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Spin-Transfer Induced Dynamic Modes in Single-Crystalline Fe/Ag/Fe Nanopillars

V. Sluka, R. Lehndorff, A. Kakáy, R. Hertel, D. E. Bürgler, and C.M. Schneider

Institut für Festkörperforschung – Elektronische Eigenschaften (IFF-9) and

JARA-FIT, Research Center Jülich GmbH, D-52425 Jülich, Germany

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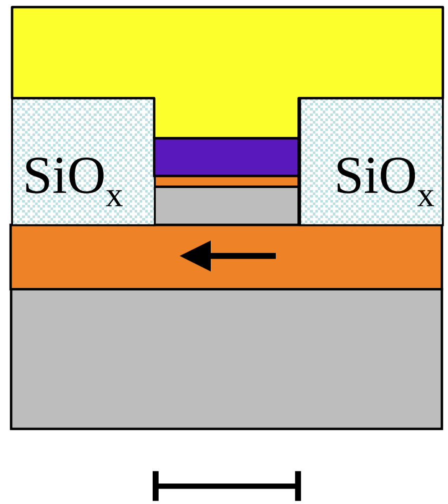
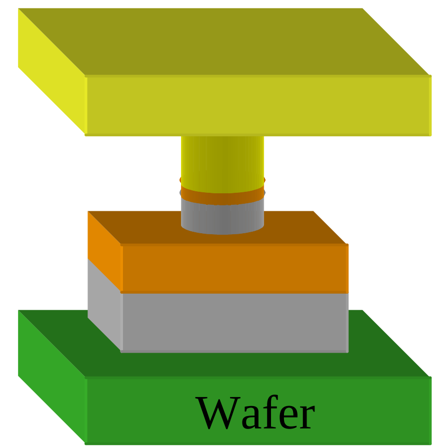
Single-crystalline, epitaxial Fe/Ag/Fe(001) nanopillars

MBE growth of fully epitaxial multilayer structure on GaAs(001)
Optical and e-beam lithography to define nanopillars with ∅ ≈ 70 nm

top electrode	Ti/Au
"free" layer	2 nm Fe
decoupled by	6 nm Ag
"fixed" layer	20 nm Fe
bottom electrode	Ag
+ SiO_x insulation	



∅ ≈ 70 nm



All layers grow epitaxially and single-crystalline
as confirmed by LEED and RHEED

H. Dassow, D. E. Bürgler *et al.*, Appl. Phys. Lett. **89**, 222511 (2006)
R. Lehndorff, D.E. Bürgler *et al.*, Phys. Rev. B**76**, 214420 (2007)

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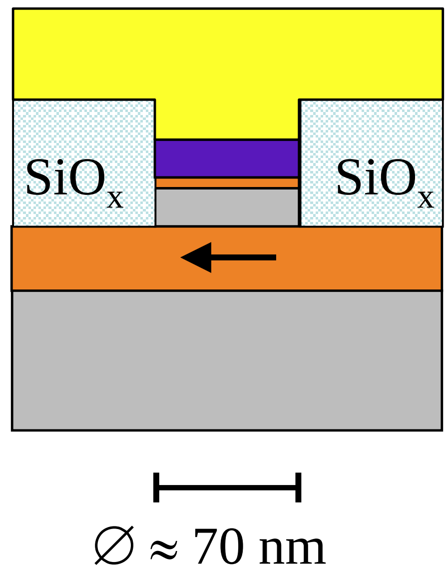

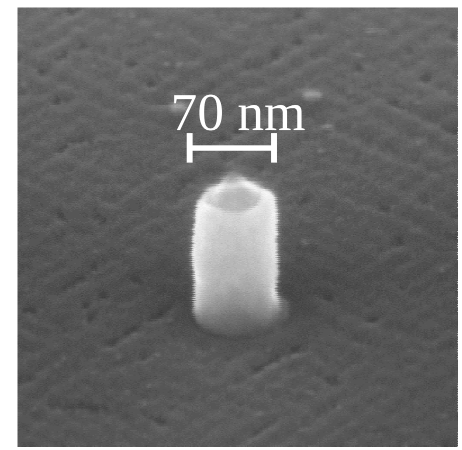

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Why single-crystalline Fe/Ag/Fe?

- Homogeneous magnetic (*e.g.* anisotropy) and electric (*e.g.* conductivity) properties

- Well defined, sharp interfaces

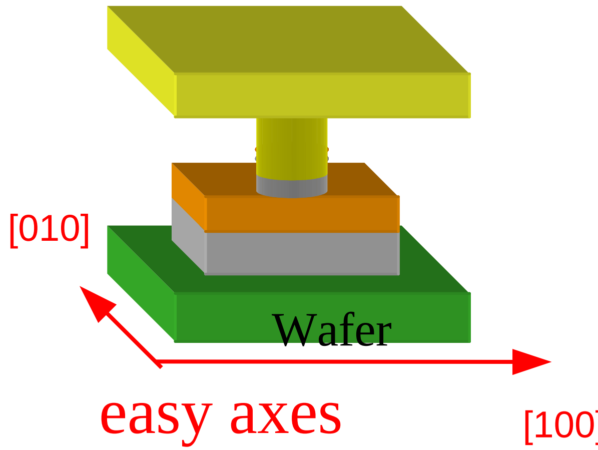
- Interplay between magnetocrystalline anisotropy and spin-transfer torque

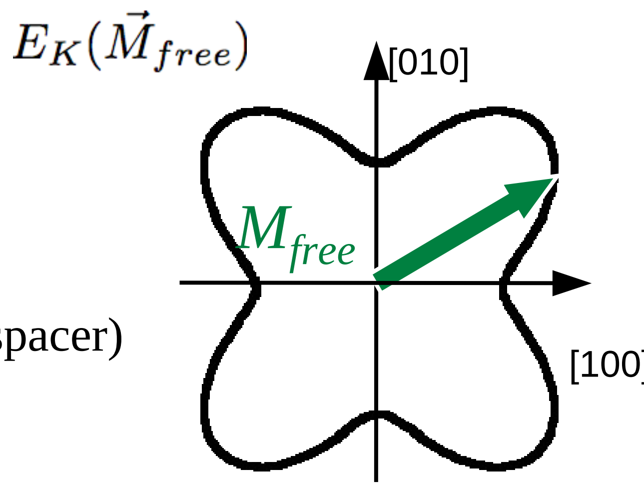
- Fe/Ag(001) interface predicted to be a good polarizer, *i.e.* large $P_r = 0.85$

- Fe/Ag/Fe(001) system predicted to exhibit strong spin accumulation, *i.e.* large asymmetry parameter $\Lambda = 4.0$

(Λ measures conductivity mismatch between FM layer and spacer)

M.D. Stiles and D.E. Penn, Phys. Rev. B **61**, 3200 (2000)



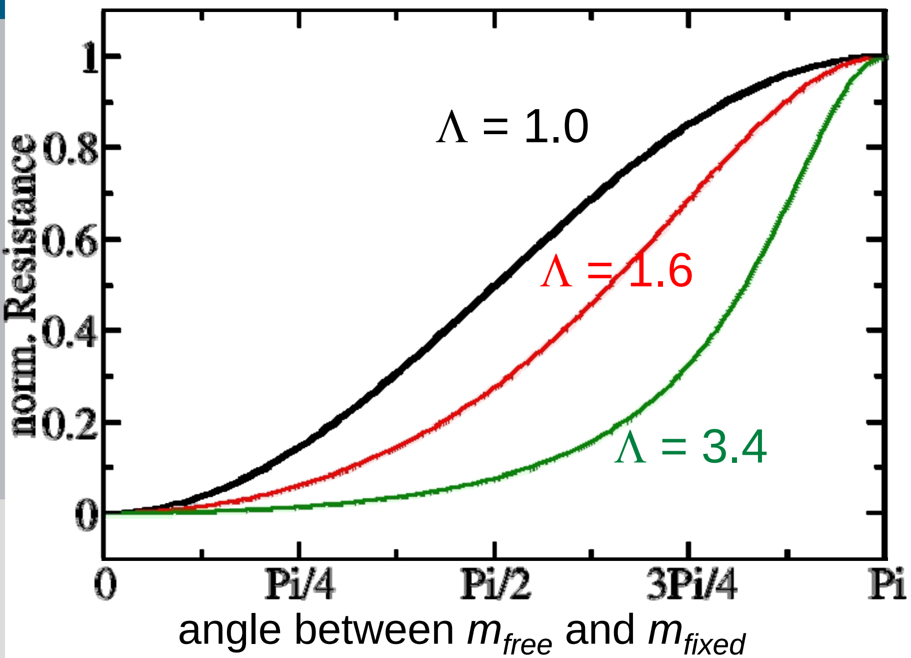


Prediction of Slonczewski's theory

J.C. Slonczewski, J. Magn. Magn. Mater. **247**, 324 (2002)

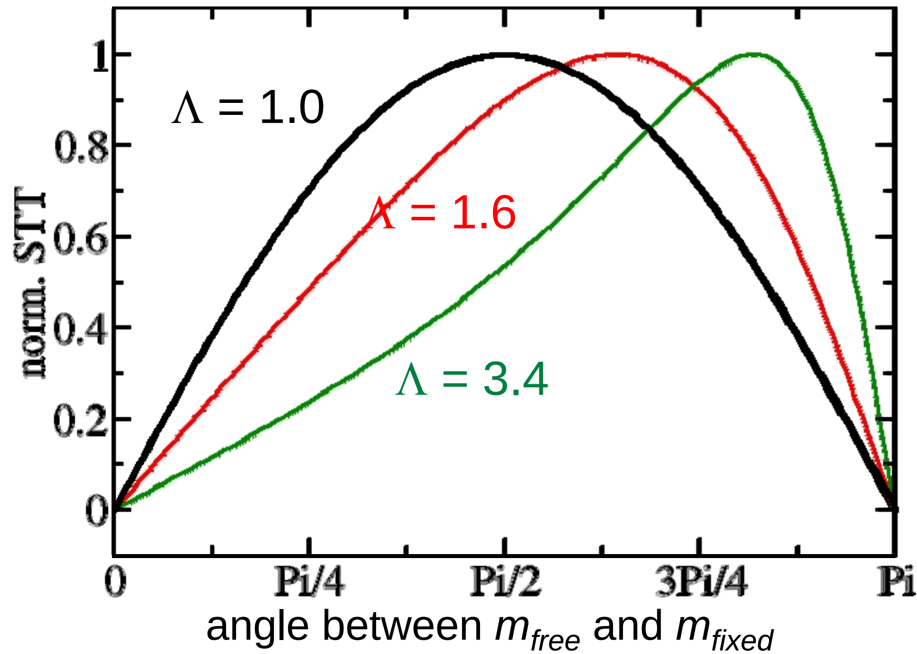
Angular dependence of GMR

$$R(\theta) \propto \frac{1-\cos^2(\theta/2)}{1+(\Lambda^2-1)\cos^2(\theta/2)}$$



Angular dependence of STT

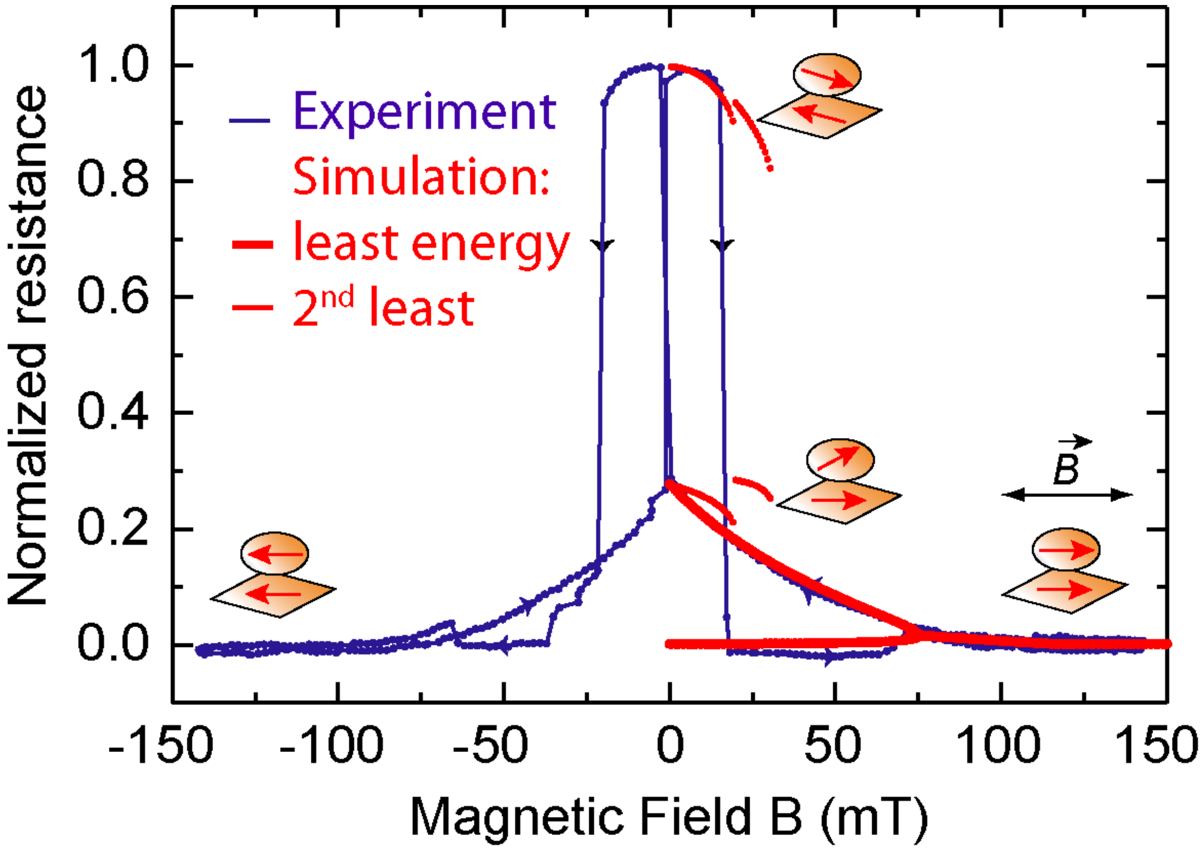
$$STT(\theta) \propto \frac{P_r \sin(\theta)}{\Lambda\cos^2(\theta/2)+\Lambda^{-1}\sin^2(\theta/2)}$$

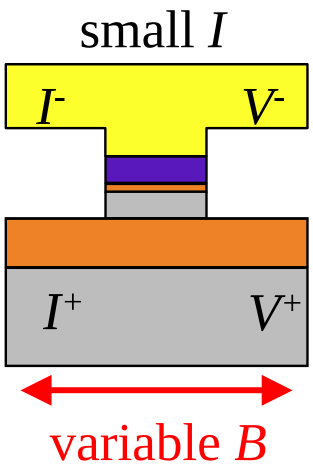


⇒ Fe/Ag/Fe(001) system is expected to exhibit strong asymmetry for both GMR and STT

CPP-GMR of a single-crystalline nanopillar

2 nm Fe / 6 nm Ag / 20 nm Fe at 5 K, field along Fe(110) hard axis





R. Lehndorff, D.E. Bürgler *et al.*, Phys. Rev. B**76**, 214420 (2007)

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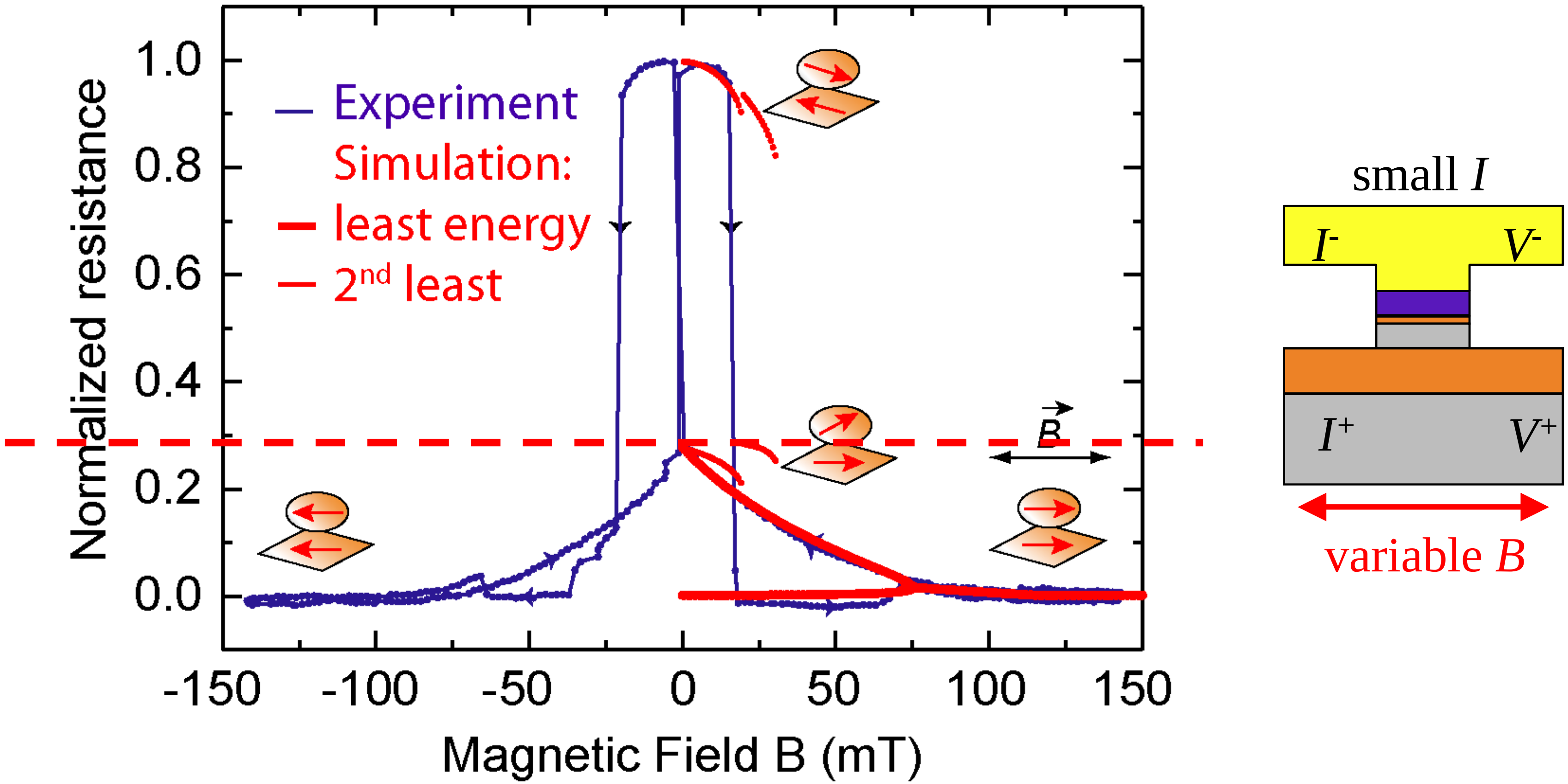
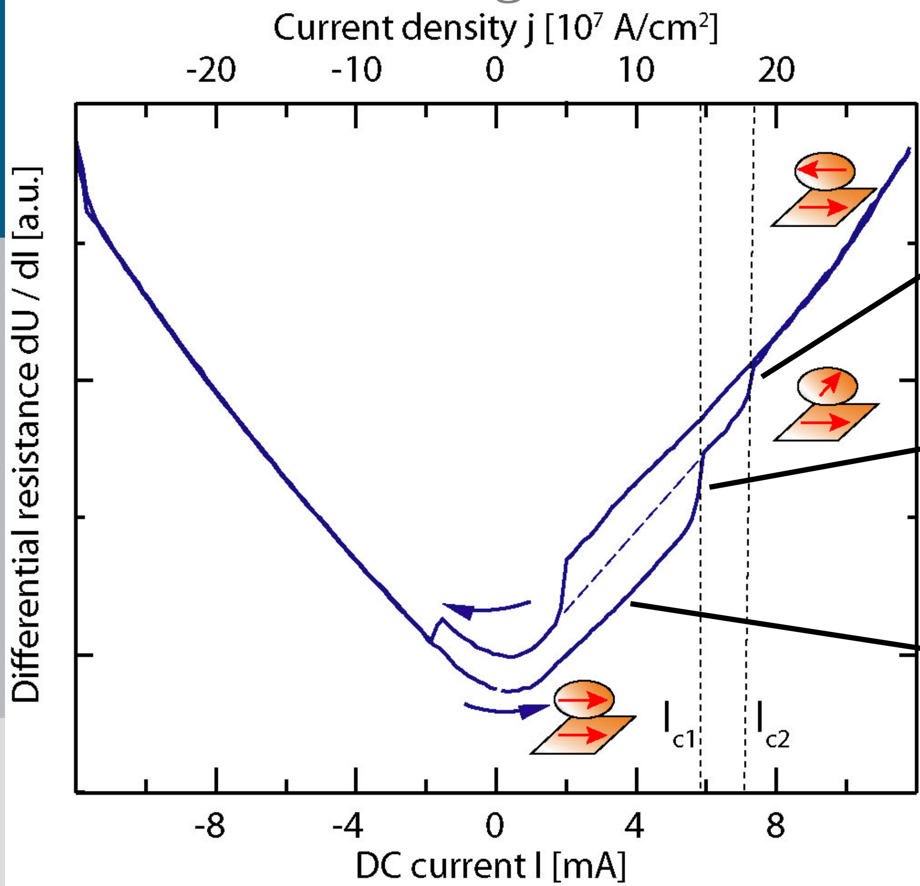


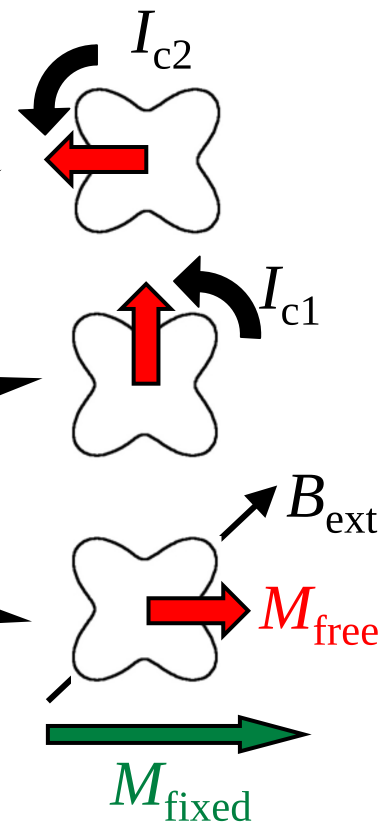
$\Rightarrow$ GMR(90°) = 0.3 yields Λ_{GMR} = 1.6

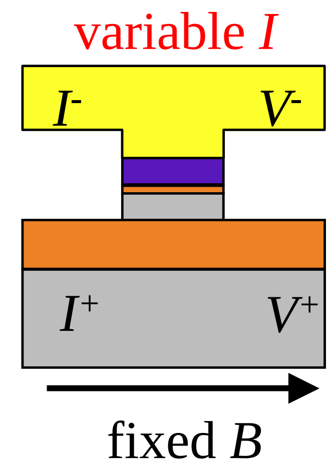
R. Lehndorff, D.E. Bürgler *et al.*, Phys. Rev. B**76**, 214420 (2007)

Two-step current-induced magnetization switching

2 nm Fe / 6 nm Ag / 20 nm Fe at 5 K; B_{ext} = 7.9 mT along hard axis





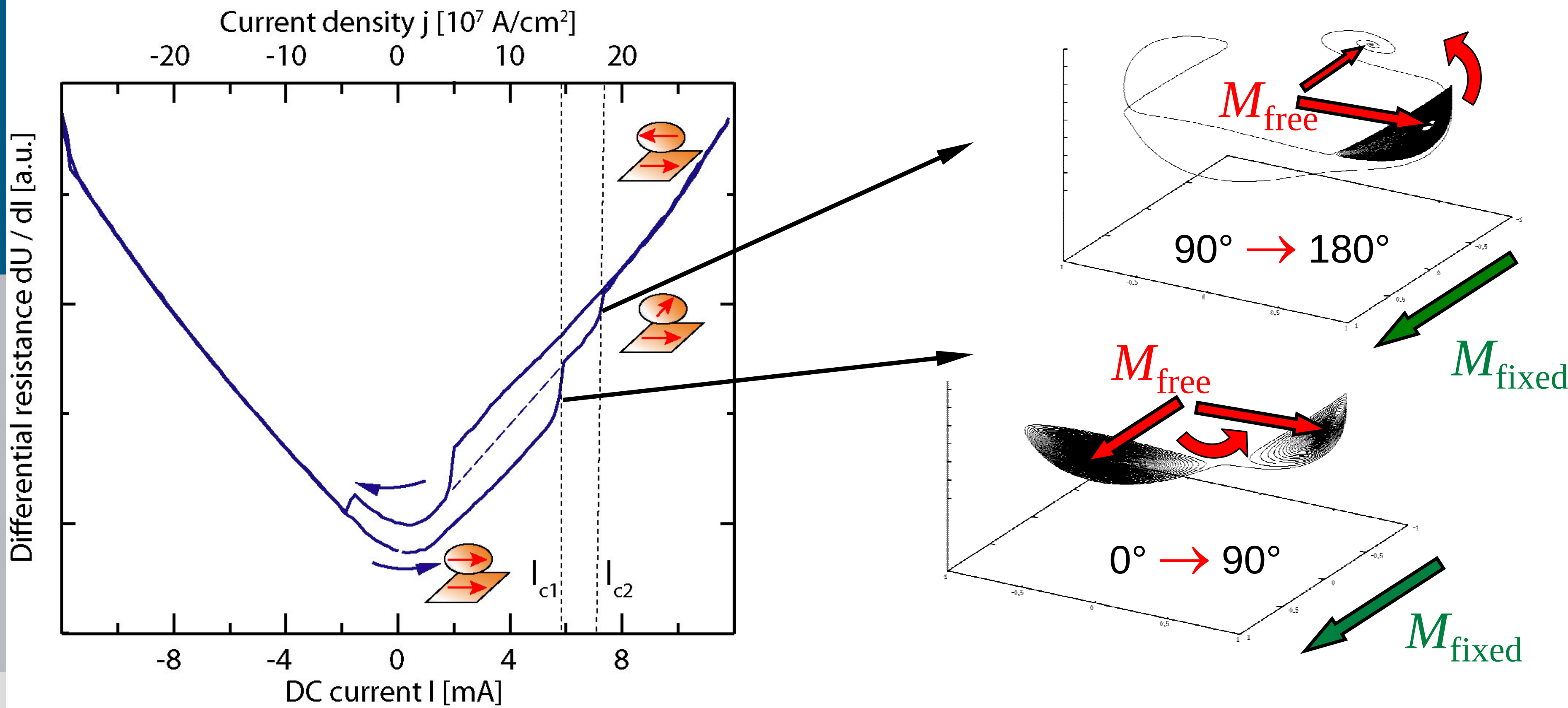


Four energetically nearly identical states give rise to two-step switching:

Parallel $\xrightarrow{I_{c1}}$ 90° $\xrightarrow{I_{c2}}$ Antiparallel

$$\Rightarrow \Lambda_{STT} = 3.4$$

Simulation of two-step switching

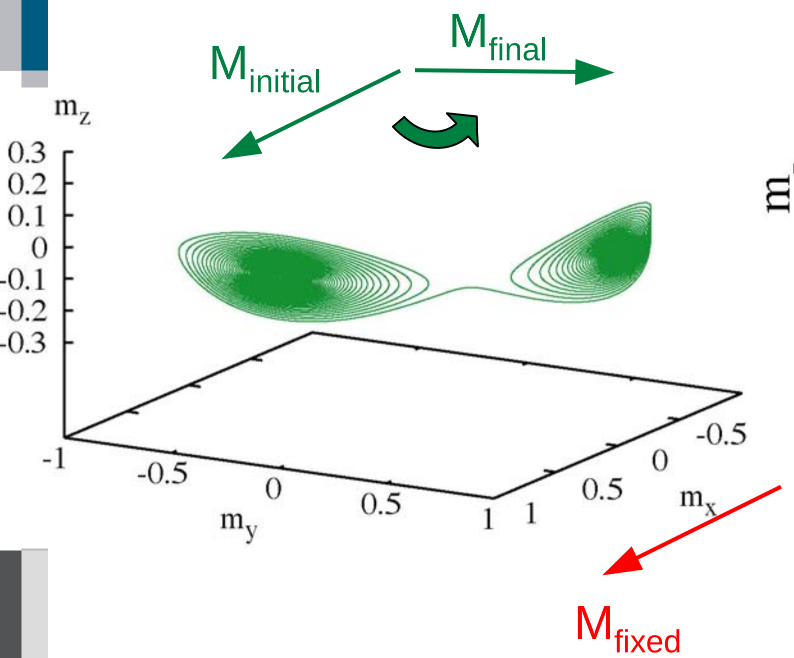


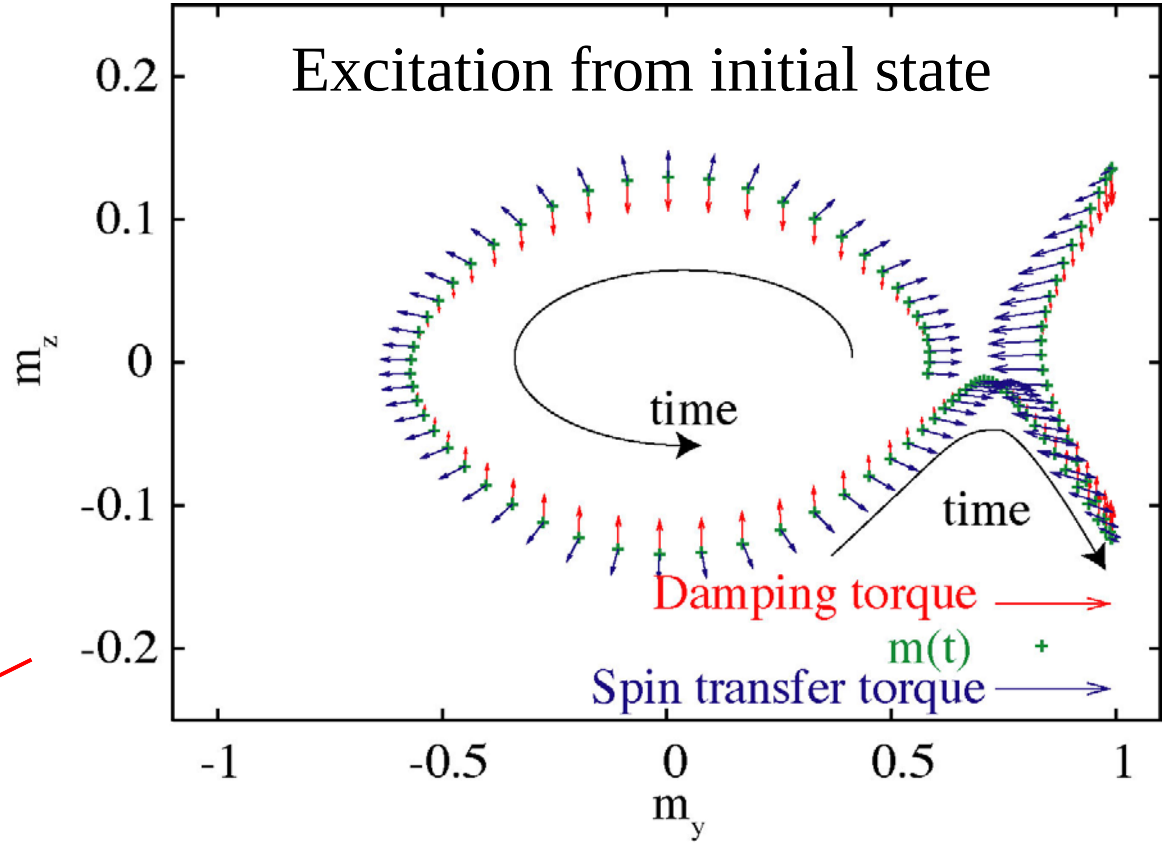
⇒ Two-step switching (0° → 90°→ 180°) can be reproduced by macrospin and micromagnetic simulations

R. Lehndorff, D.E. Bürgler *et al.*, Phys. Rev. B**76**, 214420 (2007)

Switching to the 90°-state: Simulation

I_{c1}: STT acts against damping on whole trajectory





R. Lehndorff, D.E. Bürgler *et al.*, IEEE Trans. Magn. **44**, 1951 (2008)

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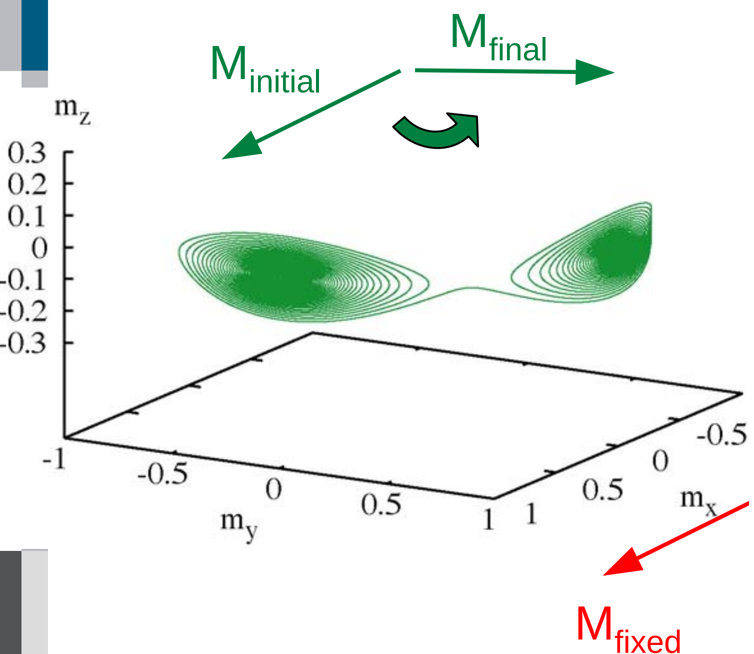
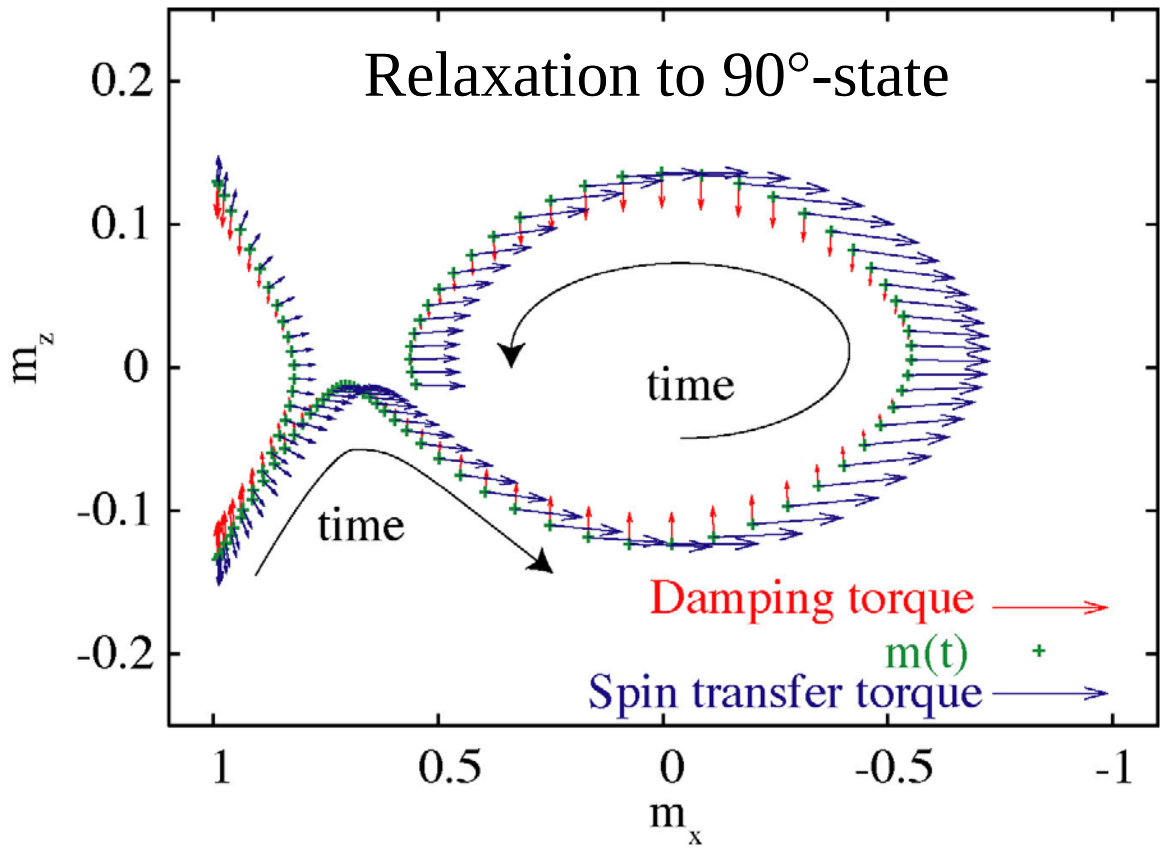
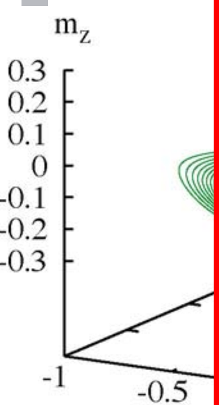


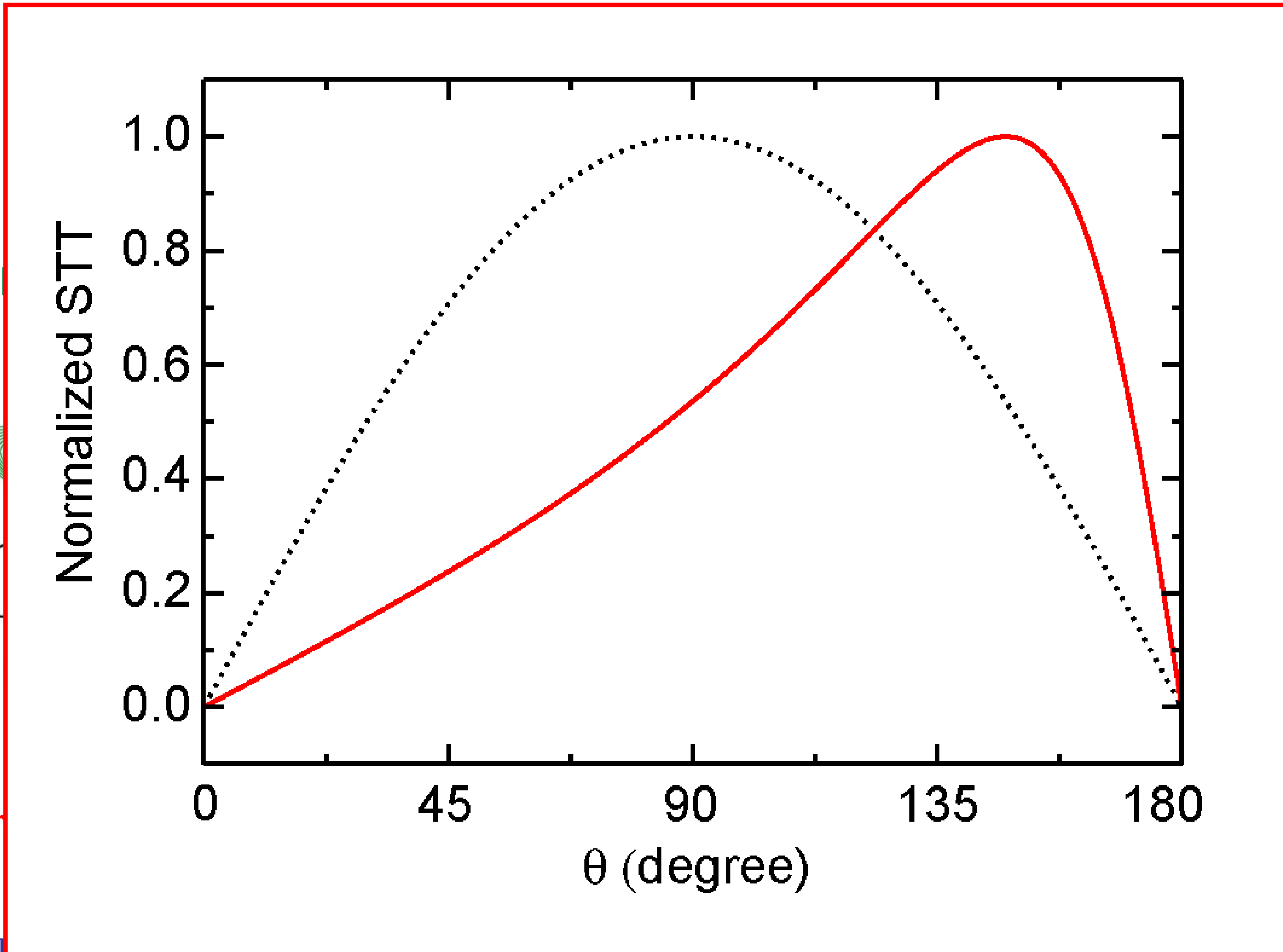


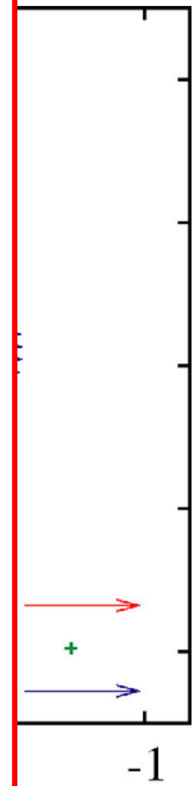
After switching the net action of the STT along the trajectory almost cancels out ⇒ relaxation in the 90°-state

R. Lehndorff, D.E. Bürgler *et al.*, IEEE Trans. Magn. **44**, 1951 (2008)

Switching to the 90°-state: Simulation



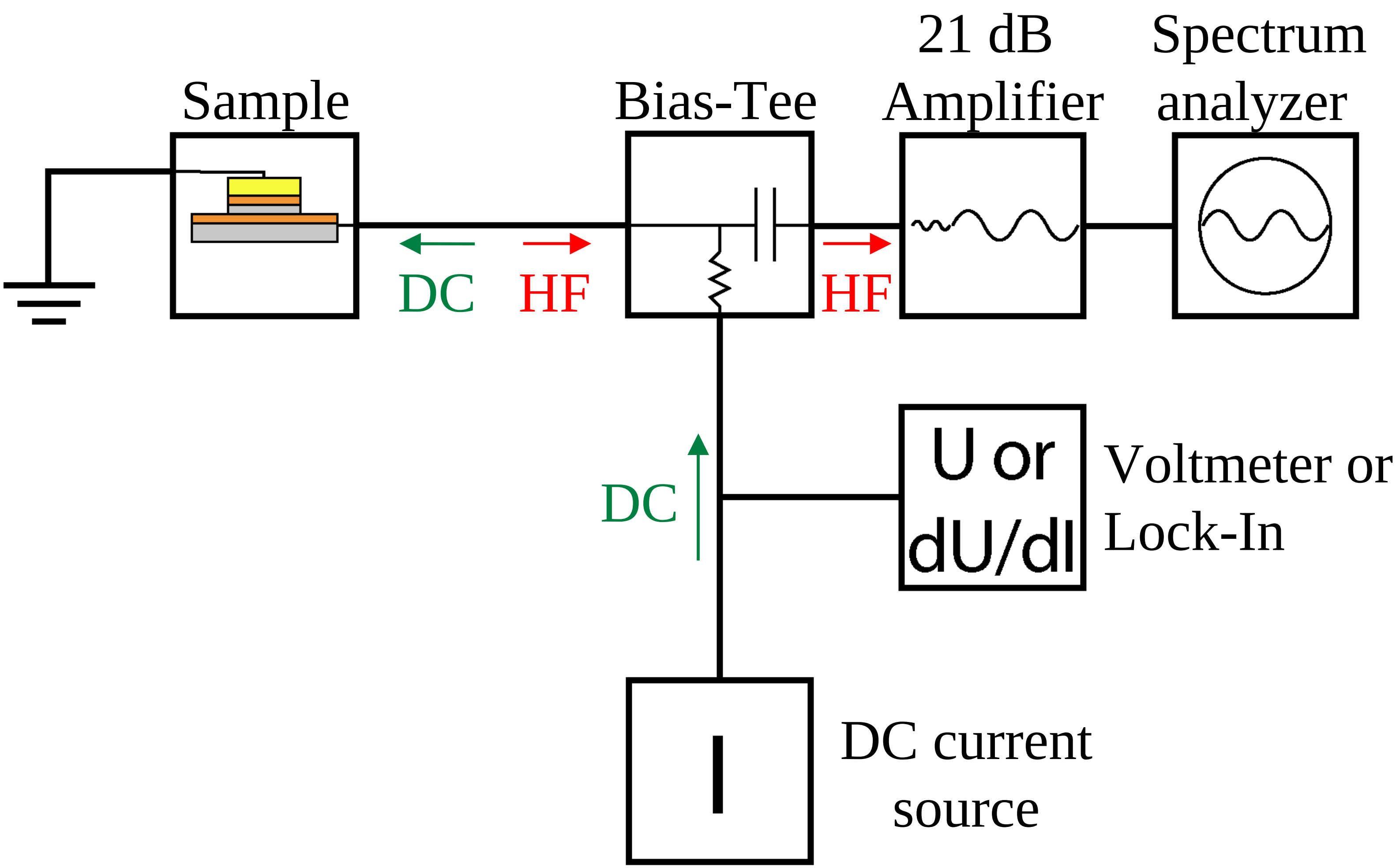




After … host

R. Lehndorff, D.E. Bürgler *et al.*, IEEE Trans. Magn. to appear (2008)

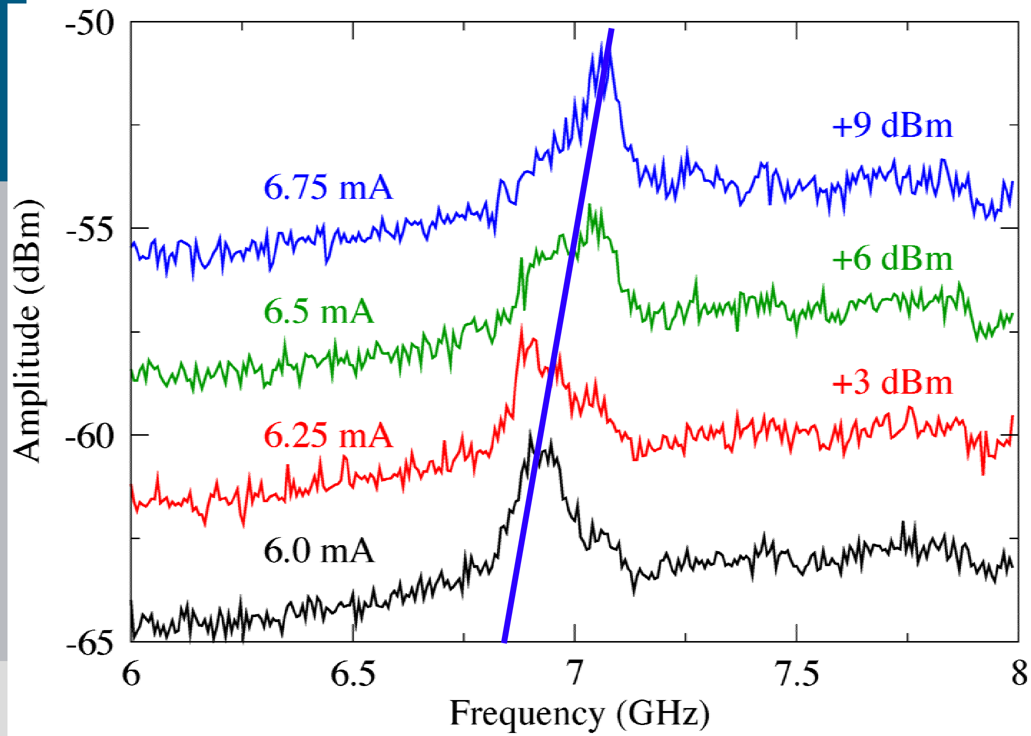
Wiring diagram for HF measurements

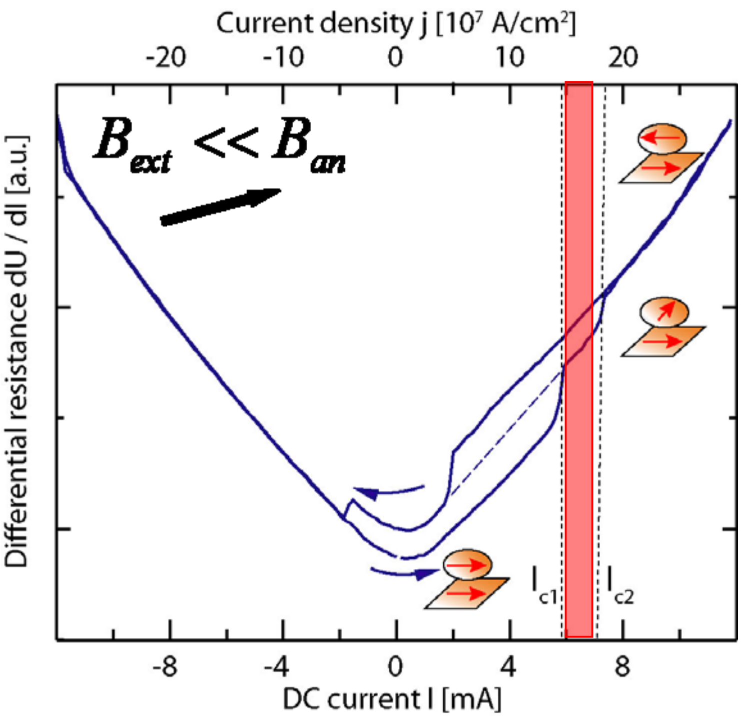


Setup similar to Kiselev *et al.*, Nature **425**, 380 (2003)

Low-field excitations: Experiment

A weak external field B_{ext} = 5 mT is applied at an angle of 15˚ relative to an easy axis, currents correspond to the 90˚-aligned state, T = 5 K.



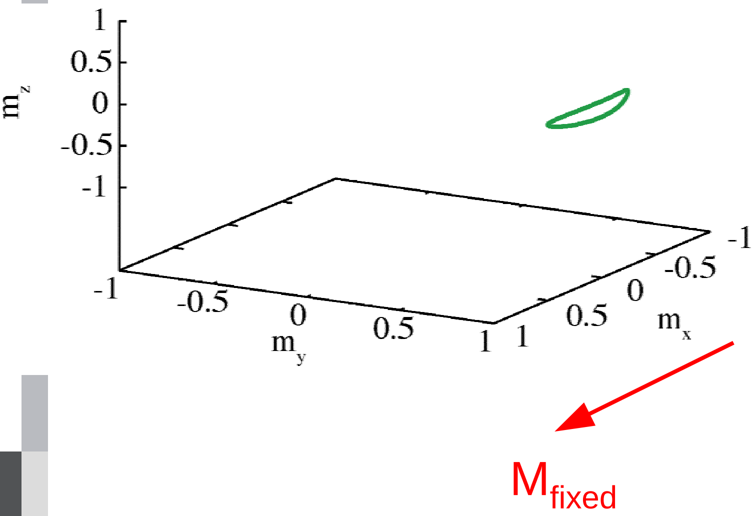


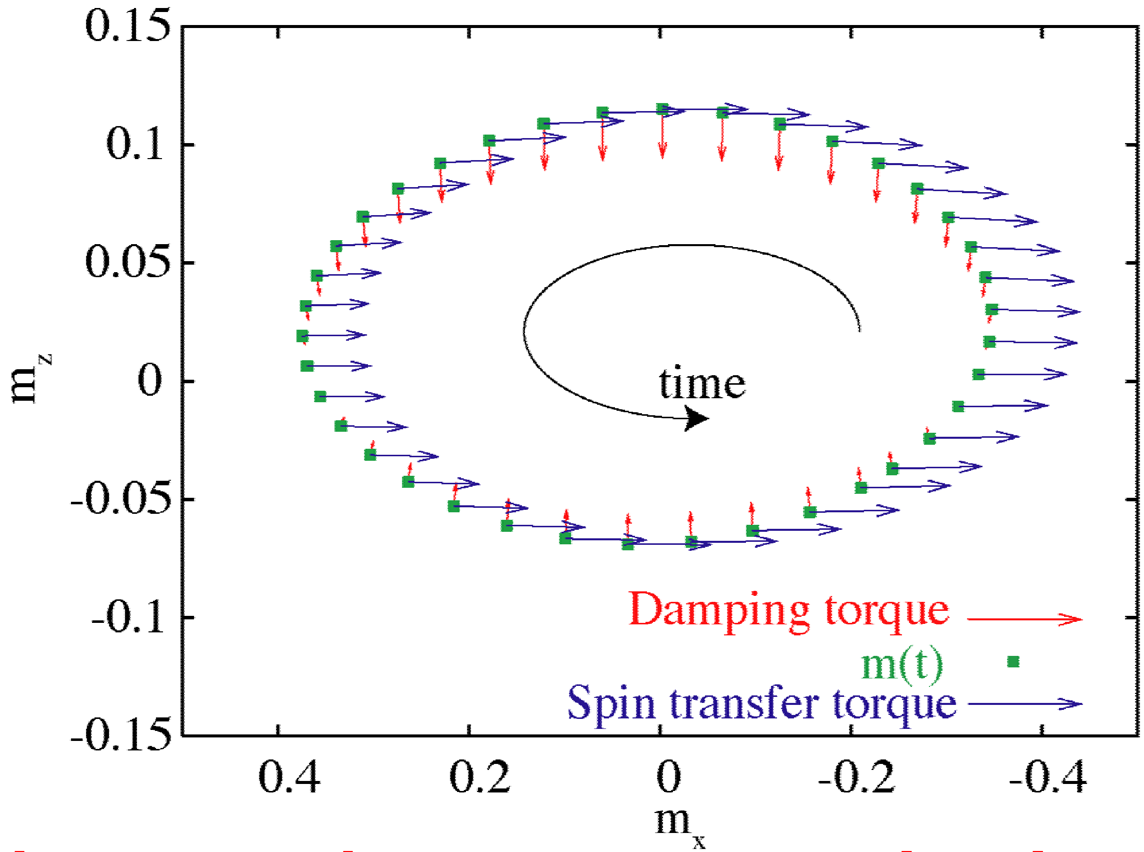
Interplay between anisotropy and STT explains the low(zero)-field excitations

R. Lehndorff, D.E. Bürgler *et al.*, IEEE Trans. Magn. **44**, 1951 (2008)

Low-field excitations: Simulation

Under low-field conditions a precession with smaller cone angle is excited



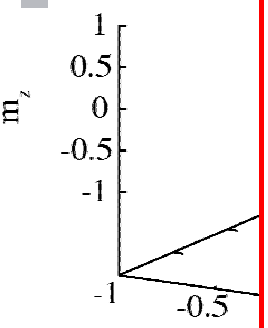


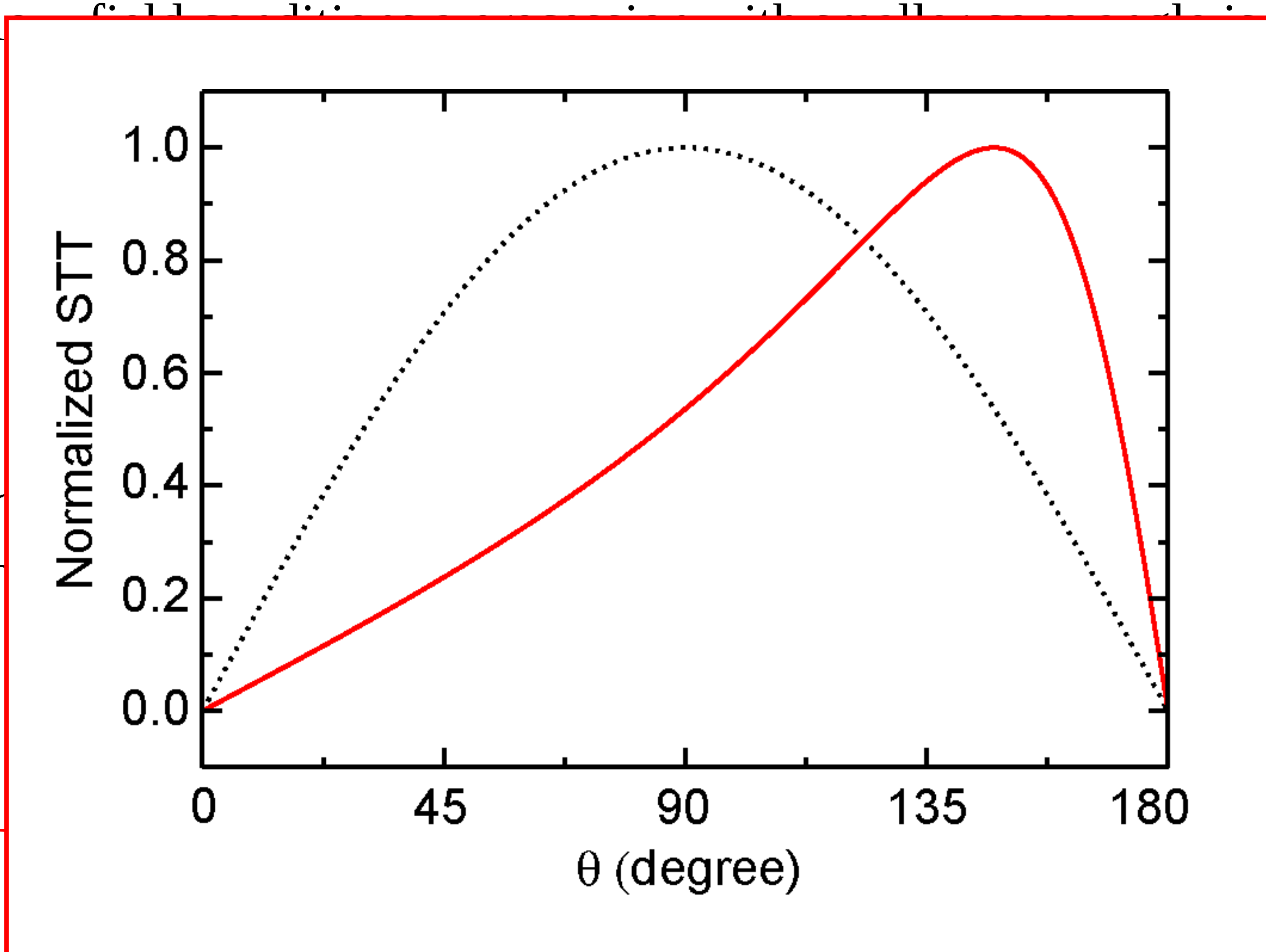
The STT is asymmetric with respect to the precession axis and partly cancels its action on M_{free} along one revolution

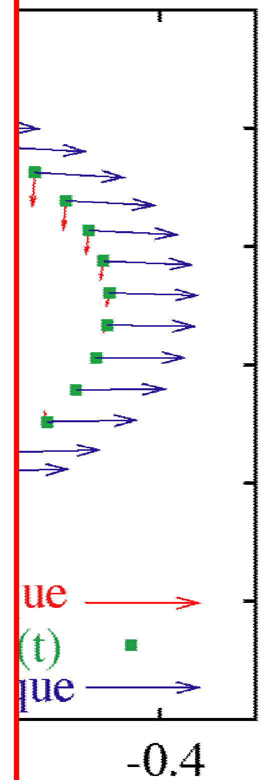
$\Rightarrow$ Low-field precession only exists due to the angular asymmetry of $g(\Theta)$

Low-field excitations: Simulation

Under l… excited







The ST… partly

⇒ Low-field precession only exist due to the angular asymmetry of $g(\Theta)$

Conclusions

Interplay between STT and cubic magnetocrystalline anisotropy in single-crystalline nanopillars:

- Two-step switching *via* an intermediate 90°-aligned state
- Low(zero)-field precession in the 90°-aligned state, where the internal anisotropy field replaces the external field
- Both effects are manifestations of an asymmetric angular dependence of the STT, *i.e.* $g(\Theta)$
- First simultaneous observation of the angular asymmetries of STT and GMR

H. Dassow, D.E. Bürgler *et al.*, Appl. Phys. Lett. **89**, 222511 (2006)
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R. Lehndorff, D.E. Bürgler *et al.*, IEEE Trans. Magn. **44**, 1951 (2008)

Thanks …

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Henning Dassow

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