Large Angle Steady State Oscillations Induced by a Perpendicular Polarizer

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Micromagnetics / Transport Simulation
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B. Rodmacq

/DIHS/LIMN C.E.A. Grenoble & MINATEC Grenoble
Nanofabrication
B. Delaët, M.-C. Cyrille, F. Ponthenier, M. Brunet, O. Redon

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Oakland University
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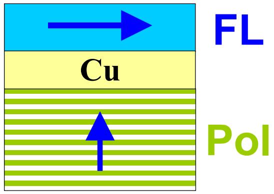

French National Grants
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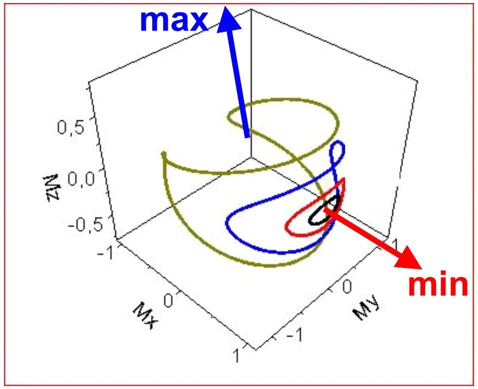
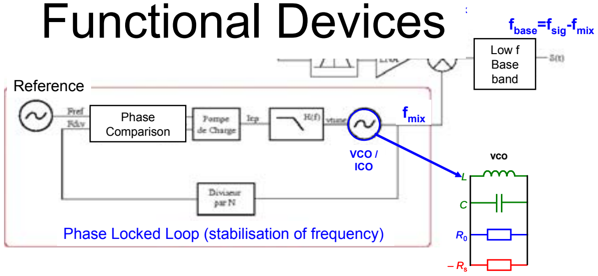
Outline

Trajectories

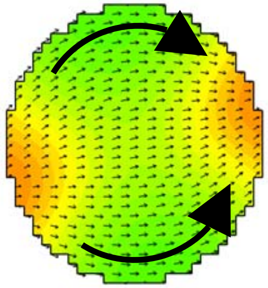


Functional Devices

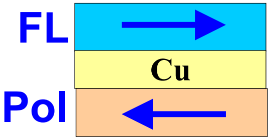


Phase Locked Loop (stabilisation of frequency)

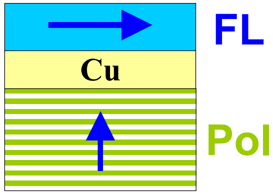
Beyond Macrospin



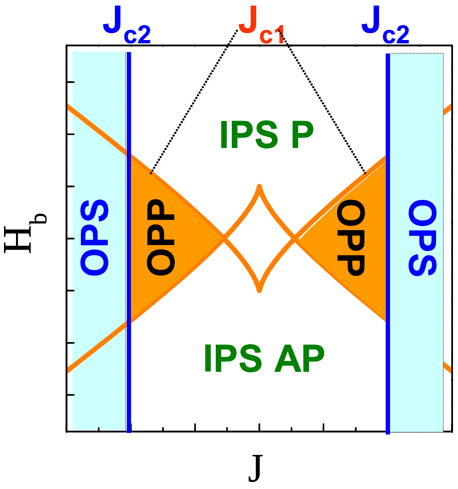
Planar



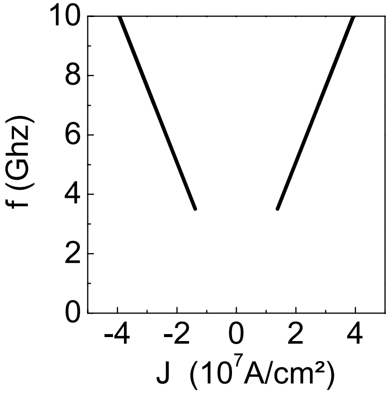
Perpendicular



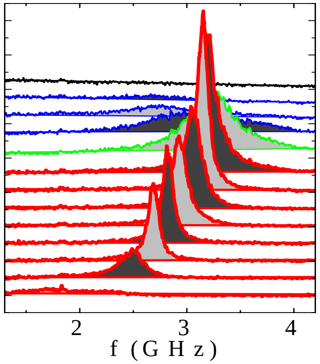
State diagram



Frequencies

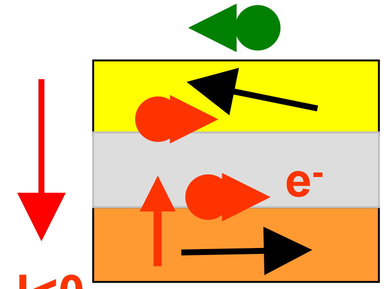


Experiments



Spintorque Oscillator

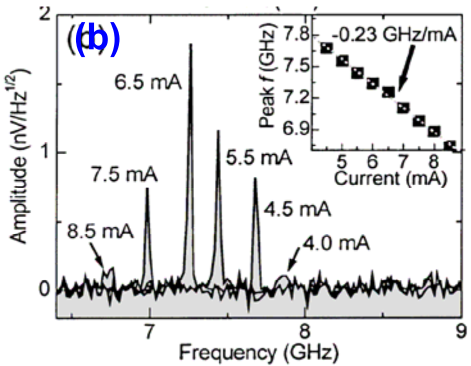
Spin momentum tra



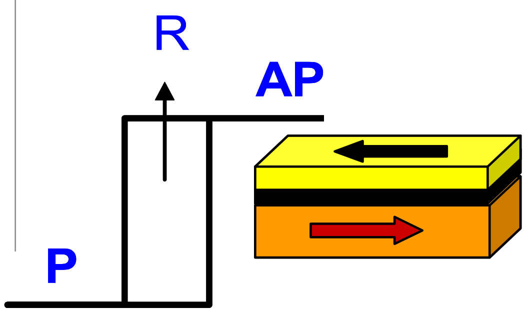
Free La

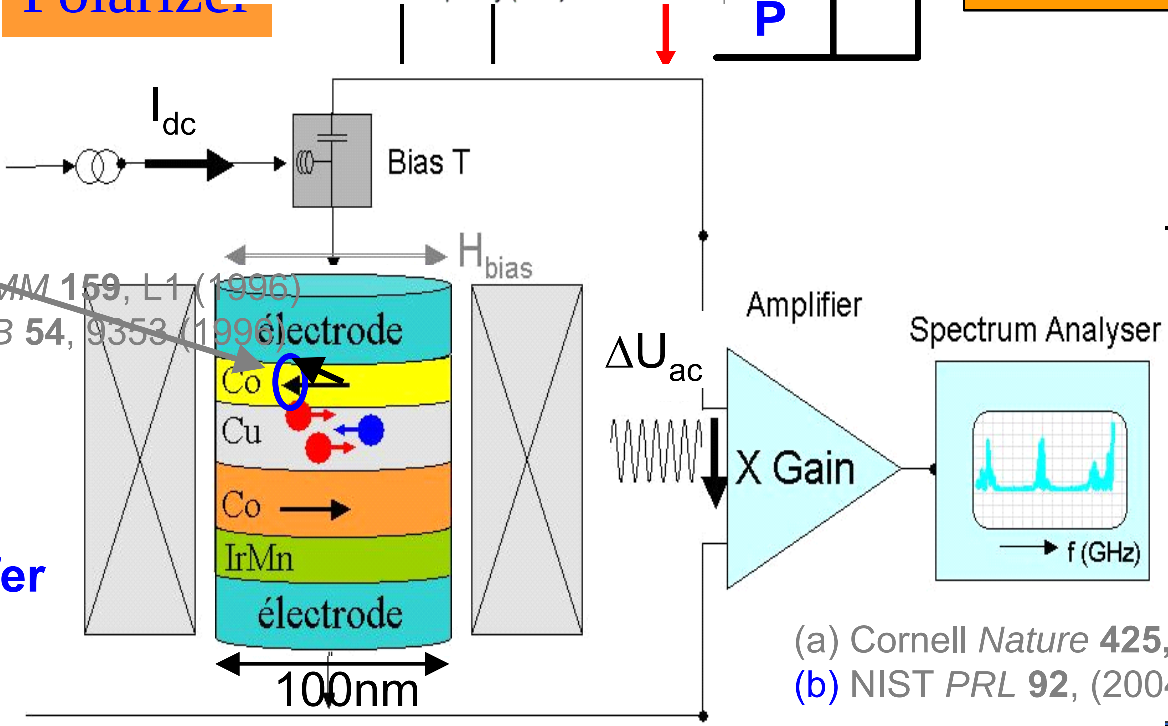
Polarize

Destabilization of the AP state



lagneto-Resistance





Steady State Oscillations

$J>J_c$

* J. C. Slonczewski, *JMMM* **159**, L1 (1996)

* L. Berger, *Phys. Rev. B* **54**, 9353 (1996)

Induced by spin momentum transfer (spin torque)

(a) Cornell *Nature* **425**, (2003)

(b) NIST *PRL* **92**, (2004)

Introduction: Equation of Motion

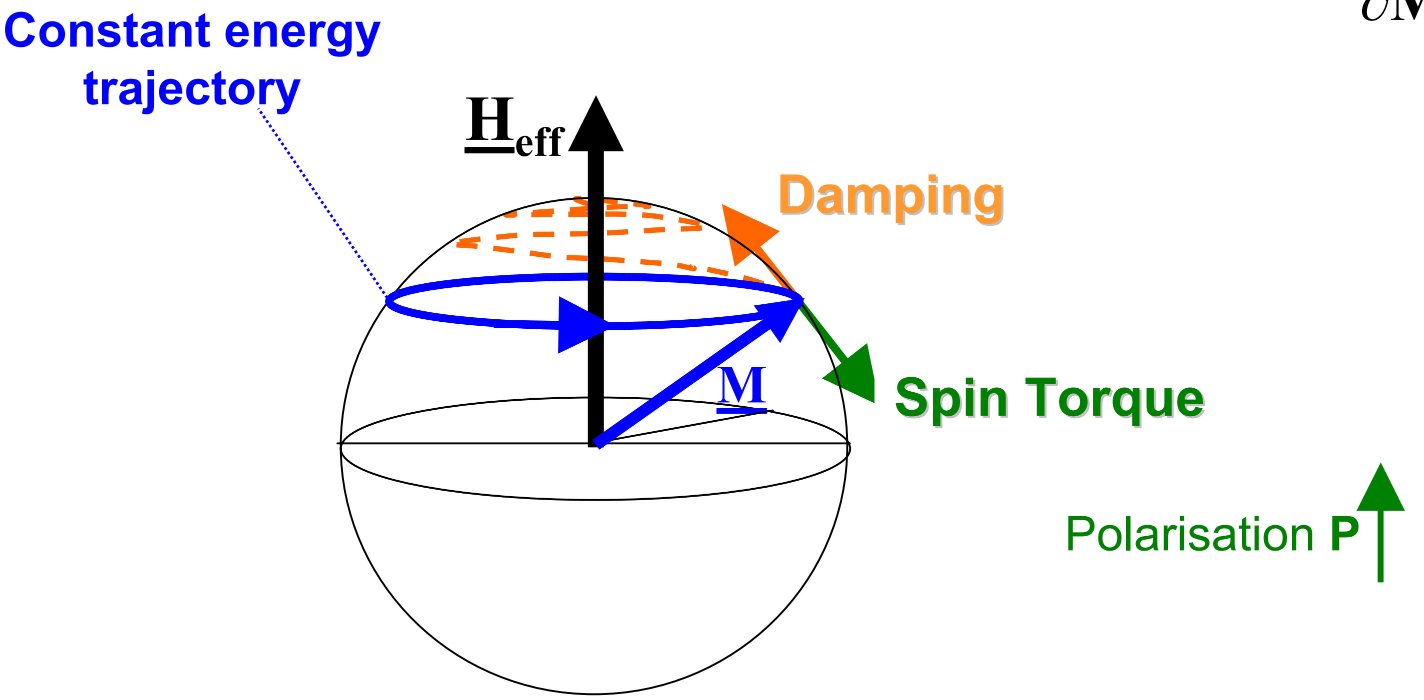
$$\frac{d\mathbf{M}}{dt} = \boxed{-\gamma(\mathbf{M}\times\mathbf{H}_{eff})} + \boxed{\cancel{\frac{\alpha}{Ms}\mathbf{M}\times\frac{d\mathbf{M}}{dt}}} + \boxed{\cancel{\frac{\gamma a_J(\theta)}{Ms}\mathbf{M}\times(\mathbf{M}\times\mathbf{P})}}$$

Precession ~~**Damping**~~ ~~**Spin torque (ST)**~~

a_J ~current J

P = spin polarization vector

$$\mathbf{H}_{eff} = -\frac{\partial E}{\partial \mathbf{M}}$$



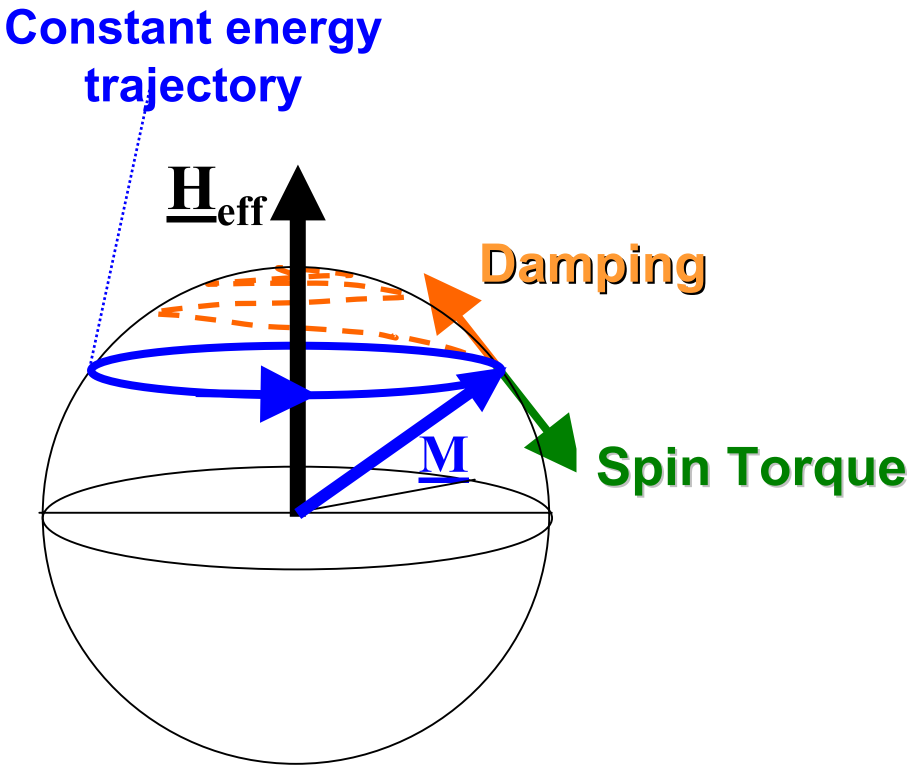
Introduction: Equation of Motion

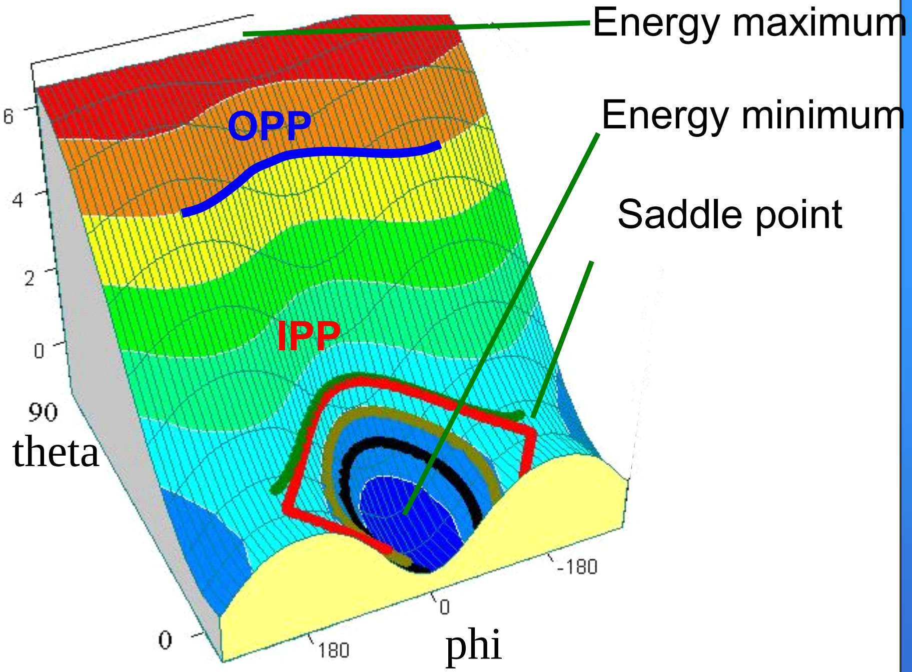
$$\frac{d\mathbf{M}}{dt} = \underbrace{\boxed{-\gamma(\mathbf{M}\times\mathbf{H}_{eff})}}_{\text{Precession}} + \underbrace{\boxed{\frac{\alpha}{Ms}\mathbf{M}\times\frac{d\mathbf{M}}{dt}}}_{\text{Damping}} + \underbrace{\boxed{\frac{\gamma\, a_J(\theta)}{Ms}\mathbf{M}\times(\mathbf{M}\times\mathbf{P})}}_{\text{Spin torque (ST)}}$$

a_J ~current J

P = spin polarization vector

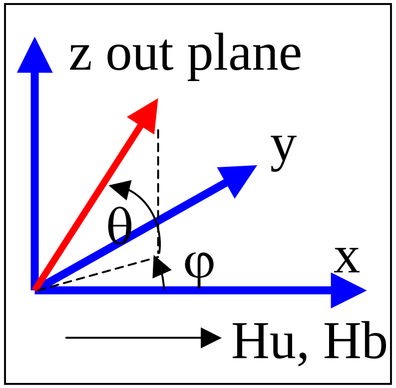
$$\mathbf{H}_{eff} = -\frac{\partial E}{\partial \mathbf{M}}$$

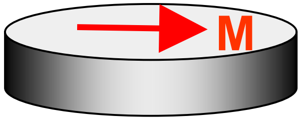




Constant Energy Trajectories

In-plane film

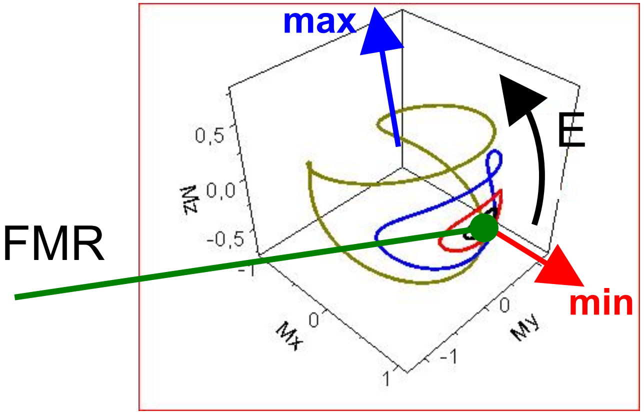


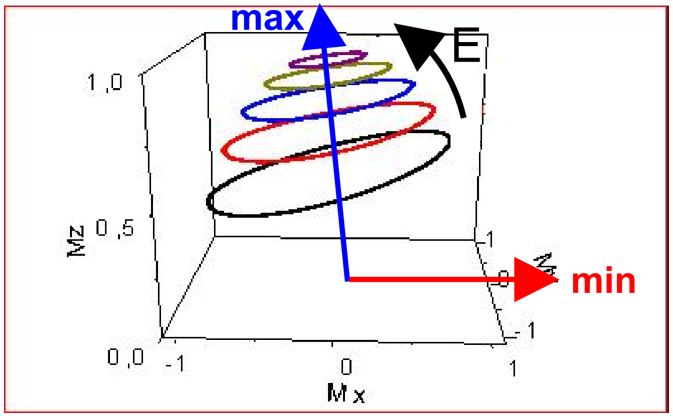


$$\frac{d\mathbf{M}}{dt} = \boxed{-\gamma(\mathbf{M}\times\mathbf{H}_{eff})}$$

In-Plane Precession IPP

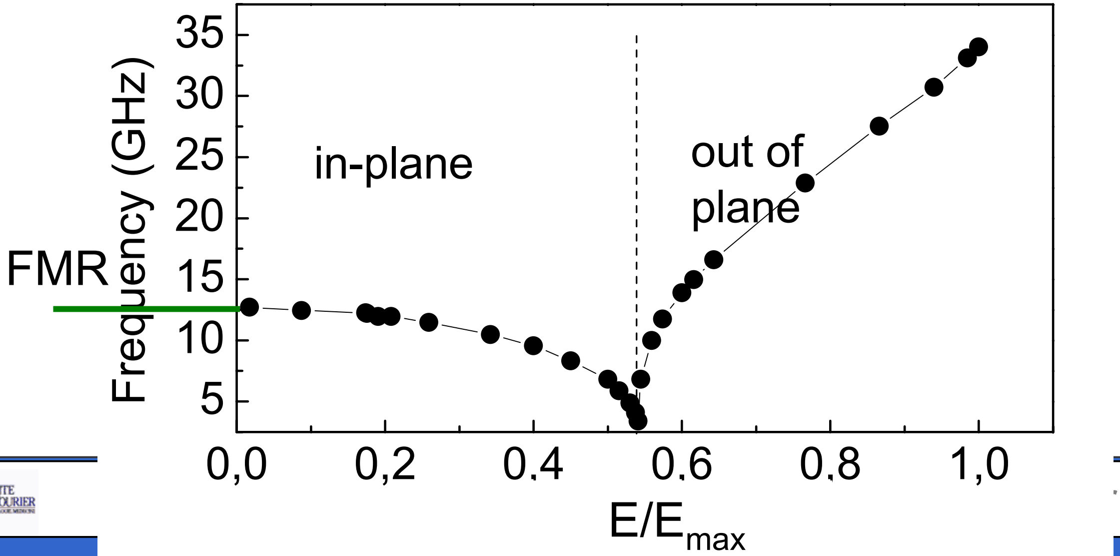
Out of Plane Precession OPP





Oscillation around energy minimum

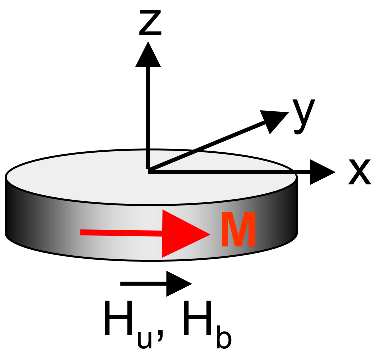
Oscillation around energy maximum



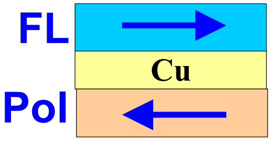
Limit Cycles as a function of polarizer

$$\frac{d\mathbf{M}}{dt} = \boxed{-\gamma(\mathbf{M}\times\mathbf{H}_{eff})} + \boxed{\frac{\alpha}{Ms}\mathbf{M}\times\frac{d\mathbf{M}}{dt}} + \boxed{\frac{\gamma\, a_J(\theta)}{Ms}\mathbf{M}\times(\mathbf{M}\times\mathbf{P})}$$

Precession **Damping** **Spin torque (ST)**

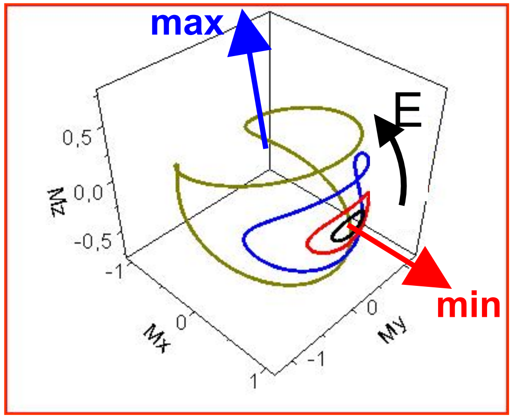


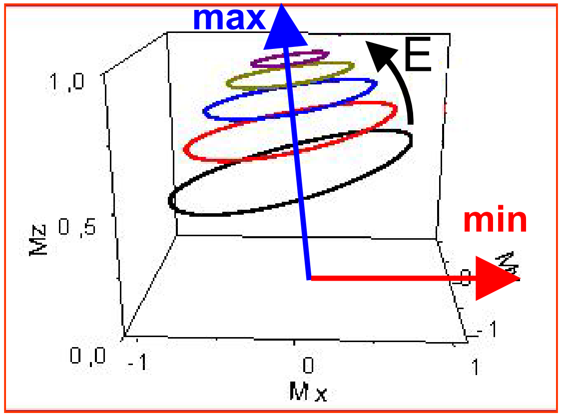
ST tends to align M parallel to P



In-Plane Precession IPP

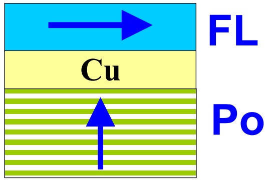
Out of Plane Precession OPP



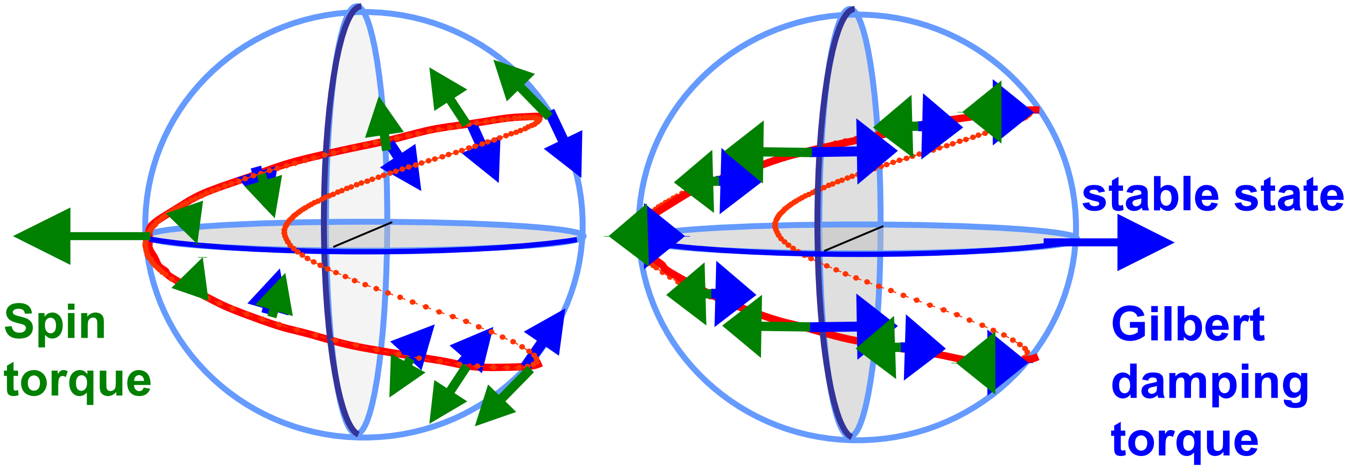


Oscillation around energy minimum

Oscillation around energy maximum



Planar Polarizer: IPP oscillations



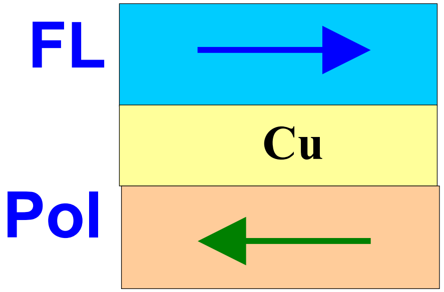
Spin torque

stable state

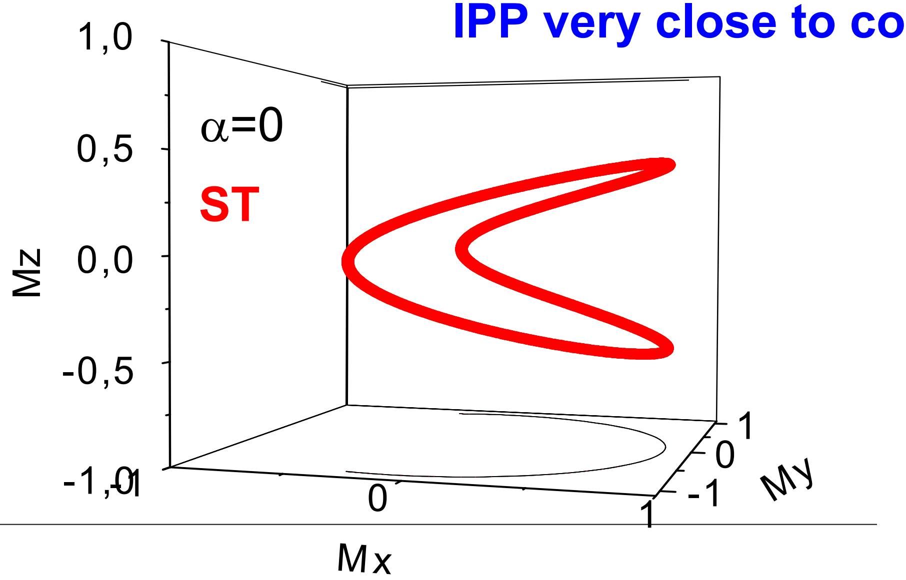
Gilbert damping torque

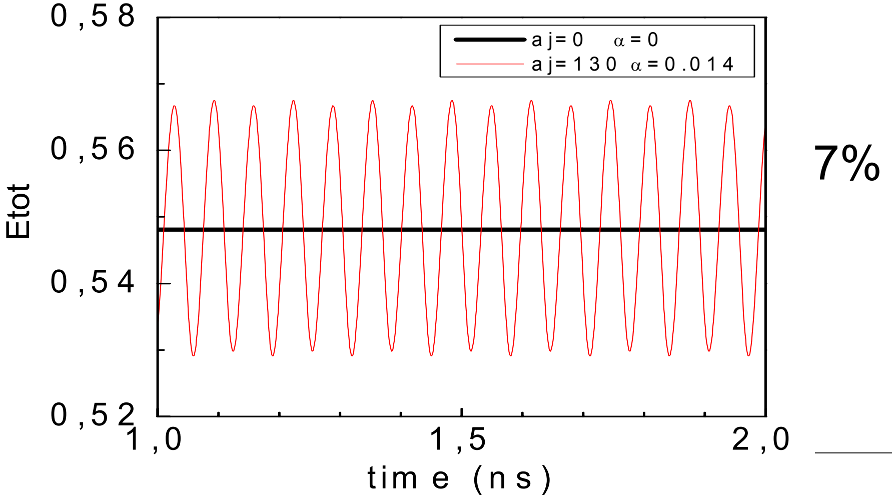
theta component

phi component

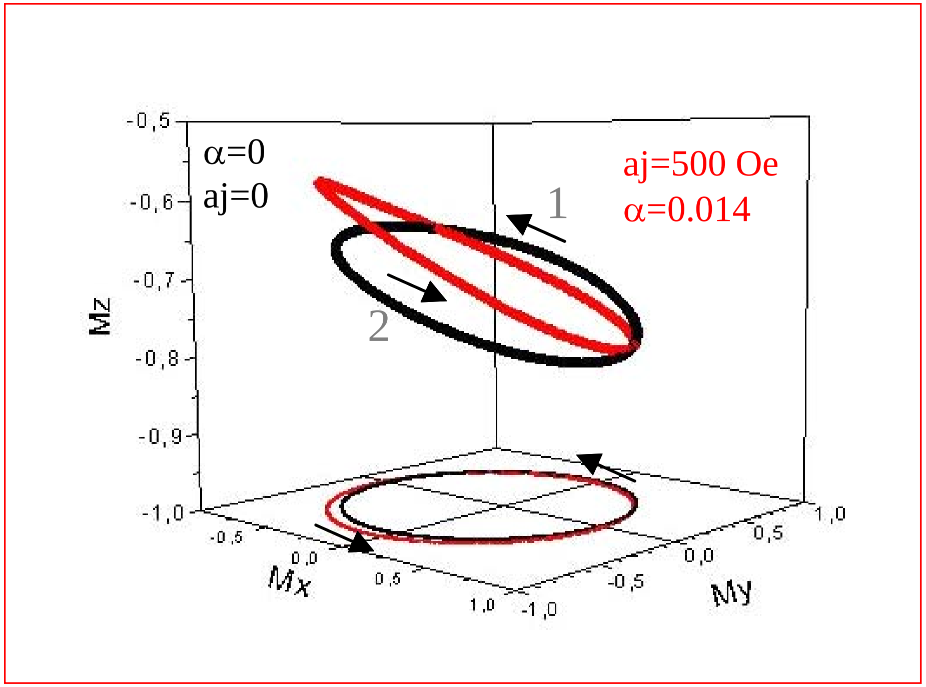


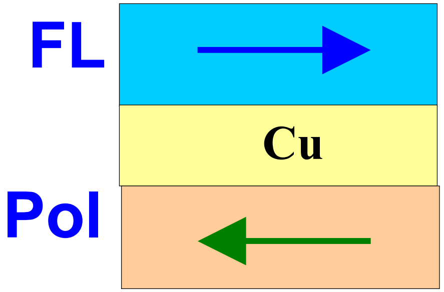
IPP very close to constant energy trajectory

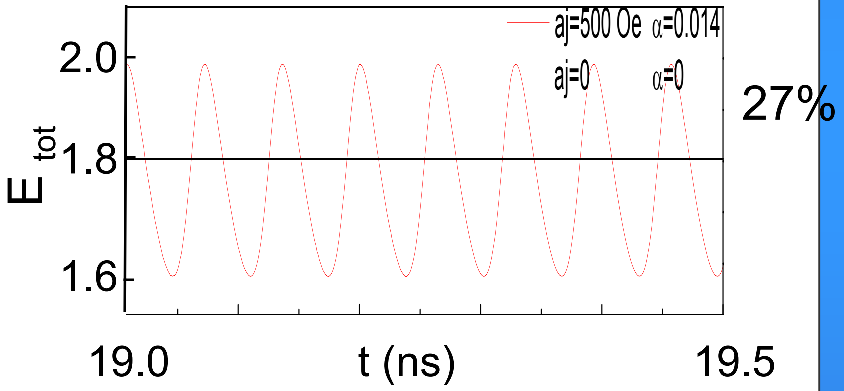




Planar Polarizer: OPP oscillations

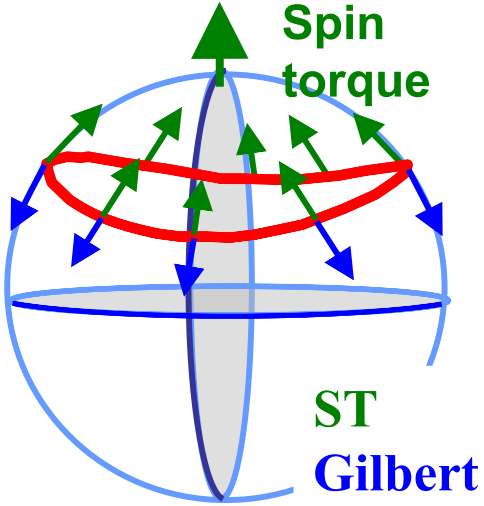




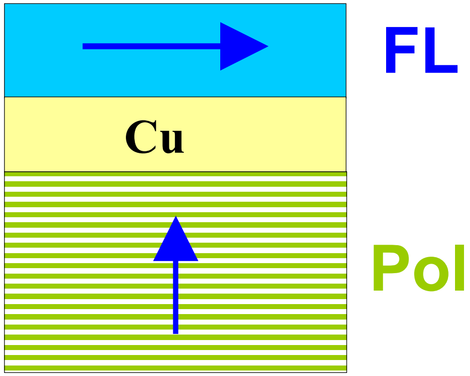


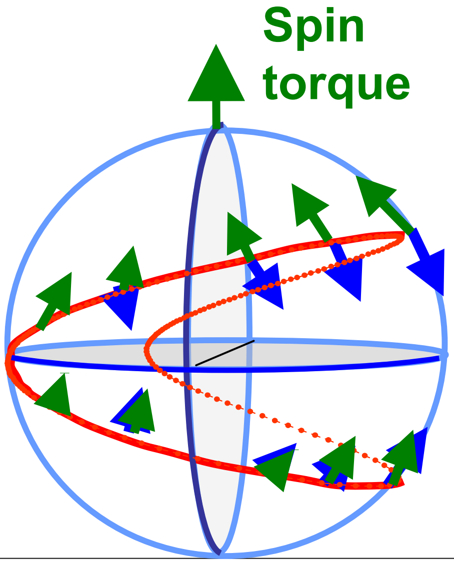
OPP close but not identical to constant energy trajectories

Perpendicular Polarizer: No IPP oscillations

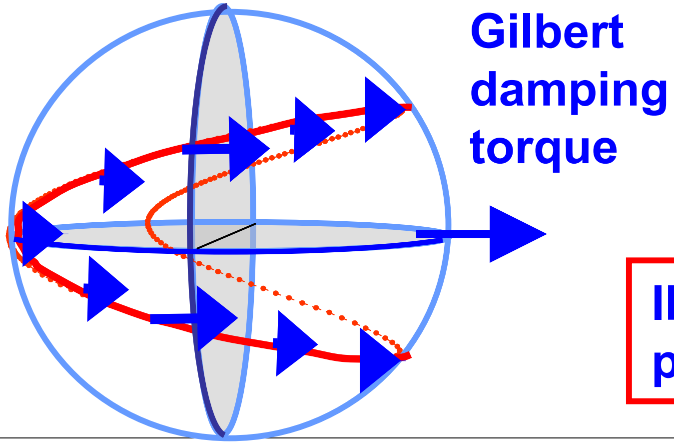


OPP stabilized by
perpendicular polarizer





theta component



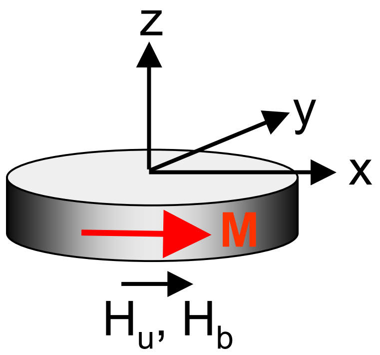
phi component

IPP not stabilized by
perpendicular polarizer

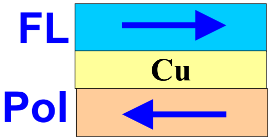
Limit Cycles as a function of polarizer

$$\frac{d\mathbf{M}}{dt} = \boxed{-\gamma(\mathbf{M}\times\mathbf{H}_{eff})} + \boxed{\frac{\alpha}{Ms}\mathbf{M}\times\frac{d\mathbf{M}}{dt}} + \boxed{\frac{\gamma\, a_J(\theta)}{Ms}\mathbf{M}\times(\mathbf{M}\times\mathbf{P})}$$

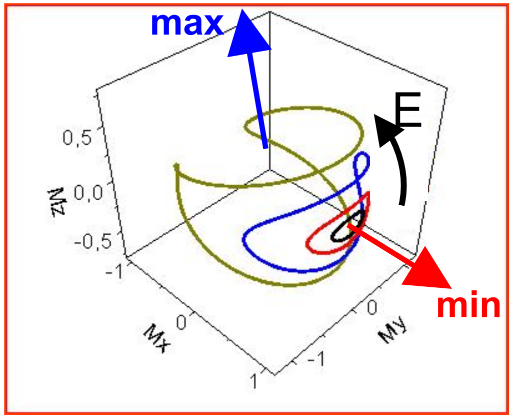
Precession **Damping** **Spin torque (ST)**



ST tends to align M parallel to P

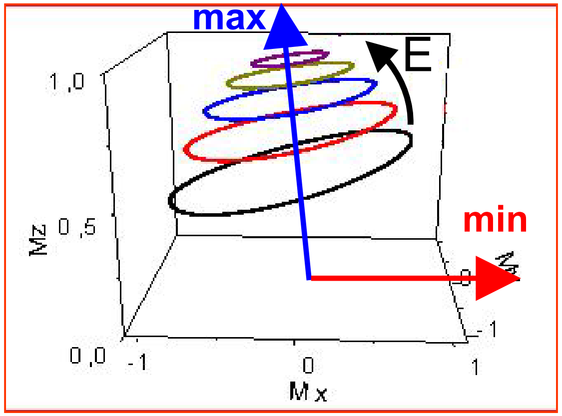


In-Plane Precession IPP

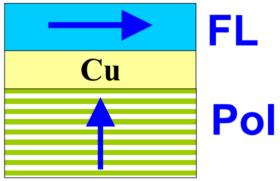


Oscillation around energy minimum

Out of Plane Precession OPP

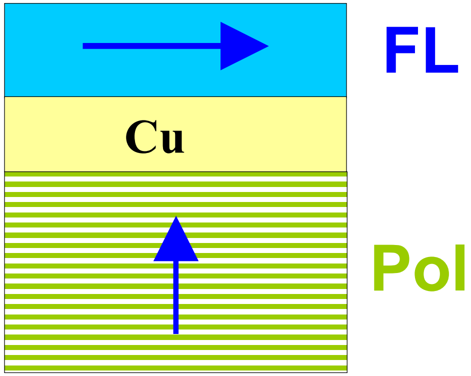


Oscillation around energy maximum



Perpendicular Polarizer

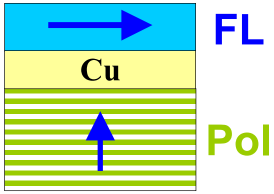
Macrospin description

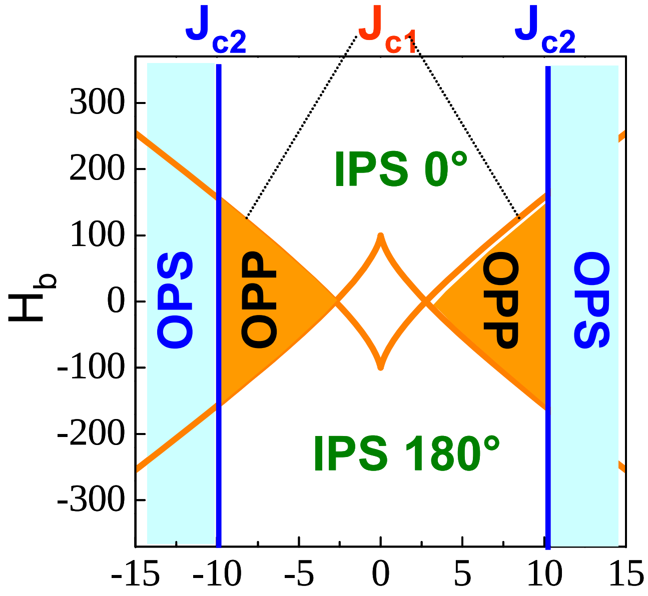


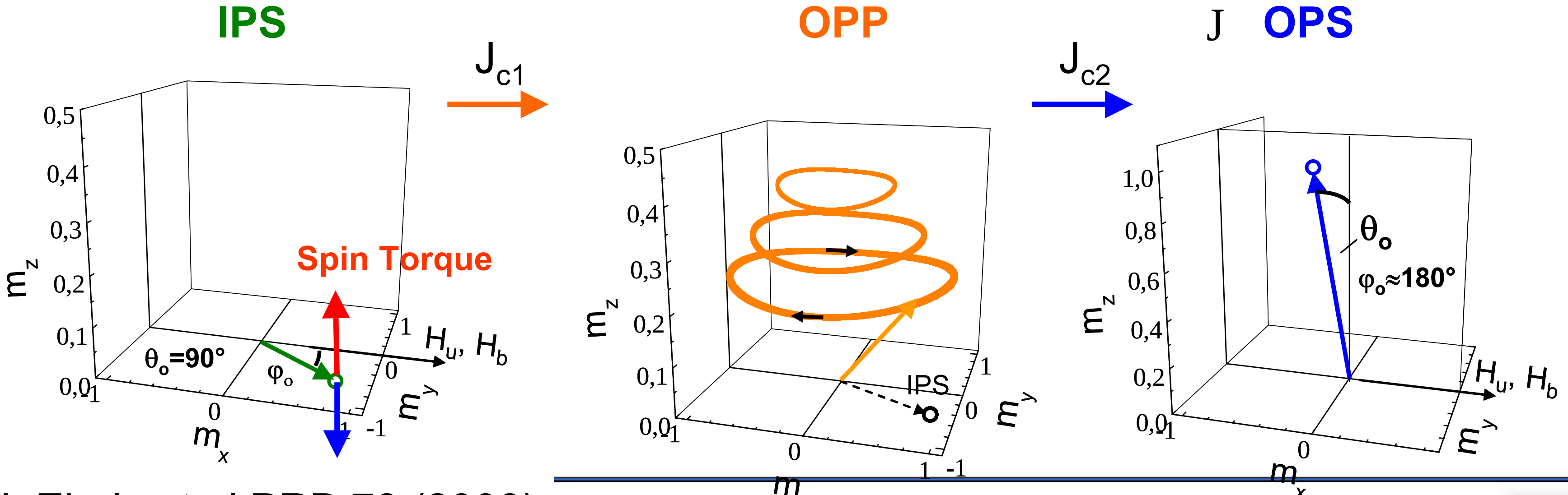
State Diagramme of Perpendicular Polarizer

Three different states

In Plane Stable	**IPS**
Out of Plane Precession	**OPP**
Out of Plane Stable	**OPS**







U. Ebels et al PRB 78 (2008)

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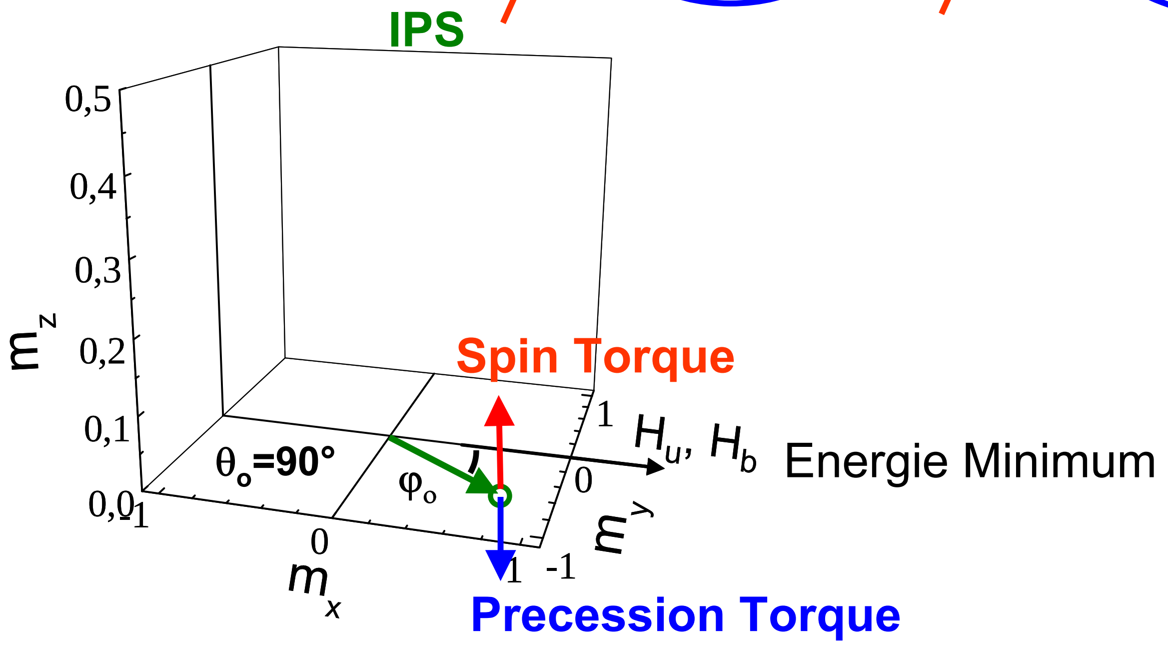
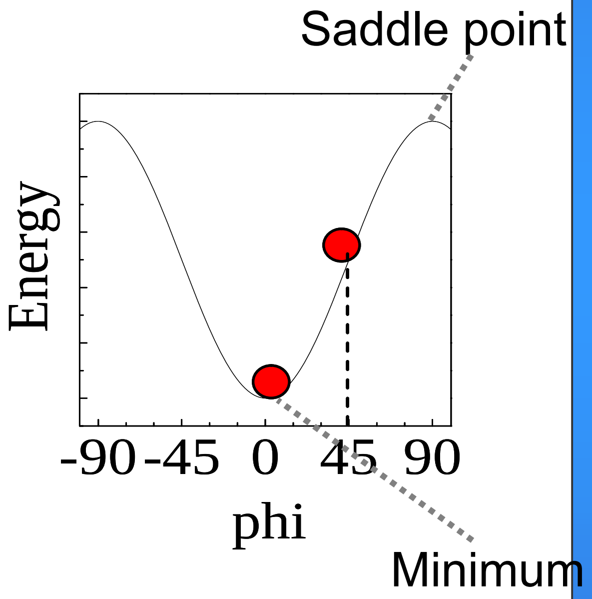
Perpendicular Polarizer IPS State

IPS : In Plane Stable **$0<J<J_{c1}$**

$$\cancel{\frac{d\mathbf{M}}{dt}} = \boxed{-\gamma(\mathbf{M}\times\mathbf{H}_{eff})} + \frac{\alpha}{Ms}\mathbf{M}\cancel{\times\frac{d\mathbf{M}}{dt}} - \boxed{\frac{\gamma a_J(\theta)}{Ms}\mathbf{M}\times(\mathbf{M}\times\mathbf{P})}$$



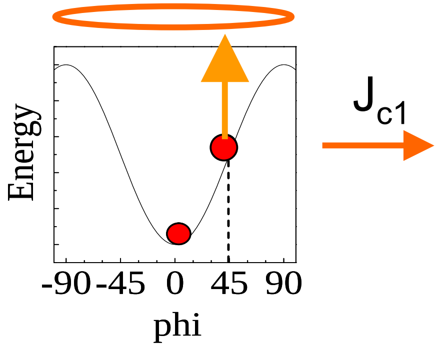


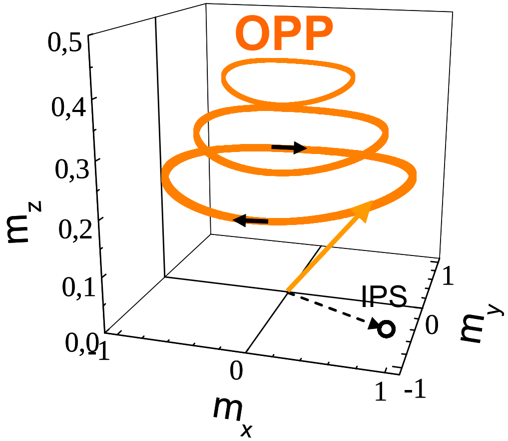
- → **Equilibrium between precession torque and spin torque**
- → **In-plane rotation, away from energy minimum**
- → **Spin torque does not counteract damping, no asymmetry wrt to current**

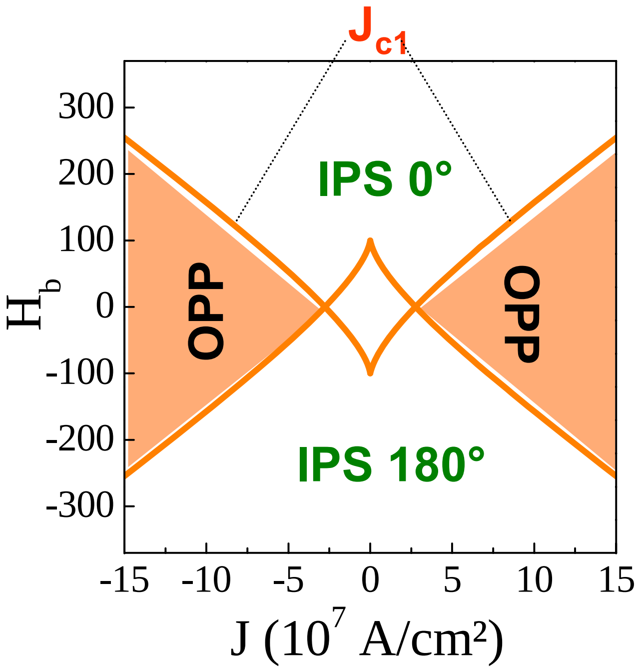
Perpendicular Polarizer IPS to OPP Transition

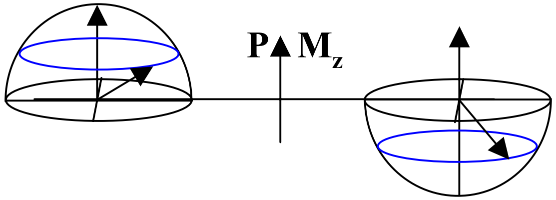
OPP : Out of Plane Precession $J_{c1}<J<J_{c2}$

$$\frac{d\mathbf{M}}{dt}=-\gamma(\mathbf{M}\times\mathbf{H}_{eff})+\frac{\alpha}{Ms}\mathbf{M}\times\frac{d\mathbf{M}}{dt}+\frac{\gamma a_J(\theta)}{Ms}\mathbf{M}\times(\mathbf{M}\times\mathbf{P})$$









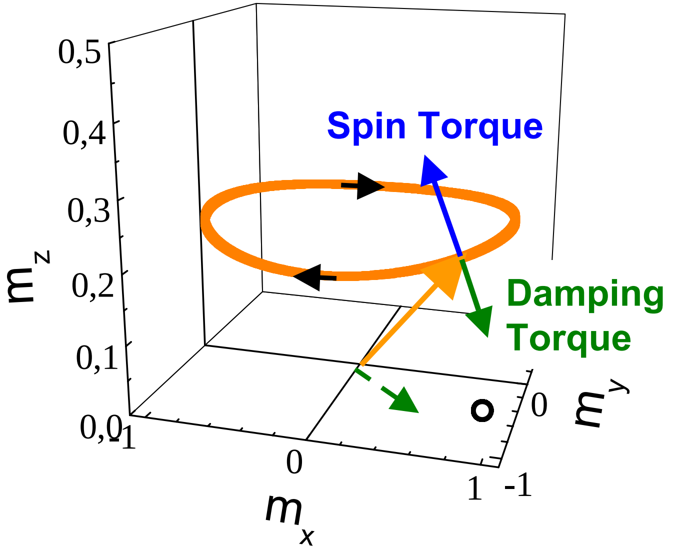
$$\cos\varphi_c=\frac{-H_b}{4H_u}+\sqrt{\frac{-H_b}{4H_u}+0.5}$$

$$a_{jc1}=H_u\cos\varphi_c\sin\varphi_c+H_b\sin\varphi_c$$

does not depend on damping

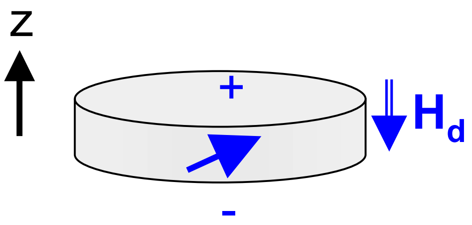
Perpendicular Polarizer OPP Oscillations

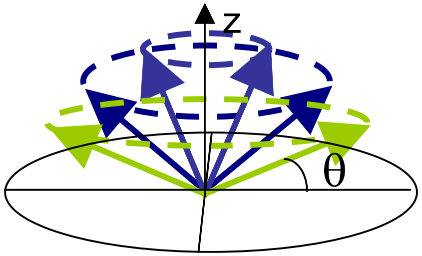
Out of Plane Precession OPP



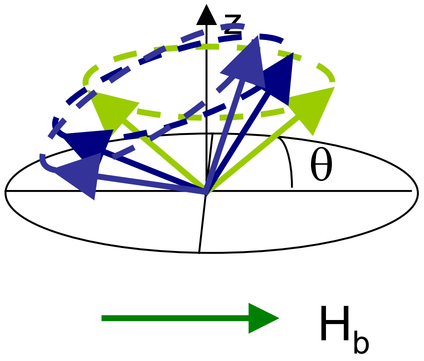
$$m_z \approx \frac{a_j}{\alpha 4\pi M_s} \propto \frac{J}{\alpha 4\pi M_s}$$

K. J. Lee et al. APL 86 (2005)

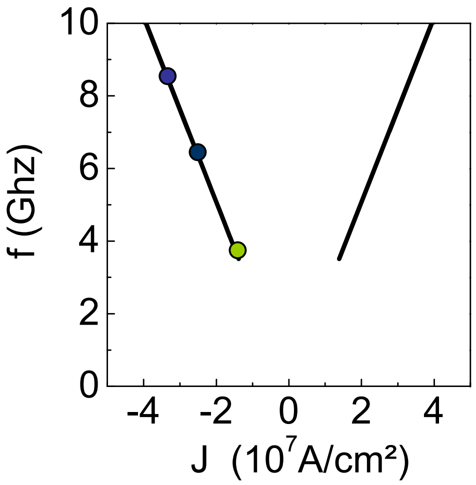




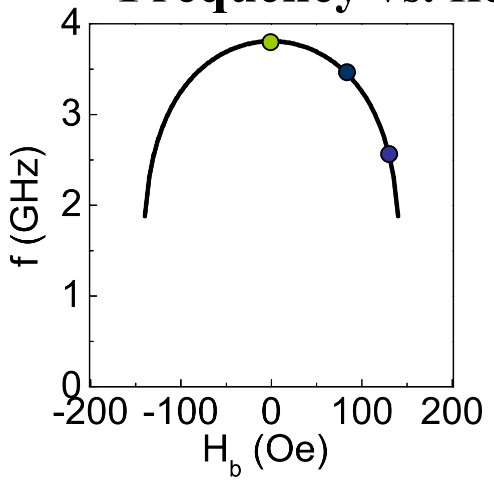
$$f \approx \frac{\gamma}{2\pi} H_d \sim m_z \sim J$$



Frequency vs. current



Frequency vs. field



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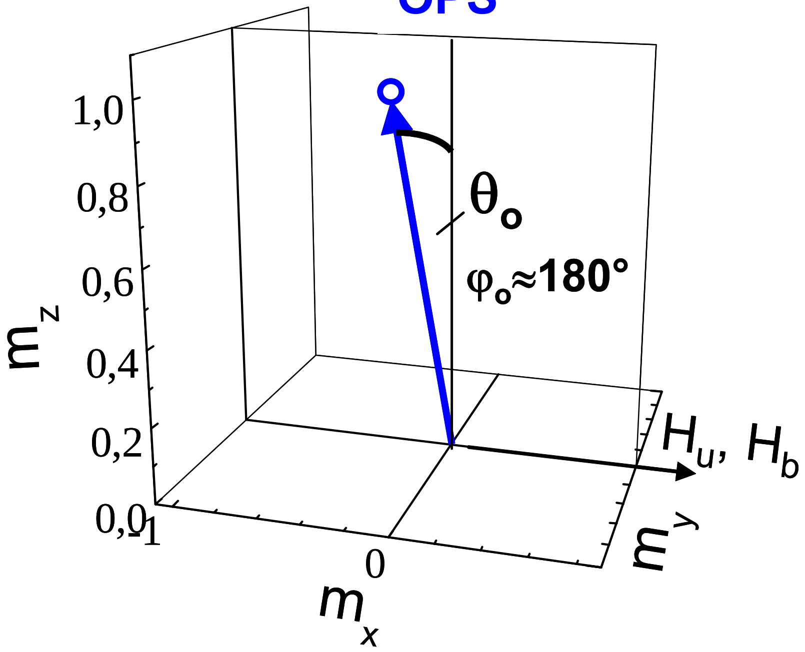
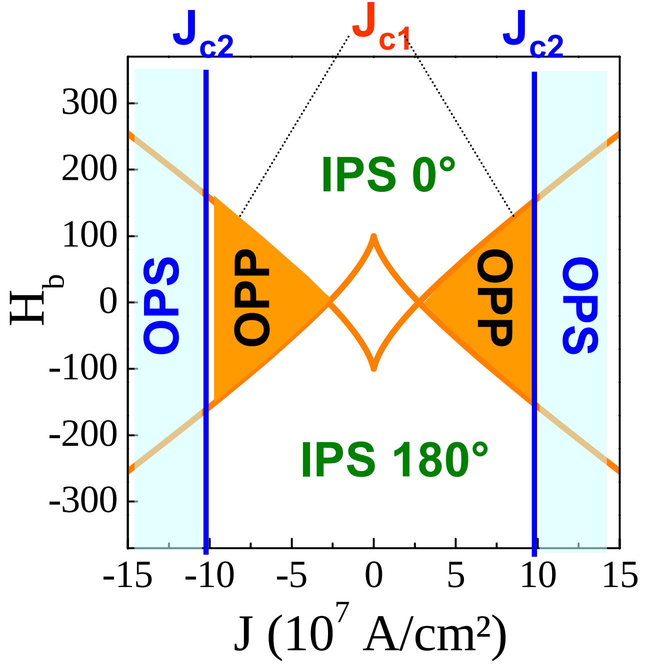
Perpendicular Polarizer OPP to OPS Transition

OPS : Out of Plane Stable State J>J_{c2}

$$m_z \approx \frac{a_j}{\alpha 4\pi M_s} = 1 \quad \Rightarrow \quad J_{c2} \prec \alpha 4\pi M_s$$

OPS





Inverted role of spin torque and damping torque

→ In OPS state, spin torque stabilizes energy maximum, while damping destablizes it

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Perpendicular Polarizer IPS - OPP Hysteresis

Diagramme for increasing current

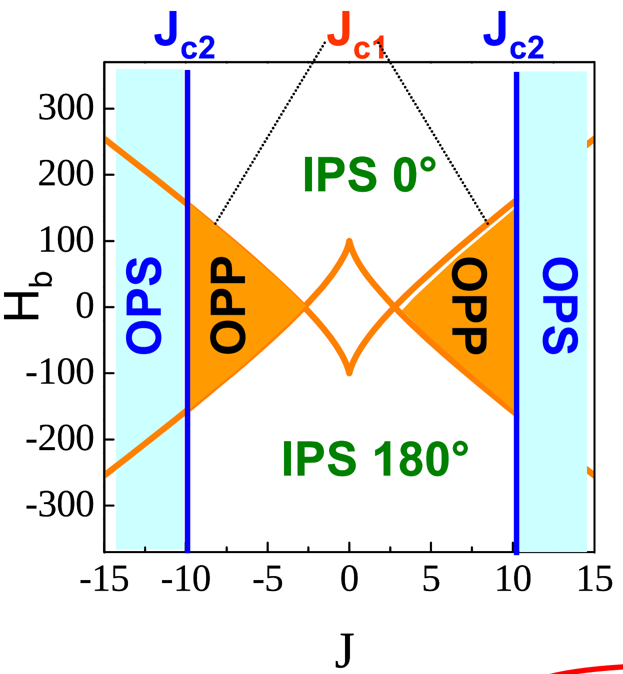
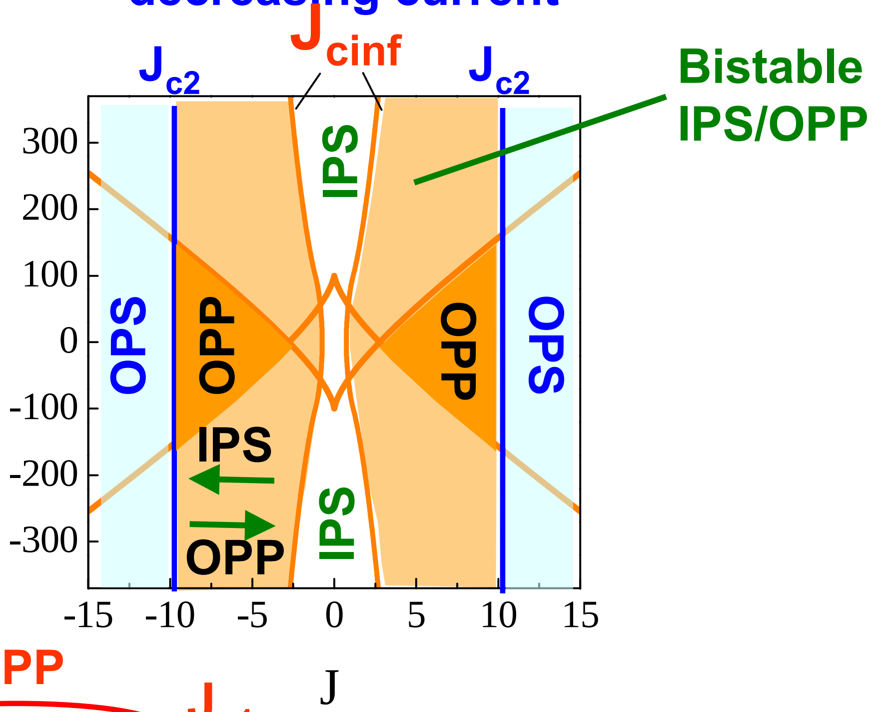
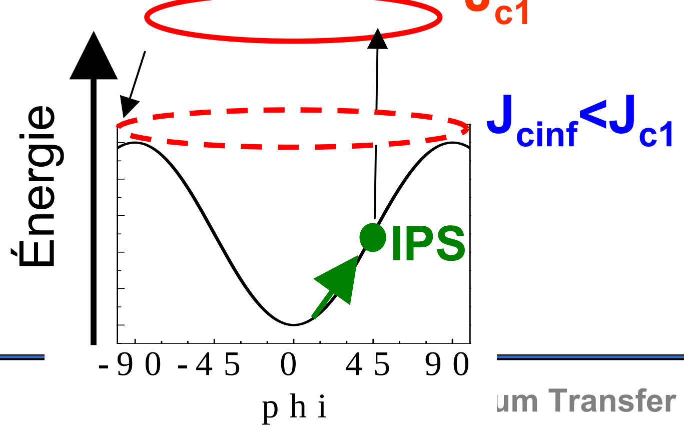


Diagramme for decreasing current





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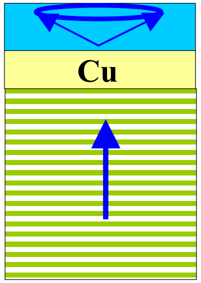
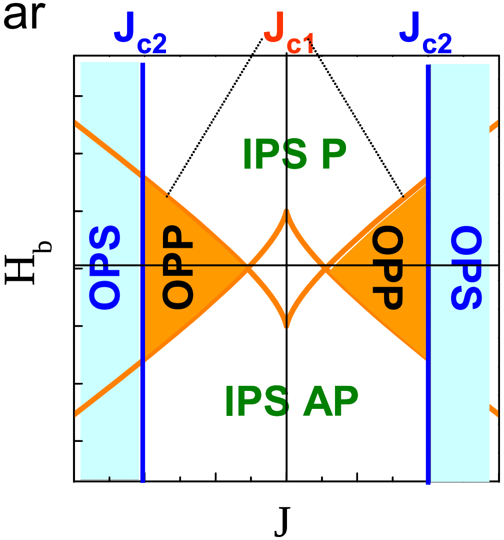
Comparison: Planar and Perpendicular Polarizer

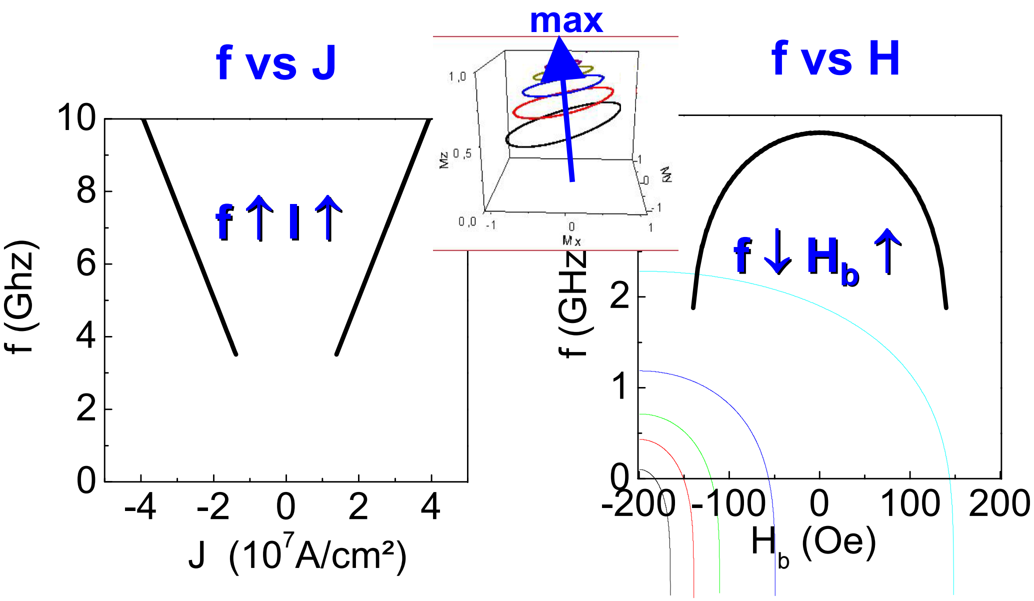
Perpendicular Polarizer



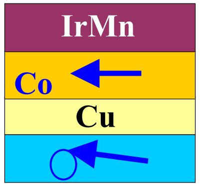


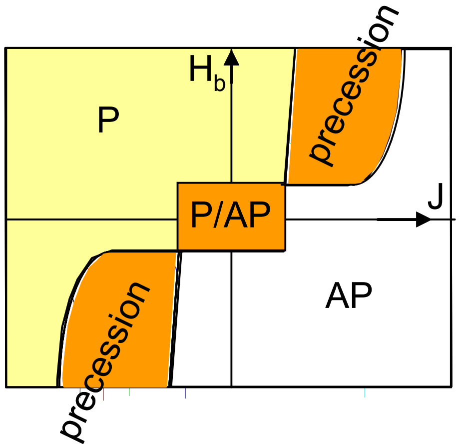
f vs J

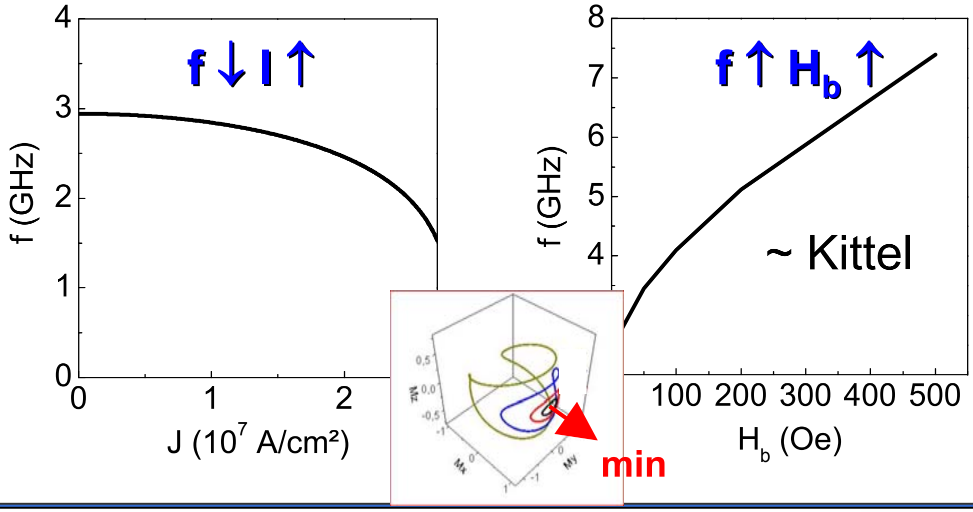
f vs H



Planar Polarizer

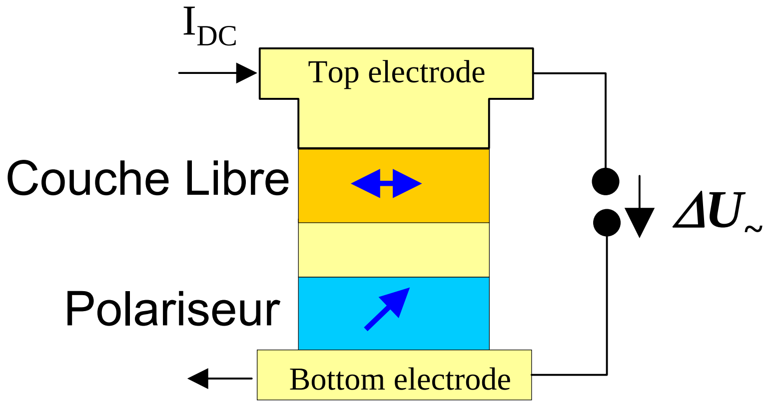




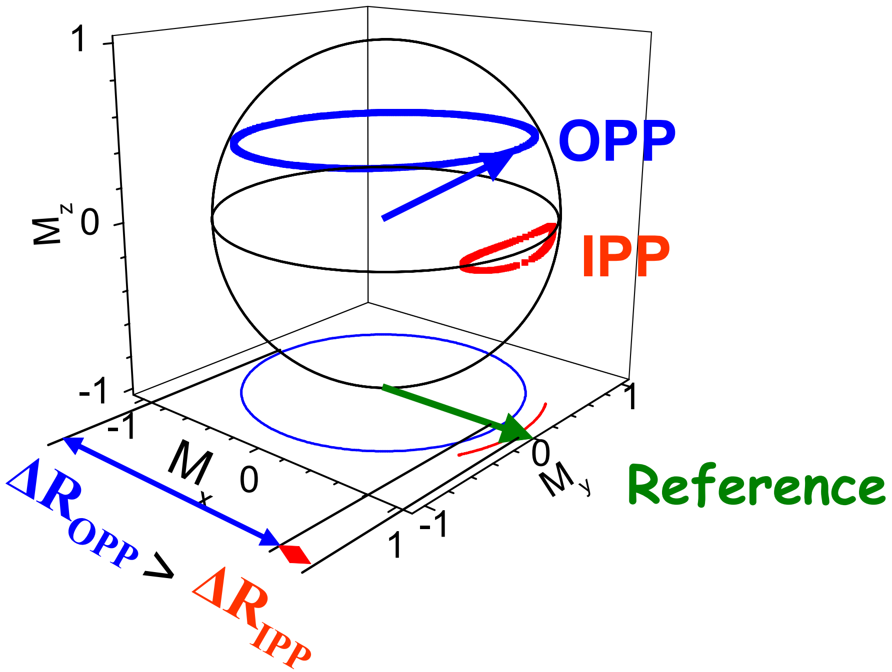


Experimental realization and studies of the perpendicular polarizer STO

J. C. Slonczewski JMMM 157, (1996)
O. Redon US6,532,164 (2002)
A. Kent et al. APL 84 (2004)
K. J. Lee et al. APL 86 (2005)



Output signal



$$\Delta M_x \propto \Delta R$$

$$\Delta U_\sim \propto \Delta R \cdot I_{DC}$$

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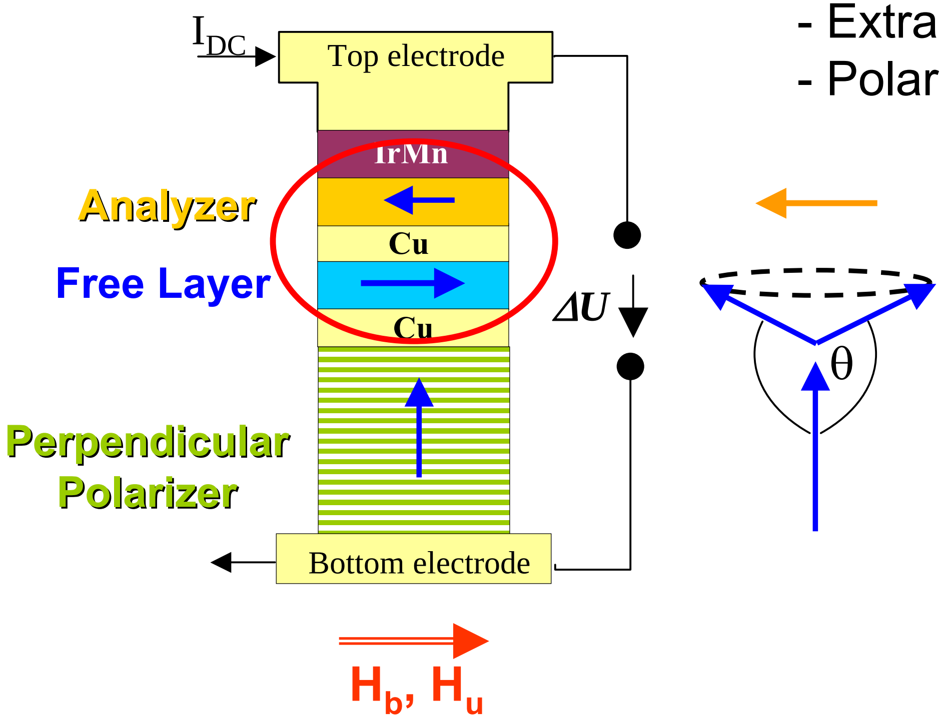
Experimental Realization of the Perpendicular STO



Two conditions:
- Extract signal
- Polarizer with sufficient spin polarization

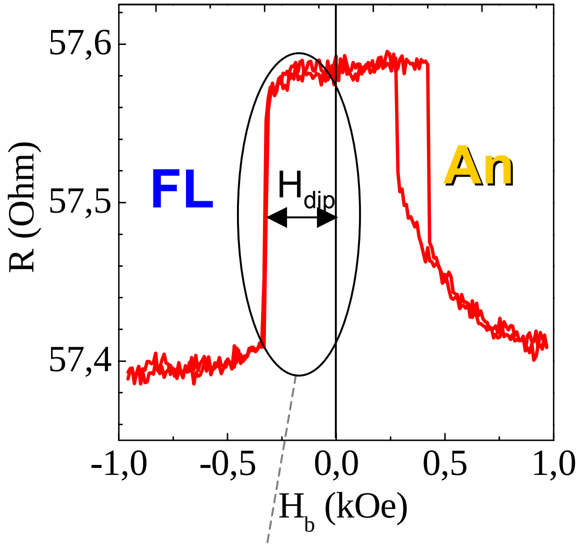
Pt / $(Co/Pt)_5/Co_{laminated}$ 1.6/Cu4/**Py3/Co0.5/**/Cu3/**Co3/IrMn5**

$Co_{laminated}$=Co0.8/Cu0.3/Co0.8*

*Delille, F. *et al*. *JAP* **100**, 13912 (2006)

Free Layer R(H) minor loops vs current

Low current



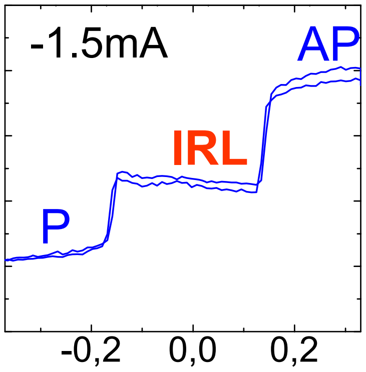
Ellipse de 60x70 nm²

I_{DC}= 0.15 mA

(J=4.5 10^6 A/cm²)

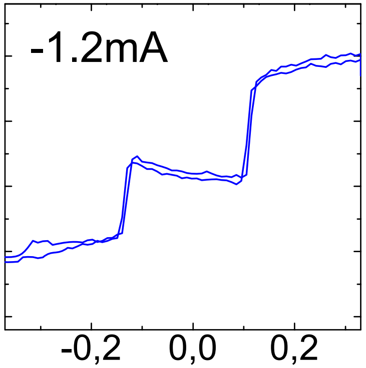
ΔR = 0.19Ω

MR=0.3%



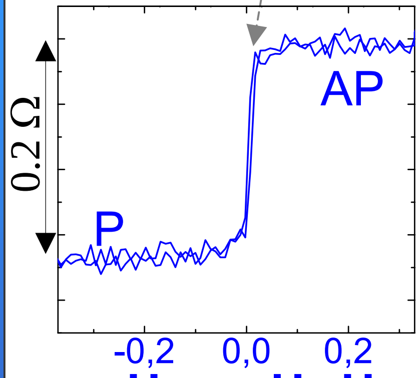
Intermediate Resistance Level

IRL @ 0.5ΔR

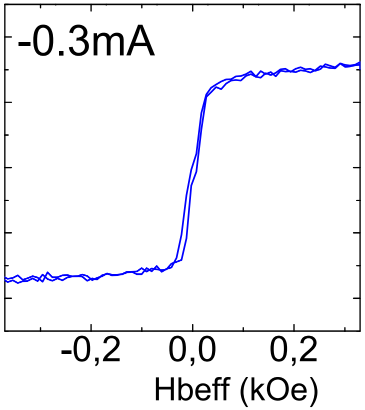


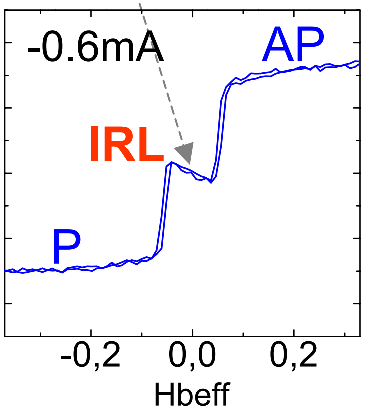
(positive and negative I_{DC})

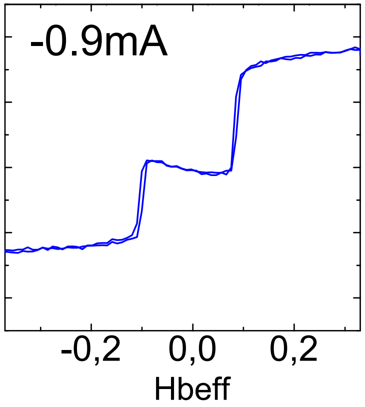
I_{DC}=-0.1mA



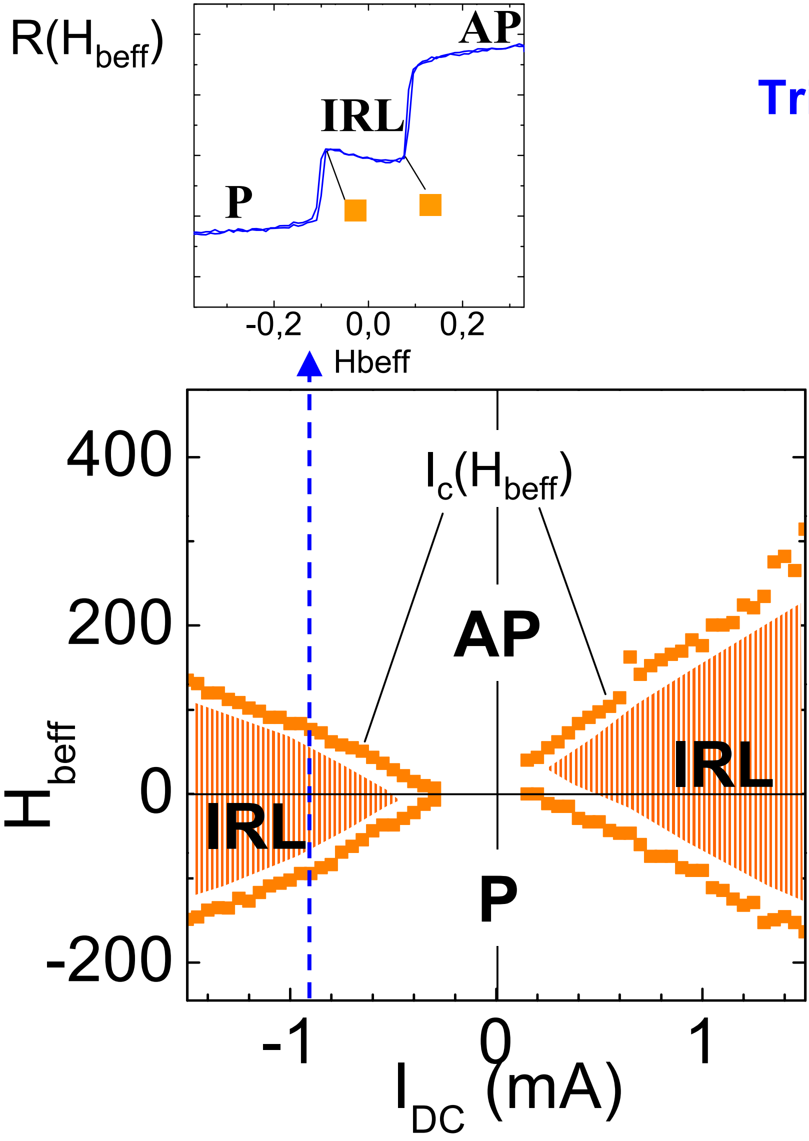
$H_{beff} = H_b - H_{dip}$



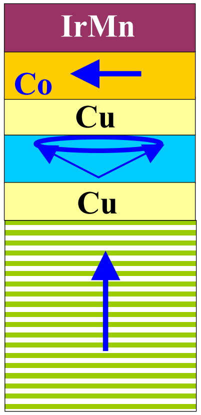




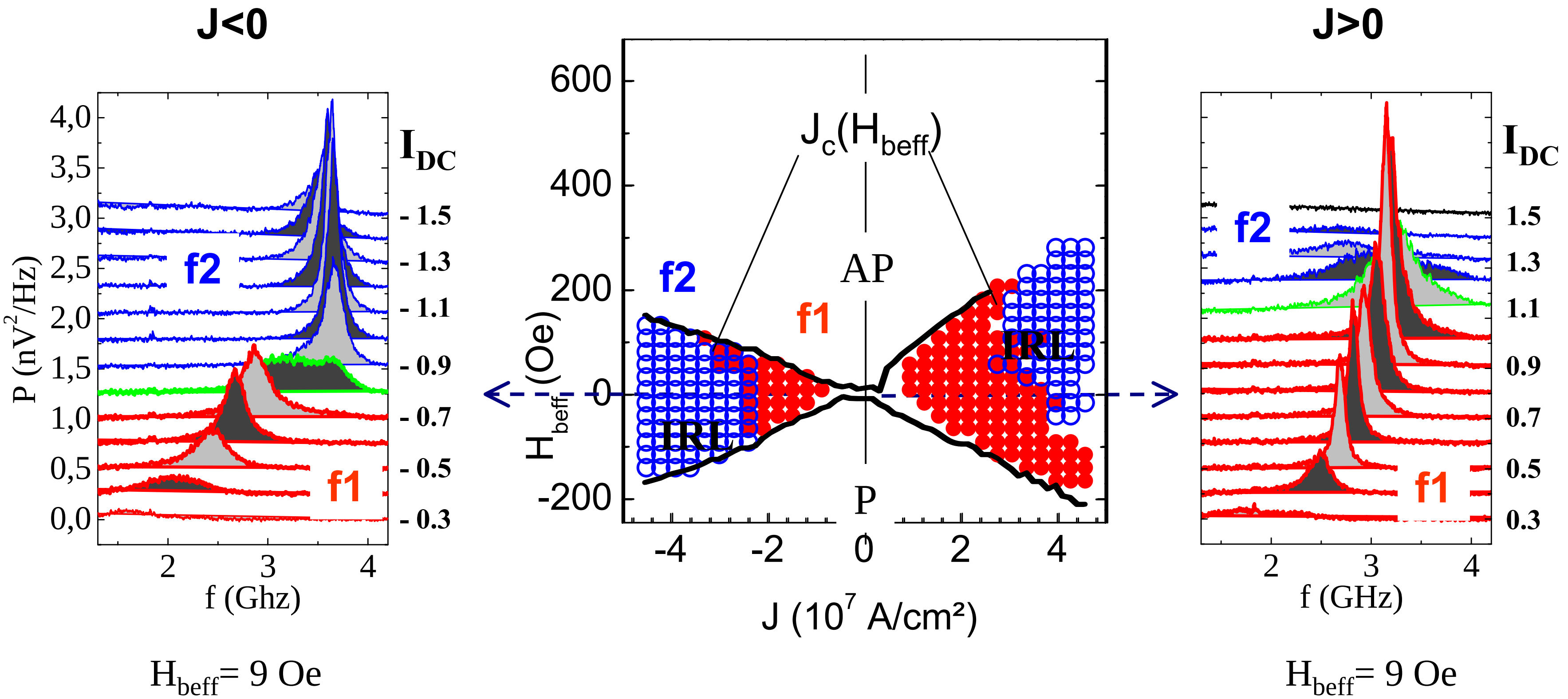
Static Experimental Diagramme I_{DC} - H_{beff}



Triangular shaped regions $I_c(H_{beff})$ of IRL



Dynamic Experimental Diagramme I_{DC} - H_{beff}



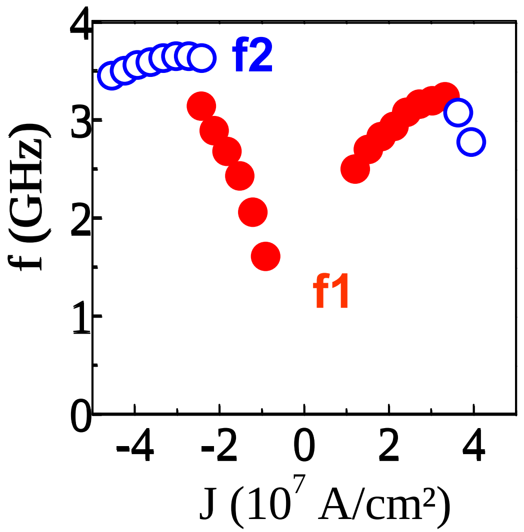
Microwave emission in the intermediate resistance level

D. Houssameddine et al. Nature Materials **6**, 447 (2007)

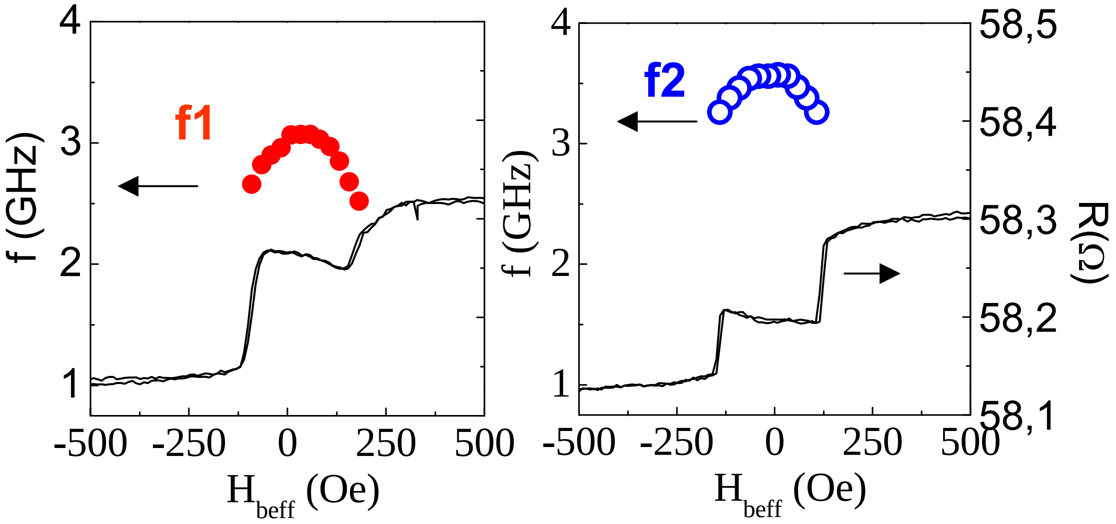
Mode Identification from Frequency Dependence

Experiment

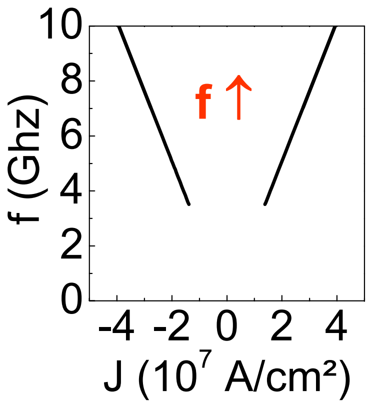
Frequency vs. Current

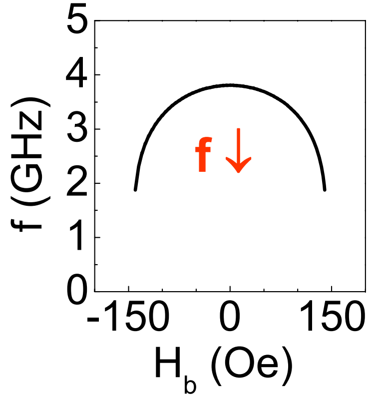


Frequence vs. field



Macrospin Simulation

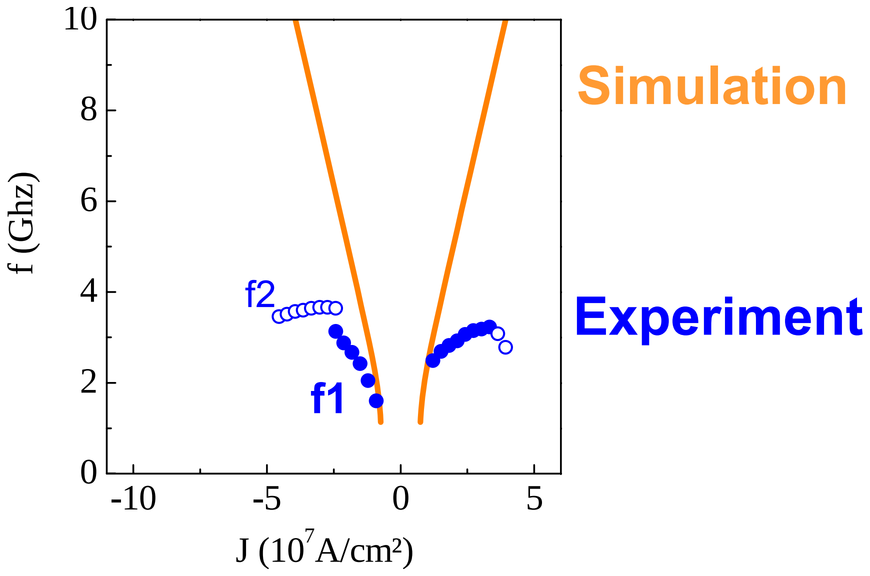




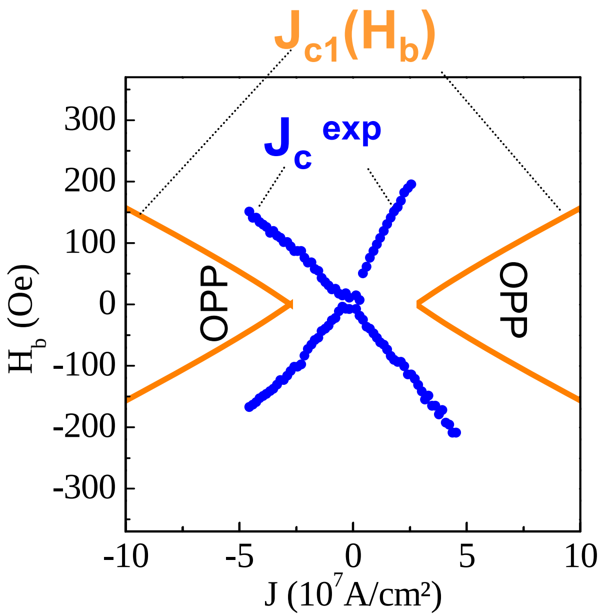
- f1 in agreement with macrospin simulations
- f2 OPP non-macrospin

Quantitative Comparison to Macrospin Simulations

Frequency



Diagramme



$$f \propto \frac{\gamma}{2\pi} \frac{g(\theta)}{M_s t} \frac{J}{\alpha}$$

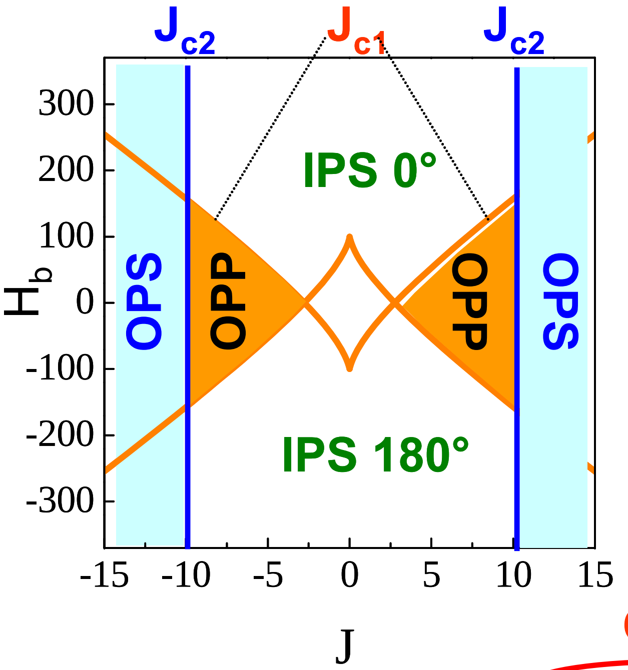
$$J_{c1} \propto \frac{M_s t}{g(\theta)} F(H_u, H_b)$$

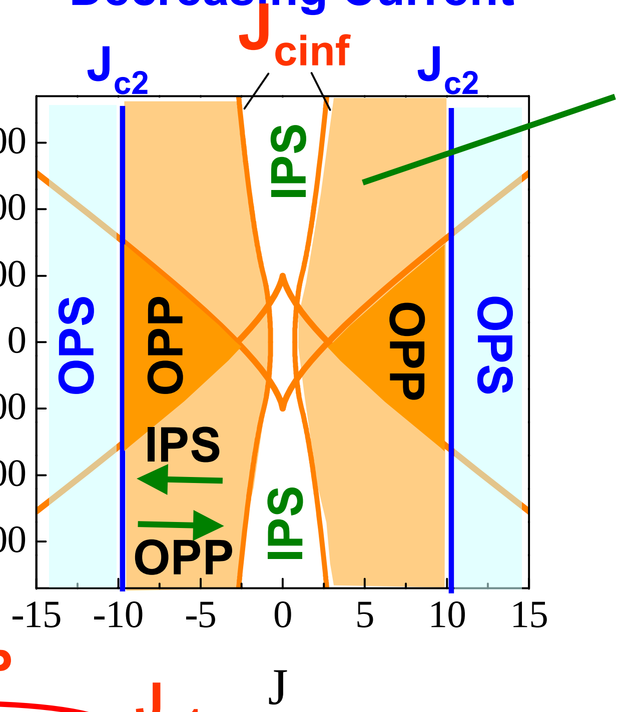
$g(\pi/2)=0.17$

$\alpha=0.02$

Ms =880 erg/cm^3

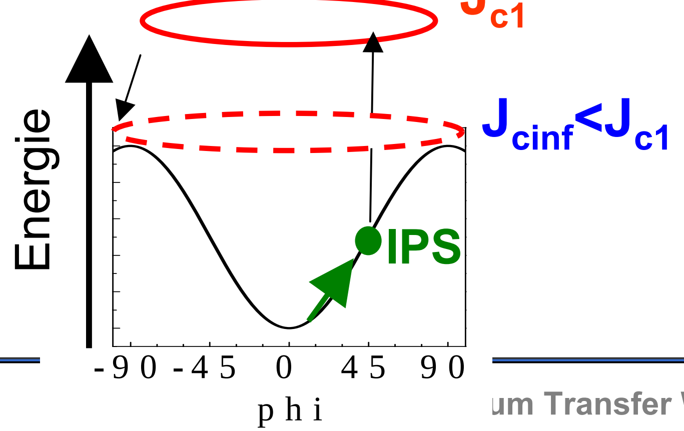
Bistability of IPS and OPP states





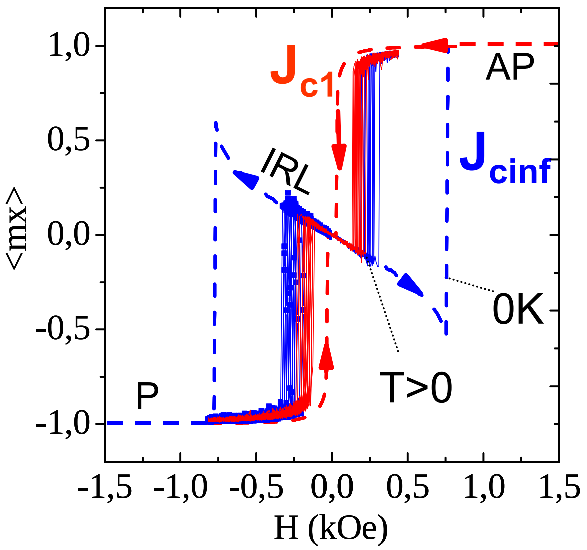
Bistable IPS/OPP

Hysteresis

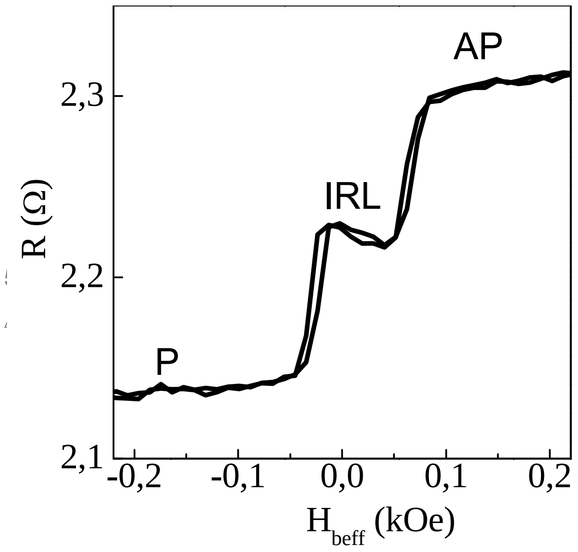


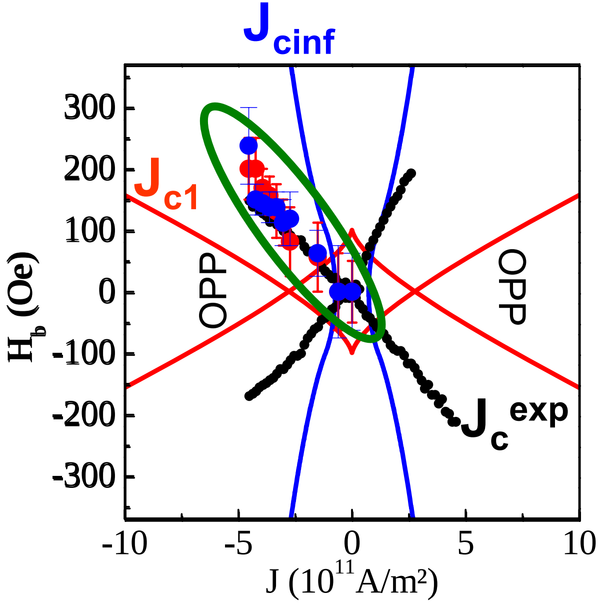
Temperature Effect

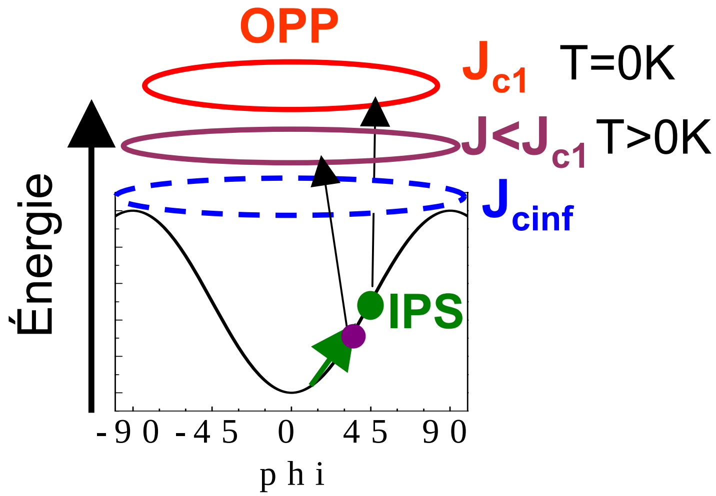
R-H Simulation



R-H experiment

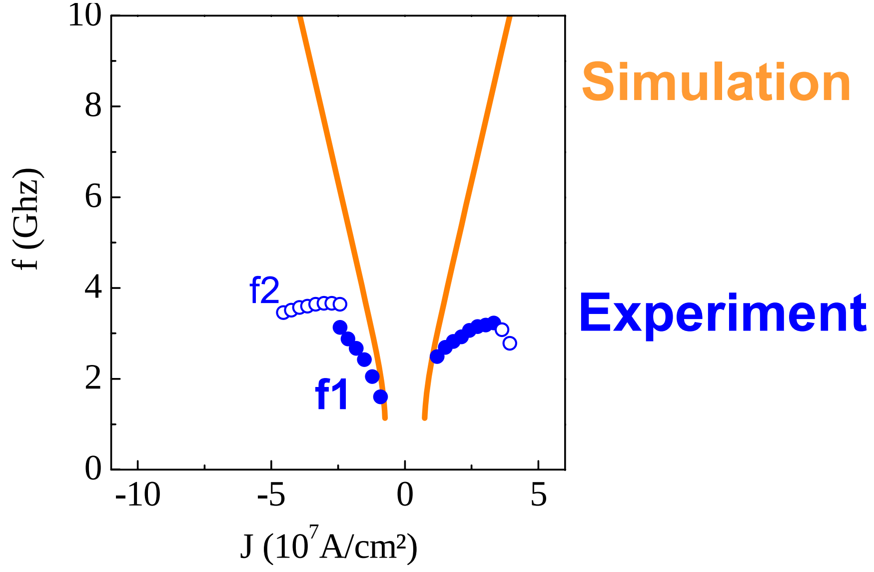




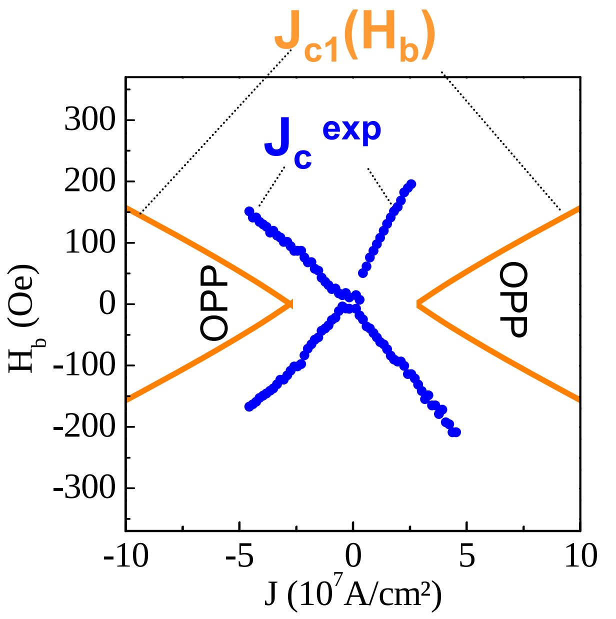


Quantitative Comparison to Macrospin Simulations

Frequency



Diagramme



$$f \propto \frac{\gamma}{2\pi}\boxed{\frac{g(\theta)}{M_s t}}\frac{J}{\alpha}$$

$$J_{c1} \propto \boxed{\frac{M_s t}{g(\theta)}} F(H_u, H_b)$$

$g(\pi/2)=0.17$
$\alpha=0.02$
Ms =880 erg/cm^3

Beyond the macrospin approach

Macrospin description

→ good qualitative agreement for branch f1
→ However, many features not well understood, such as
  - jump and saturation of f at larger current
  - overall low frequencies (even for mode f1)

Possible origins

X Inhomogeneous mode profile
X Dynamic Coupling between the layers

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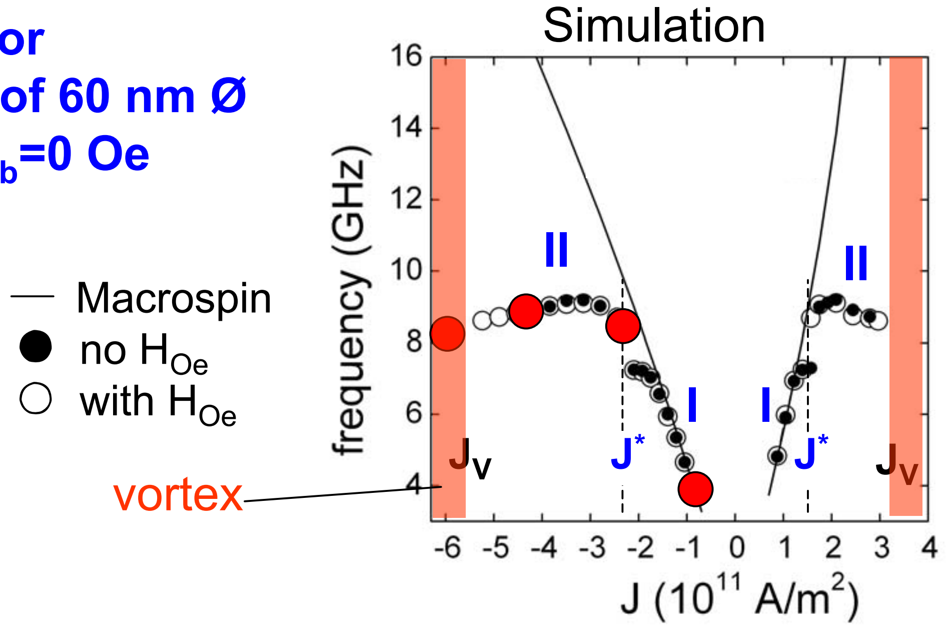
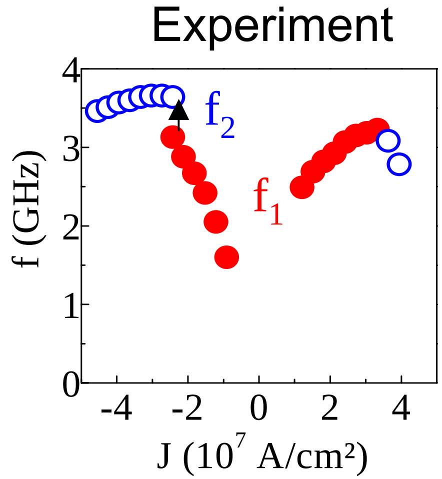
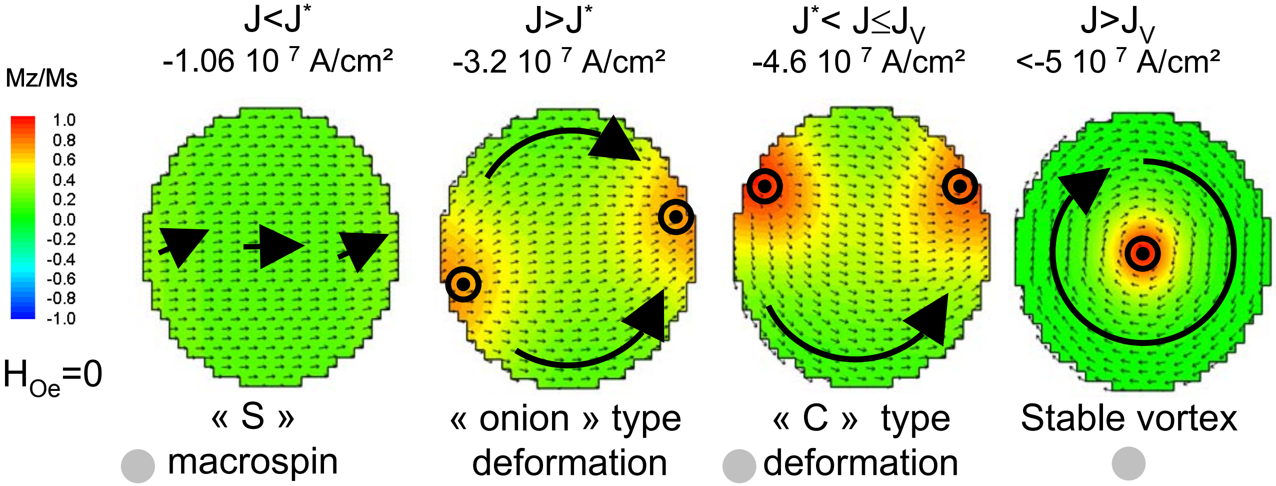
Micromagnetics Simulation

Simulations for
- circular dot of 60 nm Ø
- H_u=15 Oe, H_b=0 Oe
- α=0.01





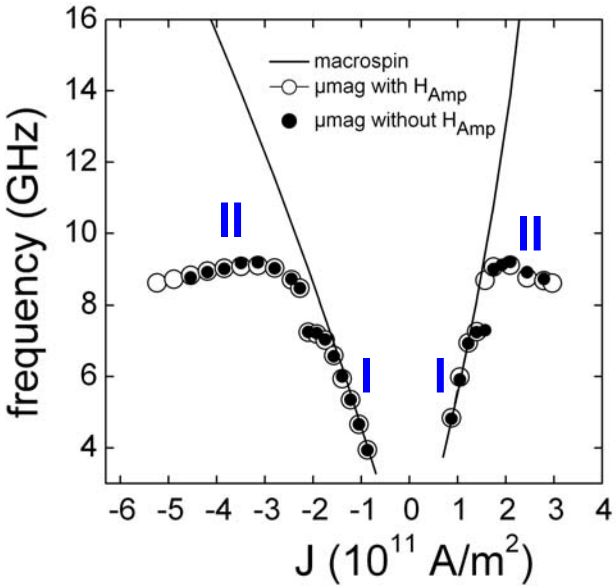
*I. Firastrau,
PRB 78 (2008)



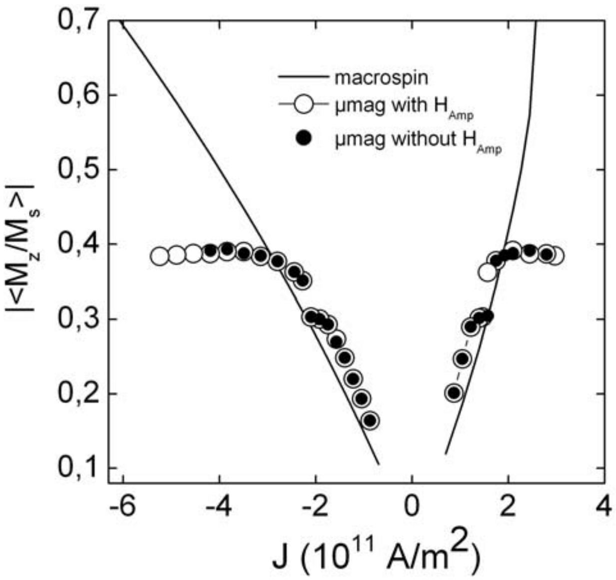
Micromagnetics Simulation

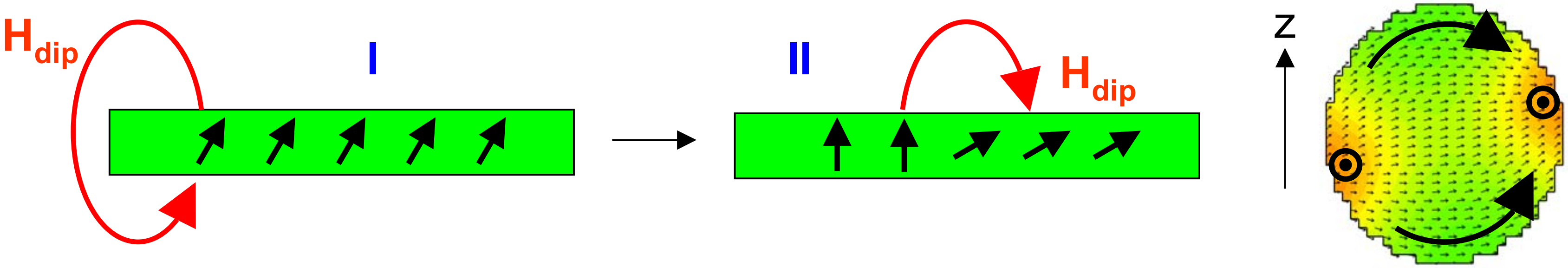
$$f \approx \frac{\gamma}{2\pi} H_d \sim m_z \sim J$$

Frequency



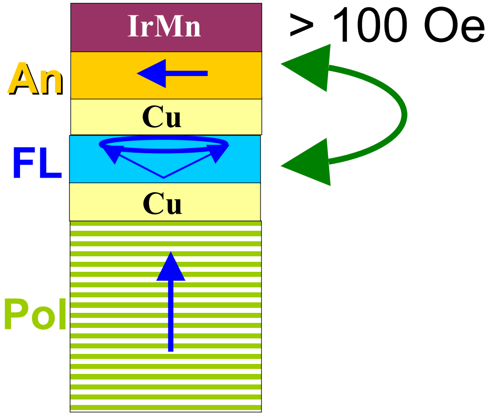
$<m_z>$



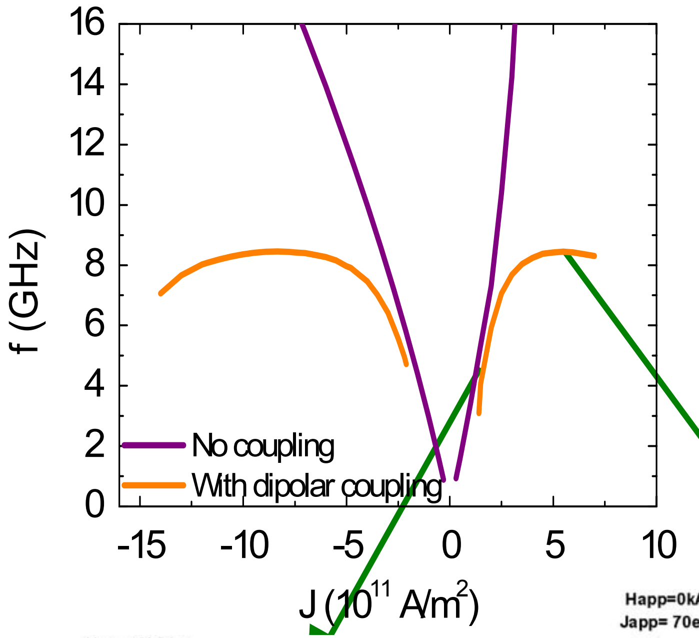


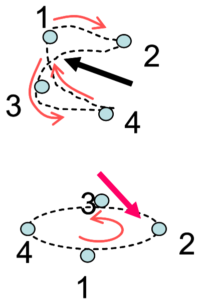
'Reduction of demagnetization energy by 'domain' formation

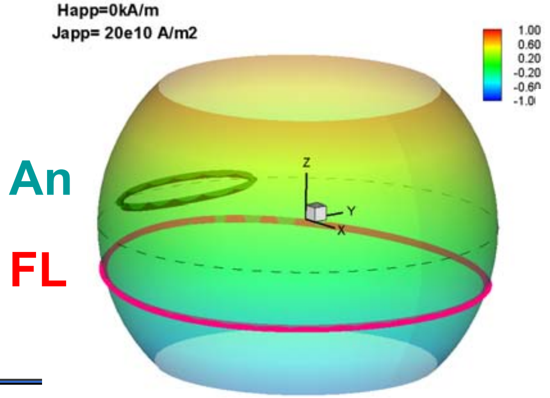
Macrospin: Dipolar Coupling between FL and An

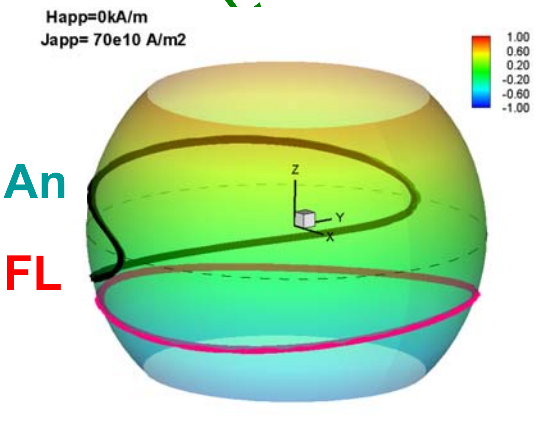


Solve LLG for both layers, taking mutual dipolar coupling into account









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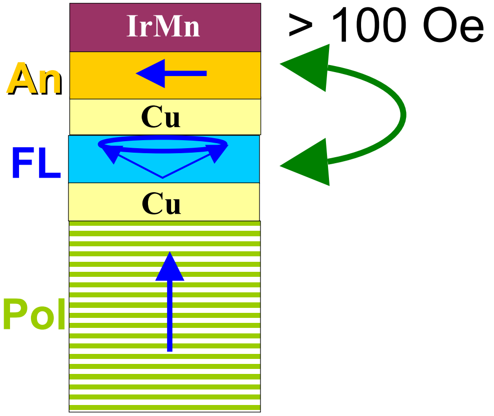
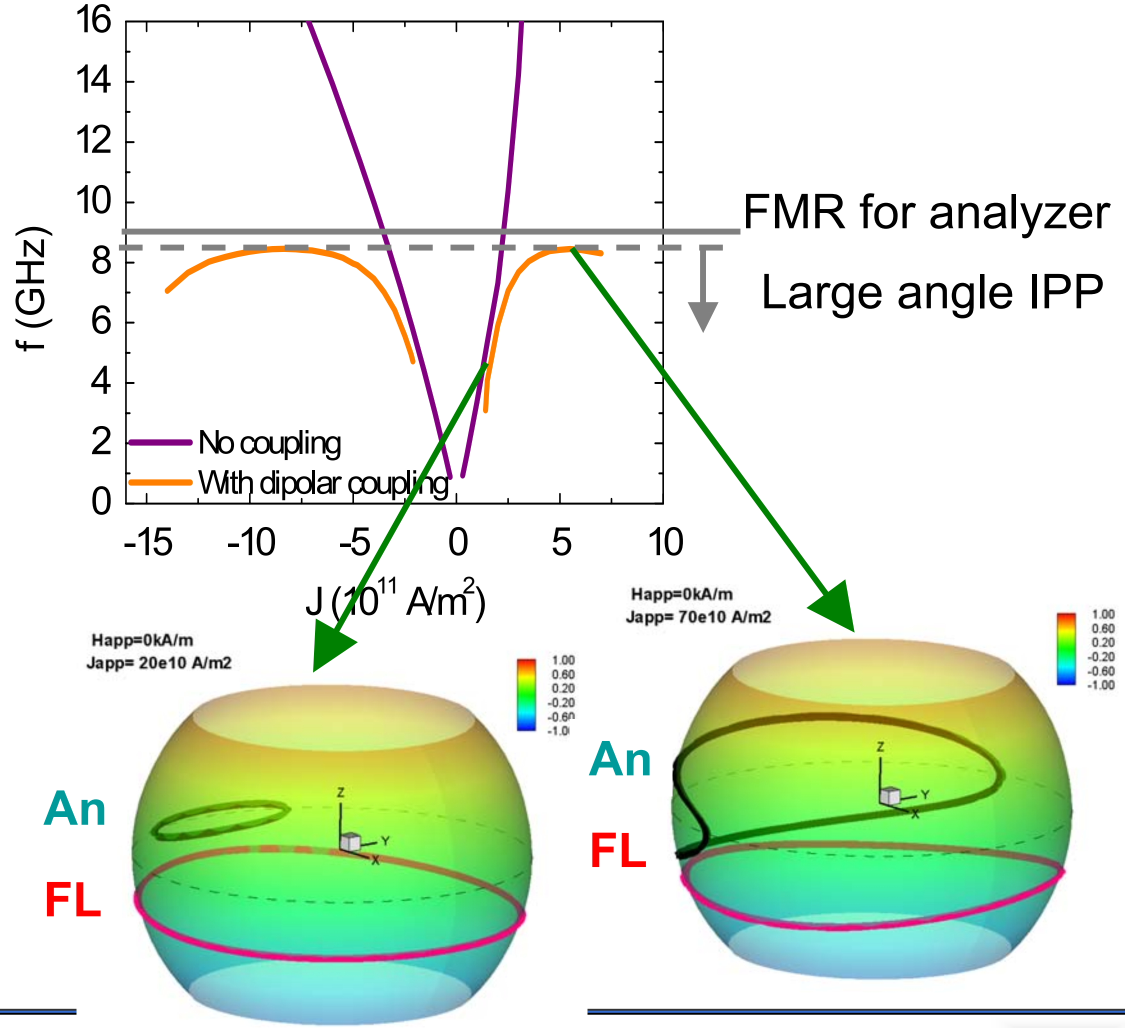
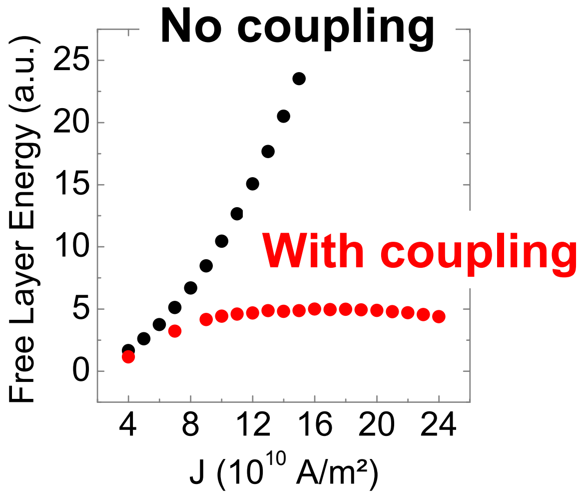
Macrospin: Dipolar Coupling between FL and An



Solve LLG for both layers, taking mutual dipolar coupling into account





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Summary on Perpendicular Polarizer

Macrospin description

State Diagram with three different states

→ IPS (in-plane rotation, no ‘antidamping’)

→ OPP oscillation, frequencies ↑ with current and ↓ with field

→ OPS state (ST acts on damped oscillations)

→ Hysteresis for increasing and decreasing current, leading to bistable regions in (J, H) for IPS and OPP

Experiments

- Static and dynamic state diagram reveal triangular regions of microwave emission in (J, H) plane
- Frequencies reveal two branches: low current branch macropspin like
- Thermal activation explains absence of hysteresis

Beyond Macrospin

Saturation of frequencies at larger currents can be explained by

- Non-homogeneous magnetization configuration that oscillates coherently and/or by
- Dipolar coupling between free layer and analyser

Functional Devices

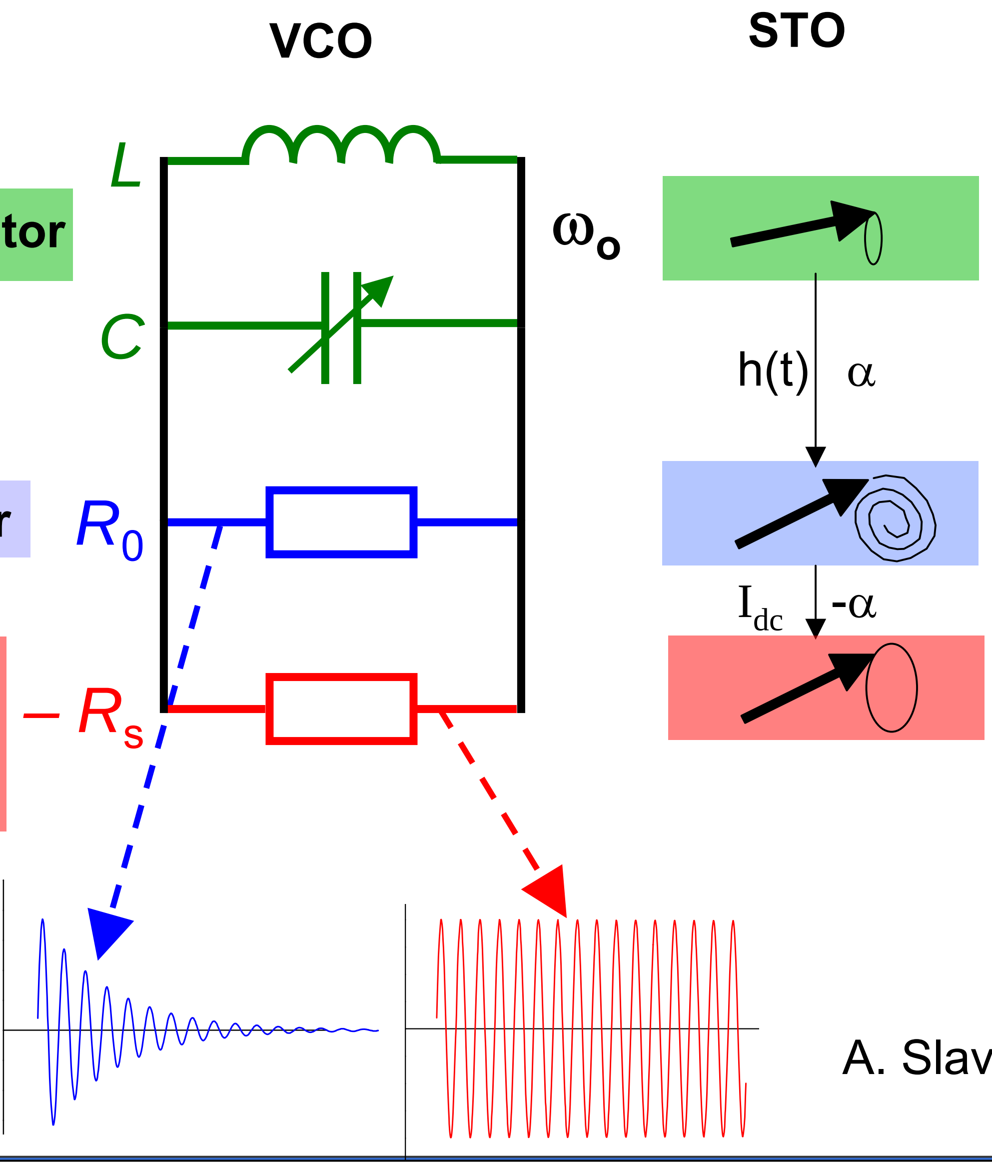
Comparison STO and VCO

Undamped Resonator

Damped Resonator

Auto-Oscillator Damped Resonator & Energy Feedback

Active element to supply external energy and compensate energy losses



$$\frac{d\mathbf{M}}{dt} = -\gamma\left(\mathbf{M}\times\mathbf{H}_{eff}\right) + \frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right) + \gamma\frac{a_j}{M_s}\mathbf{M}\times\left(\mathbf{M}\times\mathbf{P}\right)$$

A. Slavin, J. V. Kim et al

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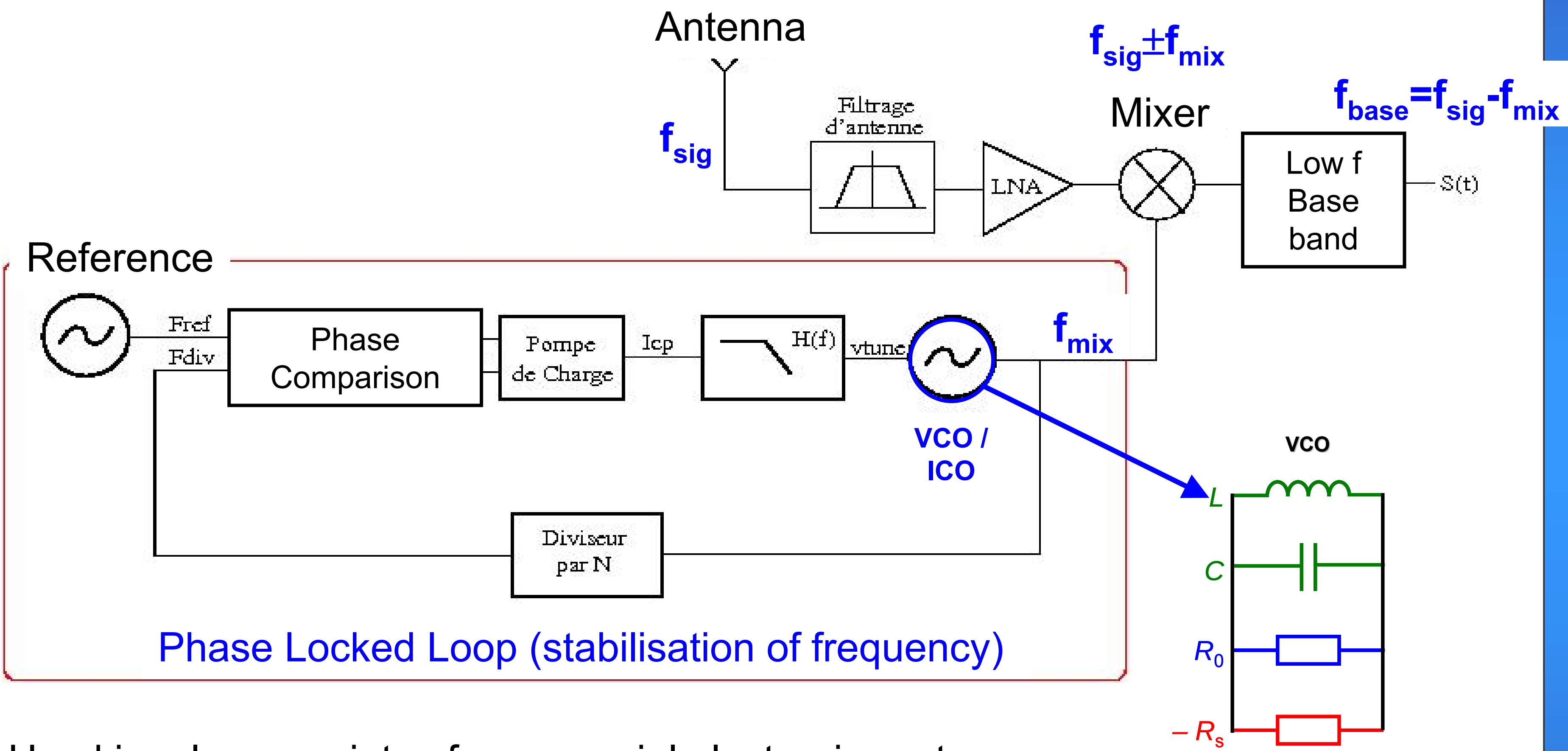
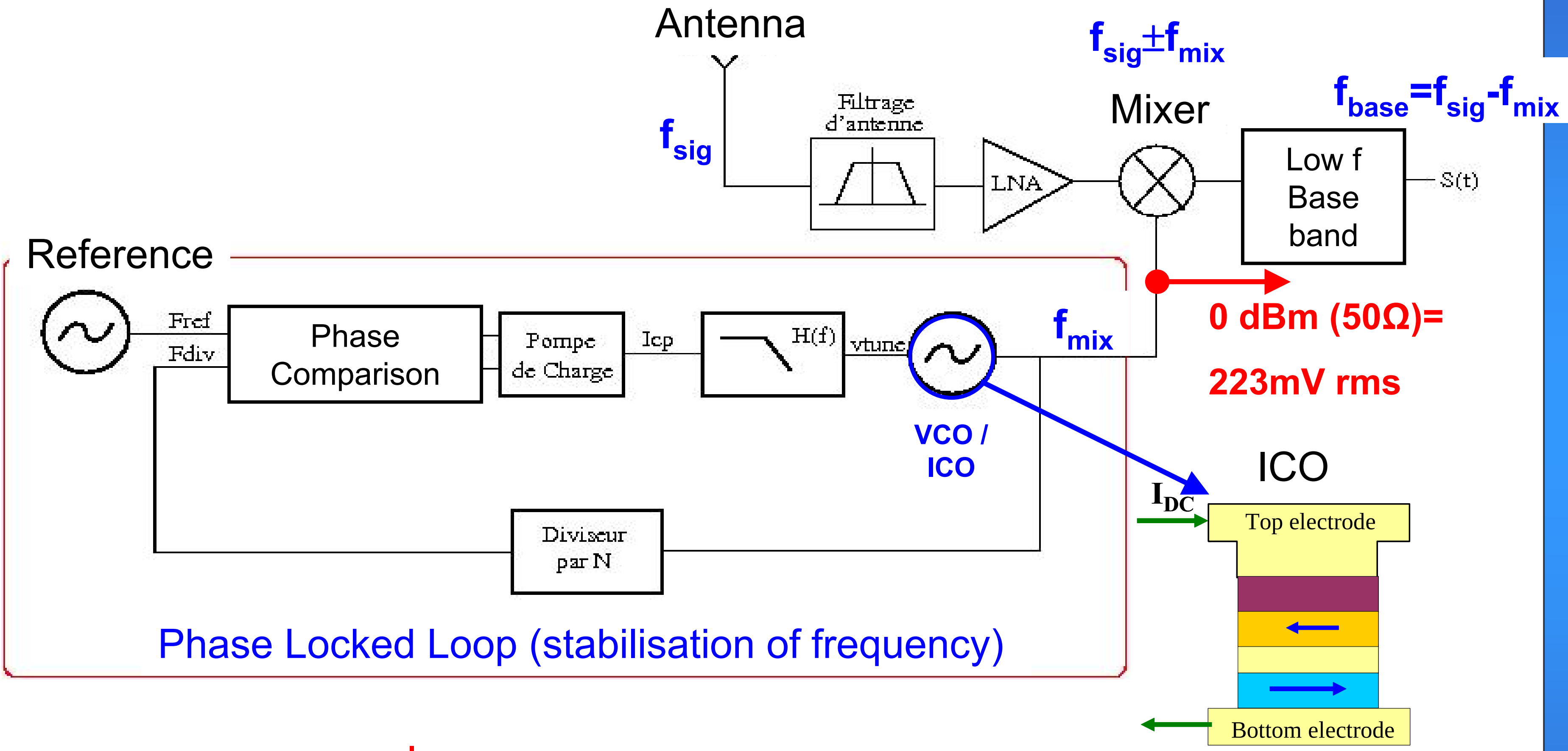
Transceiver chain



Used in a large variety of commercial electronic systems:
- radio receivers in telecom and TV applications,
- Doppler radar
- clock recovery in wireline and fibre transmission systems

Transceiver chain



Issues:
- Output power
- Linewidth (quality factor)

Comparison STO and VCO

Future telecommunications:
- multi standard / multi band applications require to cover a large range of frequencies using a single device

VCO's:
- Limited frequency tuning range (few hundred MHz)
- Large space due to inductances (mm²)
- Long tuning time (µs to ms)

STO:
- Small size (<µm²)
- Enhanced tuning range (GHz)
- Fast tuning (ns)

Issues:
- Output power
- Linewidth (quality factor)

Comparison STO and VCO

VCO

STO

Quality factor

$$Q = \frac{f}{\Delta f}$$

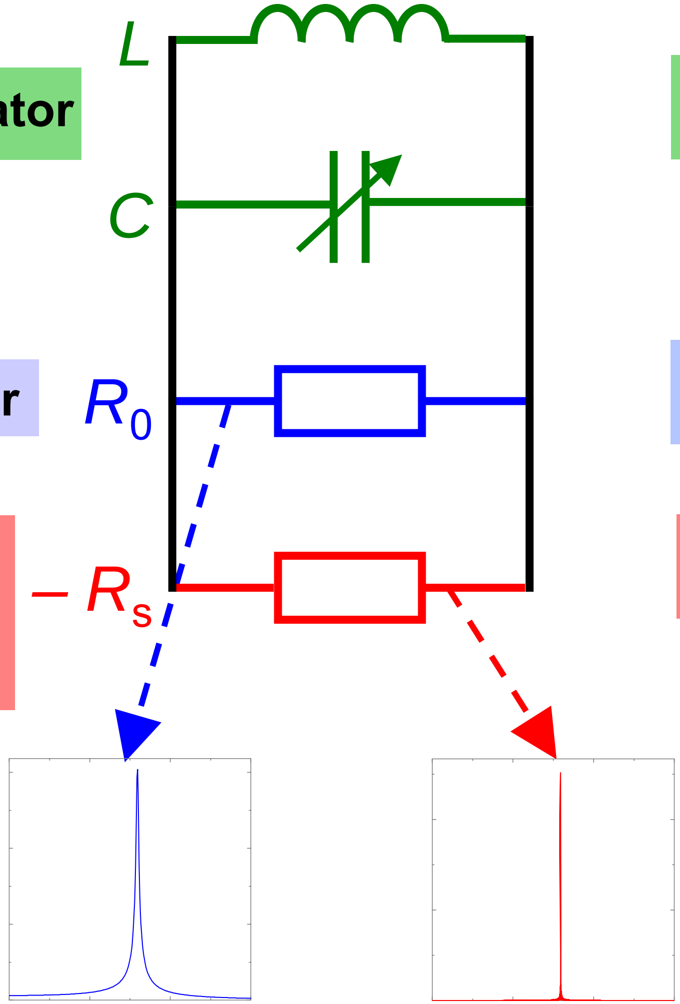
Undamped Resonator

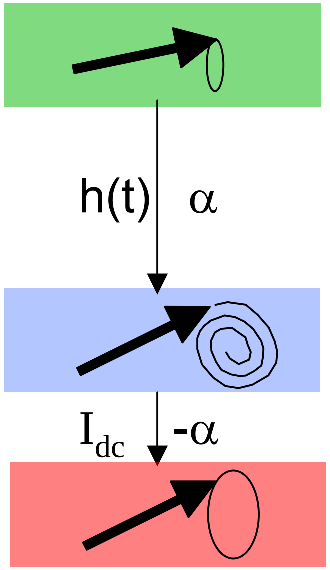
Damped Resonator

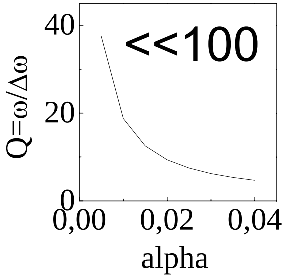
Auto-Oscillator
Damped Resonator
& Energy Feedback

↓

Active element to supply external energy and compensate energy losses







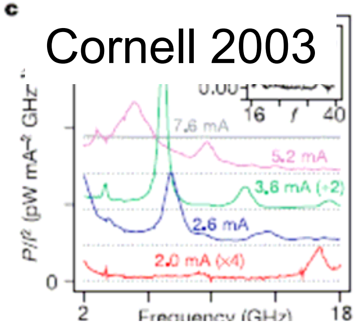
100 ….
few thousand

Linewidth Examples from Literature

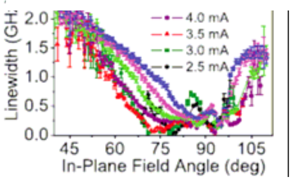
LW | **NP SV** | **NC SV** | **Vortex** | **NP MTJ**

>100MHz

Cornell 2003



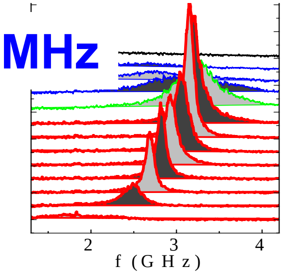
Cornell 2008
In-plane angle



10MHz

Spintec/LETI2007 ⊥

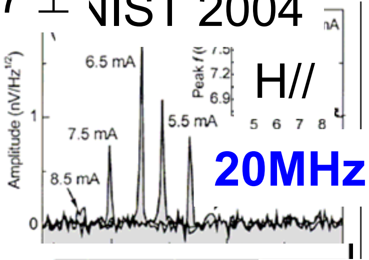
70MHz



NIST 2004

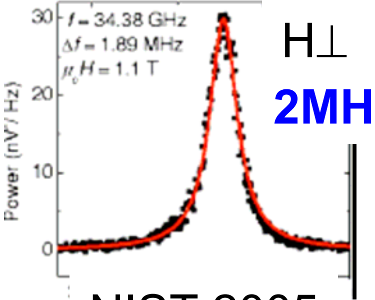
H//

20MHz



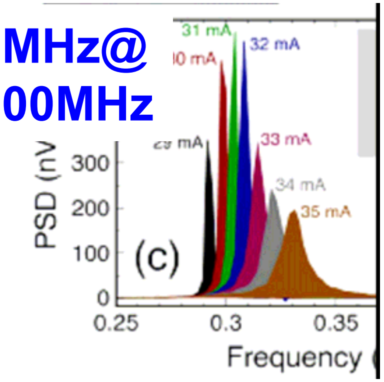
H⊥

2MHz



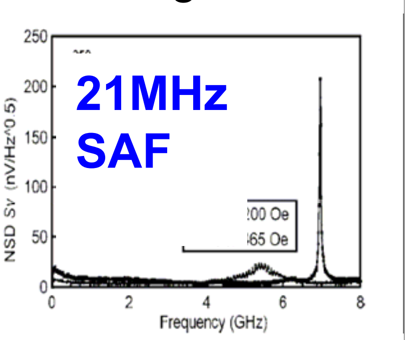
IEF/IMEC 2008

1MHz@ 300MHz



Seagate 2007

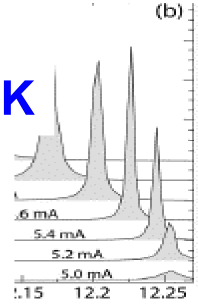
21MHz SAF



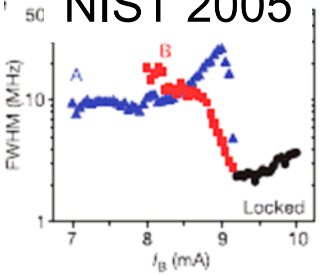
≤1MHz

IEF/Hitachi 2006

4MHz @150K

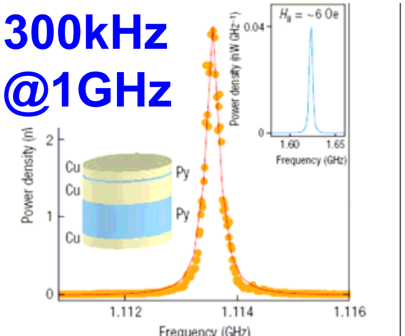


NIST 2005



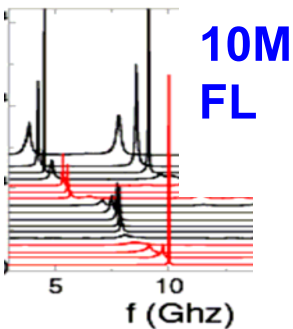
Cornell 2007 NP

300kHz @1GHz



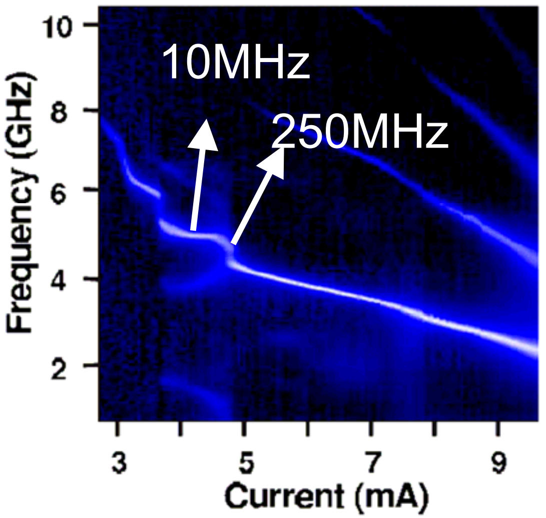
LETI/Hitachi/
Spintec 2008

10MHz FL

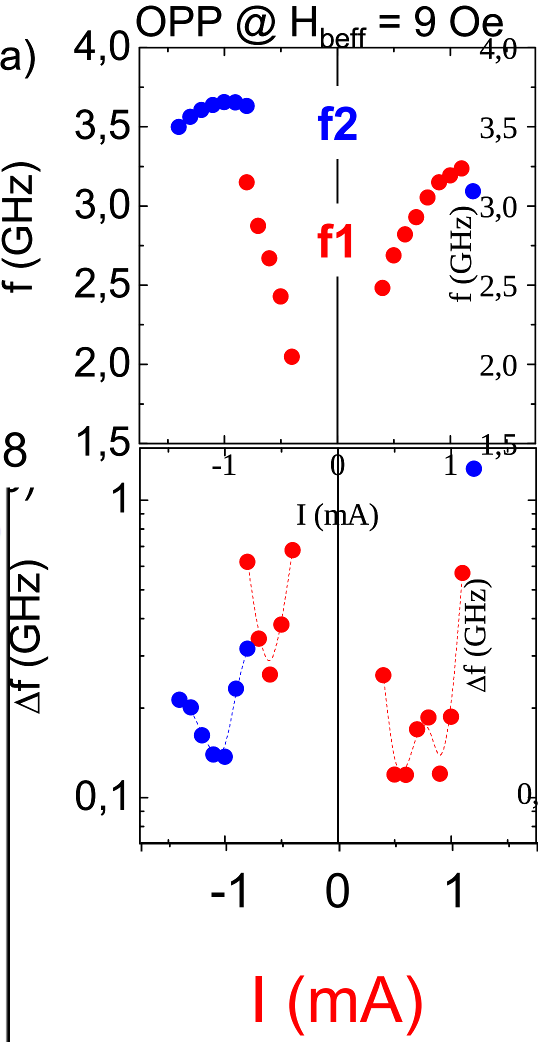


Linewidth Examples from Literature

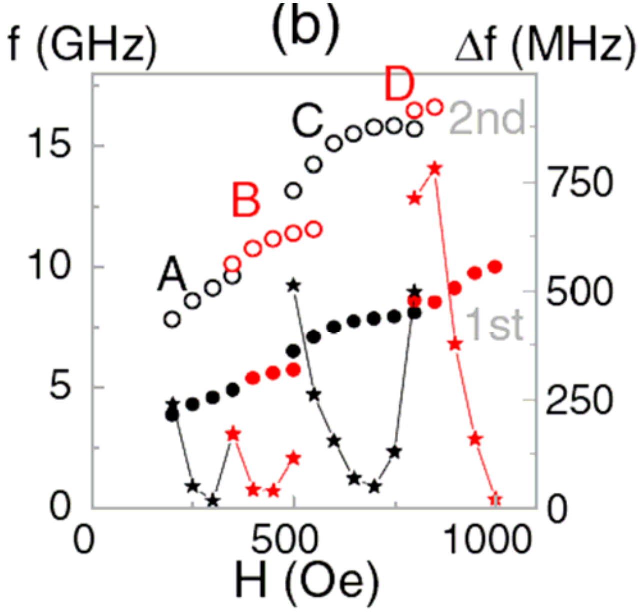
Cornell PRB 2007



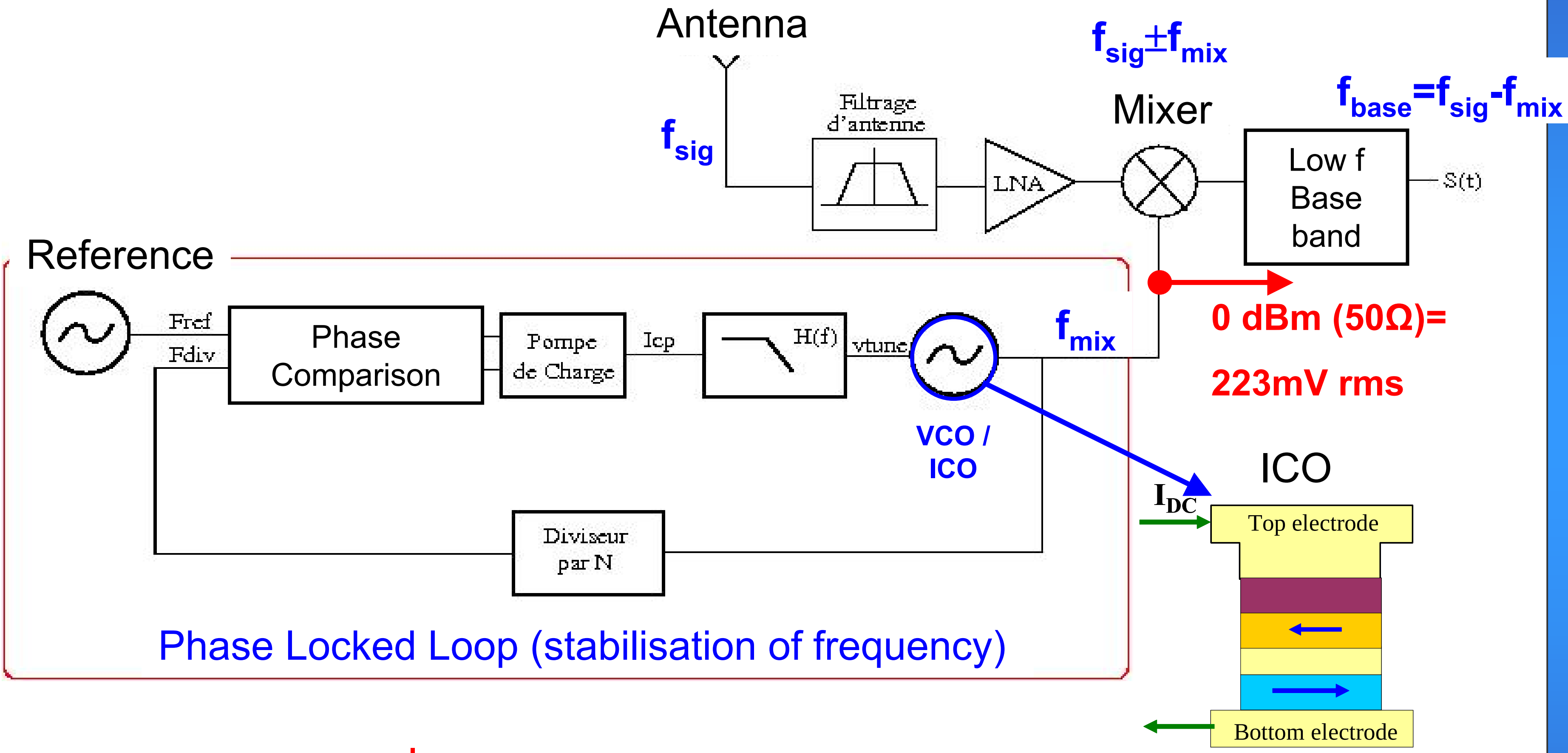
Perpendicular Polarizer



LETI/Hitachi/Spintec APL2008



Transceiver chain



Phase Locked Loop (stabilisation of frequency)

0 dBm (50Ω)=

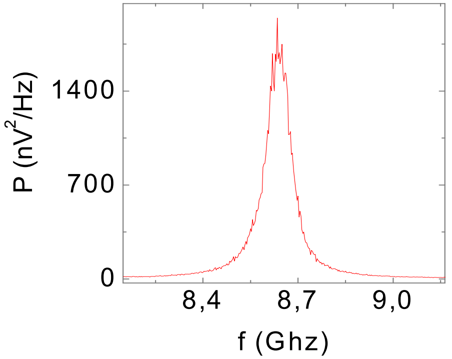
223mV rms

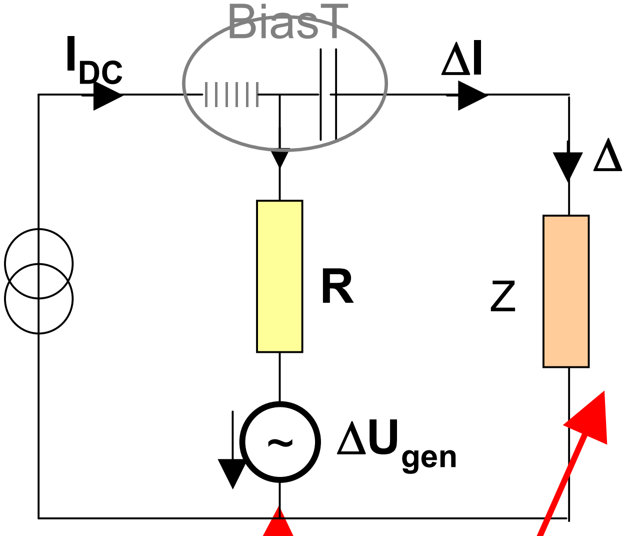
Issues:

- Output power
- Linewidth (quality factor)

Output Power

GMR vs TMR



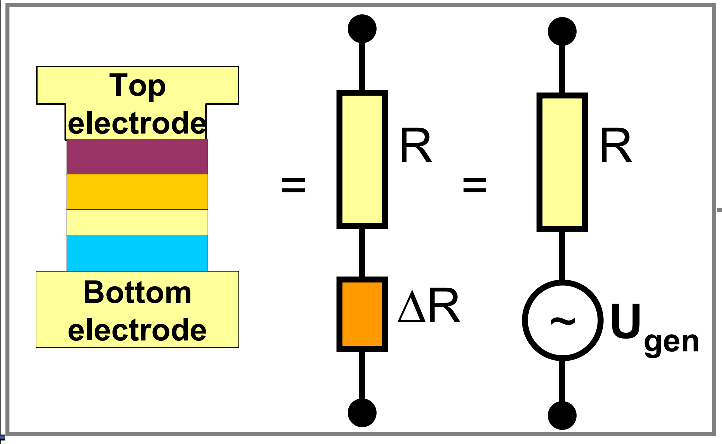


$$P_{gen} = \Delta R \cdot I_{DC}^{2} \cdot \frac{\Delta R}{Z+R}$$

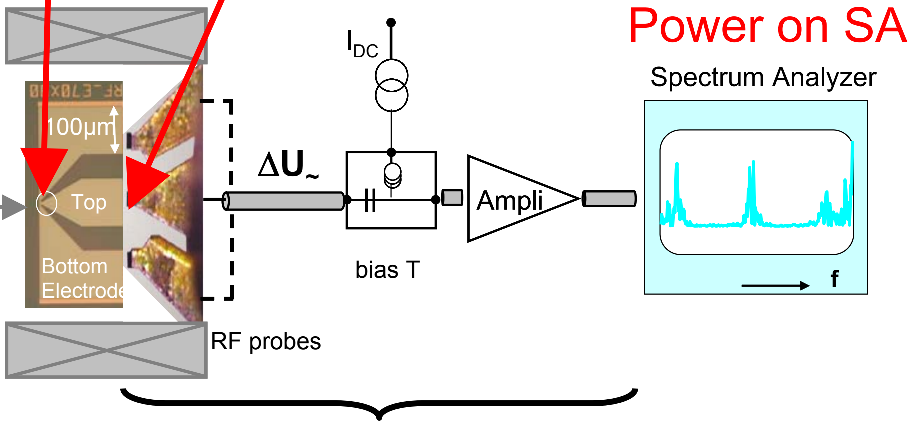
$$P_{50\Omega} = P_{gen} \cdot \frac{Z}{Z+R}$$

Generated Power: P_{gen}

Power delivered to a 50Ω load: $P_{50\Omega}$



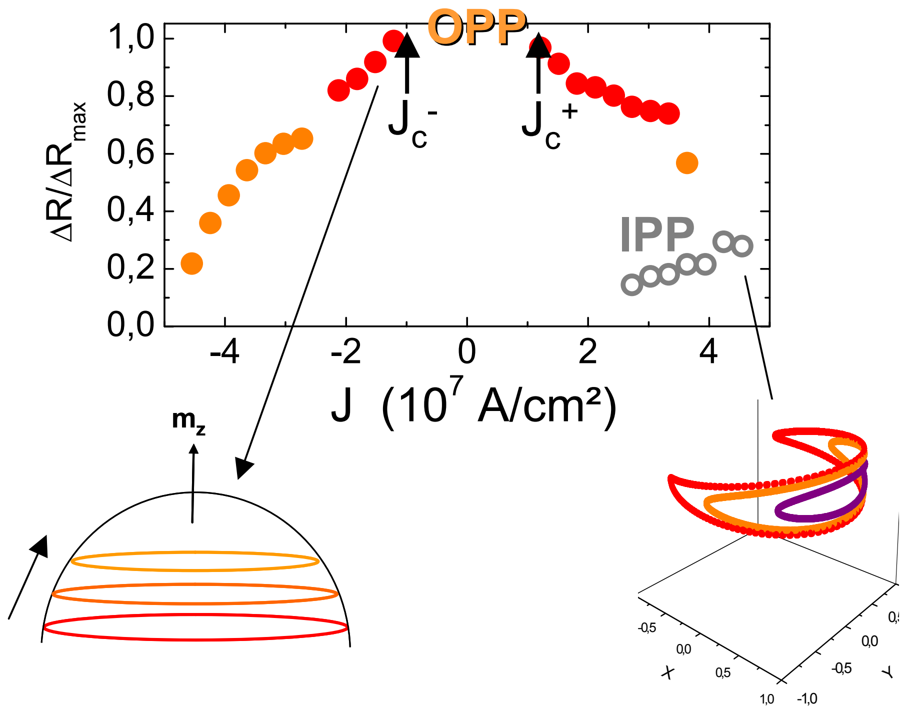
Power on SA

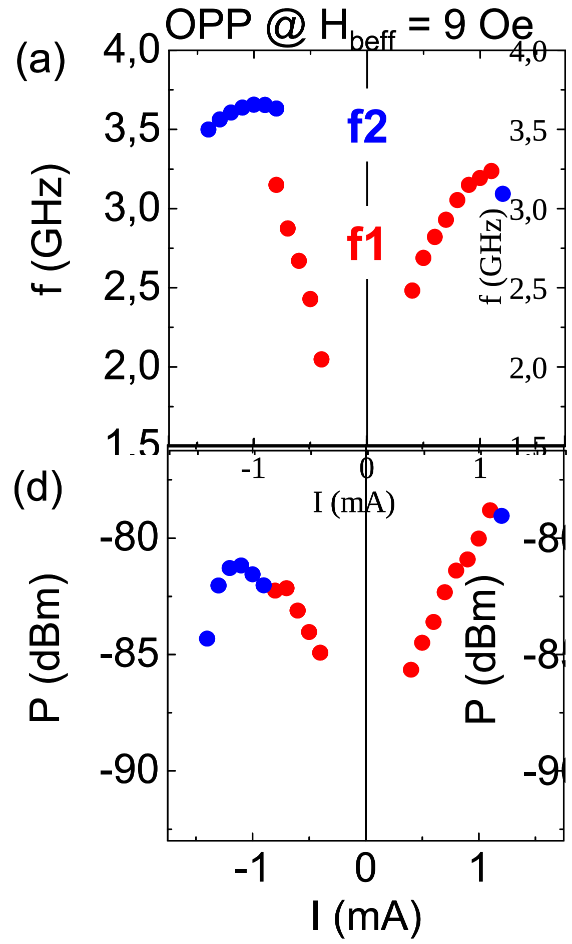


Correction of chain

Generated Voltage $\Delta U_{gen} = \Delta R * I_{DC}$

Dynamic Resistance Variation for the perpendicular polarizer

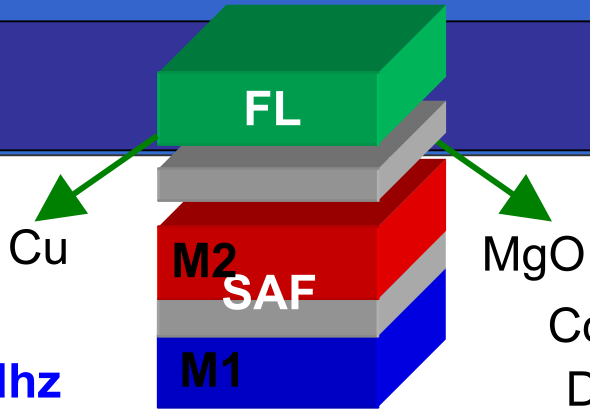




$$P_{gen} = \Delta R \cdot I_{DC}^{2} \cdot \frac{\Delta R}{Z + R}$$

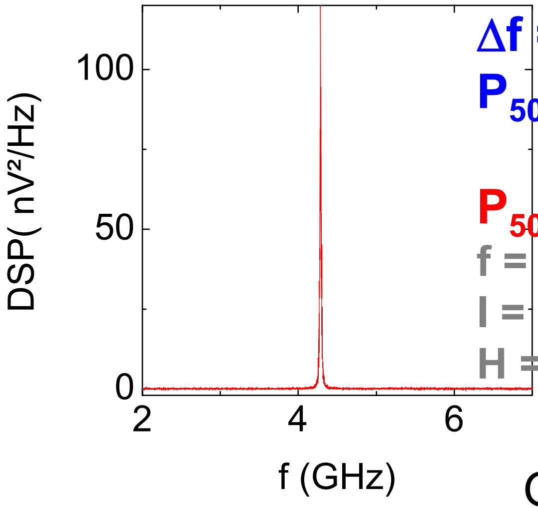
ursula.ebels@cea.fr

Output Power



Spin Valve

SAF excitation



Δf = 16 Mhz

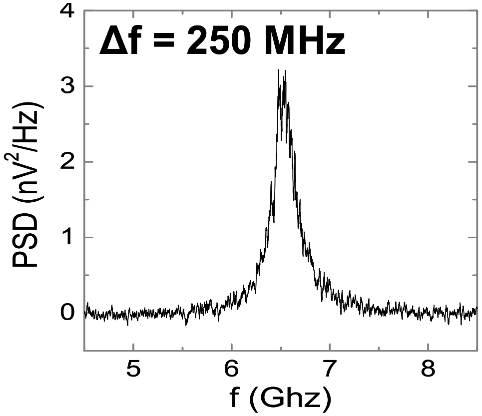
$P_{50\Omega}$ = 2.5 10^9nV²
=0.05 nW

$P_{50\Omega}$ =-73dBm

f = 4.5 GHz
I = 2.4 mA
H = 849 Oe

GMR=0.5%

FL excitation



Δf = 250 Mhz

$P_{50\Omega}$ = 1.6 10^9nV²
=0.032 nW

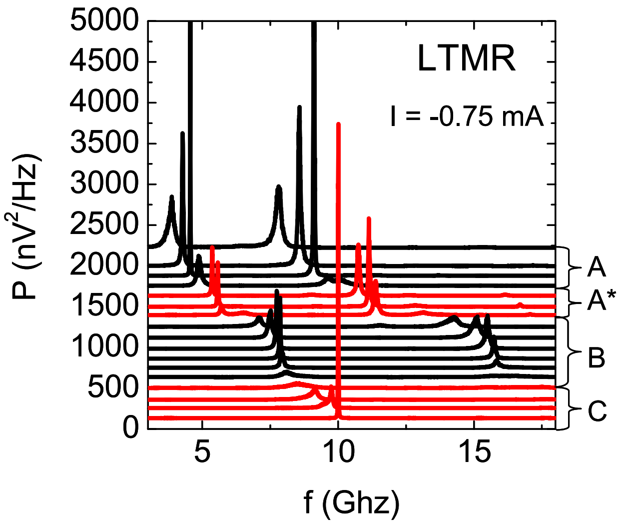
$P_{50\Omega}$ =-75dBm

f = 6.5 GHz
I = - 2.4mA
H = 850 Oe

MgO based MTJ

Collaboration LETI/Hitachi
D. Houssameddine et al
APL 93 (2008)

TMR=30%
FL excitation



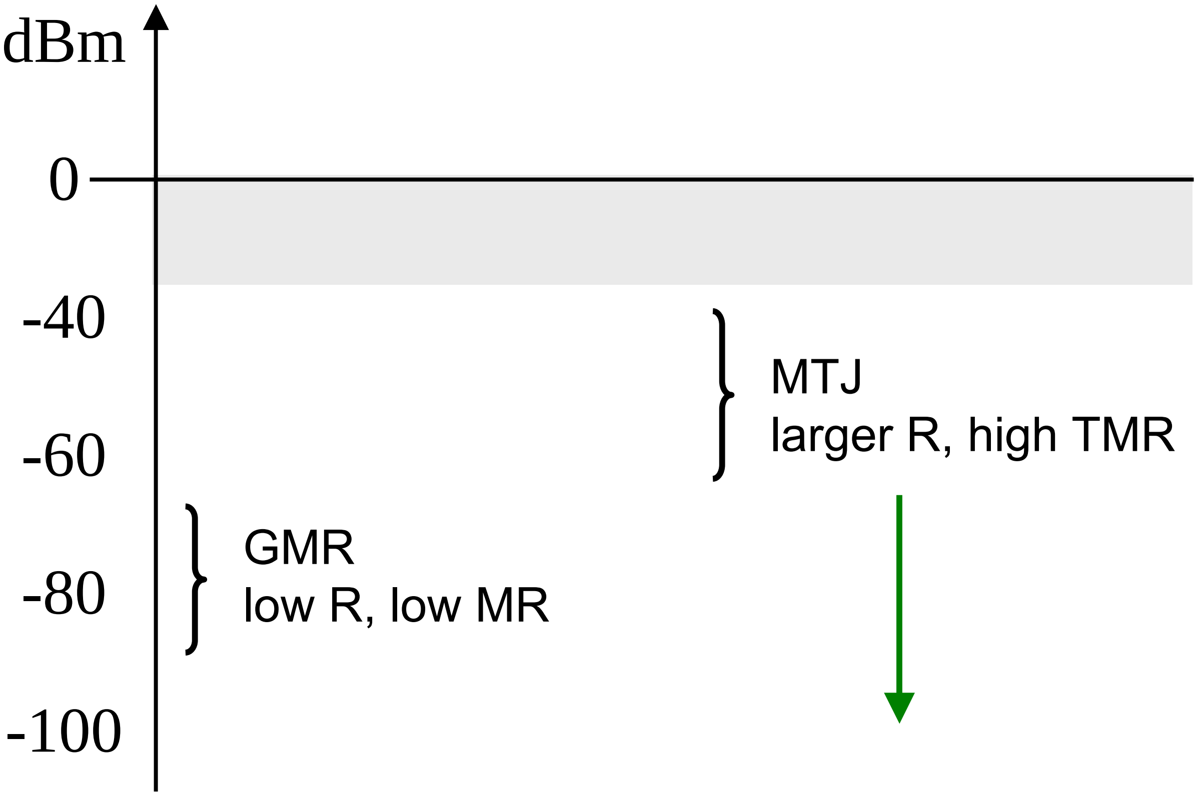
Δf = 29 Mhz

$P_{50\Omega}$ = 8.2 10^{11}nV²
= 16.4 nW

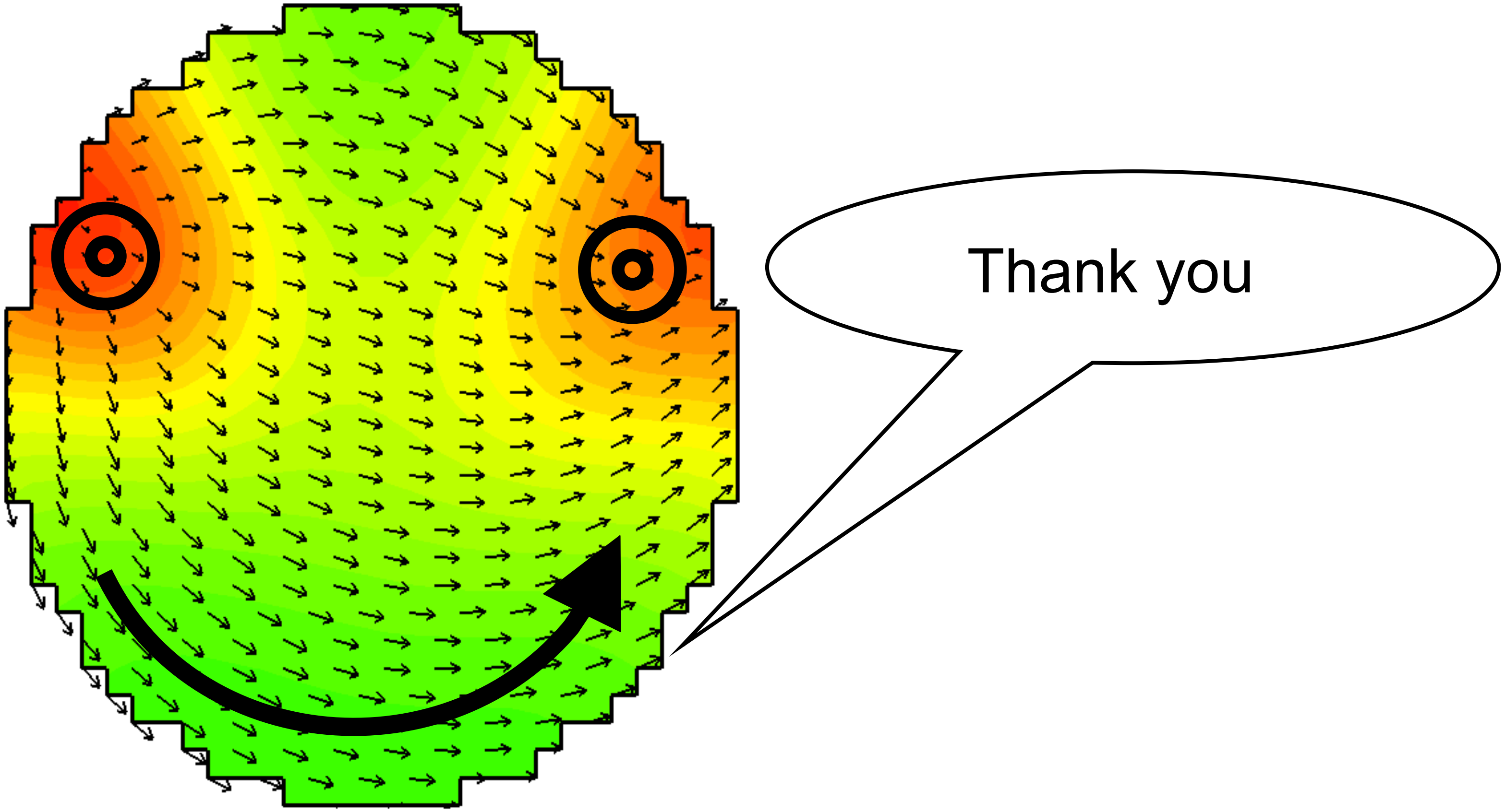
$P_{50\Omega}$ =-46dBm

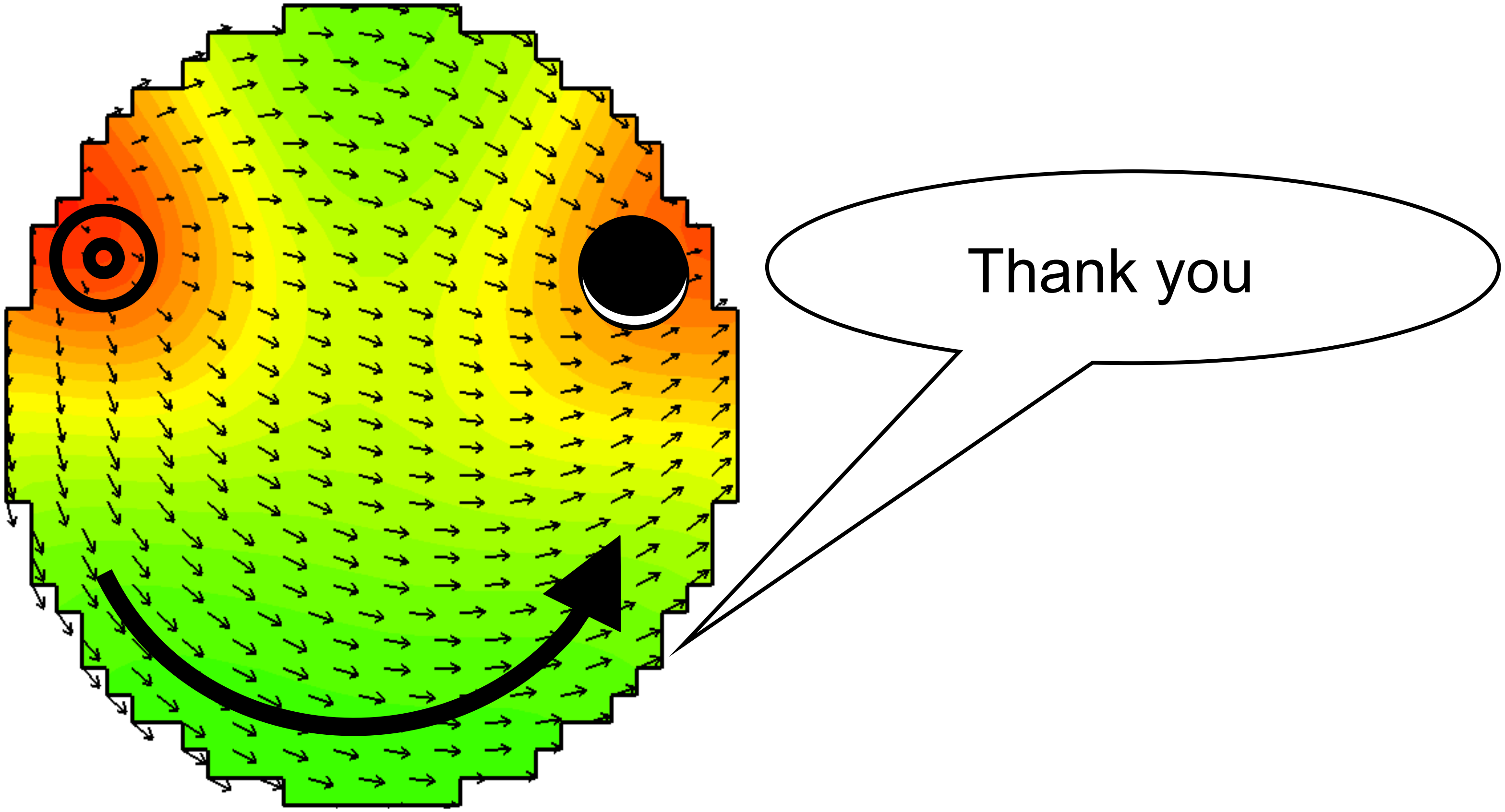
f = 5.95 GHz
I = 0.9 mA
H = 420 Oe

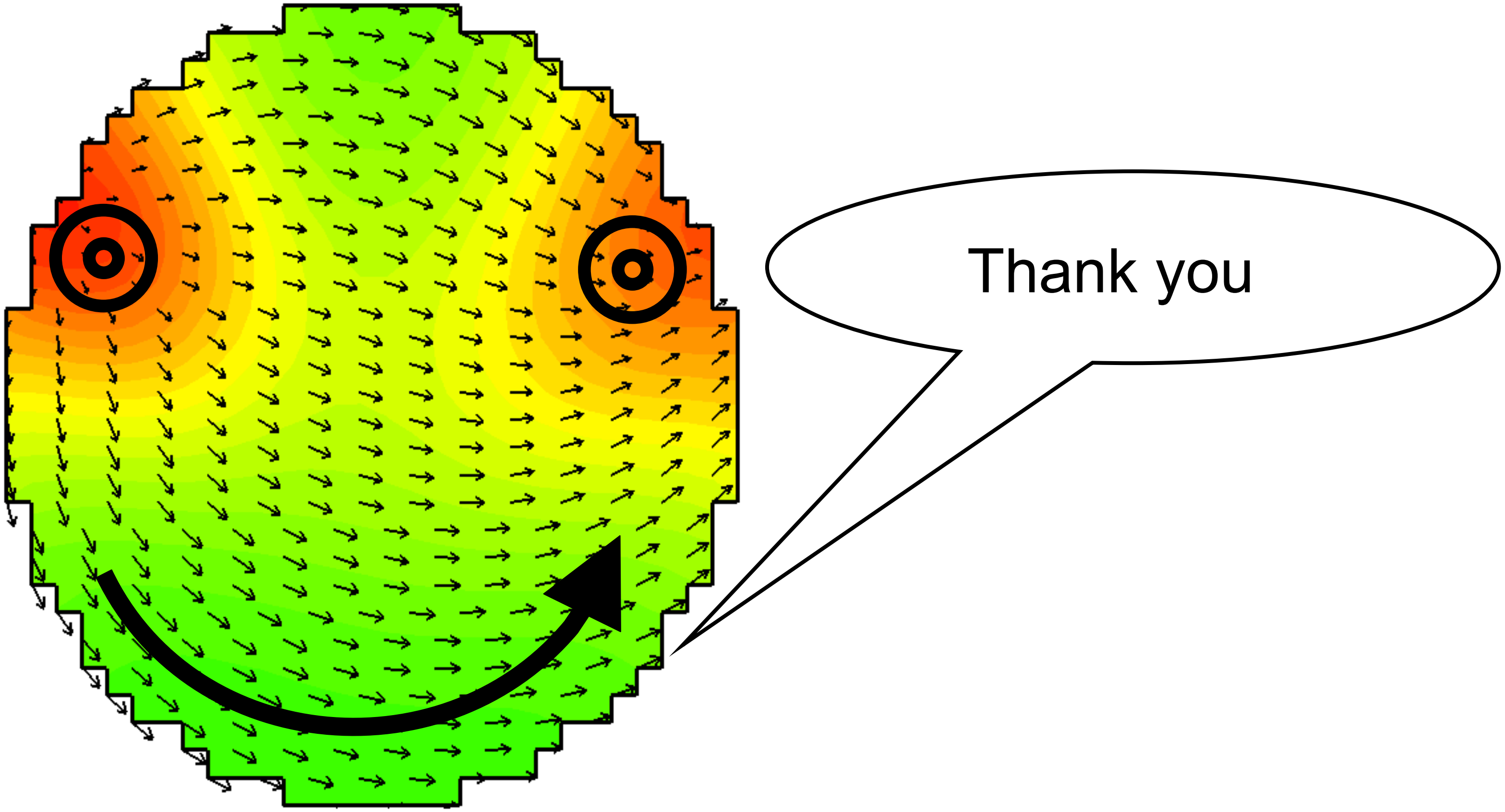
Output Power



MTJ's:
higher output power @ comparable Δf


Thank you


Thank you

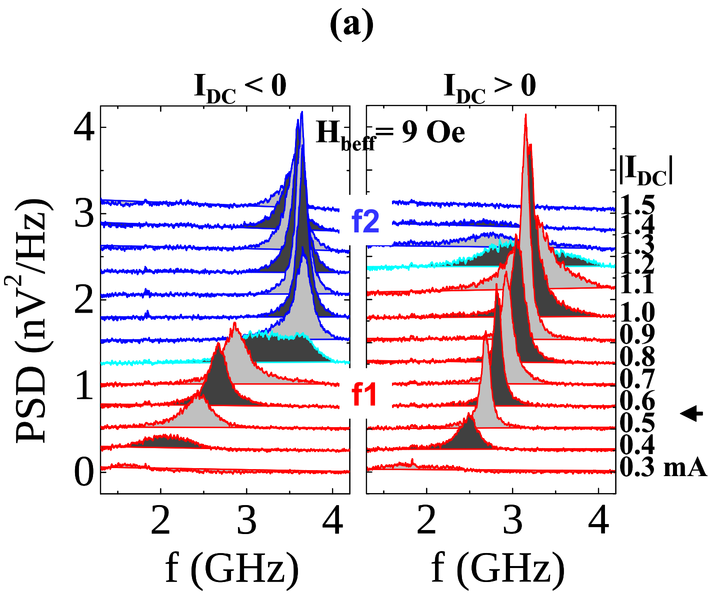

Thank you

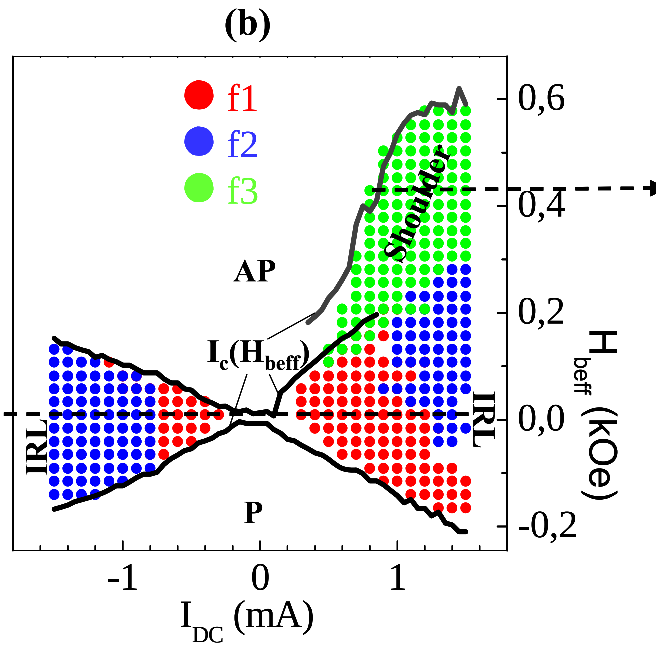
Postdoc and PhD announcement

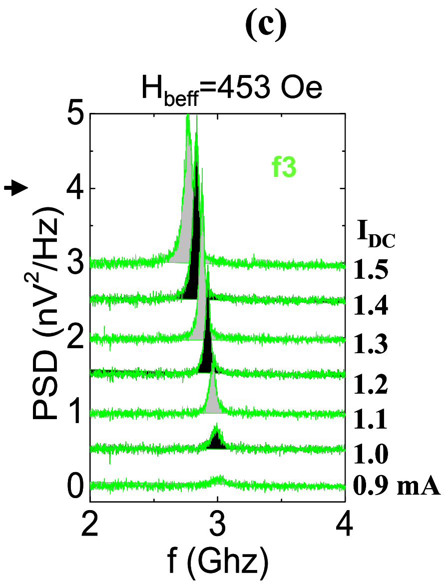
**1-2 postdoc positions available at SPINTEC/Grenoble
to study RF magnetization dynamics of
spin torque oscillators**

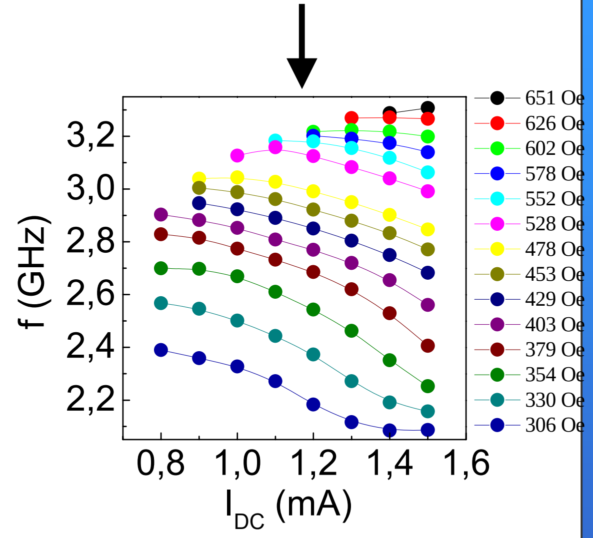
ursula.ebels@cea.fr

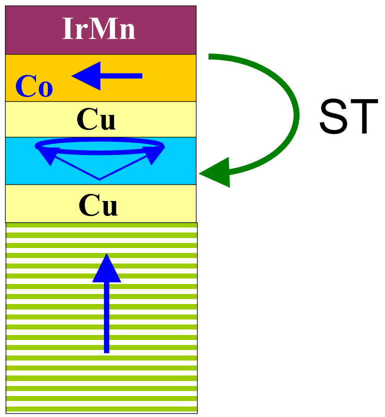
Spin torque effect from the analyzer

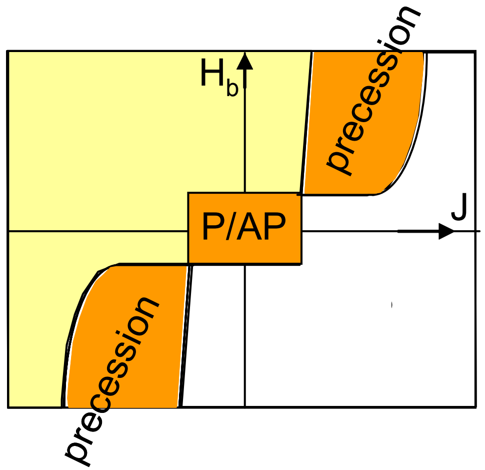




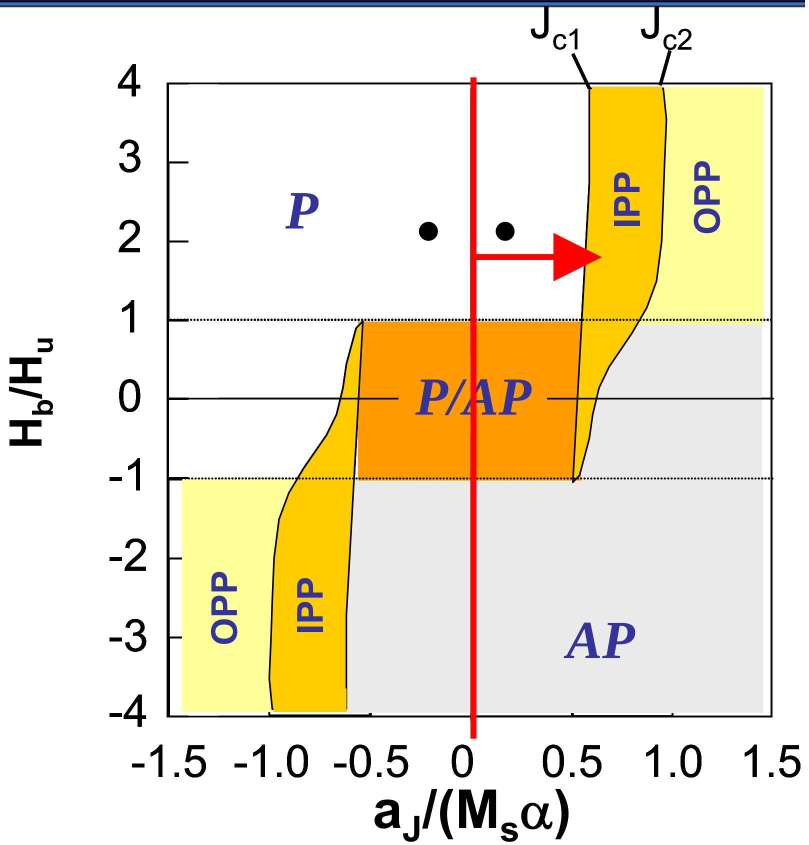


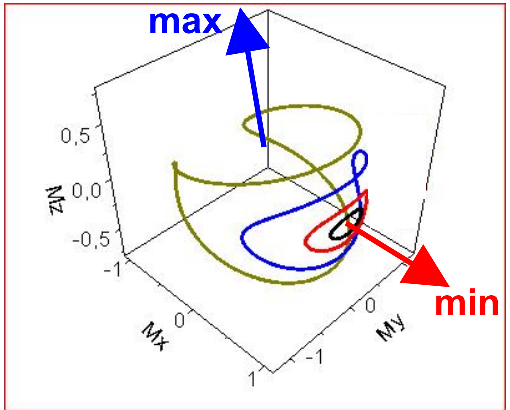






State Diagramme of Planar Polarizer





- **J=0** : stable state = energy minimum

- **$J<J_{c1}$**: stable state = energy minimum

→ Sensitivity to current sign:

e.g. J<0 ST enhances natural damping

J>0 ST counteracts natural damping

→ Damped oscillations around stable state

→ Frequency weakly depends on current

→ Linewidth depends strongly on current and goes to zero (in macrospin apporach) at J_{c1}

→ Critical current given by FMR linewidth, proportional to damping constant α

$$J_{c1} \sim \alpha(H_u+H_b+2\pi M_s)$$

- **J=Jc1** : Limit cycles develop out of damped FMR type oscillations and are thus of IPP type
- **J>Jc2**, transition to OPP or AP state depending on applied bias field