Magnetization Dynamics under Heat Currents

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Post-docs

Sylvain Bréchet,	*theory*
Pedro Saraiva	*ESR*

Present and recent grad students

Elisa Papa,	*FMR in SSE geometry*
Antonio Vetro	*time resolved FMR*
F. Comandè	*spin-dependent charge recombination in OLED*
Arndt von Bieren	*Nernst imaging of magnetization domains*

Collaborations

- S. Barnes, U. Miami, Florida
- J. Barnas, J. Dubowik, T. Stobiecki

Funding

Swiss NSF,
SpinCat, DFG
Nanospin : joint research programs with Poland

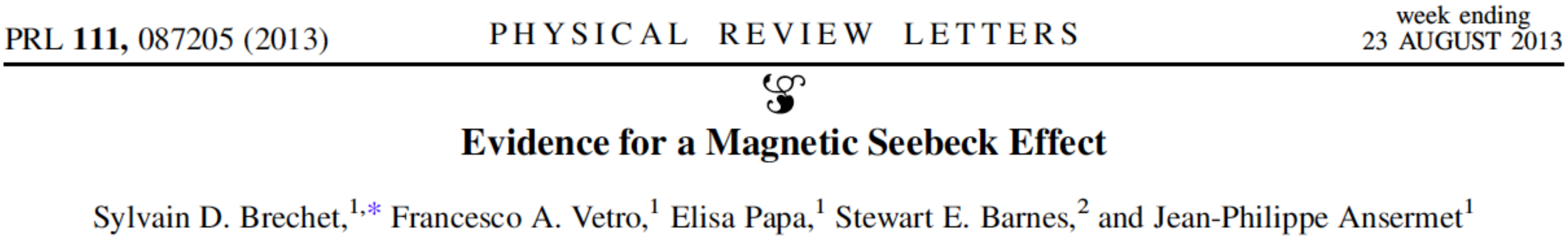
SWISS
CONTRIBUTION

Outline

- The magnetic Seebeck effect (insulator)

- Heat-driven spin current in spin valves (metals)
  - switching in spin valves
  - linear response of spin valves to heat-driven spin currents

A magnetic Seebeck effect

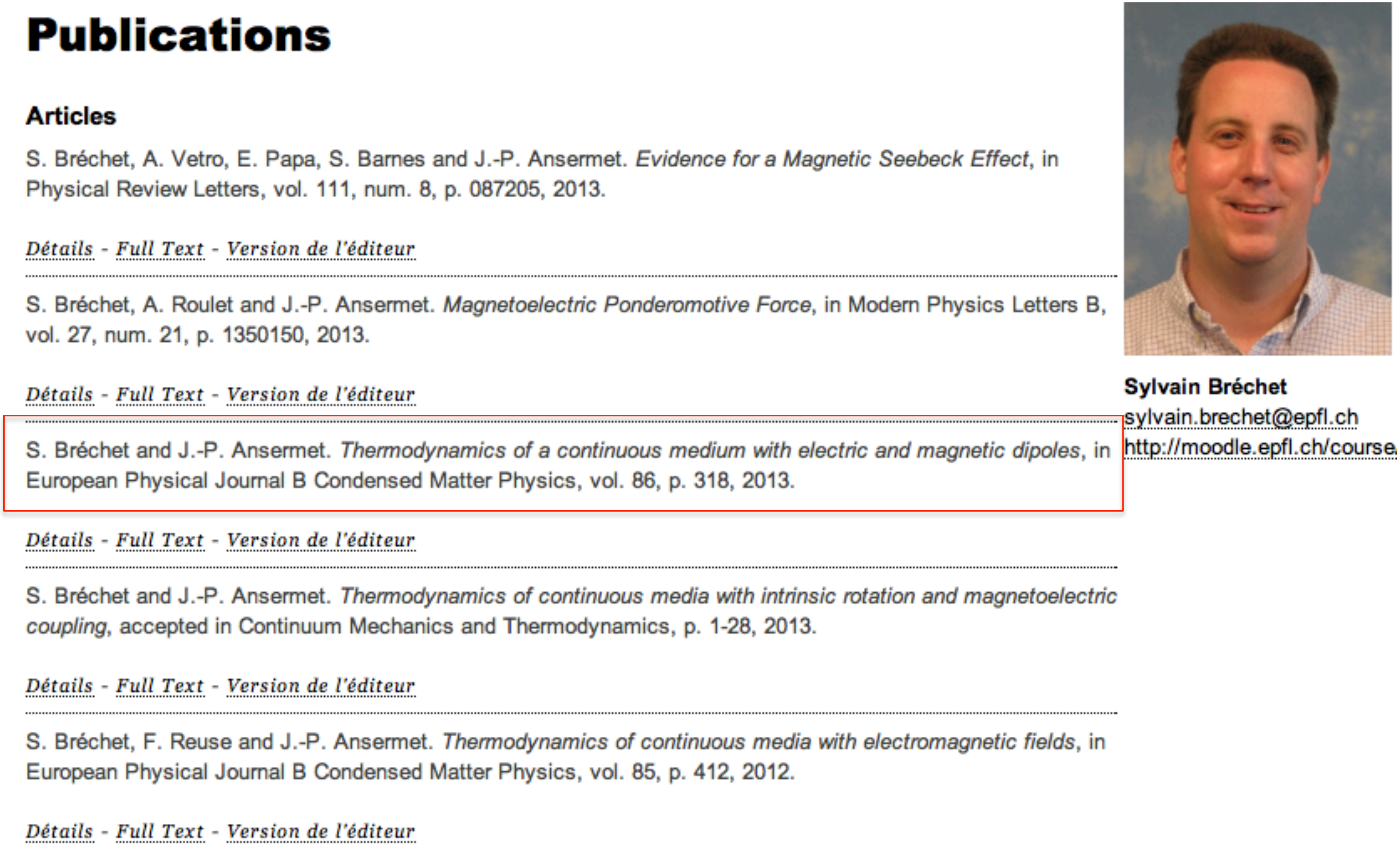


PRL **111,** 087205 (2013) PHYSICAL REVIEW LETTERS week ending
23 AUGUST 2013

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]

Thermodynamics with electromagnetic fields



Publications

Articles

S. Bréchet, A. Vetro, E. Papa, S. Barnes and J.-P. Ansermet. *Evidence for a Magnetic Seebeck Effect*, in Physical Review Letters, vol. 111, num. 8, p. 087205, 2013.

Détails - *Full Text* - *Version de l'éditeur*

S. Bréchet, A. Roulet and J.-P. Ansermet. *Magnetoelectric Ponderomotive Force*, in Modern Physics Letters B, vol. 27, num. 21, p. 1350150, 2013.

Détails - *Full Text* - *Version de l'éditeur*

S. Bréchet and J.-P. Ansermet. *Thermodynamics of a continuous medium with electric and magnetic dipoles*, in European Physical Journal B Condensed Matter Physics, vol. 86, p. 318, 2013.

Détails - *Full Text* - *Version de l'éditeur*

S. Bréchet and J.-P. Ansermet. *Thermodynamics of continuous media with intrinsic rotation and magnetoelectric coupling*, accepted in Continuum Mechanics and Thermodynamics, p. 1-28, 2013.

Détails - *Full Text* - *Version de l'éditeur*

S. Bréchet, F. Reuse and J.-P. Ansermet. *Thermodynamics of continuous media with electromagnetic fields*, in European Physical Journal B Condensed Matter Physics, vol. 85, p. 412, 2012.

Détails - *Full Text* - *Version de l'éditeur*

Sylvain Bréchet
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http://moodle.epfl.ch/course

Thermostatics and Thermodynamics

- **Thermostatics**

$$u = T\,s - \,P + \sum_A \Big(\mu_A + q_A\,V - \,\mathbf{m}_A\cdot\mathbf{B}\Big)\,n_A$$

- **Reversible thermodynamics**

$$\mathbf{j}_u = T\,\mathbf{j}_s + \sum_A \Big(\mu_A + q_A\,V - \,\mathbf{m}_A\cdot\mathbf{B}\Big)\,\mathbf{j}_A$$

- **Irreversible thermodynamics**

$$\rho_s = \frac{1}{T}\Bigg\{\sum_a \omega_a\,\mathcal{A}_a + \sum_A \boldsymbol{\Omega}_A\cdot\Big(\mathbf{m}_A\times\mathbf{B}\Big) + \mathbf{j}_s\cdot(-\,\boldsymbol{\nabla}\,T)$$
$$+\sum_A \mathbf{j}_A\cdot\Big(-\,\boldsymbol{\nabla}\mu_A - \,q_A\,\boldsymbol{\nabla}\,V - \,m_A\,\mathbf{v}_A\,\boldsymbol{\nabla}\,\mathbf{v} + \mathbf{m}_A\,\boldsymbol{\nabla}\,\mathbf{B}\Big)\Bigg\}$$

Relationships between currents and generalized forces

- Lehman effect
- Debye relaxation of electric dipoles
- Landau-Lifshitz with damping
- Coupling current of magnetic dipoles and magnetization
- Coupling heat current of metals and magnetization

Irreversible thermodynamics of electron continua

Linear relation : (Eur. Phys. J. B 86, 318 (2013))

- $\mathbf{j}_e = \mathsf{L}_{es} \cdot (-\nabla T) + \mathsf{L}_{ee} \cdot (-\nabla \mu - e \nabla V + \mathbf{m} \nabla \mathbf{B})$

Material : YIG (insulator)

- $\mathbf{j}_e = \mathbf{0}$ (no electronic transport)
- $\nabla V = \mathbf{0}$ (no charge accumulation)
- $\nabla \mu = \mathbf{0}$ (uniform spatial distribution)

Stationary state :

- $\mathbf{M} \nabla \mathbf{B} = \lambda\, n\, k_B \nabla T$ *where* $\mathbf{M} = n\, \mathbf{m}$ *and* $\lambda > 0$

Magnetic Seebeck Effect

Bulk identity :

- $\mathbf{M}\,\nabla\,\mathbf{B} = \mathbf{j_M} \times \mathbf{B}$ where $\mathbf{j_M} = \boldsymbol{\nabla} \times \mathbf{M}$

Magnetic Seebeck effect

- $\mathbf{B} = \varepsilon_{\mathbf{M}} \times \boldsymbol{\nabla}\, T$ where $\varepsilon_{\mathbf{M}} = -\,\lambda\, n\, k_B \left(\boldsymbol{\nabla} \times \mathbf{M}\right)^{-1}$

Linear response (to RF excitation field)

Linearisation :

- $\mathbf{B}_{\text{ext}} = \mathbf{B}_0 + \mathbf{b}$
- $\mathbf{M} = \mathbf{M}_S + \mathbf{m}$ where $\mathbf{m} \ll \mathbf{M}_S$

Eigenmodes :

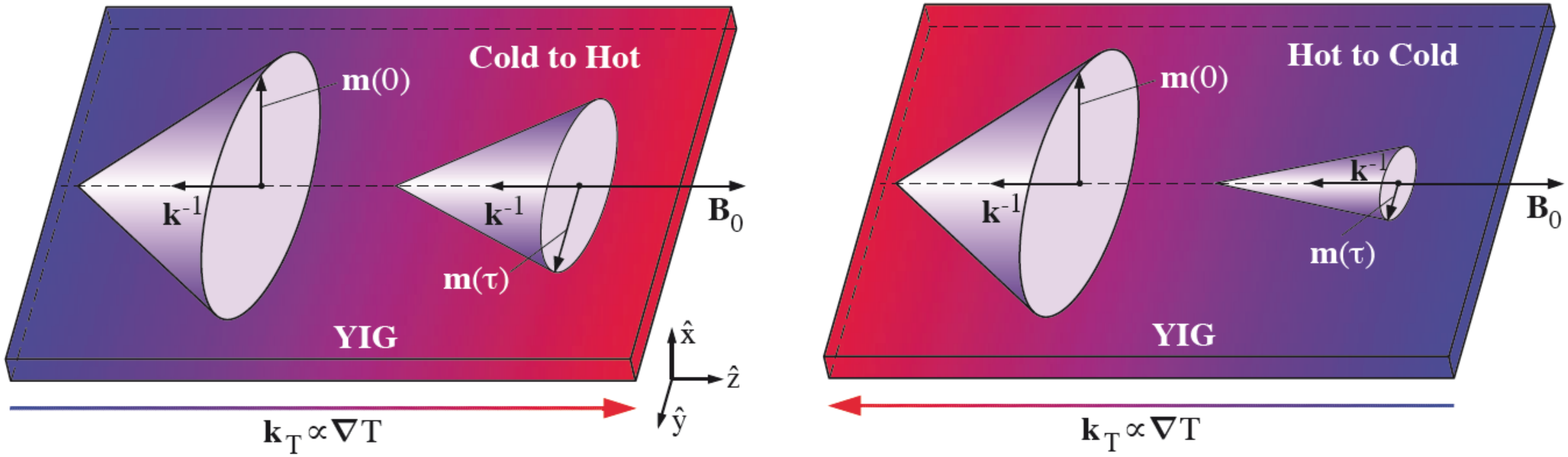
- $\mathbf{m}_{\mathbf{k}\,x,y} = \chi_{\mathbf{k}\,x,y}\,\mathbf{b}_{\mathbf{k}}$
- $$\chi_{\mathbf{k}\,x,y} = -\frac{1}{\Omega - \sqrt{\Omega_0\left(\Omega_0 + 1\right)} + i\,r_{x,y}\left(\alpha\,\Omega + \mathbf{k}_T \cdot \mathbf{k}^{-1}\right)}$$

$$\Omega = \frac{\omega}{\gamma\,\mu_0\,M_S}\,, \qquad \Omega_0 = \frac{\gamma\,B_0}{\gamma\,\mu_0\,M_S}\,, \qquad \mathbf{k}_T = \frac{\lambda\,n\,k_B}{\mu_0\,M_S^2}\,\boldsymbol{\nabla}\,T$$

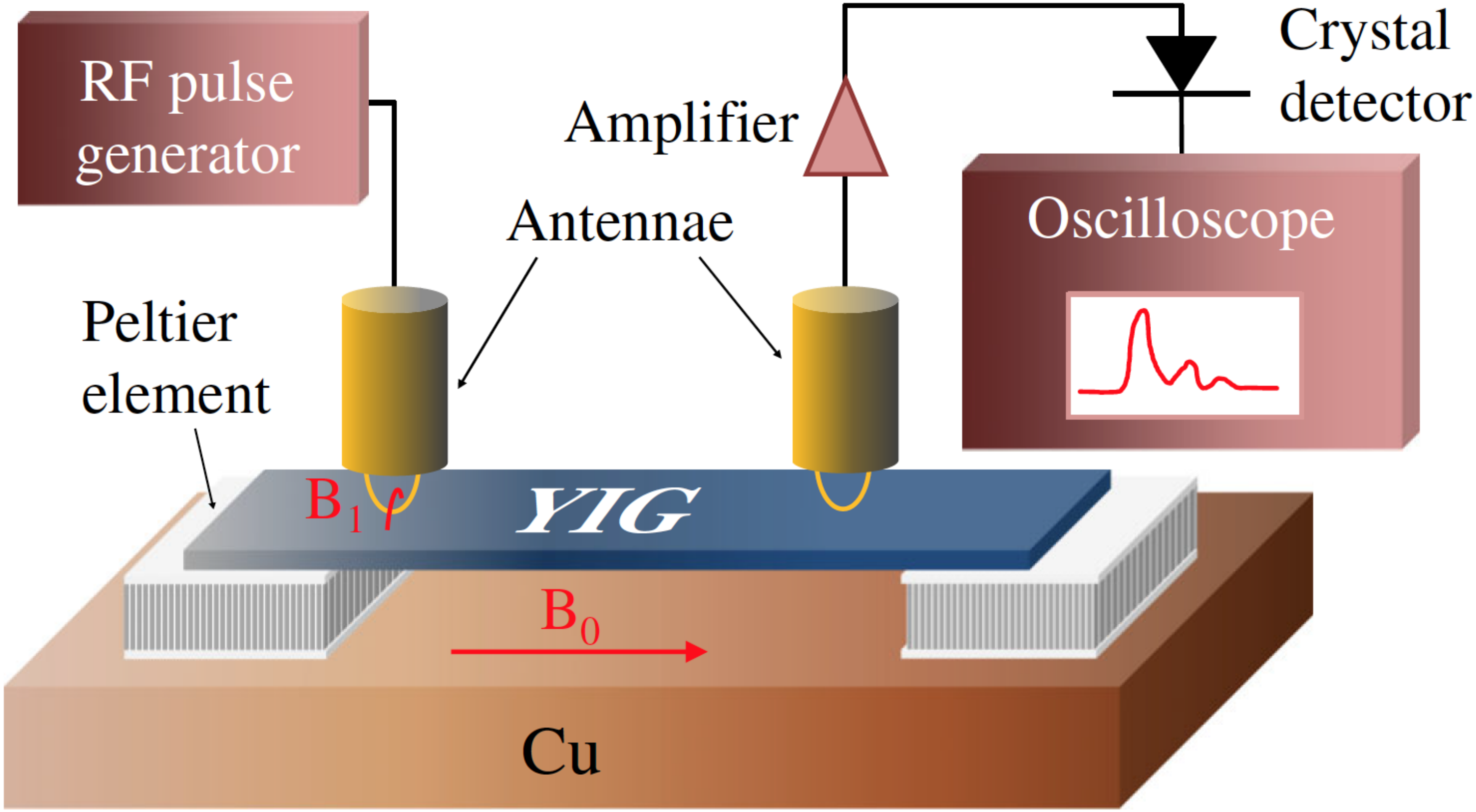
Theoretical prediction

Magnetisation waves propagation (YIG) :

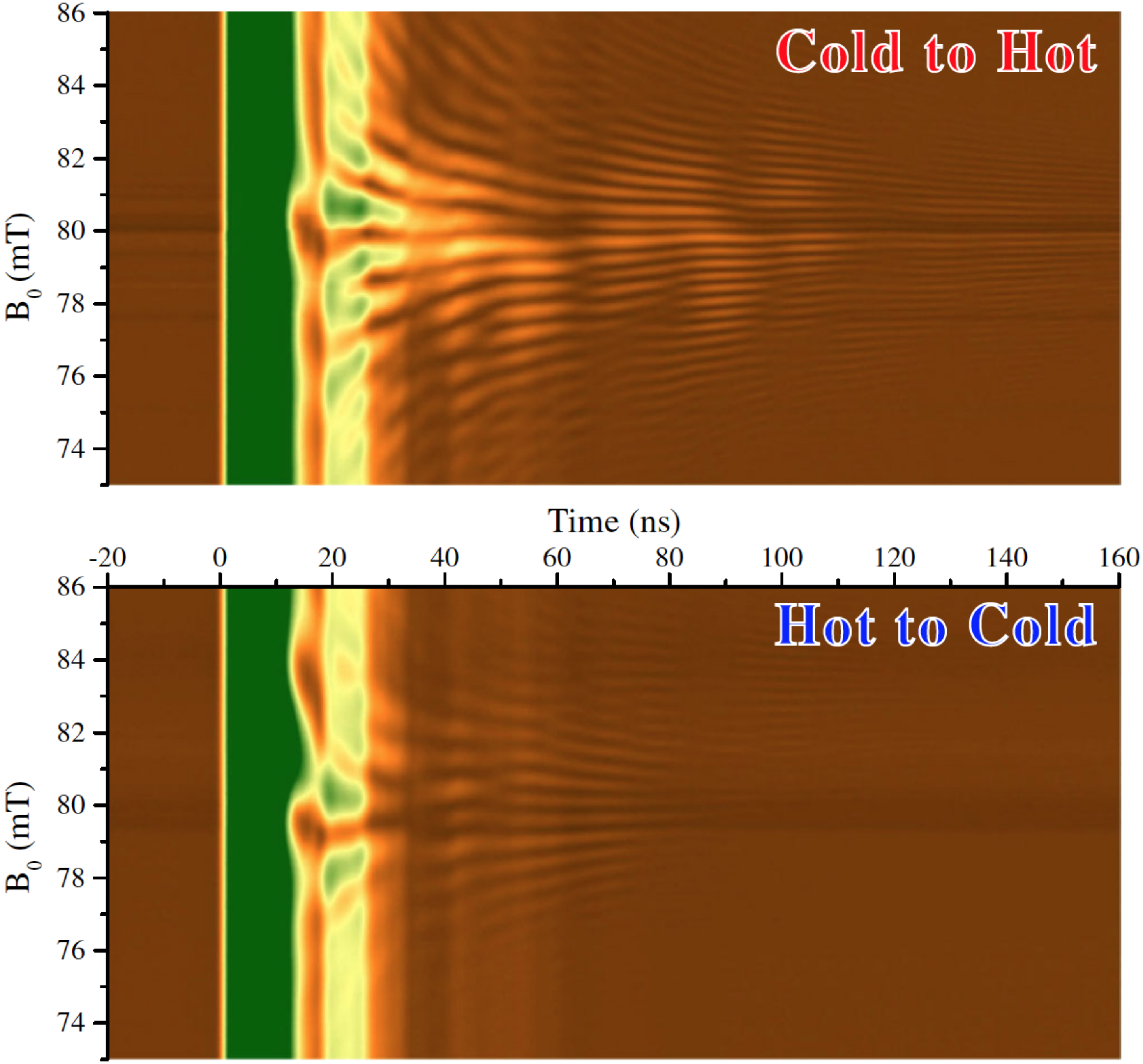
- Magnetostatic backward volume modes
- **Cold to Hot** : negative thermal damping ($\mathbf{k}_T \cdot \mathbf{k}^{-1} < 0$)
- **Hot to Cold** : positive thermal damping ($\mathbf{k}_T \cdot \mathbf{k}^{-1} > 0$)

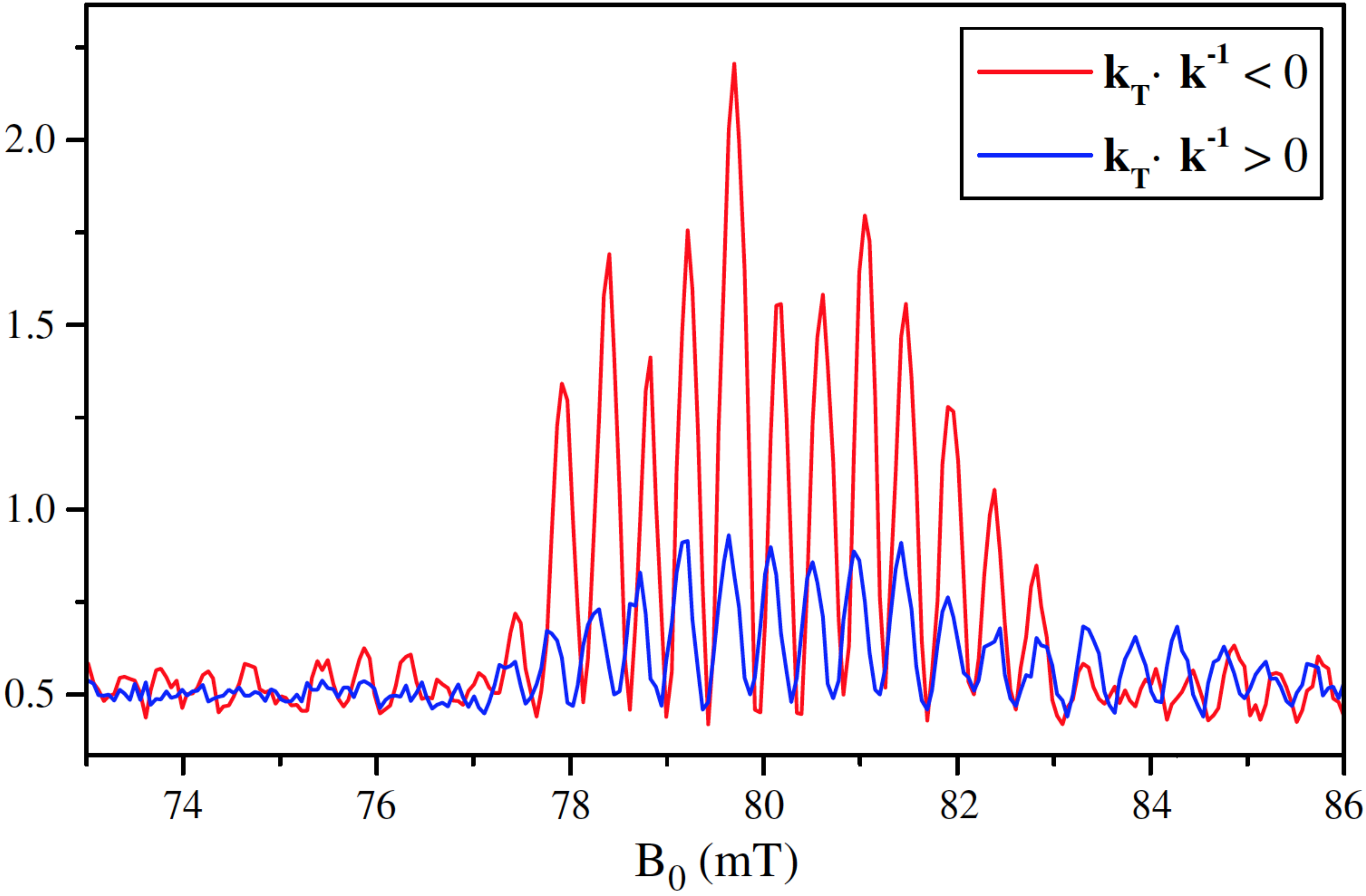


Time resolved FMR with temperature gradient



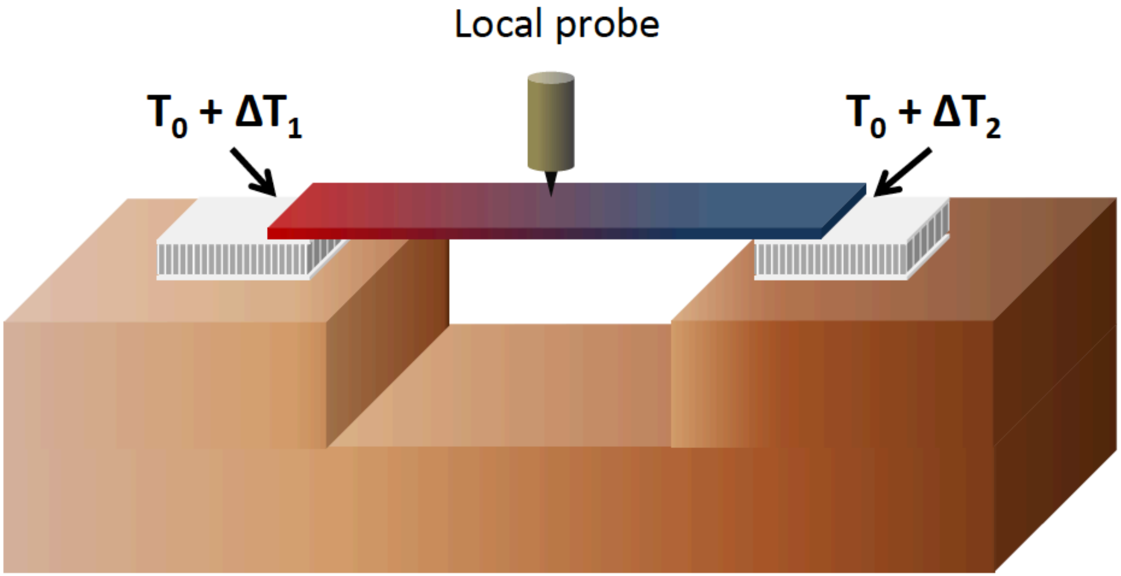
- YIG : 50 micron thick, on sapphire substrate, 7 mm long
- two Peltier elements, on heat-sinking block


Cold to Hot
Hot to Cold
B_0 (mT)
86
84
82
80
78
76
74
Time (ns)
-20
0
20
40
60
80
100
120
140
160



Signal detected 70 ns after a 15 ns pulse at 4 GHz.

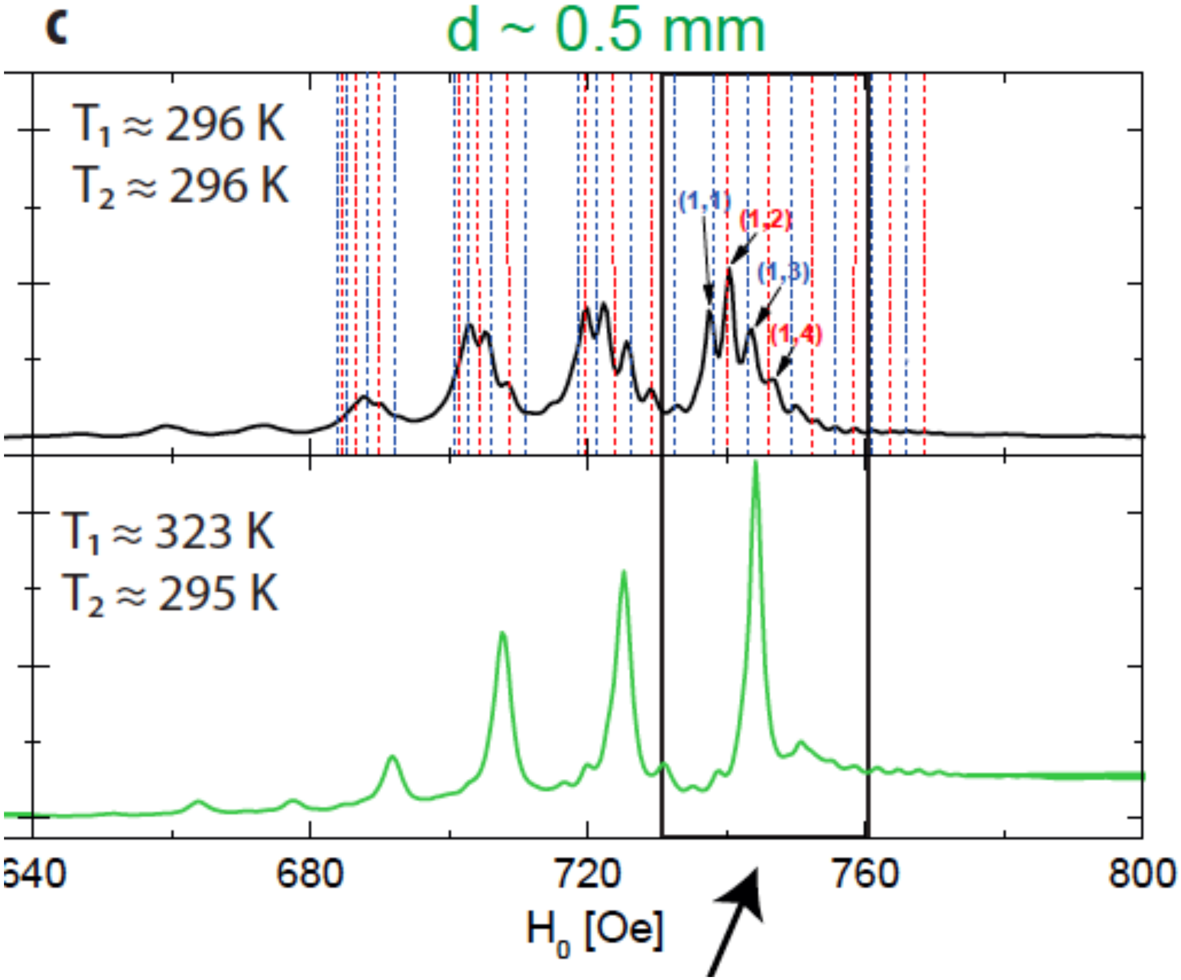
CW studies



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

Elisa Papa

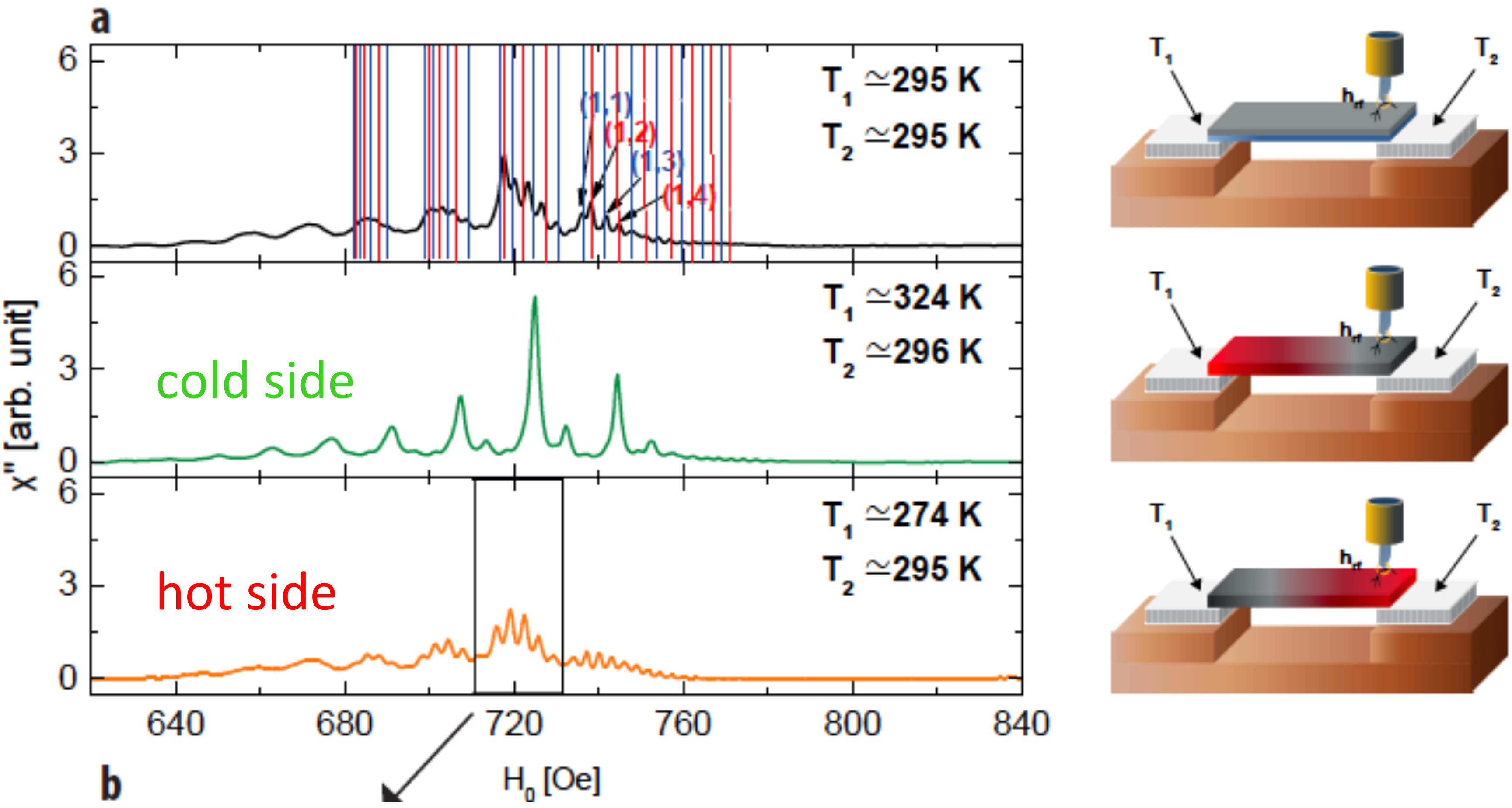
CW - FMR



isothermal

cold side, same temperature

No effect on the hotter side



Heat-driven spin currents in metallic
spin valves

Three-current model

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

$$\sigma_\pm = \frac{\sigma}{2}(1 \pm \beta) \qquad \varepsilon_\pm = \varepsilon(1 \pm \eta)$$

Bulk spin current in metal at zero charge current : $\boxed{j_p = -\sigma(\eta - \beta)\varepsilon\nabla T}$

L. Gravier et al, PRB 2006

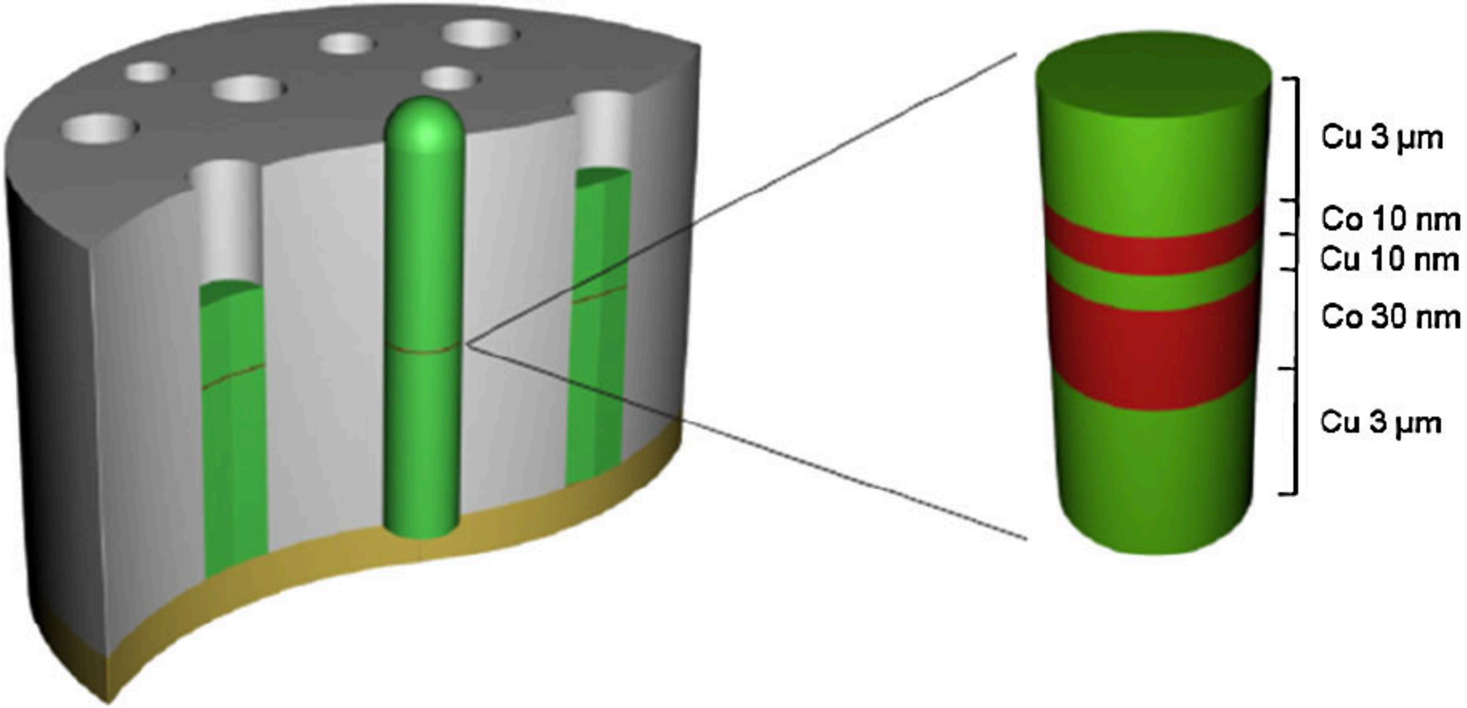
S. Brechet, J.-Ph. A., phys. Stat. Solidi 2010

Also Sachter et al., Nat. Phys. 2010

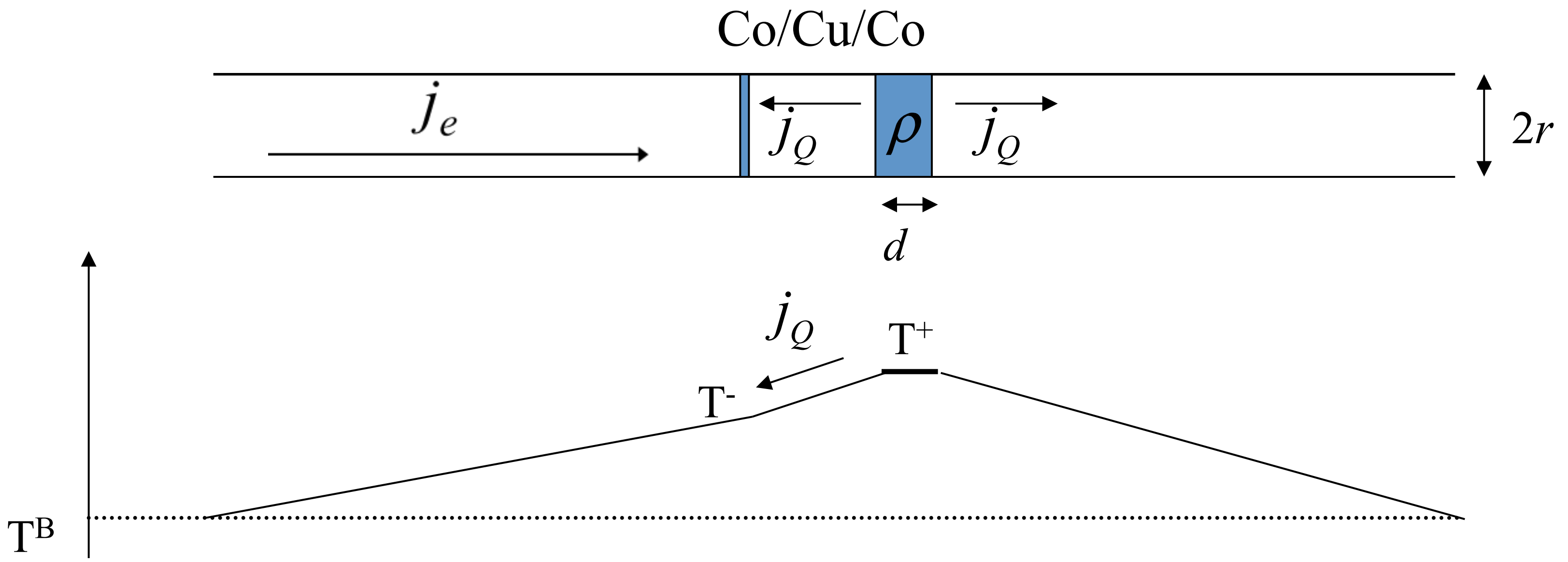
PRL **104,** 146601 (2010) PHYSICAL REVIEW LETTERS week ending
9 APRIL 2010

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*



Joule heating spin valves in a nanowire

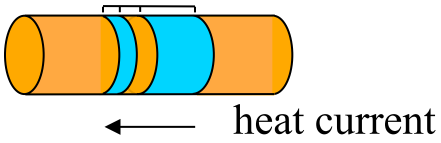


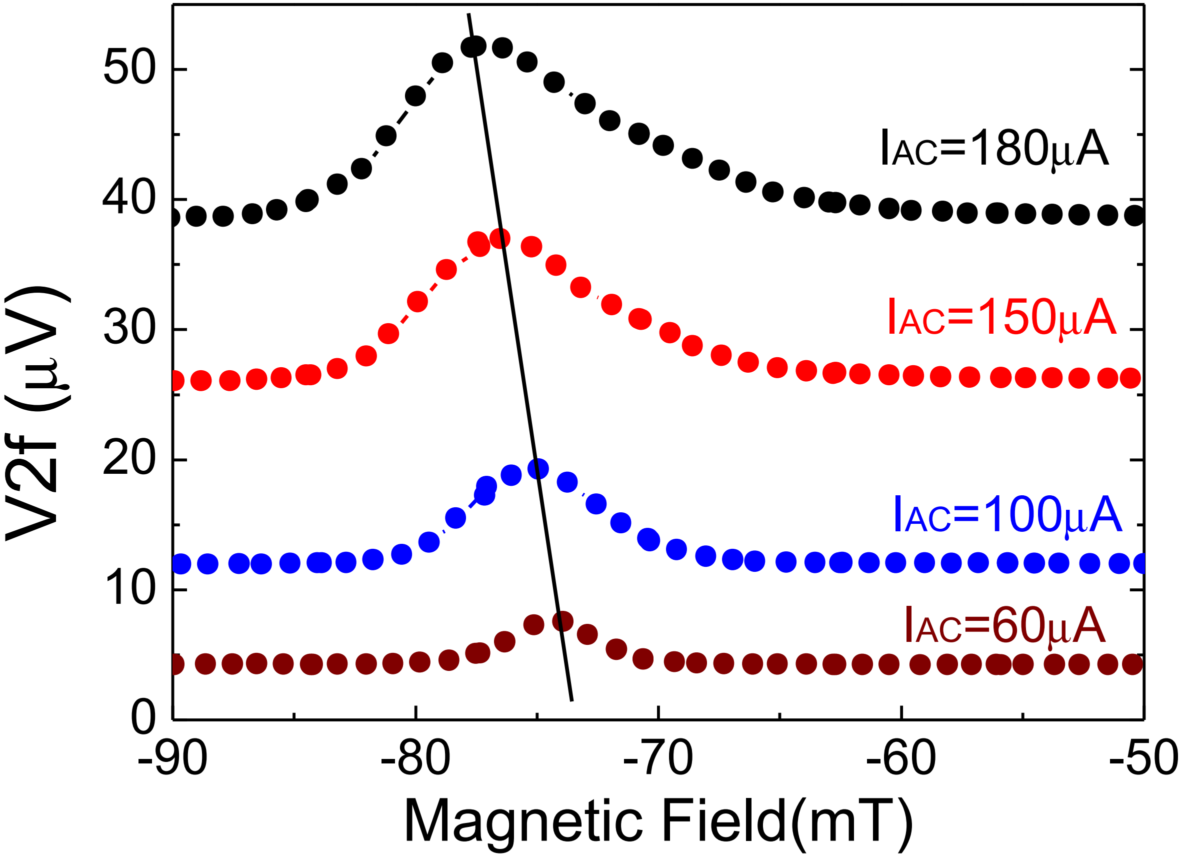
$$\boxed{\nabla T \approx 10'000 K / cm} \qquad \Delta T < 1\,\mathrm{K}$$

$$\frac{1}{2}\rho\frac{d}{\pi r^2}I^2 = j_Q \pi r^2 \quad \Longrightarrow \quad \boxed{j_Q \propto \frac{1}{r^4}}$$

Nanowires **ideal** for large j_Q

Heat current (not temperature) changes the switching field





NB : reversible, no minor loop in field

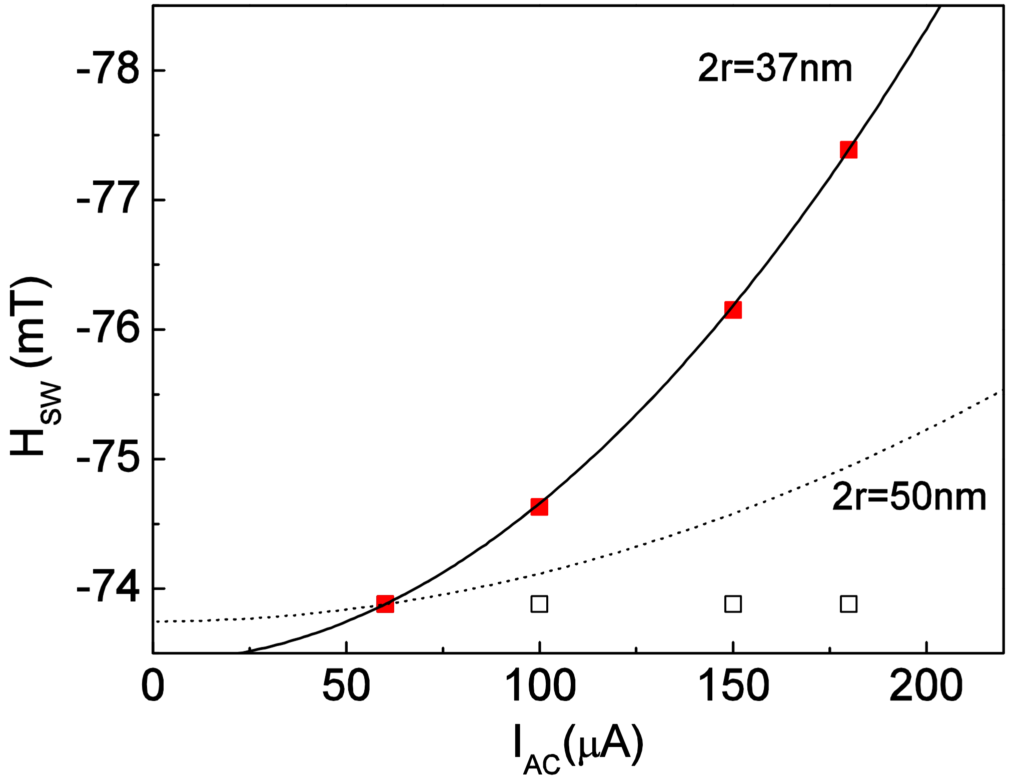
Idc = 0.1 mA

Heat-current and charge-current driven spin torques compared :

$$j_p = c\left(\nabla V - S_{eff}\nabla T\right)$$

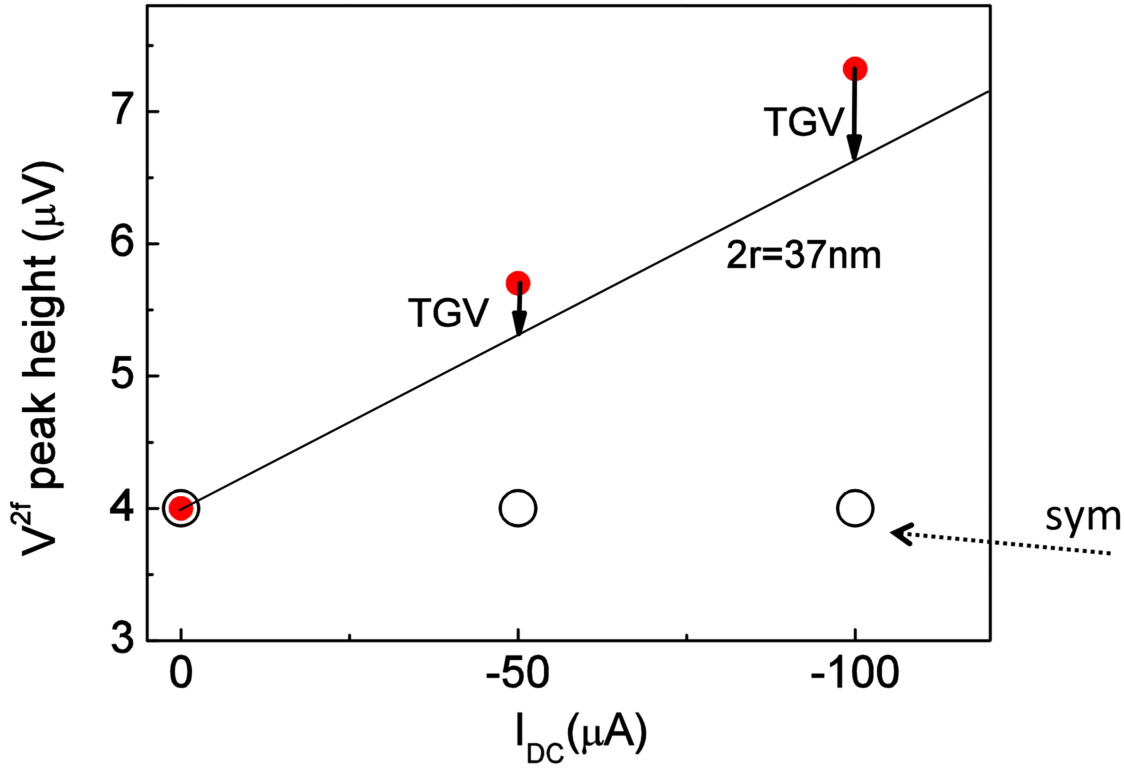
$$\frac{\Delta H_{sw}^{TST}}{\Delta H_{sw}^{STT}} = \frac{\tau_{TST}}{\tau_{STT}} = \frac{j_{p,TST}}{j_{p,STT}} = \frac{S_{eff}\nabla T}{\nabla V}$$

From 3-current model,
values measured independently



STT effect of Idc :
H. Yu, J. Dubois, …, J.-Ph. A.,
J. Phys. D 42, 175004 (2009).

Independent check : peak height vs. I_{dc}



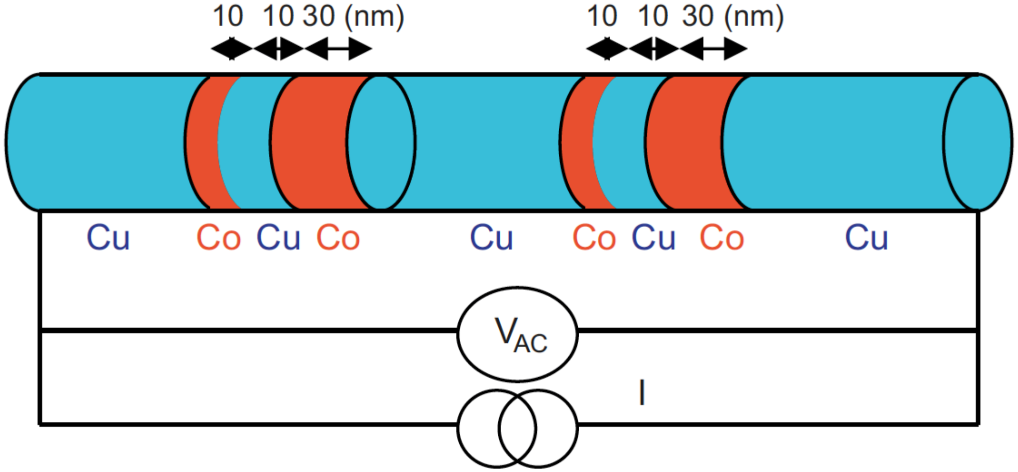
symmetric spin valve

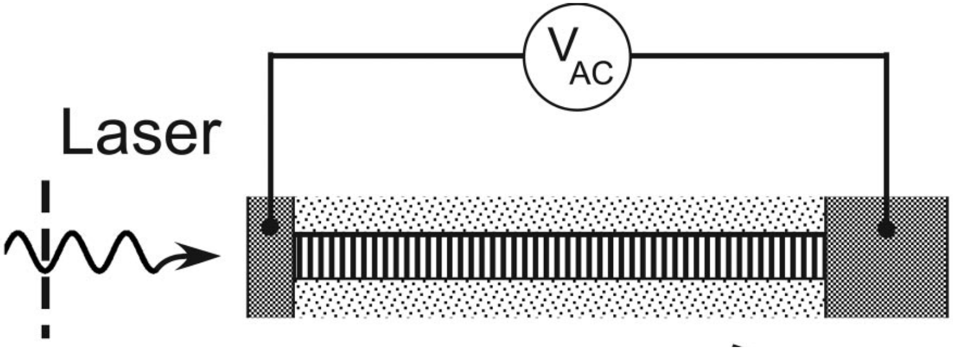
$$V^{2f}{}_{peak} = \left(\frac{\partial R}{\partial \tau} \frac{\partial \tau}{\partial j_m} 2c \left(\rho \frac{I_{AC}{}^{2}}{\pi r^2} + 3S_{eff} A_1 I_{DC} I^2_{AC} \right) \right) + \frac{\partial R}{\partial T} \Delta T^{2f} I_{DC}$$

Heat-driven spin current in metallic spin valves : Linear response

Co/Cu spin valves
stacked
in a nanowire

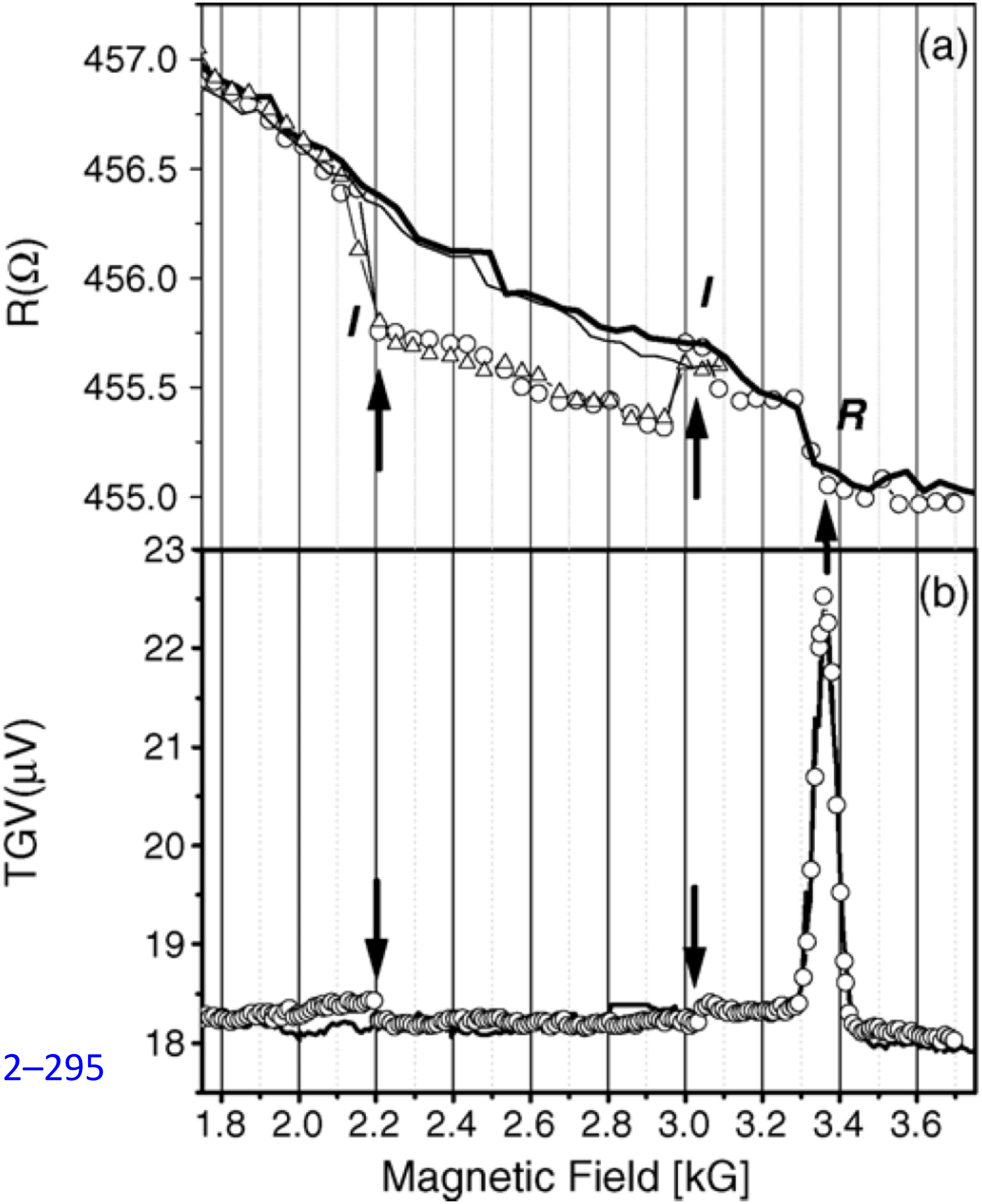
Gravier 2004





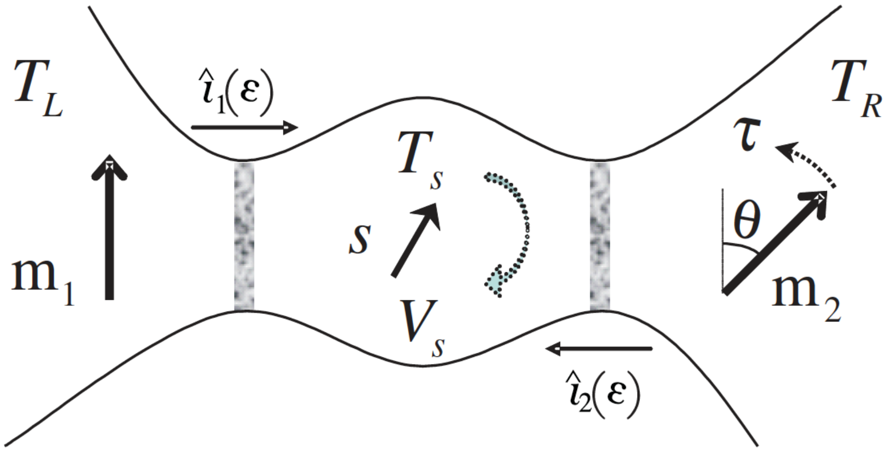
Temperature gradient about 10^4 K/cm

Co/Cu spin valves
stacked
in a nanowire



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

Other *experiments* on magnetization dynamics under heat current



M. Hatami, G.E.W. Bauer, Q. Zhang, P.J. Kelly,
Phys. Rev. Lett. 99, 066603 (2007)

nature physics

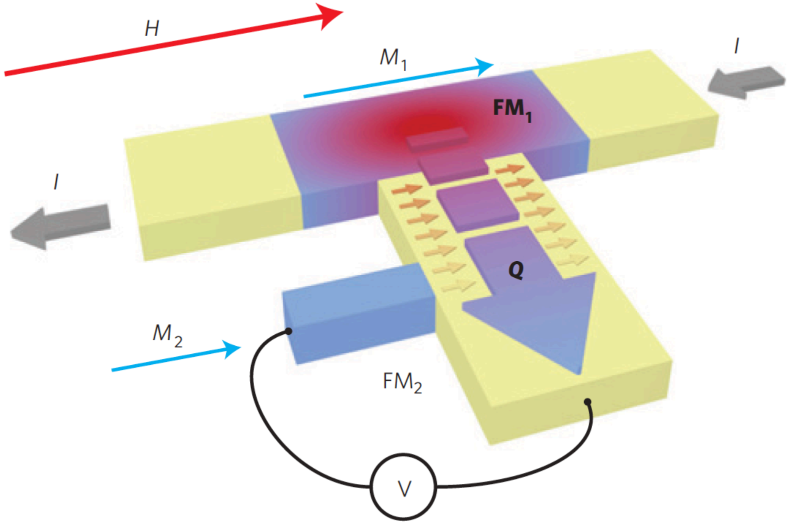
LETTERS

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

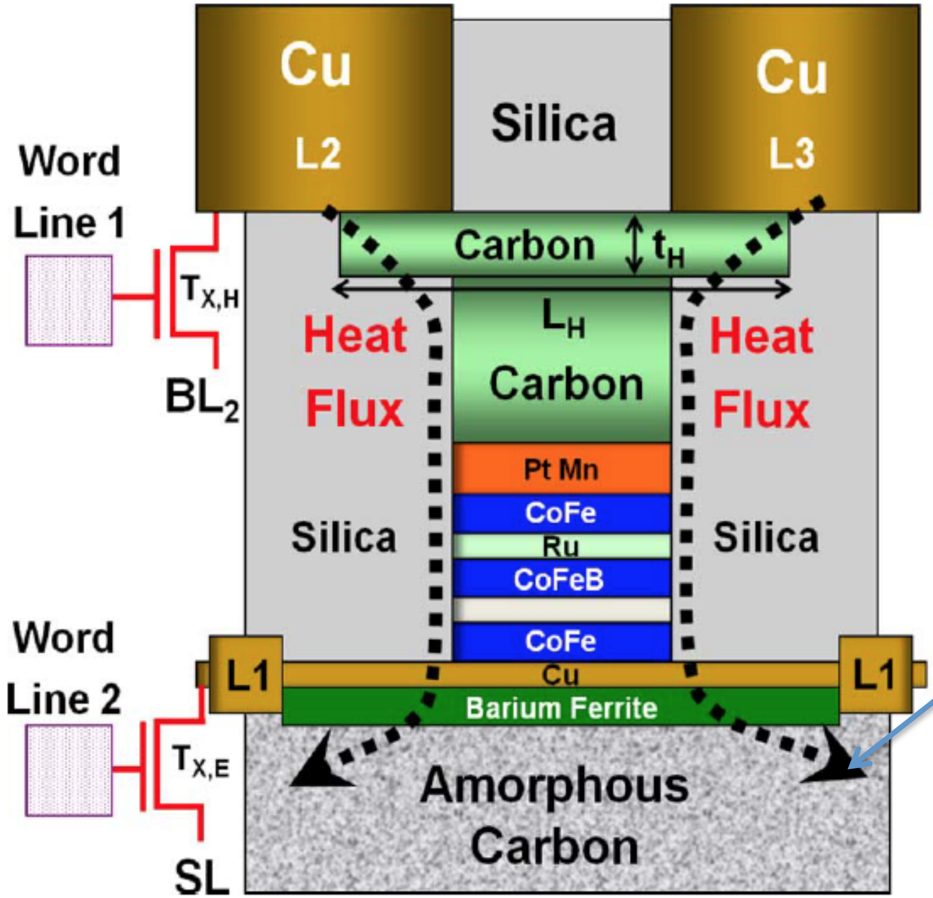
$$\begin{pmatrix} \mathbf{J}_\uparrow \\ \mathbf{J}_\downarrow \\ \mathbf{Q} \end{pmatrix} = -\begin{pmatrix} \sigma_\uparrow & 0 & \sigma_\uparrow S_\uparrow \\ 0 & \sigma_\downarrow & \sigma_\downarrow S_\downarrow \\ \sigma_\uparrow \Pi_\uparrow & \sigma_\downarrow \Pi_\downarrow & k \end{pmatrix}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



2016 IEEE TRANSACTIONS ON MAGNETICS, VOL. 48, NO. 6, JUNE 2012

Magnonic Spin-Transfer Torque MRAM With Low Power, High Speed, and Error-Free Switching

Niladri N. Mojumder[1,2], David W. Abraham[1], Kaushik Roy[2], and D. C. Worledge[1]



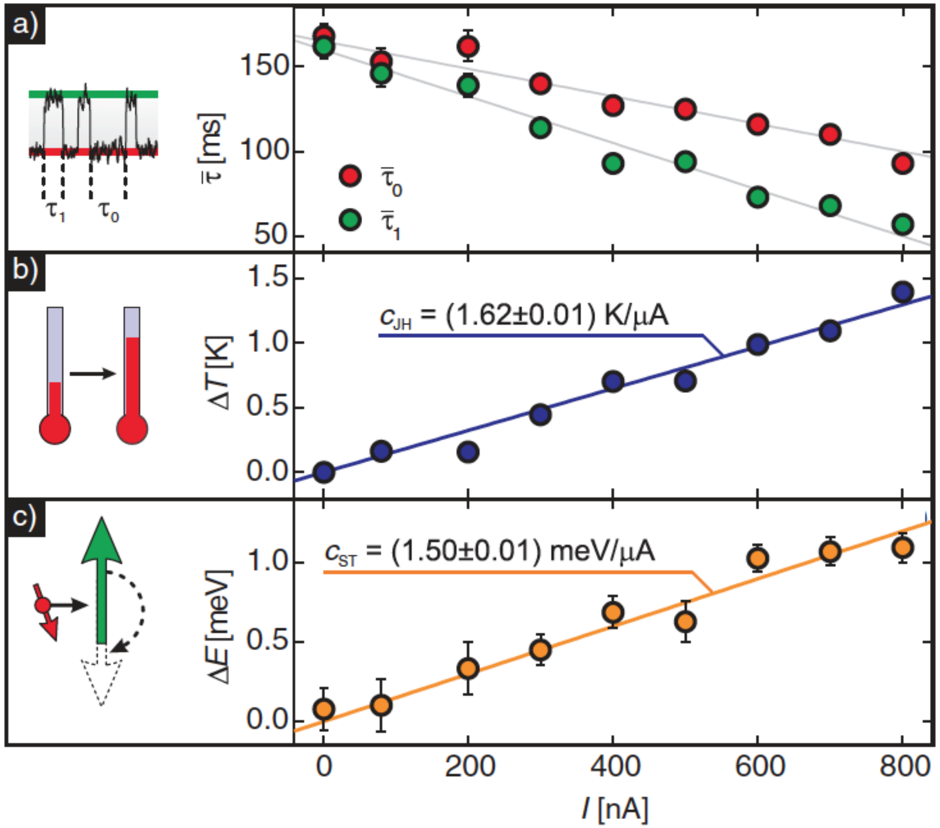
Insulating ferrite

See :
J.C. Slonczewski
PRB 82, 054403 (2010)

PRL **107,** 186601 (2011) PHYSICAL REVIEW LETTERS week ending 28 OCTOBER 2011

Joule Heating and Spin-Transfer Torque Investigated on the Atomic Scale Using a Spin-Polarized Scanning Tunneling Microscope

S. Krause,* G. Herzog, A. Schlenhoff, A. Sonntag, and R. Wiesendanger



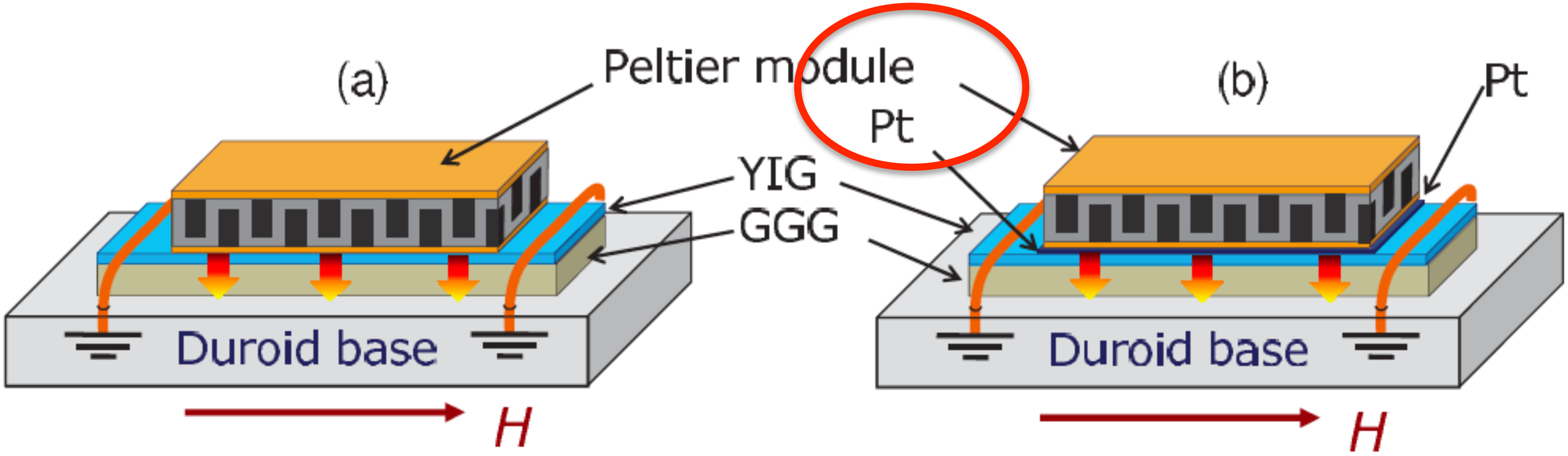
$$\bar{\tau}_{0,1}(I) = \frac{1}{f_0}\exp\left(\frac{E_b \pm \Delta E(I)}{k_B[T + \Delta T(I)]}\right)$$

2 data series

PHYSICAL REVIEW B **87**, 184401 (2013)

Controlling the relaxation of propagating spin waves in yttrium iron garnet/Pt bilayers with thermal gradients

R. O. Cunha, E. Padrón-Hernández, A. Azevedo, and S. M. Rezende*



H and grad T are perpendicular :

- no Pt : no effect (ok with our experiment)
- with Pt : damping depends on the sign of the gradient

Magnetization dynamics under heat current

- Thermodynamics with P and M as state fields

- **Magnetic Seebeck effect** :
  out-of-phase B field induced by temperature gradient when **M** ***out of equilibrium***

- Heat-driven spin currents in metals :
  - Switching assisted by heat-driven spin current
  - AC voltage due to AC heat-driven spin torque when DC current is applied