Spin Torque Oscillator from micromagnetic point of view

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Modeling & simulation

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Fabrication & characterization

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Bernard Dieny

- What is a spin torque oscillator?
- Why we are interested in ST oscillator?
- Which are the modeling tools to describe them?
- Out-of-plane precision (OPP)
- In-plane precision (IPP)

Starting point…

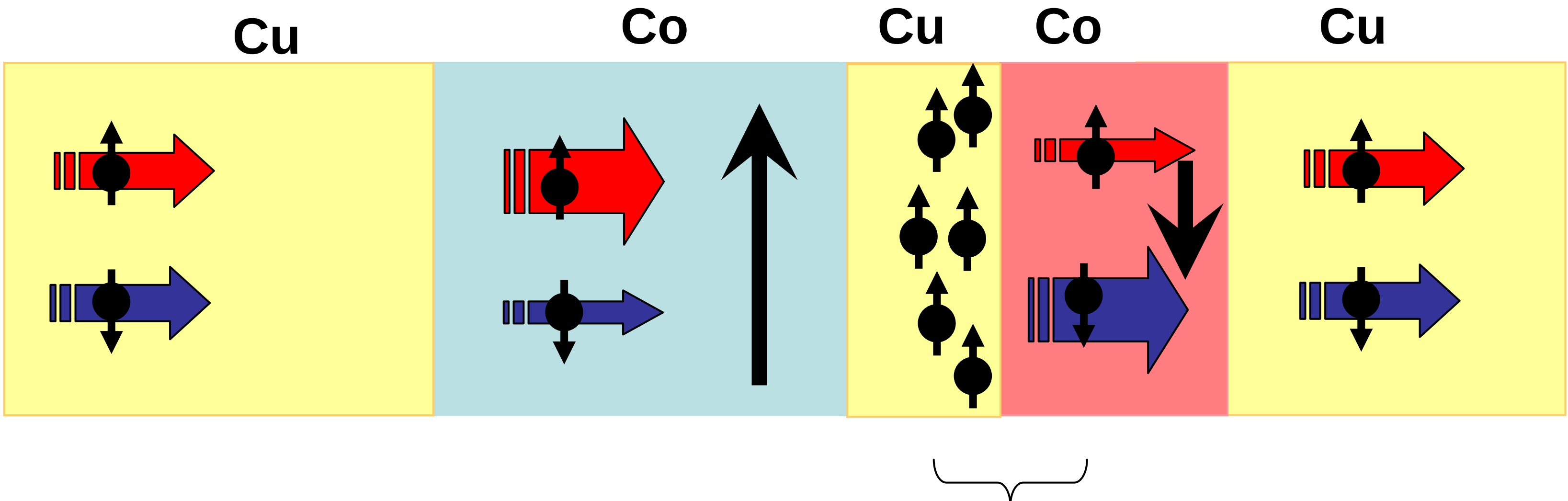
The magnetization acts on the current → **GMR / TMR phenomena**

Action-reaction principle:

"Every action has an equal and opposite reaction."

The polarized current acts on the magnetization → **Spin torque phenomena**

Basic picture … (J<0)

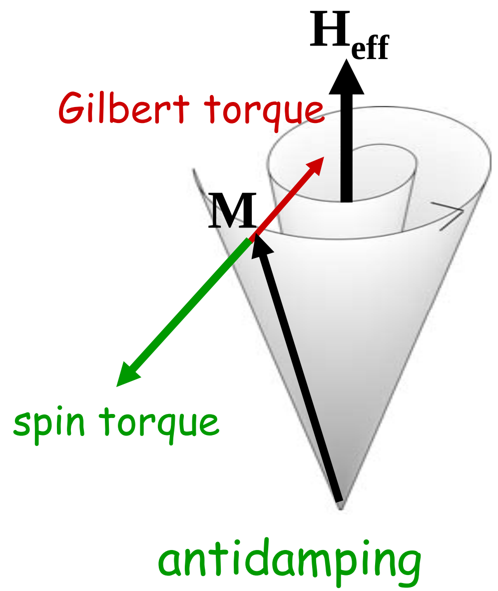


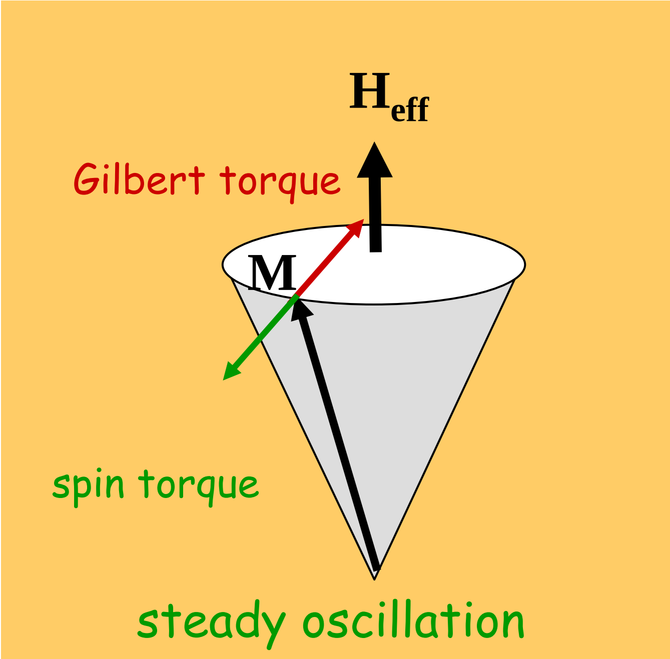
Exchange interaction between injected polarized e⁻ ↑
and local magnetization causes the magnetization switching
in the direction parallel to the spin of the injected e⁻

Starting point…

Landau-Lifshitz-Gilbert equation + polarized current

$$\begin{cases} \dfrac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \left[\mathbf{M} \times \mathbf{H}_{\mathbf{eff}} \right] + \alpha \left(\mathbf{M} \times \dfrac{\partial \mathbf{M}}{\partial t} \right) + \left(\dfrac{\partial \mathbf{M}}{\partial t} \right)_{ST} \\ \mathbf{M}^2 = 1 \end{cases}$$

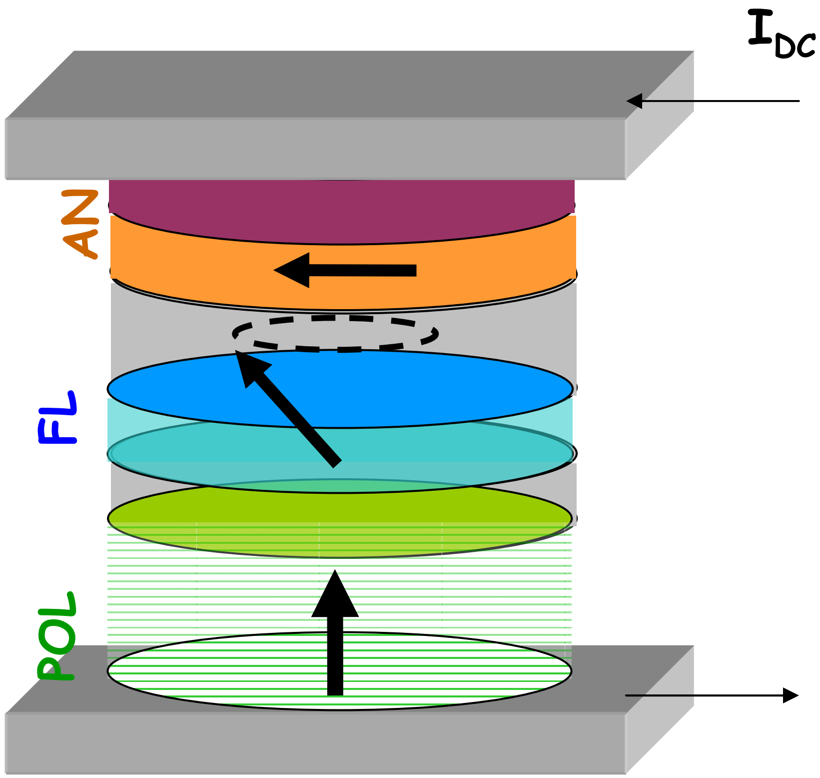


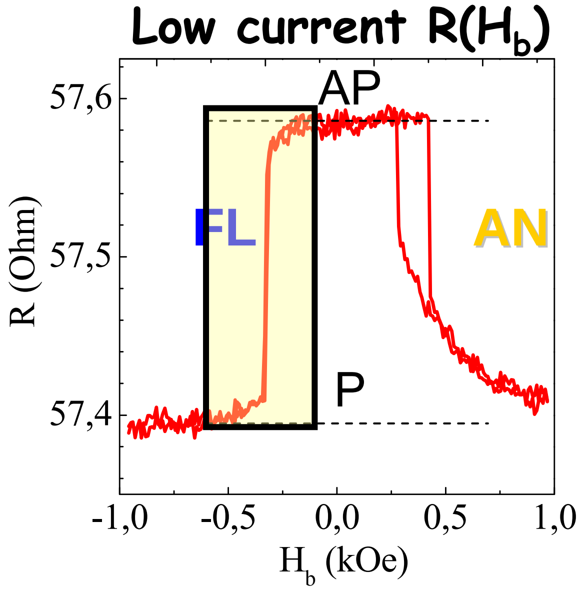


Perpendicular spin torque oscillator

Main goal → generate steady oscillations without applying field

Pt / (Co/Pt)/PEL /Cu/Py/Cu/Co/IrMn

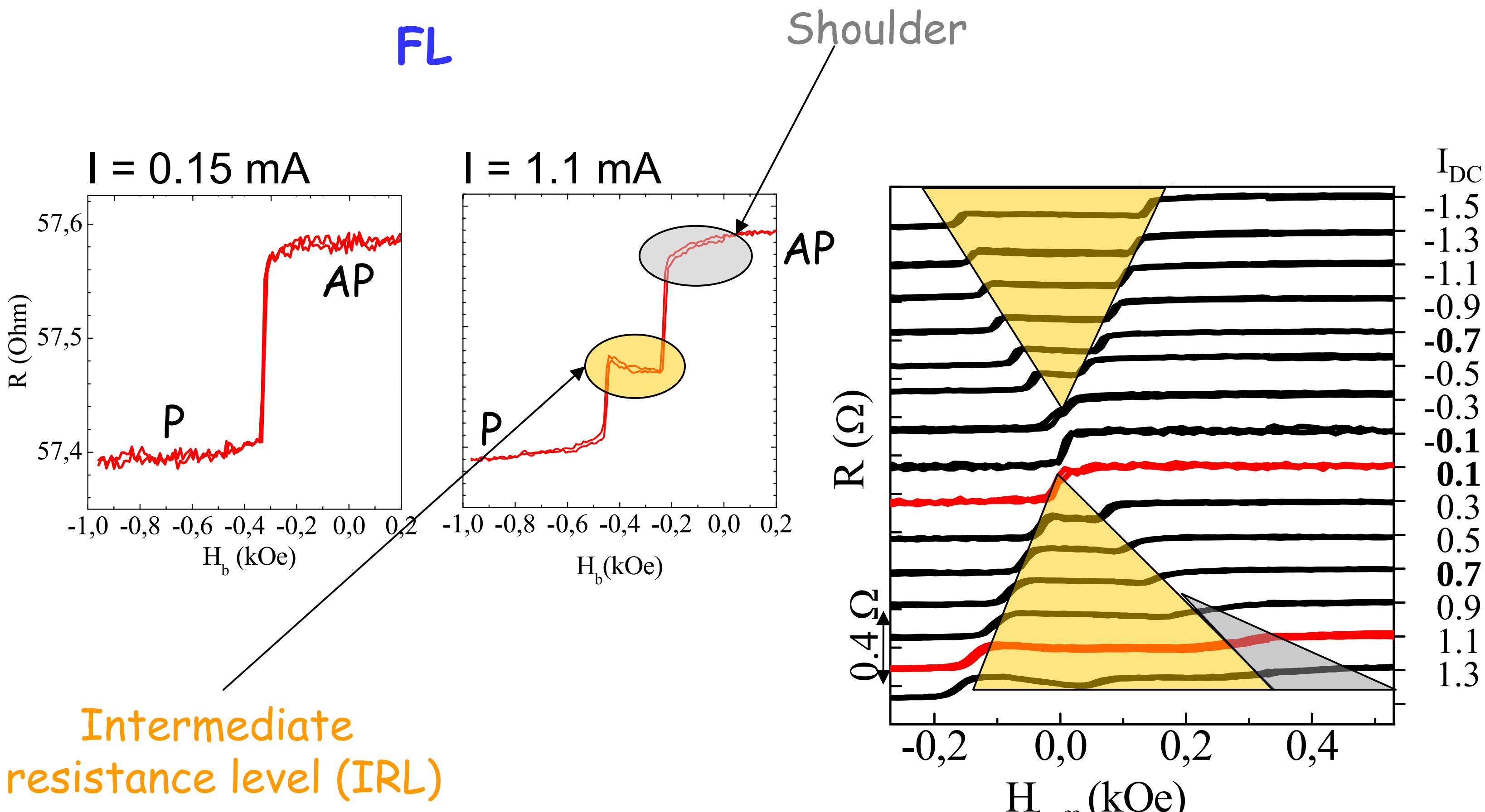




Ellipse of 60x70 nm^2
I_{DC}= 0.15 mA
ΔR = 0.19Ω
MR=0.3%

J. C. Slonczewski US5695864
K. J. Lee APL 86 (2005)
O. Redon US6,532,164 B2

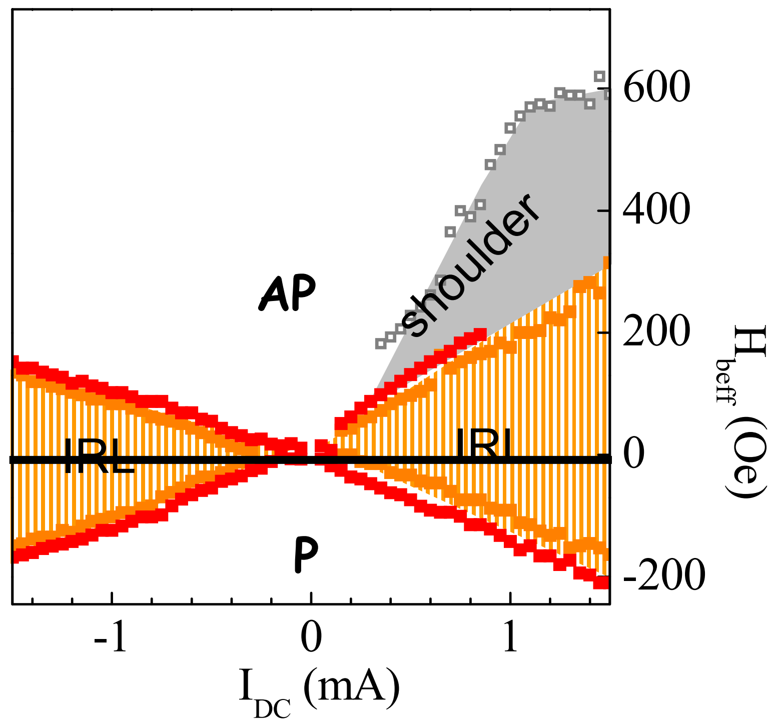
Houssameddine et al. Nat. Mat. 6, 447 (2007)

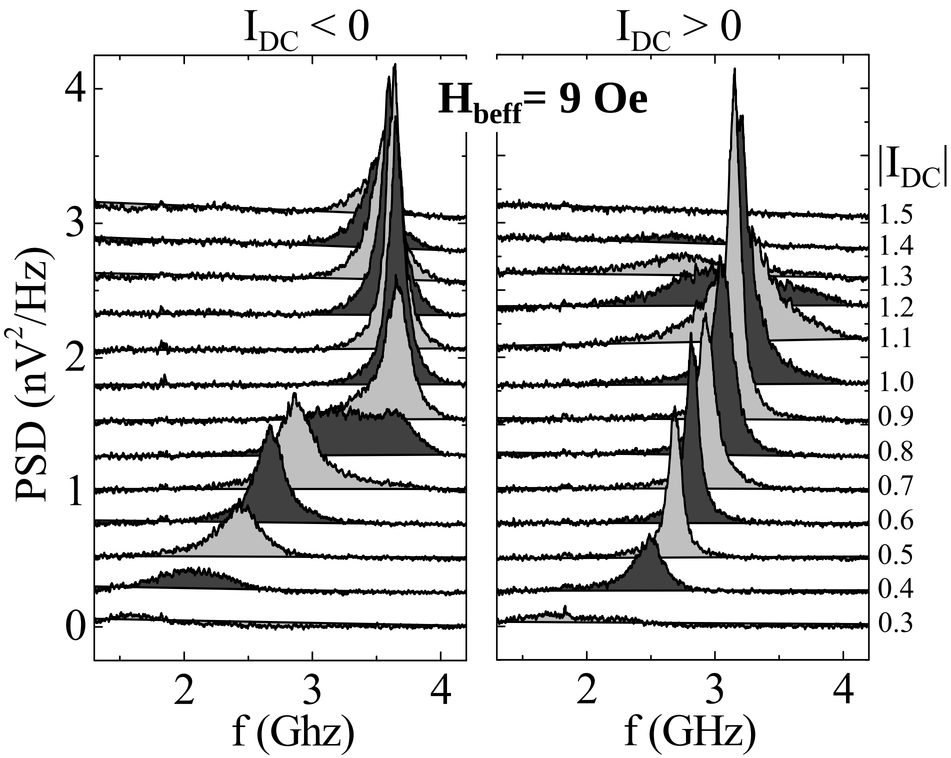


There are two magnetoresistive states

Houssameddine et al. Nat. Mat. 6, 447 (2007)

Static current- field diagram

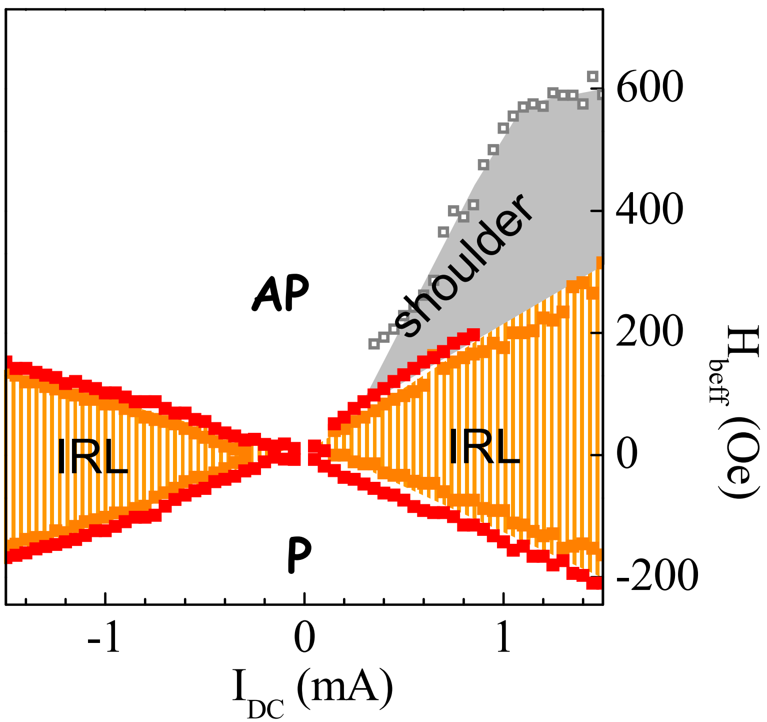




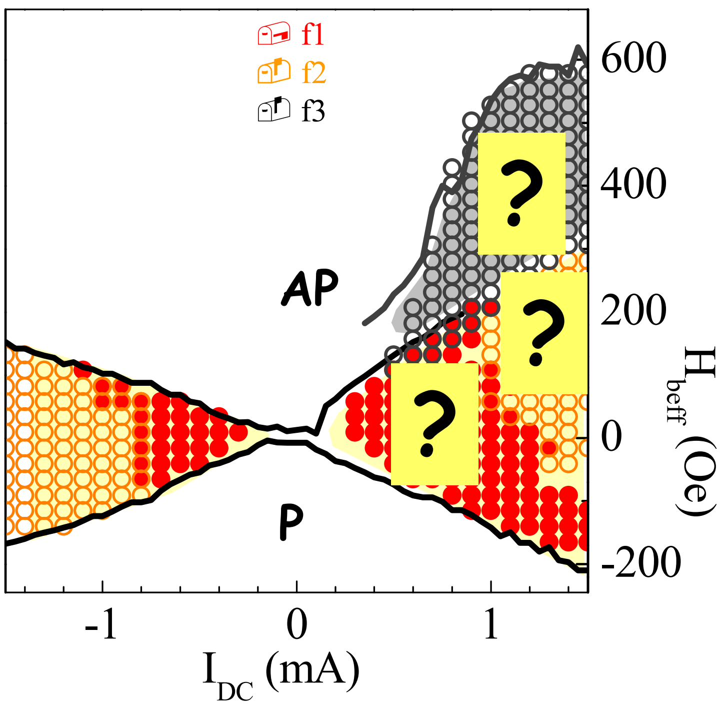
Houssameddine et al. Nat. Mat. 6, 447 (2007)

Perpendicular spin torque oscillator

Static current- field diagram



Dynamic current- field diagram



Houssameddine et al. Nat. Mat. 6, 447 (2007)

Micromagnetic model

➢ **Full 3D integration of**

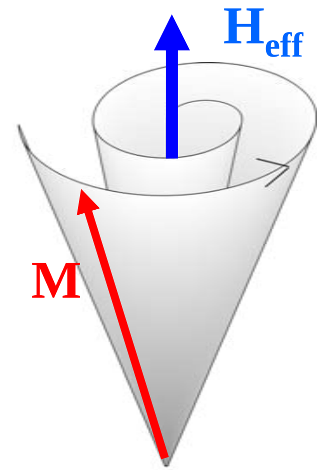
a) the Landau-Lifshitz-Gilbert (LLG) equation

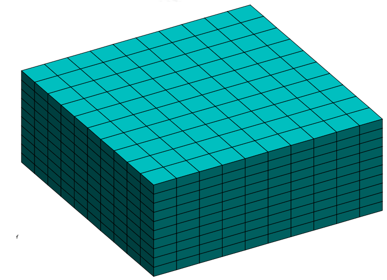
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \left[\mathbf{M} \times \mathbf{H}_{\mathbf{eff}}\right] + \alpha \left(\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right)$$

$$\mathbf{M}^2 = 1$$

$$\mathbf{H}_{\mathbf{eff}} = -\frac{1}{\mu_0 M_s} \frac{\delta E}{\delta \mathbf{M}}$$

$$E = E_{ex} + E_{anis} + E_{dem} + E_{app}$$





b) the magnetostatic equations

$$\mathbf{H}_{\mathbf{dem}}(\mathbf{r}) = -\int_V \nabla G(\mathbf{r} - \mathbf{r}')\rho_m(\mathbf{r}')dV' \quad -\oiint_S \nabla G(\mathbf{r} - \mathbf{r}')\sigma_m(\mathbf{r}')dS'$$

Micromagnetic model (2)

c) Addition term due to the spin torque transfer

$$\begin{cases} \dfrac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \left[\mathbf{M} \times \mathbf{H}_{\mathbf{eff}}\right] + \alpha\left(\mathbf{M} \times \dfrac{\partial \mathbf{M}}{\partial t}\right) + \left(\dfrac{\partial \mathbf{M}}{\partial t}\right)_{ST} \\ \mathbf{M}^2 = 1 \end{cases}$$

$$\left(\frac{\partial \mathbf{M}}{\partial t}\right)_{ST} = -\gamma_0 a_J \left[\mathbf{M} \times \left(\mathbf{M} \times \mathbf{m}_{\mathbf{PL}}\right)\right]$$

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

« ballistic transport model »

ST-GLFFT

$$\left(\frac{\partial \mathbf{M}}{\partial t}\right)_{ST} = c_0 \left[\mathbf{m} \times \mathbf{M}\right]$$

📖 A. Vedyeyev, D. Gusakova

« diffusive transport model »

LLG_SA

Micromagnetic model (3)

- **Transport equation**

$$\frac{\partial \mathbf{j}^m}{\partial z} + \frac{J_{sd}}{\eta}\mathbf{m}\times\mathbf{M} + \frac{\mathbf{m}}{\tau_{sf}} = 0$$

electron current

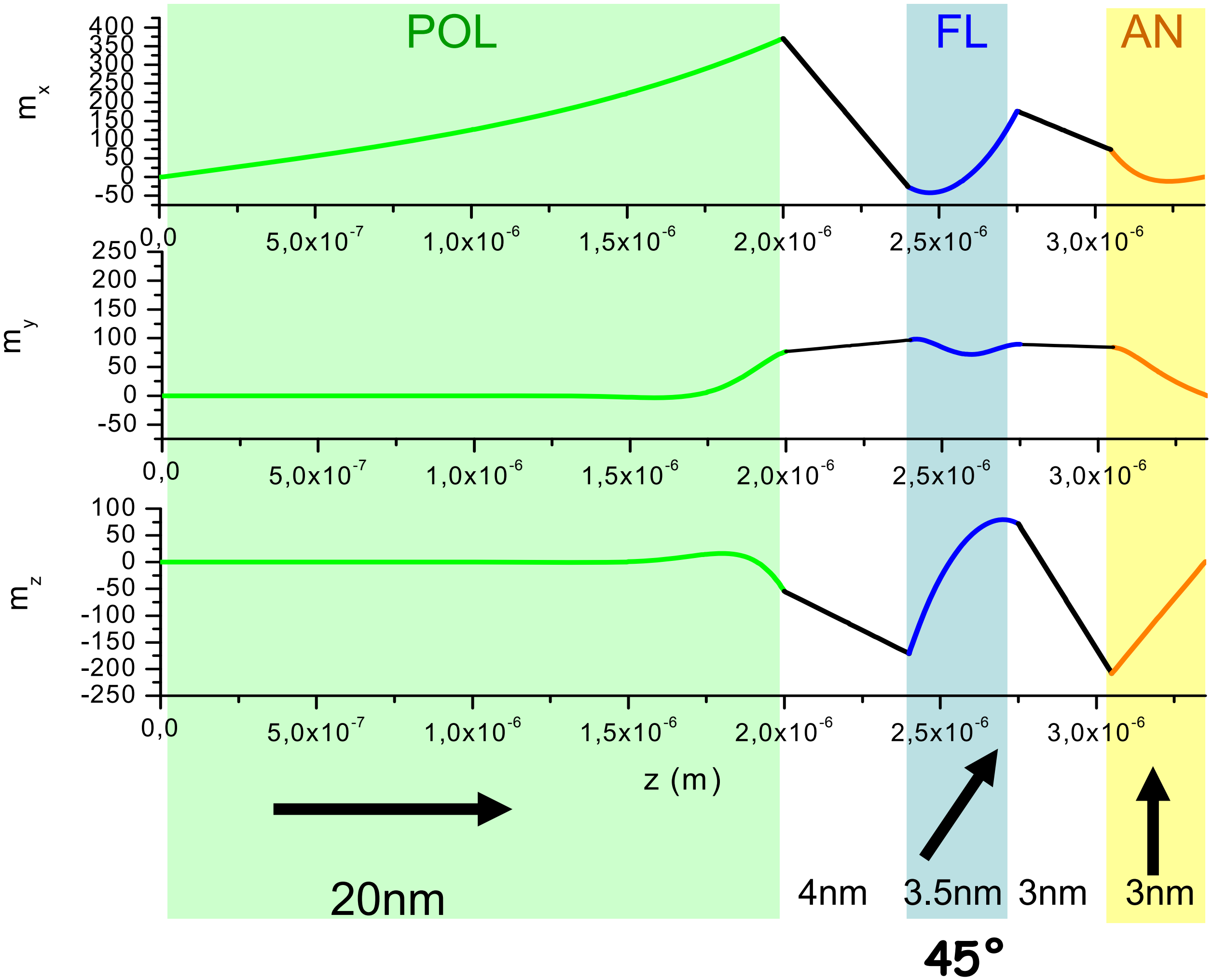
$$j^e = j^{\uparrow} + j^{\downarrow} = \sigma_0 E_z - D_0 \partial_z n - D_0 \beta' (\mathbf{M}\cdot\partial_z \mathbf{m})$$

spin current

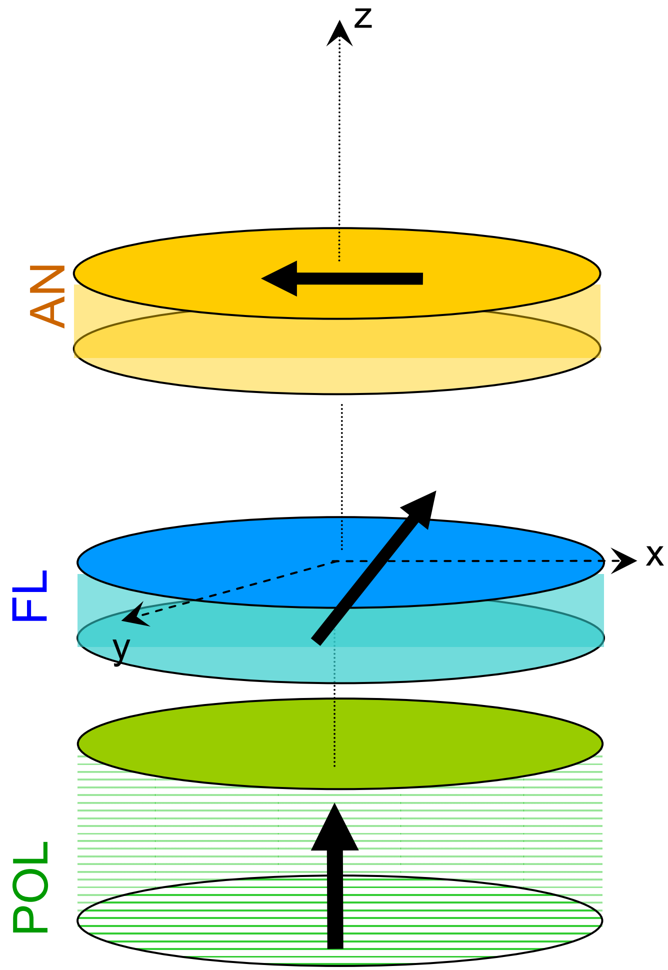
$$\mathbf{j}^m \Rightarrow \mathbf{j}^{\uparrow} - \mathbf{j}^{\downarrow} = \sigma_0 E_z \beta \mathbf{M} - D_0 \partial_z \mathbf{m} - D_0 \beta' \mathbf{M} \partial_z n$$

$$\left(\frac{\partial \mathbf{M}}{\partial t}\right)_{ST} = \frac{J_{sf}}{\mu_B}\mathbf{m}\times\mathbf{M}$$

➢Transport equation



Perpendicular spin torque oscillator



Micromagnetic parameters

Fixed layer

circular disk 60nm, thickness 3.5nm

M_s = 866 kA/m

K_u = 664.5J/m^3 || Ox (H$_u$=150e)

$A_{ex} = 2{\cdot}10^{-11}$J/m

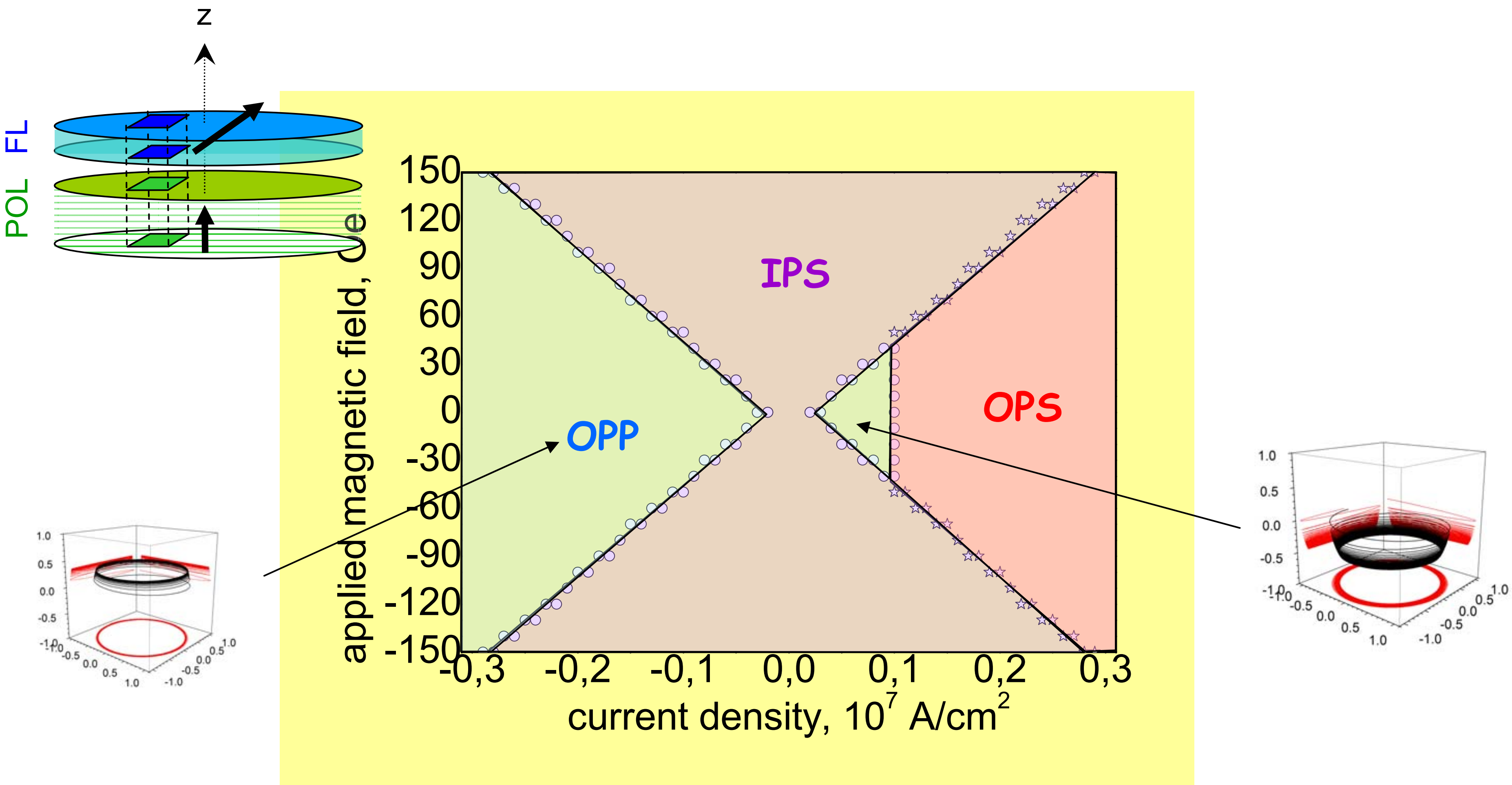
α = 0.01

Mesh size 2 x 2 x 3.5 nm^3

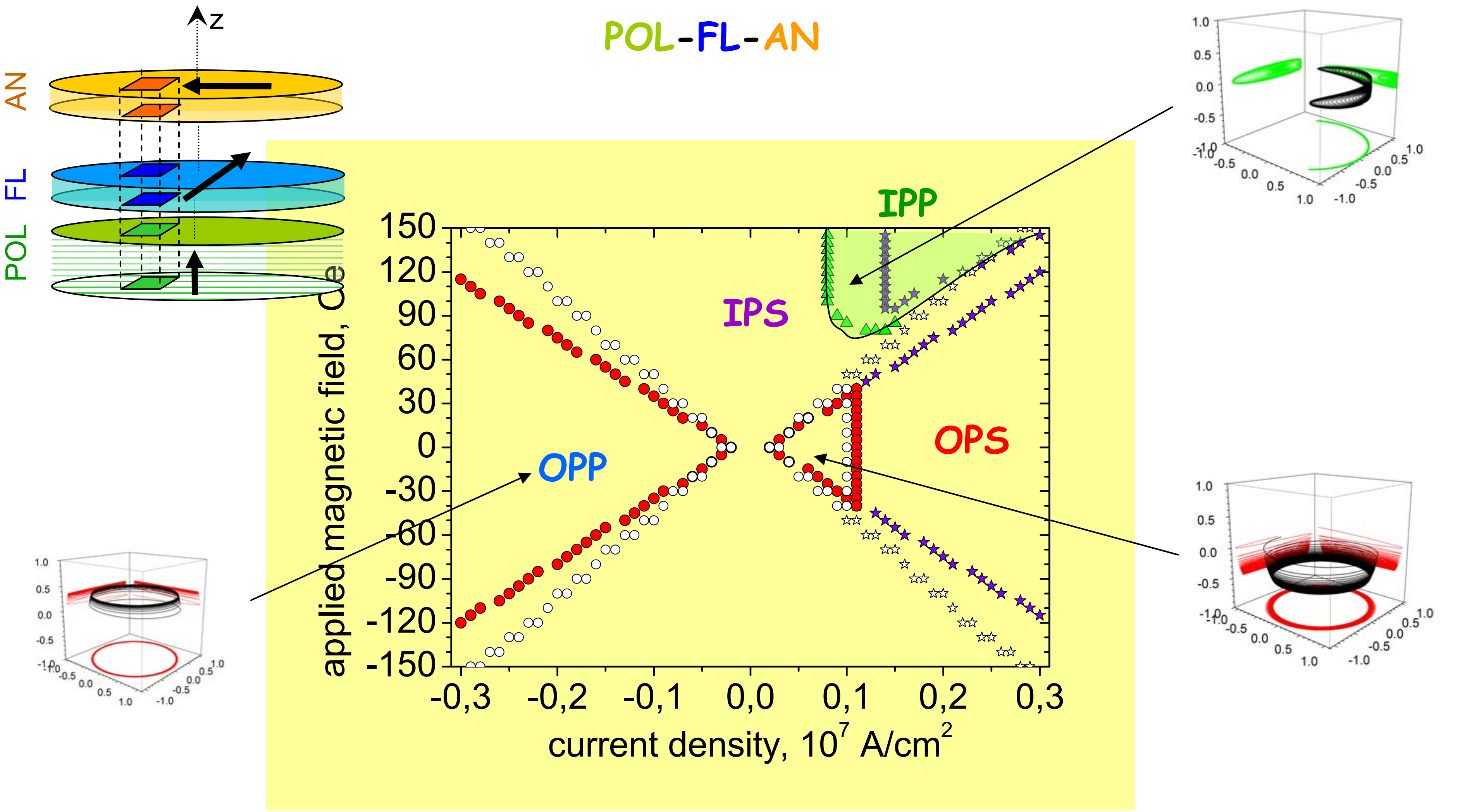
Fixed layer

Macrospin current-field diagram

POL-FL

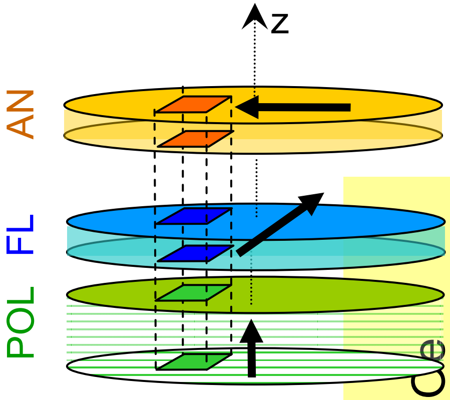


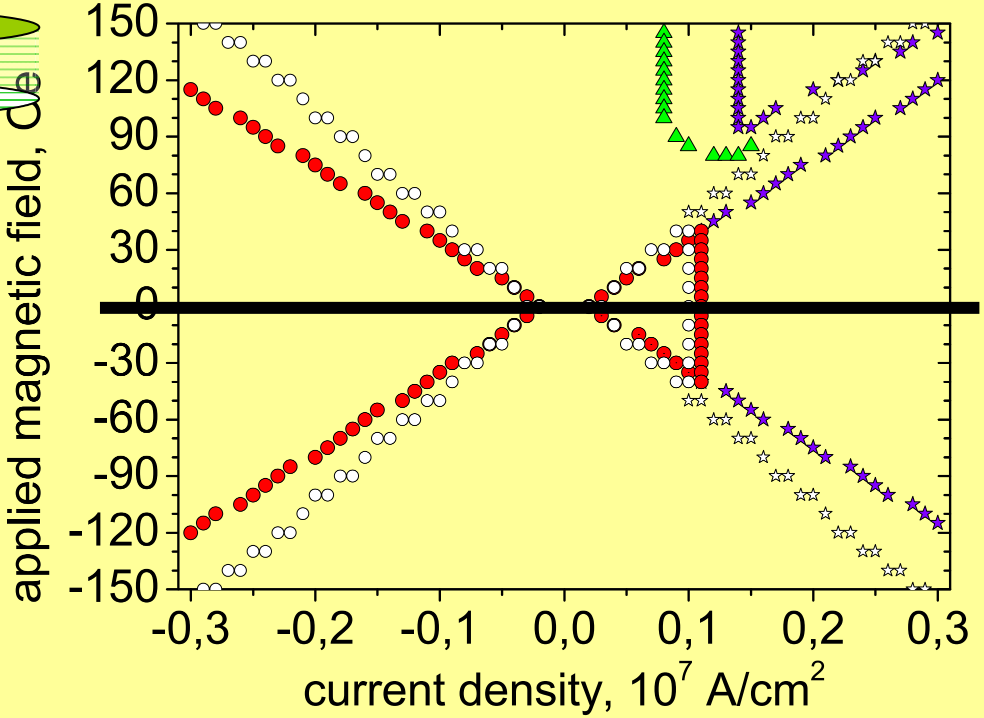
Macrospin current-field diagram



Macrospin current-field diagram

POL-FL-AN

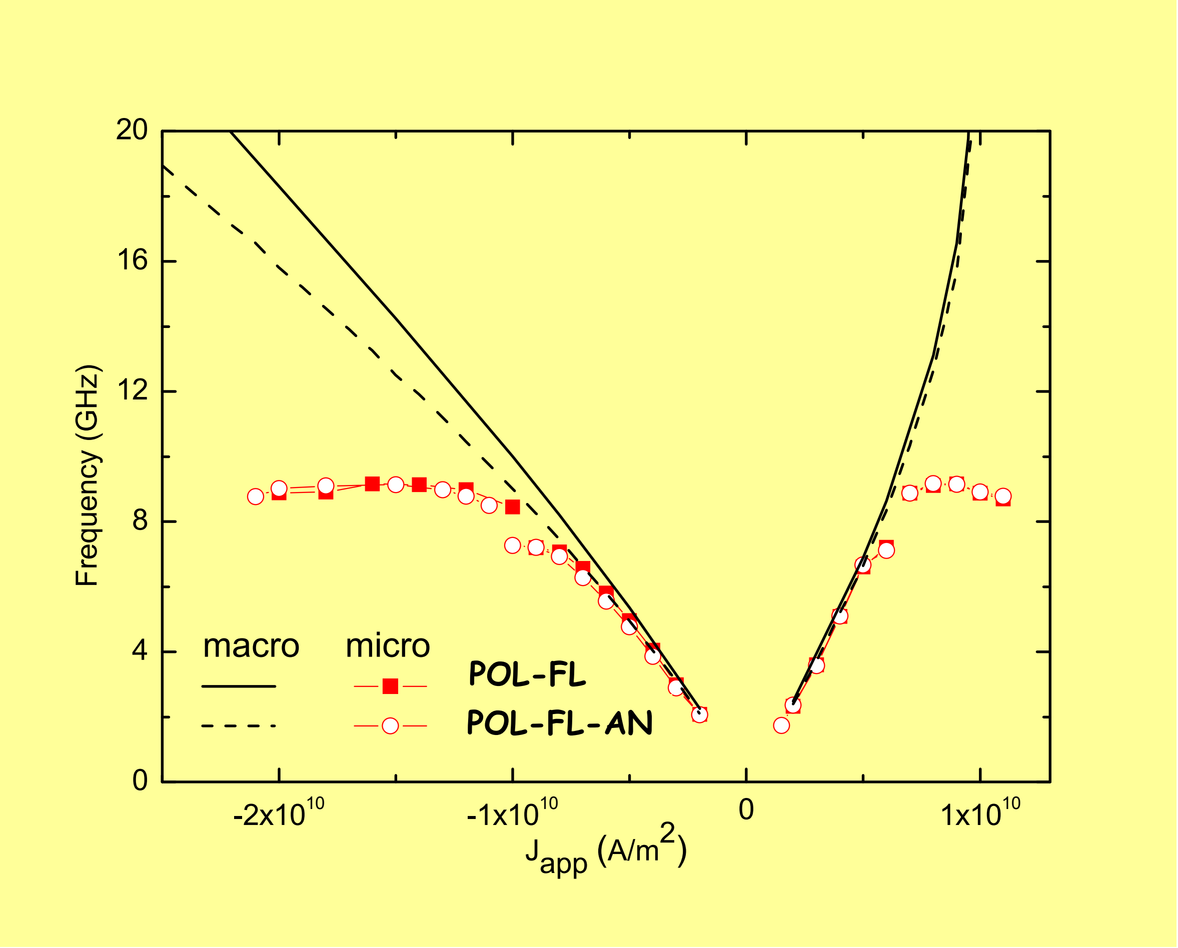




H_{app}=0

OPP frequency

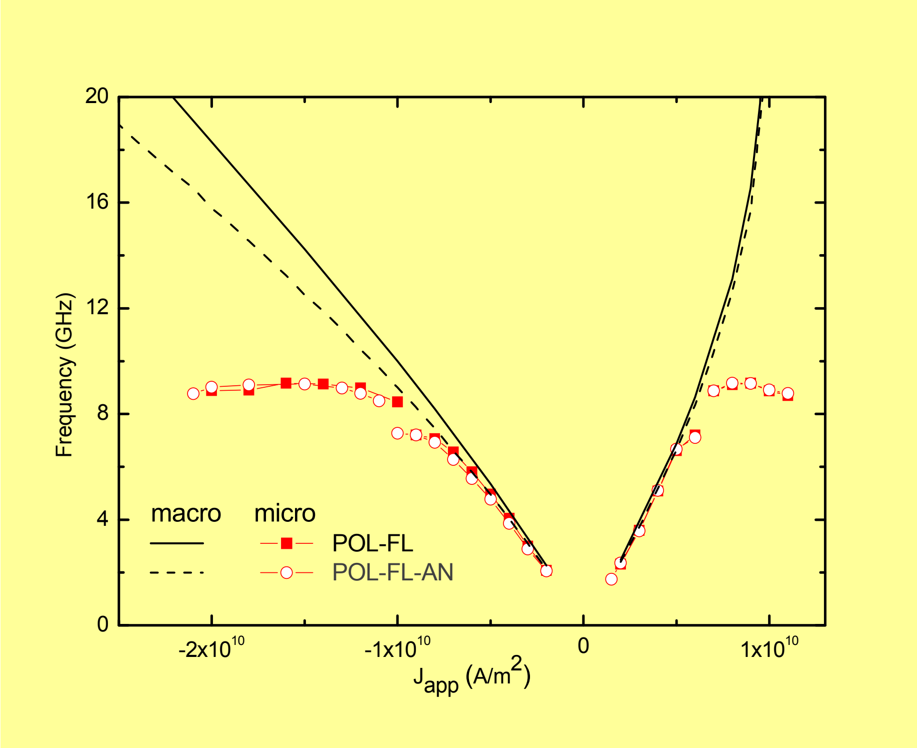
No applied field



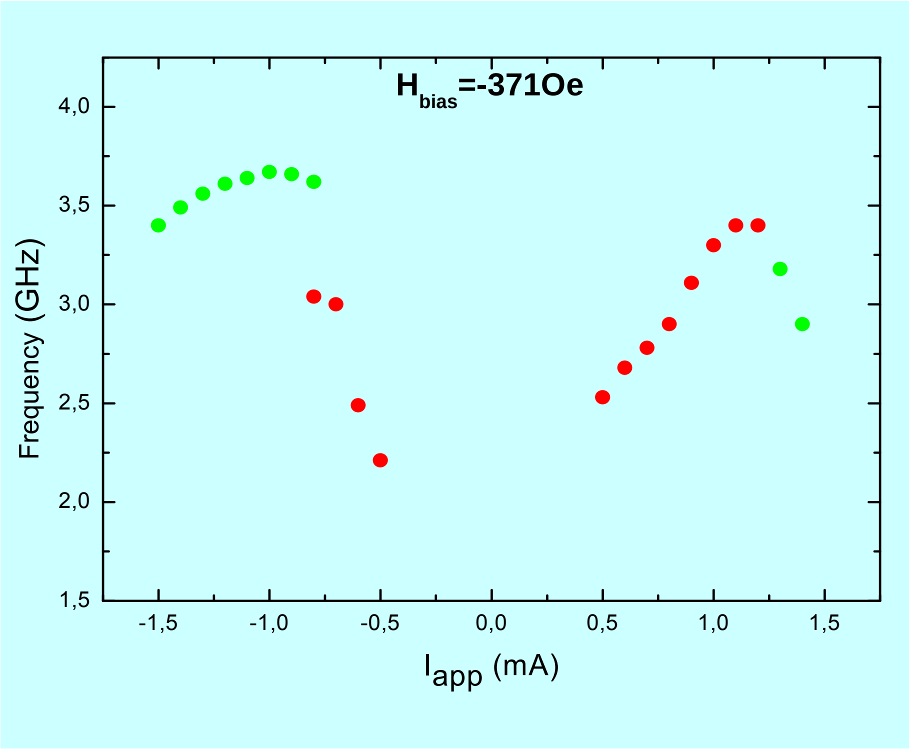
OPP frequency

No applied field

→ ***µmag simulation***

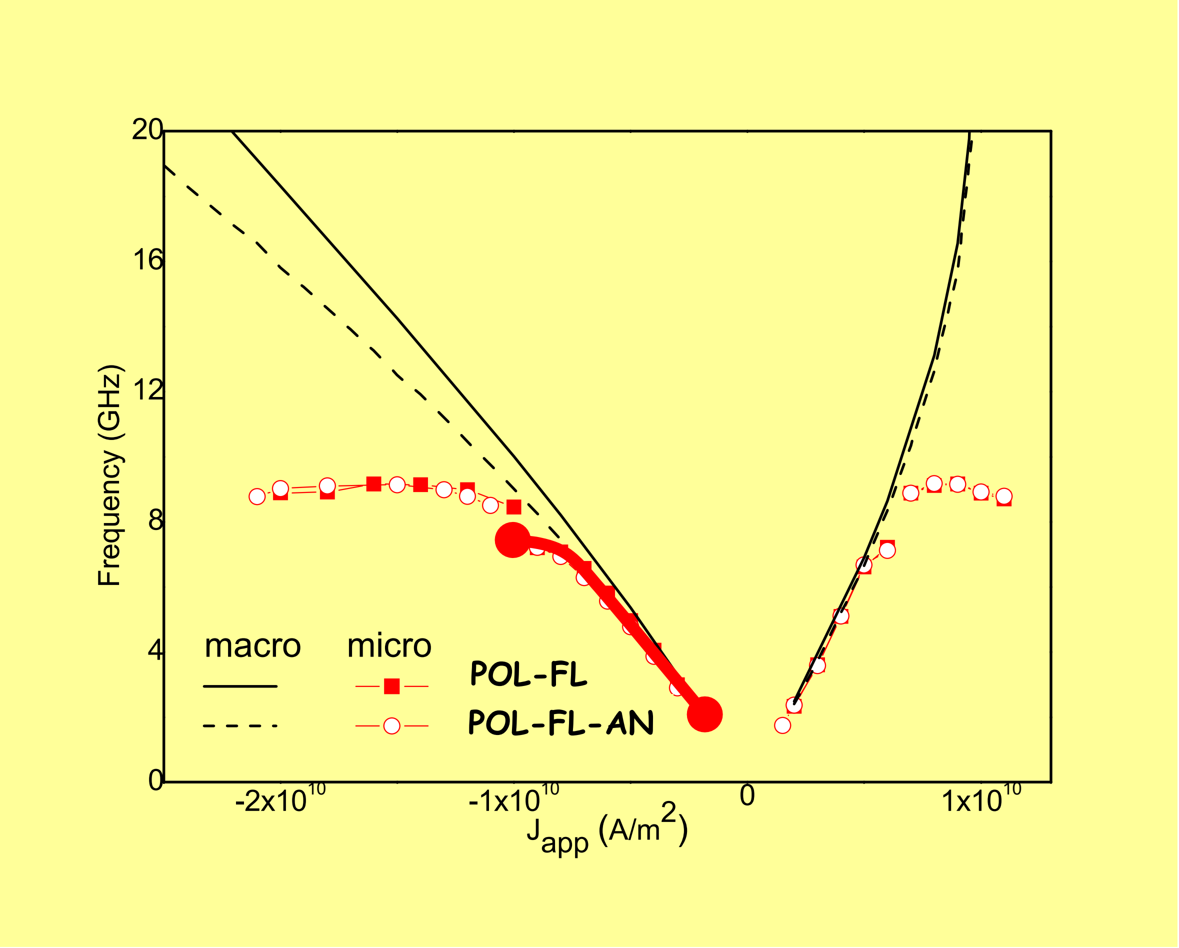


→ ***experimental data***

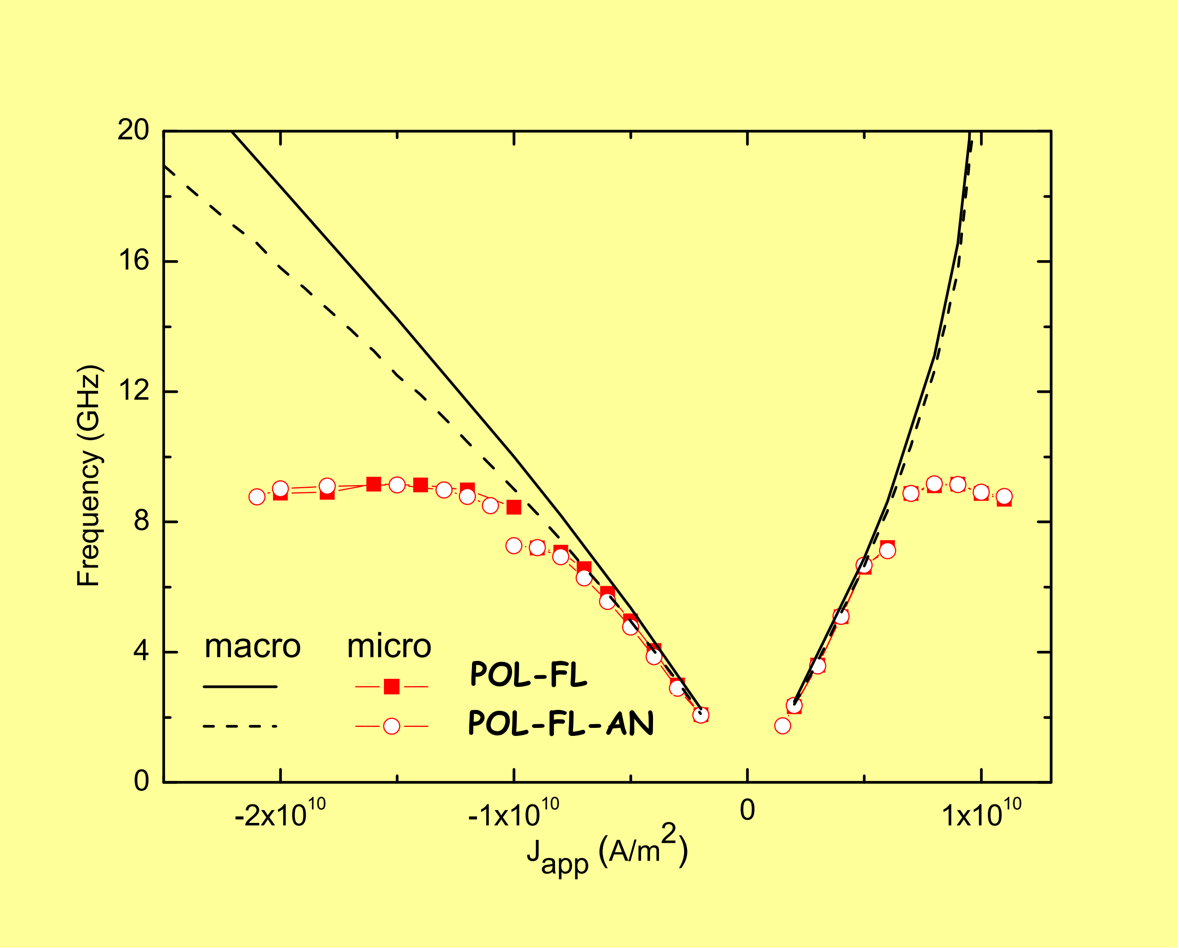


OPP frequency

No applied field

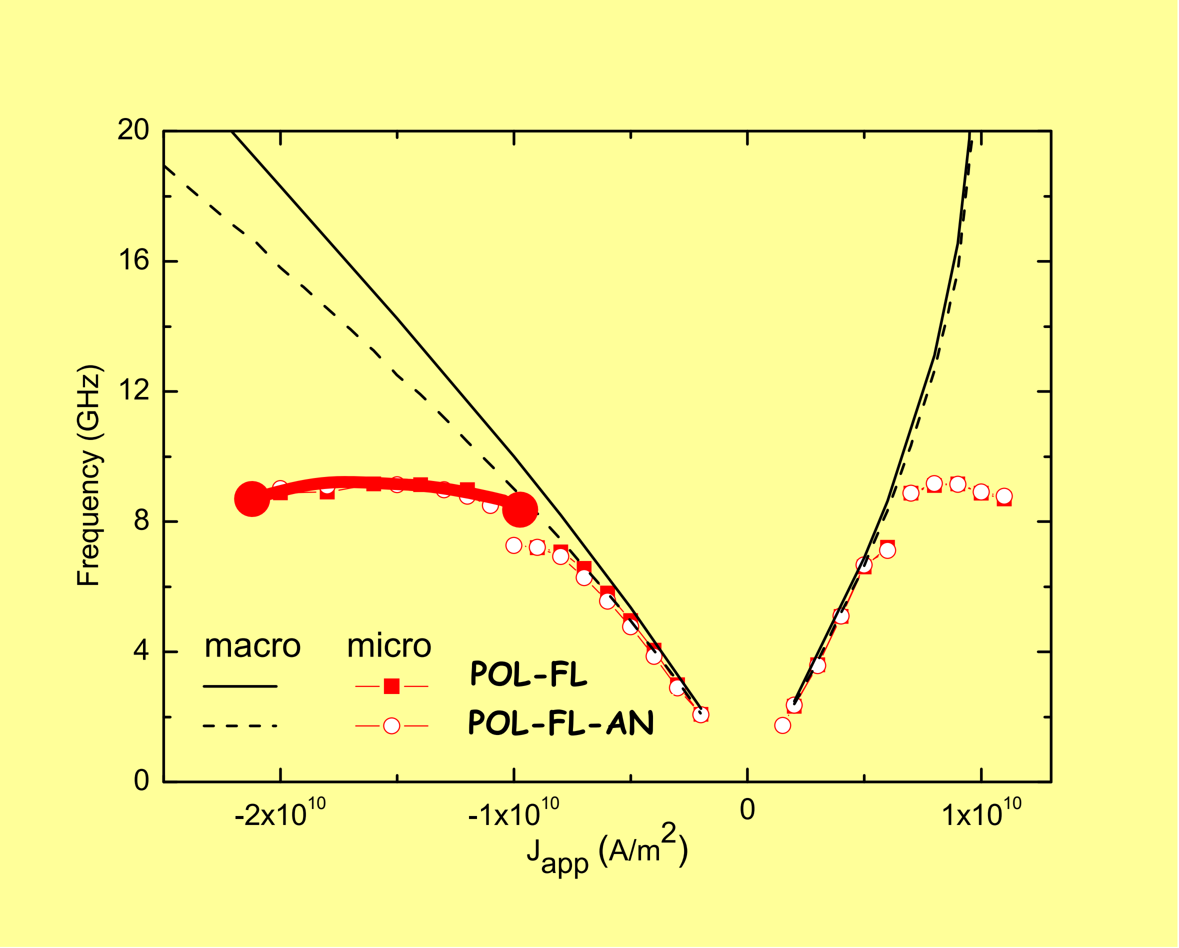


No applied field



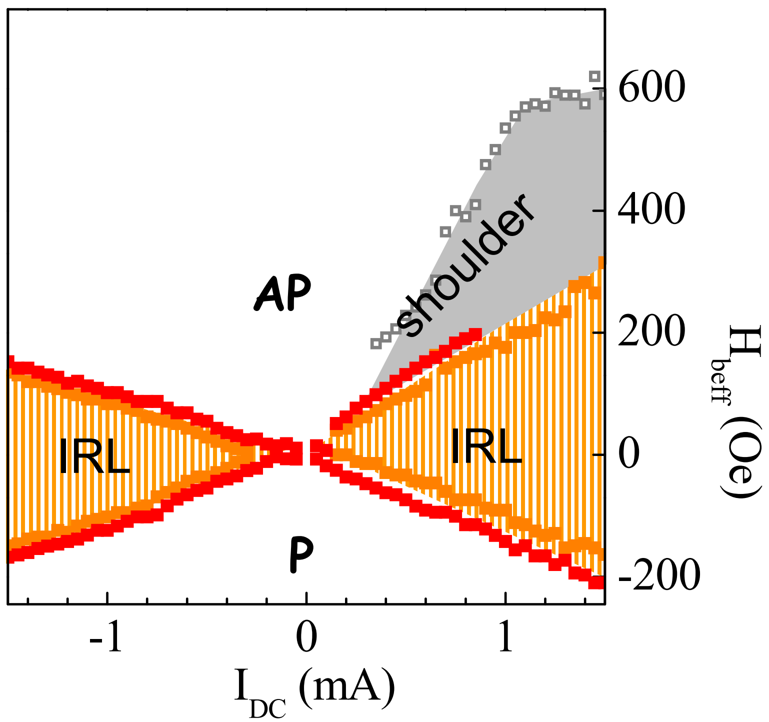
OPP frequency

No applied field

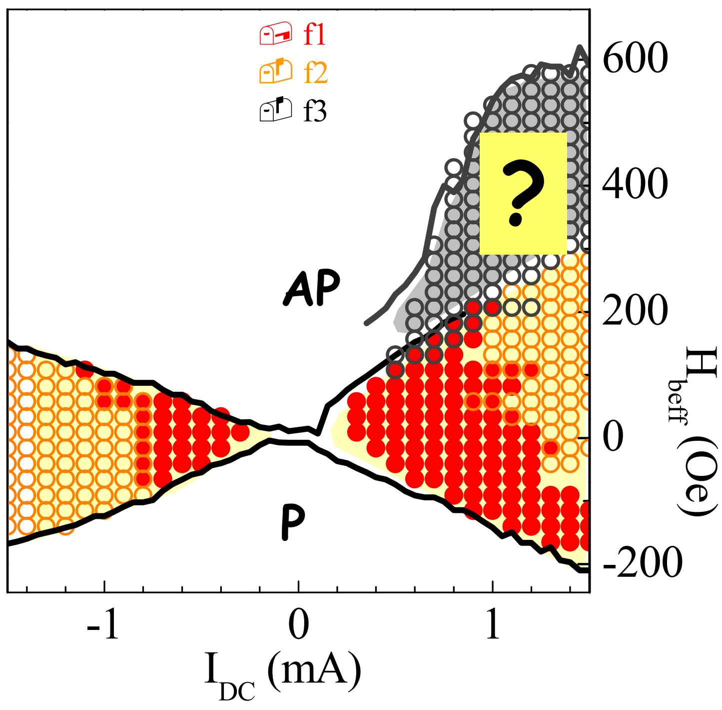


Perpendicular spin torque oscillator

Static current- field diagram



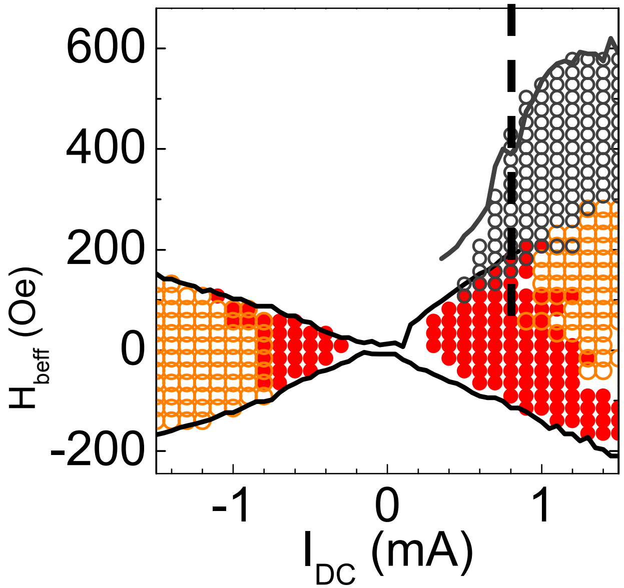
Dynamic current- field diagram

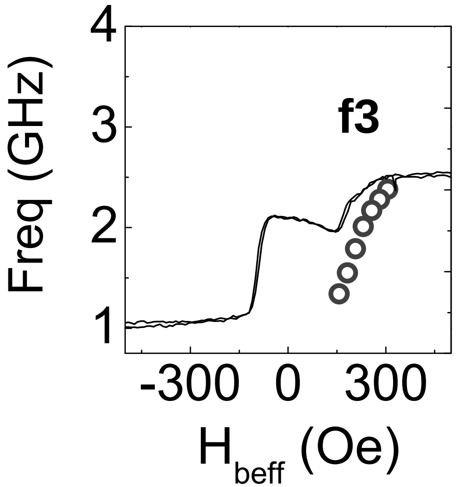


Houssameddine et al. accepted Nat. Mat.

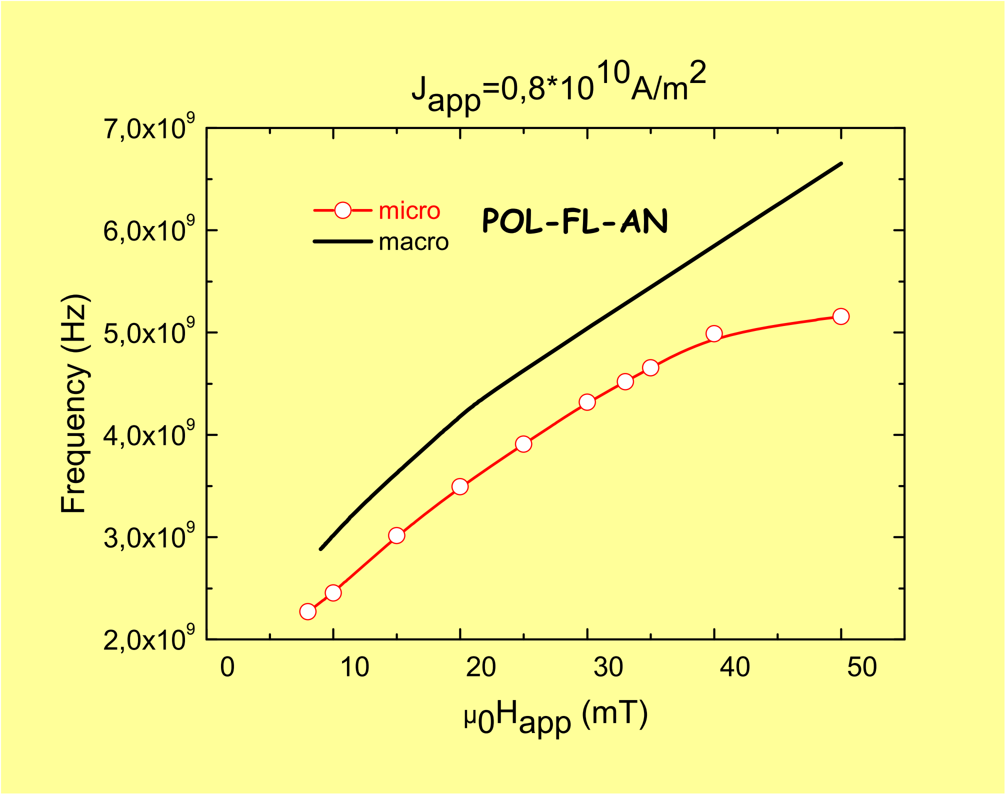
IPP frequency

→ experimental data



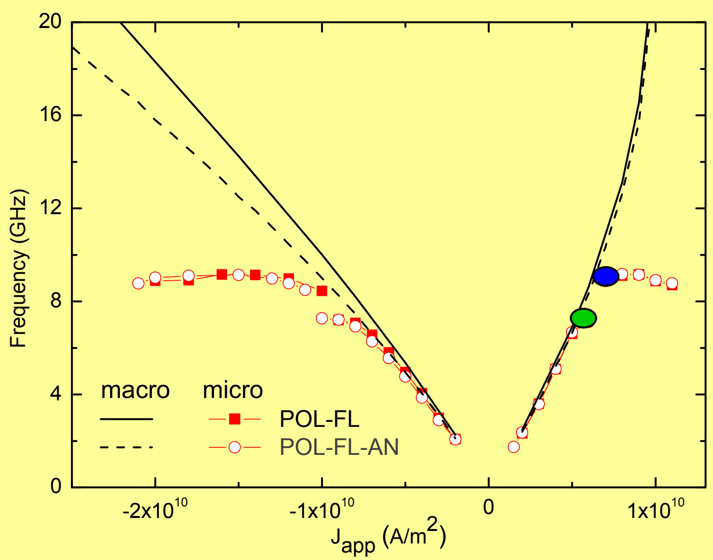


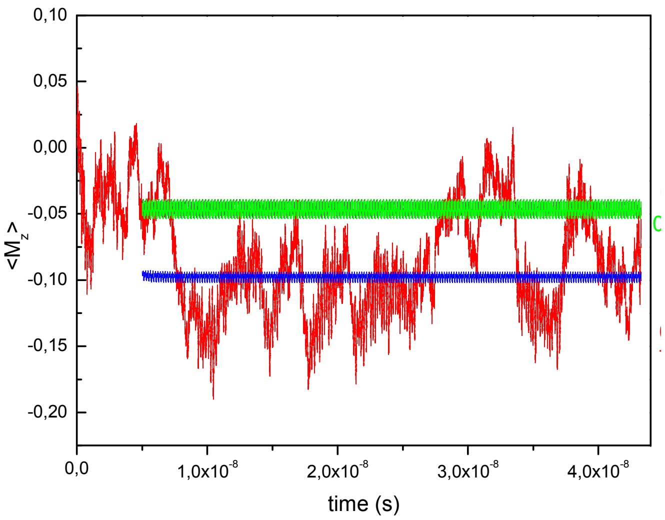
→ µmag simulation



No applied field

→ ***μmag simulation***





before jump

after jump

T=400K

Conclusion

Solving self-consistently the LLG equation and the spin dependant transport equation:

a) accurate investigation of structures with 2, 3 or more coupled magnetic layers

b) qualitative good agreement with the experimental data

c) "A toy" dedicated to the ST oscillator optimization for future device integration