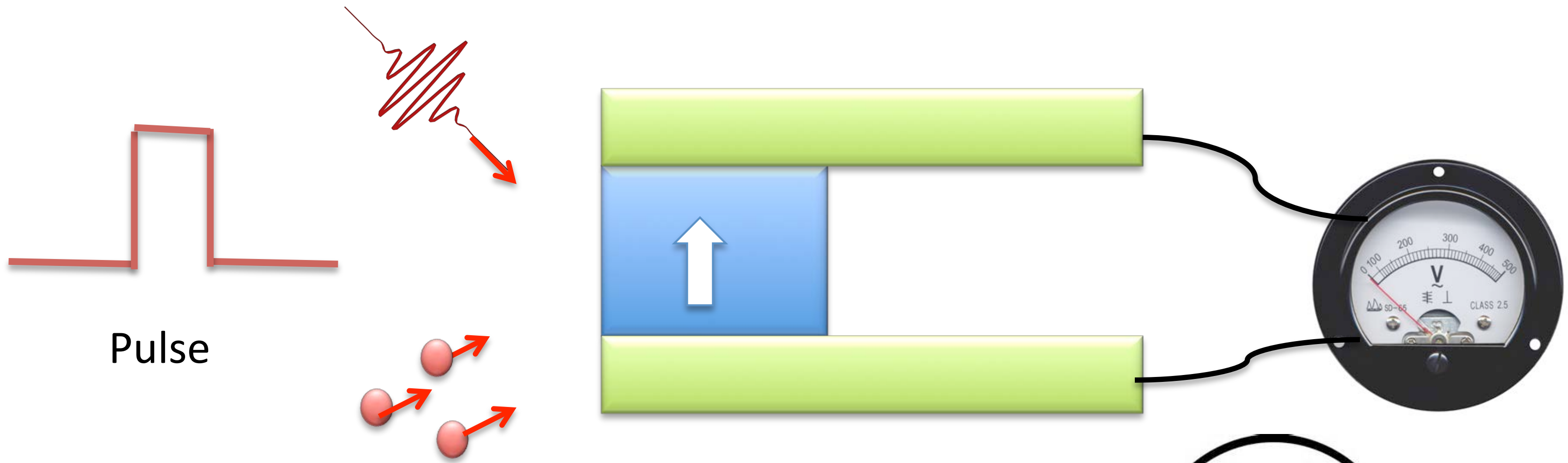
Femto-second light and electrons pulses to switch magnetisation

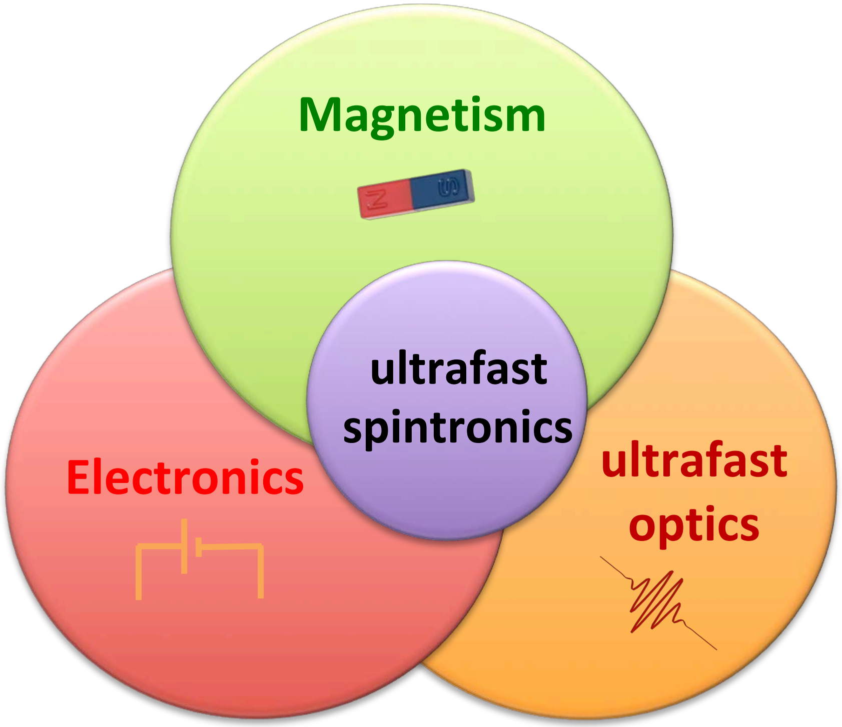
Toward ultrafast Spintronic ?

Stéphane Mangin
Institut Jean Lamour, Université de Lorraine – Nancy - France

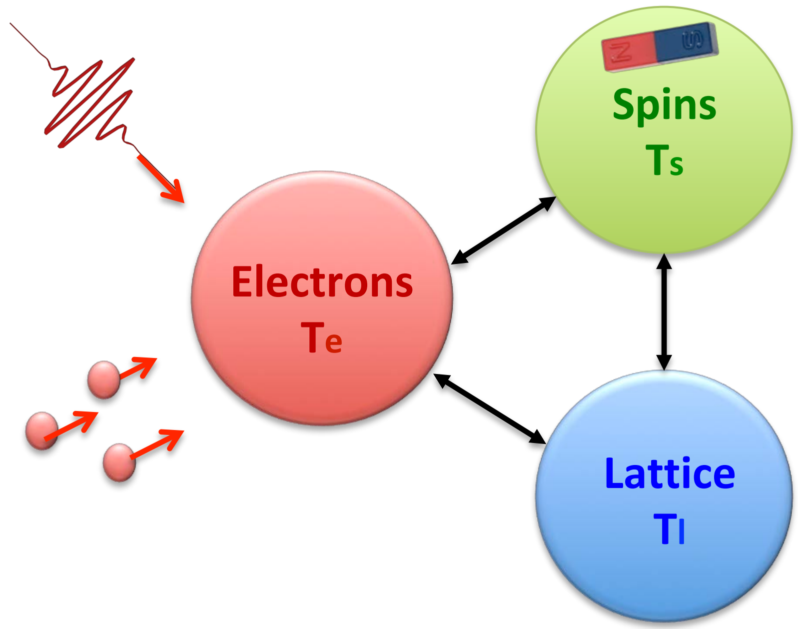


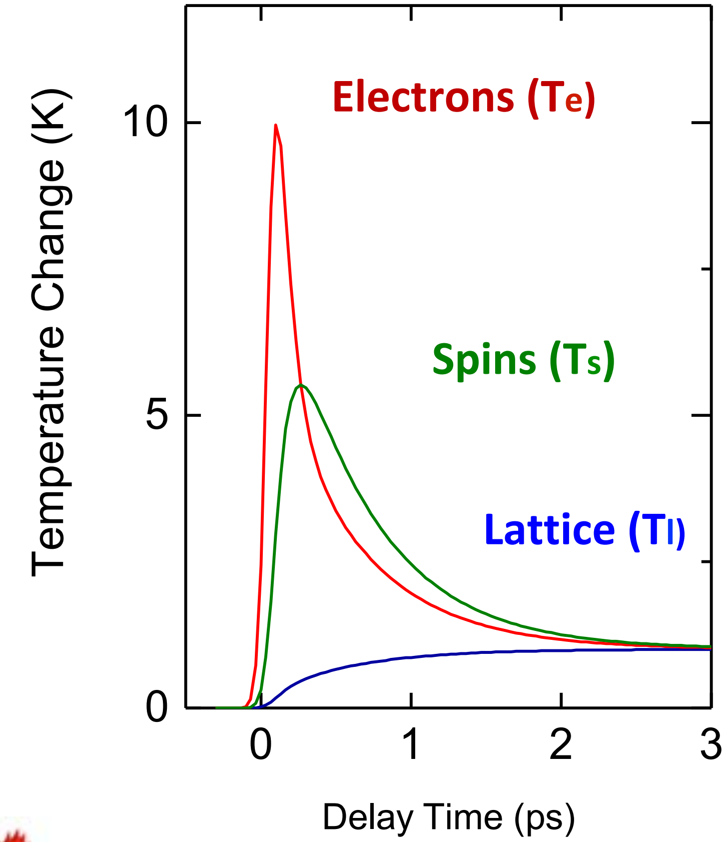
Introduction

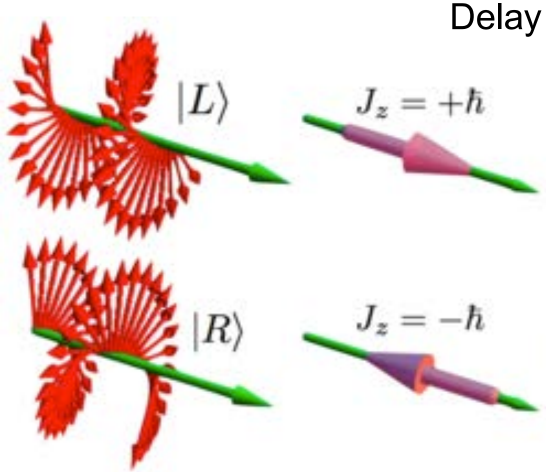
Ultrafast Spintronic ?



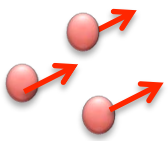
Introduction : Fundamental Interest / Fundamental timescale

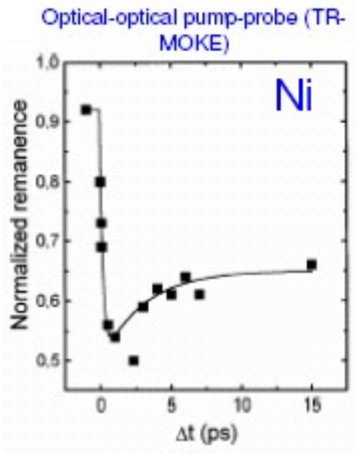
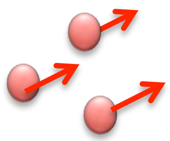




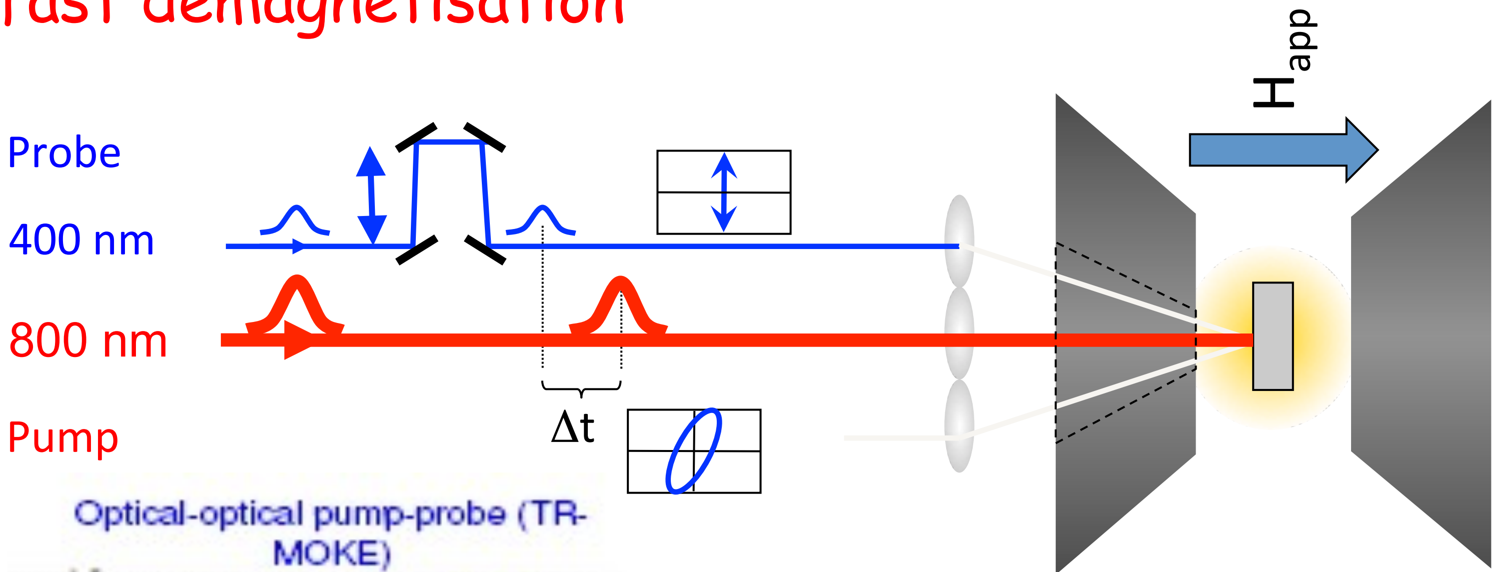


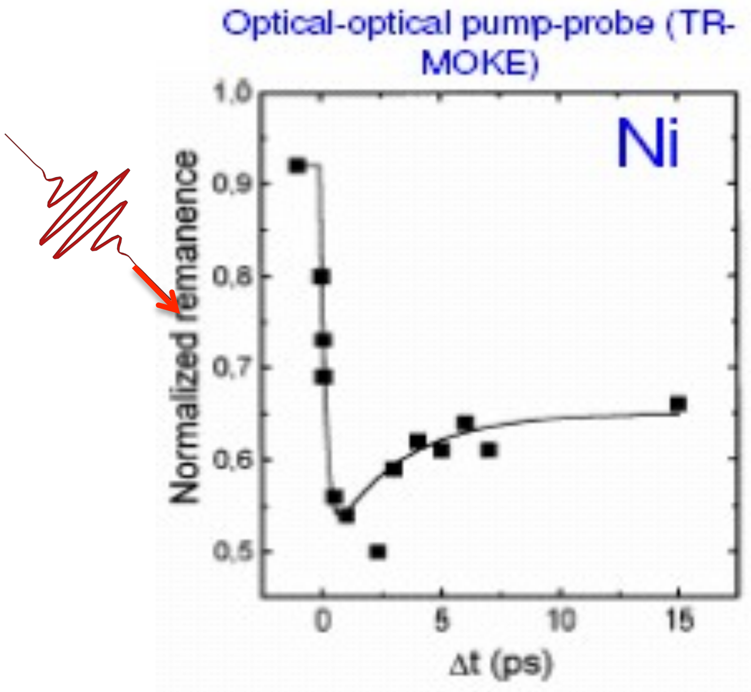
- Energy Transfer
- Angular Momentum Transfer

Magnetisation Manipulation Ultra short pulses	Ultra fast Demagnetisation	All Optical Helicity **Independent** switching (AO-HIS)	All Optical Helicity **dependent** switching (AO-HDS)	All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)
 Light				
 Electron				

Magnetisation Manipulation Ultra short pulses	Ultra fast Demagnetisation 	All Optical Helicity **Independent** switching (AO-HIS)	All Optical Helicity **dependent** switching (AO-HDS)	All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)
 Light	*E. Beaurepaire, et al PRL 76, 4250 (1996)*			
 Electron				

Ultra-fast demagnetisation

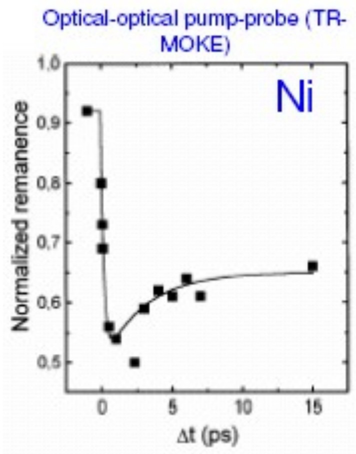
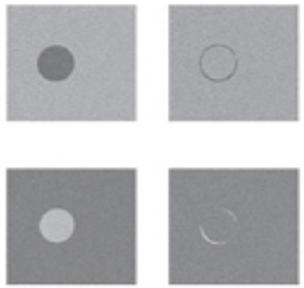
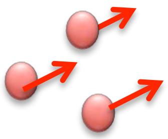




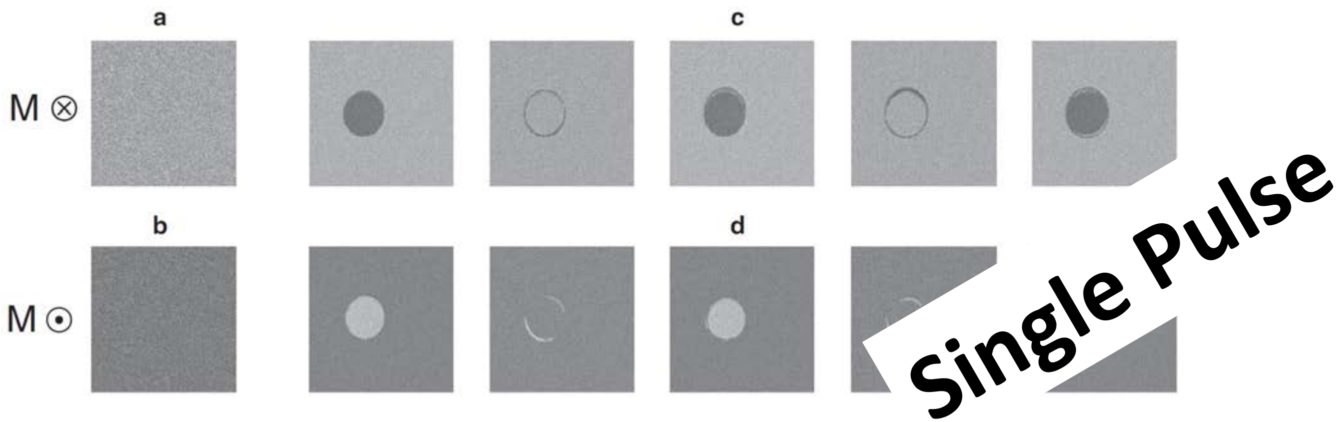
Jean Yves Bigot
1956-2018

Eric Beaurepaire
1959-2018

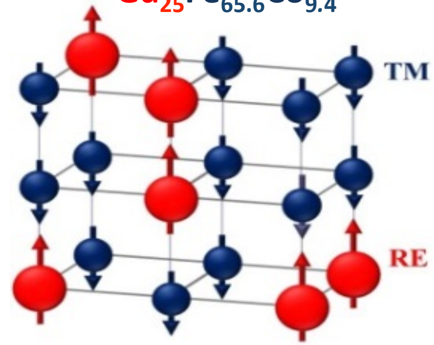
E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot
Phys. Rev. Lett. 76, 4250 (1996)

Magnetisation Manipulation / Ultra short pulses	Ultra fast Demagnetisation	All Optical Helicity **Independent** switching (AO-HIS)	All Optical Helicity **dependent** switching (AO-HDS)	All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)
				
 Light	*E. Beaurepaire, et al PRL 76, 4250 (1996)*	T. A. Ostler et al Nat. Commun. 3 666 (2012)		
 Electron				

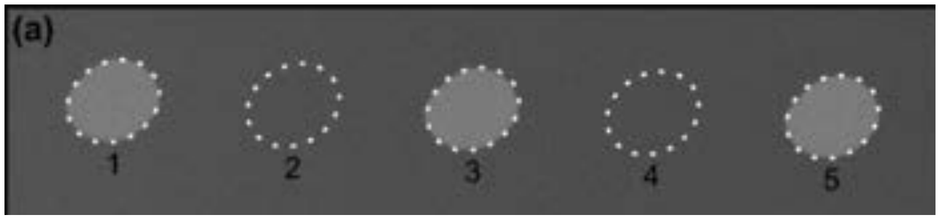
All Optical – Helicity Indepedent Switching (AO-HIS)



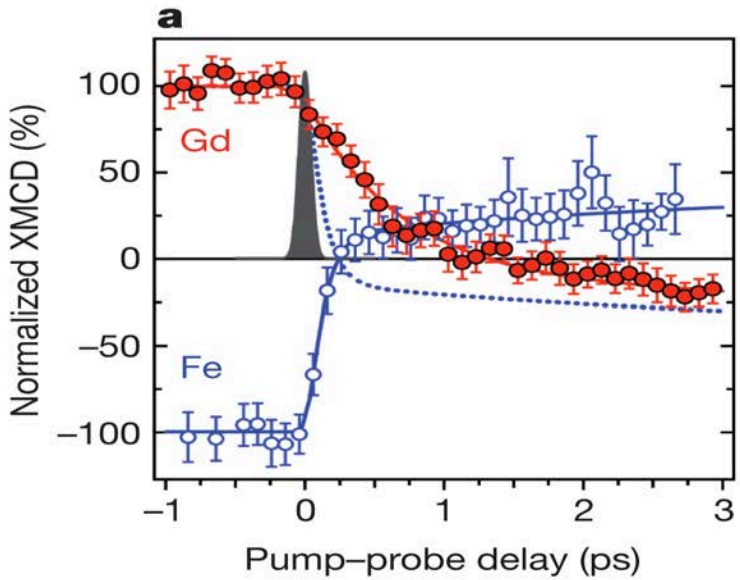
$Gd_{25}Fe_{65.6}Co_{9.4}$



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

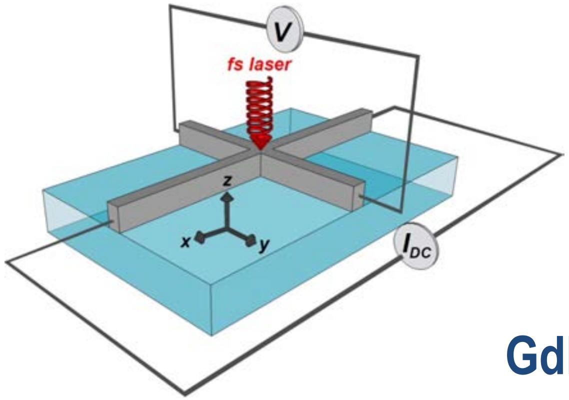


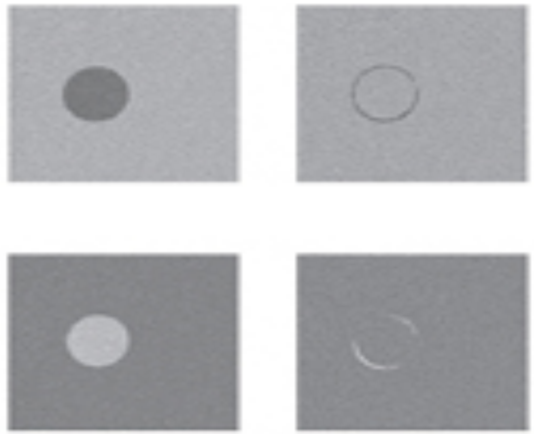
M. L. M. Lalieu et al , Phys. Rev. B **96**, 220411® 2017



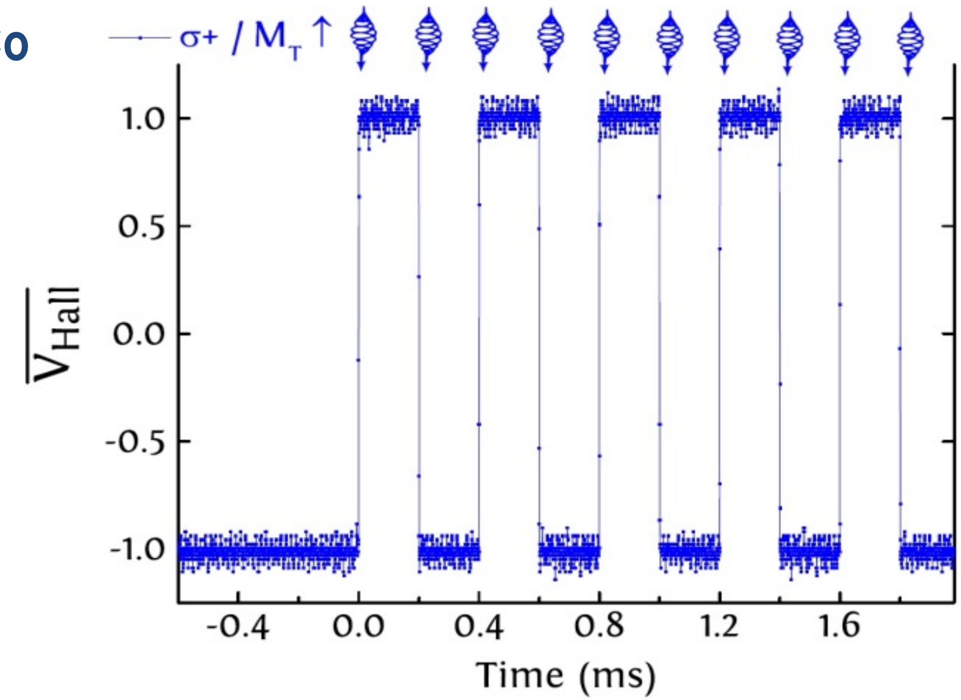
B. KOOPMANS, Tutorial (on Tuesday)

All Optical – Helicity Indepedent Switching (AO-HIS)





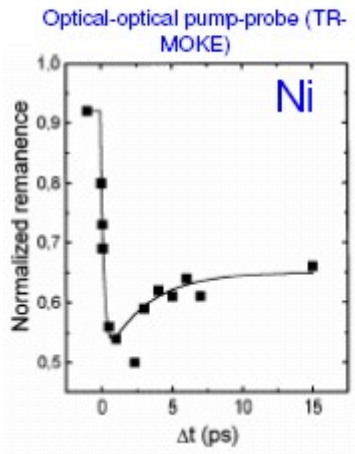
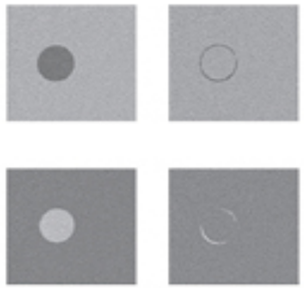
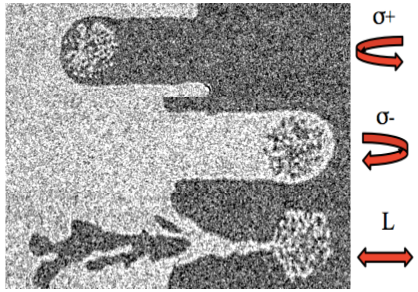
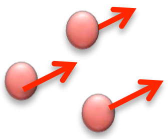
GdFeCo



Mohammed Salah El Hadri (Now in UCSD)

M.S. El Hadri, Topical revue JPhysD-110528.R1 (2017)

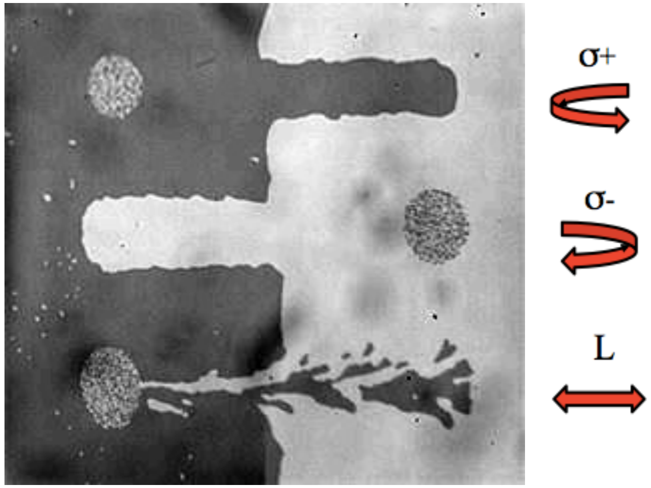
M.S. El Hadri et al., Appl. Phys. Lett. 108, 092405 (2016)

Magnetisation Manipulation	Ultra fast Demagnetisation	All Optical Helicity **Independent** switching (AO-HIS)	All Optical Helicity **dependent** switching (AO-HDS)	All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)
Ultra short pulses				
 Light	*E. Beaurepaire, et al PRL 76, 4250 (1996)*	T. A. Ostler et al Nat. Commun. 3 666 (2012)	*C. D. Stanciu et al Phys. Rev. Lett. 99, 047601 (2007)* *C.-H. Lambert et al., Science 345 (6202), 1337 (2014)*	
 Electron				

All Optical - Helicity Depedent Switching (AO-HDS)

Ferrimagnets

- GdFeCo
- Other RE : Tb, Dy, Ho
- Multilayers : [Tb/Co], [Ho/Co]
- Synthetic ferrimagnets : Co/Ir/Co/Ir



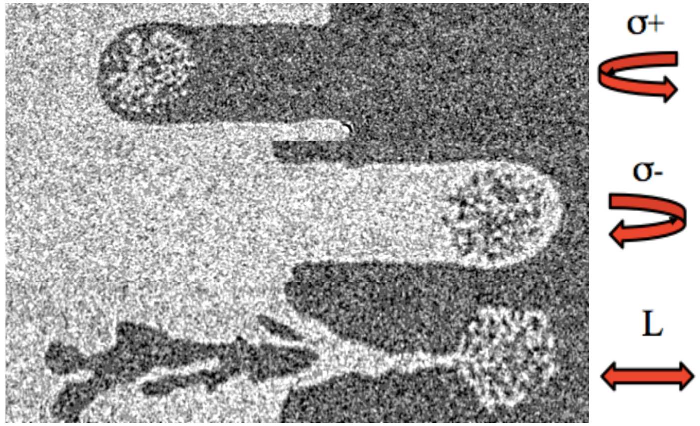
C. D. Stanciu et al Phys. Rev. Lett. 99, 047601 (2007)

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

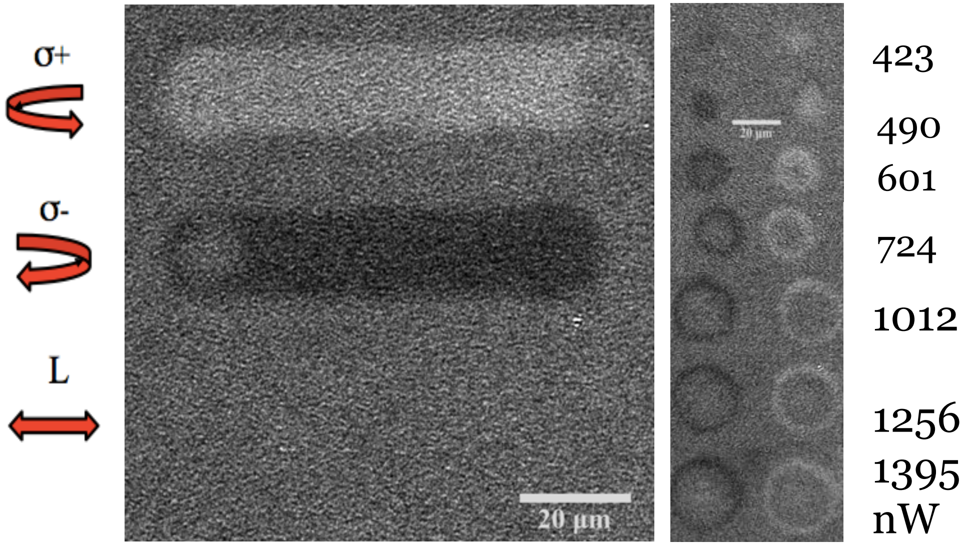
S. Mangin et al., Nat. Mater. 13, 286-292 (2014)

Ferromagnets

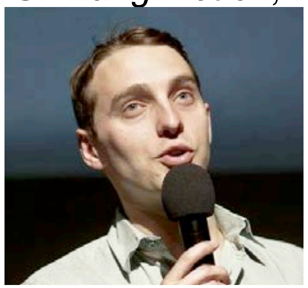
- [Co/Pt], [Co/Pd], [Co/Ni]
- CoFeB



- Granular media FePt

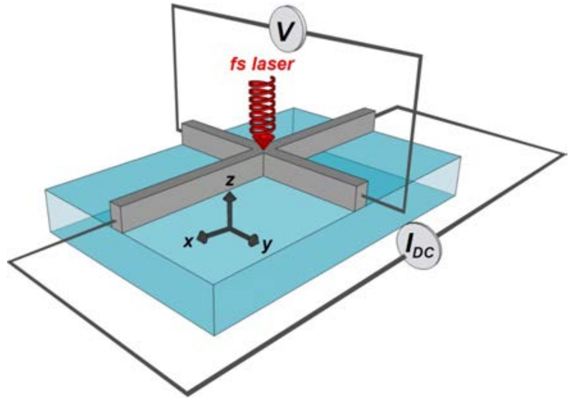


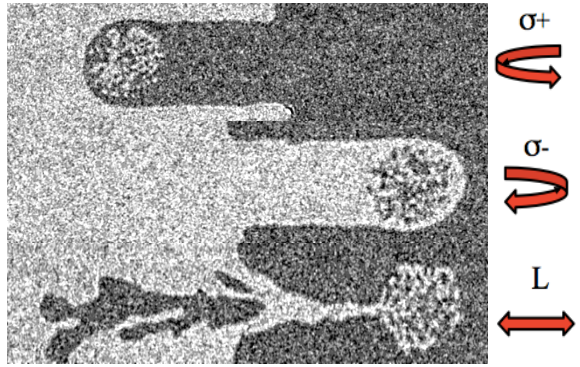
C.-H. Lambert et al., Science 345 (6202), 1337 (2014)



Charles Henri Lambert
(Now in ETH Zurich)

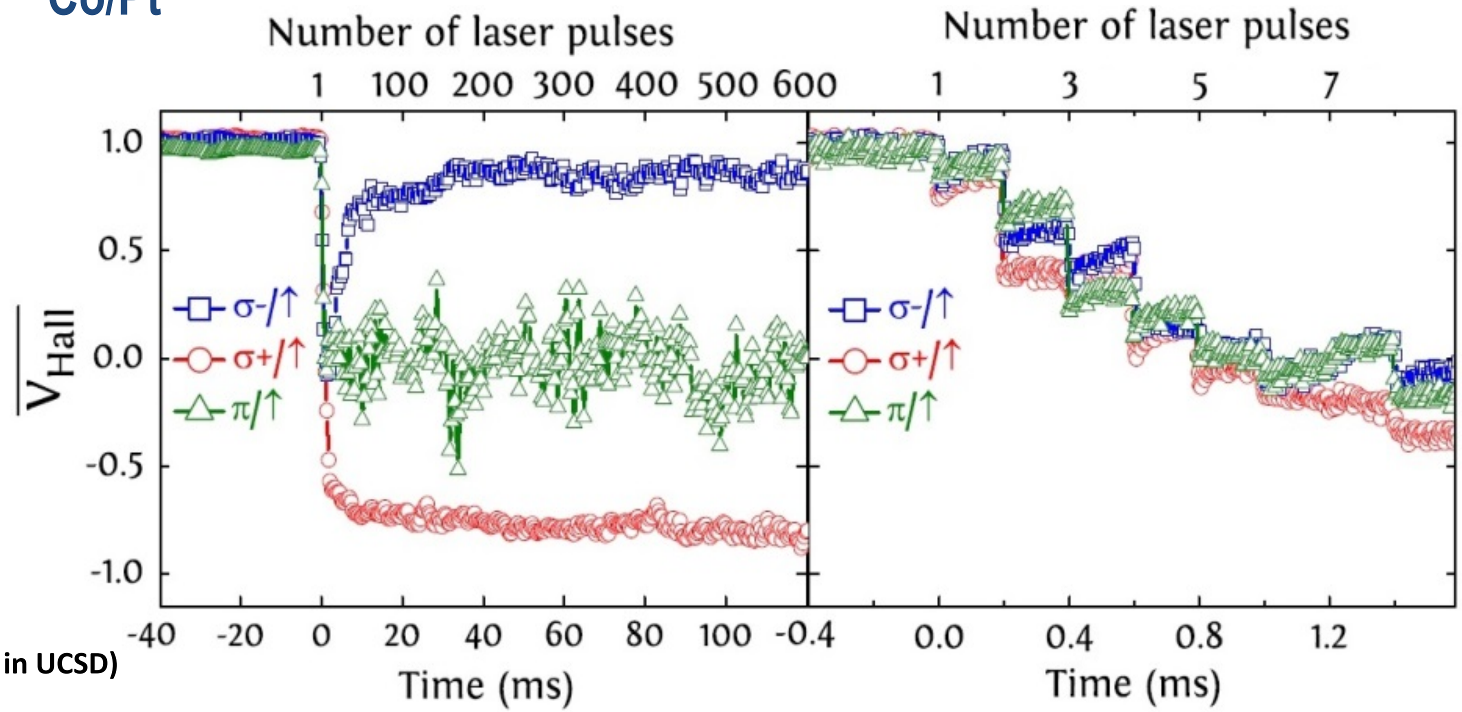
All Optical – Helicity Depedent Switching (AO-HDS)





Multiple Pulses
All Optical Helicity
dependent switching
(AO-HDS)

Co/Pt

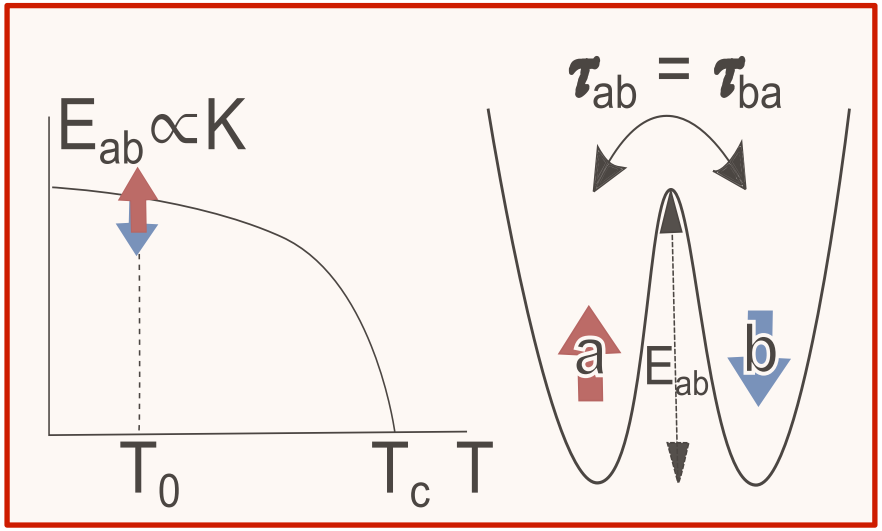


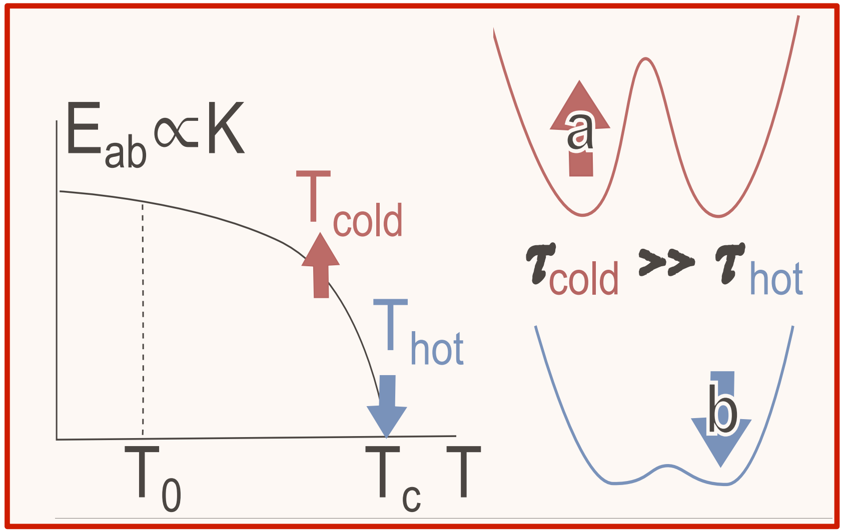
Mohammed Salah El Hadri (Now in UCSD)

R. Medapalli et al Phys. Rev. B. 96, 224421 (2017)
M.S. El Hadri, Topical revue JPhysD-110528.R1 (2017)
M.S. El Hadri et al., Appl. Phys. Lett. 108, 092405 (2016)
M. S. El Hadri et al., Phys. Rev. B 94, 064412 (2016)

All Optical - Helicity Depedent Switching (AO-HDS)

Helicity Dependence : Absorption change ?





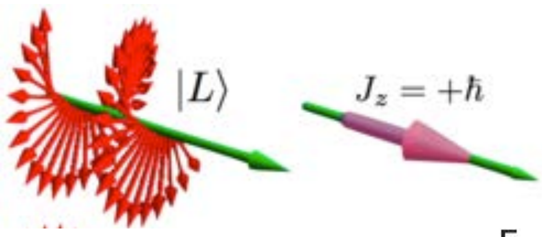
$\tau_{ab} \propto e^{E_{ab}/k_B T}$ $P_{ab}(t) = 1 - e^{-t/\tau_{ab}}$

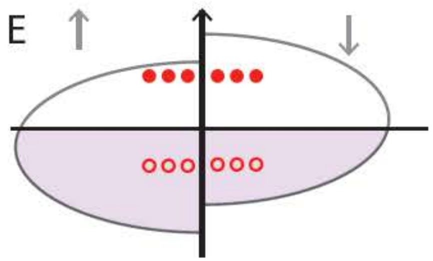
Asymmetry in heating *(magnetic circular dichroism)* →
Asymmetry in hopping➔ **Multi-shot switching**

Gorchon et al., PRB-Rapid Comm.. 94, 020409(R) (2016)

Ellis, M. et al., Scientific Reports 6, 30522 (2016)

All Optical – Helicity Depedent Switching (AO-HDS)





Heat

+ Angular Momentum transfer

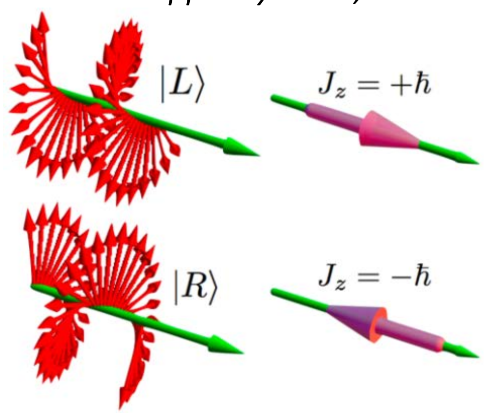
Helicity Dependence :

Inverse Faraday Effect :

$$\vec{H}_{eff} = \frac{\varepsilon_0}{\mu_0}\alpha\underbrace{\left[\vec{E}(\omega)\times\vec{E}^*(\omega)\right]}_{circular\ polarization}$$

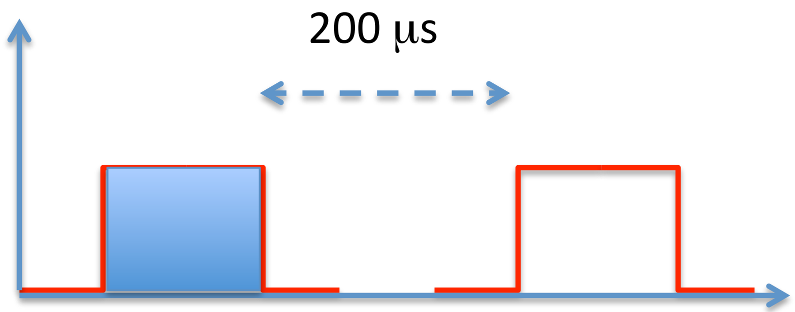
J. Appl.Phys. ***111***, *07D506 (2012)*

Angular Momentum Transfer :



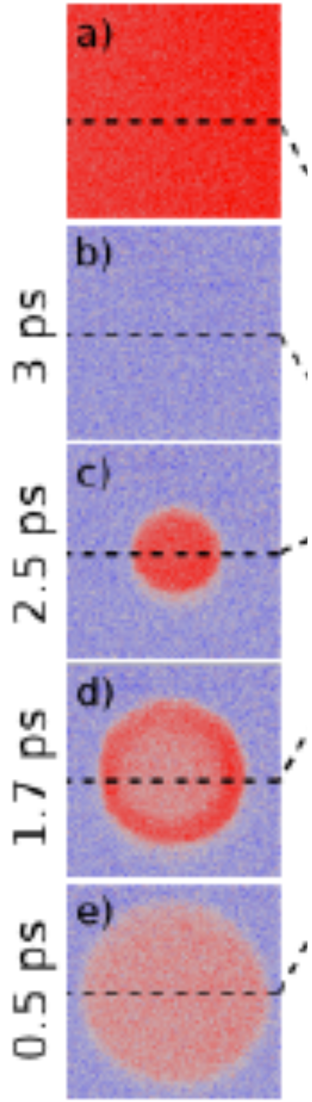
Optimization of AO-HDS in Co/Pt

Static Beam (5 kHtz repetition)



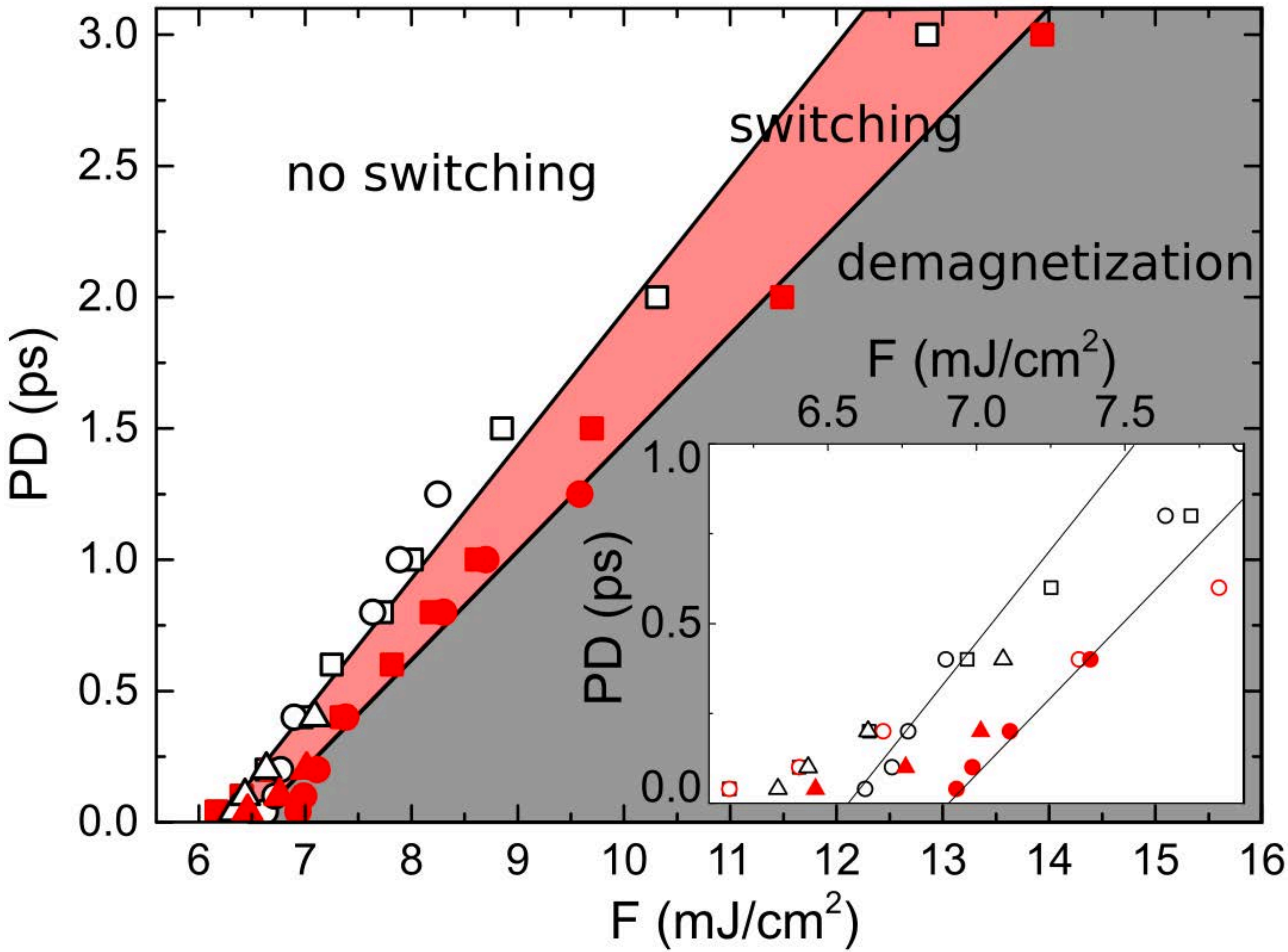
Pulse Duration, Fluence, pulse diameter

Georgy Kichin

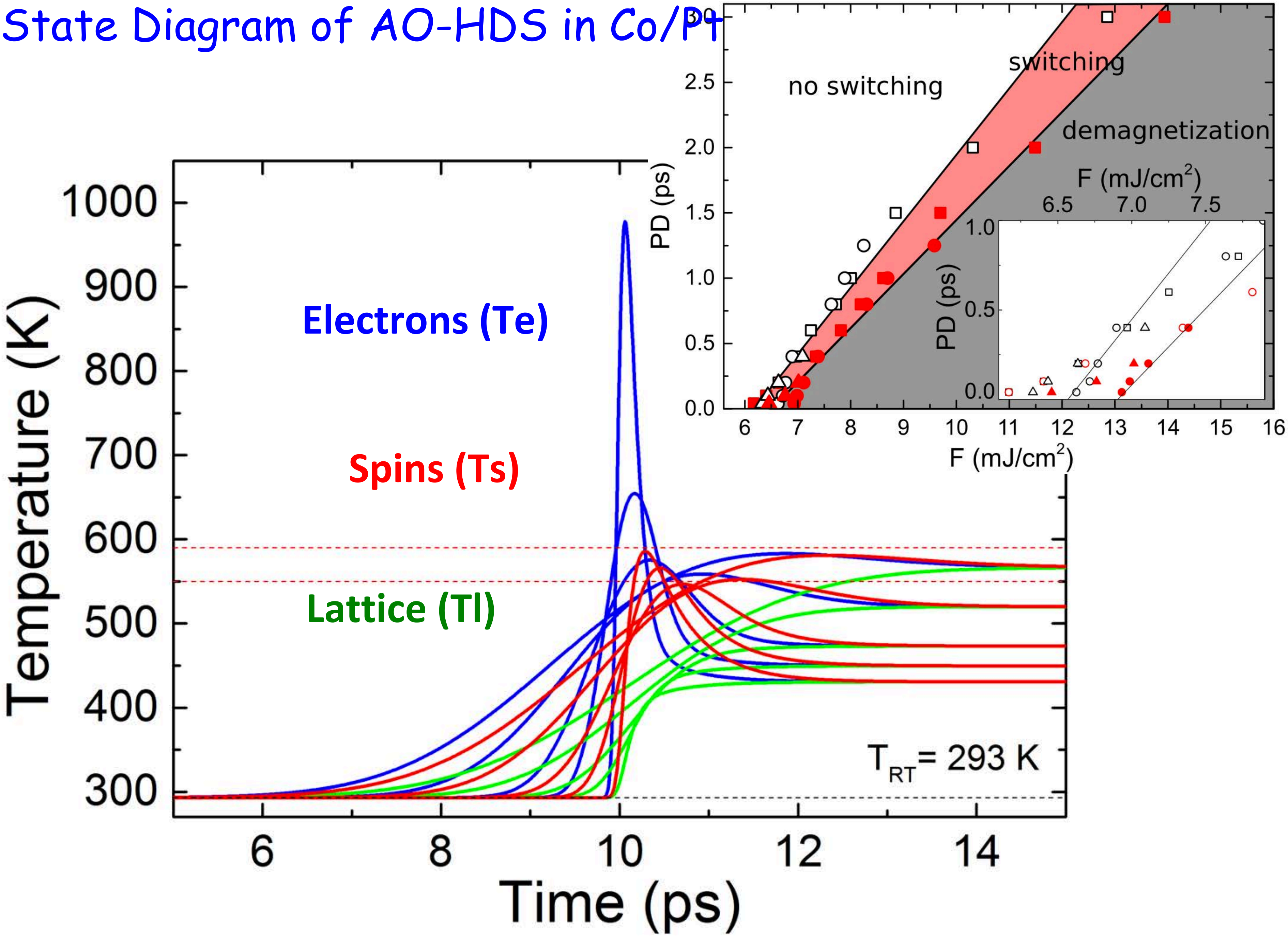


R. Medapalli et al Phys. Rev. B. 96, 224421 (2017)
G. Kichin in Preparation (2018)

State Diagram of AO-HDS in Co/Pt

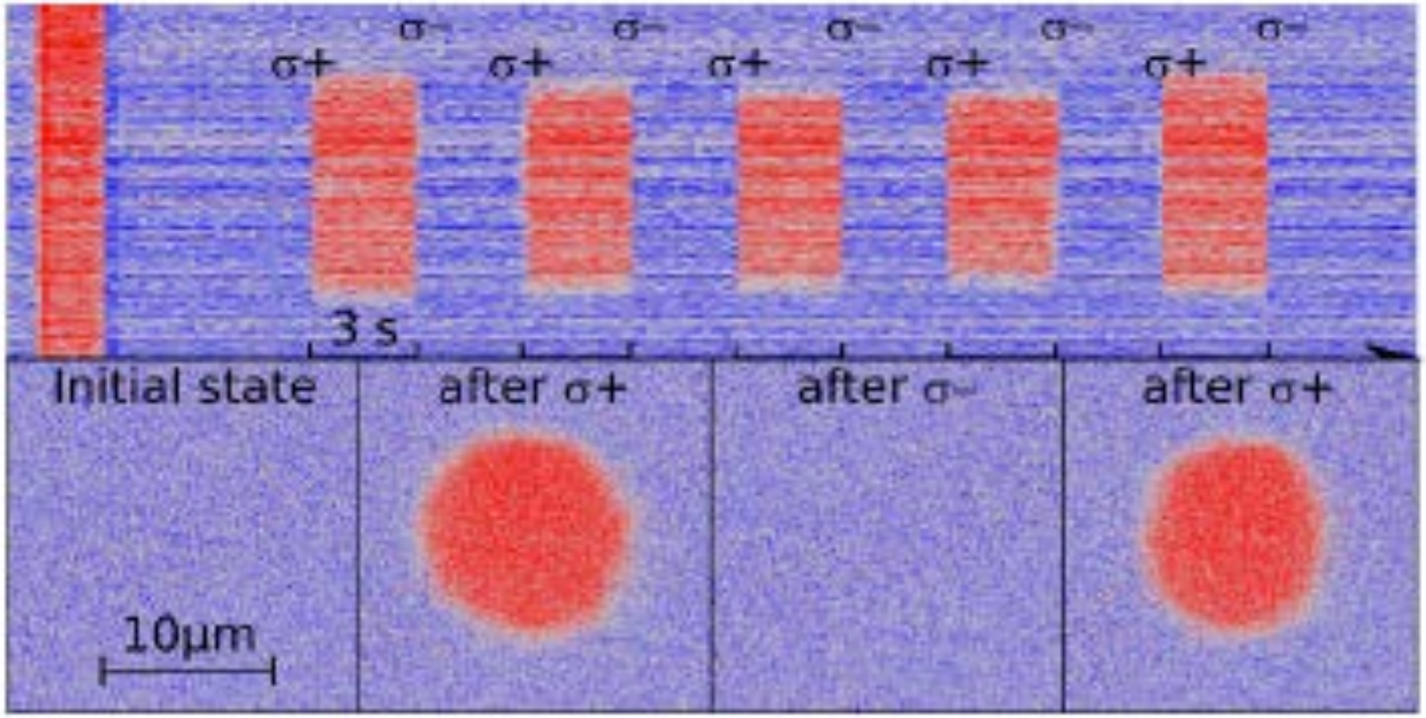


State Diagram of AO-HDS in Co/Pt



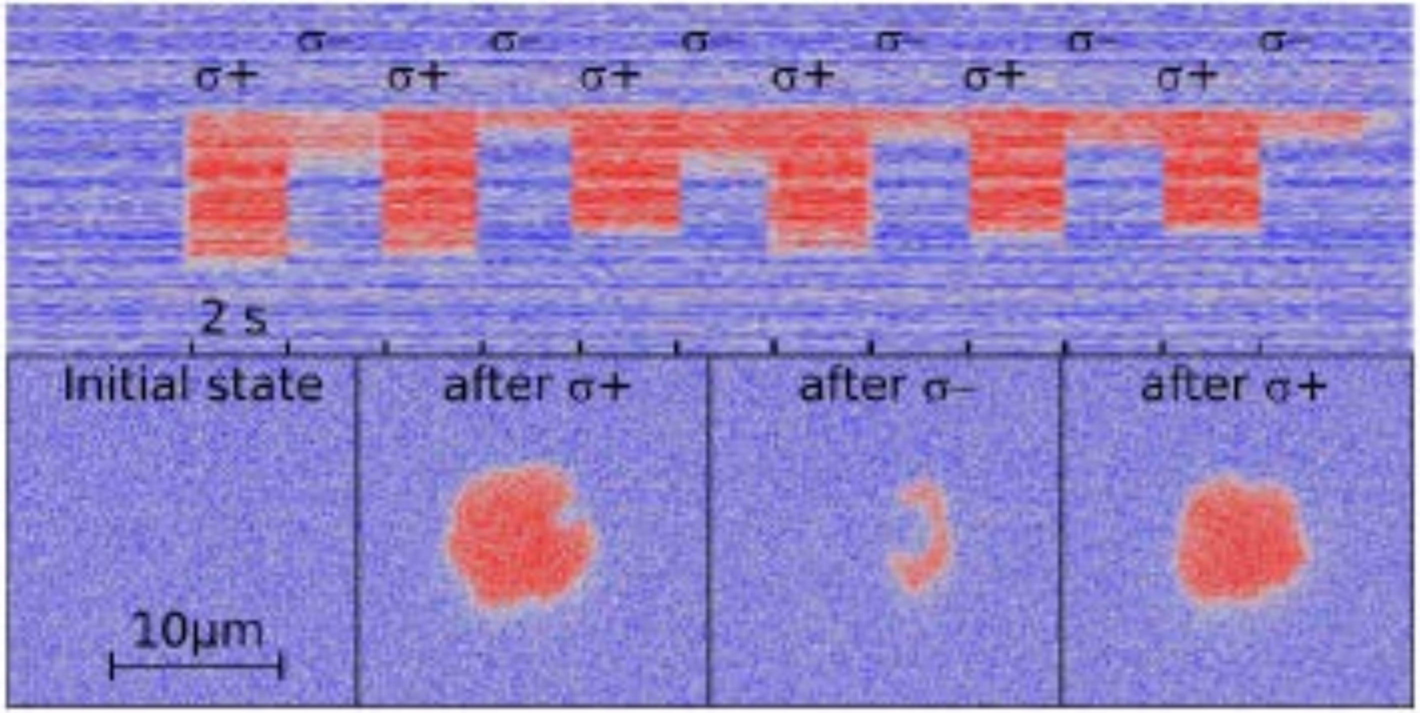
Optimization of AO-HDS in Co/Pt

50 x 2 ps Pulse Duration



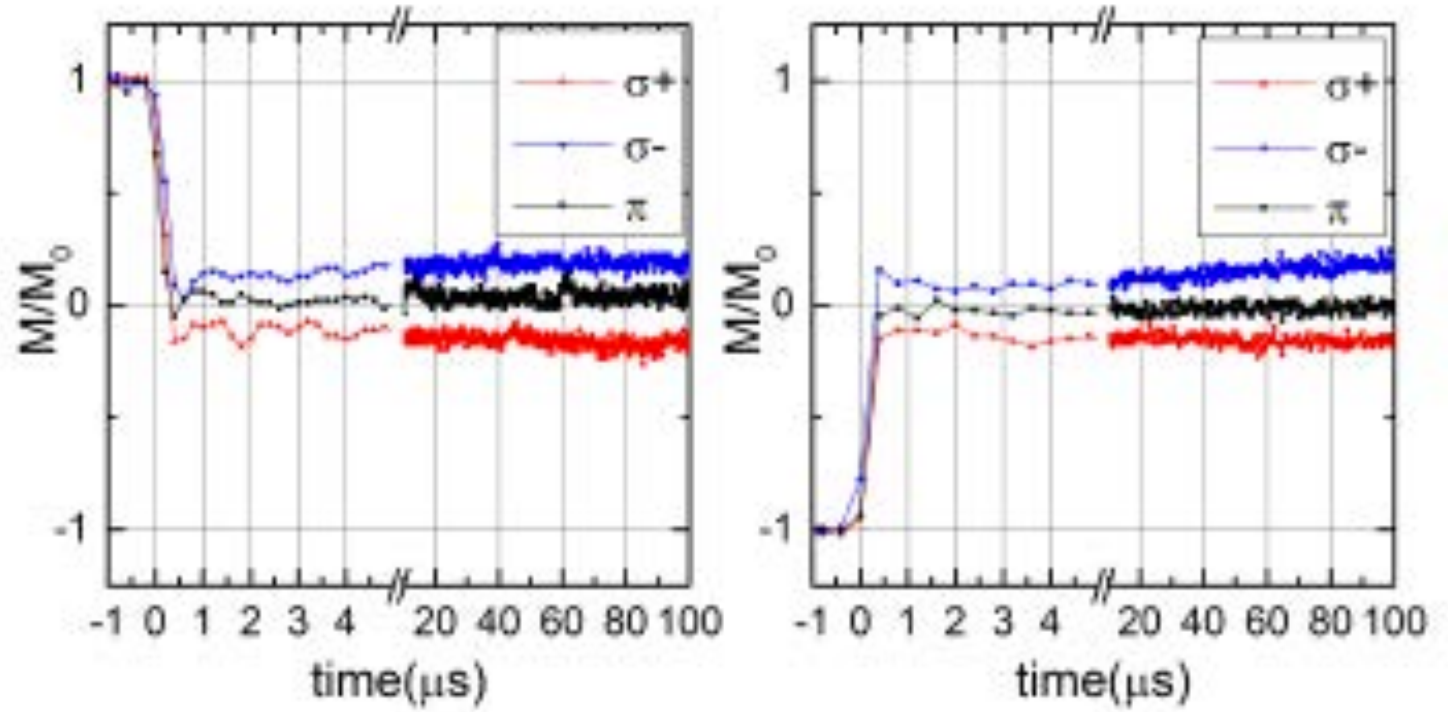
State Diagram of AO-HDS in Co/Pt

10 x 2 ps Pulse Duration



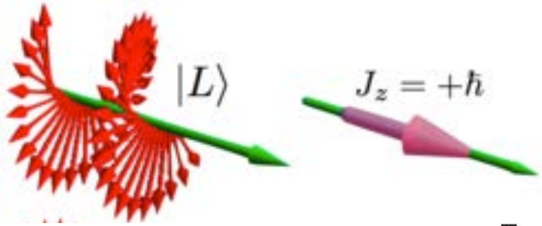
State Diagram of AO-HDS in Co/Pt

1 x 2 ps Pulse Duration



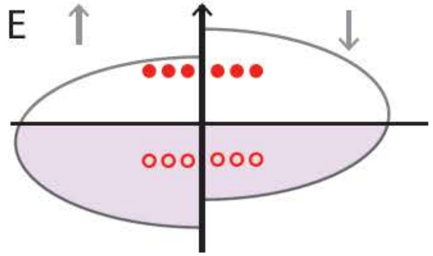
We can exclude MCD …

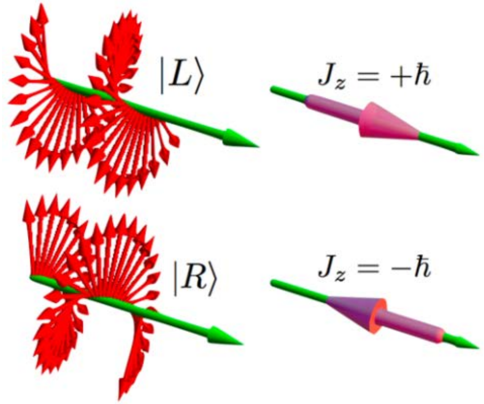
State Diagram of AO-HDS in Co/Pt



Heat

+ Angular Momentum transfer





Helicity Dependence :

Angular Momentum Transfer :

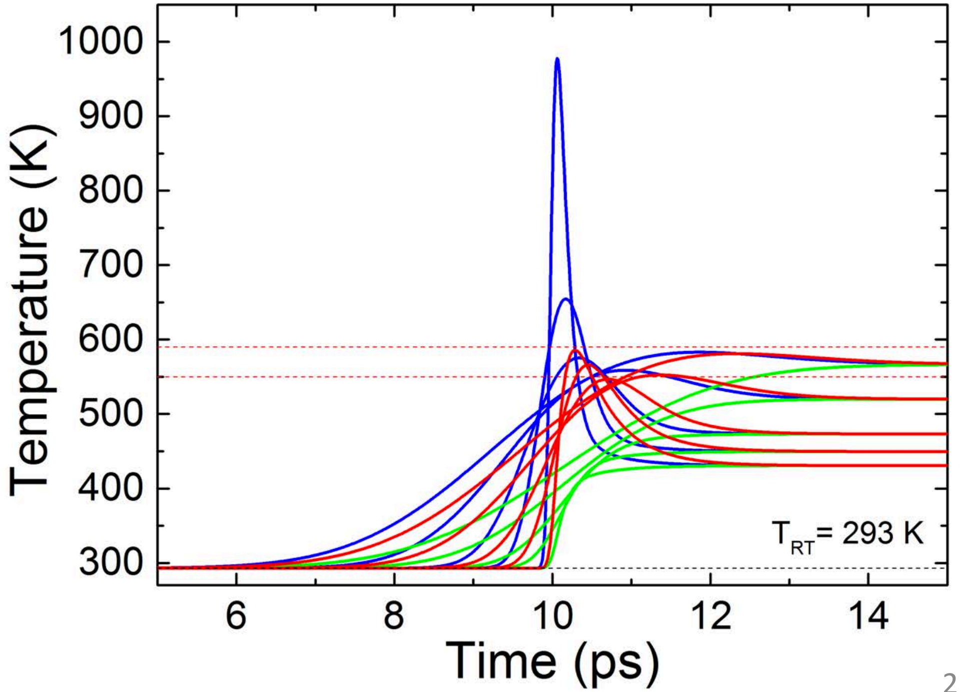
Inverse Faraday effect :

Induce Magnetisation

Tutorial from P. Oppeneer

Relevant Temperature :

Spin Temperature



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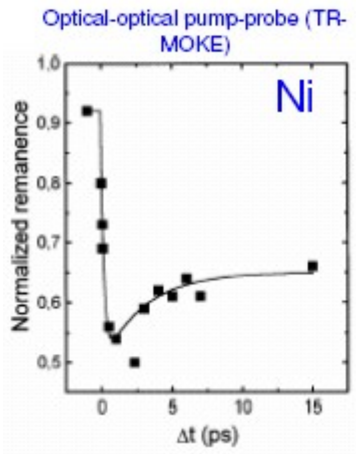
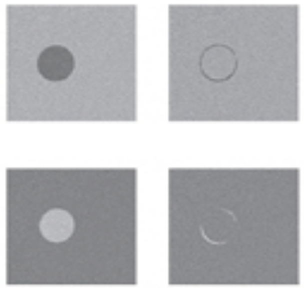
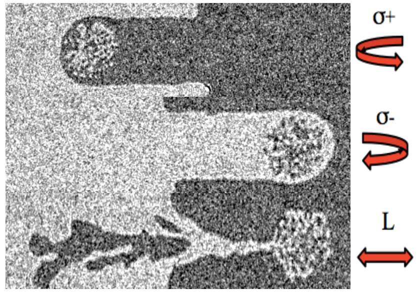
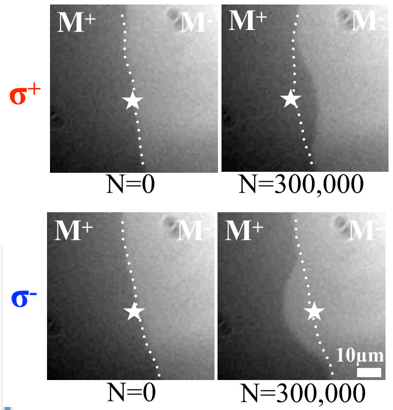
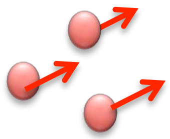
Ultra short pulses				
 Light	*E. Beaurepaire, et al PRL 76, 4250 (1996)*	T. A. Ostler et al Nat. Commun. 3 666 (2012)	*C. D. Stanciu et al Phys. Rev. Lett. 99, 047601 (2007)* *C.-H. Lambert et al., Science 345 (6202), 1337 (2014)*	Y. Quessab et al Phys. Rev. B 97, 054419 (2018)
 Electron				

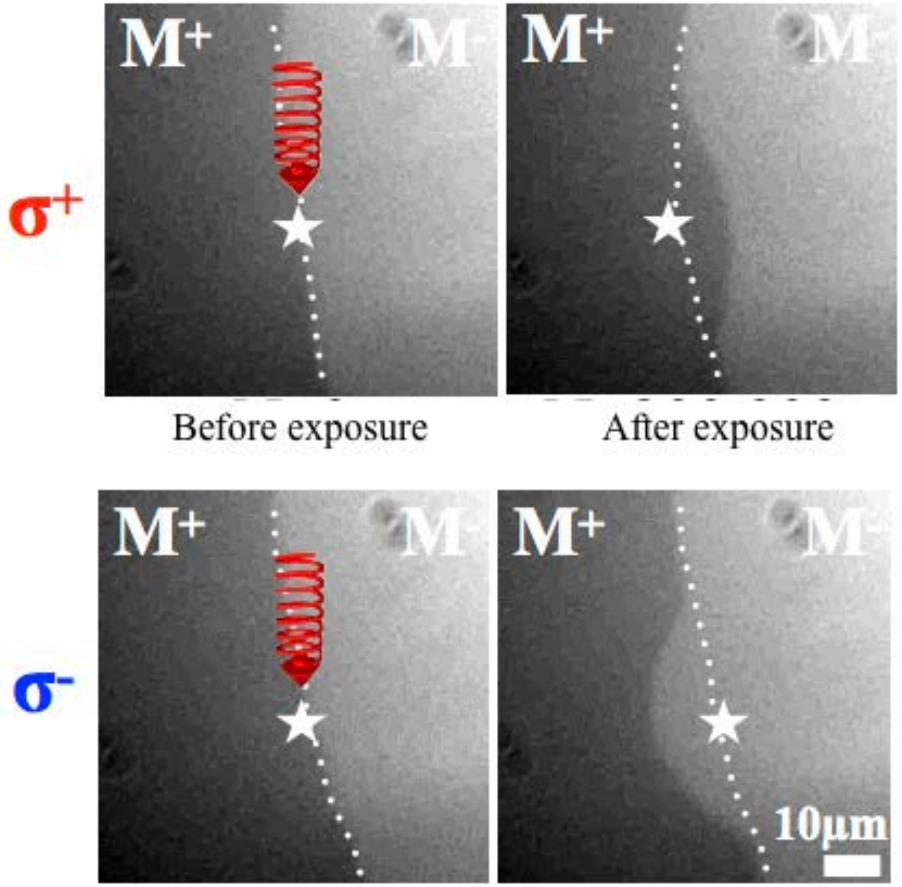
All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)

40 fs pulses

Pt/Co/Pt

Yassine Quessab
Post-Doc @ NYU

Y. Quessab et al Phys. Rev. B 97, 054419 (2018)



Before exposure After exposure

Before exposure After exposure

Laser-induced DW motion has to overcome DW Pinning. It results from the ***balance of 3 contributions***:
Temperature (thermal fluctuation), **temperature gradient** and **helicity effect**.

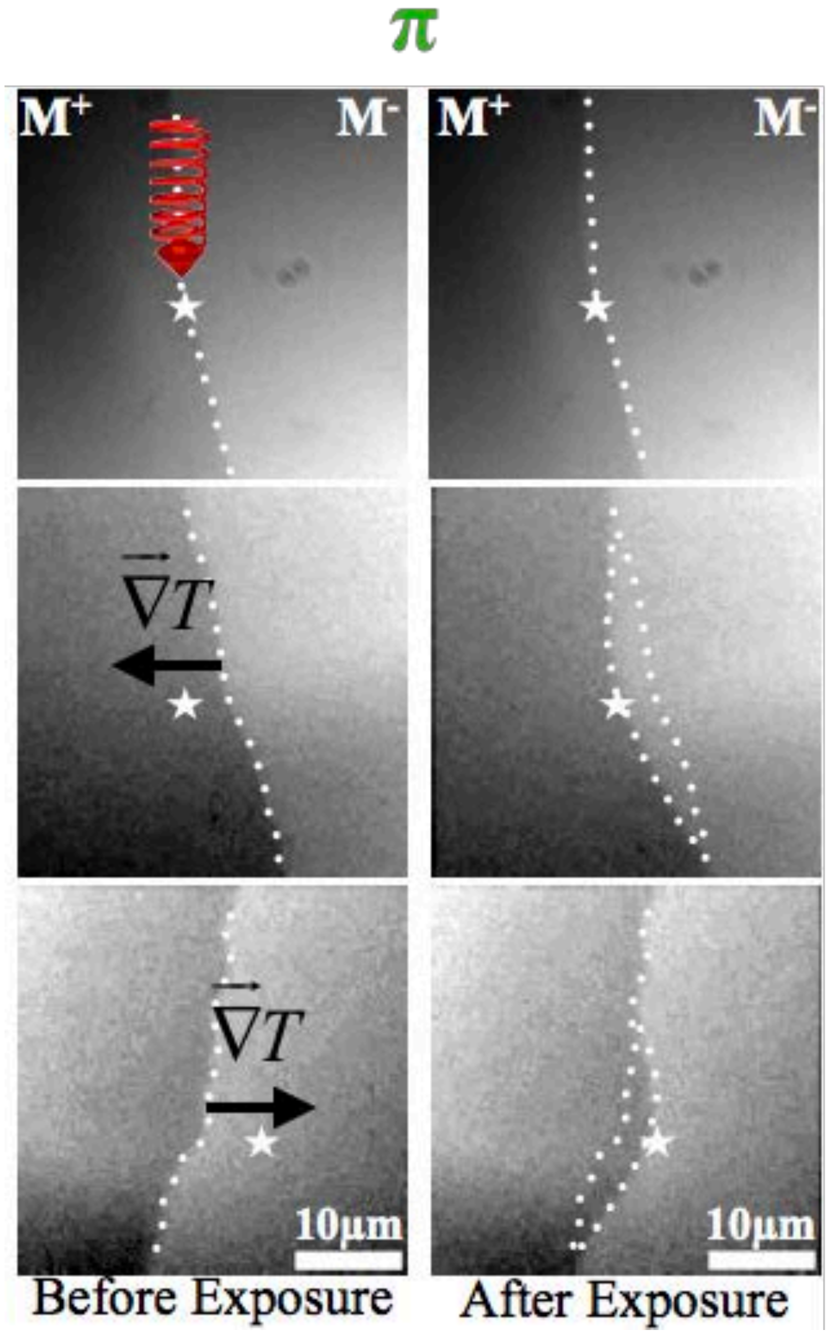
Heat effect on Domain Wall Motion

Pt/Co/Pt,
τlaser = 40 fs, linear polarisation

3 contributions:
Temperature
Temperature gradient
~~**Helicity effect**~~

Temperature gradient induces

DWM towards the hotter regions



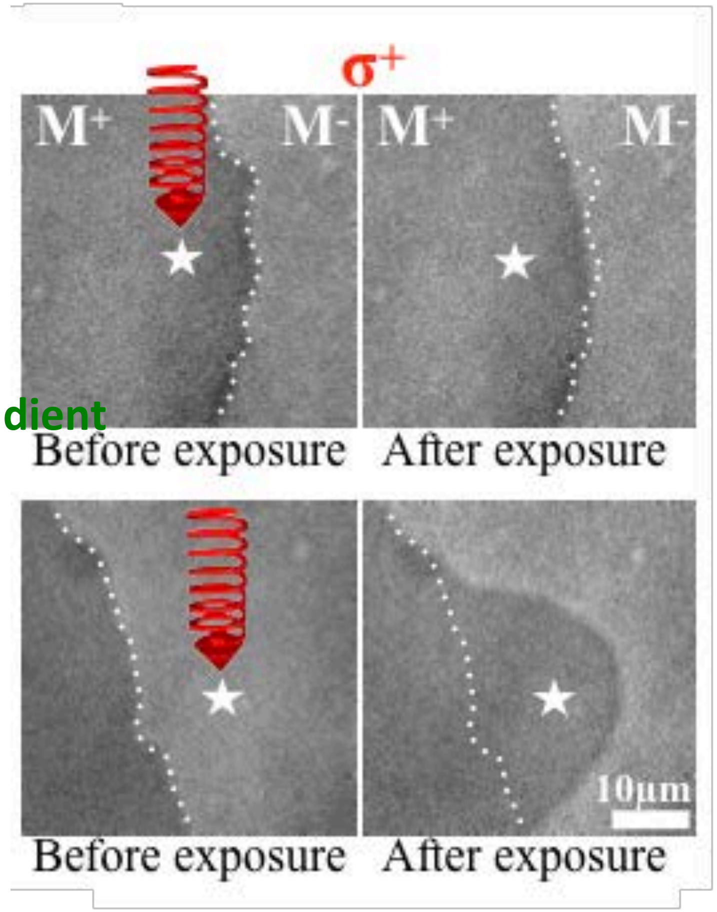
All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)

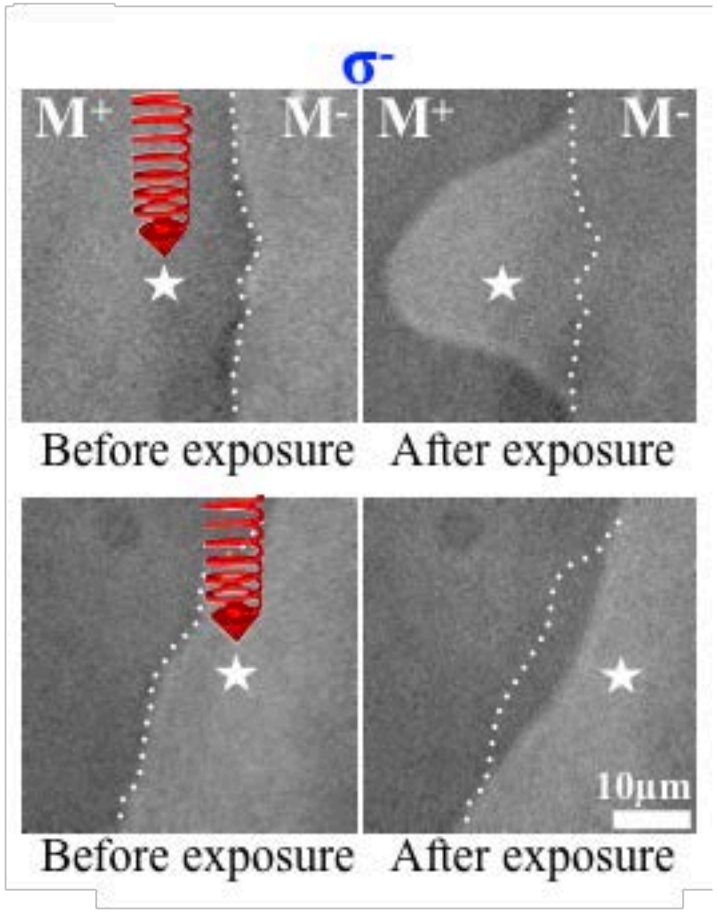
3 contributions:

Temperature

Temperature gradient

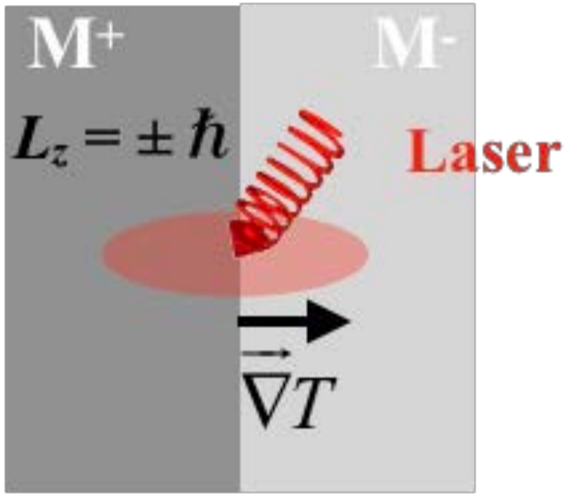
~~Helicity effect~~



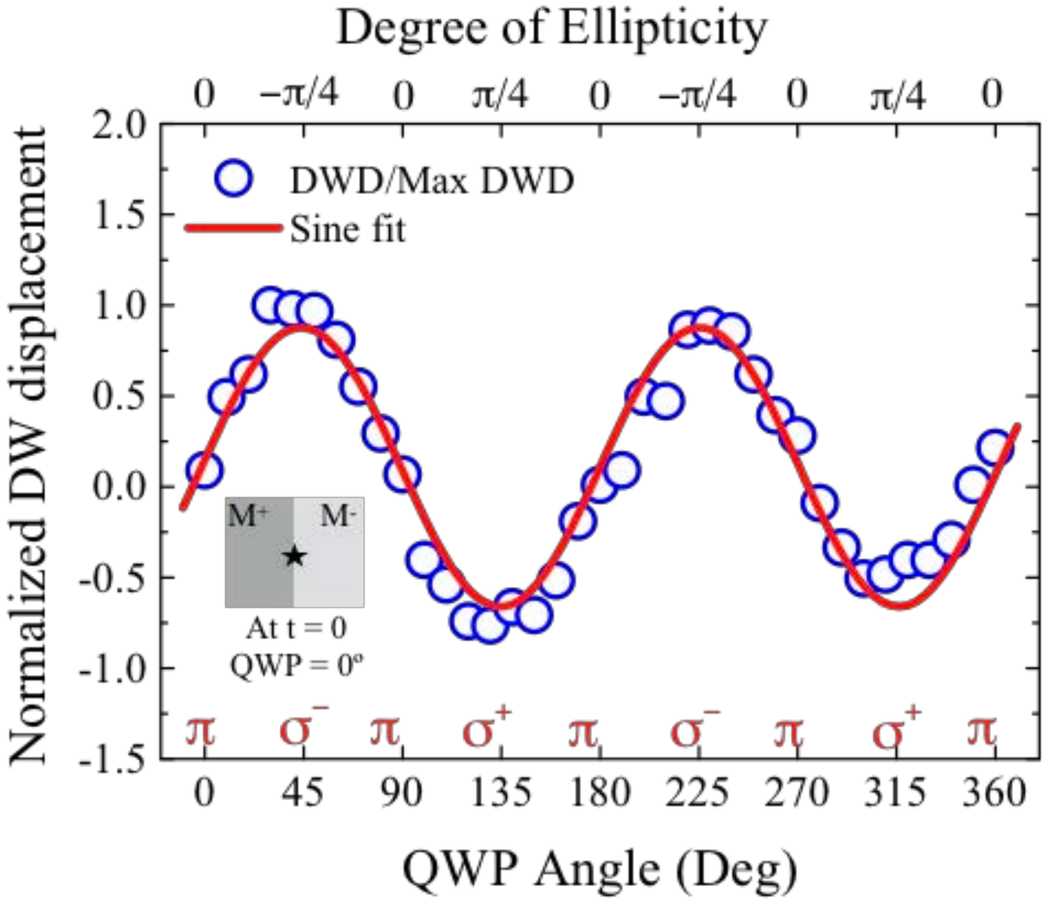


$F = 0.4\ \mathrm{mJ\ cm^{-2}}$ $\tau_{laser} = 2\ \mathrm{ps}$

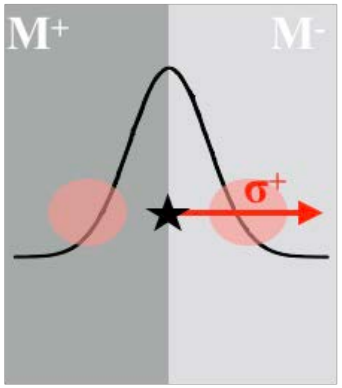
All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)

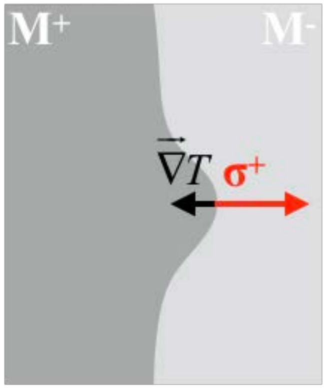


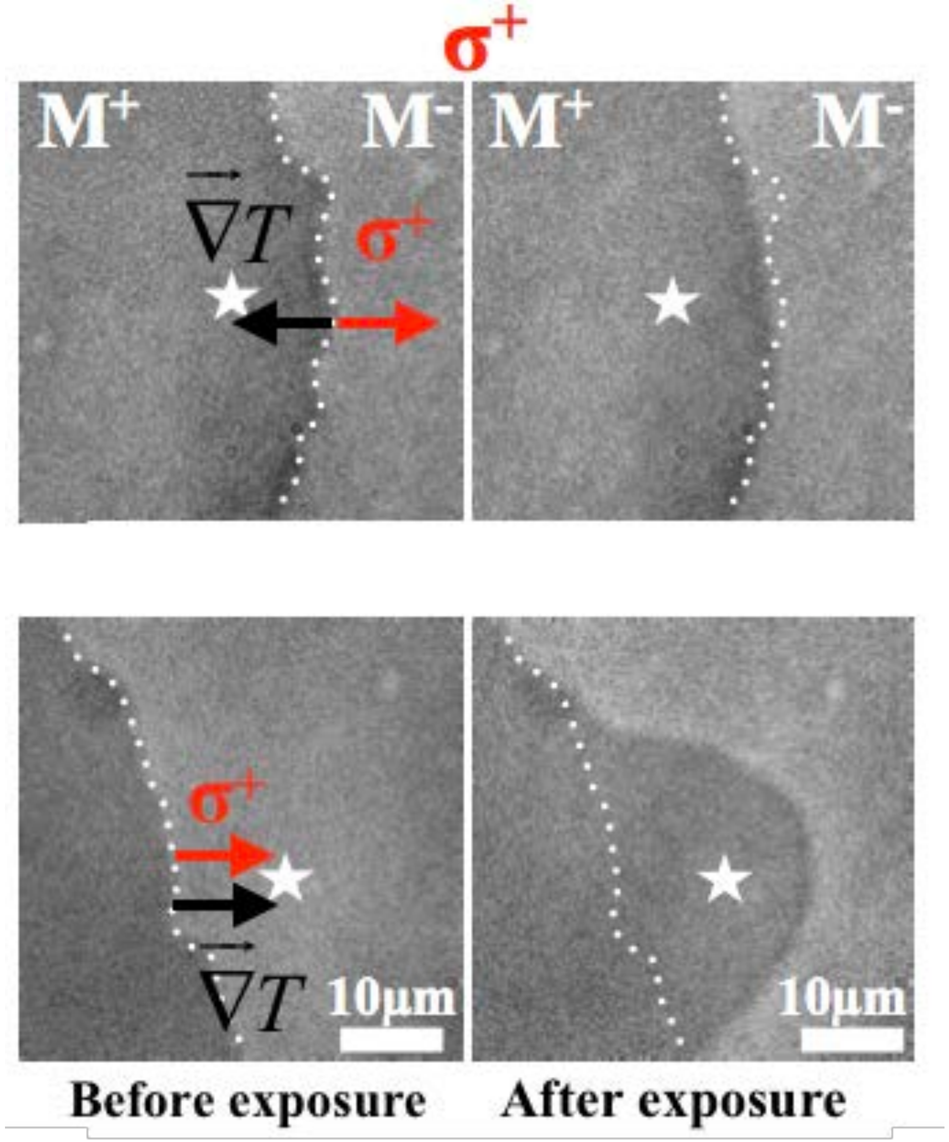
DW



All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)

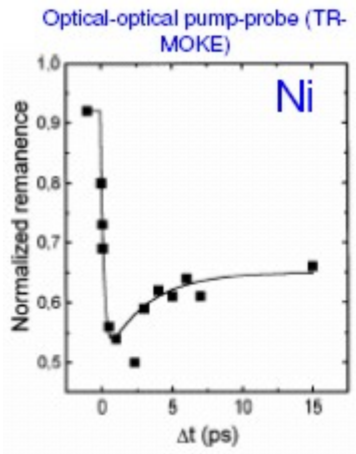
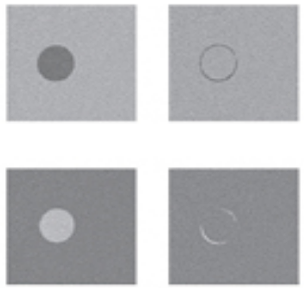
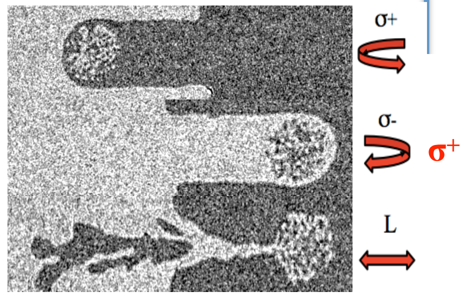
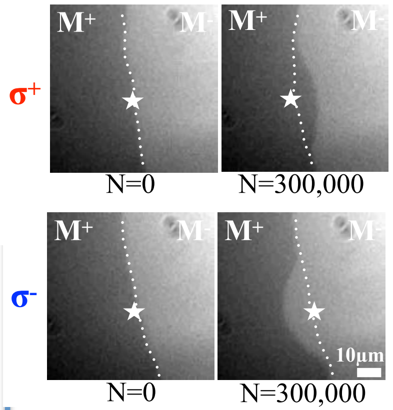
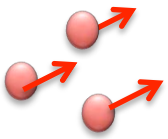






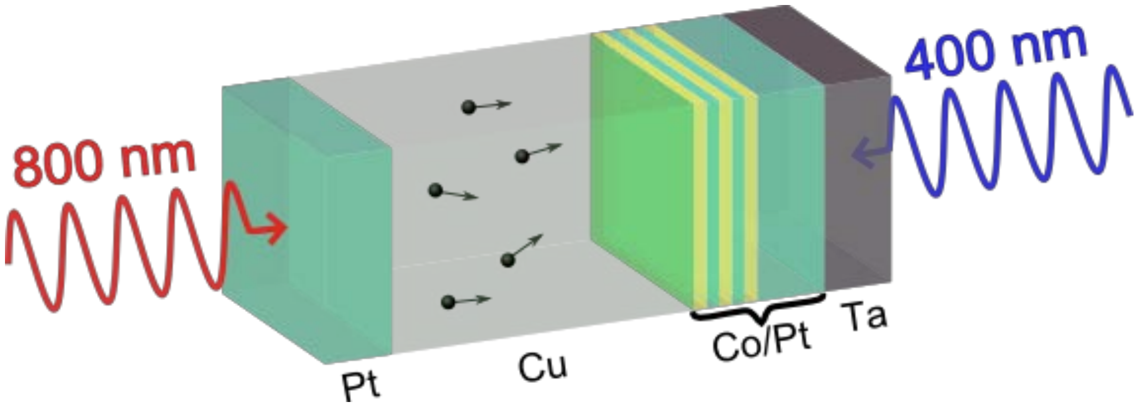
the **helicity effect** is *stronger* than the **temperature gradient**

Y. Quessab et al Phys. Rev. B 97, 054419 (2018)

Magnetisation Manipulation Ultra short pulses	Ultra fast Demagnetisation	All Optical Helicity **Independent** switching (AO-HIS)	All Optical Helicity **dependent** switching (AO-HDS)	All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)
				
 Light	*E. Beaurepaire, et al* *PRL 76, 4250 (1996)*	T. A. Ostler et al Nat. Commun. 3 666 (2012)	*C. D. Stanciu et al* *Phys. Rev. Lett. 99, 047601 (2007)* *C.-H. Lambert et al.,* *Science 345 (6202), 1337 (2014)*	Y. Quessab et al Phys. Rev. B 97, 054419 (2018
 Electron				

TRMOKE pump-probe experiments

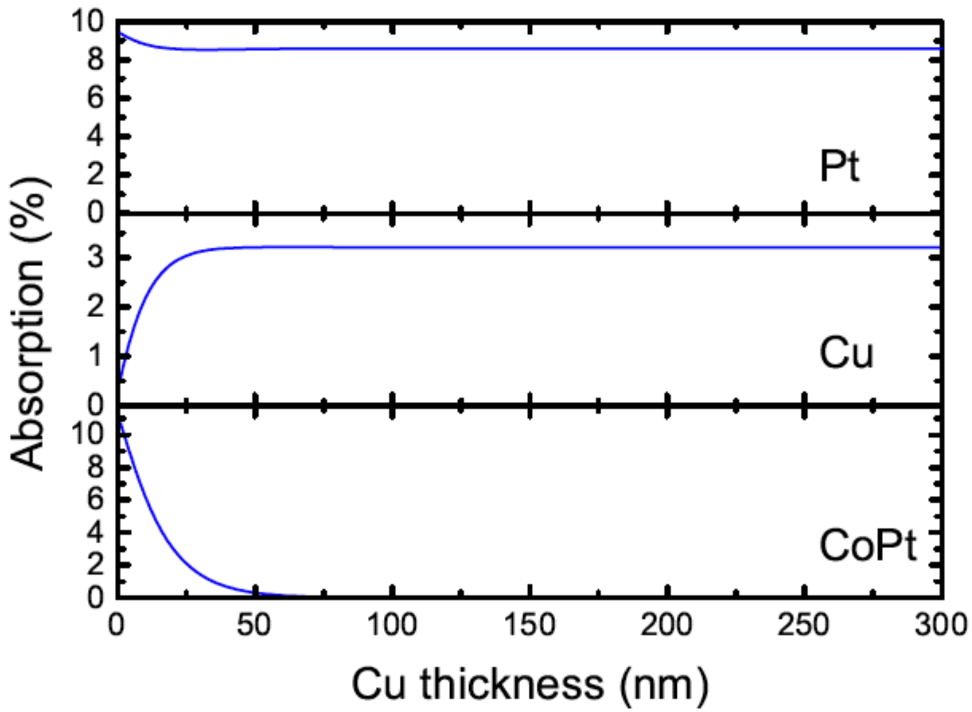
Adjusting the Cu thickness



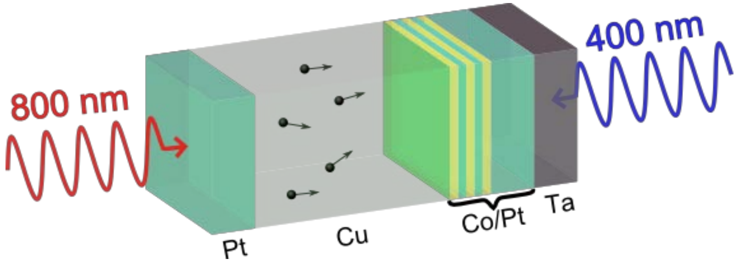
Glass/Ta(3)/Pt(3)/[Co(0.6)/Pt(1.1)]2/Co(0.6)/Cu(d)/Pt(3)

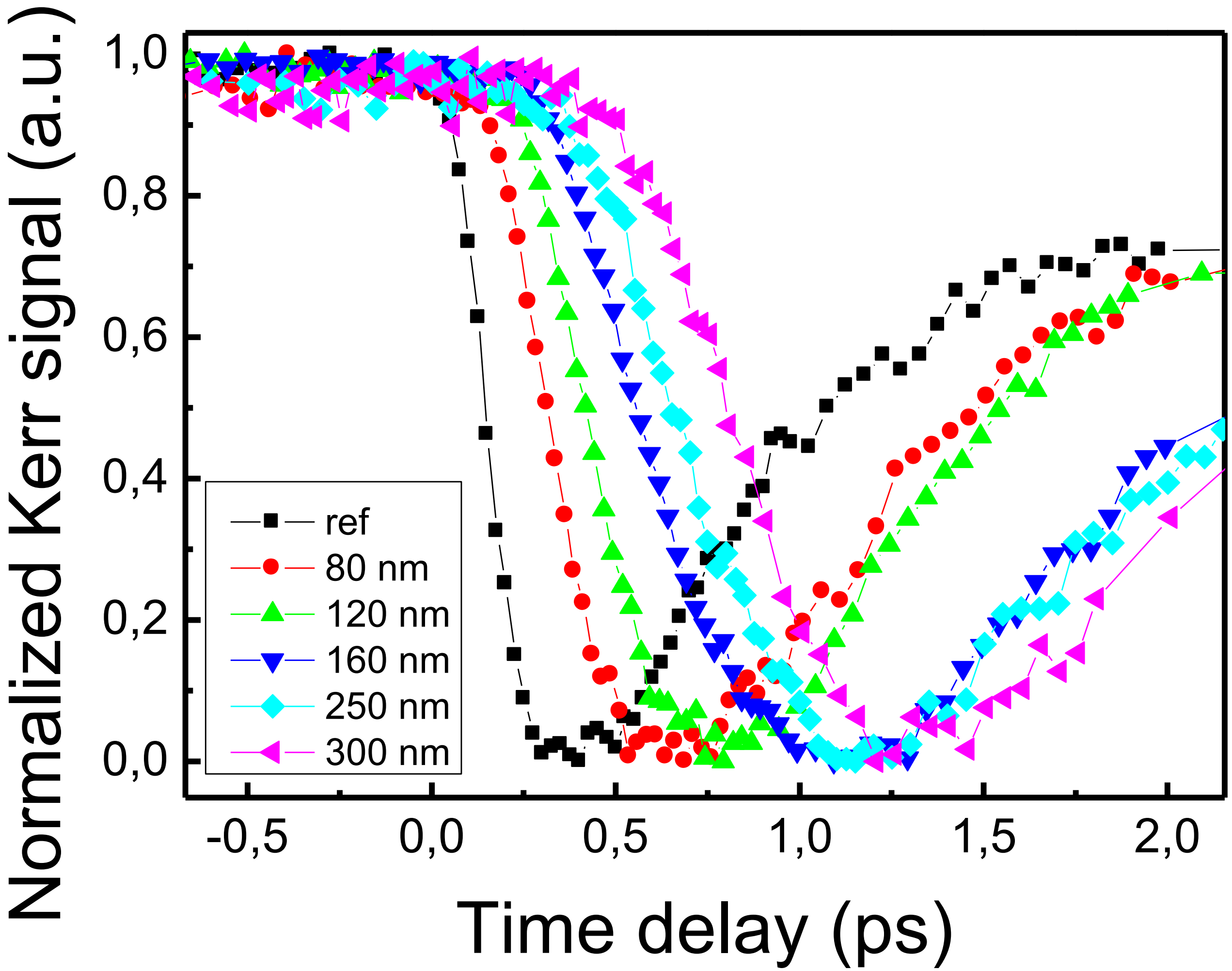
Nicolas Bergeard (now Researcher at IPCMS)

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

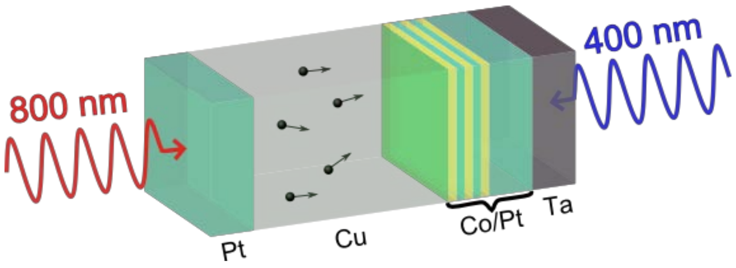


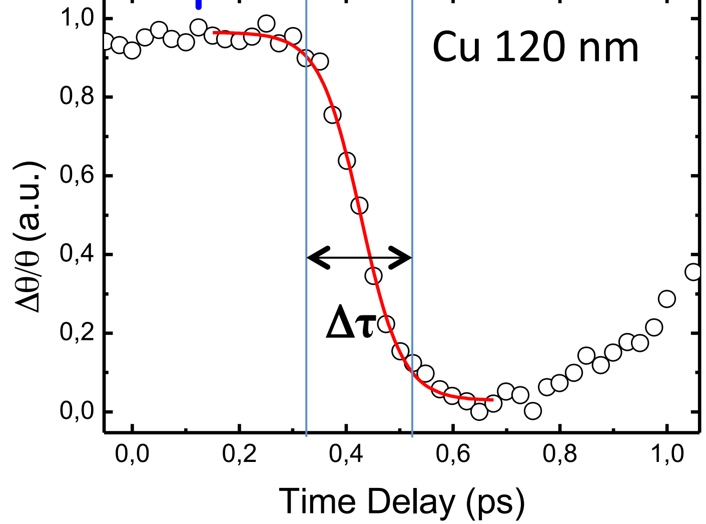
Ultra-fast demagnetisation using electron pulse

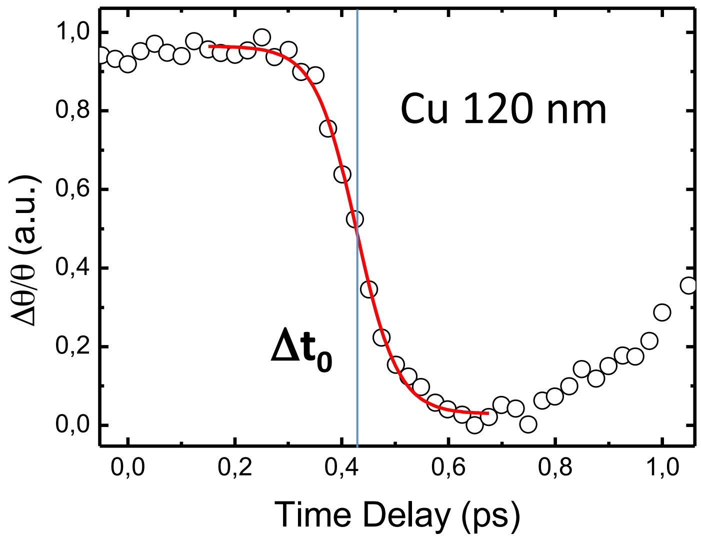


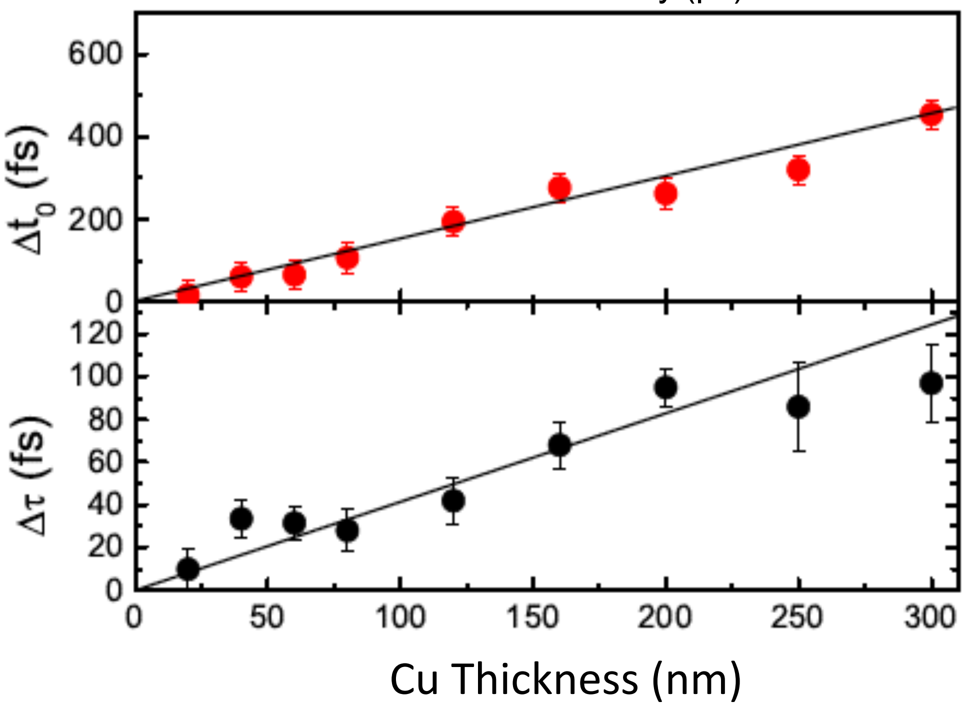


Ultra-fast demagnetisation using electron pulse



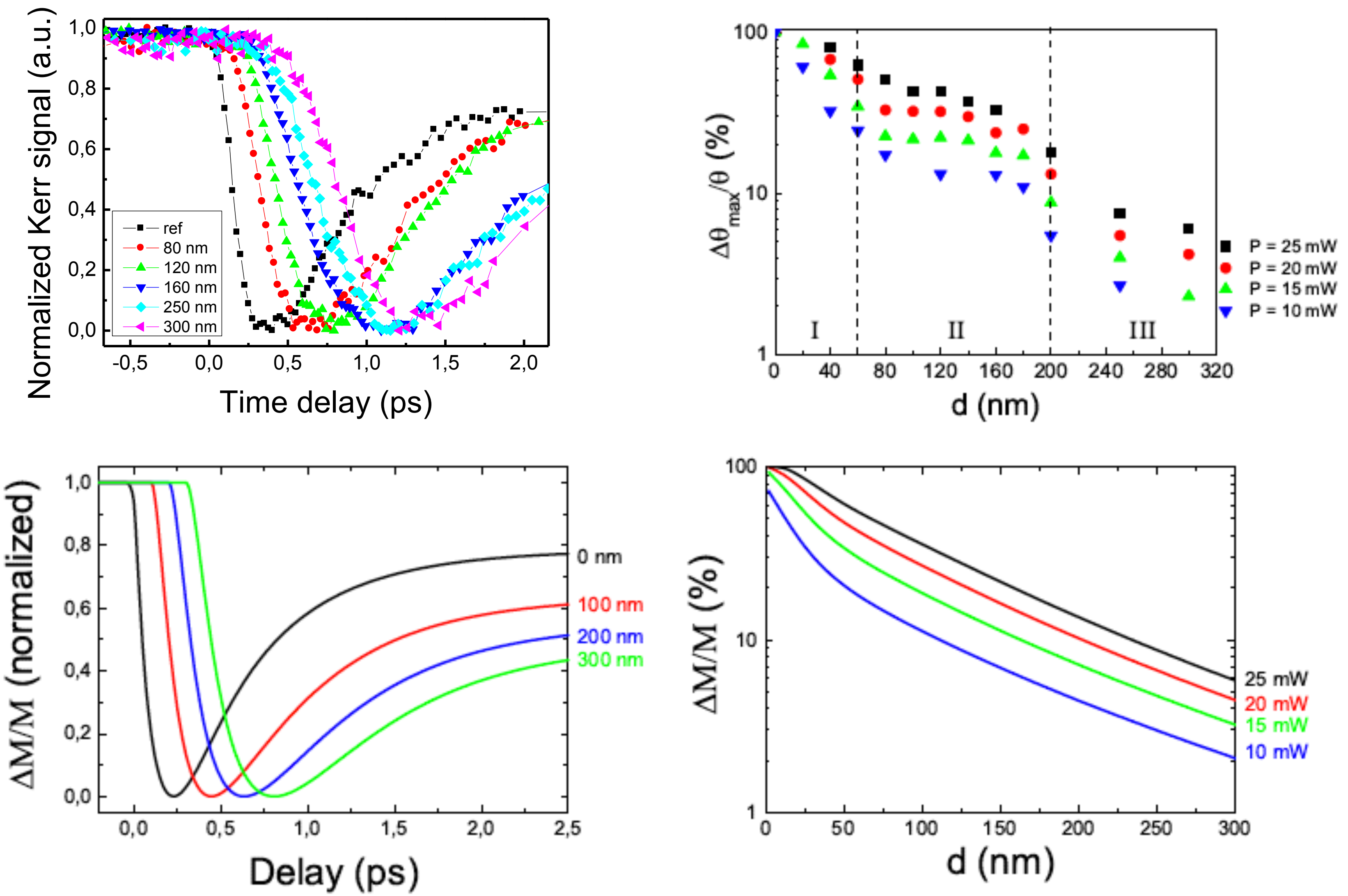






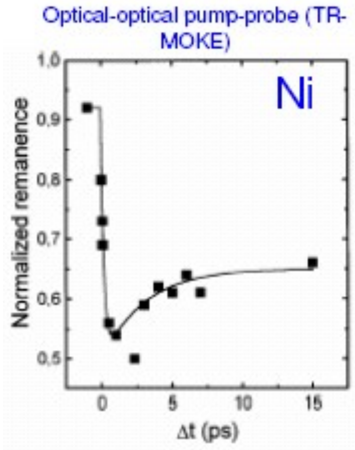
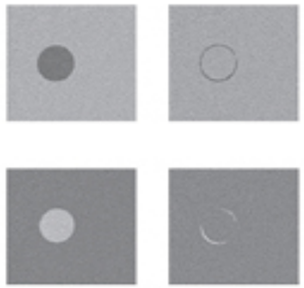
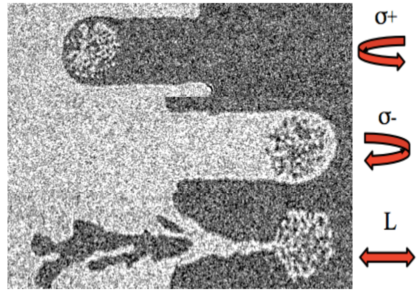
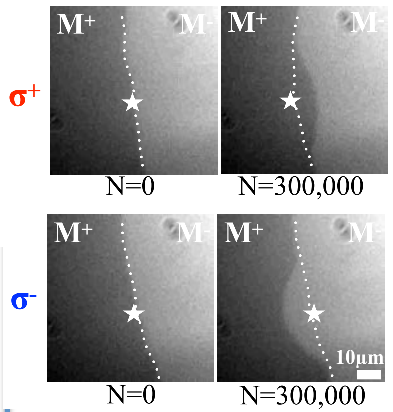
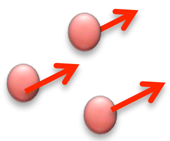
Linear variation of Δt_0 up to 300 nm /Hot electrons velocity of 0.7×10^6 m/s

Comparison between experiments and calculation



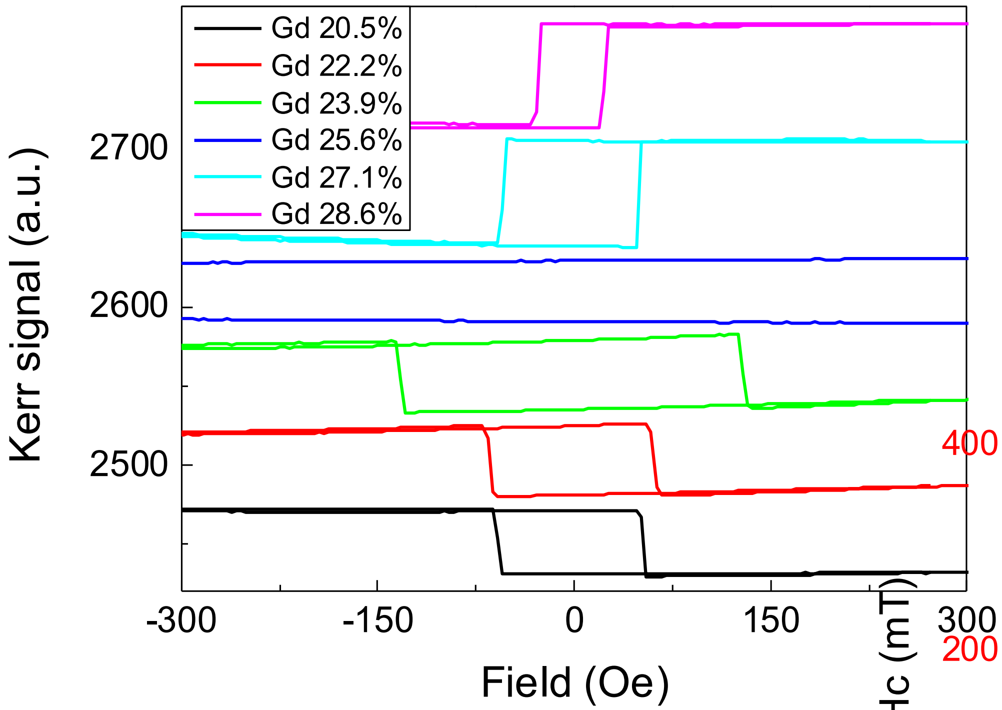
Ultra short hot Electron pulse can generate ultra-fast demagnetisation

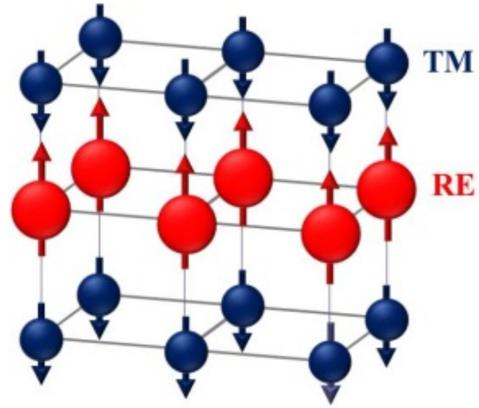
N. Bergeard,et al , Phys. Rev. Lett. 117, 147203 (2016)

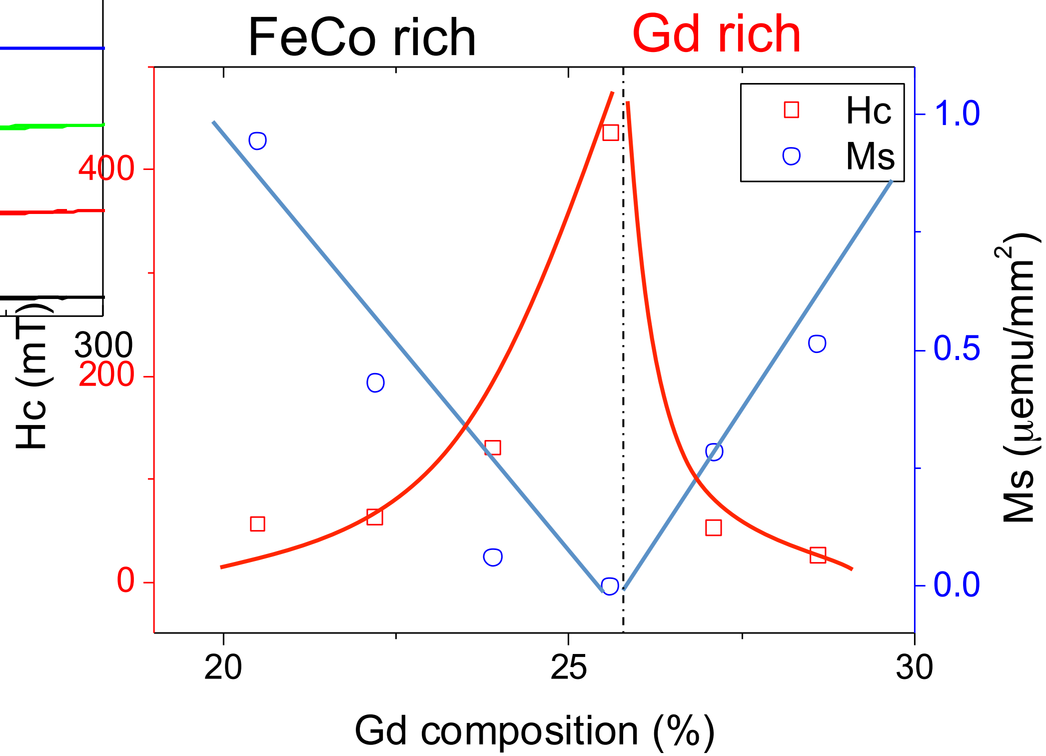
Magnetisation Manipulation / Ultra short pulses	Ultra fast **Demagnetisation**	All Optical Helicity **Independent** switching (AO-HIS)	All Optical Helicity **dependent** switching (AO-HDS)	All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)
				
 Light	*E. Beaurepaire, et al* *PRL 76, 4250 (1996)*	T. A. Ostler et al Nat. Commun. 3 666 (2012)	*C. D. Stanciu et al Phys. Rev. Lett. 99, 047601 (2007)* *C.-H. Lambert et al., Science 345 (6202), 1337 (2014)*	Y. Quessab et al Phys. Rev. B 97, 054419 (2018
 Electron	*N. Bergeard,et al Phys. Rev. Lett. 117, 147203 (2016)*			

GdFeCo properties

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



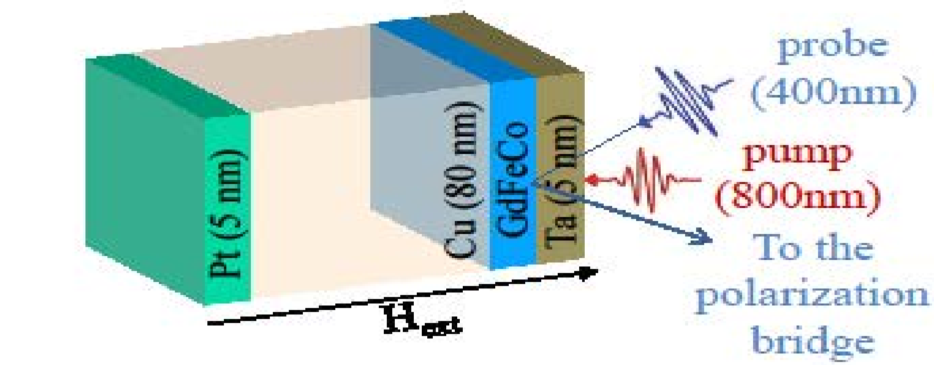


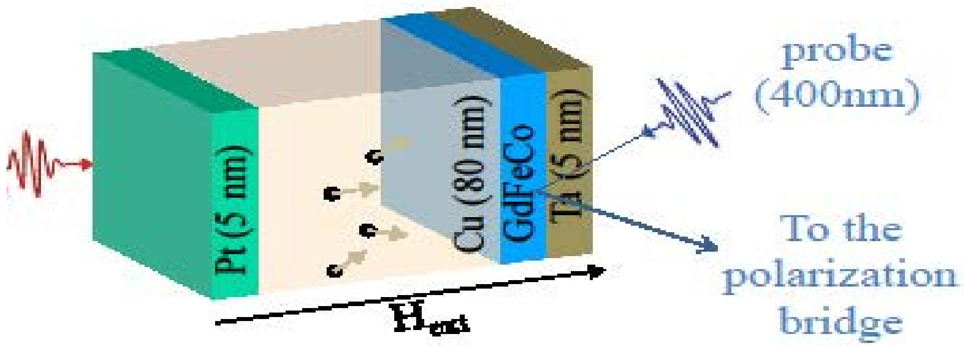


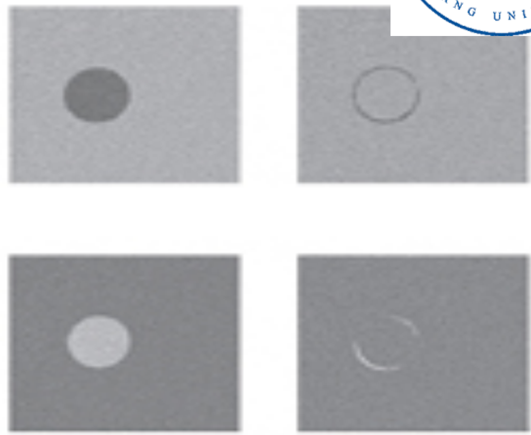
Yong Xu
(Now Beihang Univ)

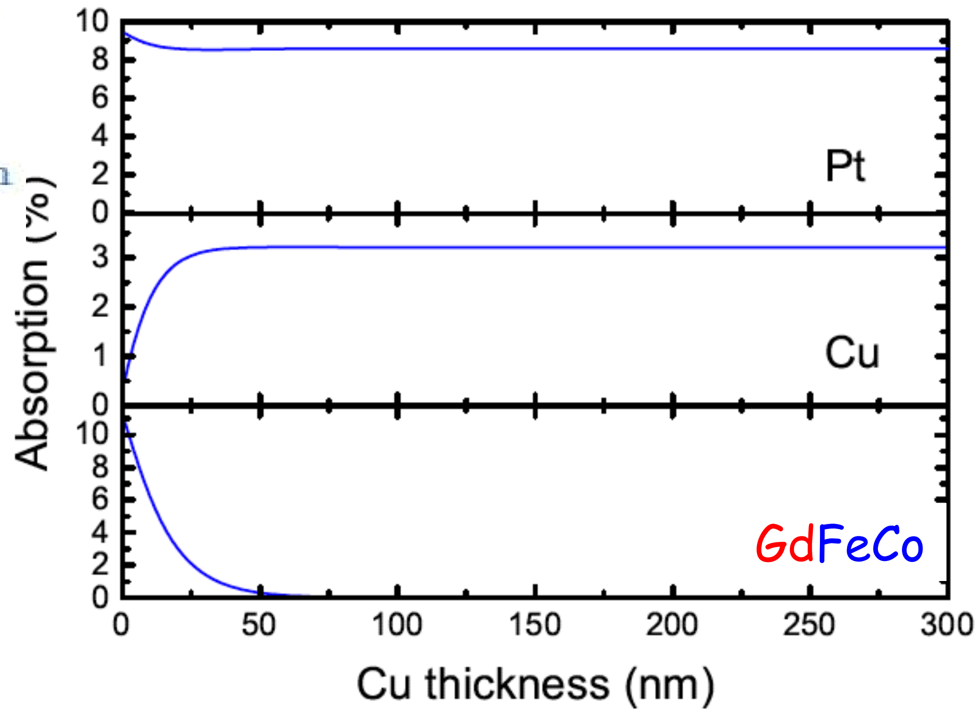
Y. Xu, et al Adv Matter **29** 42 1703474 (2017)

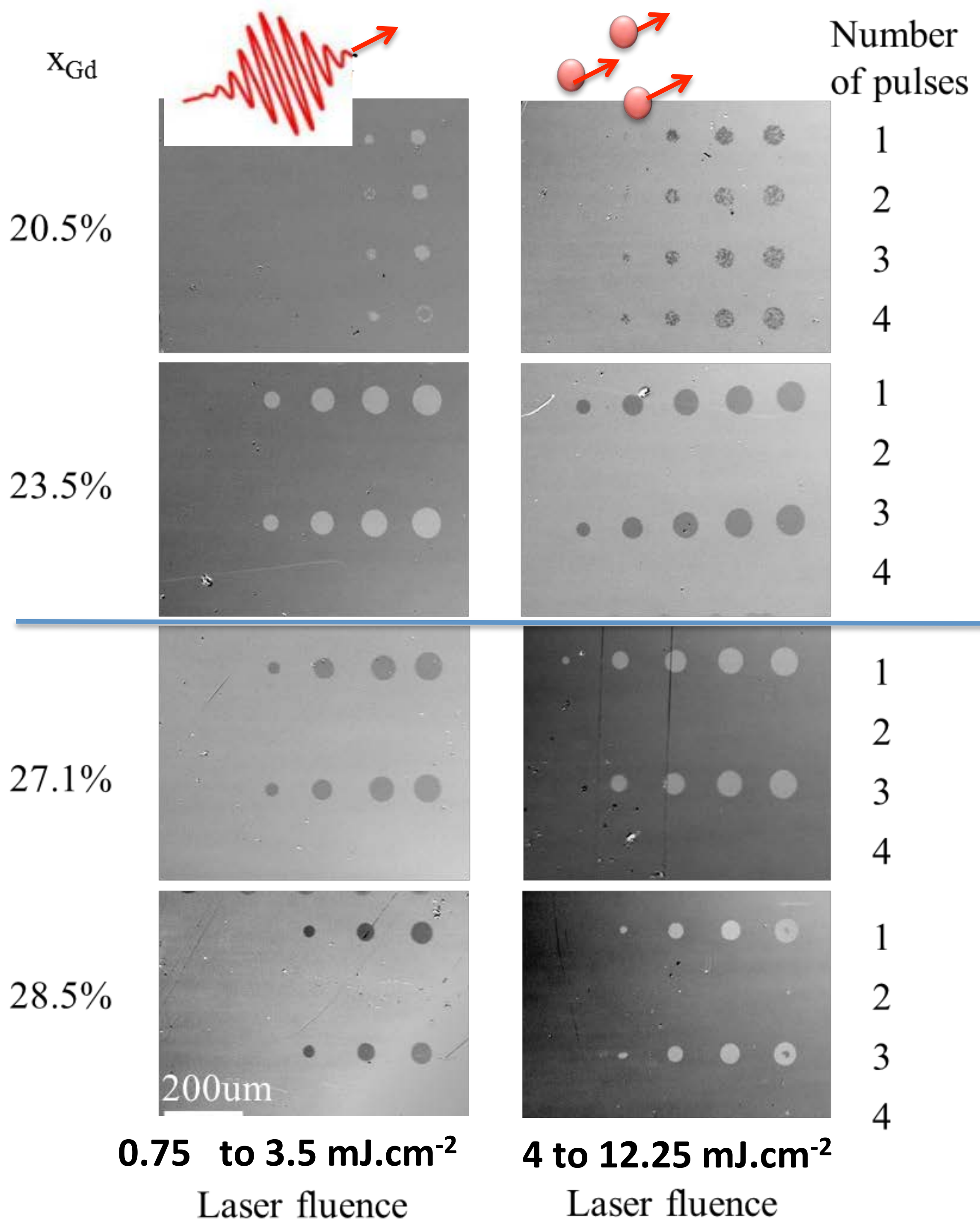
Single pulse ultra fast all optical switching GdFeCo

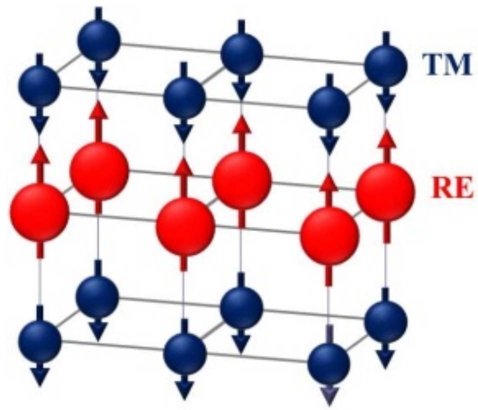












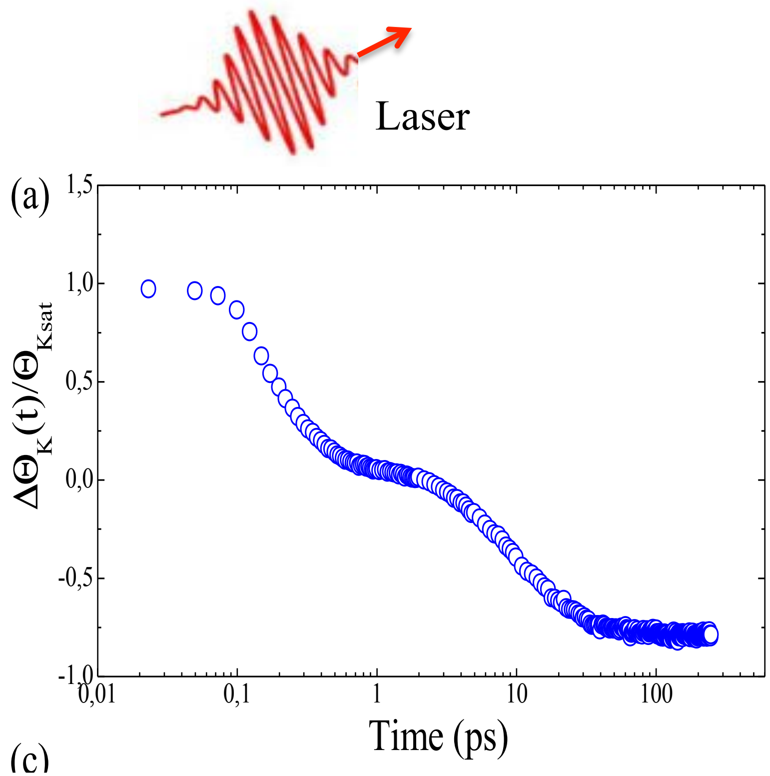
FeCo rich

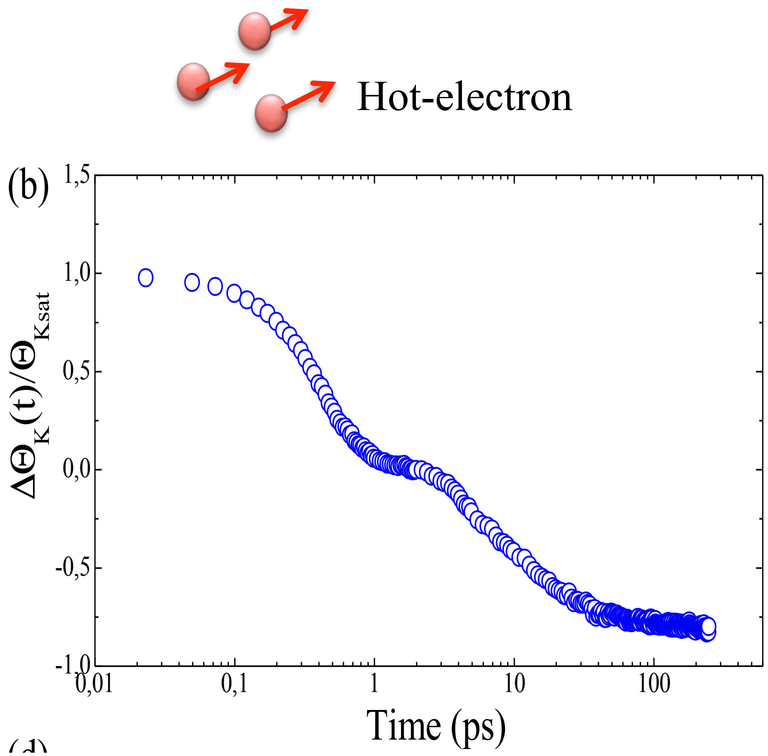
Compensation

Gd rich

Ultra short hot Electron pulse can generate GdFeCo switching

Single pulse ultra fast all optical switching GdFeCo





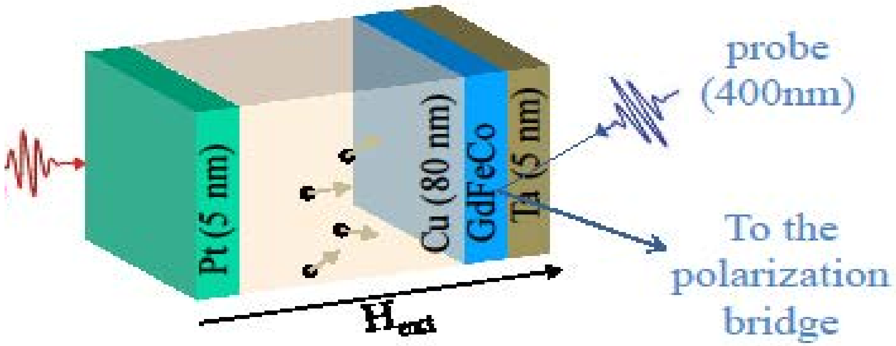
3.2 mJ.cm^{-2}

15 mJ.cm^{-2}

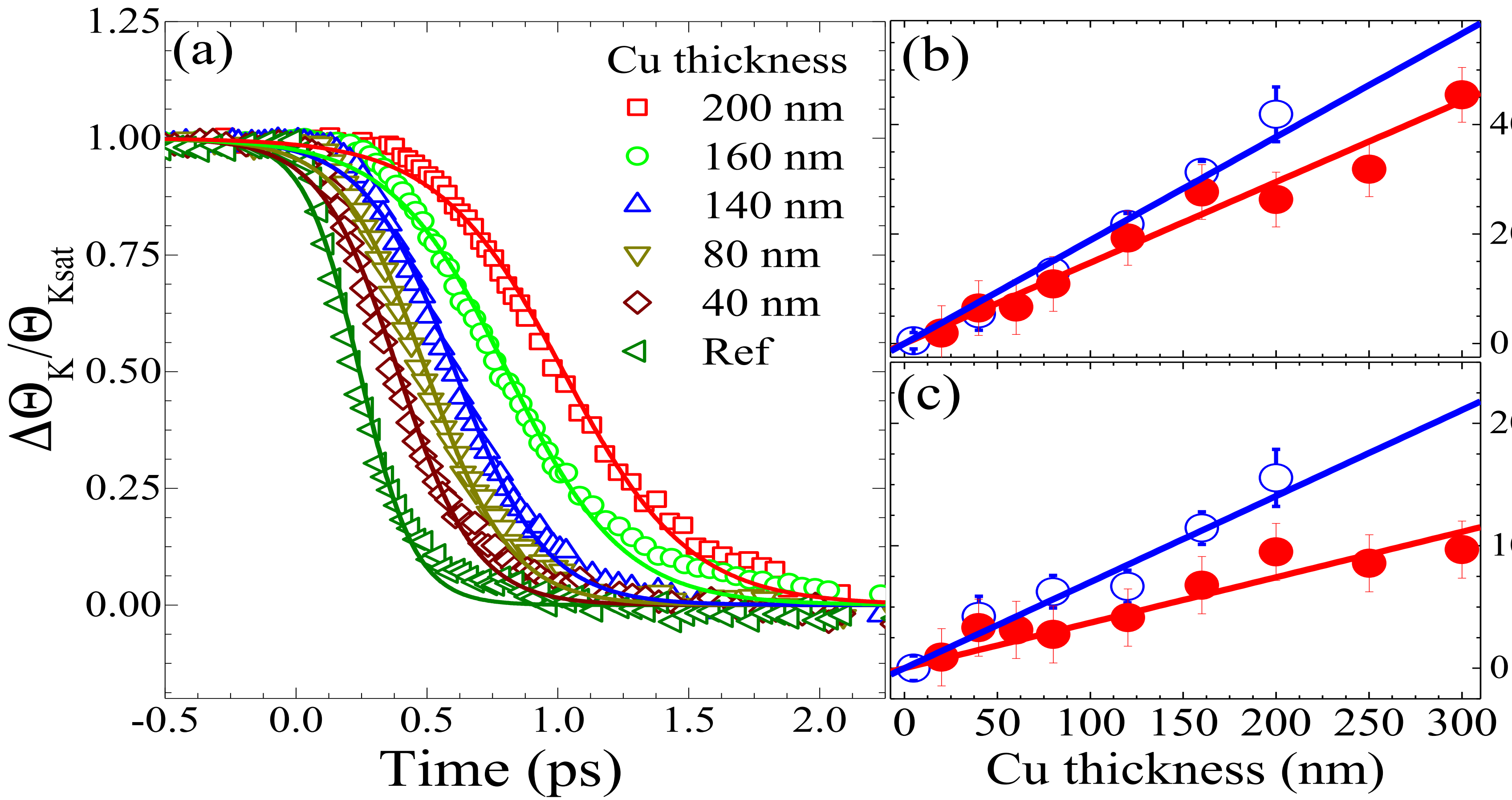
in 5 nm thick $Gd_{23,9}(FeCo)_{76.1}$ film

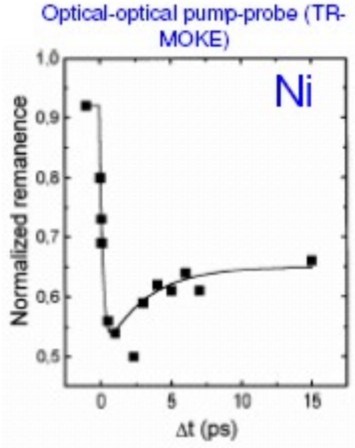
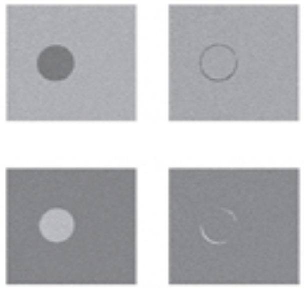
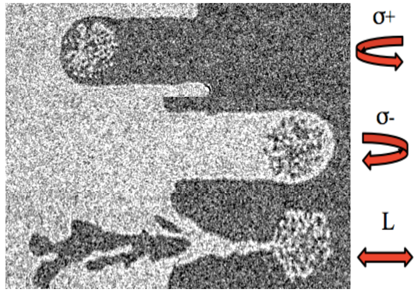
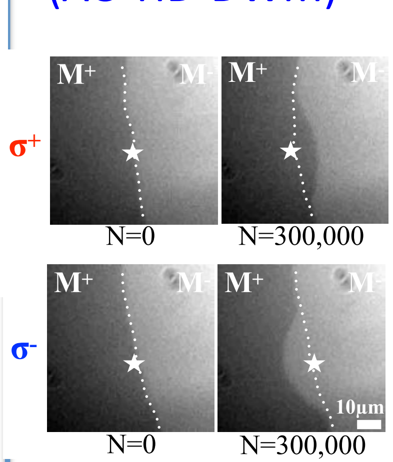
Ultra short hot Electron pulse
can generate ultra fast GdFeCo switching

Ultra fast dynamic mediated by ballistic hot electrons



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



Magnetisation Manipulation Ultra short pulses	Ultra fast Demagnetisation	All Optical Helicity **Independent** switching (AO-HIS)	All Optical Helicity **dependent** switching (AO-HDS)	All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)
				
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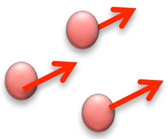
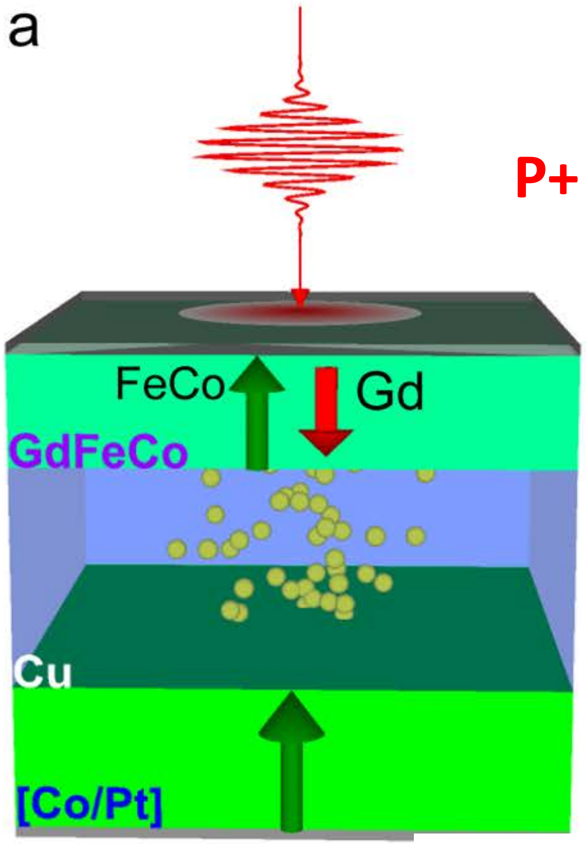
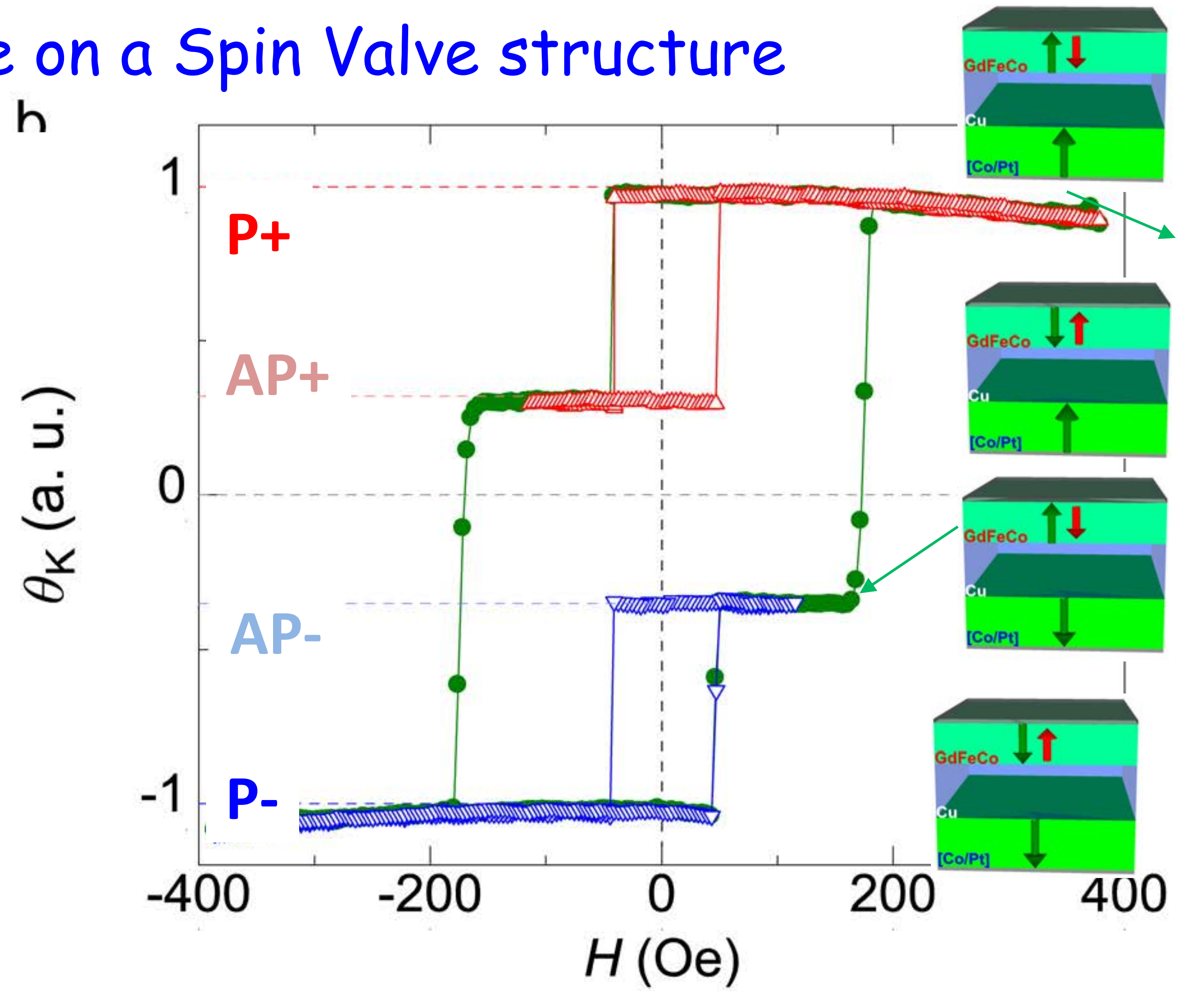
 Electron	*N. Bergeard,et al* *Phys. Rev. Lett. 117, 147203 (2016)*	*Y. Xu, et al* Adv Matter **29** 42 1703474 (2017)		

Ultra fast laser pulse on a Spin Valve structure



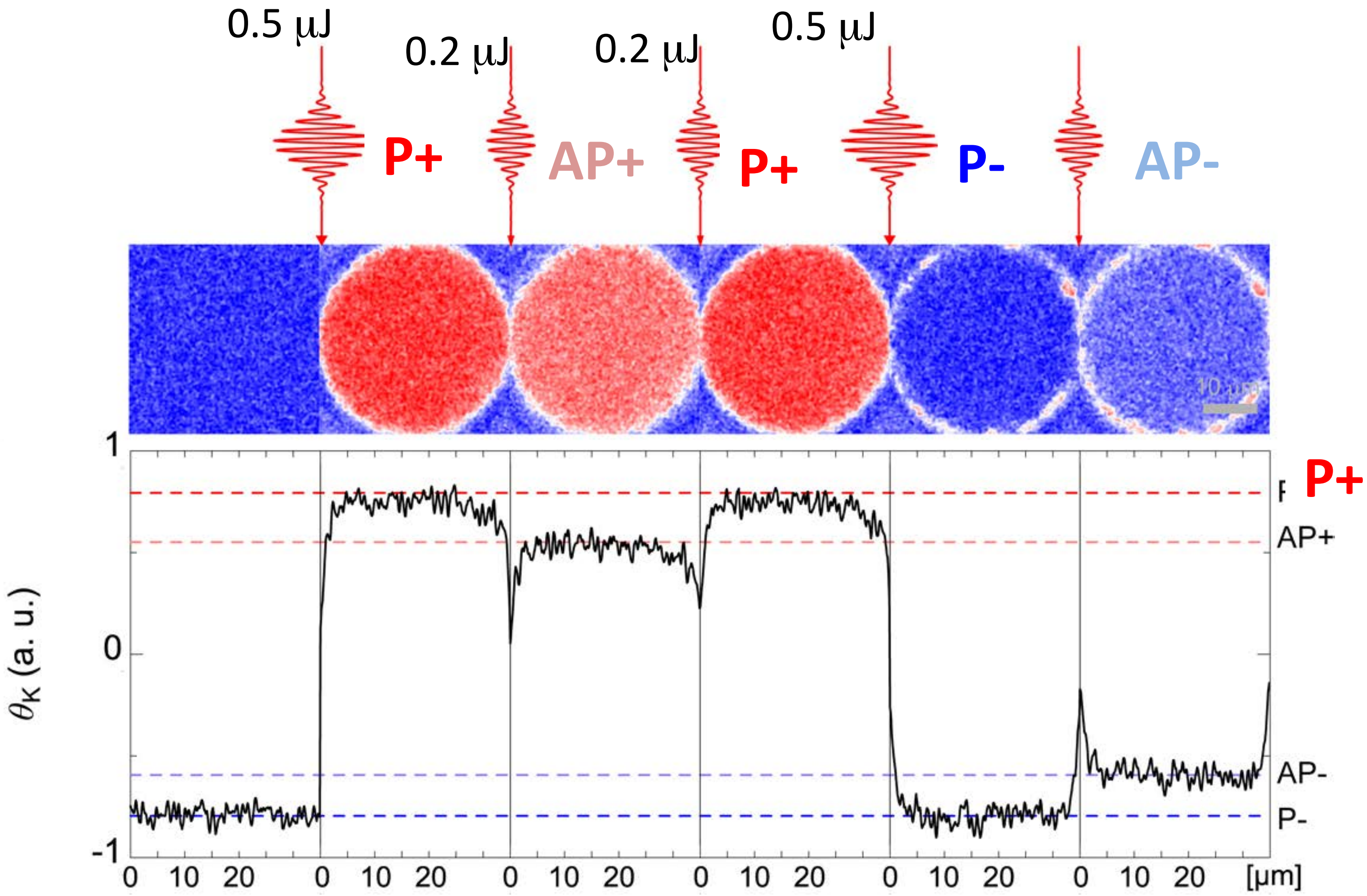


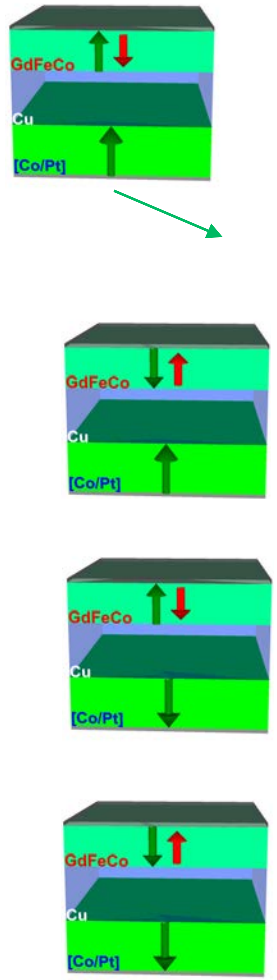
Satoshi Iihama
(Now Tohoku- AIST),

Yong Xu
(Now Beihang Univ)

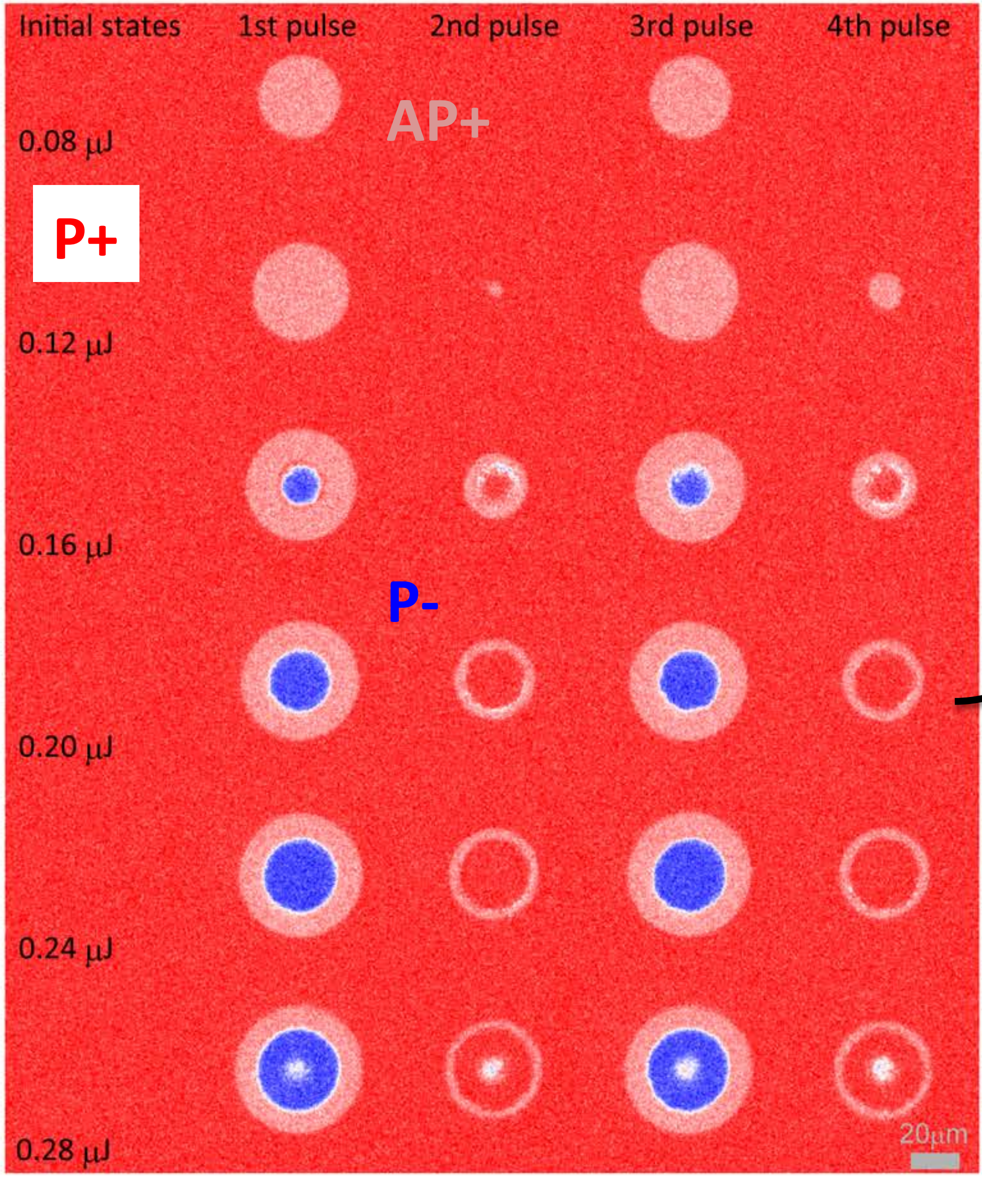
S. Iihama et al Adv. Mater. 1804004 (2018,)

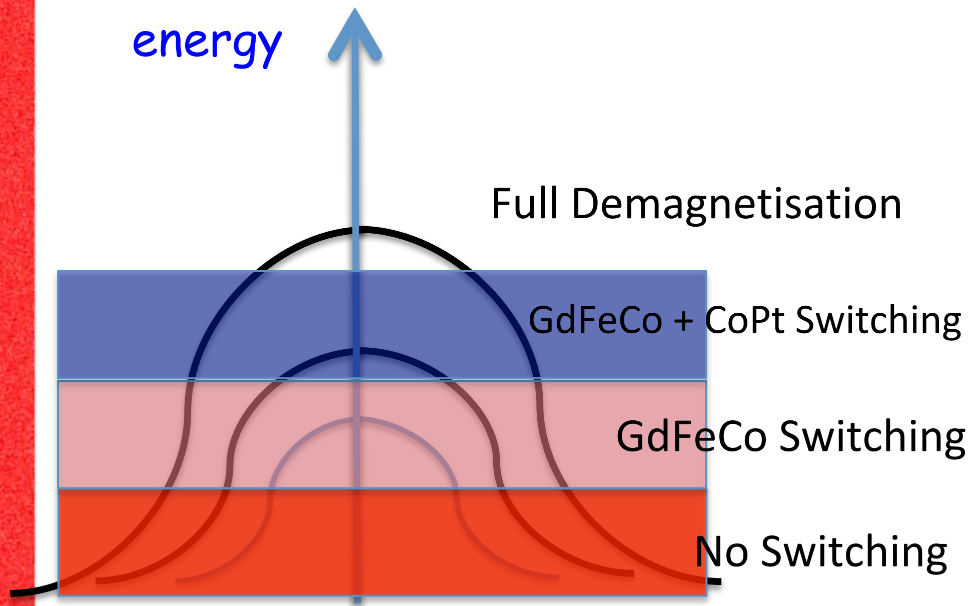
4 configurations accessible using femto-second light pulses





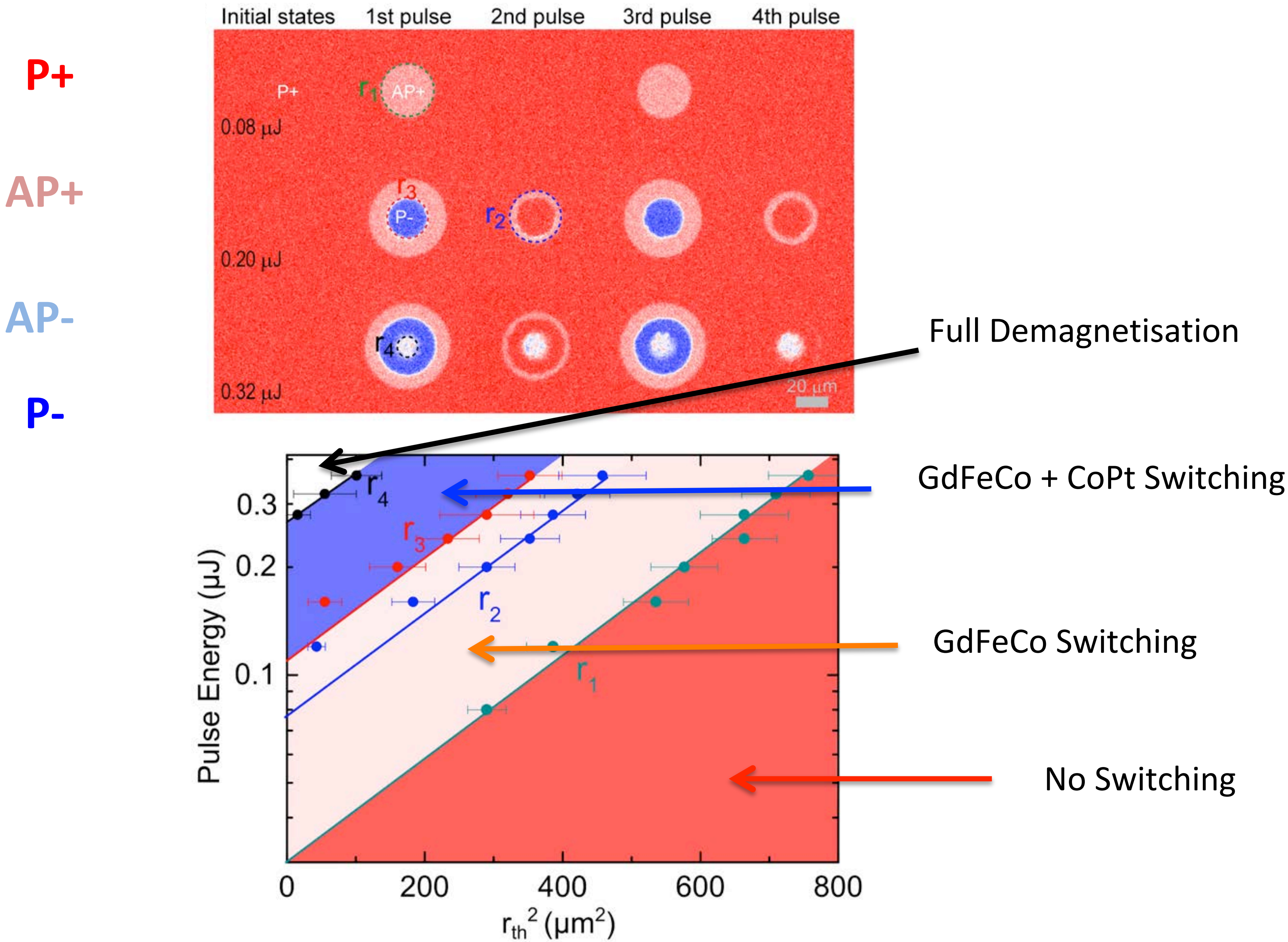
Laser pulse energy





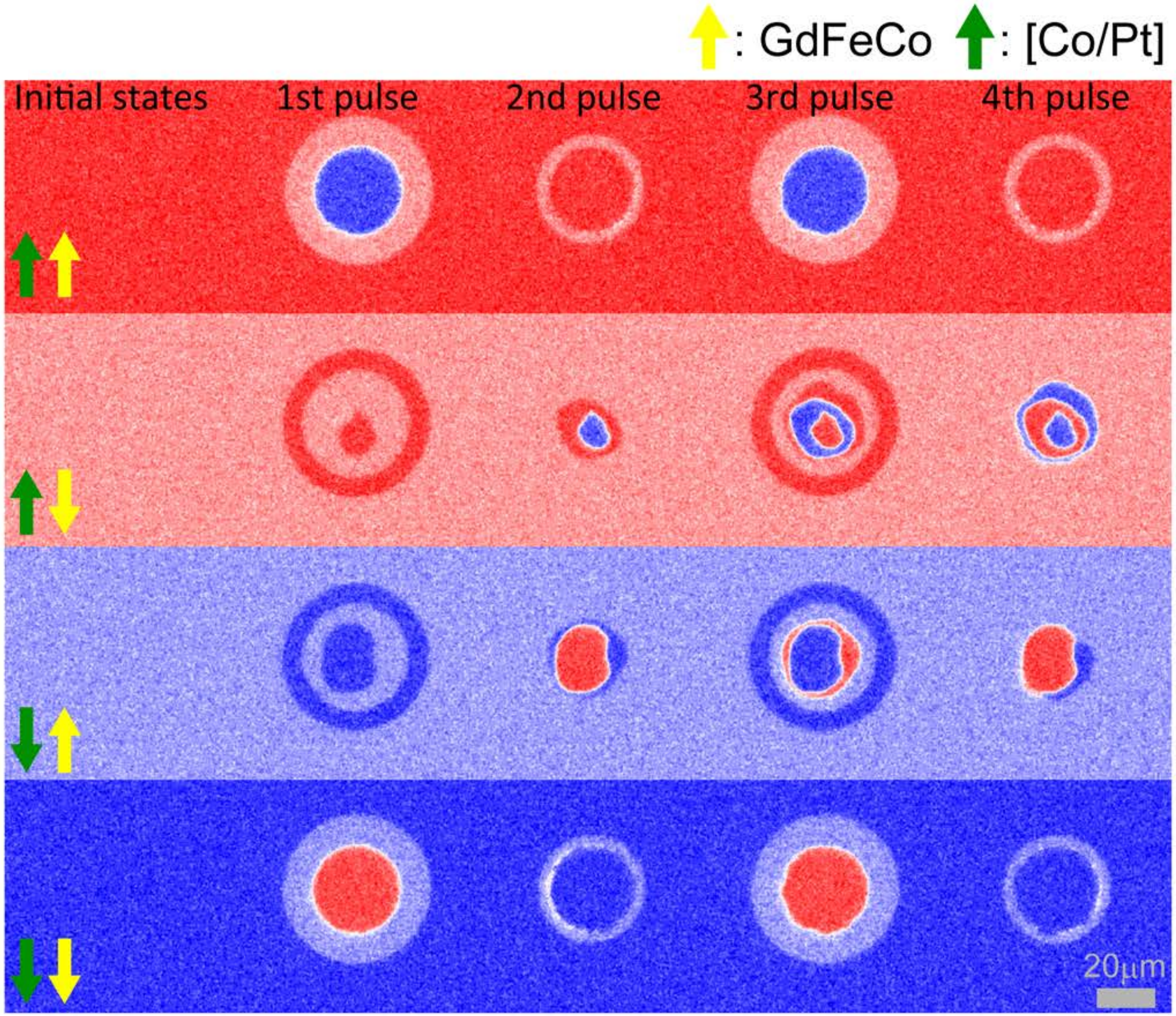
Pump energy dependence of radius of the domain can be explained by the Gaussian distribution of the pump laser

Single pulse switching States Diagram



GdFeCo (FeCo-rich) / Cu / [Co/Pt] spin-valve

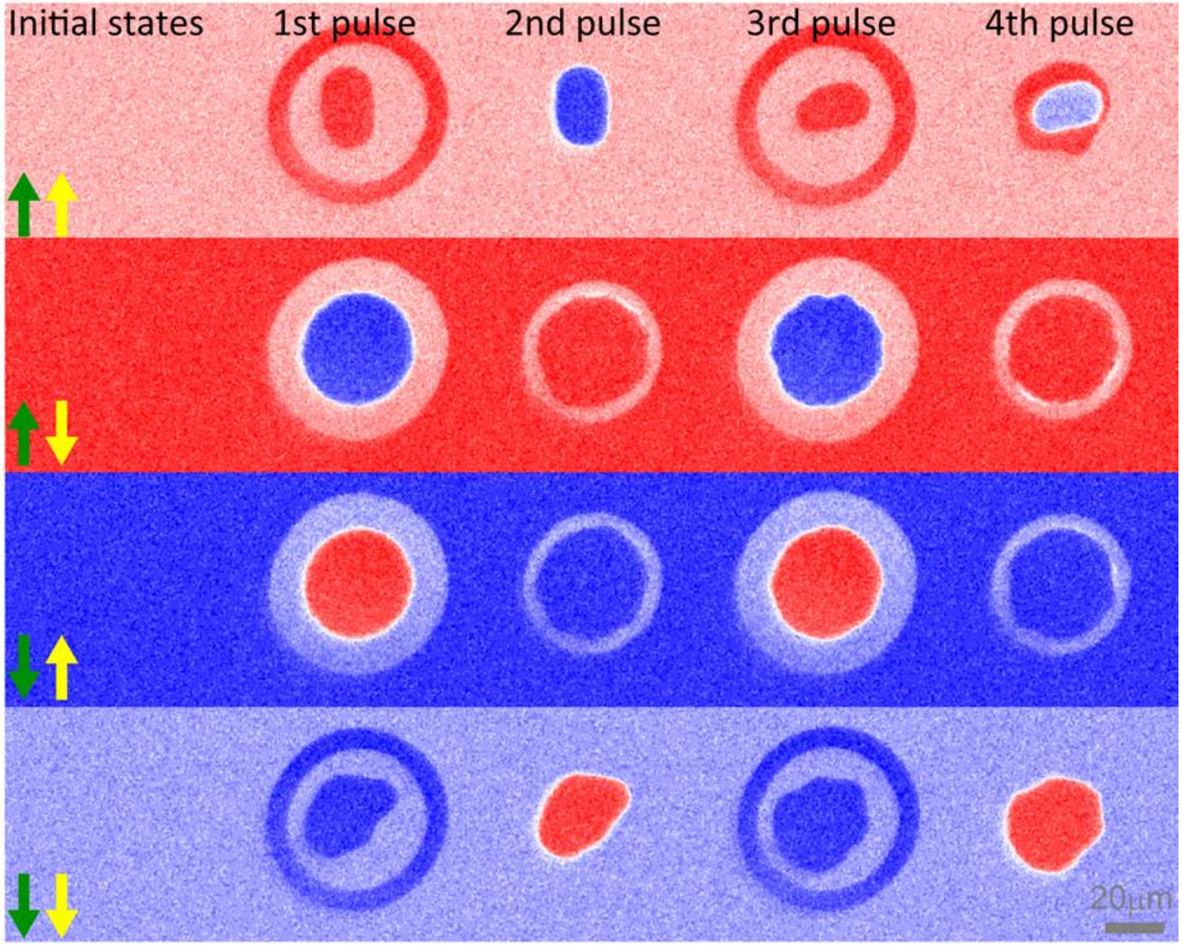
0.25μJ



- Need an antiparallel alignment between Gd and Co/Pt to observe Co/Pt switching

GdFeCo (Gd-rich) / Cu / [Co/Pt] spin-valve

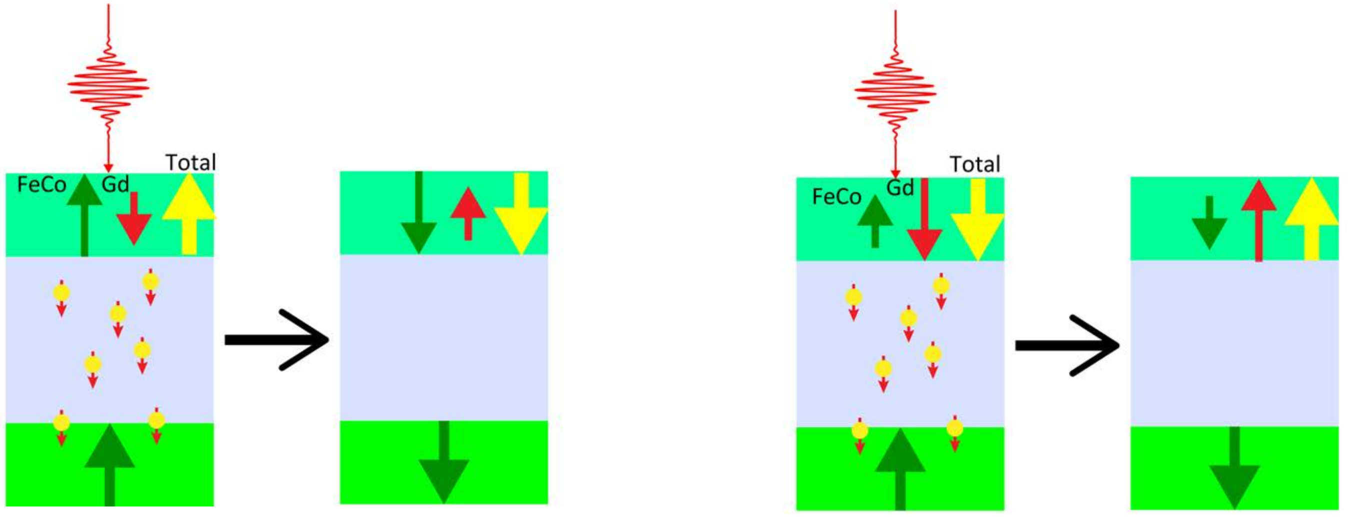
Glass sub./ Ta (5) / $[Pt(1)/Co(0.6)]_4$ / Cu (10) / $Gd_{26.4}(FeCo)_{73.6}$ (5) / Ta (5)

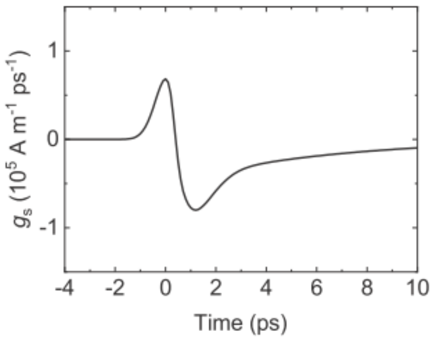


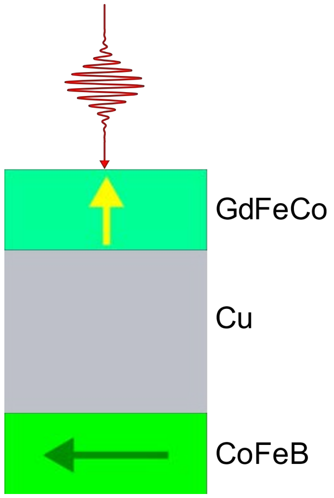
- Need an antiparallel alignment between Gd and Co/Pt to observe Co/Pt switching

Mechanism : Hot electron mediated switching

FeCo-rich GdFeCo / Cu / [Co/Pt]   Gd-rich GdFeCo / Cu / [Co/Pt]







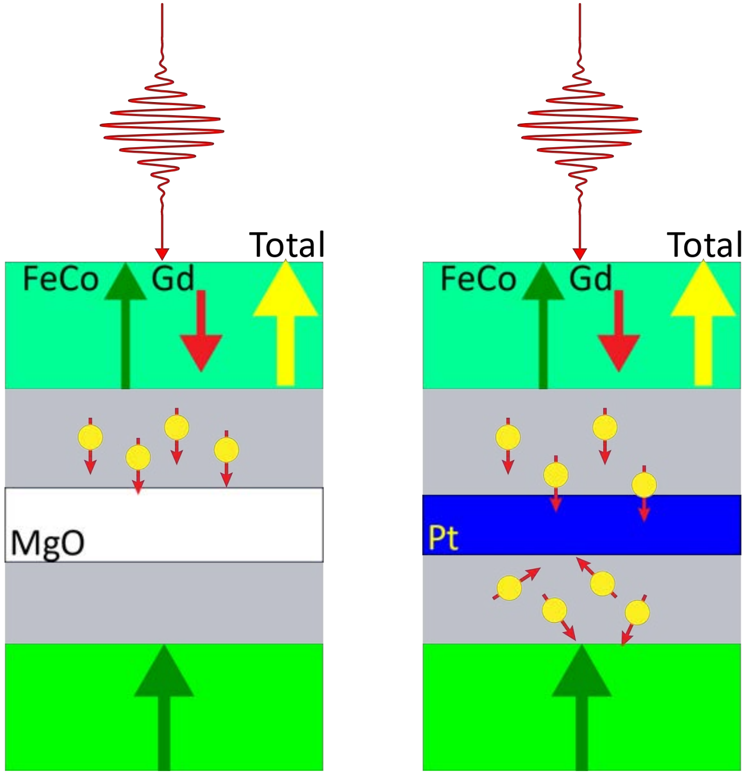
Recent experimental study demonstrated that spin-polarization of spin current generated by GdFeCo is parallel to Gd

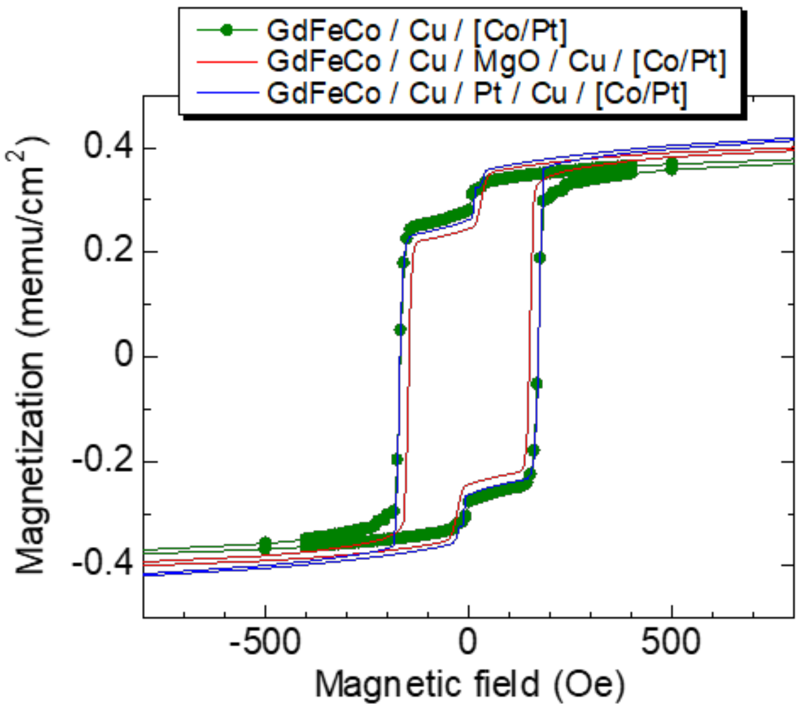
G. –M. Choi *et al*. Phys. Rev. B **97**, 014410 (2018)

To test mechanism: MgO and Pt insertion in Cu

MgO insulator insertion: Glass sub. / Ta (5) / [Pt(1)/Co(0.6)]$_4$ / Cu (4.6) / MgO (3.5) / Cu (4.6) / $Gd_{23.3}(FeCo)_{76.7}$ (5) / Ta (5)

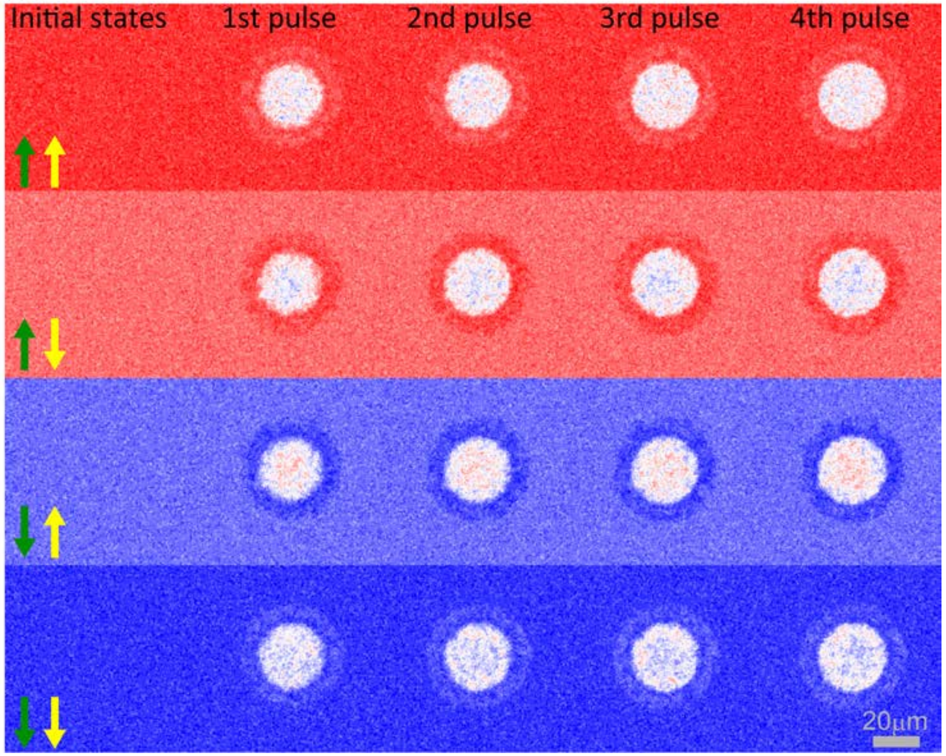
Pt insertion: Glass sub. / Ta (5) / [Pt(1)/Co(0.6)]$_4$ / Cu (7) / Pt (3) / Cu (7) / $Gd_{23.3}(FeCo)_{76.7}$ (5) / Ta (5)



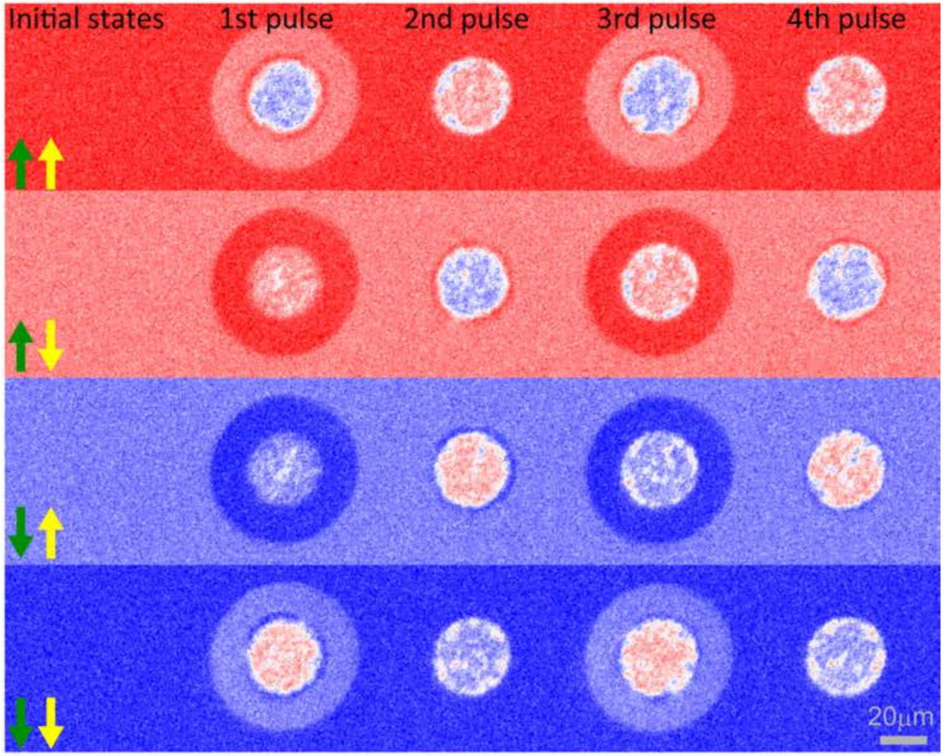


To test mechanism: MgO and Pt insertion in Cu

MgO insulator insertion

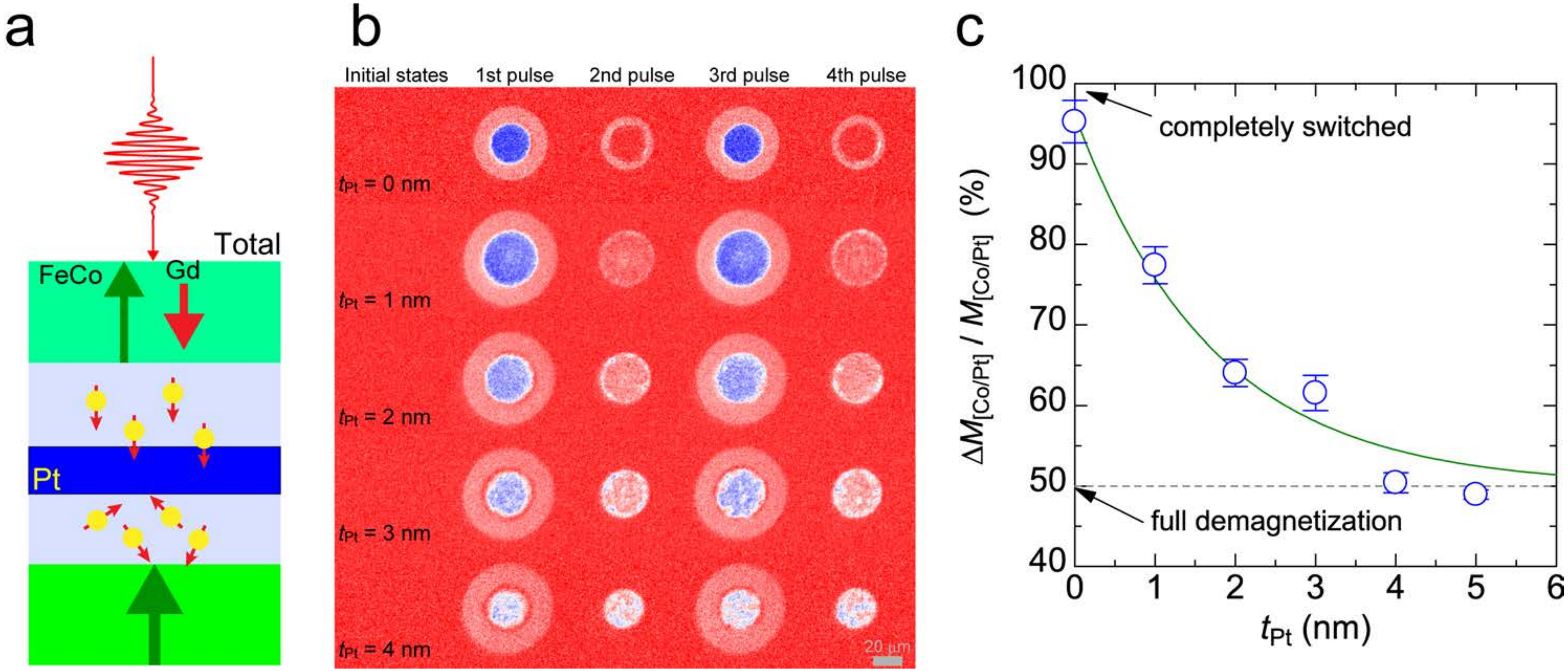


Pt insertion

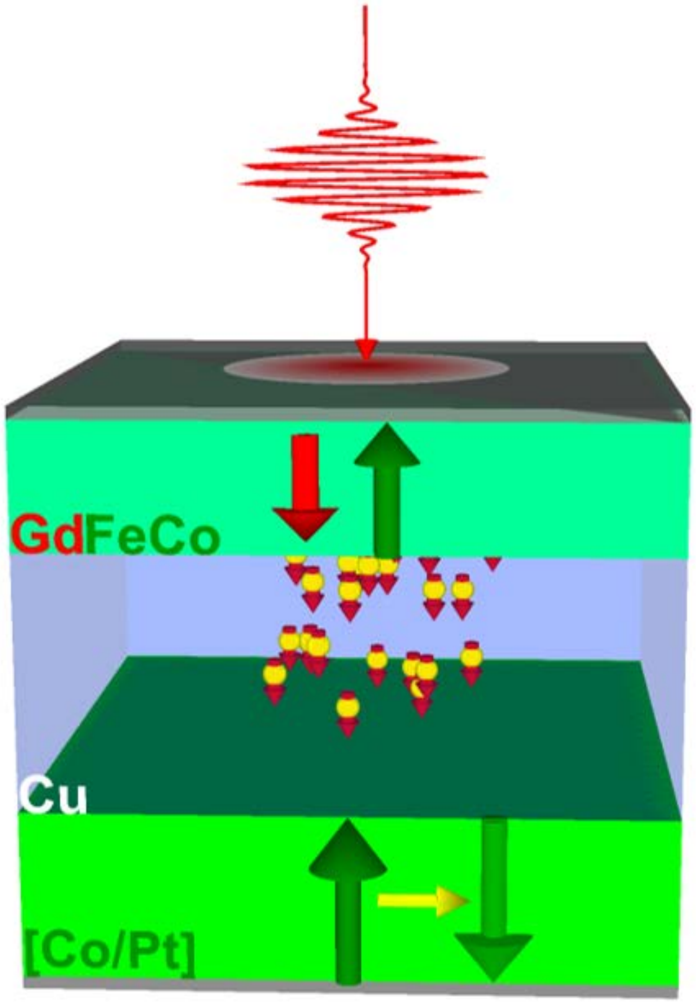


AP+ P+ P- AP-

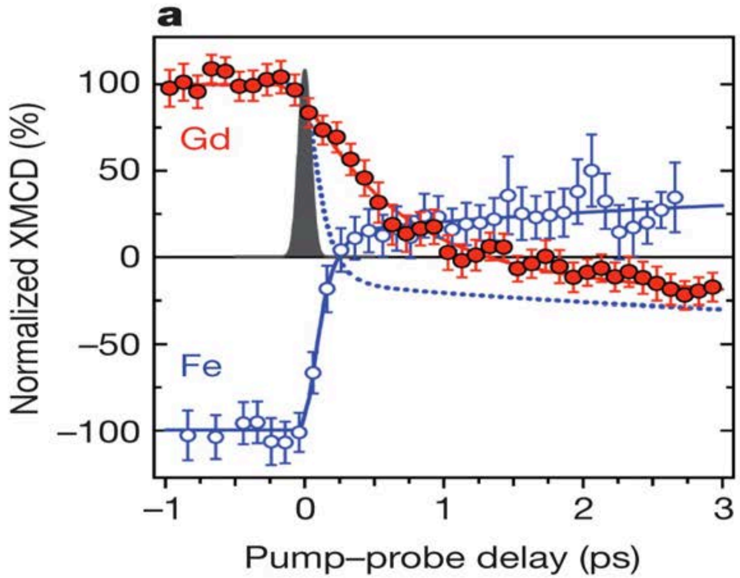
To test mechanism: Pt (thickness) insertion in Cu

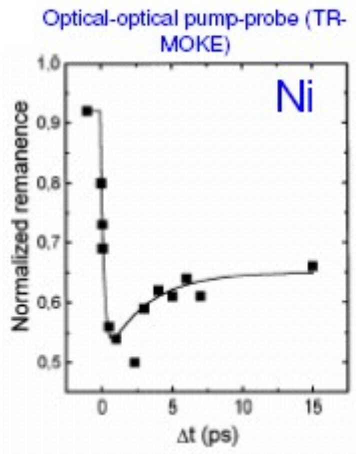
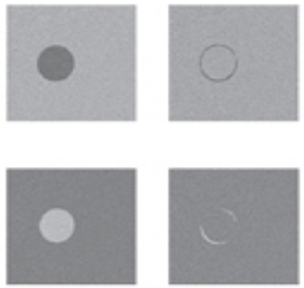
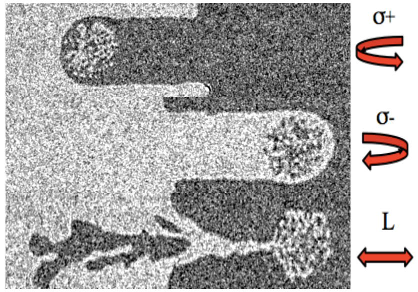
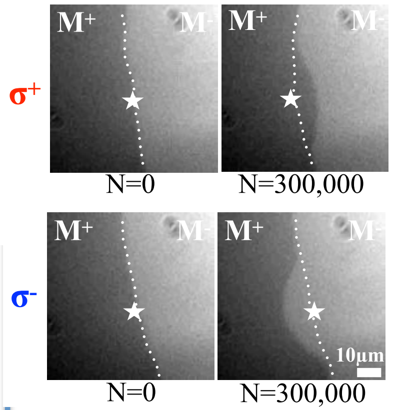
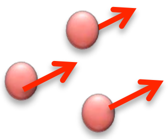


Hot electron mediated single pulse switching

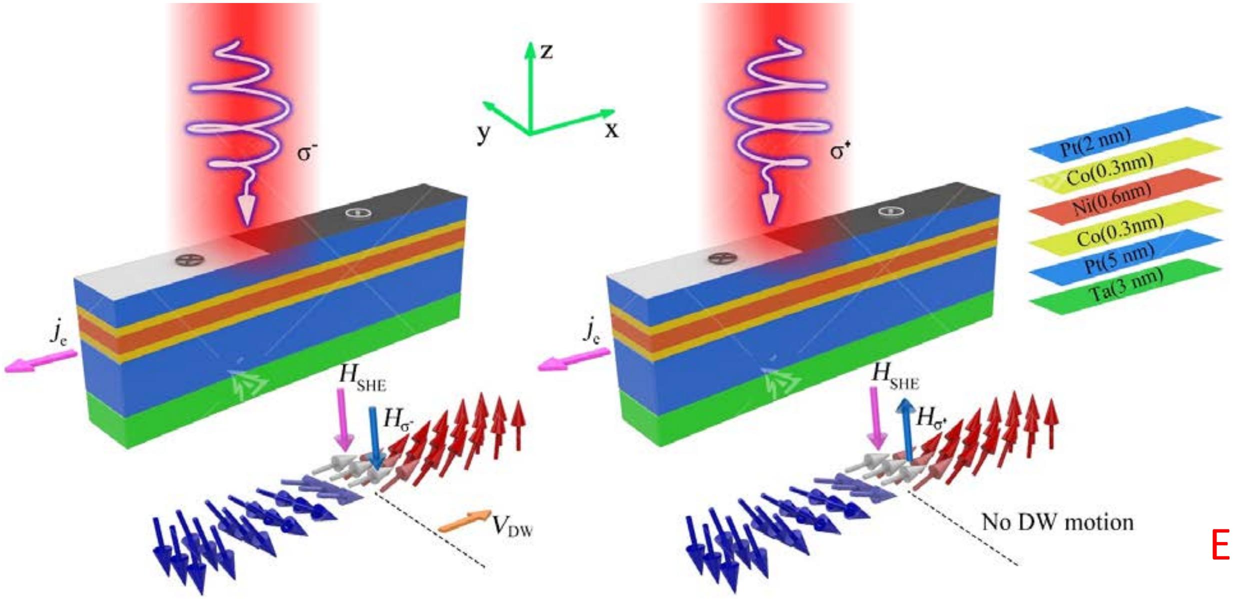


Can it generalise to all Gd based material ?

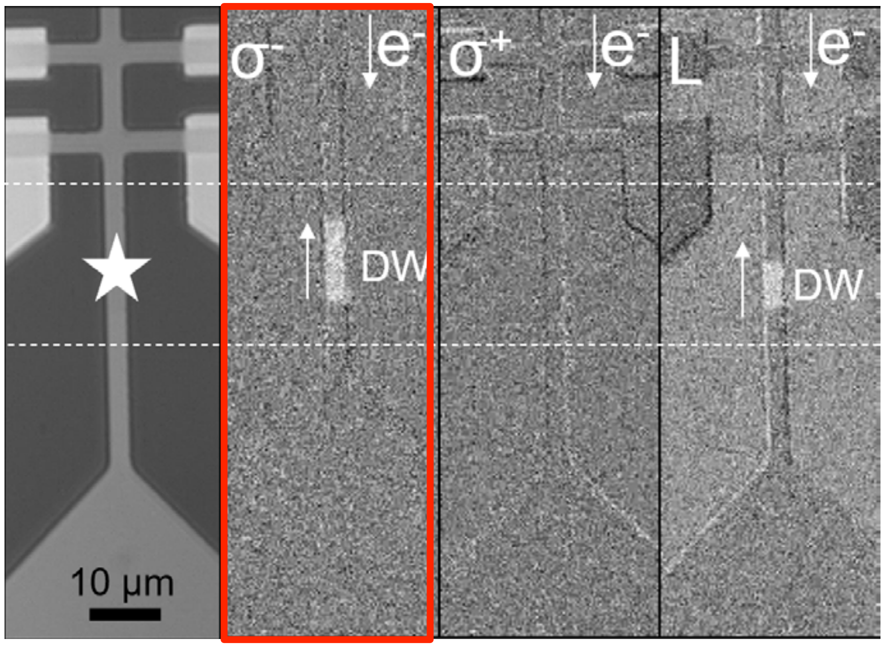


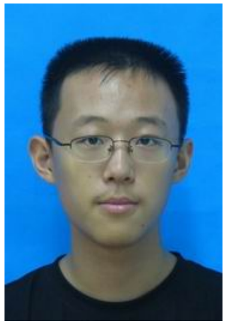
Magnetisation Manipulation Ultra short pulses	Ultra fast Demagnetisation	All Optical Helicity **Independent** switching (AO-HIS)	All Optical Helicity **dependent** switching (AO-HDS)	All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)
				
 Light	*E. Beaurepaire, et al* *PRL 76, 4250 (1996)*	T. A. Ostler et al Nat. Commun. 3 666 (2012)	*C. D. Stanciu et al* *Phys. Rev. Lett. 99, 047601 (2007)* *C.-H. Lambert et al.,* *Science 345 (6202), 1337 (2014)*	Y. Quessab et al Phys. Rev. B 97, 054419 (2018
 Electron	*N. Bergeard,et al* *Phys. Rev. Lett. 117, 147203 (2016)*	*Y. Xu, et al* Adv Matter **29** 42 1703474 (2017)	S. Iihama et al Adv. Mater 1804004 (2018,)	

Combining SOT + AO-HDS to DW motion



Energy Efficiency !





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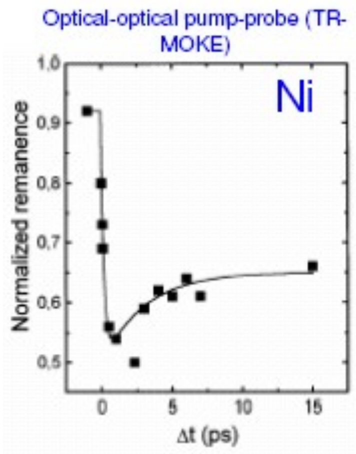
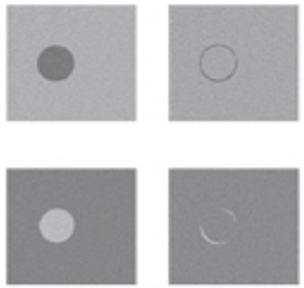
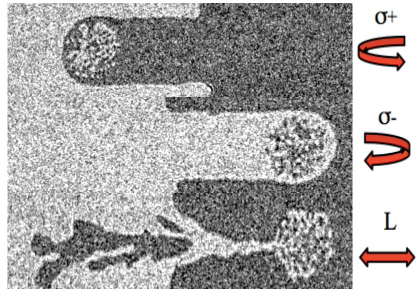
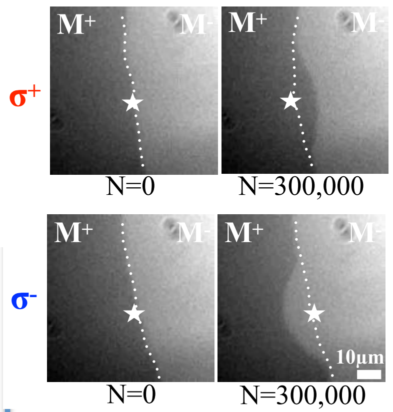
arXiv:1810.05375

Magnetisation Manipulation / Ultra short pulses	Ultra fast Demagnetisation	All Optical Helicity **Independent** switching (AO-HIS)	All Optical Helicity **dependent** switching (AO-HDS)	All Optical Helicity **dependent** Domain Wall Motion (AO-HD-DWM)
				
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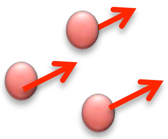 Electron	*N. Bergeard,et al* *Phys. Rev. Lett. 117, 147203 (2016)*	*Y. Xu, et al* Adv Matter **29** 42 1703474 (2017)	S. Iihama et al Adv. Mater 1804004 (2018,)	B. Zhang et al arXiv:1810.05375

Acknowledgments

Charles Henri Lambert

Mohammed Salah EL HADRI

Yassine Quessab

Marwan Deb,

Michel Hehn

Gregory Malinowsky

Jon Gorchon

Nicolas Bergeard,

Pierre Vallobra

Matthias Gottwald

Thibaud Fache

Eric E. Fullerton

R. Medapalli

Y. Fainman

V. Uhlíř

Gregory Kiching

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V. Lomakin,

Xiaoyang Lin

Yong Xu

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Sabine Alebrand

Daniel Steil

Jeff Bokor

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Martin Aeschlimann

Mirko Cinchetti

B. Varaprasad,

Y.K. Takahashi

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COST is supported by the EU Framework Programme Horizon 2020

The Magnetofon project.

Ultrafast opto-magneto-electronics for non-dissipative information technology

Andrei I. Kirilyuk
Chair of Magnetofon Project

WG1: ***All-optical switching/manipulation of magnetization***

WG2***: Optics of spin currents***

WG3: ***Ultrafast magneto-electrics***

WG4: ***Ultrafast opto-magnonics***

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