Noncollinear Spin Transport at Magnetic Interfaces

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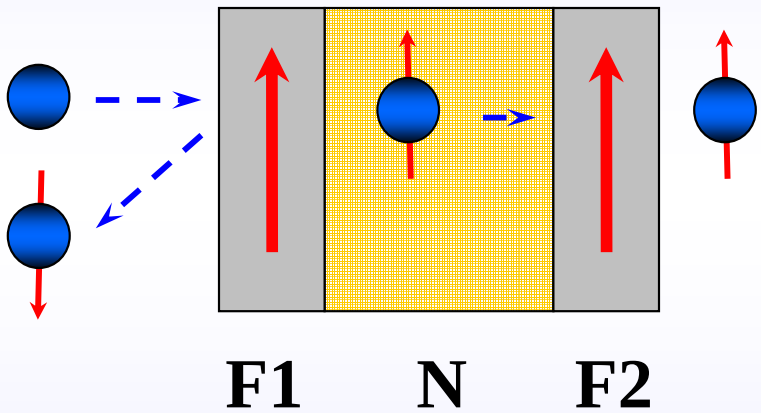
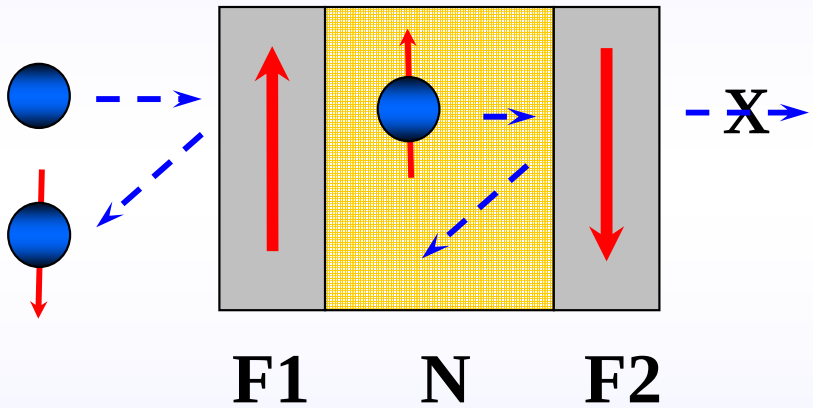
Giant Magnetoresistance (GMR)

Parallel (P)



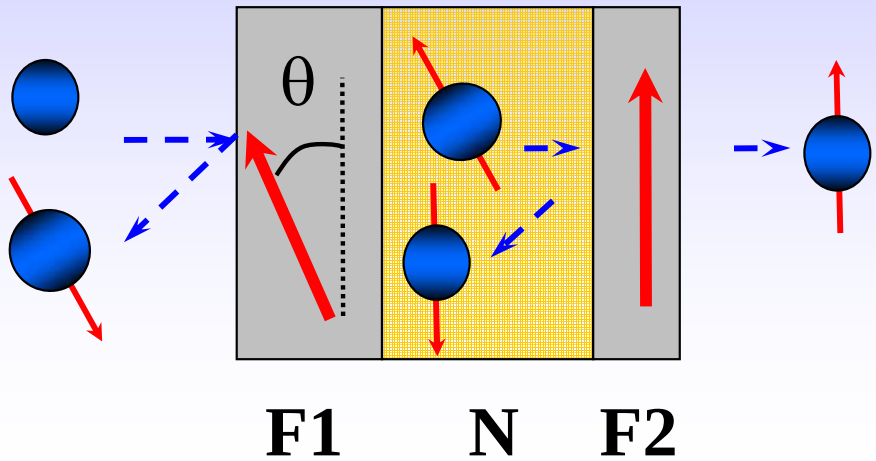
Antiparallel (AP)



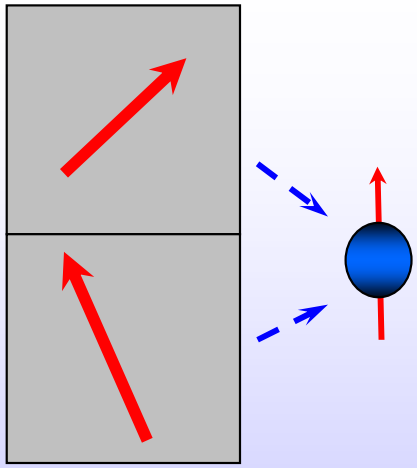
- Scattering predominantly at interfaces due to band mismatch
- Usually $R_{AP} > R_P$

Baibich *et al.* (1988)

Noncollinear Magnetizations

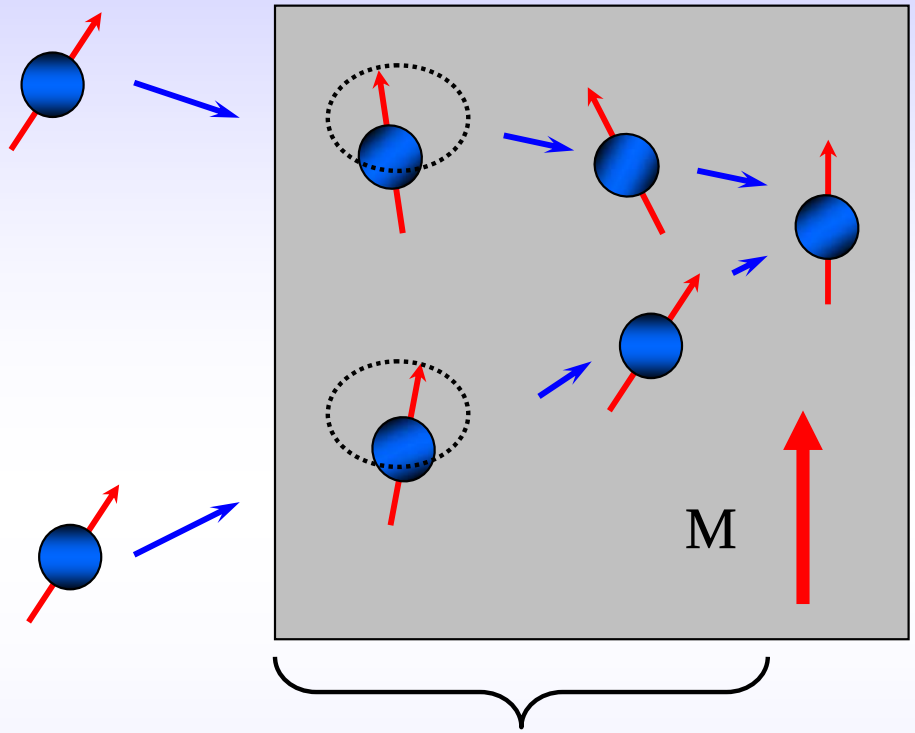


transverse spin transferred to M: spin torque Slonczewski (1996)



Transport properties?
Spin currents?

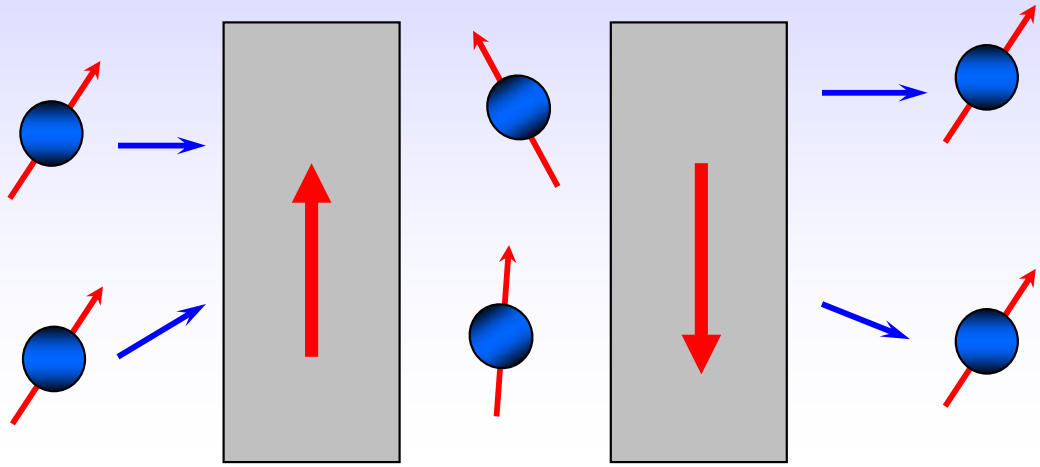
Characteristic spin transfer length scale



T2 process

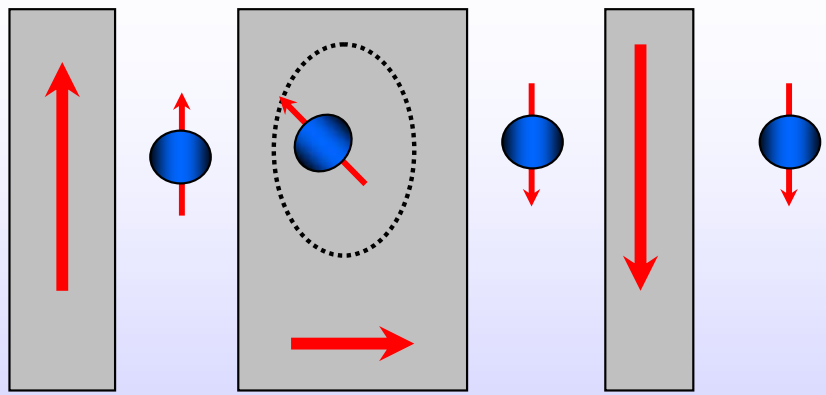
Ferromagnetic coherence length?

Spin Interference



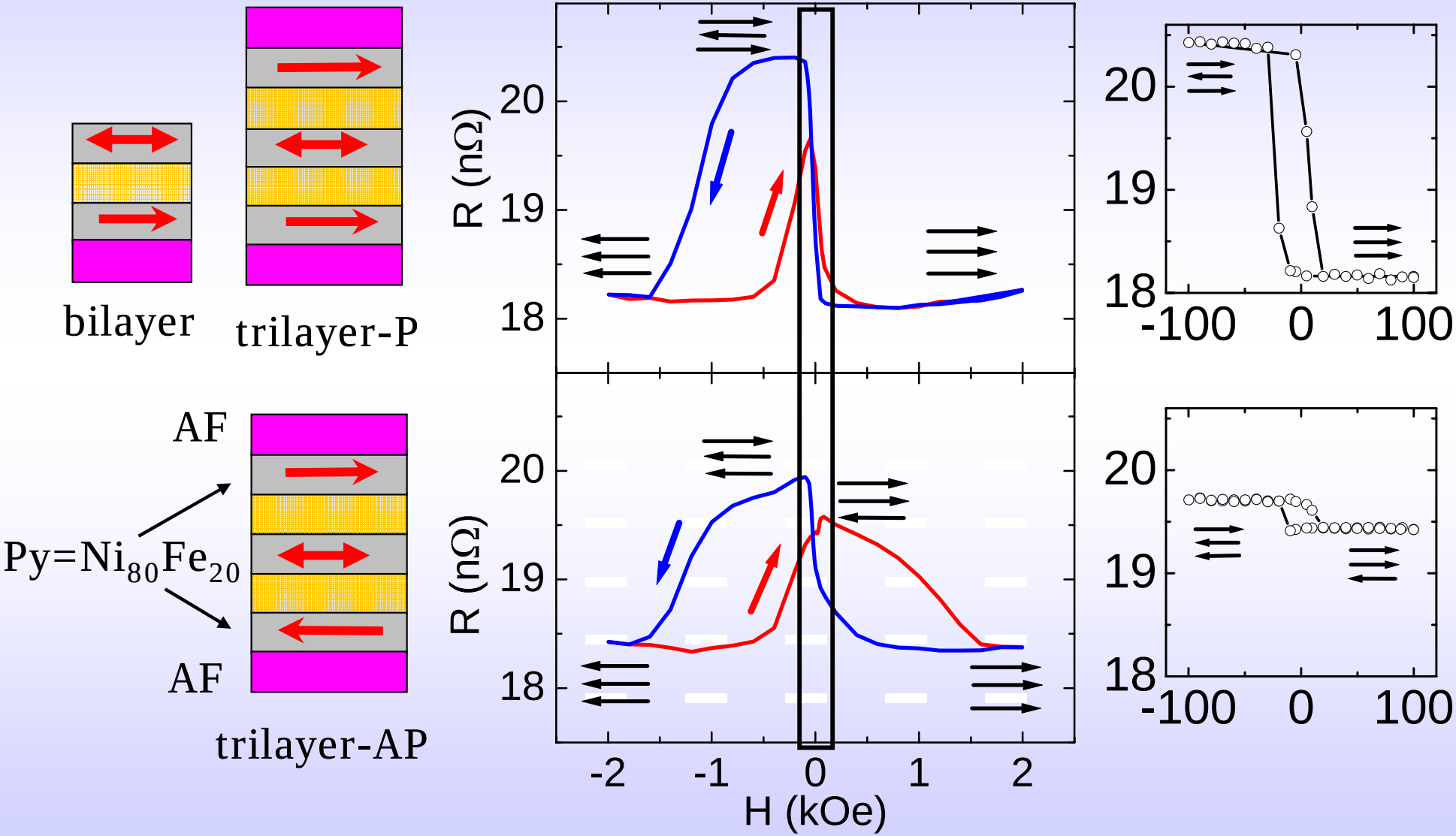
•Magnetoelectronic spin echo

A. Brataas *et al.* (2004)



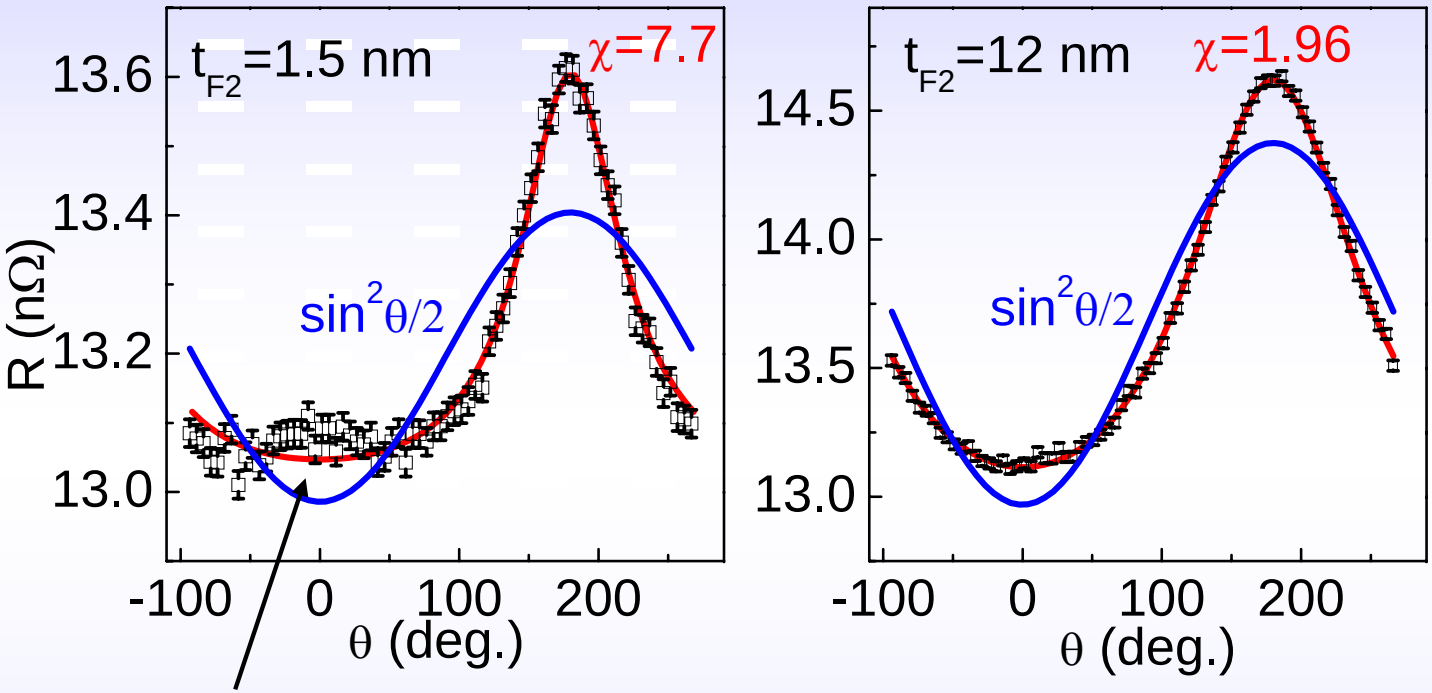
•Magnetoelectronic cross-polarizer (Hanle effect in H_{Ex})

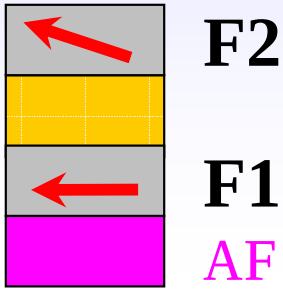
F/N/F and F/N/F/N/F



Structure1: F/N/F

FeMn(8)Py(6)Cu(5)Py(t_{F2}), t_{F2}=1.5-12 nm





Maximum in AP and P states

$$r(\theta) = \frac{R(\theta) - R(0)}{R(\pi) - R(0)} = \frac{1 - \cos^2(\theta/2)}{1 + \chi \cos^2(\theta/2)}$$

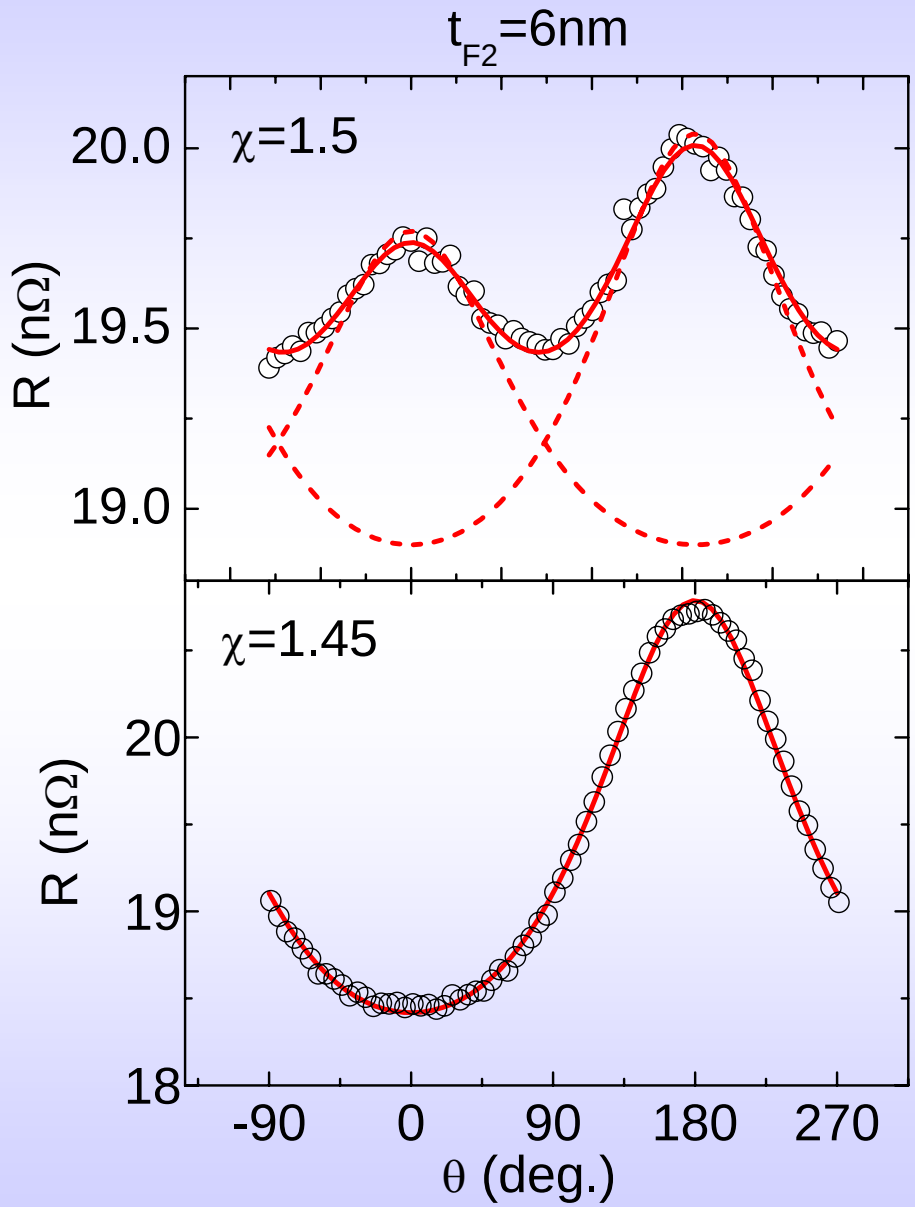
χ gives deviations from harmonic dependence

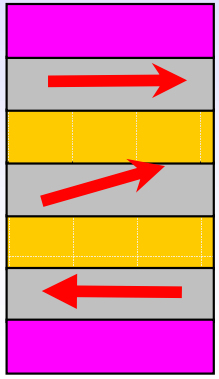
J.C. Slonczewski (2002); G.E.W. Bauer *et al.* (2003); SU, R. Loloee and W.P. Pratt (2005)

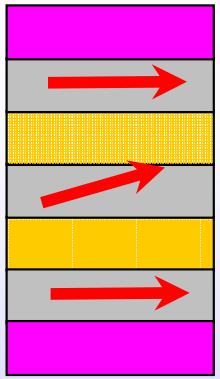
Structure 2: F/N/F/N/F

GMR only due to asymmetry

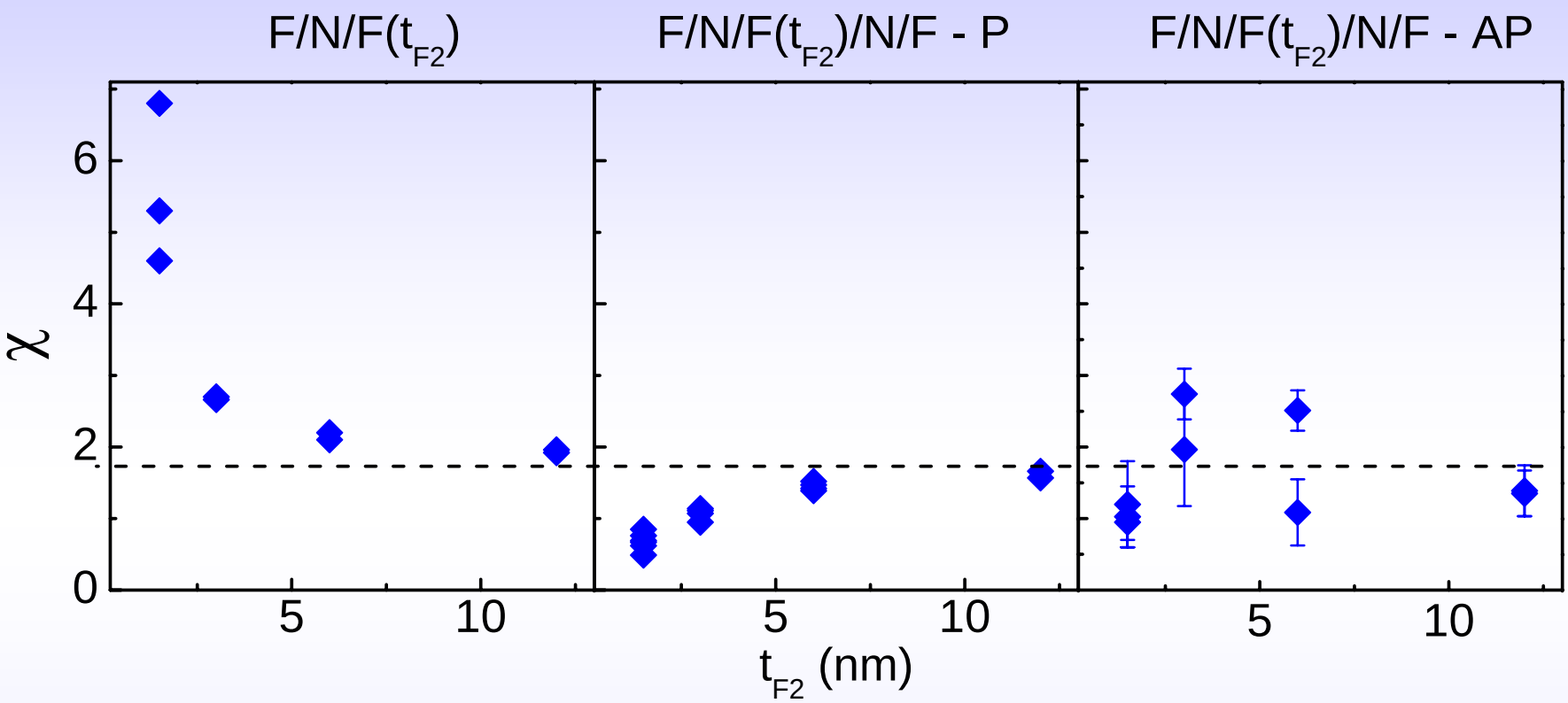
GMR 2x larger than in F/N/F







$\chi(t_{F2})$

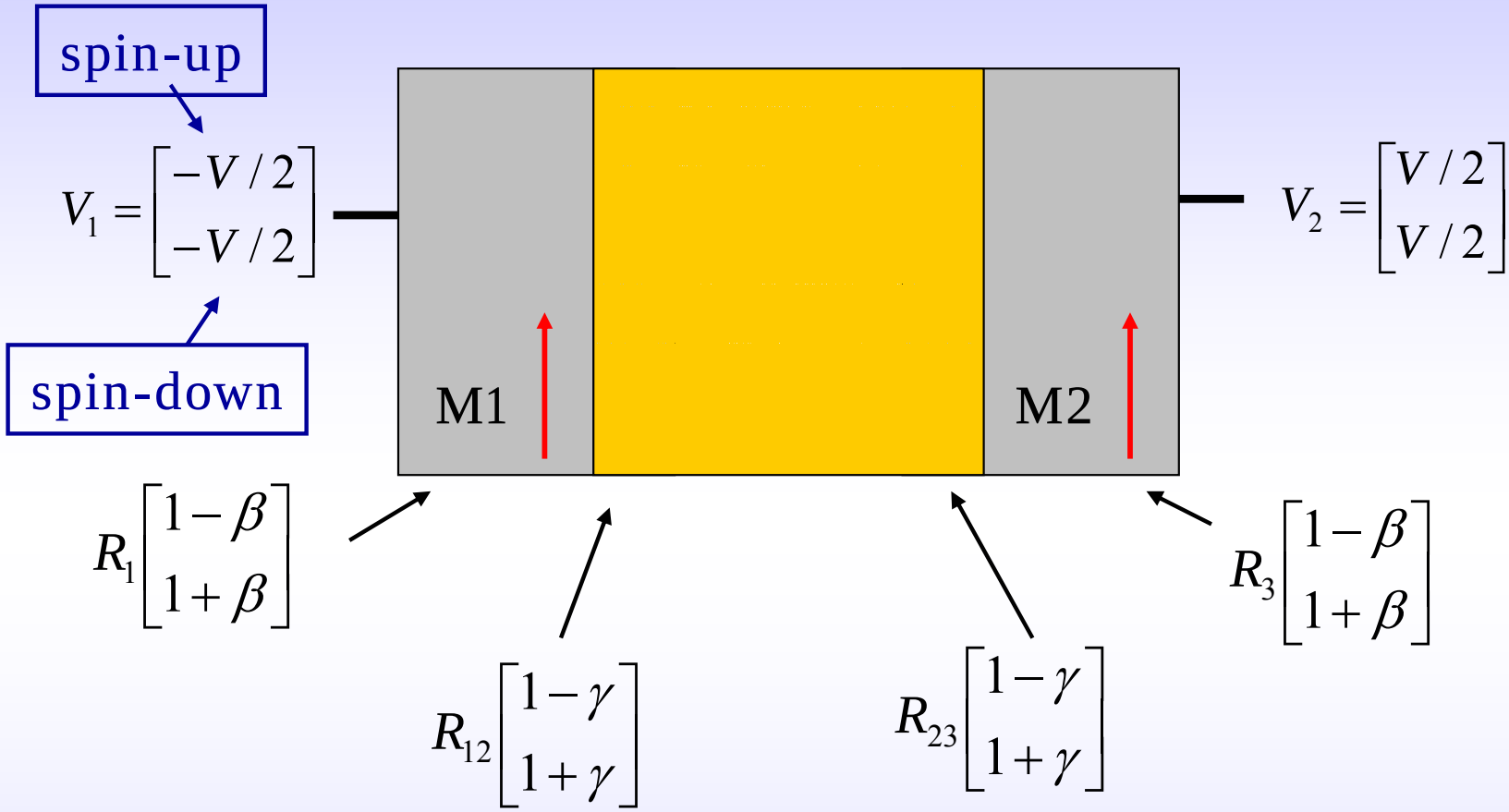


χ increases at small t_{F2}

χ decreases at small t_{F2}

too much scatter

Two Current Series Resistor Model

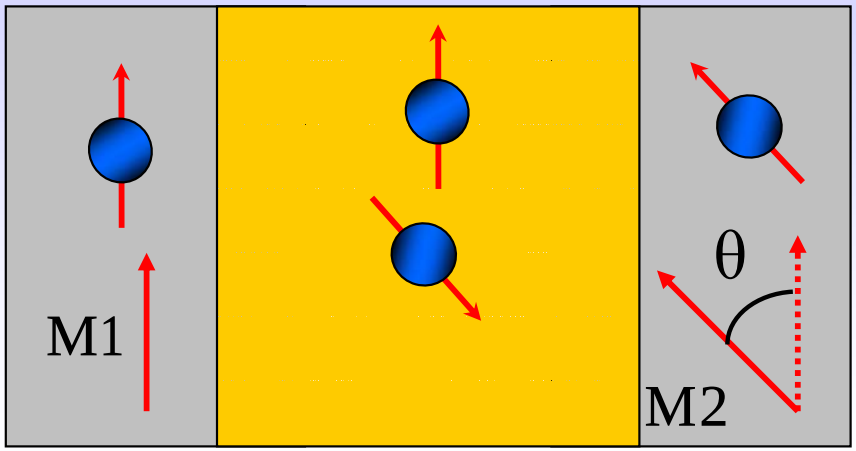


β, γ are spin asymmetries of bulk ferromagnets / their interfaces

Diffusive Transport Model

$$\hat{V}_1 = \begin{bmatrix} -\frac{V}{2} & 0 \\ 0 & -\frac{V}{2} \end{bmatrix}$$

~Spin-density matrix



$$\hat{V}_2 = \begin{bmatrix} \frac{V}{2} & 0 \\ 0 & \frac{V}{2} \end{bmatrix}$$

$$R_1 \begin{bmatrix} 1-\beta & 0 \\ 0 & 1+\beta \end{bmatrix}$$

$$R_{12} \begin{bmatrix} 1-\gamma & 0 \\ 0 & 1+\gamma \end{bmatrix}$$

$$R_{23} U \begin{bmatrix} 1-\gamma & 0 \\ 0 & 1+\gamma \end{bmatrix} U^{+}$$

$$R_3 U^{+} \begin{bmatrix} 1-\beta & 0 \\ 0 & 1+\beta \end{bmatrix} U$$

$$U = \begin{bmatrix} \cos\theta/2 & -\sin\theta/2 \\ \sin\theta/2 & \cos\theta/2 \end{bmatrix}$$

spinor rotation matrix

AGMR

$$\hat{V} = \begin{bmatrix} V & 0 \\ 0 & V \end{bmatrix} = \hat{R}_1\hat{I}_1 + \hat{R}_{12}\hat{I}_{12} + \hat{R}_{23}\hat{I}_{23} + \hat{R}_3\hat{I}_3$$

Symmetric F/N/F

$$R(\theta) = \frac{V}{I(\theta)} \approx 2R_1 + 2R_{12} - \frac{2\cos^2\theta/2(\gamma R_{12} + \beta R_1)^2}{R_{12} + R_1\cos^2\theta/2}$$

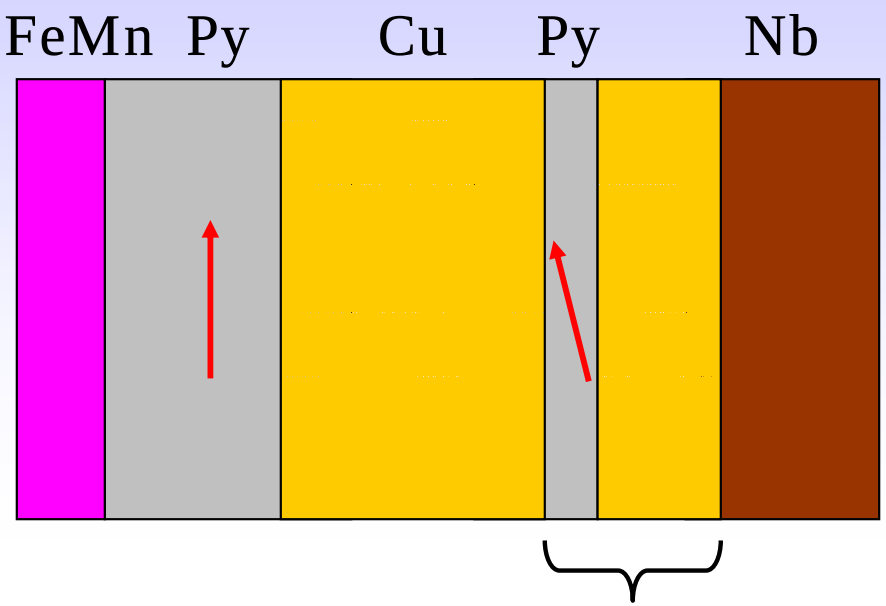
$$r(\theta) = \frac{R(\theta) - R(0)}{R(\pi) - R(0)} = \frac{1 - \cos^2(\theta/2)}{1 + \chi\cos^2(\theta/2)}$$

$$\chi = R_1 / R_{12}$$

bulk interface

$R_{12}=R_{interface}+l_t\rho_{bulk}$ depends linearly on the transverse spin penetration thickness l_t

F/N/F

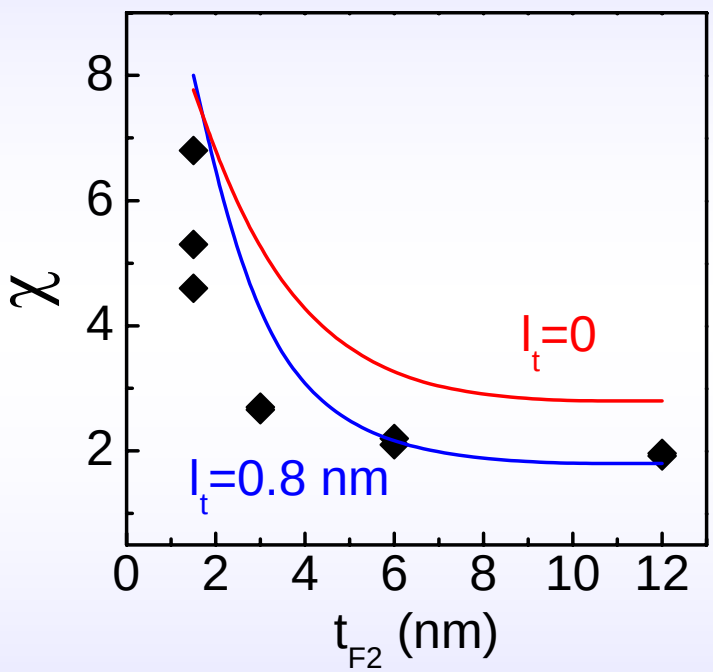


$$R_3 = \rho_{Py} t_{F2} + \alpha R_{PyNb}$$

$$0 < \alpha < 1$$

$$R_{PyNb} = 3\ f\Omega m^2 >> R_{12}, R_1$$

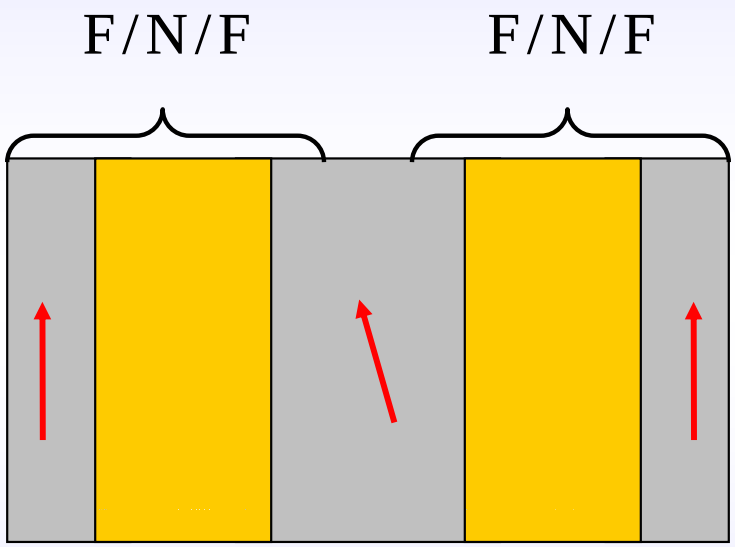
Asymmetric structure



R_3 increases when F2 is thin: $\chi \sim R_1 / R_{12} \sim R_3 / R_{12}$ increases

F/N/F/N/F – P state

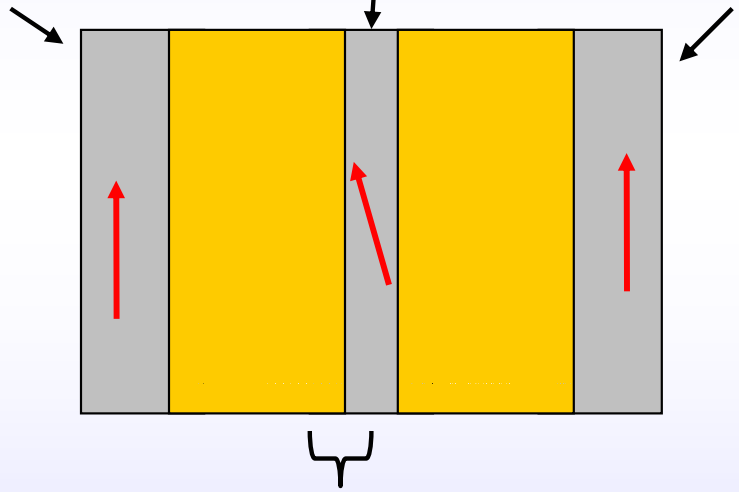
Thick middle F layer



χ same as F/N/F

Thin middle F layer

$$\begin{bmatrix} -\frac{V}{2} & 0 \\ 0 & -\frac{V}{2} \end{bmatrix} \qquad \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad \begin{bmatrix} \frac{V}{2} & 0 \\ 0 & \frac{V}{2} \end{bmatrix}$$

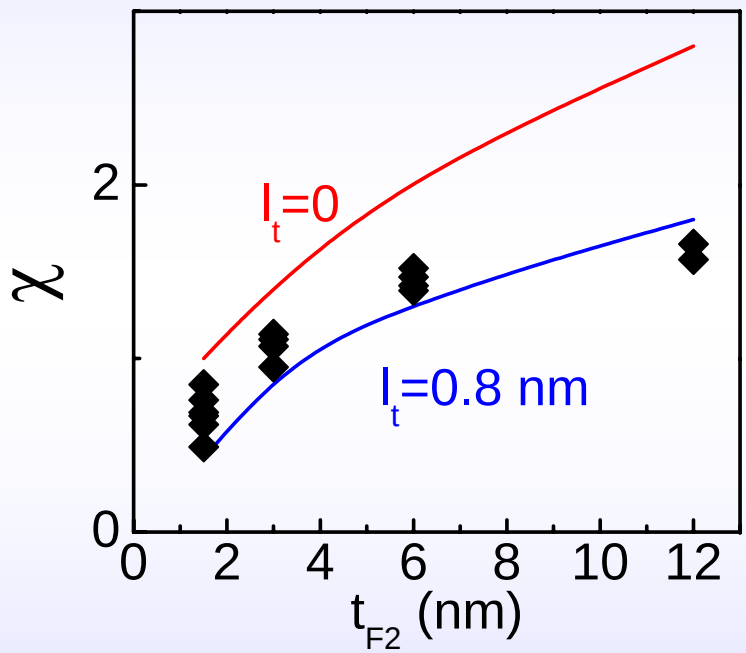


$R3=\rho_{Py}t_{F2}/2$

$$\chi \sim R_3 / R_{12}$$

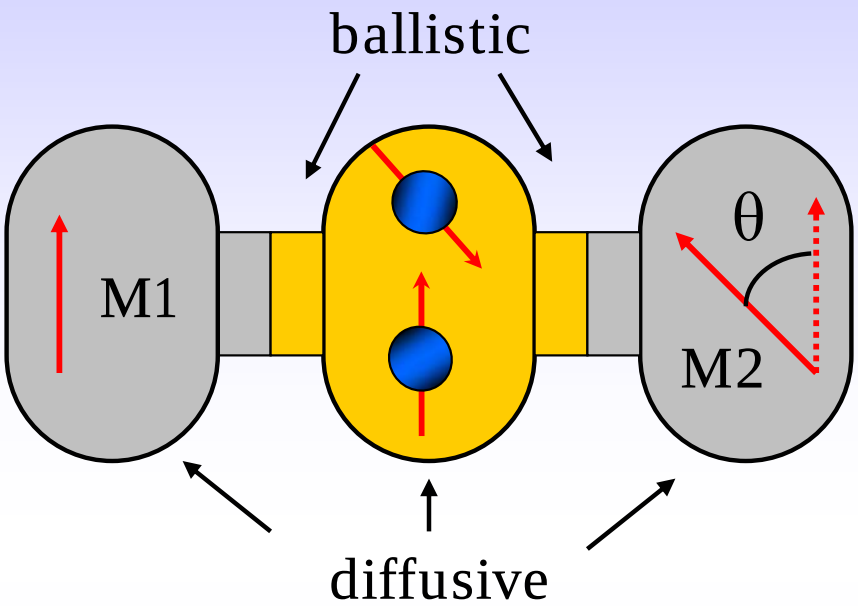
decreases at small t_{Py}

F/N/F/N/F P state



AGMR is an indirect but precise measure of transverse spin absorption at the interface

Magnetoelectronic Circuit Theory



$$\chi = 2g^{\uparrow\downarrow} R_1$$

mixing conductance of the interface

$$g^{\uparrow\downarrow} = \frac{e^2}{h} \sum_{m,n} [\delta_{nm} - r_{nm}^{\uparrow} r_{nm}^{\downarrow *}]$$

$$g^{\uparrow\downarrow} \approx g^{\uparrow}$$

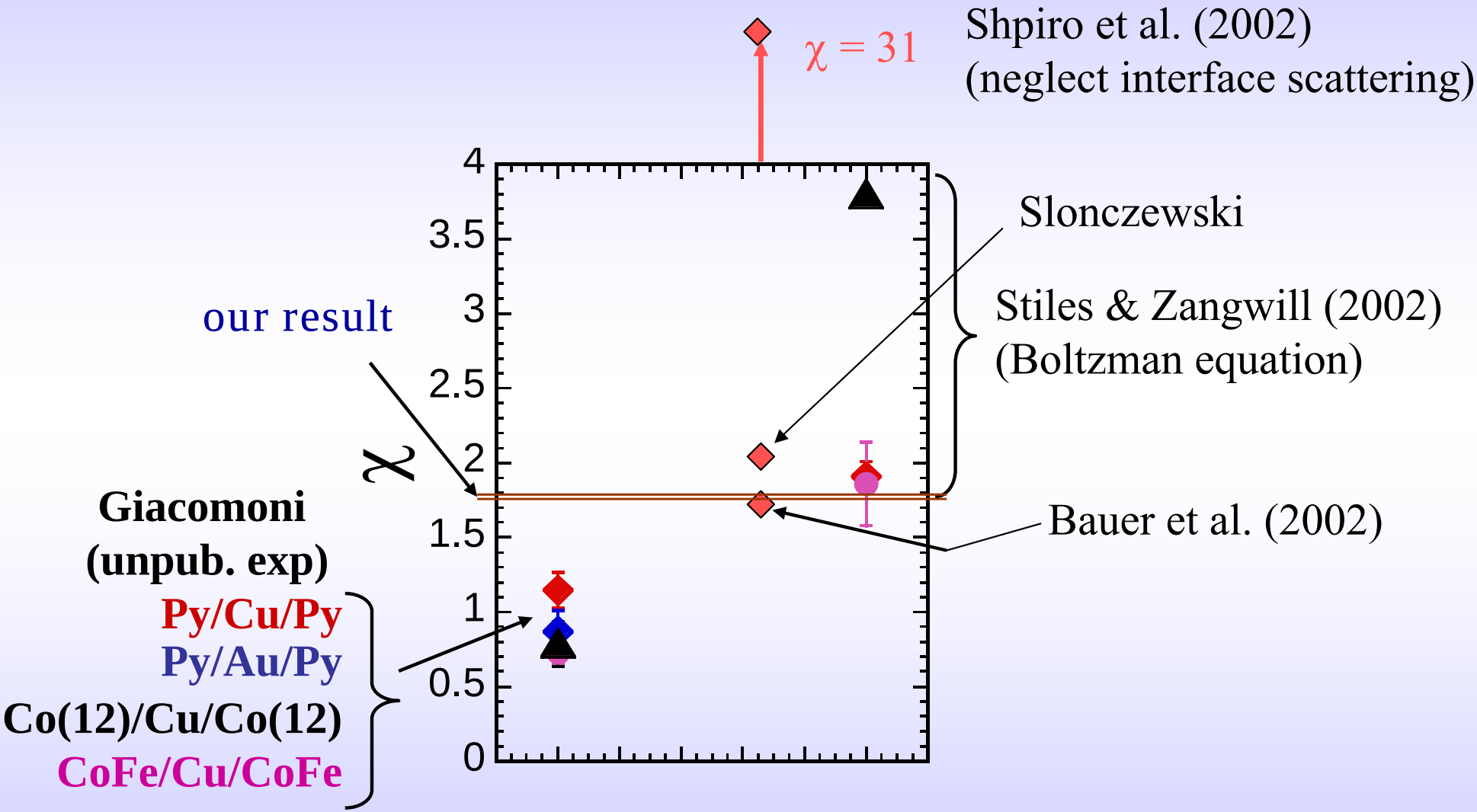
our $\chi = R_1/R_{12}$ would be equivalent to

$$g^{\uparrow\downarrow} = 2g^{\downarrow} g^{\uparrow} / (g^{\downarrow} + g^{\uparrow}) < g^{\uparrow}$$

it was too large to explain the data => finite l_t also needed in circuit theory

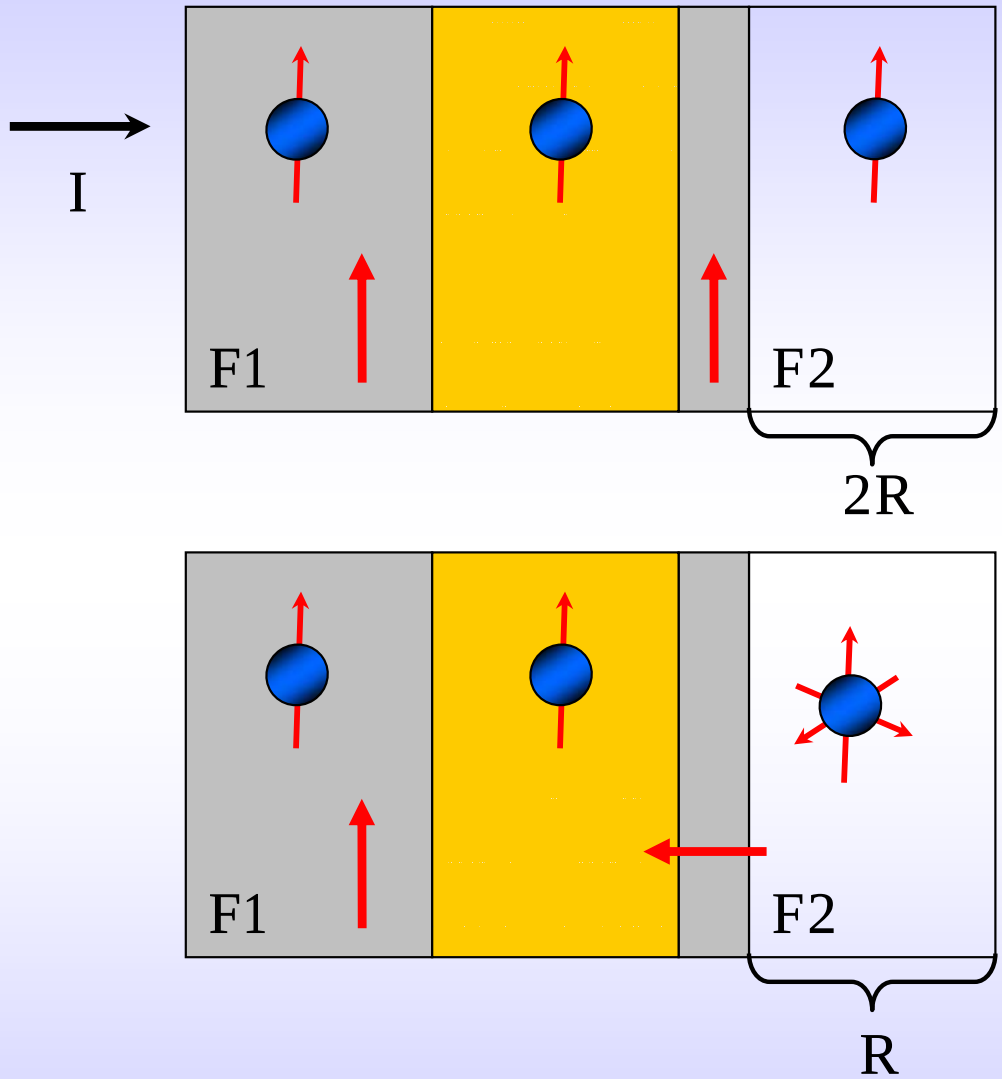
A. Brataas, Yu. Nazarov and G.E.W. Bauer (2000)

Other Results and Theories



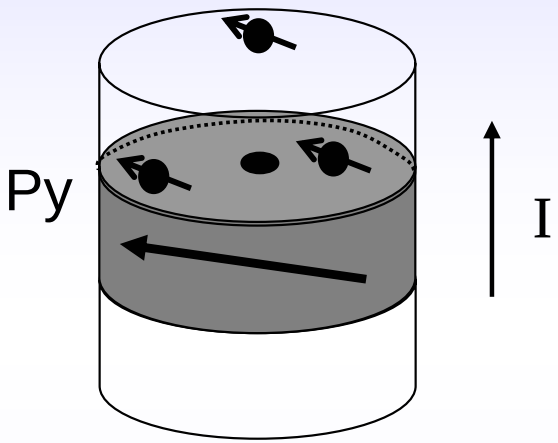
(c/o W.P. Pratt Jr.)

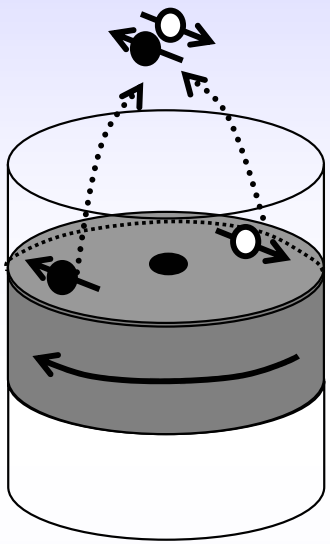
Origin of Nonmonotonic AGMR



Noncollinear M => smaller polarization=> smaller spacer resistance

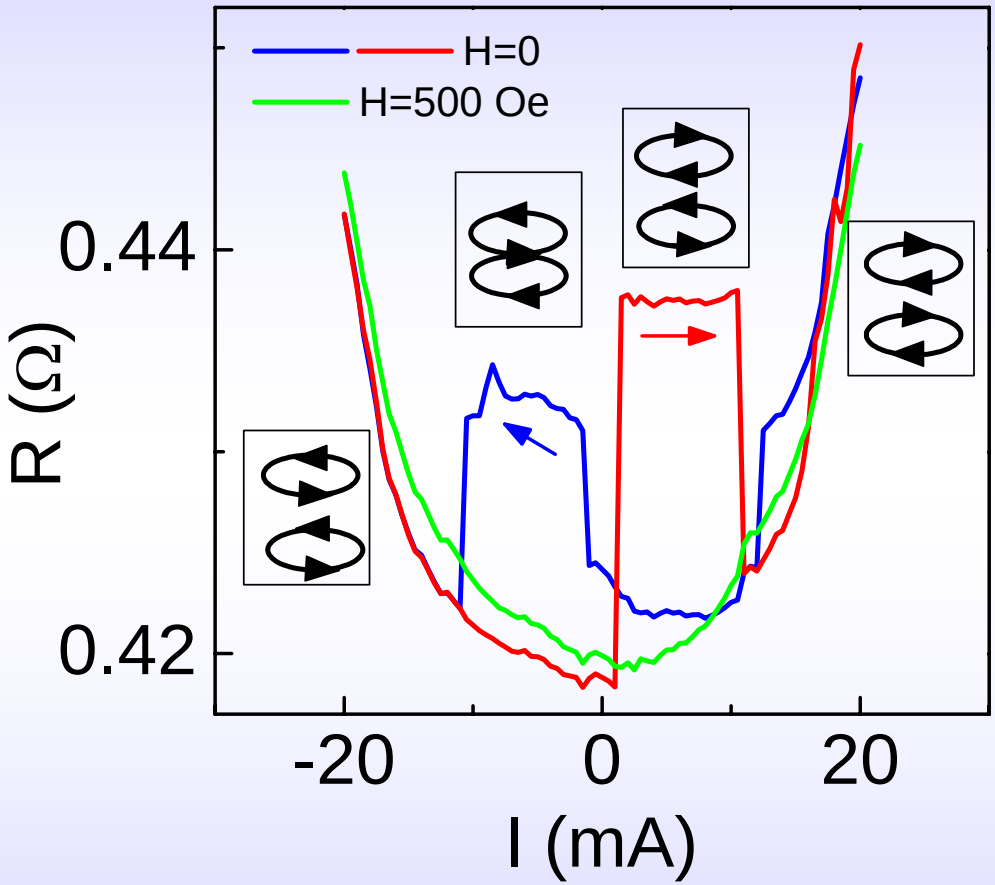
Spin Mixing in the Vortex State

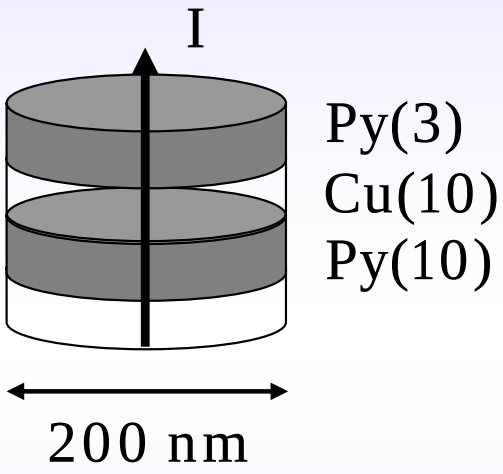




- radial spin current
- angular spin current

Magnetic Vortex State of a Nanodisc

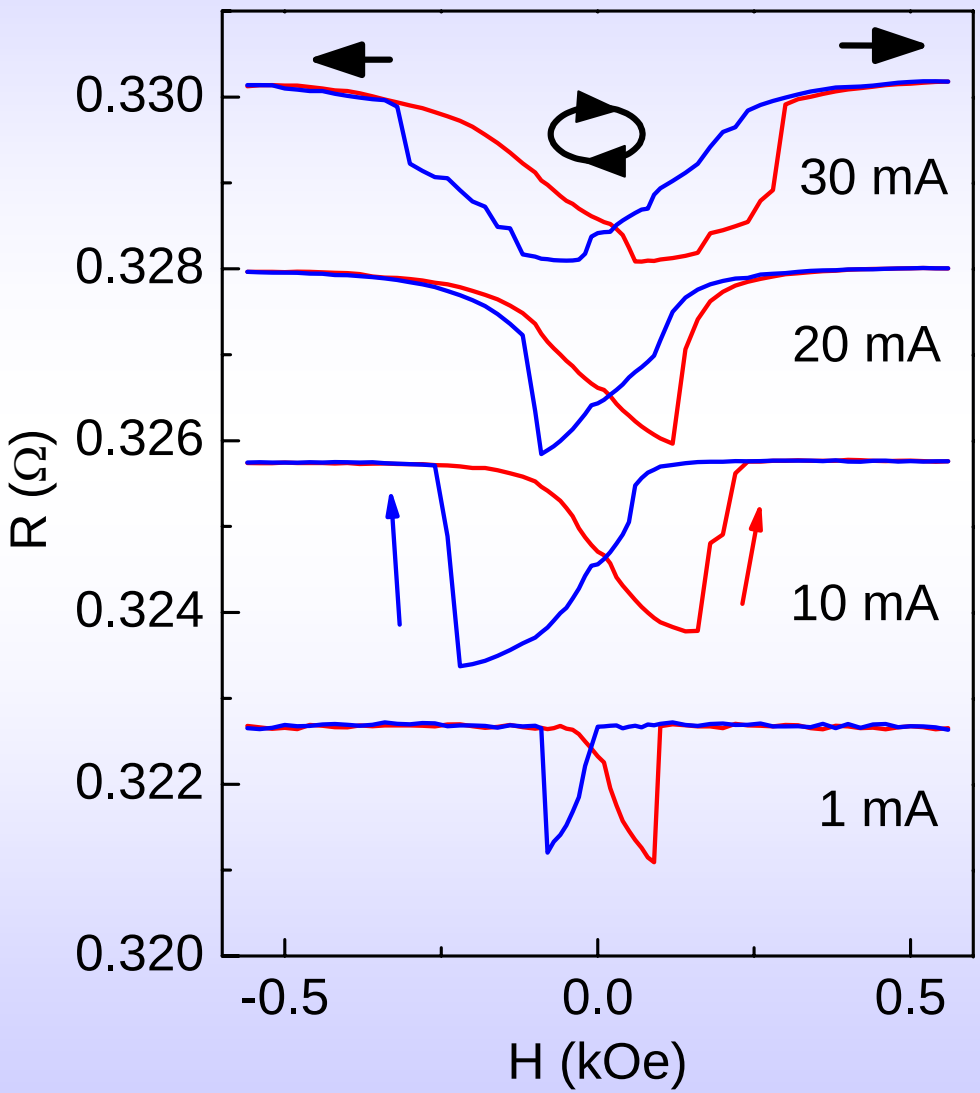


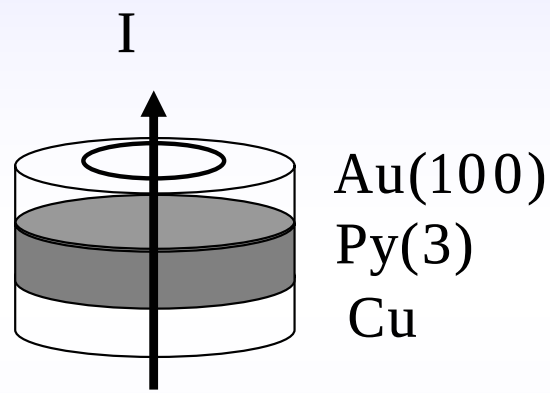


Resistance of the P-vortex state is lower than uniform P-state

SU *et. al* (unpublished)

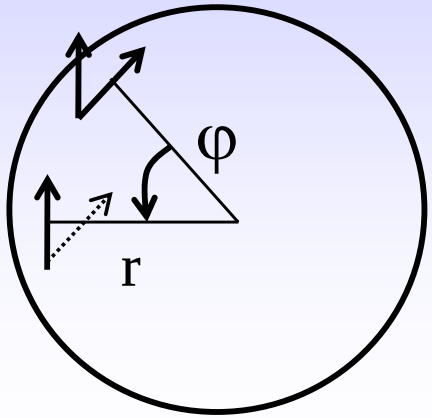
A Single-Magnet Nanodisc





Spin Currents

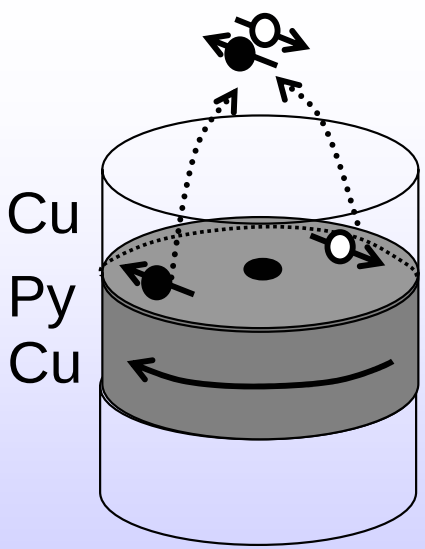
angular
spin current

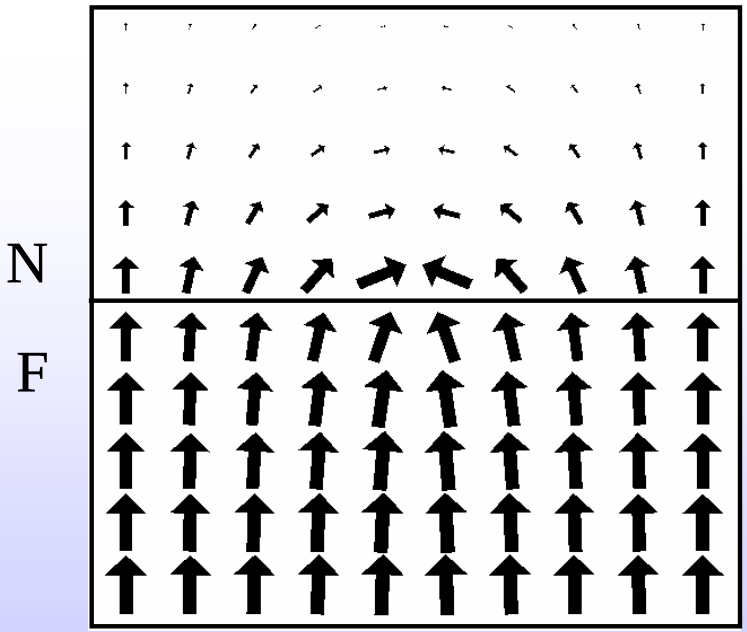


uniform $$\nabla^2 \Delta\mu - \frac{\Delta\mu}{l_{sf}} = 0$$

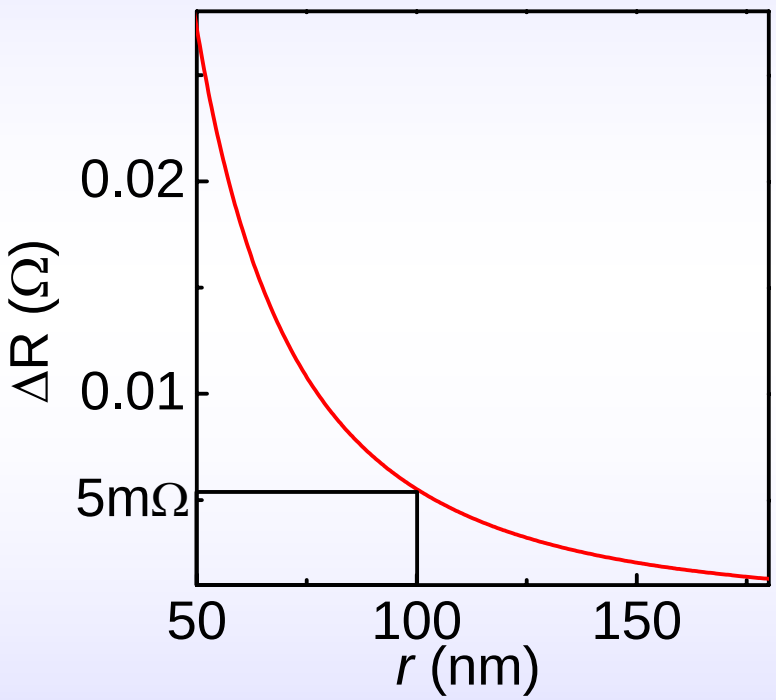
vortex $$\nabla^2 \Delta\mu - \Delta\mu\left(\frac{1}{l_{sf}} + \frac{1}{r}\right) = 0$$

radial spin current





Lowering of the vortex state resistance



semi-quantitative agreement with the data for ΔR

Conclusion

- aMR is an indirect but precise measure of noncollinear spin transport at interfaces
- Transverse spin current penetrates ~0.8 nm into Py
- Spin precession/mixing increases phase space => lowers resistance
- No coherent spin-dependent transport phenomena yet