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

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Motivation: to look for Tunneling magnetoresistance in a 2D superconductor

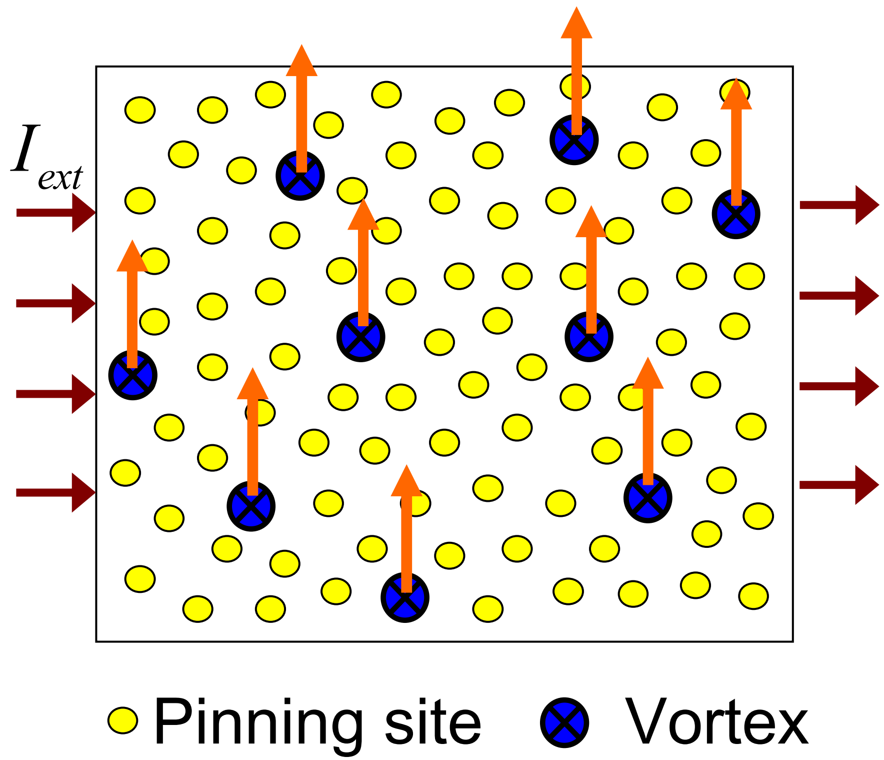
Flux flow resistance (R_{ff}) and magneto-resistance (MR) develop when an external current leads to the motion of vortices. Then:

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

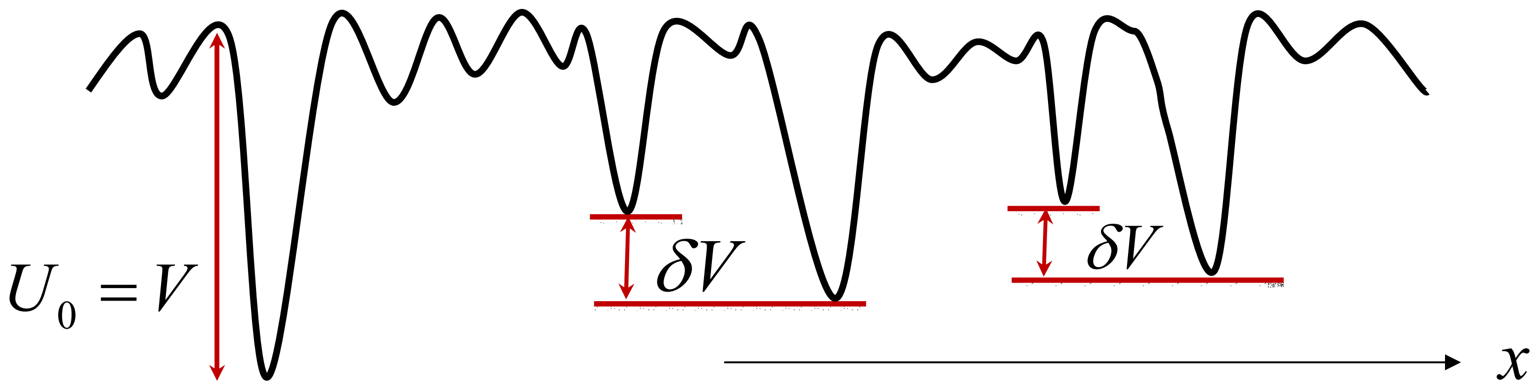
This yields

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

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



The pinning landscape 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

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

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

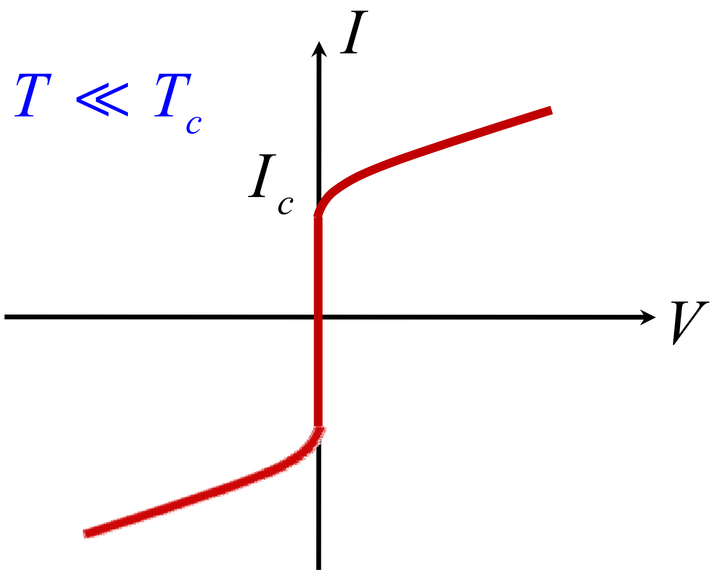
$$T_0(film) = K\delta\overline{V} \left(\frac{\pi n_S}{n_{pin} N_{layers}} \right)^2$$

Where K ~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?

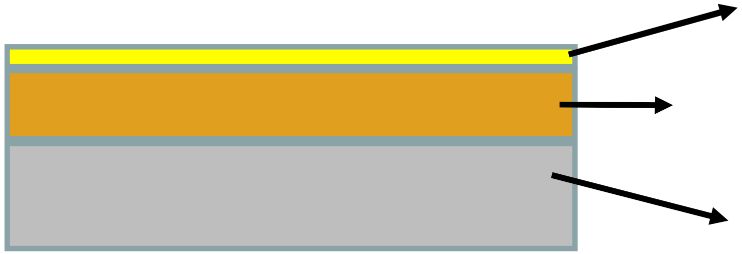


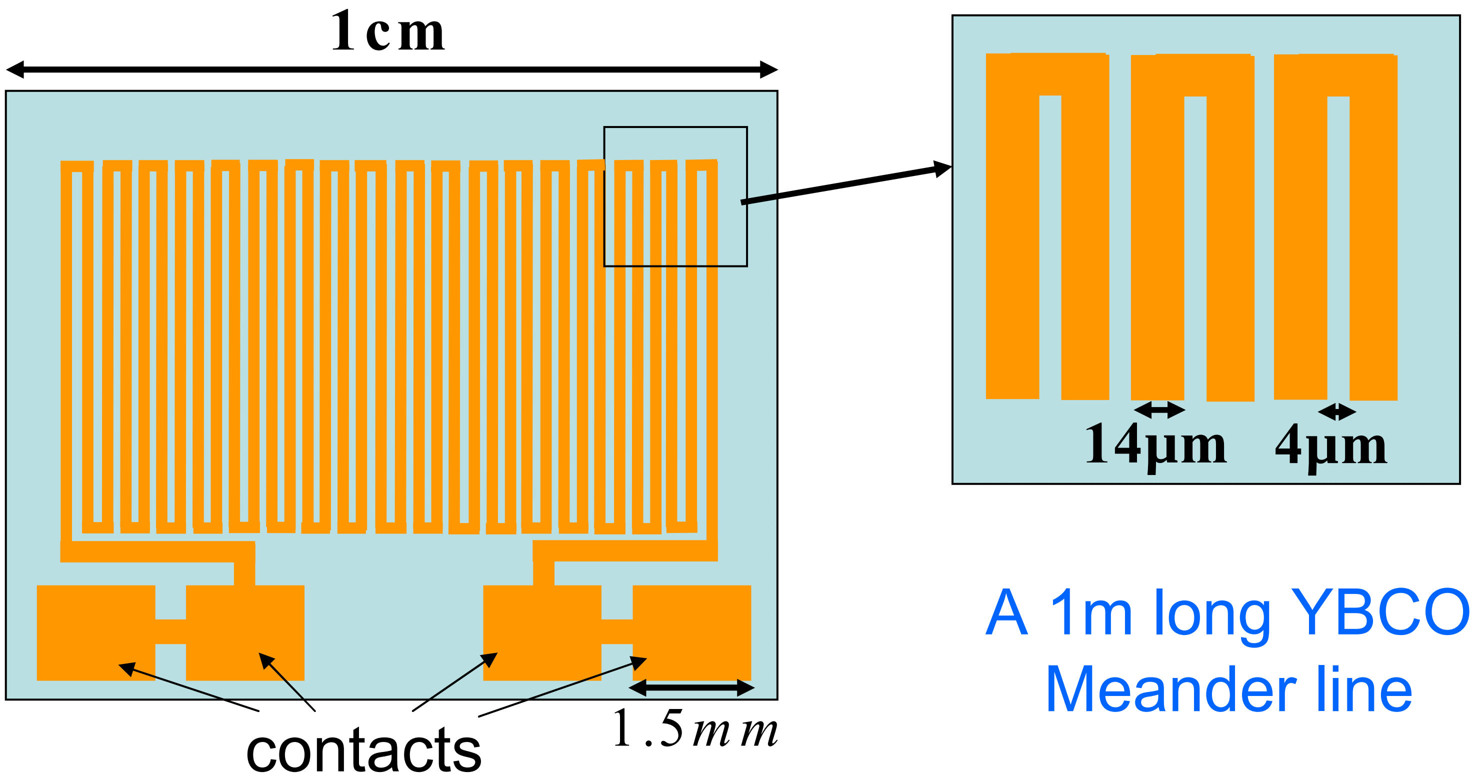
In a short microbridge under magnetic field of several Tesla, the induced voltage is very small and critical current develops already at about 10-20 K below T_c .

$\Longrightarrow$ The R_{ff} resistance can't be measured at low T

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

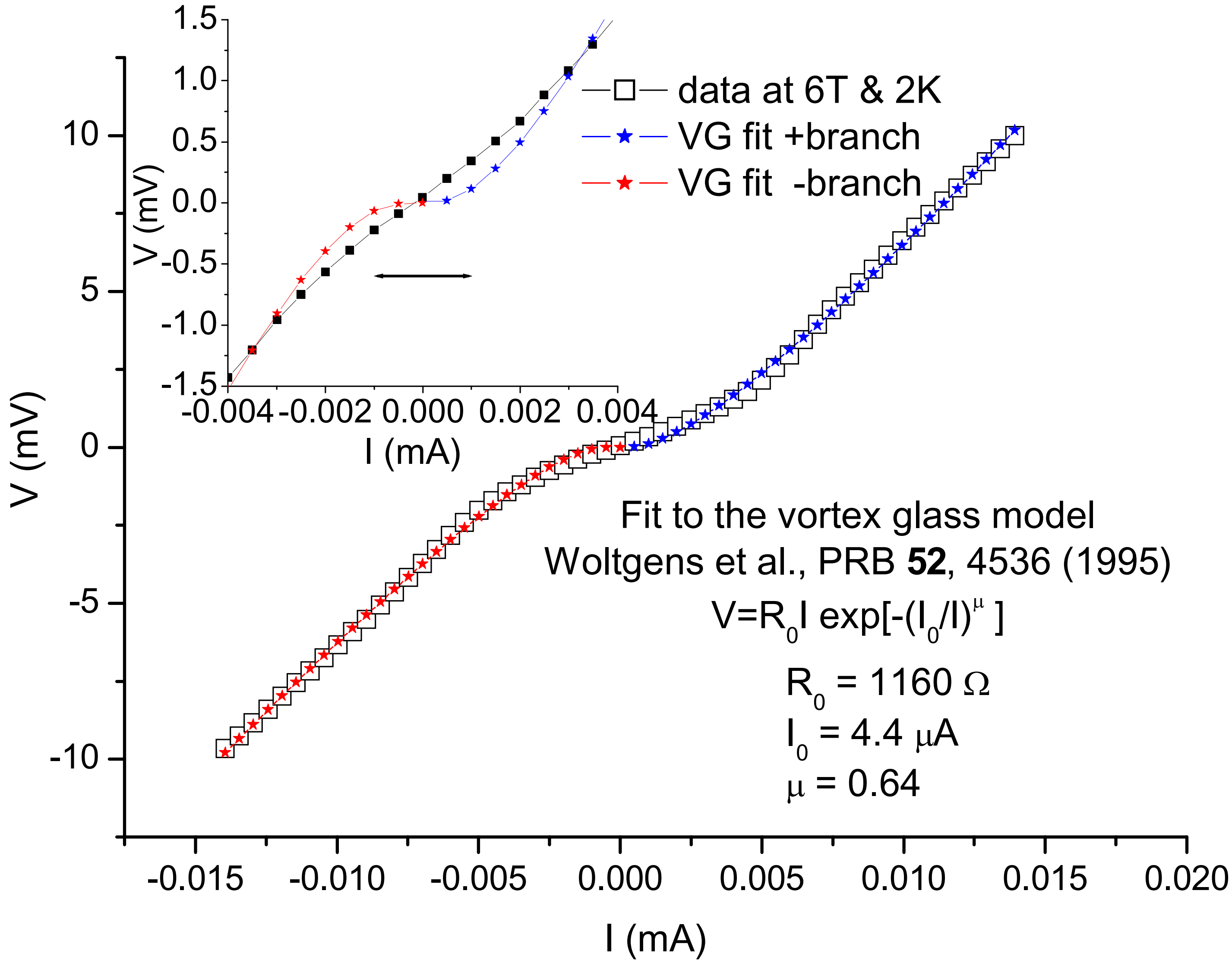
The meanderline sample





A 1m long YBCO
Meander line

Comparison to the vortex glass model

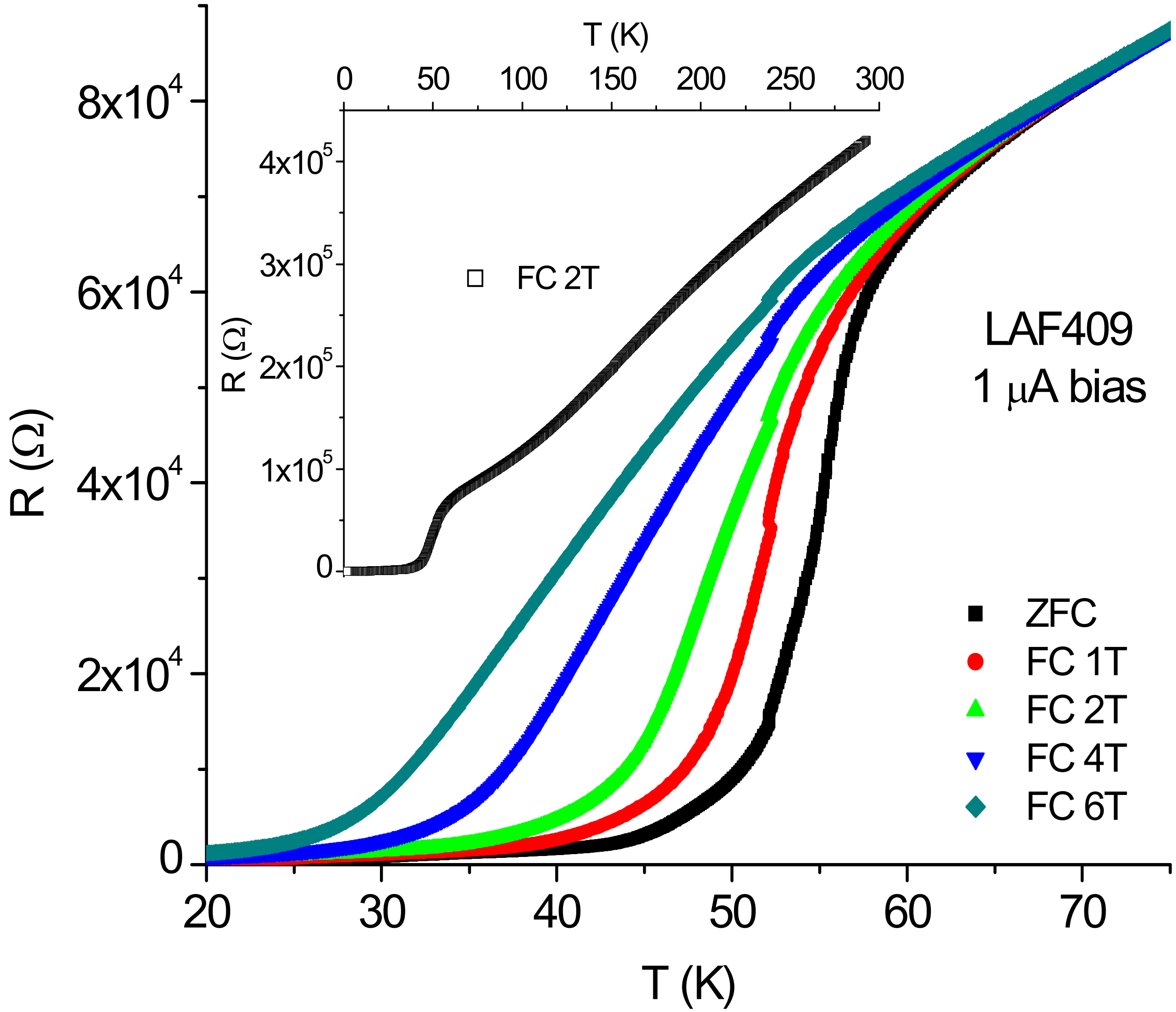


We limited the measurements of R_{ff}
only to the linear, low-bias, regime where V is linear in I

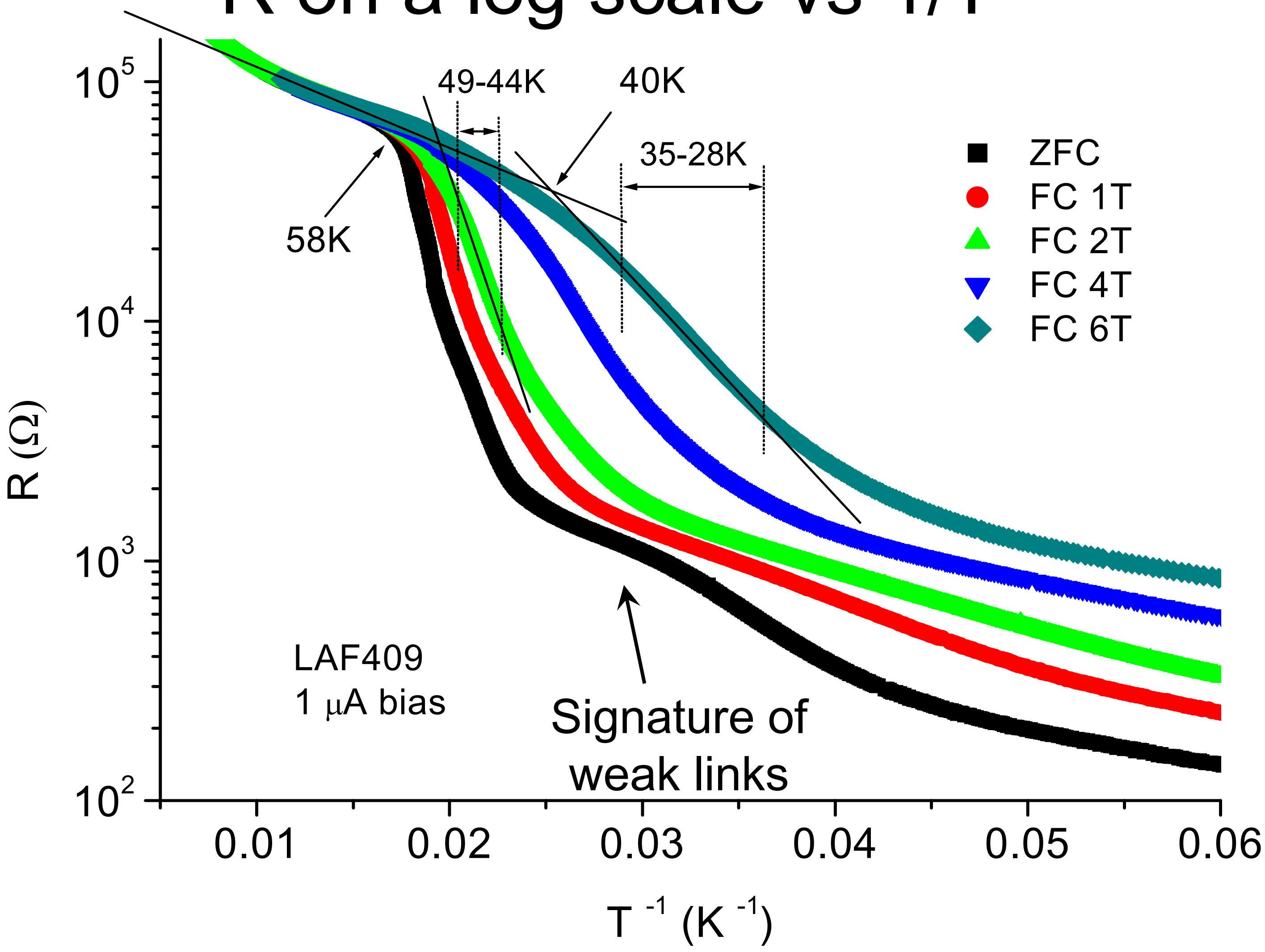
Transport results of R versus T

Metallic, underdoped, above Tc~60K

Typical broadening with field of the transition near Tc



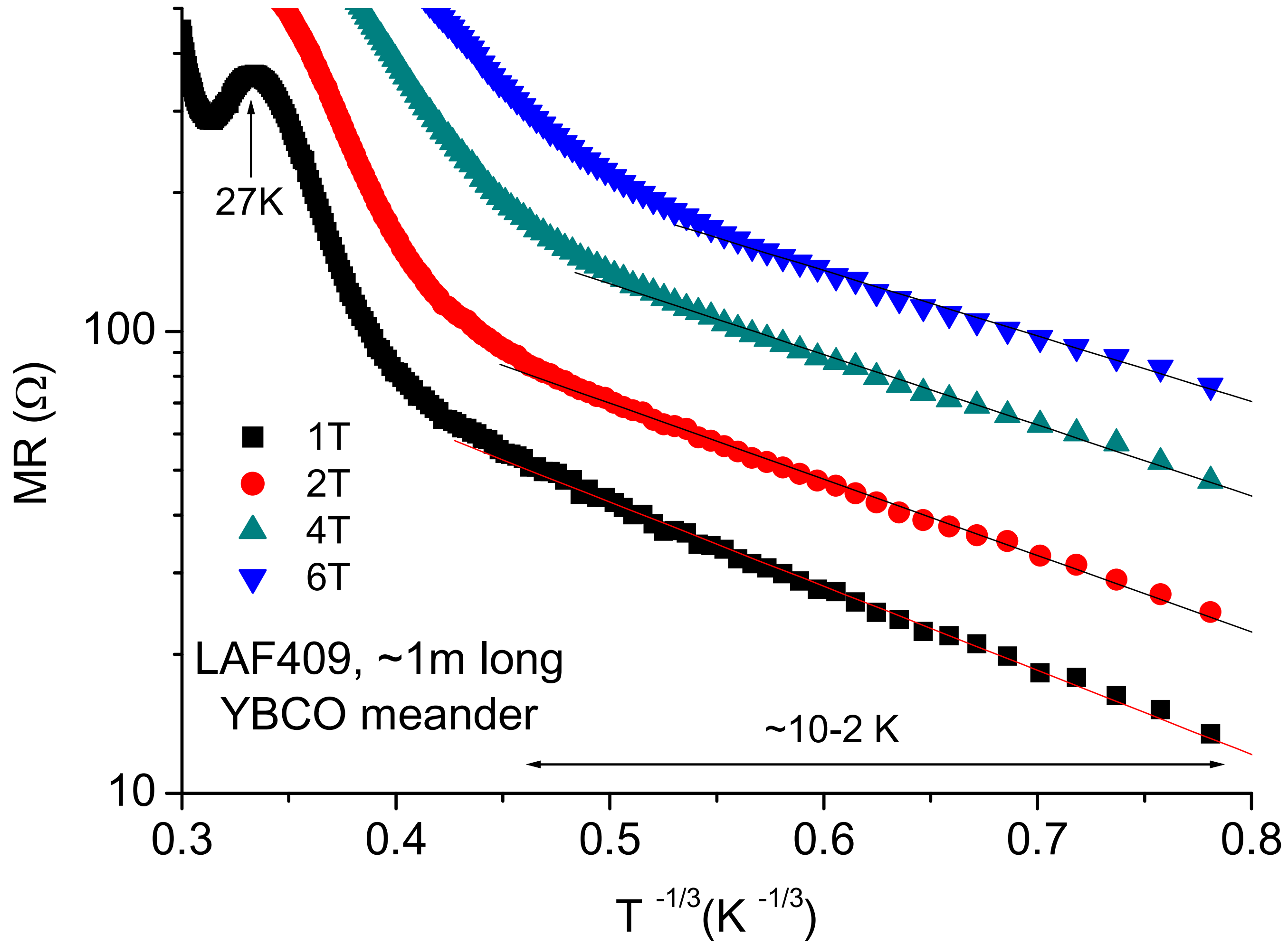
R on a log scale vs 1/T



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

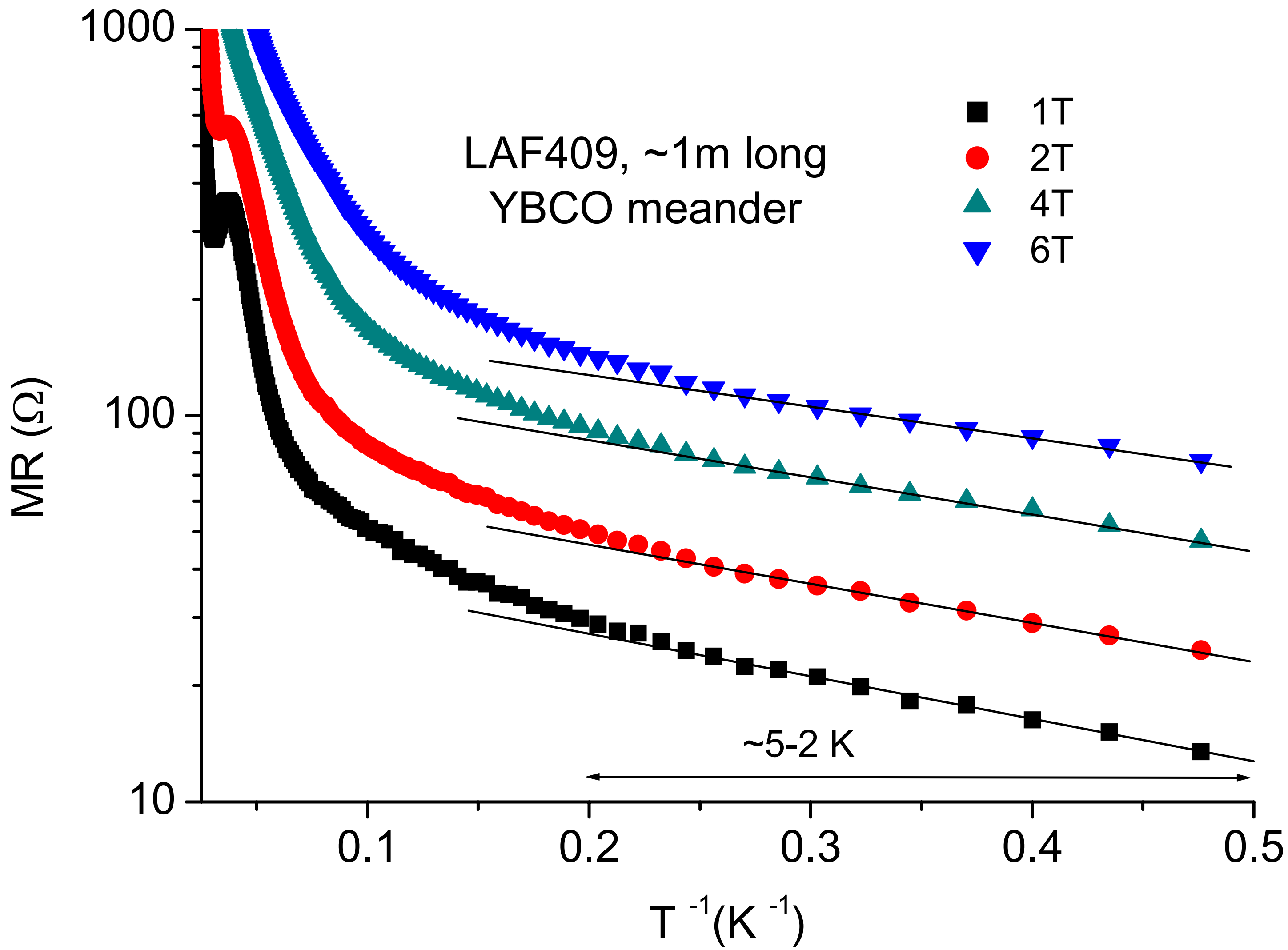
$R_{ff} \propto \exp\left(-U_0 / k_B T\right)$ and this yields: $U_0 \sim 550K$

To test the Vortex - VRH prediction:



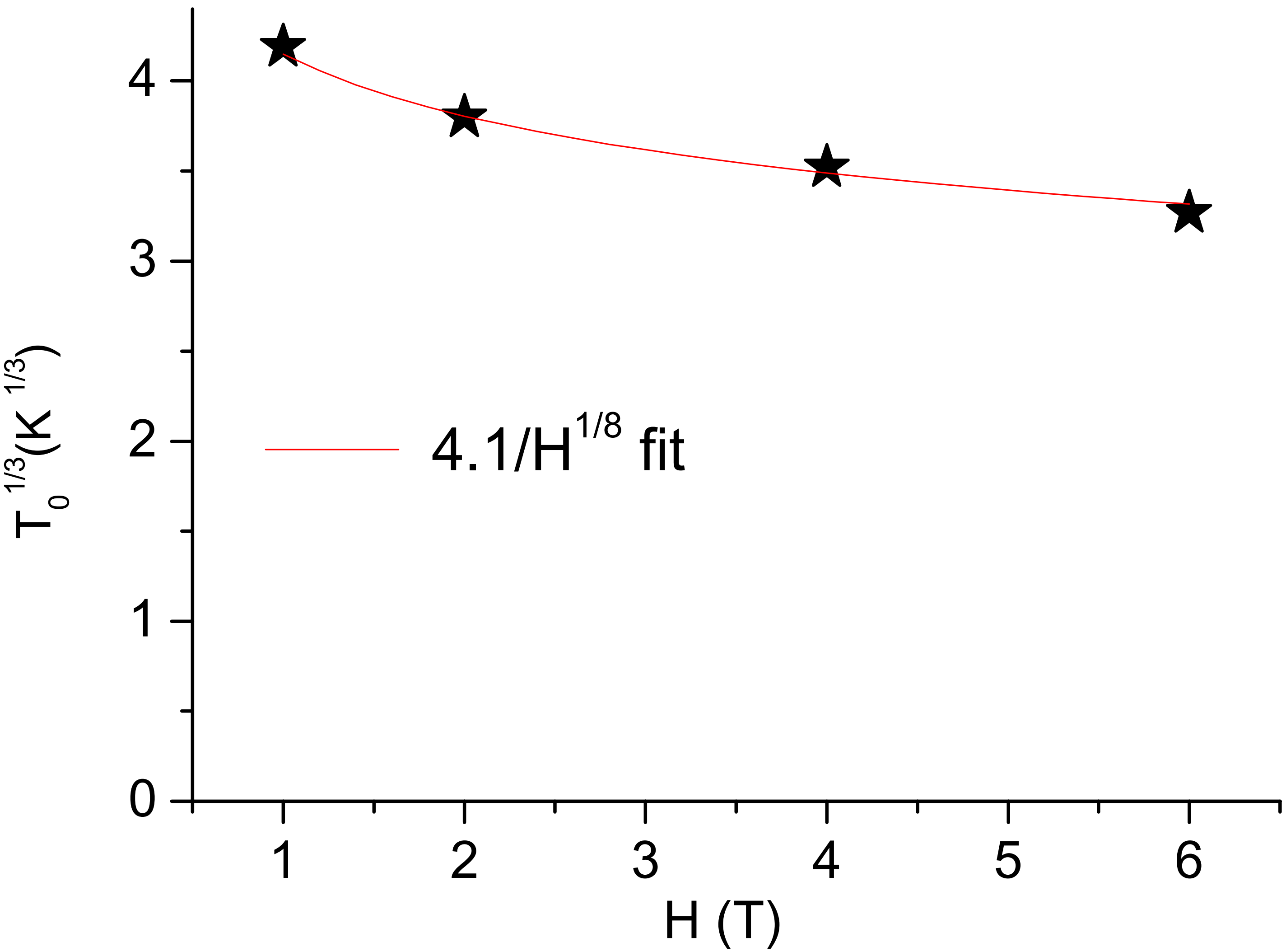
- The linear behavior indicates vortex-VRH in 2D at ~2-10 K
- T_0 can be obtained from the slopes of these lines on a ln scale

To test for possible "activation"



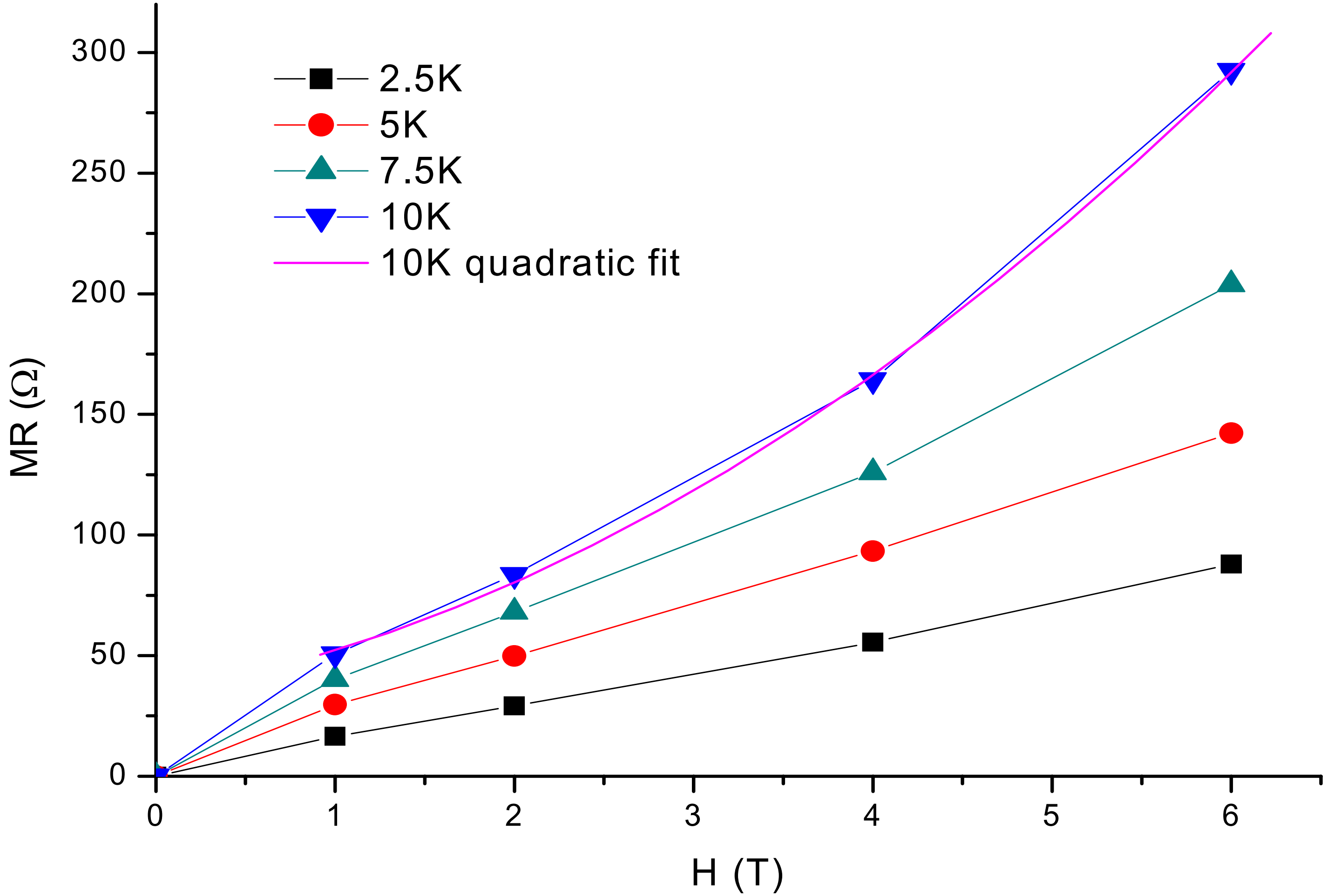
- The larger T range for observing the $1/T^{1/3}$ behavior indicates that we actually observe vortex VRH (or vortex tunneling)

Extraction of T_0 from our data



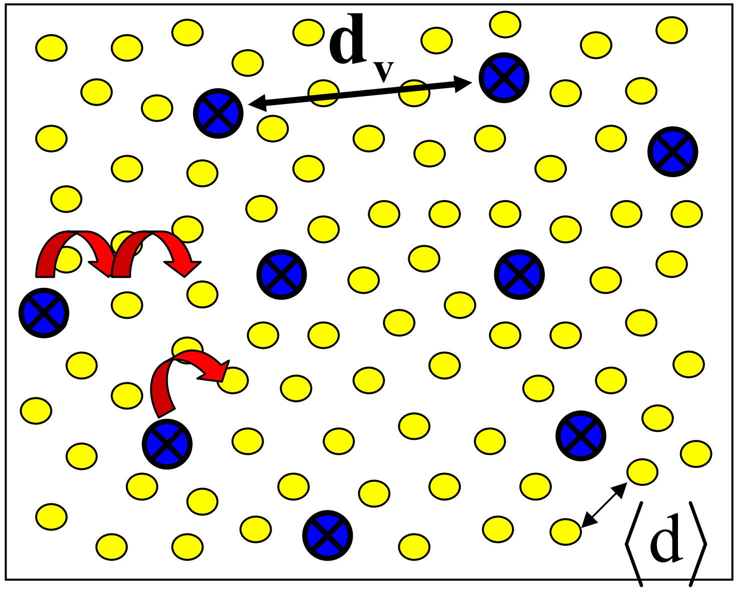
- This T_0 is varying only slowly with H

Now we check the dependence of MR on H



- At T<5K, a constant terminal vortex velocity - yields a linear dependence of the MR vs. H
- At T>7.5 K, nonlinearities develop due to the weak-links

Estimate the pinning sites density from our data



Pinning site

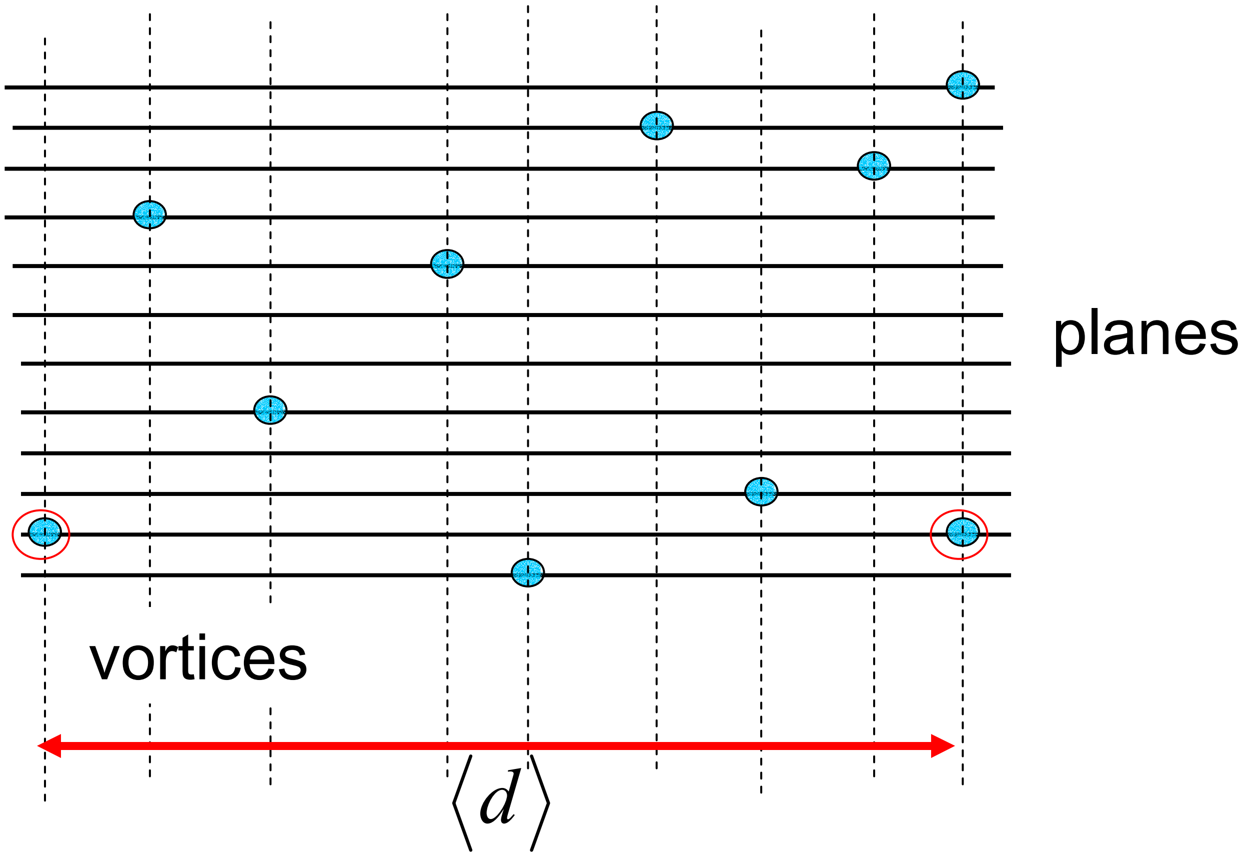
Vortex

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

- The activation energy at H=2 T just below T_c is U_0 ~ 550 K.
- For films with T_c= 60 K, the doping per copper in a CuO_2 plane is p =1/8 and thus for pairs, n_s~ p/2 =1/16.
- Assuming $\delta\overline{V} \approx 0.1U_0$, and noting that the measured T_0 ~ 55 K, one gets: $\delta\overline{V} \approx T_0$
- N_{layers} is ~170 here, thus the average distance $\langle d \rangle$ between pining sites in a CuO plane is 117Å.

And visually it looks like this:

- Pinning sites in different CuO_2 planes



In a single plane the distance between pinning sites is much larger than ξ

Conclusions

- Vortex VRH was observed in YBCO thin films in MR measurements versus temperature
- From our data we extracted the VRH "constant" T_0 which enabled us to estimate the pinning sites density n_{pin} & the average distance between pinning sites <d>
- T_0 was also found to be slightly field dependent
- Further experiments at lower temperatures are needed