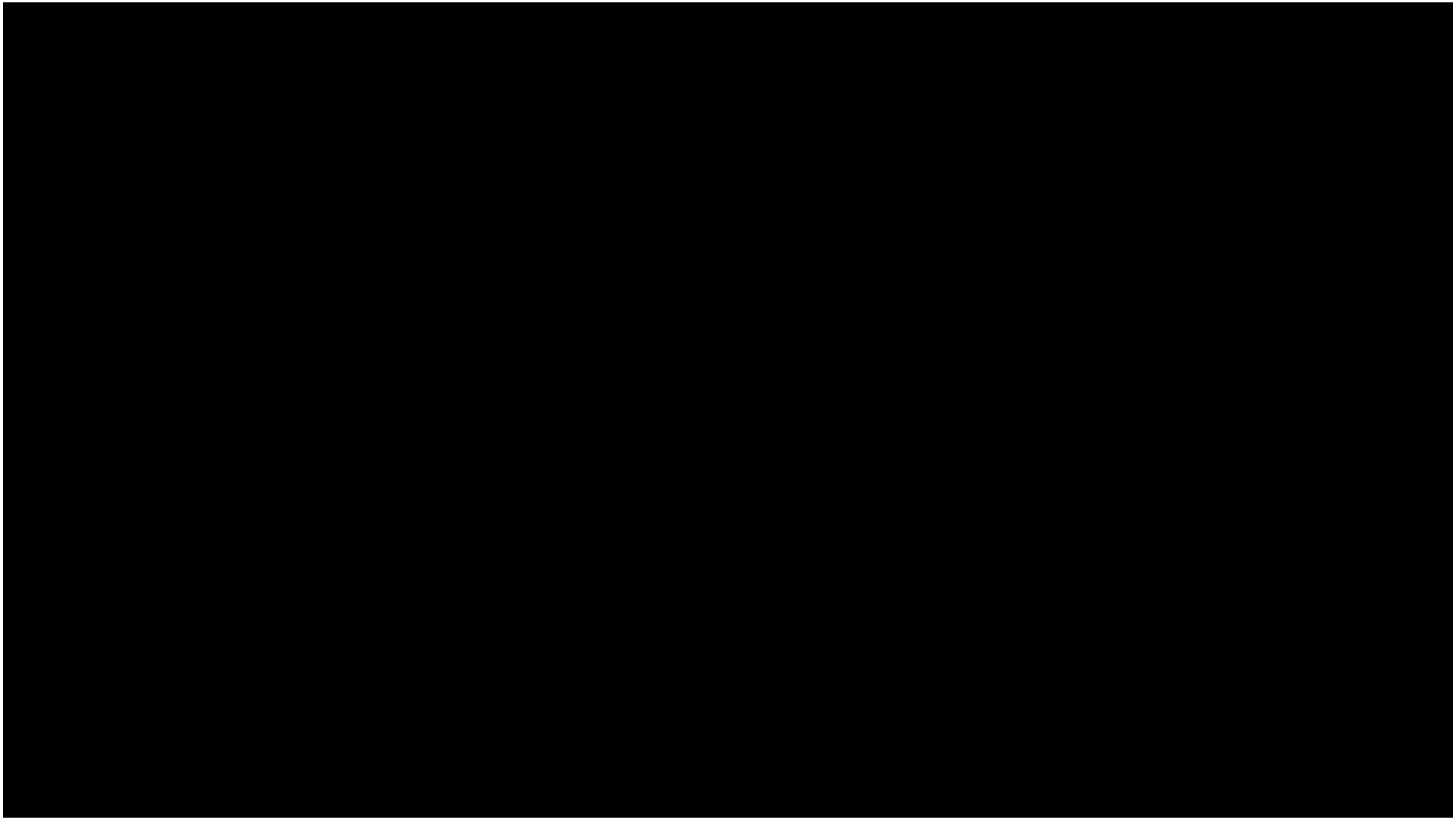


$Gd_{22}Fe_{74.6}Co_{3.4}$ (20 nm)

C.D. Stanciu et al, Phys. Rev. Lett. 99, 047601 (2007)

Andrei Kirilyuk, Alexey V Kimel and Theo Rasing Rep. Prog. Phys. 76 026501 (2013)

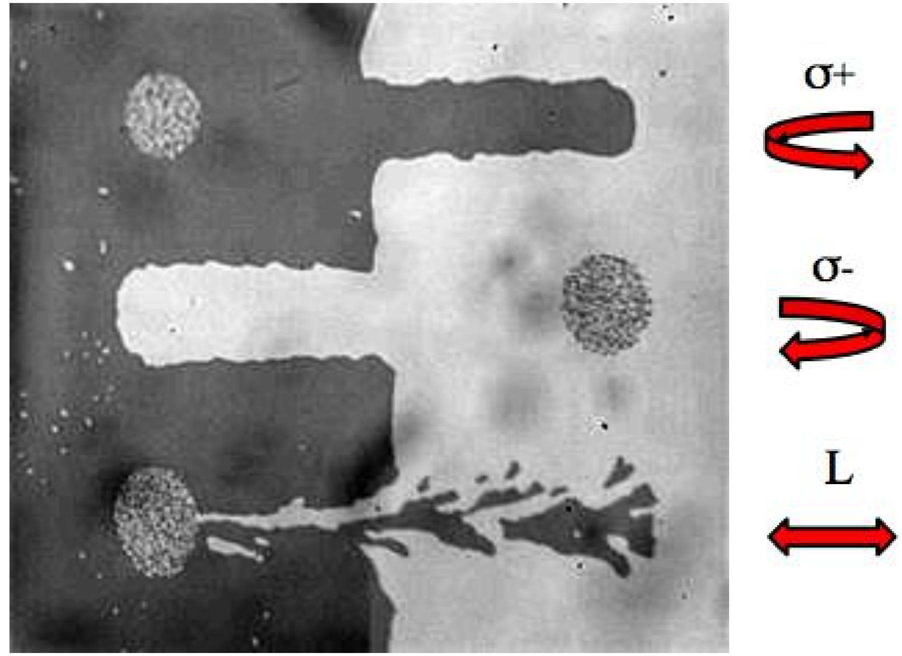
All Optical – Helicity Depent Switching (AO-HDS)

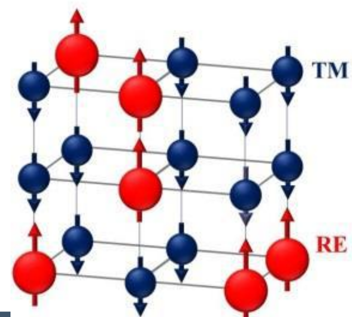


All Optical – Helicity Depent Switching (AO-HDS)

Ferrimagnets / Ferromagnets

- GdFeCo
- Other RE : Tb, Dy, Ho
- Multilayers : [Tb/Co], [Ho/Co]
- Synthetic ferrimagnets : Co/Ir/Co/Ir
- Ferromagnet Co/Pt , Co/Ni
- Granular Media





Matthias Gottwald
(Now IBM NY)

Charles Henri Lambert
(Now in ETH Zurich)

C. D. Stanciu et al Phys. Rev. Lett. 99, 047601 (2007)

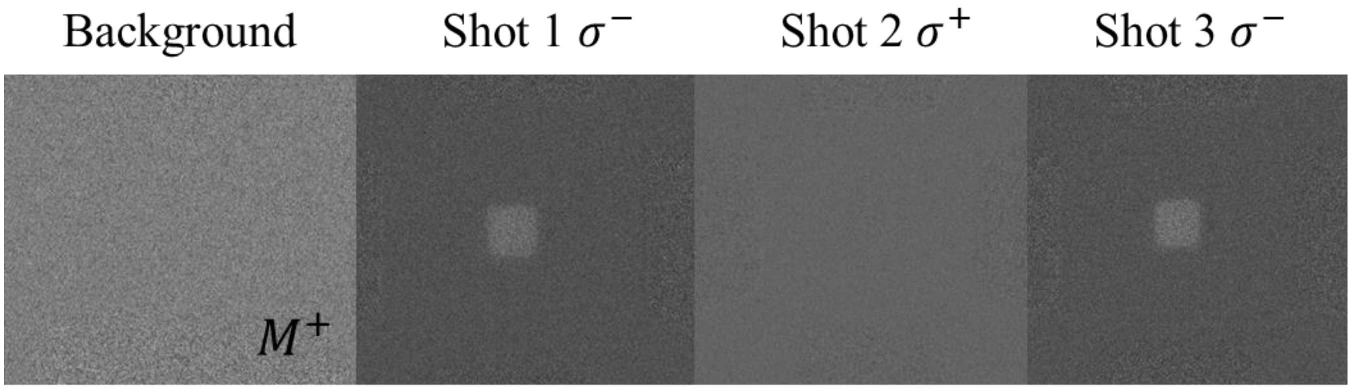
S. Alebrand et al., Appl. Phys. Lett. 101, 162408 (2012)

S. Mangin et al., Nat. Mater. 13, 286-292 (2014)

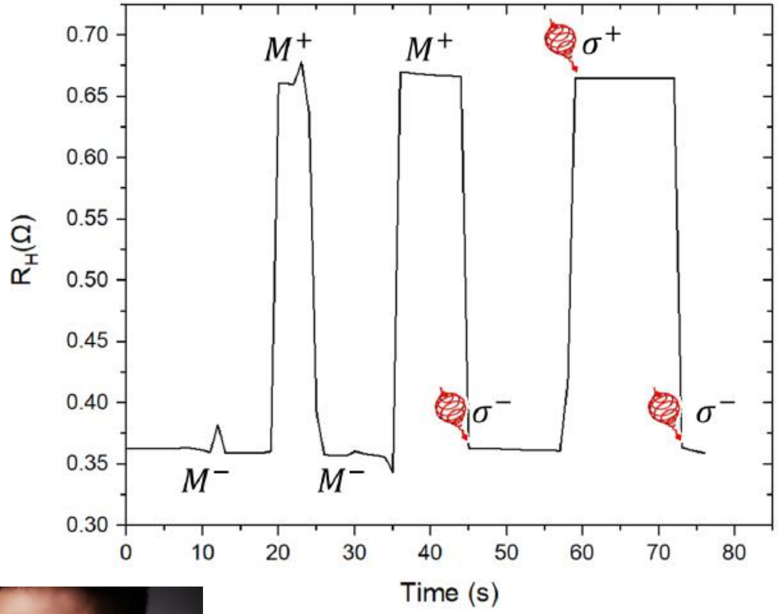
*C.H. Lambert et al Science **345** (6202), 1337 (2014)*

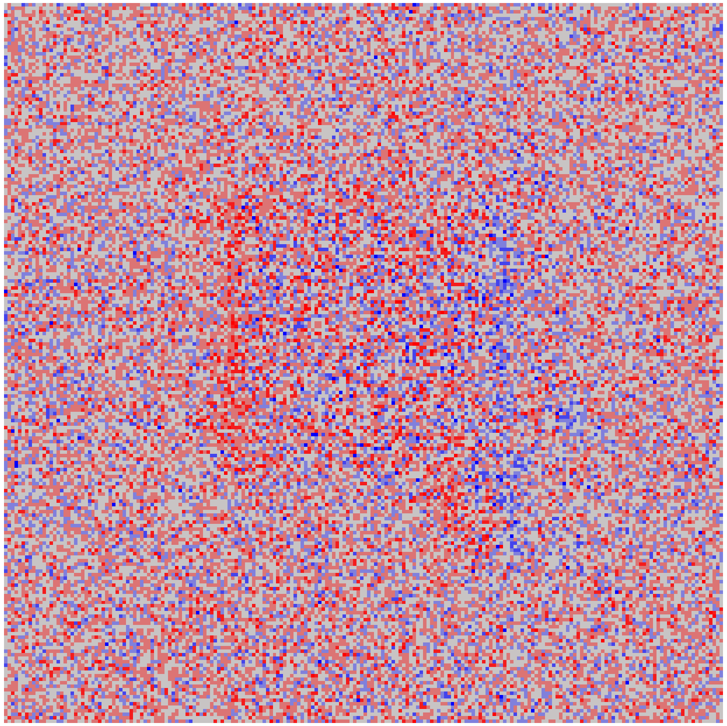
J-W Liao et al, Advanced Science. 6, 1901876 (2019)

AO-HDS: Needs multiple pulses



*1 shot = 1000 pulses

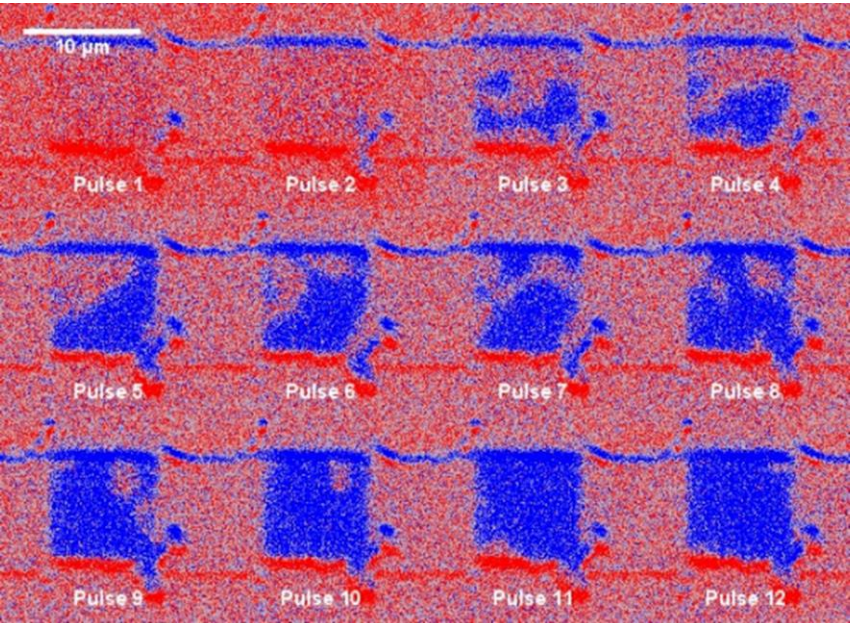


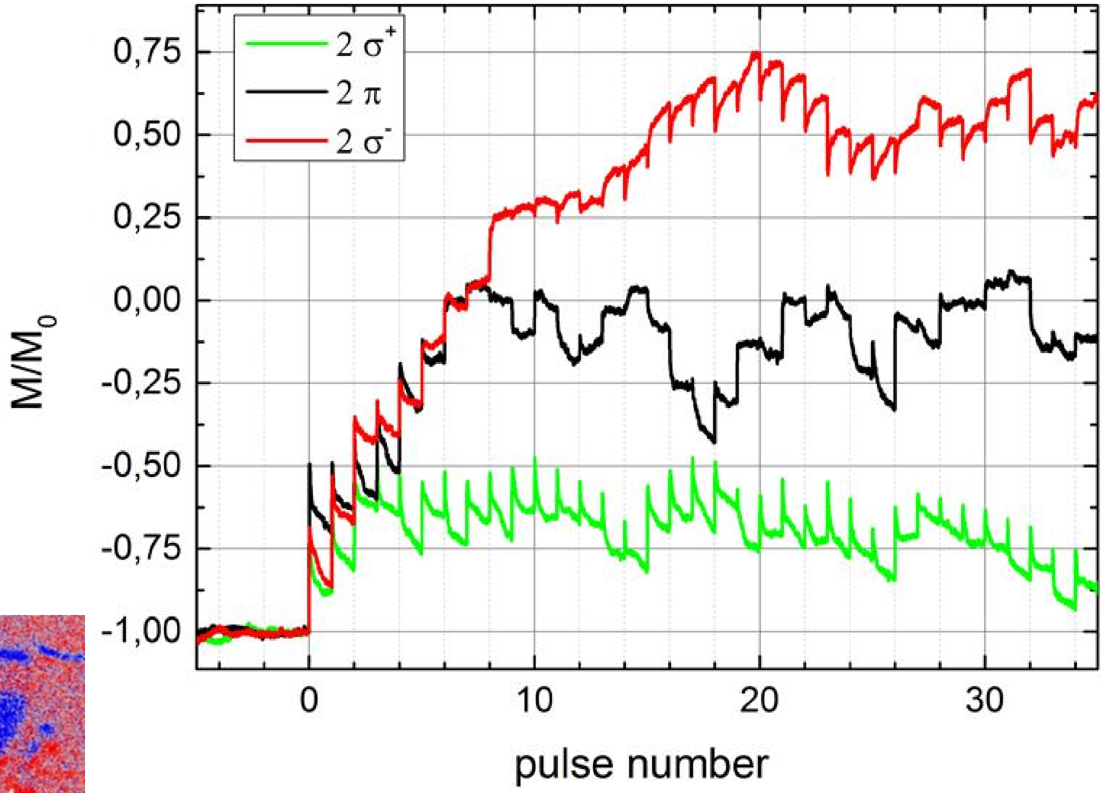


Tianxun Huang

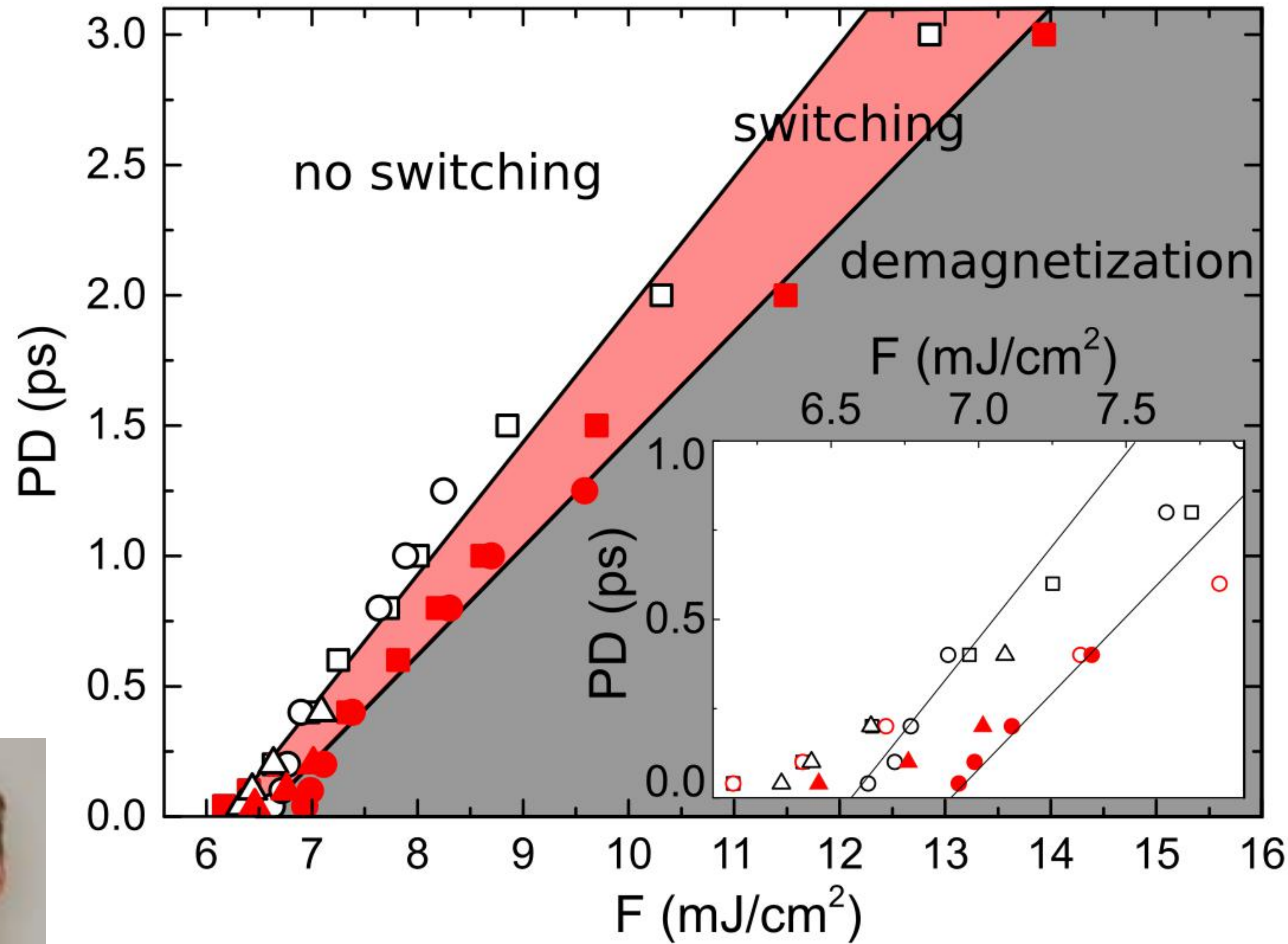
T. Huang to be published

AO-HDS: Needs multiple pulses





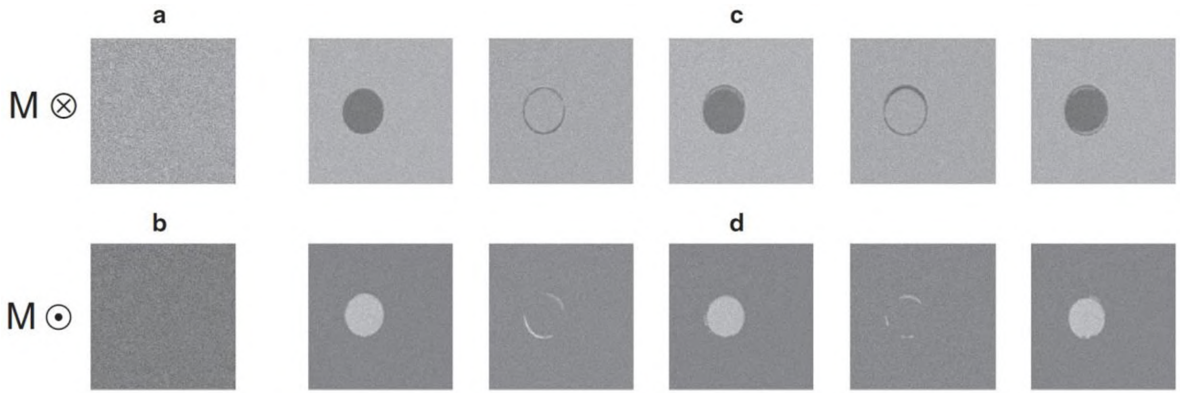
State Diagram of AO-HDS in Co/Pt



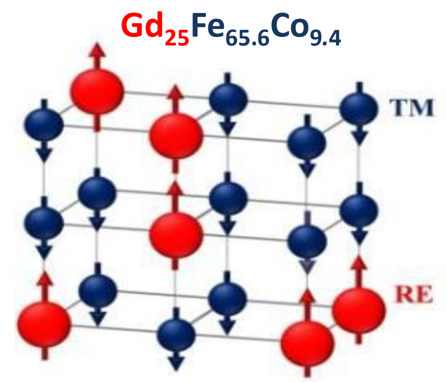
Georgy Kichin
Now RQC - Moscow

G. Kichin et al Phys. Rev. App. 12 (2), 024019 (2019)

All Optical – Helicity Indepedent Switching (AO-HIS)



T.A. Ostler *et al*, Nat. Commun. 3, 666 (2011)



M. L. M. Lalieu et al , Phys. Rev. B **96**, 220411® 2017

Gd based samples

All Optical – Helicity Independent Switching (AO-HIS)

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-020-18340-9 OPEN

Single pulse all-optical toggle switching of magnetization without gadolinium in the ferrimagnet Mn_2Ru_xGa

C. Banerjee[1], N. Teichert[1], K. E. Siewierska[1], Z. Gercsi[1], G. Y. P. Atcheson[1], P. Stamenov[1], K. Rode[1], J. M. D. Coey[1] & J. Besbas[1]✉

2020

SCIENTIFIC REPORTS

natureresearch

OPEN

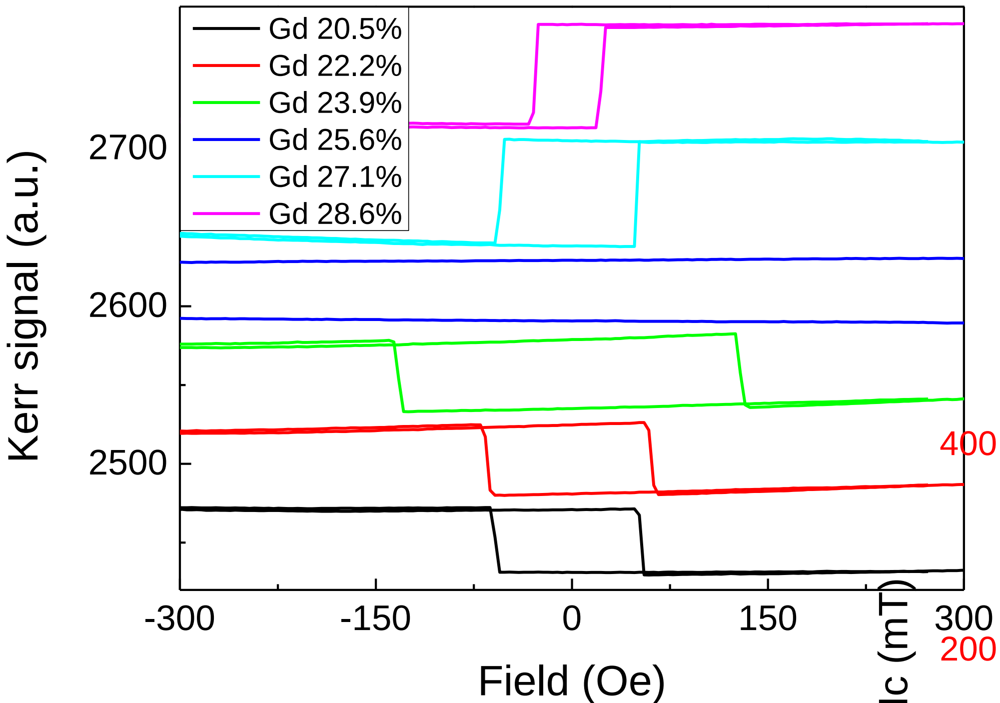
Single-shot all-optical switching of magnetization in Tb/Co multilayer-based electrodes

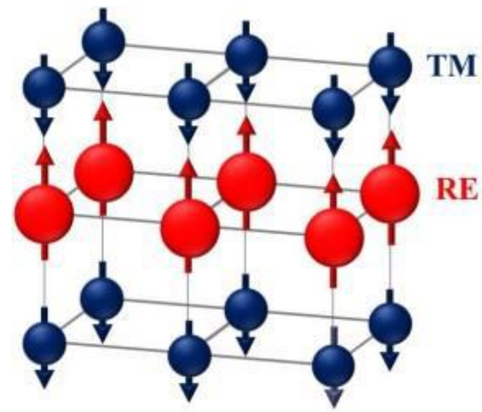
L. Avilés-Félix[1*], A. Olivier[1], G. Li[2], C. S. Davies[2,3], L. Álvaro-Gómez[1], M. Rubio-Roy[1], S. Auffret[1], A. Kirilyuk[2,3], A. V. Kimel[2], Th. Rasing[2], L. D. Buda-Prejbeanu[1], R. C. Sousa[1], B. Dieny[1] & I. L. Prejbeanu[1]

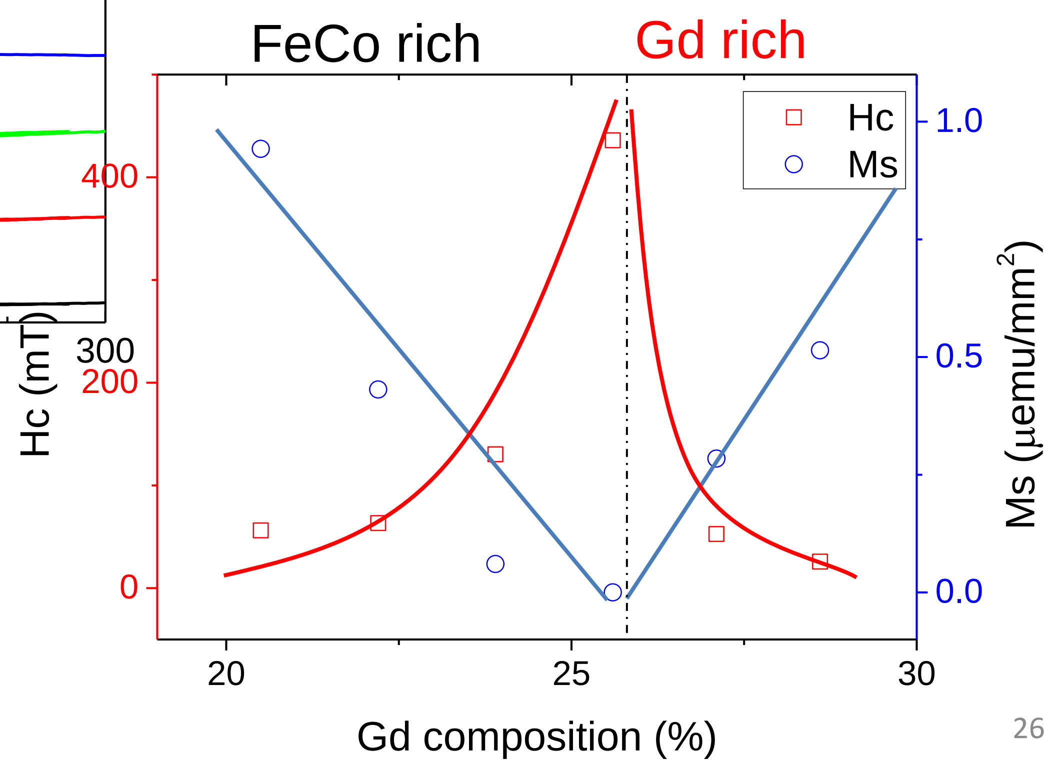
All Optical – Helicity Indepedent Switching (AO-HIS)

GdFeCo properties

Glass//Ta3/Pt5/Cu80/$Gd_x(FeCo)_{1-x}$5/Pt5

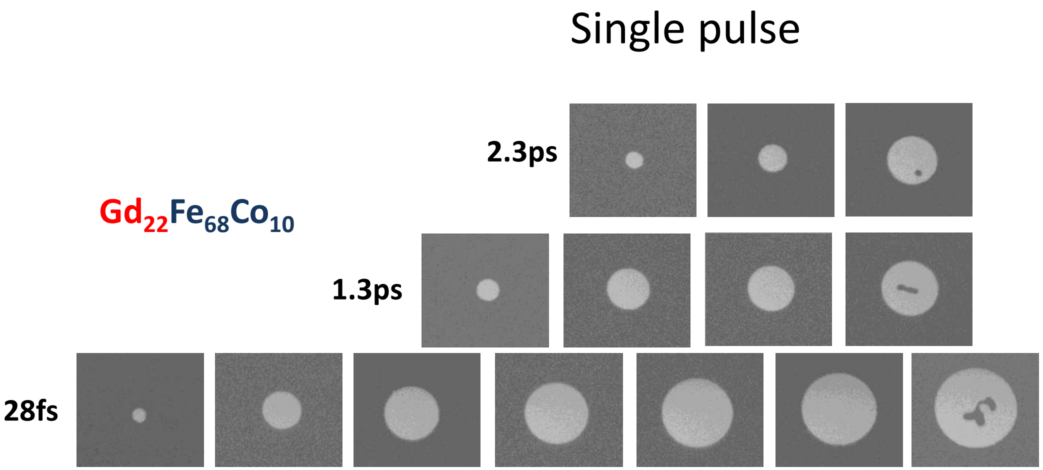




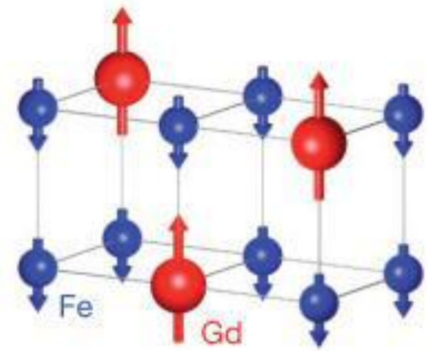


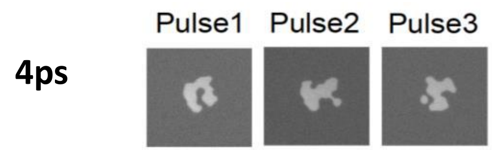
Y. Xu, et al Adv Matter **29** 42 1703474 (2017)

All Optical – Helicity Indepedent Switching (AO-HIS)

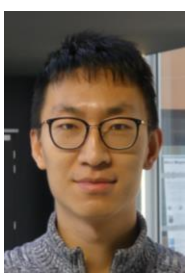


$Gd_{22}Fe_{68}Co_{10}$

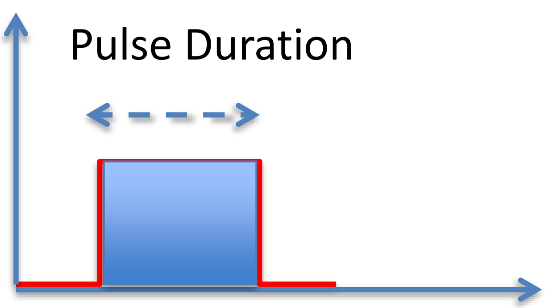




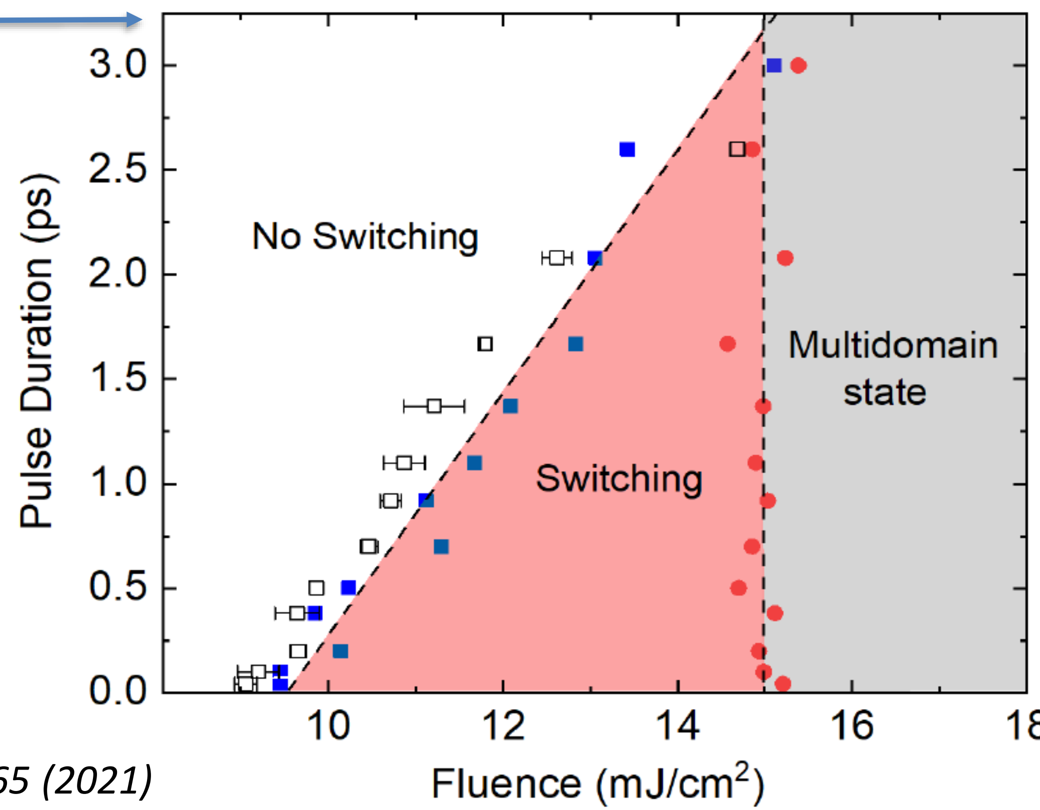
Increase Fluence



Jiaqi Wei
Univ Beihang



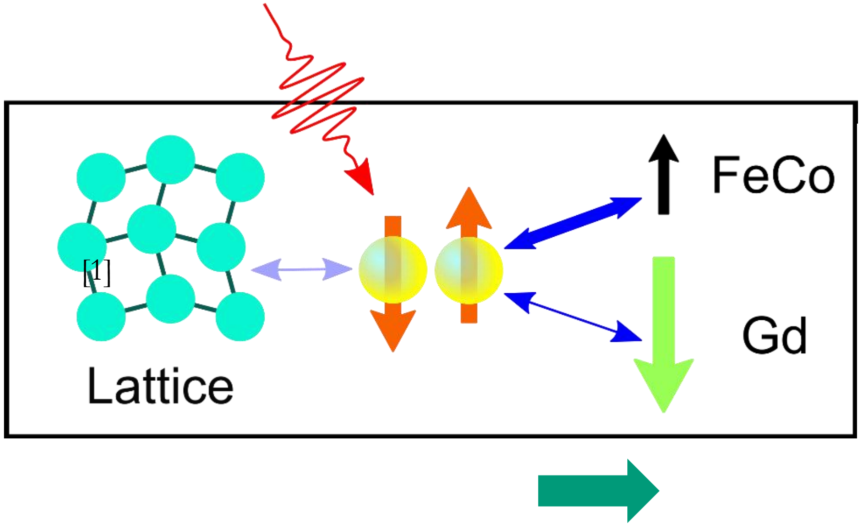
Constant Total Energy

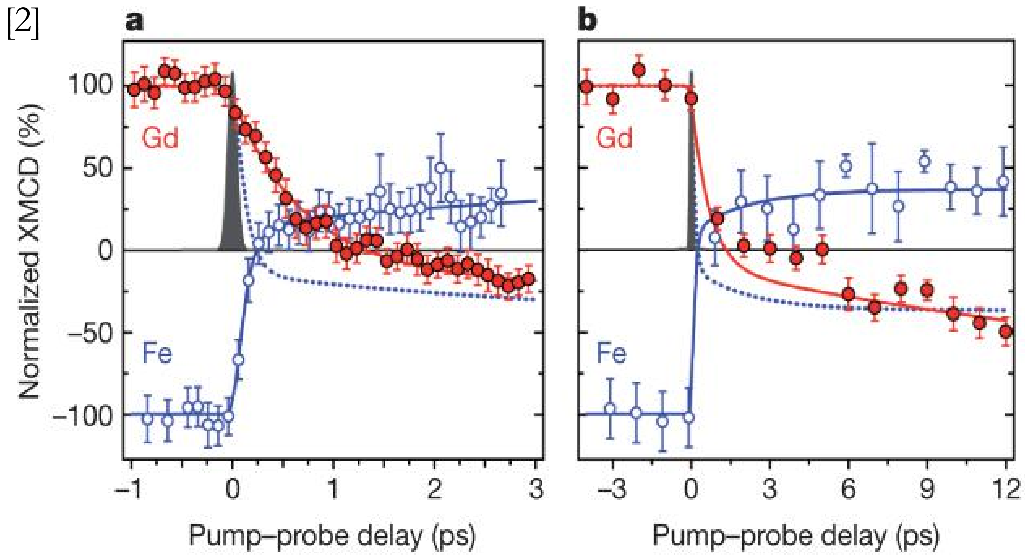


J. *Wei et al Physical Review Applied 15 (5), 054065 (2021)*

All Optical – Helicity Indepedent Switching (AO-HIS)

- Two magnetic sublattices ➔ ultrafast magnetization reversal.





- Ultrafast heating is sufficient [3] (tens of femtoseconds to tens of picoseconds stimulus [4]). There is no precession [5]. The total magnetization reverses in ~100 ps [2,6].

*[1] Gridnev, V. N. J. Phys. Condens. Matter **28**, 476007 (2016).*

*[2] Radu, I. et al. Nature **472**, 205–208 (2011).*

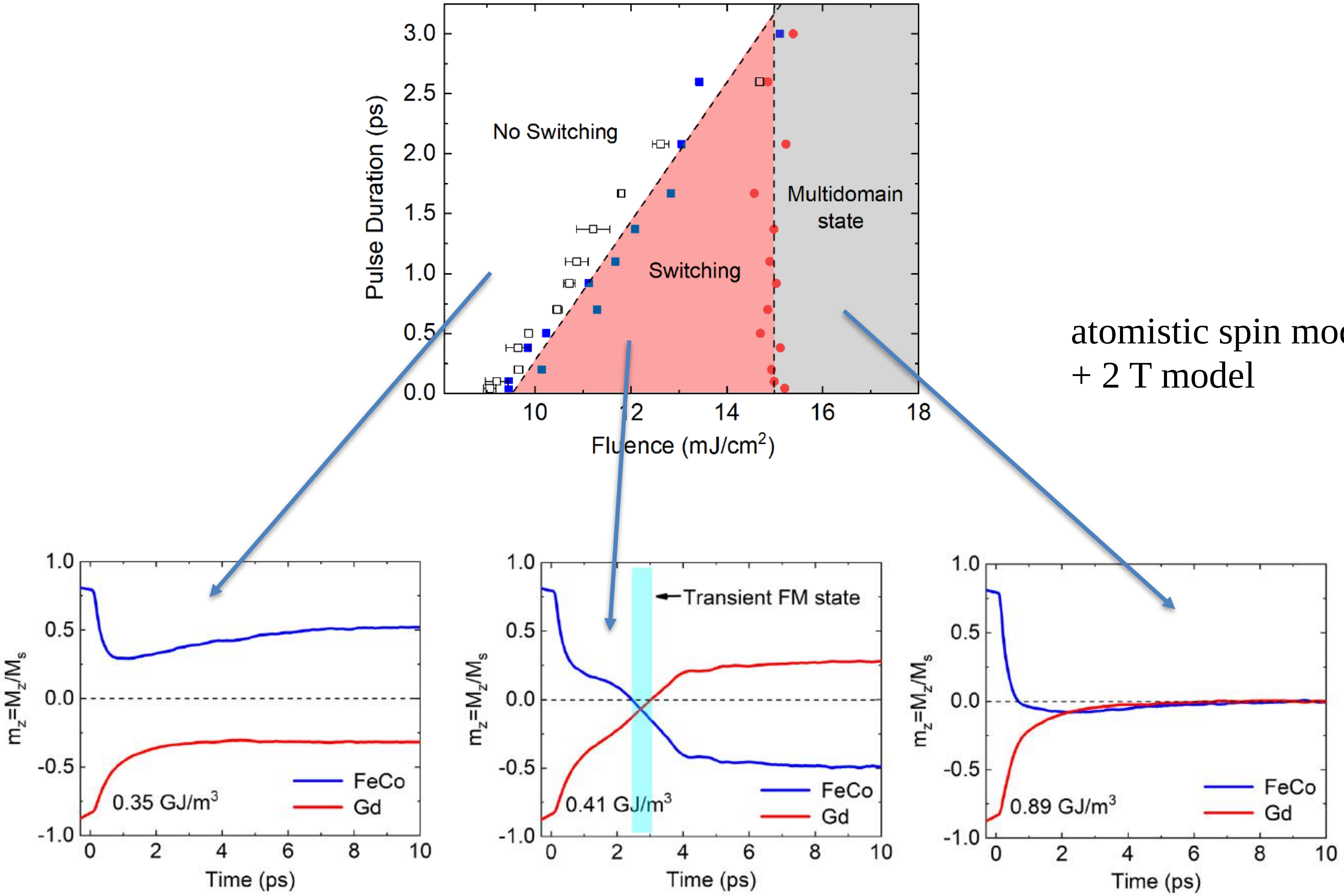
*[3] Ostler, T. A. et al. Nat. Commun. **3**, 666 (2012).*

[4] Gorchon, J. et al. Phys. Rev. B 94, 184406 (2016).

[5] Kazantseva, N., Hinzke, D., Chantrell, R. W. & Nowak, U. Europhysics Lett. 86, 27006 (2009).

*[6] Wang, S. et al. Light Sci. Appl. **10**, 8 (2021).*

All Optical – Helicity Indepedent Switching (AO-HIS)



atomistic spin model
+ 2 T model

J. Wei et al Physical Review Applied 15 (5), 054065 (2021)

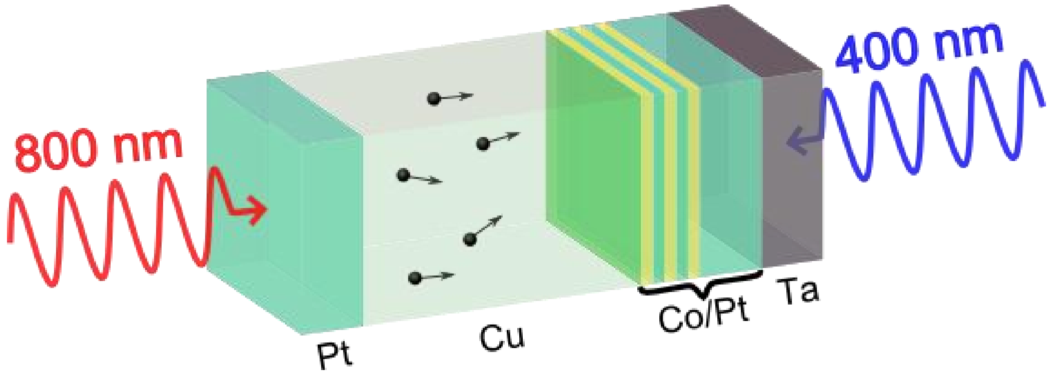
Ultra-fast Magnetization Manipulation

- Femto second light pulse magnetisation manipulation
  - All Optical Helicity Dependent Switching (AO-HDS)
  - All Optical Helicity Independent Switching (AO-HIS)

- Femto second electron pulse magnetisation manipulation
  - Demagnetisation
  - Toggle switching (GdFeCo)
  - Deterministic ultra-fast switching of a ferromagnet

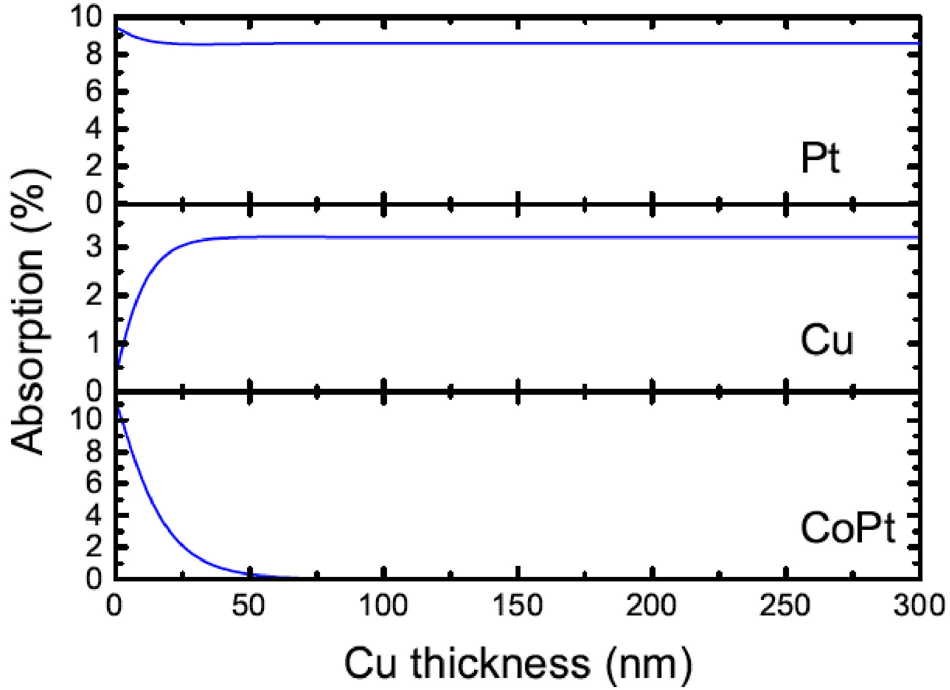
Femto second electron pulse - Demagnetization

How to generate ultra-short unpolarized current pulse



Glass/Ta(3)/Pt(3)/[Co(0.6)/Pt(1.1)]2/Co(0.6)/Cu(d)/Pt(3)

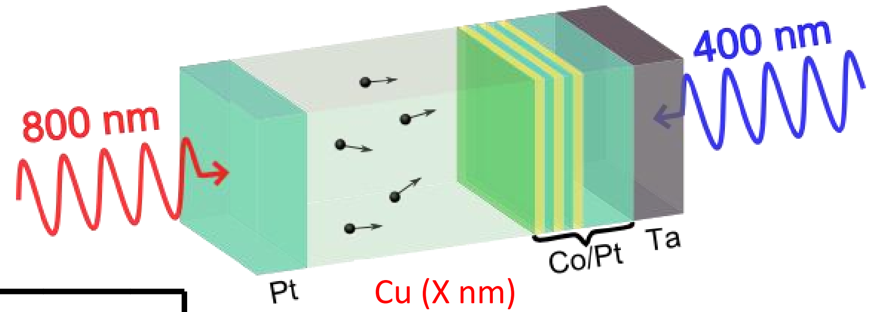
Nicolas Bergeard now at IPCMS

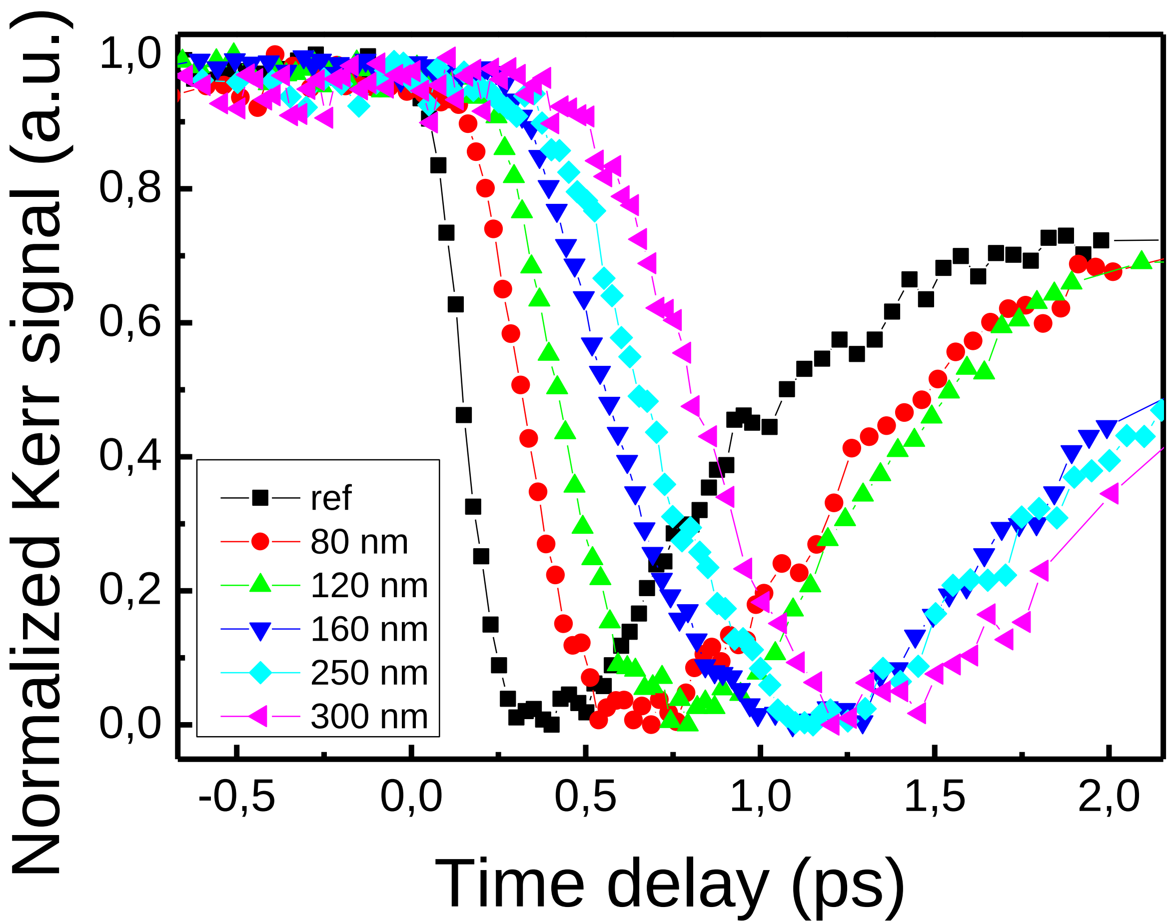


N. Bergeard,et al , Phys. Rev. Lett. 117, 147203 (2016)

Femto second electron pulse - Demagnetization

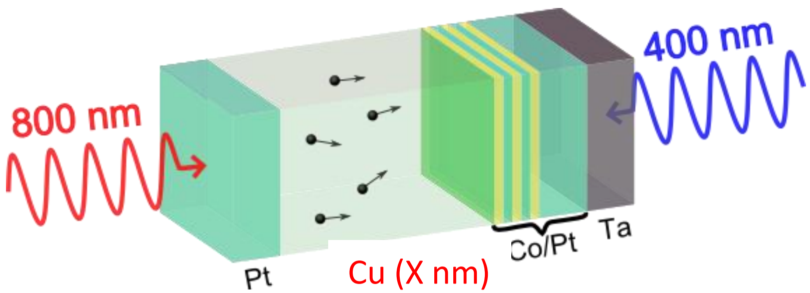
Vs Cu (X nm)



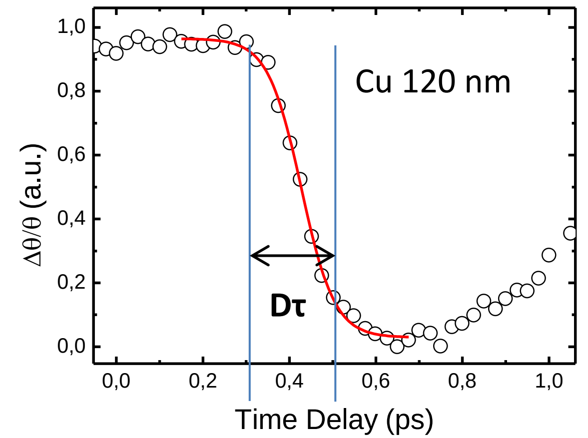


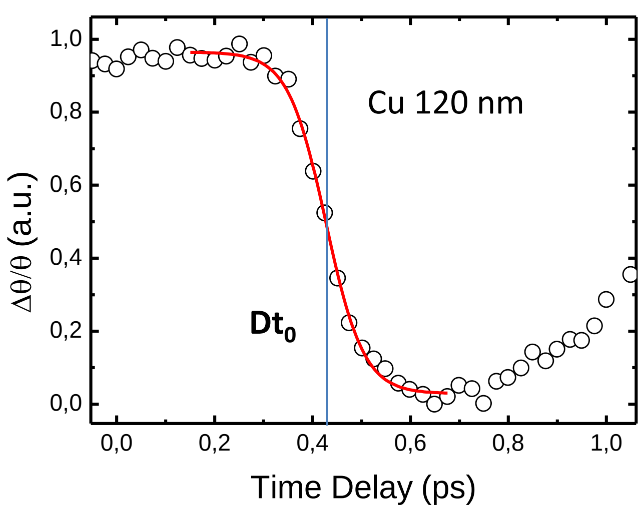
N. Bergeard,et al , Phys. Rev. Lett. 117, 147203 (2016)

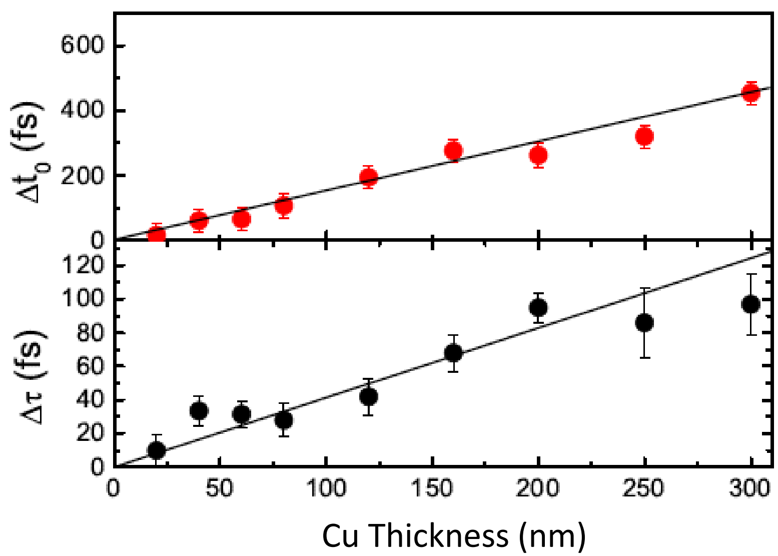
Femto second electron pulse - Demagnetization



Vs Cu (X nm)

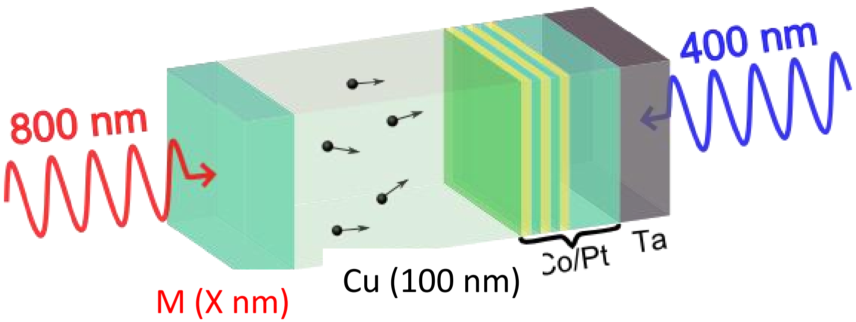


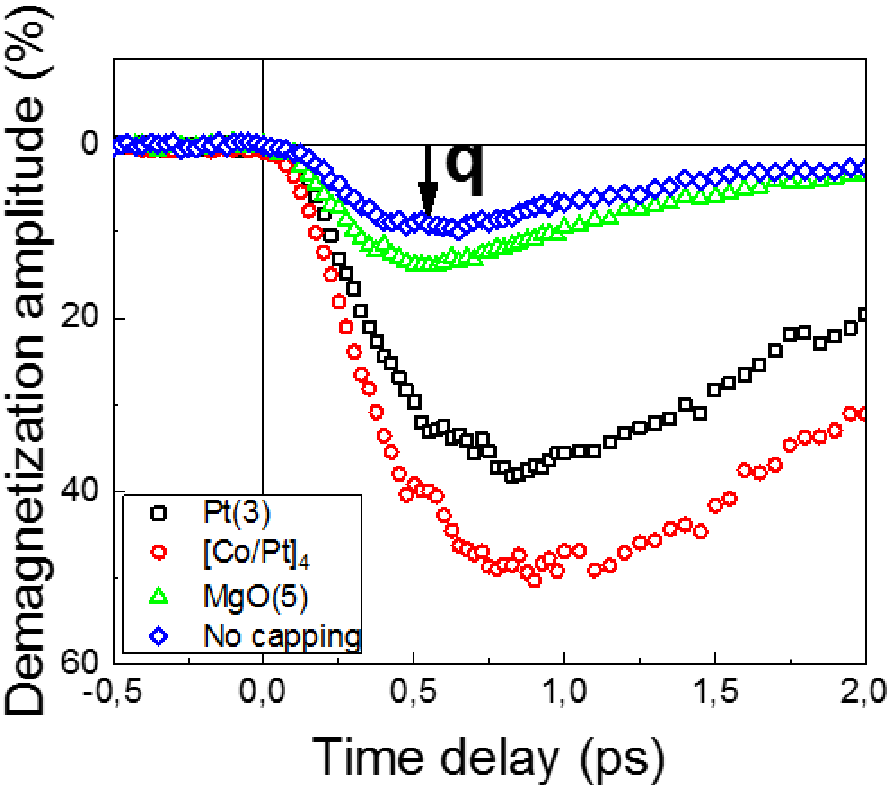




Linear variation of Δt_0 up to 300 nm /Hot electrons velocity of 0.7×10^6 m/s

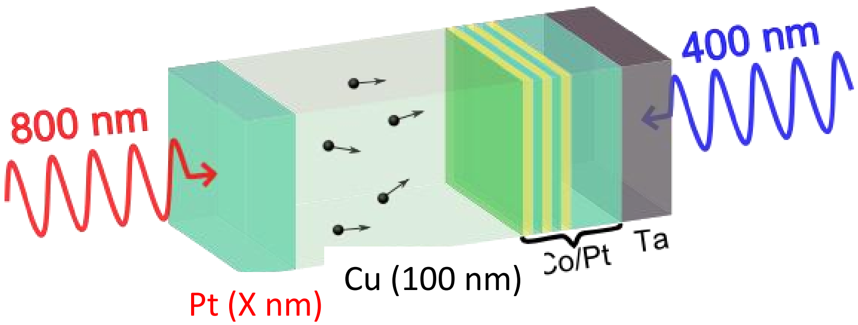
Femto second electron pulse - Demagnetization



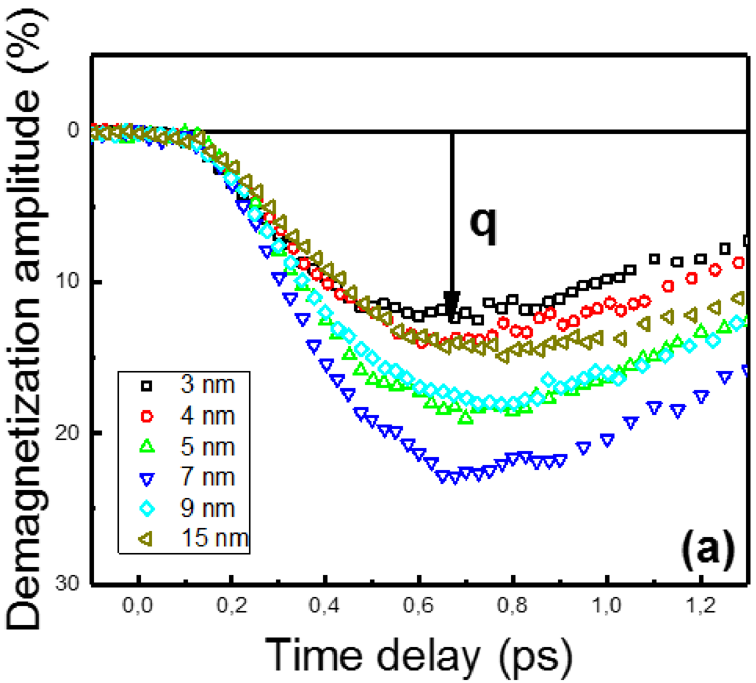


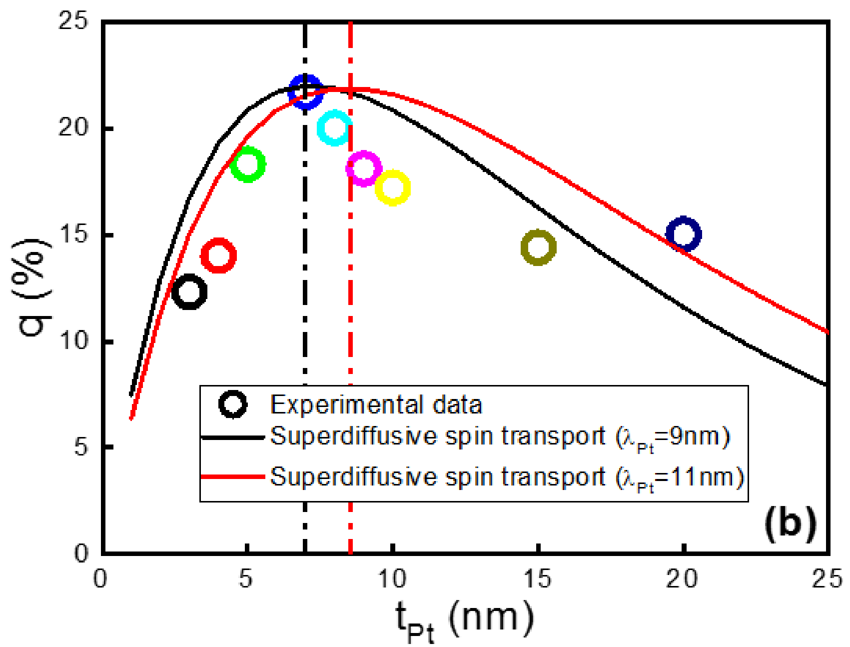
N. Bergeard Applied Physics Letters 117 (22), 222408 (2020)

Femto second electron pulse - Demagnetization



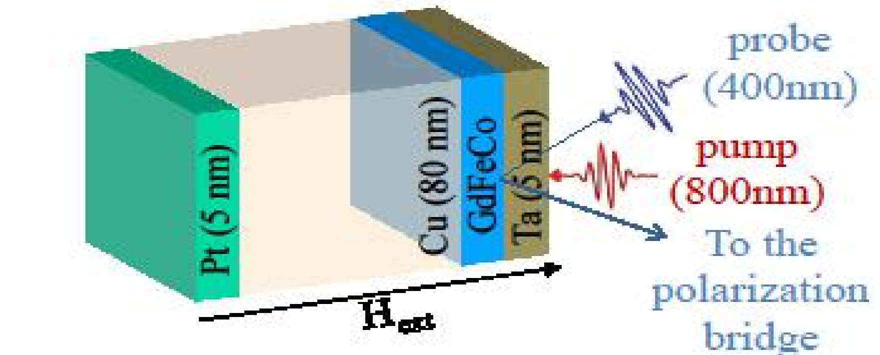
- Superdiffusive spin transport
- Optimized layers for the generation of ultrashort hot-electron pulses
- Optimum : Pt thickness of 7 nm

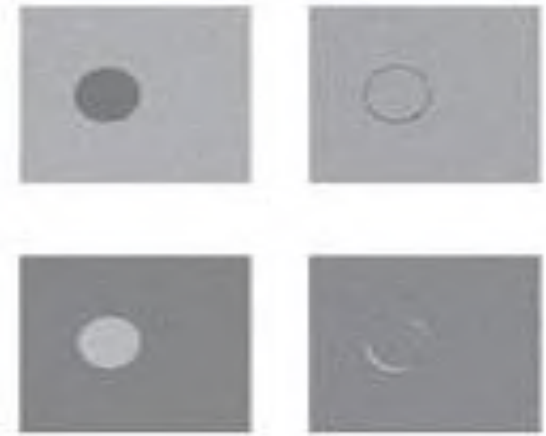


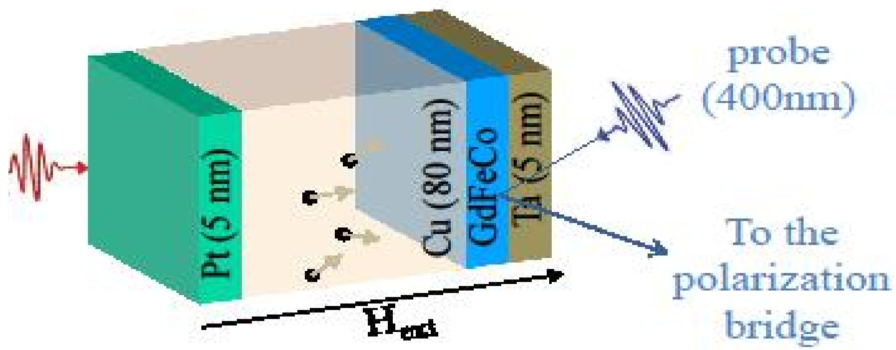


N. Bergeard Appl. Phys. Lett. 117 (22), 222408 (2020)

Switching GdFeCo with a Single electron pulse







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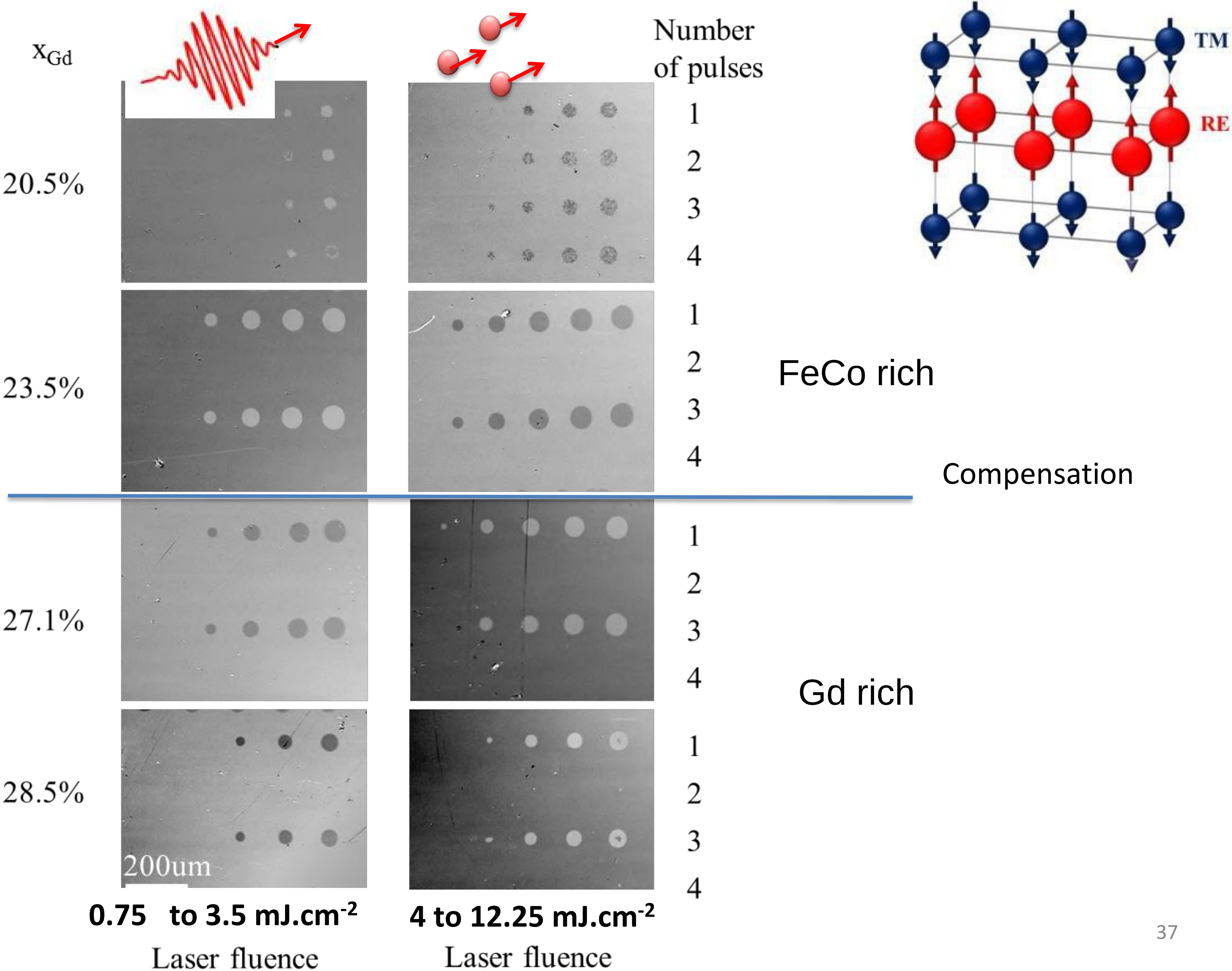
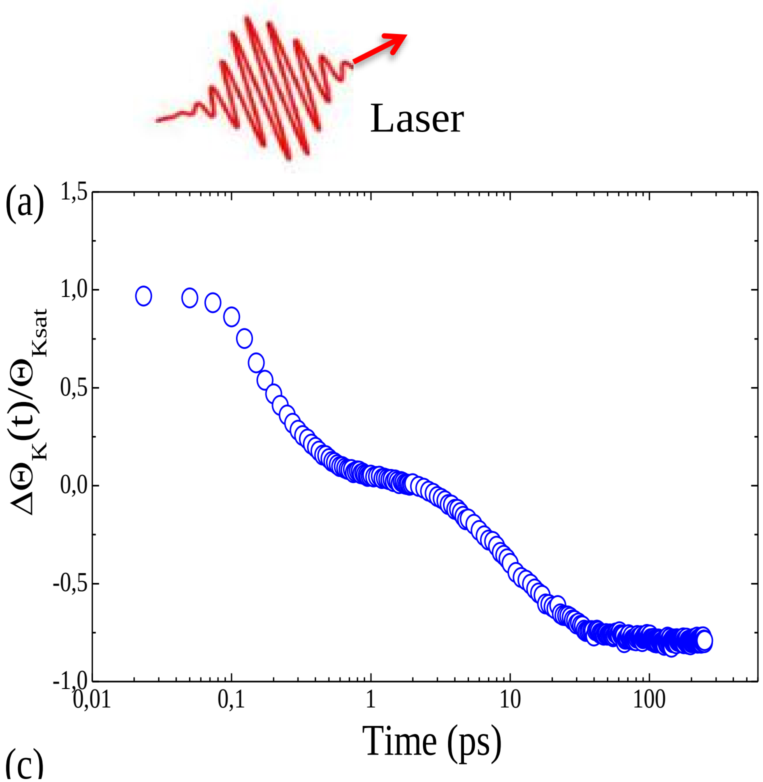
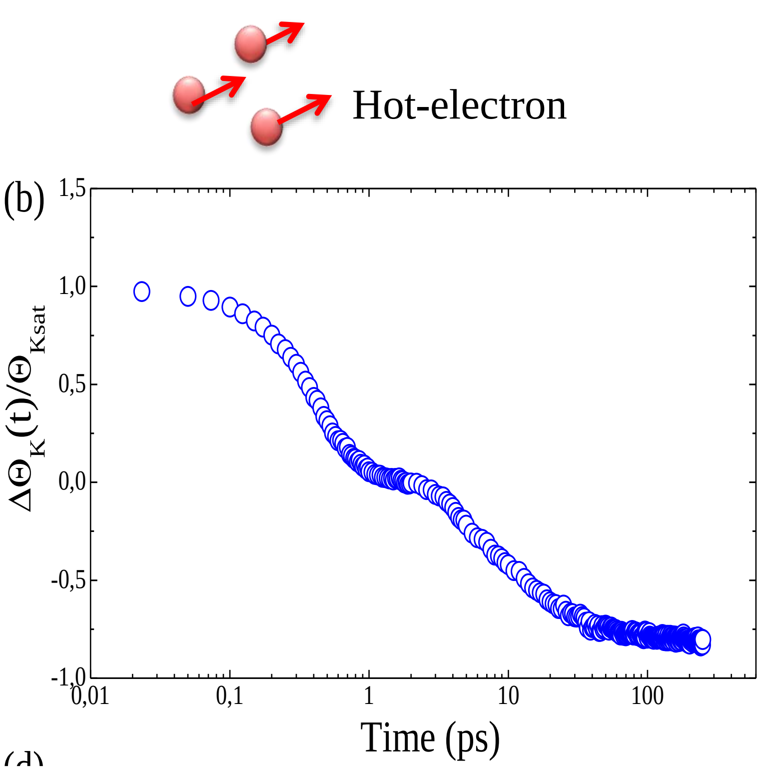
Y. Xu, et al Adv Matter **29** 42 1703474 (2017)



xGd
Number of pulses
TM
RE
20.5%
23.5%
27.1%
28.5%
1
2
3
4
FeCo rich
Compensation
Gd rich
200um
0.75 to 3.5 mJ.cm-2
Laser fluence
4 to 12.25 mJ.cm-2
Laser fluence

Switching GdFeCo with a Single electron pulse





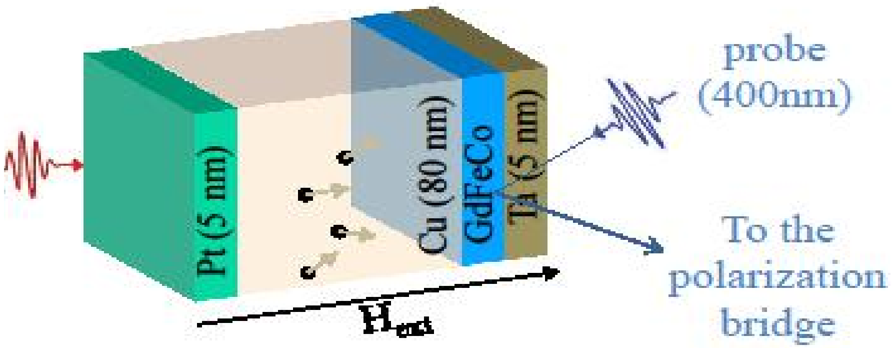
3.2 mJ.cm^{-2}

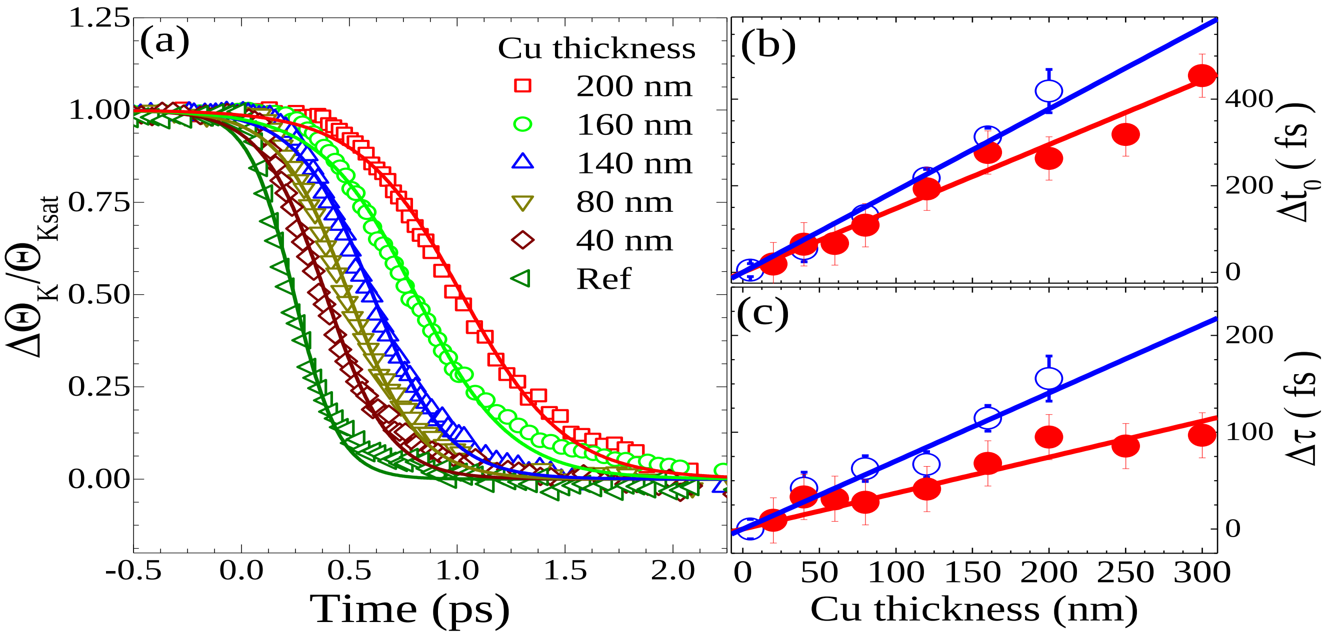
15 mJ.cm^{-2}

in 5 nm thick $Gd_{23,9}(FeCo)_{76.1}$ film

Ultra short hot Electron pulse can generate ultra fast GdFeCo switching

Switching GdFeCo with a Single electron pulse

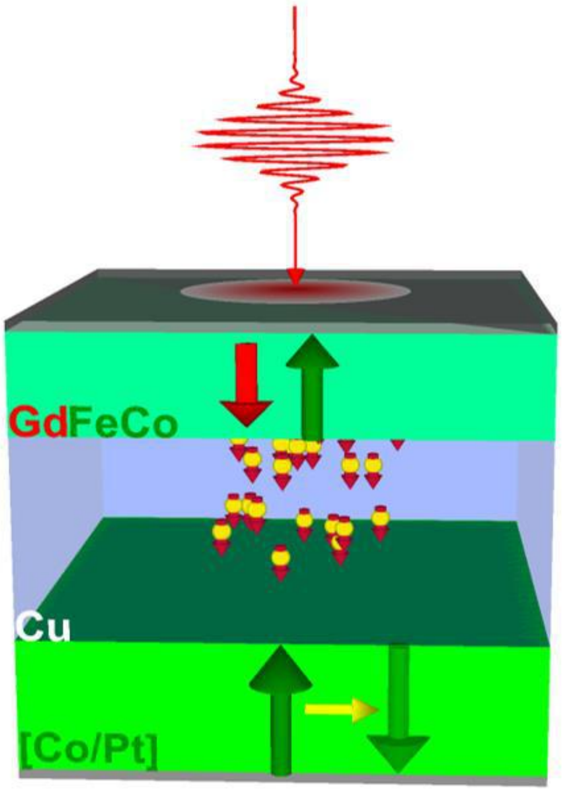


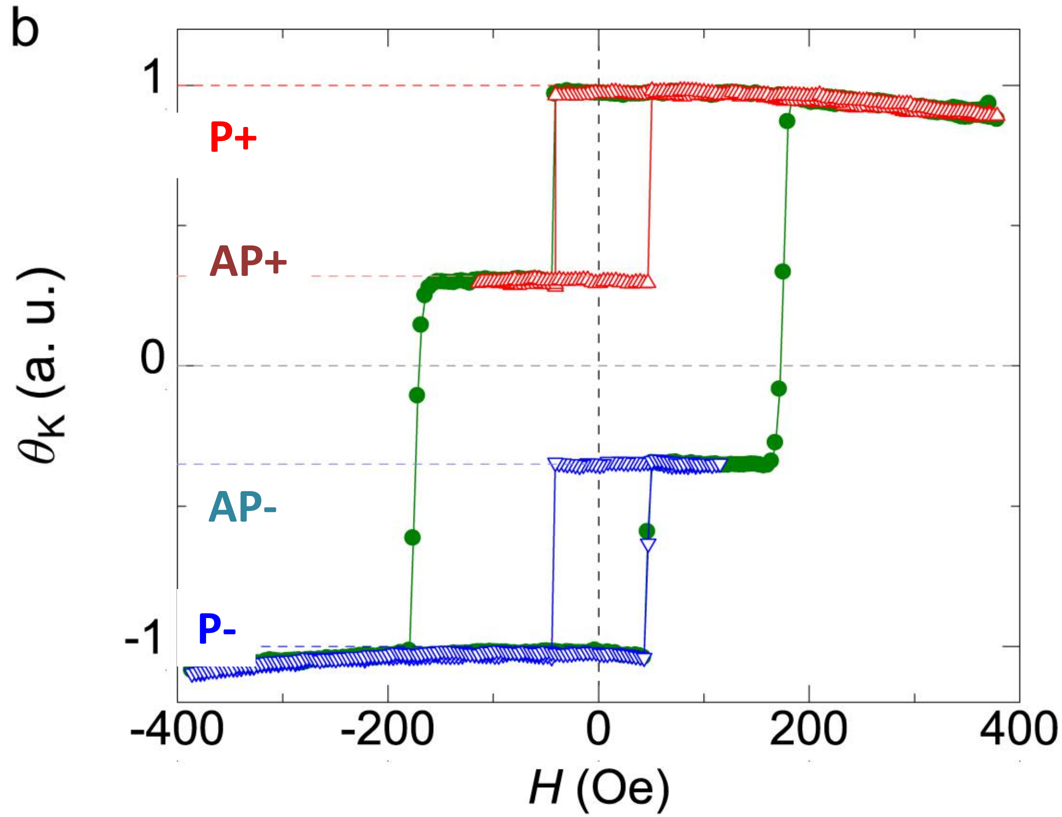


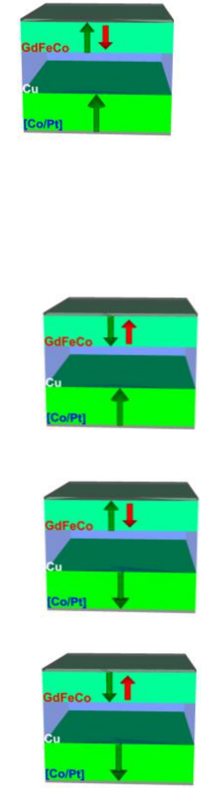
Ultra short hot Electron pulse can generate GdFeCo switching

Y. Xu, et al Adv Matter **29** 42 1703474 (2017)

Switching a ferromagnet with asingle polarised electrons pulse







Satoshi Iihama
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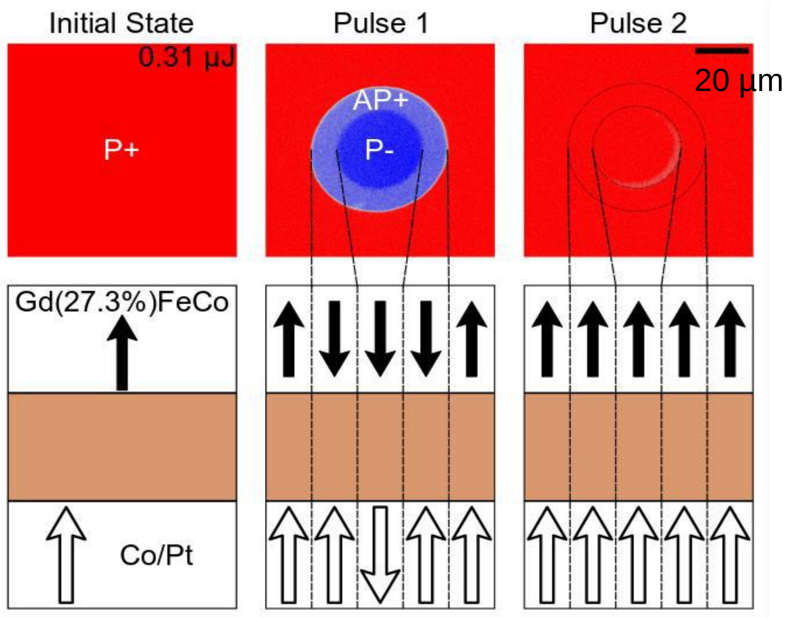
Quentin Remy
Lorraine Univ

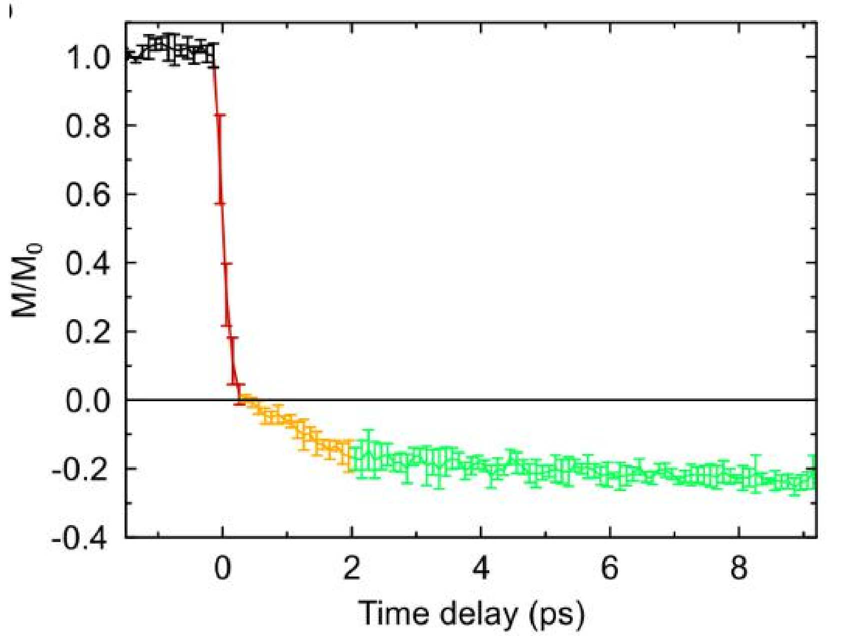
Junta Iihama
Tohoku Univ

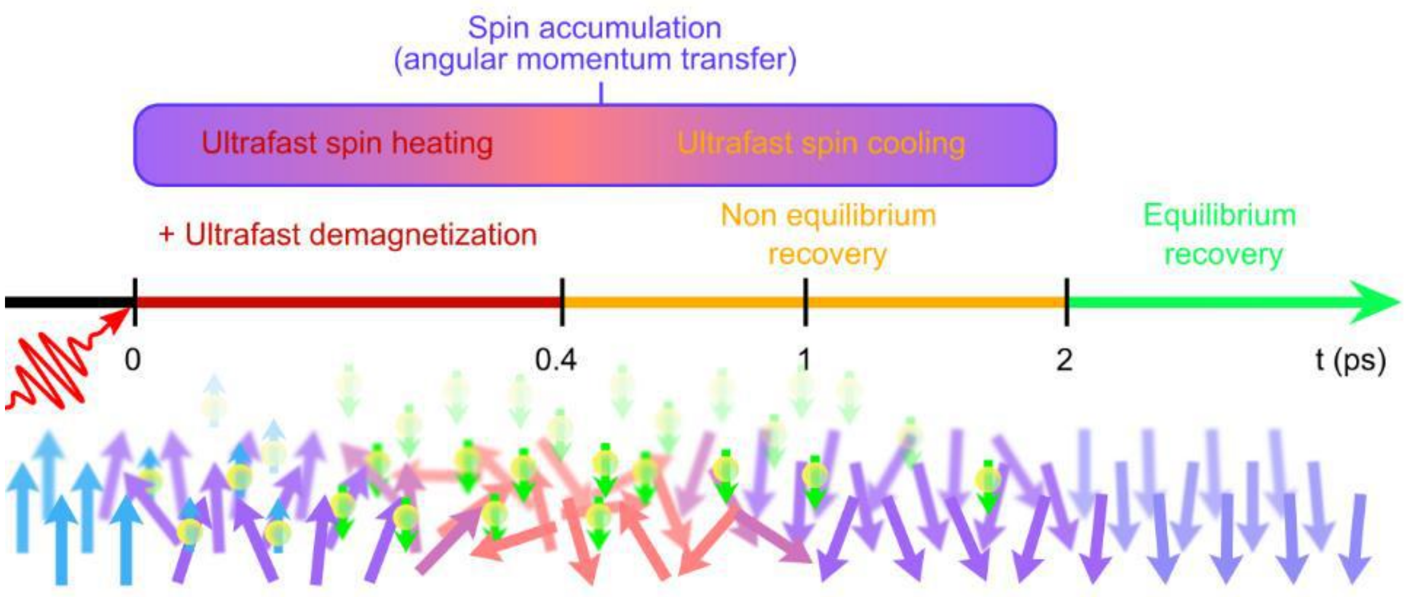
TOHOKU UNIVERSITY

S. Iihama et al. Adv. Mater. ***30****, 1804004 (2018)*

Switching a ferromagnet with asingle polarised electrons pulse



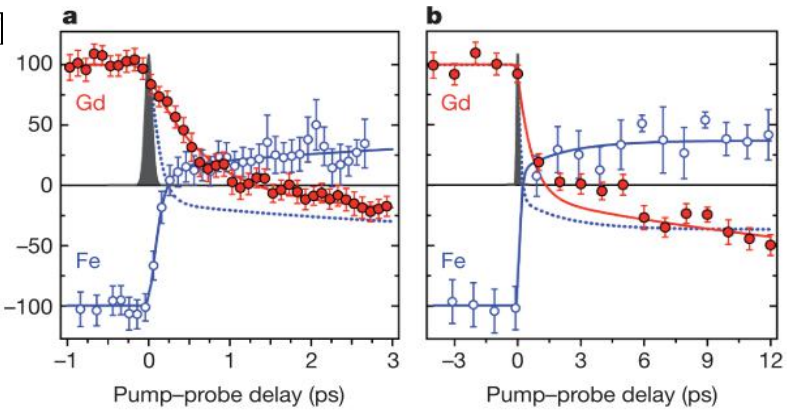


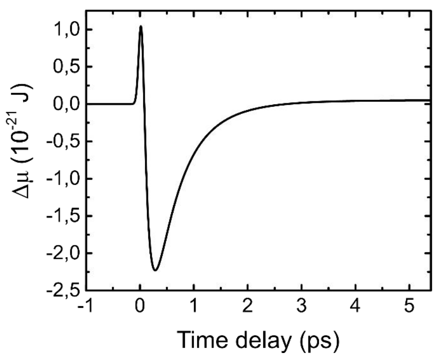


Q. Remy et al. in preparation

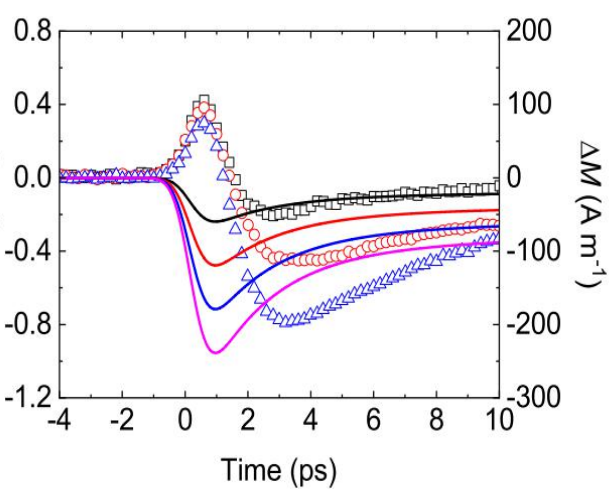
Decoupling and spin transport

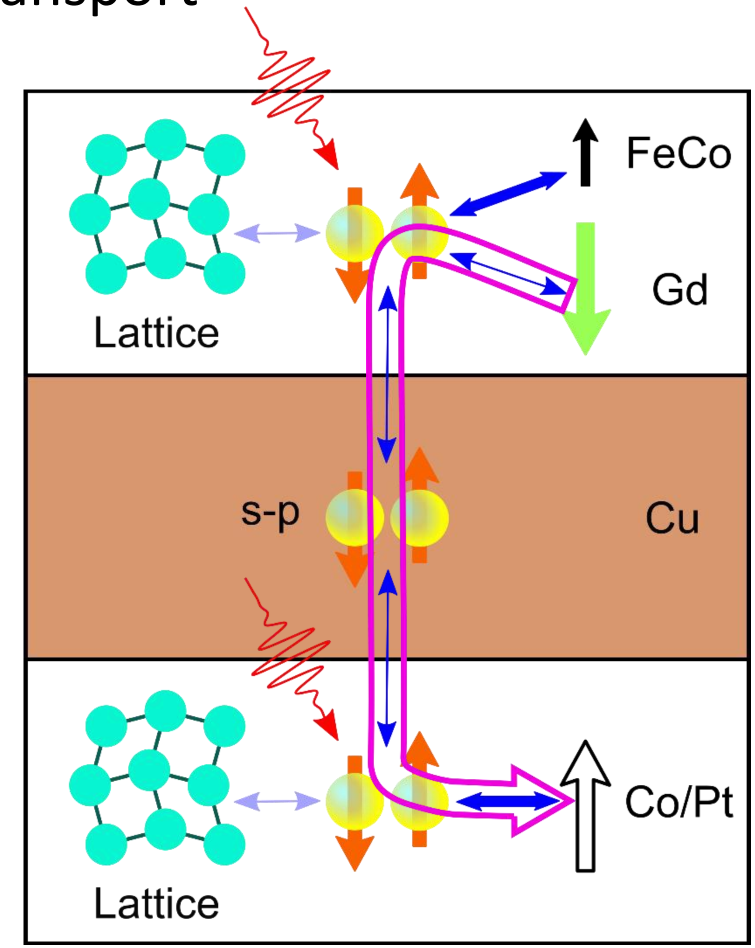
[1]





[2]

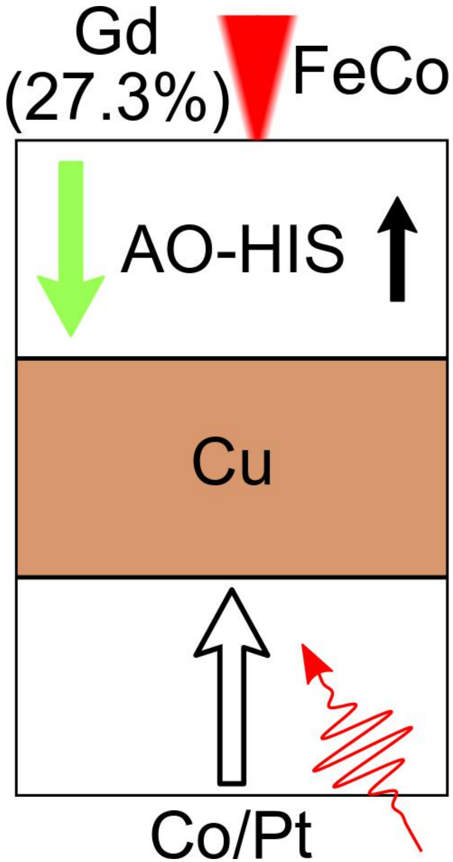


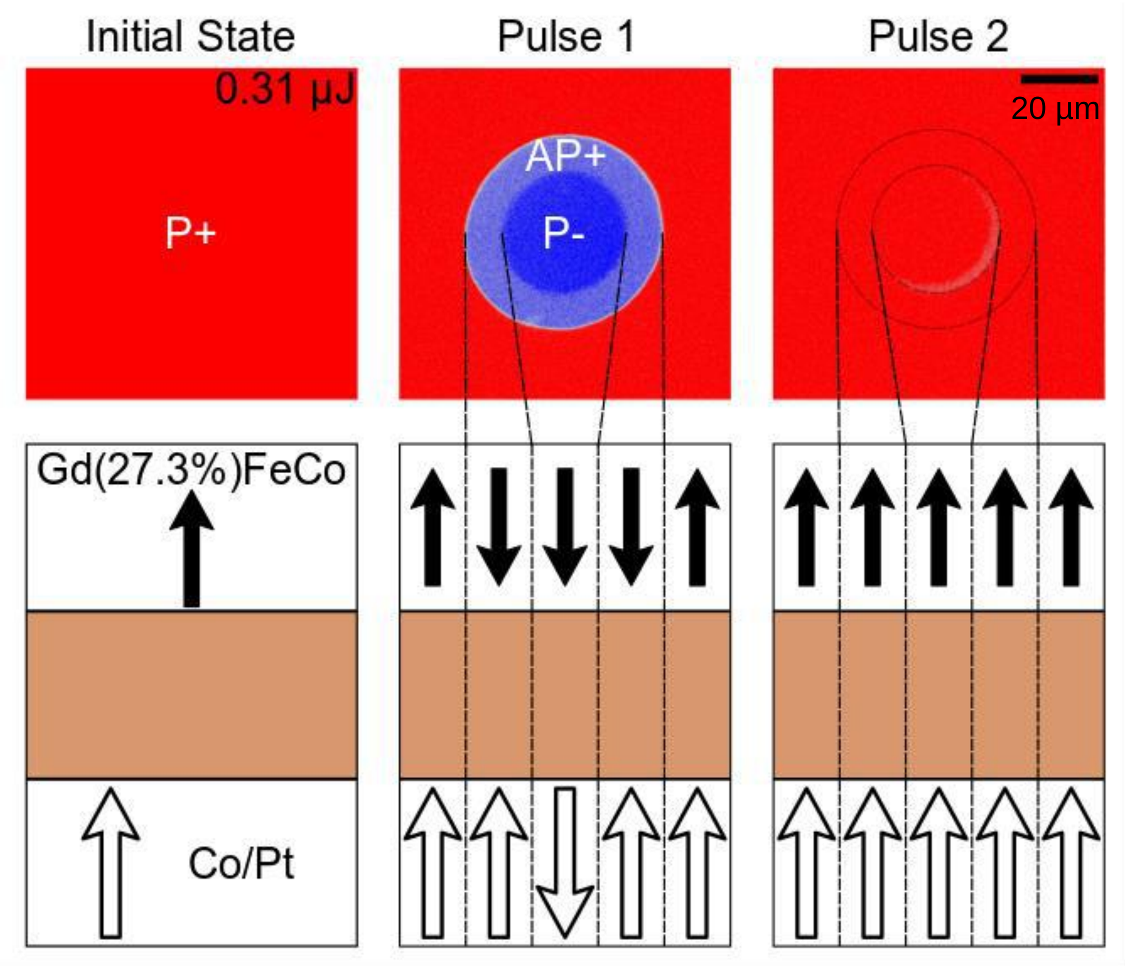


$$\Delta\mu = \mu_{\uparrow} - \mu_{\downarrow} \propto -\frac{\mathrm{d}M}{\mathrm{d}t}$$

[1] Radu, I. *et al. Nature* **472**, 205–208 (2011).
[2] Choi, G.-M. & Min, B.-C. Phys. Rev. B 97, 014410 (2018).

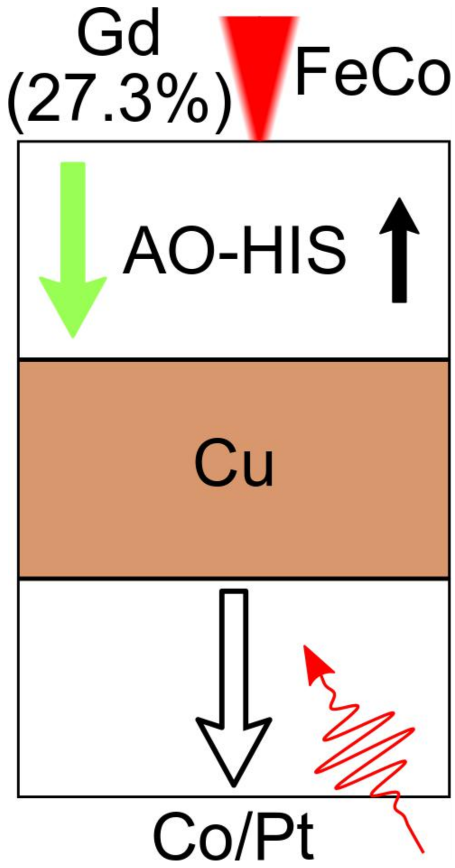
switching of ferromagnets

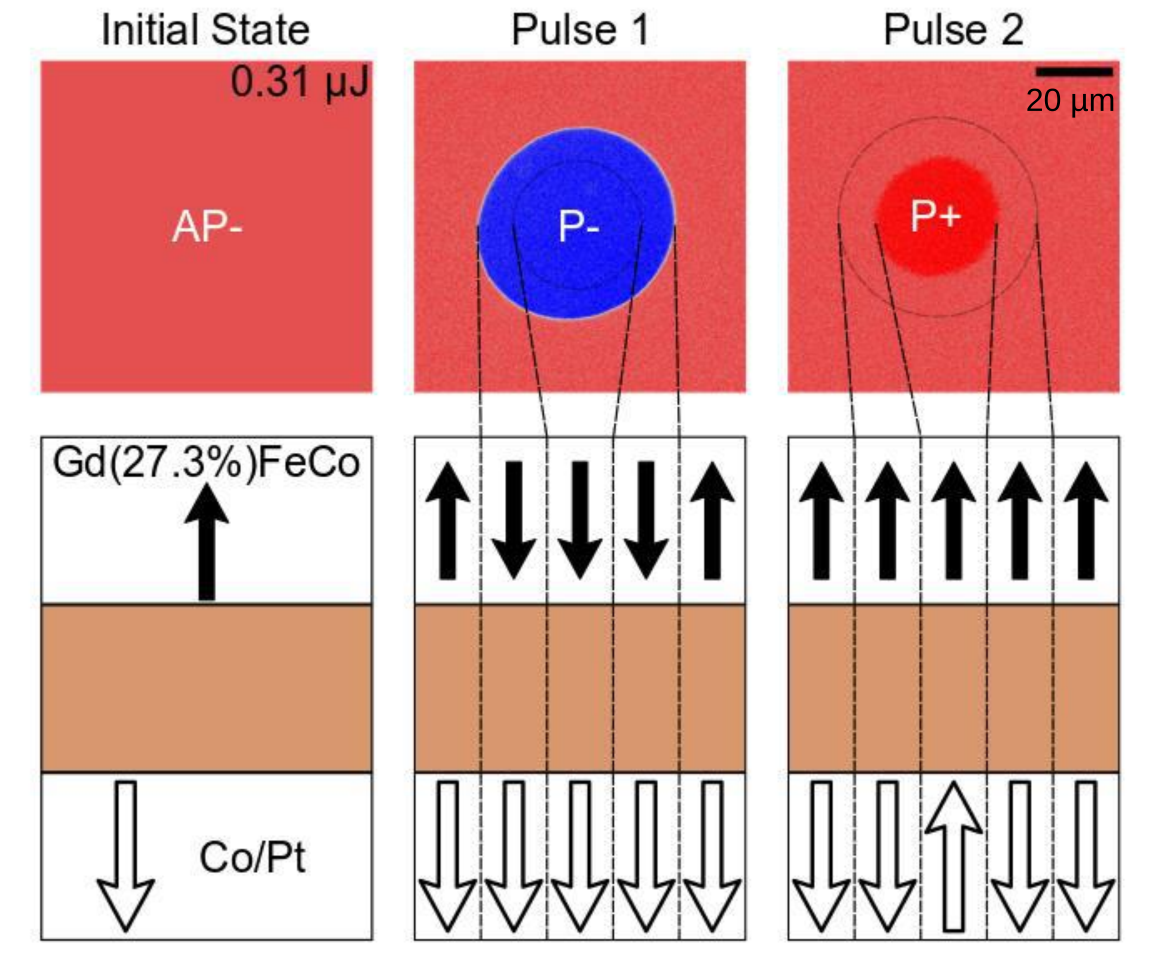




Iihama, S. *et al. Adv. Mater.* **30**, 1804004 (2018).
Remy, Q. *et al. Adv. Sci.* **7**, 2001996 (2020).

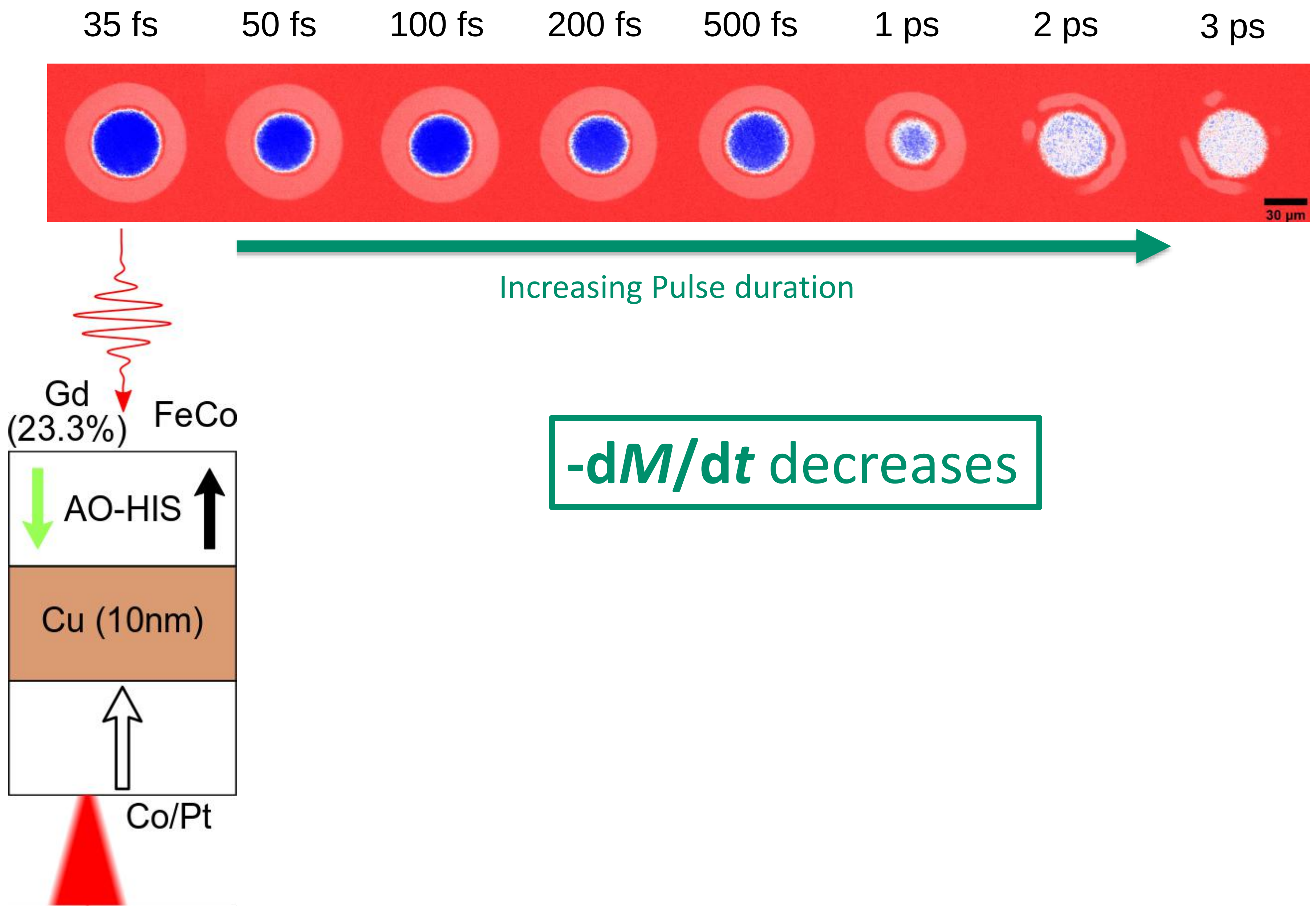
switching of ferromagnets





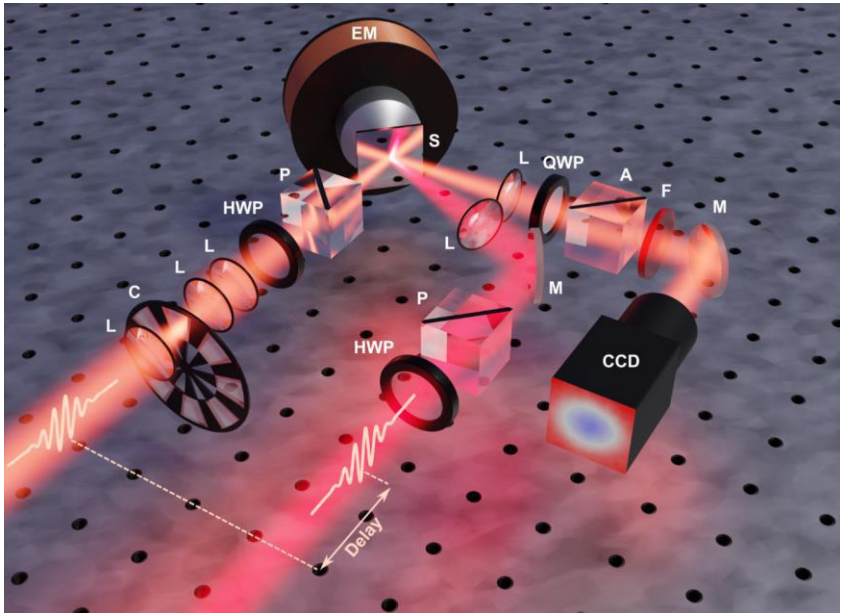
Iihama, S. *et al. Adv. Mater.* **30**, 1804004 (20
Remy, Q. *et al. Adv. Sci.* **7**, 2001996 (2020).

Tuning the spin current

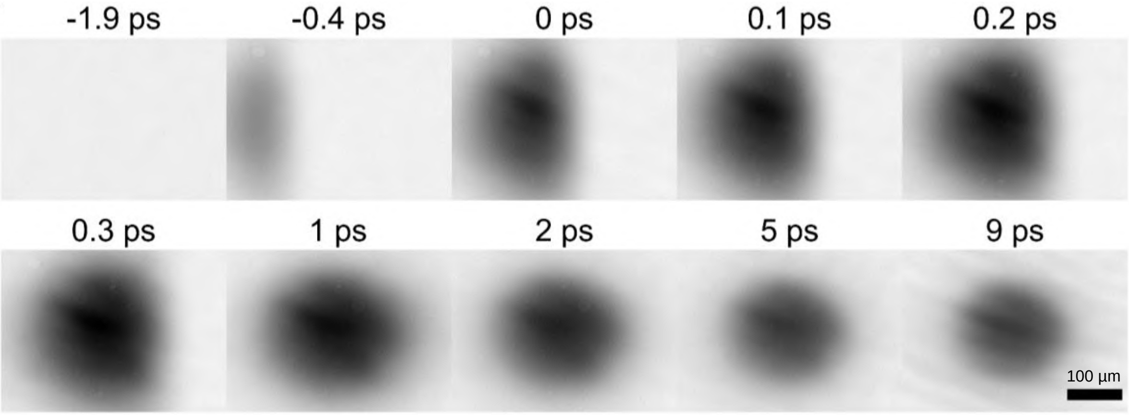


-d*M*/d*t* decreases

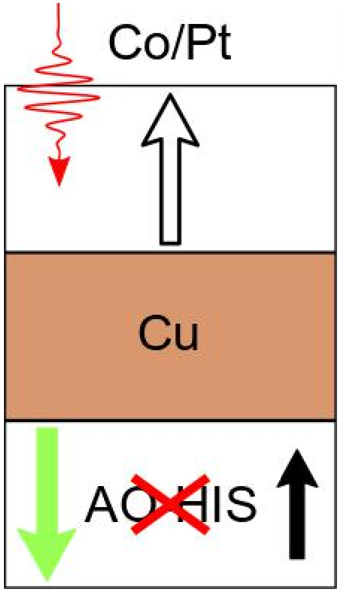
TR-MOKE microscopy measurements

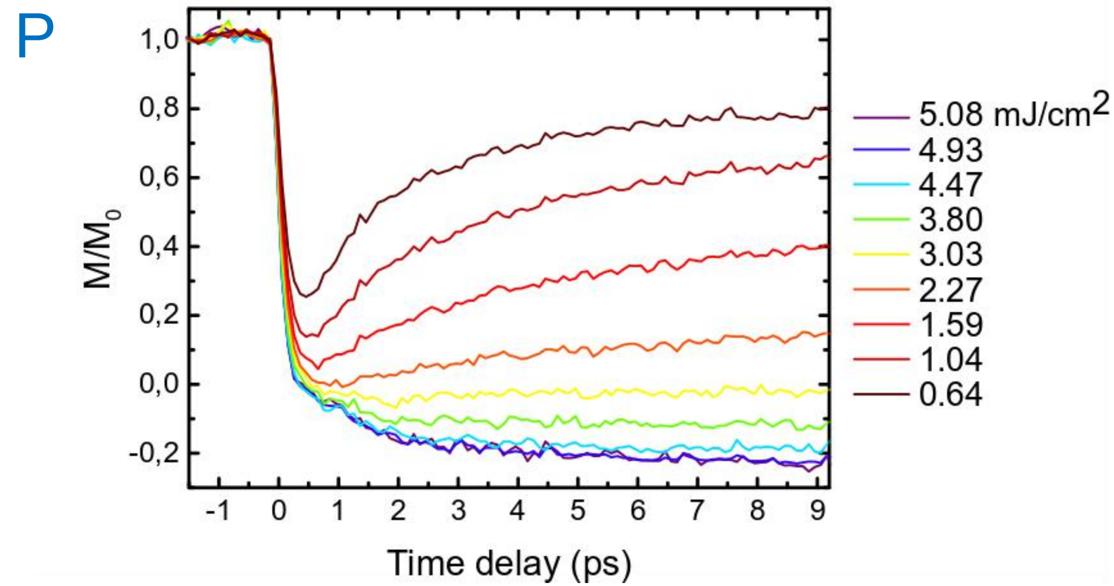


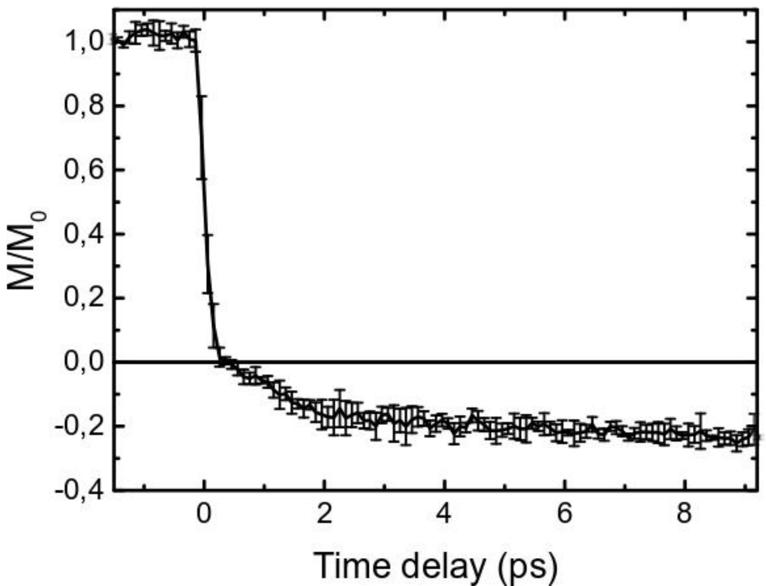
- Magnetization as a function of time and fluence.
- Real (normalized) magnetization at all times: measurements for several quarter wave plate angles.

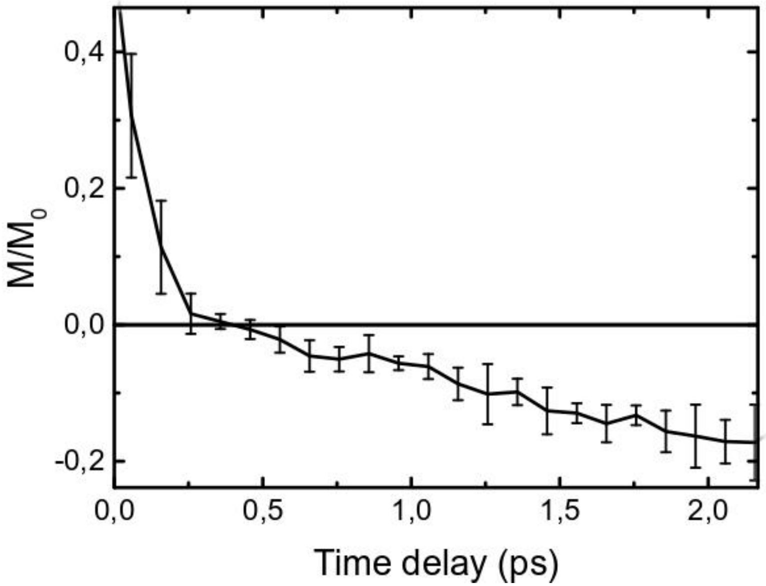


TR-MOKE microscopy measurements









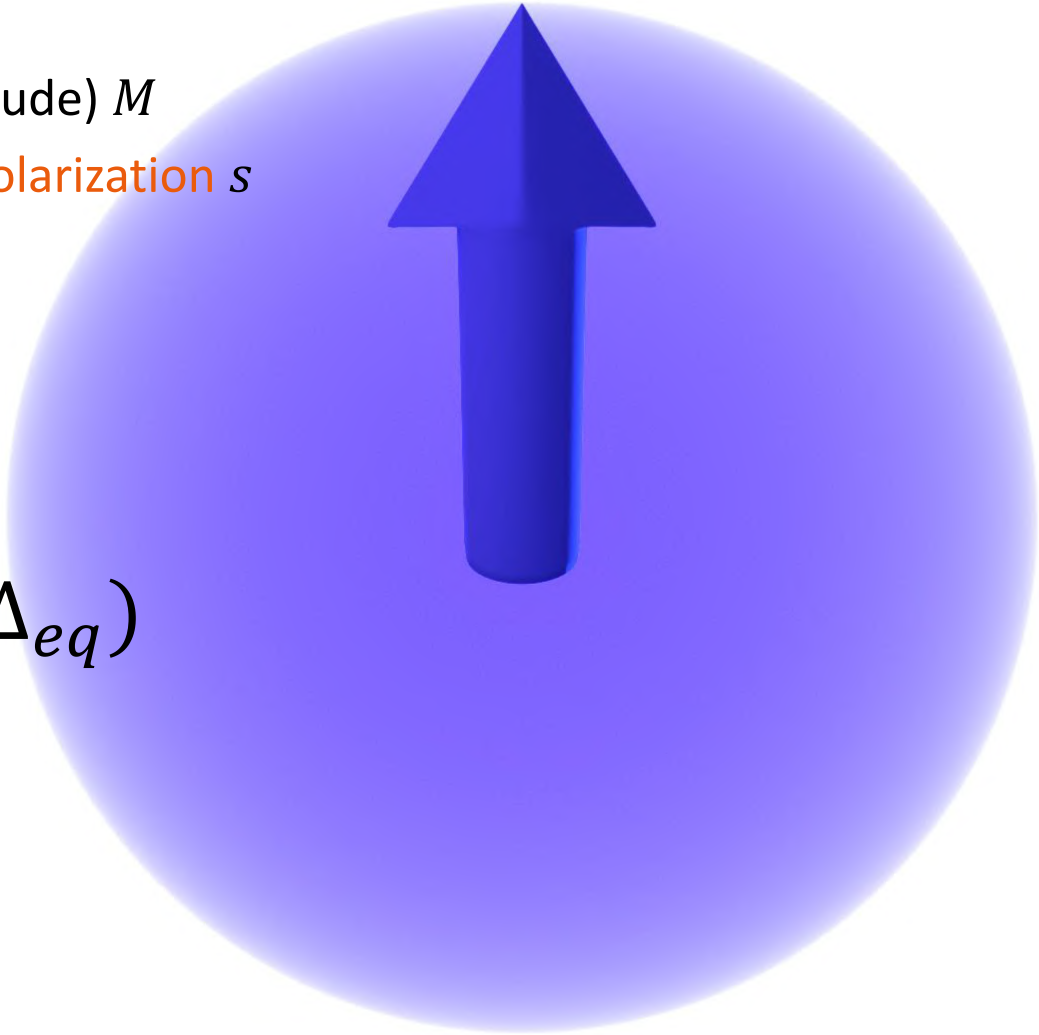
Proposed mechanism

Three quantities of interest:

- The local magnetization (amplitude) M
- The conduction electron spin polarization s
  - Not zero at equilibrium
- The spin accumulation $\Delta\mu$
  - Zero at equilibrium

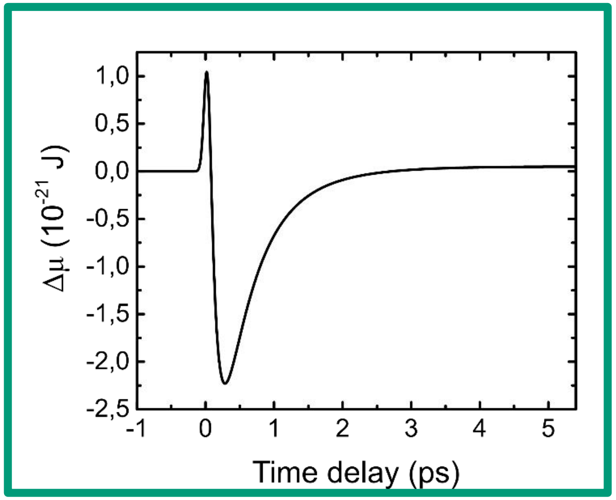
$$\Delta\mu = \frac{s - s_{eq}}{\bar{D}} + (\Delta - \Delta_{eq})$$

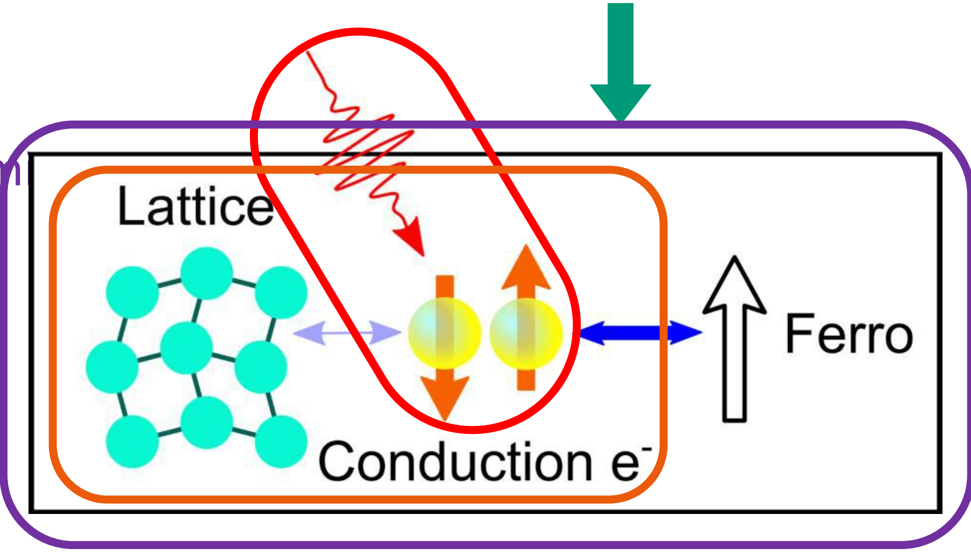
Never all zero at the same time.



Calculations of the ultrafast dynamics

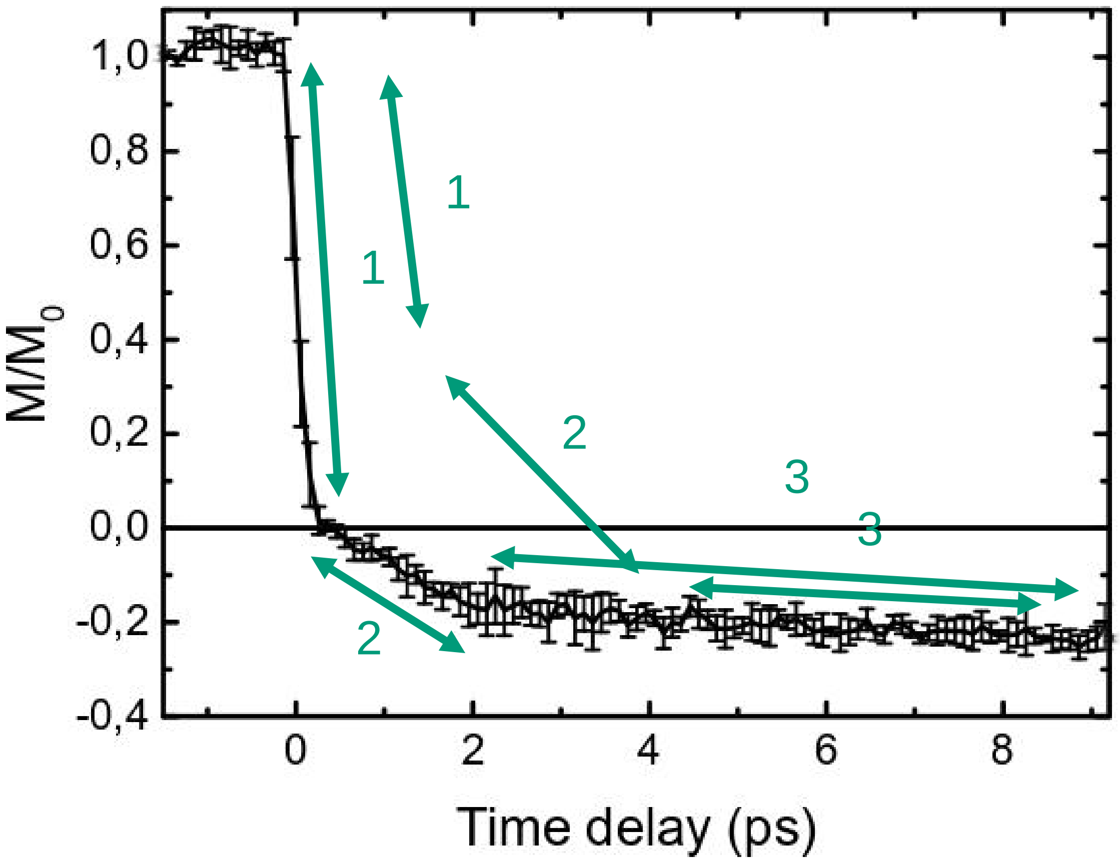
- Light pulse absorption. Energy transfer.
- Two temperature model with temperature dependent diffusion. Energy transfer.
- Phenomenological spin accumulation. Angular momentum transfer.
- Out of equilibrium magnetization dynami ferromagnets in the presence of a spin accumulation [1]. Angular momentum transfer.





[1] Beens, M., Duine, R. A. & Koopmans, B. *Phys. Rev. B* **102**, 054442 (2020).

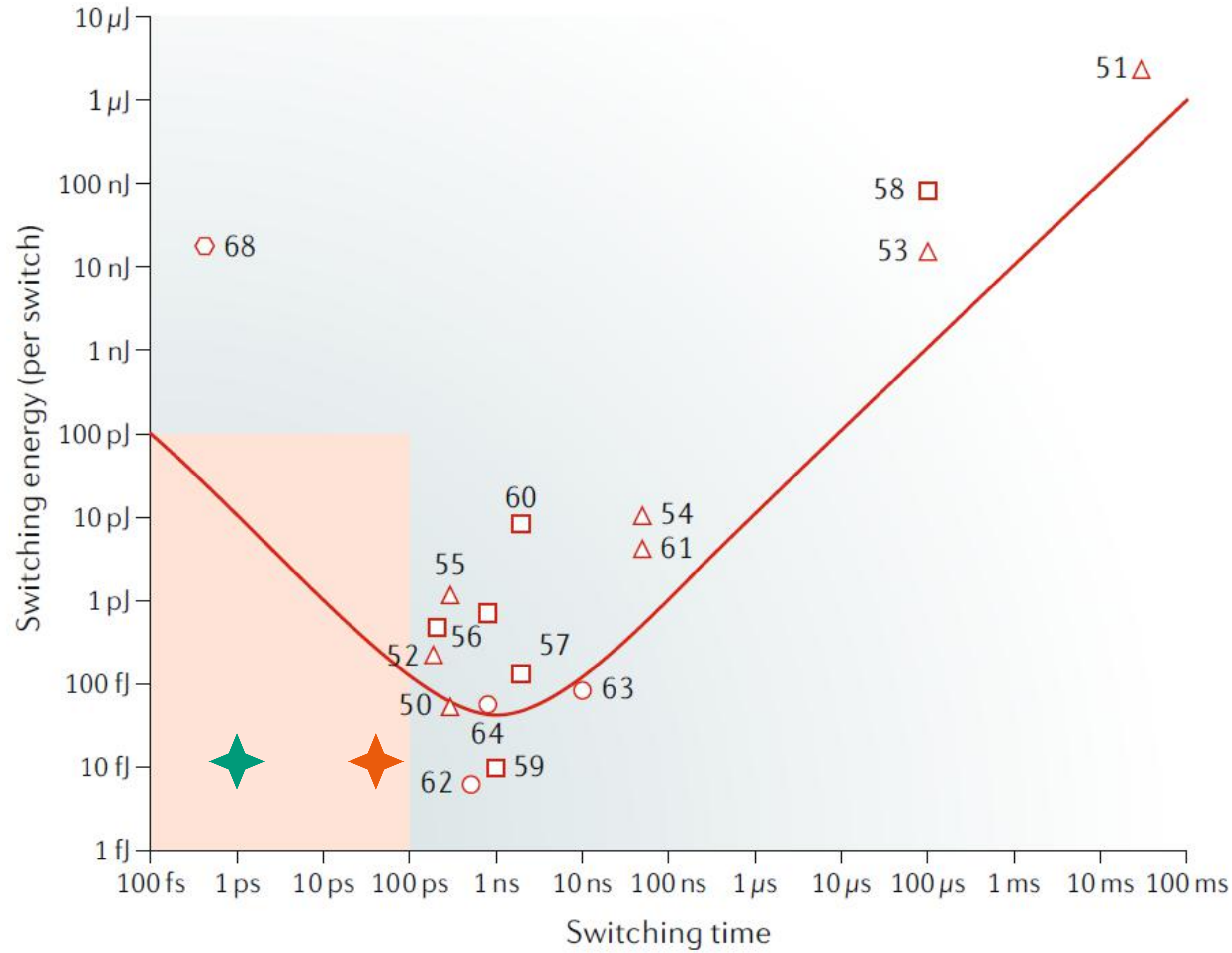
Calculations of the ultrafast dynamics



Speed and energy efficiency

GdFeCo

Co/Pt in the spinvalve



Kimel, A. V. & Li, M. *Nat. Rev. Mater.* **4**, 189–200 (2019).

<u>Out of equilibrium</u>: less dissipation in the lattice allows to be more energy efficient together with a higher speed.

Conclusions

- Femtosecond laser pulses can trigger an out of equilibrium state in metallic magnetic materials. This allows a much faster magnetization dynamics to happen.
- Ultrafast demagnetization generates ultrashort spin currents.
- These spin currents can be used to reverse the magnetization of ferromagnets in less than a picosecond.
- One can tune the spin current by changing the alloy composition and the laser pulse duration.
- Light itself is not required. A spin current combined with a heat current is sufficient.

Acknowledgments

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Yassine Quessab
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Weisheng Zhao
Wei Zhang
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Agence Nationale de la Recherche GIP ANR