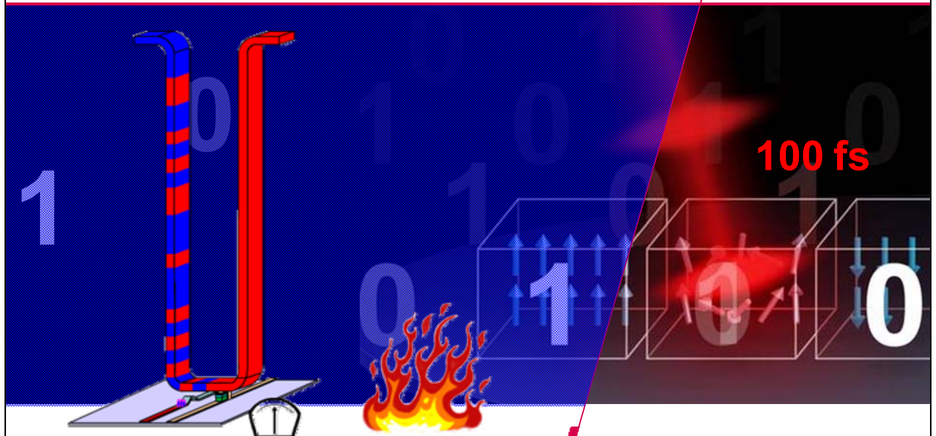
Ultrafast Laser-Induced Spin-Transfer Torque



Bert Koopmans

TU/e Technische Universiteit Eindhoven University of Technology

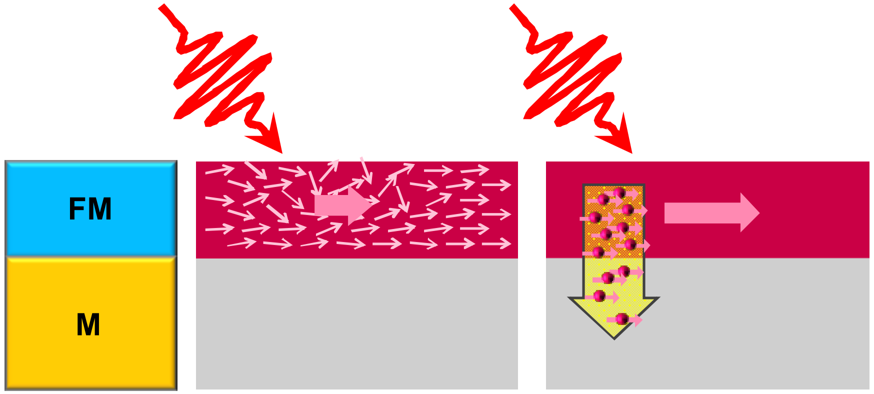
Where innovation starts

Acknowledgements

- Eindhoven University of Technology
  - Sjors Schellekens
  - Koen Kuiper
  - Wouter Verhoeven, Ruud de Wit, Taco Vader
  - Francesco Dalla Longa, Gregory Malinowski
  - Bastiaan Bergman, Jeroen Rietjens, Carlos Bosco, Csaba Jozsa, Maarten Van Kampen, Harm Kicken
- Technische Universität Kaiserslautern
  - Tobias Roth
  - Mirco Cinchetti
  - Martin Aeschlimann
- MPI Metalforschung Stuttgart
  - Daniel Steiauf
  - Manfred Fähnle

experimentalists of the week

Local dynamics *vs.* spin transport

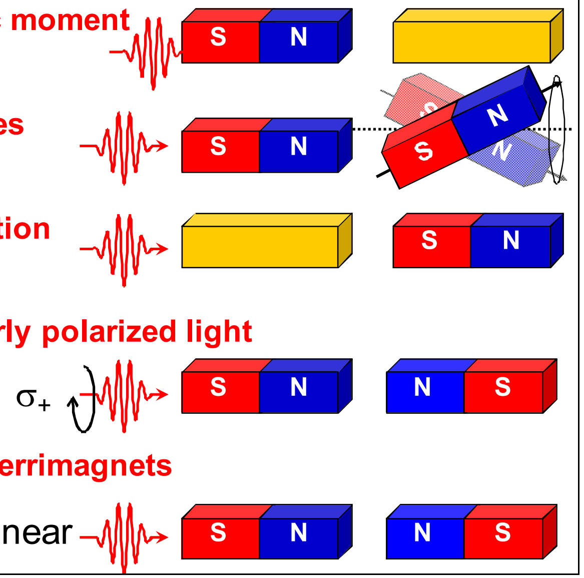


Outline

- Introduction
  - Local magnetization dynamics
  - Spin transfer (super-diffusive)
- Laser-induced spin transfer torque
  - Why efficient
  - Our recent experiments
  - A first interpretation:
    Super-diffusive spin currents or Spin-Dependent Seebeck?
- Its importance for local magnetization dynamics

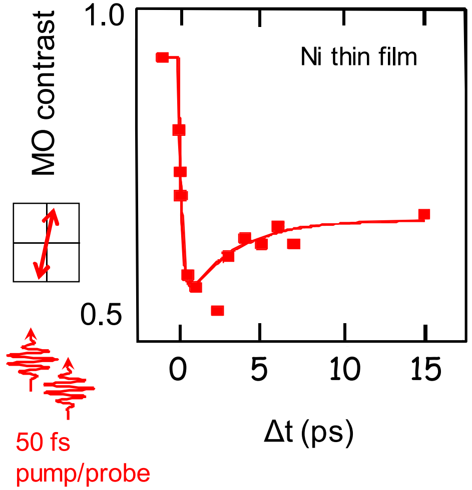
What happens after fs laser excitation?

- **Quenching magnetic moment**
  - Beaurepaire et al., PRL 1996
- **Launching spin waves**
  - Van Kampen et al., PRL 2002
- **AF → F phase transition**
  - Ju et al., PRL 2004;
    Thiele et al. APL 2004
- **Switching by circularly polarized light**
  - Stanciu et al., PRL 2007
- **"Toggle switching" ferrimagnets**
  - Radu et al., Nature 2011



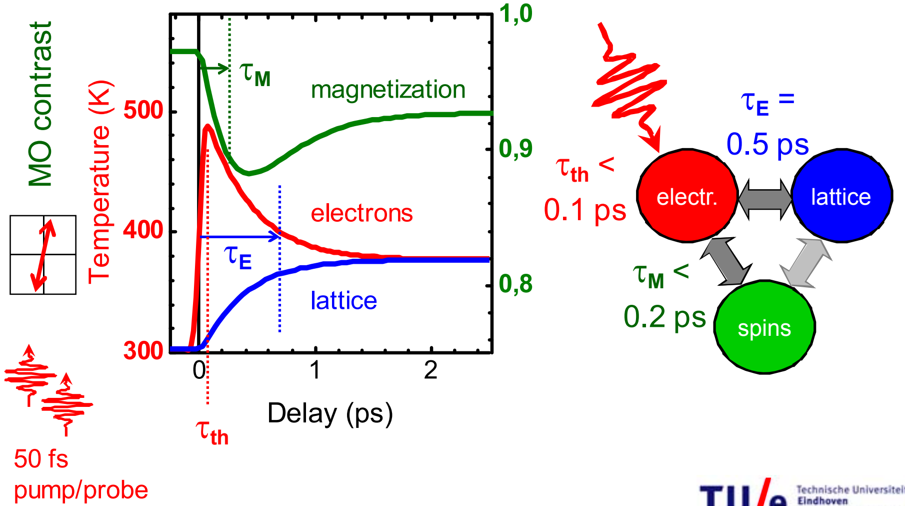
Sub-ps loss of magnetization

Beaurepaire *et al*., Phys. Rev. Lett. 1996

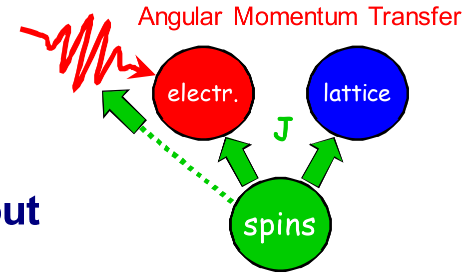


Sub-ps loss of magnetization

Beaurepaire *et al*., Phys. Rev. Lett. 1996



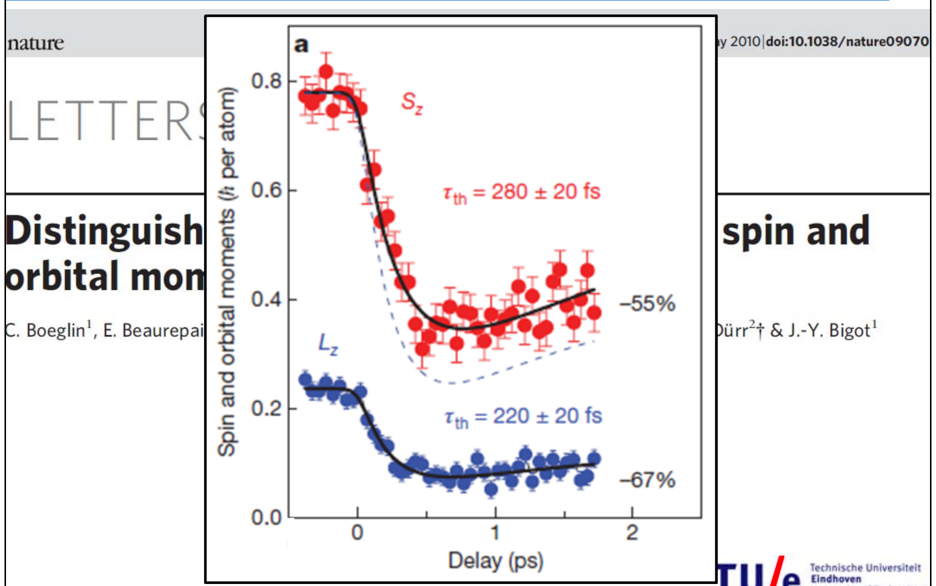
Conservation of Angular Momentum



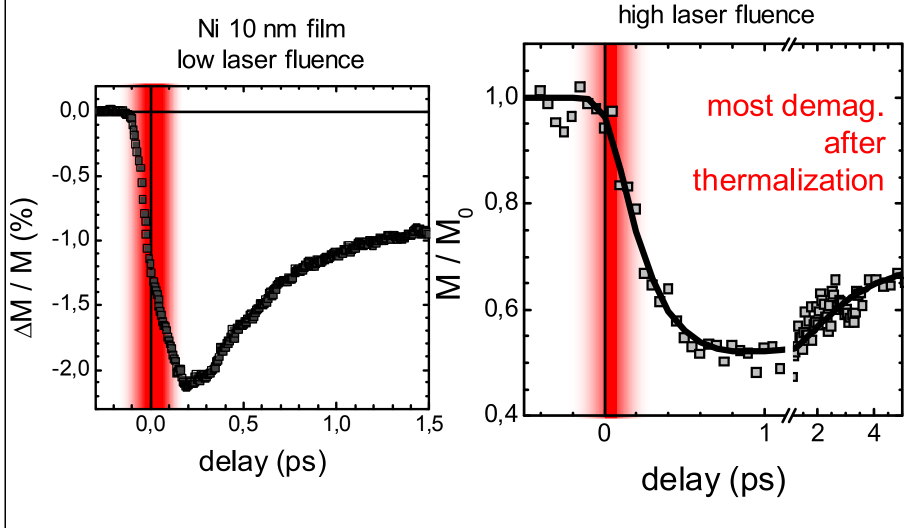
- ☐ **Photons in or out**
- ☐ **Transfer from spin to orbit**
- ☐ **From spin to the lattice**

Distinguishing orbital and spin moments

Boeglin et et al., Nature 2010



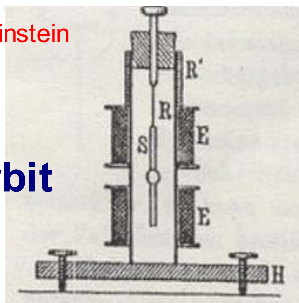
Are photons and hot (highly excited) electrons relevant?



data: TU/e & U. Kaiserslautern

The answer (?)

Like de Haas & Einstein



- ☐ **Photons in or out**
- ☐ **Transfer from spin to orbit**
- ☑ **From spin to the lattice**

- ☐ ~~**Highly-excited electrons / laser field**~~

Minimalistic model

Koopmans et al., PRL 2005
Nat. Mater. 2010

- **Electrons: Constant DOS** — D_F
- **Phonons: Einstein model (+ Debye)** — E_D, D_p
- **Spins: mean-field S = ½ Weiss model** — T_C, μ_{at}

- **e-e**
- **e-p**
- **spin flip**

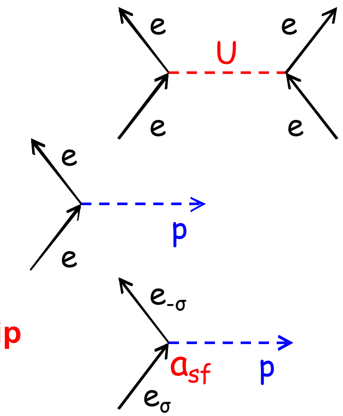


Figure of merit

$$a_{sf}\,\frac{T_C}{\mu_{at}}$$

Finite chance for spin-flip upon momentum scattering (Elliott-Yafet)

What it can reproduce

- **Slow dynamics (Gd) vs. fast dynamics**
  - Koopmans et al., Nature Mater. 2010
- **Temperature- and laser fluence dependence**
  - Roth et al., Phys. Rev. X 2012
- **Toggle switching of ferrimagnets (two spin sub-lattices)**
  - Schellekens et al., Phys. Rev. B Rapid 2012
- **Combined with experiment: a_{sf} ~ 0.1**
  - Roth et al. Phys. Rev. X 2012
  - Carva et al. Phys. Rev. Lett. 2011
- **Note: very much like atomistic LLG and LLB**
  - Kazantseva et al. PRB 2008, etc.,
  - Mentink et al., PRL 2012

Open questions

Do we treat magnetic excitations adequately? Stoner vs. Magnons

But which phonons, and how do they carry angular momentum?

Is it really possible to treat this highly nonequilibrium system thermo-dynamically?

Three-particle interaction? (e-p + spin-flip)

Isn't our picture of the rare earth dynamics too crude?

Or is it something completely else?

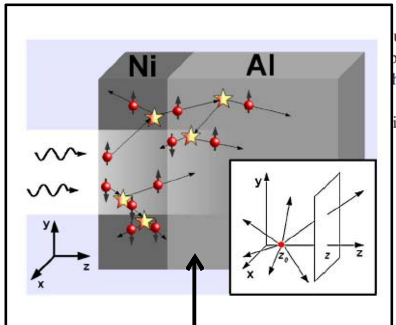
Or: Claims that spin transfer may explain all

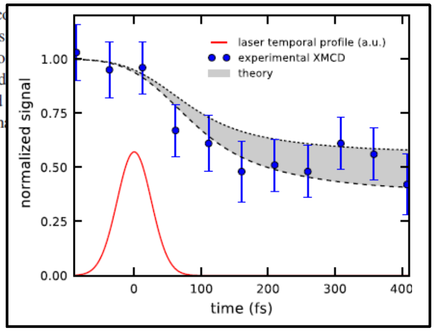
PRL 105, 027203 (2010) PHYSICAL REVIEW LETTERS week ending 9 JULY 2010

Superdiffusive Spin Transport as a Mechanism of Ultrafast Demagnetization

M. Battiato,* K. Carva,† and P. M. Oppeneer
Department of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden

(Received 31 March 2010; published 9 July 2010)





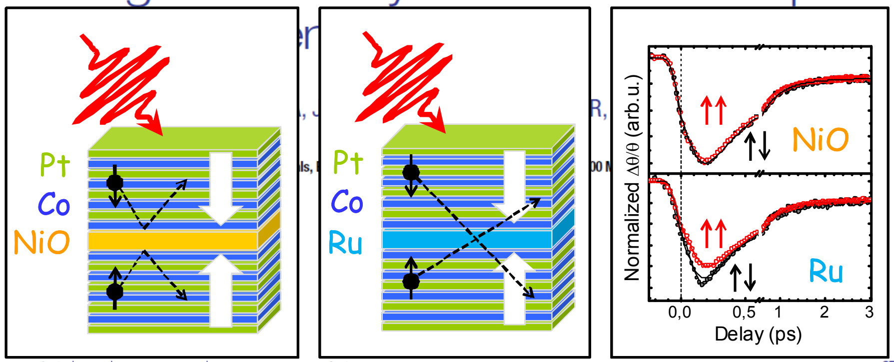
Majority spins travel further

Fs spin-transfer

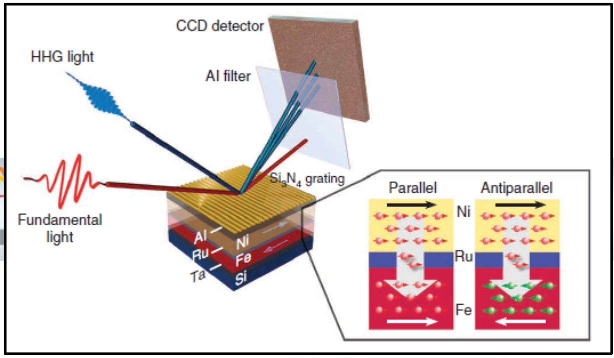
Malinowski et al. Nature Physics 2008

LETTERS

Control of speed and efficiency of ultrafast demagnetization by direct transfer of spin



And even more exciting / surprising…



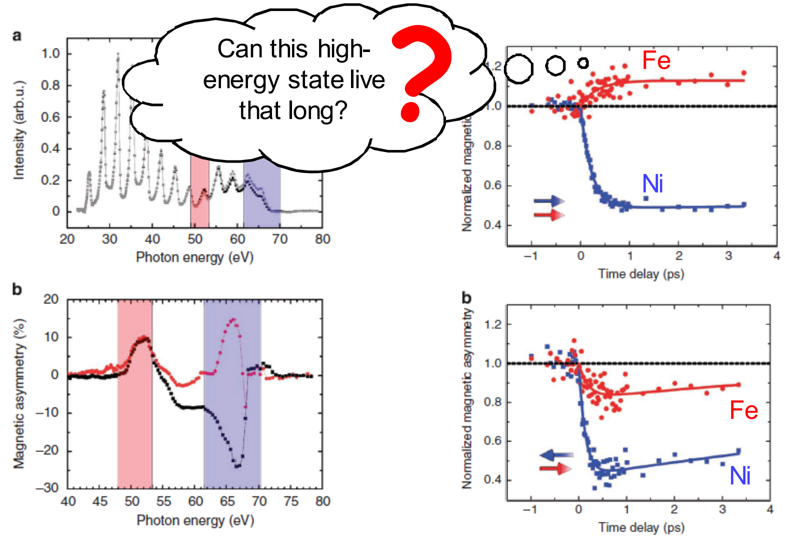
ARTICLE

Received 20 Apr 2012 | Accepted 30 Jul 2012 | Published 4 Sep 2012
DOI: 10.1038/ncomms2029

Ultrafast magnetization enhancement in metallic multilayers driven by superdiffusive spin current

Dennis Rudolf[1,*], Chan La-O-Vorakiat[2,*], Marco Battiato[3,*], Roman Adam[1], Justin M. Shaw[4], Emrah Turgut[2], Pablo Maldonado[3], Stefan Mathias[2,5], Patrick Grychtol[1,2], Hans T. Nembach[4], Thomas J. Silva[4], Martin Aeschlimann[5], Henry C. Kapteyn[2], Margaret M. Murnane[2], Claus M. Schneider[1] & Peter M. Oppeneer[3]

The approach and the surprize

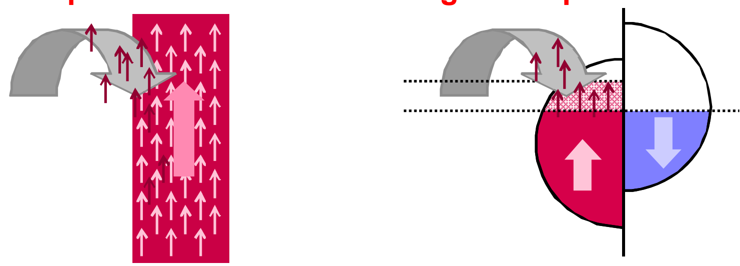


Outline

- **Introduction**
  - **Local magnetization dynamics**
  - **Spin transfer (super-diffusive)**
- **Laser-induced spin transfer torque**
  - **Why efficient**
  - **Our recent experiments**
  - **A first interpretation:**
    Super-diffusive spin currents or Spin-Dependent Seebeck?
- **Its importance for local magnetization dynamics**

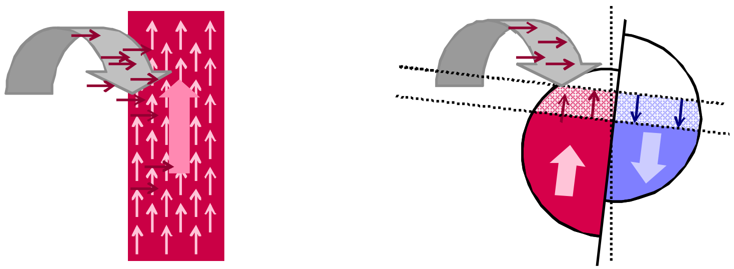
All previous results: collinear systems

- **If spin transfer assists thermodynamically stable final state: OK**
  - **Dynamics just speeds up (Malinowski)**
- **But if spin transfer creates strong non-equilibrium?**



- **Either local dissipation of angular momentum (100 fs)**
- **Or compensating spin transport**
  (also just femtoseconds) (?)

What if non-collinear spin transfer?



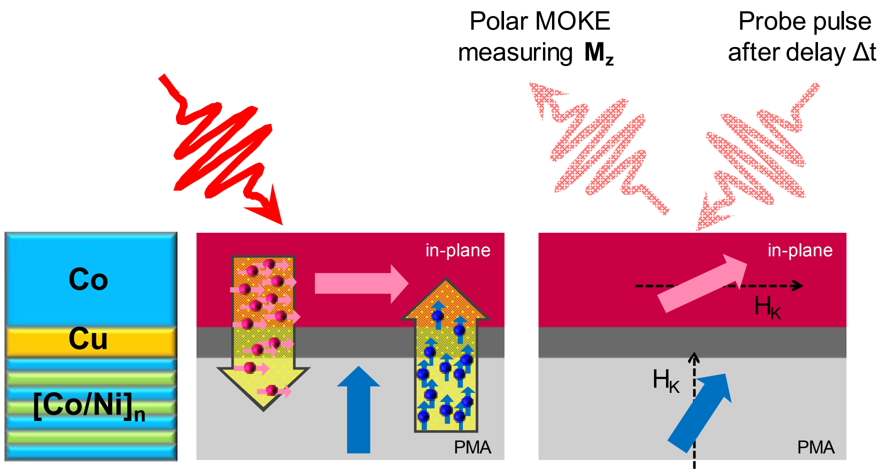
Quick dissipation of spin momentum
(mixing conductance or precession)

- Efficient absorption of angular momentum
- Causing laser-induced STT
- Final state just rotation of quantization axis
- So final state in thermal equilibrium

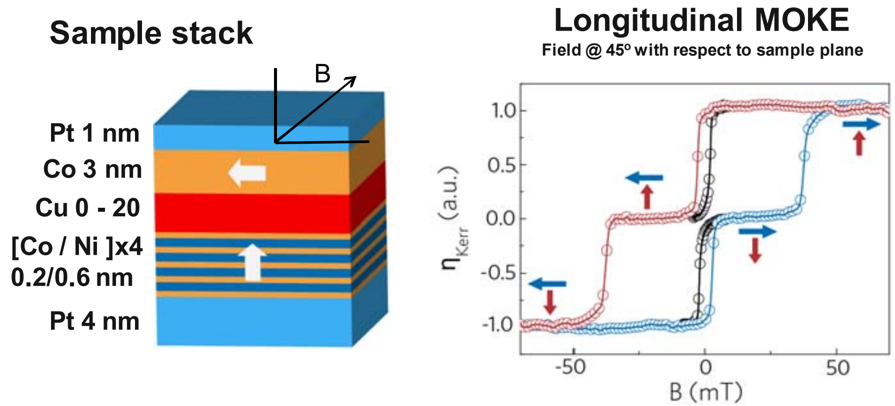
Motivation

- Ideal method for quantifying laser-induced spin transport
- Addressing role of super-diffusive spin transport to ultrafast demagnetization
- Device options? All-optical switching?
- Measuring thermal STT without lithography?

Recent experiments @ TU/e



Sample properties

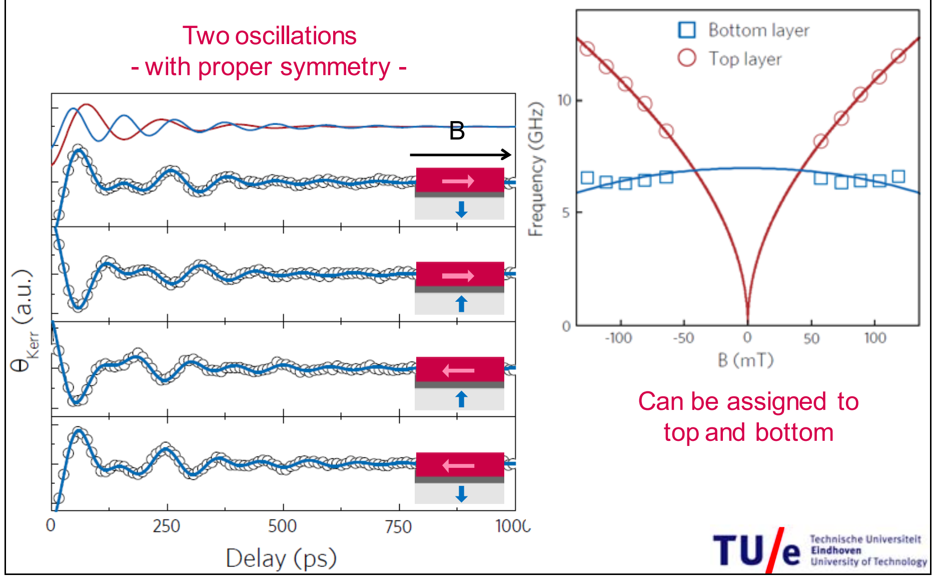


Four remnant configurations magnetic bilayer!

Indeed two precessions!

Schellekens et al. (TU/e), In preparation

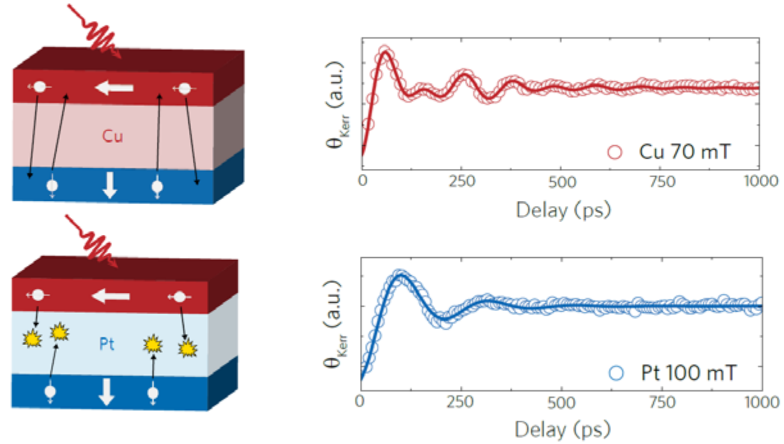
Two oscillations
- with proper symmetry -



Can be assigned to top and bottom

TU/e Technische Universiteit Eindhoven University of Technology

Cu vs Pt spacer layer

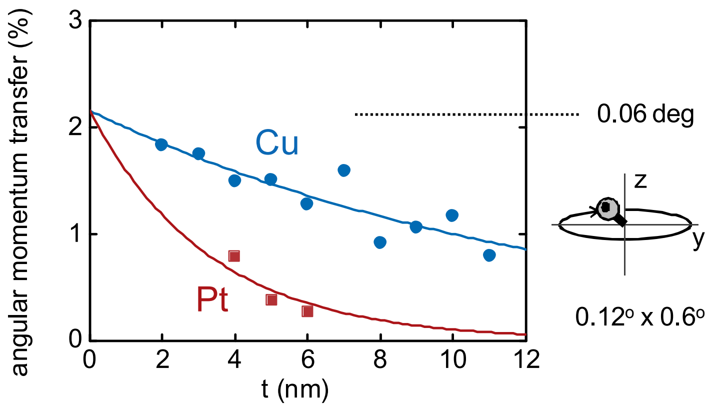


- Oscillation top in-plane layer suppressed: → STT!
- Precession bottom layer different origin → "ΔK"

TU/e Technische Universiteit Eindhoven University of Technology

Suppression of STT on top layer

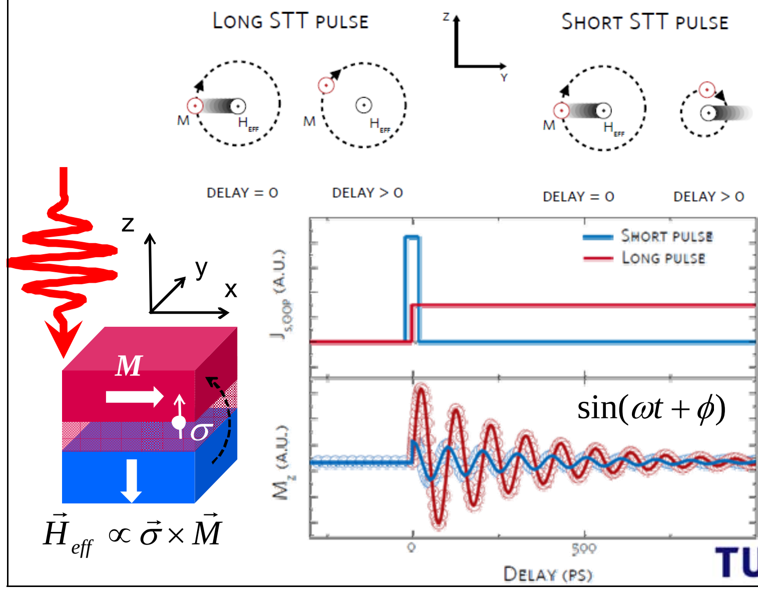
Schellekens et al. (TU/e), In preparation



All consistent with fs Spin-Transfer Torque pulse

TU/e Technische Universiteit Eindhoven University of Technology

Phase of the STT-induced precessions



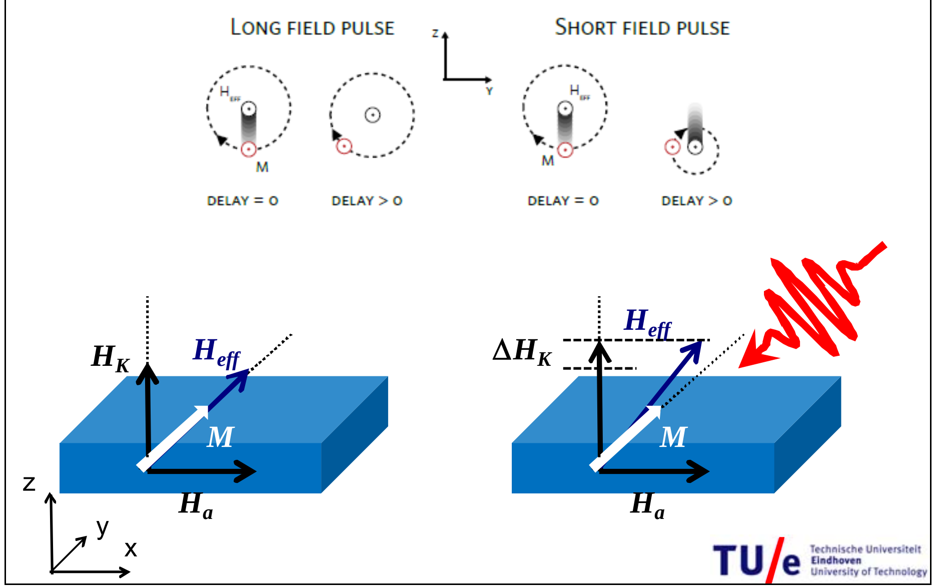
depending on
σ
maj. / min.

ϕ = 0 or π

ϕ = ±π/2

TU/e Technische Universiteit Eindhoven University of Technology

The ΔK artefact



Overview phases

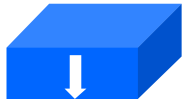
$\sin(\omega t + \phi)$

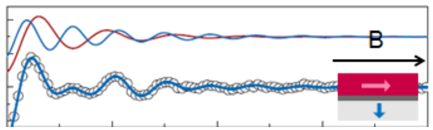
	STT short		STT long		ΔK short		ΔK long	
	Maj.	Min.	Maj.	Min.	dec.	inc.	dec.	inc.
IP	−π/2	π/2	π	0	0	π	−π/2	π/2
OOP	π/2	−π/2	0	π	0	π	−π/2	π/2

majority

minority

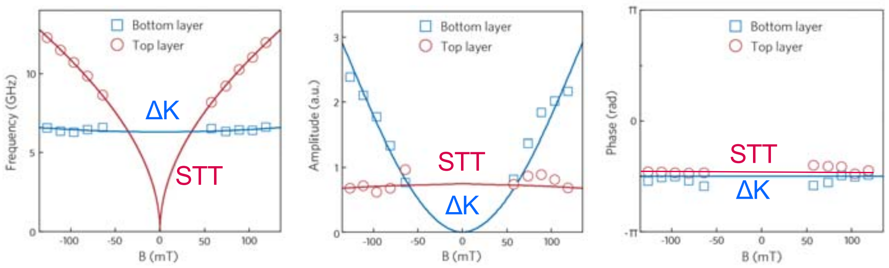
decrease





experiment: $\phi = -\pi/2$, $\phi = -\pi/2$,

Analysis
Field dependence



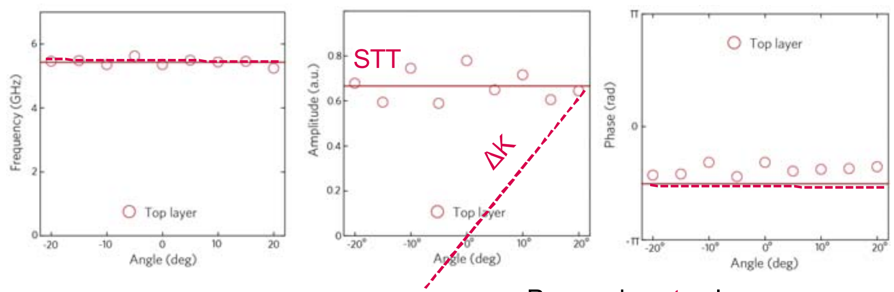
Top layer

	STT	ΔK
Frequency	✓	✓
Amplitude	✓	✗
Phase	✓	✓

Bottom layer

	STT	ΔK
Frequency	✓	✓
Amplitude	✗	✓
Phase	✗	✓

Analysis
Angle dependence



Top layer

	STT	Anisotropy
Frequency	✓	✓
Amplitude	✓	✗
Phase	✓	✓

Precessions top layer consistent with USTT! ΔK inefficient due to large Tc

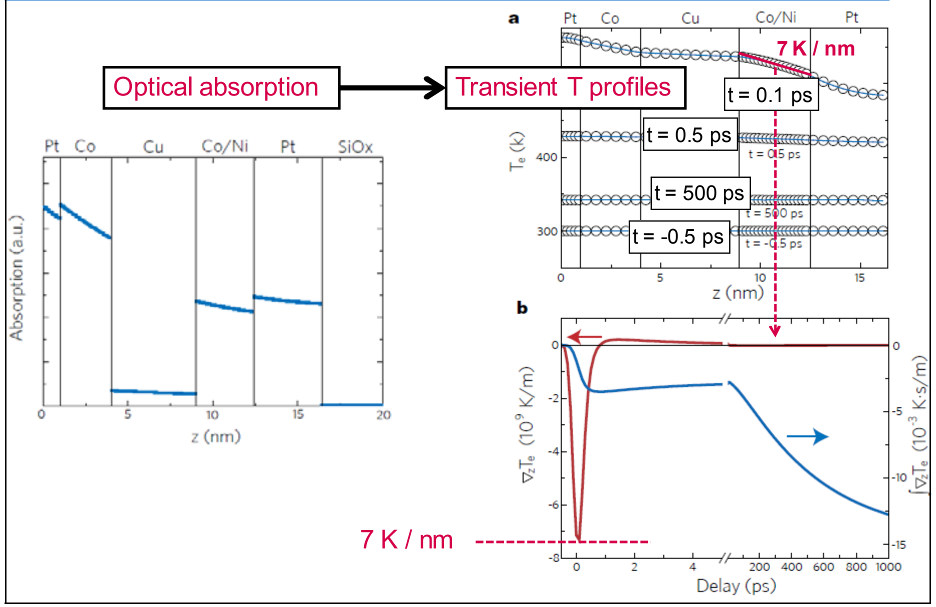
Precessions bottom layer consistent with ΔK, USTT not visible (poor sensitivity bottom layer + overwhelmed by ΔK)

Possible origin of laser-induced STT

Laser-induced torques: $\vec{\tau} = \tau_{sd} + \tau_{\nabla T} + \tau_{sc} + \tau_{\nabla K}$

- Super-diffusive spin currents (+ screening currents)
- Spin-Dependent Seebeck effect due to large T gradients

Calculated transient temperature profile



Calculated spin currents due to SDS

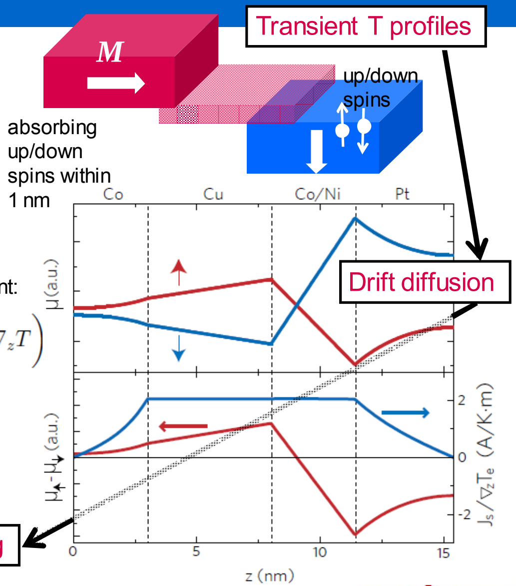
Continuity equations:

$$\nabla_z^2 \mu_s(z) = \frac{\mu_s(z)}{\lambda^2},$$

$$J_\uparrow(z) + J_\downarrow(z) = 0,$$

Spin dependent current with T gradient:

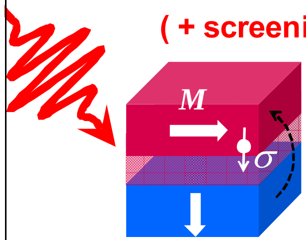
$$J_{\uparrow(\downarrow)}(z) = -\sigma_{\uparrow(\downarrow)} \left(\frac{1}{e} \nabla_z \mu_{\uparrow(\downarrow)} + S_{\uparrow(\downarrow)} \nabla_z T \right)$$



experiment: 60 mdeg

The alternative: Super-diffusive

- **Experiment (top IP layer):**
  - **Amplitude of precession:**
    Spin transfer corresponds to 2% of demagnetization OOP layer
  - **Phase of precession:**
    Majority spin flow from bottom OOP layer
- **Both consistent with super-diffusive spin current (+ screening spin polarized charge current)**

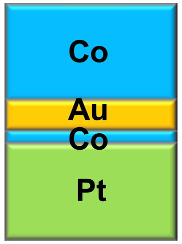


Similar results for Co / spacer / Pt/Co/Pt

36

But more difficult to interpret… (combination of ΔK and STT)

- **Also positive results and rich data for Co/Pt/Au/Co**



TU/e Technische Universiteit Eindhoven University of Technology

Outline

37

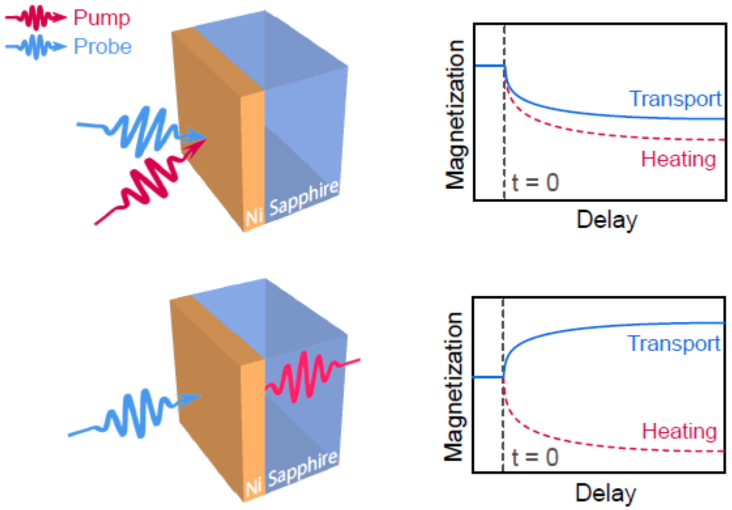
- **Introduction**
  - **Local magnetization dynamics**
  - **Spin transfer (super-diffusive)**
- **Laser-induced spin transfer torque**
  - **Why efficient**
  - **Our recent experiments**
  - **A first interpretation:**
    Super-diffusive spin currents or Spin-Dependent Seebeck?
- **Its importance for local magnetization dynamics**

TU/e Technische Universiteit Eindhoven University of Technology

A decisive experiment?

Schellekens, Verhoeven et al. APL 2013

38



TU/e Technische Universiteit Eindhoven University of Technology

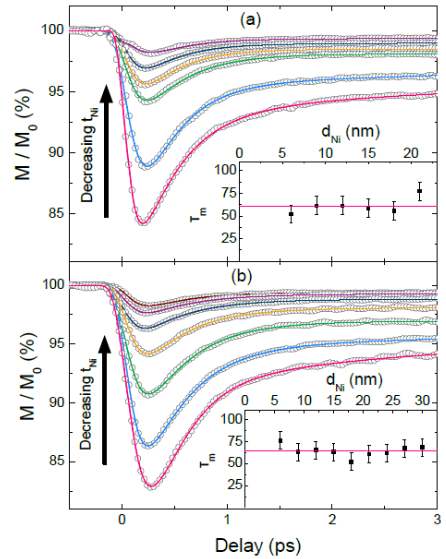
… nothing …

Schellekens, Verhoeven et al. APL 2013

39

Front pump

Back pump



~~Conclusions~~ Questions

40

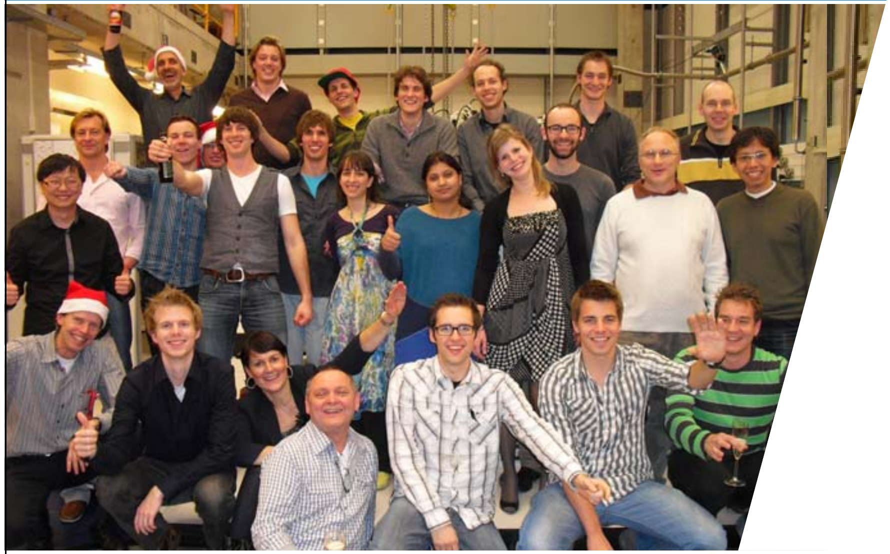
- **Thermo-dynamical model using Elliott-Yafet process seems to explain all local magnetization dynamics**
- **Did we prove minor rol of spin transport?**
  - **Or are we too naïve?**
  - **What about all the questions I posed?**

And what about using the effect?

- **Laser-induced spin transfer *can* play a role (?)**
- **And *can* exert a STT (?)**
- **Likely of super-diffusive (and not SDS) origin (?)**
  - **Are there pitfalls in our interpretation?**
  - **Is our optical / thermal / SDS correct?**
  - **How to model super-diffusive STT more accurately?**
  - **What about back flow / screening charge?**
  - **Etc. etc.**

TU/e Technische Universiteit Eindhoven University of Technology

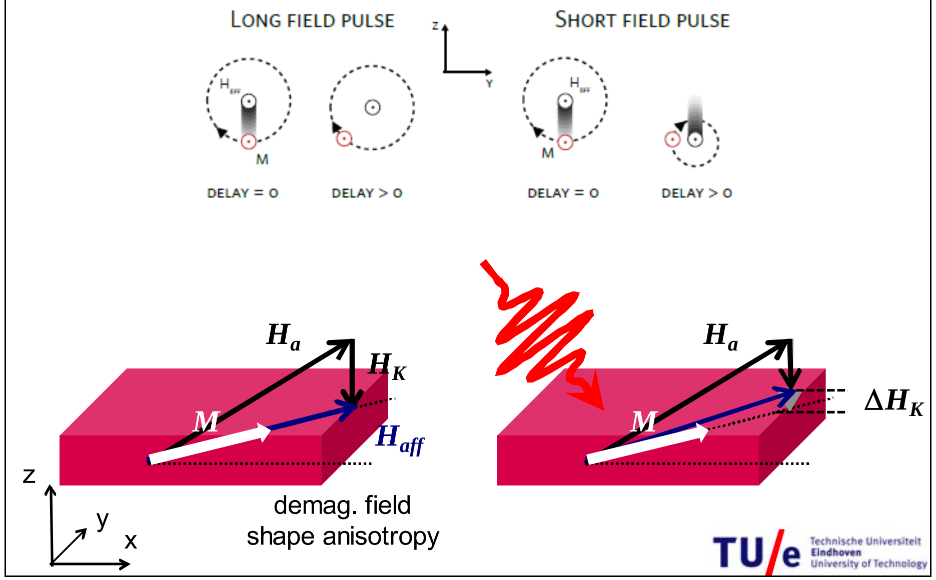
Acknowledgements



TU/e Technische Universiteit Eindhoven University of Technology

The ΔK artefact

42

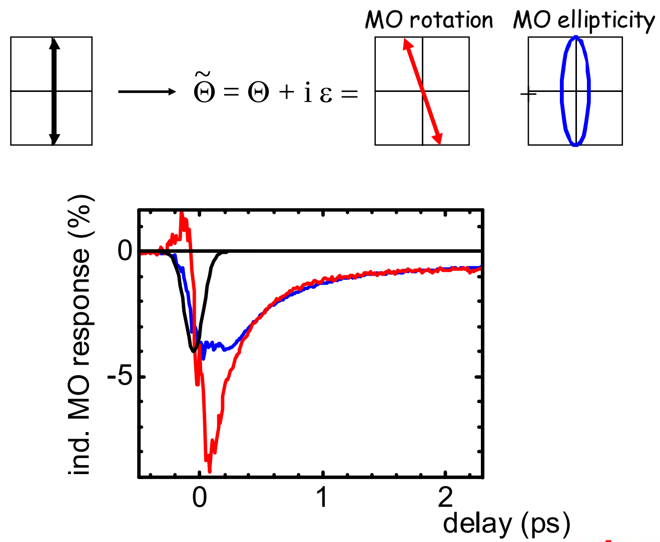


TU/e Technische Universiteit Eindhoven University of Technology

Is it magnetism at all in Ni?

Koopmans et al. PRL 2000
Regensburger et al. PRB 2000
Guidoni et al. PRL 2002

43



TU/e Technische Universiteit Eindhoven University of Technology