Scanning magnetic imaging of Sr_2RuO_4

-or-

Where are the spontaneous fields?

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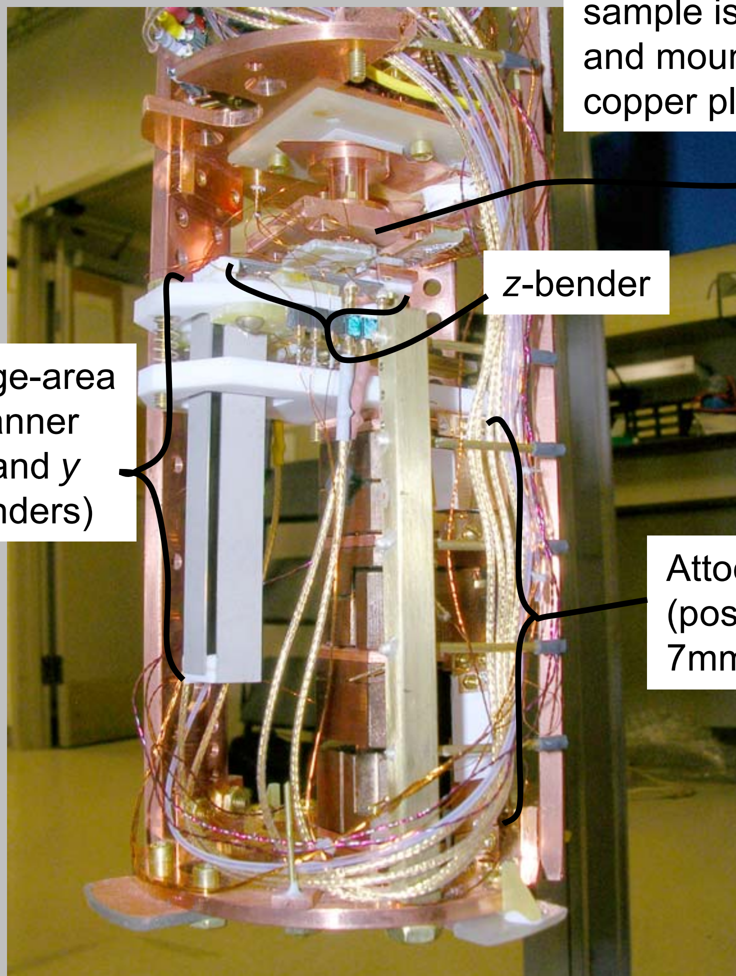
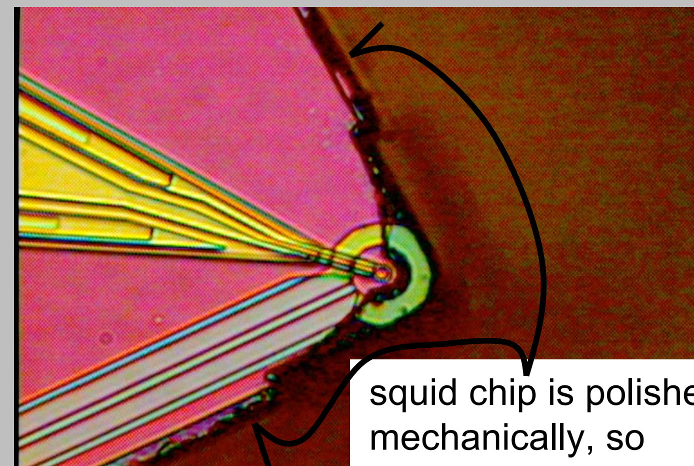
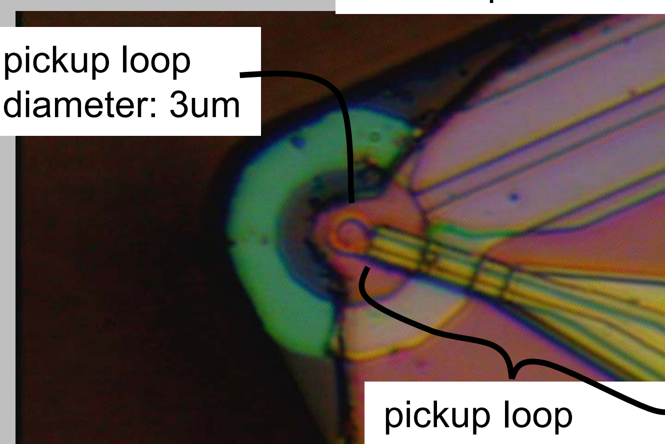
Our tools:

The scanner:



3µm SQUID, polished:



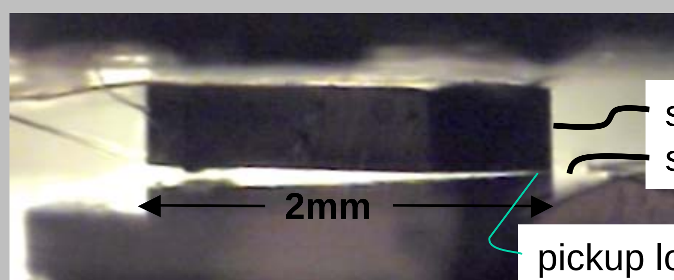


Scanning procedure:

1) Locate the surface. That is, detect "touchdown"
2) Touchdown at a several more points within the range of the scanner
3) Perform a first- or second-order fit to these points
4) During scanning, the probe is kept a controlled height above this surface fit.

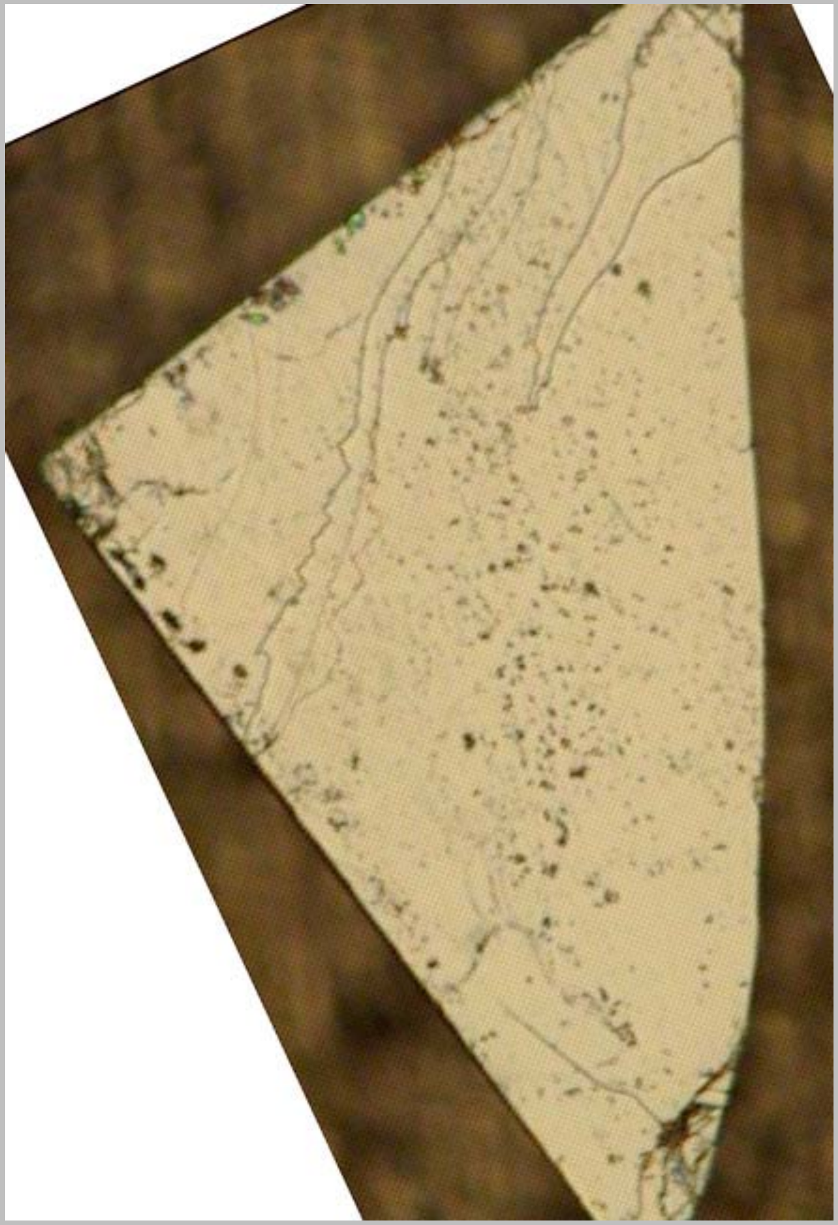
Typical "lift heights" are 200-1000nm.

sensor alignment with the sample:

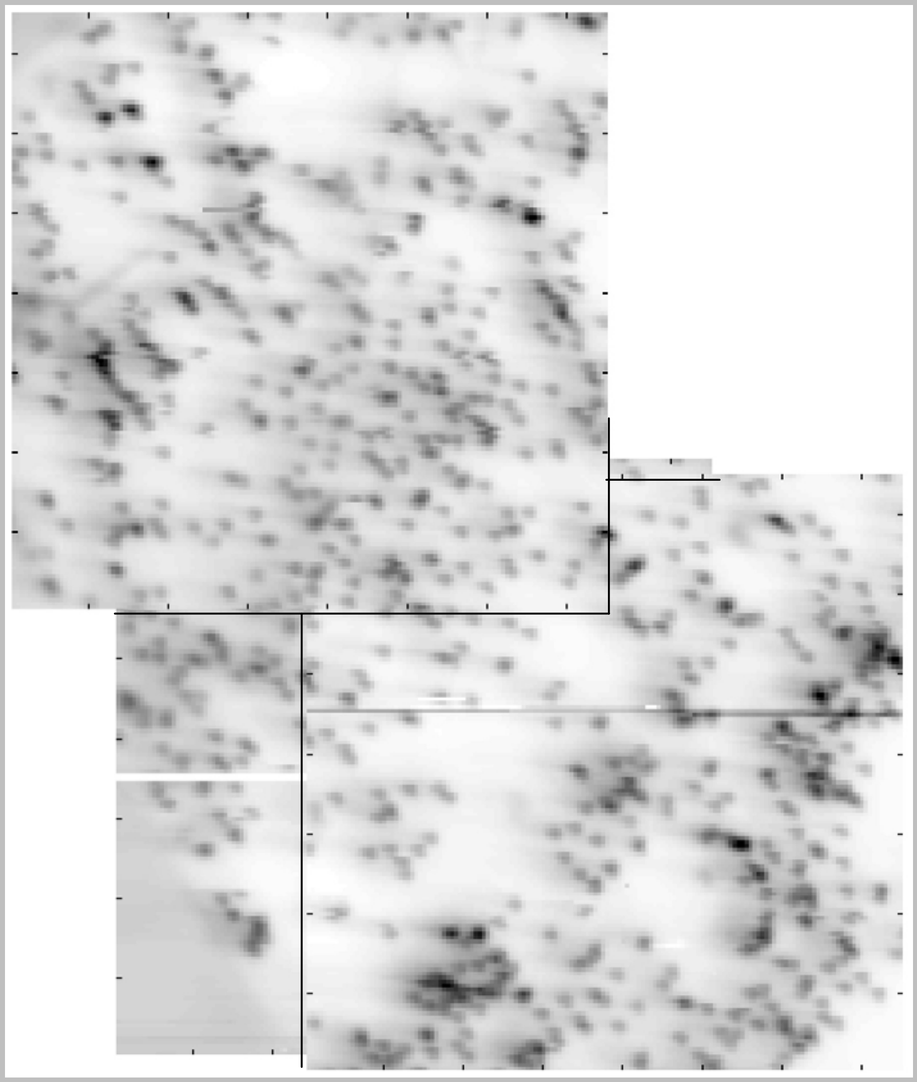


Pickup loop has area ~10um^2, so a flux of 1Φ_0 corresponds to a field of ~2G.

Strontium ruthenate in the ambient field (Earth's field):



each square is 136μm on a side; color scale is 2.2Φ_0 full-scale.

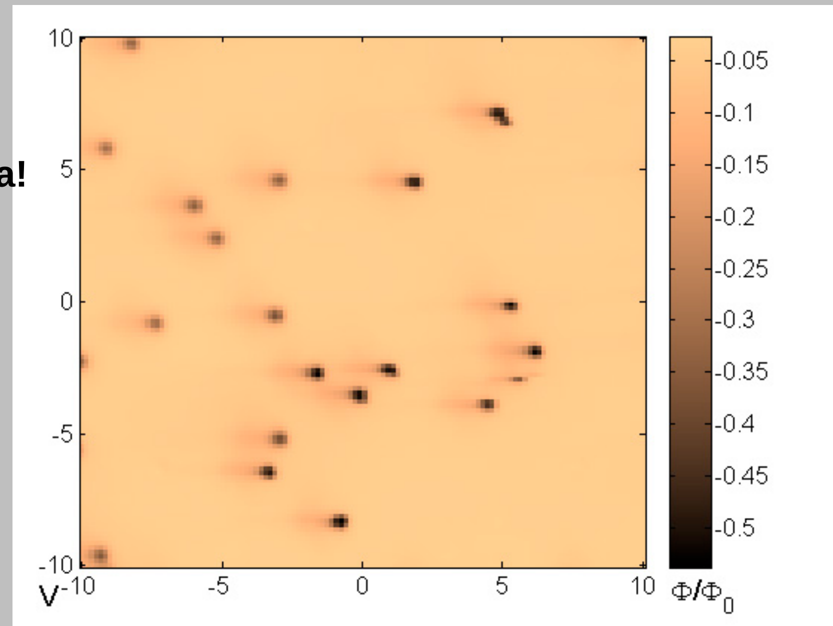


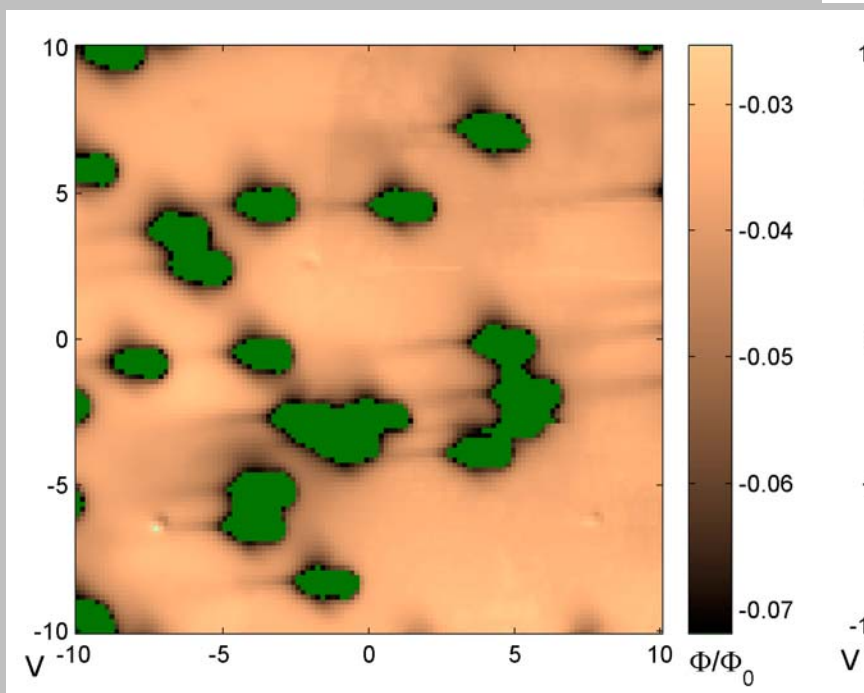
Now with fewer vortices:

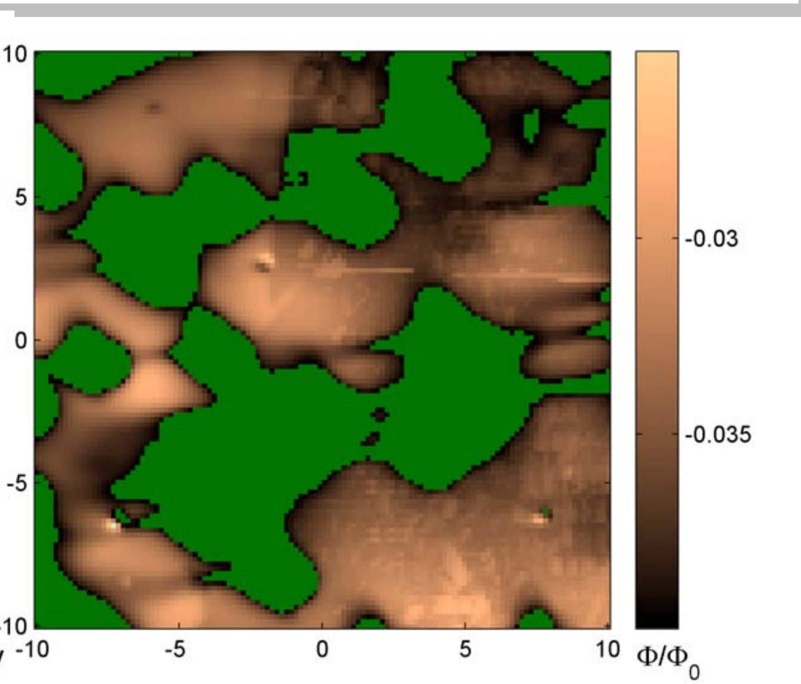
All three of these images are the same data!
Different color scales.

lift height: 0.1V (~200nm)
no applied field
images are approx 140μm on a side.

Note the surface features. These are likely to be artifacts of the surface roughness, not magnetic features.





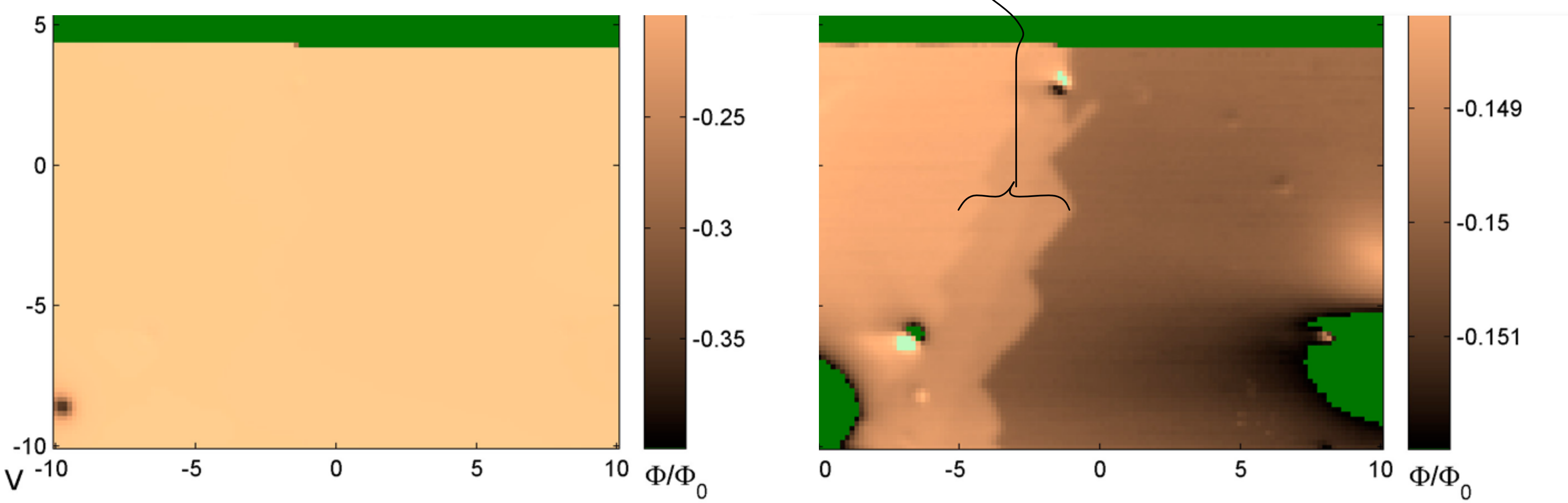


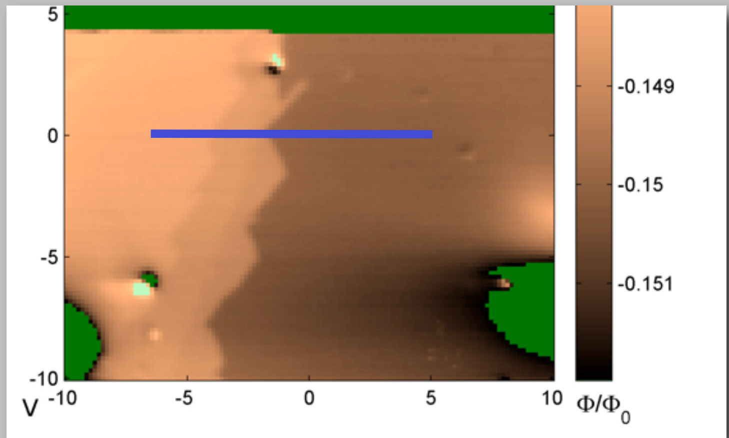
The same area with almost no vortices.

Applied field, cooling and scanning: 21mG (to cancel ambient field).
lift height = 0.2V (~400nm)
images are approx 140µm on a side.

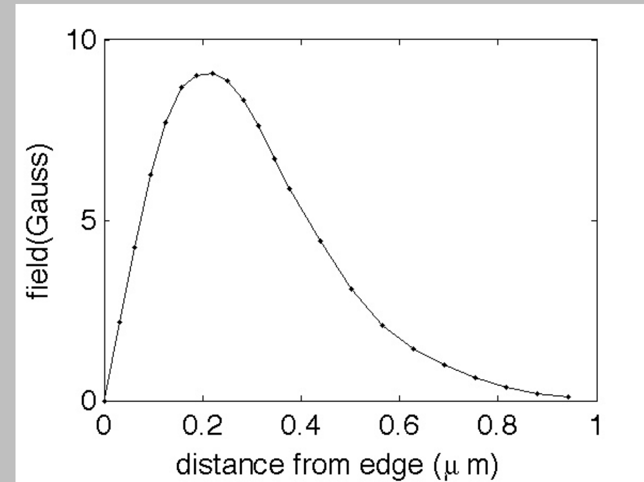
There are three terraces here, visible in optical images of the sample. Their combined height is ~700nm

left: raw data; right: expanded color scale



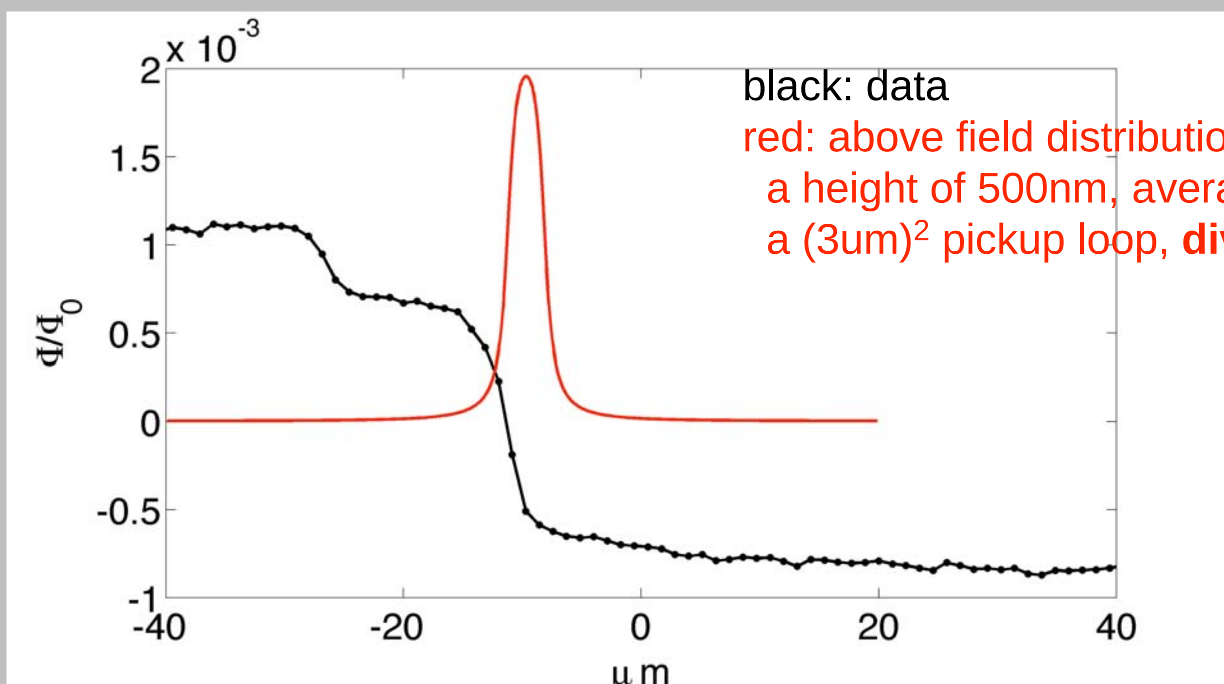


Anticipated field at the sample edge, **within** the sample: (Matsumoto & Sigrist)



Extend to z>0, using lambda=150nm:

$$\tilde{B}_z(k,z) = \frac{K}{k+K}\tilde{B}_z(k,z=0)e^{-kz} \qquad K=\sqrt{k^2+(1/\lambda)^2}$$

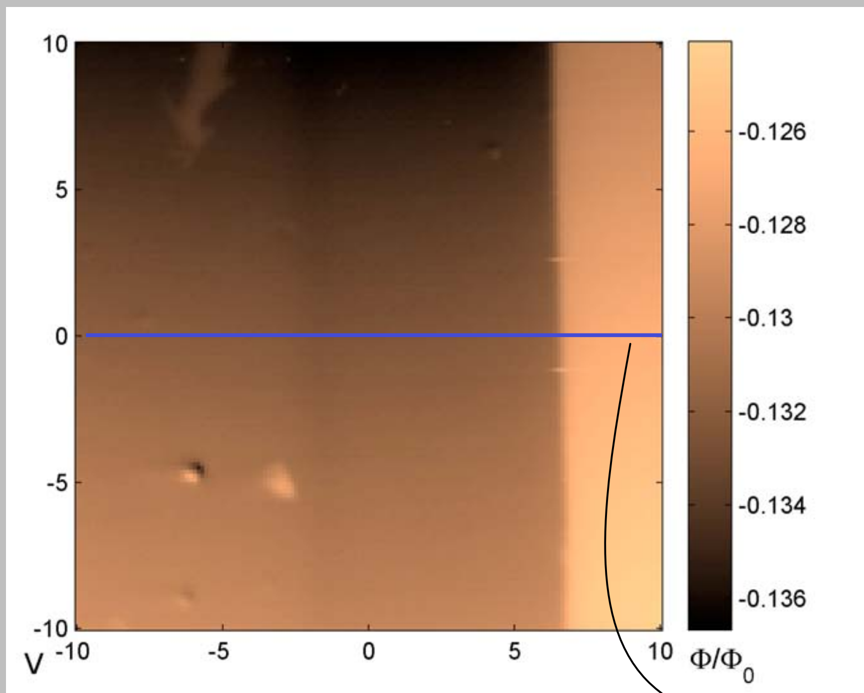


black: data

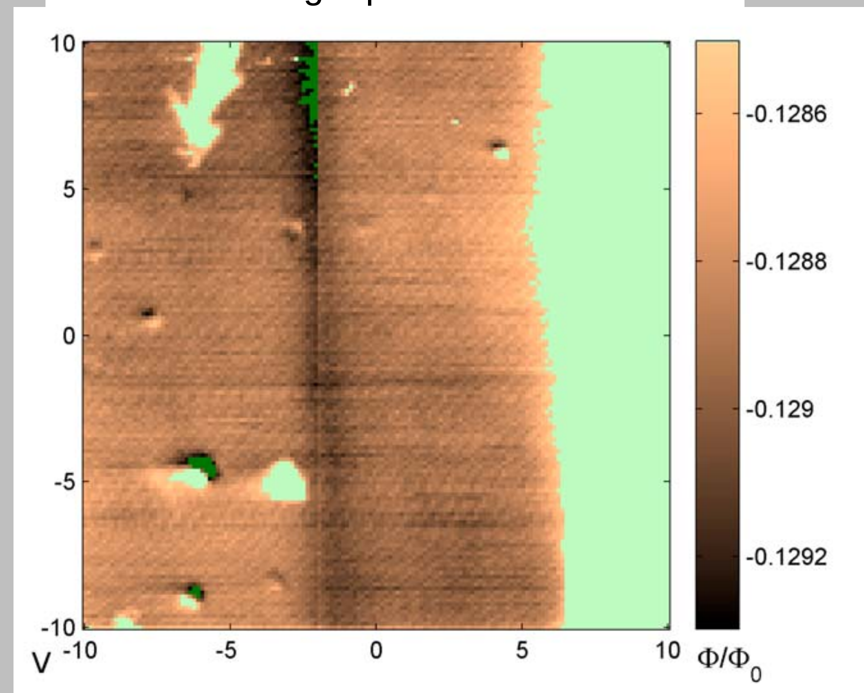
red: above field distribution, extended to a height of 500nm, averaged over a $(3um)^2$ pickup loop, **divided by 200**.

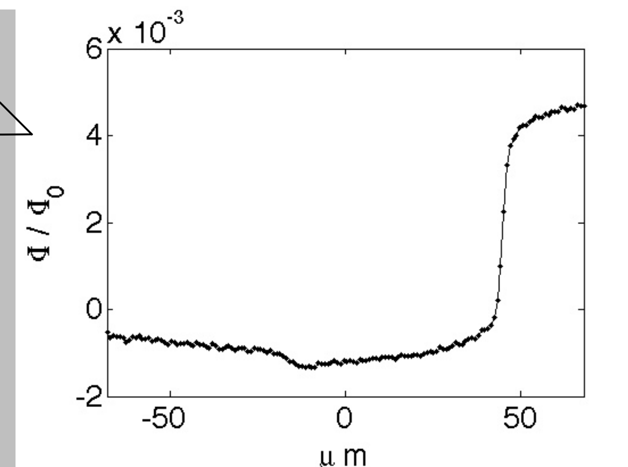
Now move to the sample edge:

applied field: 22mG (to cancel ambient B_z)
lift height = 0.2V (~400nm)



same data, with expanded color scale and 2nd-order fits subtracted separately from left and right portions:





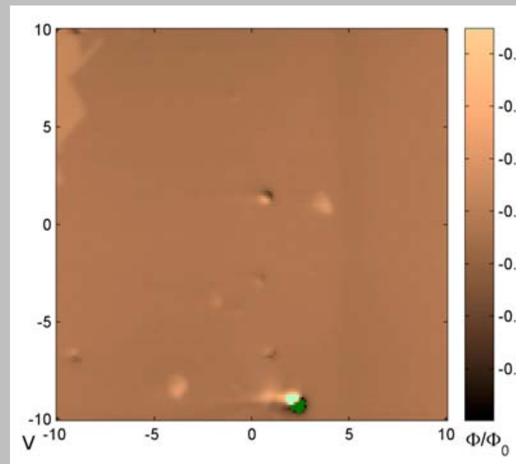
Separating any chiral edge magnetization from focusing of ambient field is likely to be difficult.

Now move back away from the edge.

applied field: 22mG

lift height = 0.3V (~600nm)

Two successive scans, without thermal cycling between.



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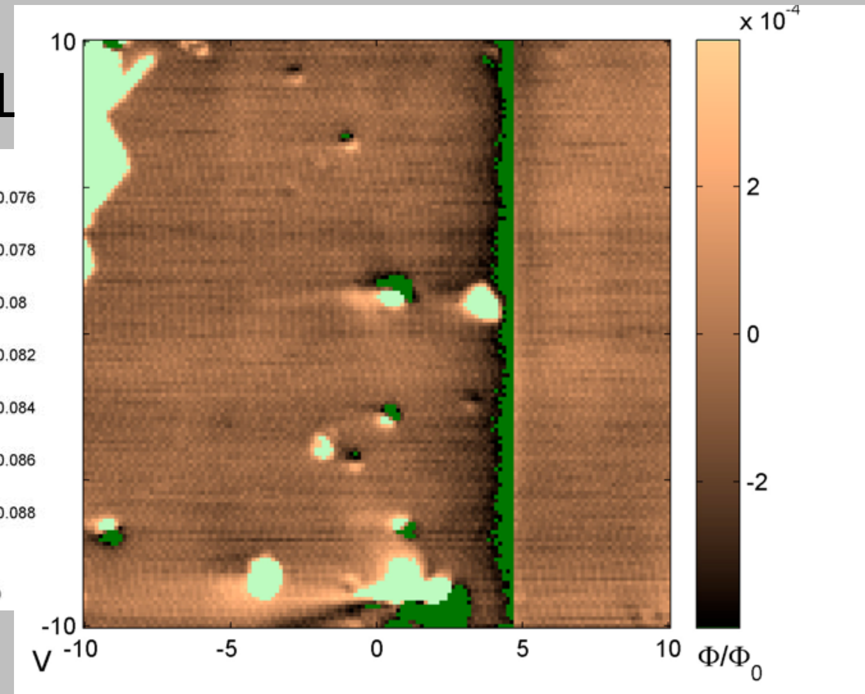
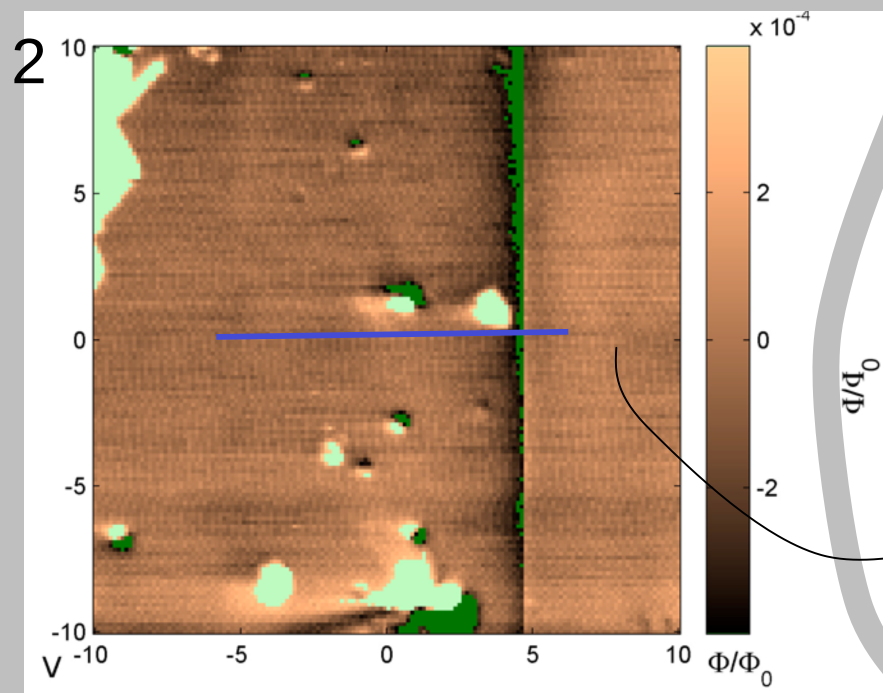
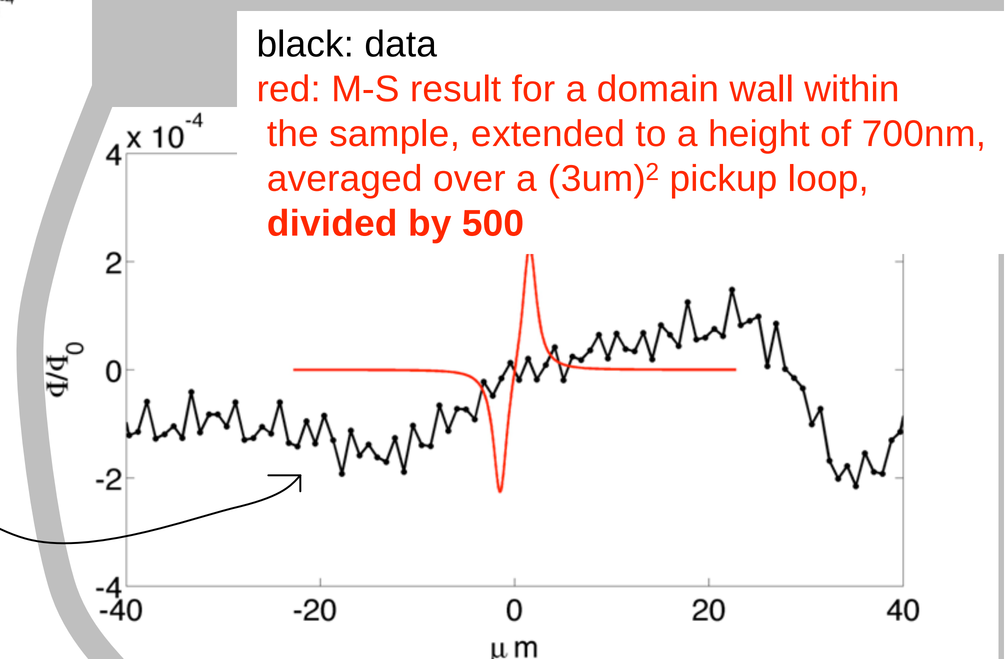


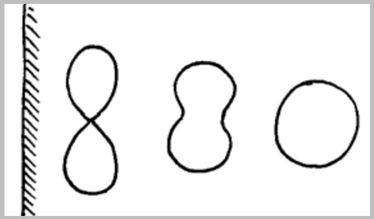




Why are we not seeing any edge magnetization? Some ideas

(1) Very large healing length?

The edge current is generated over a length *larger than* ξ:



But a factor of >100 reduction seems difficult to obtain this way.

(2) The angular momentum per Cooper pair is less than *hbar?*

The gap on the γ-sheet is known to have deep nodes, whereas model calculations assume a cylindrically symmetric $\psi \sim \exp(i\varphi)$ perhaps it is something like $\psi \sim \exp(i\phi)+\alpha\exp(-3i\phi)$?

But again, a factor of >100?

(3) Very small *ab* domains?

However Kerr effect measurements suggest an *ab* domain size of ~50um.

van Harlingen group's phase-sensitive edge measurements suggest ~1um domains.

Y Liu group's experiments: phase maintained across entire crystal? single domain?

Domain structure may be locked in at $T \sim T_c$, where ξ and λ are larger.

(4) Fine structure along the *c*-axis?

ξ_c=1.2nm

Again, can this be squared with Liu and van Harlingen group experiments?

(5) The pairing potential is only significant near E_F; does this have any effect?

If only electrons within ω_c of E_F contribute to the edge current then this is a reduction by ~30.

At right: solution of the BCS equation

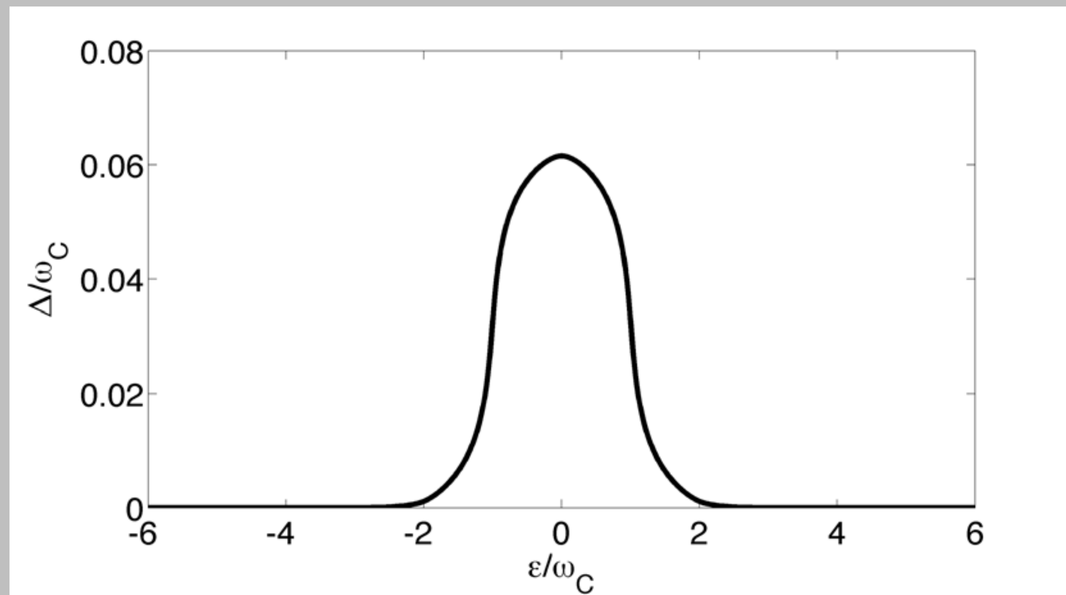
$$\Delta_k = -\sum_l V_{kl} \frac{\Delta_l}{2\left(\xi_l^2 + \Delta_l^2\right)^{1/2}}$$

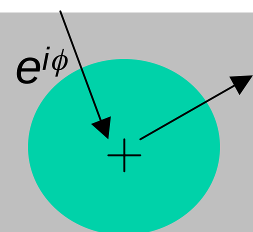
with the condition

$$V_{kl} = V, |\xi_l - \xi_k| < \omega_C$$

instead of the usual

$$V_{kl} = V, |\xi_l| < \omega_C, |\xi_k| < \omega_C$$





Particles seeing a very weak pairing potential might recover from impurity scattering only very slowly.

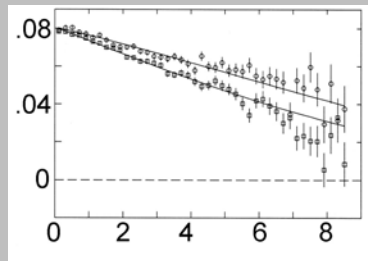
(6) Parasitic effects from the other bands?

The main SC band is the γ-band, but there are also the α and β bands. The gap is very large: $\Delta(T=0) = (4\text{-}6)k_B T_C$.

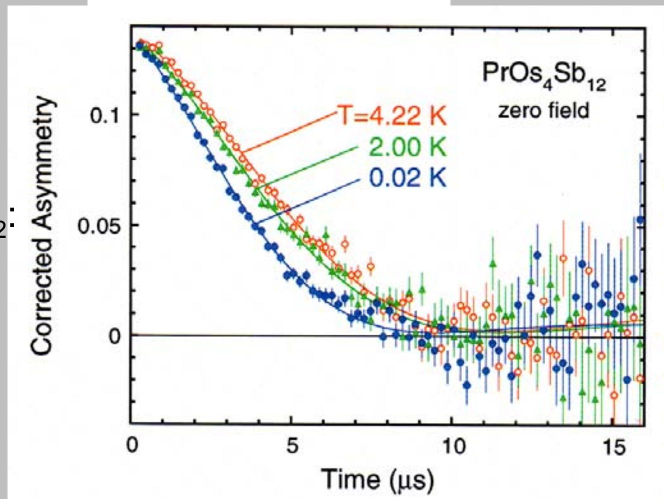
(7) Sr_2RuO_4 is not a *p+ip* superconductor.

What about the muon spin rotation data?

Sr_2RuO_4:



$PrOs_4Sb_{12}$:



Y Aoki *et al*, PRL **91** 067003 (2003), fig 1

muon gyromagnetic ratio: .085 μsec^{-1}G^{-1};
ie a 74μsec oscillation period at 1G.
So if after 2μsec the muons have depolarized noticeably more than in the normal state, **fields of up to ~5G occupy a significant volume fraction of Sr_2RuO_4.**

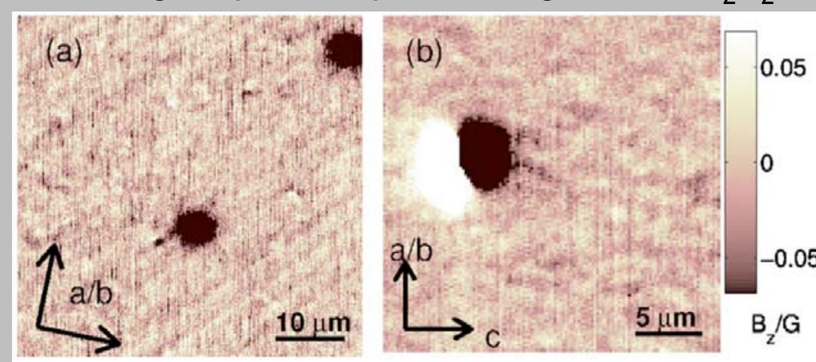
MuSR data on Sr_2RuO_4 suggest that ~10% of muons are seeing fields of ~5G. Where is this field?

($PrOs_4Sb_{12}$: a similar situation, where muons see a ~10G field, but scanning magnetic imaging shows no such large fields.)

Empirically: these fields must have small length scales or/and short (but >~1usec) timescales.

Might this magnetization have a different origin than chiral domains?

Scanning 0.5μm Hall probe images of $ErNi_2B_2C$:



H Bluhm *et al*, PRB **73** 014514 (2006)