Heat-driven spin torque in metals and insulators

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Group

Post-docs

• Sylvain Bréchet,	theory
• *Christian Caspers,*	*sub-THz resonance in antiferromagnets*
• Marcin Bialek	(Prof. Wojciech Knap, Warsaw)
• Dongyoung Yoon	dynamic nuclear polarization (DNP)
• Alexandros Dimitriades	TeraHertz components, simulations

Present and recent grad students

• *Arndt von Bieren*	*Nernst imaging*
• Antonio Vetro	FMR under heat current
• Sa Tu	sub-THz resonance in antiferromagnets
• Ping Che	FMR under heat current
• Murari Soundararajan	dynamic nuclear polarization (DNP)
• Felix Blumenschein	spin-dependent transport in electrolytes

Collaborations

- Haiming Yu (Bejing), Bi Lei (Chengdu)
- J. Barnas, J. Dubowik, T. Stobiecki (Poznan, Krakow)
- K. Niesch (Hamburg), D. Gruendler (Munich),
- Swiss Plasma Research Center : SPC
- Alonso-Vante (Poitiers), A.M. Haider (Delhi)

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Swiss funding : *NSF + CTI*
Germany : SpinCat,
China/Switzerland : SSSTC
Poland/Switzerland : Nanospin

Why heat can drive a spin torque ?

- Metals :
  - 3-current model
  - Experimental : switching of spin valves

- Insulators :
  - Thermodynamic approach
  - Variational principle
  - Experimental : time-resolved and continuous wave

- Propects

Heat-driven spin torque in **metals**

Three-current model

$$\begin{pmatrix} j_Q/T \\ j_\uparrow \\ j_\downarrow \end{pmatrix} = \begin{pmatrix} L_{ss} & L_{s\uparrow} & L_\downarrow \\ L_{\uparrow s} & L_{\uparrow\uparrow} & L_{\uparrow\downarrow} \\ L_{\downarrow s} & L_{L\downarrow\uparrow} & L_{\downarrow\downarrow} \end{pmatrix} \begin{pmatrix} \nabla T \\ \nabla \mu_\uparrow \\ \nabla \mu_\downarrow \end{pmatrix}$$

$$j = j_\uparrow + j_\downarrow \qquad \text{spin current} : j_s = j_\uparrow - j_\downarrow$$

$$\sigma = \sigma_\uparrow + \sigma_\downarrow \qquad \epsilon = \frac{\sigma_\uparrow \epsilon_\uparrow + \sigma_\downarrow \epsilon_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \qquad \epsilon_p = \frac{\sigma_\uparrow \epsilon_\uparrow - \sigma_\downarrow \epsilon_\downarrow}{\sigma_\uparrow - \sigma_\downarrow}$$

$$\sigma_p = \sigma_\uparrow - \sigma_\downarrow$$

$$\begin{pmatrix} j_Q/T \\ j \\ j_s \end{pmatrix} = - \begin{pmatrix} \kappa & q\sigma\epsilon & q\sigma_p\epsilon_p \\ \sigma\epsilon & \sigma & \sigma_p \\ \sigma_p\epsilon_p & \sigma_p & \sigma \end{pmatrix} \begin{pmatrix} \nabla T \\ \nabla V \\ \nabla \left(\Delta\mu\right)/q \end{pmatrix}$$

L. Gravier et al, PRB 2006

Heat-driven spin current over long distances !

spin-dependent conductivity

$$\sigma_{\pm} = \frac{\sigma}{2}(1 \pm \beta)$$

spin-dependent thermopower

$$\varepsilon_{\pm} = \varepsilon(1 \pm \eta)$$

far from an interface, and without charge current :

Spin current at long distances :

$$j_s = -\sigma\,(\eta - \beta)\,\epsilon \nabla T$$

S. Brechet, J.-Ph. A., phys. Stat. Solidi 2010

nature physics

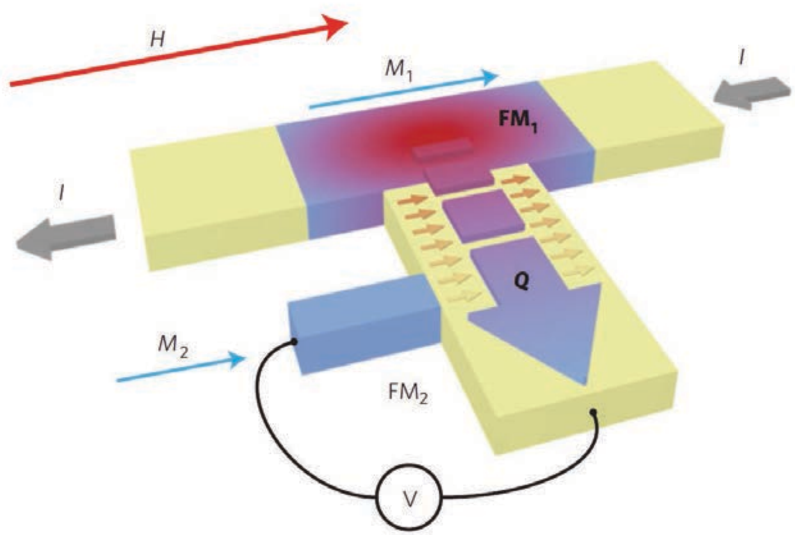
LETTERS

PUBLISHED ONLINE: 19 SEPTEMBER 2010 | DOI: 10.1038/NPHYS1767

Thermally driven spin injection from a ferromagnet into a non-magnetic metal

A. Slachter*, F. L. Bakker, J-P. Adam and B. J. van Wees

$$\begin{pmatrix} \mathbf{J}_\uparrow \\ \mathbf{J}_\downarrow \\ \mathbf{Q} \end{pmatrix} = -\begin{pmatrix} \sigma_\uparrow & 0 & \sigma_\uparrow S_\uparrow \\ 0 & \sigma_\downarrow & \sigma_\downarrow S_\downarrow \\ \sigma_\uparrow \Pi_\uparrow & \sigma_\downarrow \Pi_\downarrow & k \end{pmatrix} \cdot \begin{pmatrix} \nabla \mu_\uparrow / e \\ \nabla \mu_\downarrow / e \\ \nabla T \end{pmatrix}$$



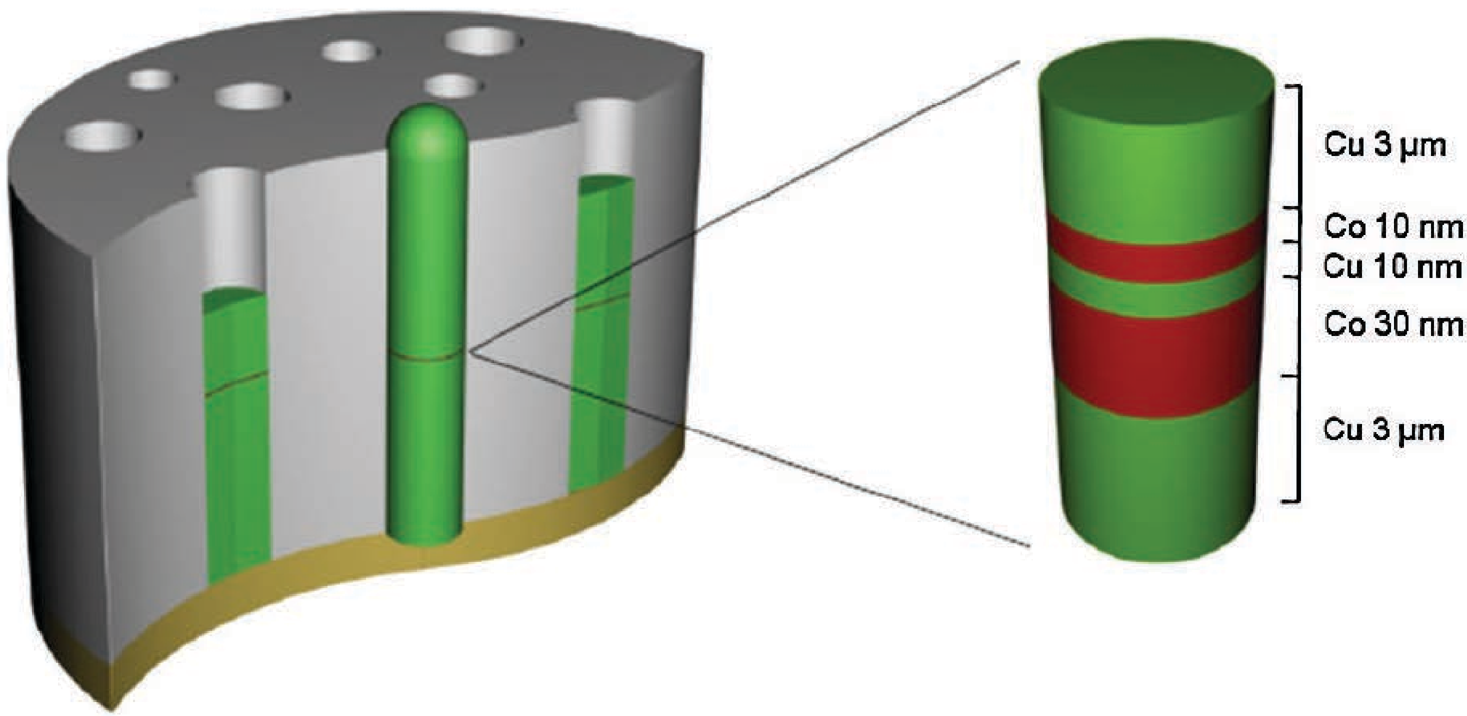
Experimental evidence :

magnetization switching

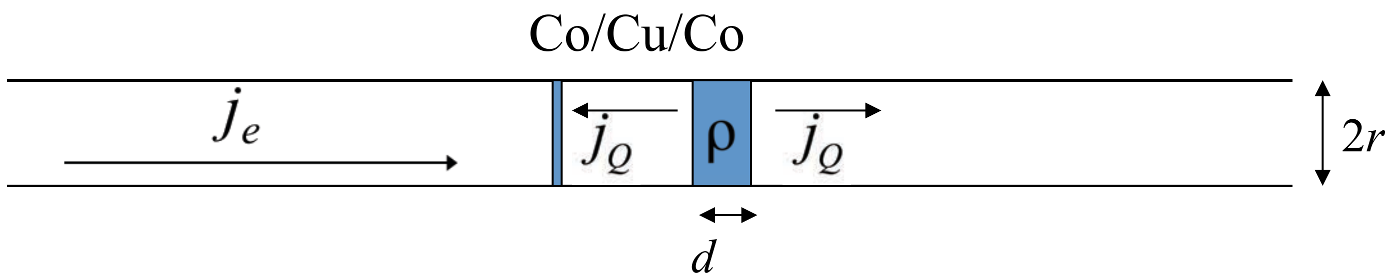
in metallic spin valves

Evidence for Thermal Spin-Transfer Torque

Haiming Yu,[1,2] S. Granville,[1] D. P. Yu,[2] and J.-Ph. Ansermet[1]
[1]*Ecole Polytechnique Fédérale de Lausanne, IPMC, Station 3, CH-1015 Lausanne-EPFL, Switzerland*
[2]*State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, People's Republic of China*

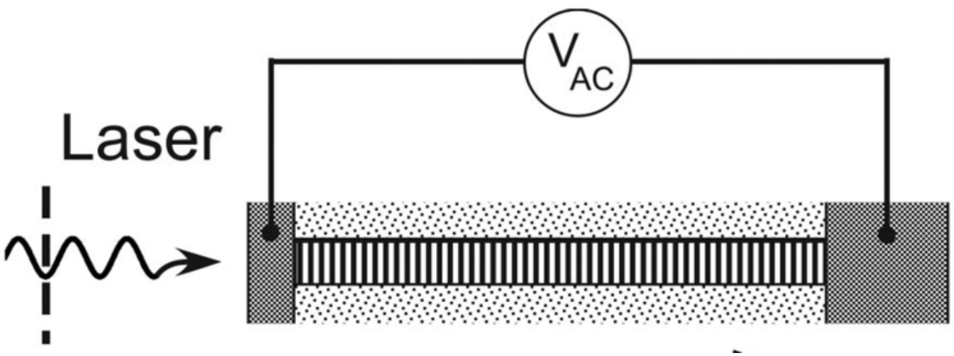


Large heat current, small temperature change



$$\nabla T \approx 10'000 \text{ K } /\text{cm}$$

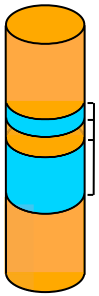
$$\Delta T < 1\text{K}$$

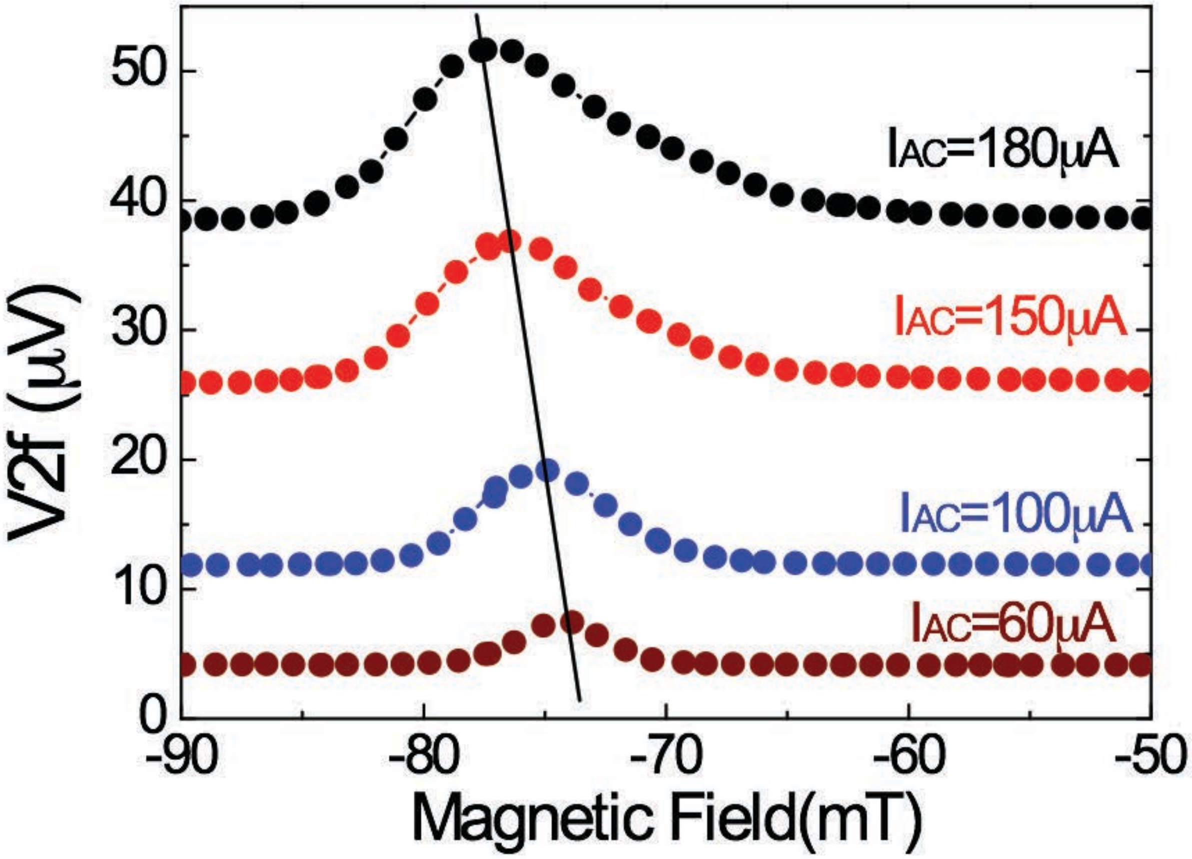


$$\nabla T \approx 10^4 K cm^{-1}$$

Fitoussi et al, APL 2014

Effect of heat-driven spin current on switching





NB : reversible, no minor loop if field cycled over small range

$I_{DC} \approx 0.1mA$

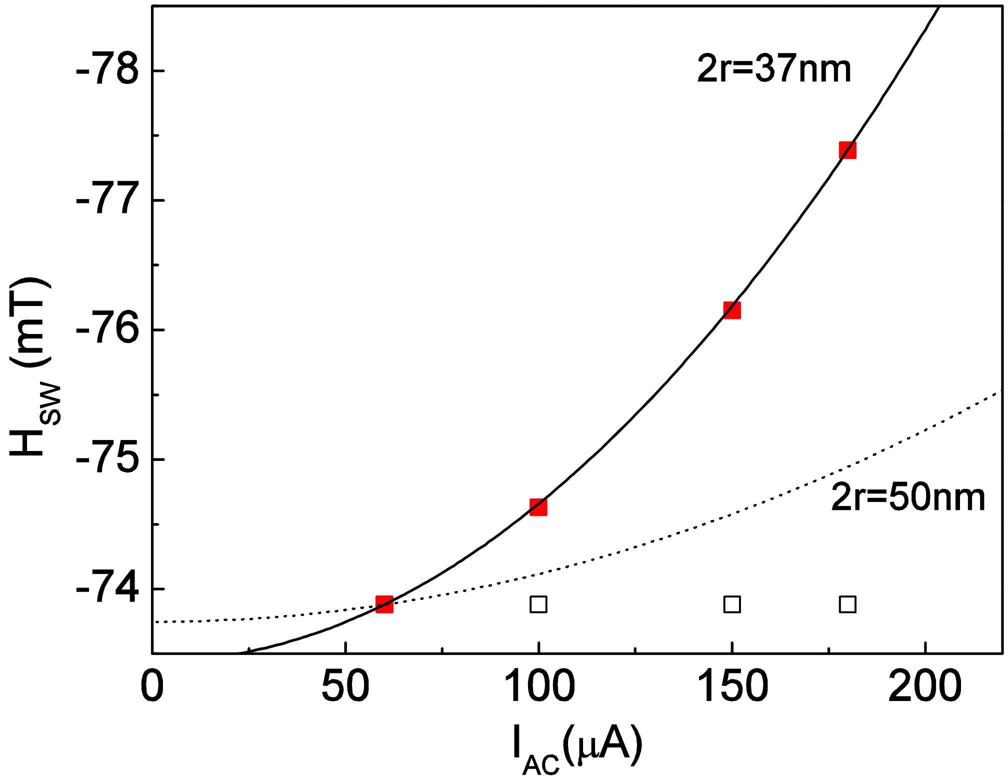
Heat-driven spin torque

First heat-driven spin prediction : M. Hatami, G. E. W. Bauer, Q. Zhang, and P. J. Kelly, Phys. Rev. Lett. 2007

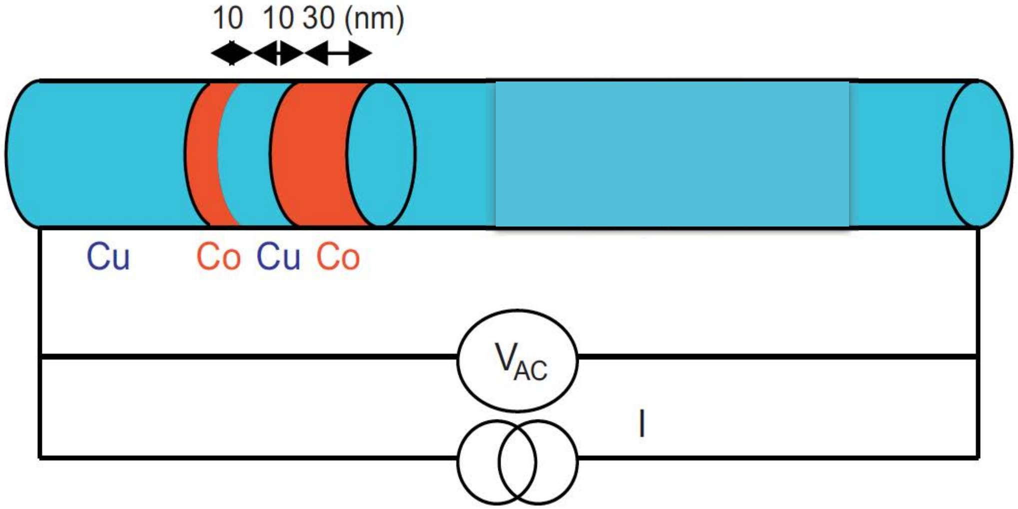
3-current model :

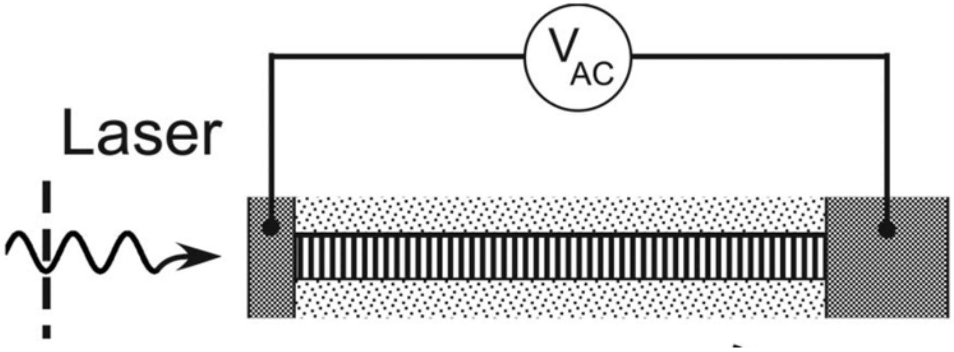
$$j_s = -\sigma_p \left(\nabla V - \epsilon_p \nabla T \right)$$

$$\frac{\Delta H_{heat}}{\Delta H_{charge}} = \frac{\tau_{heat}}{\tau_{STT}} = \frac{\epsilon_p \nabla T}{\nabla V}$$



Co/Cu spin valves
in a nanowire

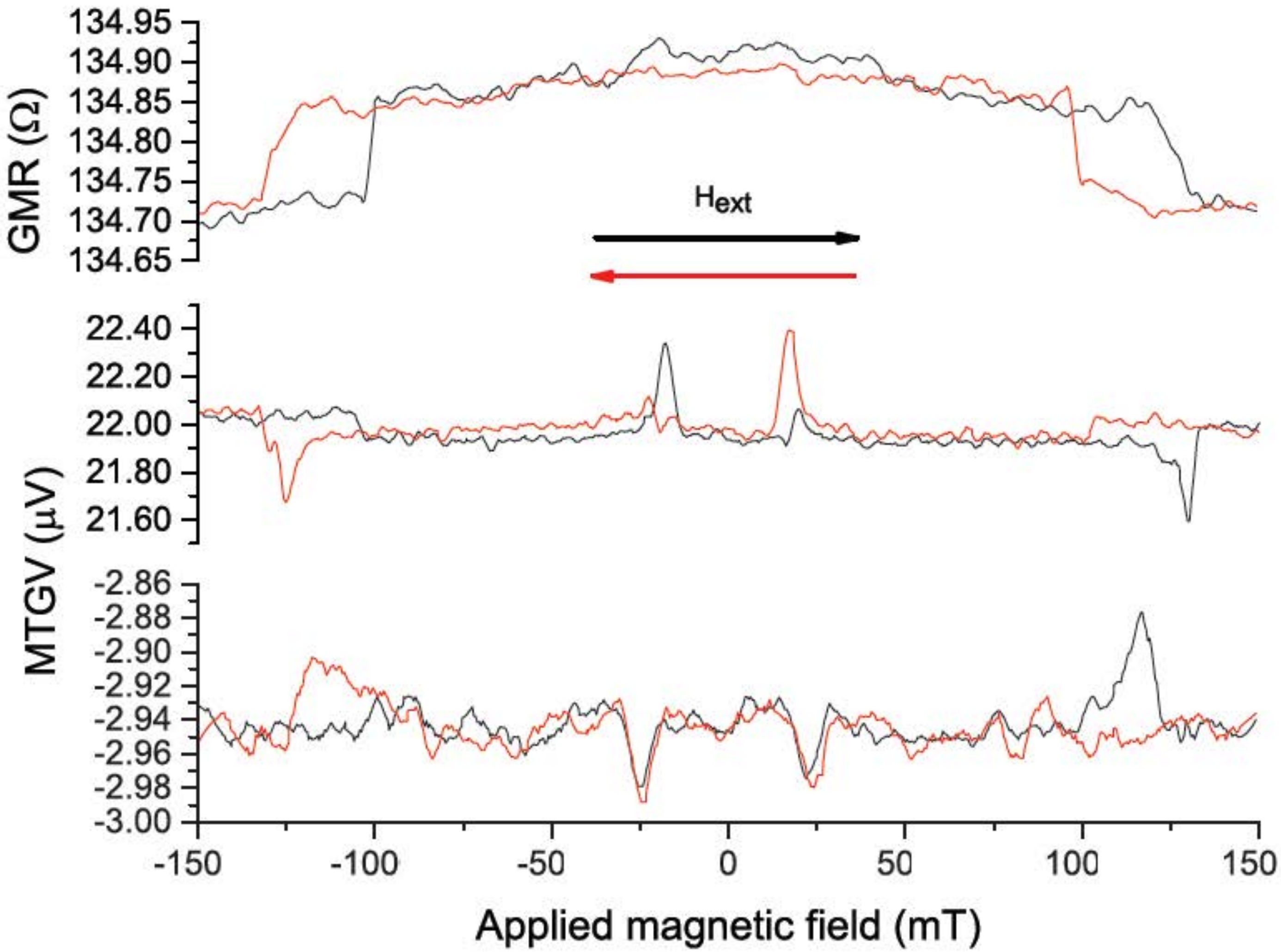


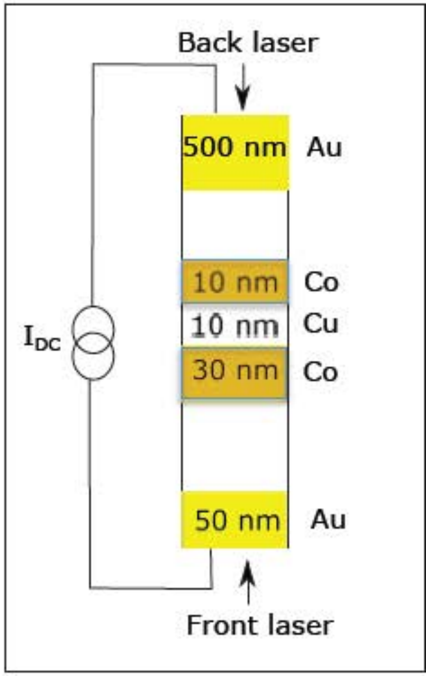


$$\nabla T \approx 10^4 K cm^{-1}$$

Serrano-Guisan, Gravier, Mat. Sc. and En. B 126 (2006) 292–295

Heat-driven spin torque



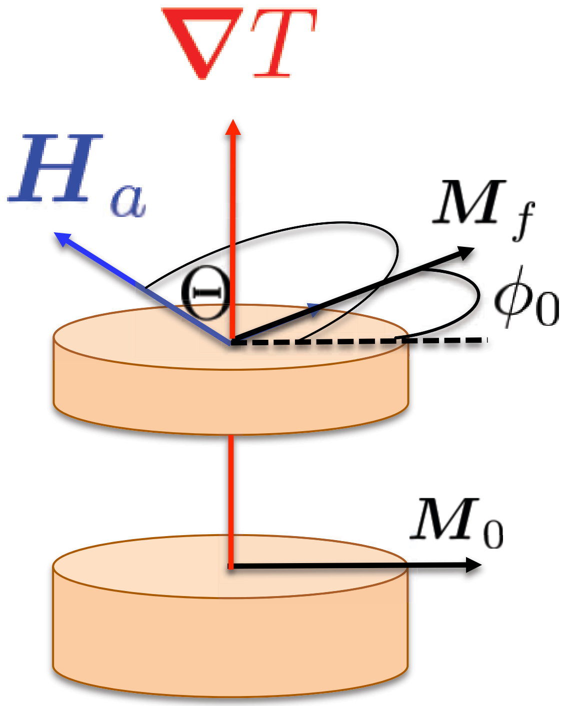


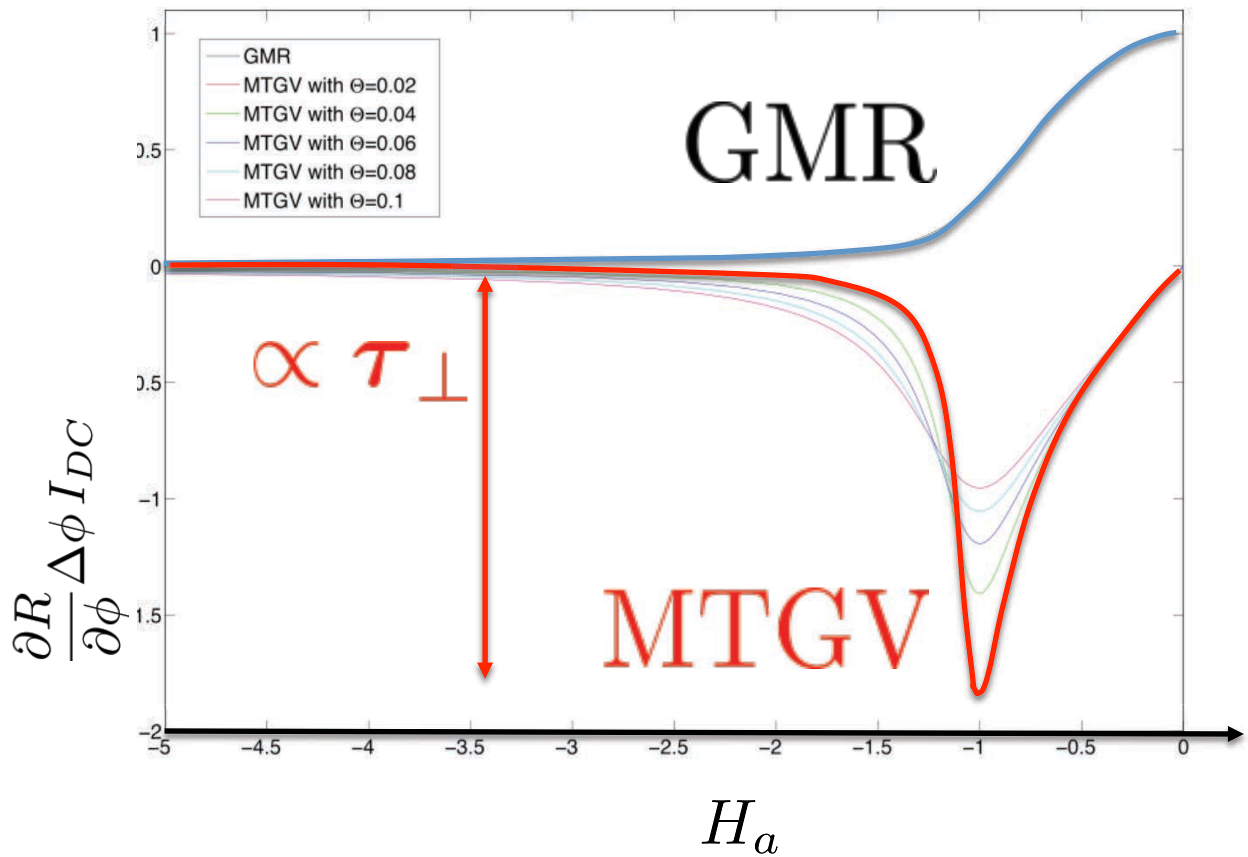
Lucas Fitoussi, 2014

Landau-Lifshitz,
linear response to torque

$$\Delta\phi = \frac{1}{\mu_0 M_s d} \frac{\tau_\perp}{H_{||}\cos(2\phi_0) + H_{app}\cos(\Theta - \phi_0)}$$

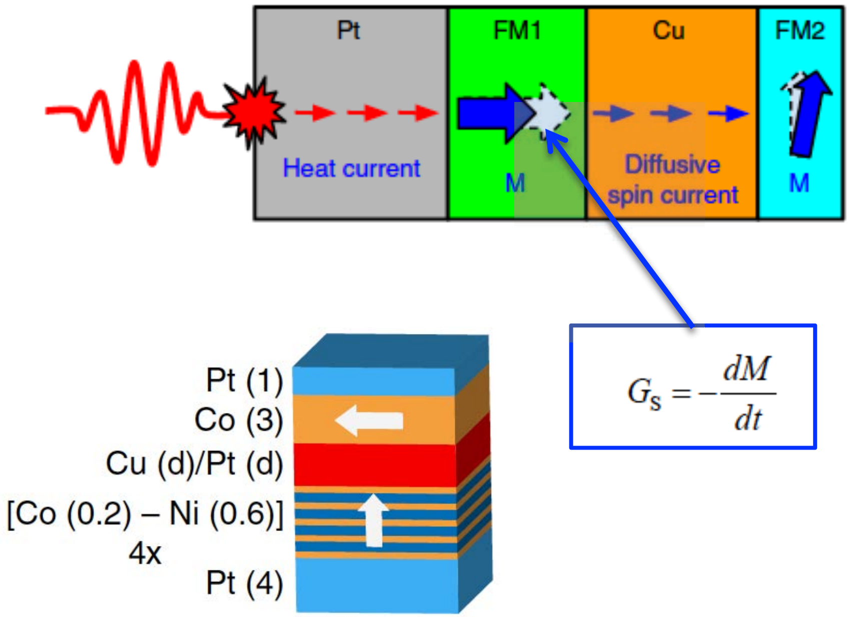
$$\left(H_{||}\sin\phi_0\cos\phi_0 - H_{app}\sin(\Theta - \phi_0) = 0\right)$$



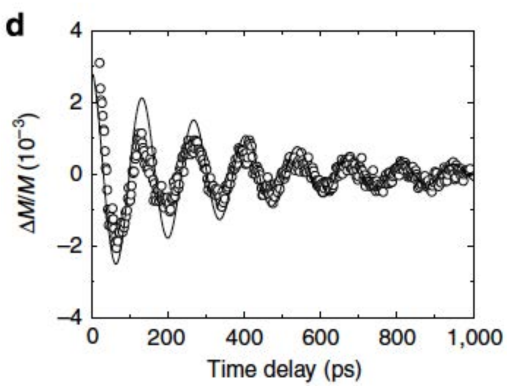


Fitoussi, ..., JPHA, APL 2015

Spin current generated by thermally driven ultrafast demagnetization

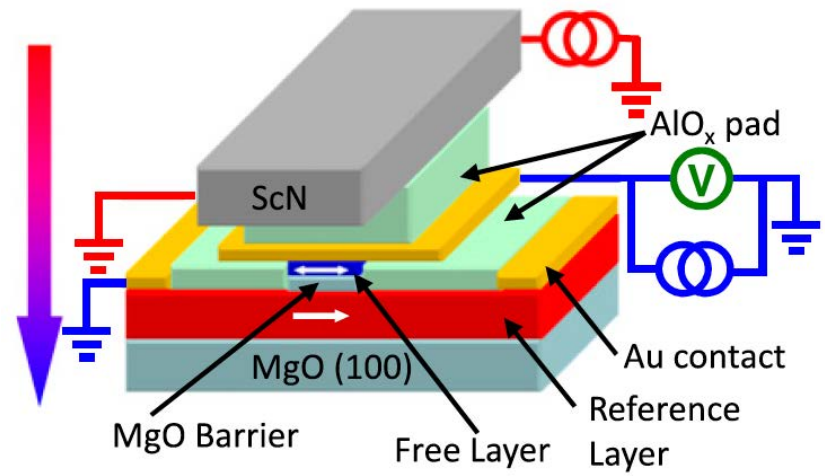


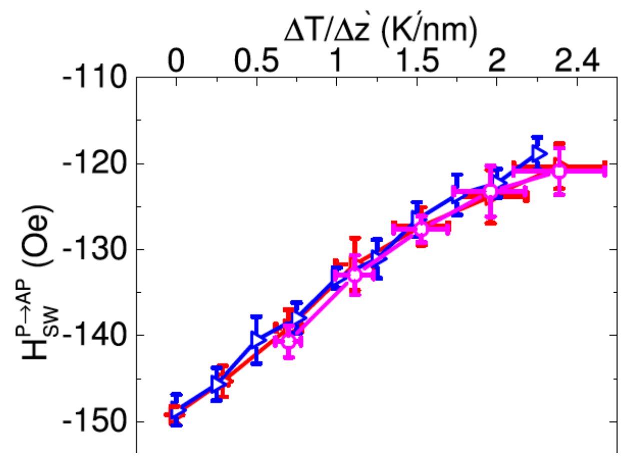
Koopmans et al., Nat. Comm 2014



Cahill et al., Nat. Comm 2014

Spin torque generated by heat across magnetic tunnel junctions

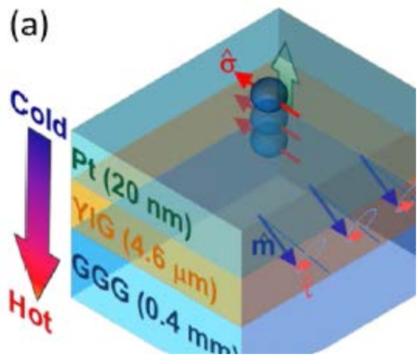




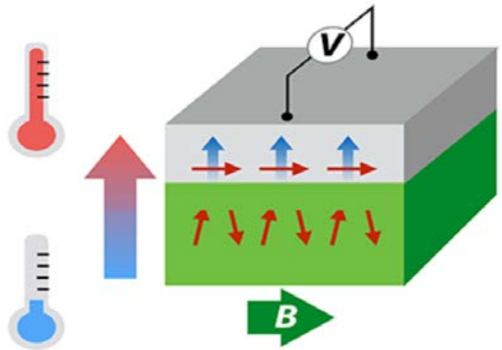
S.S.P. Parkin et al., PNAS 2015

Does a heat current
couple to
magnetization dynamics

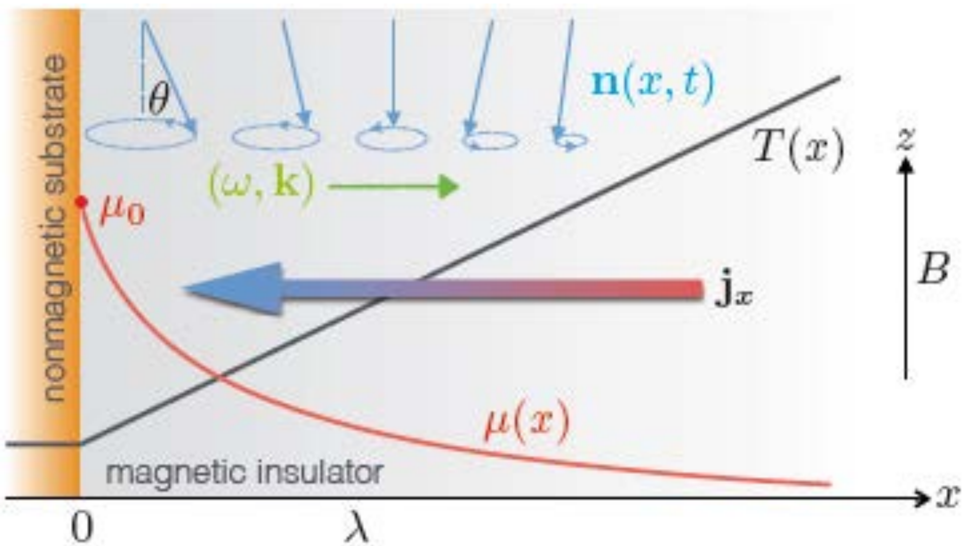
in insulator ?



Interfacial effect
Lu, Sun, Jantz, Wu, PRL 2012



Antiferromagnets
Seki *et al.*, PRL 2015



Theory magnons in insulators
Tserkovniak et al.
PRB2016 +arXiv 2016

arXiv:1604.03706 [pdf, other]

Magnon spin transport driven by the magnon chemical potential in a magnetic insulator

Ludo J. Cornelissen, Kevin J.H. Peters, Rembert A. Duine, Gerrit E.W. Bauer, Bart J. van Wees

Subjects: **Mesoscale and Nanoscale Physics (cond-mat.mes-hall)**

Thermodynamics of Irreversible processes with electromagnetic fields

entropy production

$$\rho_s = \frac{1}{T}\boldsymbol{j}_s\left(-\boldsymbol{\nabla}T\right) + \frac{1}{T}\sum_A \boldsymbol{j}_A\left(-\boldsymbol{\nabla}\mu_A - q_A\boldsymbol{\nabla}V + \boldsymbol{m}_A\boldsymbol{\nabla}\boldsymbol{B}\right)$$

generalized 'force' $\boldsymbol{F}_A$

Onsager matrix :

$$\boldsymbol{j}_s = L_{ss}\left(\boldsymbol{\nabla}T\right) + L_{sA}\boldsymbol{F}_A$$
$$\boldsymbol{j}_A = L_{As}\left(\boldsymbol{\nabla}T\right) + L_{AA}\boldsymbol{F}_A$$

Bréchet, Ansermet, Europhys. J. B**86**:318 (2013)

Electric and Magnetic Seebeck effects

Zero current $\Rightarrow$

$$0 = L_{As}\left(\boldsymbol{\nabla} T\right) + L_{AA}\left(-\boldsymbol{\nabla}\mu_A - q_A \boldsymbol{\nabla} V + \boldsymbol{m}_A \boldsymbol{\nabla} \boldsymbol{B}\right)$$

Cross effect : $-\boldsymbol{\nabla} V$ with $-\boldsymbol{\nabla} T$: the Seebeck effect

Cross effect : $\boldsymbol{B}$ field with $-\boldsymbol{\nabla} T$

The magnetic Seebeck effect

$$\boldsymbol{m}_A \boldsymbol{\nabla} \boldsymbol{B} = L_{AA}^{-1} L_{As} \boldsymbol{\nabla} T$$

vectorial calculus $\rightarrow$

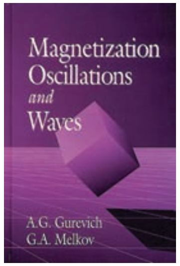
$$\boldsymbol{B}_{ind} = \boldsymbol{\epsilon} \times \boldsymbol{\nabla} T$$

$$\boldsymbol{\epsilon} = -\lambda n_A k_B \left(\boldsymbol{\nabla} \times \boldsymbol{M} \right)^{-1}$$

To be determined by other means ...

Reconsidering the derivation of the LL equation

Bréchet, Ansermet, Europhys Lett. Oct 2015



$$\text{equilibrium}: \delta \int_V u dV = 0 \qquad u\left(\boldsymbol{M}, \boldsymbol{\nabla} \times \boldsymbol{M}\right)$$

$$\boldsymbol{B}_{eff} = \frac{\delta u}{\delta \boldsymbol{M}} = \frac{\partial u}{\partial \boldsymbol{M}} + \boxed{\boldsymbol{\nabla} \times \frac{\partial u}{\partial (\boldsymbol{\nabla} \times \boldsymbol{M})}} \qquad \color{red}{\boldsymbol{B}_{HST}}$$

$$\dot{\boldsymbol{m}} = \gamma\left(\boldsymbol{m} \times \boldsymbol{B}_0 + \boldsymbol{M}_S \times \boldsymbol{b}\right) + \frac{\alpha}{M_S} \boldsymbol{M}_S \times \dot{\boldsymbol{m}} \quad \color{red}{+\gamma \boldsymbol{M}_S \times \boldsymbol{B}_{HST}}$$

$$\frac{\partial\left(\boldsymbol{\nabla} \times \boldsymbol{m}\right)}{\partial u} = \boldsymbol{\nabla} \times \frac{\partial \boldsymbol{m}}{\partial u} = \boldsymbol{\nabla} \times \left(\frac{\partial u}{\partial \boldsymbol{m}}\right)^{-1} \qquad \boldsymbol{b} = \chi^{-1} \boldsymbol{m}$$

$$\boldsymbol{B}_{HST} = -\mu_0 \hat{\boldsymbol{z}} \cdot \boldsymbol{\nabla}^{-1} \left(\frac{\partial}{\partial z} \left(\chi^{-1} \boldsymbol{m}\right)\right) \qquad \chi \propto M_s \left(T(z)\right)$$

Heat-driven (vectorial) spin current

$$\boldsymbol{\tau}_{HST} = \frac{k_T}{M_S^2}\,\boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{j}_s)$$

with the spin current :

$$\boldsymbol{j}_s = \frac{\mu_0\, M_S}{k}\; \boldsymbol{m}_k$$

Heat-driven (tensorial) spin current

$$\boldsymbol{\tau}_{HST} = -\mu_0\, \boldsymbol{k}_T \cdot \mathsf{j}_s$$

with the spin current :

$$\mathsf{j}_s = \boldsymbol{M}_S \times \boldsymbol{\nabla}^{-1}\, \boldsymbol{m}$$

spin wave spin current : $\mathsf{j}_s = \boldsymbol{M} \times \boldsymbol{\nabla}\, \boldsymbol{M}$

(see Saitoh, Ando, in *Concepts in Spin Electronics* Maekawa Ed. 2012

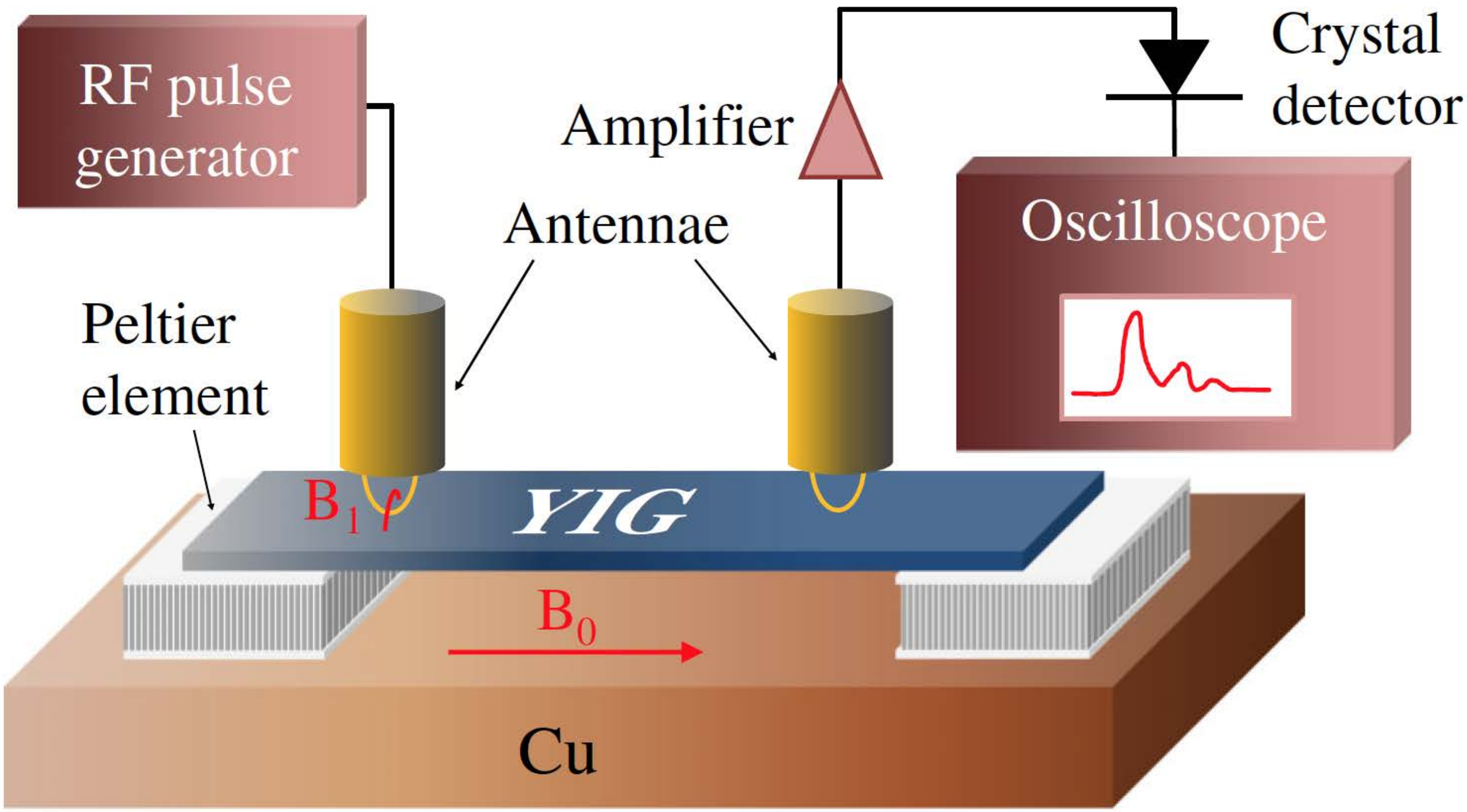
Experimental evidence for heat-driven spin torques in insulators

PRL **111,** 087205 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

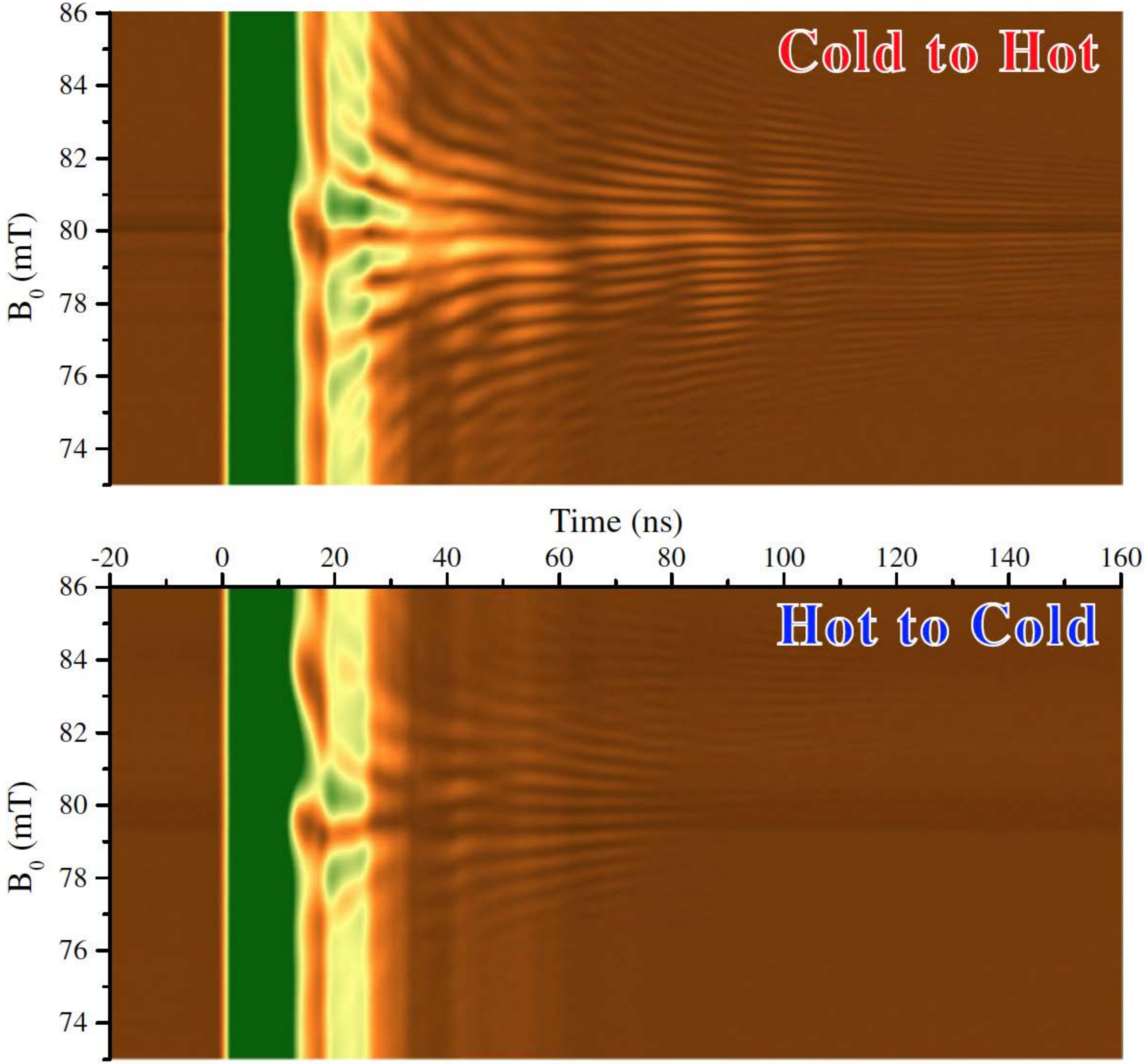
Evidence for a Magnetic Seebeck Effect

Sylvain D. Brechet,[1,*] Francesco A. Vetro,[1] Elisa Papa,[1] Stewart E. Barnes,[2] and Jean-Philippe Ansermet[1]

Time resolved FMR with temperature gradient



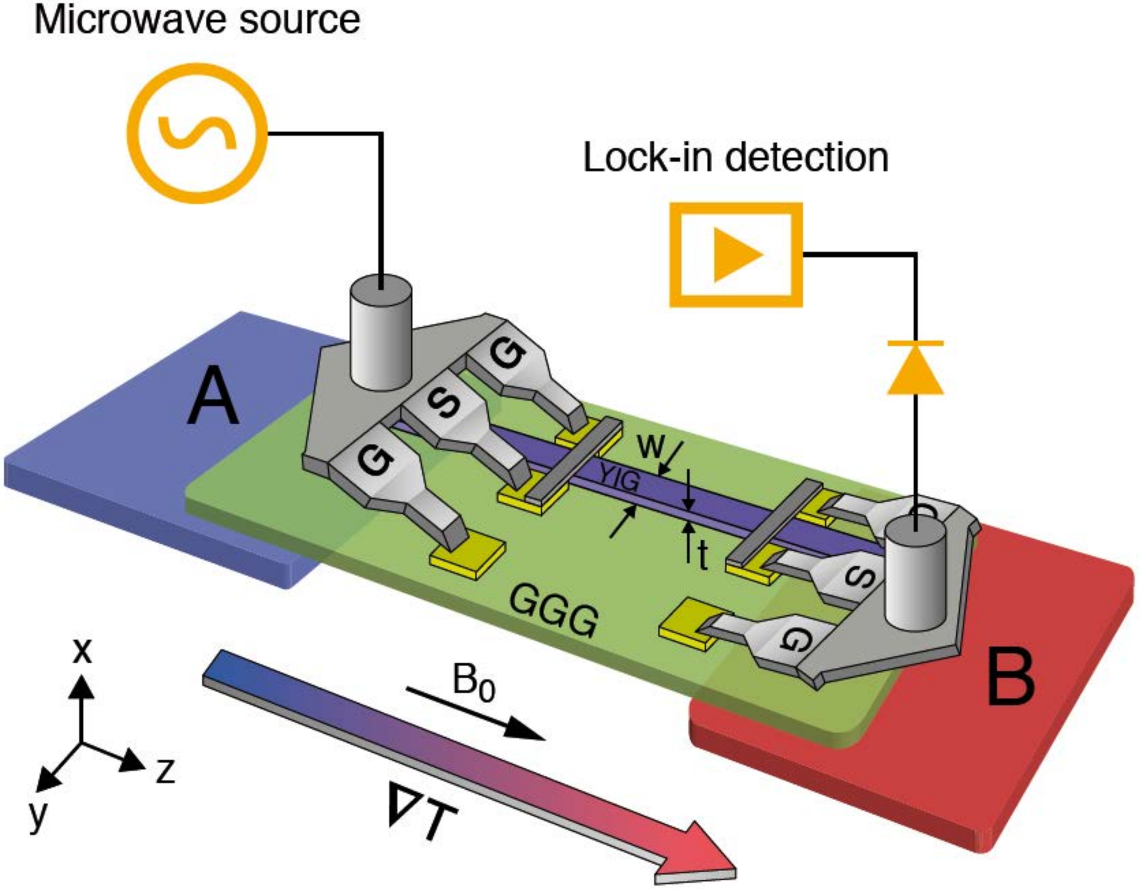
- YIG : 50 micron thick, on sapphire substrate, 7 mm long
- two Peltier elements, on heat-sinking block

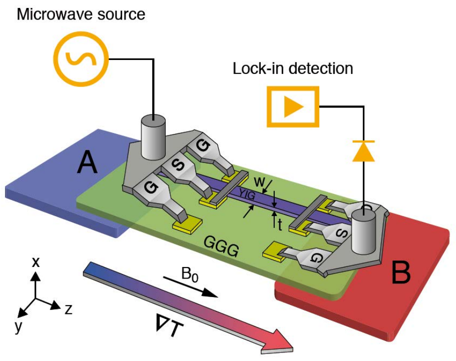


S. Brechet, JPA et al., PRL 2013

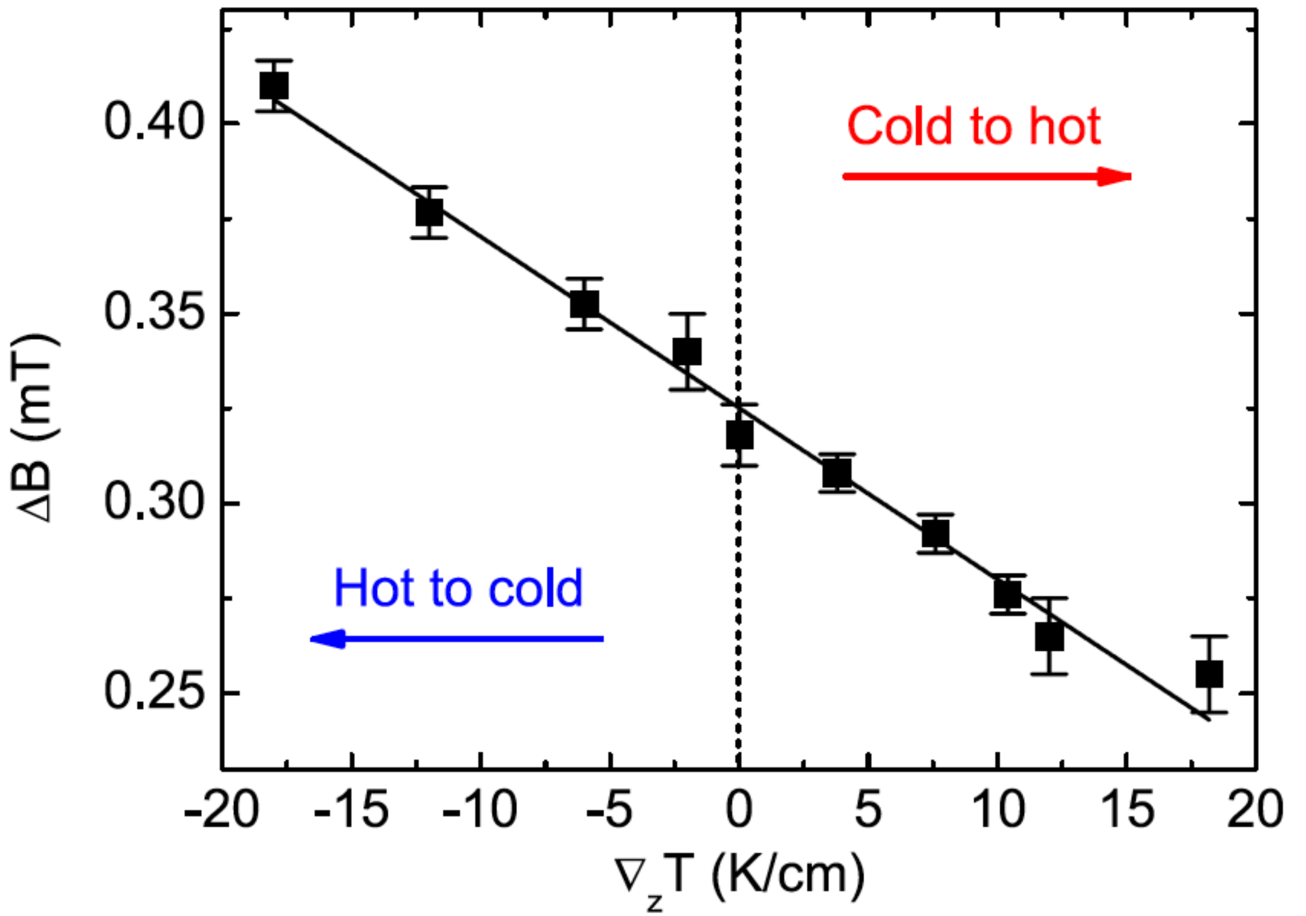
Recent results

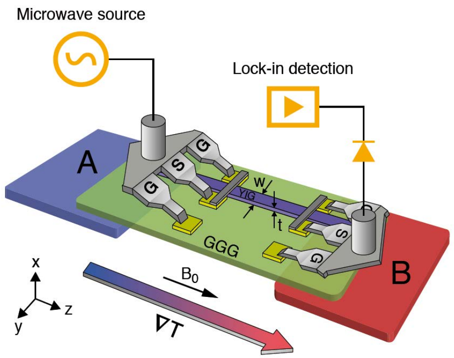
Continuous wave



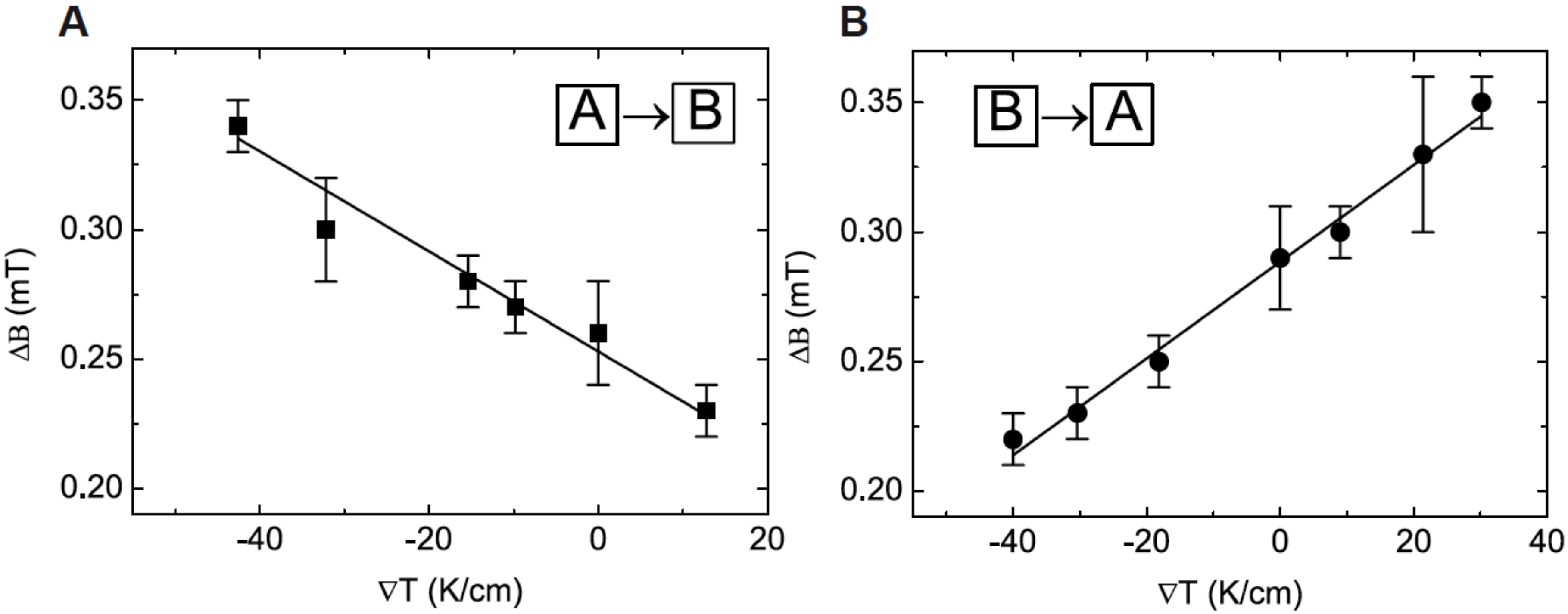


Line width proportional to temperature gradient



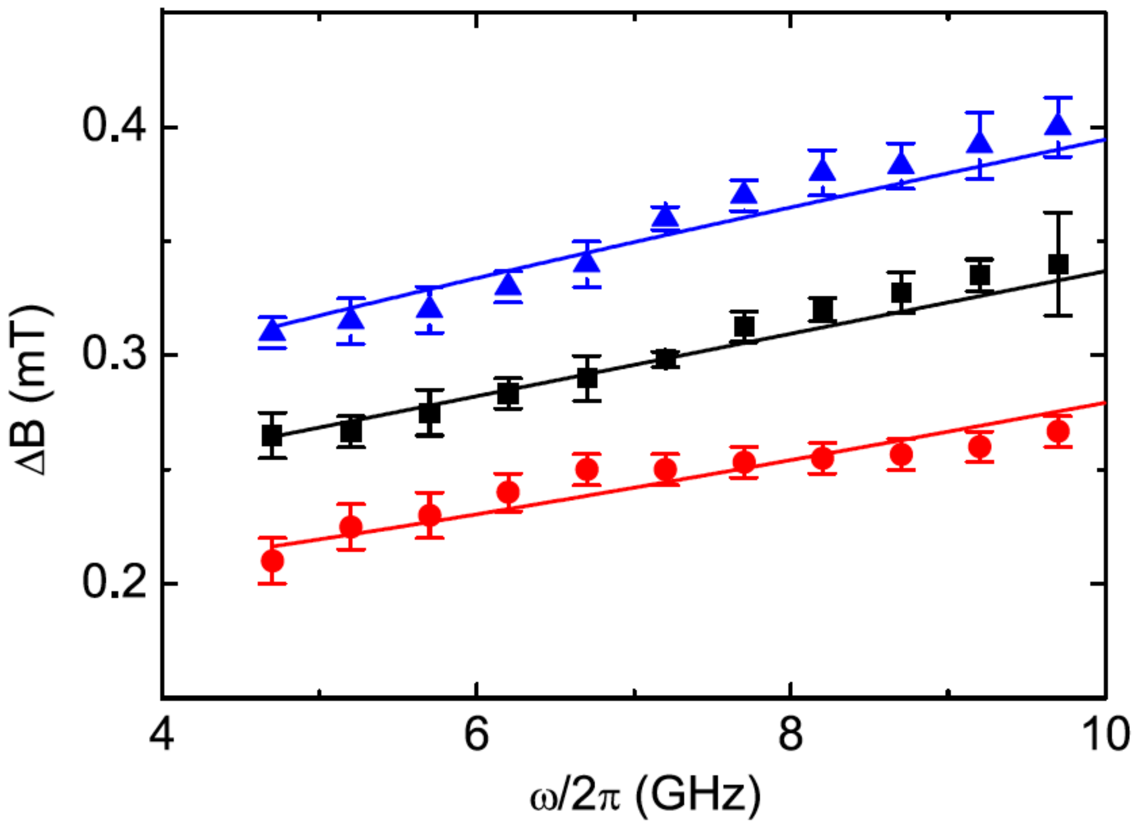


Propagation direction is essential !



Fit with no adjustable parameter !

$$\Delta B = \Delta B_0 + \frac{2}{\sqrt{3}}\alpha \left|\frac{\omega_K}{\gamma}\right| - \frac{2}{\sqrt{3}}\left|\frac{\omega_K - \omega_0}{\gamma}\right| \left|\frac{1}{M_S}\frac{dM_S}{dT}\right| \frac{1}{k}\nabla_z T$$

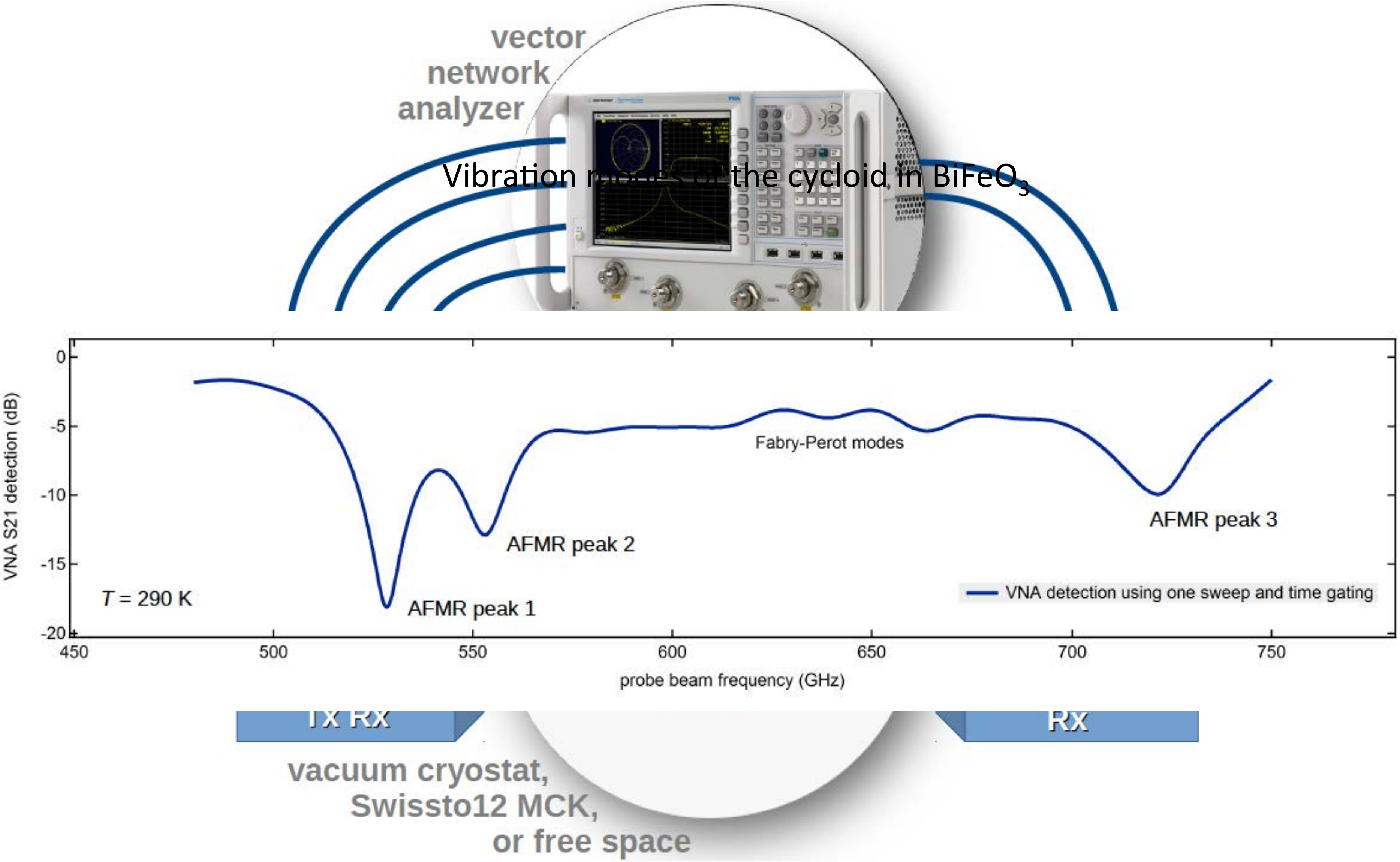


Prospects ?

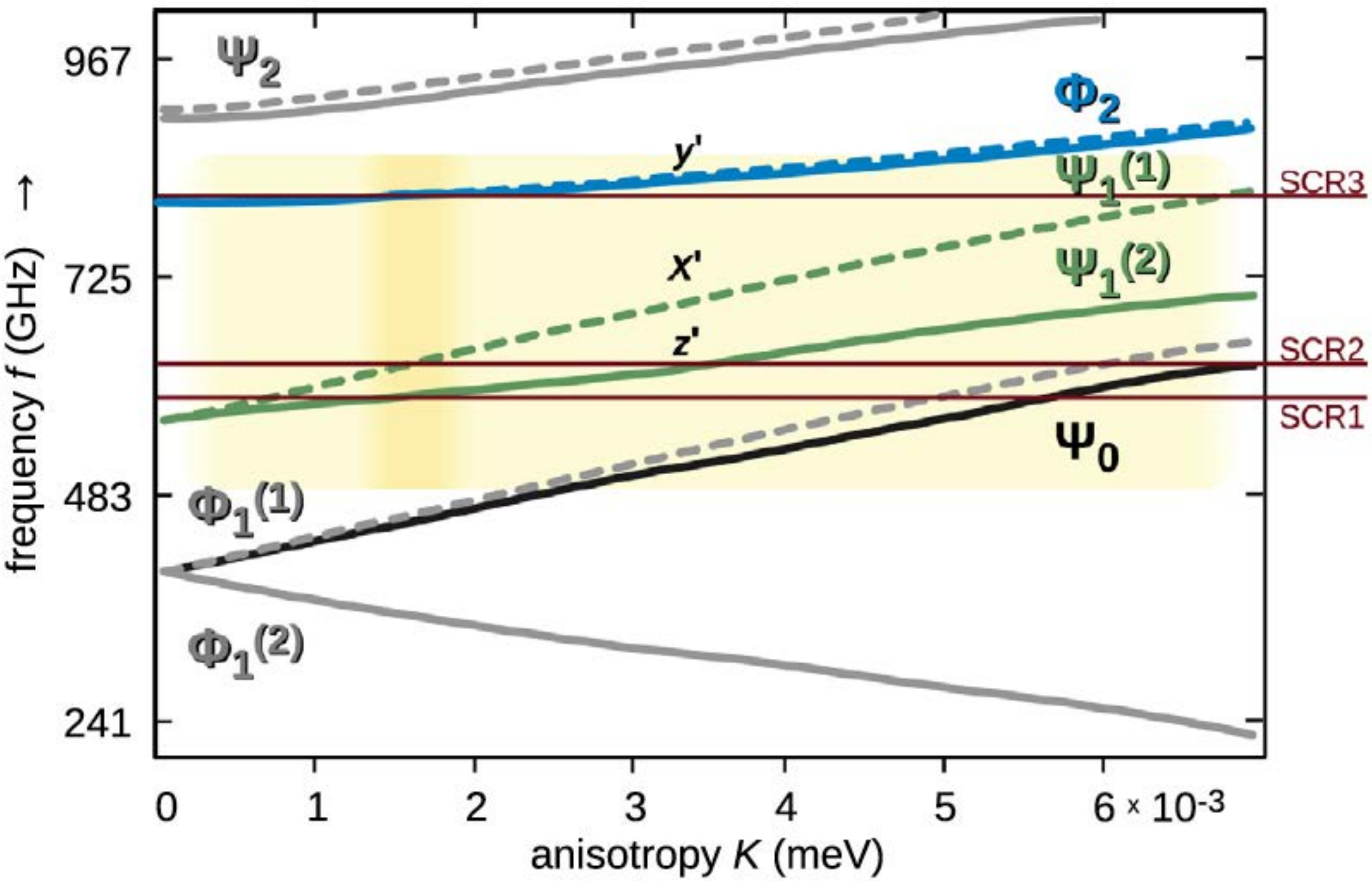
Spintronics with Antiferromagnets

Sub-THz dynamics in antiferromagnets

Vibration modes of the cycloid in $BiFeO_3$



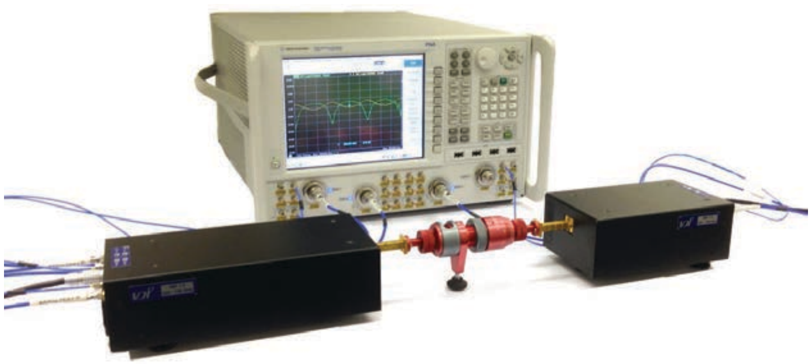
Resonance of the cycloid in $BiFeO_3$

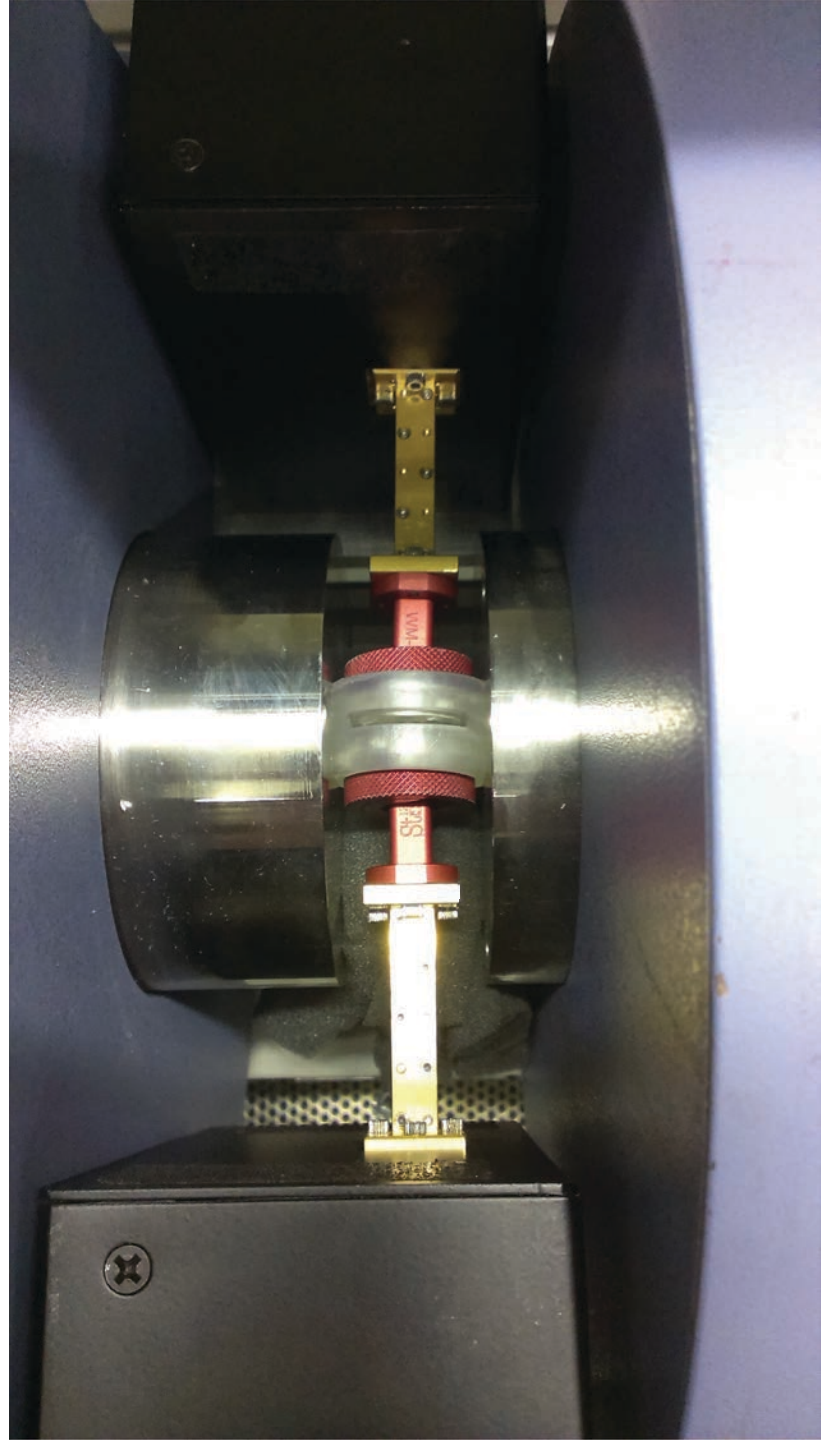


Caspers, Gandhi, Magrez, De Rijk, Ansermet, APL 2016, 108, 241109

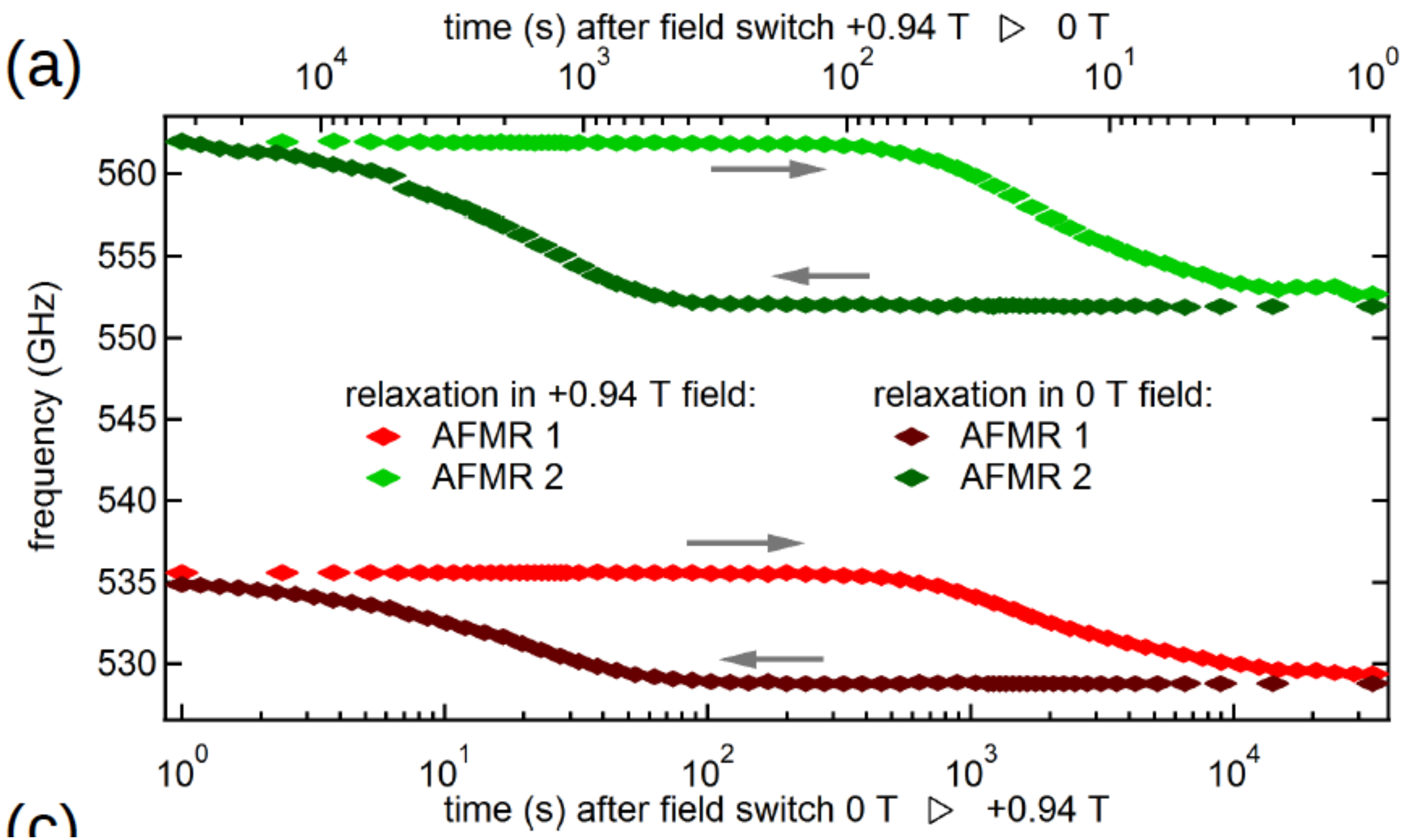
Vector Network Analyzer

For magnetic resonance





Magnetic After-Effect seen in the cylcoid resonances of BFO !



Heat-driven spin torques

over large distances ?

in metals :
the Seebeck effect depends on spin
implies
a spin current over large distances

$$\boldsymbol{j}_s = -\sigma\,(\eta - \beta)\,\epsilon \boldsymbol{\nabla T}$$

$$\boldsymbol{\tau}_{STT} \propto \boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{j}_s)$$

in insulators :
the magnetic Seebeck effect
implies
a ***heat-driven spin current***

$$\boldsymbol{j}_s = \frac{\mu_0\, M_S}{k}\, \boldsymbol{m}_k$$

$$\boldsymbol{\tau}_{HST} \propto \partial_z T\ \boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{j}_s)$$