Prokhorov General Physics Institute
of the Russian Academy of Sciences

LMHS LABORATORY OF MAGNETIC HETEROSTRUCTURES AND SPINTRONICS MIPT

Spin pumping and probe in permalloy dots-topological insulator bilayers

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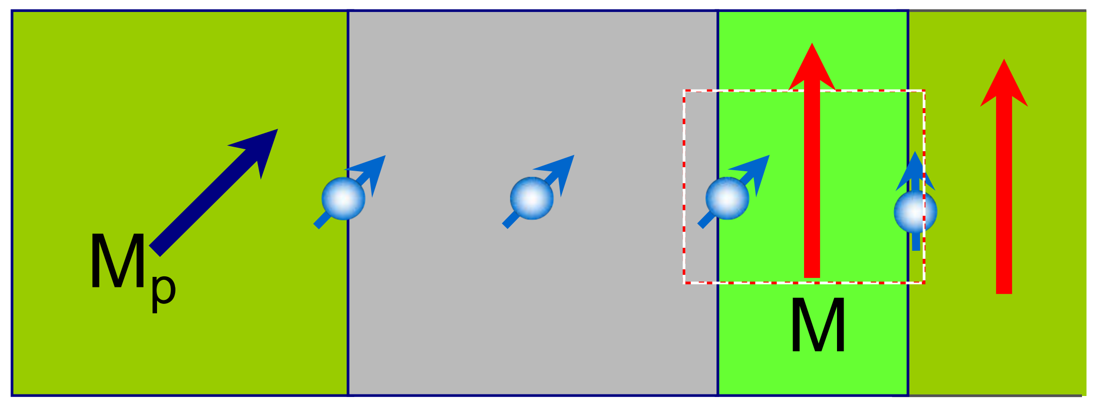
NCKU
National Cheng Kung University

Outline

- Motivation
- FMR Spin-pumping experiment on magnetic dots
- Simulations: homogeneous case
- Simulations: spin-pumping from magnetic vortex
- Conclusions

STT Spintronics

Spin Transfer Torque

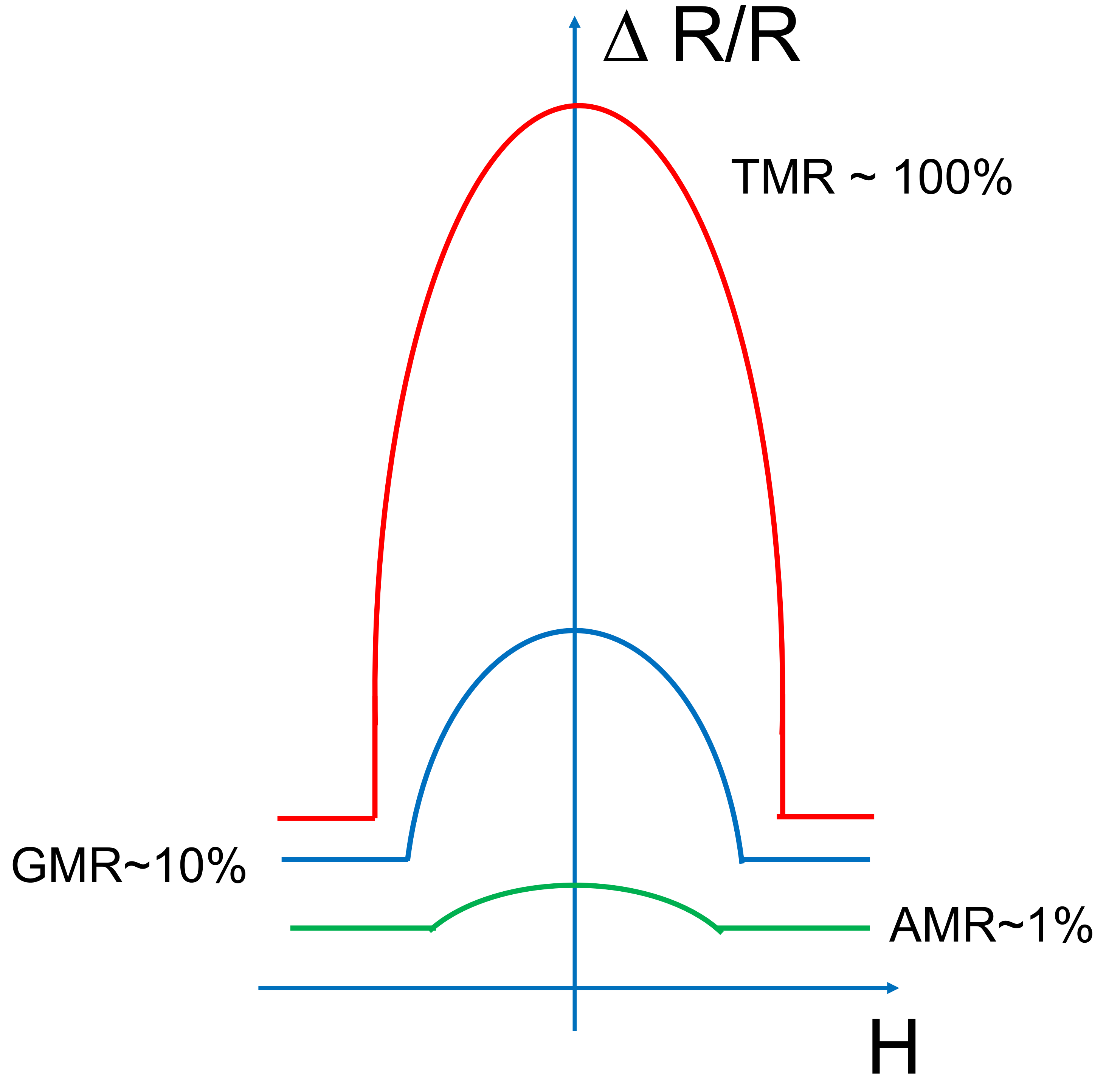


$$\hat{Q} = \sum \vec{S}_k \otimes \vec{V}_k$$

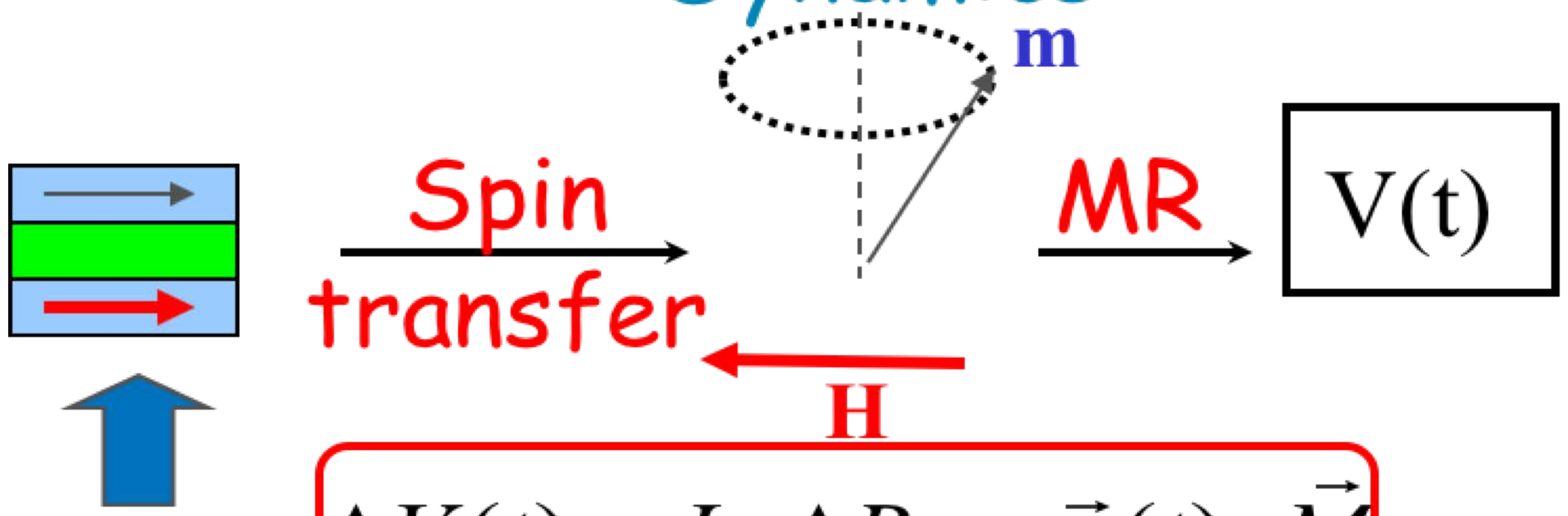
$$\vec{S} = \hbar/_2\,\vec{\sigma}$$

$$\vec{T} = \vec{\nabla}\cdot\hat{Q} = \nabla_k Q_{ik}$$

Magnetoresistance

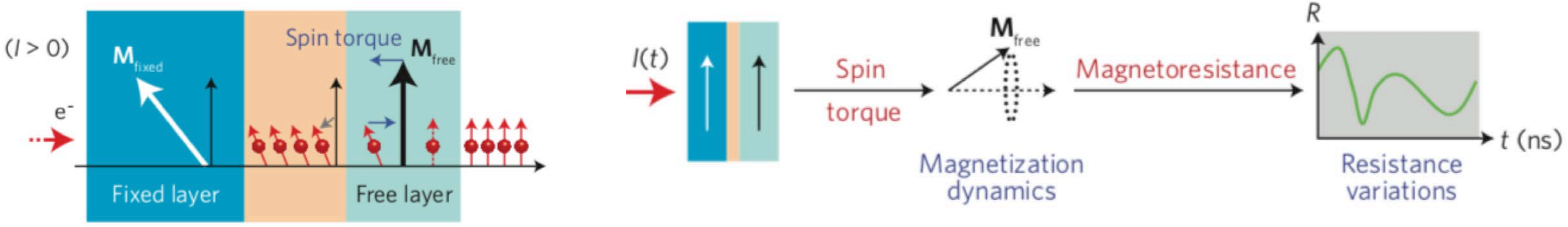


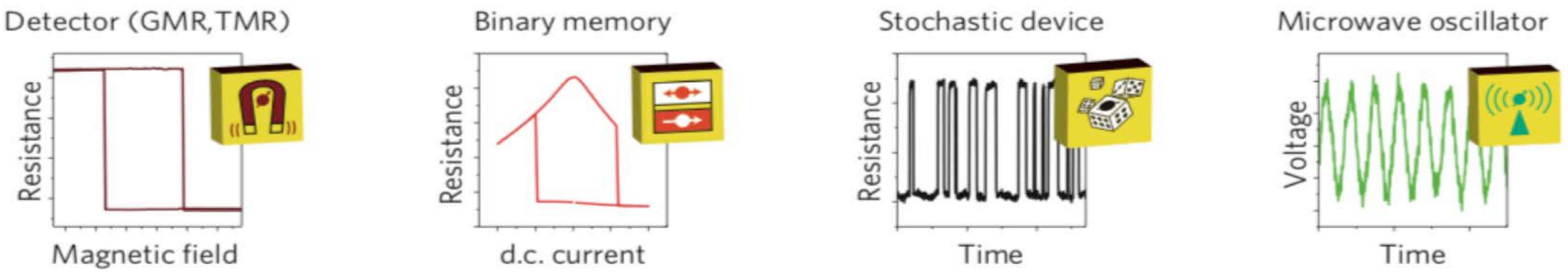
Magnetization Dynamics

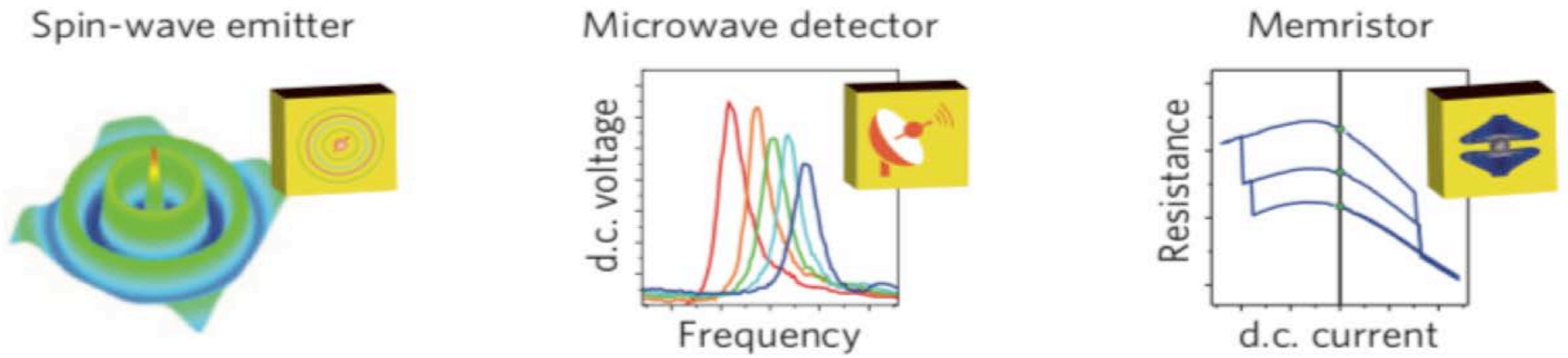


$$\Delta V(t) = I_{dc}\Delta R_{GMR}\vec{m}(t)\cdot\vec{M}$$

STT Spintronics - building blocks



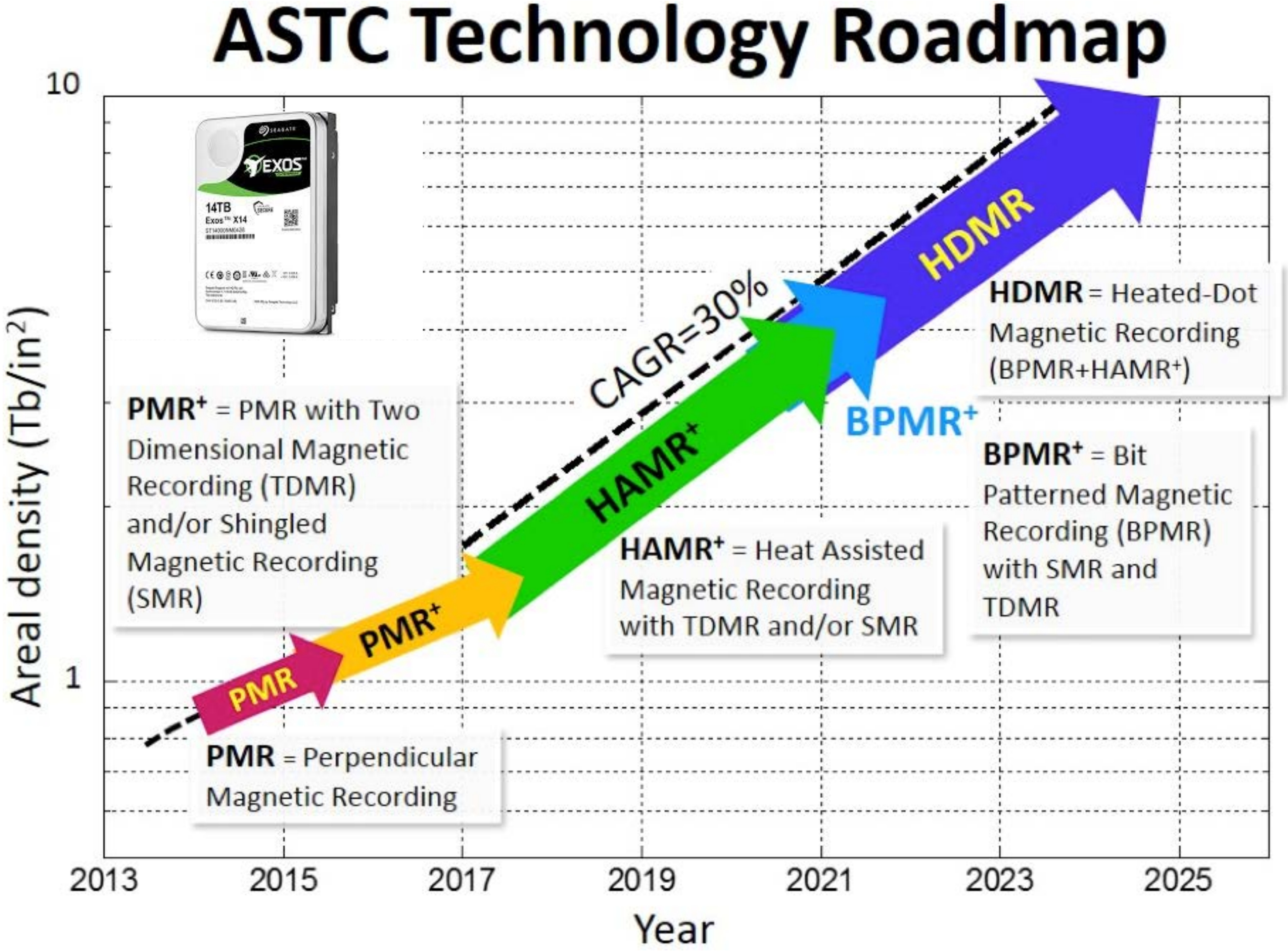




N.Locatelli, V.Cros, J.Grollier,
Nature Mat., 2013

... some numbers from HDD industry

1956: IBM350 first HDD
3.75 MB, 1000 kg
Leased at $3,200 per month

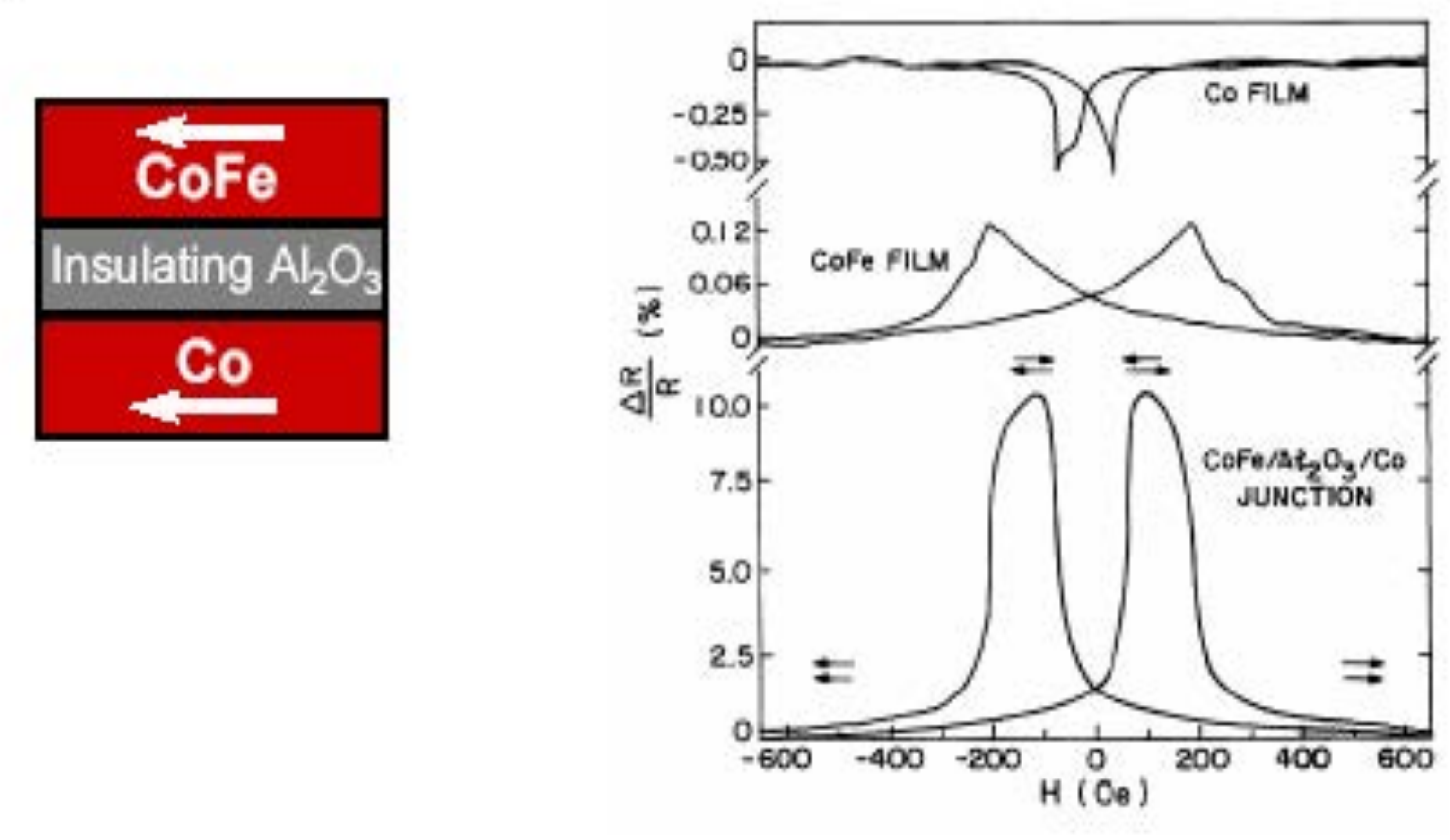


2018: 14 TB Helium-filled PMR HDD

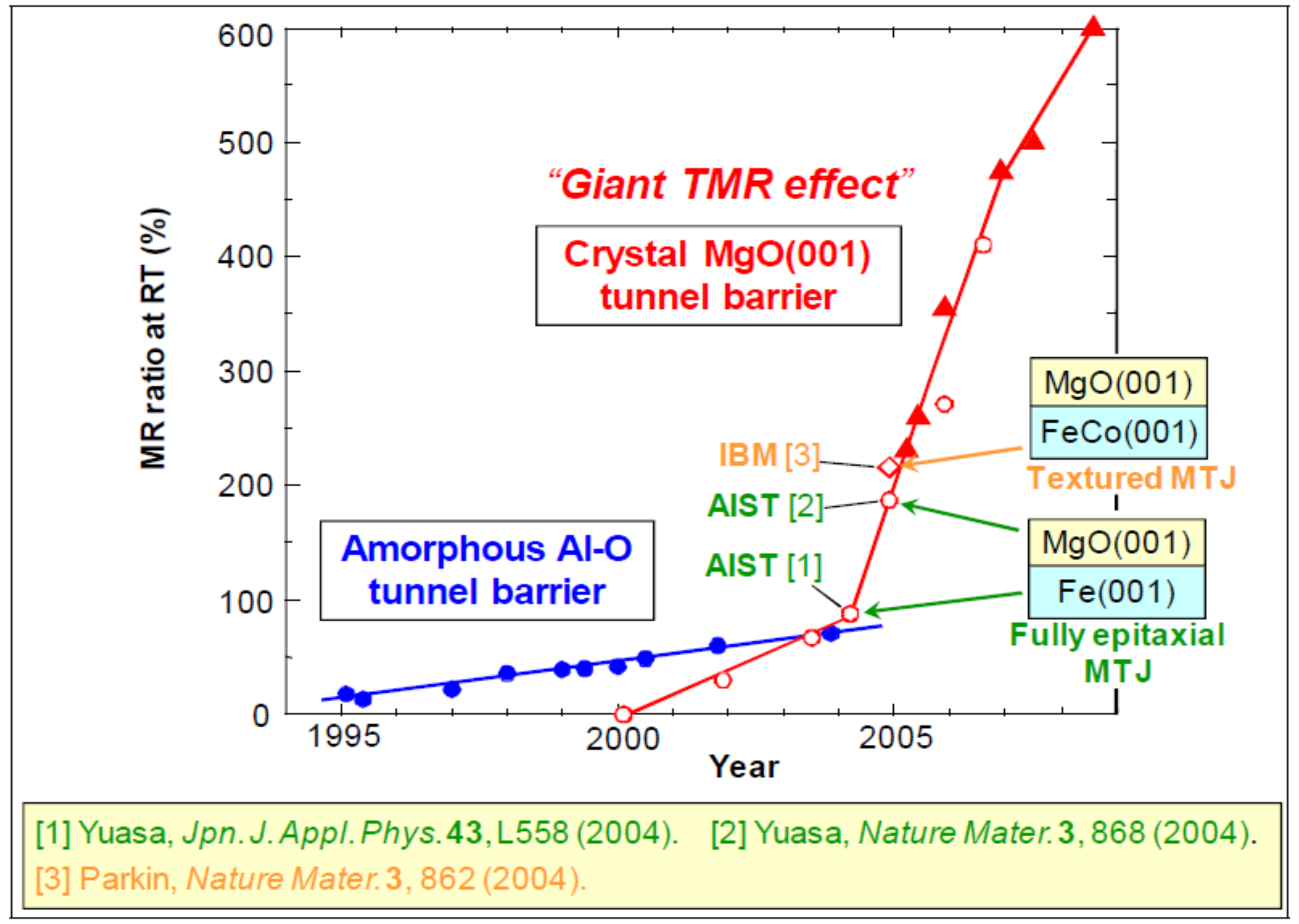
1.000.000.000 increase of areal density!

MTJ Stack

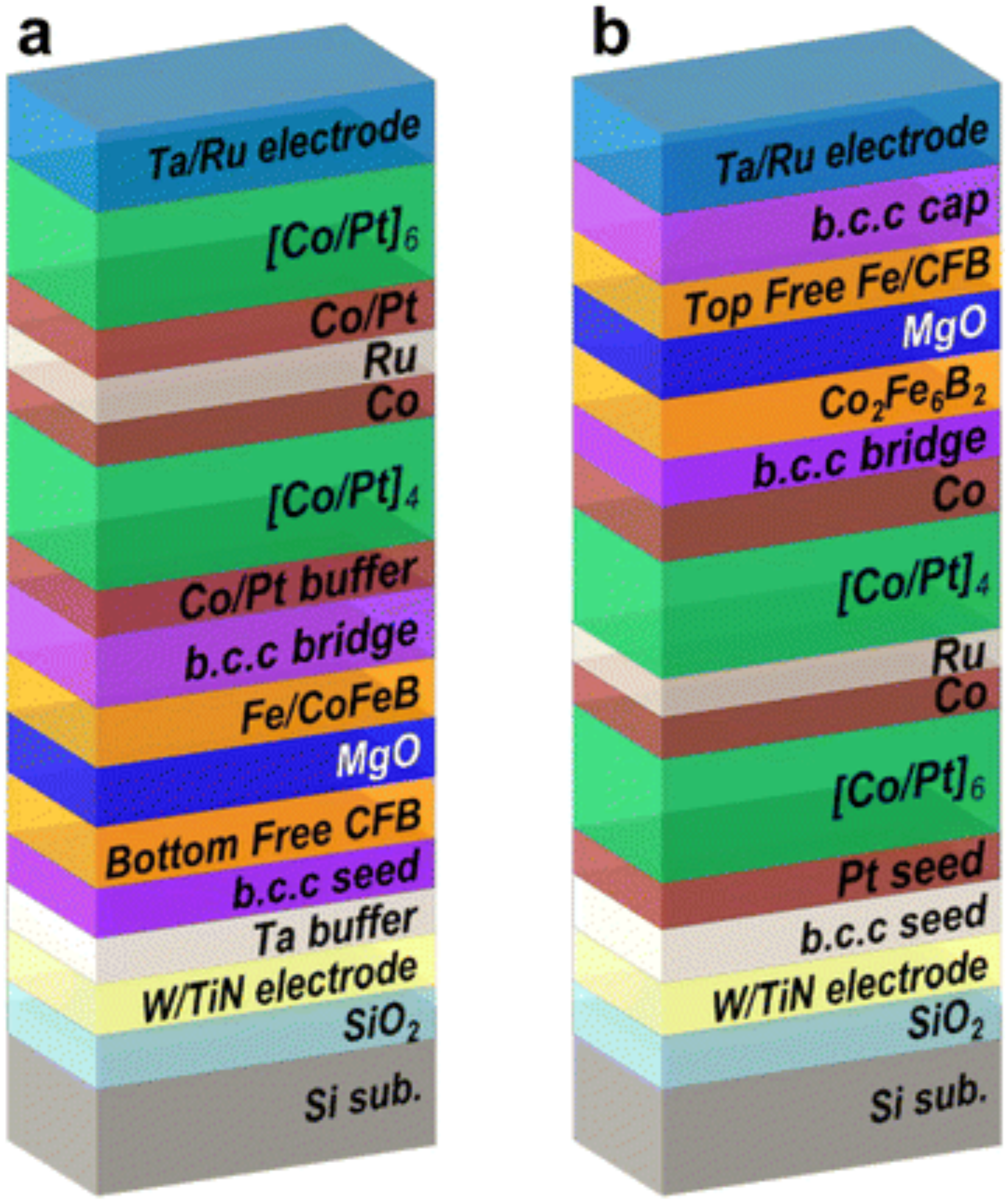
First observation of a TMR at RT



Moodera J S, Kinder L R, Wong T M and Meservey R *PRL* **74** 3273 (1995)

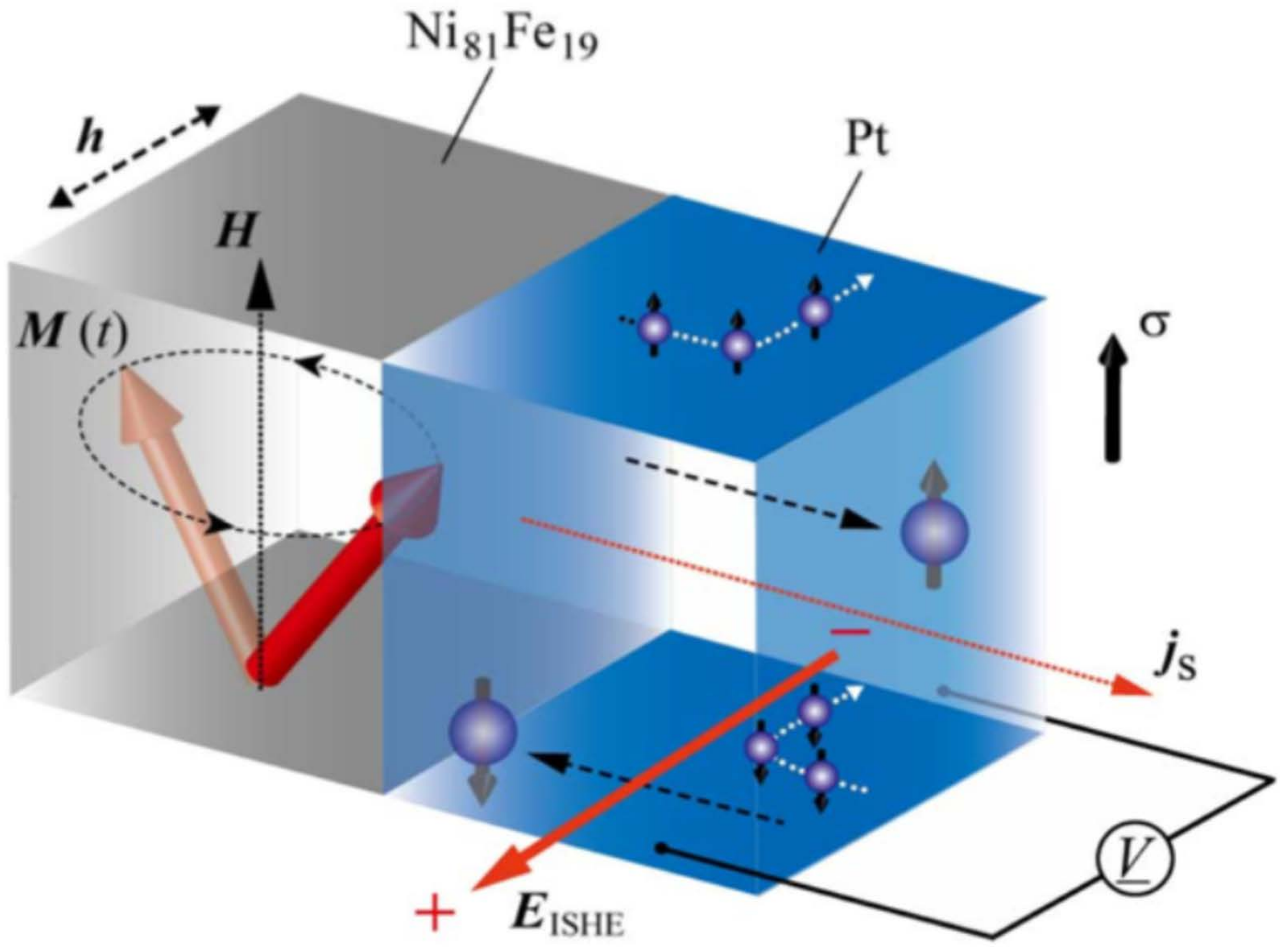


Courtesy S.Yuasa

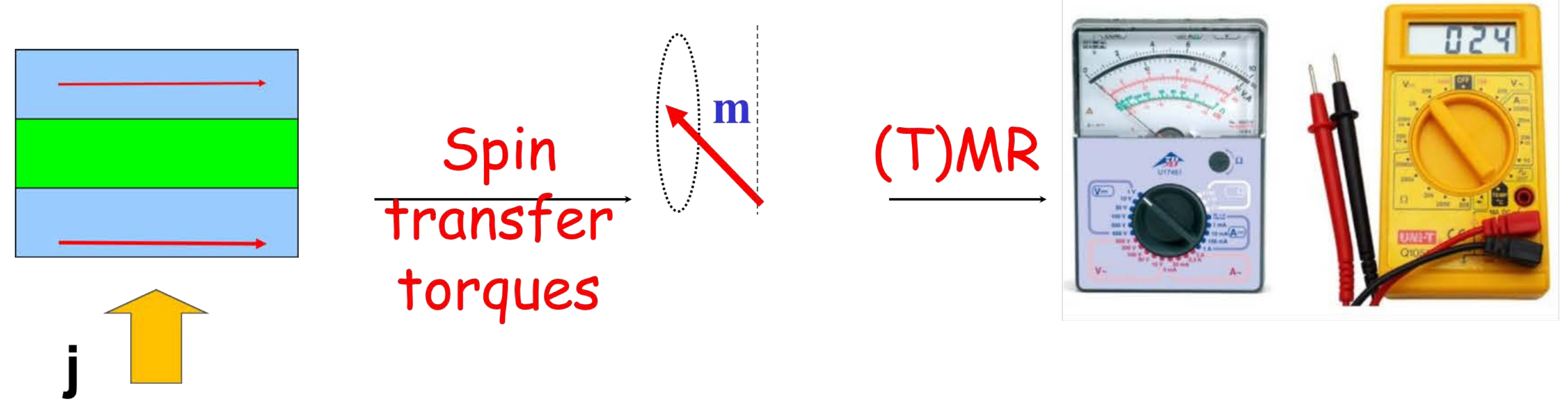


Du-Yeong Lee et al.,
Nanoscale Research Letters (2016)
11:433

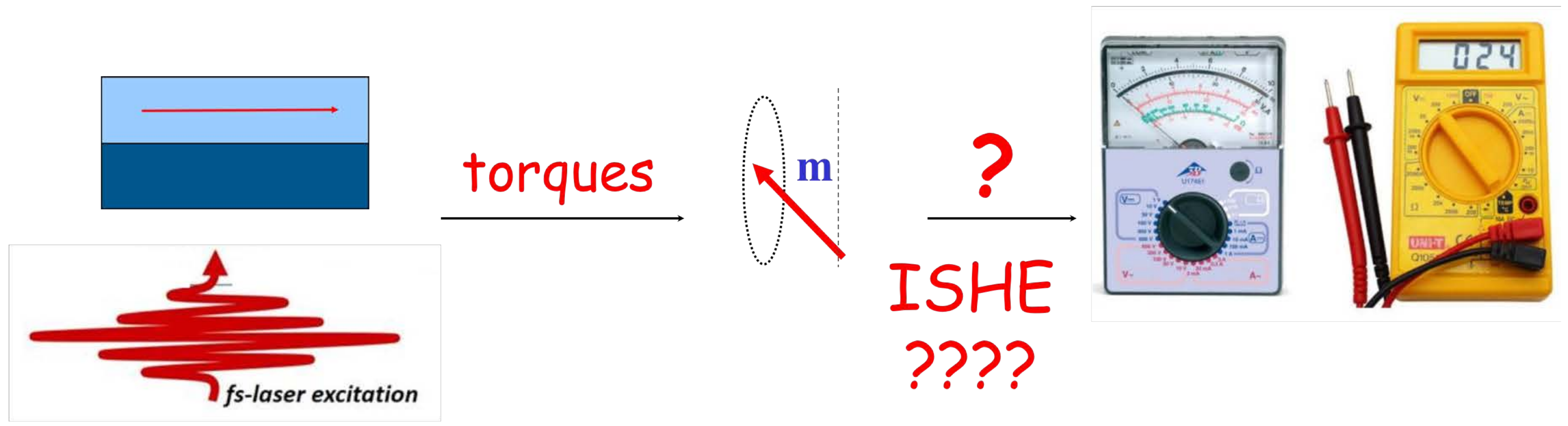
Inverse spin Hall effect as a probe?



STT spintronics



THz spintronics



Q1: SOC Material choice

Q2: Nanostructuring

Q1. SOC Materials: TI sensing layer

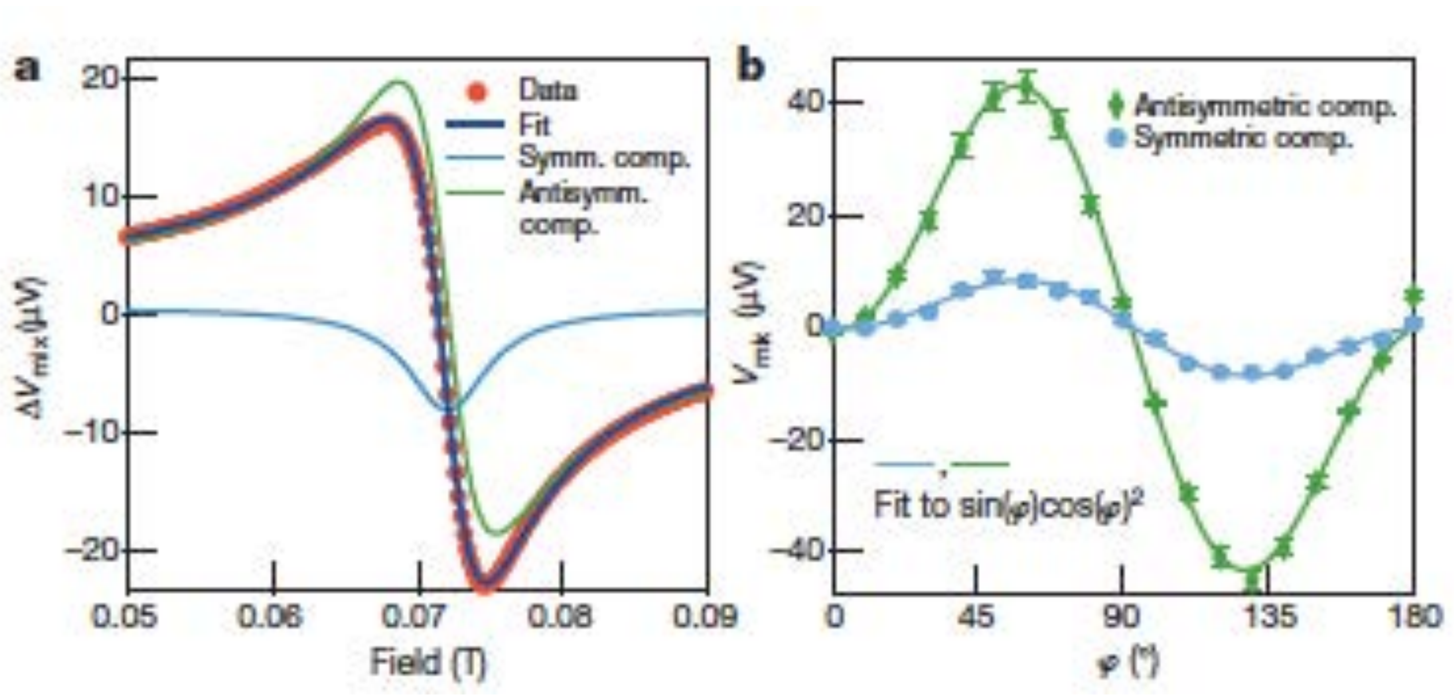
nature
International weekly journal of science

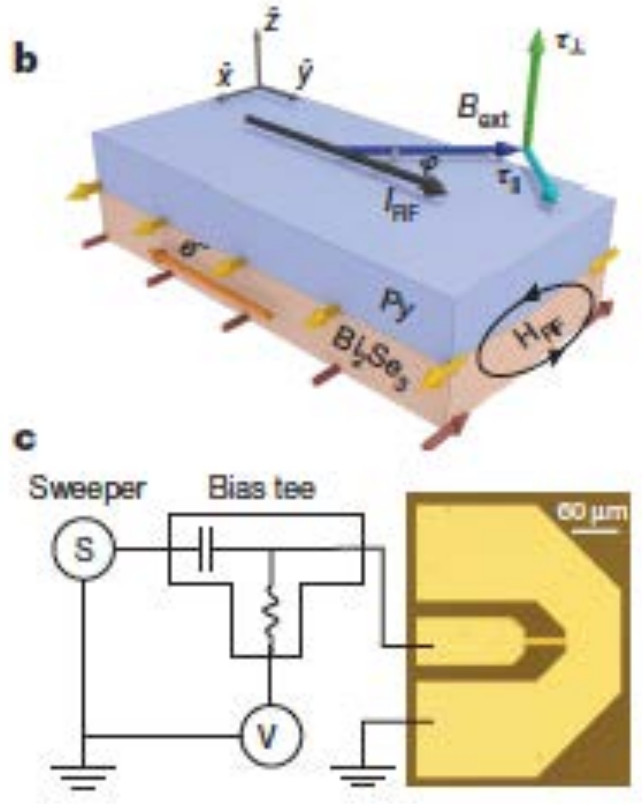
LETTER

doi:10.1038/nature13534

Spin-transfer torque generated by a topological insulator

A. R. Mellnik[1], J. S. Lee[2], A. Richardella[2], J. L. Grab[1], P. J. Mintun[1], M. H. Fischer[1,3], A. Vaezi[1], A. Manchon[4], E.-A. Kim[1], N. Samarth[2] & D. C. Ralph[1,5]





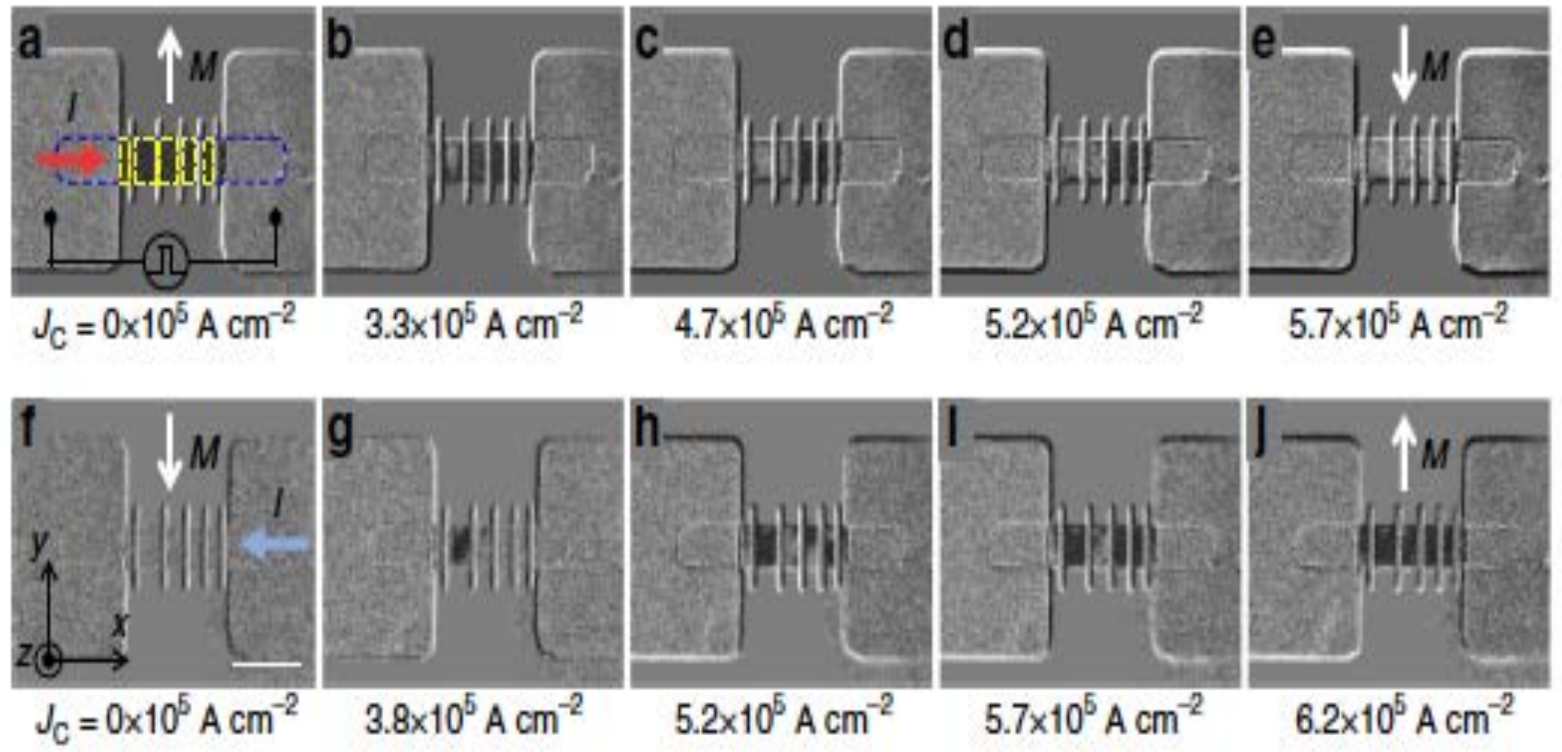
nature COMMUNICATIONS

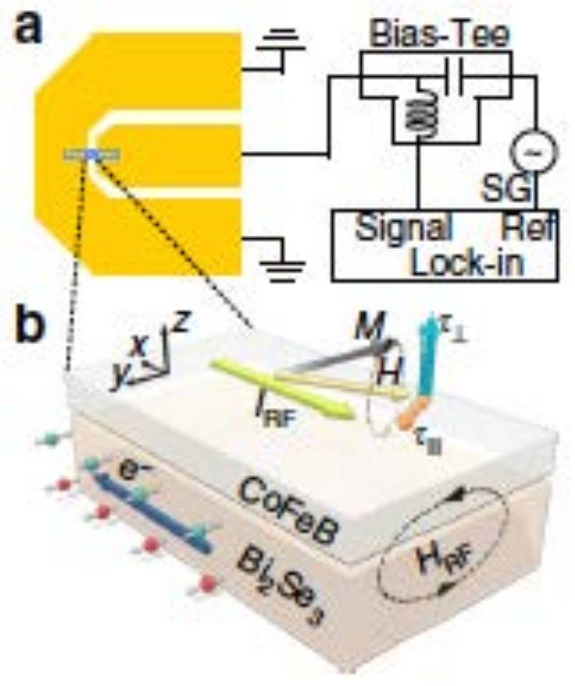
ARTICLE

DOI: 10.1038/s41467-017-01583-4 OPEN

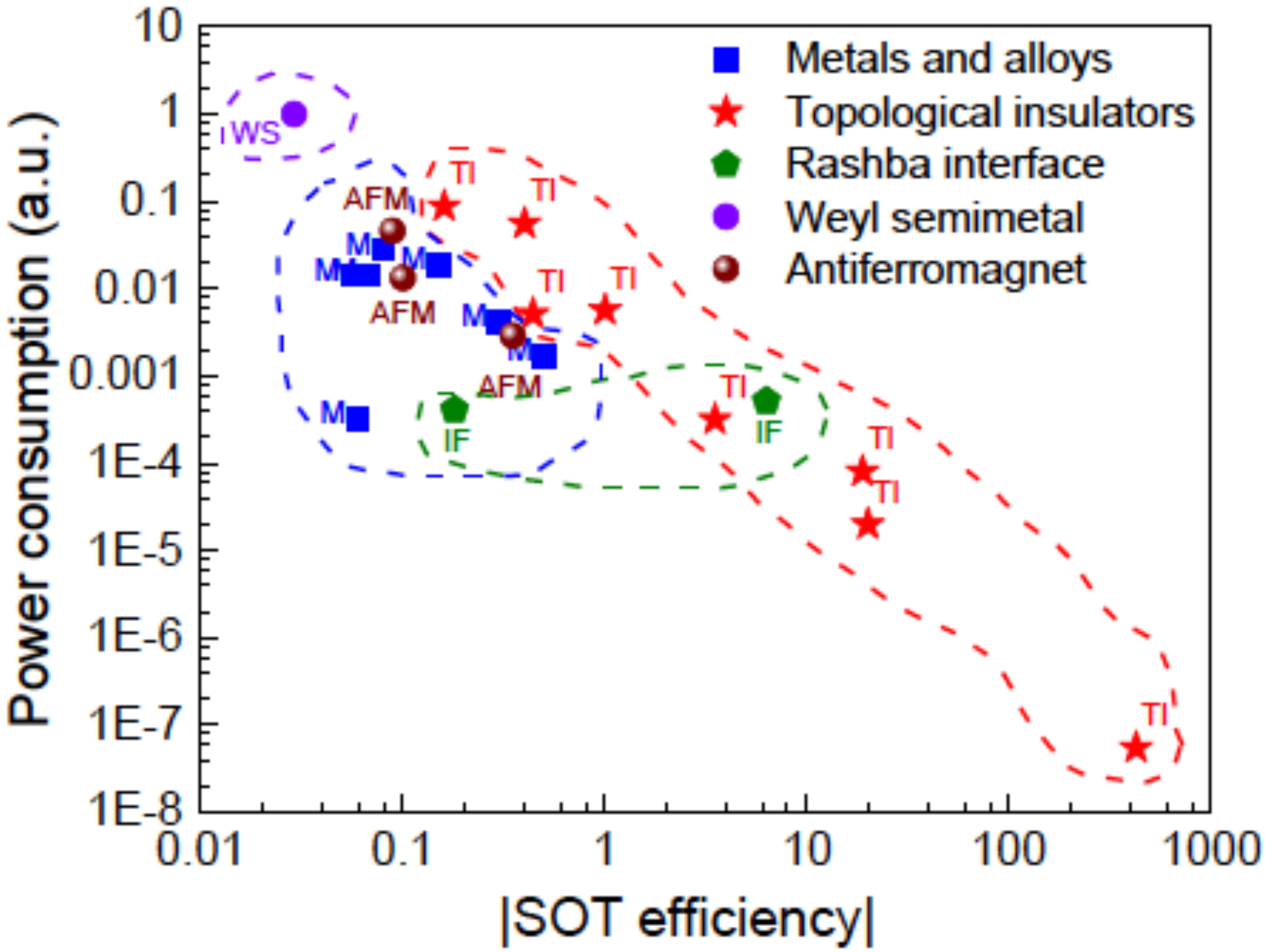
Room temperature magnetization switching in topological insulator-ferromagnet heterostructures by spin-orbit torques

Yi Wang[1], Dapeng Zhu[1], Yang Wu[1], Yumeng Yang[1], Jiawei Yu[1], Rajagopalan Ramaswamy[1], Rahul Mishra[1], Shuyuan Shi[1,2], Mehrdad Elyasi[1], Kie-Leong Teo[1], Yihong Wu[1] & Hyunsoo Yang[1,2]



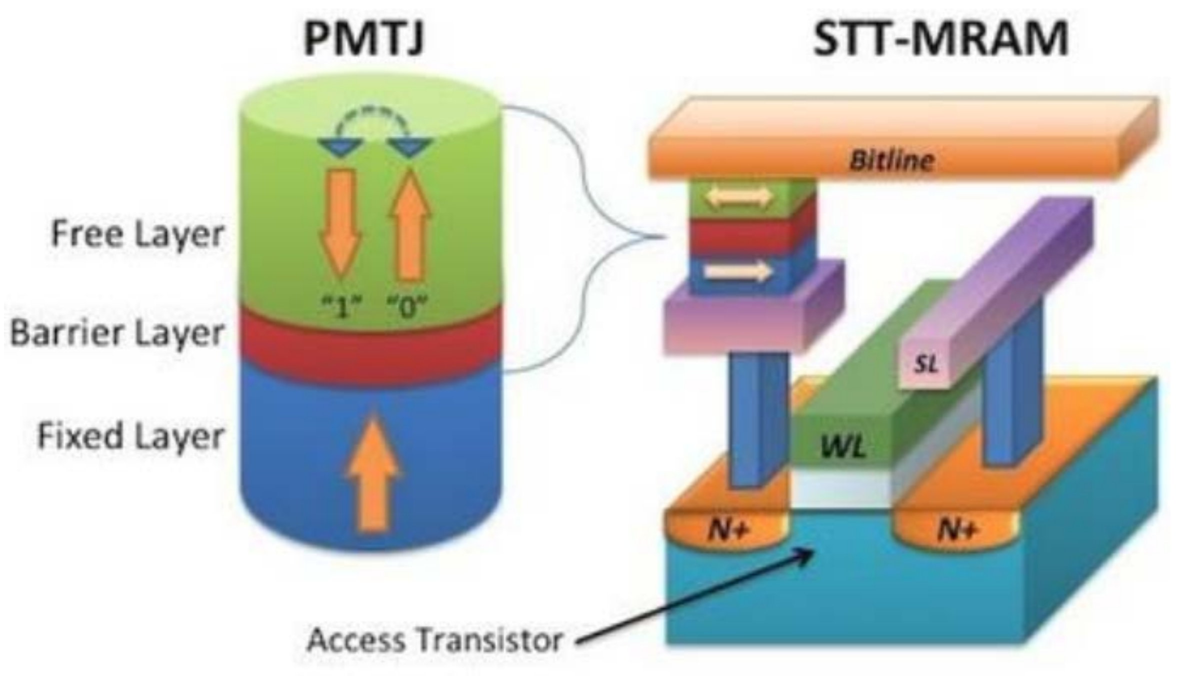


Q1.SOC Materials: TI sensing layer

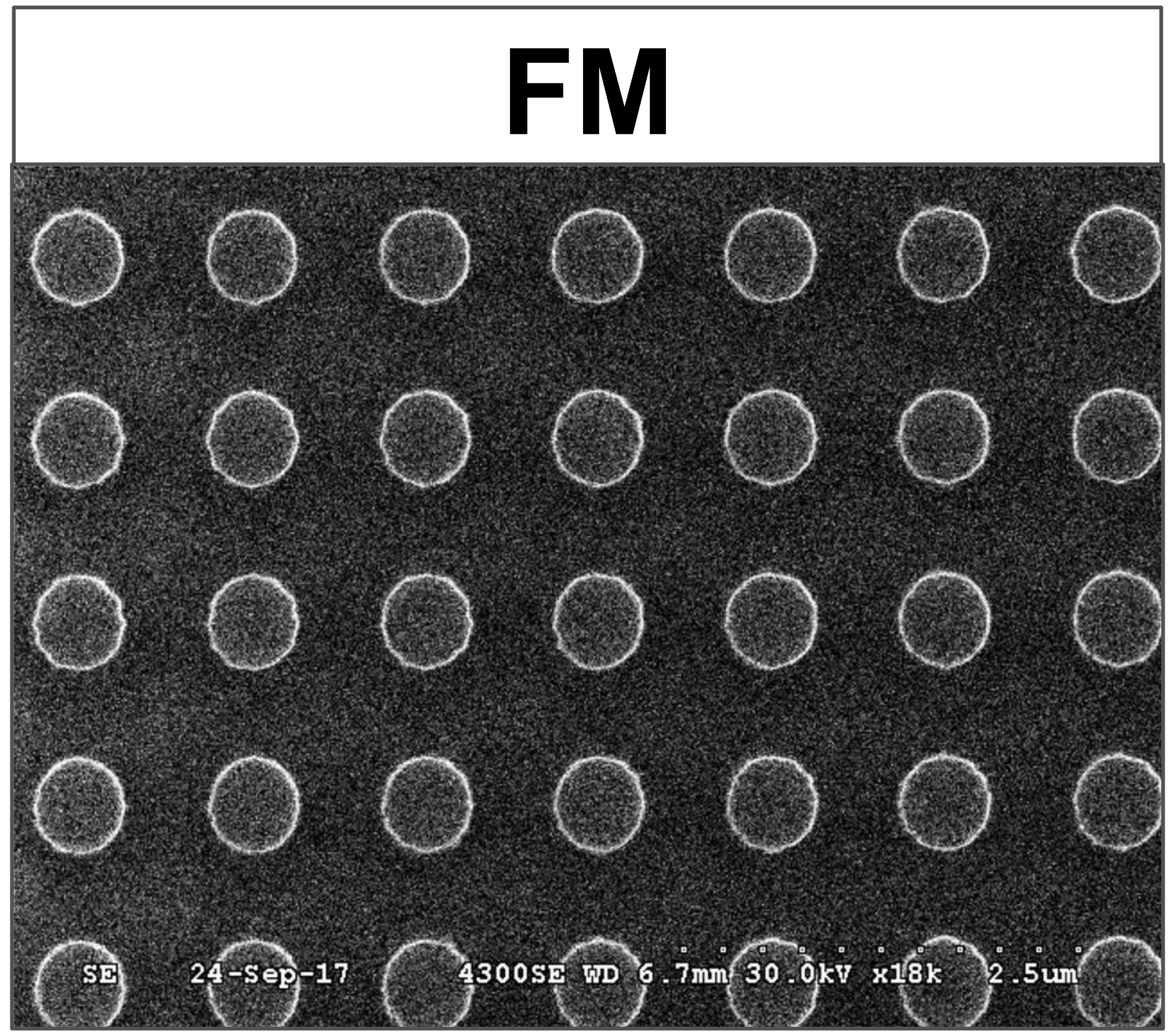


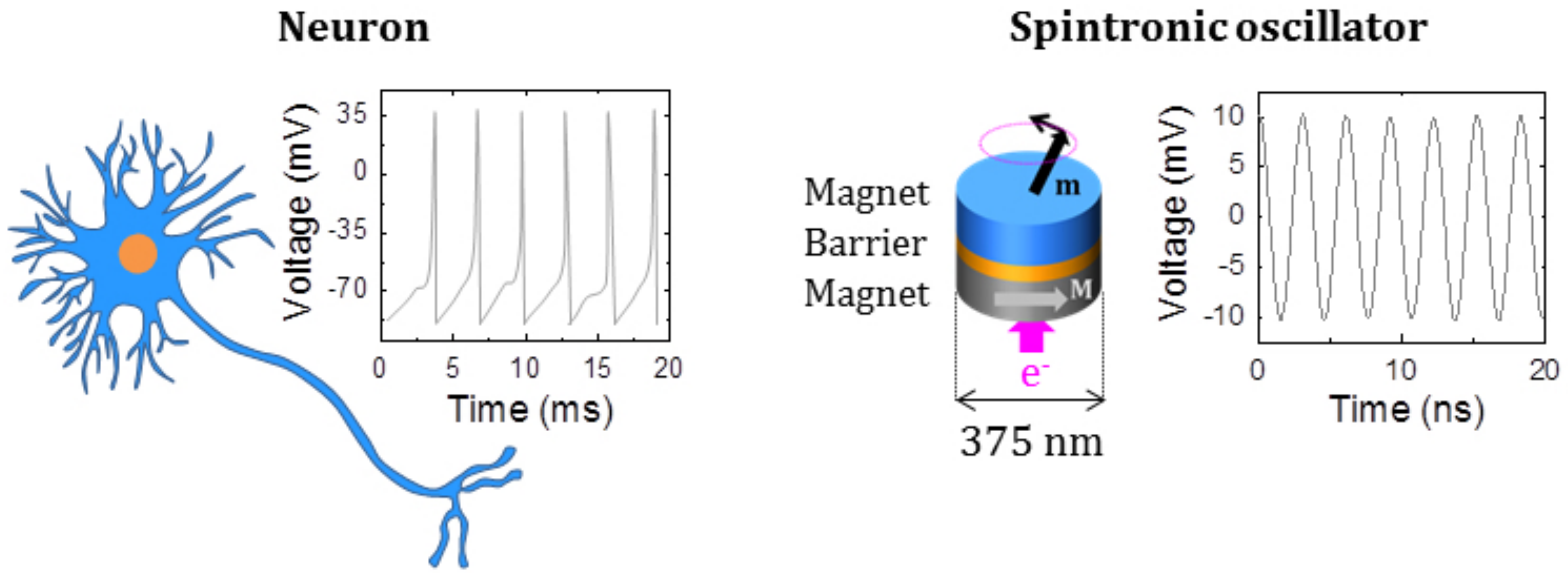
Yi Wang *et al.*, *J. Phys. D: Appl. Phys.* 2018

Q2. Nanostructuring

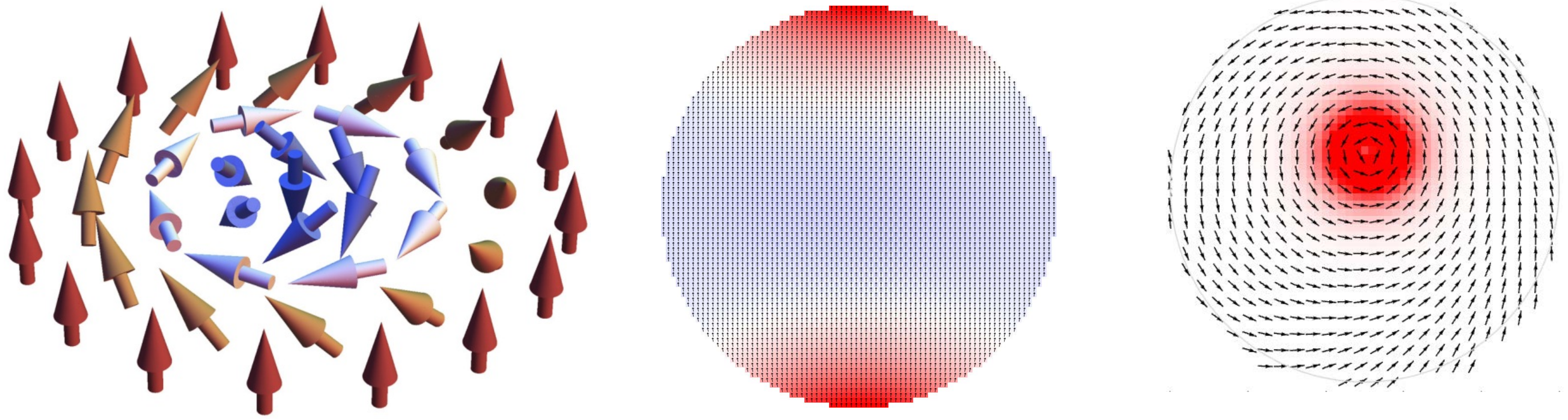


Real spintronic devices:
- magnetic random access memory
- spin-torque nanooscillators and spin-torque diodes
- racetrack memory
- spintronic neuromorphic devices



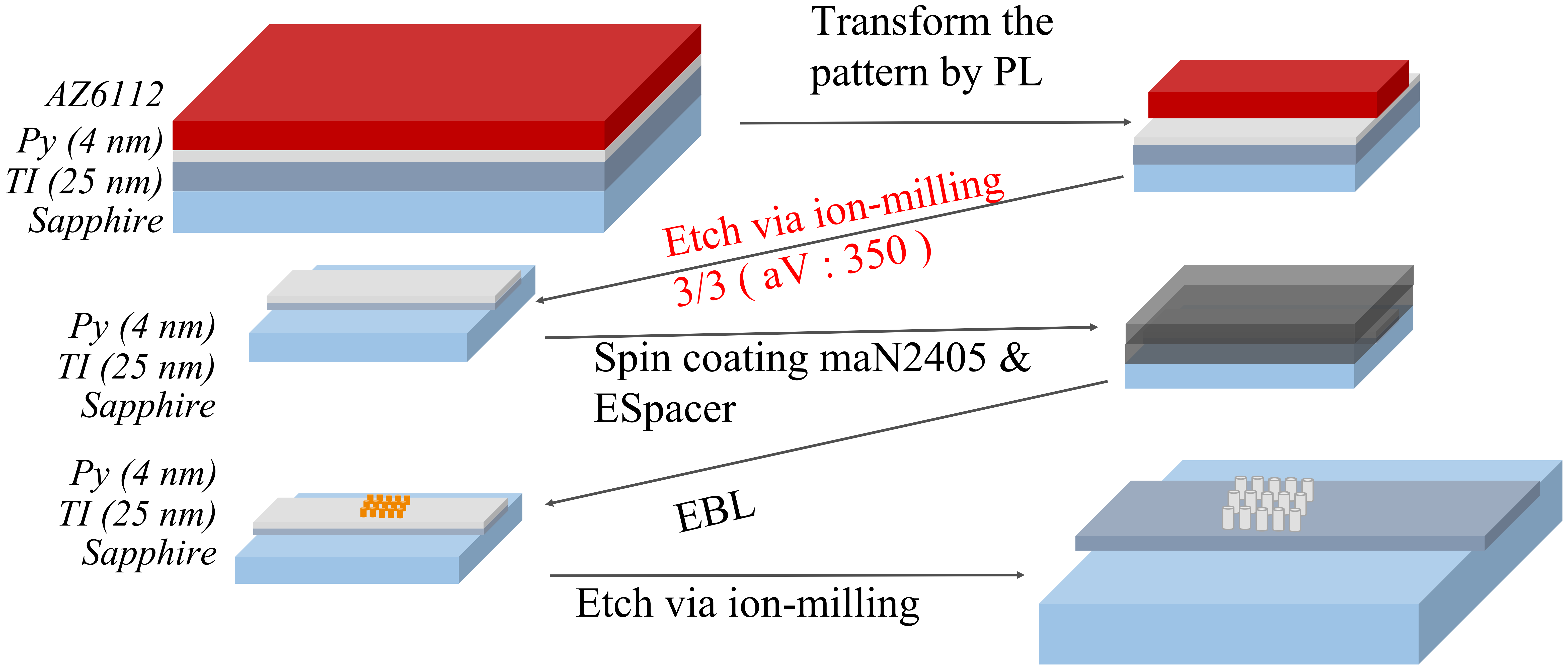


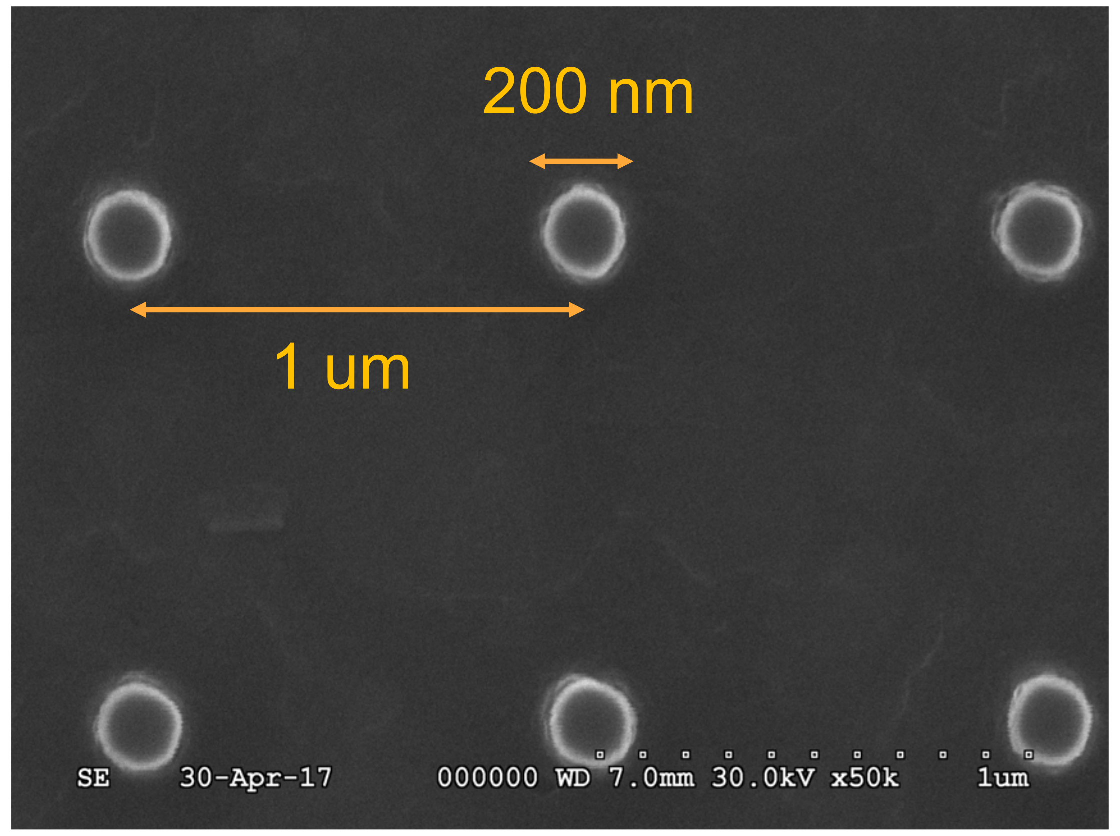
Phenomena:
- nonlinear synchronization and collective dynamics
- sophisticated magnetization distribution (vortex, skyrmion, domain wall)



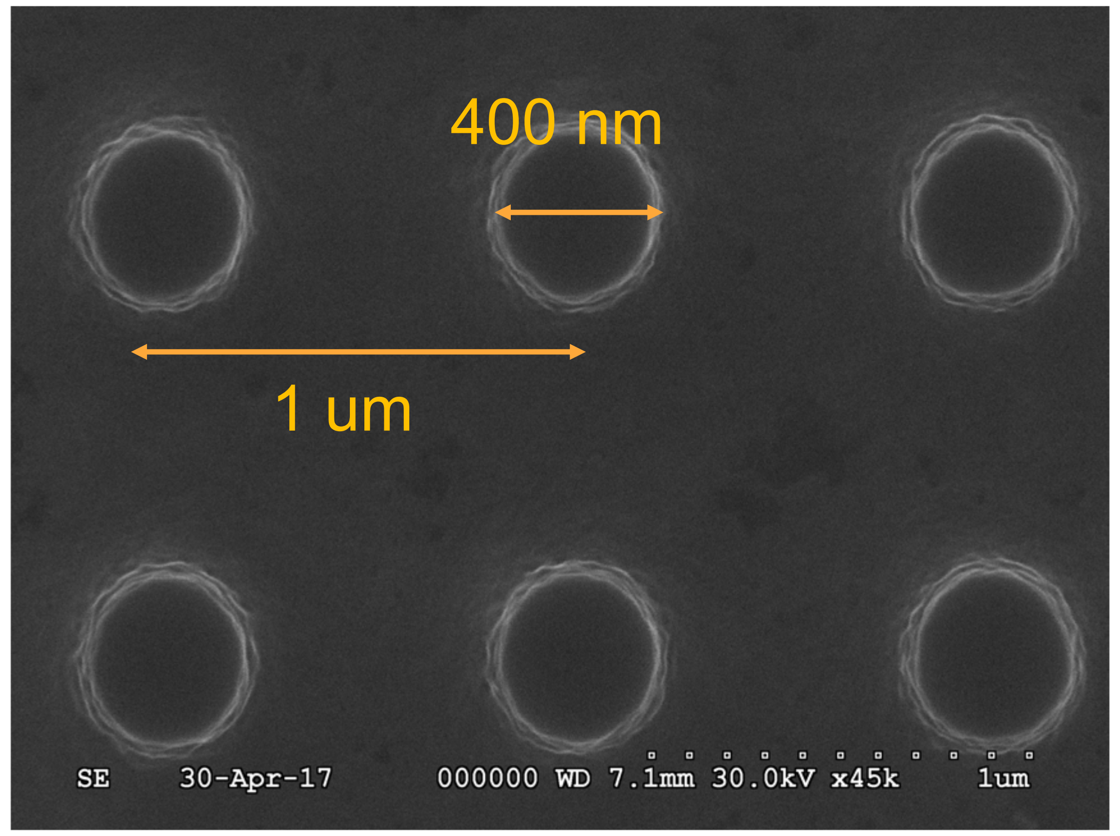
Torrejon J. et al., Nature 547, 7664, 428 (2017)

Experiment: Samples fabrication





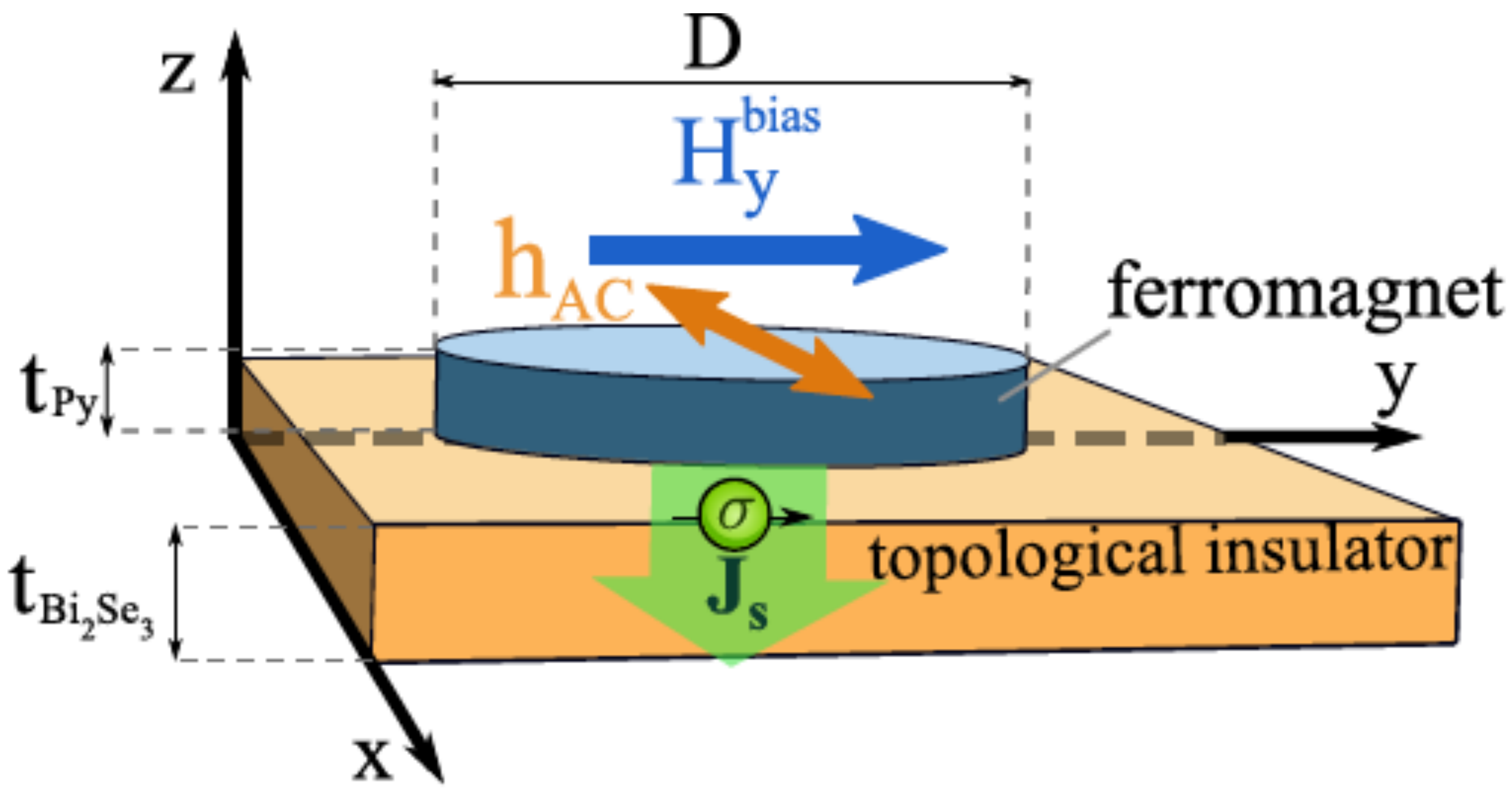
The image of dots in 200 nm diameter and 1um pitch via SEM

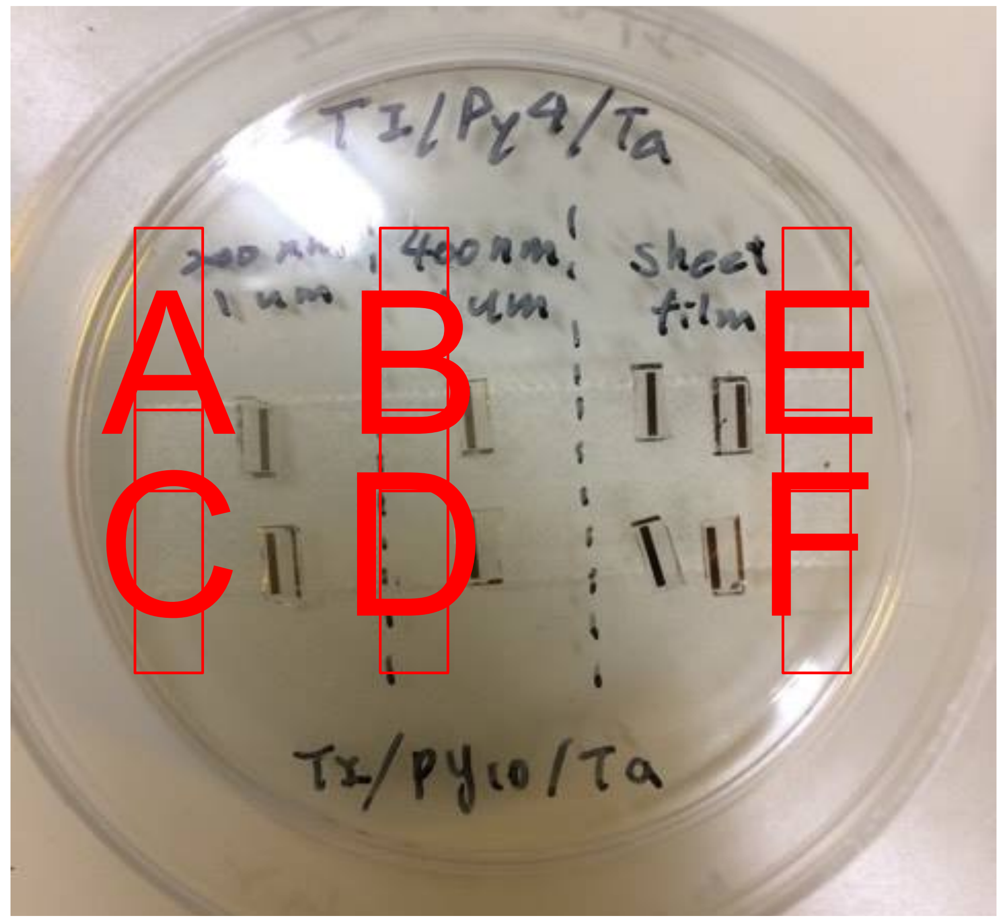


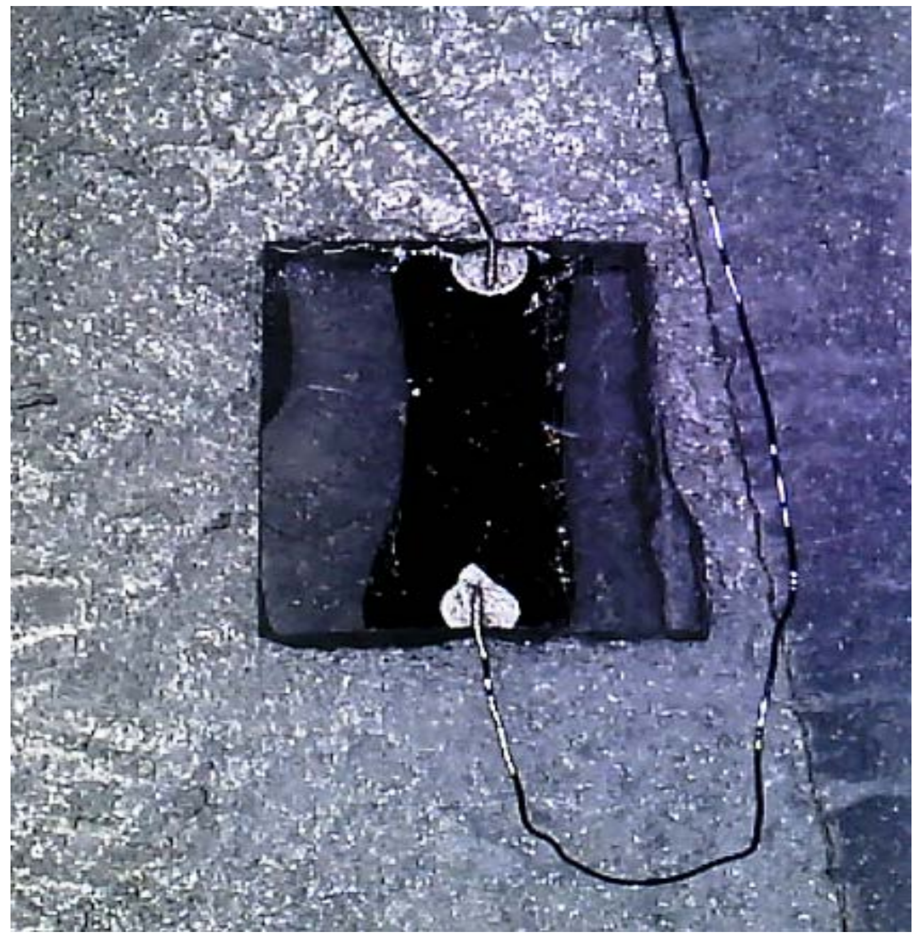
The image of dots in 400 nm diameter and 1um pitch via SEM

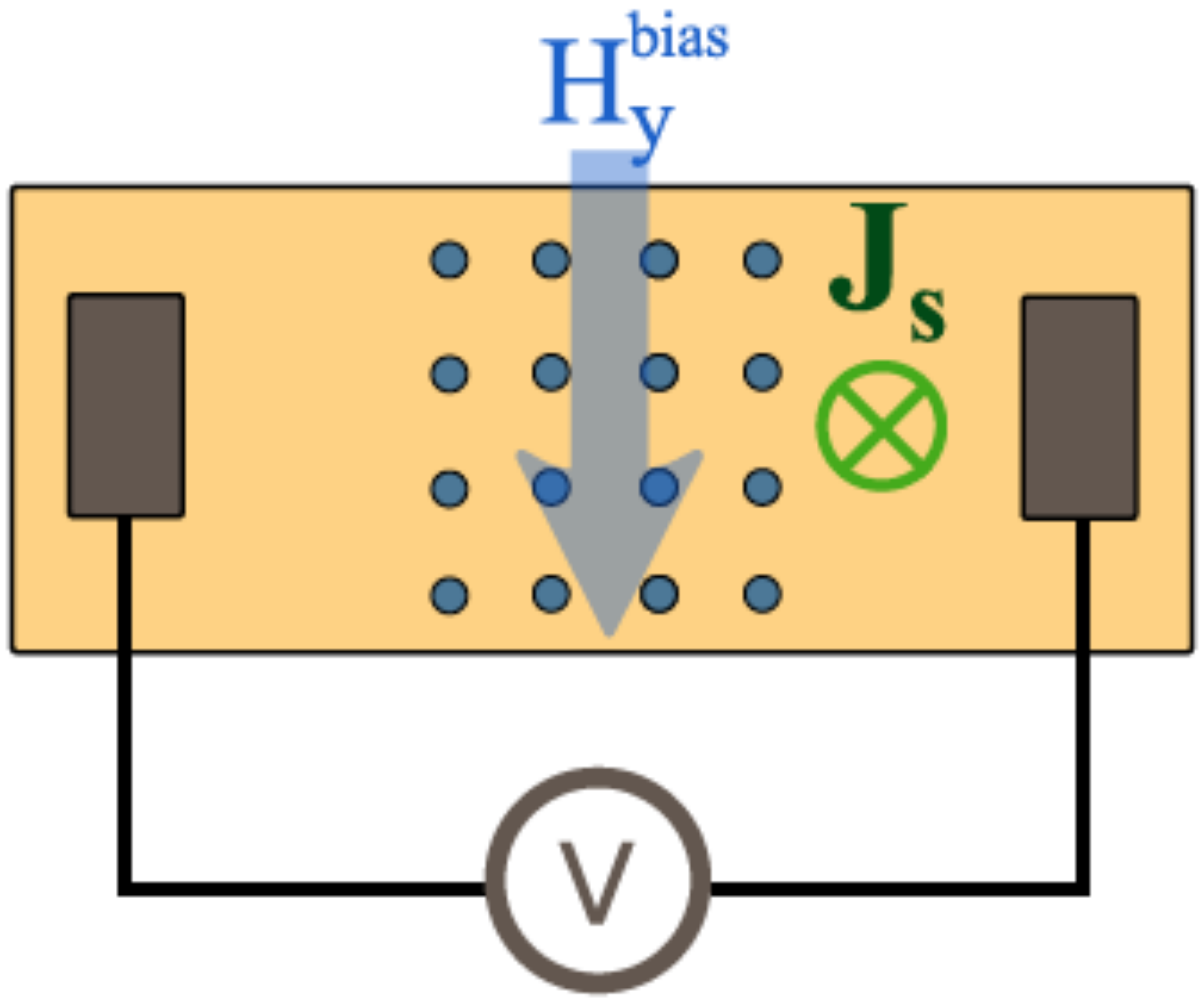
	Samples' structure	Diameter(nm)	Center to center(um)	Area of dots array	Piece(s)
A	TI (25 nm) / Py(4 nm) / Ta(1 nm) Dots array	200	1	0.5mm*1mm	1
B		400			1
C	TI (25 nm) / Py(10 nm) / Ta(1 nm) Dots array	200	1	0.5mm*1mm	1
D		400			1
E	TI (25 nm) / Py(4 nm) / Ta(1 nm) Sheet film				2
F	TI (25 nm) / Py(10 nm) / Ta(1 nm) Sheet film				2

Experiment: FMR spin-pumping





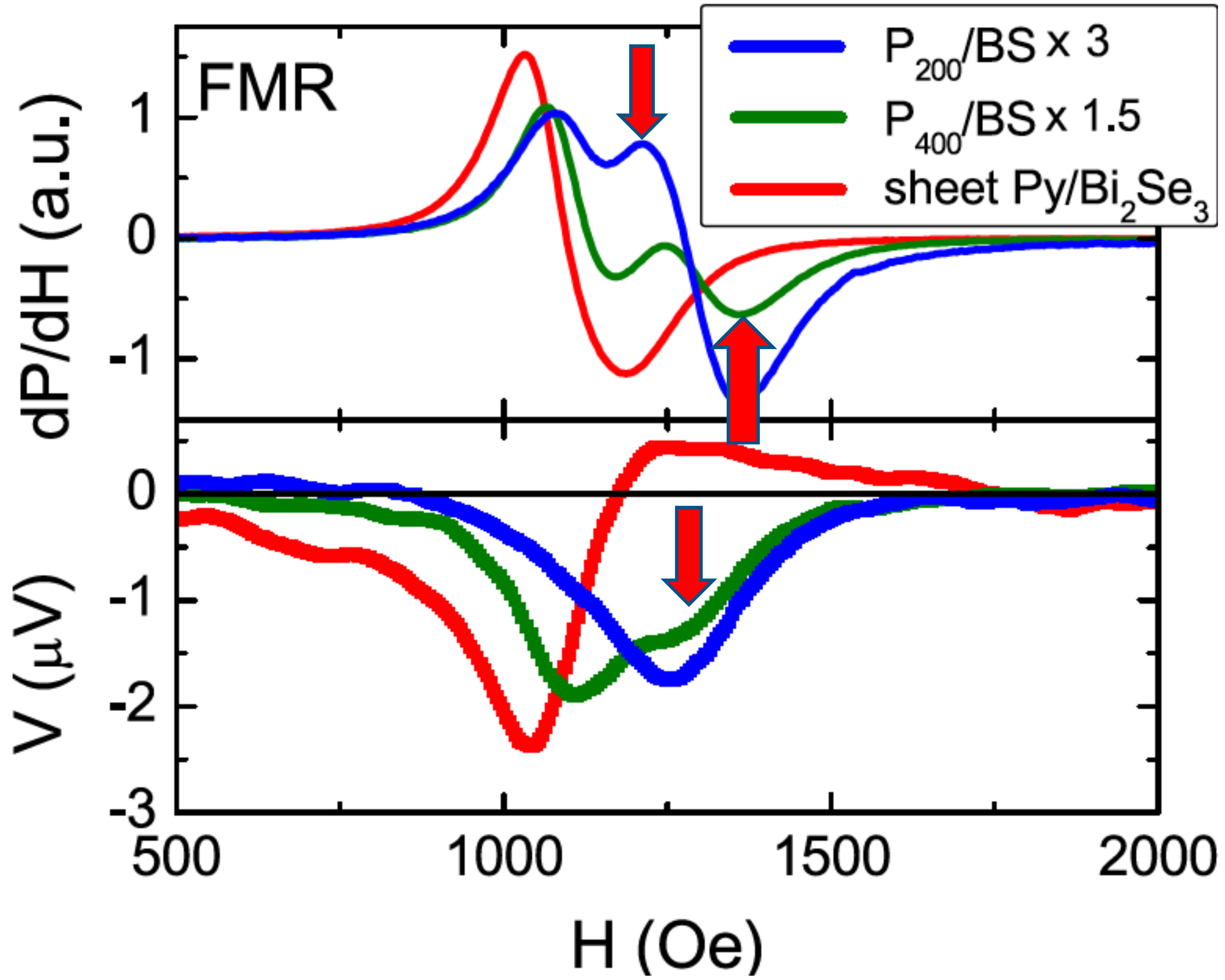




TE102 microwave cavity

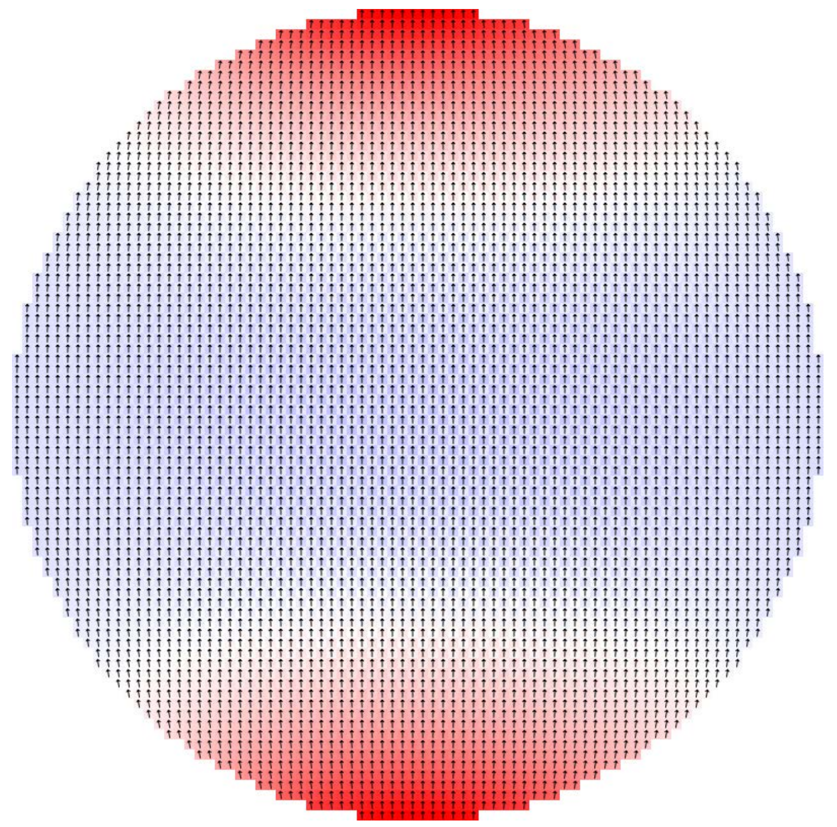
H_{AC} = 0.44 Oe (X-band- 50 mW, 9.8 GHz)
H_{DC}=(500-2500)Oe

Experiment: FMR spin-pumping



Spin-pumping voltage origin:

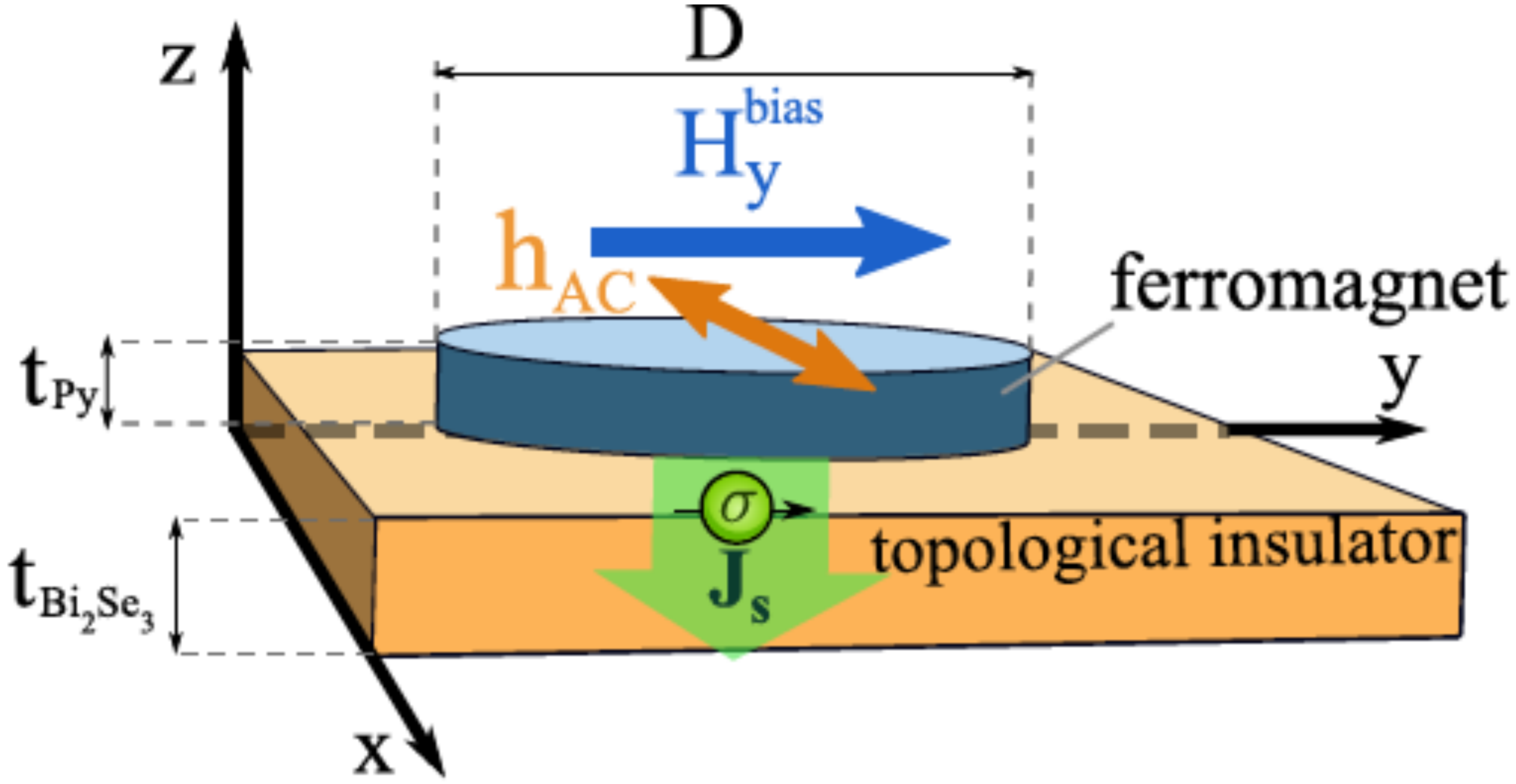
- AHE
- AMR
- Spin-to-charge conversion:
  - ISHE
  - IREE



	P200/BS	P400/BS	Sheet film
V_{ISHE}	463 nV	948 nV	2.094 nV

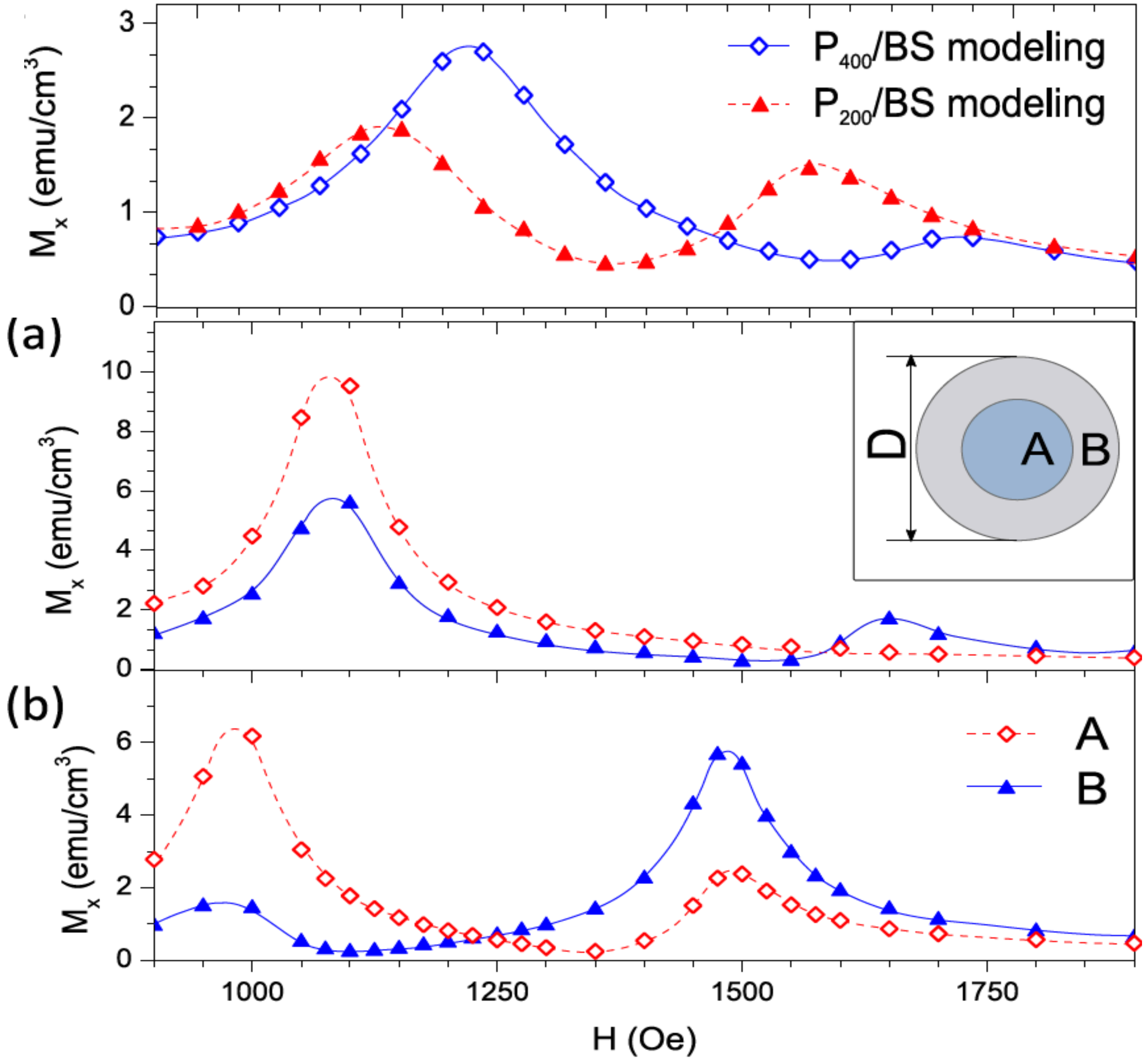
J. M. Shaw et al., *Phys. Rev. B 79, 184404 (2009)*.

Micromagnetic Modeling



The magnetization dynamics is investigated using numerical integration of the Landau-Lifshitz-Gilbert Dynamics (LLG) with additional spin-transfer term:

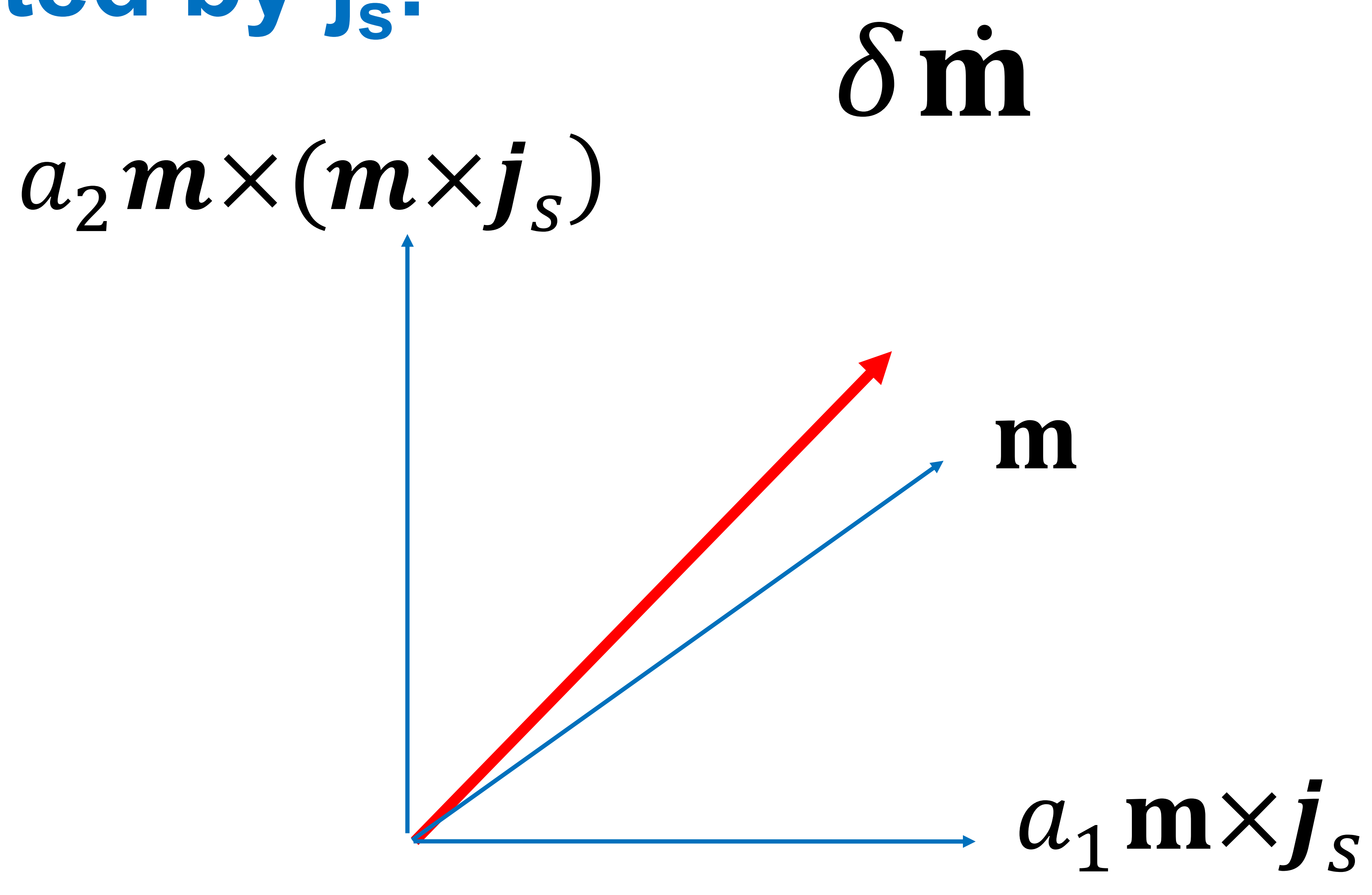
$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M}\times\mathbf{H}_{eff} + \alpha \mathbf{M}\times\dot{\mathbf{M}} - \frac{\gamma_0 a_J}{M_s}\mathbf{M}\times\left[\mathbf{M}\times\mathbf{m}_{ref}\right] - \gamma b_J \mathbf{M}\times\mathbf{m}_{ref}$$



Spin PM
Micromagnetic Solver

FMR spin-pumping modeling

Direct task: magnetization dynamics excited by j_s:

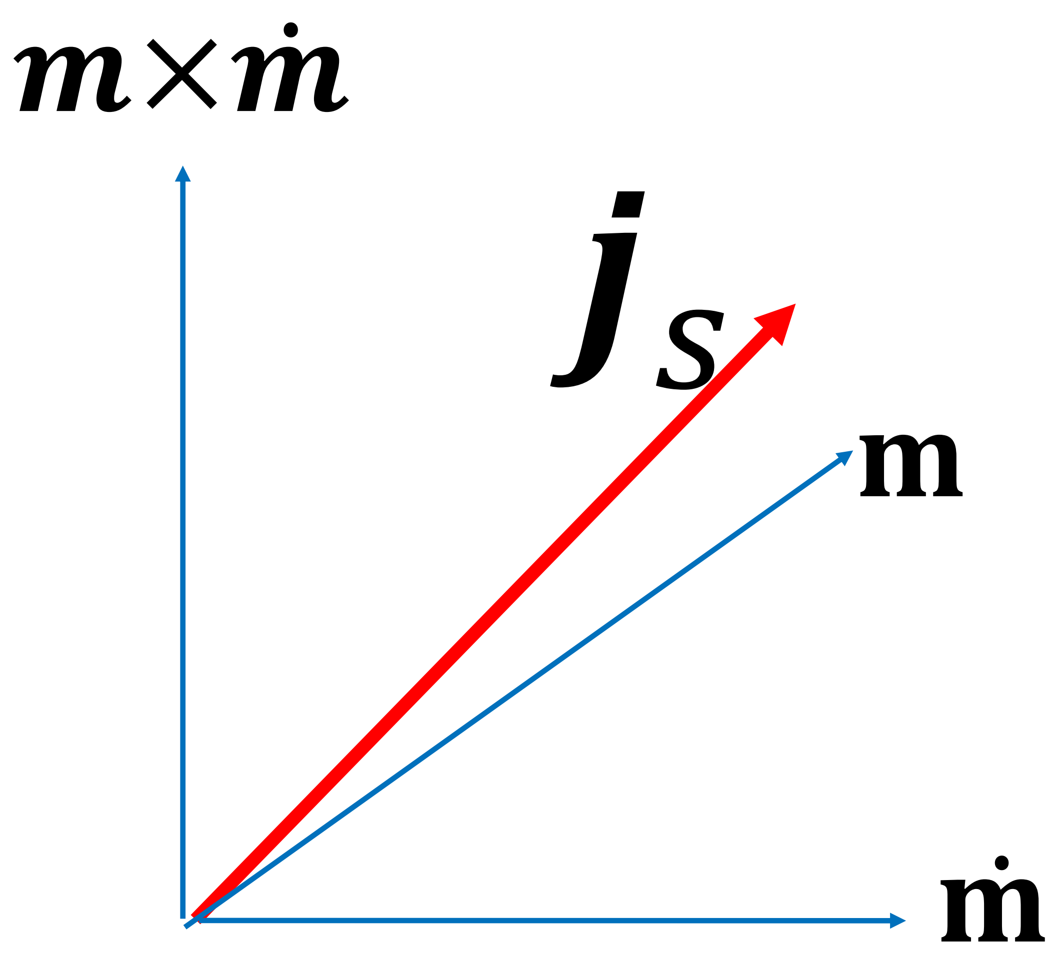


$$\delta\dot{\mathbf{m}} = a_1\mathbf{m}\times\boldsymbol{j}_s + a_2\boldsymbol{m}\times(\boldsymbol{m}\times\boldsymbol{j}_s)$$

$$|\mathbf{m}| = |\mathbf{m}_{ref}| = 1 \qquad \mathbf{m}\cdot\dot{\mathbf{m}} = 0$$

$$\boldsymbol{j}_s = \frac{\hbar}{2}\frac{j_c}{e}\boldsymbol{m}_{ref}$$

Inverse task: j_s excited by magnetization dynamics:



$$\boldsymbol{j}_s = b_1\dot{\mathbf{m}} + b_2(\boldsymbol{m}\times\dot{\boldsymbol{m}})$$

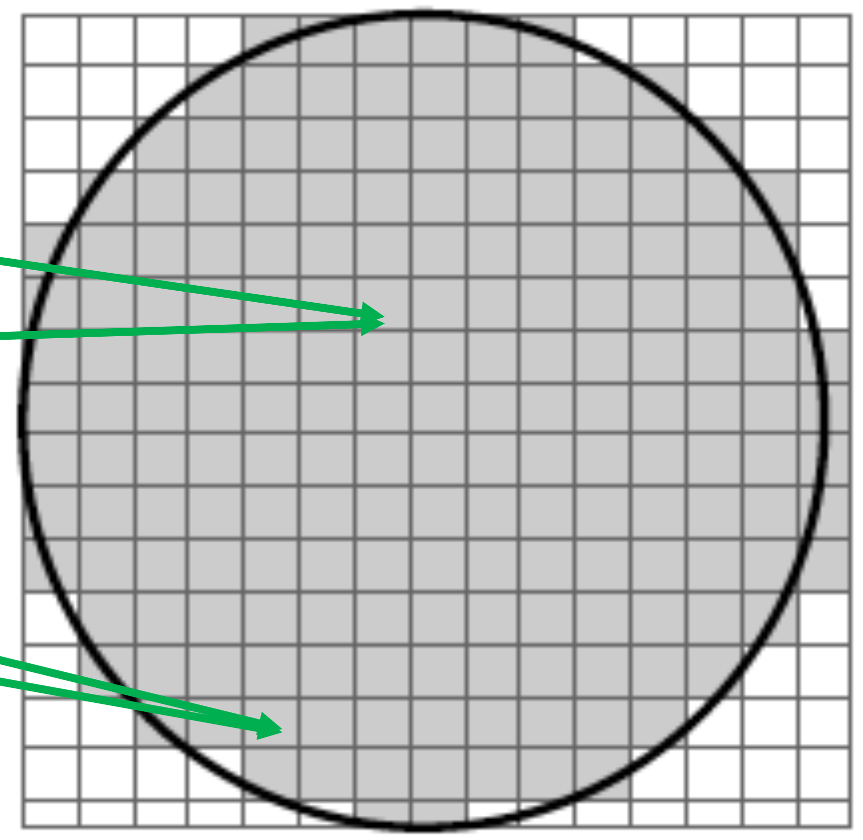
$$\boldsymbol{j}_s\cdot\mathbf{m} = 0$$

Basement for STT spintronics & Spin-orbitronics!

FMR spin-pumping modeling

Spin current in ferromagnet-normal metal (and bulk TI) systems

$$(\mathbf{j}_s)_z \otimes \boldsymbol{\sigma} = \mathbf{e}_z \otimes \frac{1}{M_s^2}\frac{\hbar}{4\pi} g_{eff}\left[\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right]$$



Y. Tserkovnyak, A. Brataas, G. E. W. Bauer, and B. I. Halperin,Rev. Mod. Phys. 77, 1375 (2005)
K. Chen and S. Zhang, Phys. Rev. Lett. 114, 126602 (2015)

Effective damping constant

$$\alpha^{eff} = \alpha_0 + \Delta\alpha_{sp}$$

	P200/BS	P400/BS	Sheet film
α^{eff}	0.0237	0.0223	0.0275

FMR spin-pumping modeling

Spin-mixing constant

$$g^{eff} = \frac{4\pi M_s \Delta\alpha_{sp} t_{FM}}{g\mu_B}$$

Tserkovnyak et al. Phys. 77, 1375 (2005)

	P200/BS	P400/BS	Sheet film
g^{eff}	3 10^{19} m^{-2}	2.7 10^{19} m^{-2}	3.8 10^{19} m^{-2}

Inside TI the spin current decays exponentially!

$$(\mathbf{j}_s(z))_z \otimes \boldsymbol{\sigma} = \mathbf{e}_z \otimes \frac{\sinh((t_{Bi_2Se_3} - z)/\lambda_{Bi_2Se_3})}{\sinh(t_{Bi_2Se_3}/\lambda_{Bi_2Se_3})} \mathbf{j}_s(0)$$

Chen and Zhang, Phys. Rev. Lett. 114, 126602 (2015)

Spin-diffusion length in Bi_2Se_3

$$\lambda_{Bi_2Se_3} \approx 6.2 \text{ nm}$$

Deorani et al.,
Phys. Rev. B 90, 094403 (2014).

ISHE charge current in TI

Levi-Civita symbol

$$(j_c)_i = \theta_{ISHE} \frac{2e}{\hbar} \epsilon_{ijk} (j_s)_j \sigma_k$$

E. Saitoh et al., Applied
Physics Letters 88, 182509 (2006)

FMR spin-pumping modeling

ISHE voltage

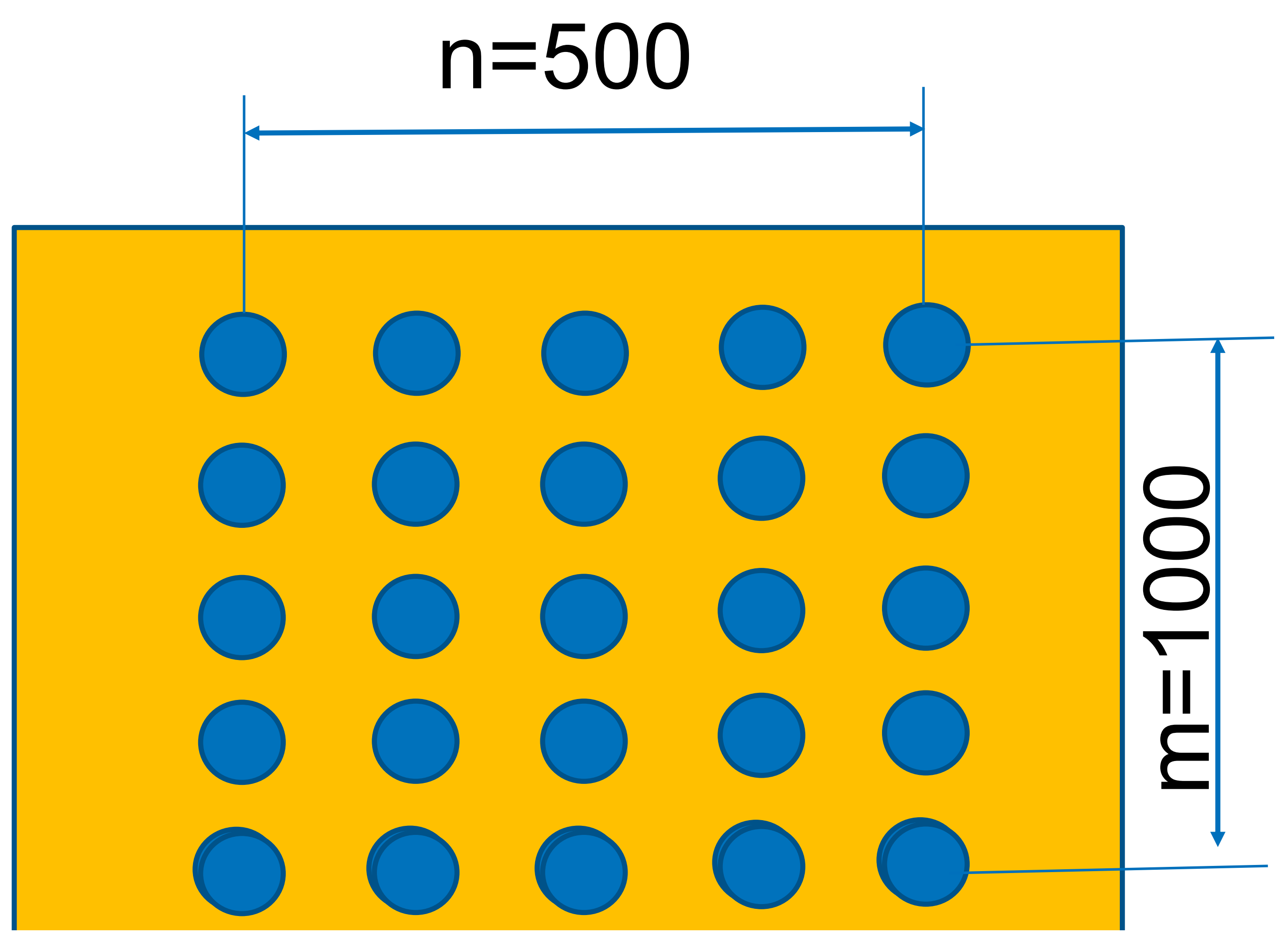
$$V = \langle j_c \rangle R t_{Bi_2Se_3} D n$$

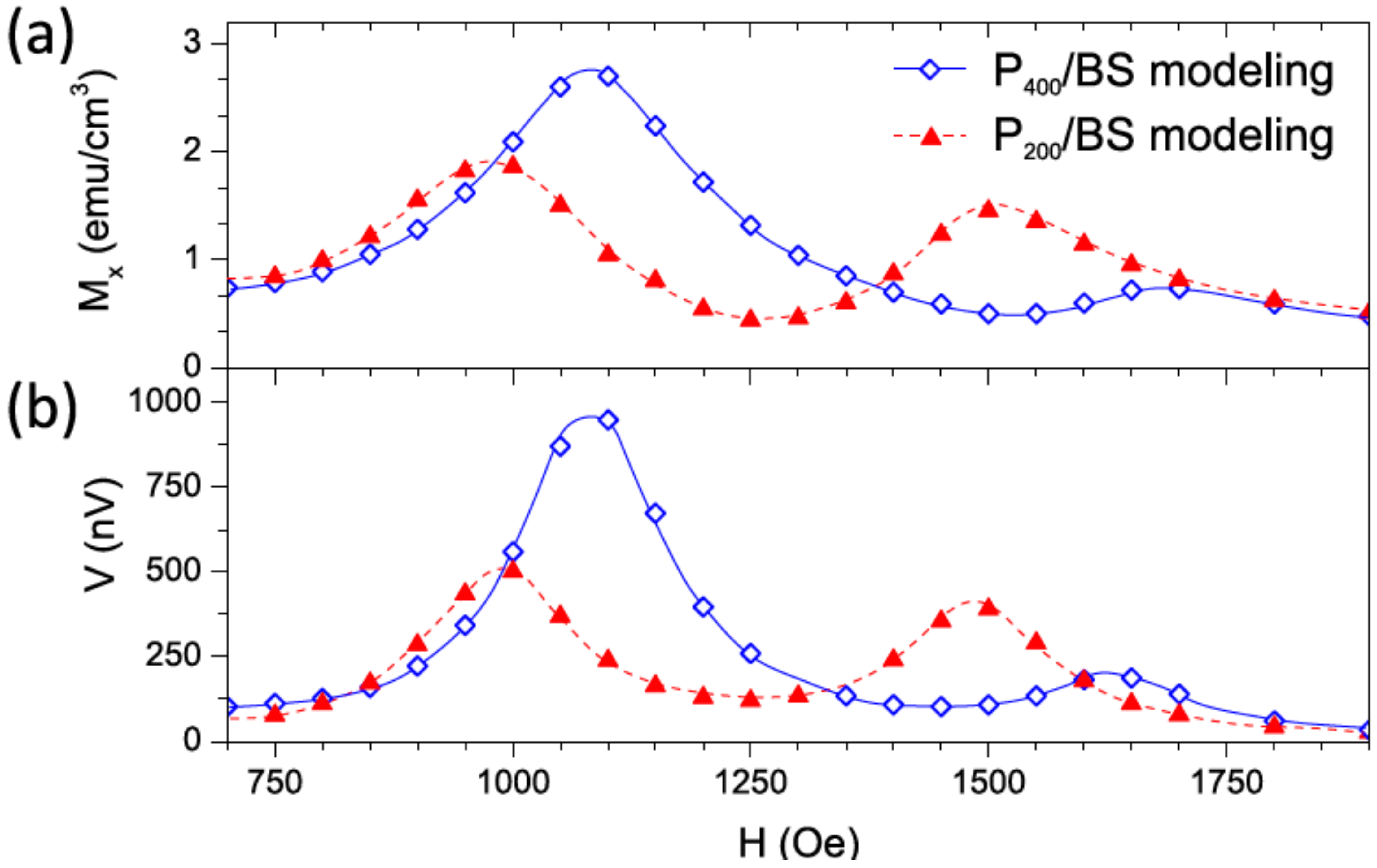
Spin Hall angle

	P200/BS	P400/BS	Sheet film
θ_{ISHE}	0.00232	0.0088	0.0124

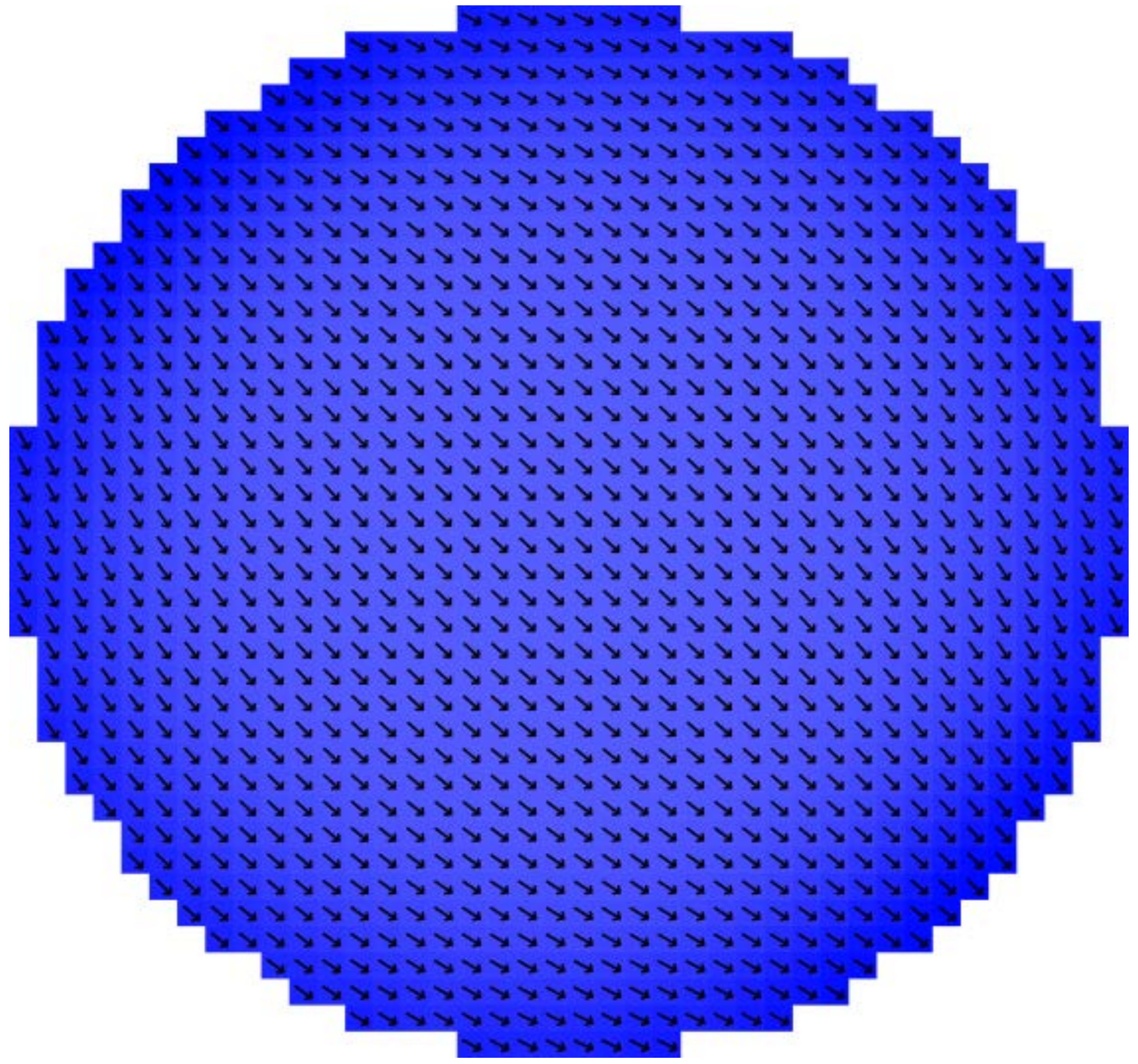
Efficiency vs. nanostructuring

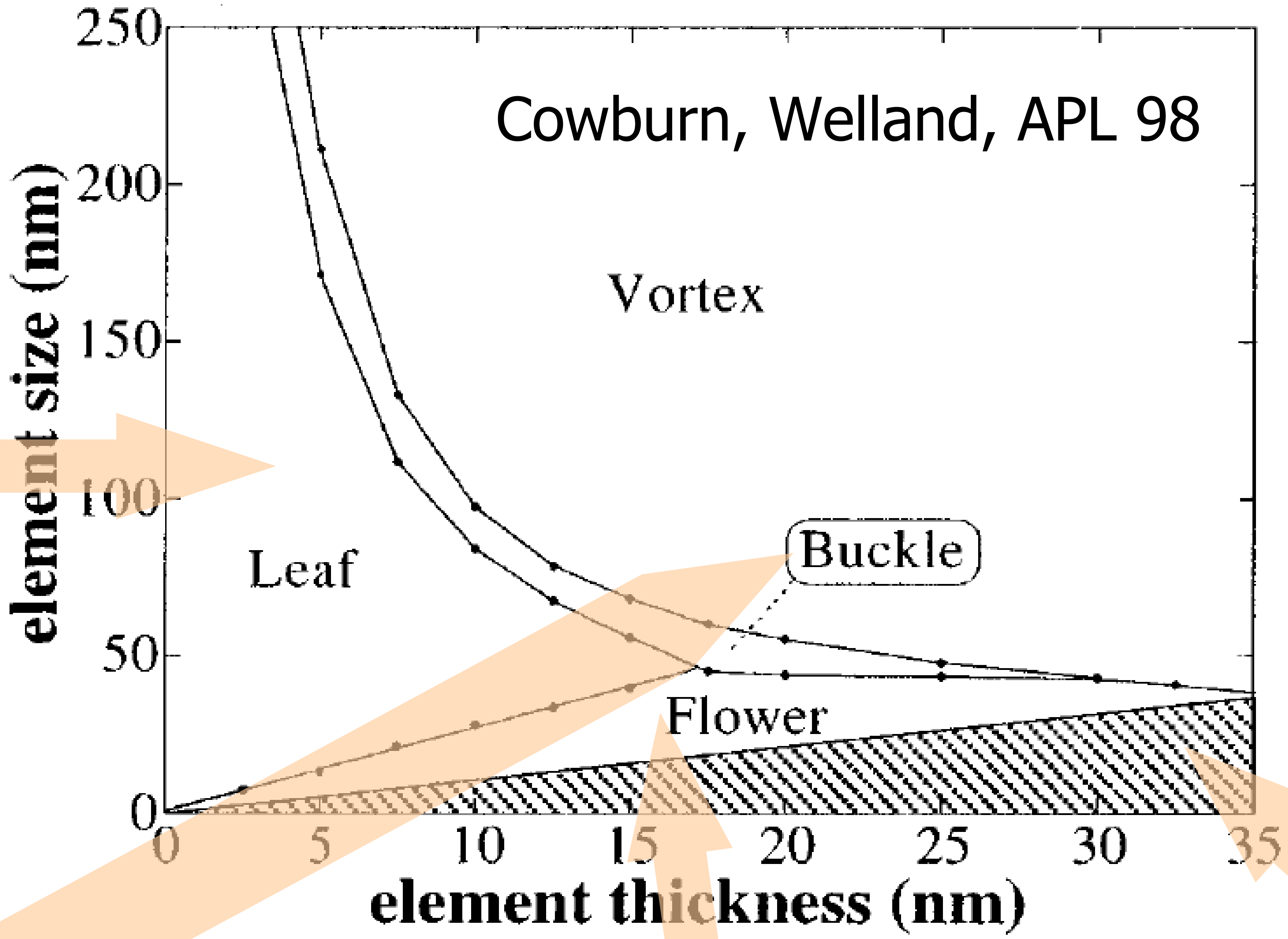
$(V_{ISHE})_{200}/(V_{ISHE})_{sheet} \approx 0.23$
$(V_{ISHE})_{400}/(V_{ISHE})_{sheet} \approx 0.31$

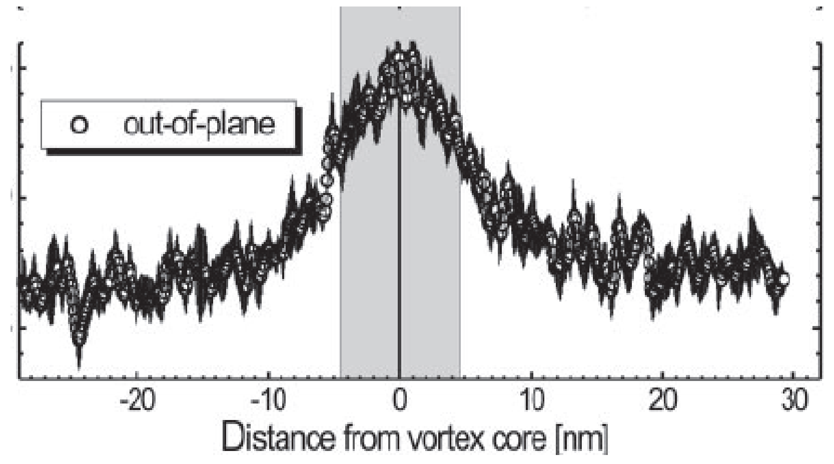




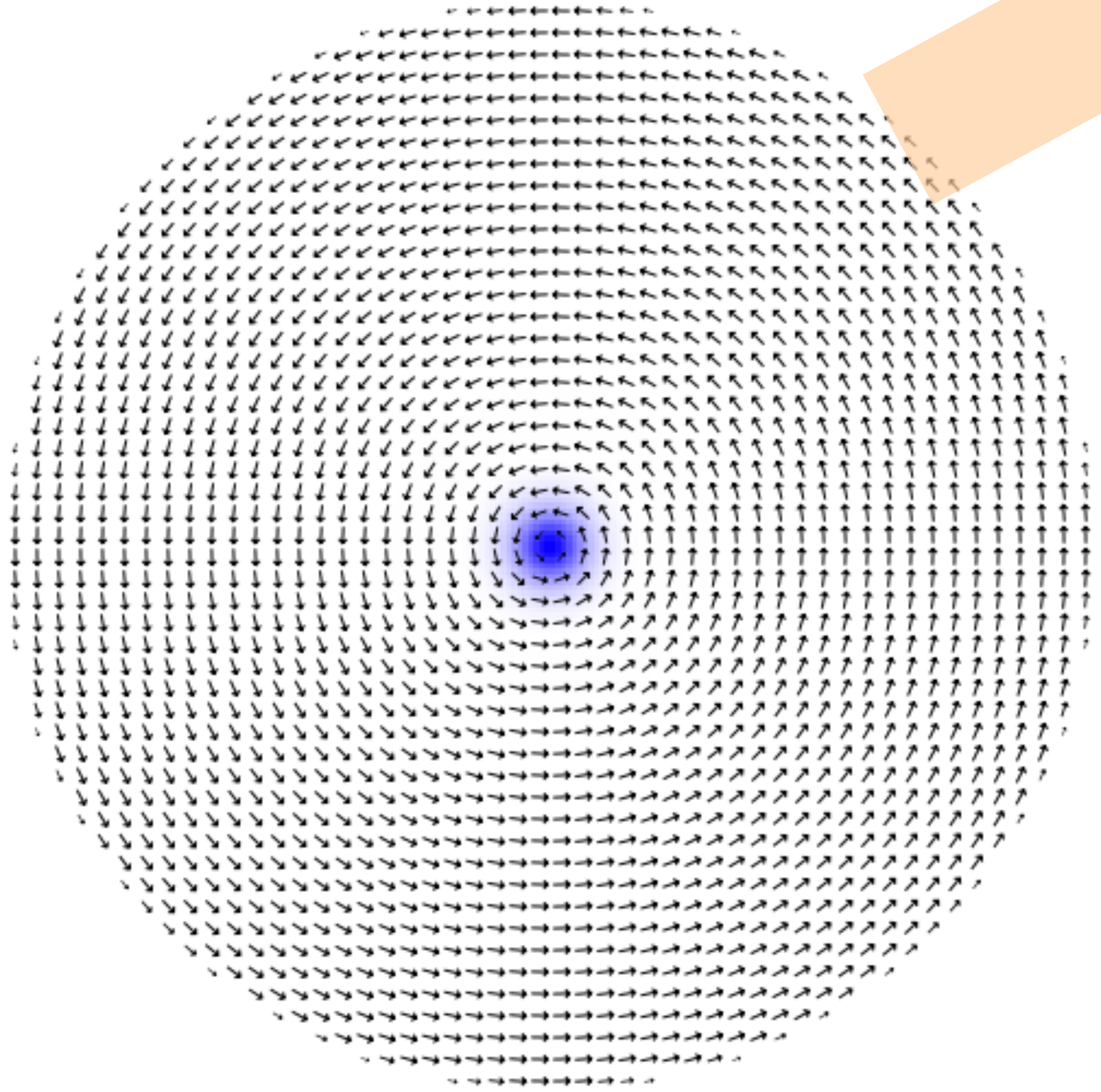
ISHE capturing the vortex dynamics

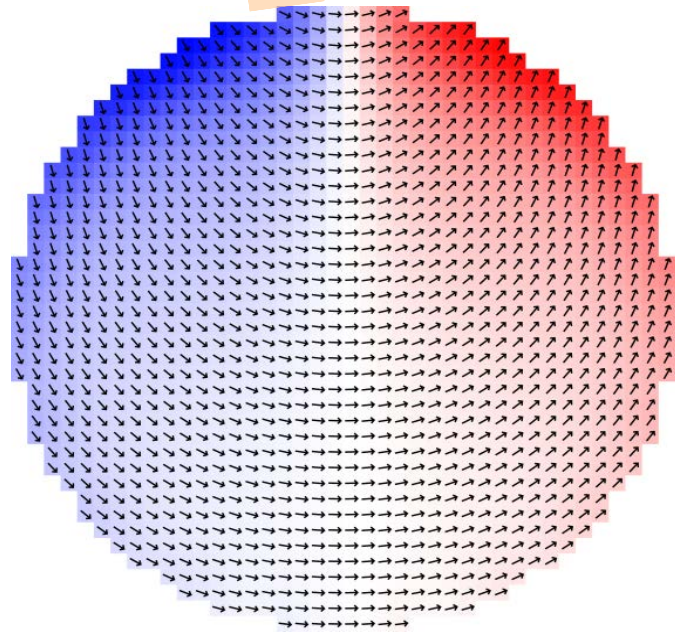


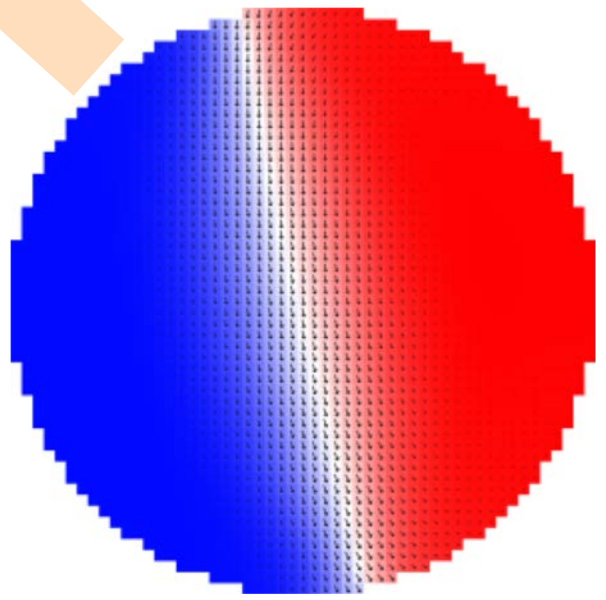




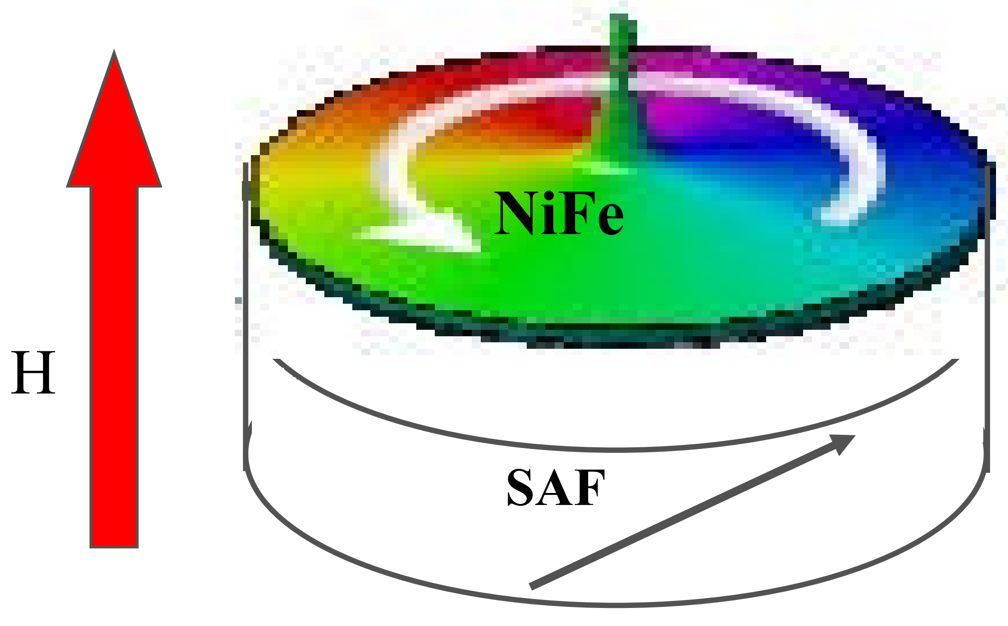
Wachowiak et al.,
Science 2002

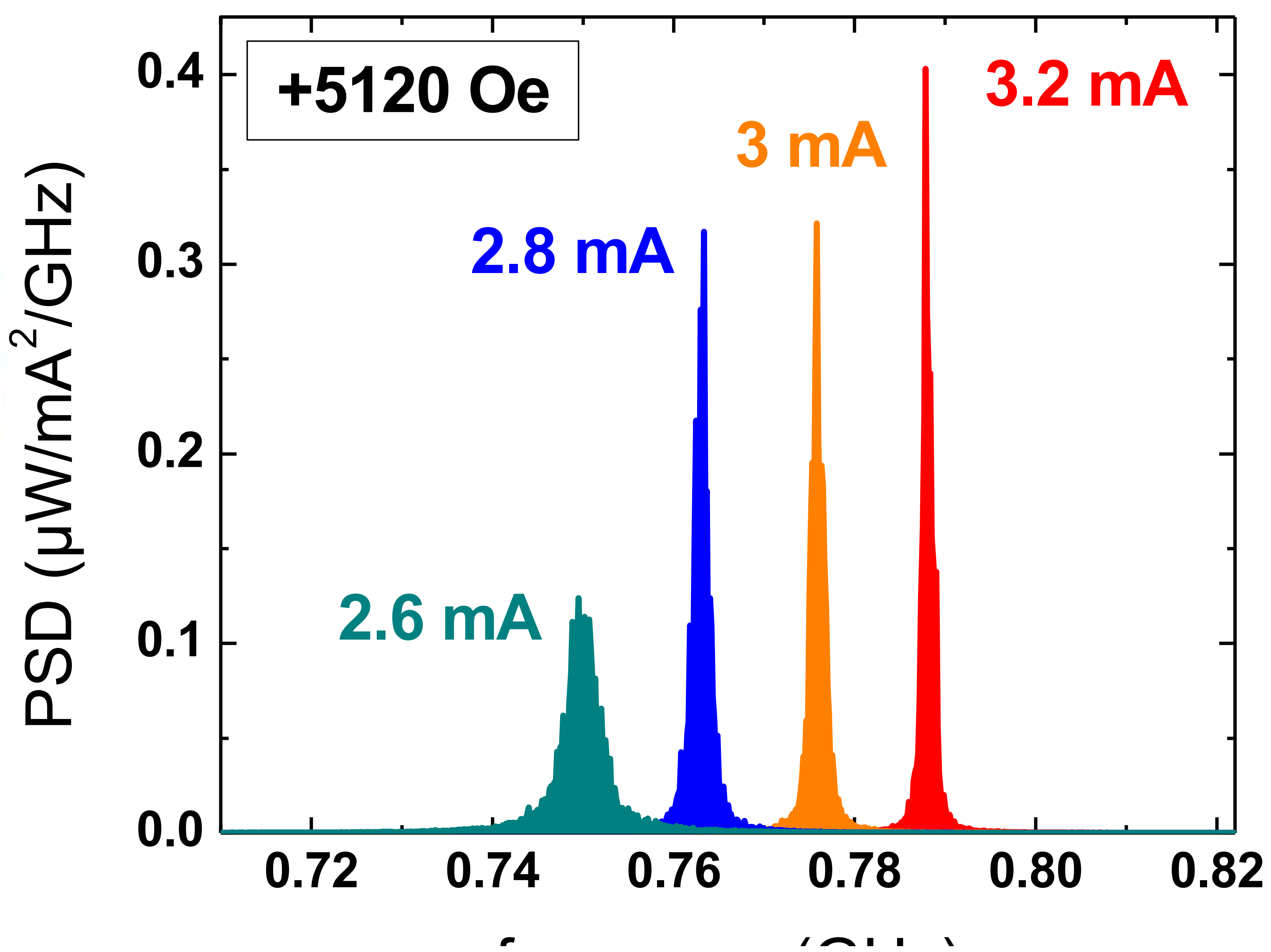


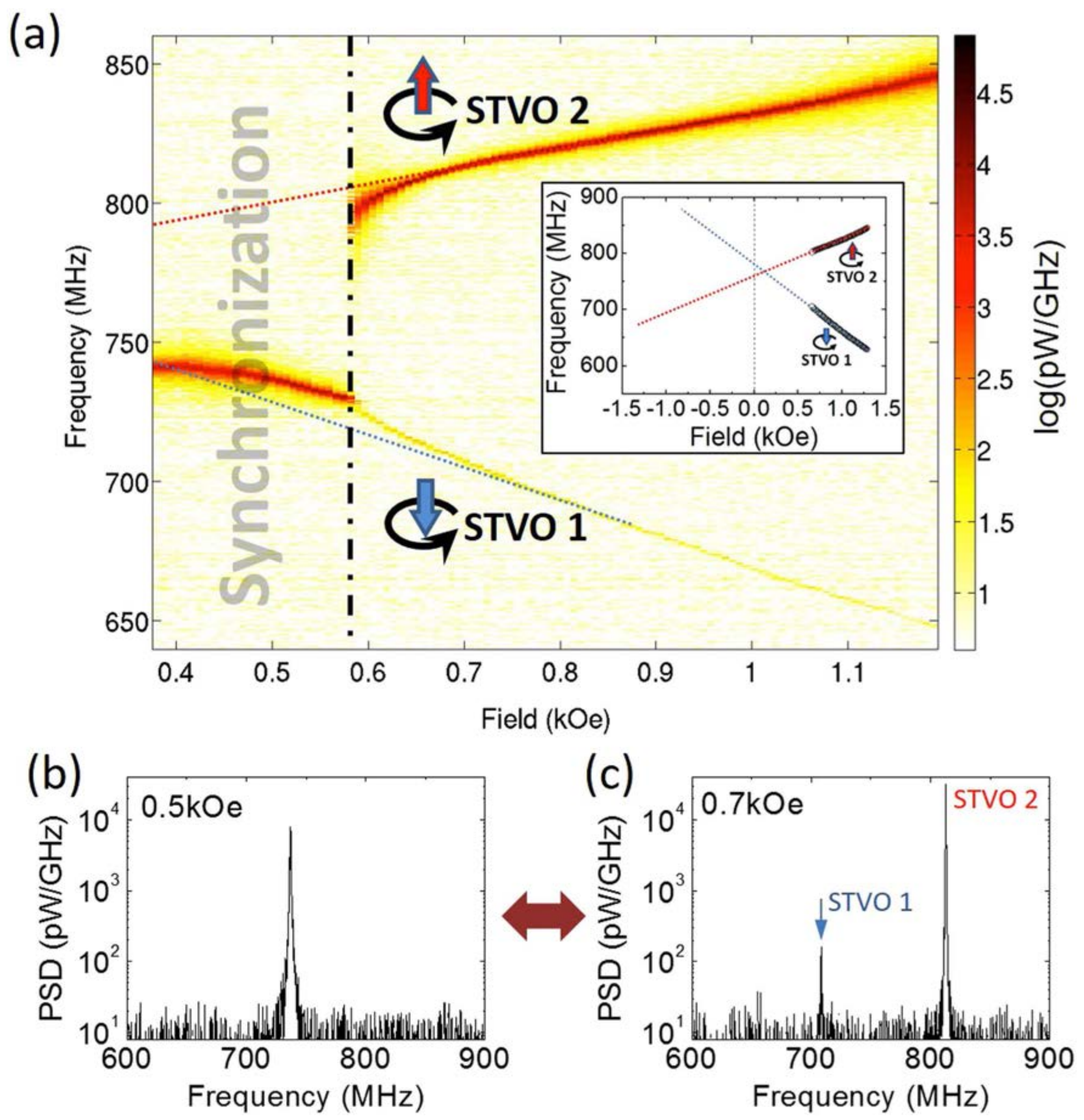


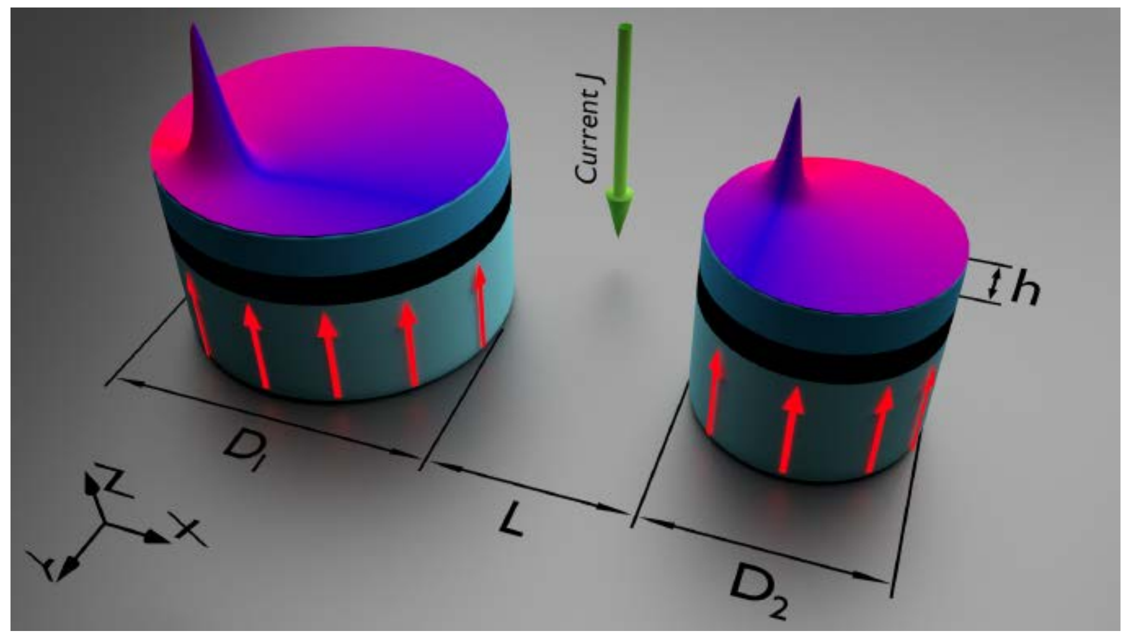


Magnetic Vortex Dynamics









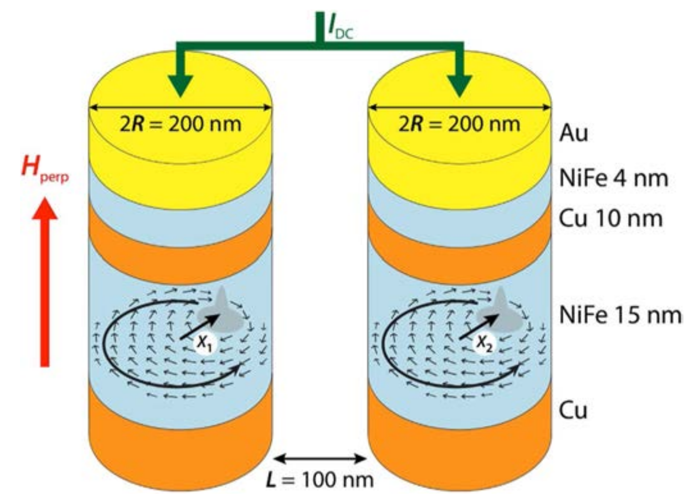
ARTICLE

Received 12 Jan 2010 | Accepted 4 Mar 2010 | Published 12 Apr 2010 DOI: 10.1038/ncomms1006

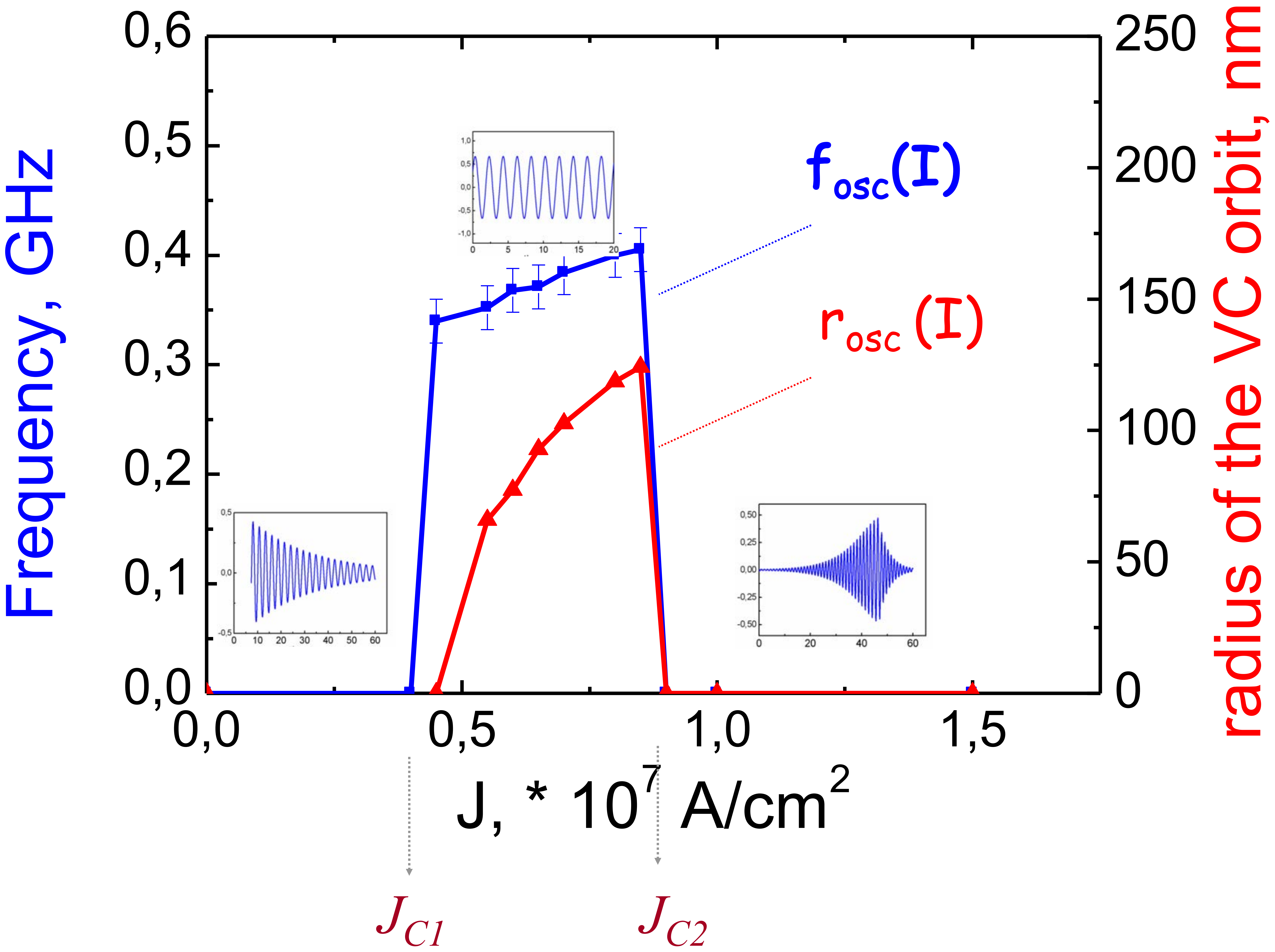
Large microwave generation from current-driven magnetic vortex oscillators in magnetic tunnel junctions

A. Dussaux[1], B. Georges[1], J. Grollier[1], V. Cros[1], A.V. Khvalkovskiy[1,2], A. Fukushima[3], M. Konoto[3], H. Kubota[3], K. Yakushiji[3], S. Yuasa[3], K.A. Zvezdin[2,4], K. Ando[3] & A. Fert[1]

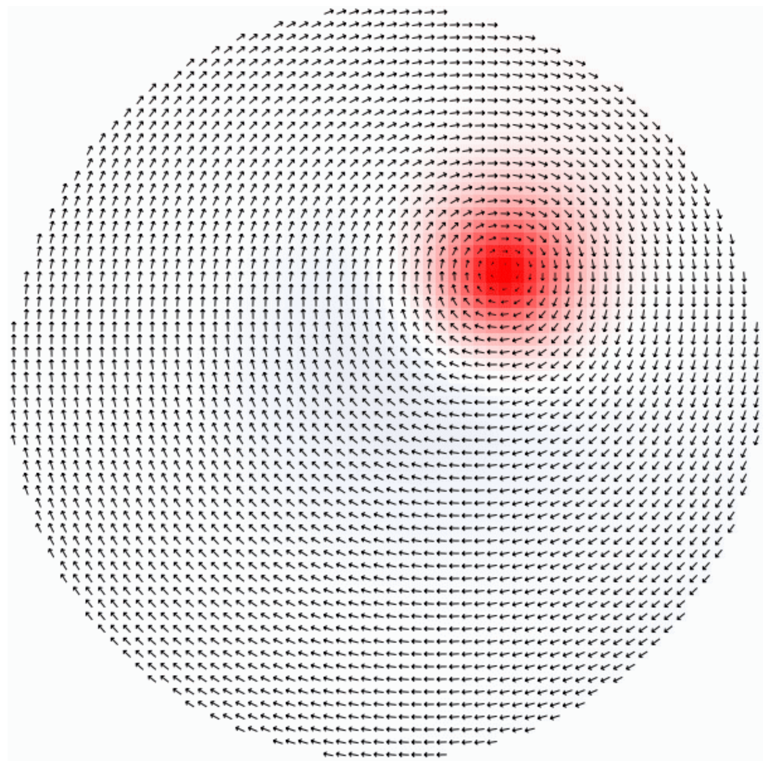
SCIENTIFIC REPORTS | 5:17039 | DOI: 10.1038/srep17039

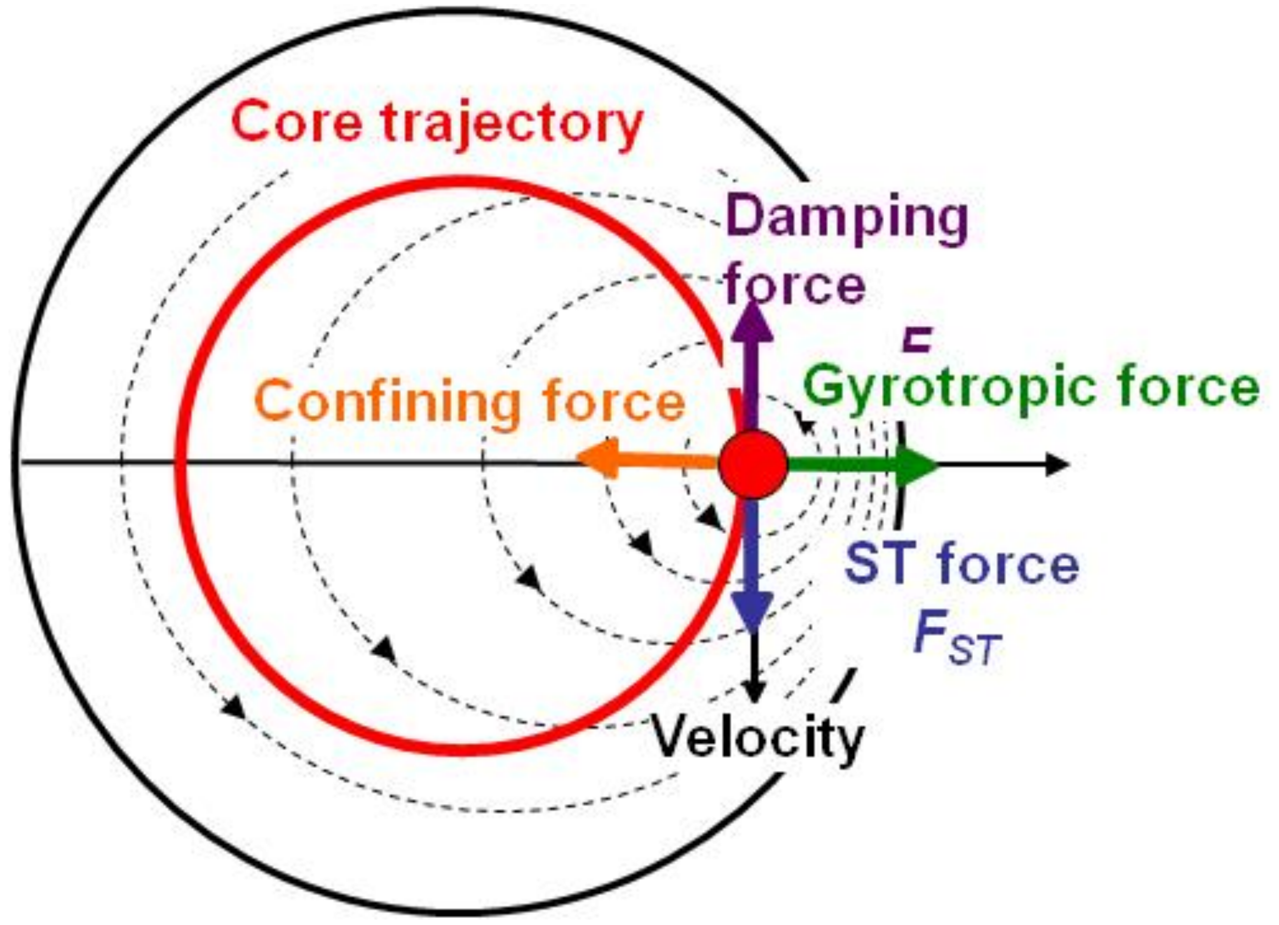


Magnetic Vortex Dynamics



$$-\frac{\partial W}{\partial \mathbf{X}} + \mathbf{G} \times \dot{\mathbf{X}} - \alpha\eta\dot{\mathbf{X}} + \mathbf{F}_{ST} = 0$$





A.V. Khvalkovskiy, KAZ, et al Phys. Rev. B. 80, 140401(R) (2009)

Spin-pumping from magnetic vortex

$$\frac{d\mathbf{M}}{dt} = -\gamma\mathbf{M}\times\mathbf{H}_{eff} + \alpha\mathbf{M}\times\dot{\mathbf{M}} - \frac{\gamma_0 a_J}{M_s}\mathbf{M}\times\left[\mathbf{M}\times\mathbf{m}_{ref}\right] - \gamma b_J\mathbf{M}\times\mathbf{m}_{ref}$$

Parameters:

$D = 100\,nm; t_{TI} = 100\,nm;\; t_{Py} = 4\,nm;$

$M_s = 720\,\frac{\mathrm{emu}}{\mathrm{cm}^3};$

$\theta_{ISHE} = 0.38$

$g_{eff} = 3\times10^{19}\,m^{-2}$

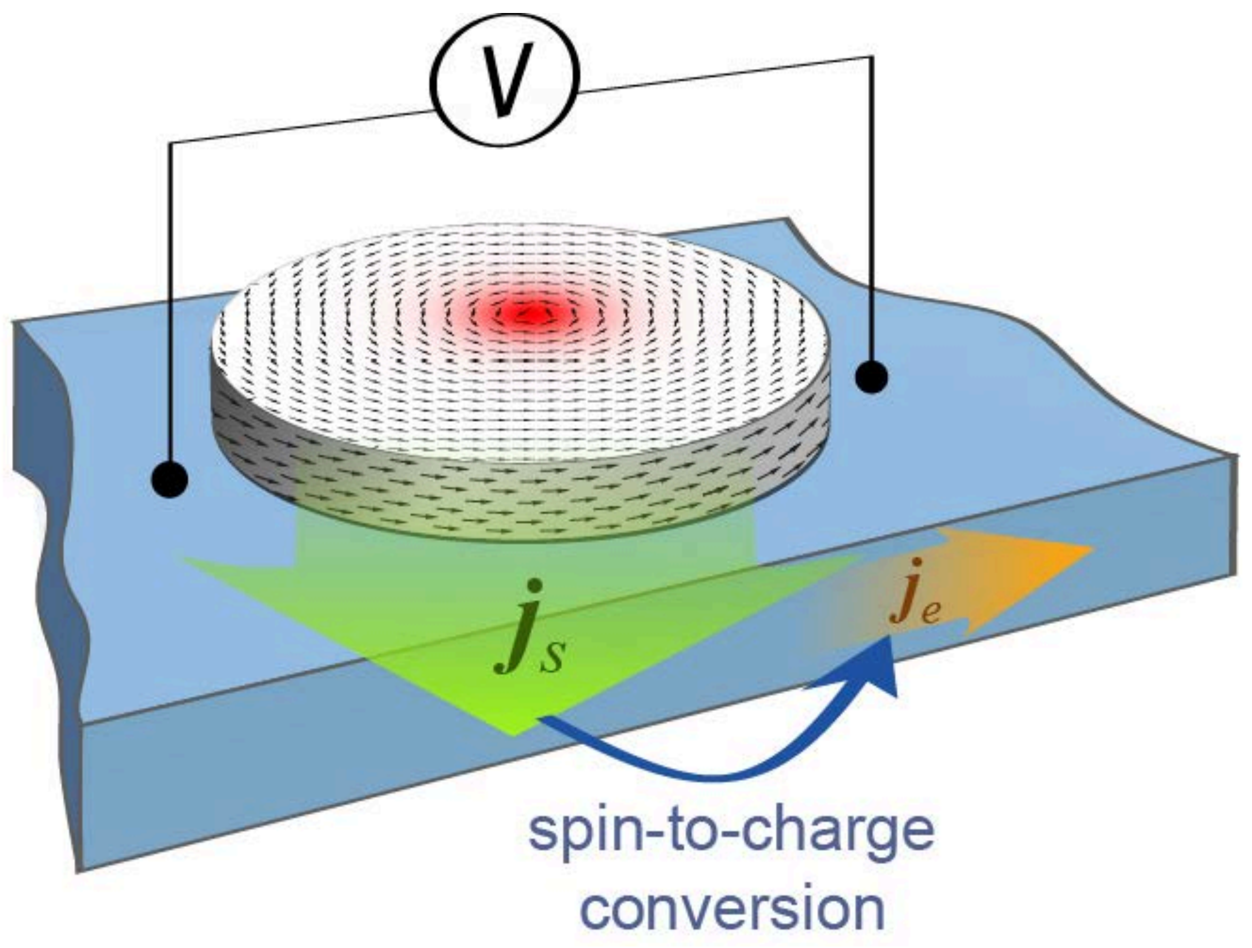
$\lambda = 6\,nm$ (spin-diffusion length)

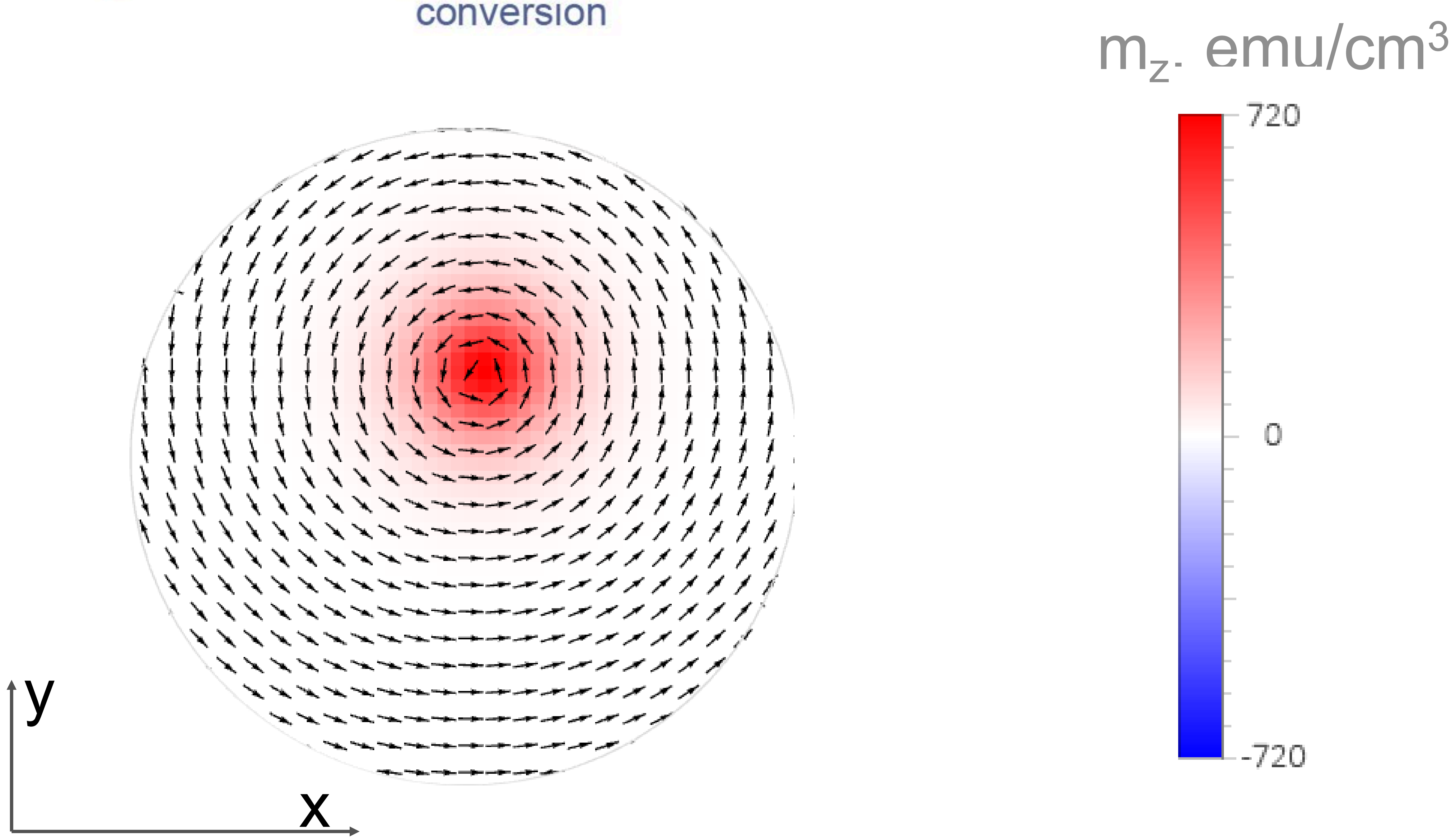
Oscillations period: 17.3 ns

RF field 0.5 Oe

Cell 2x2 nm

Bias field 60 Oe

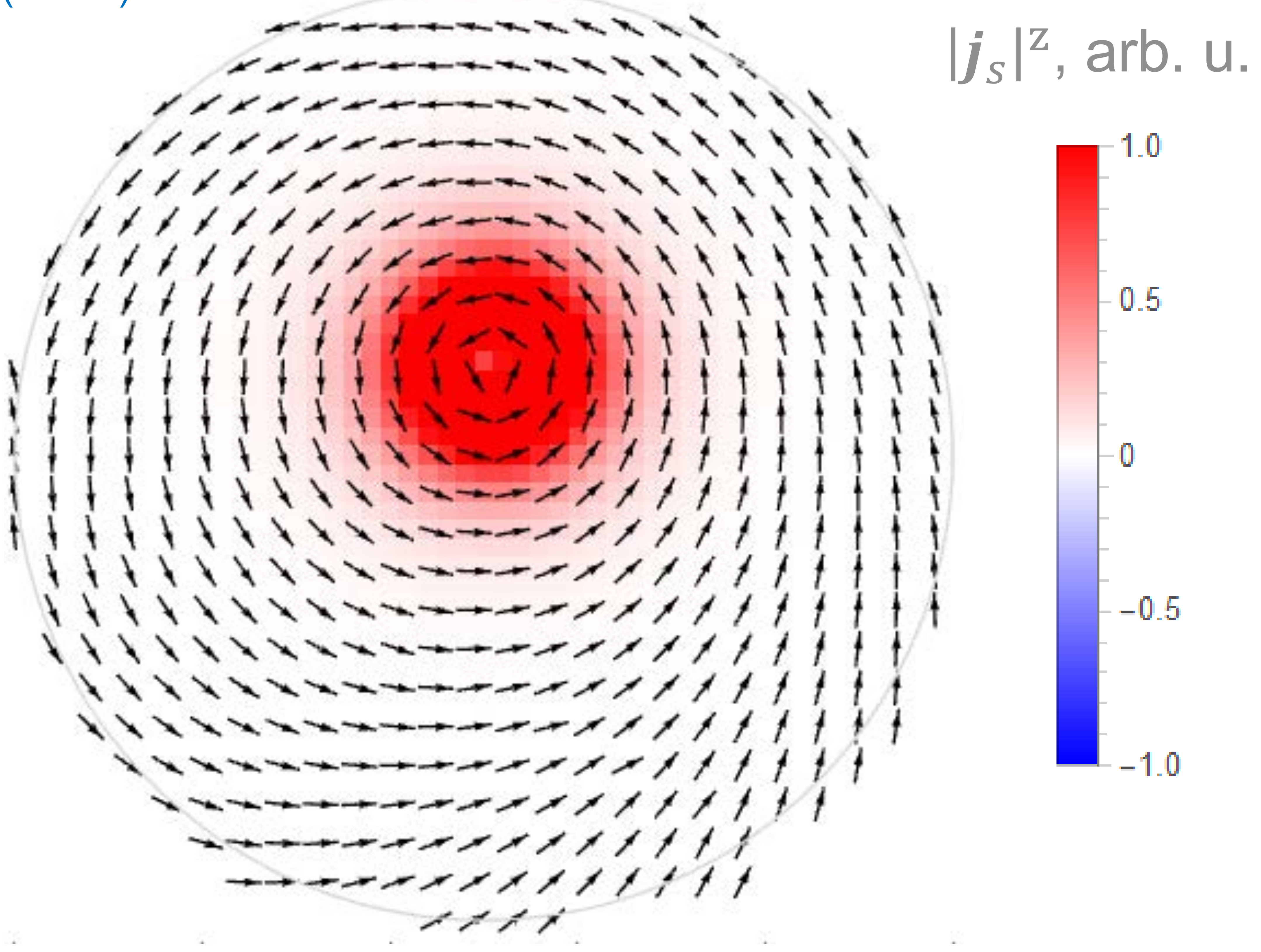




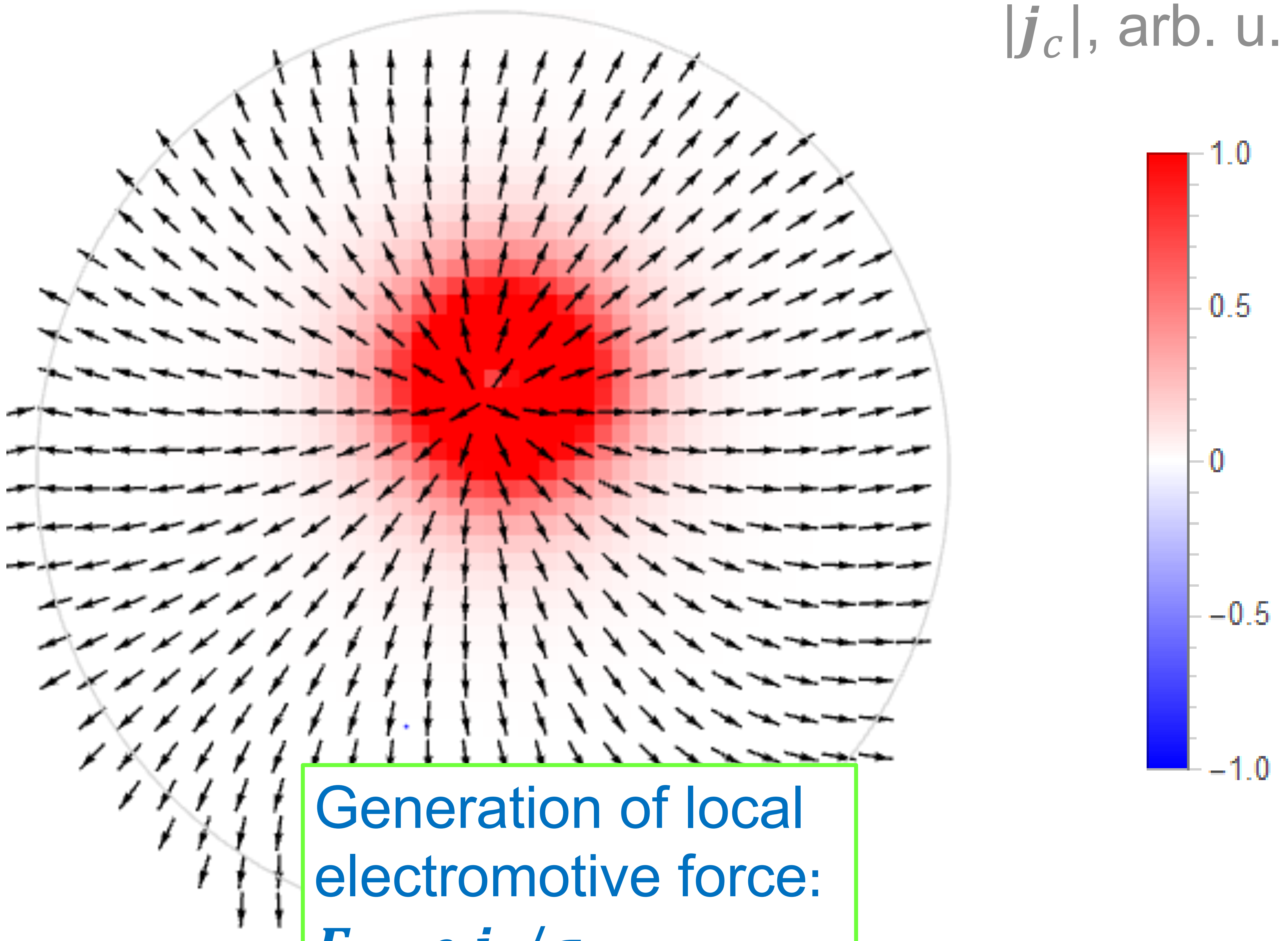
Spin-pumping from magnetic vortex

Distribution of generated spin current density during vortex dynamics:

Average over the oscillations period of generated spin current with regard to spin polarization (arrows) and absolute value (color)



Distribution of the ISHE-generated charge current density during vortex dynamics:



Generation of local electromotive force:
$\boldsymbol{F} = e\, \boldsymbol{j}_c/\sigma$

Spin-pumping from magnetic vortex

Distribution of spin current inside the bulk of TI

Spin-diffusion equation (adiabatic limit):

$$\bar{\mu}_s(z) = \mu_s(z) - eV(z)$$

$$\frac{e}{\sigma_s}\frac{\partial J_s}{\partial z} = \frac{\bar{\mu}_s - \bar{\mu}_{-s}}{l_s^2}$$

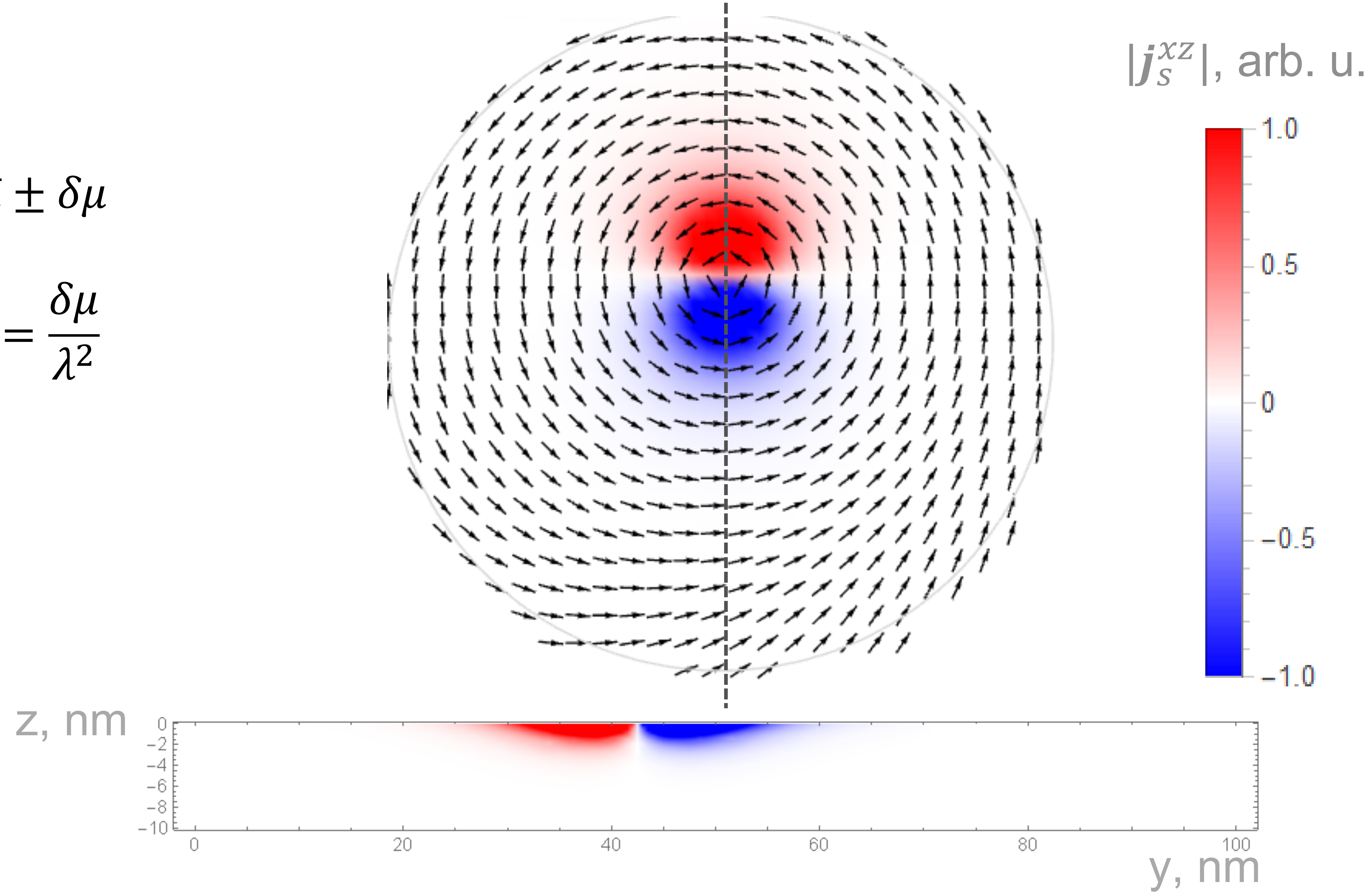
→

$$\bar{\mu}_\pm = \bar{\mu} \pm \delta\mu$$

$$\Delta(\delta\mu) = \frac{\delta\mu}{\lambda^2}$$

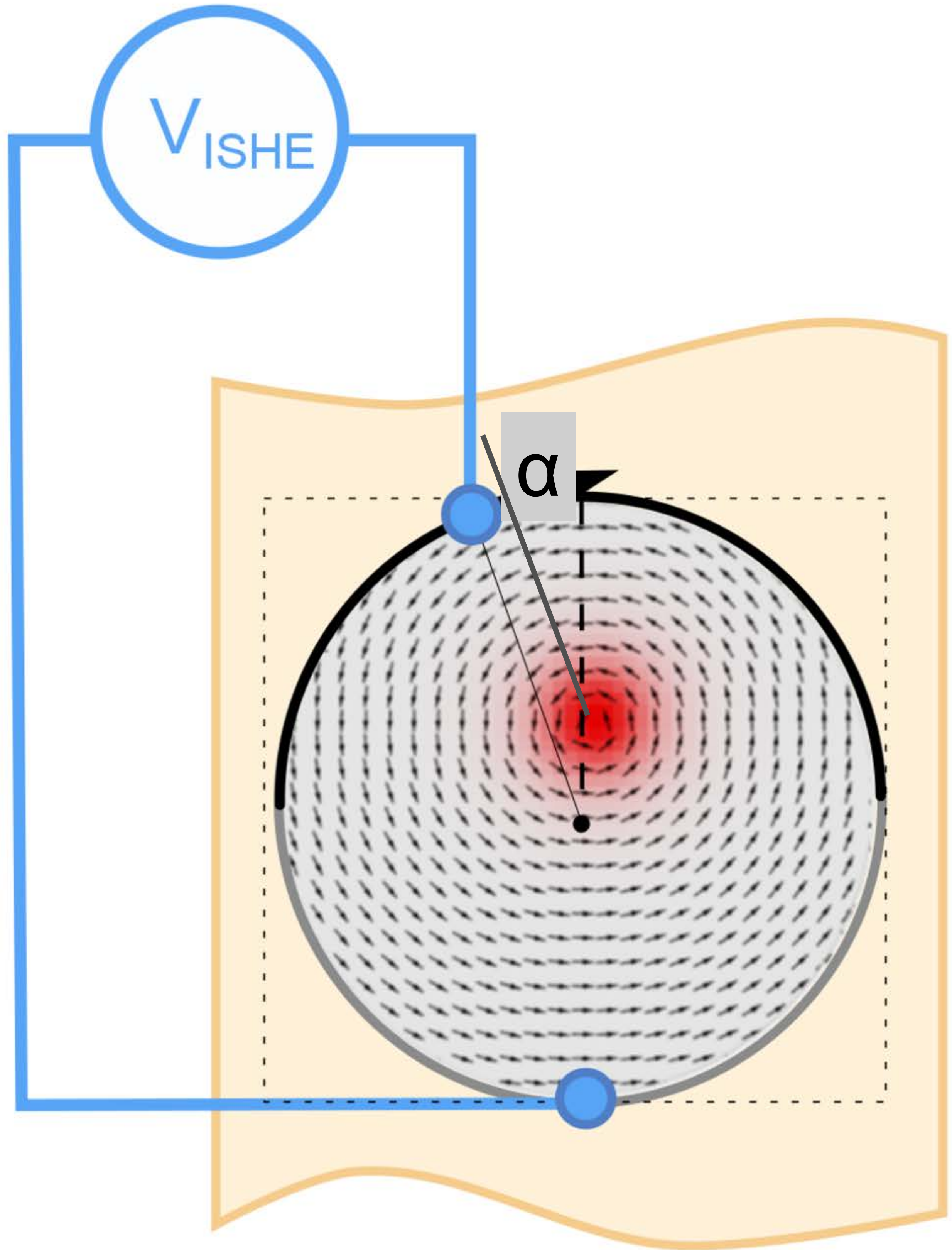
+ appropriate boundary conditions

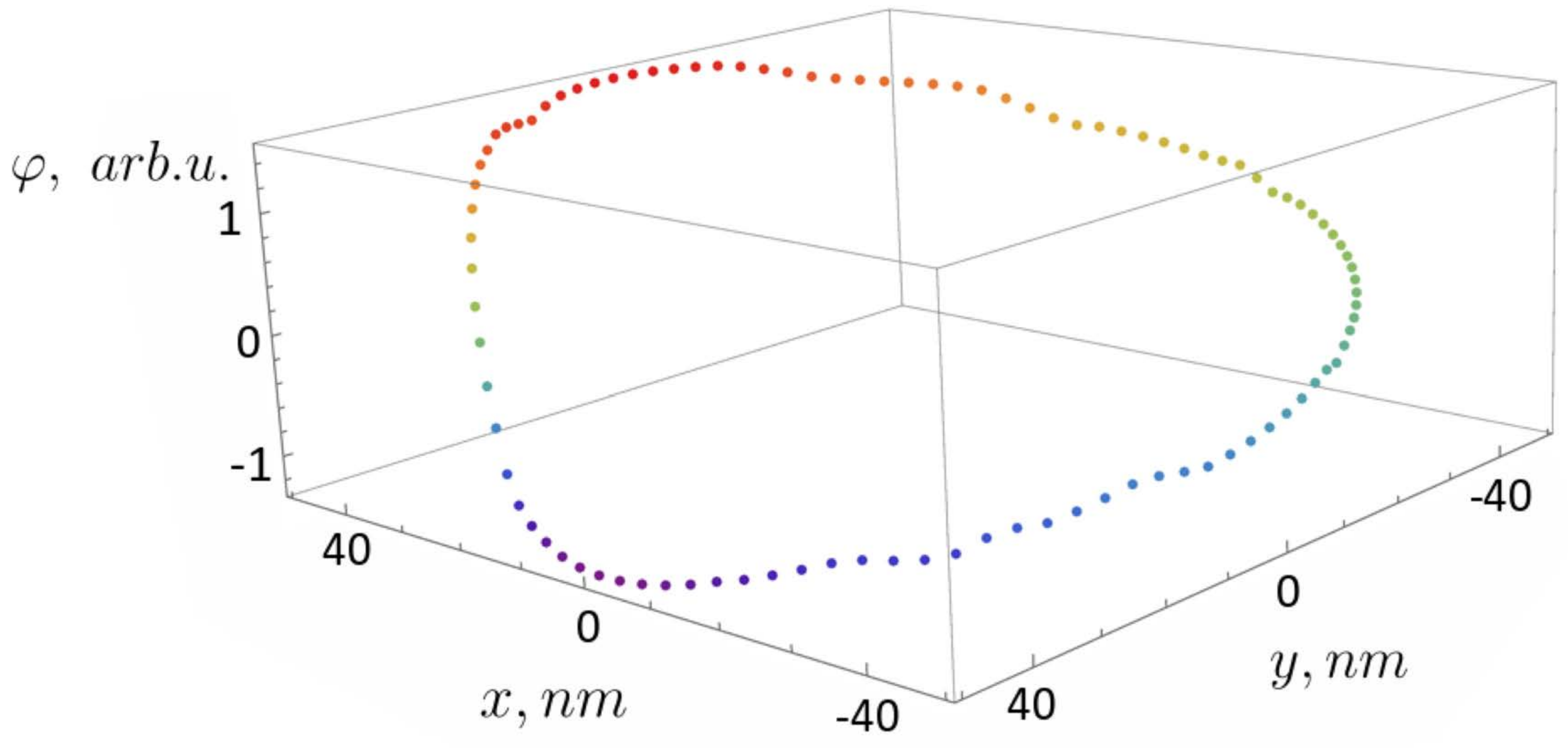
x-polarized component of spin current in TI:



Spin-pumping from magnetic vortex

We calculate the distribution of the potential from integrating the known distribution of electromotive force.





Conclusions

Two cases of magnetization dynamics analysis via TI ISHE were considered, both experimentally and theoretically.

Our results suggest that ISHE probing through TI sensing layer is a prospective tool to electrically detect fast magnetization dynamics.

The outlook is to extend this method for ultrafast magnetization dynamics.

Thank you for your attention!!!