2D superconductivity in single crystals of LSCO

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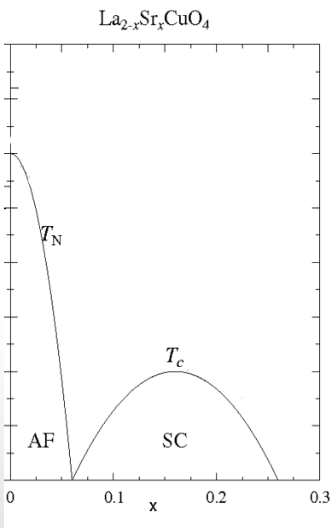
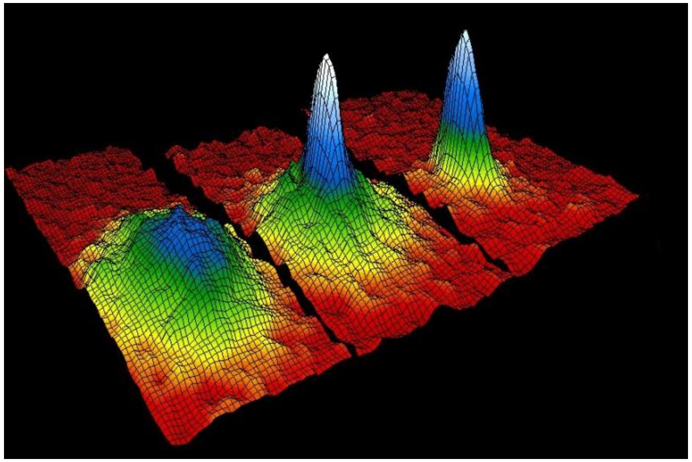
Outline

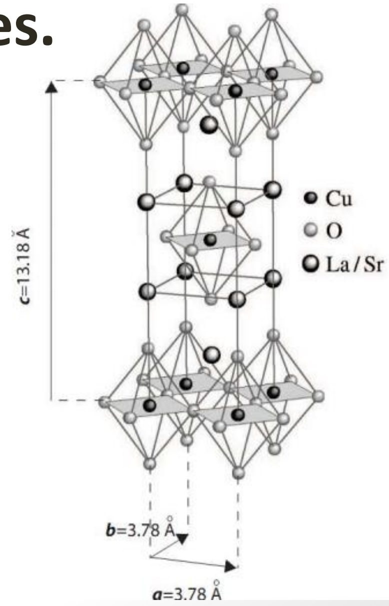
- Motivation
- Previous work and theoretical predictions
- Sample preparation
- Results
- Experimental Tests

Motivation

- The layered structure of cuprates might imply that SC phase is two dimensional.
- Theoretically, phase transitions with long range order are forbidden in a two-dimensional systems. (BEC, 2D solid, 2D magnet, 2D SC).
- **Recent theoretical and experimental evidence show that SC can work in two dimensions. The Cu-O planes can decouple while SC in the planes survives.**







Previous work

Magnetic-field-induced uniaxial resistivity in a high-T_c superconductor

Jinsheng Wen,[1,2] Qing Jie,[1,2] Qiang Li,[1] M. Hücker,[1] M. v. Zimmermann,[3] Su Jung Han,[1,2] Zhijun Xu,[1,4] D. K. Singh,[5,6] Liyuan Zhang,[1] Genda Gu,[1] and J. M. Tranquada[1]

- Experimental evidence of a distinct field-induced state in LBCO.
- Zero resistivity was measured in two dimensions (2D), parallel to the planes.
- Large resistivity was measured for the same temperature, perpendicular to the planes.

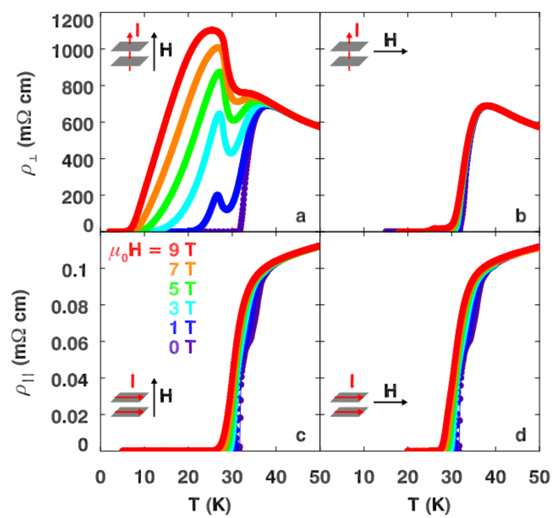


FIG. 1: **Magnetoresistance in $La_{2-x}Ba_xCuO_4$ with $x =$ 0.095.** Resistivities vs. temperature for a range of magnetic fields, corresponding to the configurations: **a**, $\rho_\perp$ in $H_\perp$; **b**, $\rho_\perp$ in $H_\parallel$; **c**, $\rho_\parallel$ in $H_\perp$; **d**, $\rho_\parallel$ in $H_\parallel$. The values of $\mu_0 H$, ranging from 0 T (violet) to 9 T (red), are indicated in **c**. The orientations of the measuring current, I, and the magnetic field are indicated in the insets.

Arxiv:1009.0031v2 (2010)

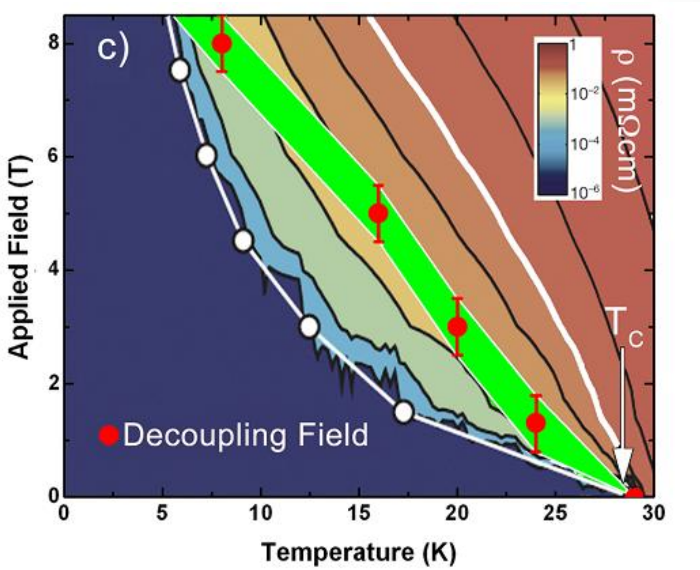
Previous work

PRL **104**, 157002 (2010) PHYSICAL REVIEW LETTERS week ending 16 APRIL 2010

Towards a Two-Dimensional Superconducting State of $La_{2-x}Sr_xCuO_4$ in a Moderate External Magnetic Field

A. A. Schafgans,[1,*] A. D. LaForge,[1] S. V. Dordevic,[2] M. M. Qazilbash,[1] W. J. Padilla,[1] K. S. Burch,[1] Z. Q. Li,[1] Seiki Komiya,[3] Yoichi Ando,[4] and D. N. Basov[1]

- An optical reflectance study probed the superfluid density between CuO_2 below T_c.
- A complete suppression of the interlayer coupling was observed upon application of a ?perpendicular? magnetic field.
- The in-plane SC properties was found to be intact.



The Red dots represent the decoupling field at a certain T.

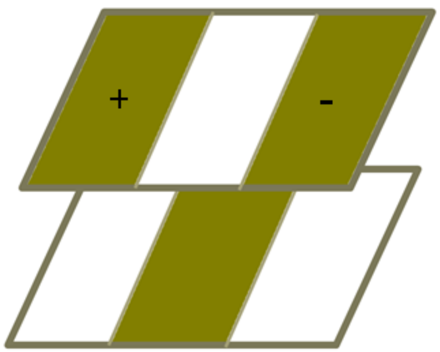
Previous work

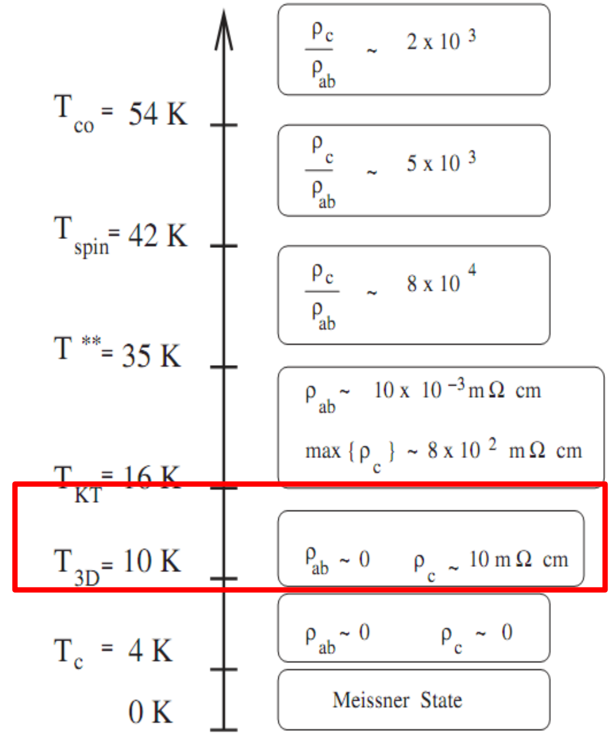
PRL 99, 127003 (2007) PHYSICAL REVIEW LETTERS week ending 21 SEPTEMBER 2007

Dynamical Layer Decoupling in a Stripe-Ordered High-T_c Superconductor

E. Berg,[1] E. Fradkin,[2] E.-A. Kim,[1] S. A. Kivelson,[1] V. Oganesyan,[3] J. M. Tranquada,[4] and S. C. Zhang[1]

- When stripe order is present, frustration of the Josephson coupling may occur.





- The frustration leads to layer decoupling and gives rise to a 2D-like superconducting state.

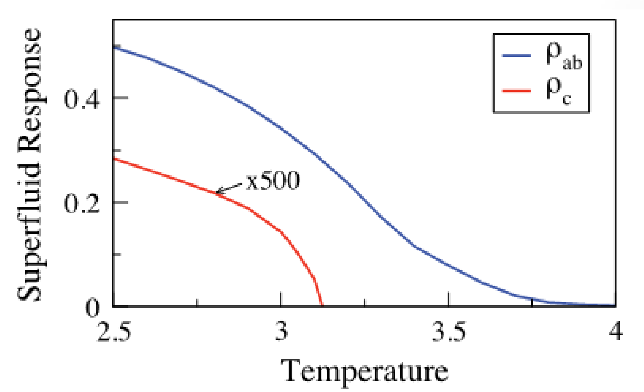
Previous work

PRL **105,** 085302 (2010) PHYSICAL REVIEW LETTERS week ending 20 AUGUST 2010

Finding the Elusive Sliding Phase in the Superfluid-Normal Phase Transition Smeared by *c*-Axis Disorder

David Pekker,[1] Gil Refael,[2] and Eugene Demler[1]

- Interplay between disorder along the c-axis, and the a-b planes KT physics gives rise to an anomalous phase.
- In this region of the phase diagram, superfluid becomes split into an array of 2D puddles with no response along the c axis.
- The discussion here is about BEC, but it is also valid for layered superconductors as well.



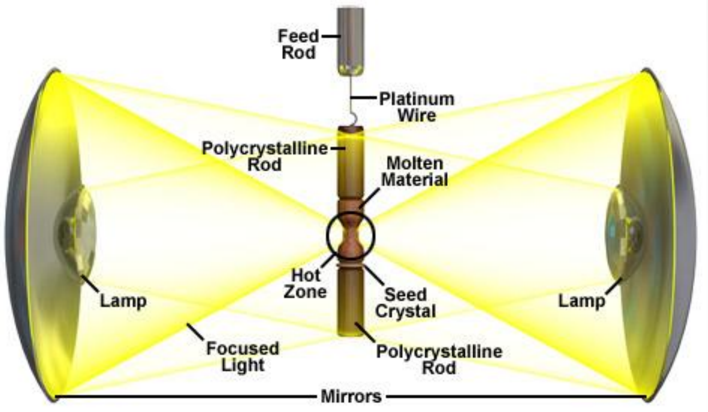
P. Mohan and T. Vojta , PRL 105, 085301 (2010)

Motivation

- The experiments were done at relatively high magnetic field, up to 9 Tesla. This could alter the ground state of the system.
- We believe that we a state of 2D superconductivity measure, in a zero field regime.
- We discovered this unintentionally while measuring magnetization of single crystal of LSCO with different orientations.

Crystal growth technique we use:

Traveling Solvent Floating Zone Method (Crystal Systems Corp. Japan) image furnace. It is in operation in our laboratory since 2007.

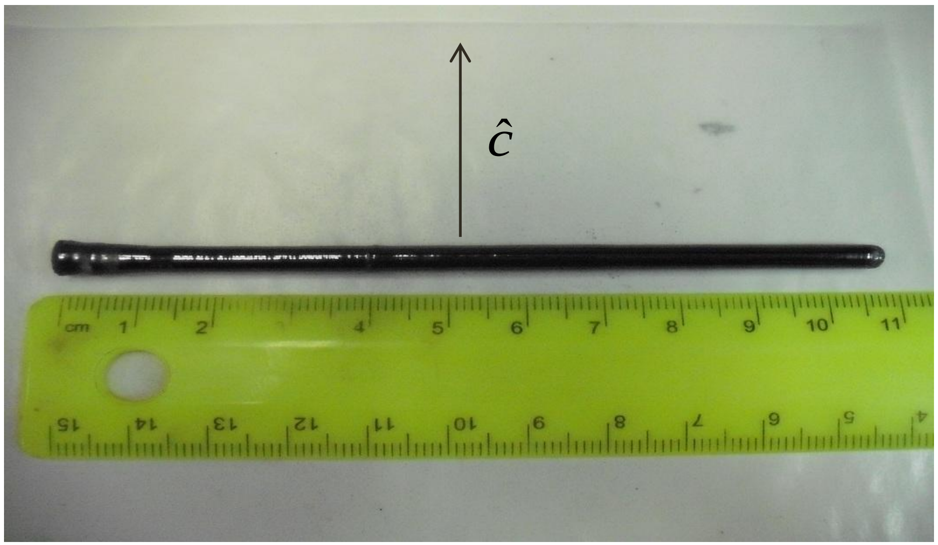


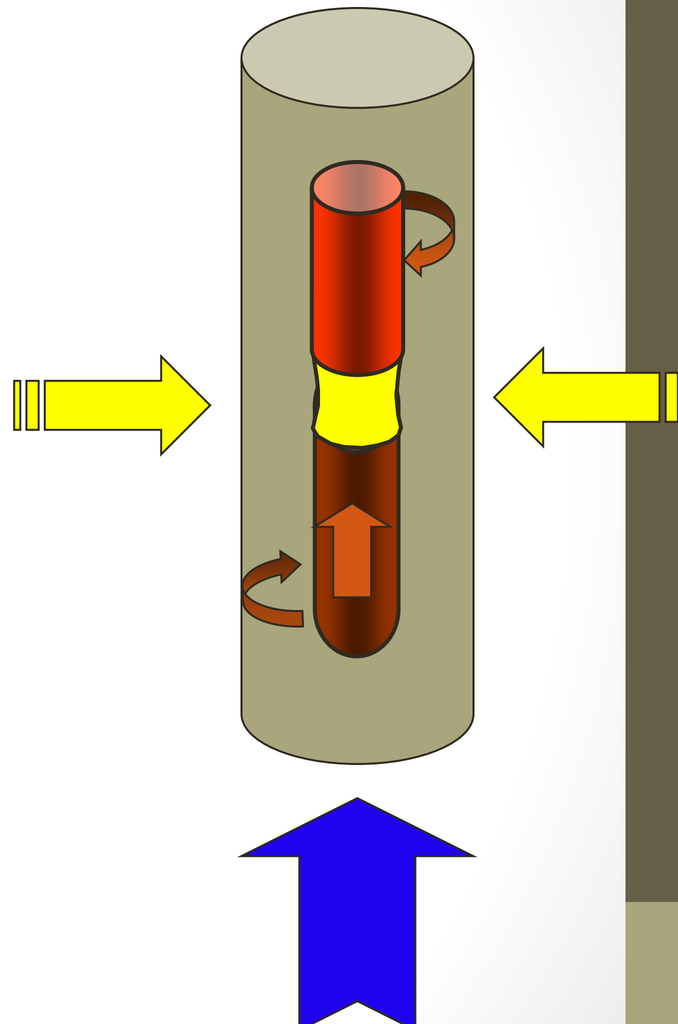
Crystal growth "technology"

1. Synthesis of the starting material

2. Pressing and sintering of the feed rods Ø7-9mm, length 50-200mm!!
(hydrostatic pressing 60000 PSI)

Growth parameters which can be controlled

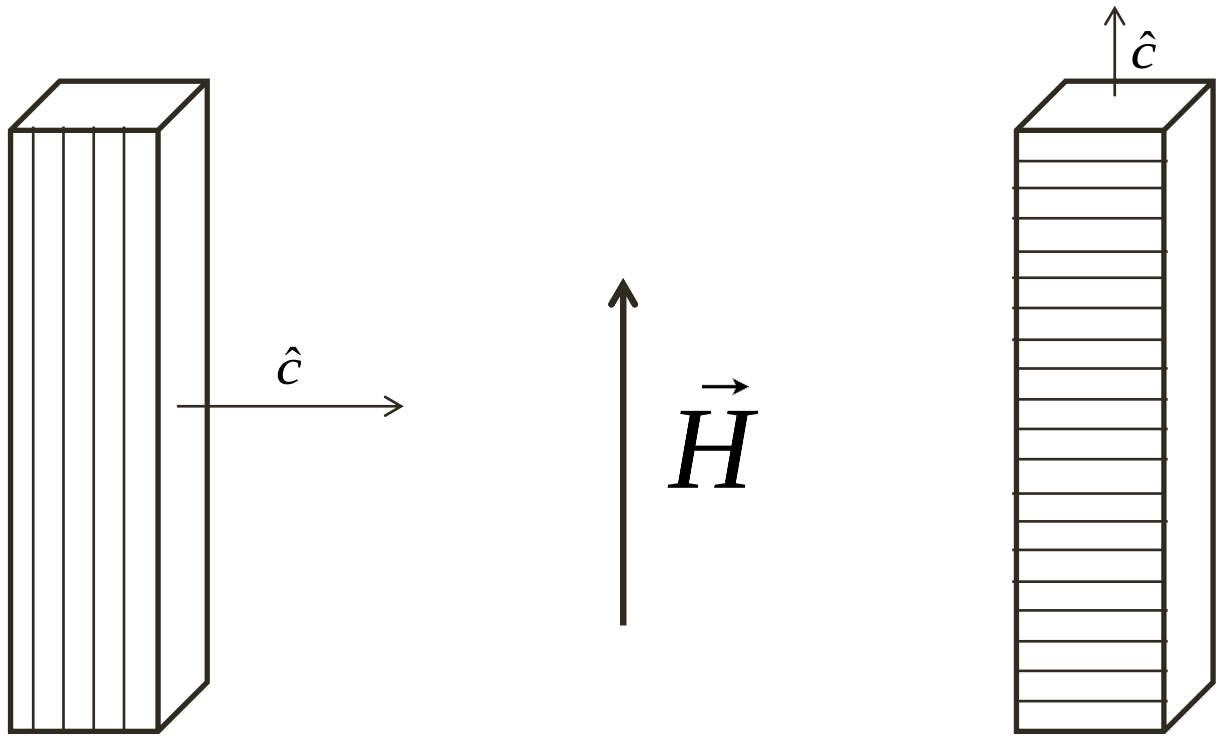




It appears that LSCO grows with it's c-axis pointing from the side.

The samples – Rectangular Needles

A-needle C-needle



A-needle C-needle

<u>Typical dimensions</u>

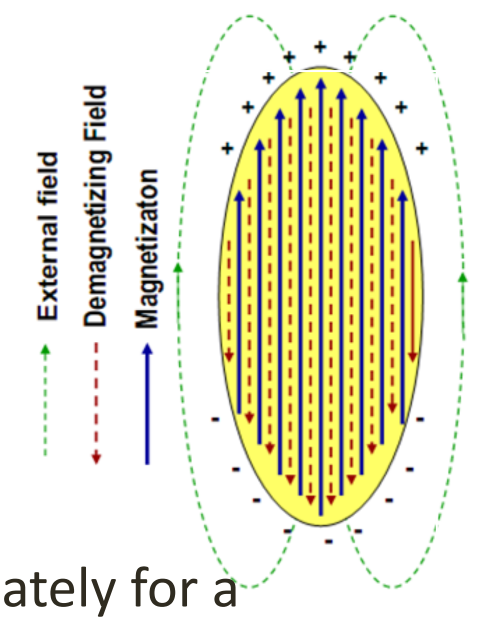
1x1x10 mm **1x1x5mm**

Why needles?

- **Demagnetization factor** - ***D*.**

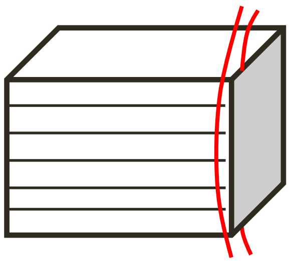
  apparent susceptibility is not the intrinsic one:

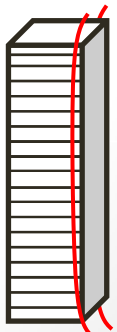
$$\chi_a = \frac{\chi}{1 + D\chi}$$



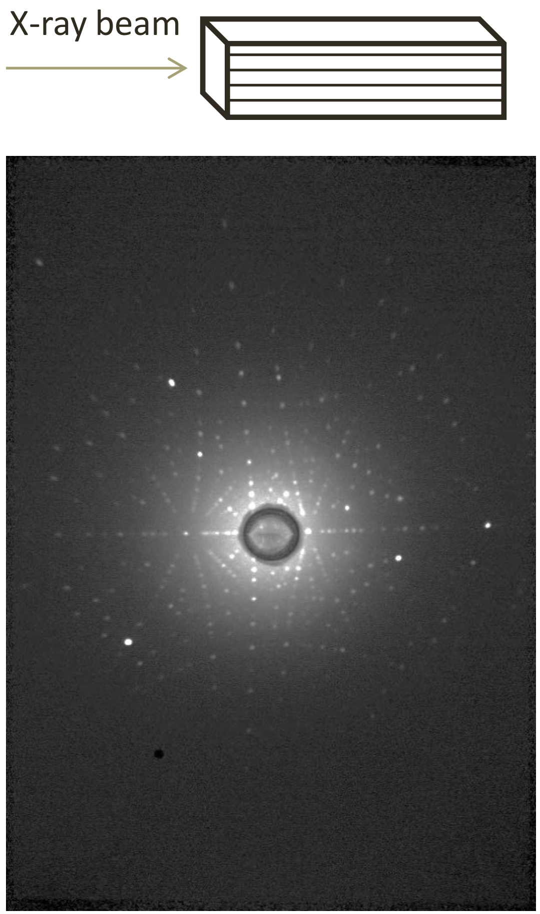
D depends only on sample geometry, but fortunately for a needle ***D*≅*0***.

- With rectangular needles we can measure **“clean”** susceptibility for the two directions.

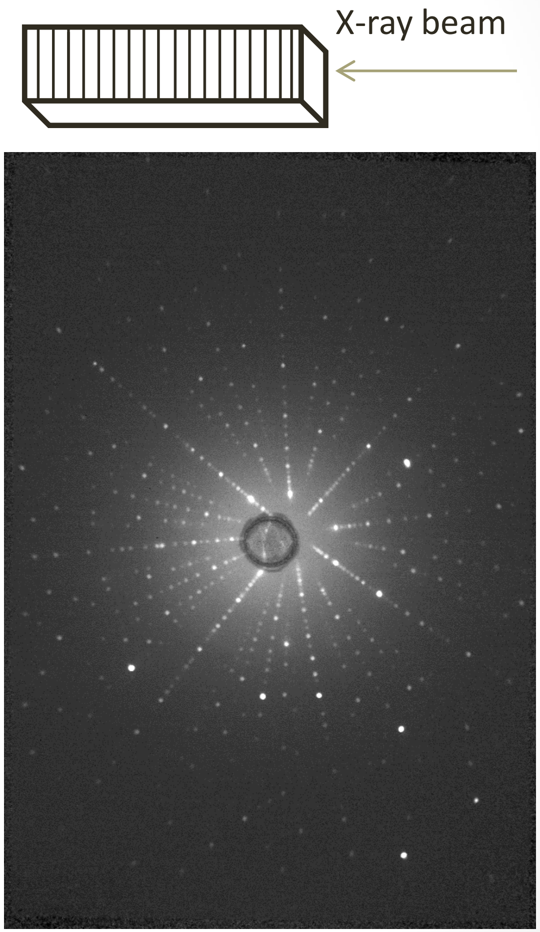




Orientation

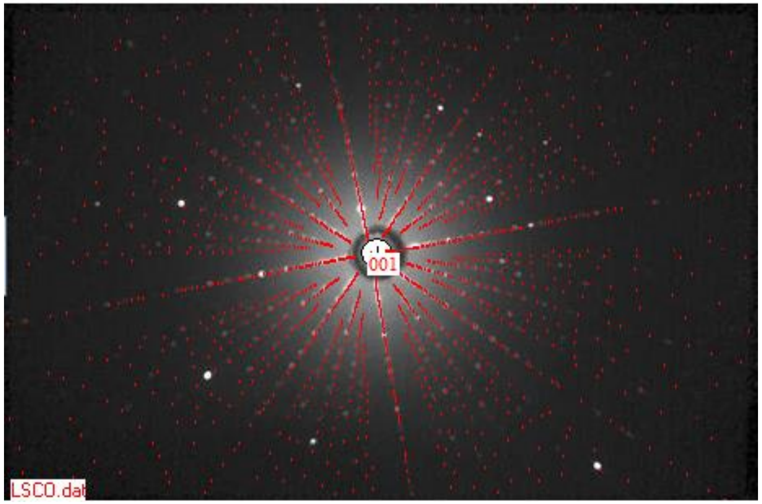


Laue of (100) direction (AB)

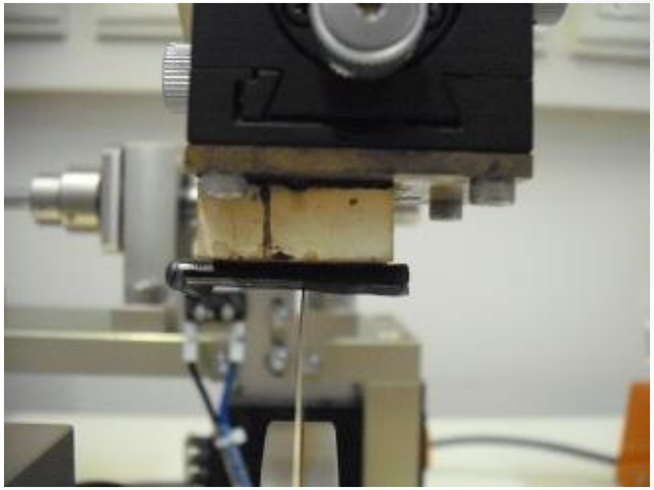


Laue of (001) direction (c-axis)

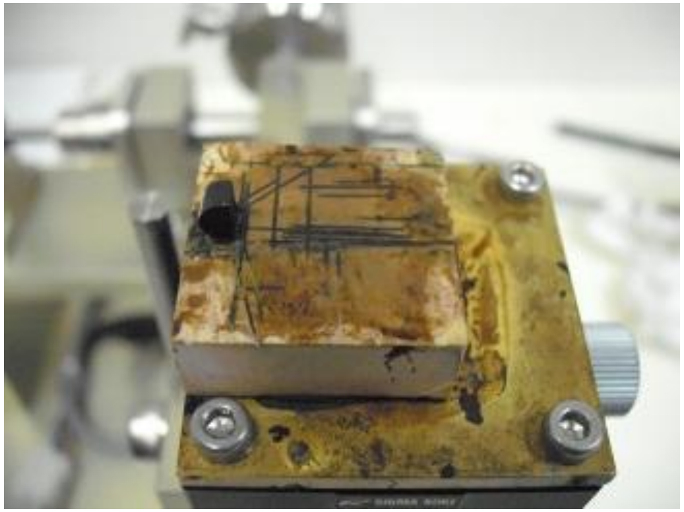
Cutting the samples



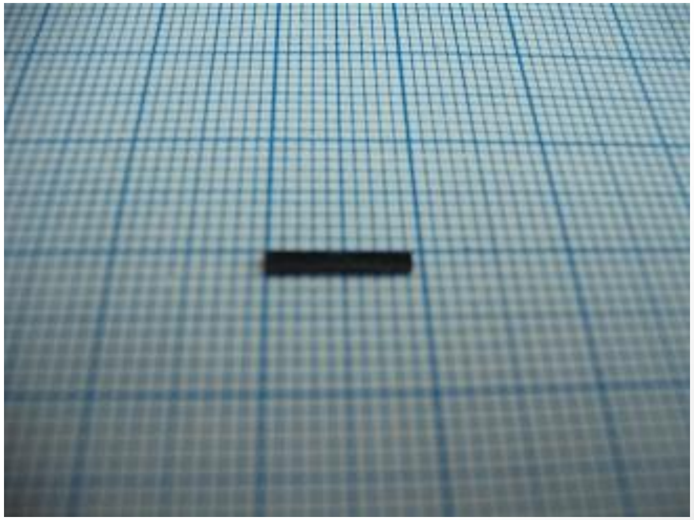
Orientation with A Laue Camera



Cut the crystal



Cut some more…



1x1x10mm needle

Cutting the samples

- It was extremely difficult to cut a C-Needle.
- The crystal easily breaks on its natural cleavage plane perpendicular to c-axis.
- A wire saw, which applies minimal

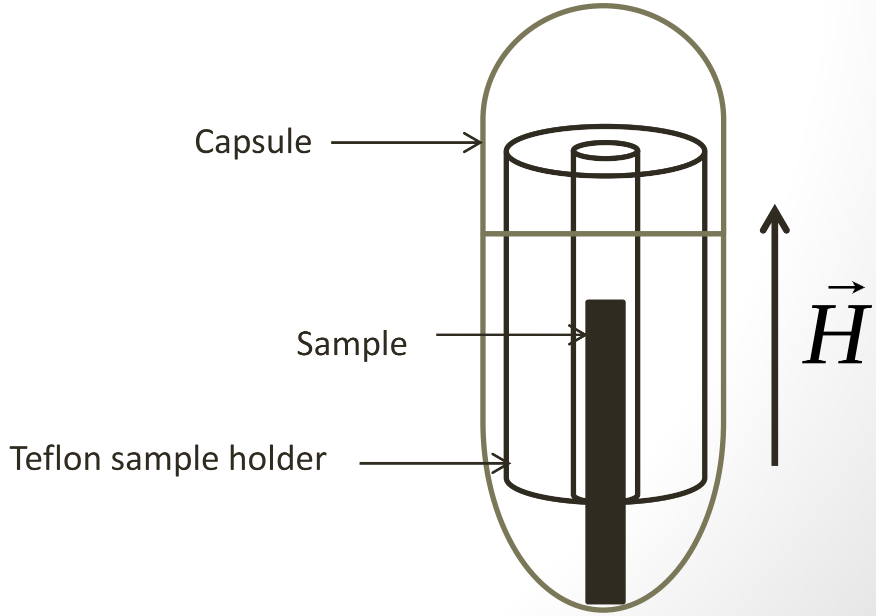
  pressure, can do the job.

Spontaneously cleaved crystal
(C-axis going out from to page)

Experimental Setup

- Measurement was conducted in cryogenic Limited SQUID Magnetometer.
- Field Resolution of 0.01Oe at field up to 200Oe.

- Prior to each measurement batch the field was degaussed and calibrated with a type I SC.
- The measurement were performed after slowly cooling the sample at zero field.

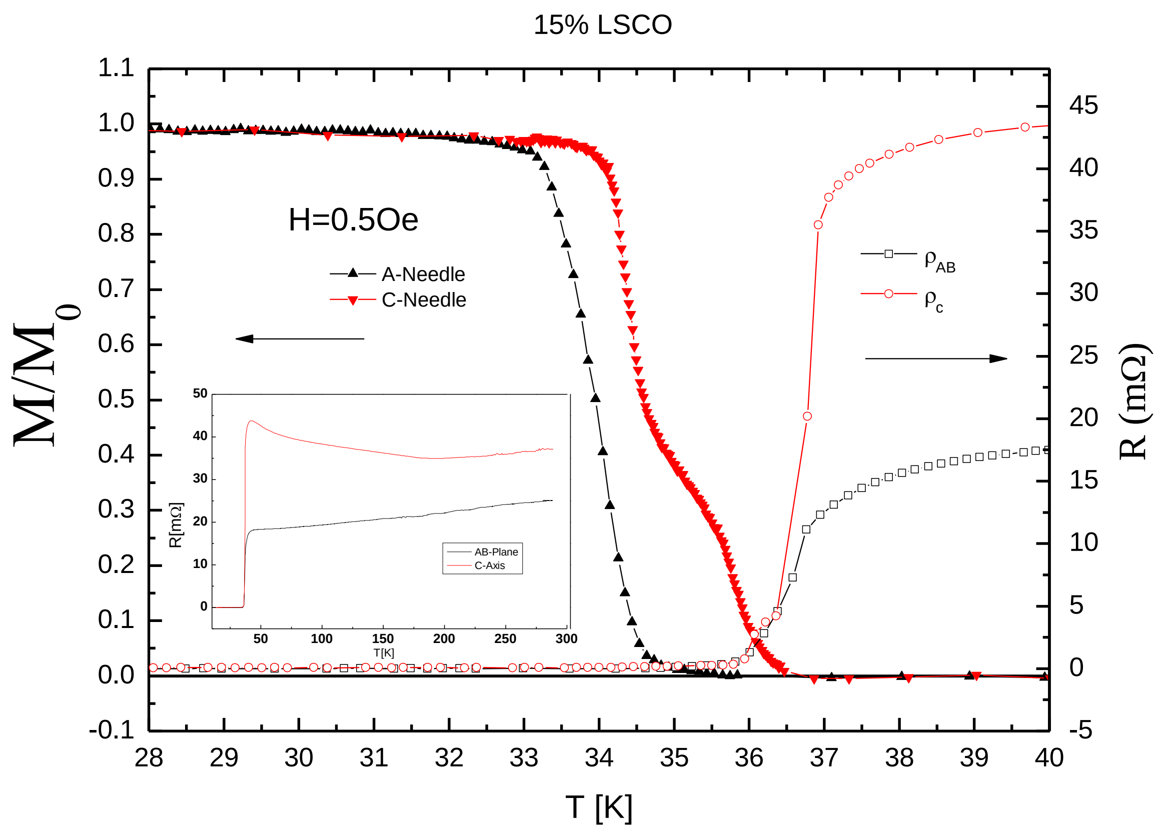


What did we measure?

- **We mainly measured magnetization vs T in two directions, parallel and perpendicular to the C axis.**
  This was done for:

- Different doping.
- Different applied magnetic fields.
- Different sample geometries.
- Sample Homogeneity via T_c.
- Different angular tolerance
- Critical fields for various temperature close to $T_{c.}$

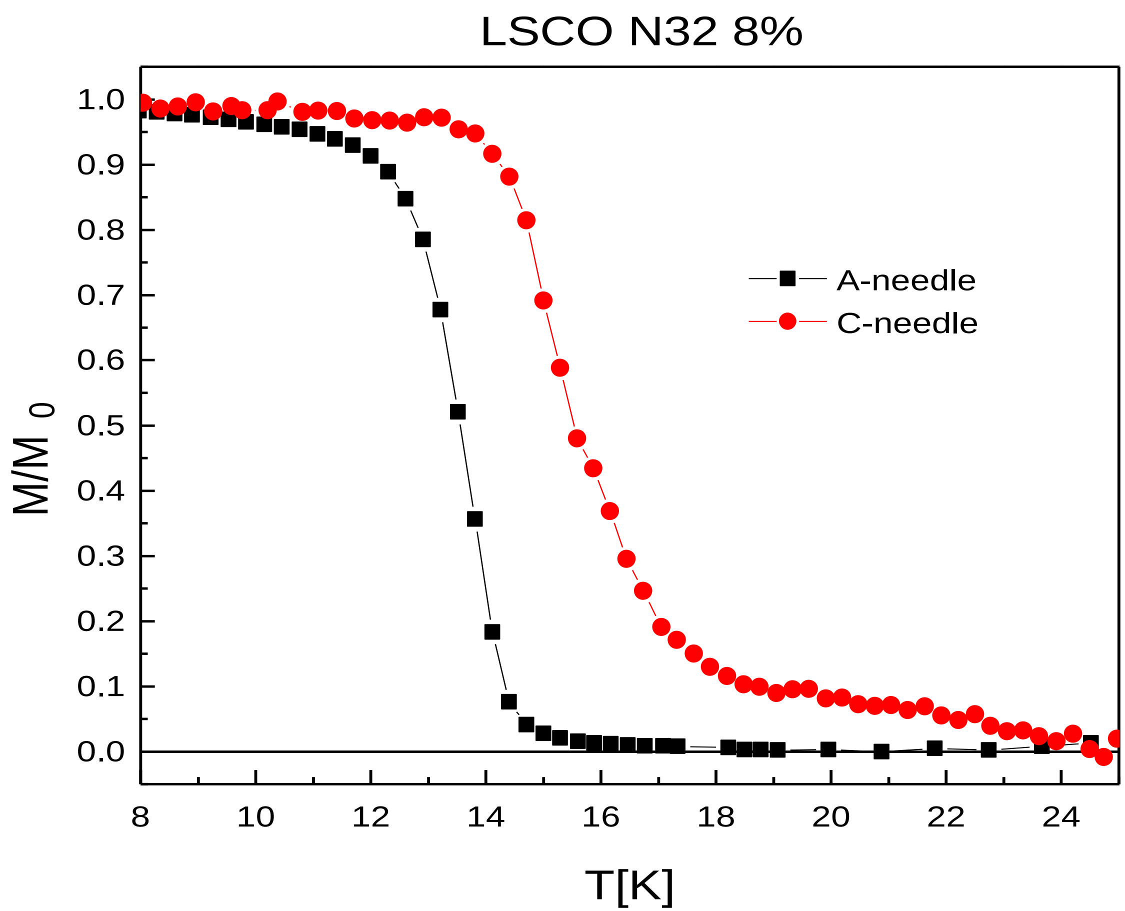
The main and surprising result



It looks like we have two different T_c for the two directions in χ, while resistivity shares the same T_c.

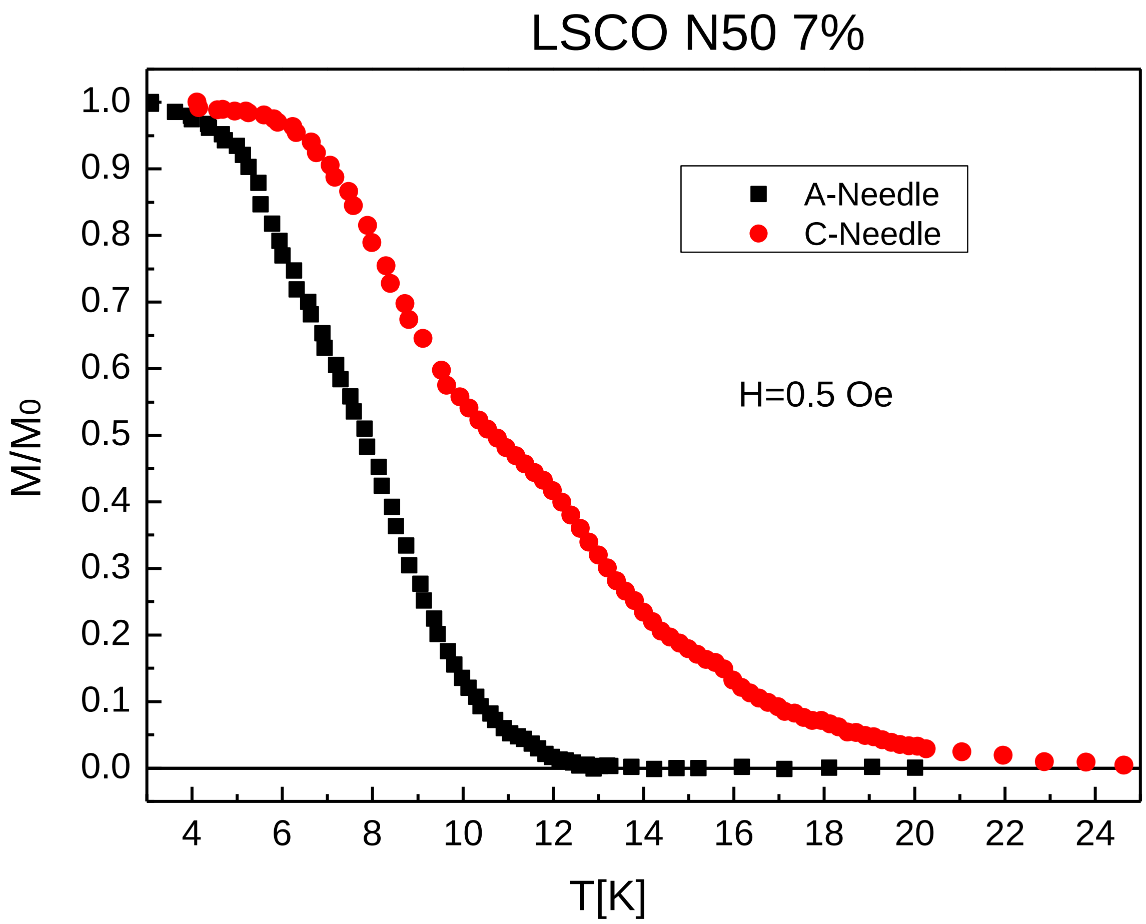
$\Delta T_c = 0.7 \pm 0.05K.$

Other Doping



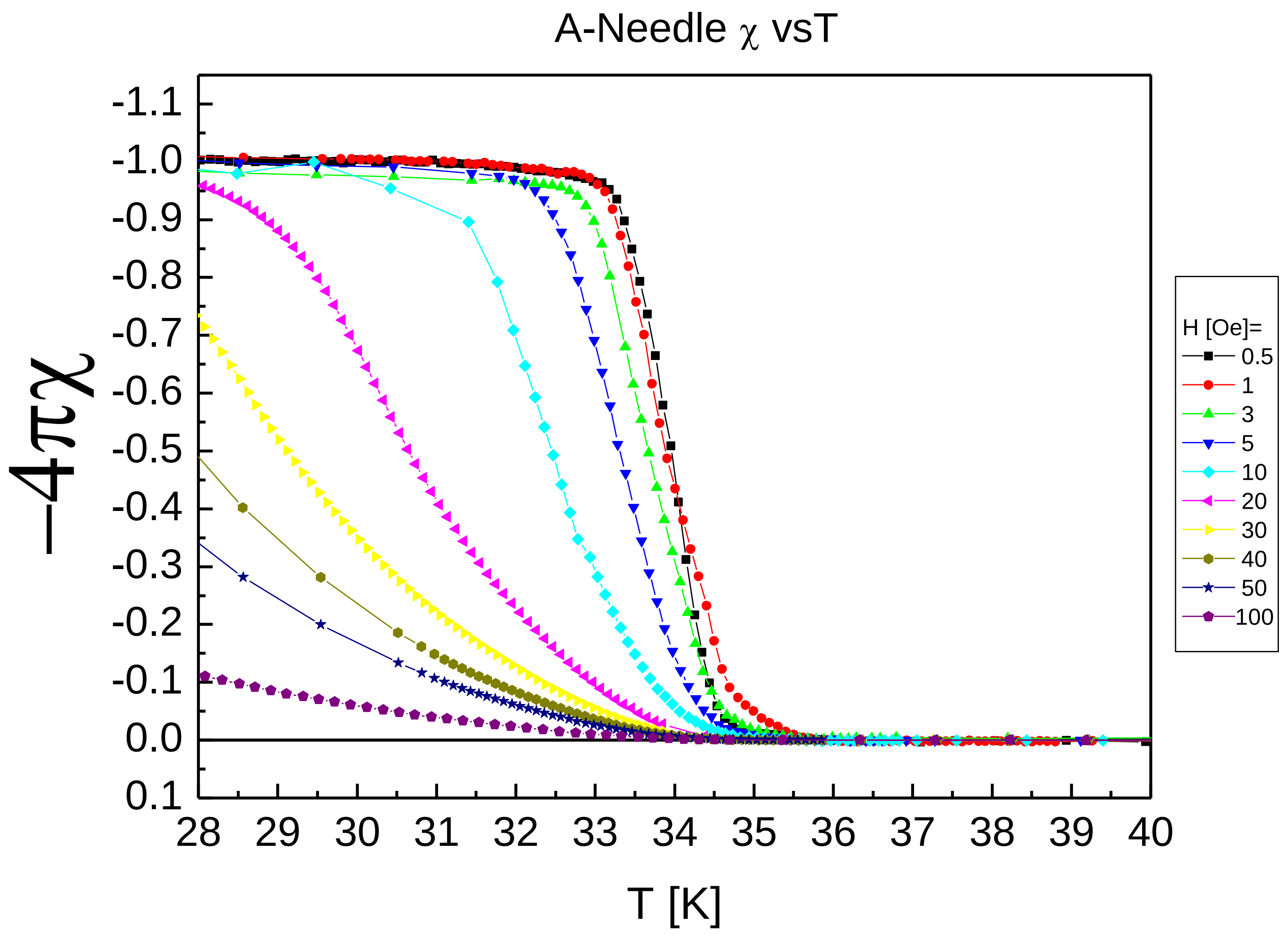
We observer the same effect for x=0.08 doping with $\Delta T_c = 2.6 \pm 0.1K$.

Other Doping

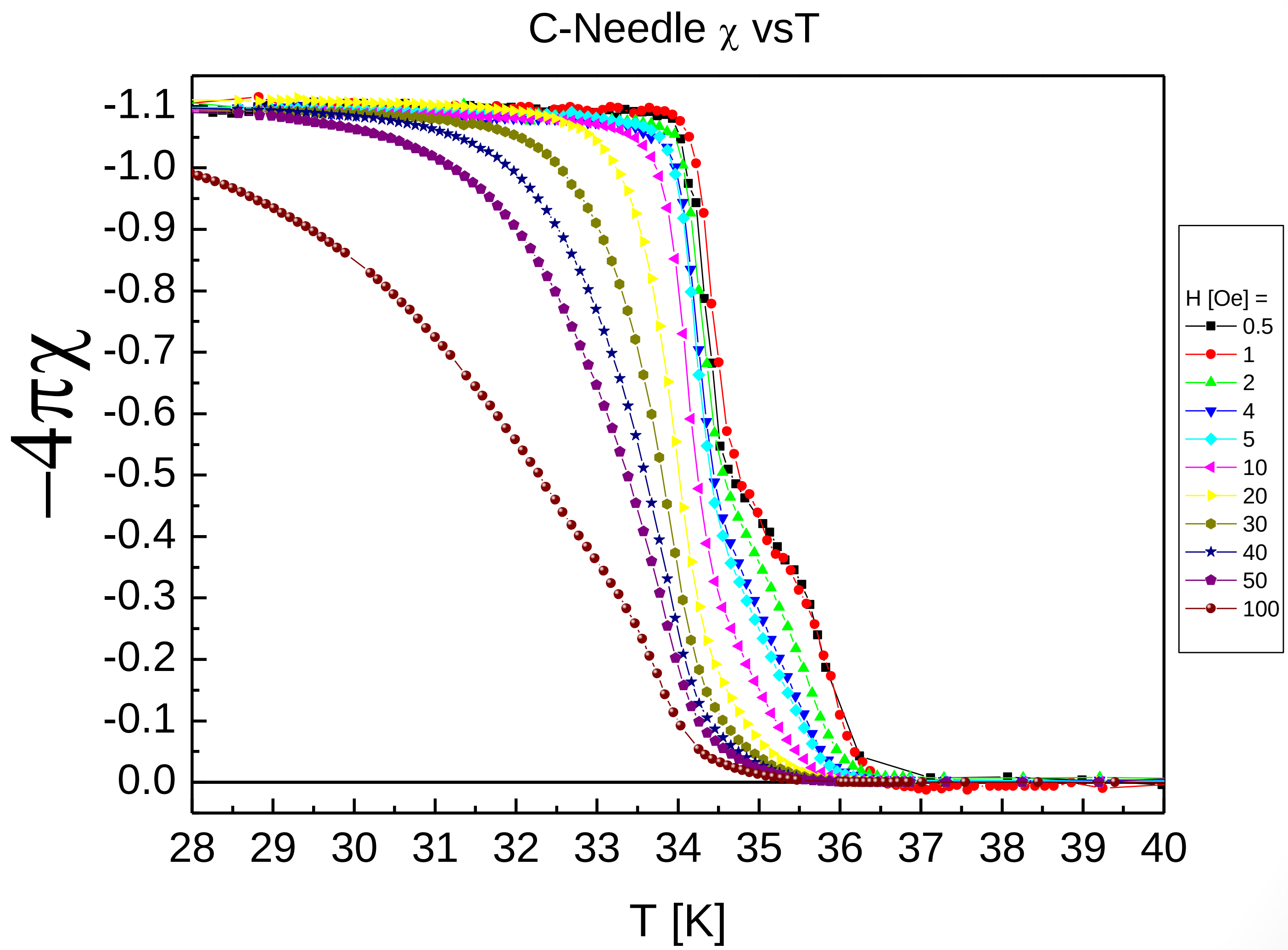


- We observer the same effect for x=0.07 doping with $\Delta T_c = 4.5 \pm 0.5K$ (probably larger).
- At x=0.06 we could not observe the saturation of the magnetic moment, so x=0.07 was our limit.

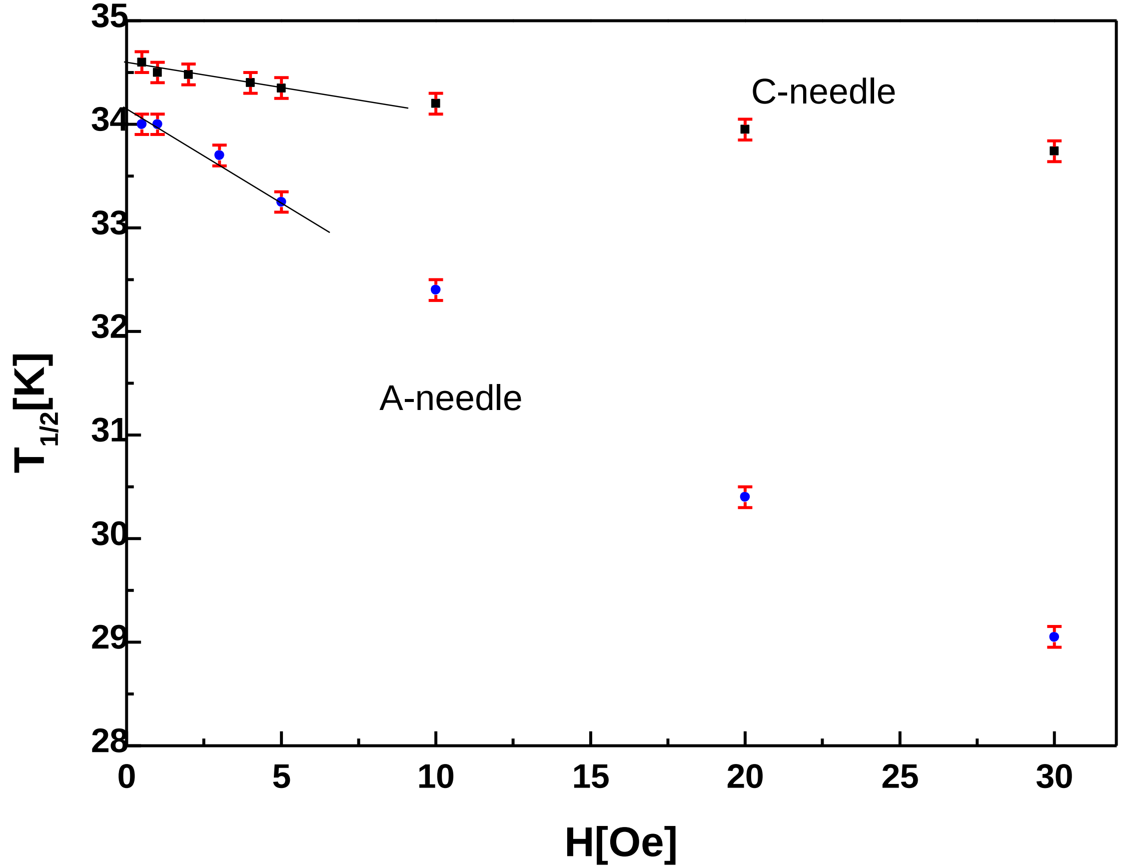
Field Dependence



Field Dependence

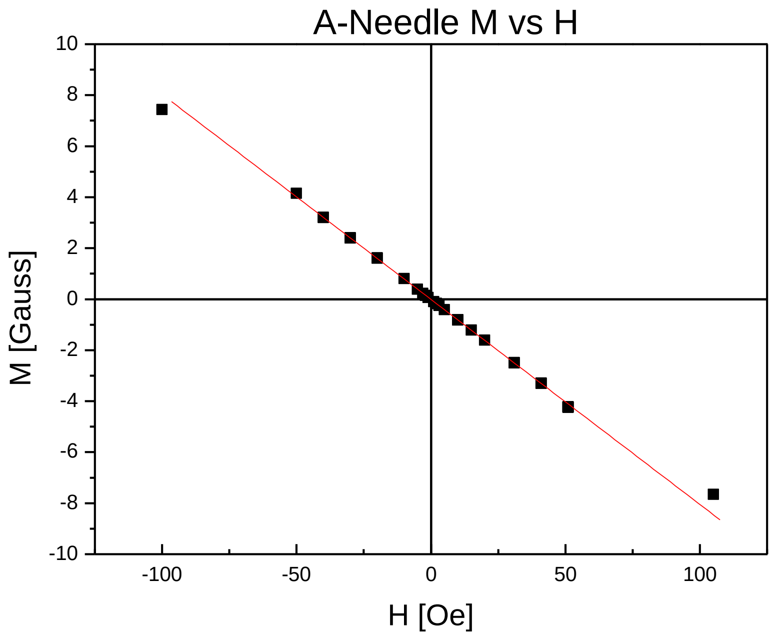


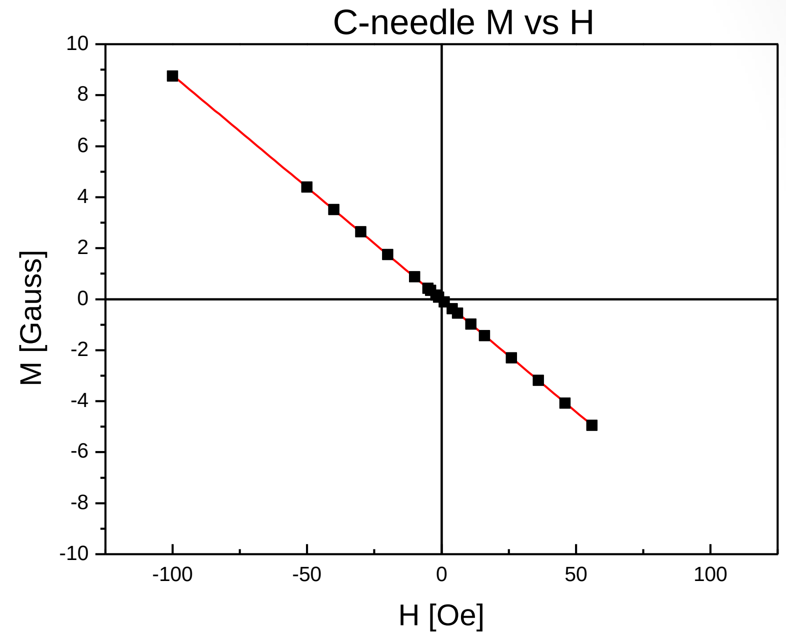
Field Dependence of T ½



- T ½ is the temperature where the susceptibility is 50% of it’s max value.
- We see that in the H=0 limit there is a clear difference between the two directions at H=0.
- The A-needle has a sharper T dependence of the transition width.

Volume fraction

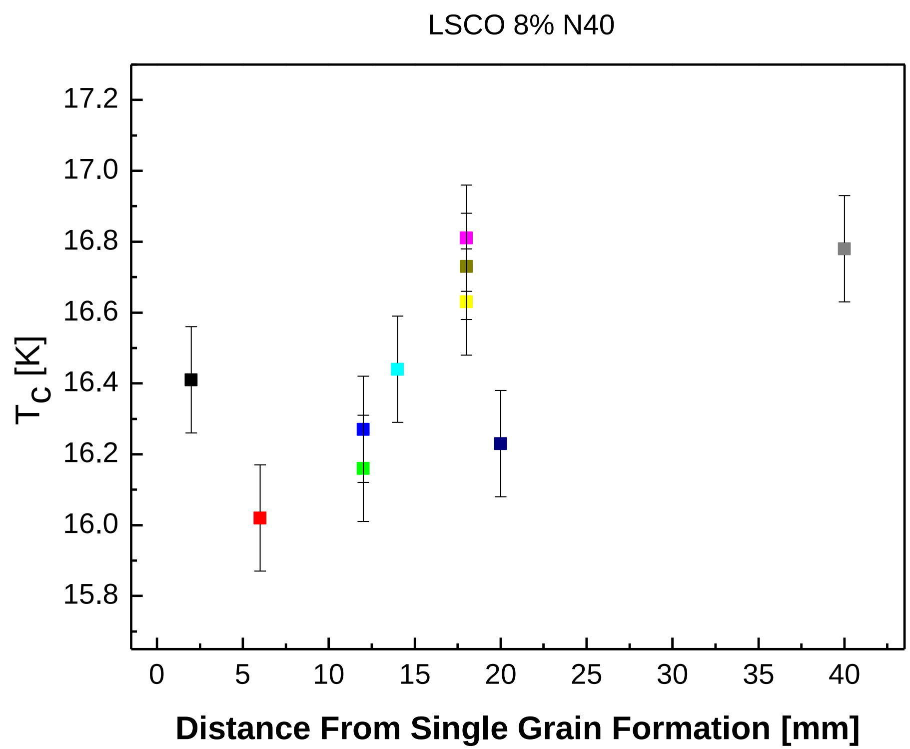


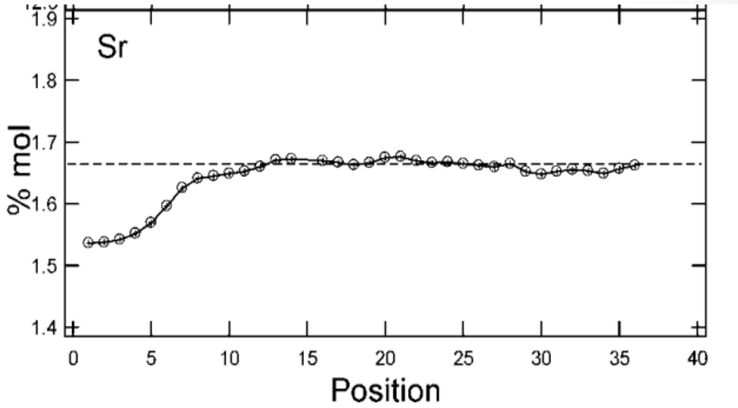


@T=4K

We measured full volume fraction for our sample at the lowest temperature.

Sample Homogeneity

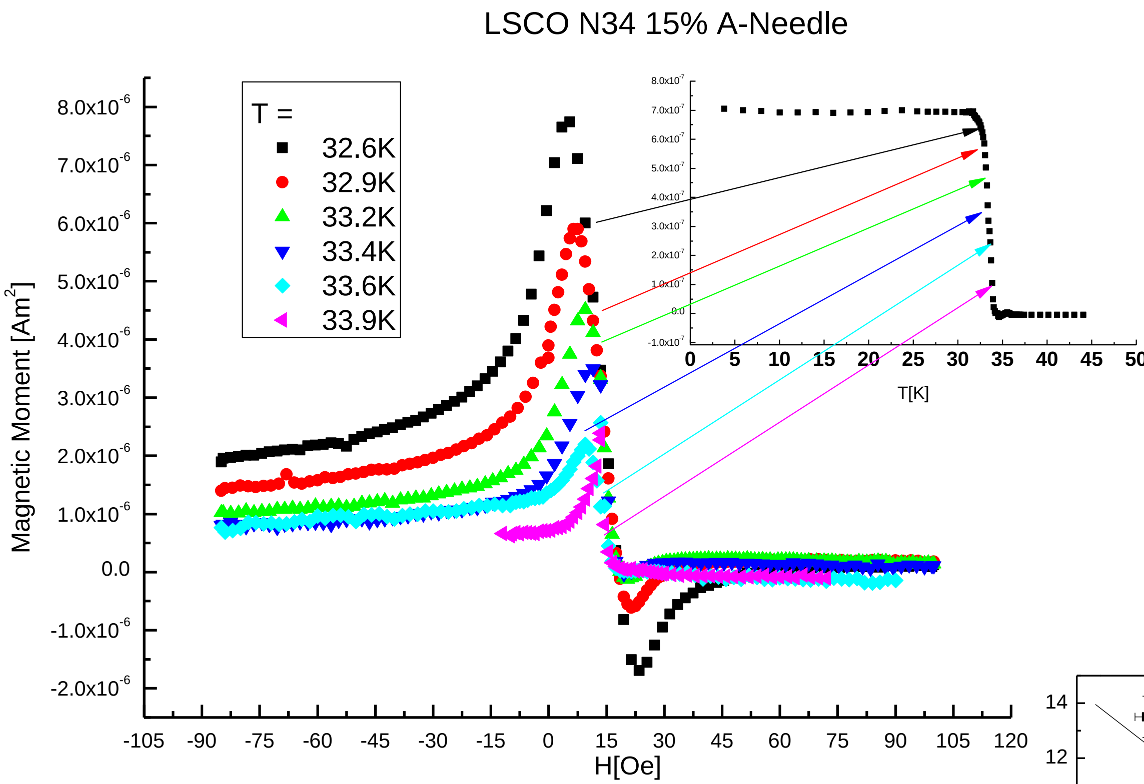


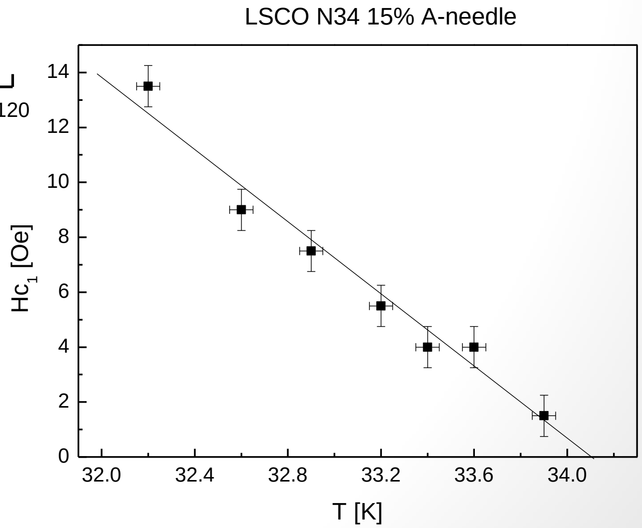


Dashed line shows the Sr content for the nominal composition.

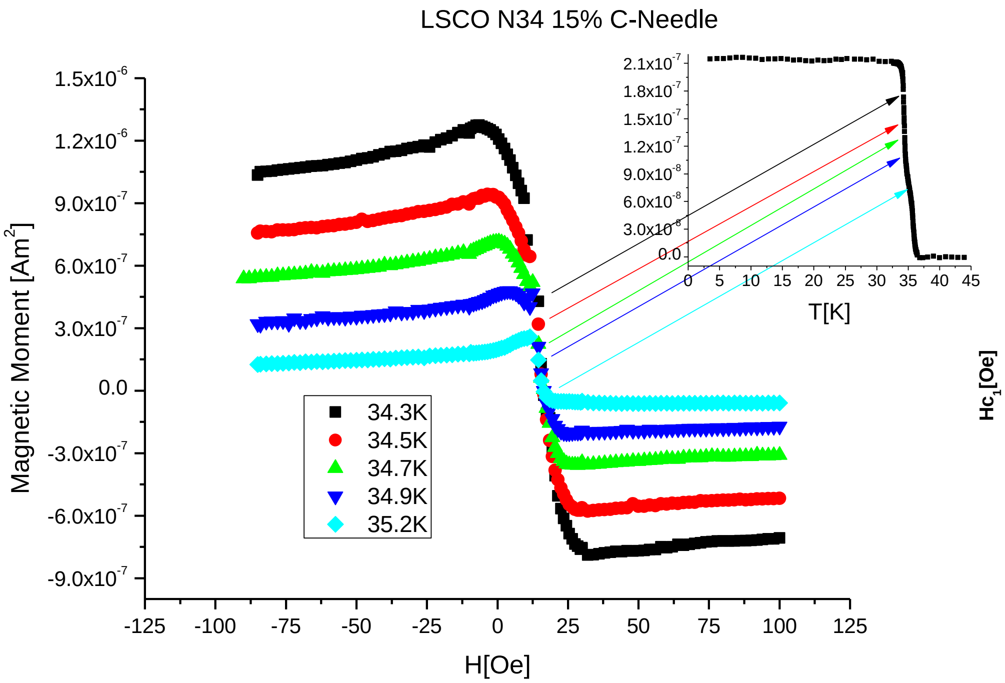
- T_c is fluctuates within measurement errors with STDEV 0.25K along the grown sample while $\Delta T_c = 2.6 \pm 0.1K$ was measured.
- Previous works has shown that Sr content is stabilized after 20mm of crystal growth.

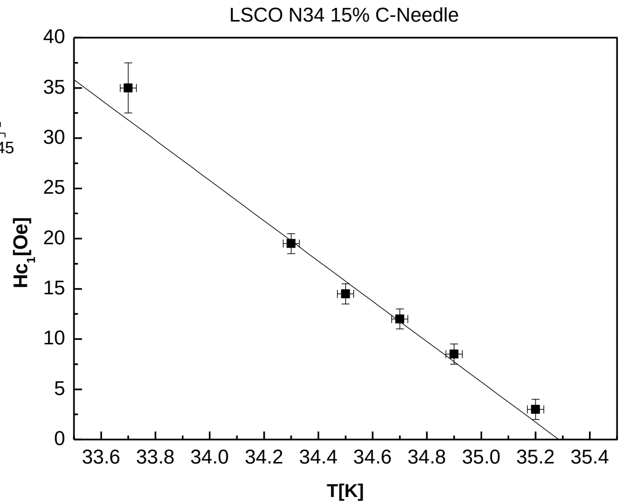
Critical Field Temperature Dependence A-needle





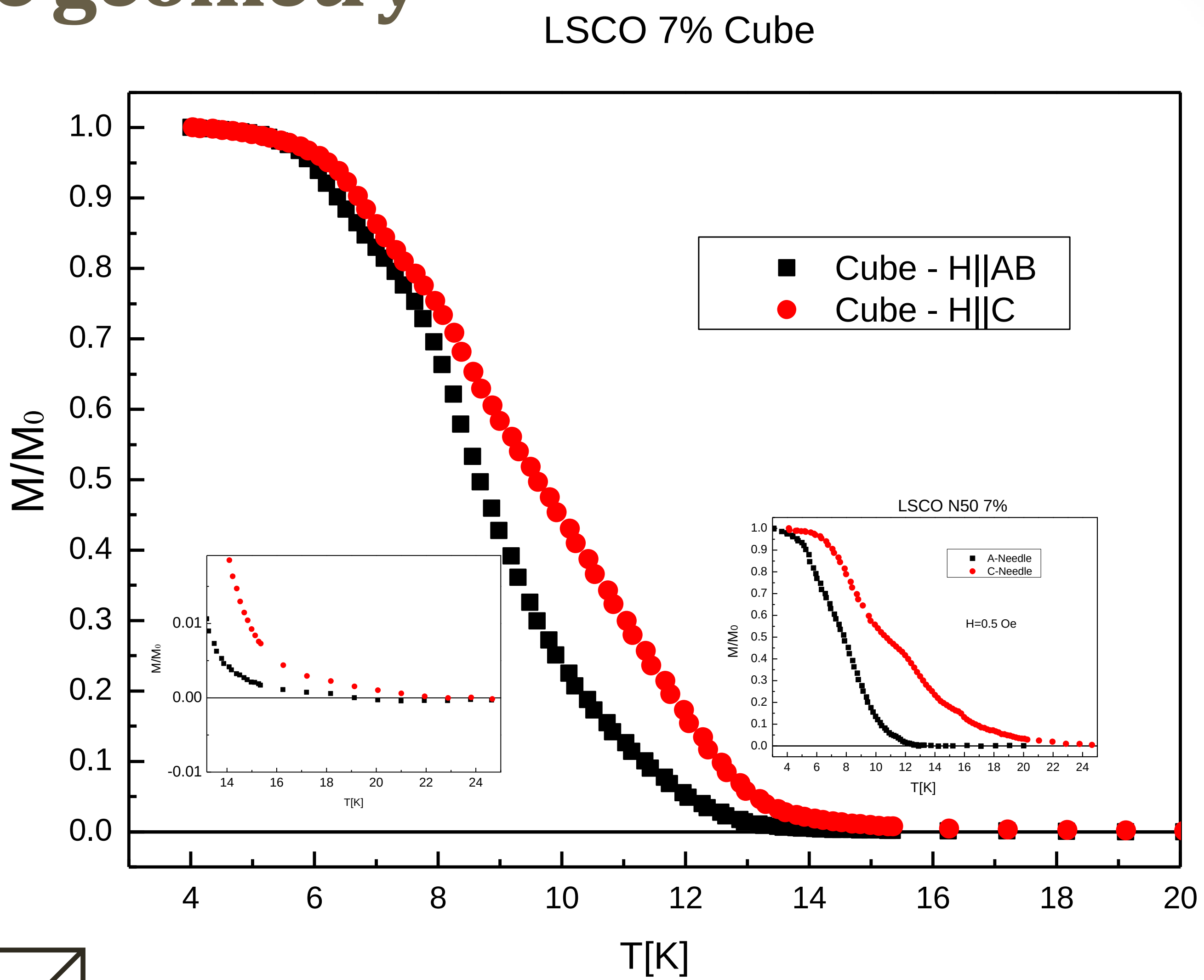
Critical Field Temperature Dependence C-needle

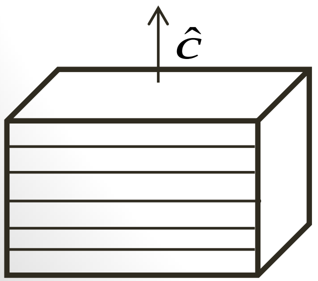




- The measurements were preformed under H_{c1} for all the temperature range on the transition.
- T at which Hc_1 goes to zero is different between the samples.

Cube geometry

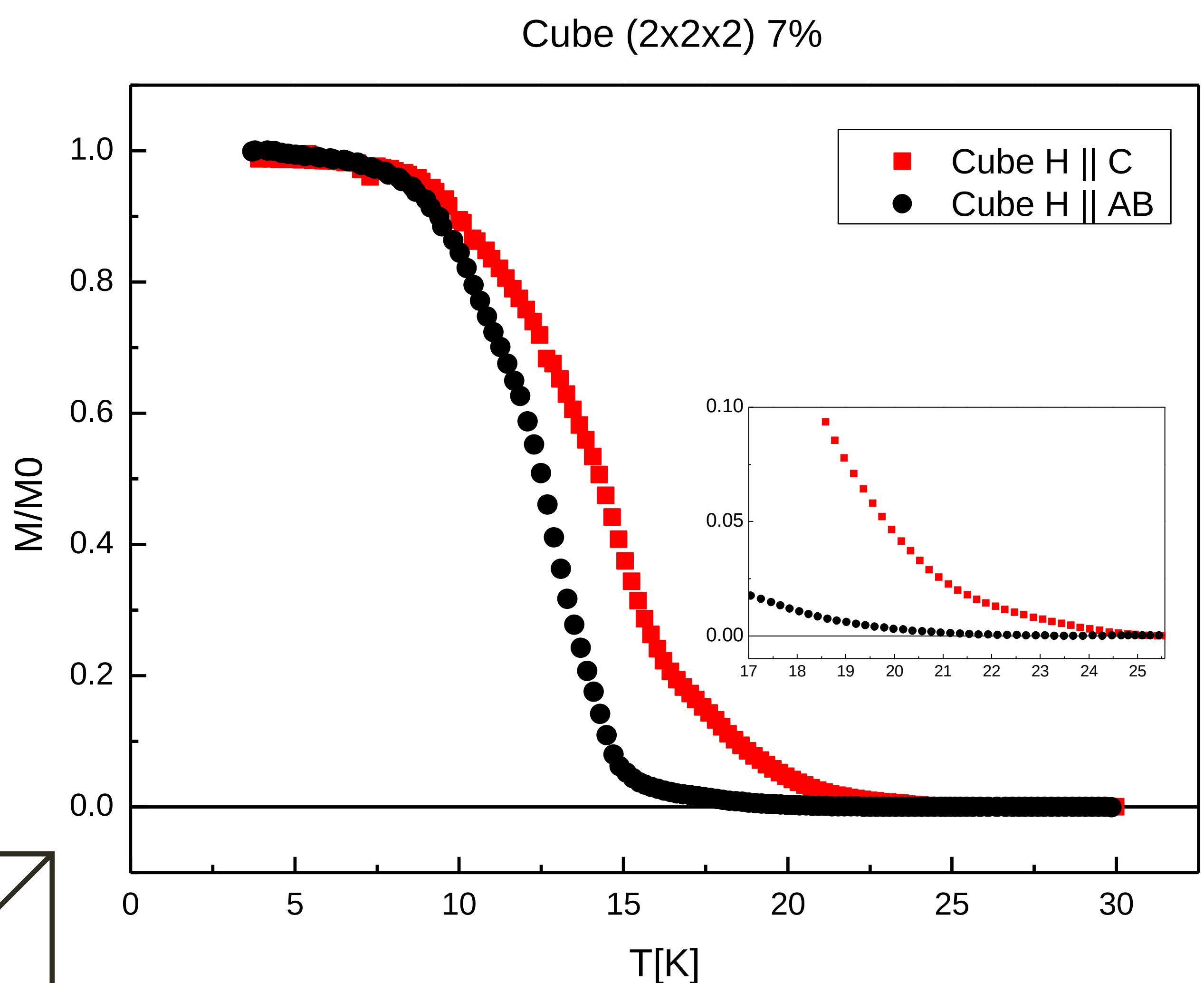


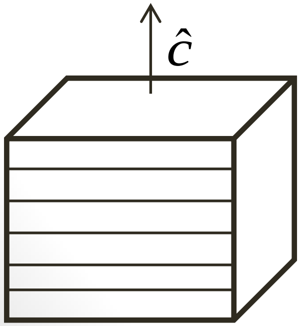


4x4x3 mm

When measure the same sample we see clear difference between the two directions – our results are sample independent.

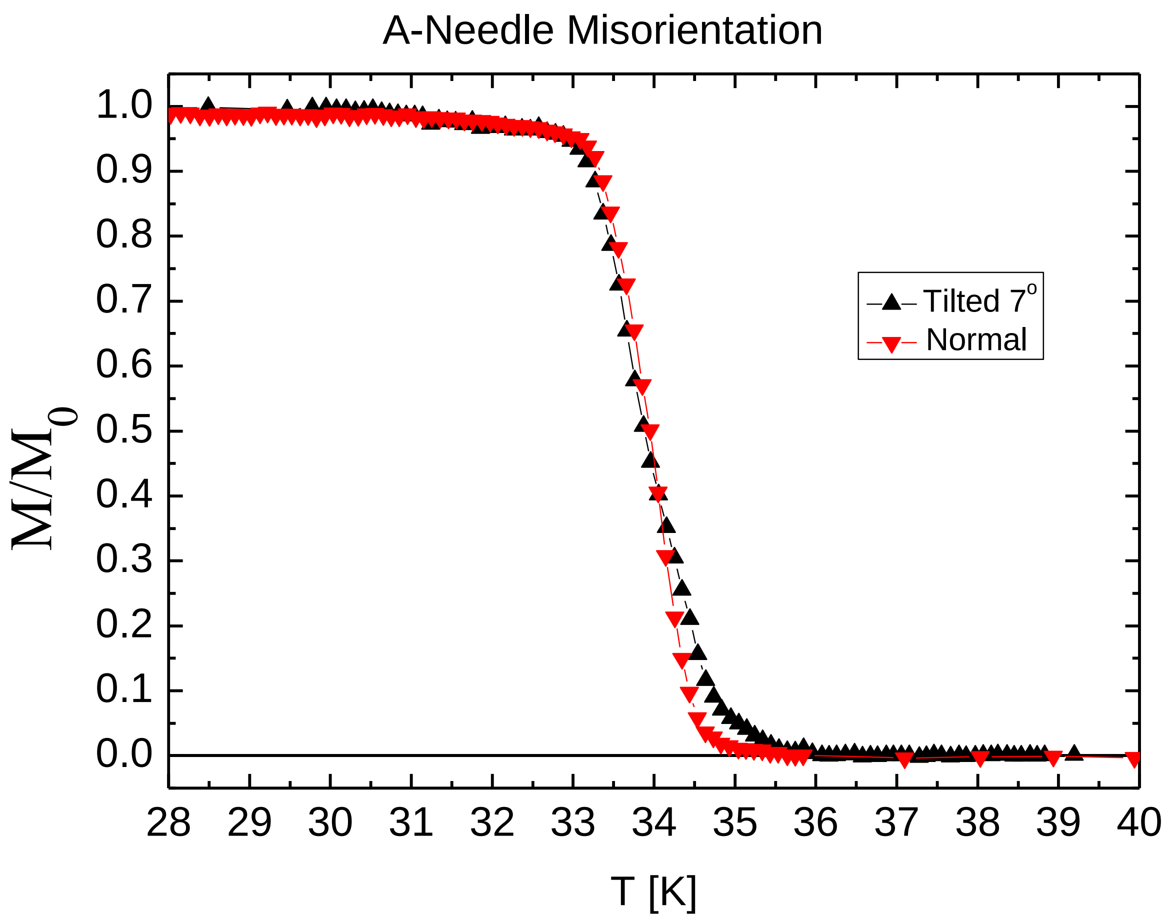
Cube geometry





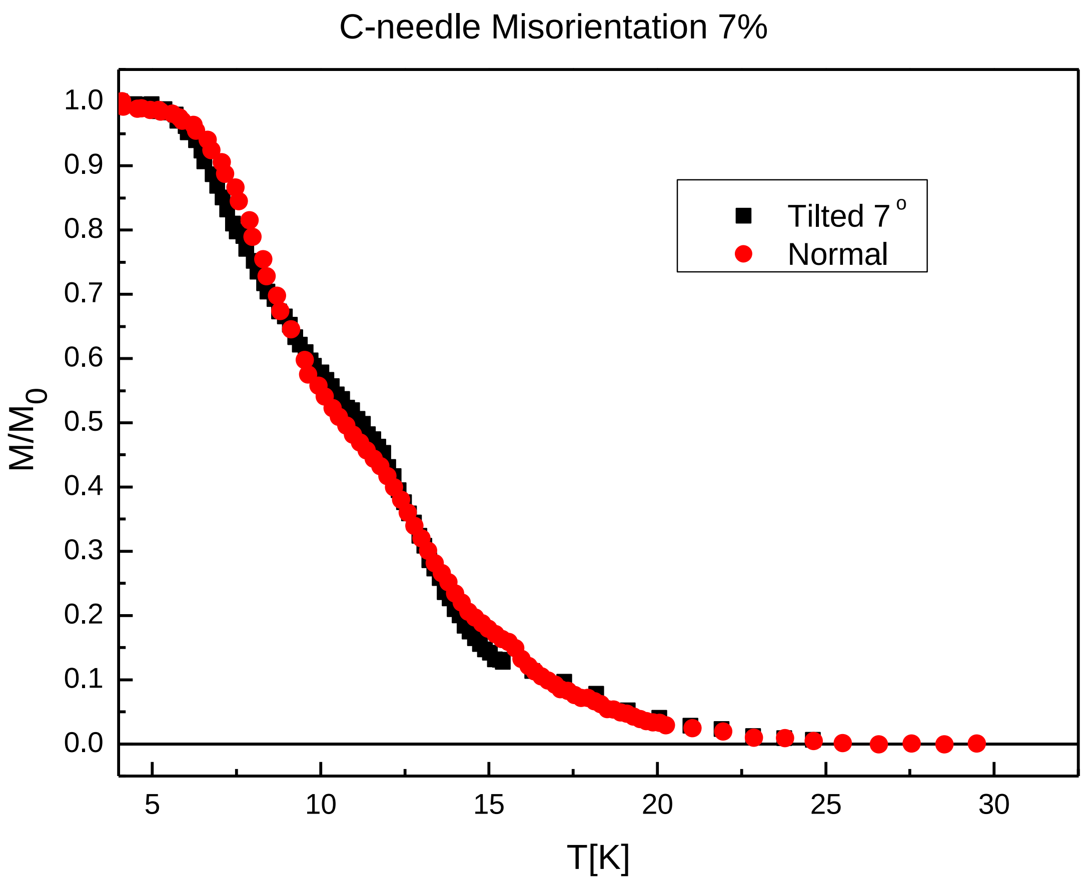
2x2x2mm

Misorientation



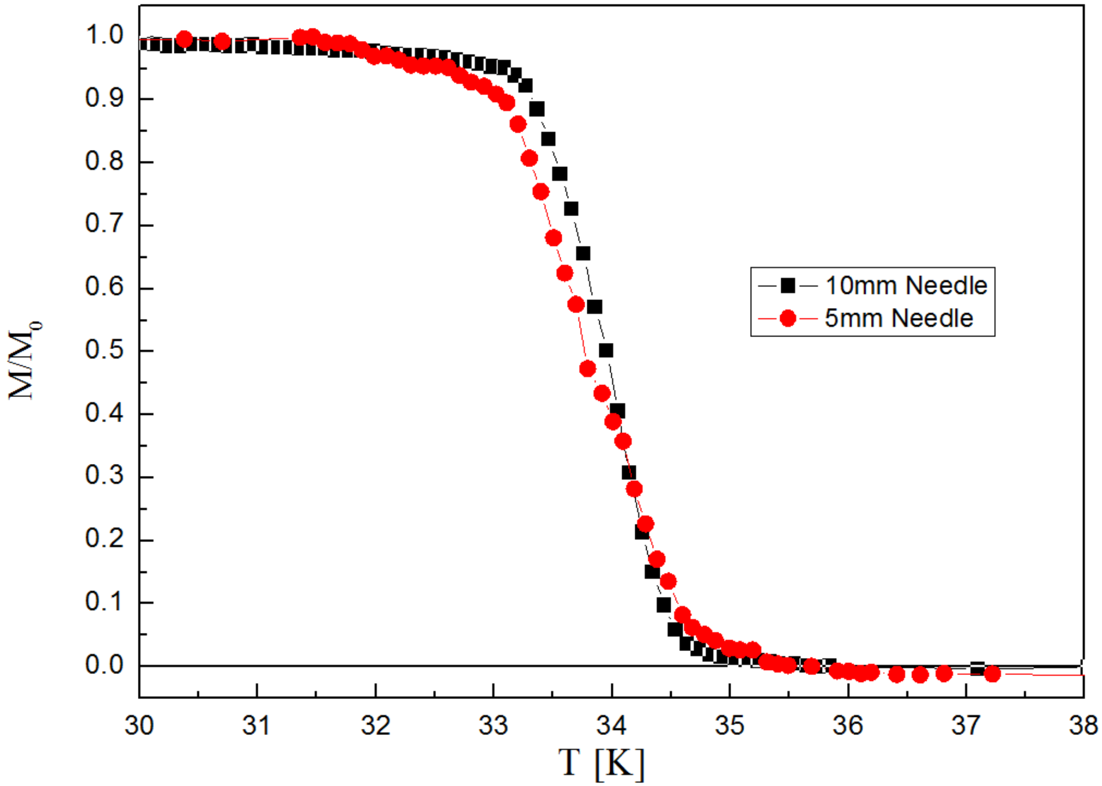
No significant difference for artificial misorientation For the A-needle.

Misorientation



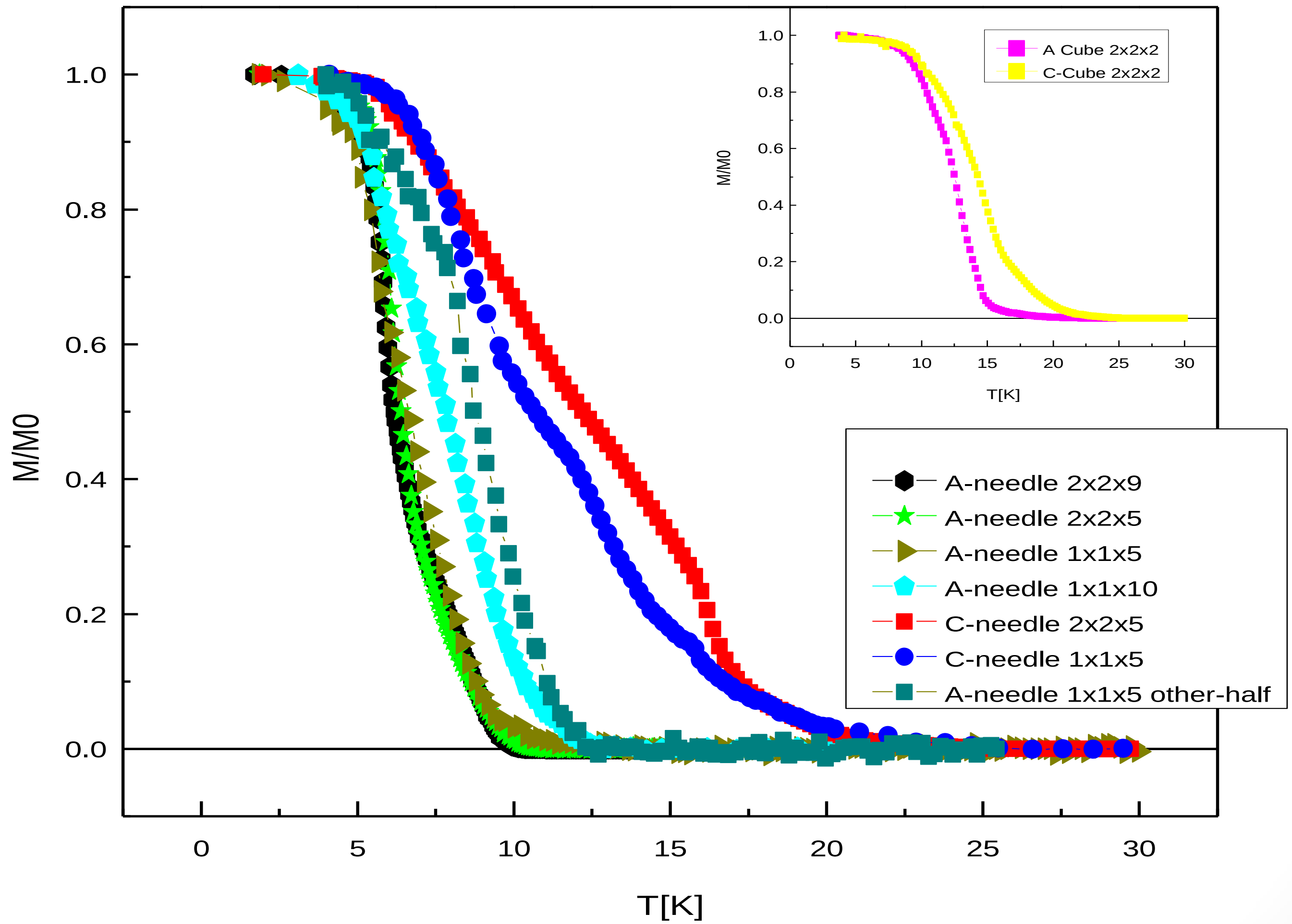
No significant difference for artificial misorientation For the C-needle.

Length Dependence



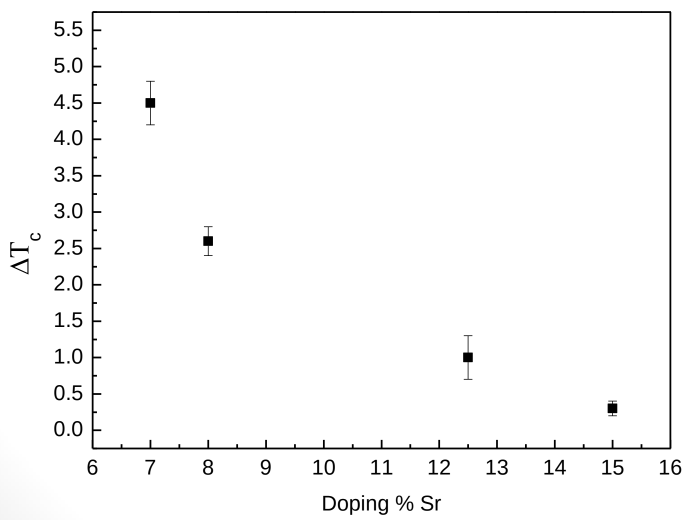
No significant difference between different sample lengths.

Reproducibility



Summary

- We grew Single crystals of LSCO with various Sr doping.
- We measured magnetization on needle shape sample with different orientations.
- We found that for the A and C needle samples there is a consistent difference in T_c. This is independent of external factors.
- The difference in T_C depends on doping, it increases as doping decreases

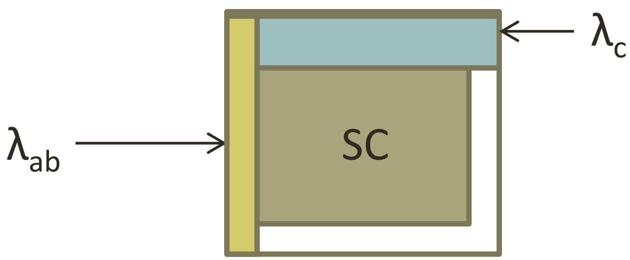


Is there another explanation

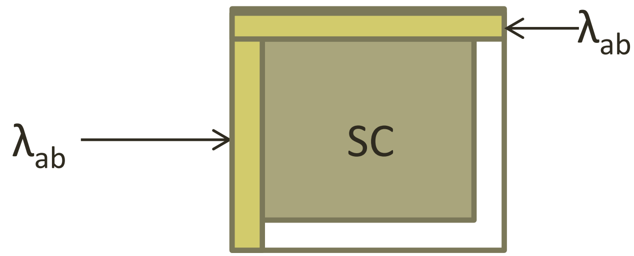
- Is the penetration depth larger than sample dimensions?
- The standard London equation:

$$\nabla^2 B = \frac{1}{\lambda^2}B$$

- The London equation in two dimensions (Valid below H_{c1}):



A-needle



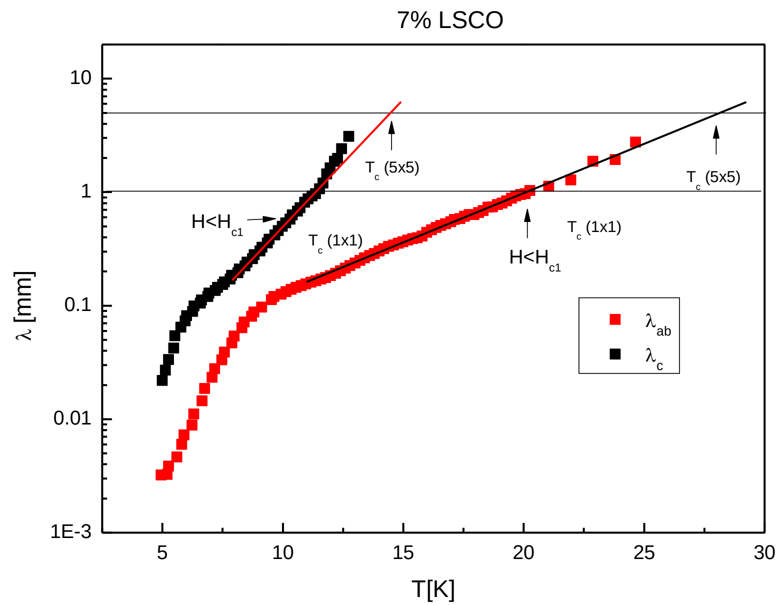
C-needle

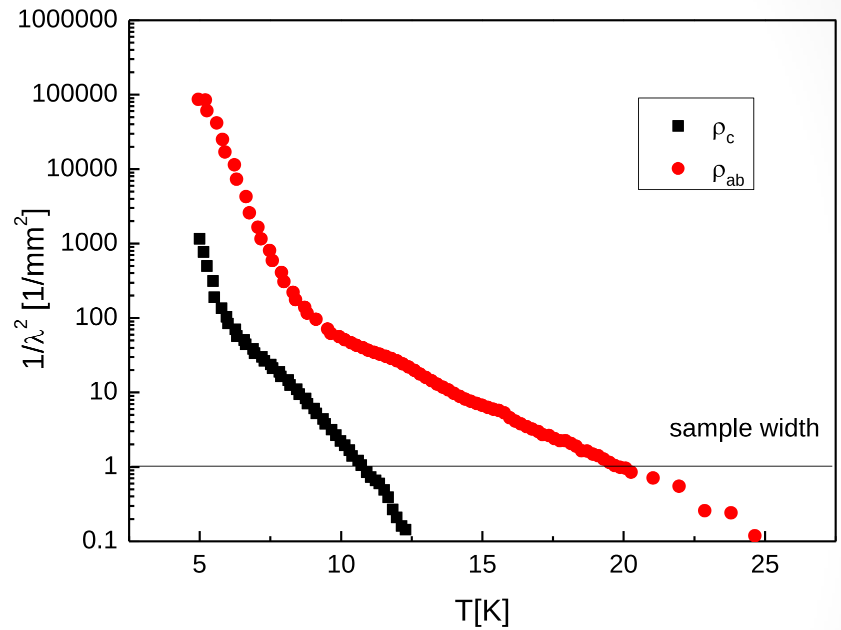
$$\lambda_c^2 \frac{\partial^2 \chi_a}{\partial x^2} + \lambda_{ab}^2 \frac{\partial^2 \chi_a}{\partial y^2} = \chi_a$$

$$\lambda_{ab}^2 \frac{\partial^2 \chi_c}{\partial x^2} + \lambda_{ab}^2 \frac{\partial^2 \chi_c}{\partial y^2} = \chi_c$$

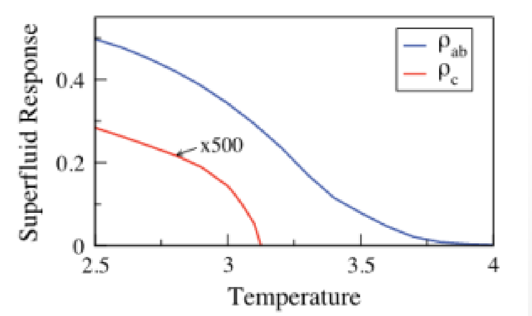
- From the c-needle data we can calculate λ_{ab} (T).
- With λ_{ab} (T) we can now extract λ_c (T).

Is there another explanation





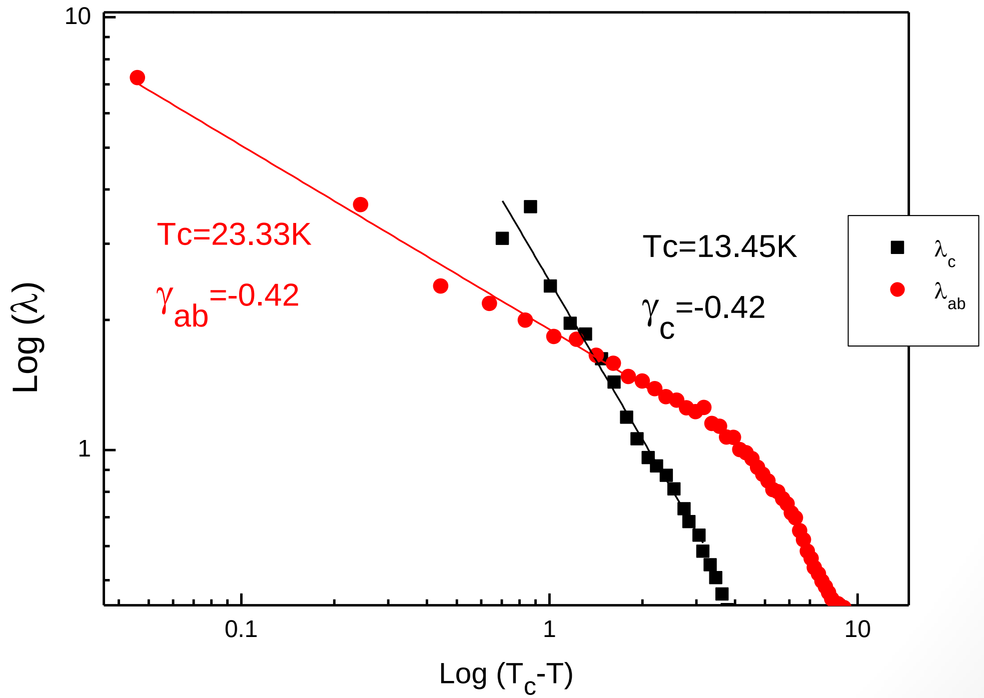
λ_c decreases much faster then λ_{ab}.



If we will increase our sample size by a factor of 5, we except to see a larger difference in T_c.

Conclusions

Contrary to theoretical wisdom, we do measure two different T_c's.



The End