Ultrafast Spin Current Generation, for AF switching ? (in Rare Earth Ferromagnets)

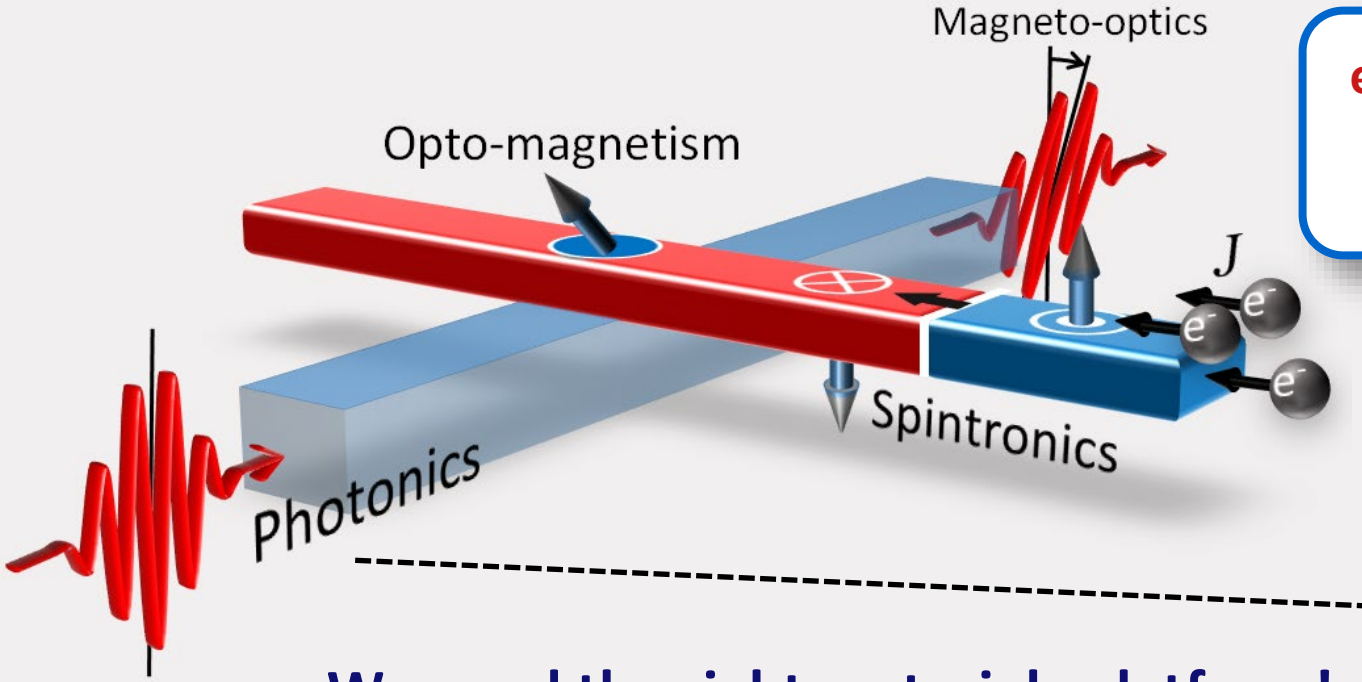
Youri van Hees, Tom Lichtenberg, Maarten Beens, Jesper Levels, Bert Koopmans, Reinoud Lavrijsen

Department of Applied Physics, Eindhoven University of Technology

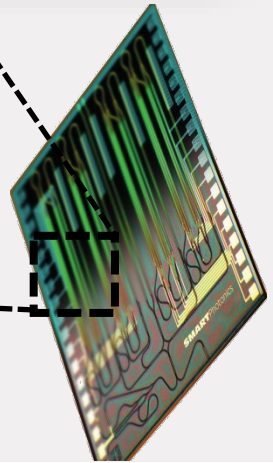
r.lavrijsen@tue.nl

Physics of Nanostructures Group

Towards Integrated Magneto-Photonics



e.g. Photonic Racetrack Memory…



We need the right materials platform!

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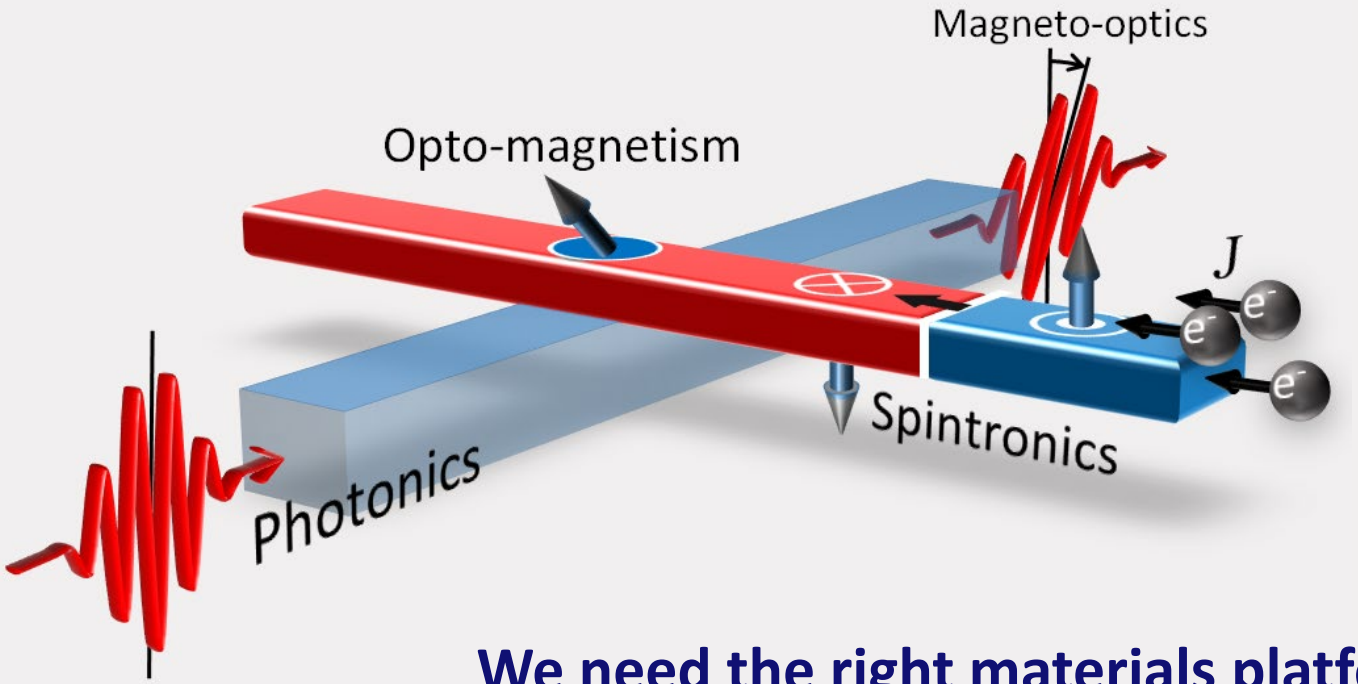
Towards Integrated Magneto-Photonics



Synthetic FiM
10 ps. rewrite AOS*
Low threshold Fl.**
2500 m/s CIDWM**
Enough?

We need the right materials platform → AFs!?

*Steinbach *et al.* APL 120 (2022), Hees *et al.* arXiv:2204.01459
**Pingzhi Li and Thomas Kools, *et al.*, ArXiv:2204.11595

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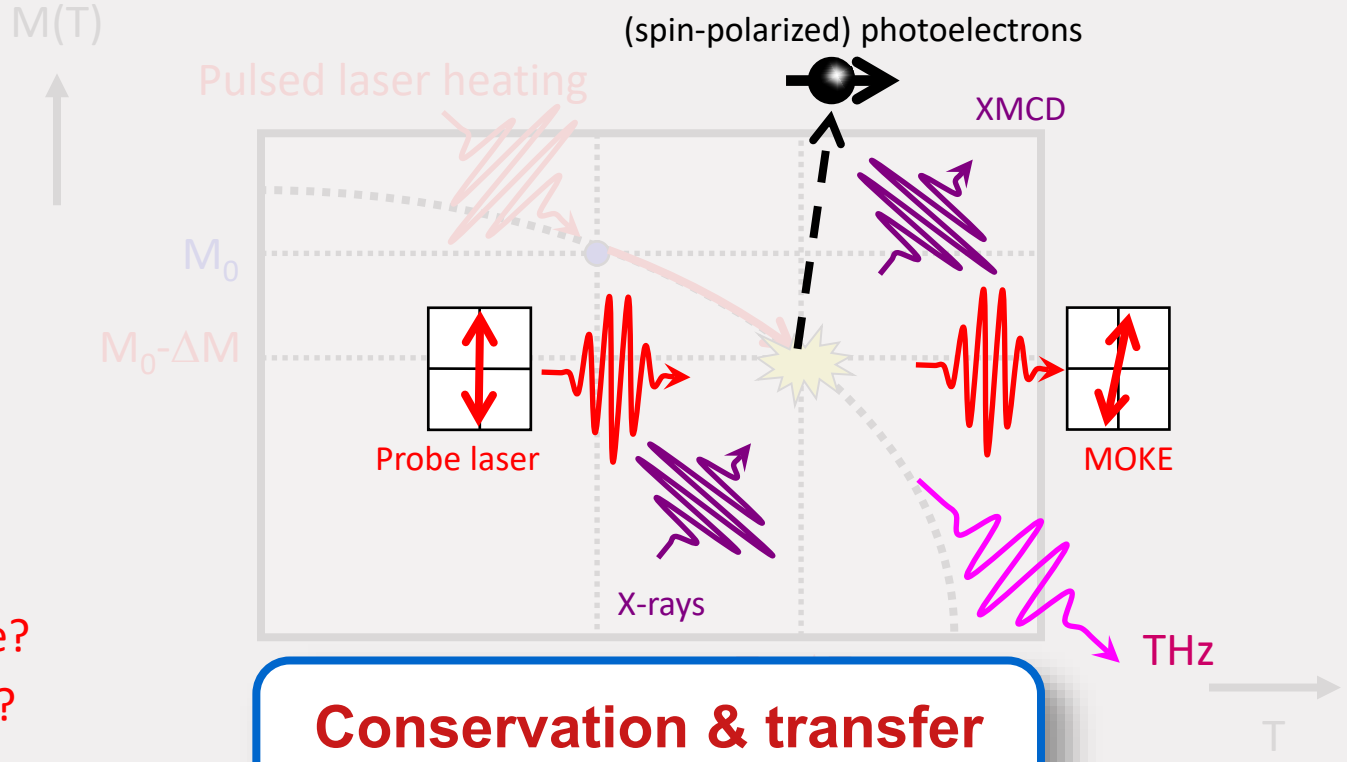
25 Years of Femtomagnetism



Time scale?

Processes?

Conservation & transfer of angular momentum

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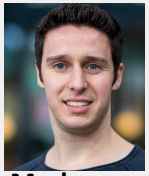
Acknowledgements


Youri van Hees


Maarten Beens

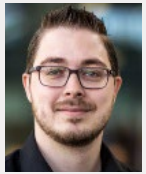

Mark Peeters


Anni Cao


Ece Demirer


Luding Wang


Pingzhi Li


Tom Lichtenberg


Mark Lalieu


Marielle Meijer


Hamed Pezeshki


Casper Schippers


Thomas Kools


Jianing Li


Michal Grzybowski


Zilu Wang

TU/e, Eindhoven: Bert Koopmans, Diana Leitao, Henk Swagten, Rembert Duine, and Jos van der Tol
Universite Lorraine, Nancy: Stephane Mangin, Gregory Malinowski, Quentin Remy, and team members
Beihang University, Beijing: Weisheng Zhao and team members
All partners in the EEX (NWO), COST network, Magnefi ITN and COMRAD ITN

Outline

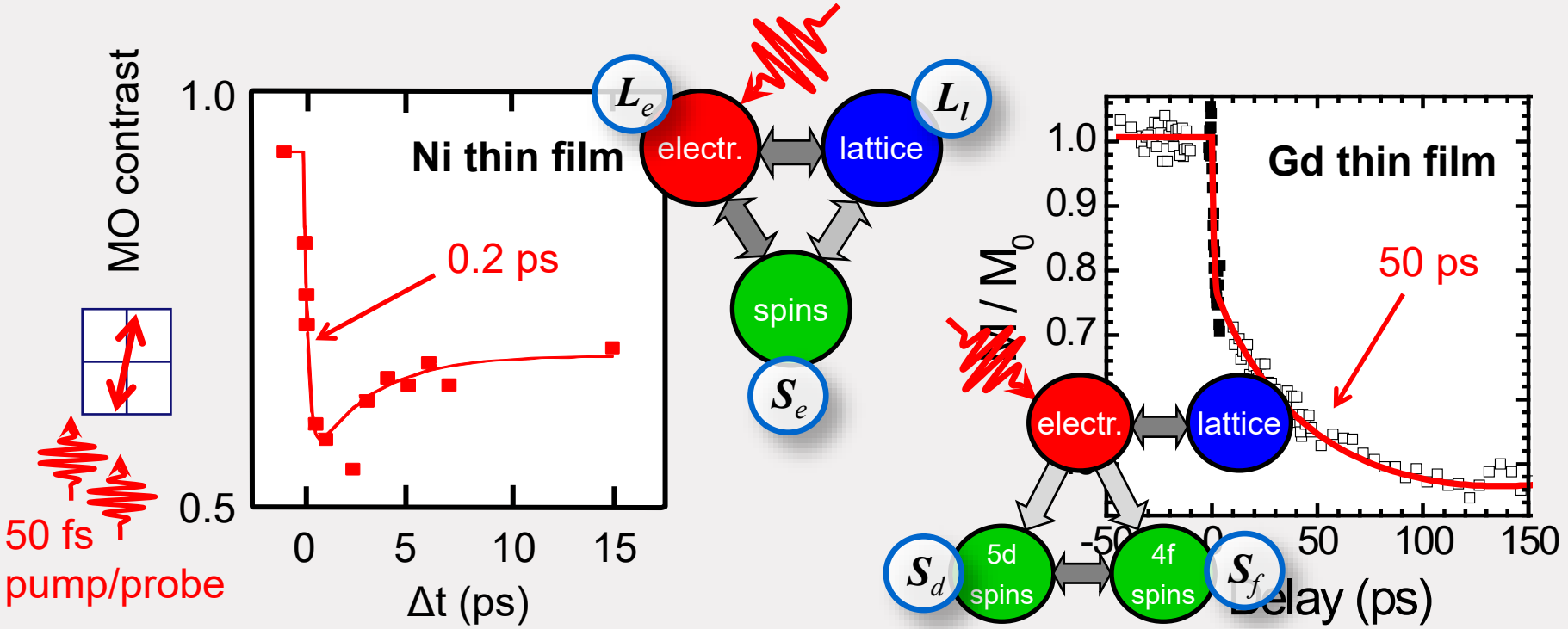
Femto-magnetism – a tutorial introduction

- Laser-induced fs demagnetization and beyond
- Local and non-local transfer of angular momentum

Some new results

- Spin-current assisted All-Optical Switching in Co/Gd
- A Fourier view on mechanisms for fs spin currents
- Resolving spin currents from Co/Gd bi-layers
- (AOS and Current induced domain wall model in $[Co/Gd]_2$)

Femtosecond demagnetization



Beaurepaire, Bigot *et al.*, Phys. Rev. Lett. 76, 4250 (1996)

Wietstruk, Weinelt, Bovensiepen *et al.*, Phys. Rev. Lett. (2011)

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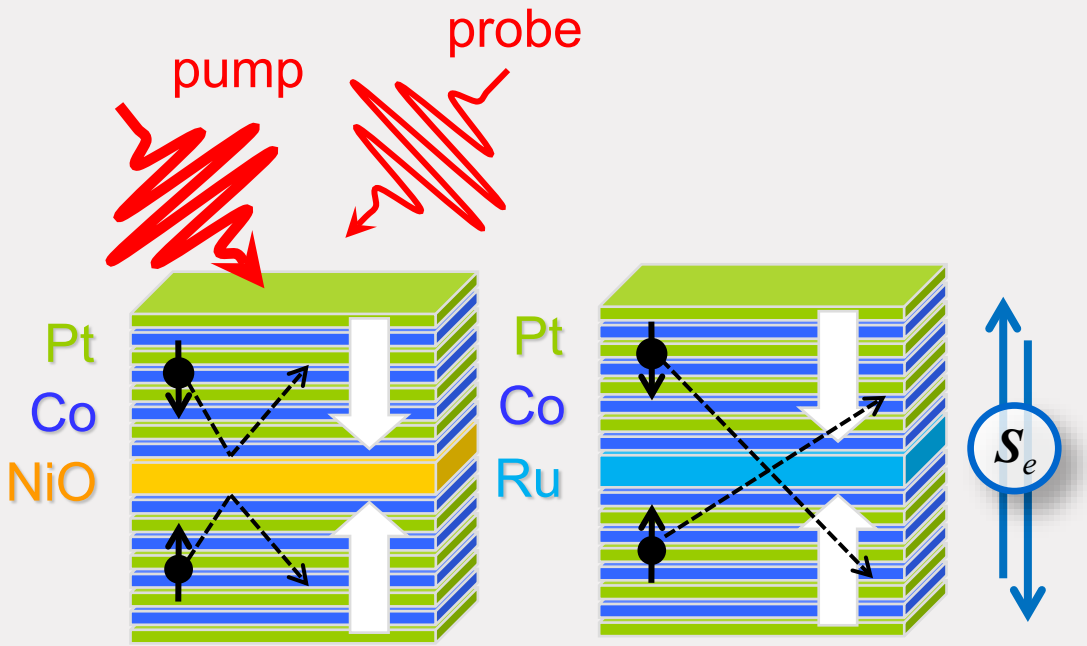
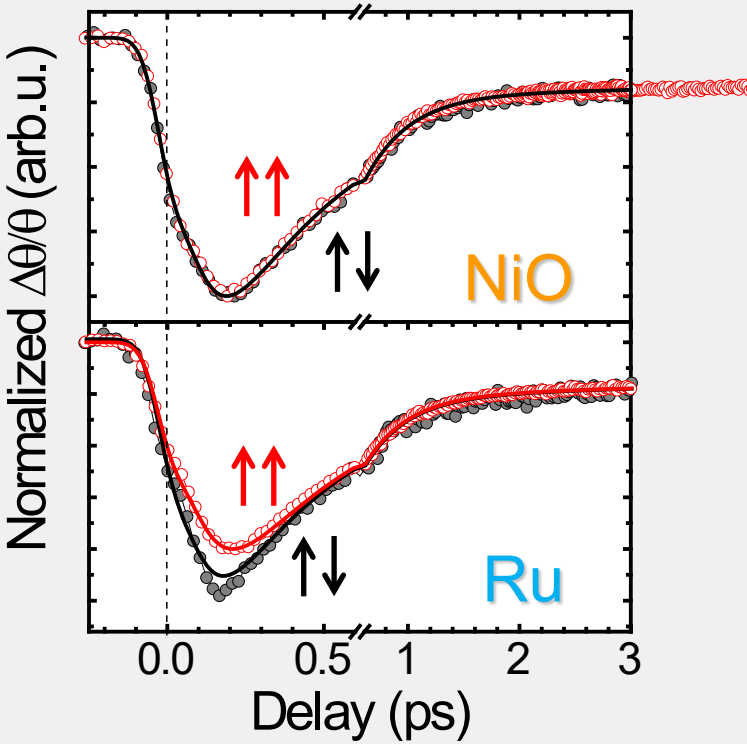
Nonlocal transfer of spin angular momentum





Malinowski *et al.*, Nature Physics (2008)

See also:

Rudolf *et al.*, Nat. Comms. 2011
Melnikov, Bovensiepen *et al.*, PRL 2011
Choi, Cahill *et al.*, Nat. Comms. 2014
Hofherr, Aeschlimann, *et al.*, PRL 2017

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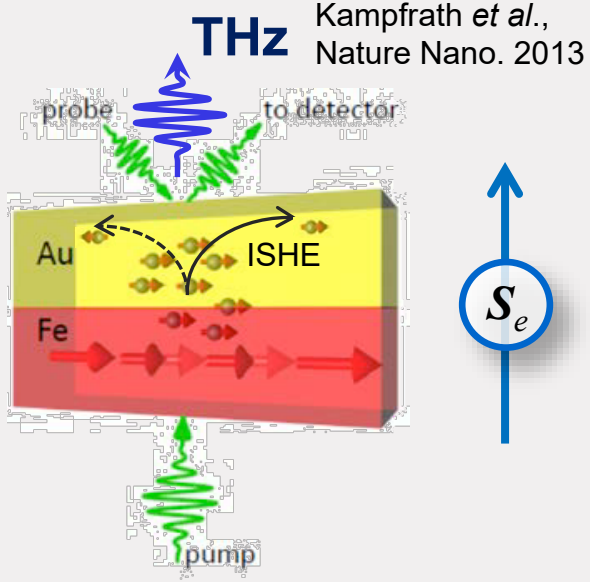
Spin currents confirmed

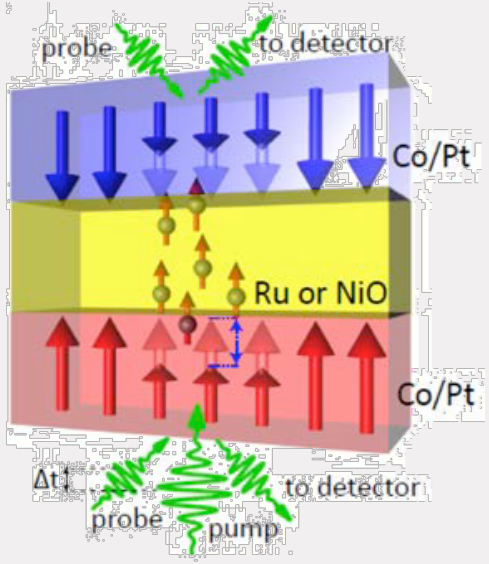
Spin accumulation



Kampfrath *et al.*, Nature Nano. 2013

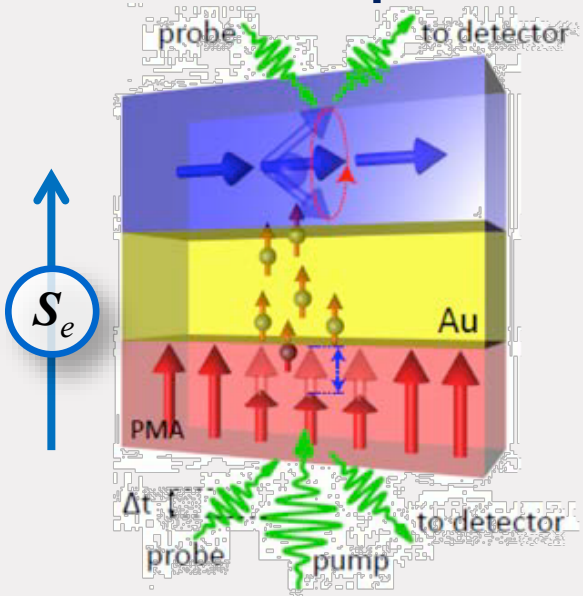
Melnikov, Bovensiepen *et al.*, PRL 2011,
Choi, Cahill *et al.*, Nat. Comms. 2014
Hofherr, Aeschlimann, *et al.*, PRL 2017

Magnetization



Malinoswki *et al.*, Nat. Phys. 2008
Rudolf *et al.*, Nat. Comms. 2011

ST-Torque



Schellekens *et al.*, Nat. Comms. 2014
Choi *et al.*, Nat. Comms. 2014
Razdolski, Melnikov *et al.*, Nat. Comms. 2017

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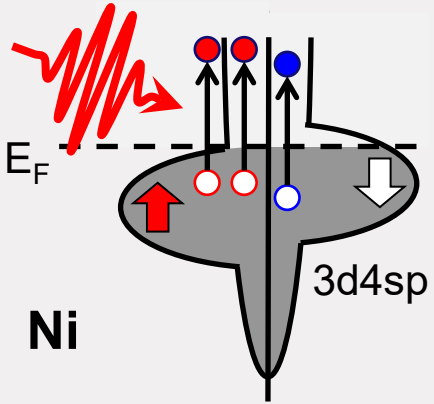
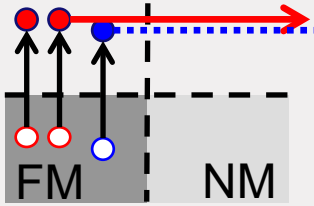
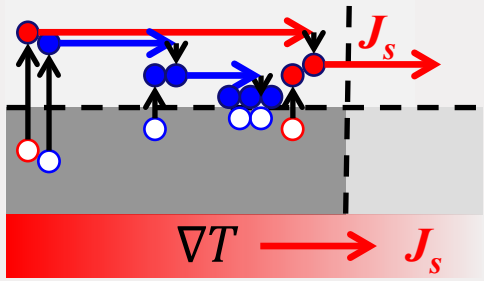
Models for Optical spin current generation

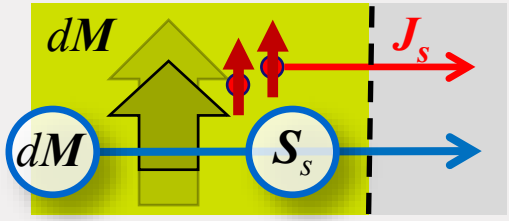


Spin dep. life time:

$\tau_\uparrow > \tau_\downarrow$







1. **Balistic injection of hot spin pol. e$^-$**

2. **Super-diffusive transport, spin filtering**
   Battiato, Oppeneer *et al.*, PRL 2010

3. **Spin-dependent Seebeck effect**
   Choi *et al.*, Nat. Phys. 2015

4. **"dM/dt" (s-d model)**
   See also Choi *et al.*, Nat. Comms. 2014;
   Tveten *et al.*, PRB 2015

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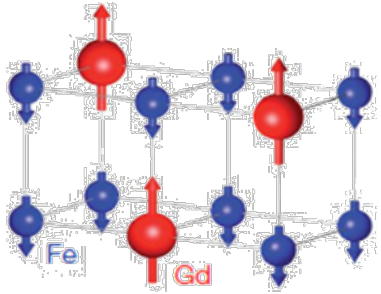


Ferrimagnet

50 fs laser pulses

Magnetic writing with light

left

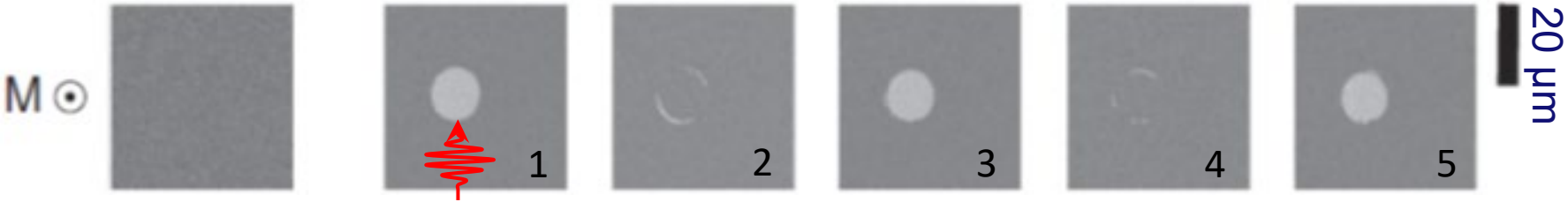
right

left polarized

or GdFeCo

down

Toggle mechanism (linearly polarized!)



Ostler *et al.*, Nature Comms. 2012

Stanciu, Kimel, Rasing et al., Phys. Rev. Lett. 2007

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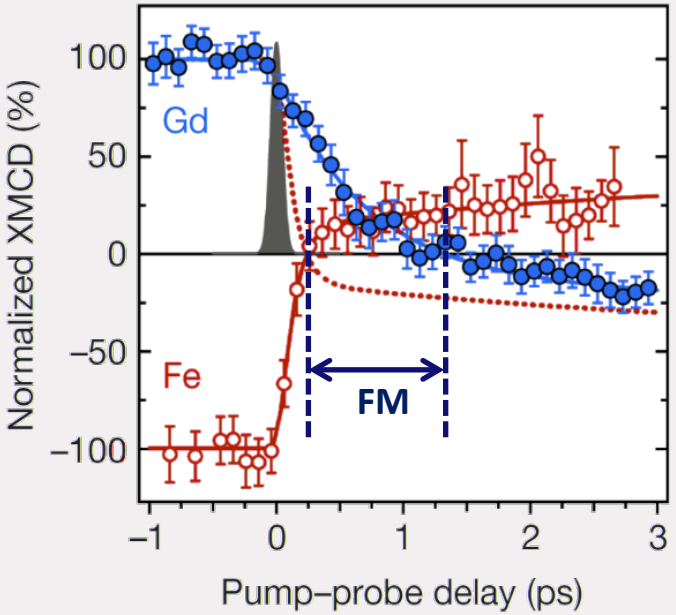
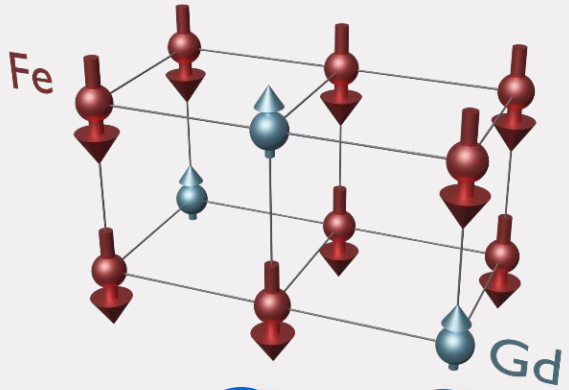
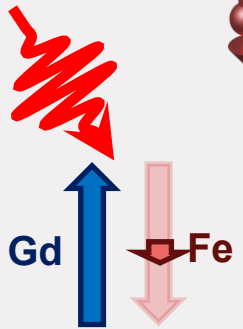
Detailed insight in AOS from fs-XMCD



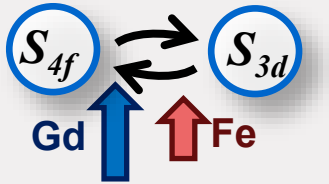
Radu, Dürr *et al.*, Nature (2011)

Ferrimagnetic GdFe

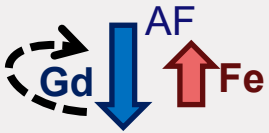




demagnetization



exchange-scattering



reversal

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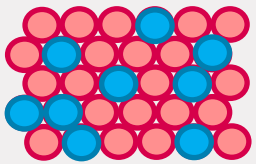
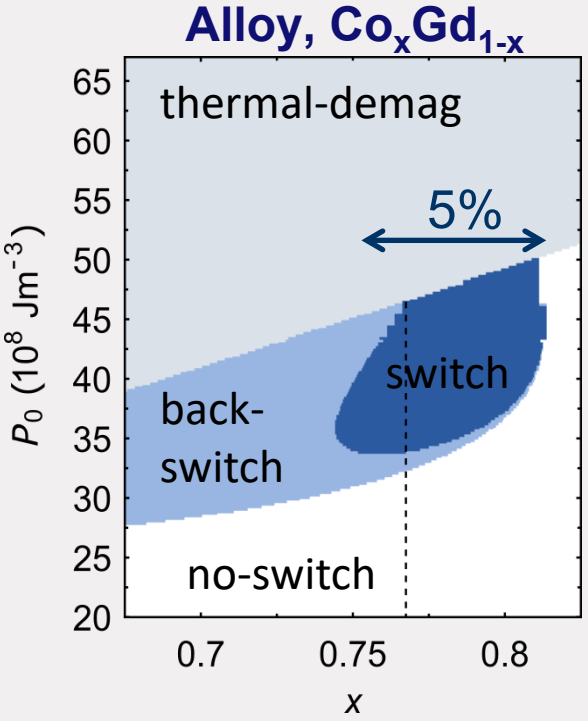
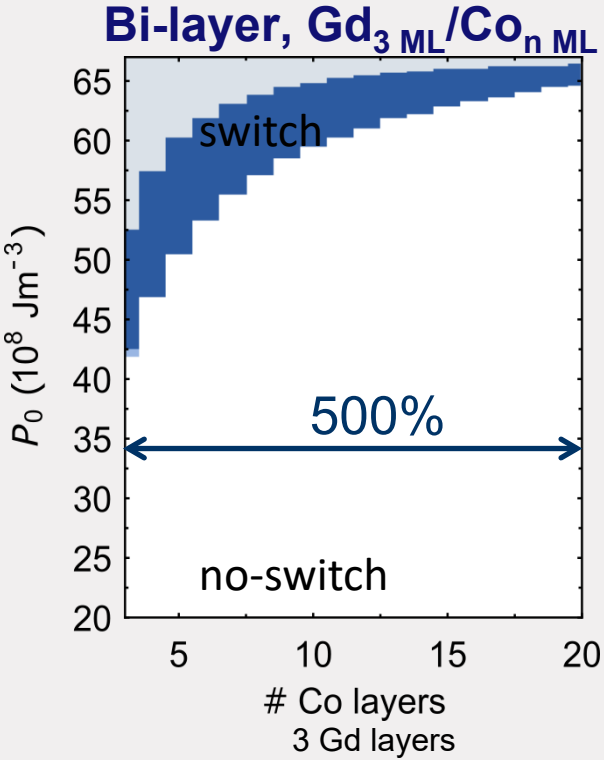
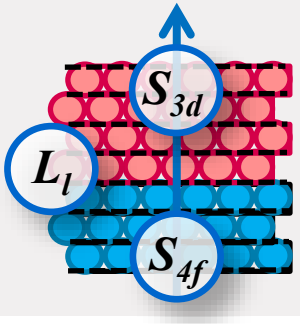
Understanding its behavior (M3TM)









Maarten Beens *et al.*, PRB (R) 2019

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- Local and non-local transfer of angular momentum

Some new results

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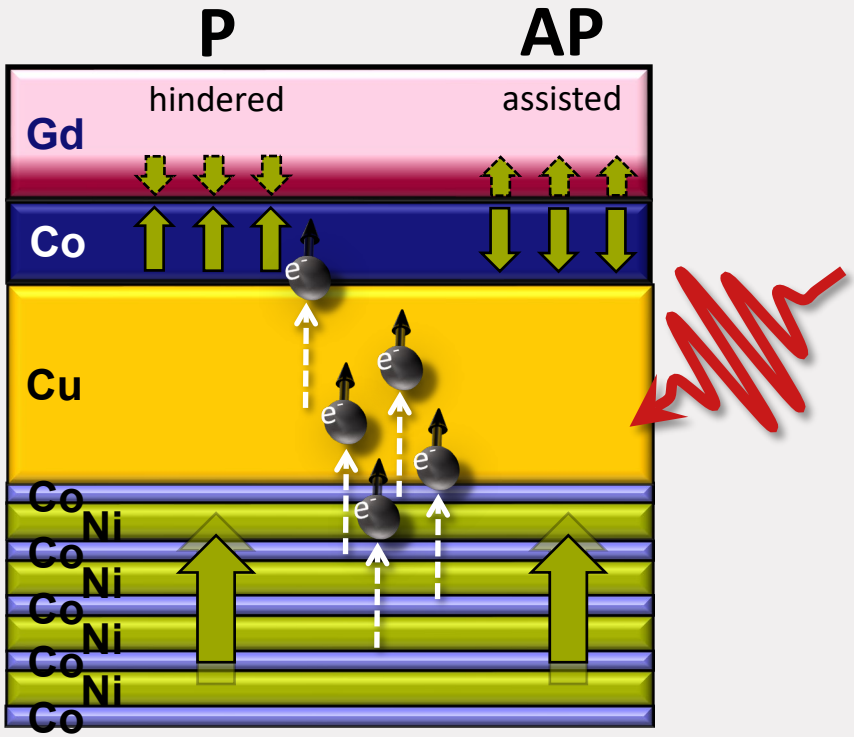
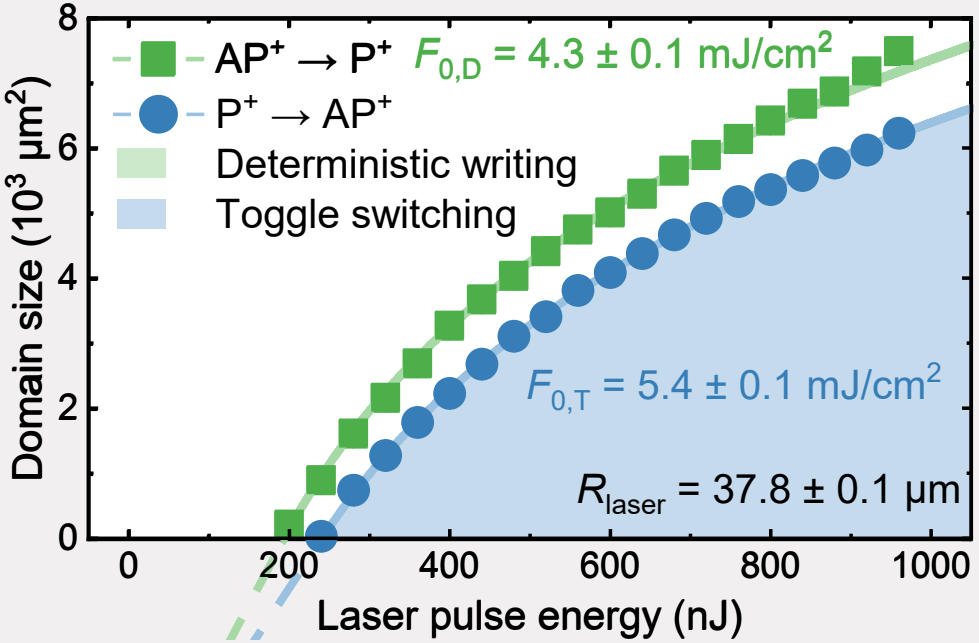
- B. A Fourier view on mechanisms for fs spin currents
- C. Resolving spin currents from Co/Gd bi-layers
- D. (AOS and Current induced domain wall model in $[Co/Gd]_2$)

AOS: local vs. non-local spin transfer

Case A





Youri van Hees *et al.*, Nature Comms. (2020)

See also Quentin Remy, Mangin *et al.*, Adv. Sci. (2020)

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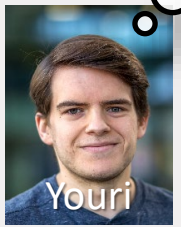
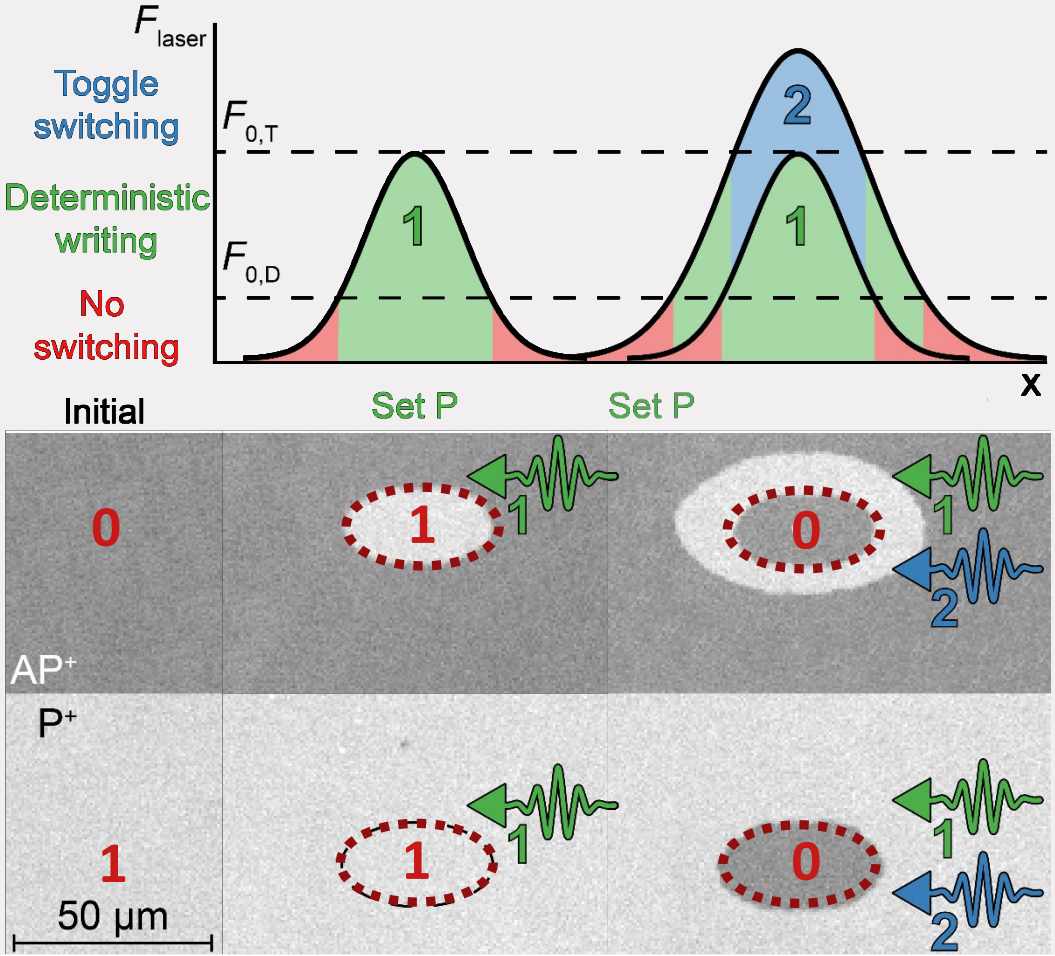
Deterministic writing

How to write a logic 0 or 1, rather than just toggle?



Youri van Hees *et al.*, Nature Comms. (2020)



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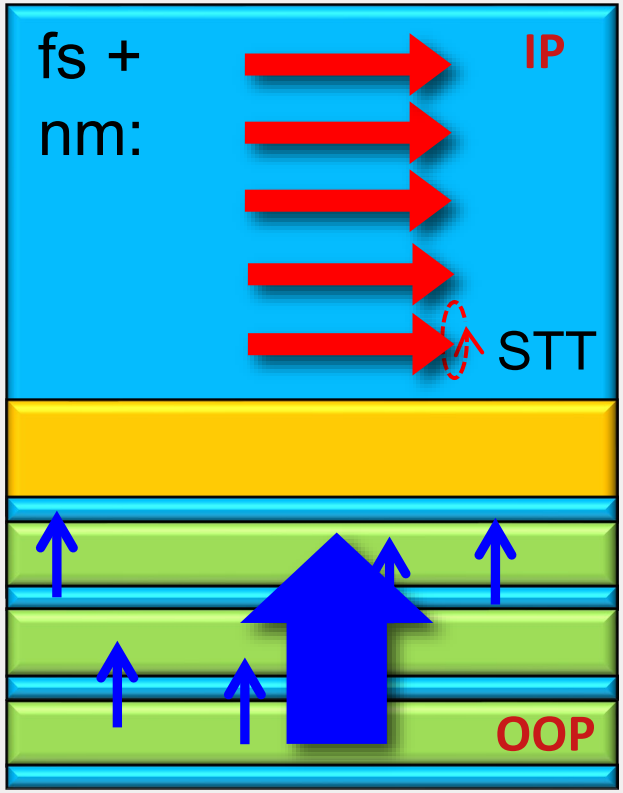
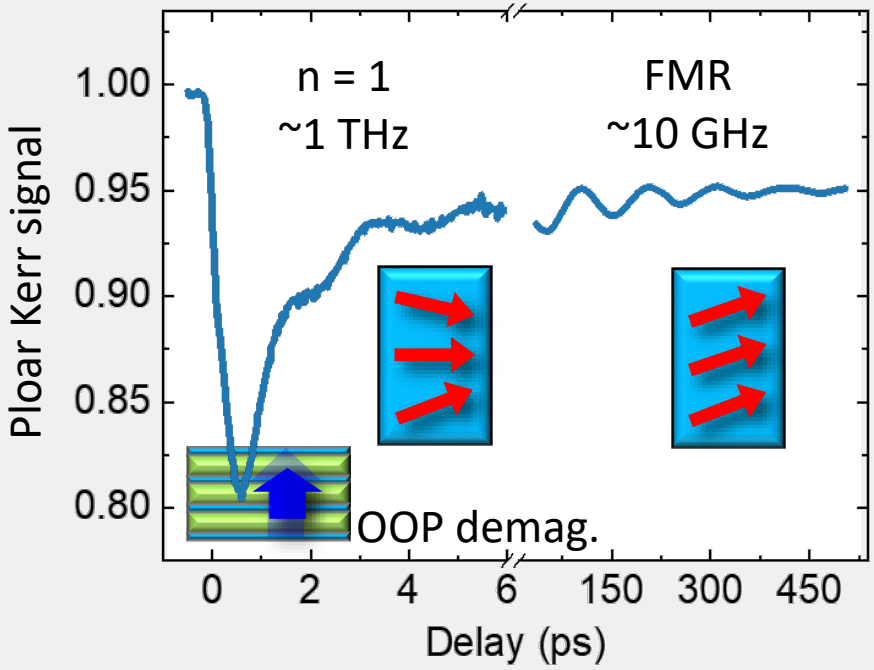
Towards THz magnonics

Case B





Razdolski, Melnikov *et al.*, Nat. Comms. (2017)

Lalieu *et al.*, PRB (2017, 2019)
Lichtenberg *et al.*, PRB (2022)

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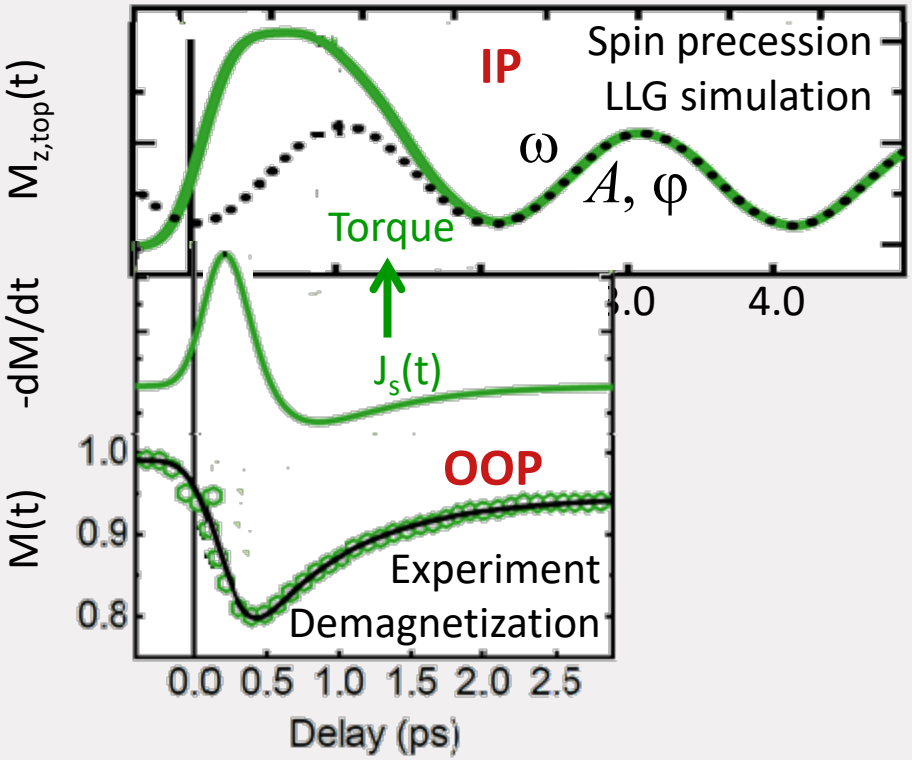
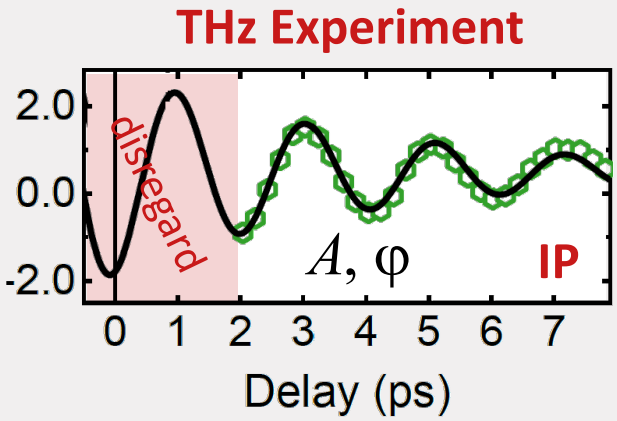
A Fourier domain image on spin transfer





Fitted A, φ reflect $J_s(\omega)$ (FT)

THz ω tuned by thickness IP

GHz ω tuned by ext. field

Lichtenberg, *et al*., PRB (2022)

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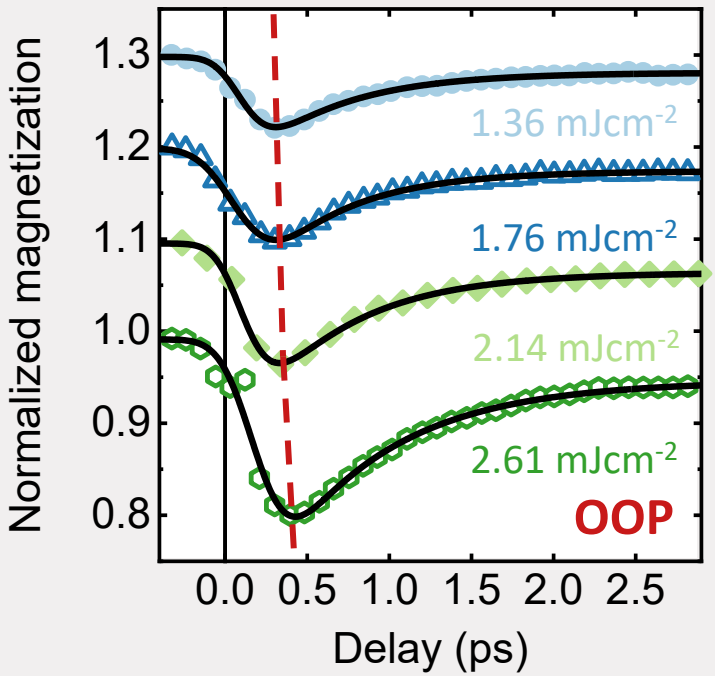
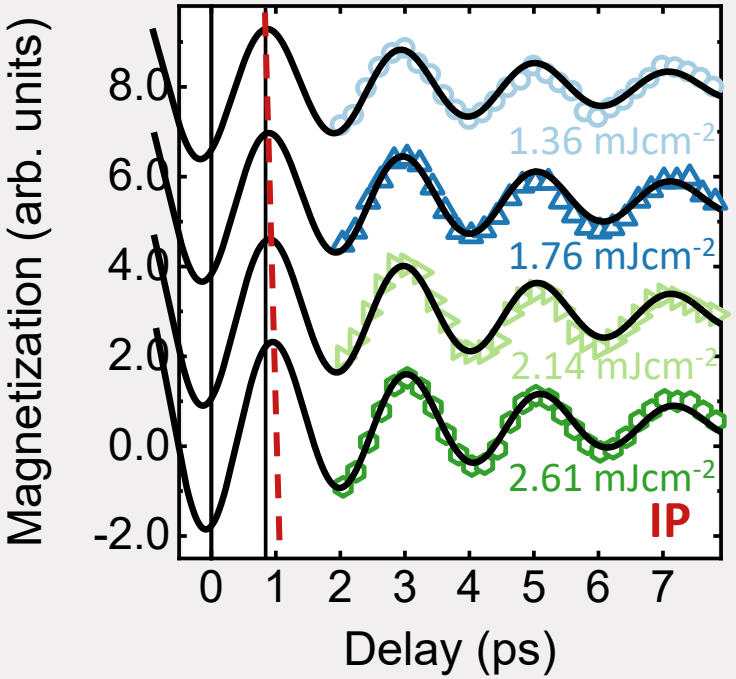
‘Probing’ fs spin current profiles

Fluence dependence of pulse shape



Fluence dependence of phase



Lichtenberg, *et al*., PRB (2022)

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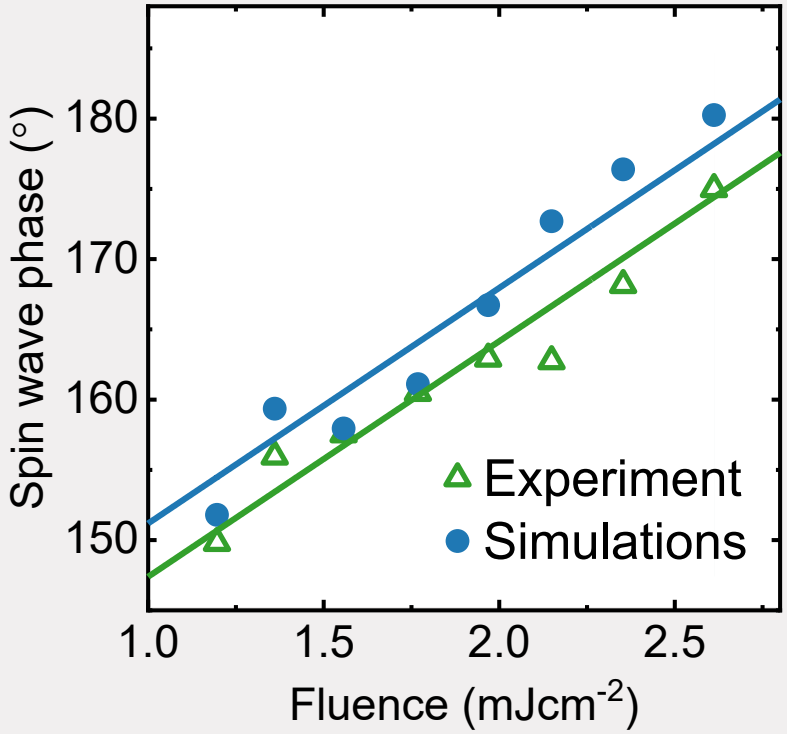
Conclusions



Simulations:
OOP experimental $M(t)$ → dM/dt
→ LLG simulation IP → φ

- Results indicate the generated spin current closely follows $\mathrm{d}M/\mathrm{d}t$
- Ballistic optically excited carriers do **not** match: $\varphi \approx 0$

Lichtenberg, *et al*., PRB (2022)

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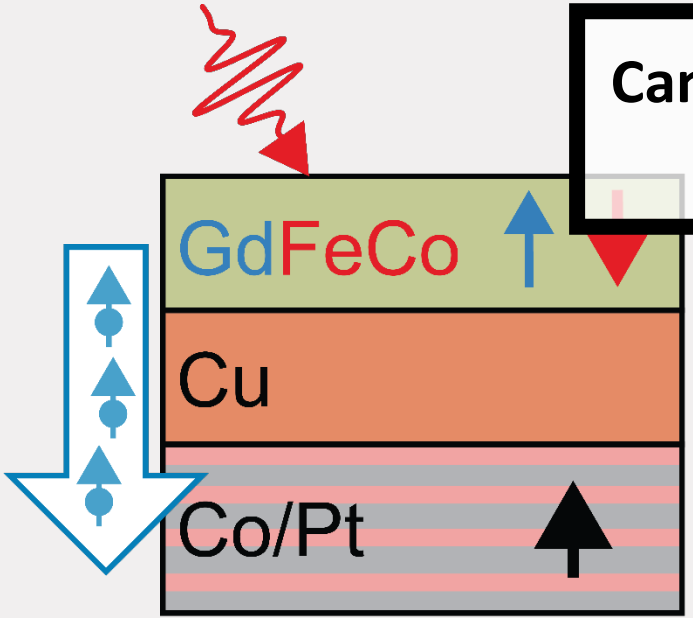
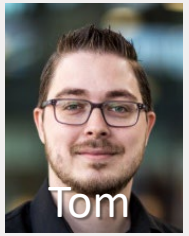
Case C

Non-local spin transport and AOS



Can we quantify spin current generation by Gd?



Iihama et al. *Advanced Materials* 30.51 (2018): 1804004.
Remy et al. *Advanced Science* (2020): 2001996.

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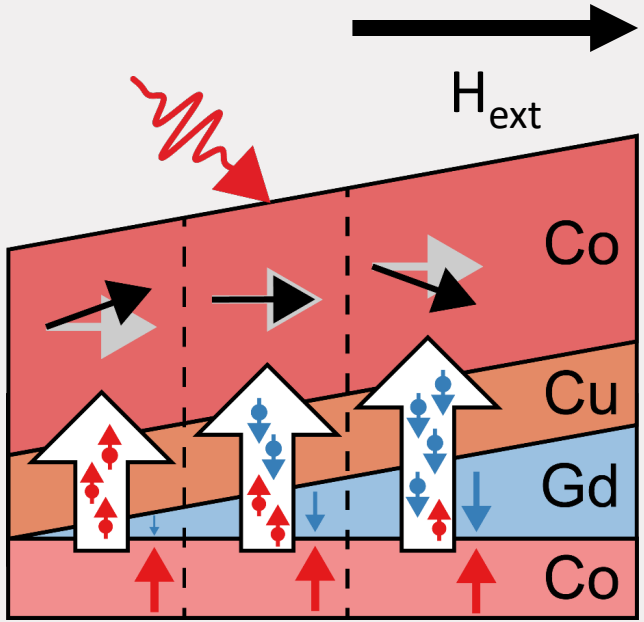
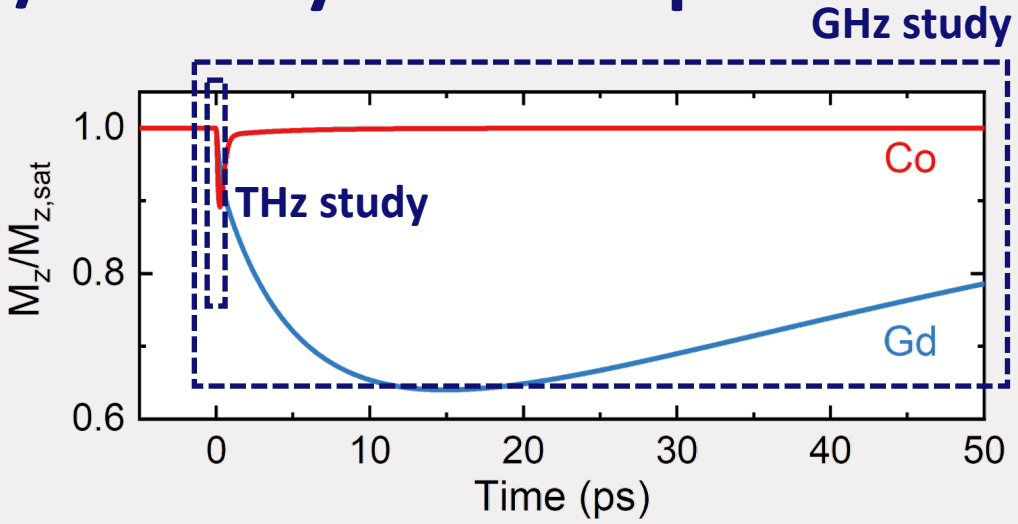
Spin currents from Co/Gd bilayers: set-up



Phase shift



$$j_s \propto -\frac{\partial M}{\partial t}$$

Co and **Gd** spin currents affect dynamics **differently**

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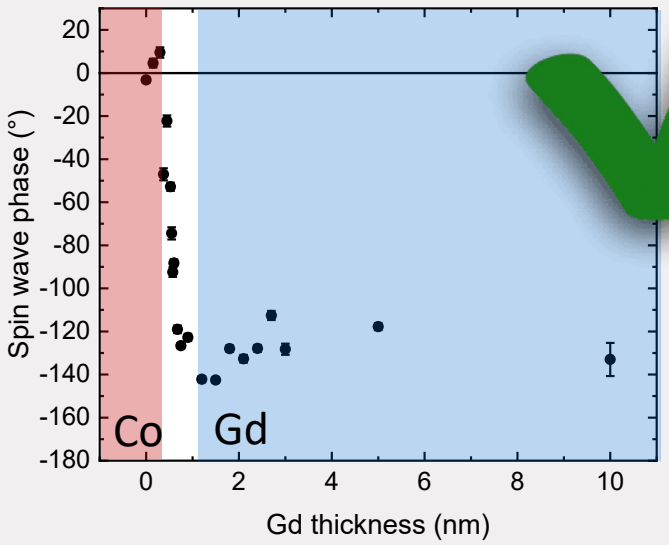
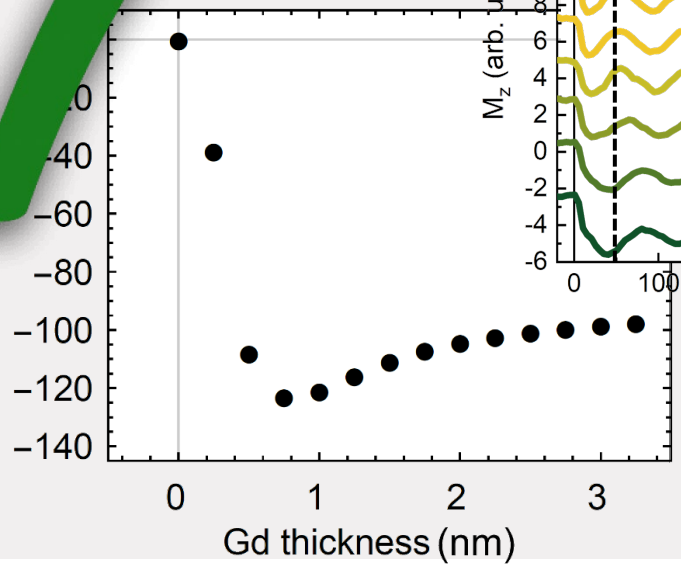
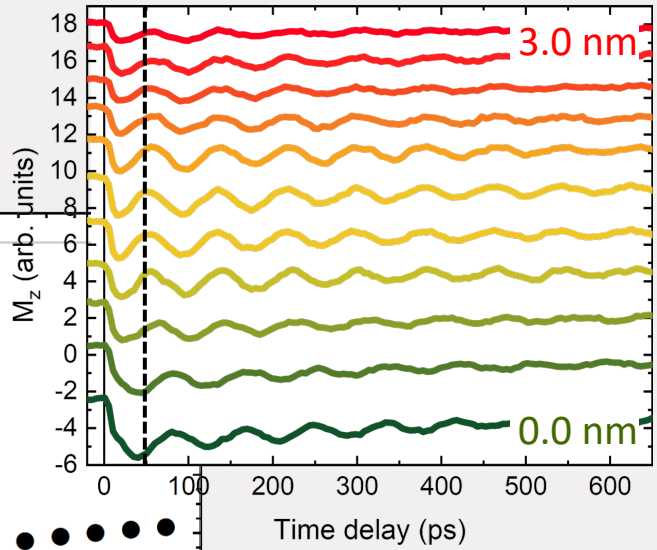
GHz result – spin current time-integrated

Sign changes from Co-dominated (+) to Gd-dominated (-) at 0.7 nm



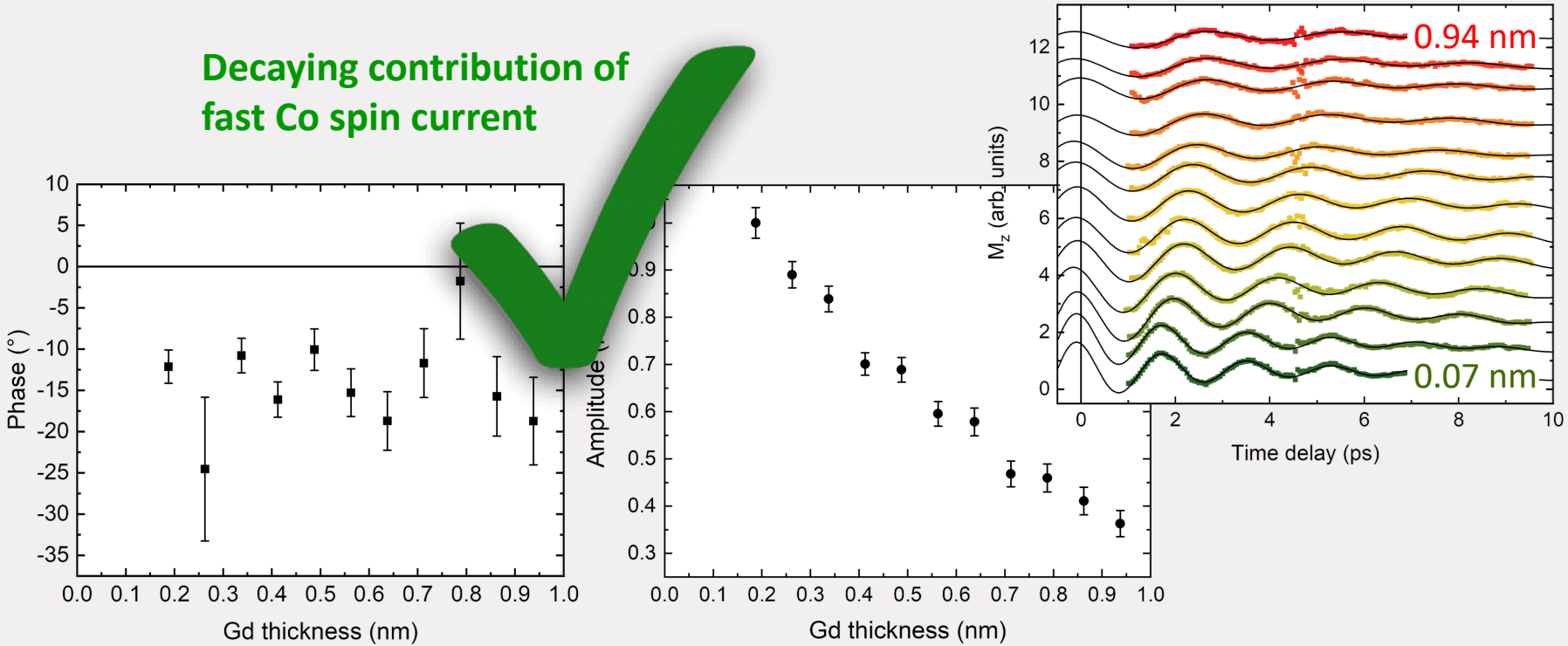




Youri van Hees, Tom Lichtenberg, Maarten Beens *et al.*, in preparation

THz result – spin current during first ps

Decaying contribution of fast Co spin current



Youri van Hees, Tom Lichtenberg, Maarten Beens, *et al.*, in preparation

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Take home message

Femto-magnetism – a tutorial introducti

- Laser-induced fs demagnetization and
- Local and non-local transfer of angular

It's all about local & non-local spin transfer Gd → slow, Co → fast (dM/dt) For AF's ?

Some new results

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- B. A Fourier view on mechanisms for fs spin currents
- C. Resolving spin currents from Co/Gd bi-layers
- D. AOS and Current induced domain wall model in $[Co/Gd]_2$

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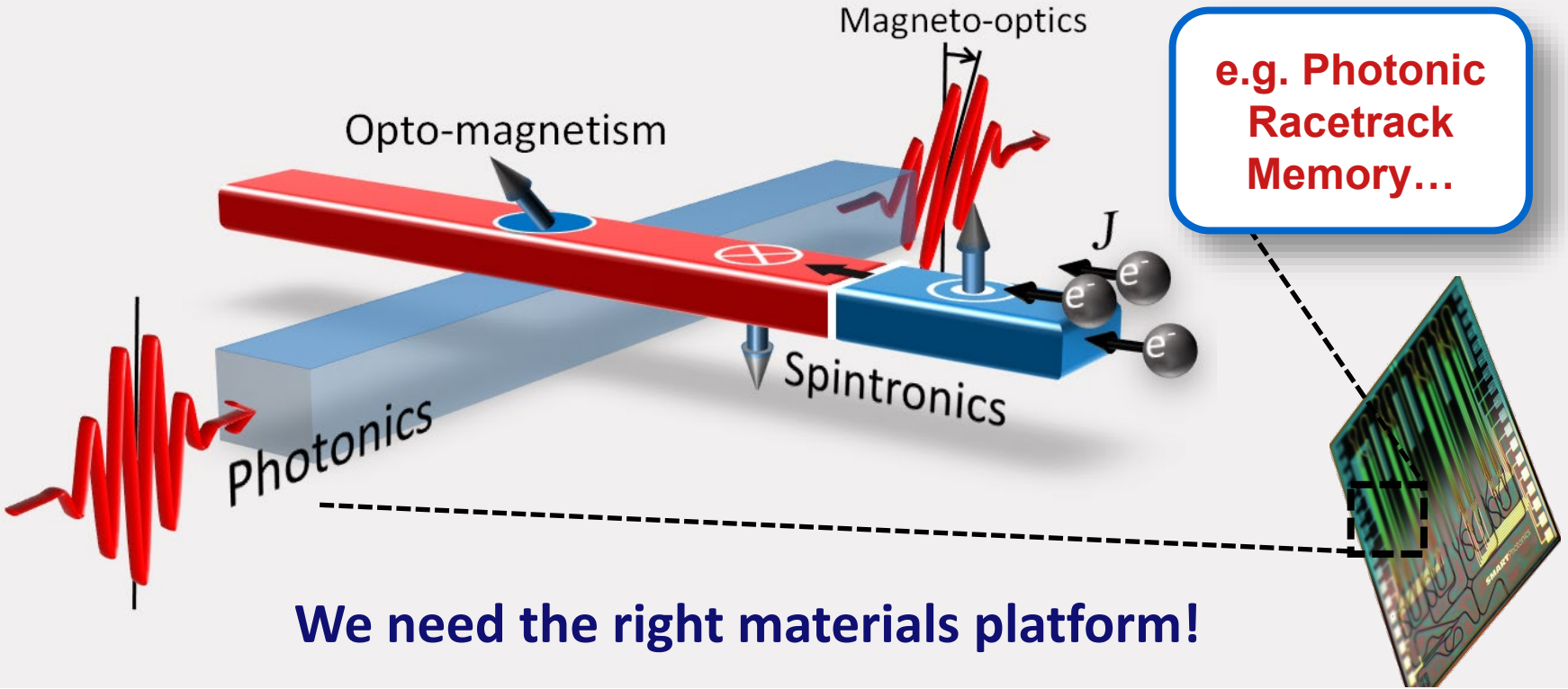
- A. Spin-current assisted All-Optical Switching in Co/Gd
- B. A Fourier view on mechanisms for fs spin currents
- C. Resolving spin currents from Co/Gd bi-layers
- D. AOS and current induced domain wall model in $[Co/Gd]_2$

Towards Integrated Magneto-Photonics

D

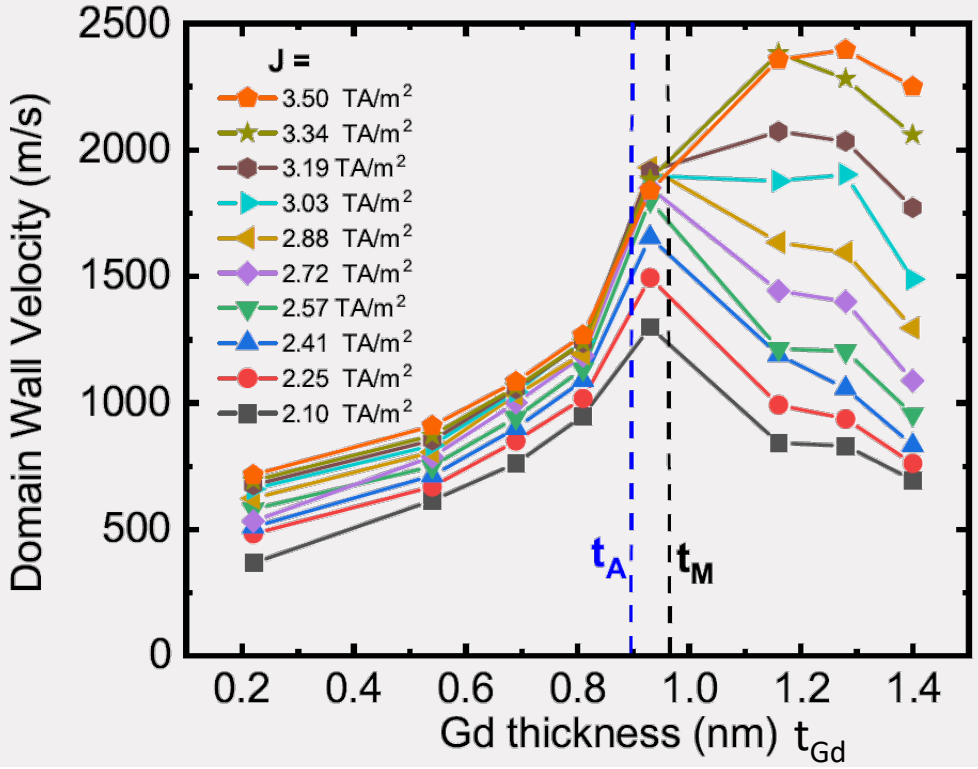


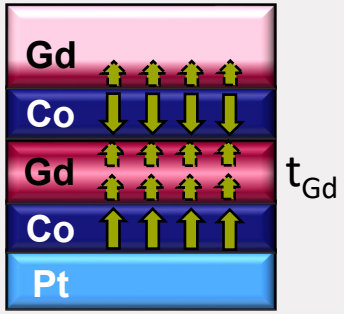
e.g. Photonic Racetrack Memory…

We need the right materials platform!

TU/e

High current induced domain wall velocity



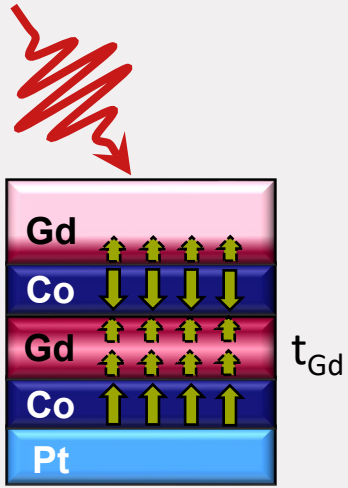


3x Co/Gd interface
RT Compensation @ 0.9 nm

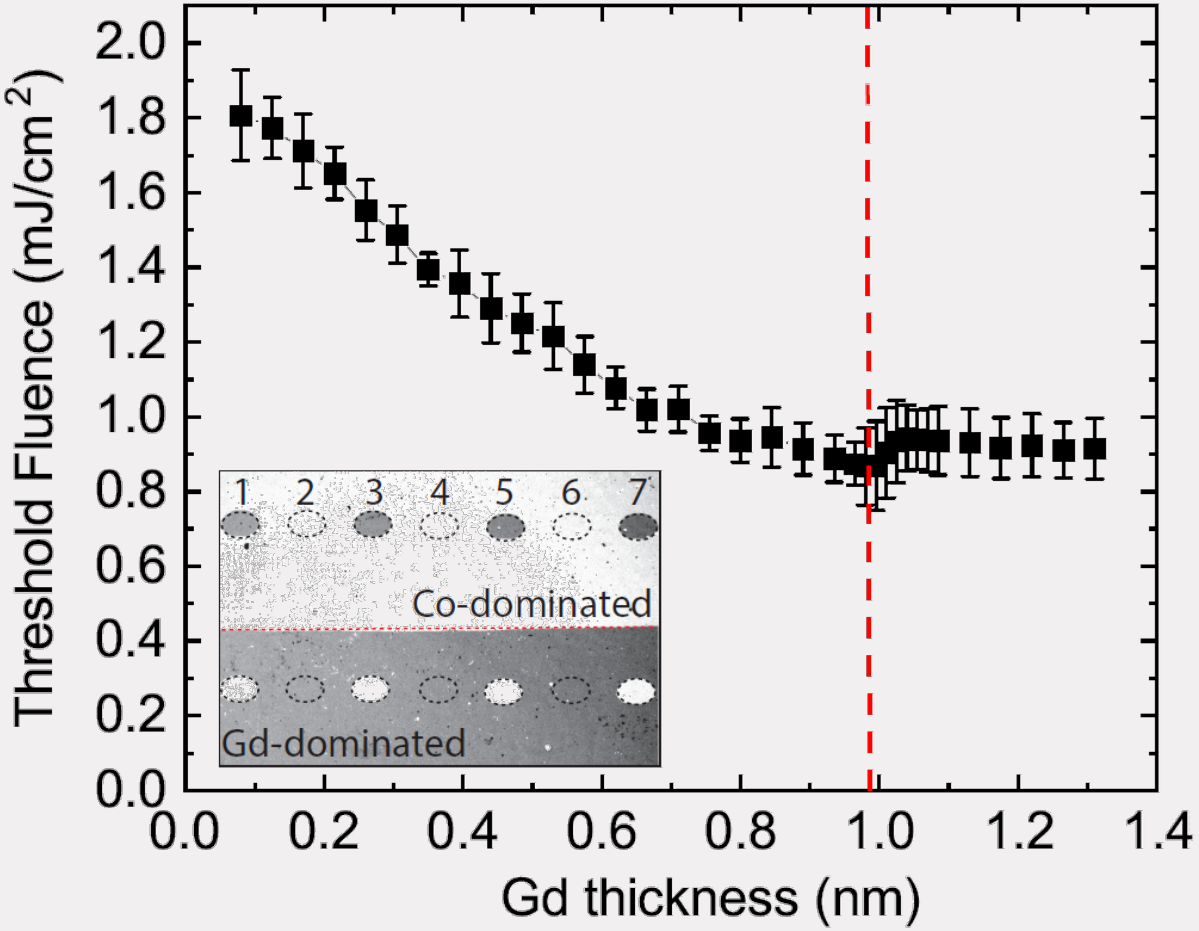
Pingzhi Li and Thomas Kools, *et al.*, ArXiv:2204.11595

TU/e

Fluence dep.



AOS verified!



Pingzhi Li and Thomas Kools, *et al.*, ArXiv:2204.11595

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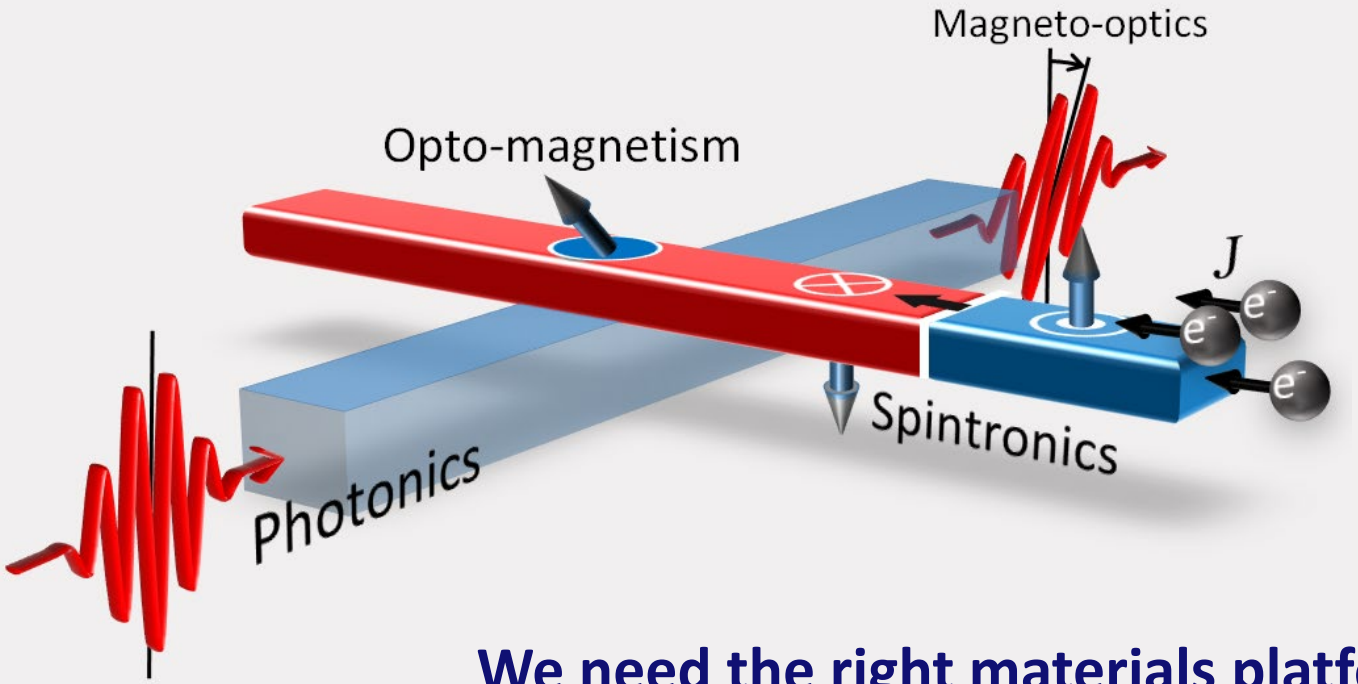

10 ps. rewrite AOS*
Low threshold Fl.
2500 m/s CIDWM
Enough?

We need the right materials platform → AFs!

*Steinbach *et al.* APL 120 (2022), Hees *et al.* arXiv:2204.01459

TU/e