KITP Workshop --- Sr_2RuO_4 --- December 11, 2007

Phase-sensitive Symmetry Measurements in Unconventional Superconductors

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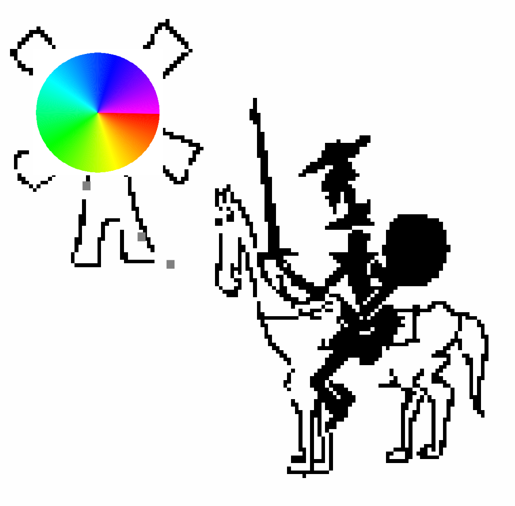
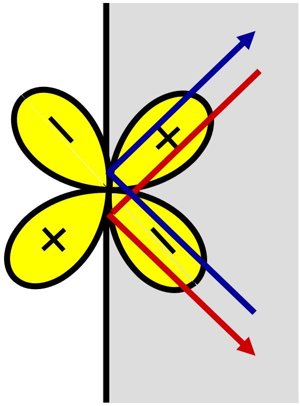
The Quest for Complex Superconductors

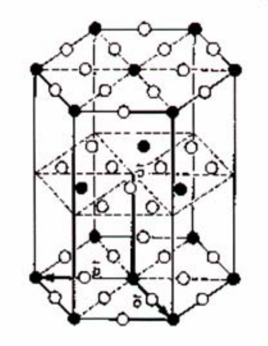


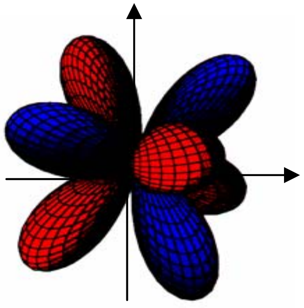
Surface states in anisotropic superconductors:

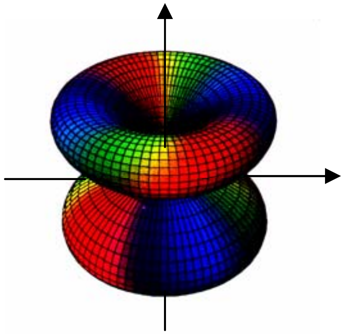


Heavy Fermion superconductors:

UPt$_3$ $T_{cA} = 0.50$ $T_{cB} = 0.45\text{K}$



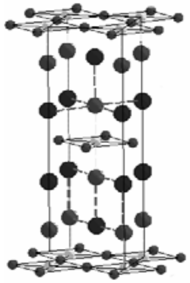


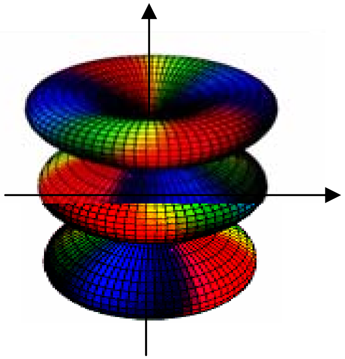


$(k_x^2-k_y^2)\ k_z$ $(k_x + ik_y)^2\ k_z$

Ruthenate superconductors:

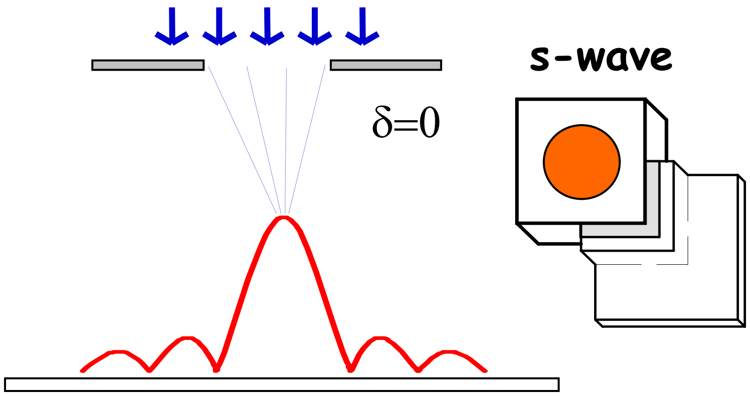
Sr$_2$RuO$_4$ $T_c = 1.5\text{K}$



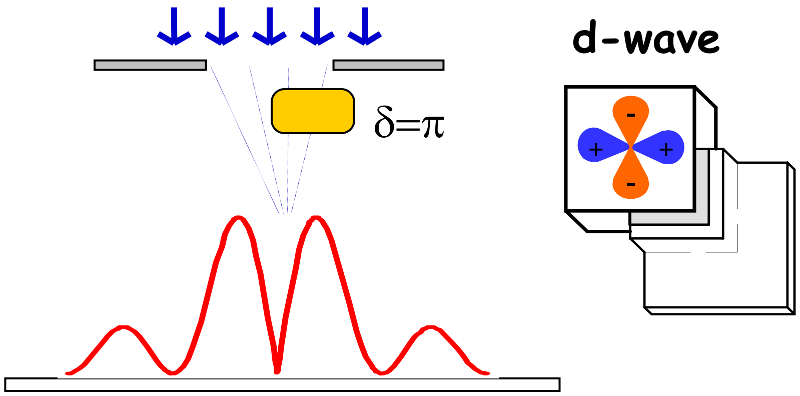


"complex p-wave"

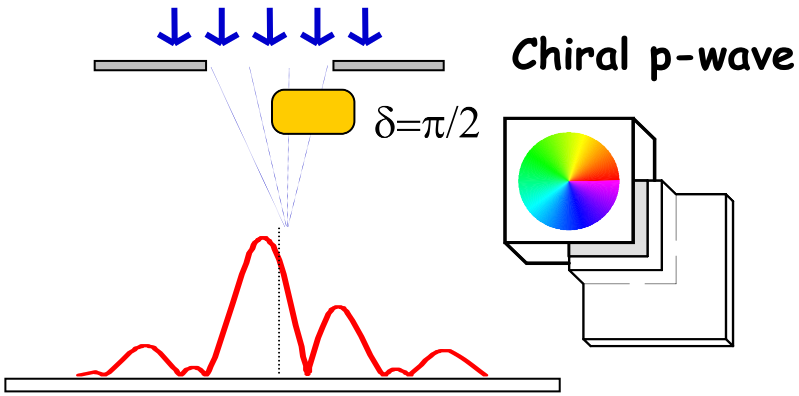
Josephson phase interferometry



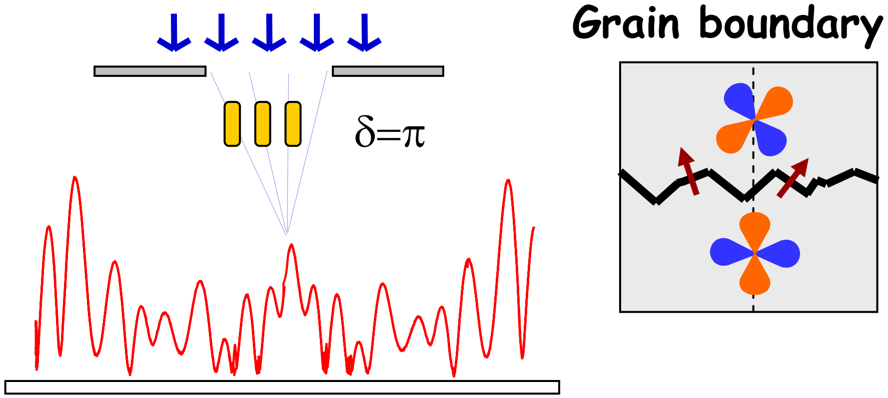
Fraunhofer diffraction pattern



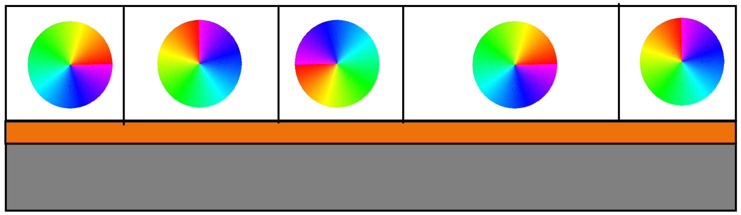
Minimum at zero field



Polarity asymmetry



Multiple phase interference

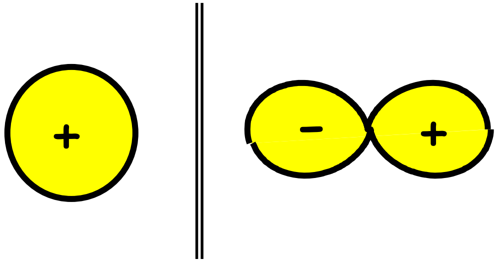


Chiral domains

The Parity Problem

Josephson Coupling of EVEN (singlet) and ODD (triplet) Superconductors

THEORY



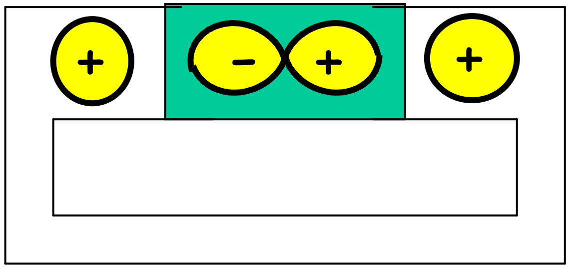
1st order Josephson effect cancels

2nd order Josephson effect allowed:
weak coupling $\sim |T|^4$
distinguishable by Shapiro steps

EXPERIMENT

Spin-orbit scattering breaks spin symmetry ---
net supercurrrent possible

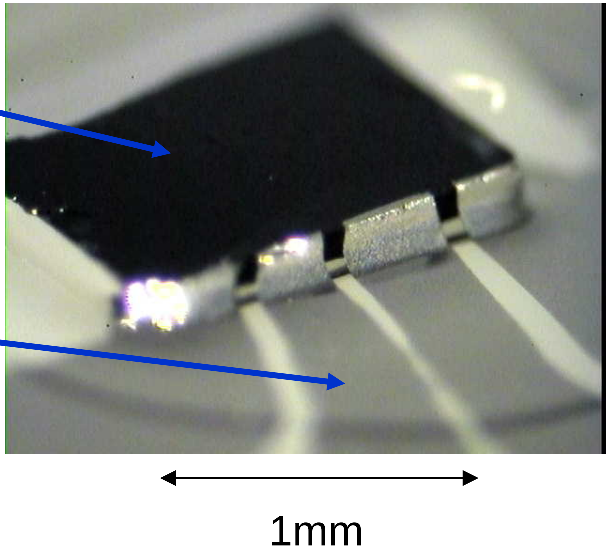
INTERFEROMETRY



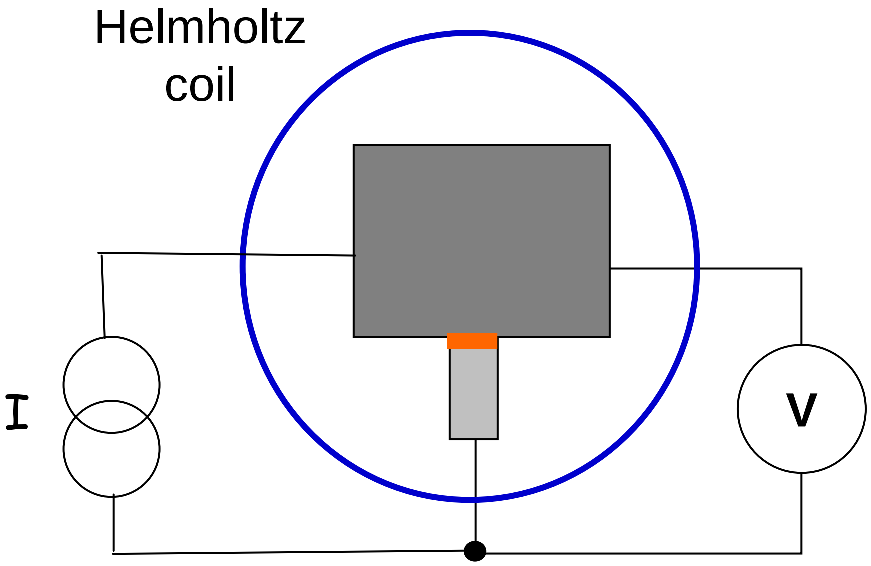
- Could couple to either lobe ---
  bi-modal results (0 or π phase shift)
- Domain structure nucleation at surface

Sample fabrication

- Cleave or polish single crystal
- Glue on substrate, mask leads
- Ion mill surface to clean
- Thermal evaporation of Cu and Pb
- Can make edge or corner junctions



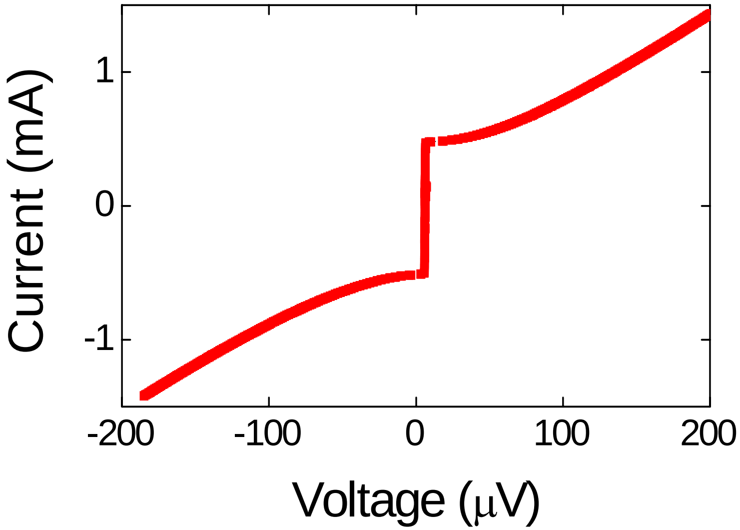
Measurement setup

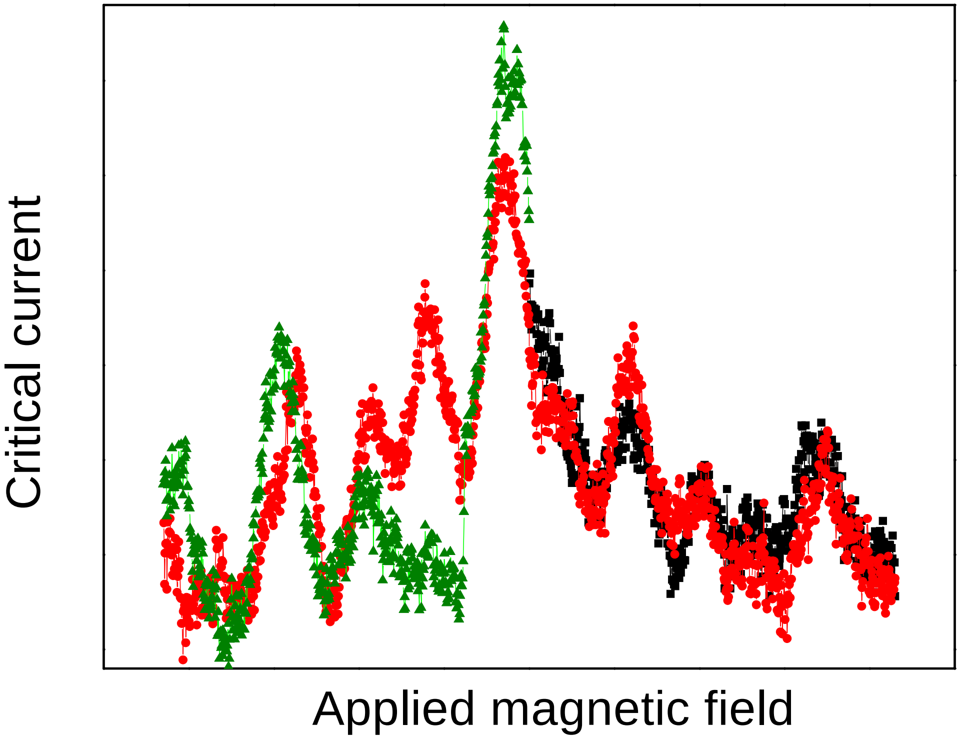


- Measurements in ^{3}He refrigerator
- dc SQUID potentiometer for voltage measurements
- Helmholtz coil to apply vertical field

Critical current modulation in Sr_2RuO_4/Au/Pb junctions

Resistively-shunted junction
IV characteristics

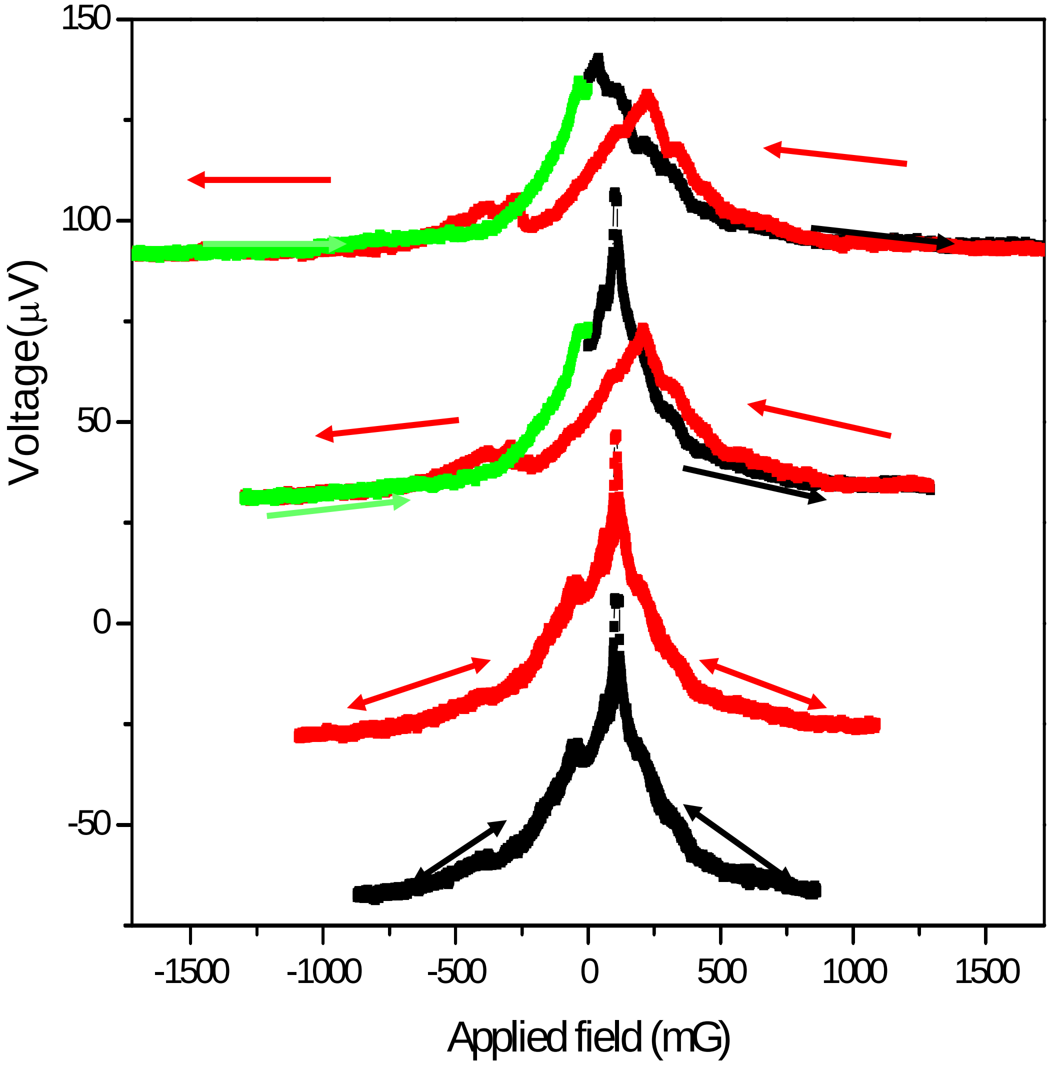




Many features never seen in cuprates or conventional superconductors:

- Polarity asymmetry
- Hysteresis
- Abrupt jumps in critical current
- Two-level "telegraph" switching noise
- Different patterns on different crystals/faces/thermal cycles

Critical current/voltage hysteresis in magnetic field sweeps

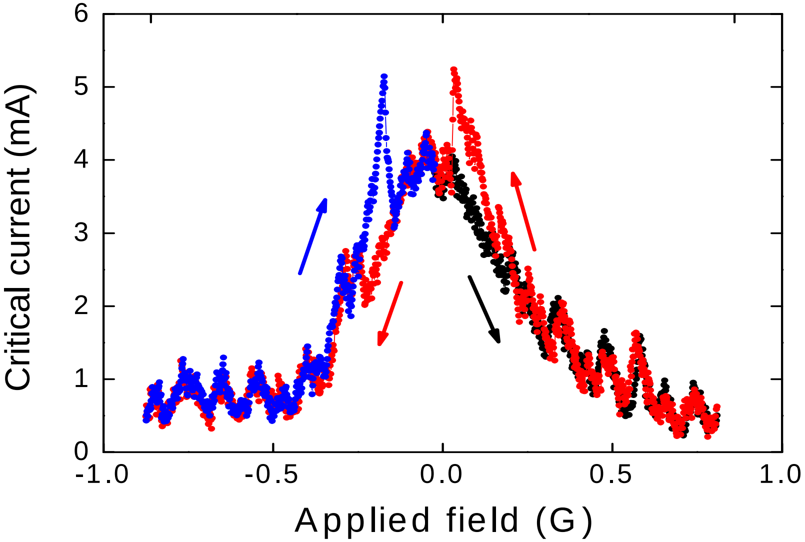


- Retraces below threshold field (~1.2G for this sample)
- Constant hysteresis above threshold field
- Hysteresis "heals" if sweep reduced (de-Gaussing?)

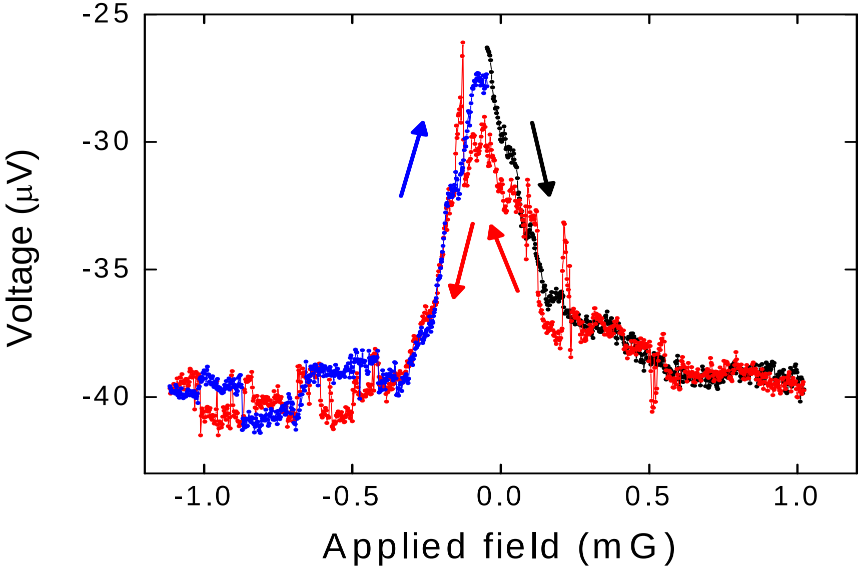
Pinned domains interacting with magnetic field?

Critical current switches noise in SRO junctions

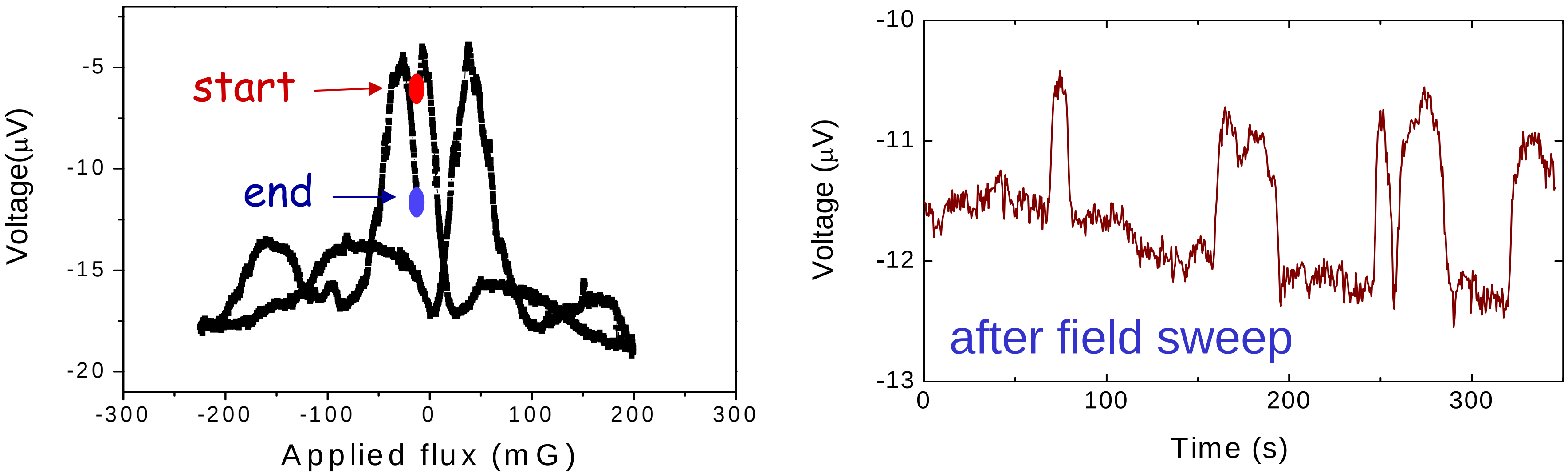
Abrupt switches



Telegraph noise

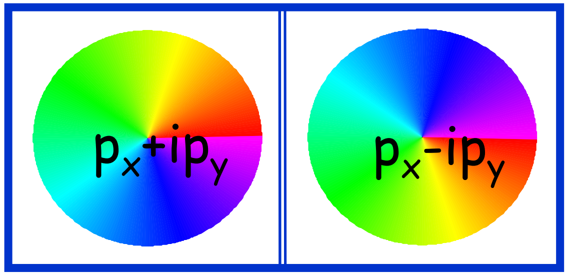


Switches in timetraces



Chiral order parameter domains

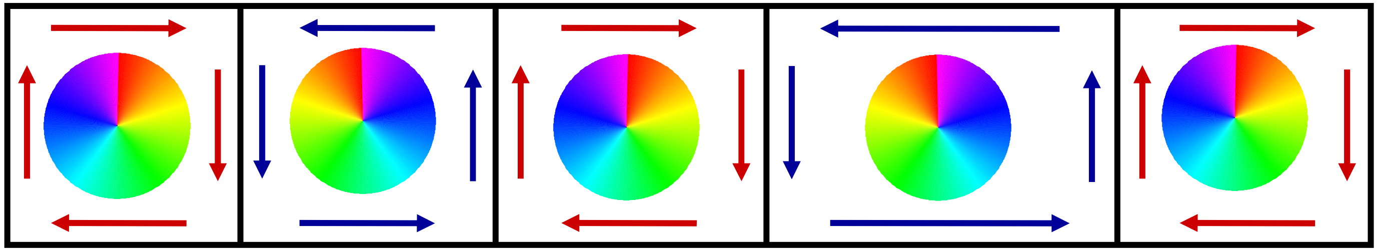
Francoise Kidwingira, J. D. Strand, D. J. Van Harlingen, Yoshiteru Maeno, Science 314, 1267 (2006)



Evidence for domains

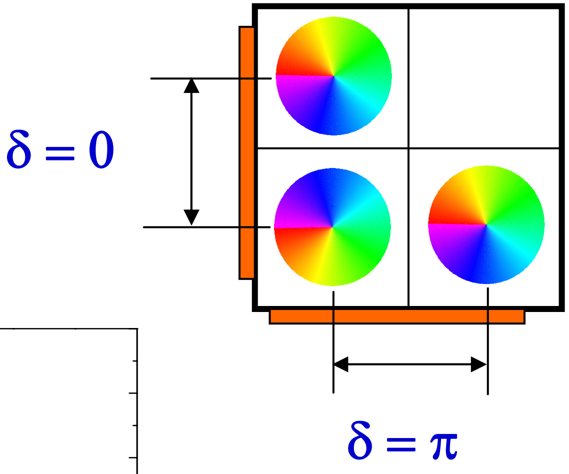
- Phase interference explains variety of diffraction patterns
- Switching between different domains configurations
- Hysteresis caused by domain wall motion and pinning

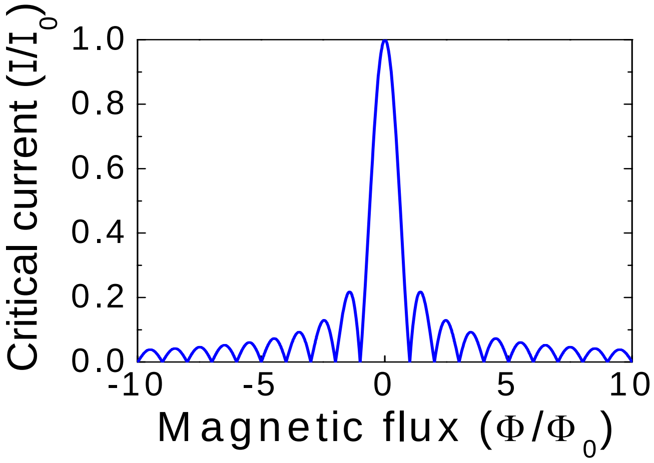
Chiral currents flow around domain edges --- estimated domain size ~ 1μm from number of "periods" in diffraction pattern envelope



Not observed by SSM: J. R. Kirtley, C. Kallin, C. W. Hicks, E.-A. Kim, Y. Liu, K. A. Moler, Y. Maeno, and K. D. Nelson Phys. Rev. B **76**, 014526 (2007)

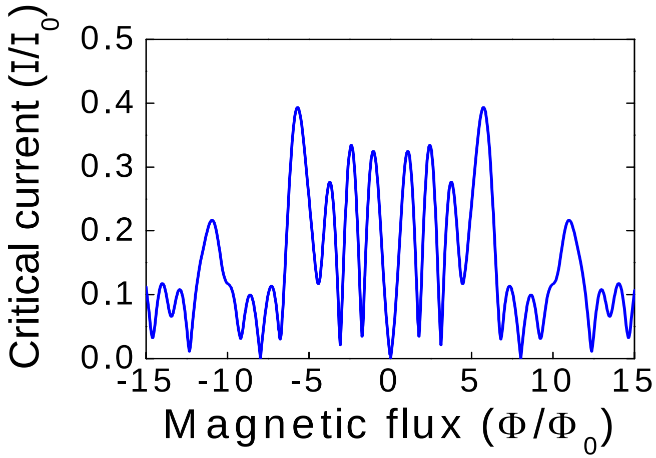
Diffraction patterns: chiral domains

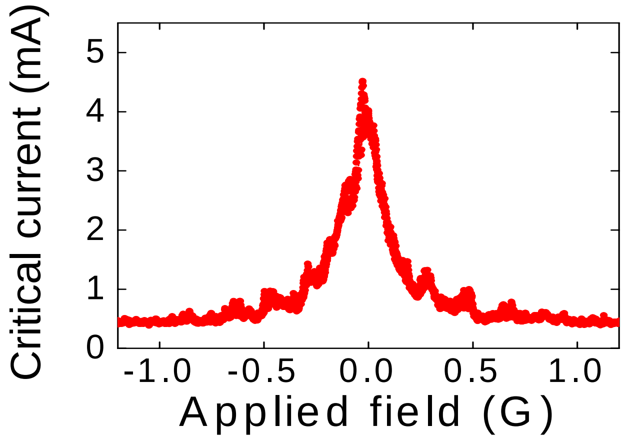




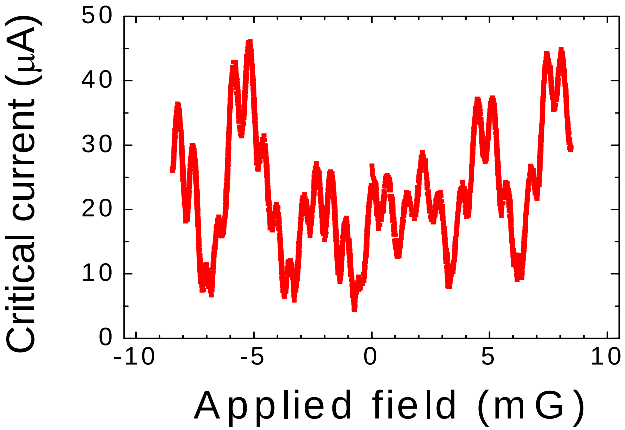
Simulation

(10 domains)



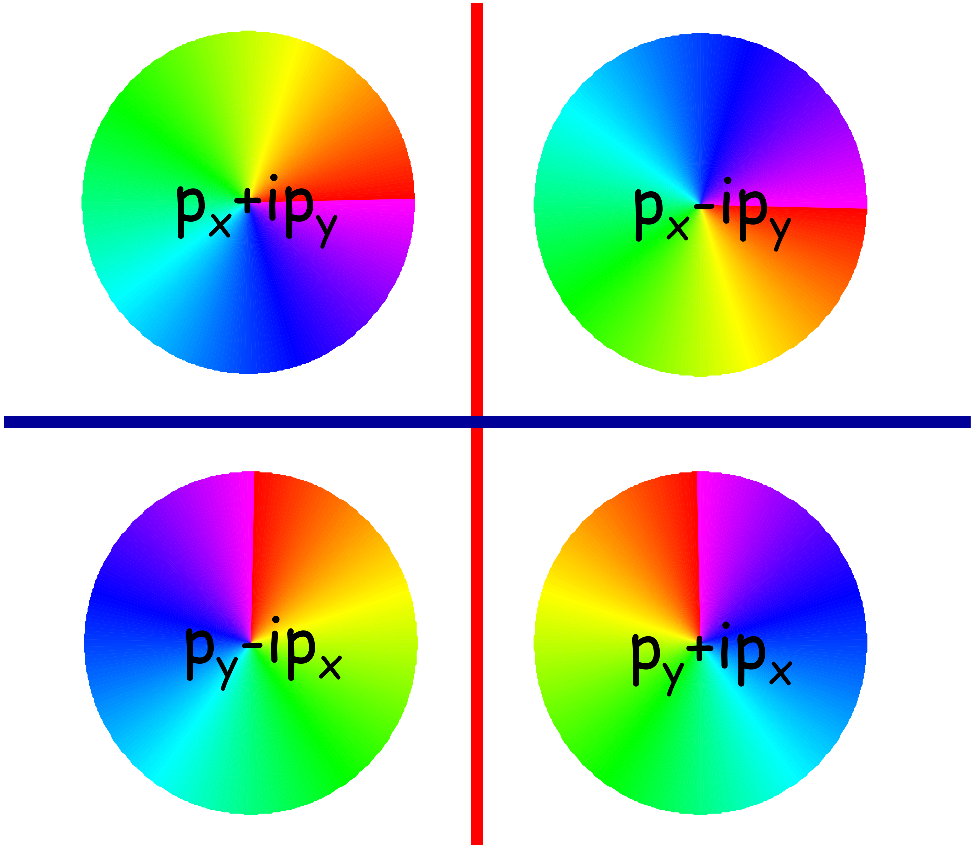


Measurement



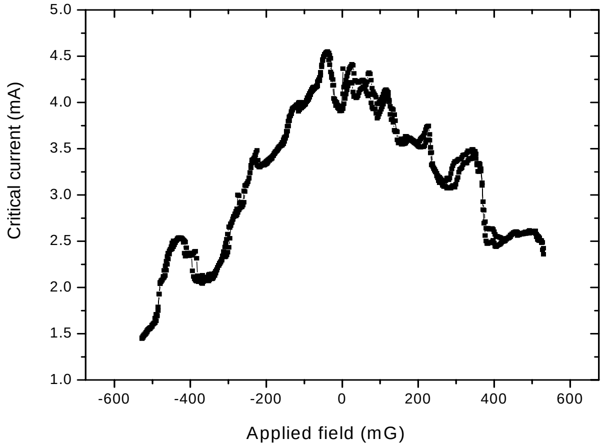
Two types of chiral domain walls

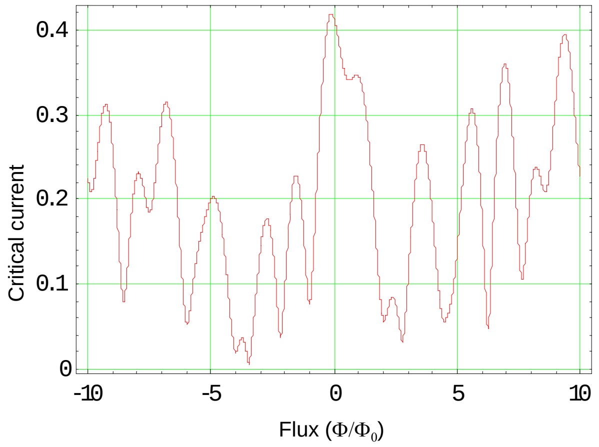
PARALLEL
chiral domains
(change in rotation of phase)

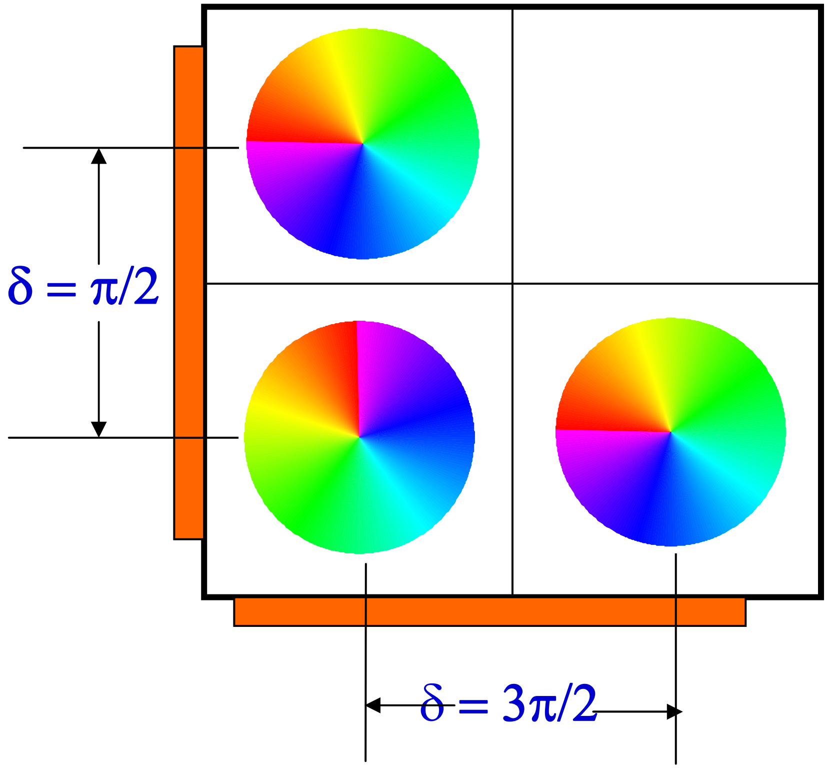


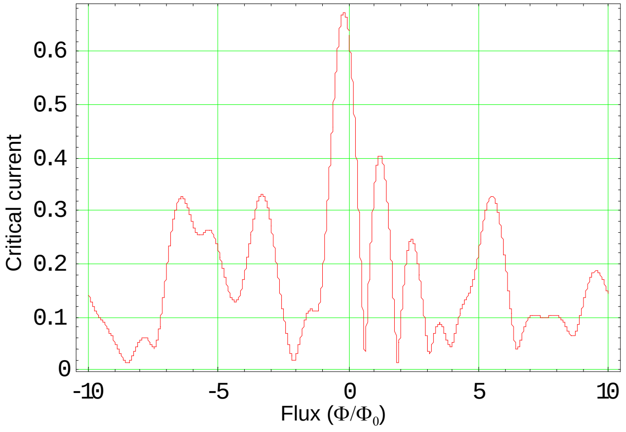
PERPENDICULAR
chiral domains
(change in alignment of the real component)

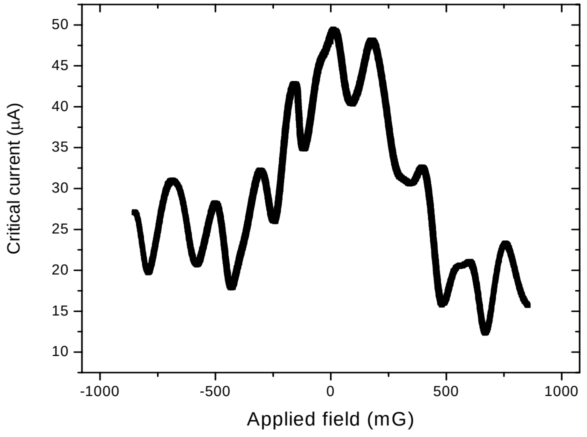
Perpendicular chiral domains





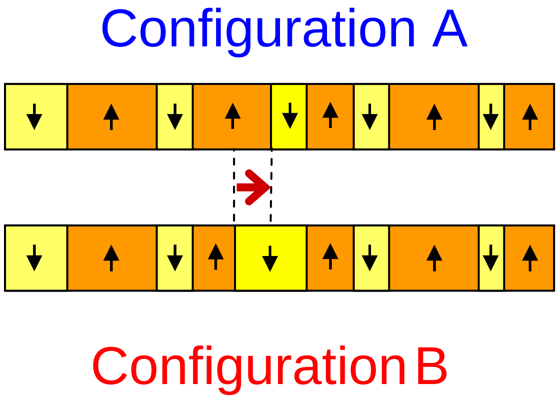


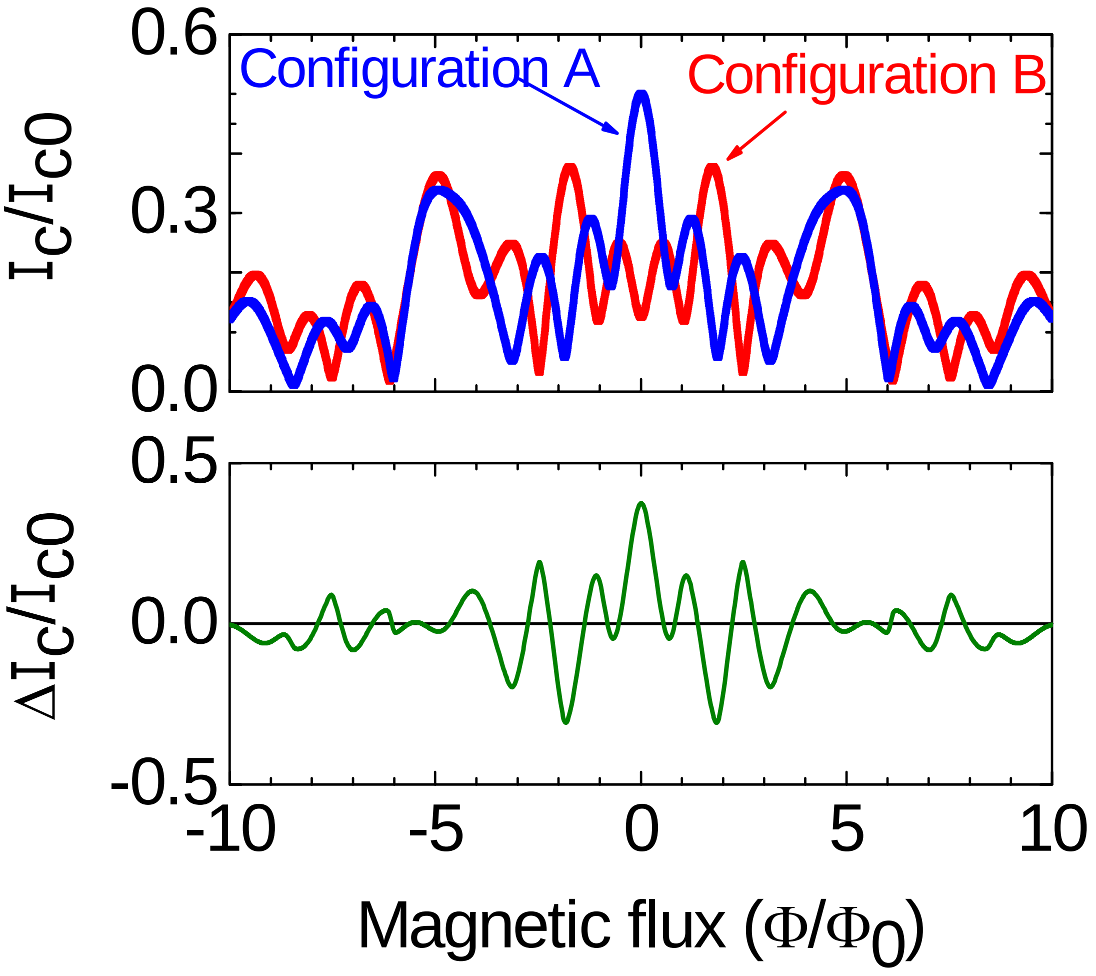




Sensitivity to single domain switching

Motion of a single domain wall dramatically changes the critical current diffraction pattern → accounts for switching noise observed

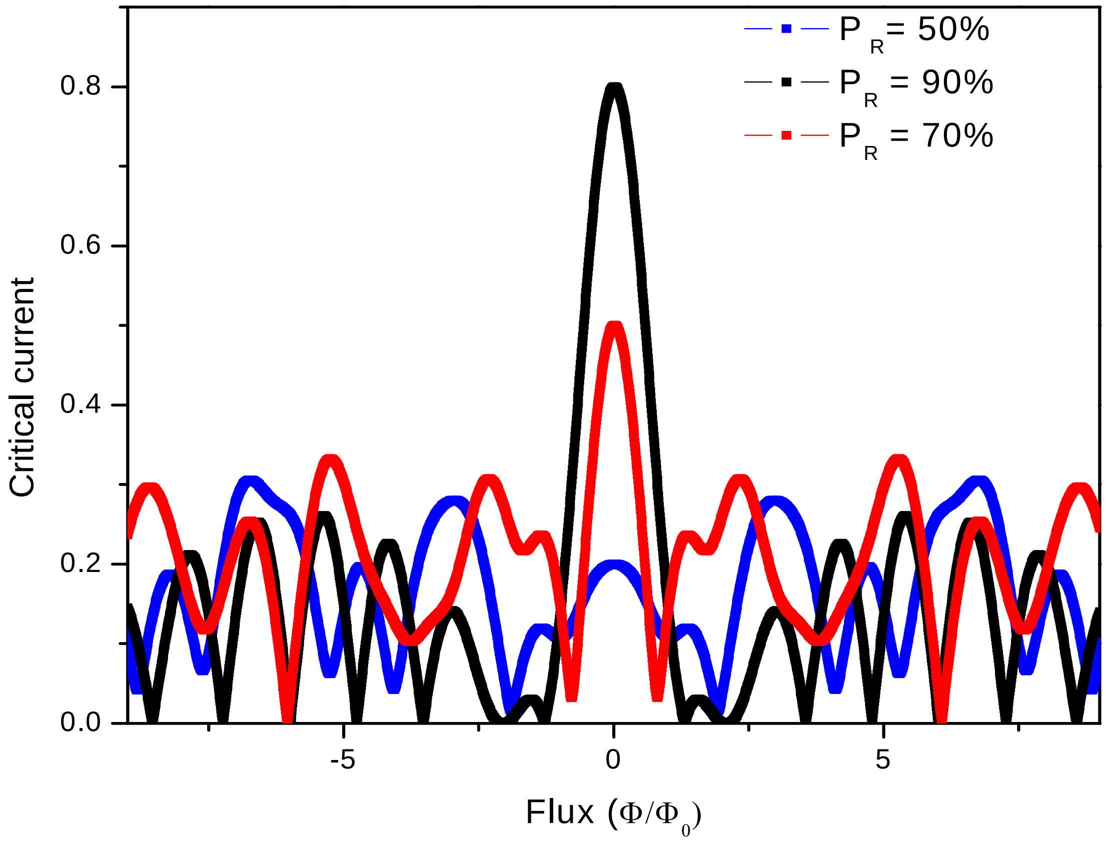




Field cooling: simulations

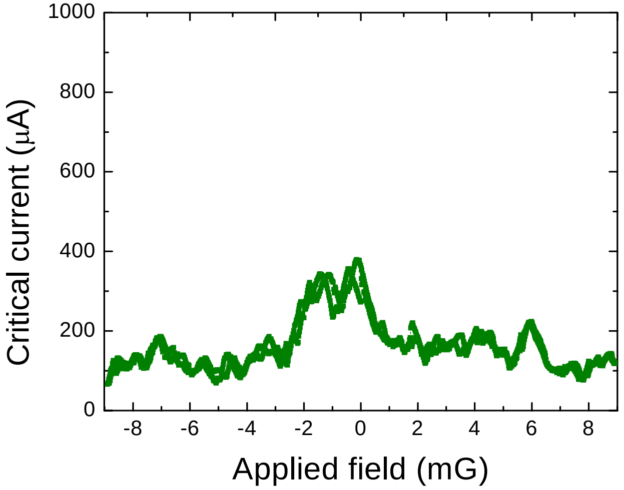
Chiral domain currents couple to applied magnetic fields

Applied field breaks chiral degeneracy, favoring on chirality

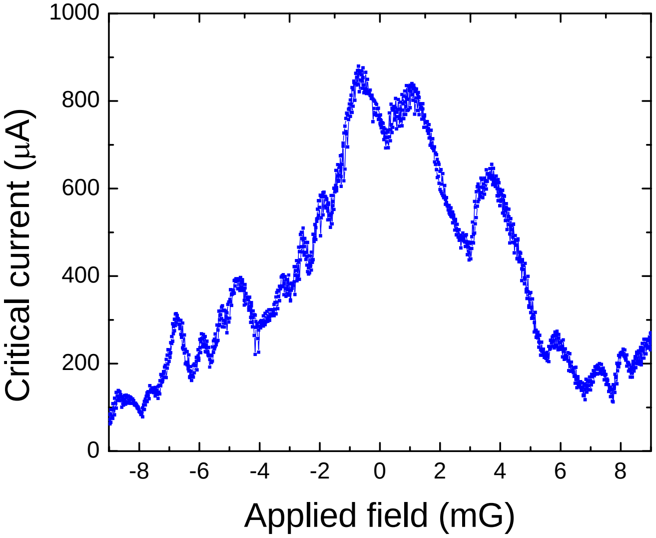


- Enhancement of I_c from alignment of domains
- Changes structure from "grating-like" to "Fraunhofer-like"

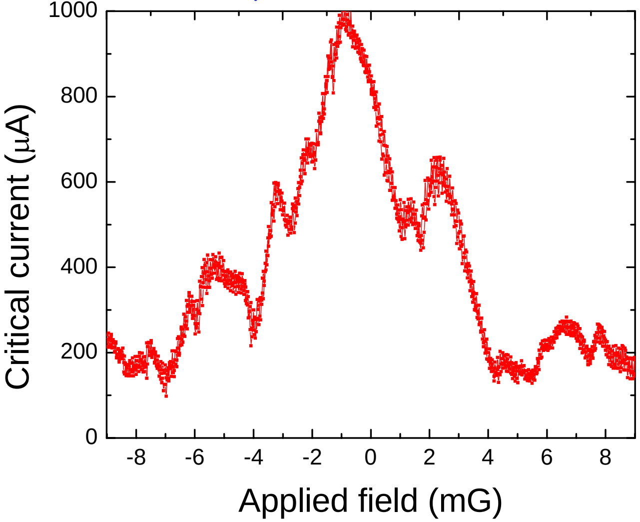
Field cooling: critical current enhancement



Zero field Cooled



30μG field Cooled



-30μG field Cooled

Enhancement only for limited field range because of vortex trapping

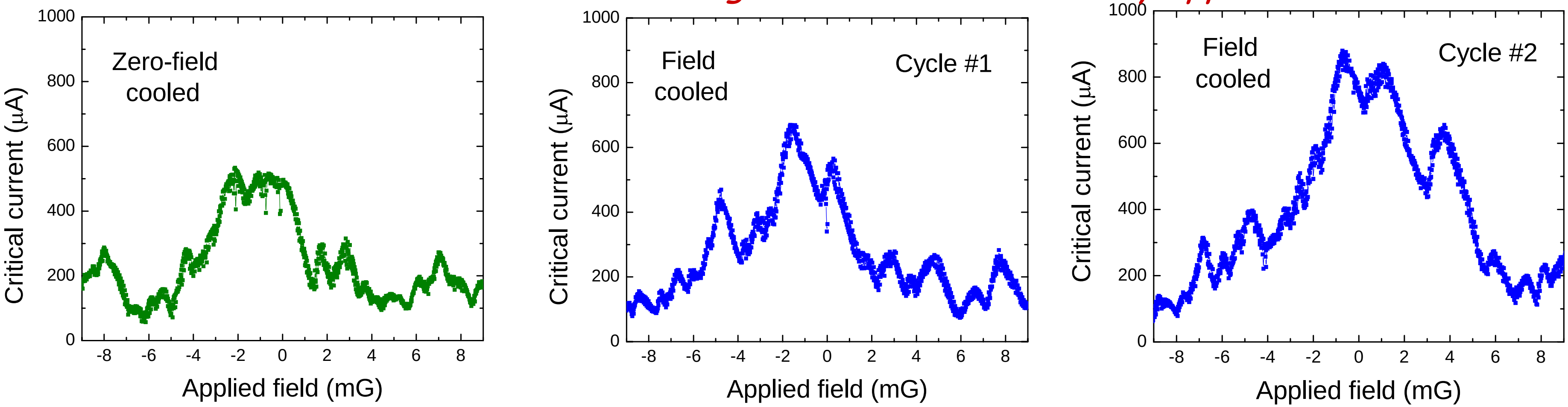
Dramatic increase in I_c for both polarities

Field range scales with junction size but is surprisingly small (< 1mG)

Field cooling: domain training and memory effects

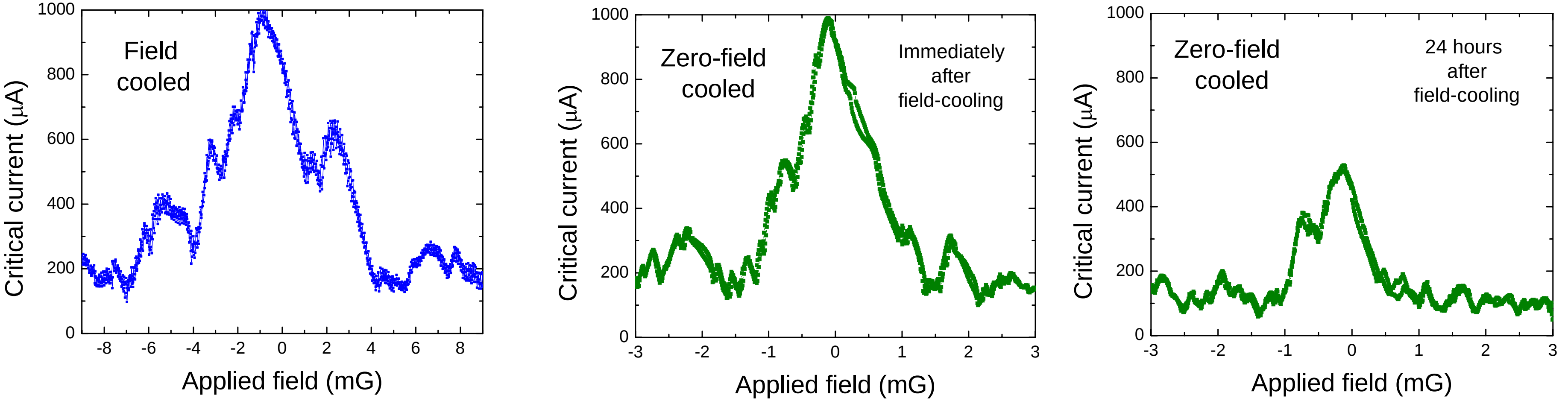
Critical current increases gradually with successive field-cooling cycles

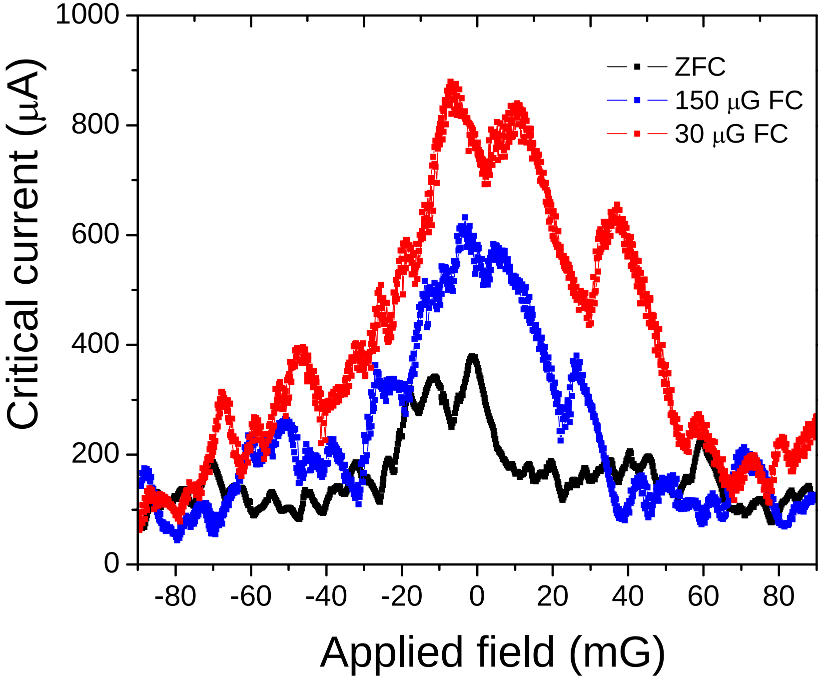
Possible mechanism: domain alignment can be trained by applied field



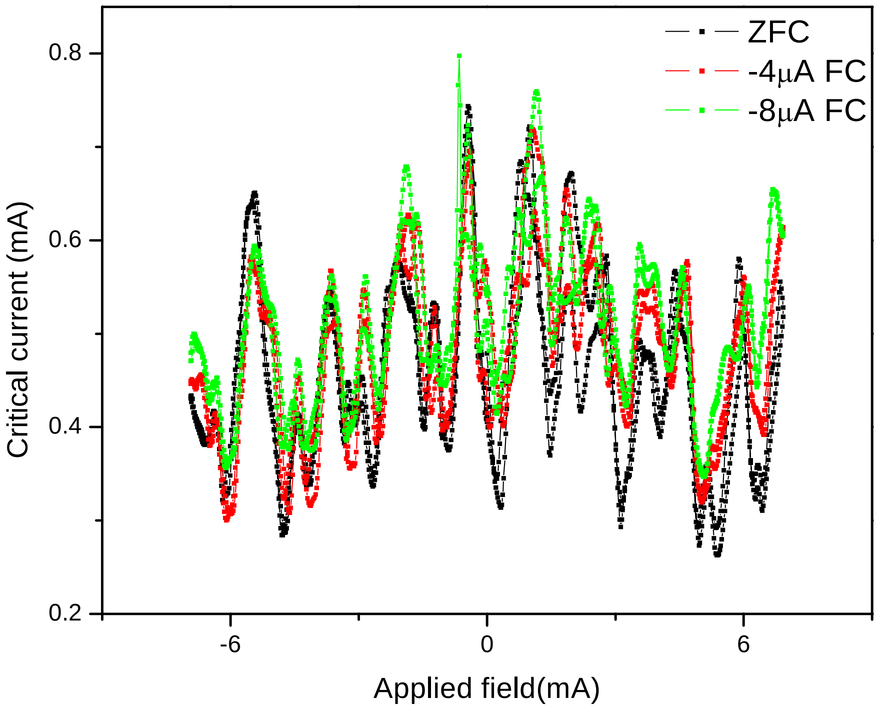
Critical current retains enhancement after zero-field cooling, decays over time

Possible mechanism: magnetic inclusions ($Sr_3Ru_2O_7$) or surface states





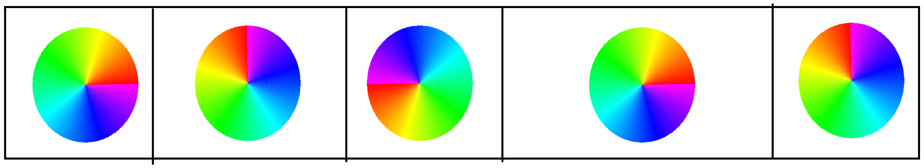
Effect of high fields --- critical current is reduced. Trapped flux?



Field along tunneling direction --- no change in critical current

Conclusions

Evidence for dynamical chiral order parameter domains



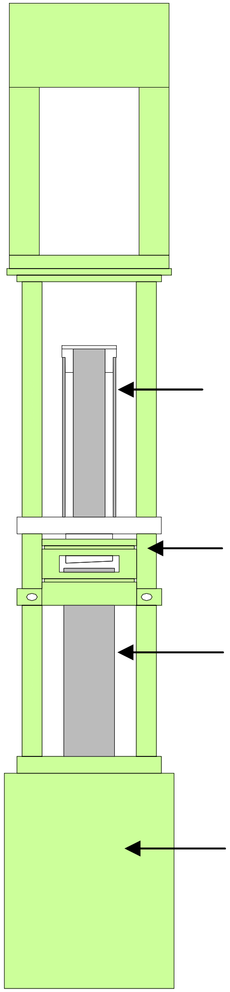
- Field-induced domain wall motion
  (hysteresis, switching, telegraph noise with field and time, ..)
- Field cooling shows dramatic enhancement of critical current
- Memory effect shows training of domain configurations

Issues

- Large IcR products (~1mV) --- comparable to cuprates and
  large for odd-even Josephson effect
- Nodes --- where located?
- Vortices?
- Observation of chiral currents?

Imaging chiral domains: Scanning SQUID Microscopy

Developing instruments to map domain structure via chiral current distribution
Designed for Oxford top-loading dilution refrigerator temperatures (2K-10mK)

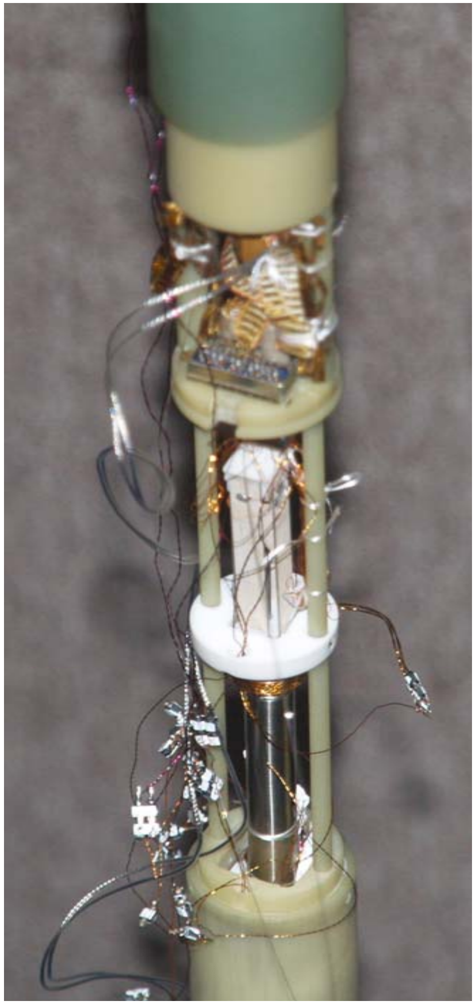


Bimorph piezo
x-y scanner

Sample and
Helmholtz coil

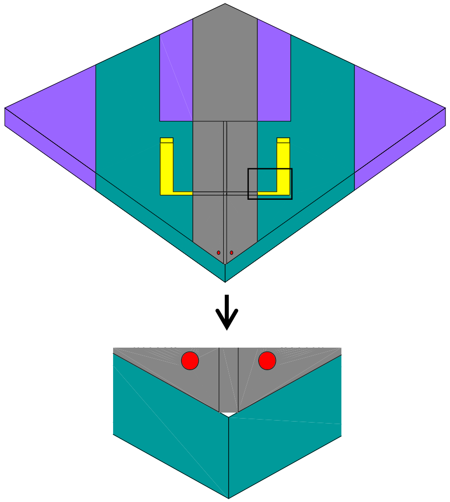
Piezo z-control
interferometer
feedback

Inertial walker
z-positioning

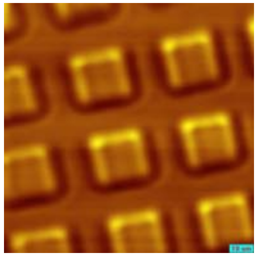


Sensors: dc SQUIDs

Spatial resolution: $<1\mu m$

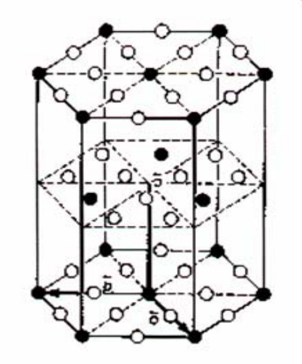


Simultaneous imaging of topography
and magnetic field distribution



Chiral triplet superconductor? heavy fermion UPt_3

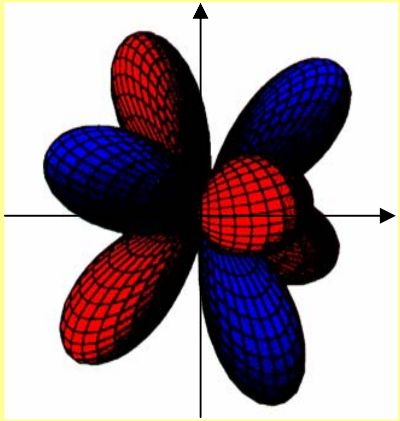
Two superconducting phases:



hexagonal
structure

upper-phase <u>real</u>

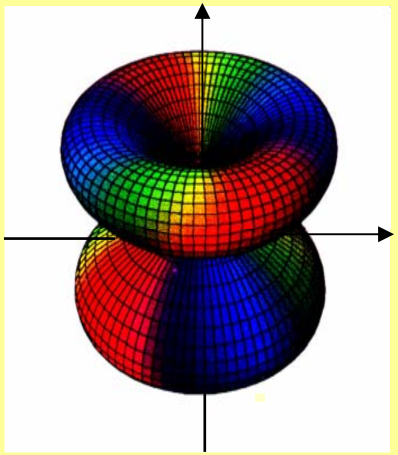
$(k_x^2 - k_y^2)\, k_z$



$T_{cU} \sim 0.50\text{K}$

lower-phase <u>complex</u>

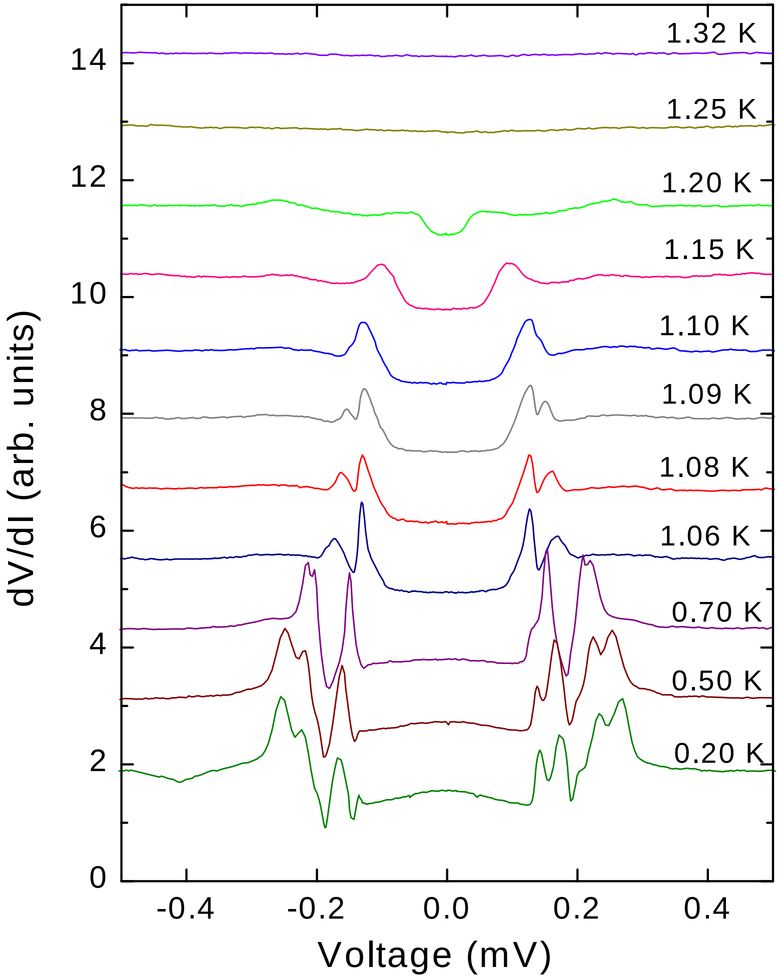
$(k_x + i k_y)^2\, k_z$

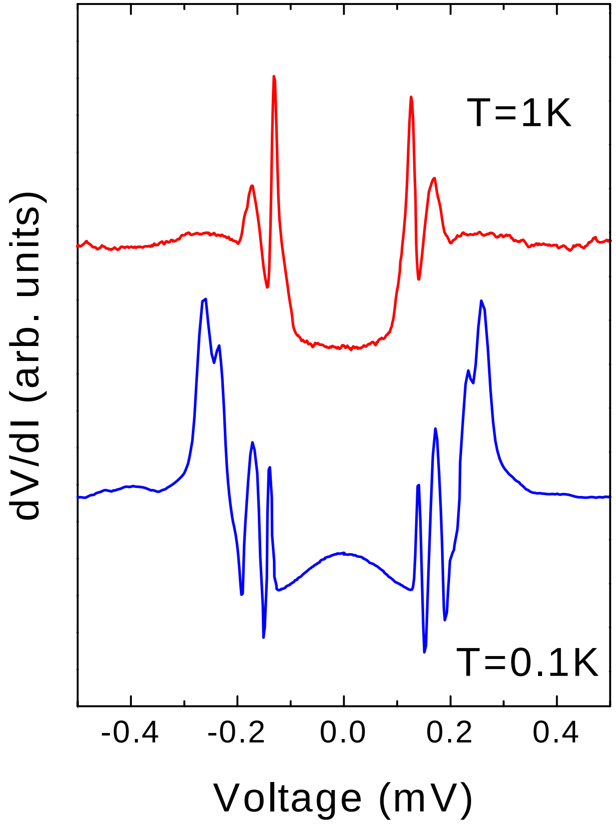


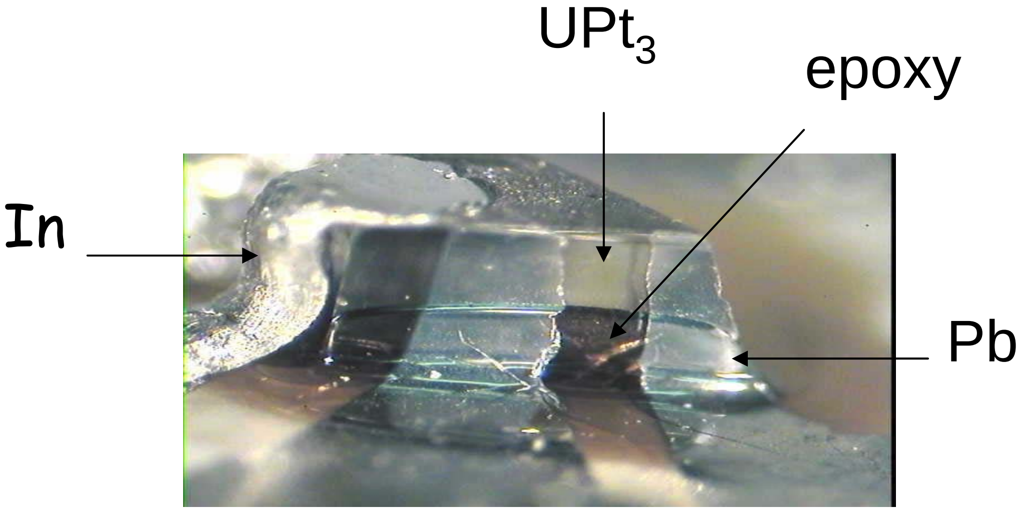
$T_{cL} = T_{cU} - 50\text{mK}$

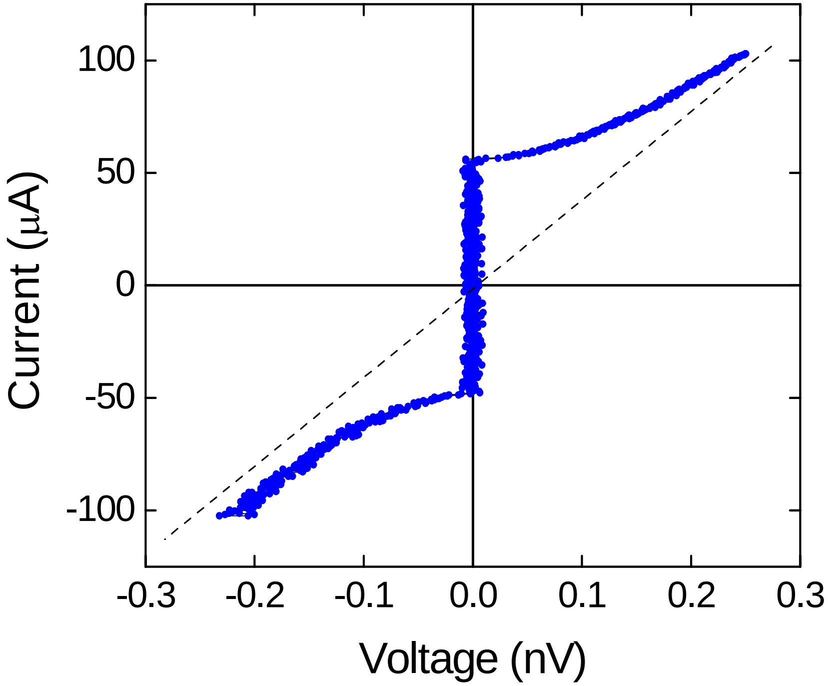
UPt_3 experiments --- results

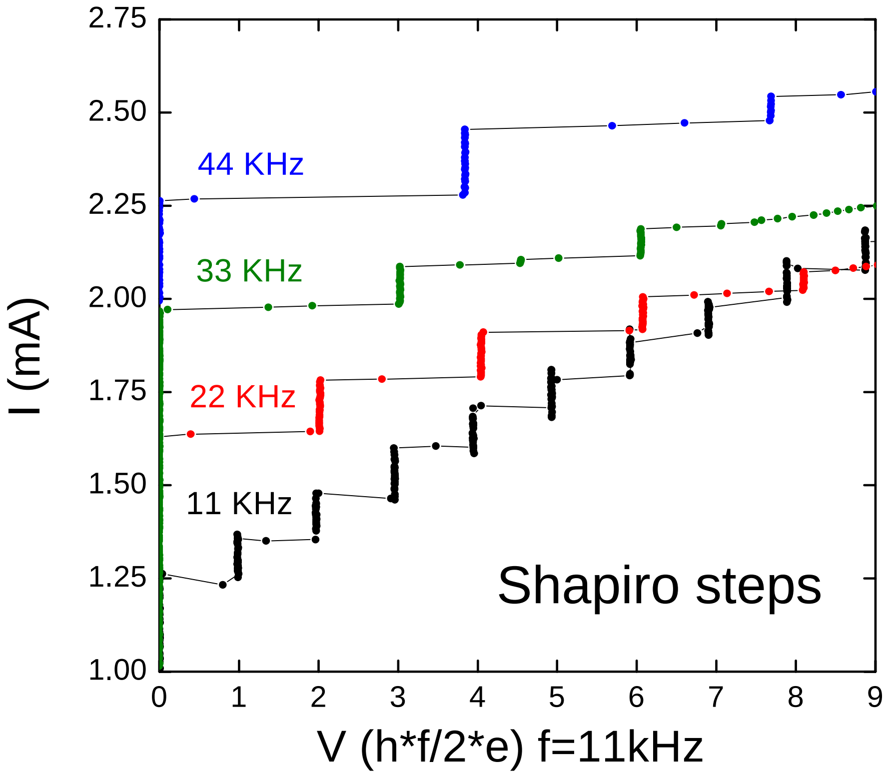
- NO supercurrents: Intrinsic? Indication of p-wave?
  (Sumiyama et al. – supercurrents observed: J_c<1A/cm², I_cR~10nV)
- Observe complex structure in IV's: Al gap opening
  sharp features above gap
  zero-bias peak in resistance

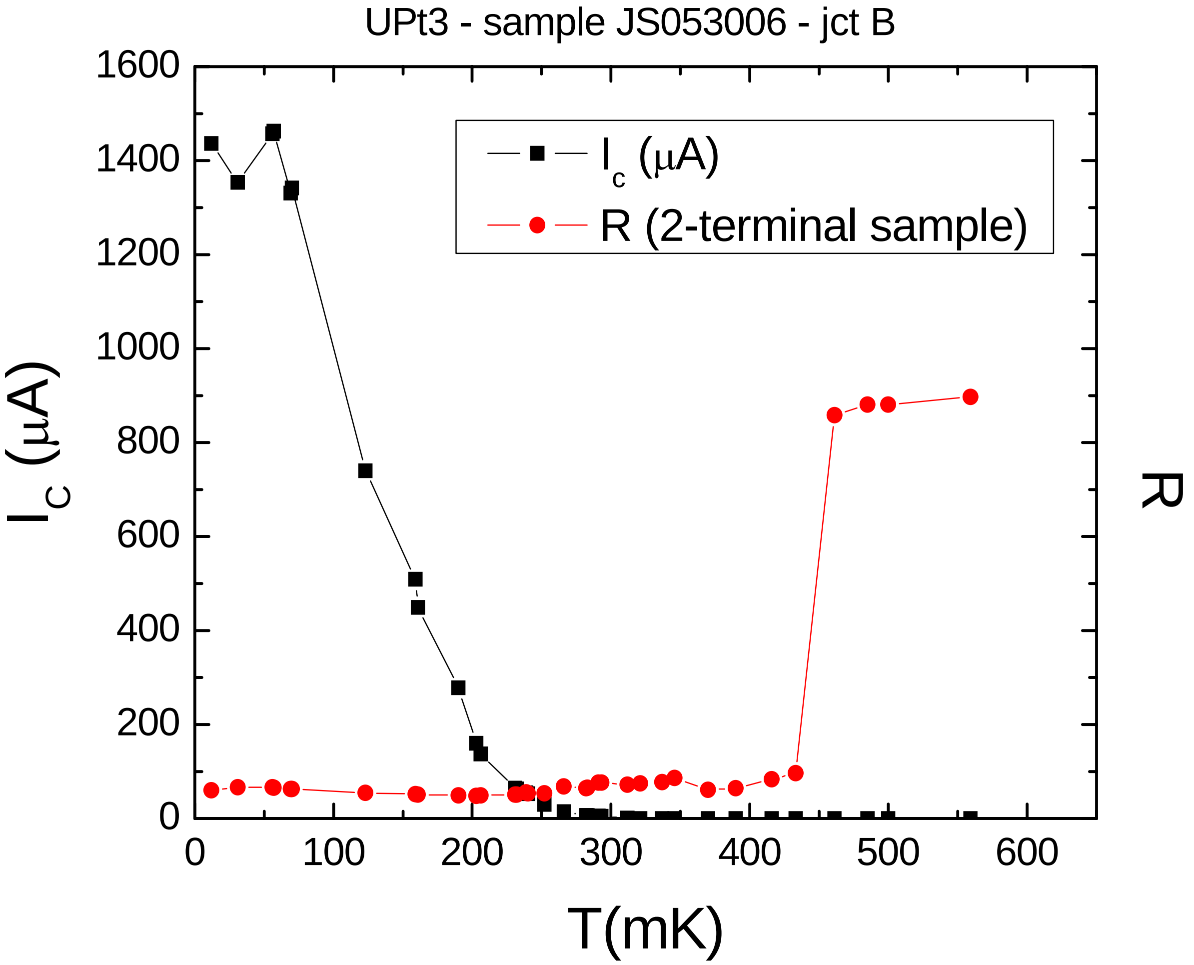





UPt$_3$
epoxy
In
Pb


Current (μA)
100
50
0
-50
-100
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
Voltage (nV)


I (mA)
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
44 KHz
33 KHz
22 KHz
11 KHz
Shapiro steps
0
1
2
3
4
5
6
7
8
9
V (h*f/2*e) f=11kHz



1st polished: 300mK

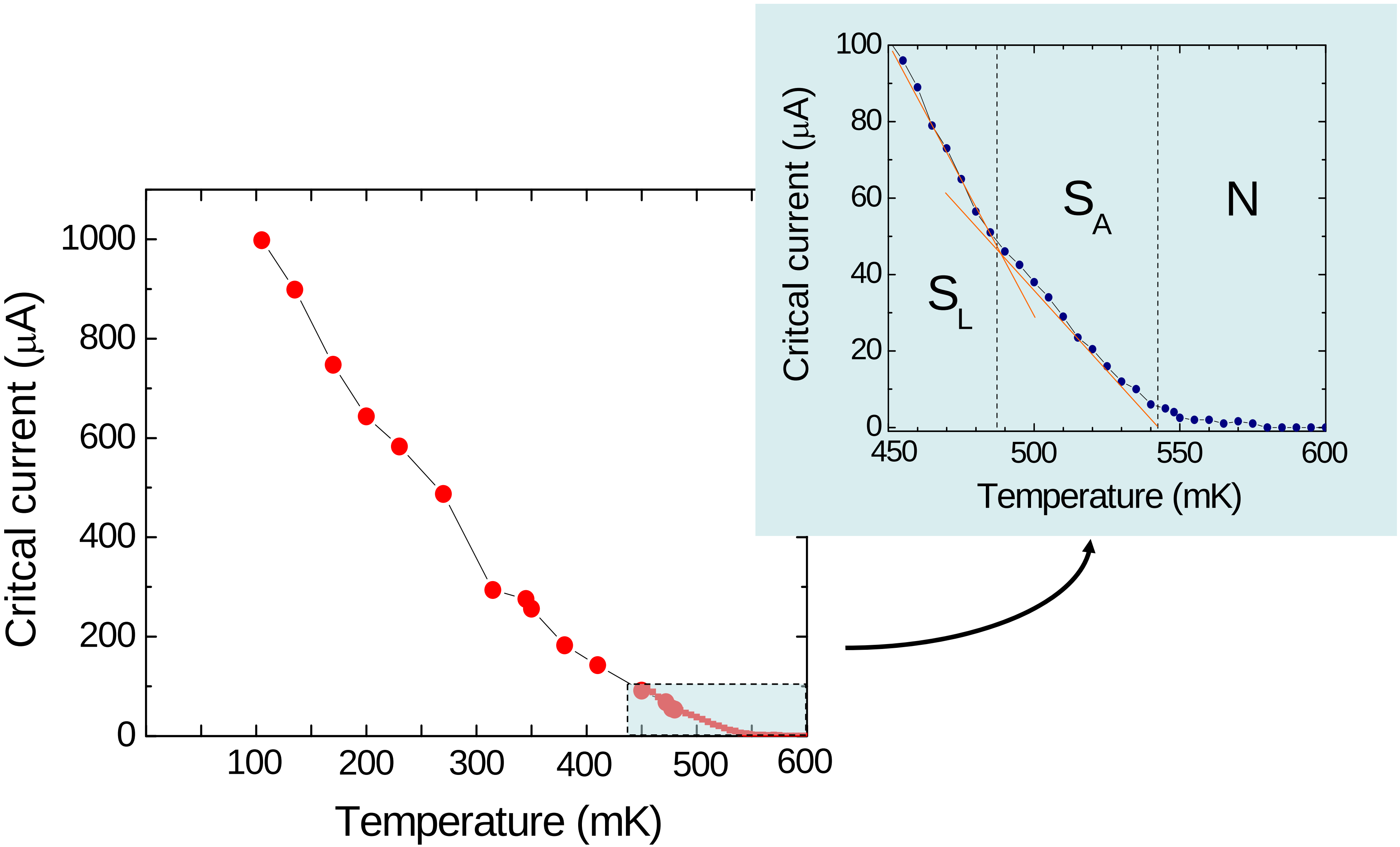
★ 2nd polished: 600mK

3rd polished: 360mK

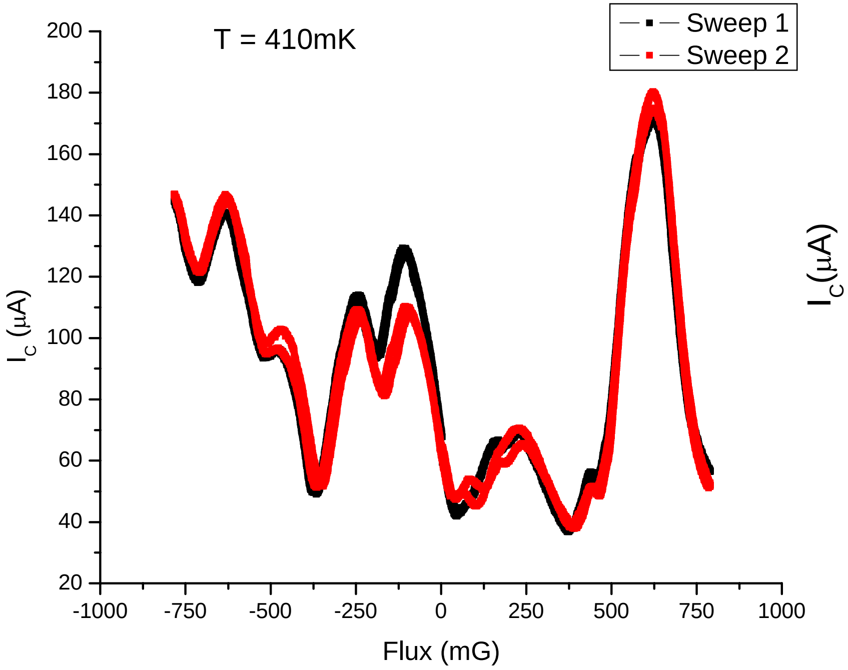
1st etched: 300mK

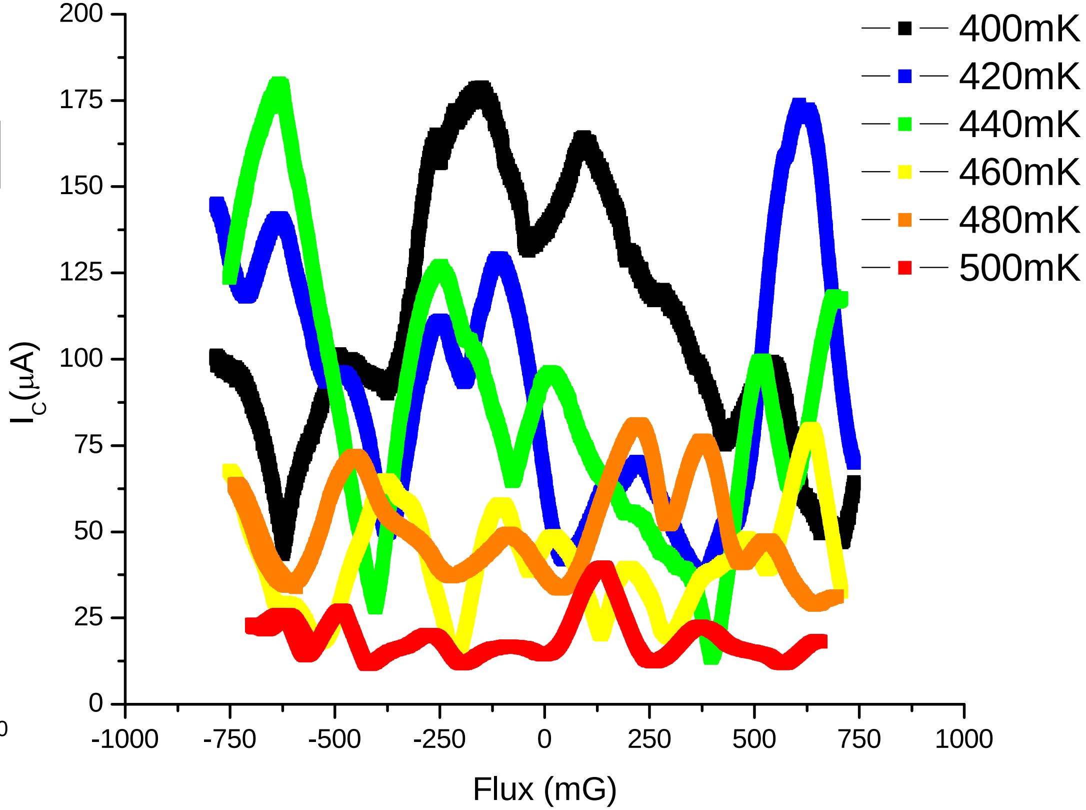
2nd etched: 380mK

Similar to Sumiyama et al.


Critical current (μA)
1000
800
600
400
200
0
100
200
300
400
500
600
Temperature (mK)
Critical current (μA)
100
80
60
40
20
0
450
500
550
600
Temperature (mK)
S_L
S_A
N

UPt_3 --- preliminary diffaction patterns





Complicated but not at all like Sr_2RuO_4

- Patterns retrace --- no hysteresis, no switching noise
- Patterns at fixed temperature are reproducible
- Patterns at different temperatures are dramatically different!
  evidence for magnetic surface states or domains?