AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY

SWISS CONTRIBUTION

Micromagnetic simulations of spin-diode effect

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NANOSPIN PSPB-045/2010 Nanoscale spin torque devices for spin electronics

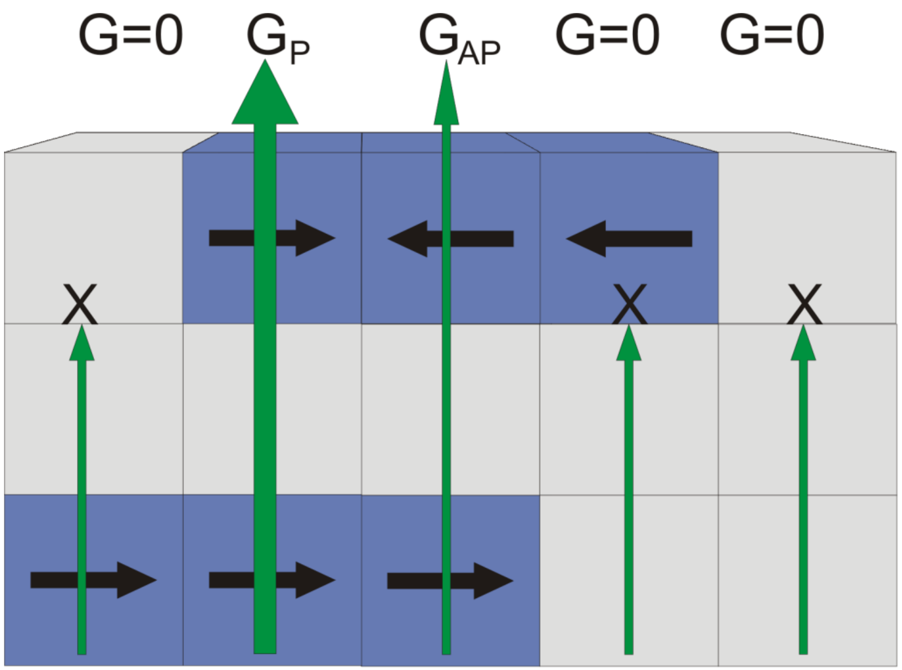
Summarizing MEETING, 11th - 12th July 2016

Outline

- Current flow model – resistance calculations
- Localized magnetization probing
- Spin-diode effect
- Voltage-induced dynamics
- Calculations of lineshape
  - Voltage-induced
  - Current-induced (STT)
  - Field-induced

Current flow model

Channels connected in parallel

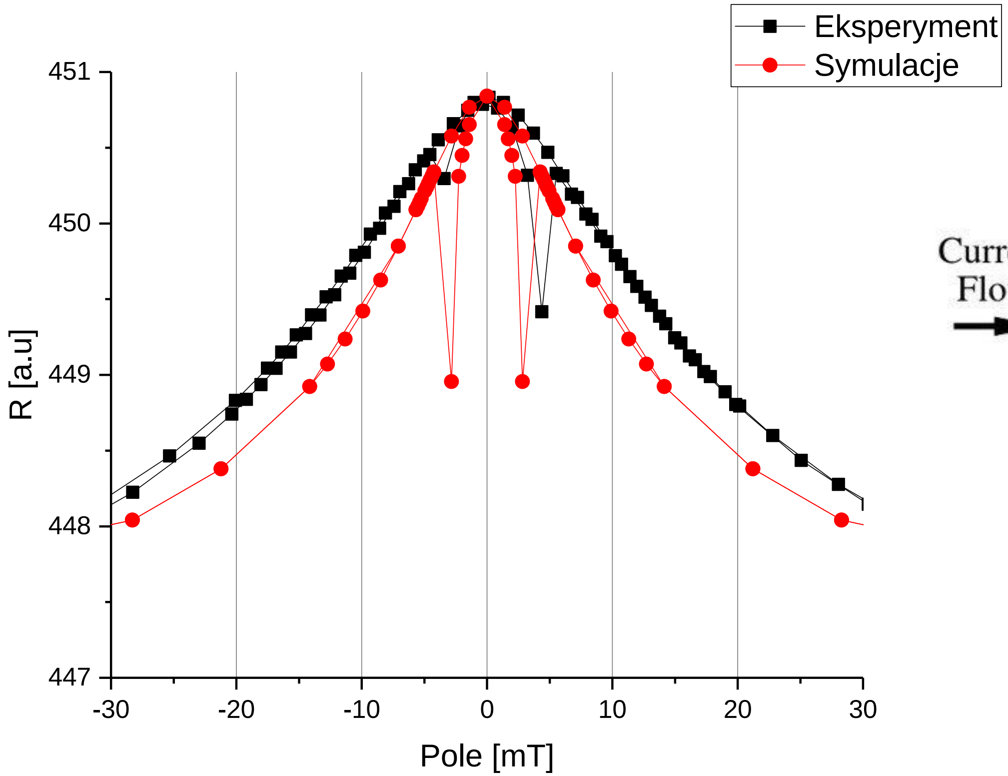


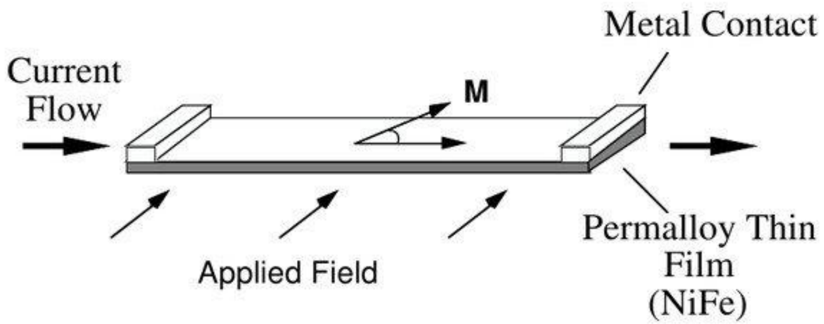
resistance given by formula:

$$R = R_P + \frac{R_{AP} - R_P}{2}(1 - cos\theta)$$

$$\theta = 0 \rightarrow R_P$$
$$\theta = 180° \rightarrow R_{AP}$$

AMR

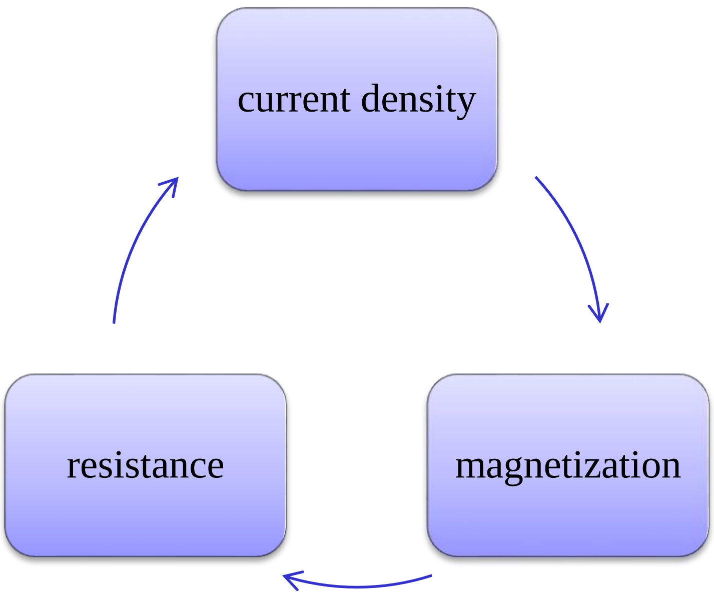

Eksperyment
Symulacje
451
450
449
448
447
R [a.u]
-30
-20
-10
0
10
20
30
Pole [mT]


Metal Contact
Current Flow
M
Applied Field
Permalloy Thin Film (NiFe)

Spin-Transfer-Torque

LLG equation with Slonczewski's component

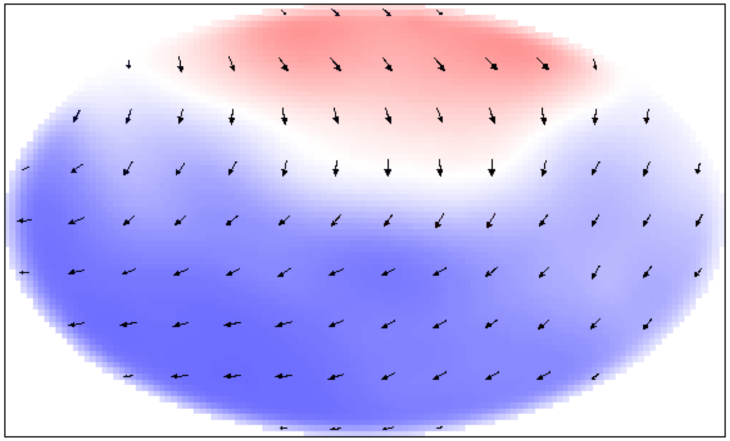
$$\frac{d\vec{m}}{dt} = \underbrace{-\gamma_0 \vec{m} \times \vec{H}_{eff}}_{\text{precession}} + \underbrace{\alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t}}_{\text{damping}} + \underbrace{\gamma_0 a_J \vec{m} \times (\vec{m} \times \vec{p})}_{\text{in-plane torque}} + \underbrace{\gamma_0 b_J \vec{m} \times \vec{p}}_{\text{prependicular torque}}$$



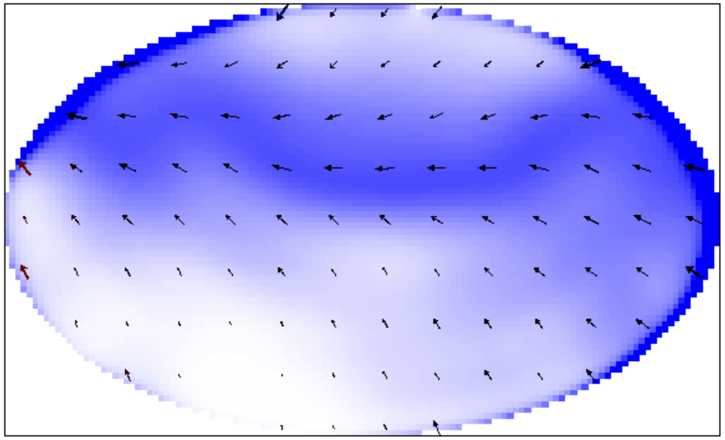
current-resistance feedback
due to STT and magnetoresitance

Simulation outputs

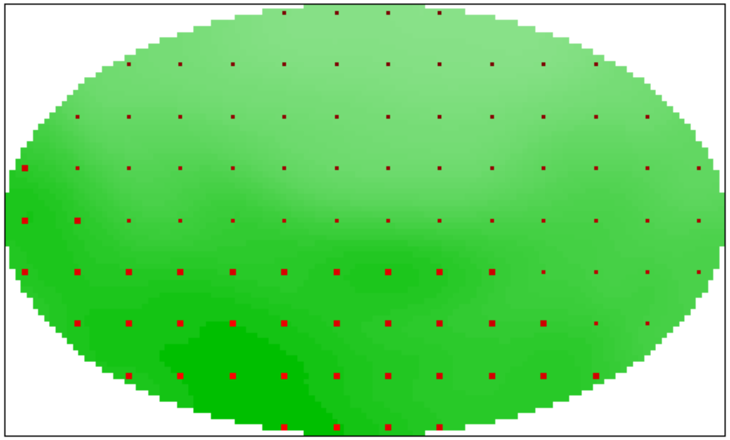
free layer magnetization distribution



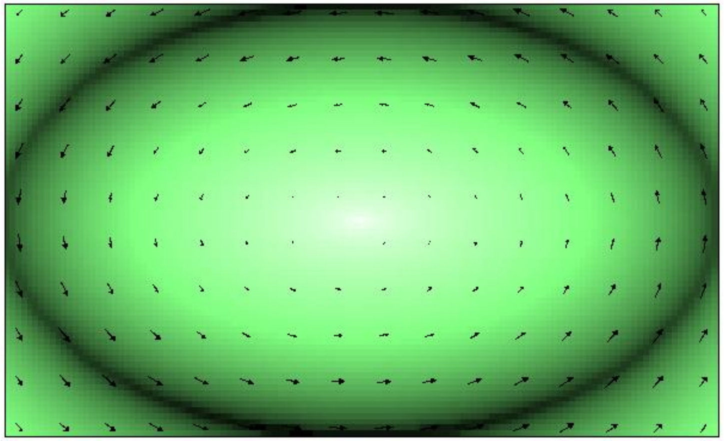
in-plane torque in free layer distribution



current density distribution

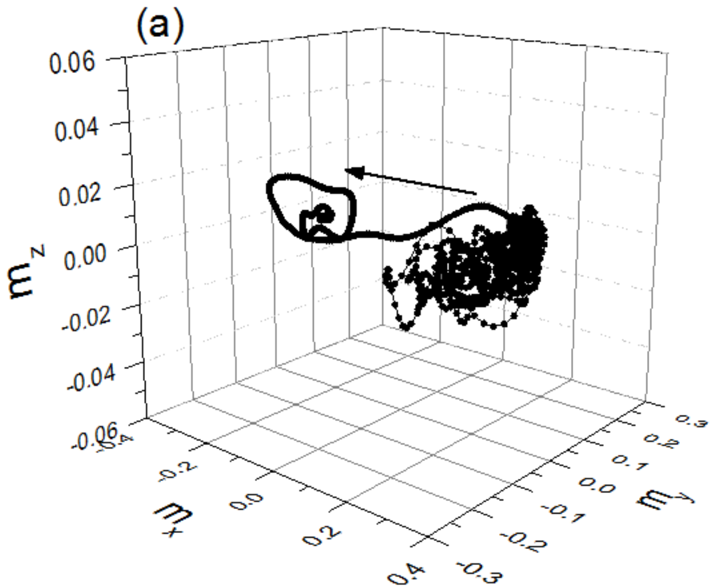


Oersted field distribution

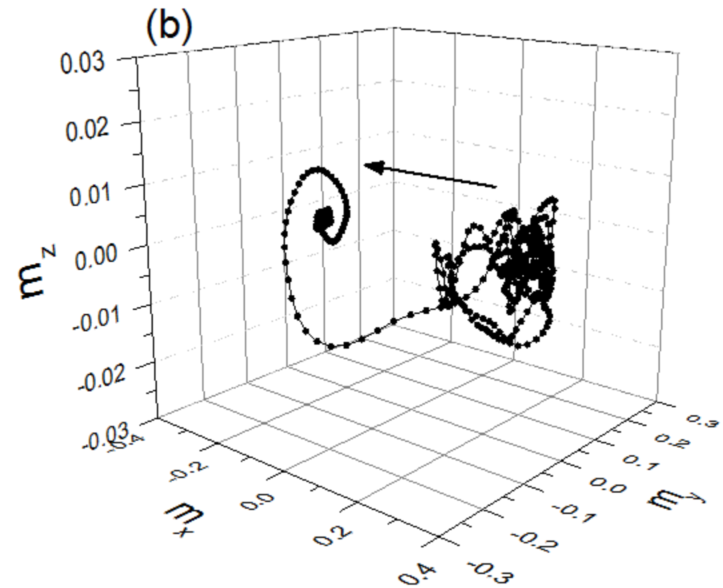


Difference in dynamics

magnetization trajectories

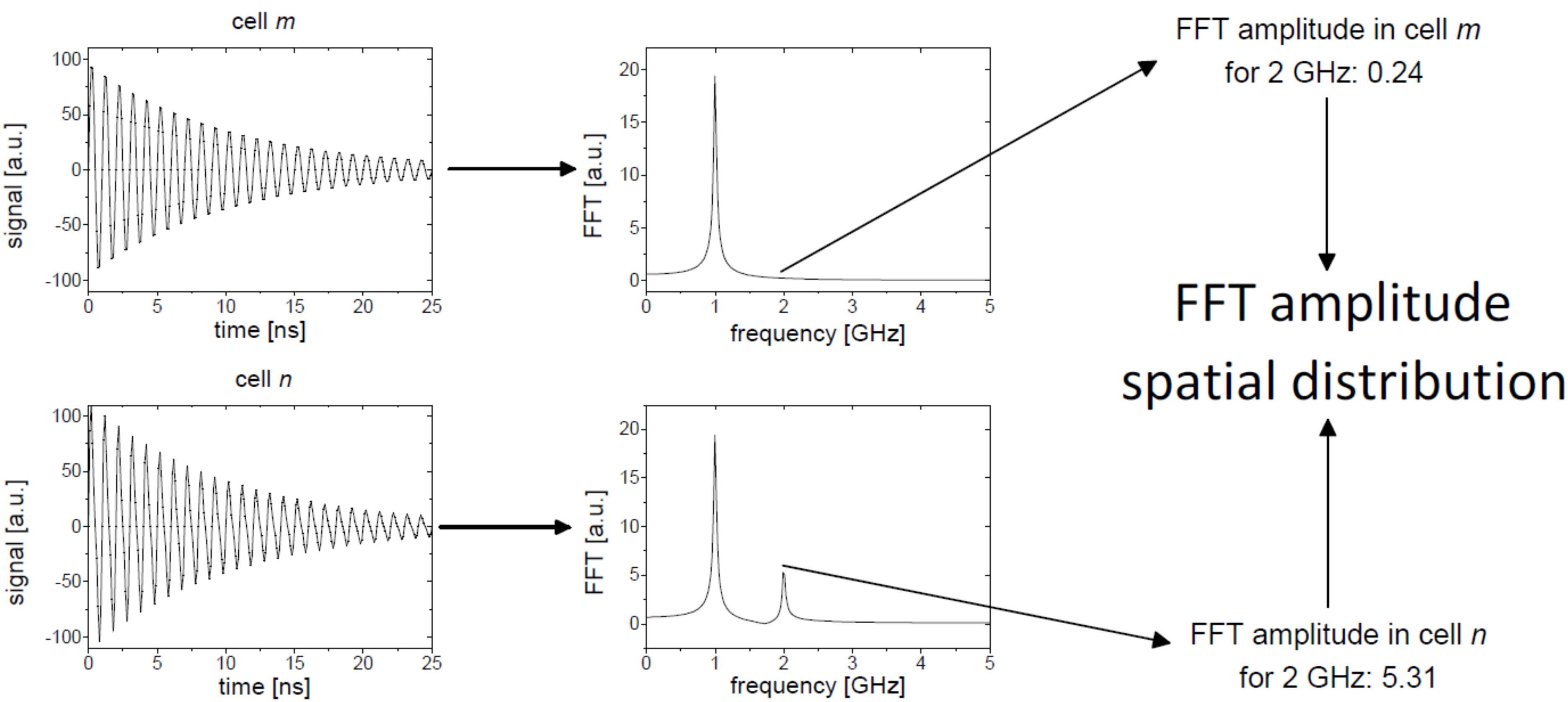


fixed current

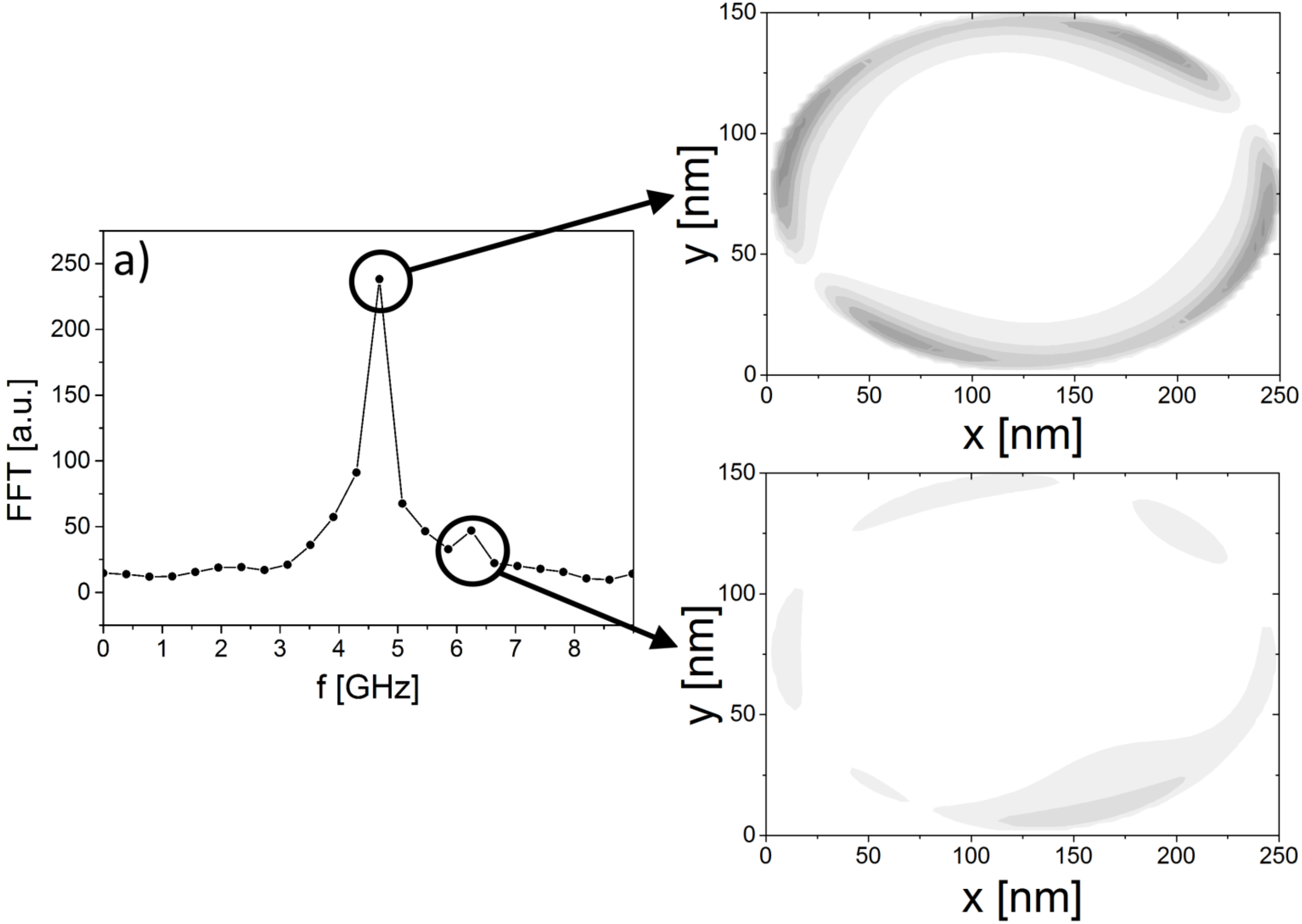


current-resistance feedback

FFT spatial distribution



Results - local analysis



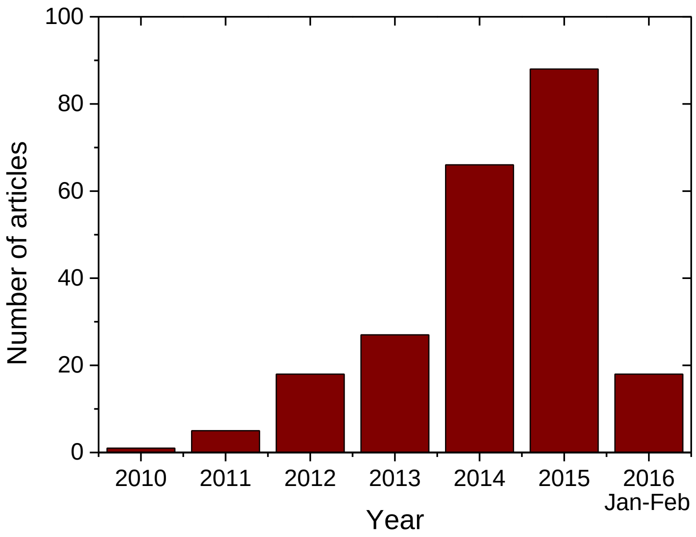
Voltage-driven dynamics

MTJ with thick tunnel barrier > 1.5 nm

High resistance of the device

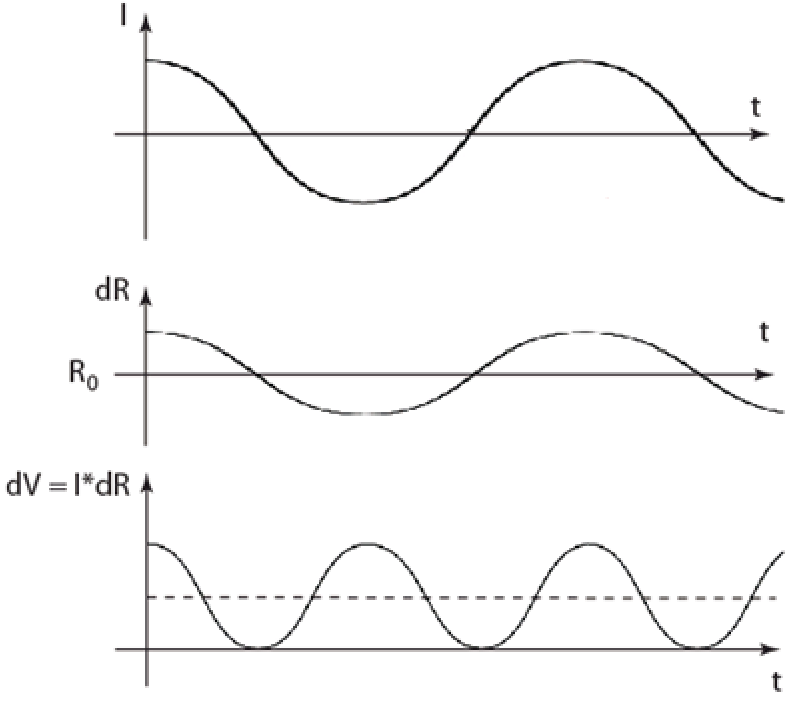
Negligible current in comparison to current-controlled devices

AC voltage control of PMA desired for low energy consumption applications

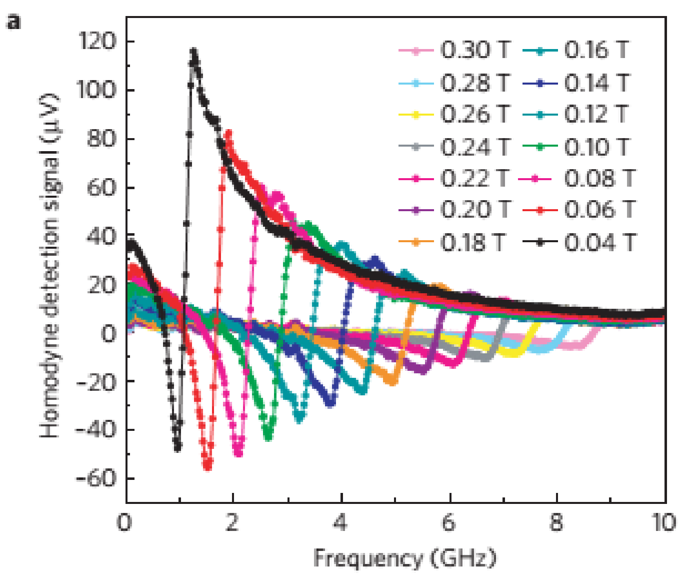


Spin-diode effect

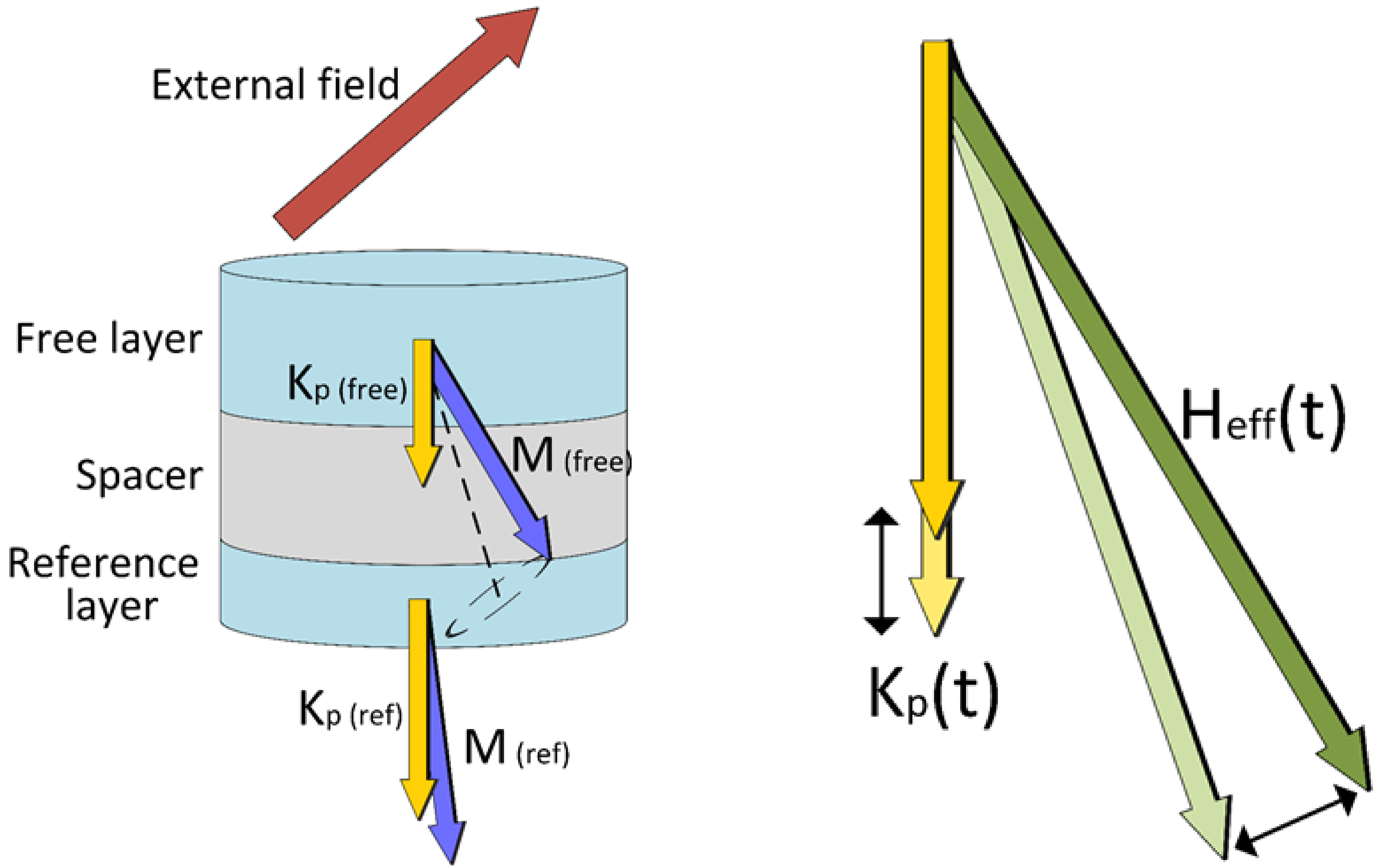
- MTJ supplied with radio frequency signal
- Precession of magnetization in phase with input signal – mixing results in a DC signal generation



Tulapurkar et al. Nature 438, 339, 2005
Nozaki et al. Nature Phys 8, 491, 2012



Voltage-induced dynamics: magnetization equilibrium manipulation



PMA vs. in-plane anisotropy

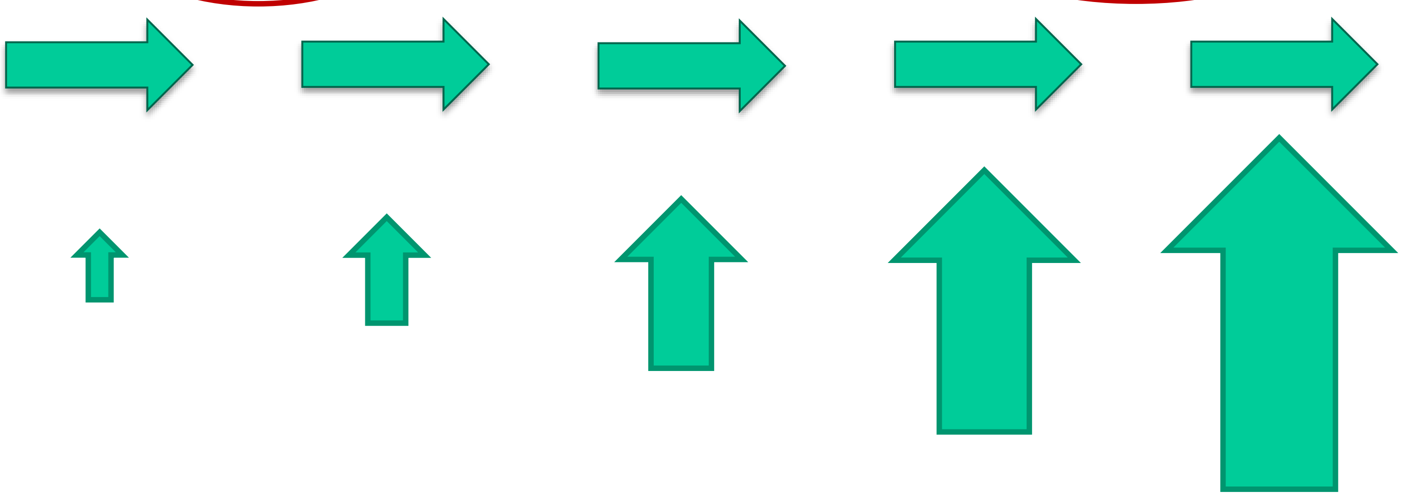
Recently reported:
Skowroński et. al., APEX 8.5 (2015): 053003

Commonly investigated in literature

Effective anisotropy	In-plane regime	Transition regime	Perpendicular regime

In-plane component

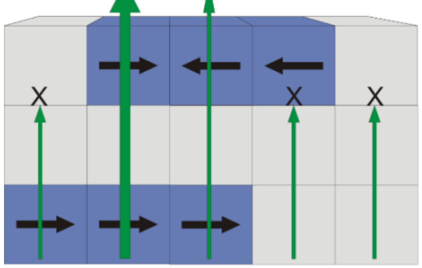
PMA component



Micromagnetic approach

OOMMF-based simulations

$$\frac{d\vec{m}}{dt} = -\gamma_0 \vec{m} \times \vec{H}_{eff} + \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t}$$



M.J. Donahue, D.G. Porter, NIST Report (1999).
M. Frankowski et. al. Phys. B 435, 105–108 (2014).

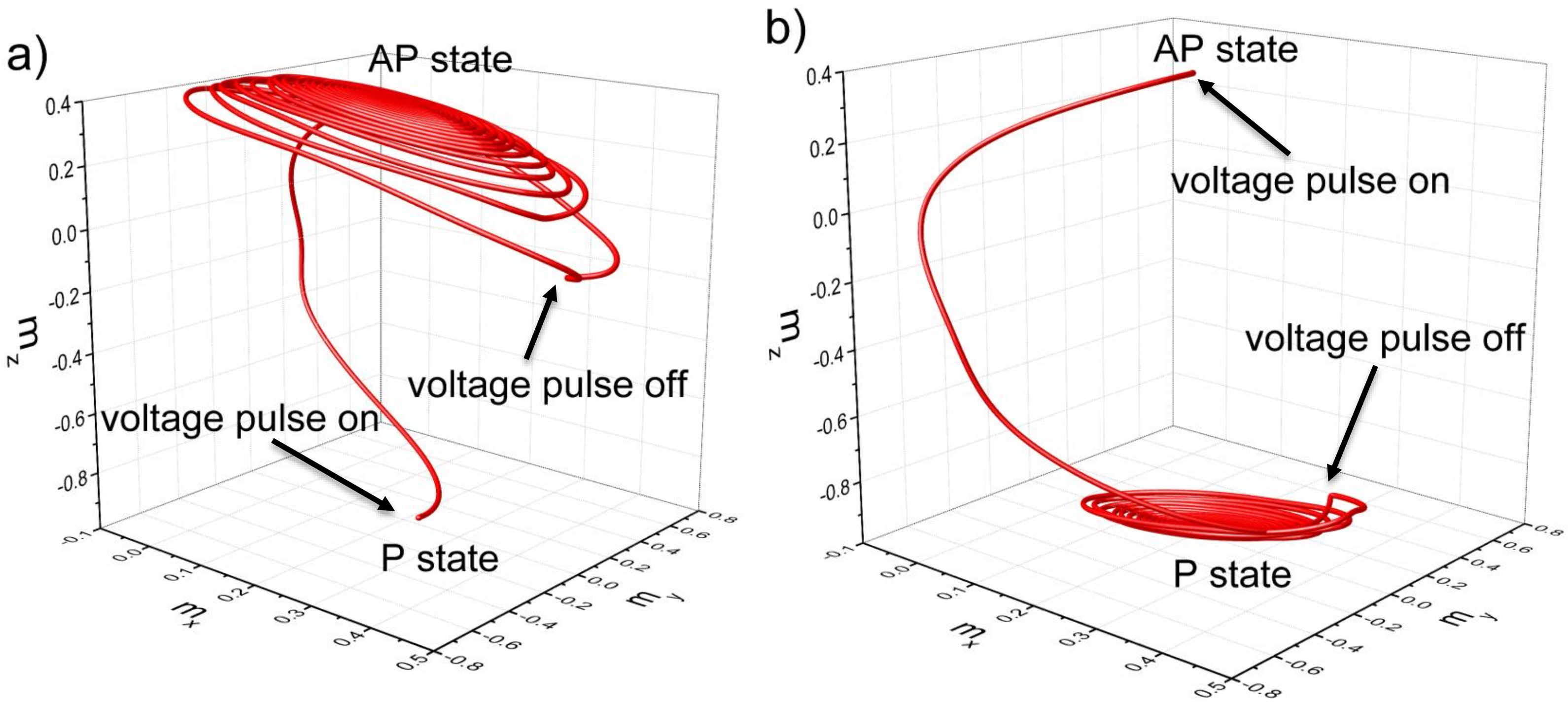
Ferromagnetic free layer: 1.4 nm (2 cells), Ms 1200 kA/m, K out-of-plane VARIABLE kJ/m^3

MgO barrier: 1.4 nm (2 cells)

Ferromagnetic reference layer: 0.7 nm (1 cell), Ms 1000 kA/m, K out-of-plane 1500 kJ/m^3

- **Diameter 70 nm**
- **Intrinsic (Gilbert) damping constant 0.017**
- **Bias of 40 mT constant magnetic field applied angle 45° to the plane**
- **Alternating anisotropy contributes to the effective field H_{eff}**

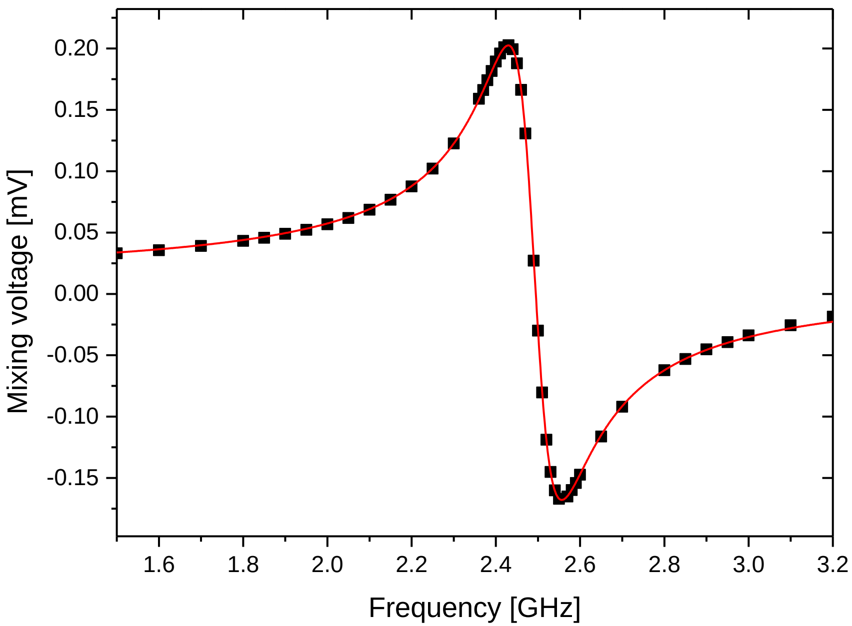
Voltage induced switching



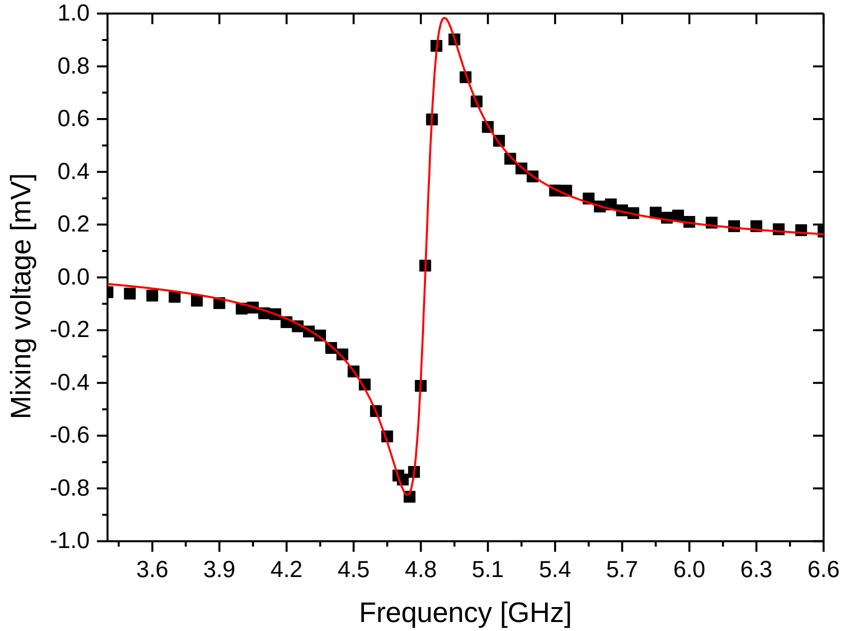
Magnetization trajectories for voltage-induced switching, single pulse (duration of 0.55 ns) and amplitude 100 kJ/m^3, field bias 40 mT 45° to sample plane

Calculations of lineshape

K_p=675kJ/m^3
$K_{effective}$: in-plane

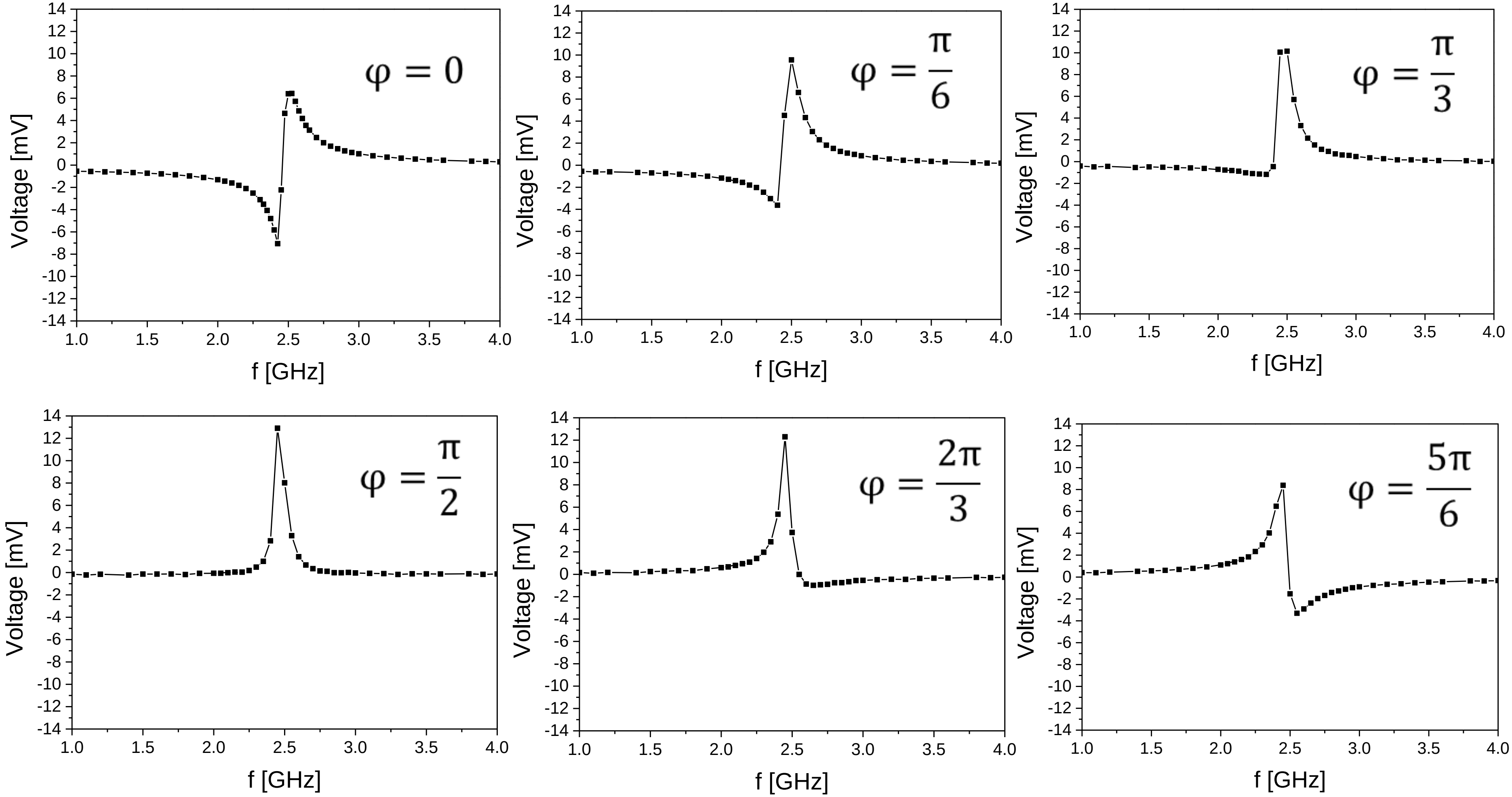


K_p=950kJ/m^3
$K_{effective}$: PMA



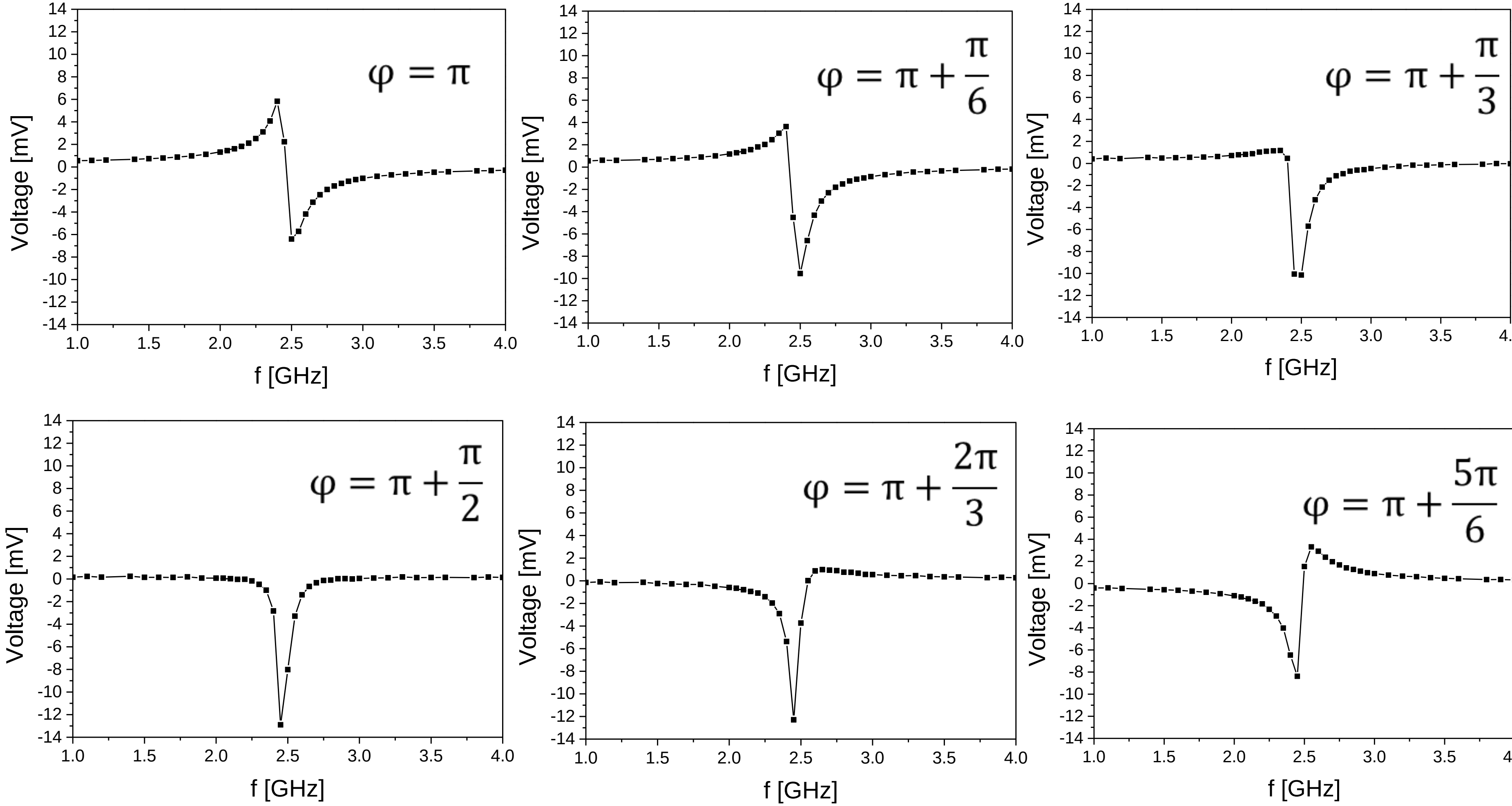
Line shape analysis

Influence of current-voltage phase shift

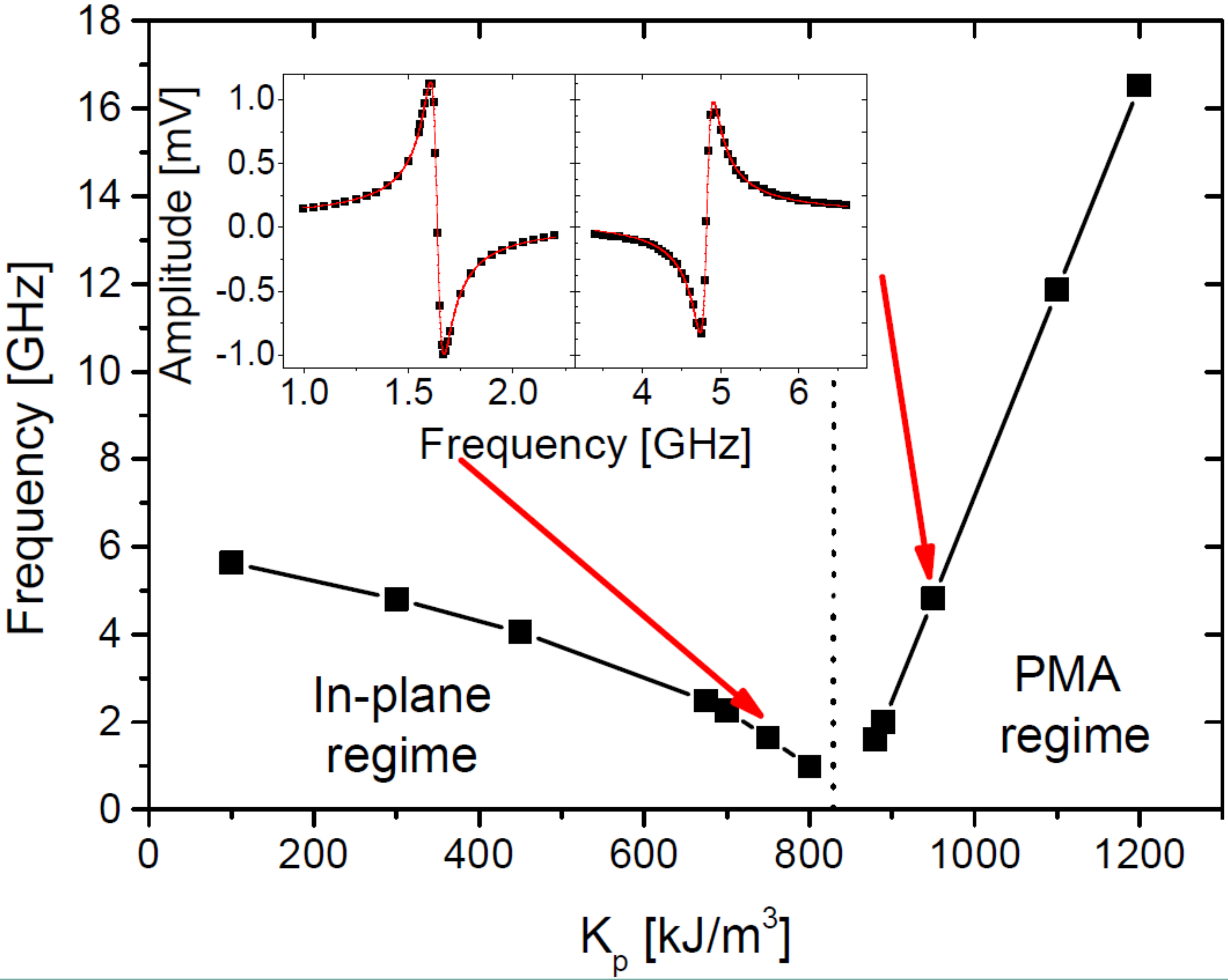


Line shape analysis

Influence of current-voltage phase shift

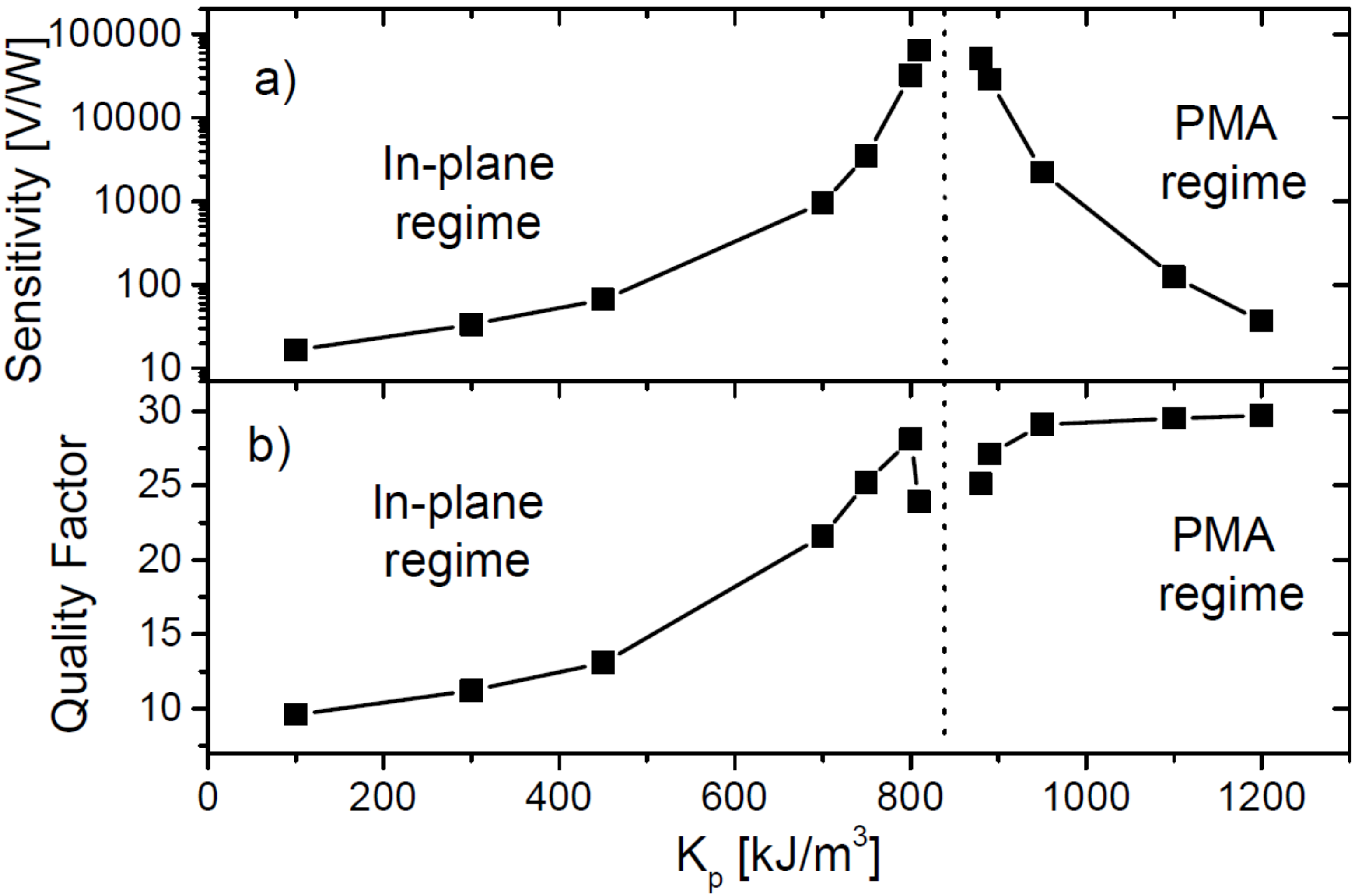


Frequency



Frequency [GHz]
Kp [kJ/m3]
Amplitude [mV]
Frequency [GHz]
In-plane regime
PMA regime

Sensitivity and Q-factor



How is the effective damping calculated?

$$\alpha_{eff} = \frac{\sqrt{3}\Delta f_{pp}}{\frac{\gamma}{2\pi}(H_1+H_2)}$$, where

$$H_1 = \left(H_{ext} + H_{ref}\right)\sin(\theta_H - \theta_M) - H_d sin^2\theta_M$$

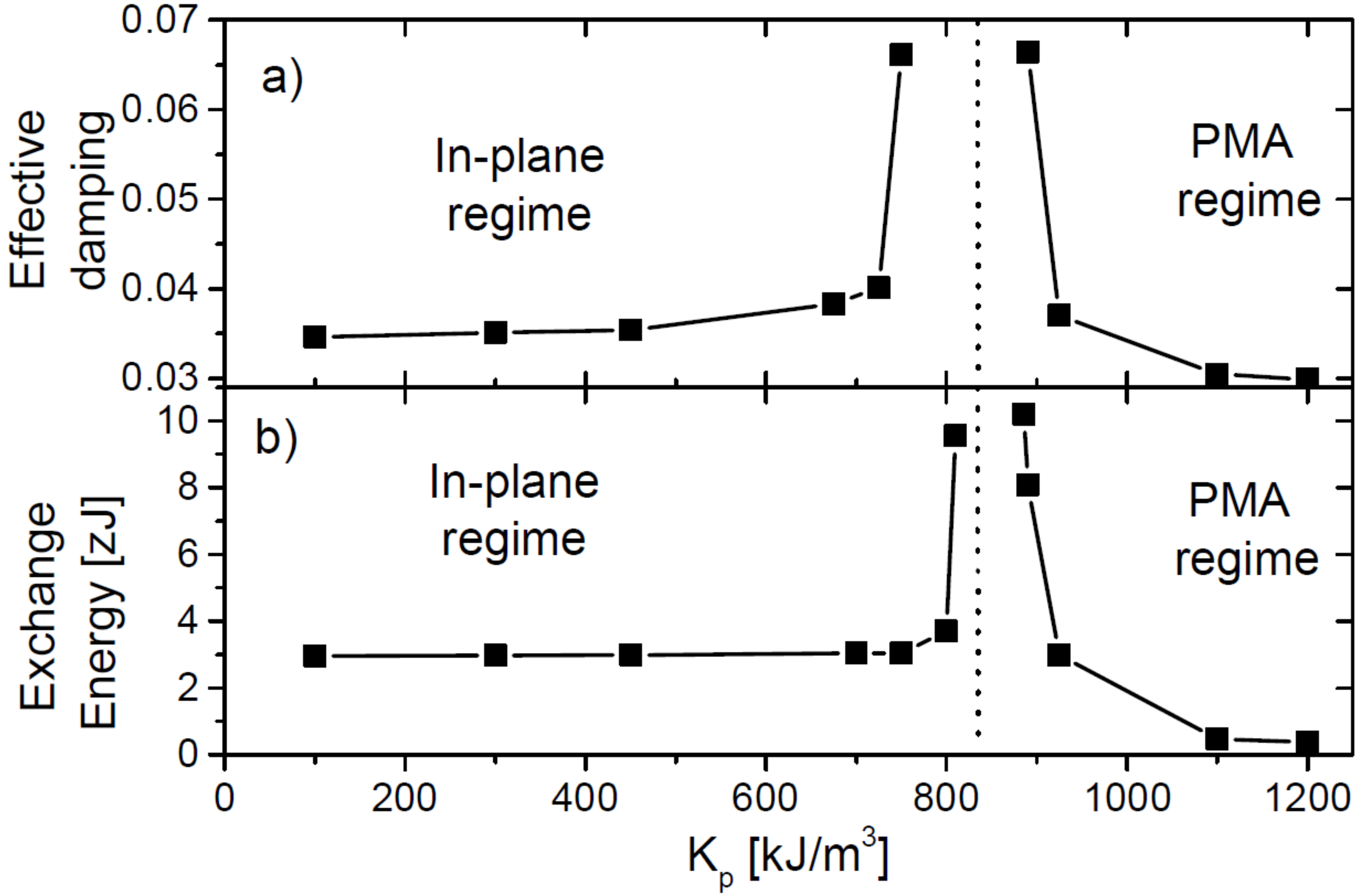
$$H_2 = \left(H_{ext} + H_{ref}\right)\sin(\theta_H - \theta_M) + H_d cos2\theta_M$$

are fitted from the $f = \frac{\gamma}{2\pi}\sqrt{H_1 H_2}$ relationship,

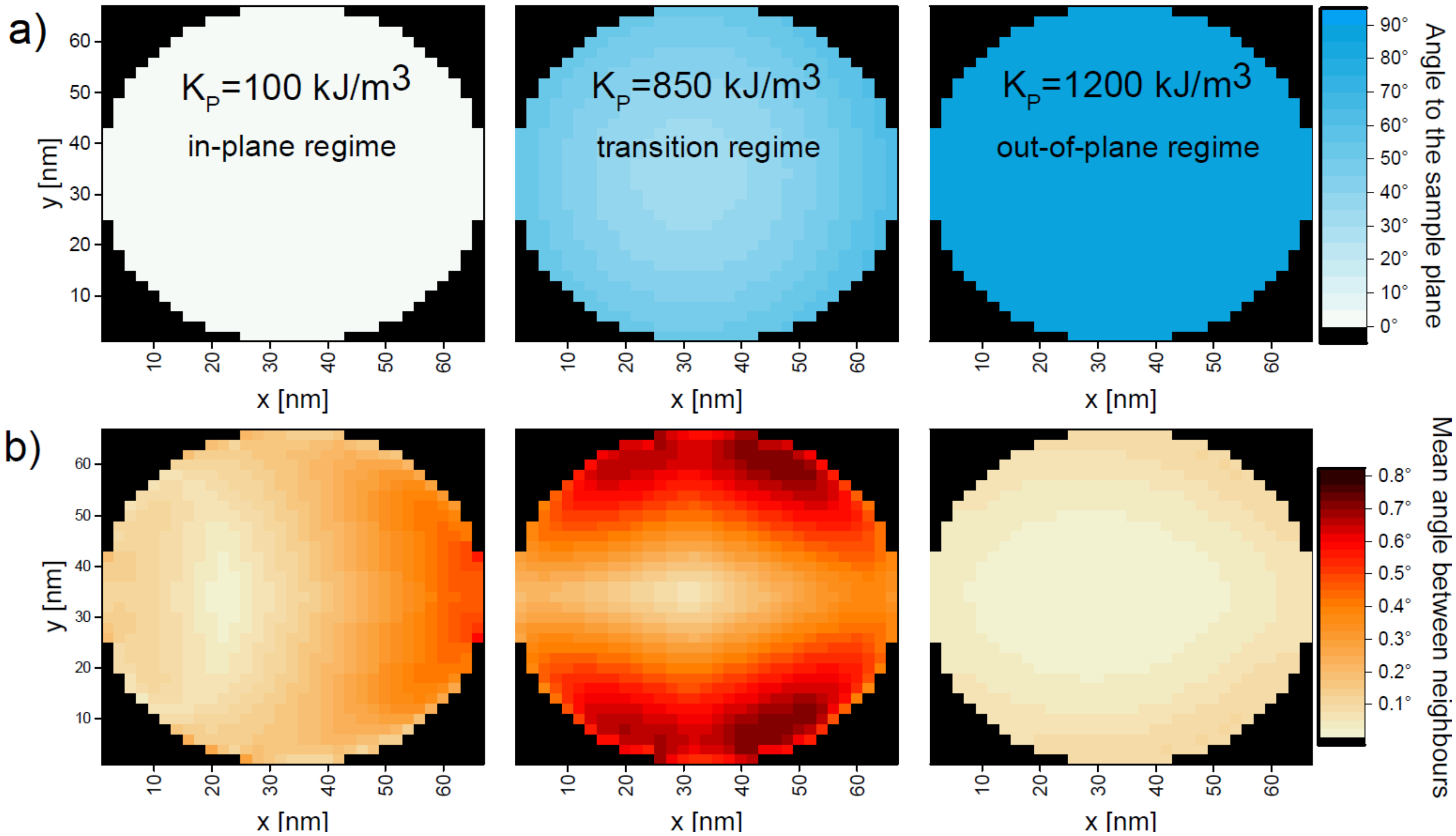
and Δf_{pp} is obtained from fitting the antisymmetric Lorentz formula to the simulated lineshape.

based on: *Nozaki, Takayuki, et al., APEX 7.7 (2014): 073002.*

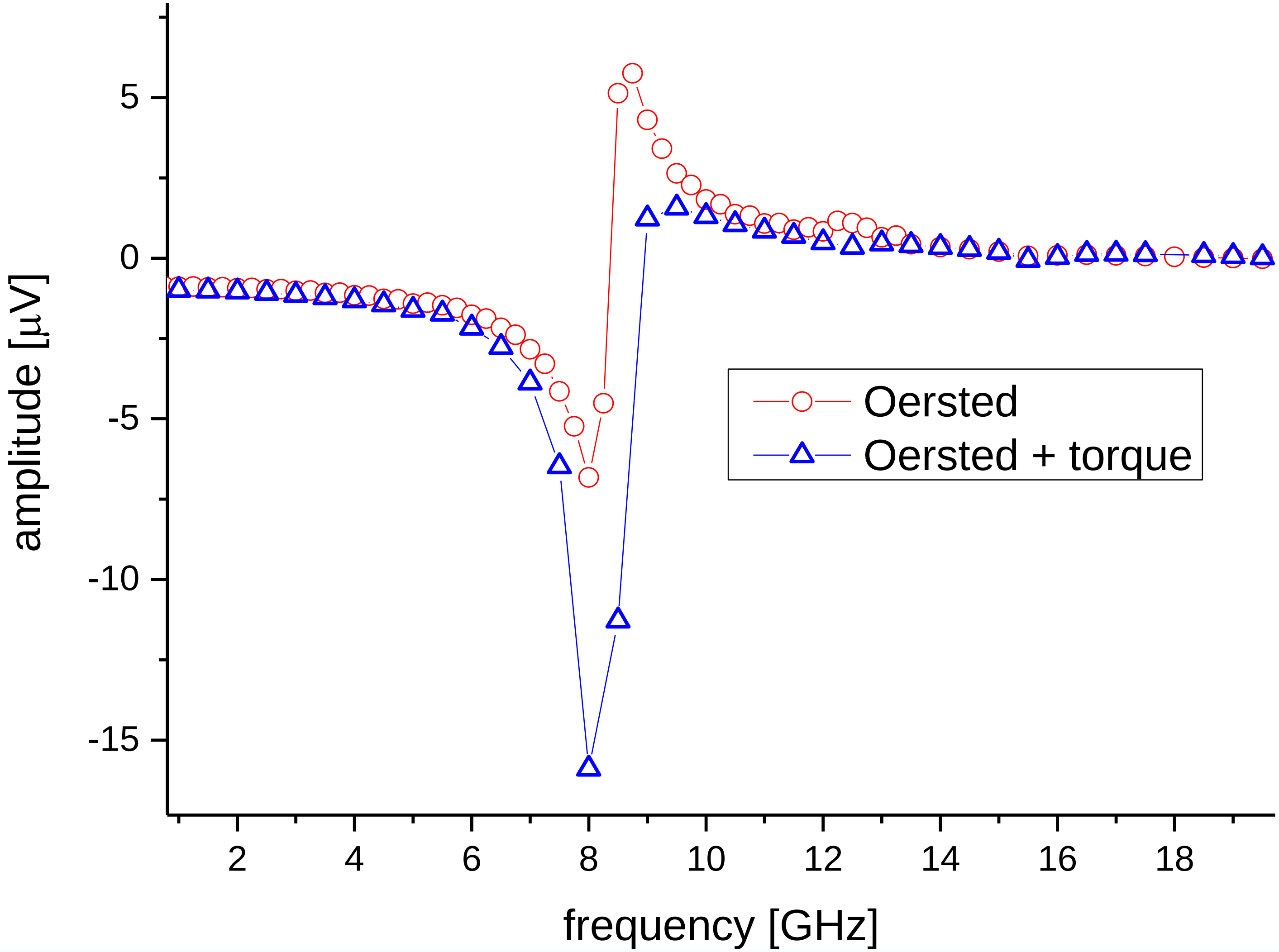
Effective damping



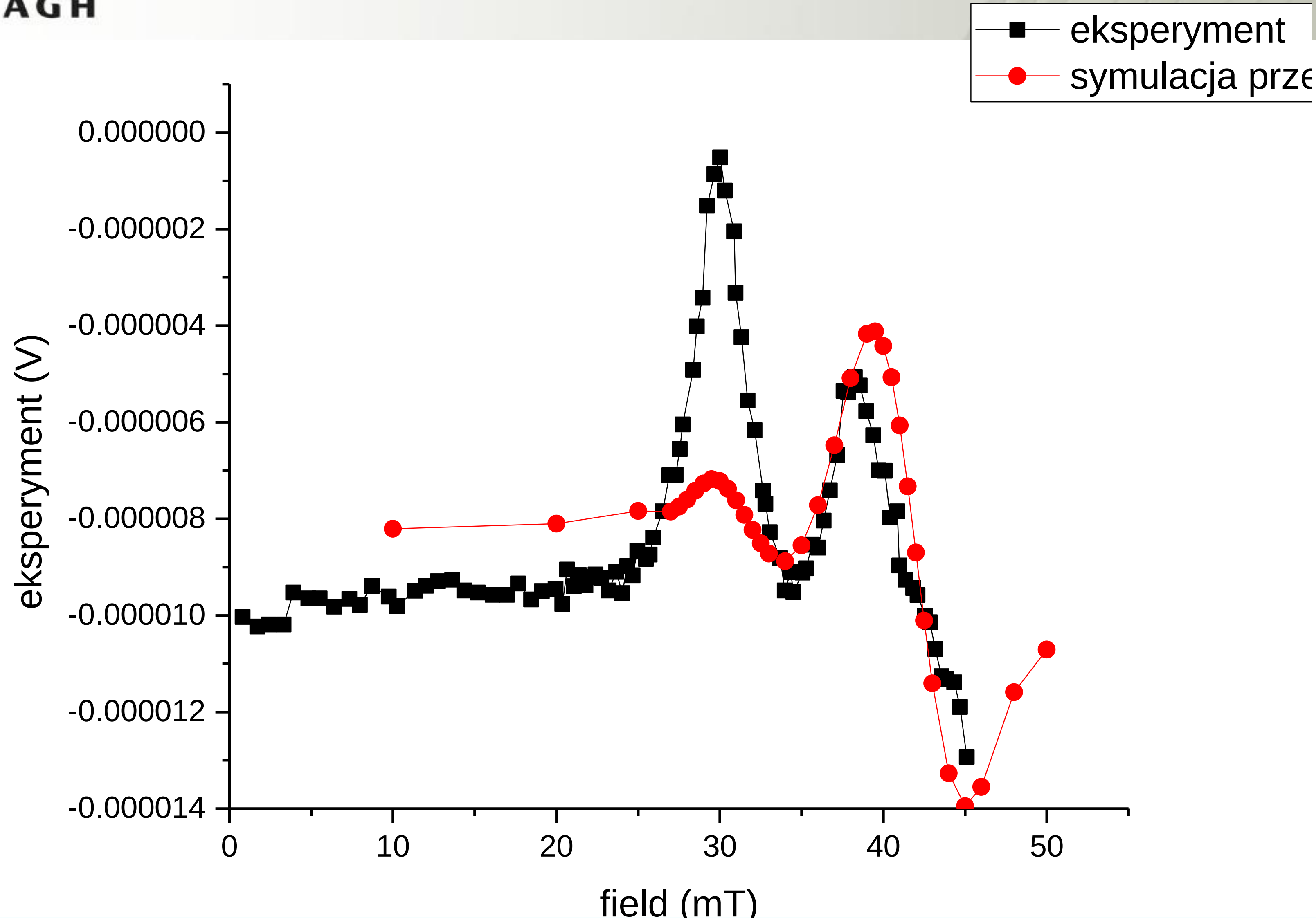
Exchange energy



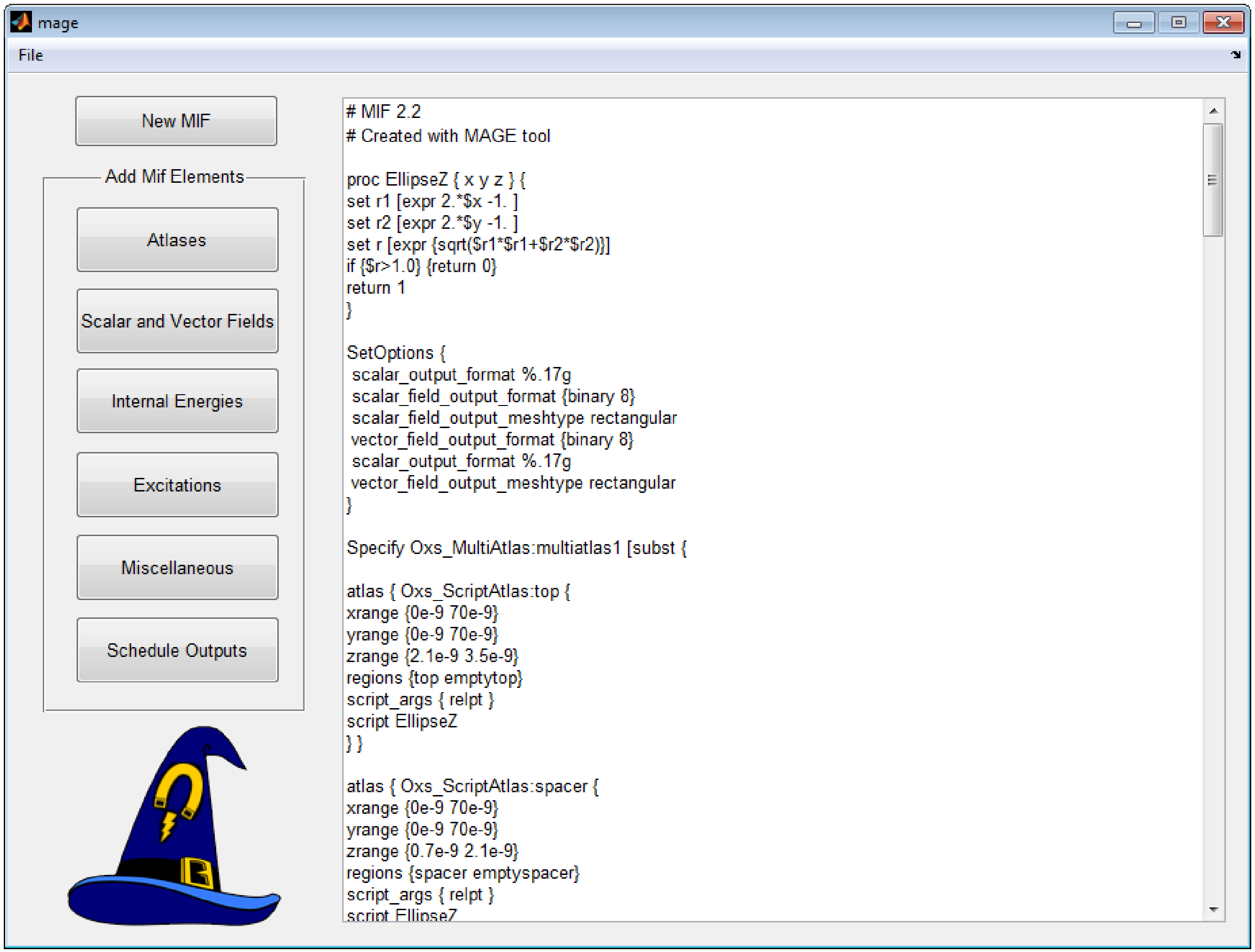
Nanowire from Lausanne



NiFe stripes



MAGE


mage
File
New MIF
Add Mif Elements
Atlases
Scalar and Vector Fields
Internal Energies
Excitations
Miscellaneous
Schedule Outputs
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# Created with MAGE tool
proc EllipseZ { x y z } {
set r1 [expr 2.*$x -1.]
set r2 [expr 2.*$y -1.]
set r [expr {sqrt($r1*$r1+$r2*$r2)}]
if {$r>1.0} {return 0}
return 1
}
SetOptions {
scalar_output_format %.17g
scalar_field_output_format {binary 8}
scalar_field_output_meshtype rectangular
vector_field_output_format {binary 8}
scalar_output_format %.17g
vector_field_output_meshtype rectangular
}
Specify Oxs_MultiAtlas:multiatlas1 [subst {
atlas { Oxs_ScriptAtlas:top {
xrange {0e-9 70e-9}
yrange {0e-9 70e-9}
zrange {2.1e-9 3.5e-9}
regions {top emptytop}
script_args { relpt }
script EllipseZ
} }
atlas { Oxs_ScriptAtlas:spacer {
xrange {0e-9 70e-9}
yrange {0e-9 70e-9}
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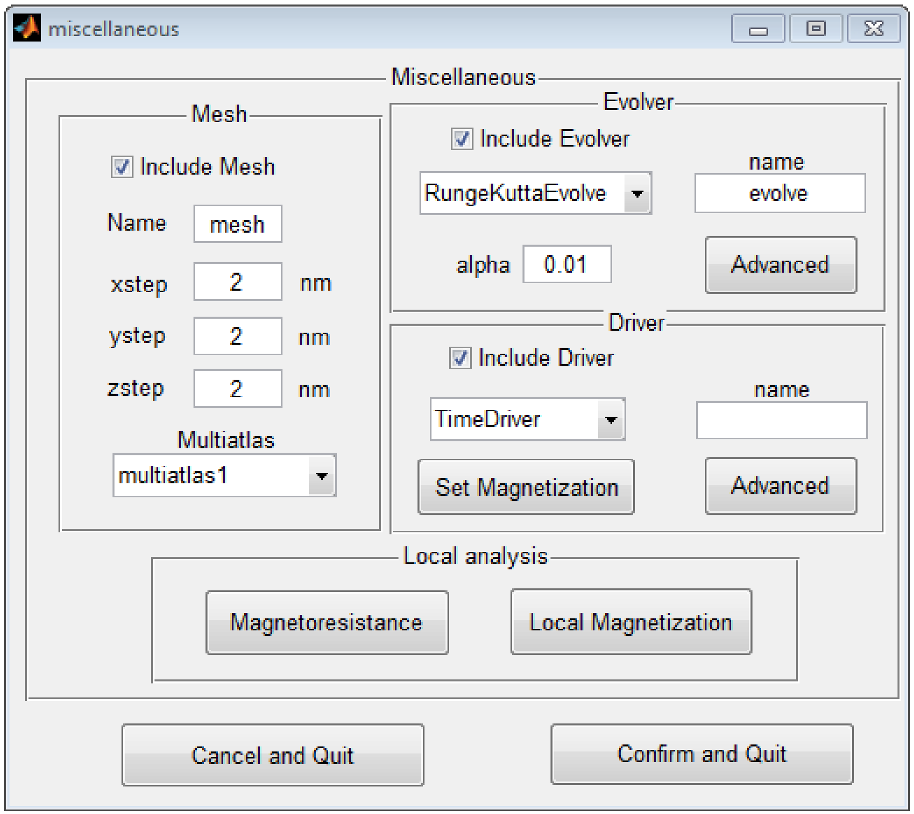
script EllipseZ

MAGE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Miscellaneous
Mesh
Include Mesh
Name
mesh
xstep
2
nm
ystep
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nm
zstep
2
nm
Multiatlas
multiatlas1
Evolver
Include Evolver
RungeKuttaEvolve
name
evolve
alpha
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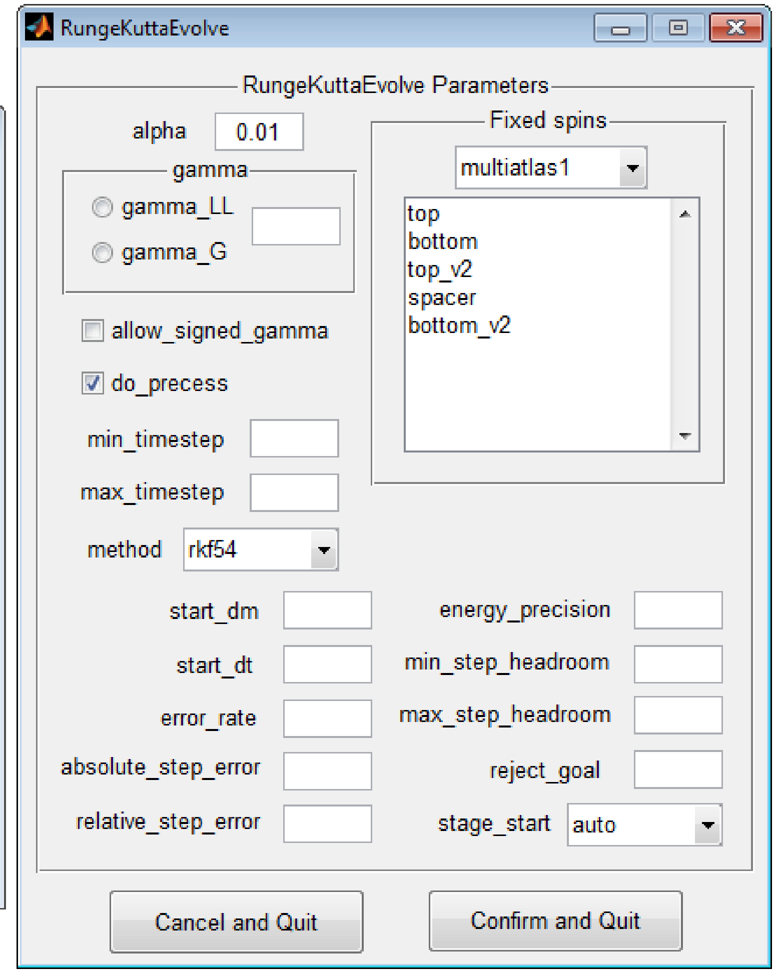
Advanced
Driver
Include Driver
TimeDriver
name
Set Magnetization
Advanced
Local analysis
Magnetoresistance
Local Magnetization
Cancel and Quit
Confirm and Quit


RungeKuttaEvolve
RungeKuttaEvolve Parameters
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gamma
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gamma_G
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min_timestep
max_timestep
method
rkf54
Fixed spins
multiatlas1
top
bottom
top_v2
spacer
bottom_v2
start_dm
start_dt
error_rate
absolute_step_error
relative_step_error
energy_precision
min_step_headroom
max_step_headroom
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stage_start
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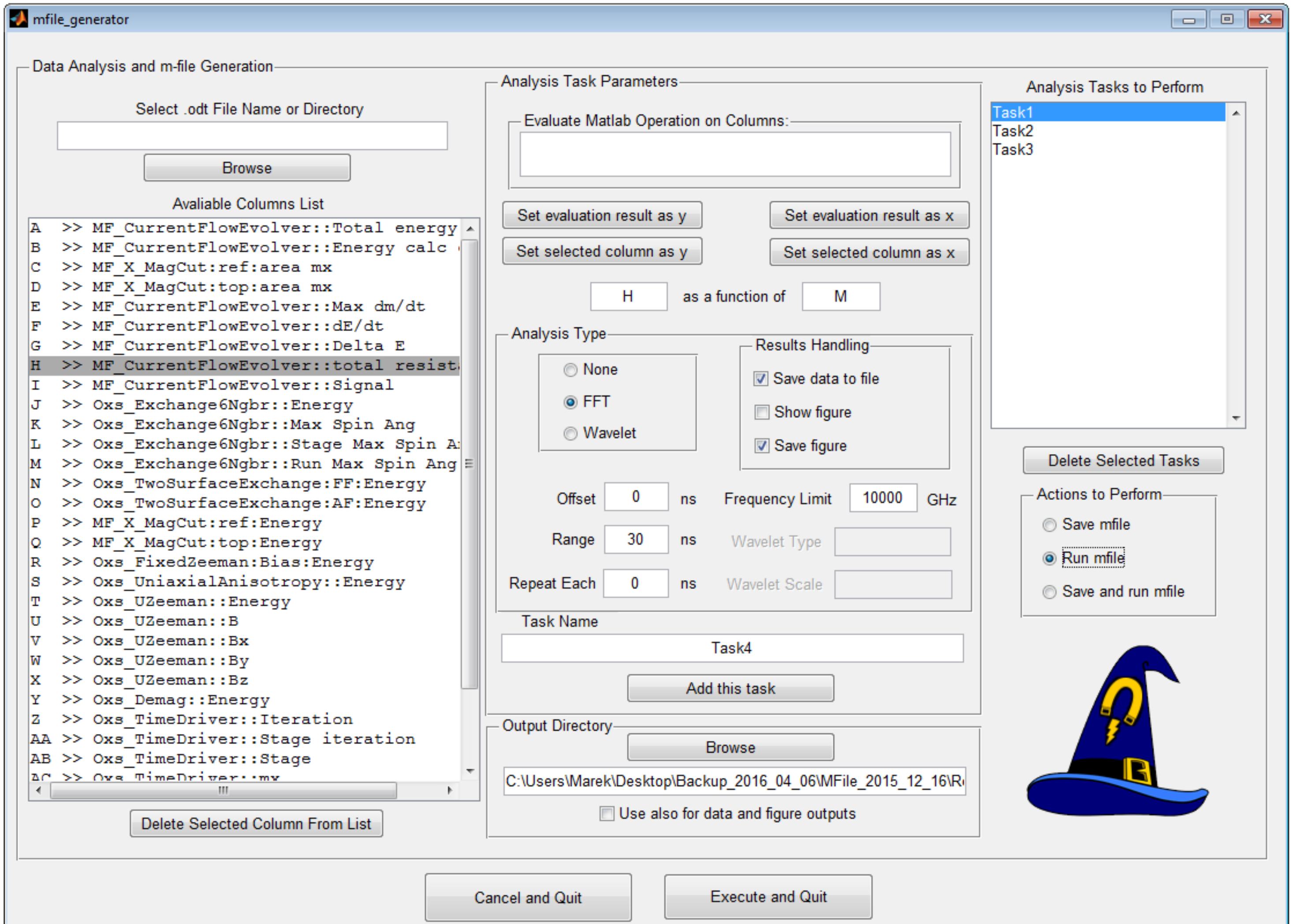
Cancel and Quit
Confirm and Quit

MAGE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Data Analysis and m-file Generation
Select .odt File Name or Directory
Browse
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B >> MF_CurrentFlowEvolver::Energy calc
C >> MF_X_MagCut:ref:area mx
D >> MF_X_MagCut:top:area mx
E >> MF_CurrentFlowEvolver::Max dm/dt
F >> MF_CurrentFlowEvolver::dE/dt
G >> MF_CurrentFlowEvolver::Delta E
H >> MF_CurrentFlowEvolver::total resist
I >> MF_CurrentFlowEvolver::Signal
J >> Oxs_Exchange6Ngbr::Energy
K >> Oxs_Exchange6Ngbr::Max Spin Ang
L >> Oxs_Exchange6Ngbr::Stage Max Spin A
M >> Oxs_Exchange6Ngbr::Run Max Spin Ang
N >> Oxs_TwoSurfaceExchange:FF:Energy
O >> Oxs_TwoSurfaceExchange:AF:Energy
P >> MF_X_MagCut:ref:Energy
Q >> MF_X_MagCut:top:Energy
R >> Oxs_FixedZeeman:Bias:Energy
S >> Oxs_UniaxialAnisotropy::Energy
T >> Oxs_UZeeman::Energy
U >> Oxs_UZeeman::B
V >> Oxs_UZeeman::Bx
W >> Oxs_UZeeman::By
X >> Oxs_UZeeman::Bz
Y >> Oxs_Demag::Energy
Z >> Oxs_TimeDriver::Iteration
AA >> Oxs_TimeDriver::Stage iteration
AB >> Oxs_TimeDriver::Stage
Delete Selected Column From List
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Evaluate Matlab Operation on Columns:
Set evaluation result as y
Set evaluation result as x
Set selected column as y
Set selected column as x
H
as a function of
M
Analysis Type
None
FFT
Wavelet
Results Handling
Save data to file
Show figure
Save figure
Offset
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Range
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ns
Wavelet Type
Repeat Each
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ns
Wavelet Scale
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Task4
Add this task
Output Directory
Browse
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Use also for data and figure outputs
Analysis Tasks to Perform
Task1
Task2
Task3
Delete Selected Tasks
Actions to Perform
Save mfile
Run mfile
Save and run mfile
Cancel and Quit
Execute and Quit

Summary

- Local effect taken into account
- Voltage induced effect modelled
- Lineshape for different cases reproduced
- Realistic experiment-like approach for lineshape requires micromagnetic simulations (becouse of disorder)

Thank you for your attention.