Quantum vortex tunneling (QVT) in YBCO thin films and supercurrents in c-axis junctions of the cuprates in the pseudogap regime

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Observation of quantum vortex tunneling
in a 2D superconductor at low T
or
Vortex variable range hopping in $YBa_2Cu_3O_{7-\delta}$ thin films

Study done in 2006-7 in collaboration with Assa

PHYSICAL REVIEW B **76**, 134516 (2007)

Quantum vortex tunneling in $YBa_2Cu_3O_{7-\delta}$ thin films

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(Received 5 July 2007; published 31 October 2007)

Motivation was to test the QVT prediction of:

PHYSICAL REVIEW B **74**, 064511 (2006)

Quantum tunneling of vortices in two-dimensional condensates

Assa Auerbach,[1] Daniel P. Arovas,[2] and Sankalpa Ghosh[3,*]

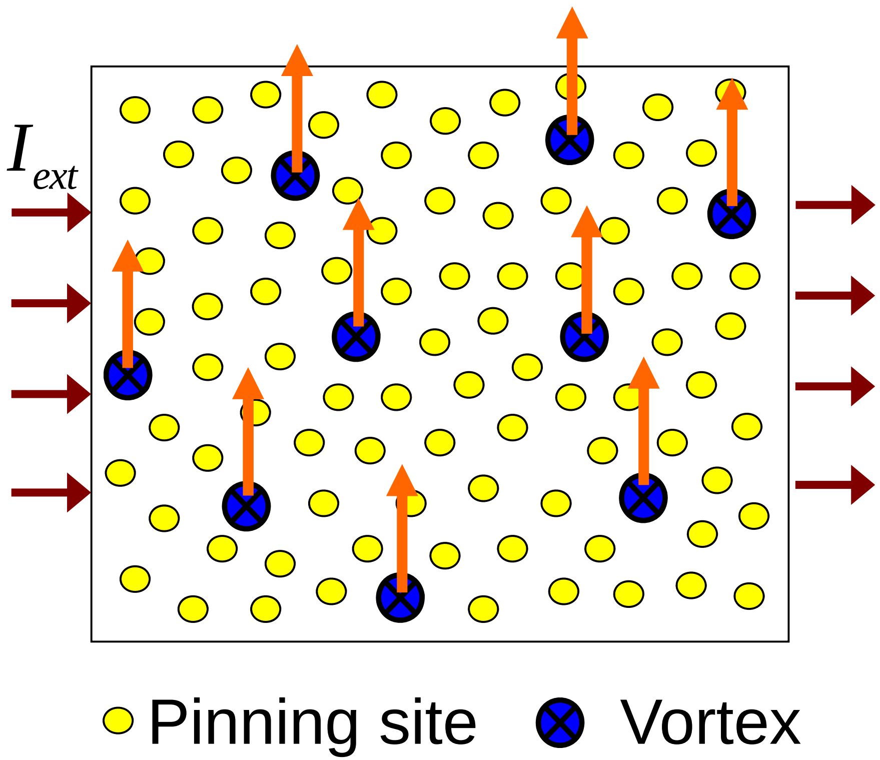
Flux flow resistance (R_{ff}) and magneto-resistance (MR) develop under a magnetic field when an external current leads to the motion of vortices. Then:

$$\Rightarrow V_{induced} = -\frac{d\phi}{dt}$$

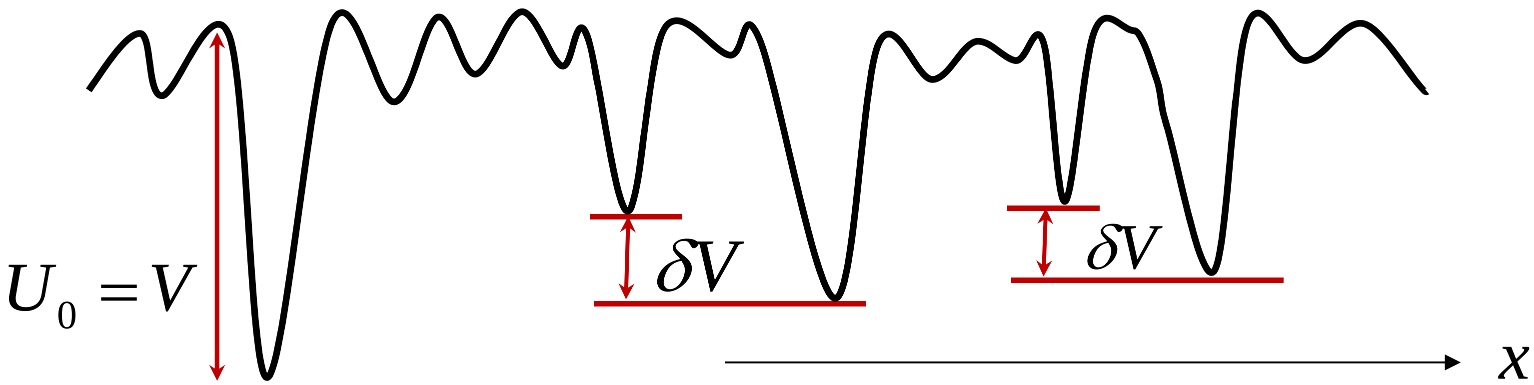
This yields

$$R_{ff} = \frac{V_{induced}}{I}$$

Note that $MR \equiv R(H) - R(0)$



The pinning potential in a superconductor:



Specifically, one can distinguish between two regimes

1. At high temperatures the pinning energy U_0 is much weaker than thermal activation $\Rightarrow$ flux flow or flux creep

$$R_{ff} \propto \exp\left(-\frac{U_0}{k_B T} \right)$$

2. At low temperatures the pinning energy U_0 is much stronger than thermal activation $\Rightarrow$ vortex motion via quantum tunneling

A . Auerbach, D. P. Arovas and S. Ghosh
[Phys. Rev. B **74**, 064511 (2006)], had found tunneling MR

$$\rho = \left(\frac{h}{2e}\right)^2 \gamma_0 \left[n_v(B)\right] \mathrm{e}^{\left(-\frac{T_0}{T}\right)^{\frac{1}{3}}}$$

where γ_0 is the vortex conductivity, n_ν is the vortex density and T_0 is given by:

$$T_0(film) = K\delta\overline{V}\left(\frac{\pi n_S}{n_{pin} N_{layers}}\right)^2$$

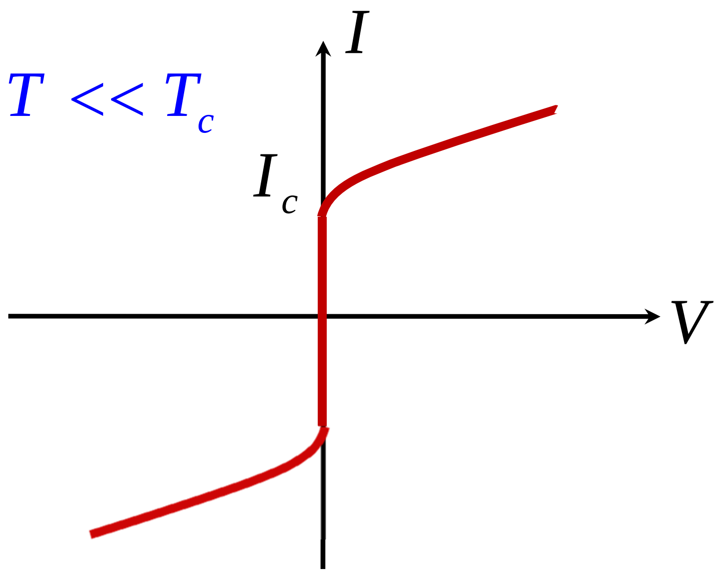
Where $K \sim 1$, $\delta\overline{V}$ is the average pinning energy variation, n_s is the pairs density, n_{pin} is the pinning sites density and N_{layers} is the number of CuO_2 planes in the film

- The 1/3 exponent indicates VRH in 2D
- For 3D VRH this power would be 1/4

In order to test Auerbach, Arovas and Gosh prediction we used a 1m long YBCO Meander line

Why should one use a long meander line?

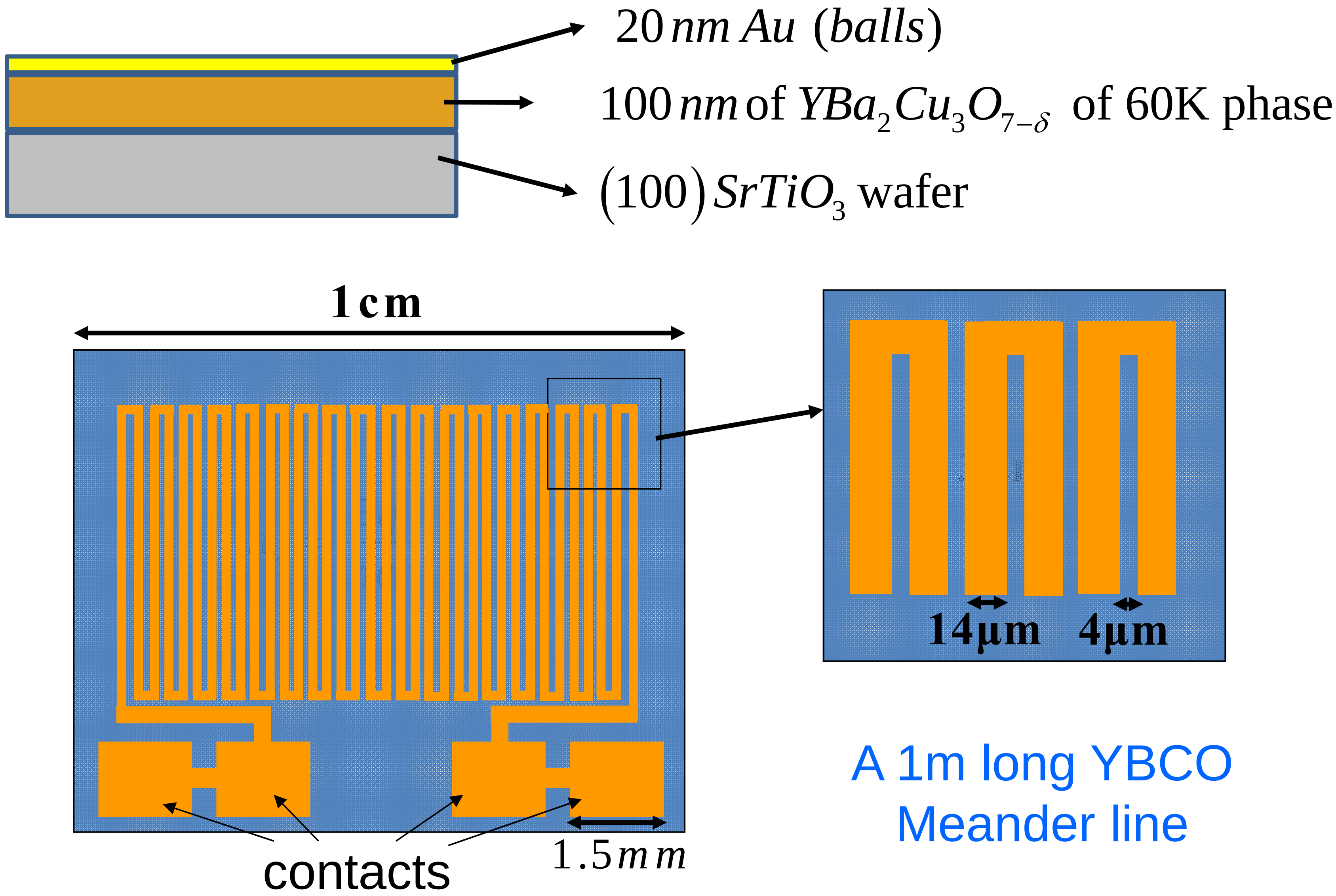
In a short microbridge under magnetic field of several Tesla, the induced voltage is very small and critical current develops already at about 10-20 K below T_c .



$\Rightarrow$ No R (& no R_{ff} resistance) below Ic

In contrast, in a long meander line the induced voltage is large, and the resistance can be measured down to very low T.

The meanderline sample

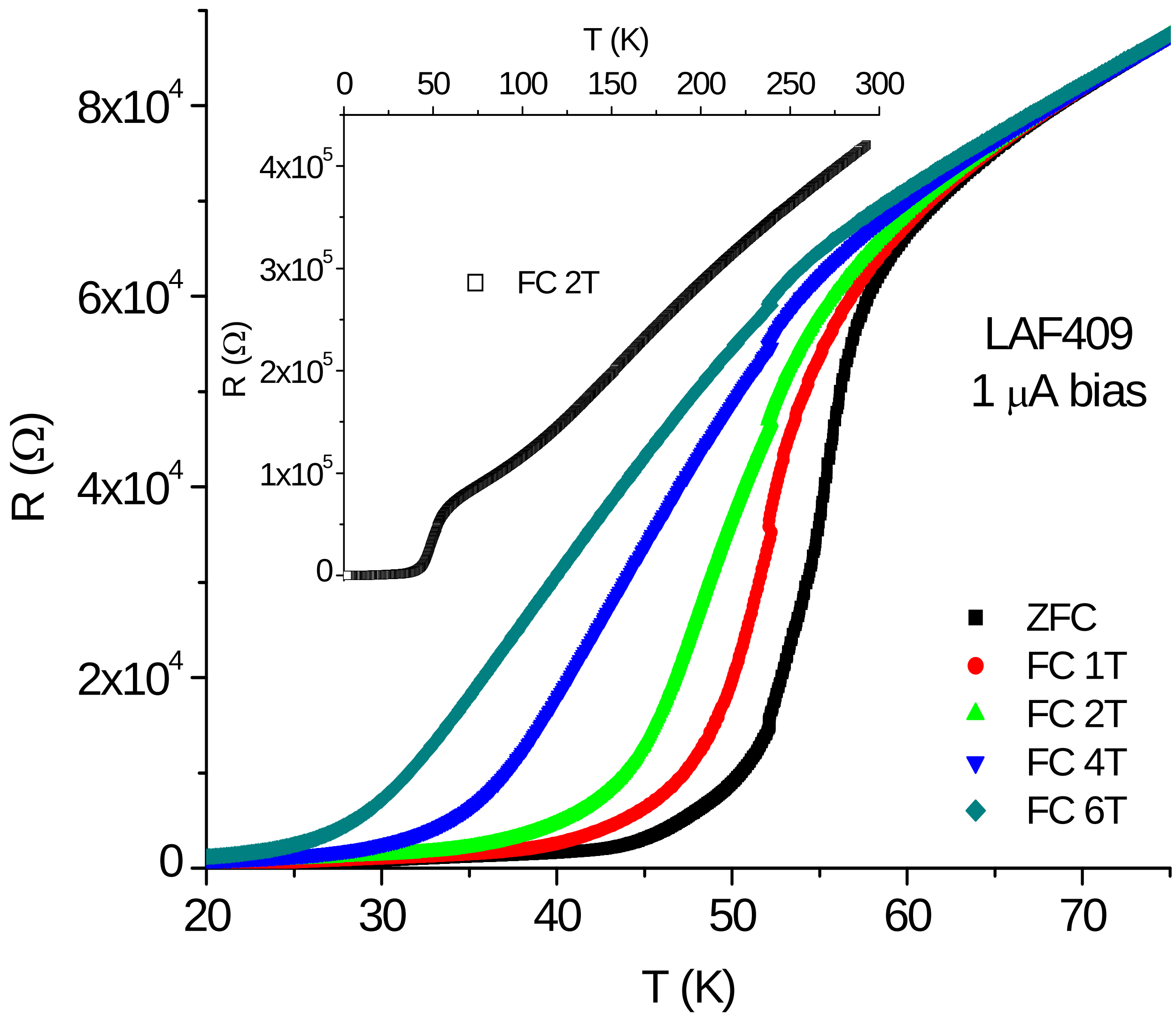


A 1m long YBCO Meander line

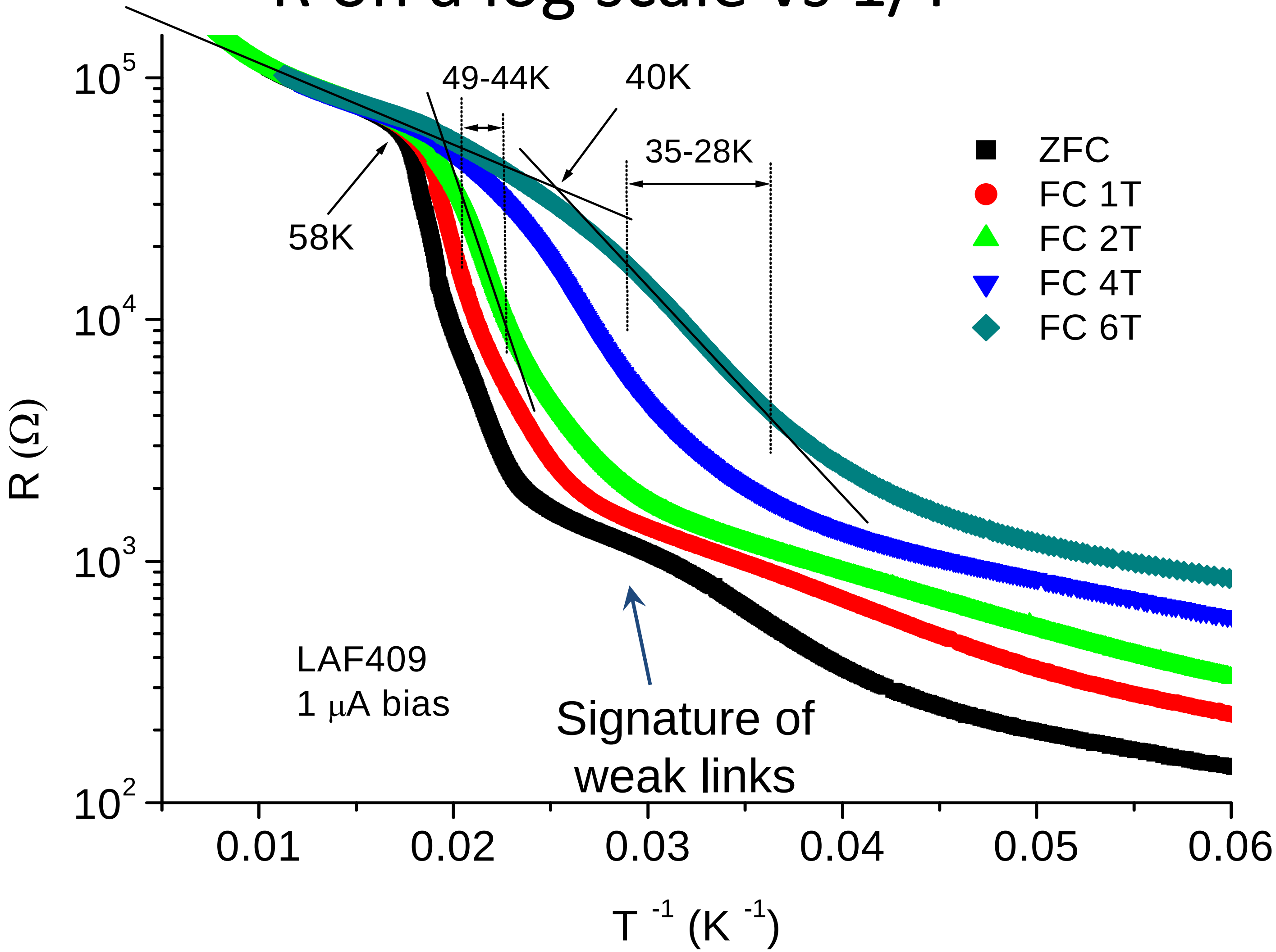
Transport results of R versus T

Metallic, underdoped, above Tc~60K

Typical broadening with field of the transition below Tc



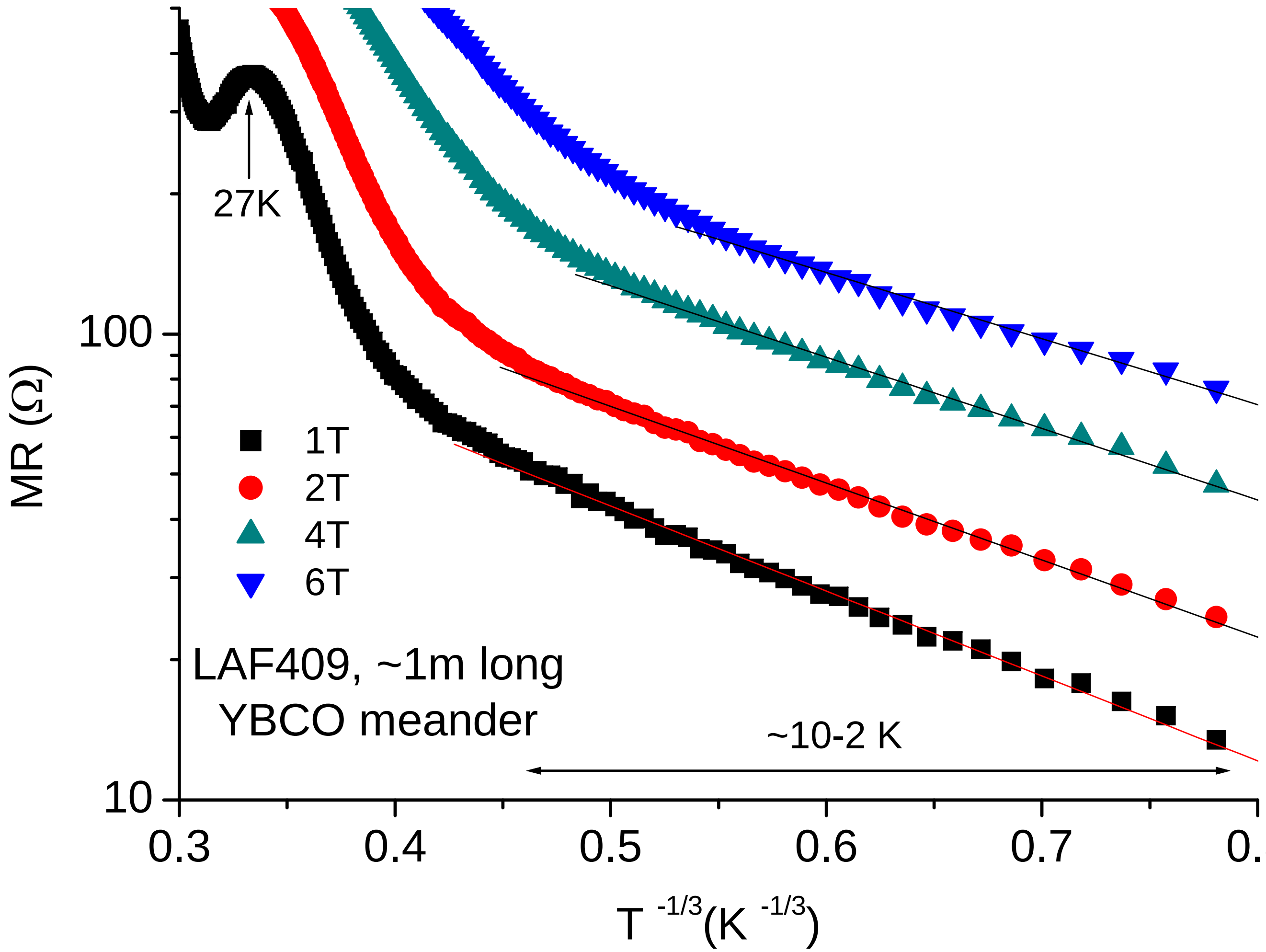
R on a log scale vs 1/T



- The activation energy at 2 T can be extracted from R_{ff} :

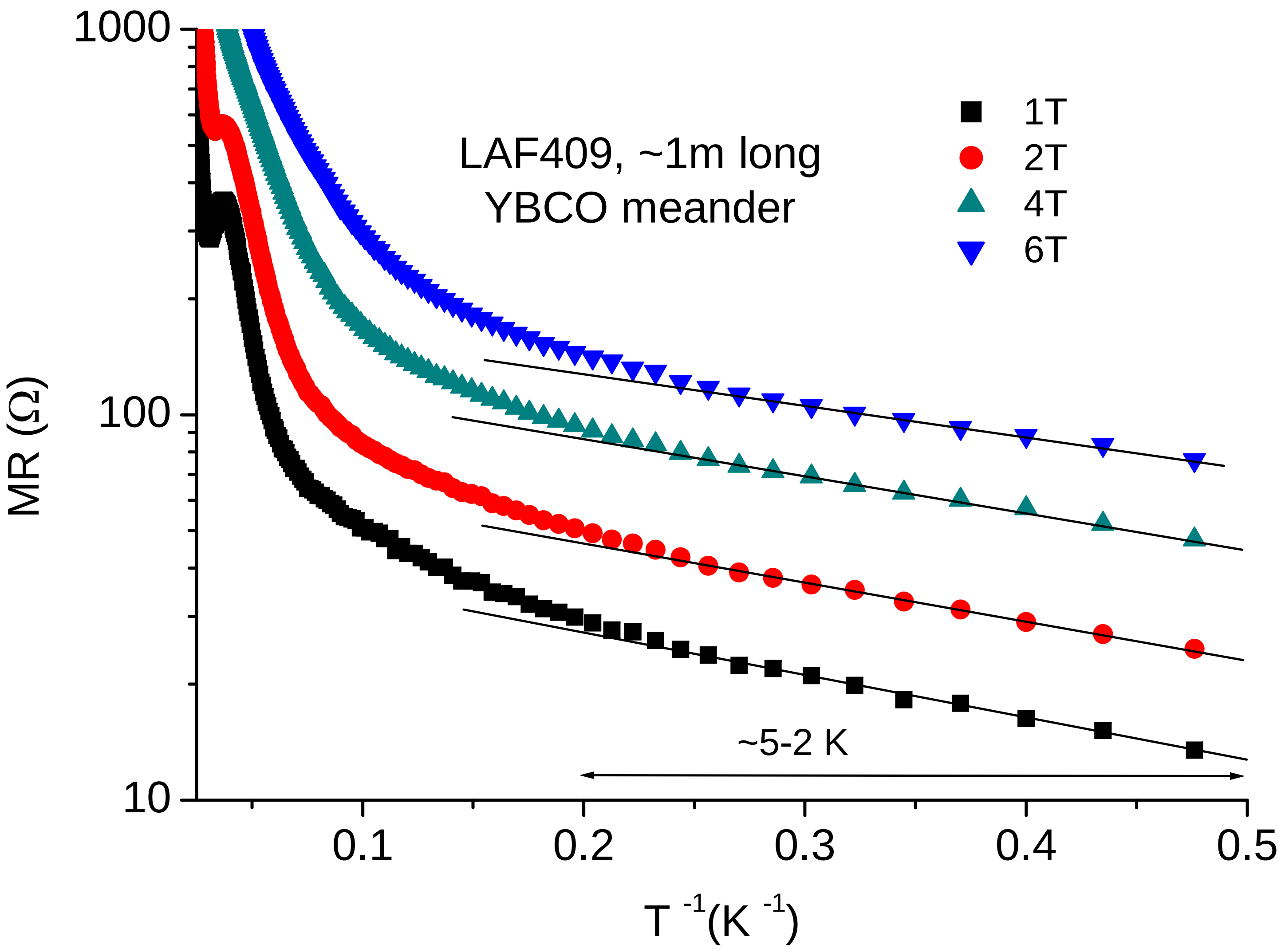
$R_{ff} \propto \exp\left(-U_0/k_B T\right)$ and this yields: $U_0 \approx 550K$

To test the Vortex - VRH prediction:



- The linear behavior indicates vortex-VRH in 2D at ~2-10 K
- T_0 can be obtained from the slopes of these lines on a ln scale

To test for possible “activation”



- The larger T range for observing the $1/T^{1/3}$ behavior indicates that we actually observe vortex VRH (or vortex tunneling)

Conclusions I

- QVT was observed in YBCO thin films in MR measurements versus temperature
- Further experiments at lower temperatures are needed

Part II is next:

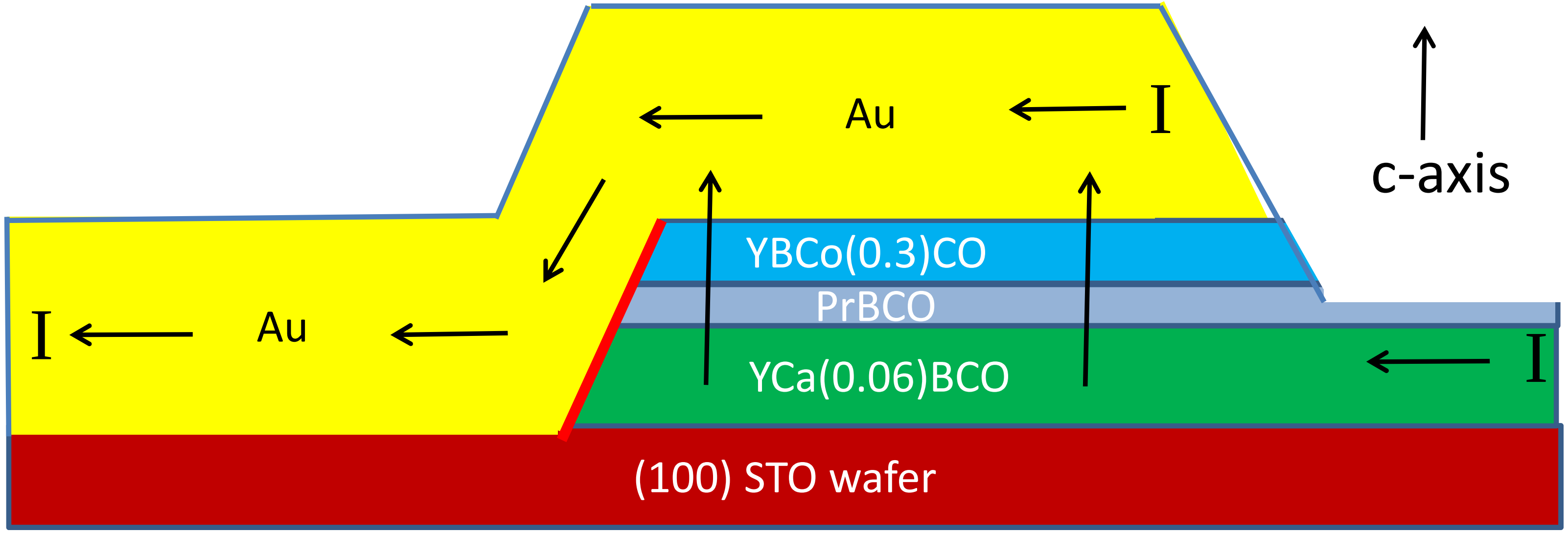
supercurrents in c-axis junctions of the cuprates in the pseudogap regime

Is there an Ic in S1-I-S2 junction when S1 is SC and S2 is in the PG regime?

**In collaboration with Patrick Lee*

We originally looked for Amperian pairing (PDW) as predicted in PRX **4**, 031017 (2014), but found no such effect

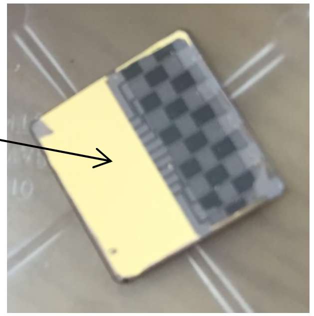
The c-axis junction (CJ) cross-section



The base electrode comprises a trilayer deposited *in-situ* on a (100) $SrTiO_3$ (STO) wafer

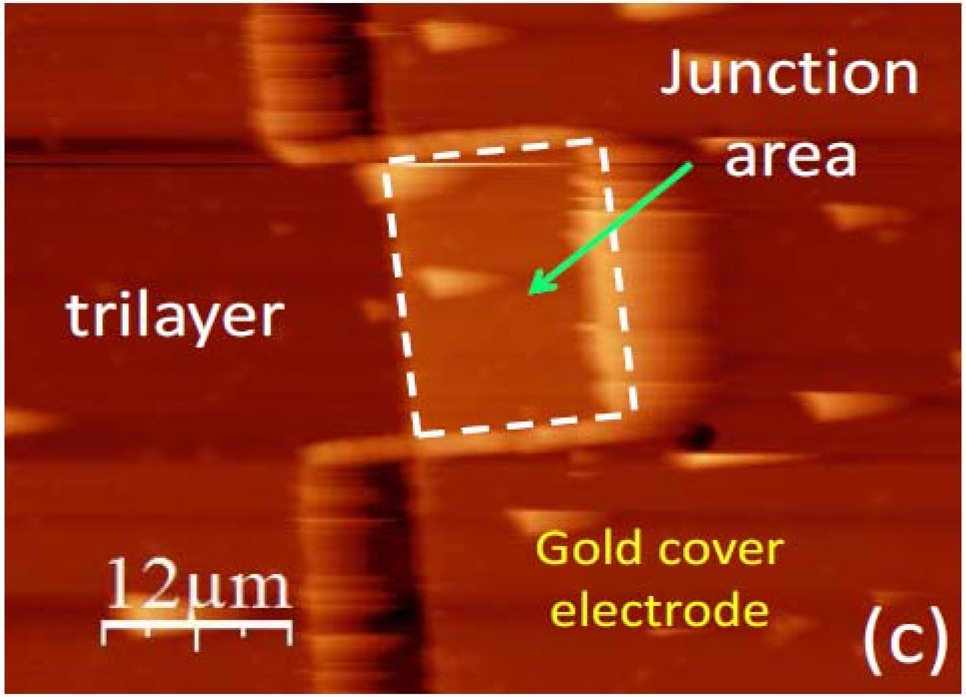
- The YCa(0.06)BCO layer is 200nm thick over-doped $Y_{0.94}Ca_{0.06}Ba_2Cu_3O_{7-\delta}$
- The PrBCO barrier layer is 25nm thick $PrBa_2Cu_3O_y$
- The YBCo(0.3)CO layer is 100nm thick underdoped $YBa_2Co_{0.3}Cu_{2.7}O_{7-\delta}$

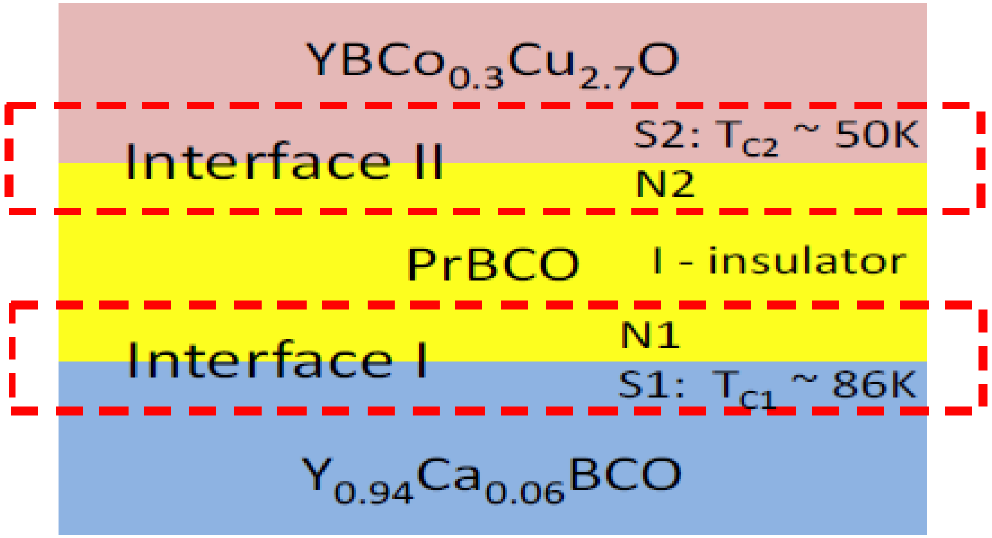
The Au cover electrode layer is 500nm thick



The junctions area is $12 \times 20 = 240\ \mu m^2$

AFM image of a c-axis junction





Model of a c-axis junction

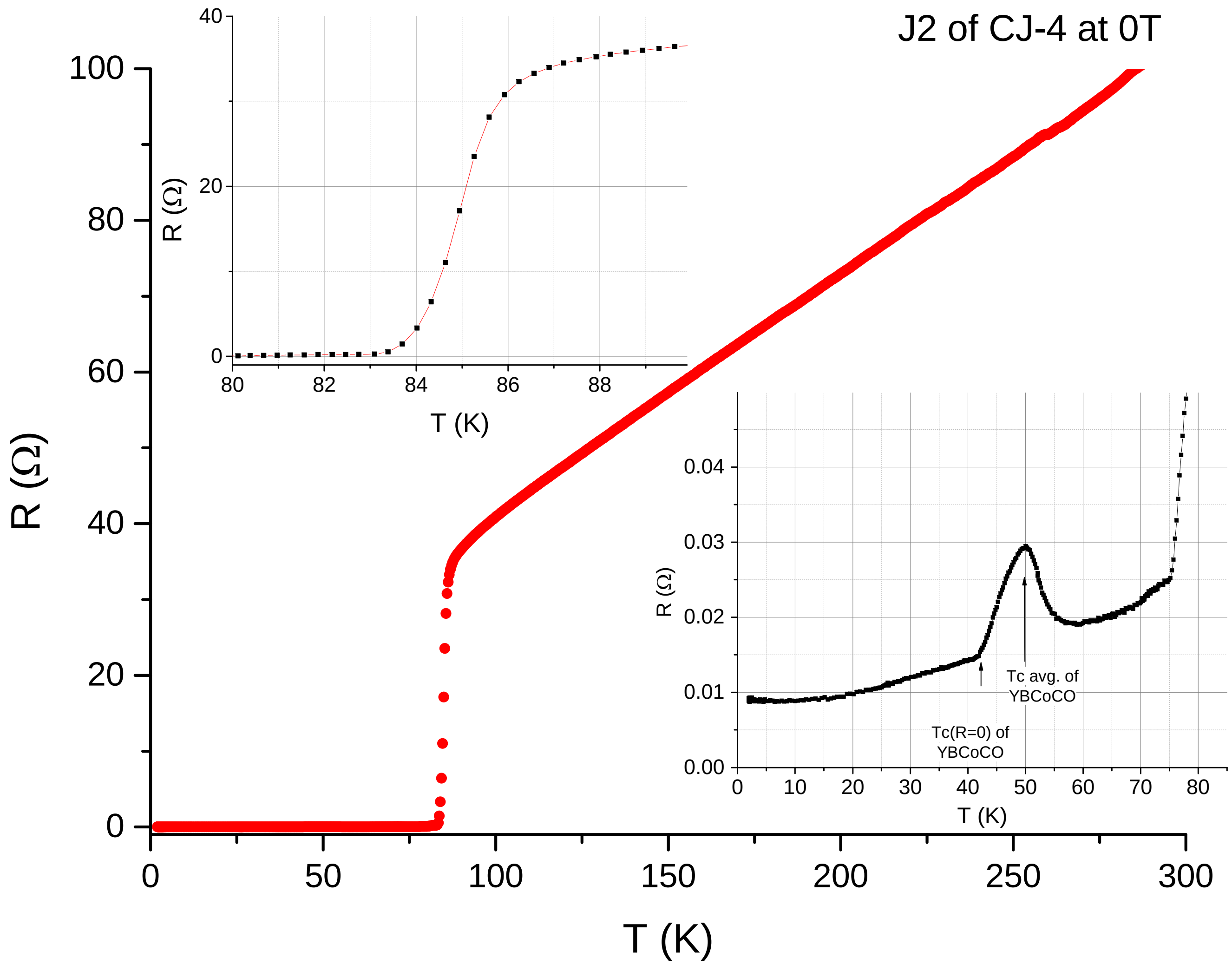
5 wafers were prepared with 10 junctions on each

TABLE I: *c-axis* junction parameters. YBCO and PrBCO are optimally doped $YBa_2Cu_3O_{7-\delta}$ and $PrBa_2Cu_3O_{7-\delta}$, respectively and YBCoCO is underdoped $YBa_2Co_{0.3}Cu_{2.7}O_y$. All junctions were prepared on (100) $SrTiO_3$ wafers. Last column is the overlap junction area.

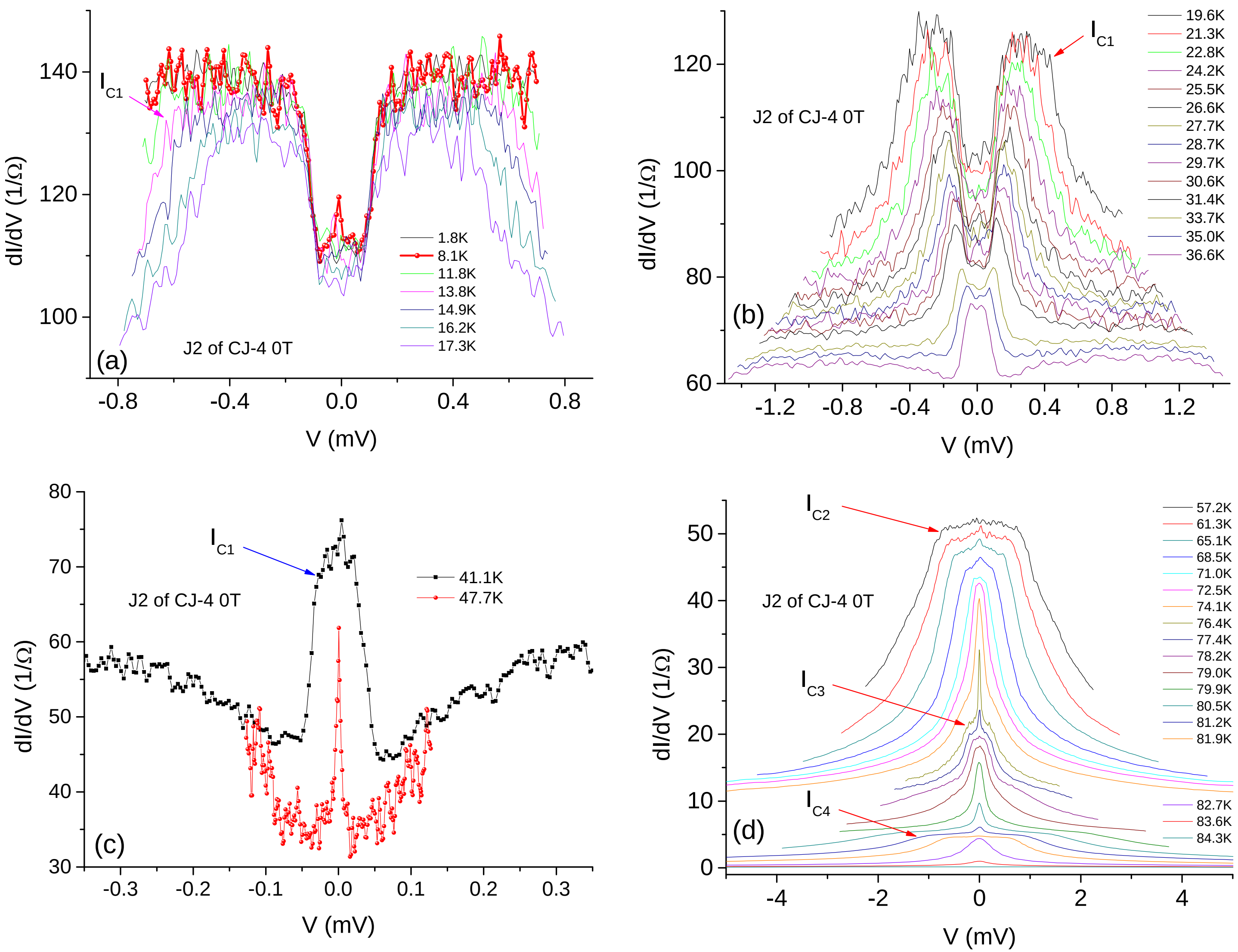
wafer #	layer 1	layer 2	layer 3	area (μm^2)
CJ-1	300nm YBCO	50nm PrBCO	100nm YBCoCO	7×5
CJ-2	200nm YBCO	25nm PrBCO	100nm YBCoCO	20×15
CJ-4	200nm $Y_{0.94}Ca_{0.06}Ba_2Cu_3O_y$	25nm PrBCO	100nm YBCoCO	20×15
CJ-5	200nm YBCO	25nm PrBCO	100nm $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_y$	20×15
CJ-6	200nm $Y_{0.94}Ca_{0.06}Ba_2Cu_3O_y$	25nm PrBCO	100nm $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_y$	7×5

CJ-1, 2 & 4 – Have a pseudogap electrode
CJ-4 – Has no CDW or PDW
CJ-5 & 6 – Have no pseudogap electrode
CJ-6 – Has no CDW or PDW either

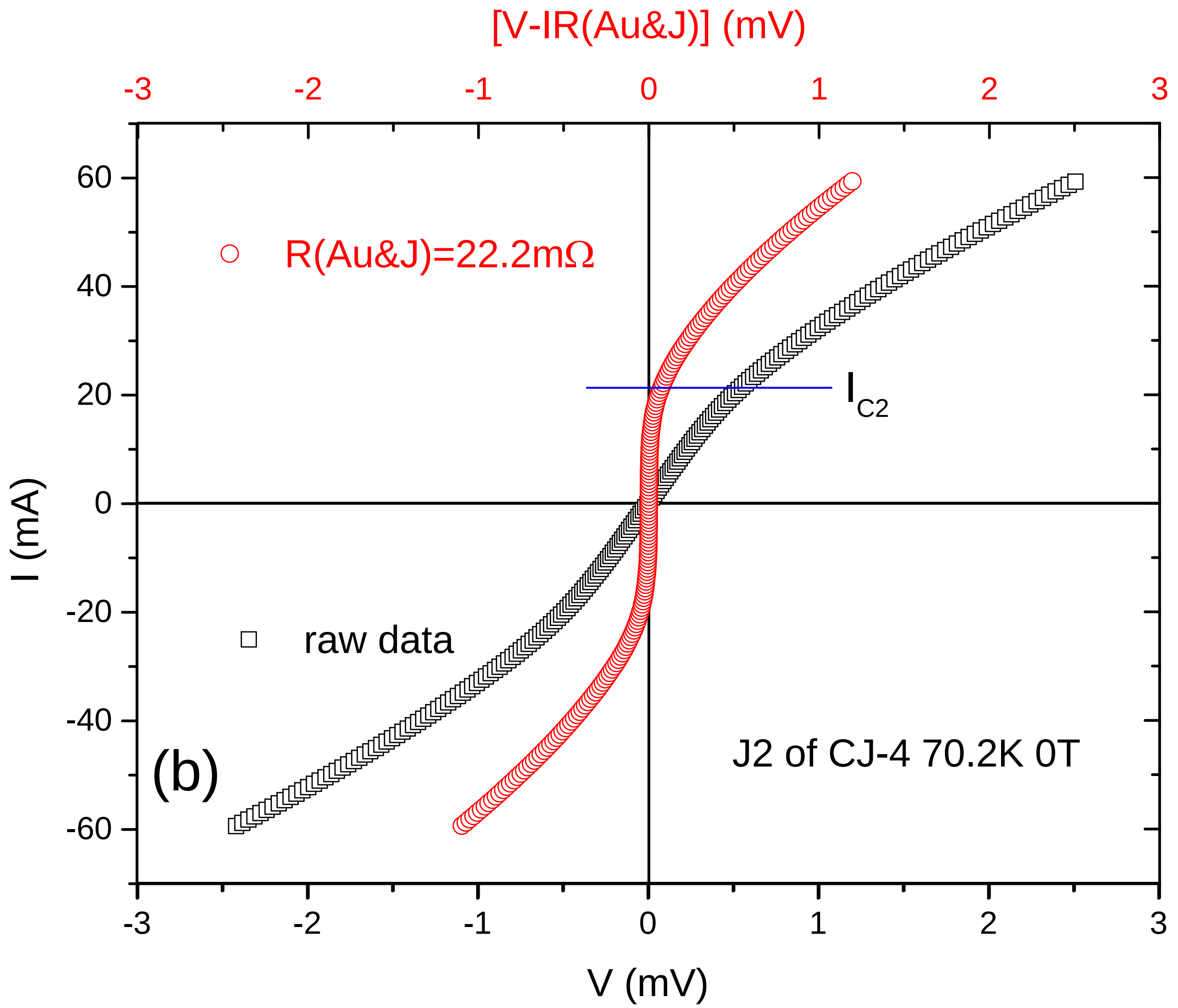
R versus T



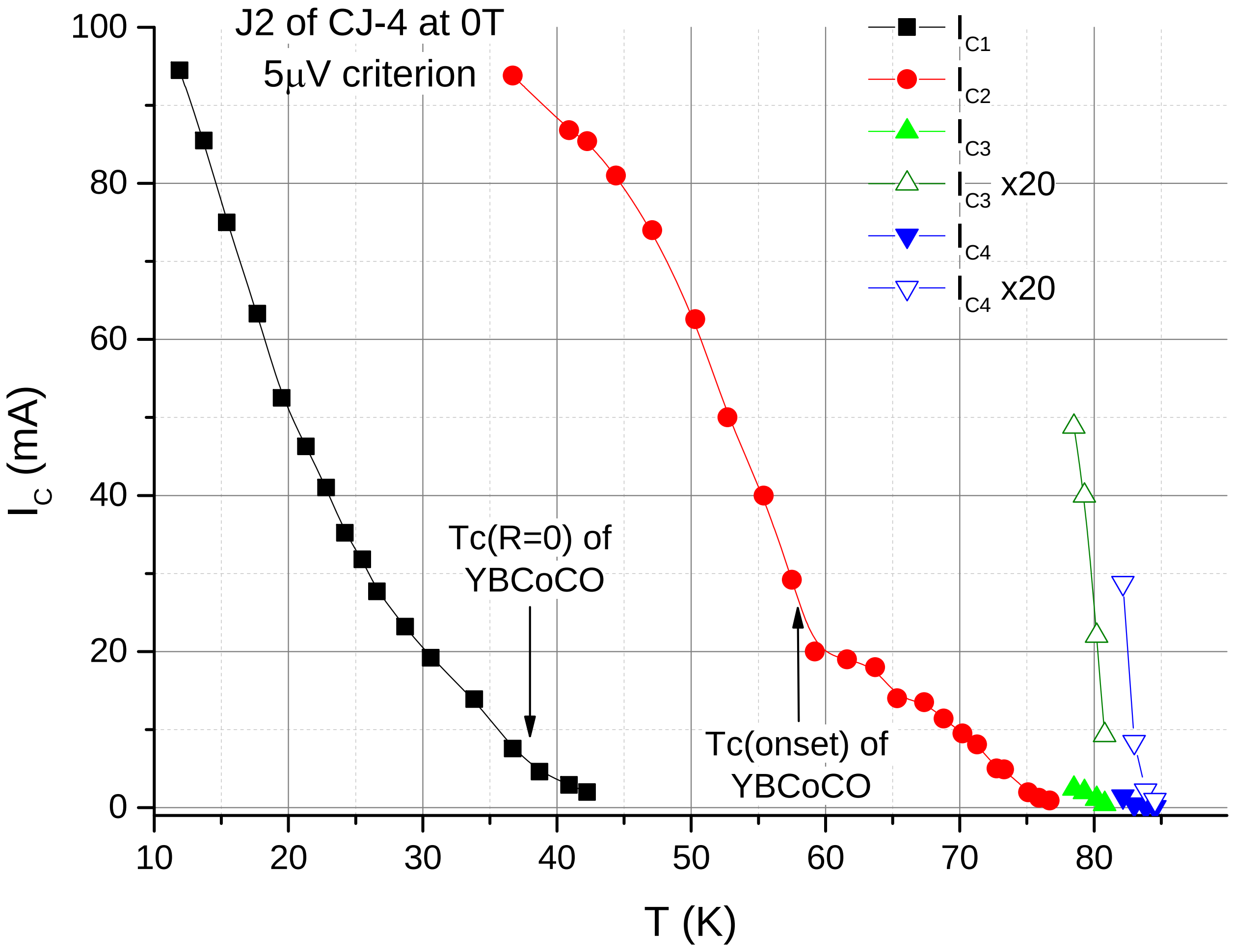
Conductance spectra (current bias measurements)



I-V curve for determination of I_{C2} by a 5μV criterion

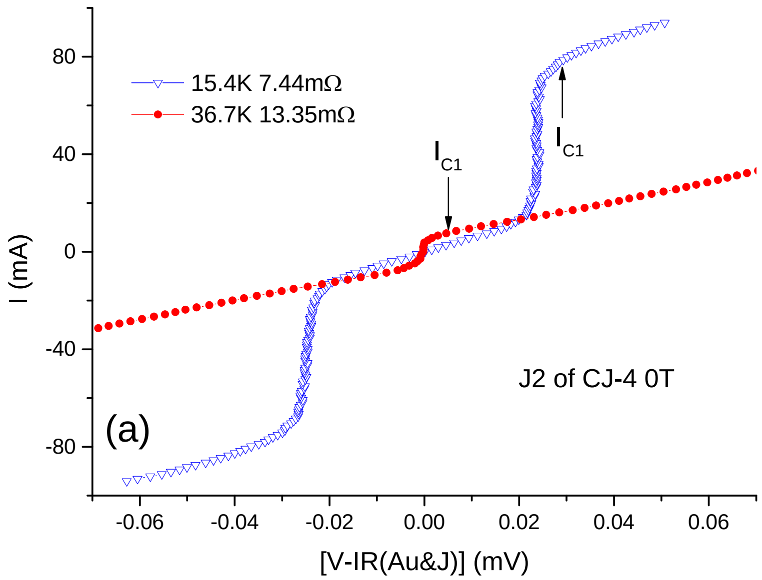


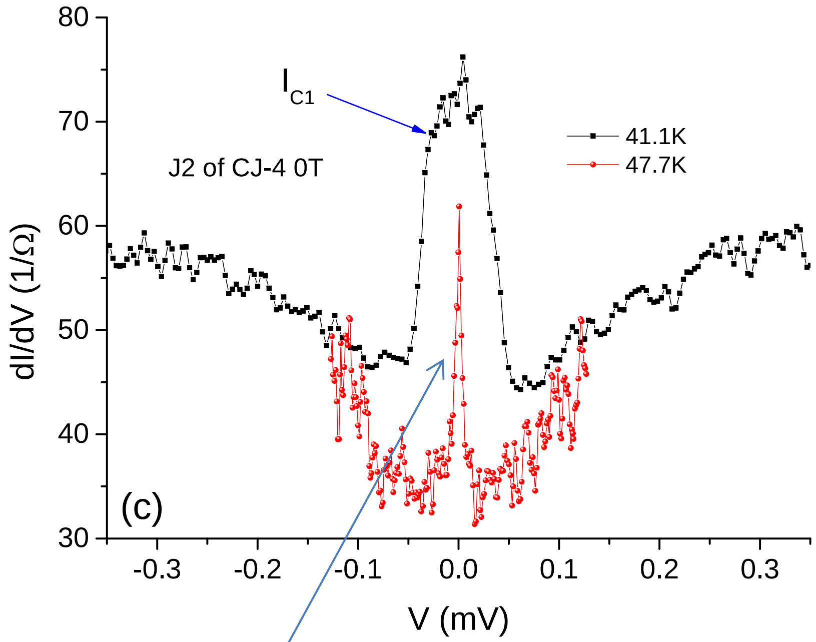
All I_{Ci} of J2 vs temperature at 0T

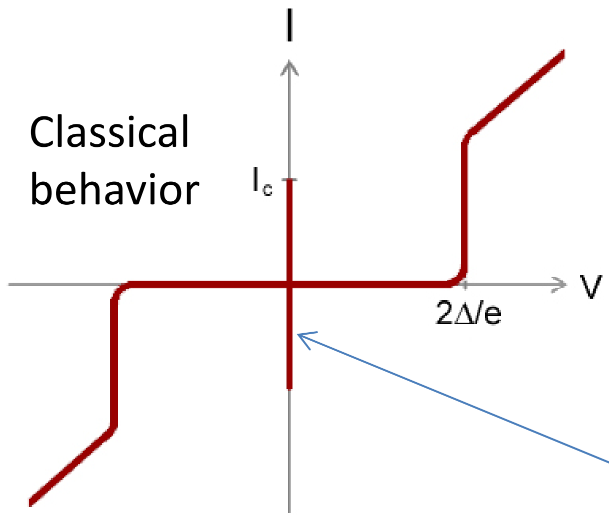


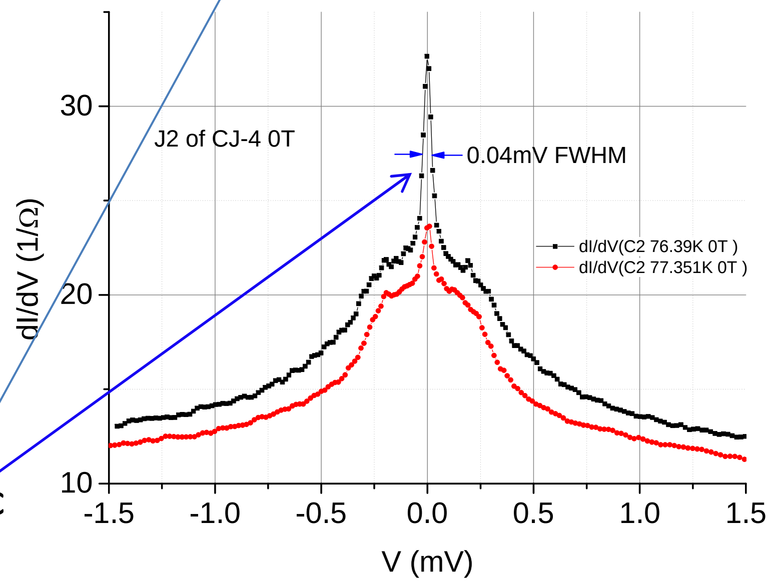
- Can't detect bending in IVC which marks I_{C2} below ~37K, since close to the I-limit at 100mA
- Supercurrent in the pseudogap regime of YBCoCO in the range of 58-76K
- No such effect was found in CJ-5 & CJ-6 where no pseudogap electrode existed

Josephson Ic in a tunneling junction









If the very narrow peak at V=0 is Josephson pairs Ic

Than we see pairs supercurrent in the PG regime!

Conclusions II

- We observed fluctuating pairs current in an S1-I-S2 junction at 76K below Tc(S1) = 85K & above Tc(S2) = 50K
- This proves that the pseudogap phase contains (uncorrelated) pairs
- Supports the precursor superconductivity scenario in which pre-formed pairs exist in the pairs-fluctuation (PG) regime (Emery & Kivelson)

N. BERGEAL, J. LESUEUR et al., Nature Physics 2008,
also observed excess currents in this regime. Their title reads:

"Pairing fluctuations in the pseudogap state of copper-oxide superconductors probed by the Josephson effect"

Implying that they observed Josephson supercurrents.....
There was no follow up to this paper until this study.