Upper limit on spontaneous supercurrents in Sr_2RuO_4

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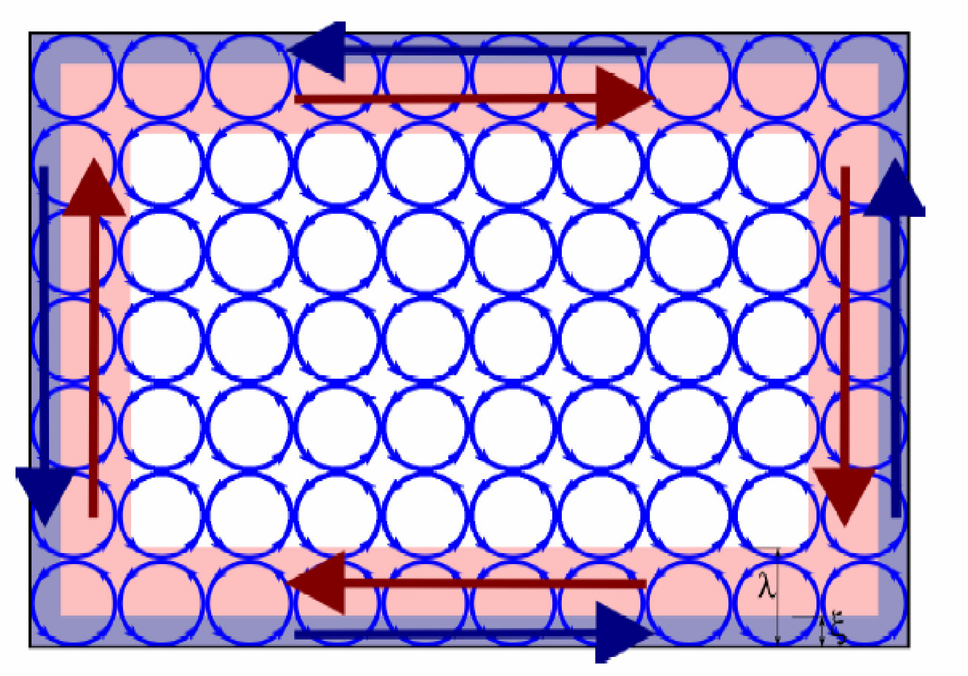
Spontaneous supercurrents predicted to occur at edges of p_x+ip_y superconductors

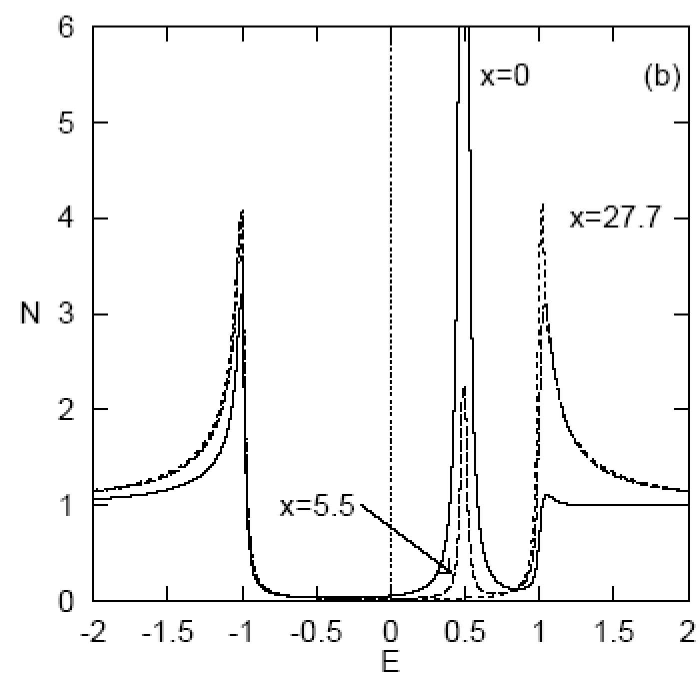
each Cooper pair has angular momentum- edges not cancelled out

alternate view:

sub-gap surface states not at zero energy- carry current



for Sr_2RuO_4 - 2.8μA/plane

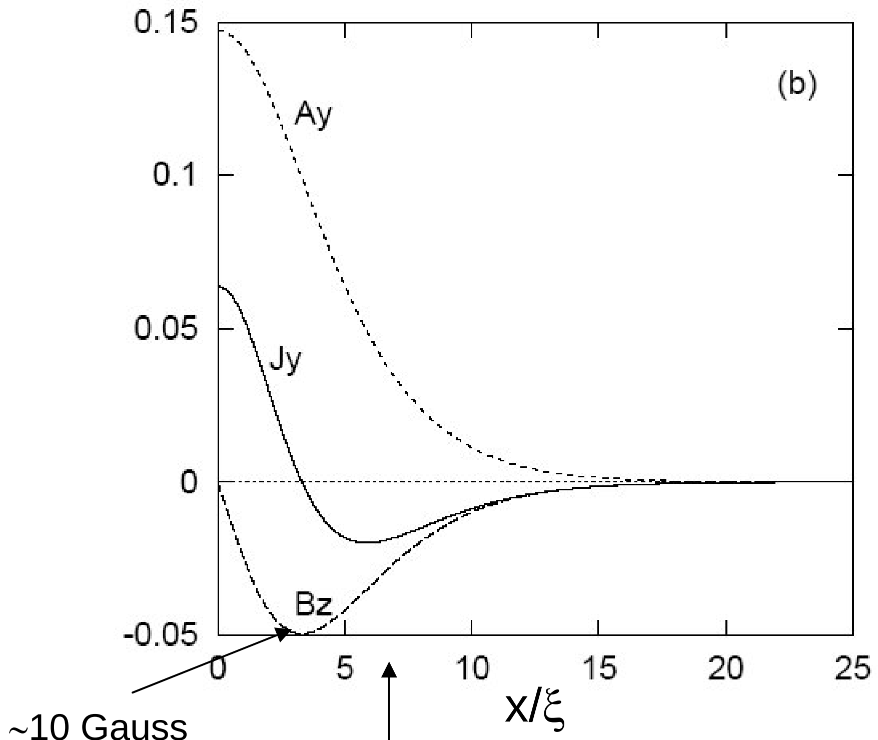


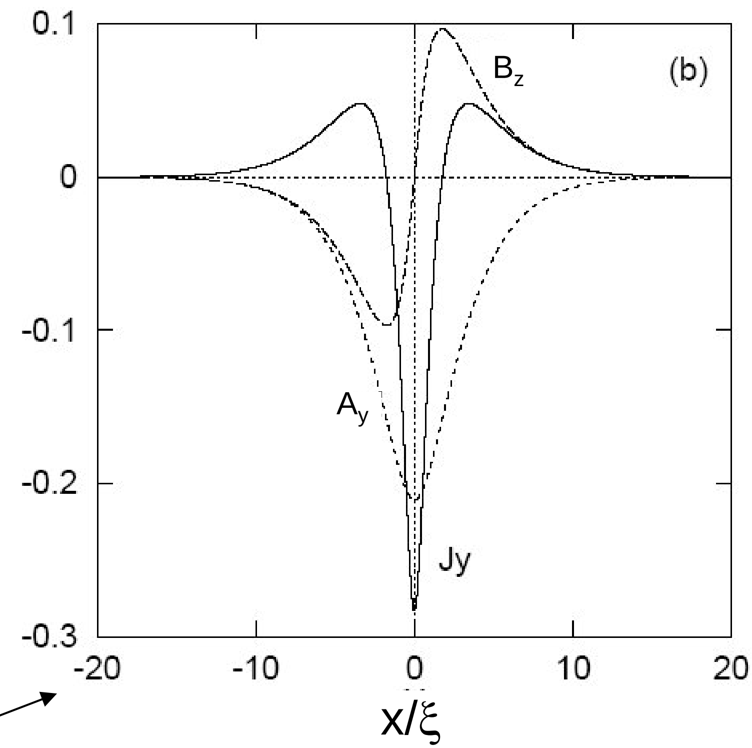
H-J Kwon, V.M. Yakovenko and K. Sengupta, cond-mat/0111071

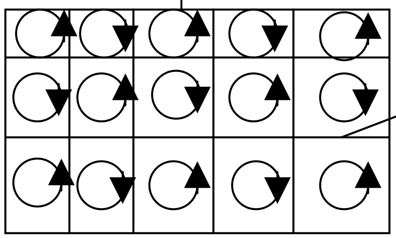
M. Masumoto and M. Sigrist, J. Phys. Soc. Jpn. **68**, 994 (1999)

Spontaneous currents and fields at edge of $p_x \pm ip_y$ superconductor

Spontaneous currents and fields at domain boundaries of $p_x \pm ip_y$ superconductor





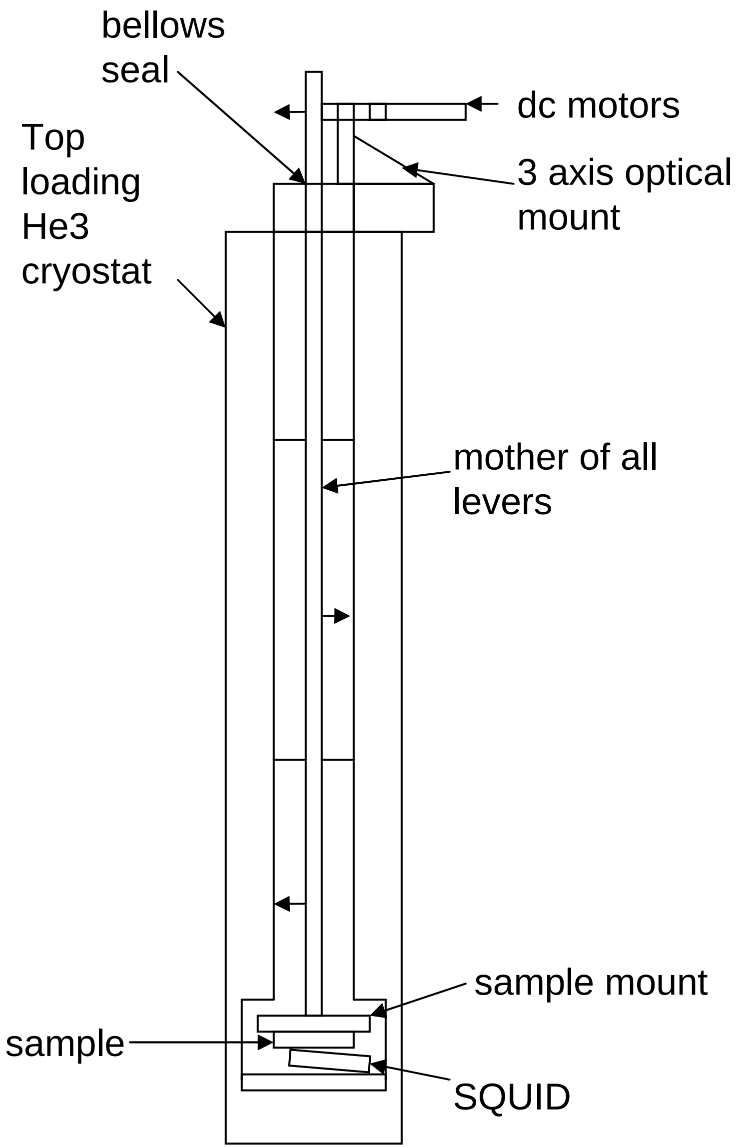


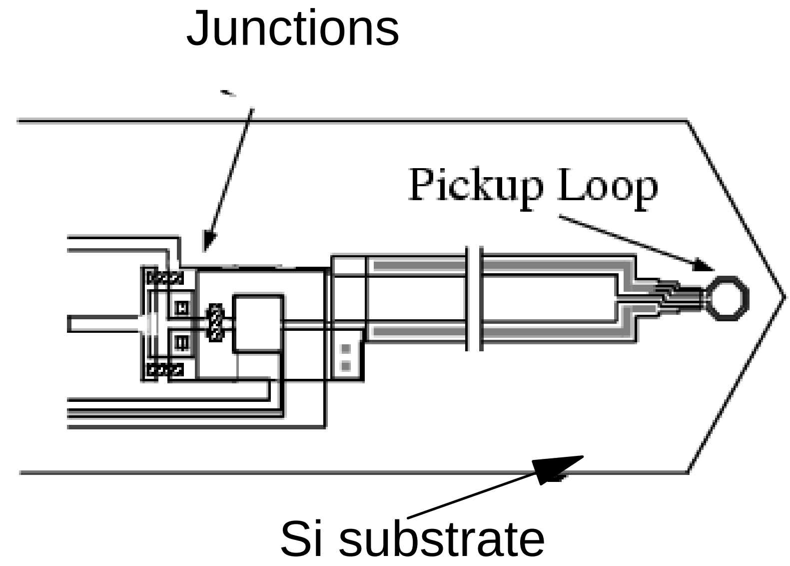
ξ~66nm

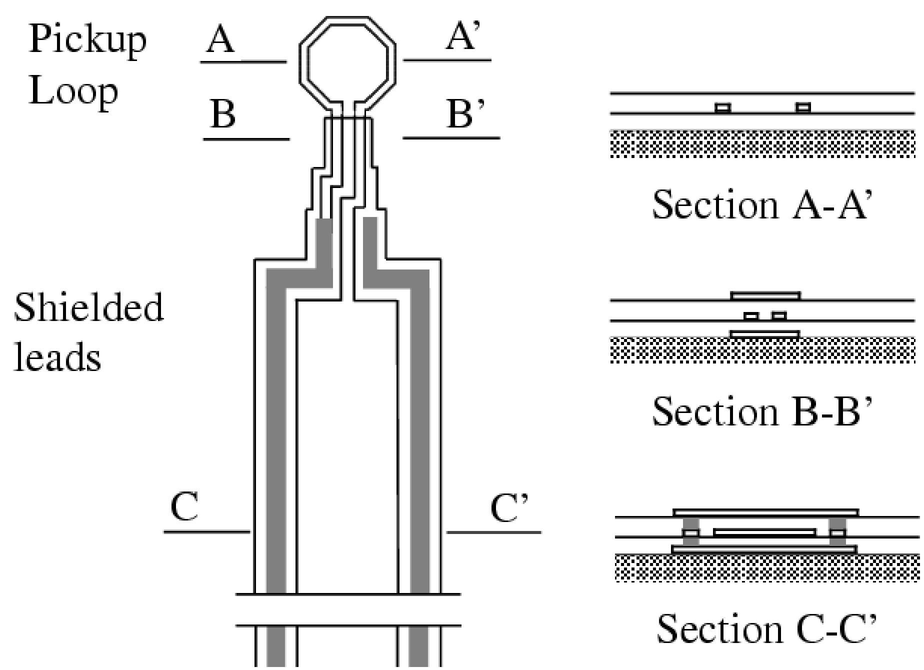
10 Gauss x 8μm pickup loop -> $30\Phi_0$!

M. Masumoto and M. Sigrist, J. Phys. Soc. Jpn. **68**, 994 (1999)

He3 Scanning SQUID microscope



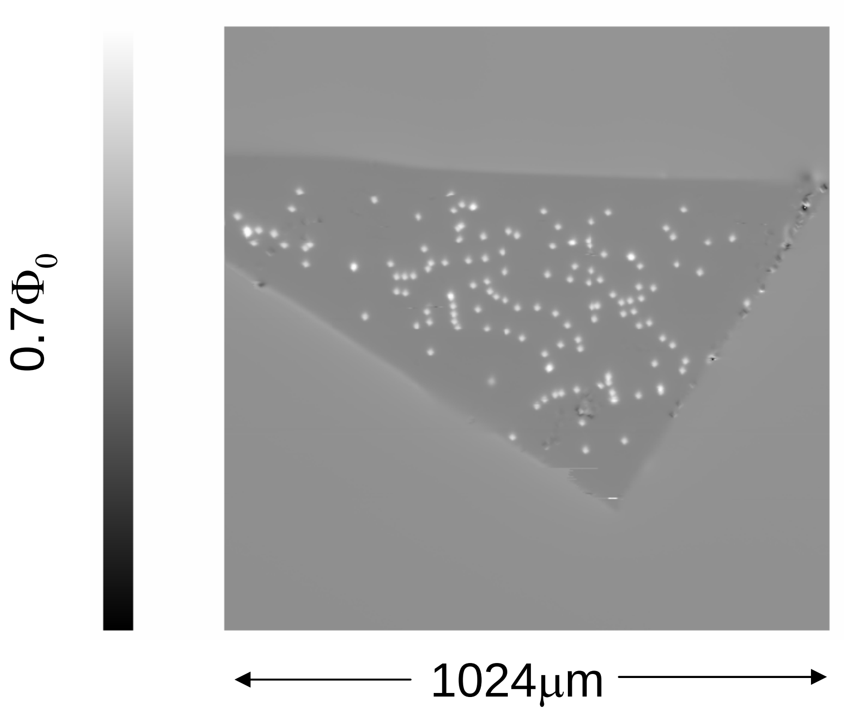


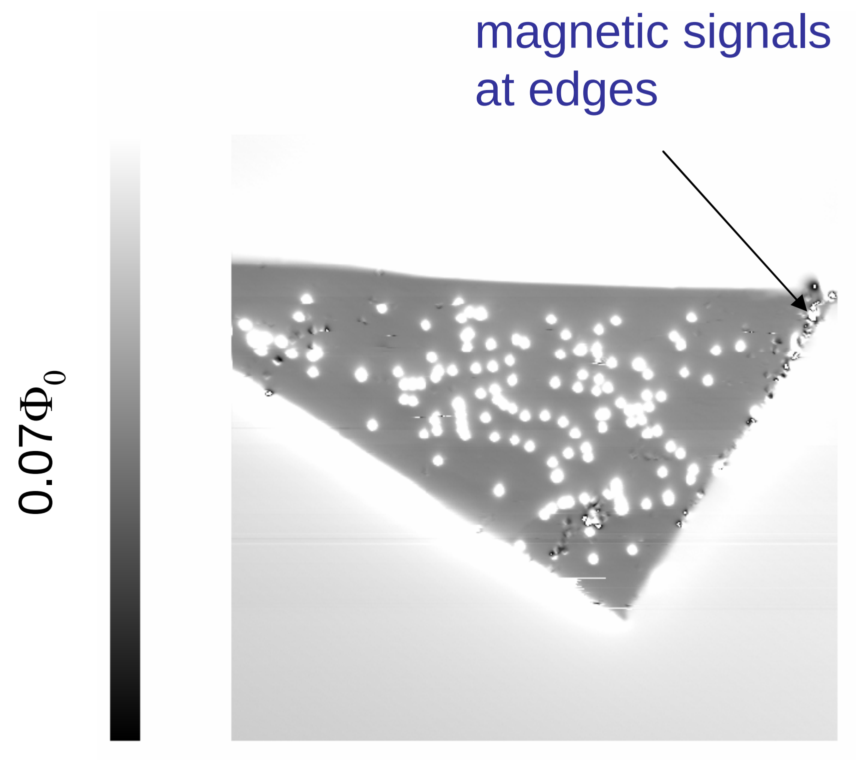


Scanning SQUID microscopy of "conventional" d-wave superconductor - YBCO

11.2μm pickup loop

T=4.2K

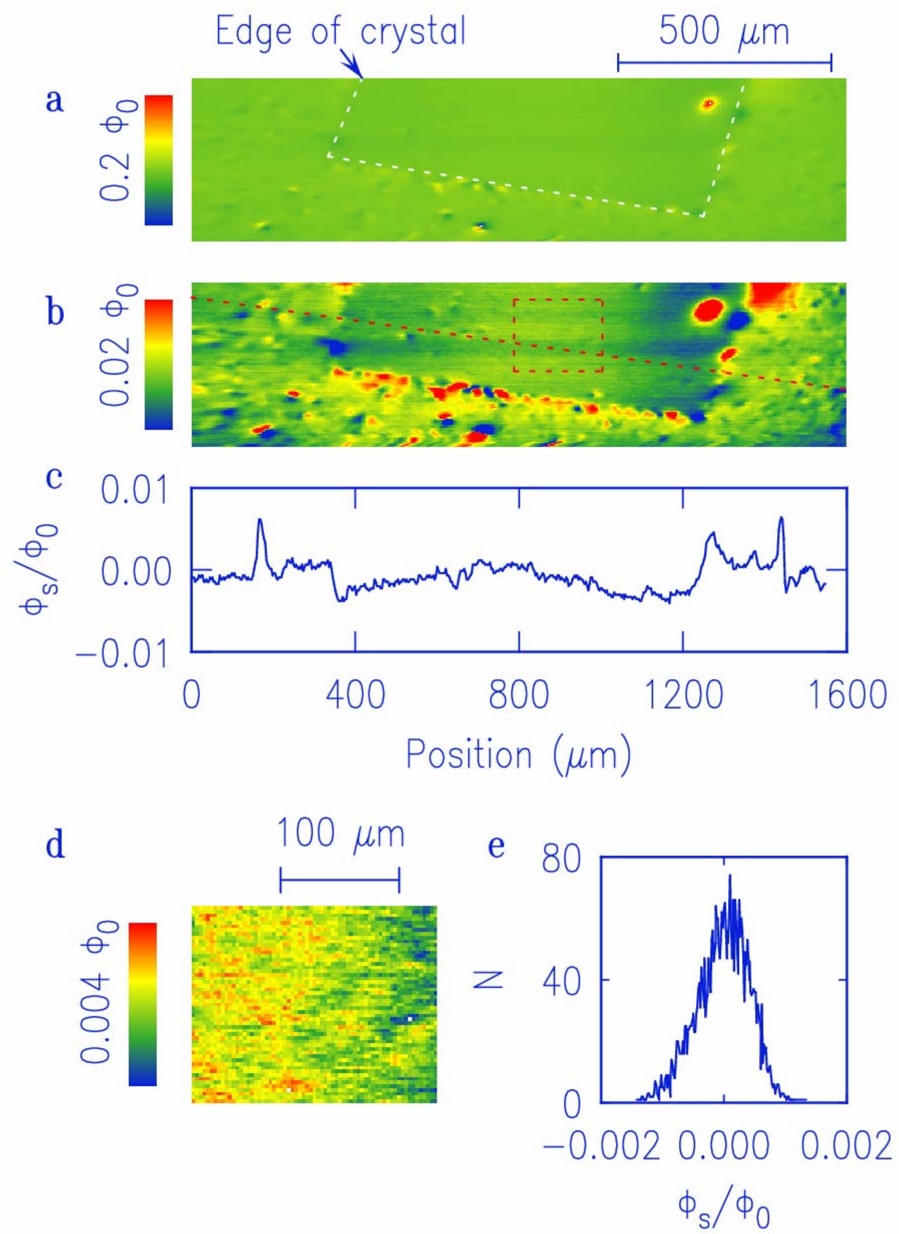




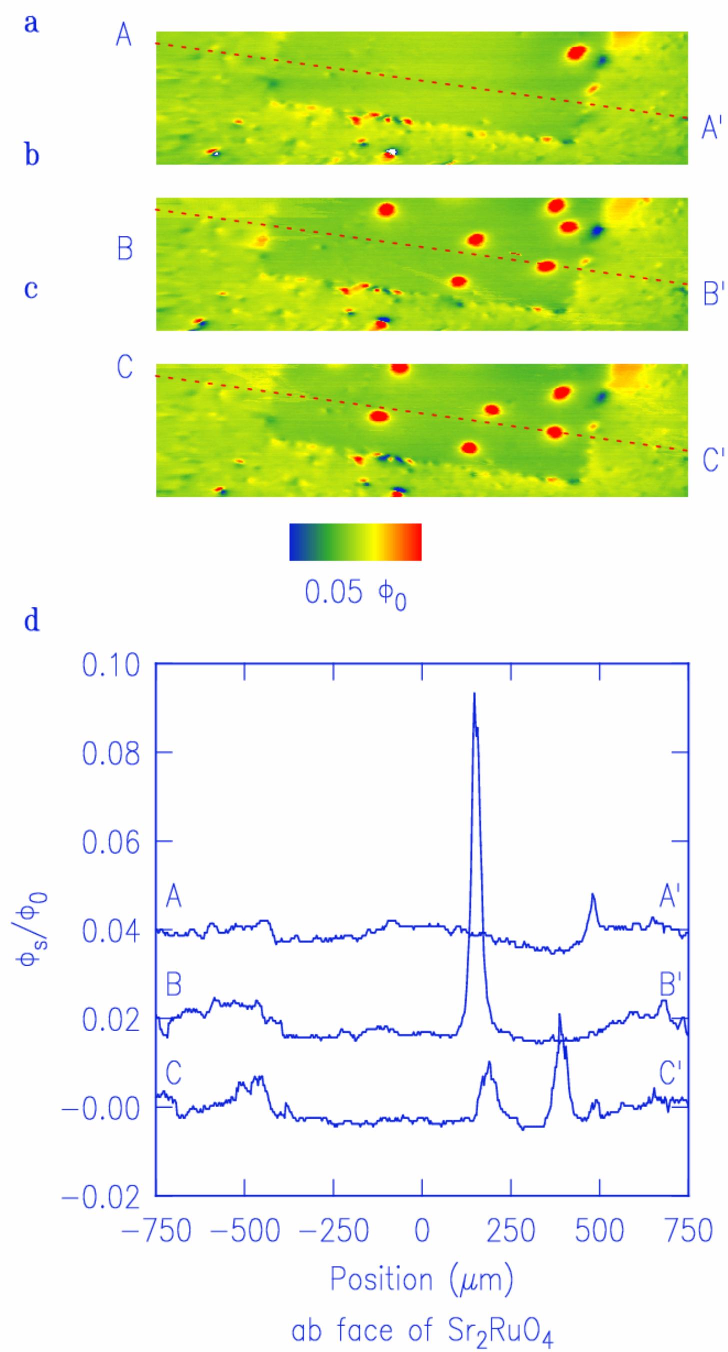
K.A. Moler et al. PRB 55, 12753 (1997)

SQUID microscope image of ab face of Sr_2RuO_4 single crystal- T=0.27K

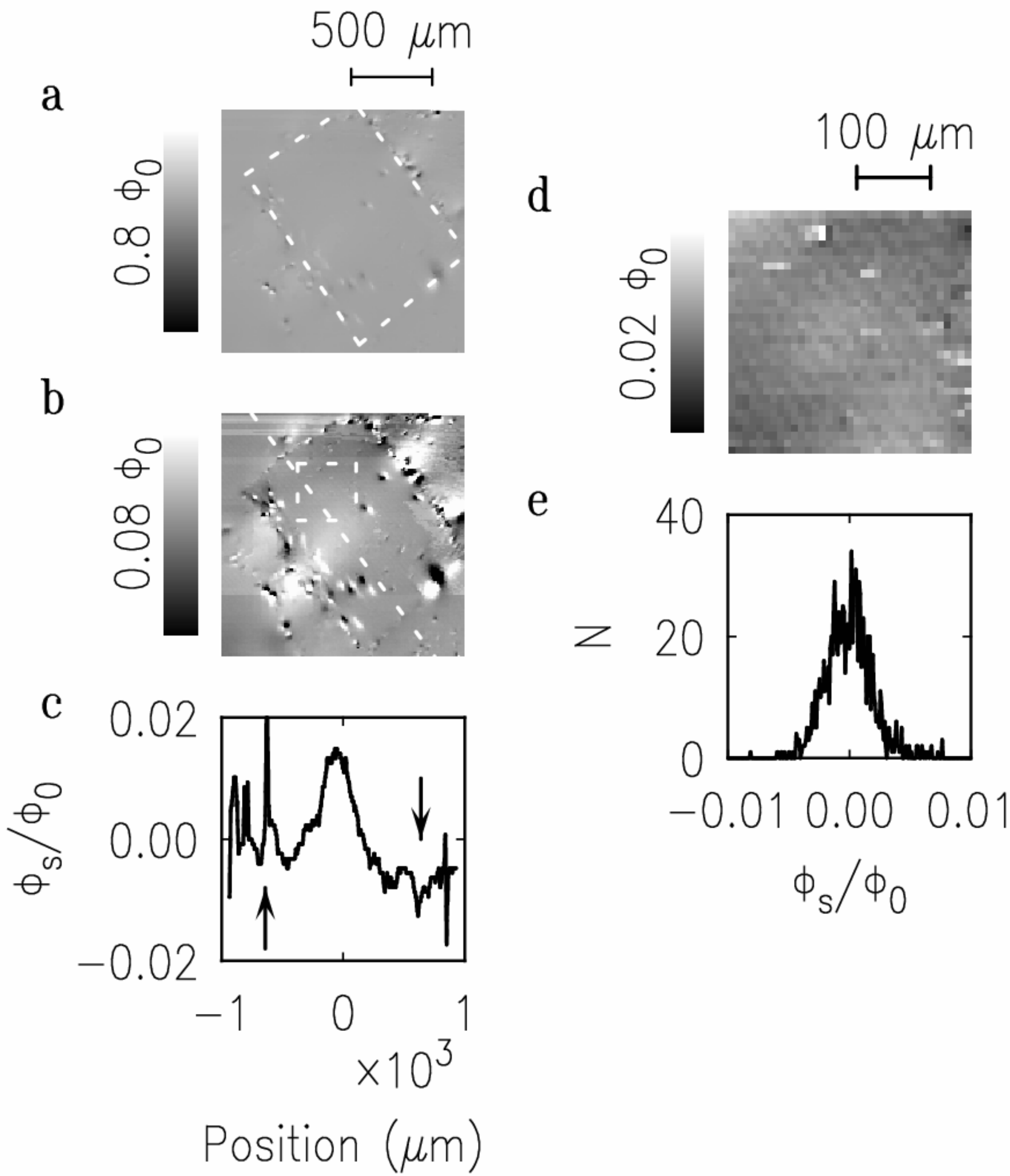
8μm pickup loop



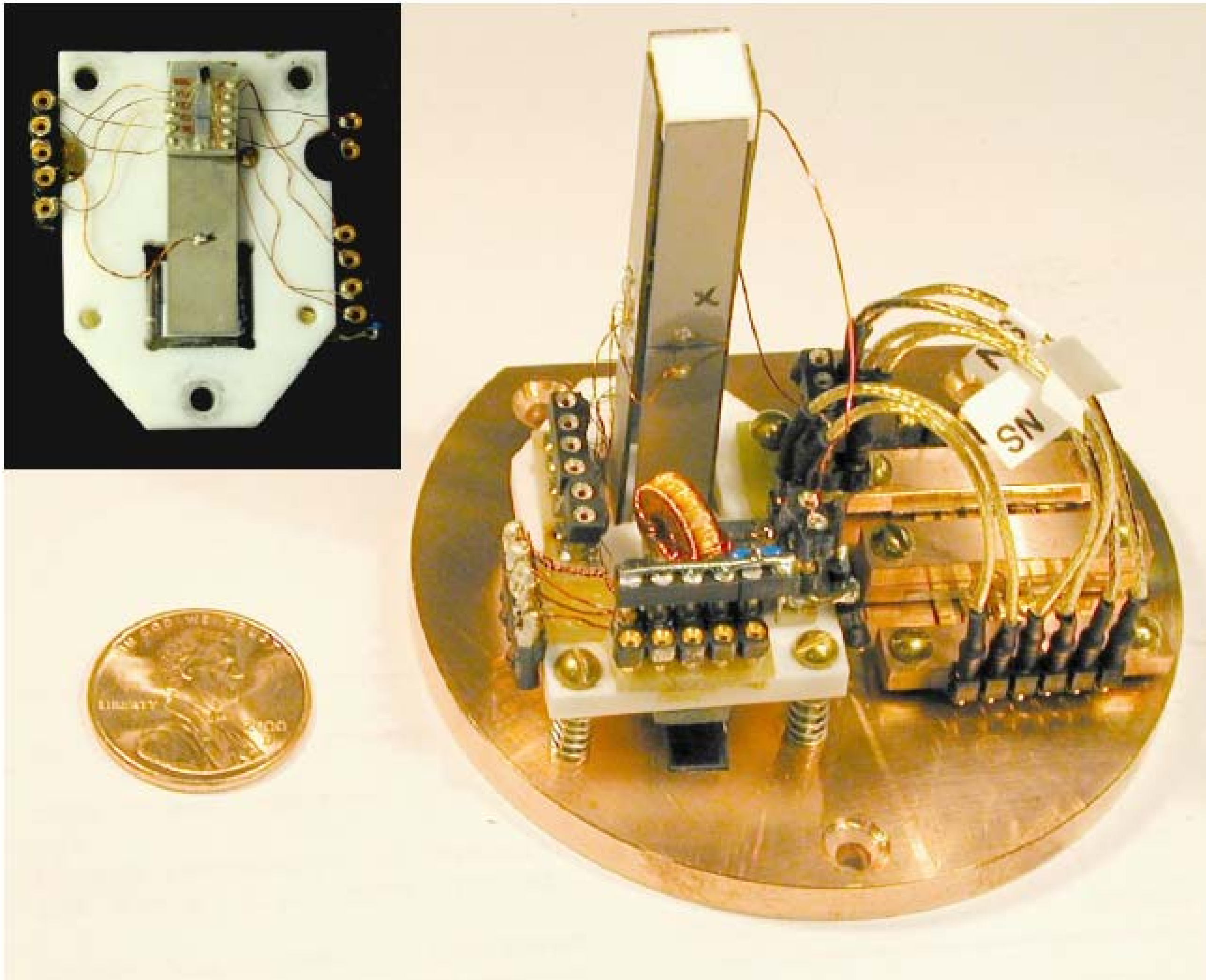
Three cooldowns of ab face in slightly difference fields



SSM image of ac face of Sr_2RuO_4

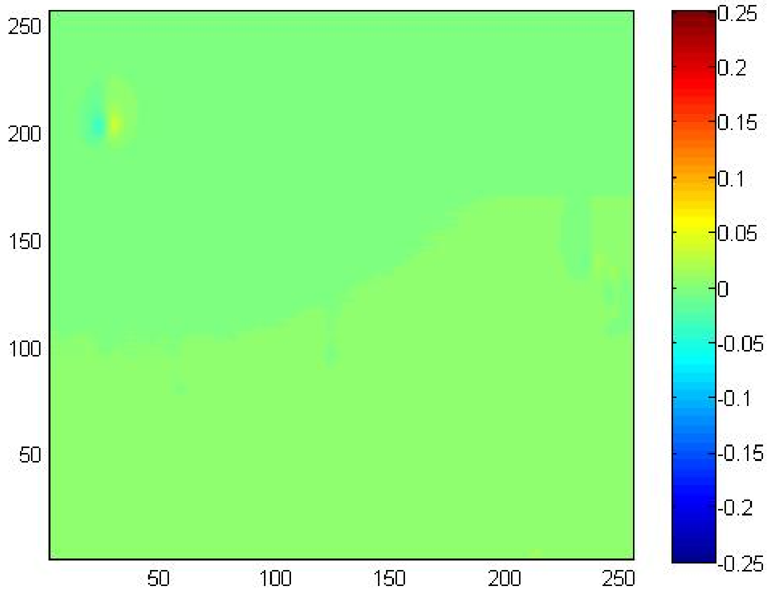


Stanford dilution refridgerator based scanning SQUID microscope

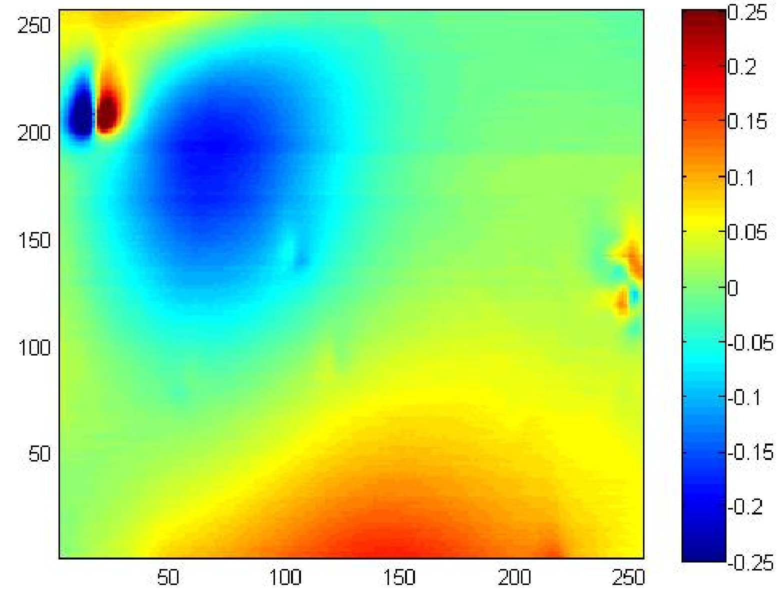


P. Bjornsson et al., RSI 72, 4153 (2001).

SQUID microscope image of
Sr_2RuO_4 single crystal ac face



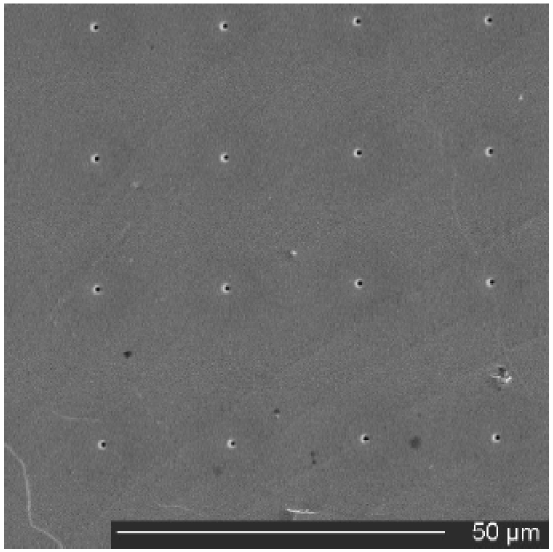
T=4K

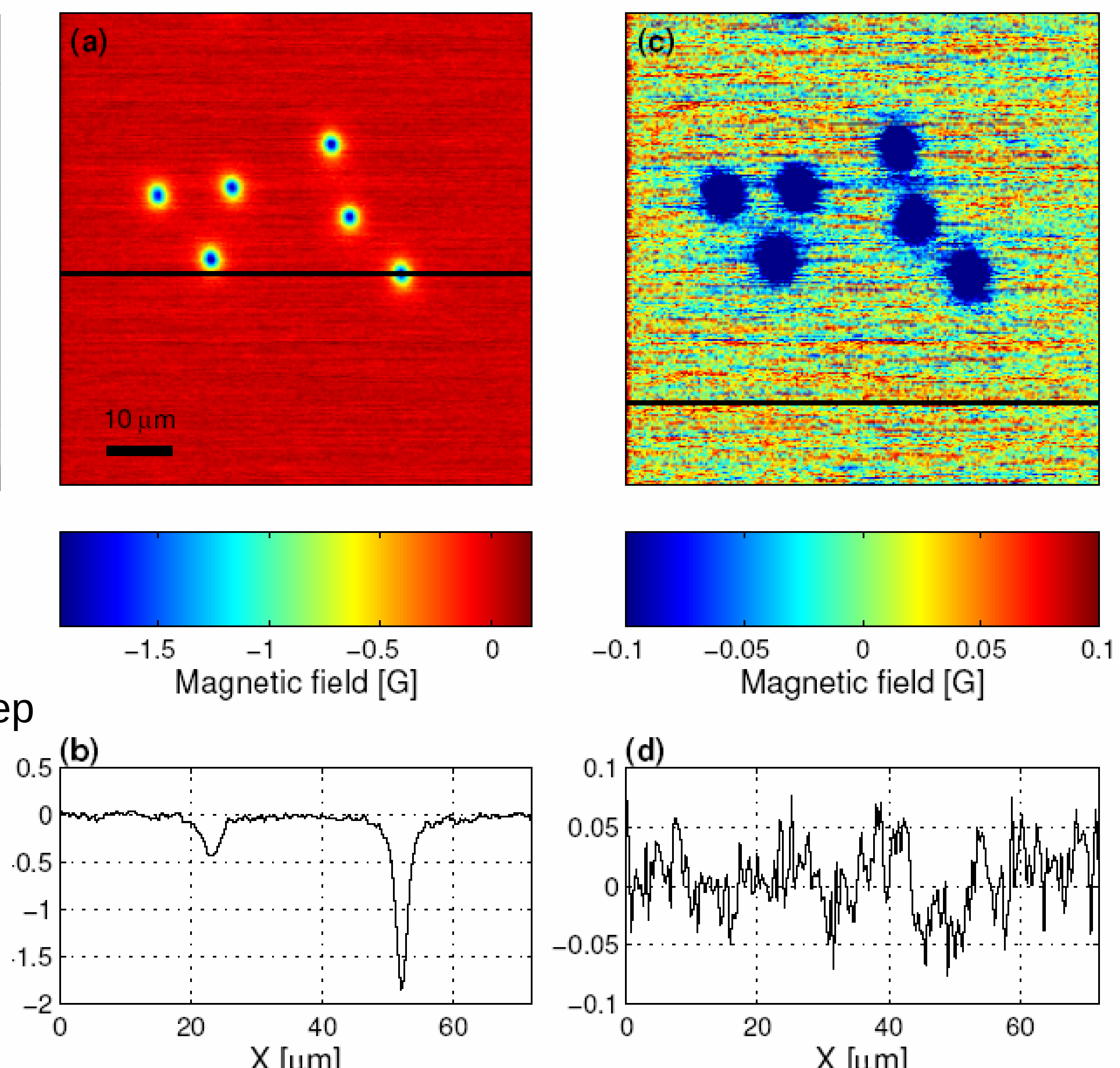


T=100mK

P. Bjornsson et al., PRB 72, 012504 (2005)

Hall bar images of Sr_2RuO_4 single crystal -ab face





FIB etched holes 1µm deep

0.5µm Hall bar

z=1.2µm

T=100mK

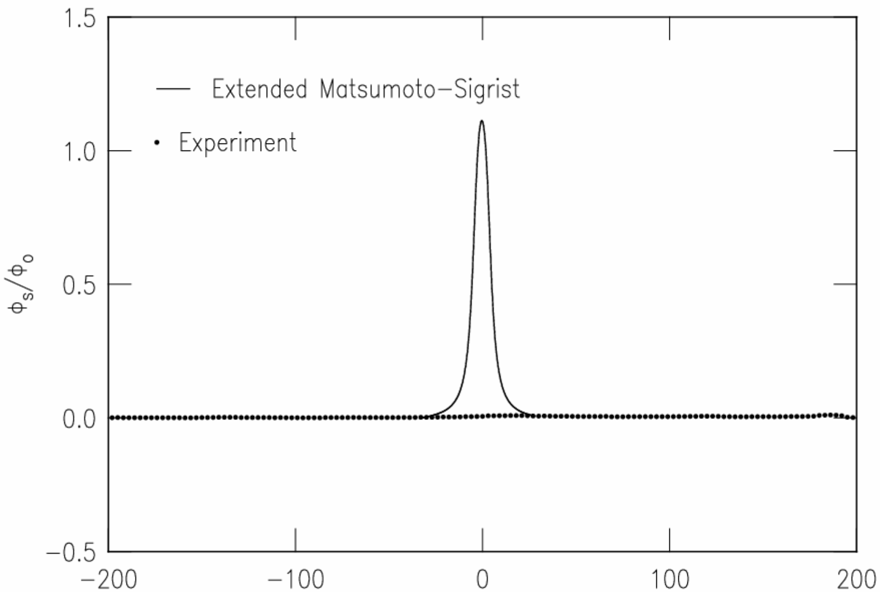
Predicted magnetic signal above $p_x \pm ip_y$ superconductor

(assuming B_z at surface same as B_z in bulk)

$$b_z(k_x, k_y, z) = b_z(k_x, k_y, 0)e^{-Kz} \qquad K = (k_x^2 + k_y^2)^{1/2}$$

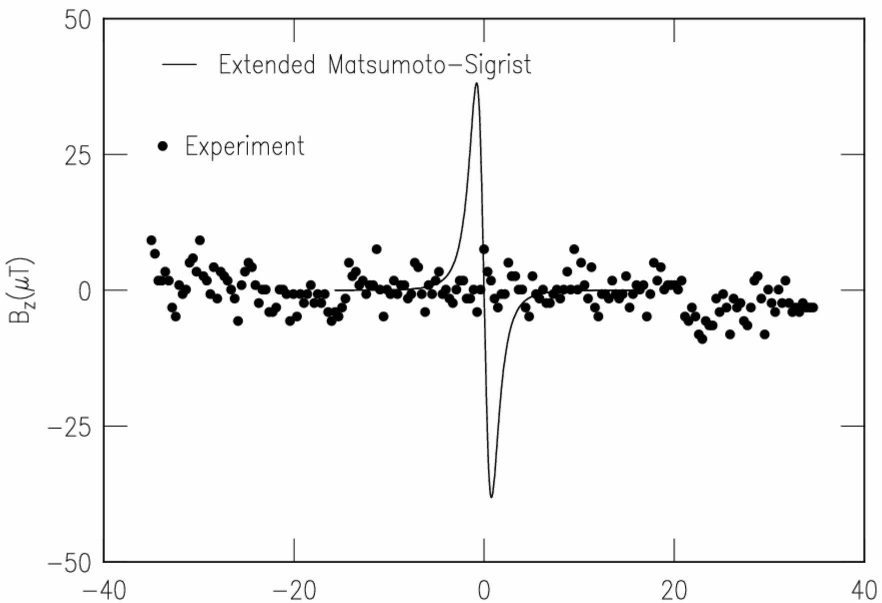
$$b_z(k_x, k_y, 0) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\, e^{i(k_x x + k_y y)} B_x(x, y, 0)$$

$$\Phi = \int_{-L/2}^{L/2} dx \int_{-L/2}^{L/2} dx\, B_z(x, y, z)$$



Position relative to sample edge (μm)

Scanning SQUID microscope − Edge



Position (μm)

Scanning Hall bar microscope − Domain wall

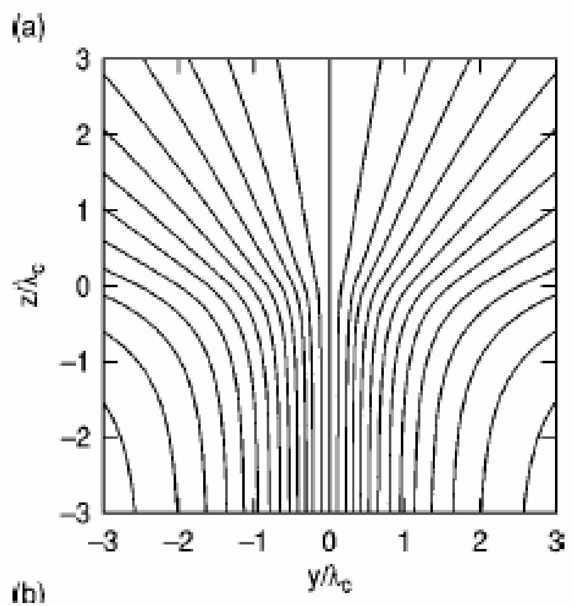
What about the effects of surface screening?

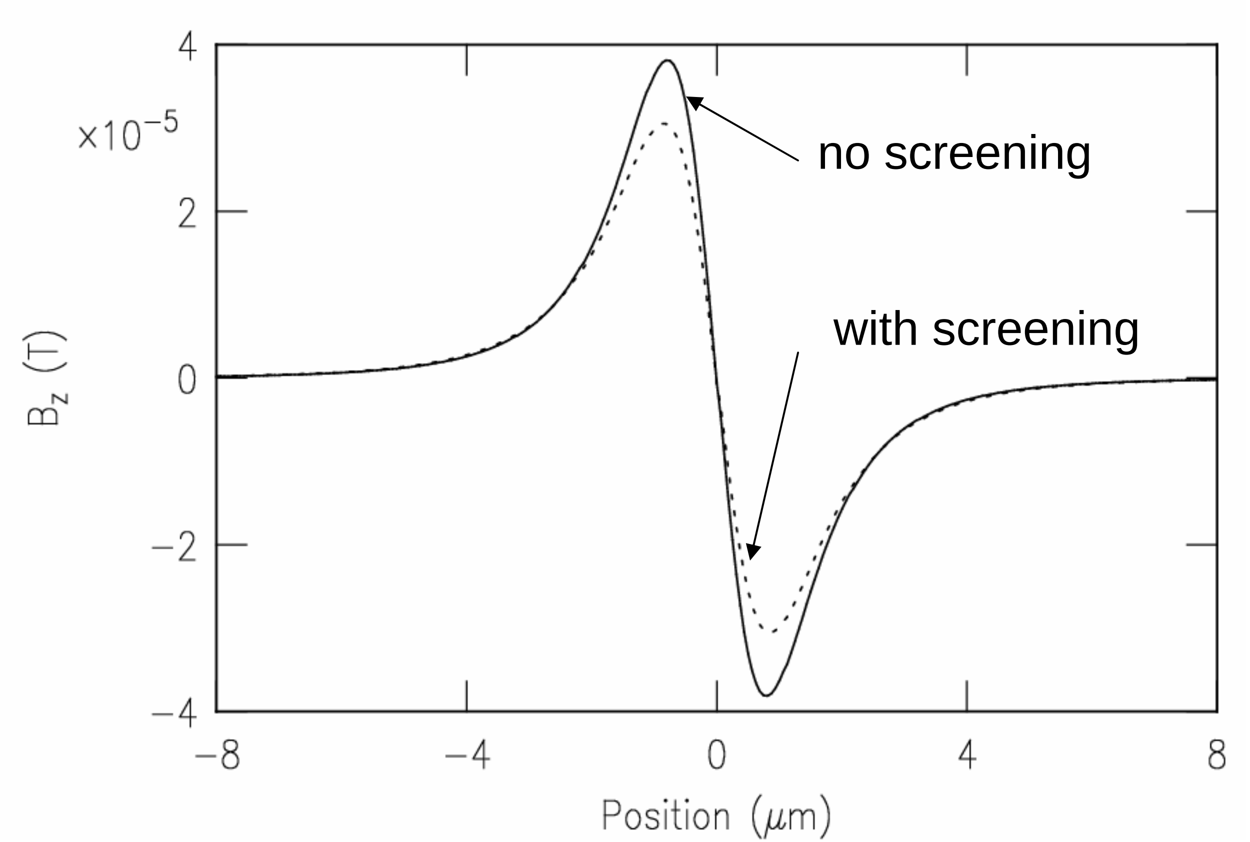
$$\tilde{B}_z(k,z) = \frac{K}{k+K}\tilde{B}_{0z}(k,0)e^{-kz}$$

$\tilde{B}_z(k,z)$ - screened field

$\tilde{B}_{0z}(k,0)$ - bulk field

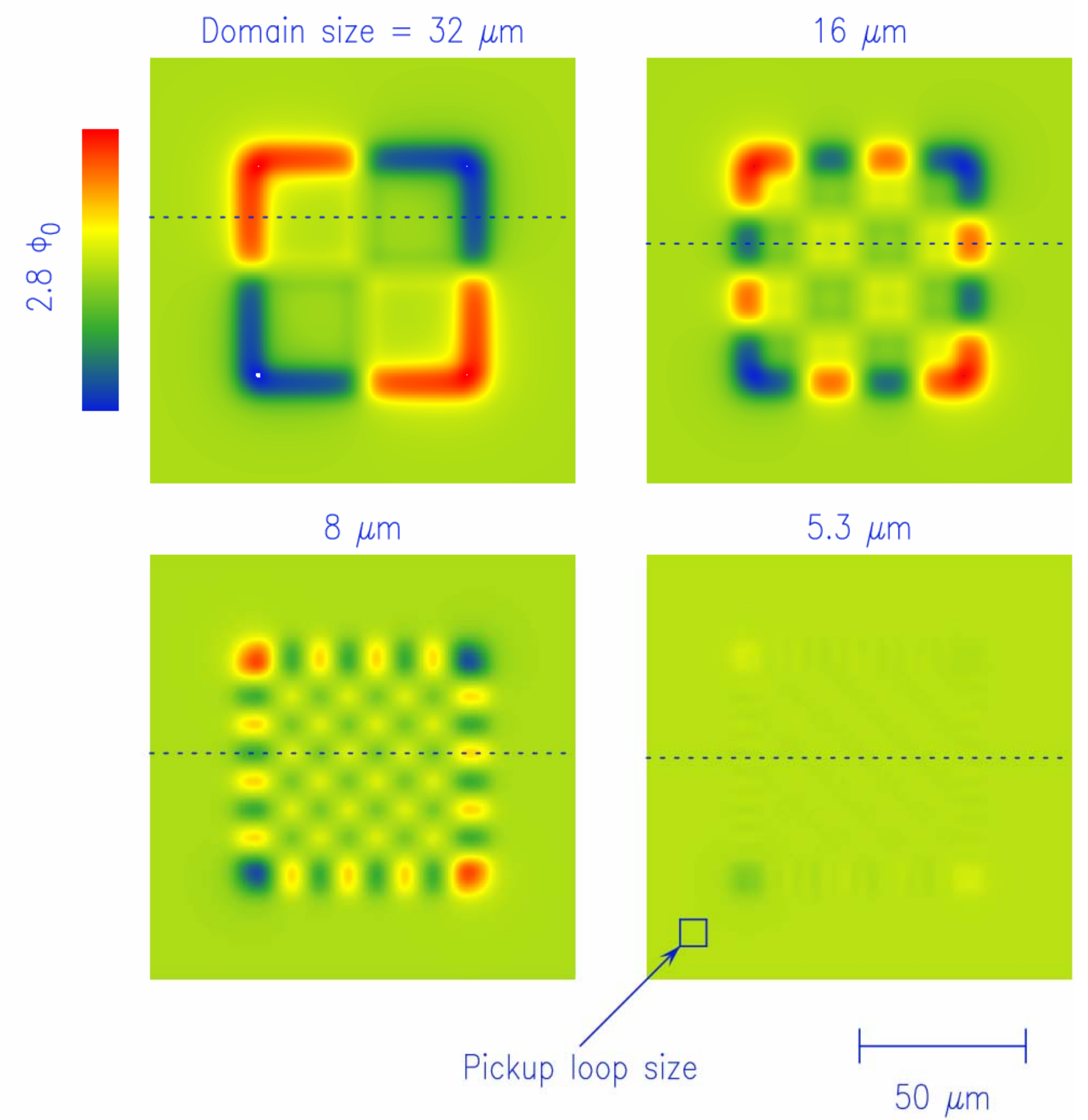
$$k = \sqrt{k_x^2 + k_y^2} \qquad K = \sqrt{k^2 + 1/\lambda^2}$$



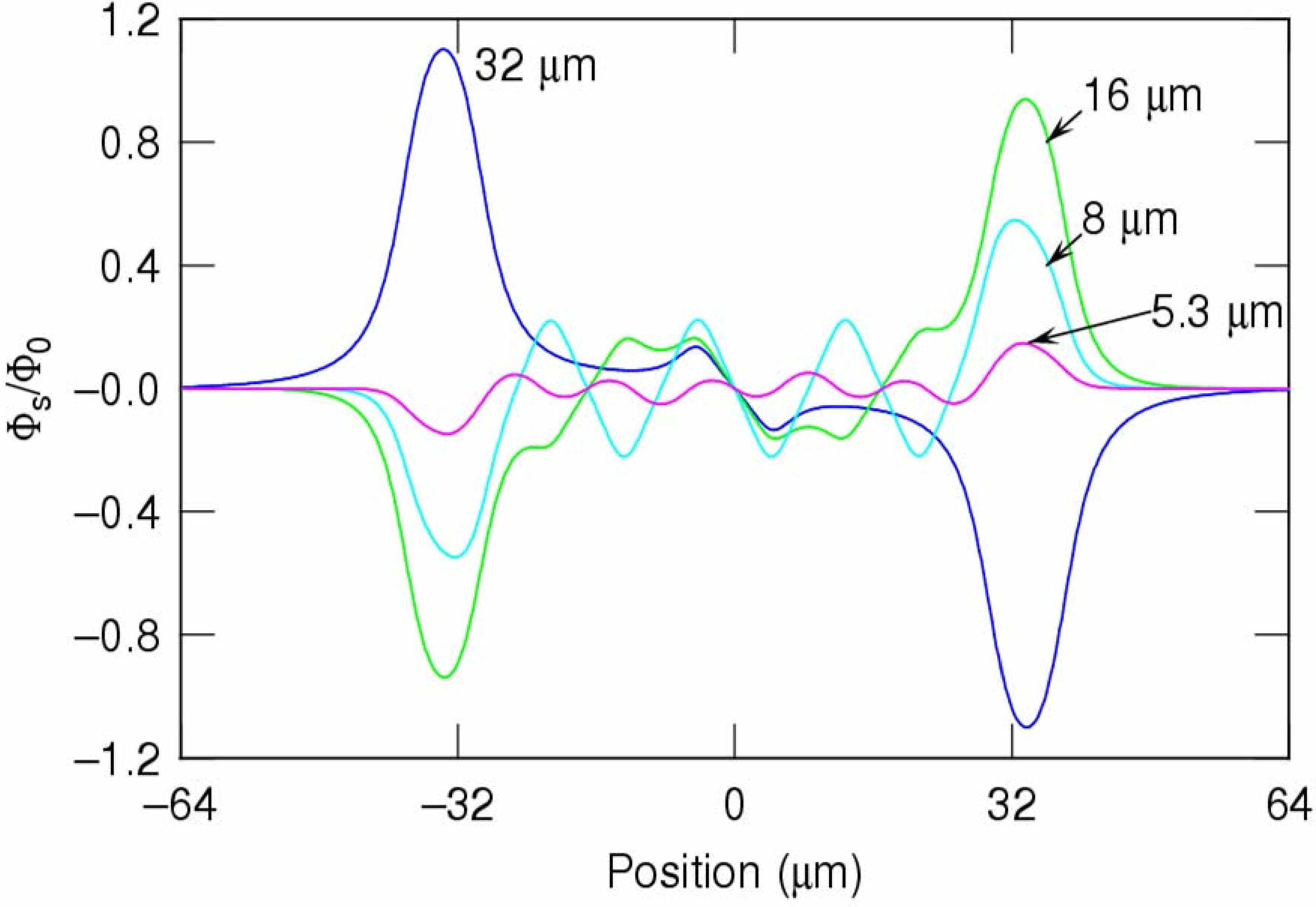


Kirtley et al., PRB 59, 4343 (1999)

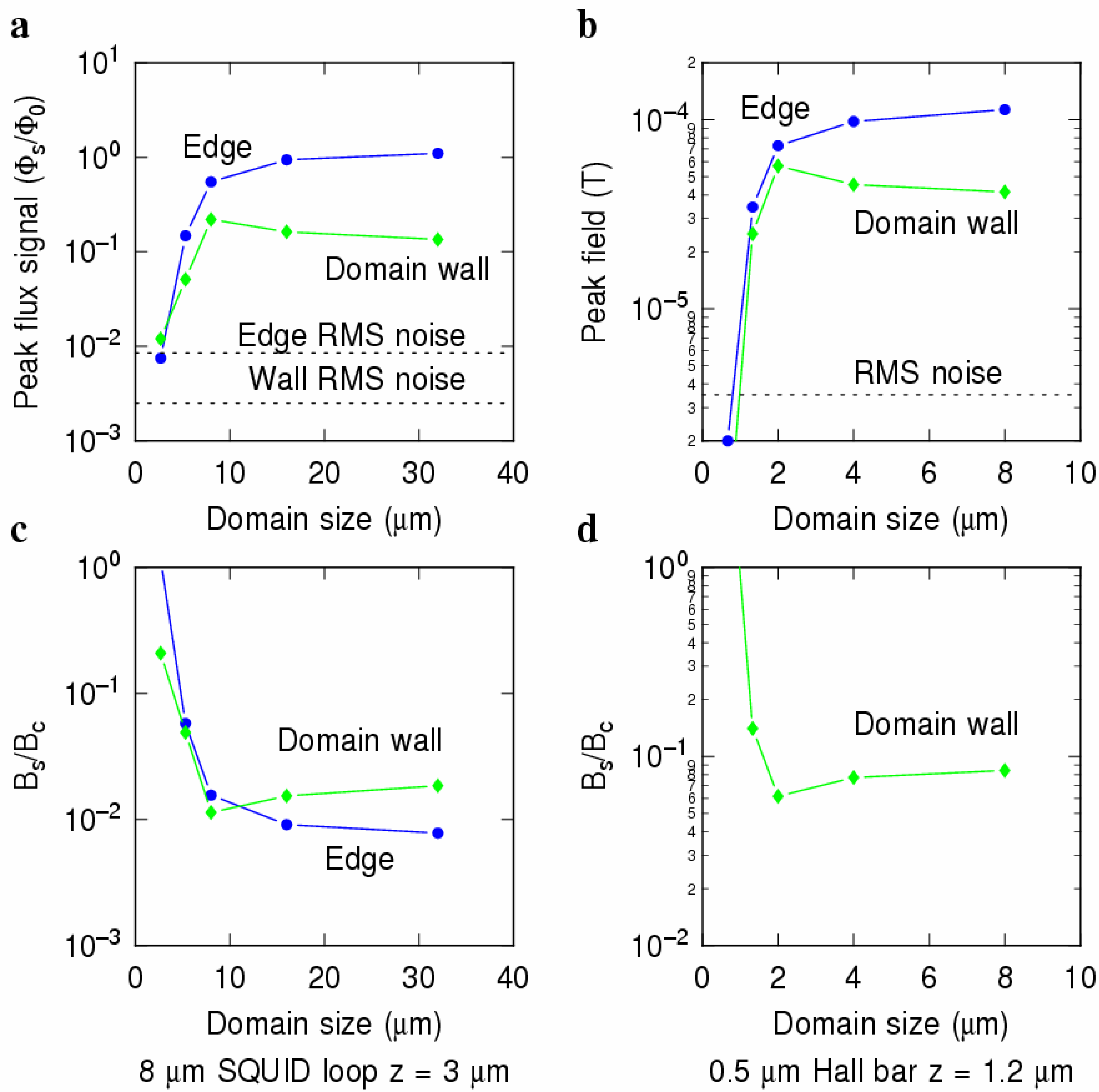
0.5μm Hall bar 1.2μm above the surface



Domain size = 32 μm
16 μm
8 μm
5.3 μm
2.8 Φ0
Pickup loop size
50 μm



32 µm
16 µm
8 µm
5.3 µm
1.2
0.8
0.4
−0.0
−0.4
−0.8
−1.2
Φ_s/Φ_0
−64
−32
0
32
64
Position (µm)



a
Peak flux signal (Φ_s/Φ_0)
Edge
Domain wall
Edge RMS noise
Wall RMS noise
Domain size (μm)
b
Peak field (T)
Edge
Domain wall
RMS noise
Domain size (μm)
c
B_s/B_c
Domain wall
Edge
Domain size (μm)
8 μm SQUID loop z = 3 μm
d
B_s/B_c
Domain wall
Domain size (μm)
0.5 μm Hall bar z = 1.2 μm

Conclusions:

1. Sharp, large spontaneous currents are not observed

2. Explanation A: Large spontaneous currents exist but the domain sizes are (conservatively) less than a few microns

to be compared with

1 micron - van Harlingen - Illinois Urbana-Champaign

50-100 microns - Kaptitulnik - Stanford

1mm - Ying Liu - Penn State

3. Explanation B: Large spontaneous currents don't exist

a. Not (simple) $p_x \pm ip_y$

b. ?