Dynamic measurements of S/F bilayers

(preliminary understandings)

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Outline

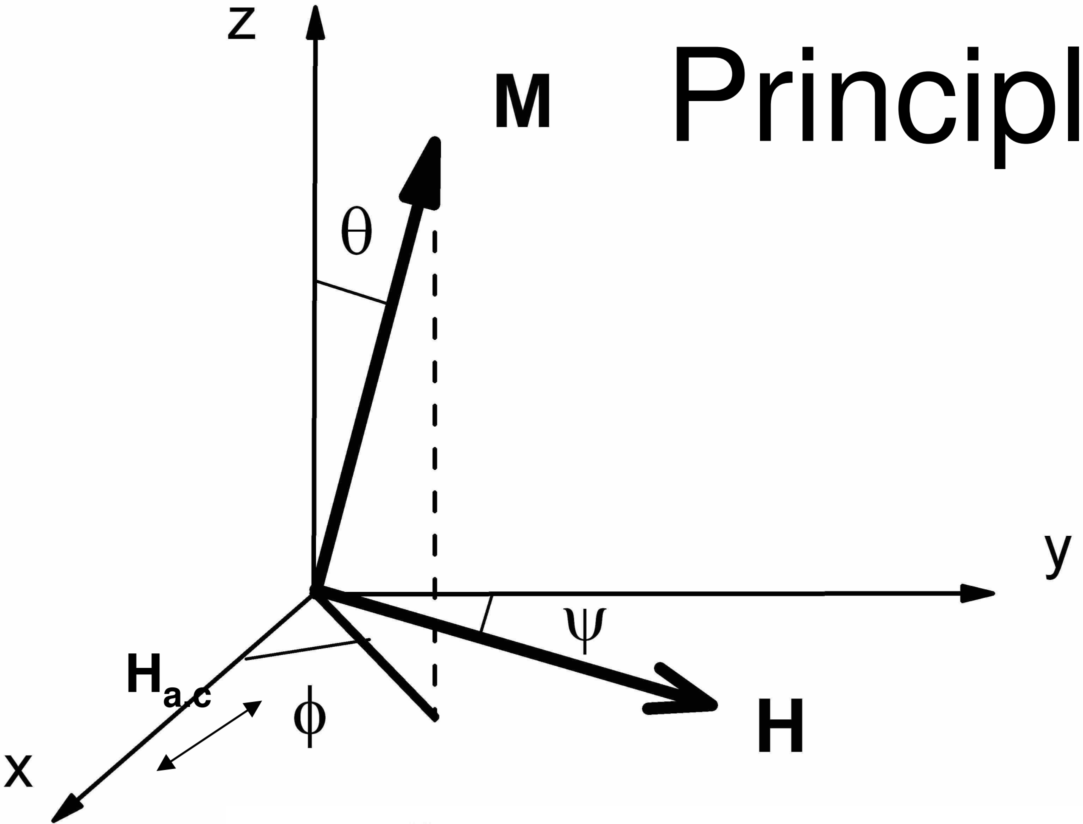
- Introduce different resonances
- Describe damping mechanisms and spin pumping
- Introduce EPR
- Initial samples and results
- Interpretations
- New and even newer samples
- Outlook and other ideas

Ideas for laser pump-probe measurements of S/F heterostructures

Chris Bell

Group meeting 17/05/06

Principle of FMR



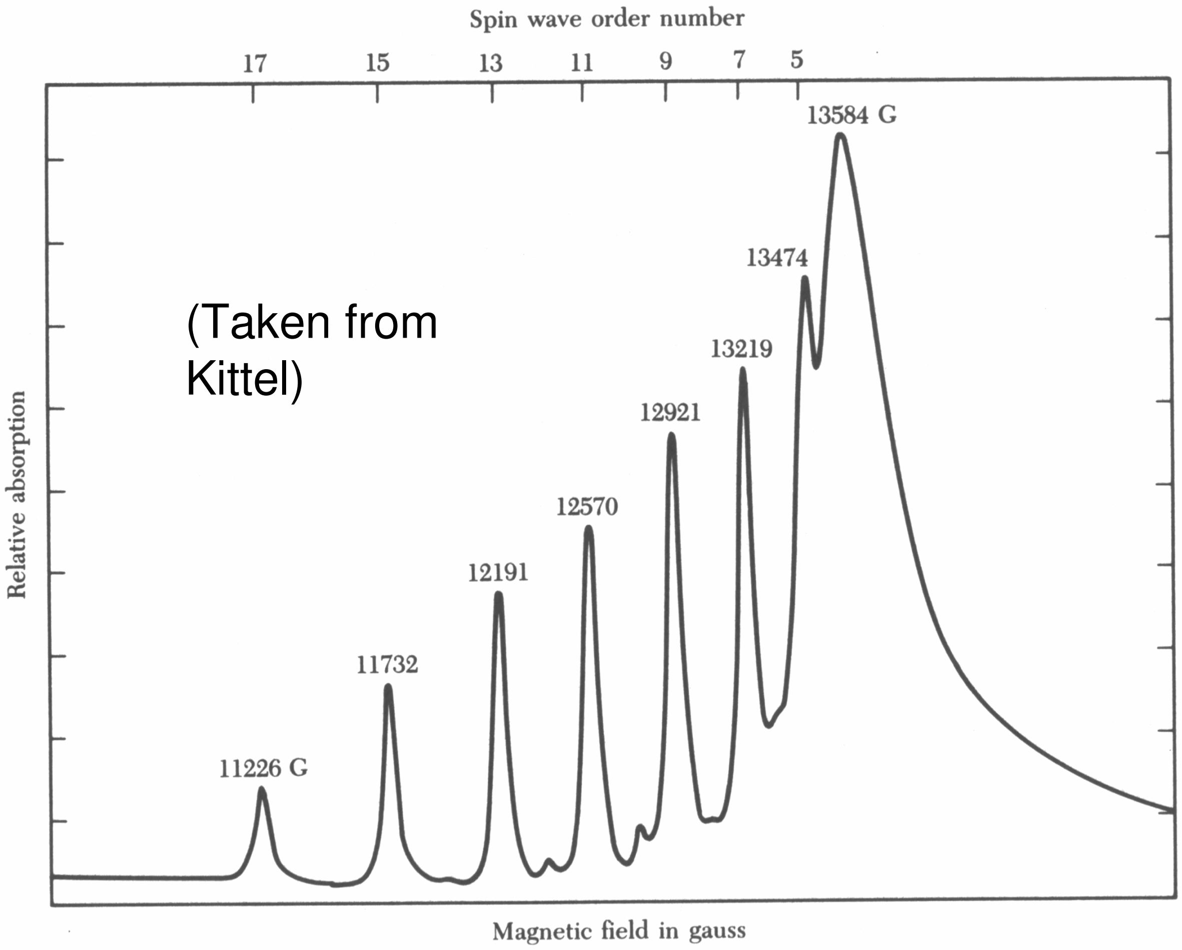
M precesses around **H**

Kick it repeatedly with $H_{a.c.}$
(μ–wave or r.f.)

$$\left(\frac{\omega}{\gamma}\right)^2 = \left(H\sin(\phi+\psi) + 4\pi M - \frac{2K_u}{M}\cos^2\phi + \frac{4K_s}{dM}\right) \times \left(H\sin(\phi+\psi) - \frac{2K_u}{M}\cos(2\phi)\right)$$

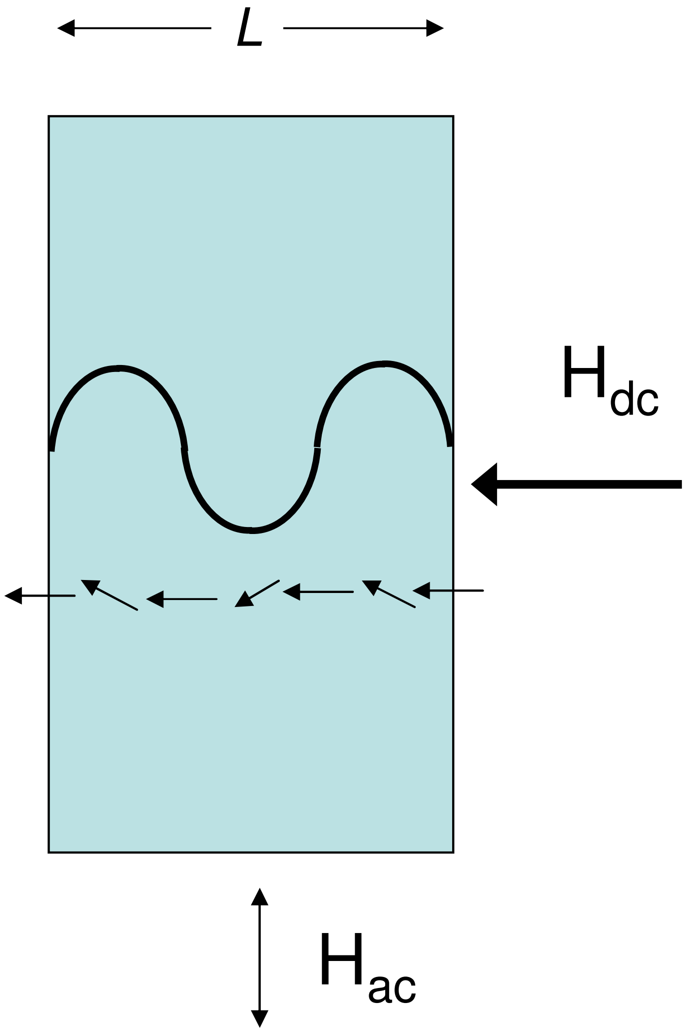
$$f_{\text{Kittel}} = \frac{|\gamma|}{2\pi}\mu_0\sqrt{(H_{\text{ext}}+H_k)(H_{\text{ext}}+H_k+4\pi M_S)}.$$

Spin waves & Walker modes



(Taken from Kittel)

Figure 17 Spin wave resonance spectrum in a Permalloy (80Ni20Fe) film at 9 GHz. The order number is the number of half-wavelengths in the thickness of the film. (After R. Weber.)



(uniform)

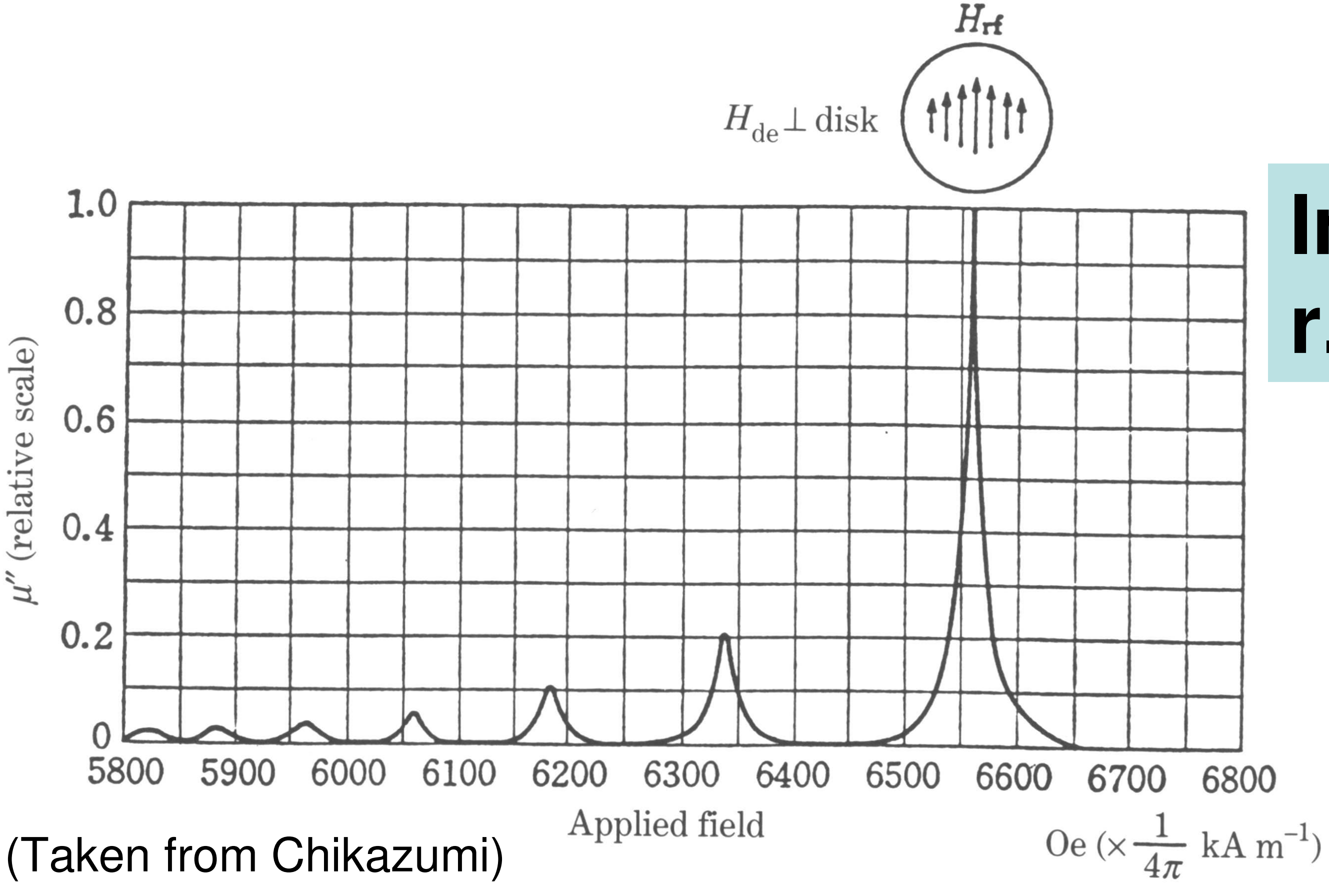
Surface anisotropy pins spins: Odd harmonics only

$$\omega_0 = \gamma(B_0 - 4\pi M) + Dk^2 = \gamma(B_0 - 4\pi M) + D(n\pi/L)^2$$

(CGS)

D = spin wave exchange constant

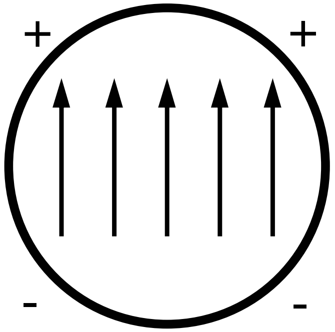
Spin waves & Walker modes



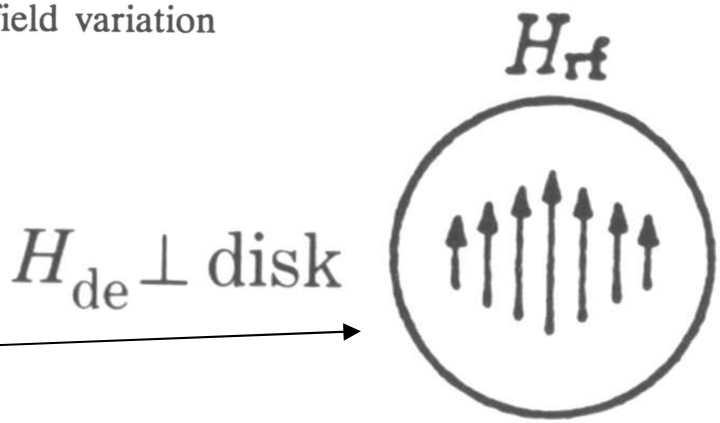
Inhomogeneous r.f. field

(Taken from Chikazumi)

Fig. 20.24. Multiple absorption peaks in a (100) disk of Mn ferrite. The RF field variation across the disk is indicated. (Experiment by Dillon[27], after Walker[28])



Uniform mode would produce poles at surfaces: higher energy than Walker mode



Damping mechanisms in F_{bulk}

Many things:

- Hysteresis loss (mainly domain wall motion, relatively low frequencies)
- Eddy currents (i.e. direct EM coupling with electrons – power goes as f^2 but reduced for thin films)
- Coupling of spins to phonons: spin orbit, magnetoelastic

$$\frac{d\vec{M}}{dt} = \gamma\mu_0(\vec{M} \times \vec{H}) + \frac{\alpha}{M}\left(\vec{M} \times \frac{d\vec{M}}{dt}\right)$$

Spin pumping / battery model

Spin polarised current is injected into the surrounding medium orthogonal to the precessing spin.

Crucially the spins are pumped at the <u>Fermi energy</u>

The important parameter is the spin mixing conductance $g^{\uparrow\downarrow}$ ~ Sharvin conductance between the F and proximity layer

Lots more theory: see RMP **77** (2005)

For a nice clean metal in proximity the spin diffuse in and out (to maintain charge neutrality) without being spin flipped → no damping on the F layer.

(video 1)

‘Opposite’ of spin torque

(video2)

Good spin sink in proximity

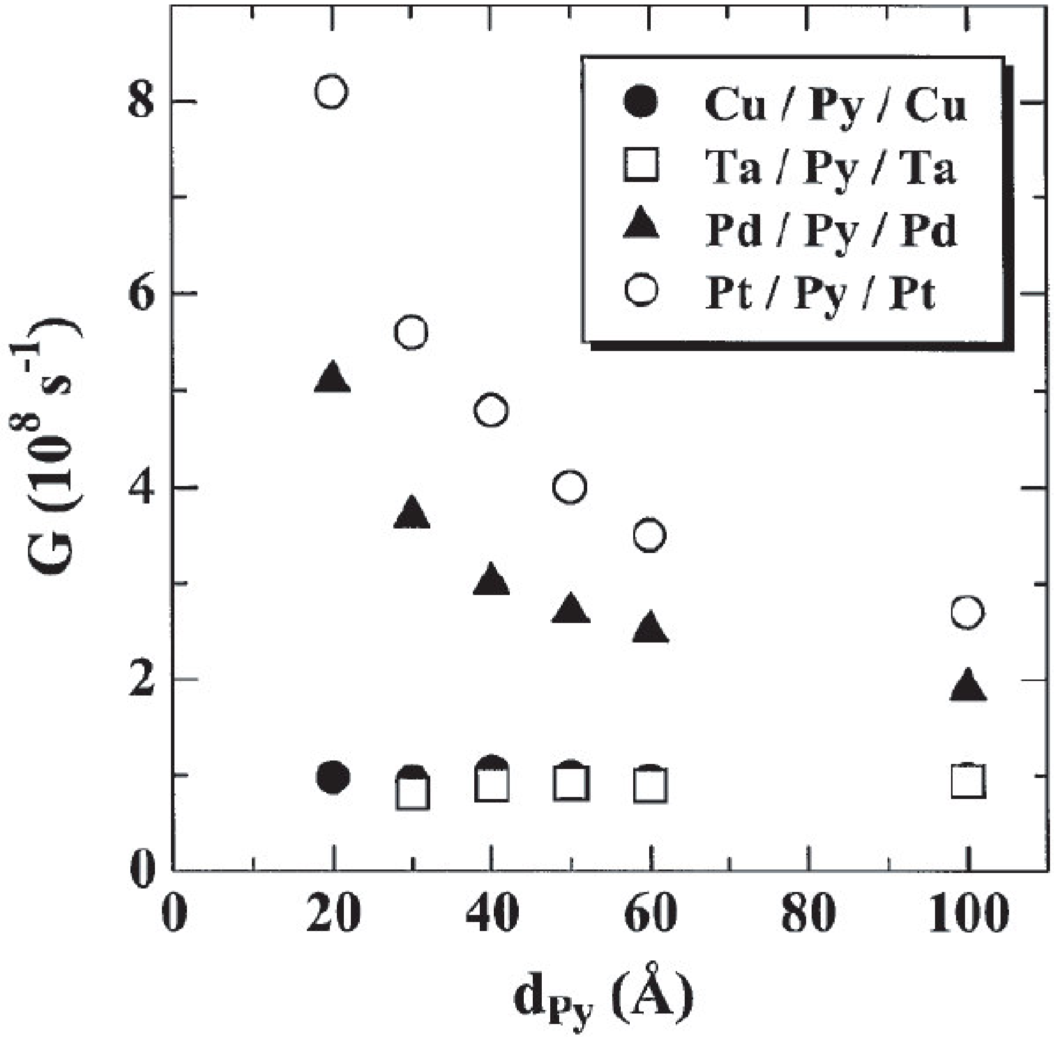
Strong back-action of decaying spins on the F layer: decay is fast

(video3)

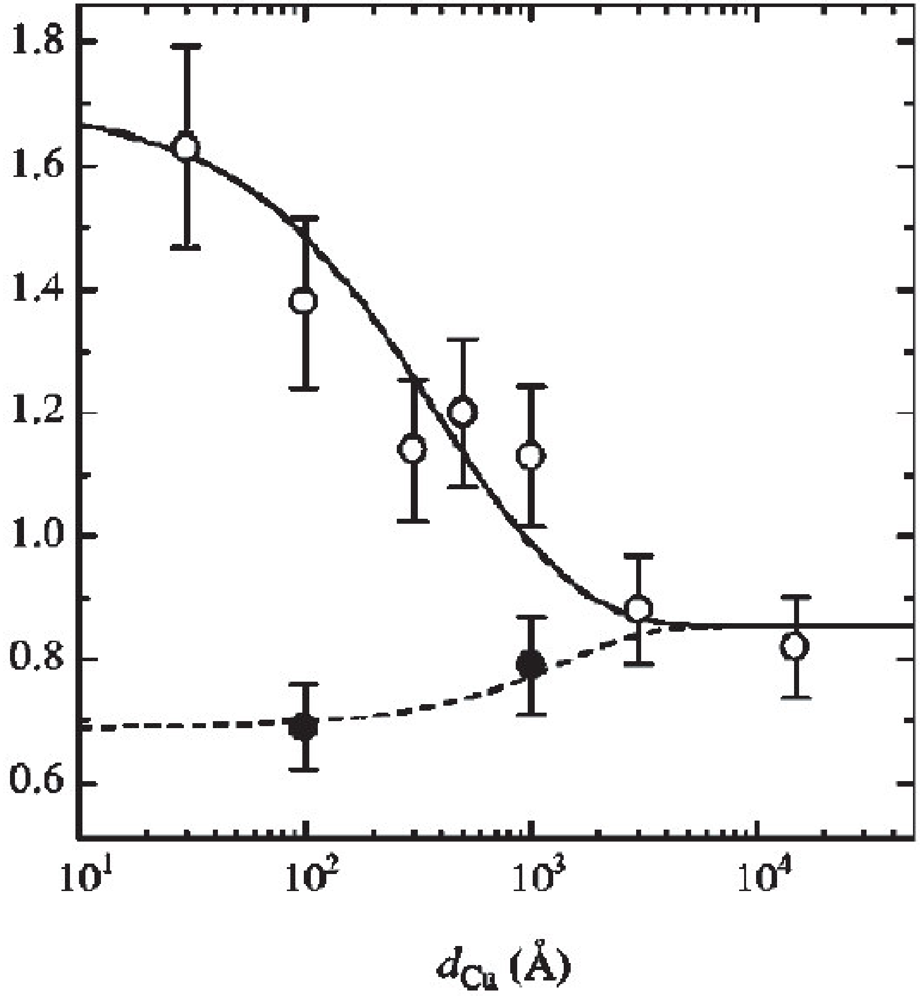
Good example: Pt: has a strong spin orbit coupling and so $\mathbf{l}_{sd}$ is short, but $\mathbf{l}_e$ is relatively long (contrast to e.g. $Fe_{50}Mn_{50}$)

$\varepsilon = 1/3(\mathbf{l}_e/\mathbf{l}_{sd})^2 \geq 0.1 \rightarrow$ good spin sink (also Pt, other ferromagnets)

Damping mechanisms in $F_{\text{thin film}}$

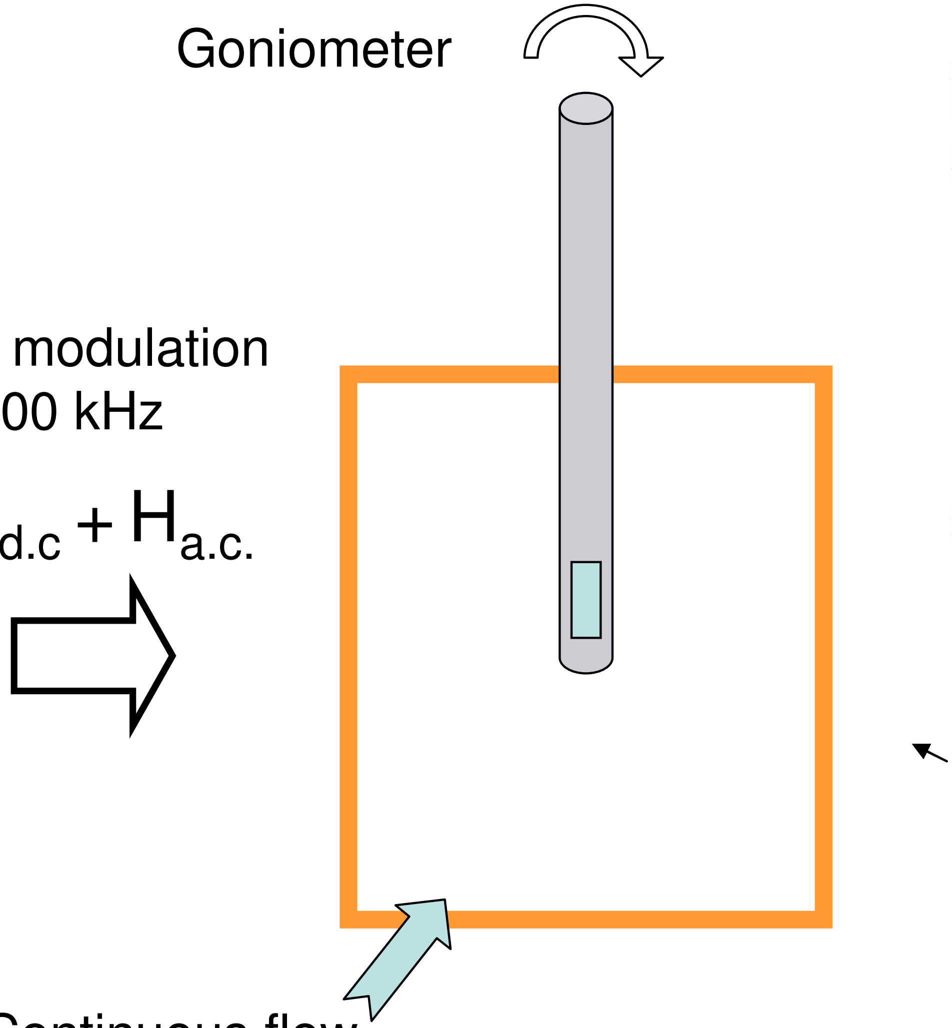


Cu/Py ~30 Å/Cu (d_{Cu})/Pt



Mizukami et al PRB

Principle of EPR

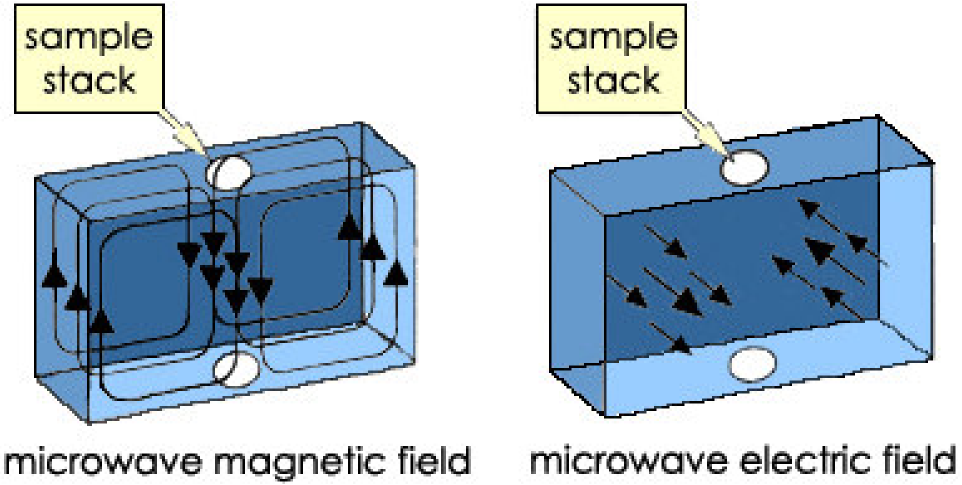


Goniometer

5 G modulation
at 100 kHz

$H_{d.c} + H_{a.c.}$

Continuous flow
of liquid helium



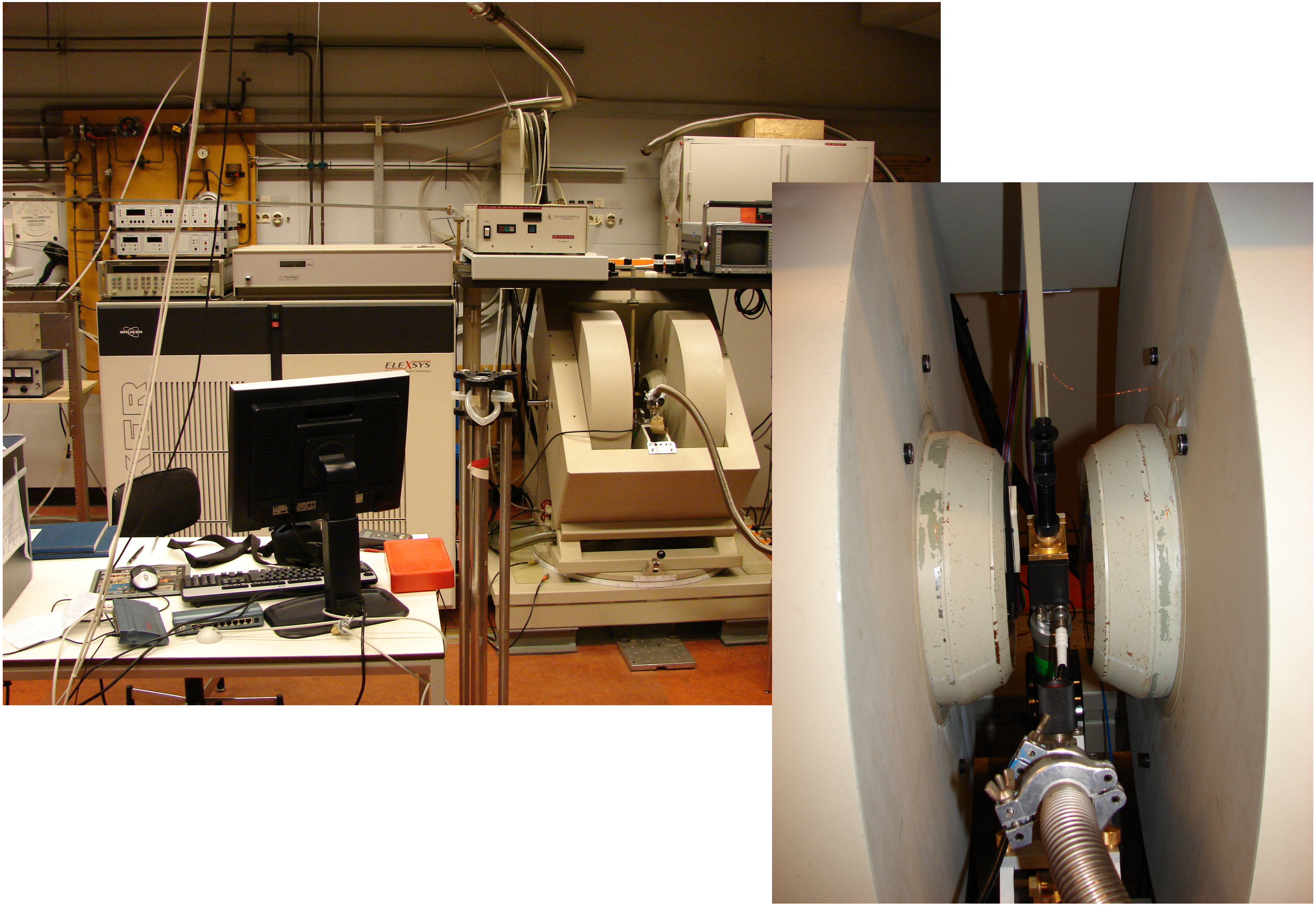
From Bruker website

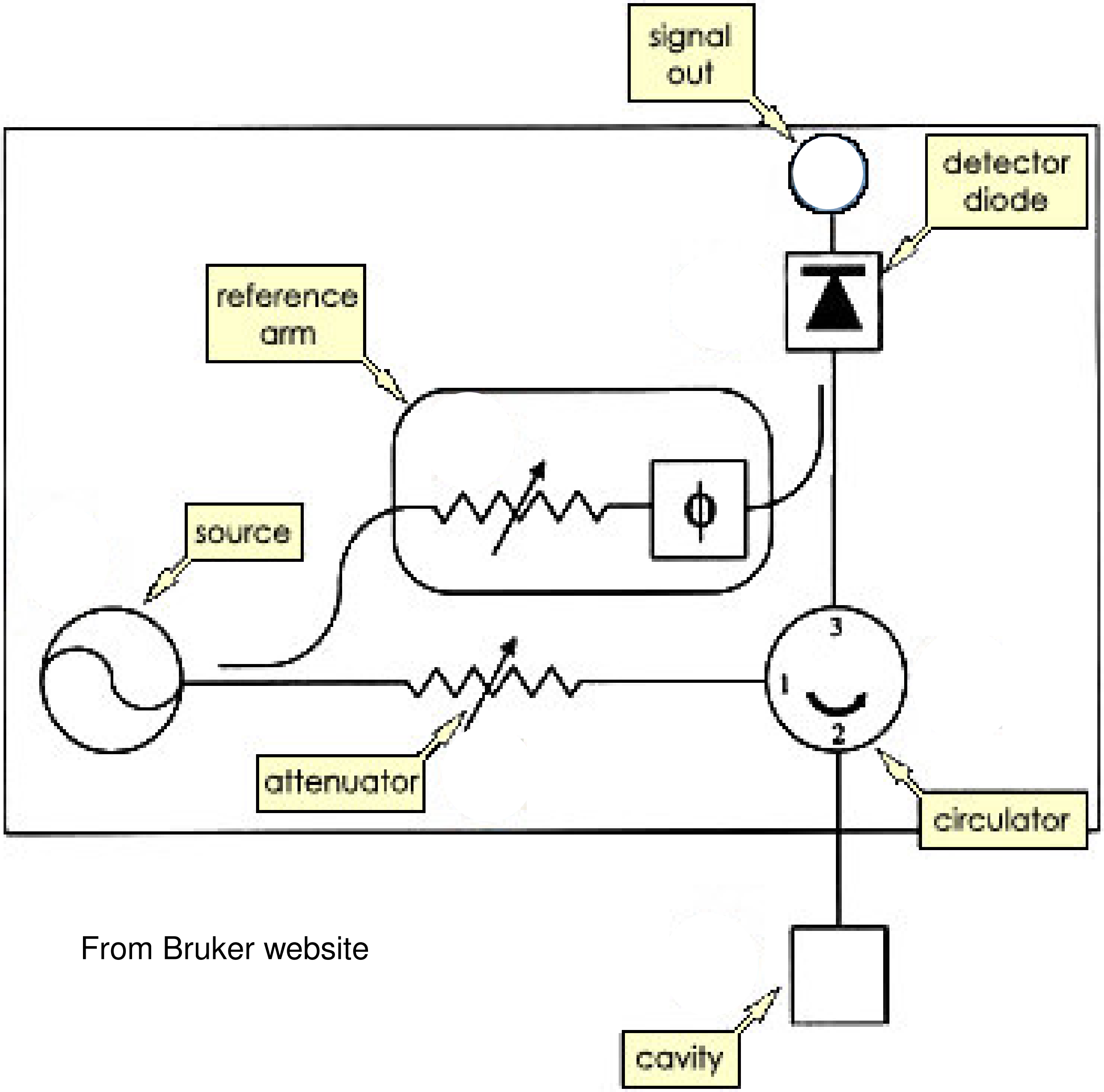
High Q microwave cavity
resonance frequency ~ 9.5 GHz
(X-band)

New systems: Q ~ 25000

Sensitivity 10^7 spins
We have ~ 3mm X 3mm X 5nm Py ~ 10^{16} spins

EPR system





From Bruker website

Tune impedence of waveguide / cavity iris & sit at resonance for the cavity:
NO reflected μ–waves for empty cavity

Around resonance of the sample: μ–waves are absorbed. Q goes down and cavity impedance changes

μ–waves reflected and signal measured

For lower noise, use lockin detection: 100 kHz modulation field ➔ modulation of reflected μ–waves

Result: Measure differential power absorption vs $H_{d.c.}$

Sample characteristics

- Two samples grown in UHV:

quartz / Nb (70 nm) / Py (5 nm)
T_C ~ 8.2 K

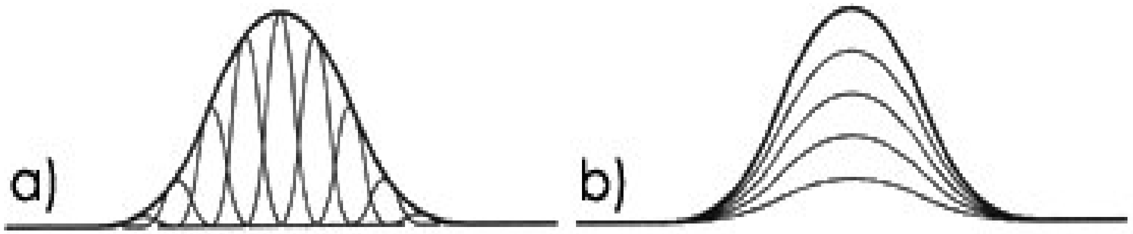
quartz / Nb (9 nm) / Py (5 nm)
no T_C

No capping layer (also want to do pulse-probe MOKE – see end)
All measurements in plane, nominally parallel to easy axis

Results

Lineshapes

Gaussian
$$f(\nu) = \sqrt{\frac{2}{\pi}}\frac{1}{\Gamma}\exp\left[-2\left(\frac{\nu-\nu_0}{\Gamma}\right)^2\right]$$



Taken from Bruker website

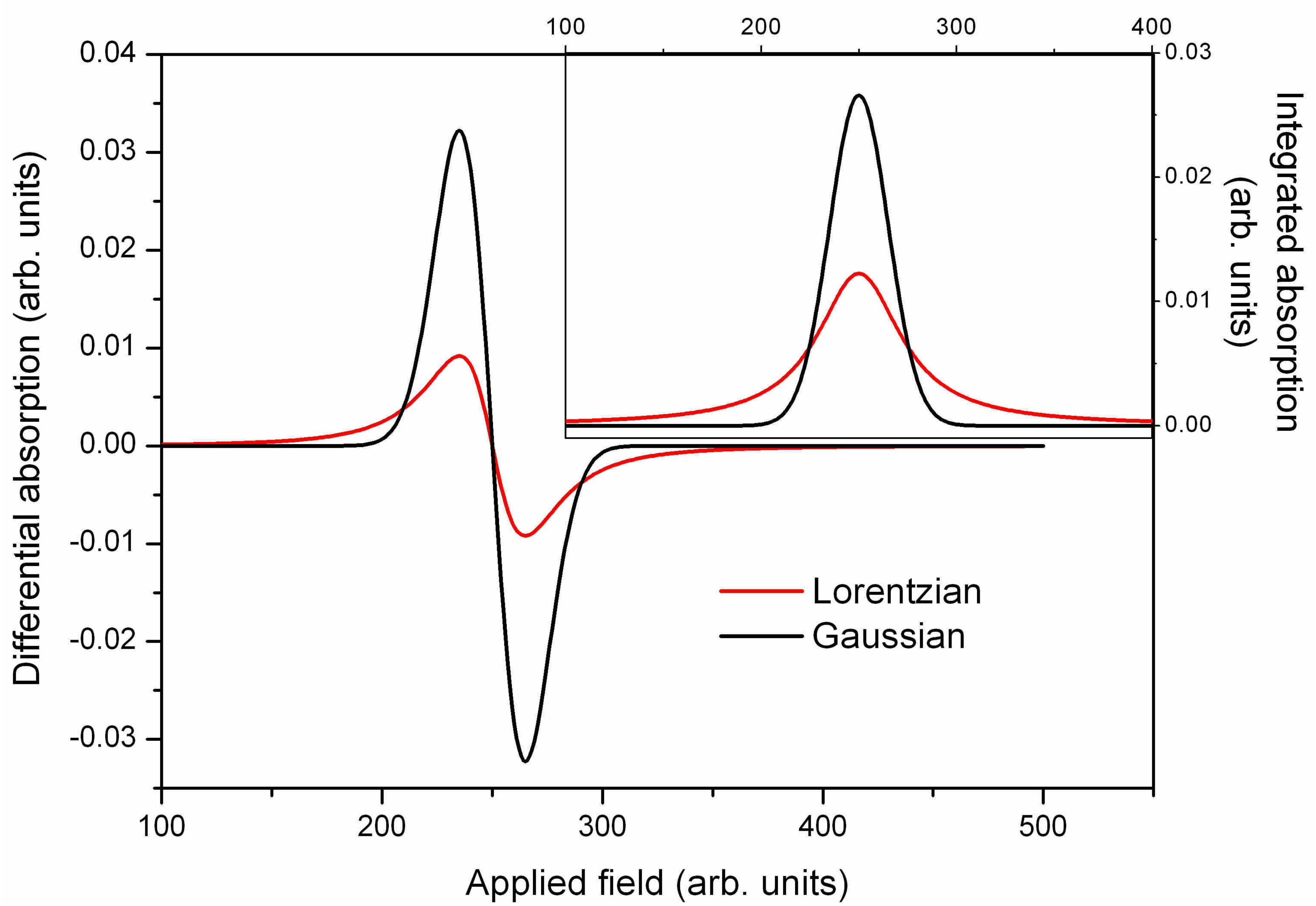
a) Inhomogeneous broadening: Sum of a many narrower spectra shifted with respect to each other. **Gaussian** lineshapes are common.

b) Homogeneous broadening: Sum of a many spectra each having the same shift and the linewidth is determined by the relaxation times. **Lorentzian** lineshapes are common

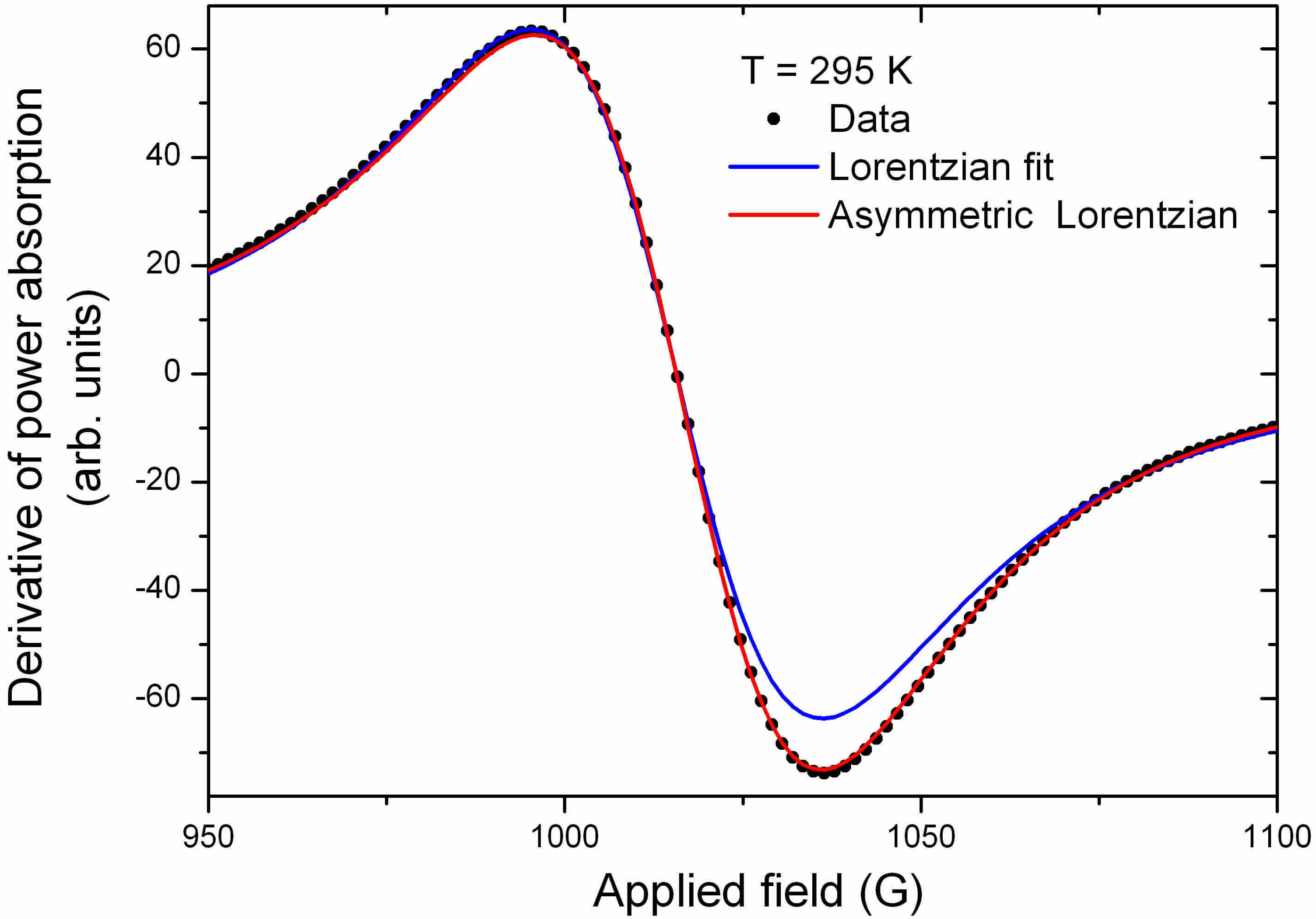
Lorentzian
$$f(\nu) = \frac{2}{\pi\Gamma\sqrt{3}}\left[1+\frac{4}{3}\left(\frac{\nu-\nu_0}{\Gamma}\right)^2\right]^{-1}$$

Normalised such that integral over ν gives 1 and Γ is the distance between inflexion points $= \frac{1}{\sqrt{3}} \times$ FWHM for Lorentzian

Lineshapes


Differential absorption (arb. units)
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
100
200
300
400
500
Applied field (arb. units)
Lorentzian
Gaussian
Integrated absorption (arb. units)
0.03
0.02
0.01
0.00
100
200
300
400

Present data



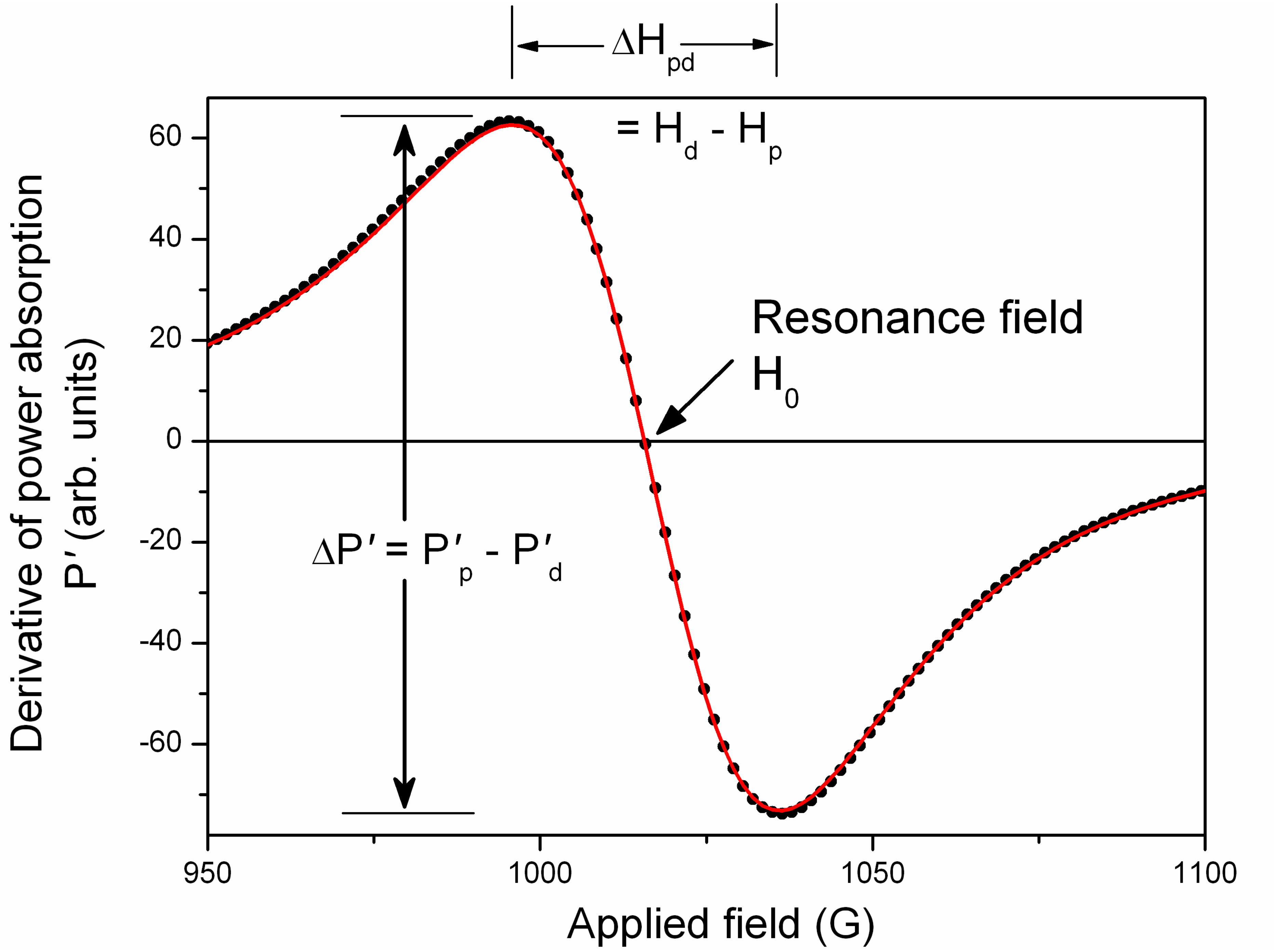
Asymmetries caused by variations in M_S across the sample and variations in the anisotropy field (not surprising for uncapped 5nm thick Py).

Interesting to do a full angular scan to investigate, but not relevant for this work.

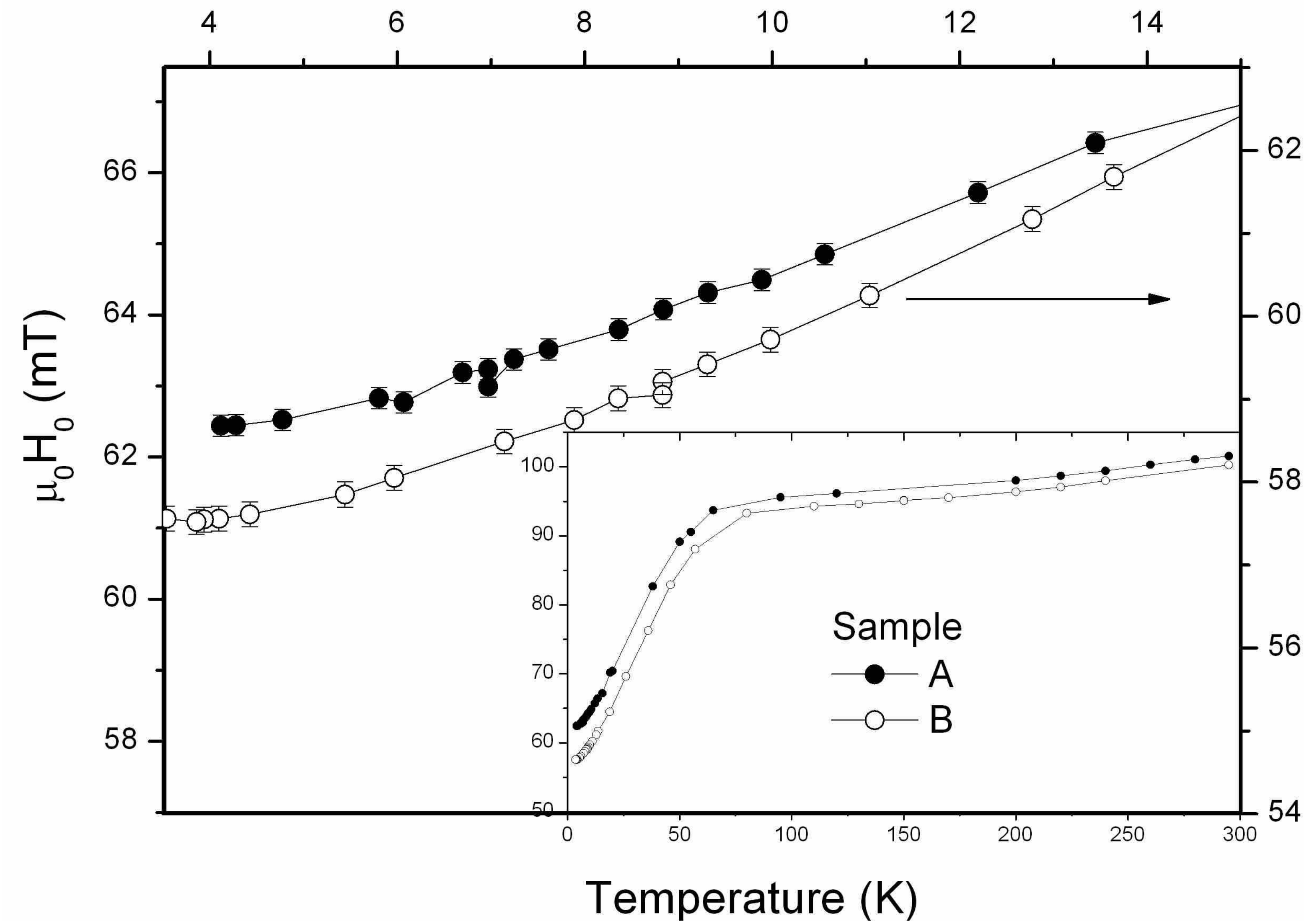
Not normalised, A, B, C and D now non-trivially related to curve compared to symmetric lineshapes

$$\mathrm{P(H)} = A\frac{1+B(\mathrm{H}-C)}{1+D(\mathrm{H}-C)^2}$$

Some definitions



Resonance field

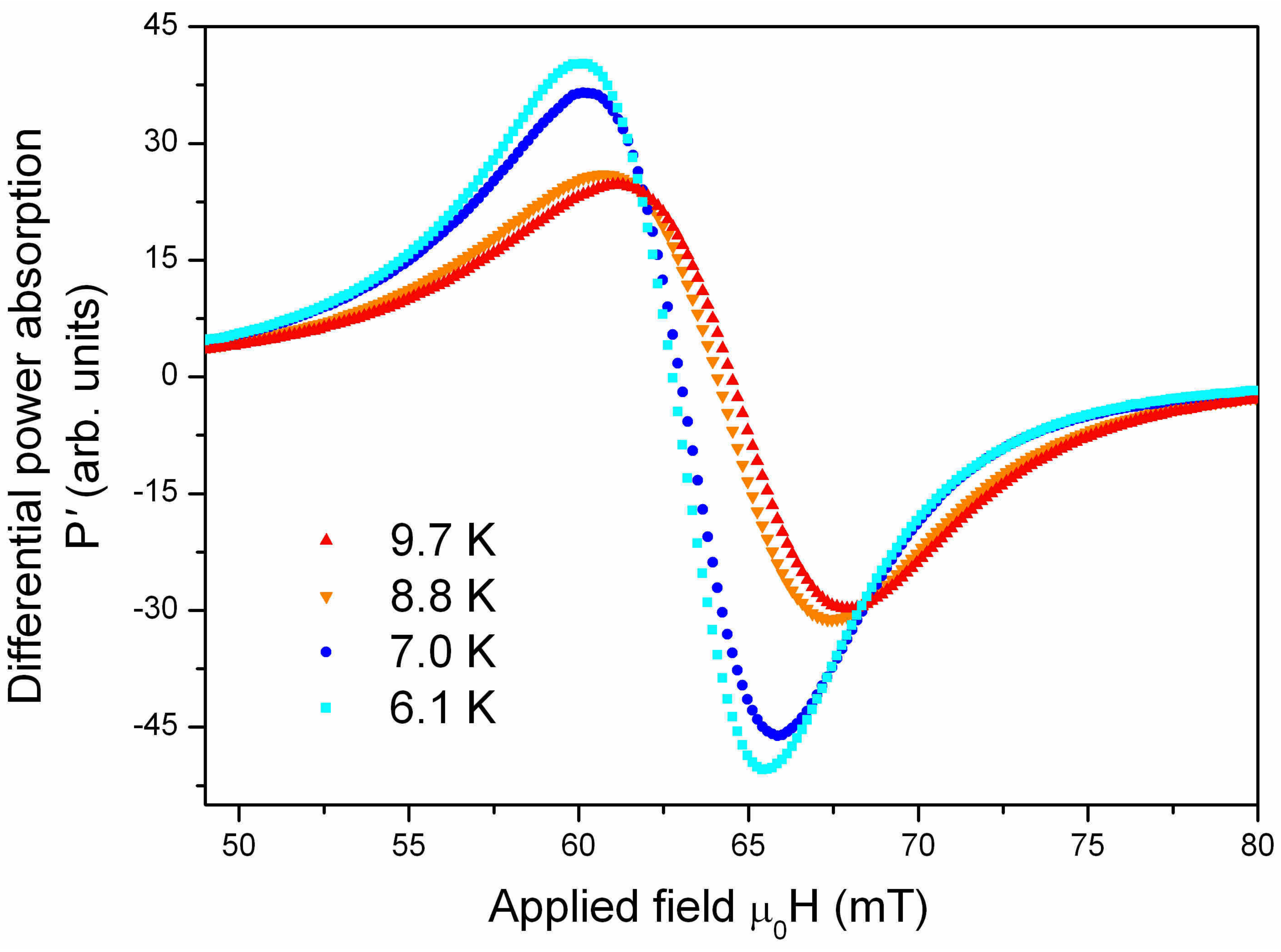


Low T variation of H_0 the same for both samples

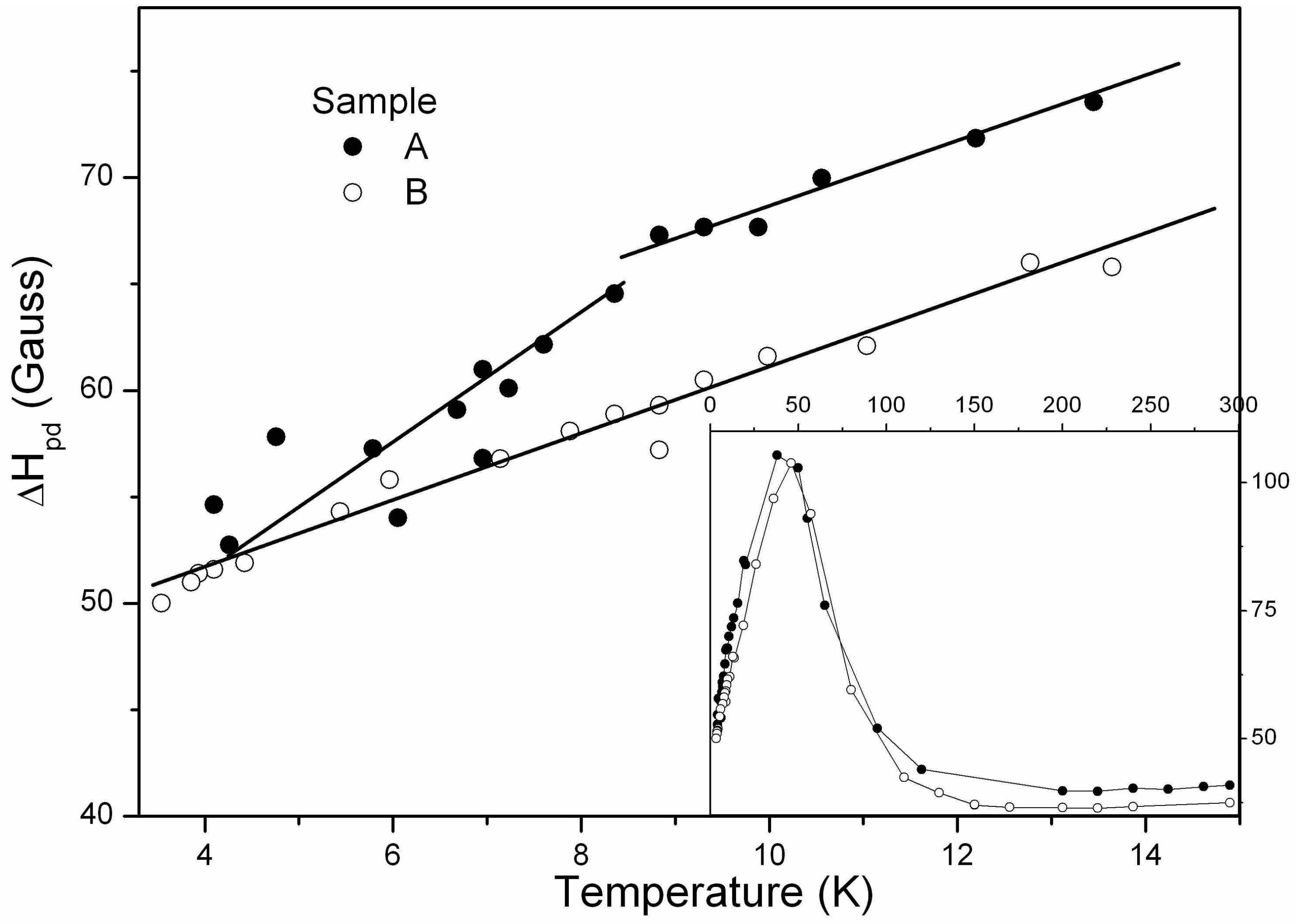
This means that the superconductivity doesn't change M_S or H_{anis}

Not surprising given $T_{Curie} >> T_C$ and $\lambda >> d_S$ ➔ no local change in field seen by Py

Some curves at low T

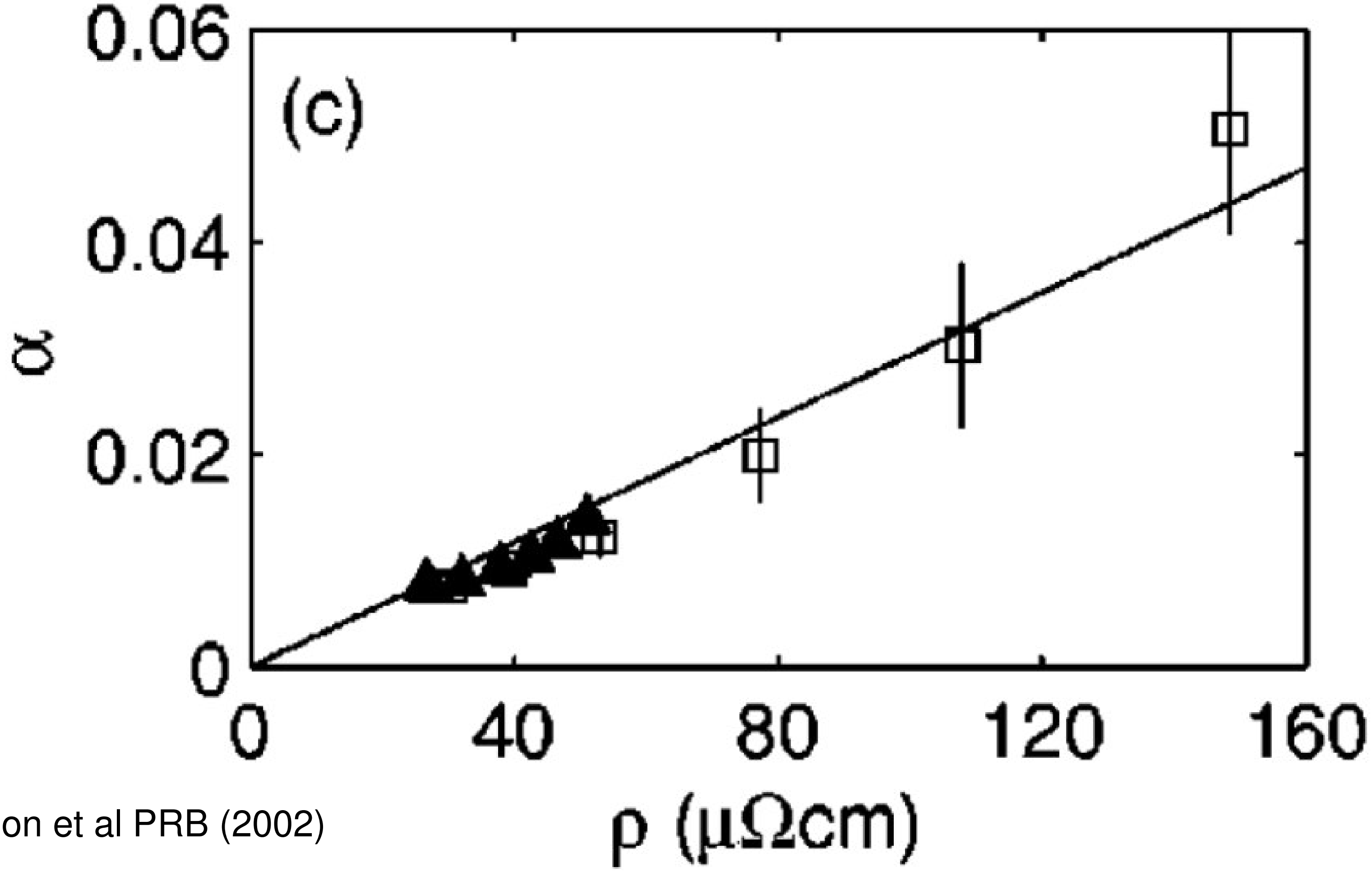


Linewidth and height



Linewidth reduced relatively fast below Tc, height increases relatively fast below Tc. This implies that the resonance of the FMR is becoming cleaner: i.e. the damping is reduced below Tc. NOT to do with vortices: this gives a broad background absorption, and at this frequency there are oscillations rather than flux flow (I think)

Interpretation of high T data



Ingvarsson et al PRB (2002)

Direct relation with resistivity, (not possible to measure directly on sample due to current shunting into Nb). This reasonable since $g^{\uparrow\downarrow}$ controls the spin pumping.

Reason for dip in ρ(T) Probably some magnon freezing / spin mixing thing I have worked out yet: I need to read Fert and Campbell 1976 properly!!

Interpretation

Related to work by Pratt's group: Py/Nb/Py: measure spin diffusion length l_{sd} in Nb above and below Tc: changes from ~50nm above, to ~20nm below (t = 0.3)

Now this simply measures something which is basically the coherence length in the Nb: although in this case the polarisation of the electrons is relatively small (I haven't thought about what we have in our case!).

So around Tc the spin pumping efficiency changes since now spins cannot get so easily into the Nb: they hang around in the Py and the decay is slower.

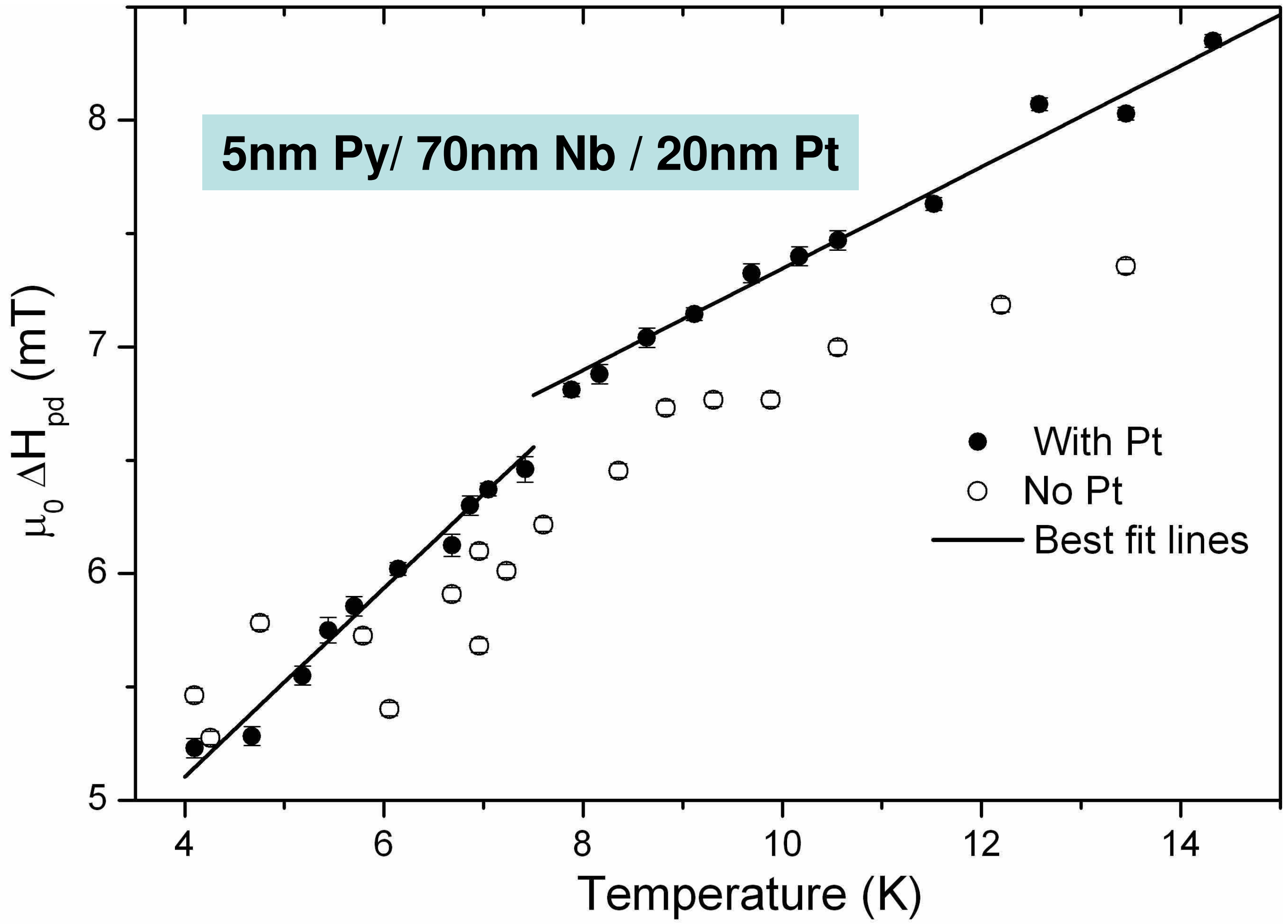
(video 4)

Sample with Pt

- Reminder: Pt has a strong spin orbit coupling and so $\mathbf{l}_{sd}$ is short, but $\mathbf{l}_e$ is relatively long $\varepsilon \geq 0.1$ → good spin sink

  The ε parameter for Nb is not so big: it's not a good spin sink above Tc: so you don't see a big change when it superconducts
- Idea: If we can put Pt close to the Py, the spins are killed off quickly above Tc, but the Pt is screened by the Nb below Tc → large change in Py damping.

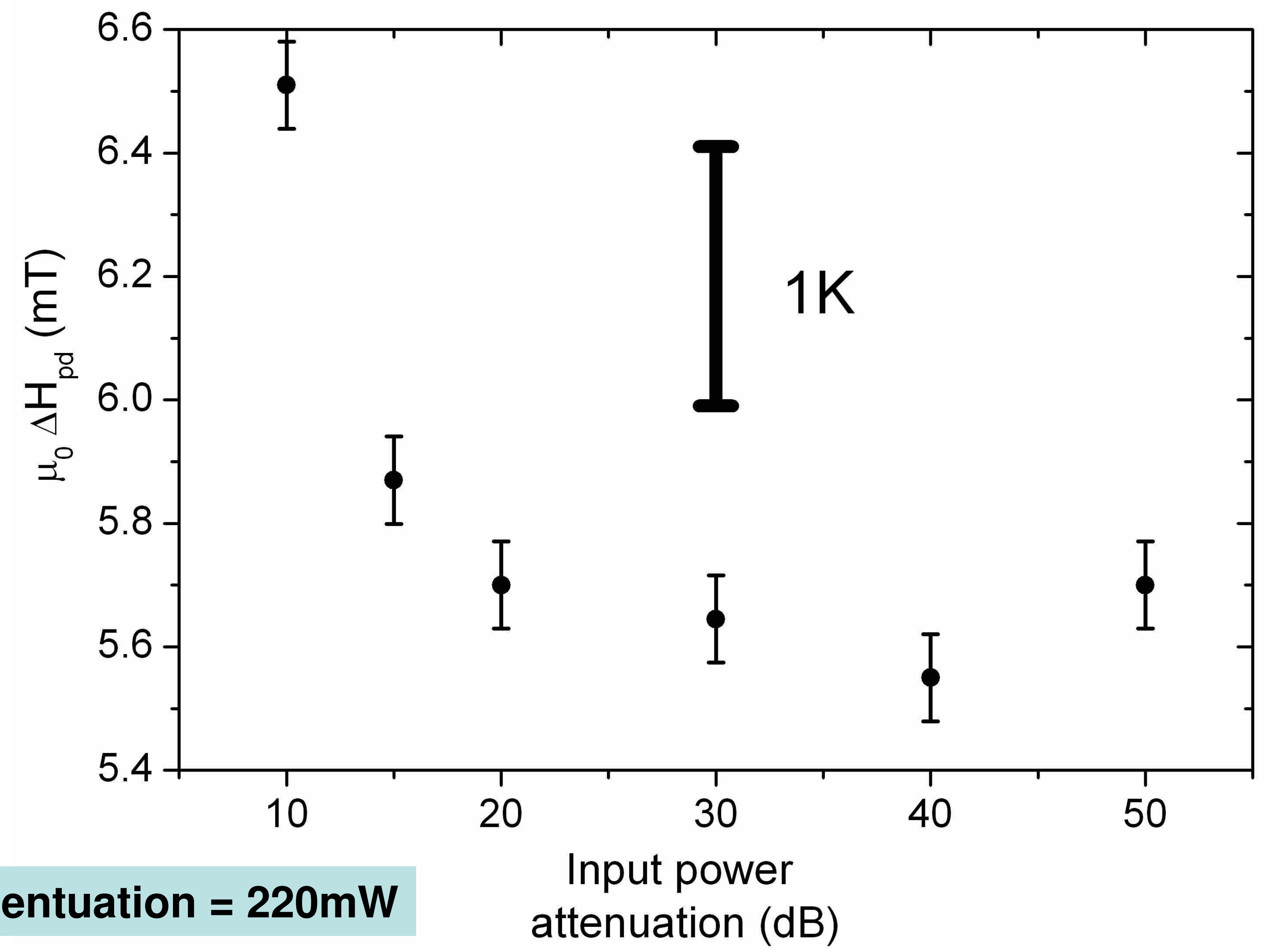
Results with Pt



- Much cleaner data, but not significantly different linewidth above Tc compared to before
- Reason l_{sd} for Nb ~50nm, and we have 70nm: not so many spins get to see the Pt
- But if we make the Nb too thin it doesn’t have a Tc….

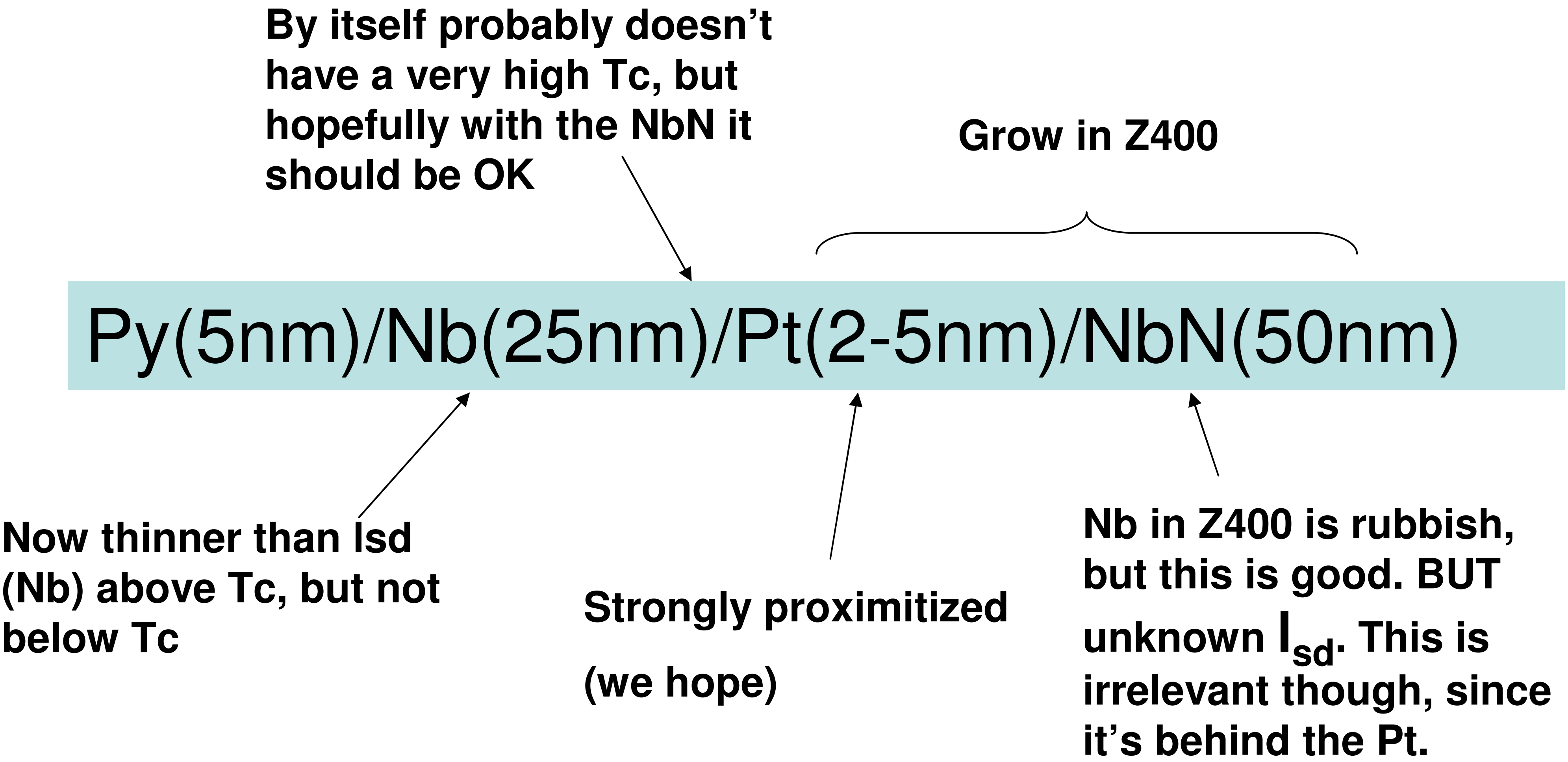
Issues of heating

- Microwaves are absorbed – can heat the sample. Need to be sure that T is really what we think….



Zero attentuation = 220mW

Better idea (growing later today & tomorrow)



By itself probably doesn't have a very high Tc, but hopefully with the NbN it should be OK

Grow in Z400

Py(5nm)/Nb(25nm)/Pt(2-5nm)/NbN(50nm)

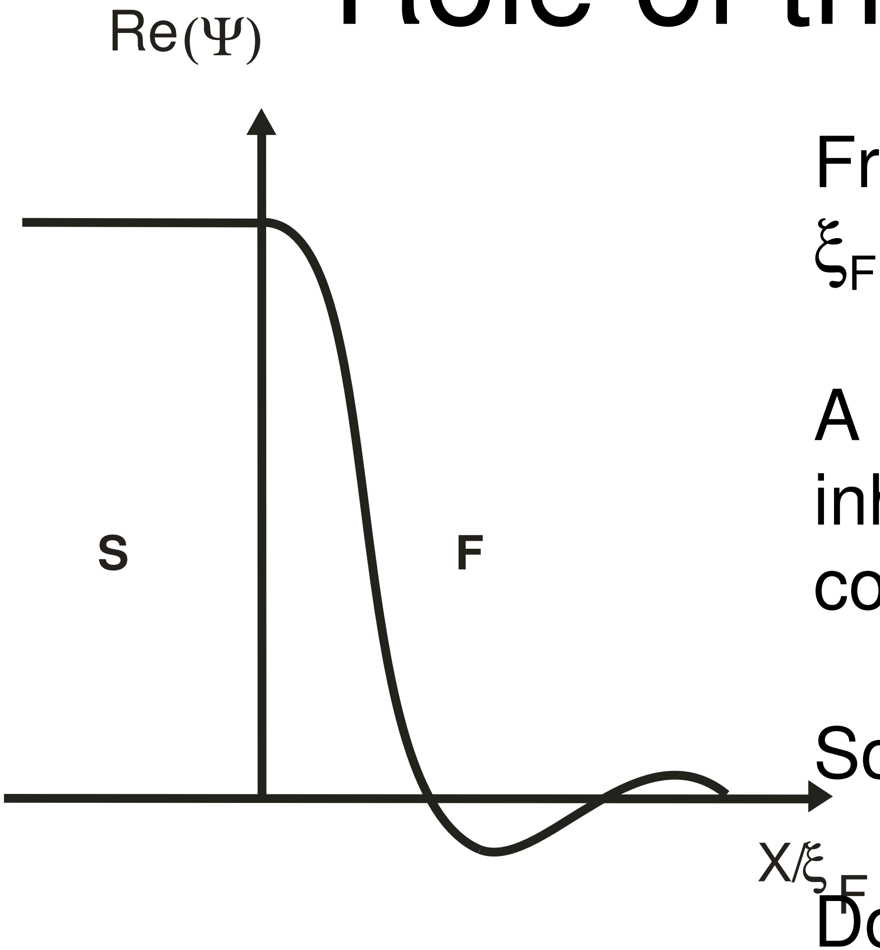
Now thinner than lsd (Nb) above Tc, but not below Tc

Strongly proximitized

(we hope)

Nb in Z400 is rubbish, but this is good. BUT unknown l_{sd}. This is irrelevant though, since it's behind the Pt.

Role of the LOFF state?



From data in Nb/Py/Nb junctions:
ξ_F ~1-1.5nm

A significant fraction of the Py has inhomogeneous superconducting correlations induced in it

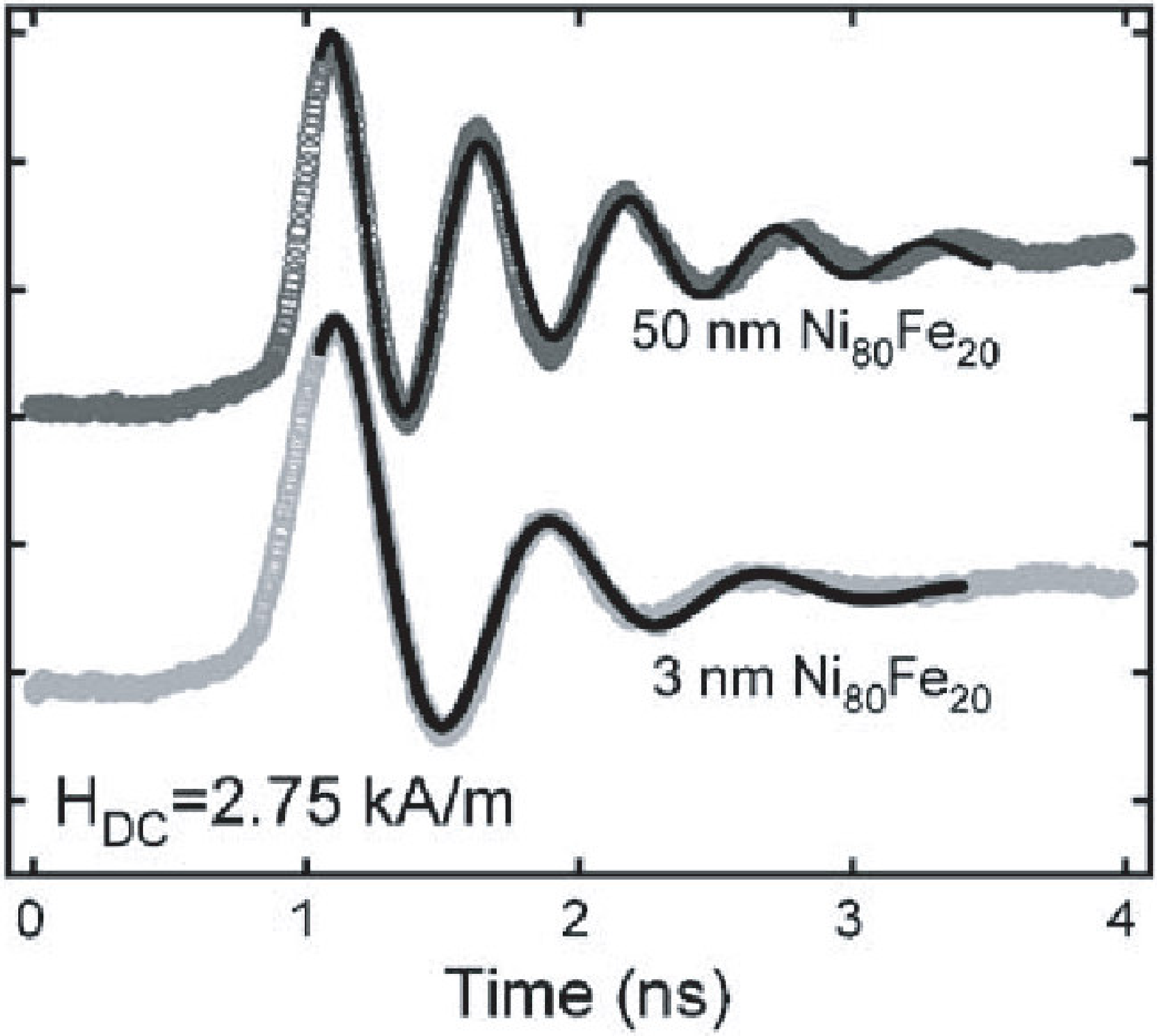
So what?

Do you decrease the ‘internal’ damping of the Py in addition to the proximity damping case due to block Andreev reflection?

How can you separate these out?

Further measurements

(with Roman Sobolewski - Ivan's old boss - in New York)



Time domain measurement of the same thing:

Femto second pulse probe MOKE above and below Tc

<u>Now we should expect:</u>

NO change in period of oscillation (~ resonance field)

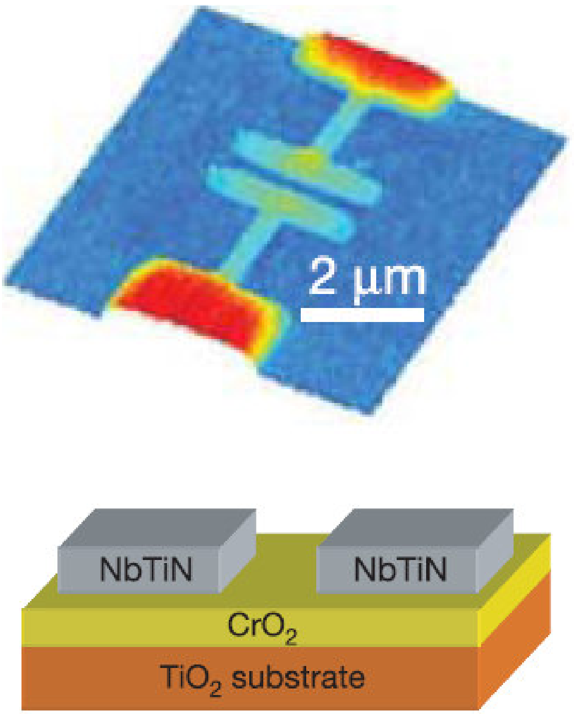
BUT a change in decay envelope longer decay time below Tc (~linewidth)

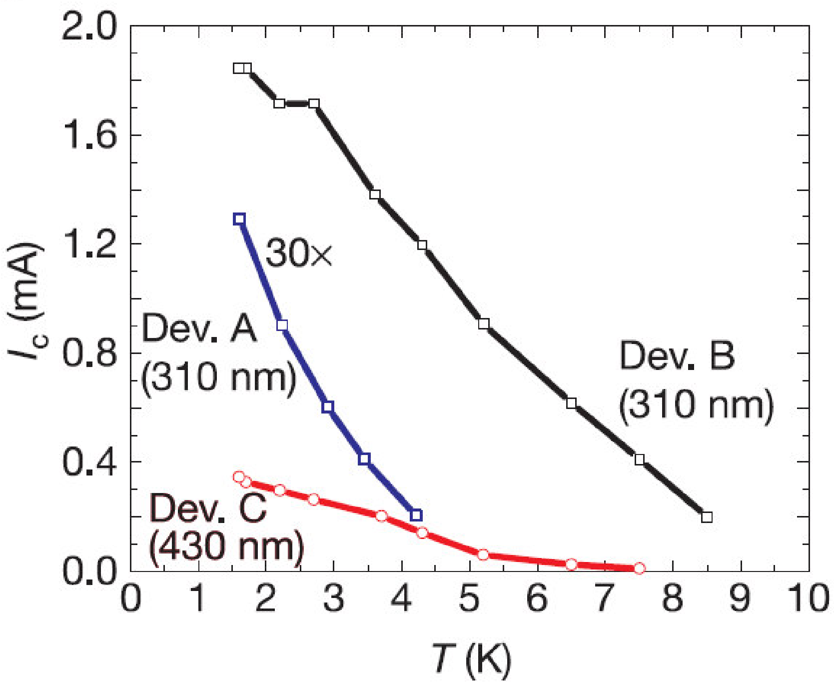
Further measurements

If there are triplet Cooper pairs induced in the F layer, now what happens to the damping? (Some theory says it should be different, but system not quite the same)

But then you still have the Andreev issue (now even more enhanced because the polarisation is 100%!) So again you have to separate them out

If it is long range then the S layer at the interface presumably becomes less important for thick CrO2 ➔ this is an advantage over singlet components





Keizer et al., Nature 2006

Conclusions

We see an inverse proximity effect associated with changes in the spin pumping from the F to S layer

This is because it is not the Curie temperature that controls things, but the low voltage electronic properties of the Py: this can be affected by the superconductor

Can’t directly find Gilbert damping parameter without measuring at some different frequencies (to remove other contributions) but basic picture seems clear