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The Stiffnessometer: a magnetic-field-free superconducting stiffness meter and the nature of the phase transition in LSCO

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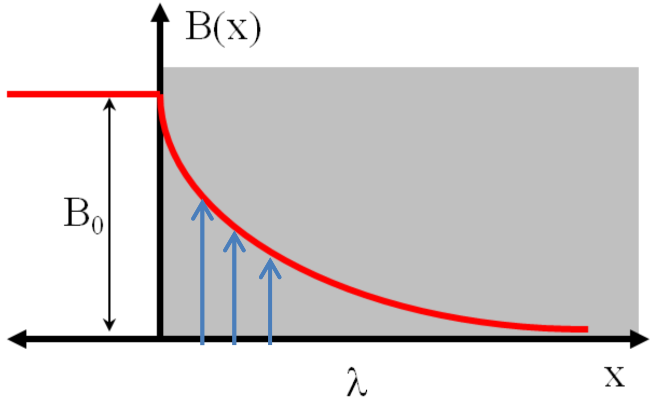
Introduction

London's Eq. $\mathbf{J}_s = -\rho_s \mathbf{A}$ ρ_s is the **stiffness**

$\nabla\times$Ampere's Law $\nabla\times\nabla\times\mathbf{B} = \mu_o \nabla\times\mathbf{J} = -\mu_o\rho_s\nabla\times\mathbf{A} = -\mu_o\rho_s\mathbf{B}$

Solution $\nabla^2\mathbf{B} = \frac{1}{\lambda^2}\mathbf{B} \xrightarrow{1D} B(x) = B_0 e^{-x/\lambda}$ λ is the **penetration depth**

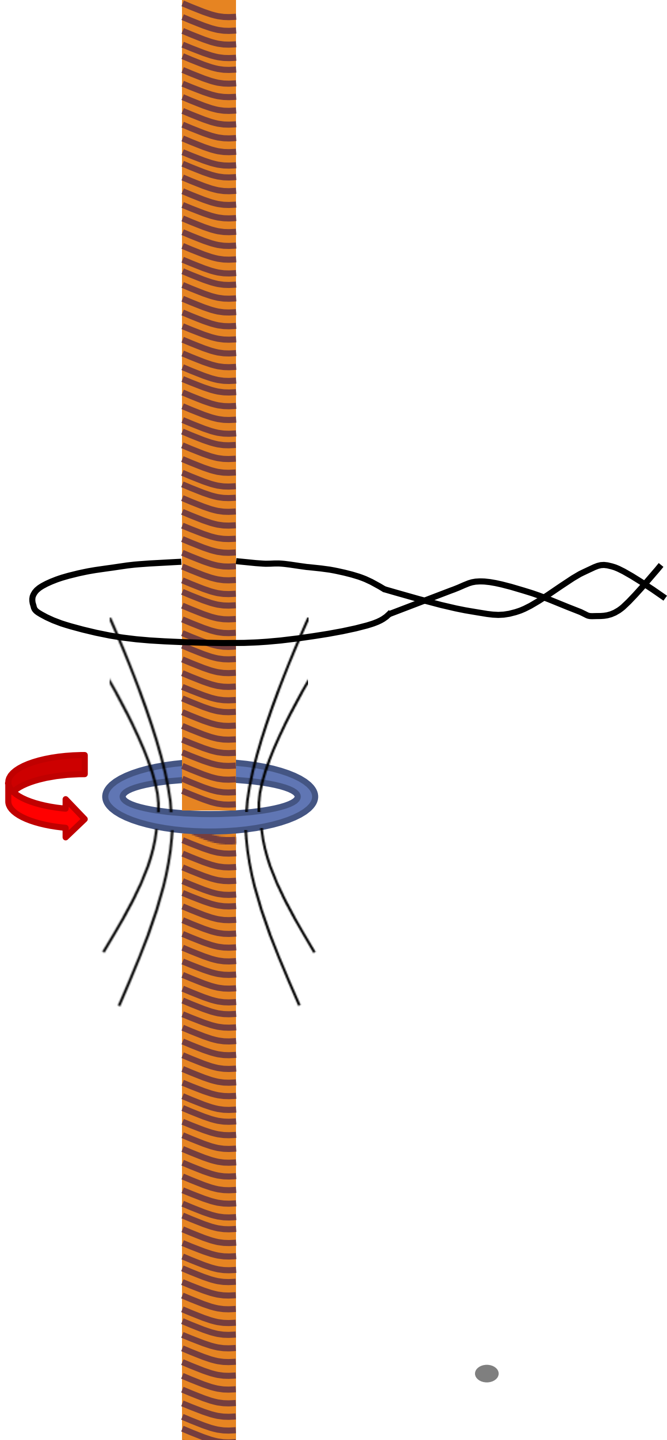
$$\rho_s = \frac{1}{\mu_o\lambda^2}$$



One usually measures λ by applying a magnetic field. We want to measure ρ_s directly.

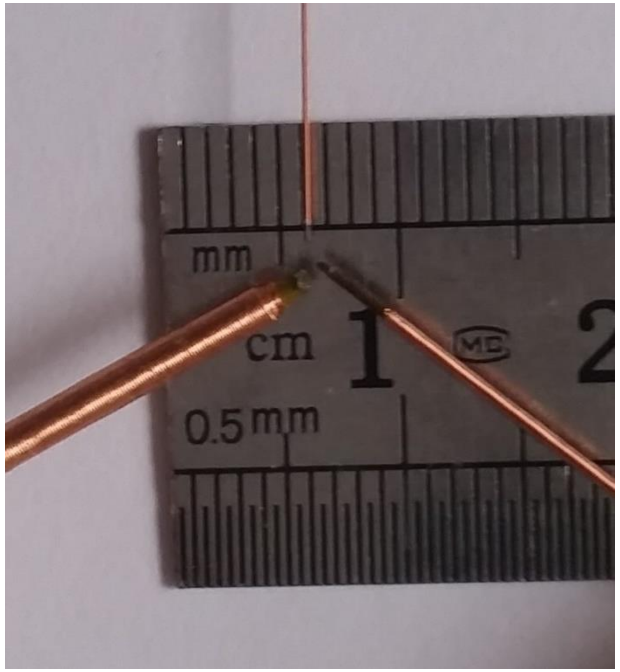
The Stiffnessometer

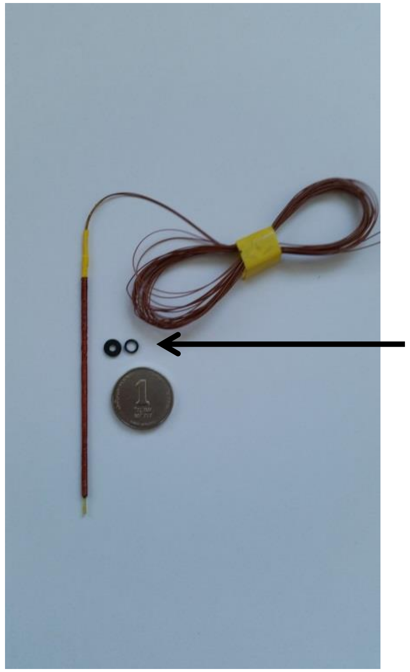
- Use infinitely long coil in the center of a superconducting ring to generate **A** with **B=0**.
- **A** creates **J**.
- **J** creates magnetic moment ***m***.
- We measure ***m*** by moving the ring inside a pickup loop.



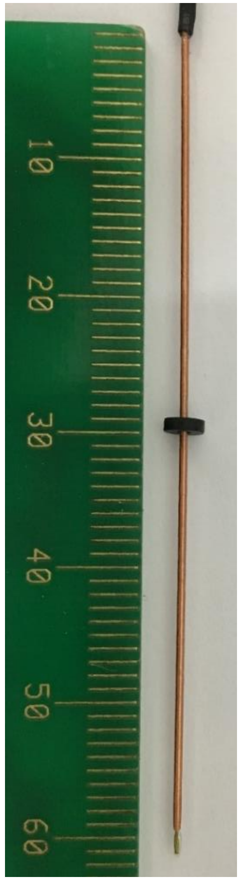
Experimental setup

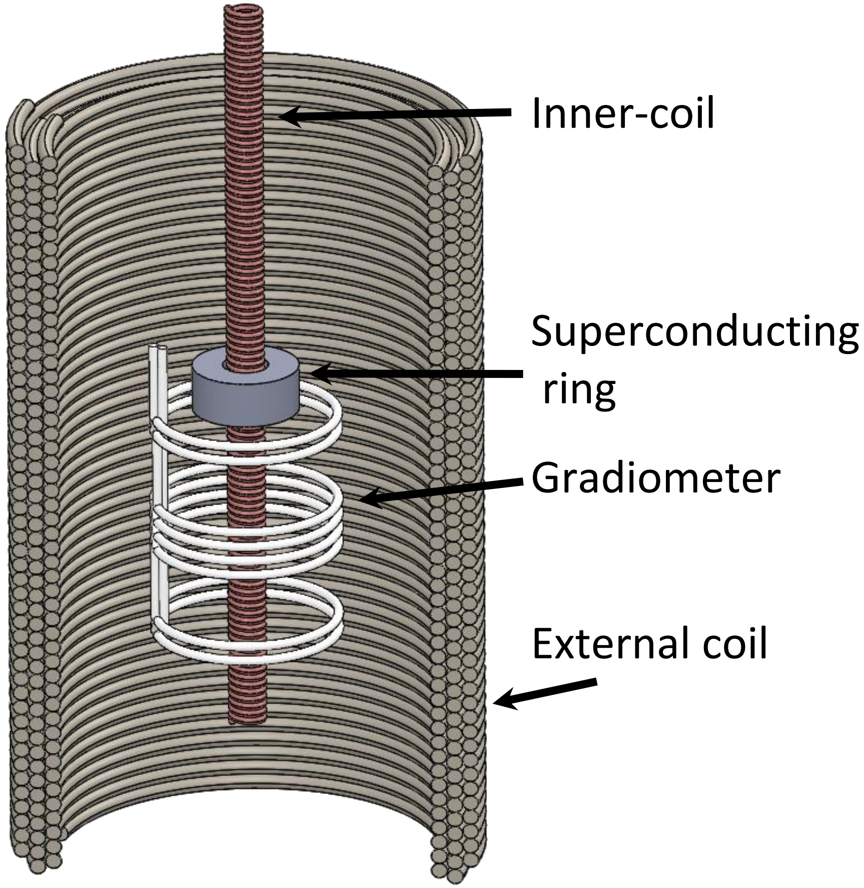
60mm coil 2 layers, 9300 turns,
10µm wire, 0.25mm outer diameter.





LSCO Ring
2mm inner hole diameter
5mm outer diameter
1mm height.

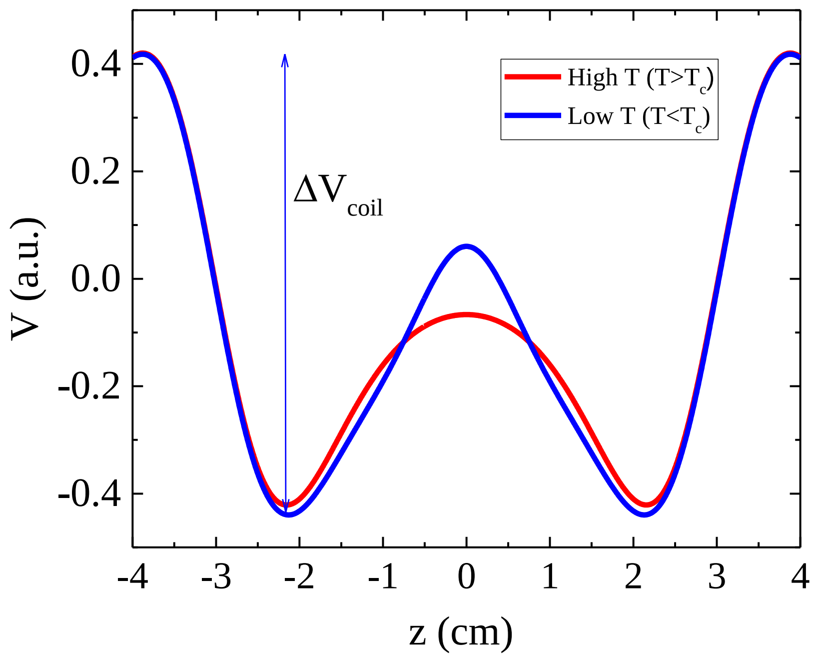




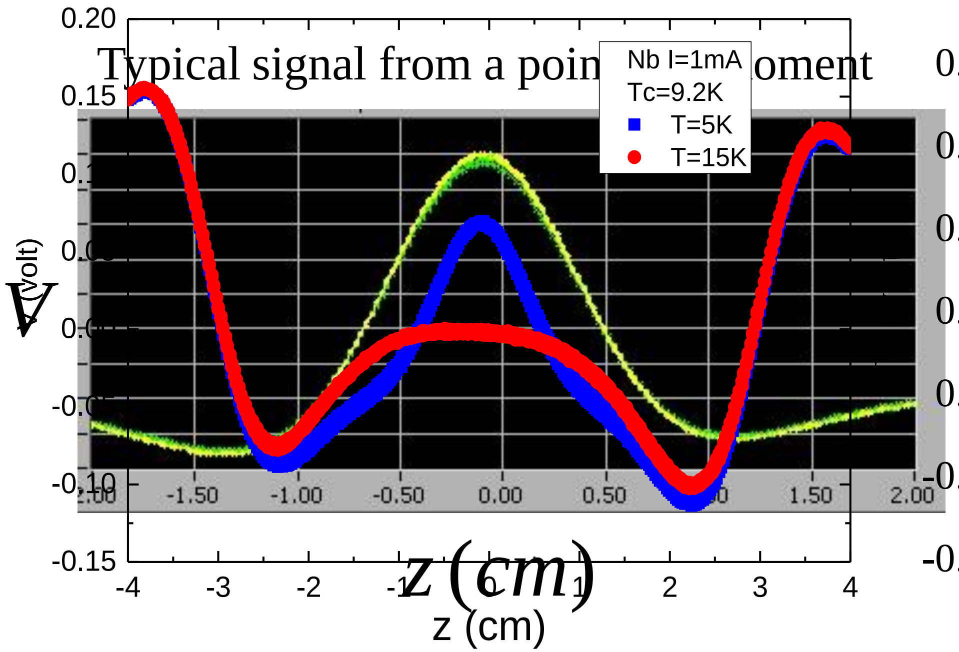
Expected vs. measured Stiffnessometer signal

We measure the flux through the pickup coil $\phi(z) = \int_0^{t(z)} \dot{\phi} dt = 2\pi R_{PL} A(R_{PL})$

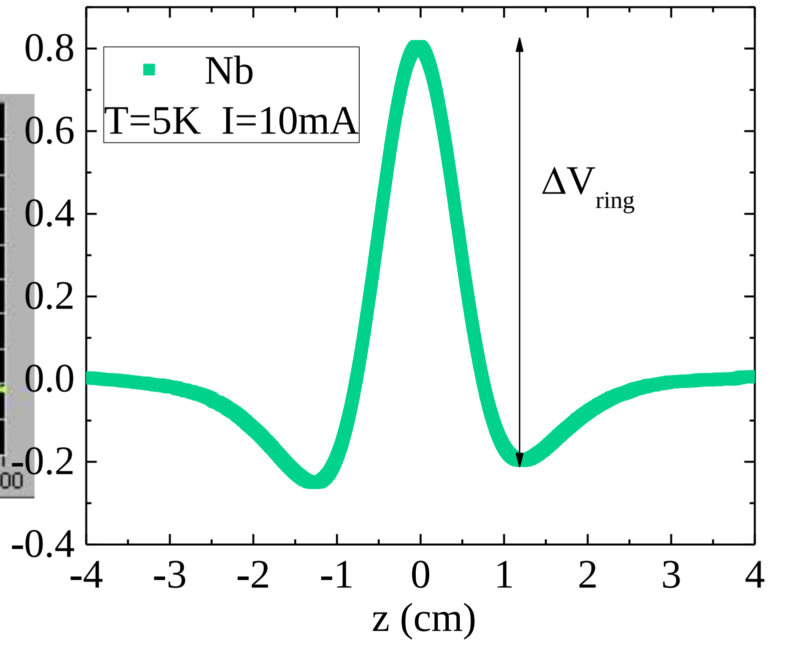
Expected Stiffnessometer signal



Measured signal



Difference signal



- ΔV_{coil} is the signal from the coil. ΔV_{ring} is the addition due to the ring.

Extracting the stiffness

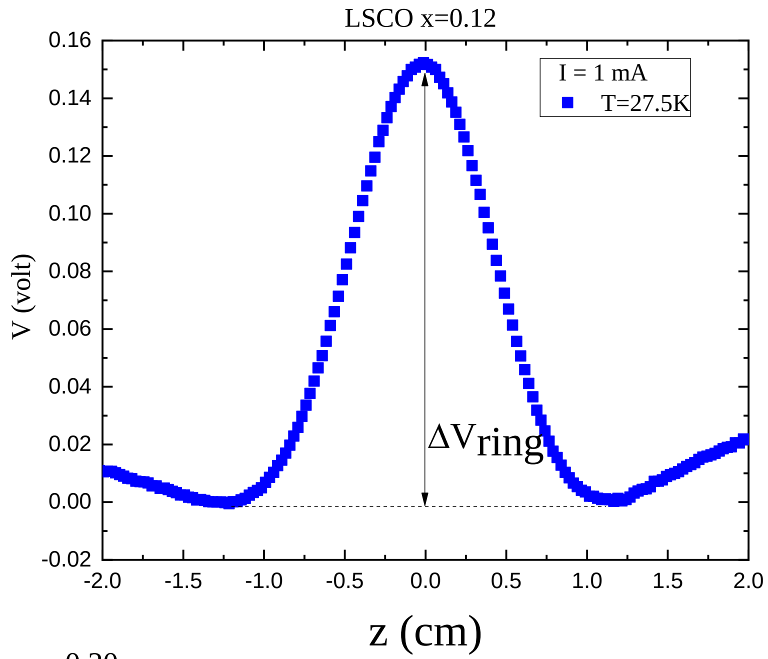
The important quantity is:

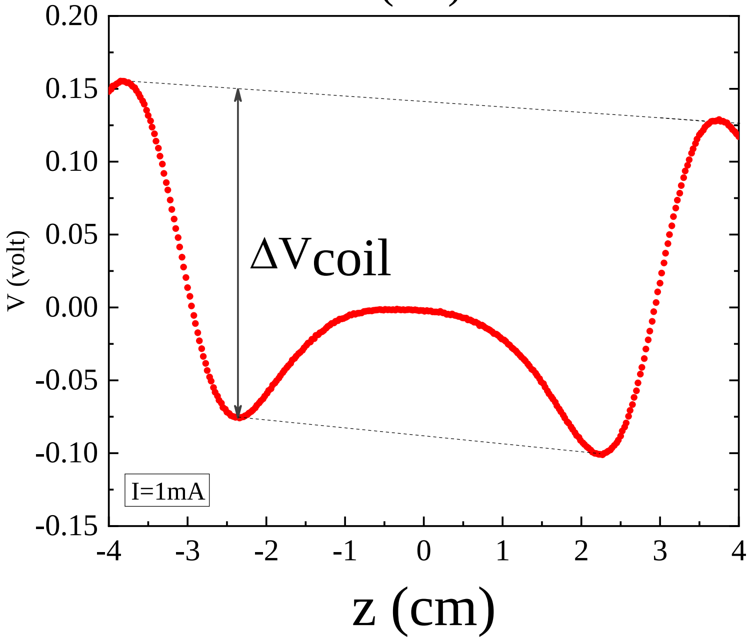
$$\frac{\Delta V_{ring}}{\Delta V_{coil}} = G\,\frac{A_{ring}(R_{PL})}{A_{coil}(R_{PL})}$$

R_{PL} is the radius of the pickup loop.

G~1 is the Gradiometer numerical constant.

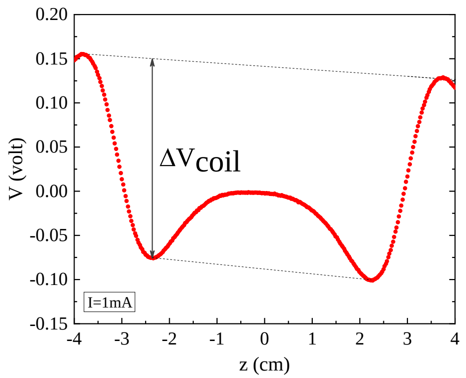
So we need to calculate $A_{ring}(\lambda)$ and invert it.

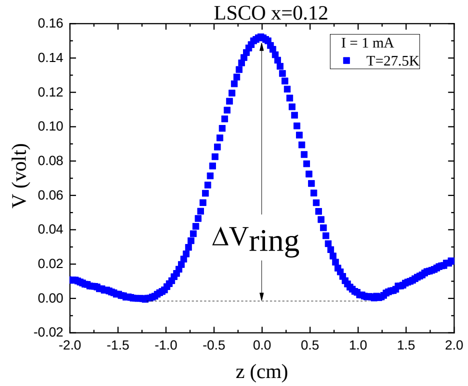




Estimating the stiffness (λ^{-2}) near Tc

Close to T_c, when ρ_s is small, the ***A*** generated by the ring itself compared to ***A*** from the coil is negligible.





$$I_{Ring} = \rho_s A_{Coil} h \cdot \delta r$$

$$m = \pi r^2 I_{Ring}$$

$$A_{ring}(R_{PL}) = \frac{m}{R_{PL}^2}$$

$$\frac{\Delta V_{ring}}{\Delta V_{coil}} = G \frac{A_{ring}(R_{PL})}{A_{coil}(R_{PL})} = G \frac{r \cdot h \cdot \delta r}{4R} \frac{1}{\lambda^2}$$

r is the ring radius.

h = height and δr = width

m = magnetic moment of the ring.

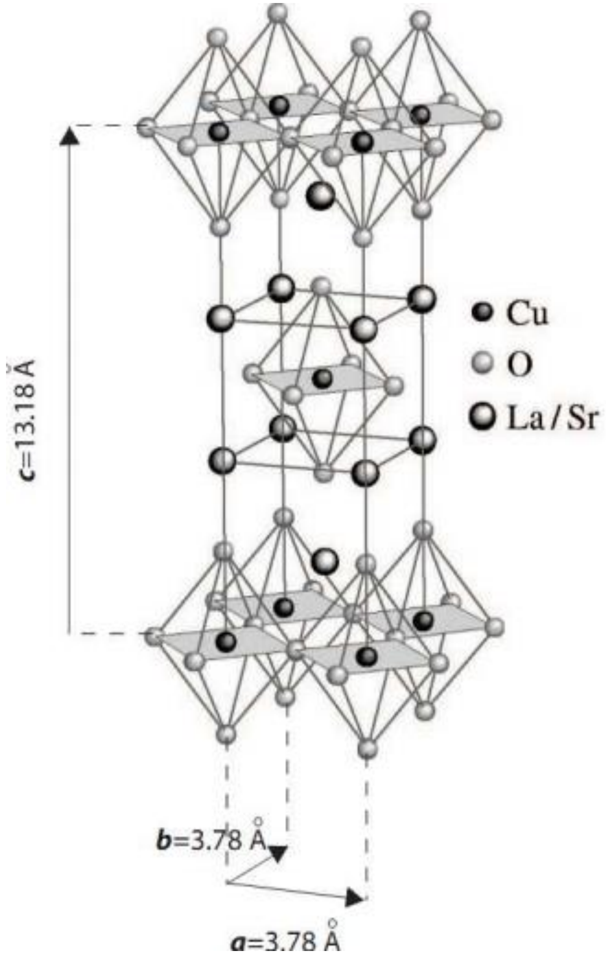
R_{PL} is the pickup coil radius.

$\Delta V_{ring}/\Delta V_{coil} \sim 0.01$, r, h, δr, $R_{PL} \sim 1$mm.

$\lambda \sim 1$mm

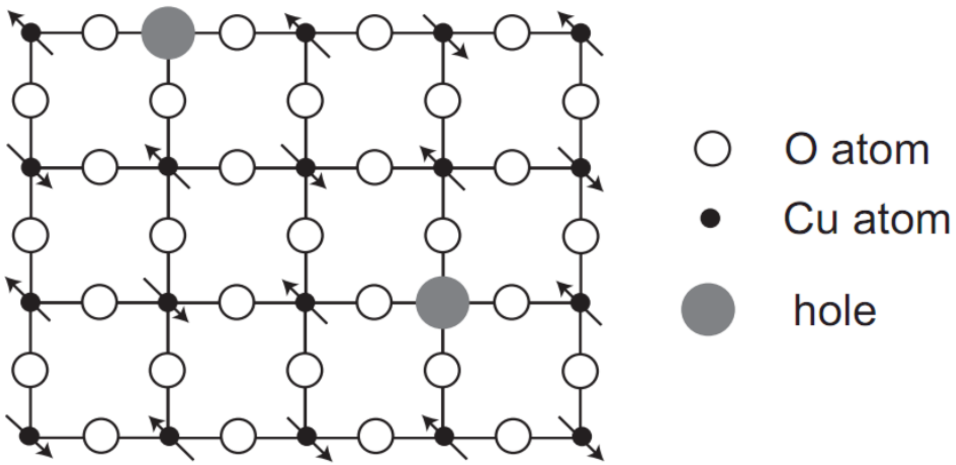
$La_{2-x}Sr_xCuO_4$ (LSCO) Compound

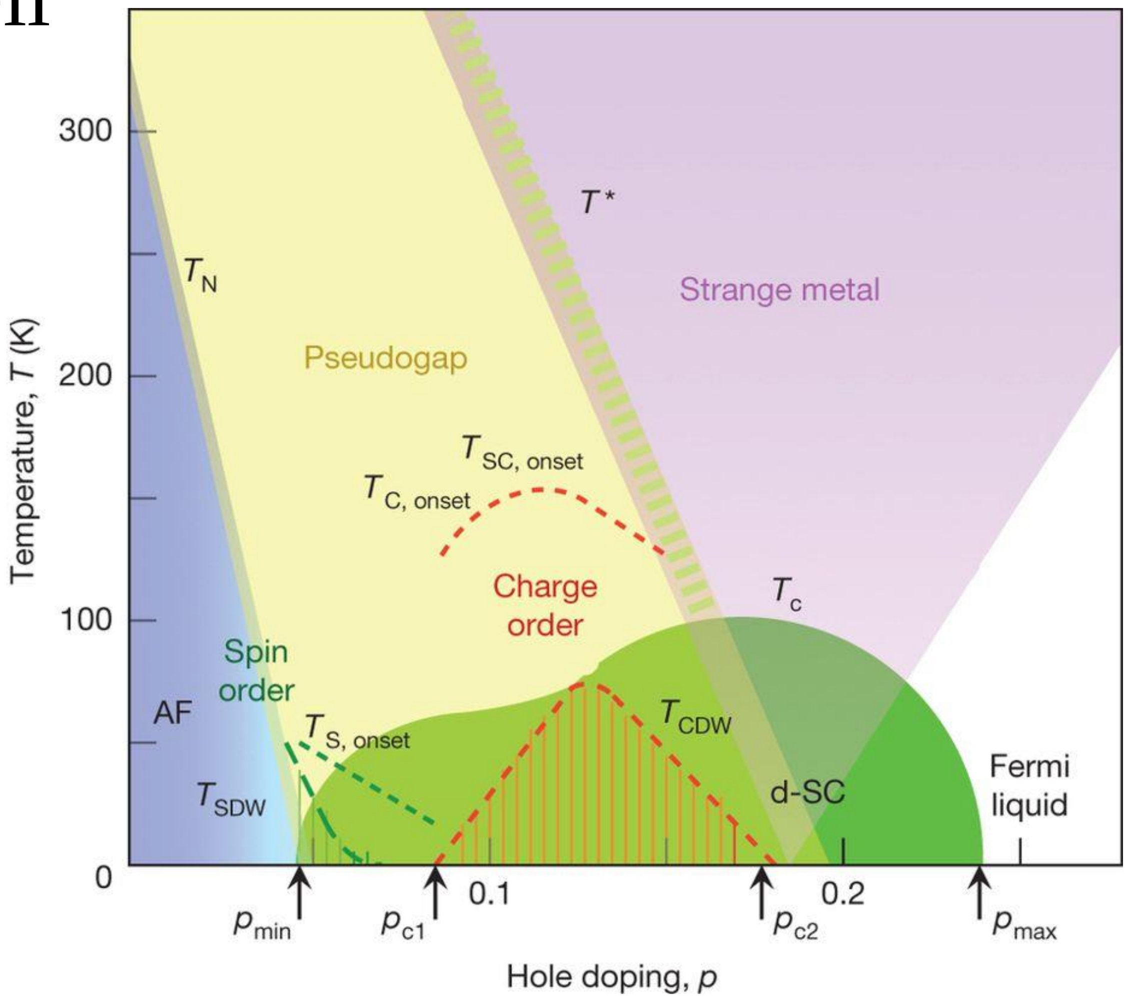
- Cuprates family
- Max Tc ~ 38 K
- One CuO_2 plane/unit cell
- Layered structure with “spacer layers” which control the carrier concentration



LSCO Compound

- La_2CuO_4 has 1 electron per unit cell ➔ spin ½ .
- Antiferromagnet Mott insulator
- $La^{3+} \rightarrow Sr^{2+}$: $La_{2-x}Sr_xCuO_4$ hole doping



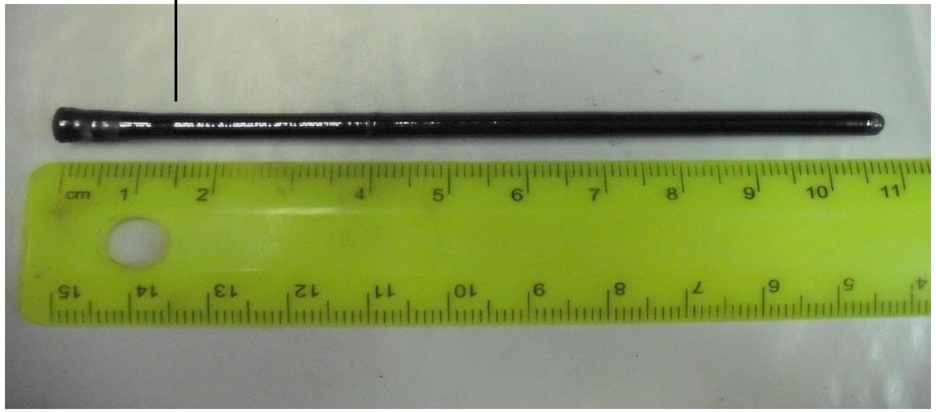


B. Keimer, Nature 518, 179 (2015)

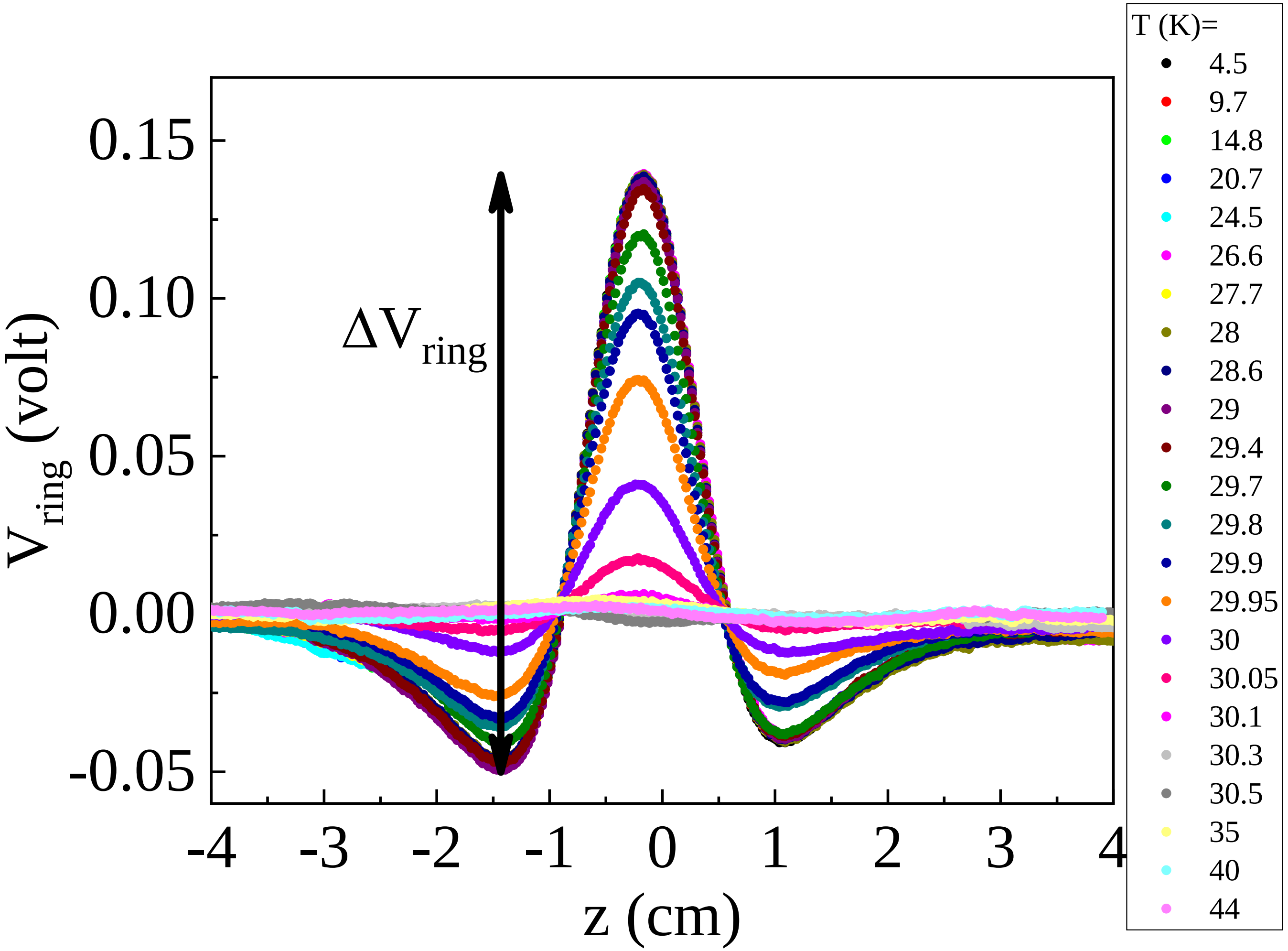
Single crystal growth

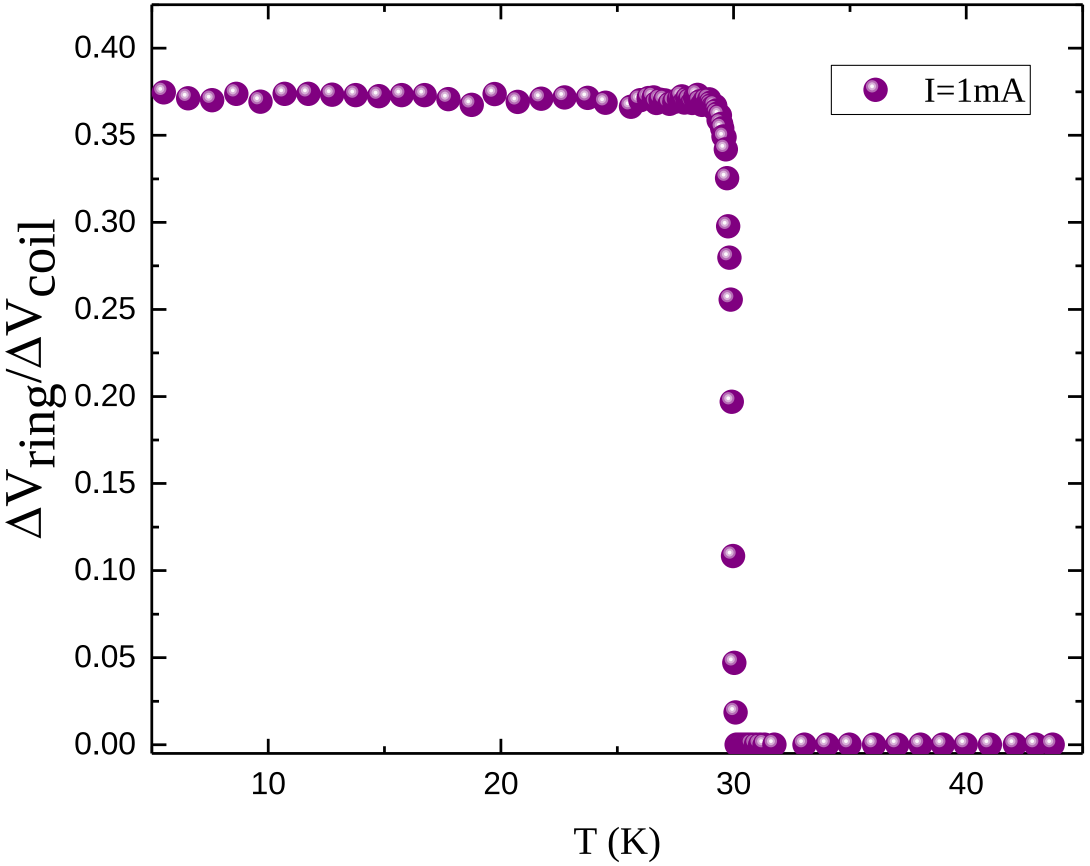
- Travelling Solvent Floating Zone (TSFZ)

$\hat{c}$

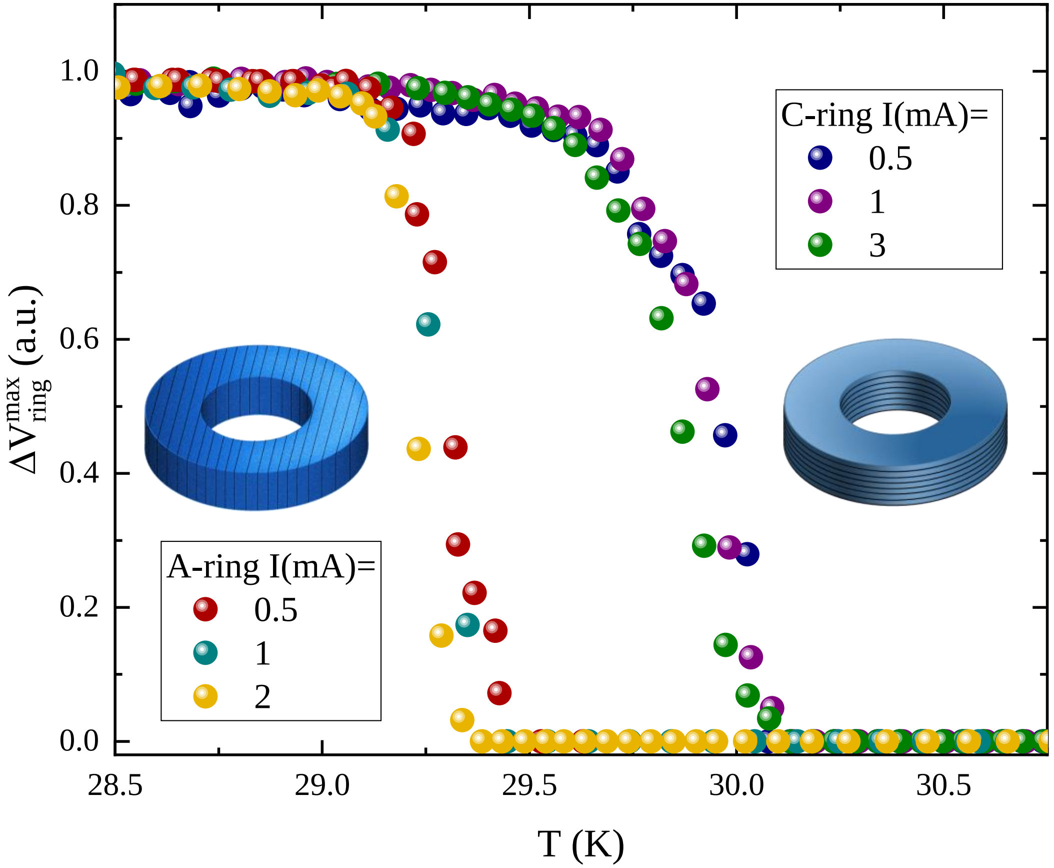


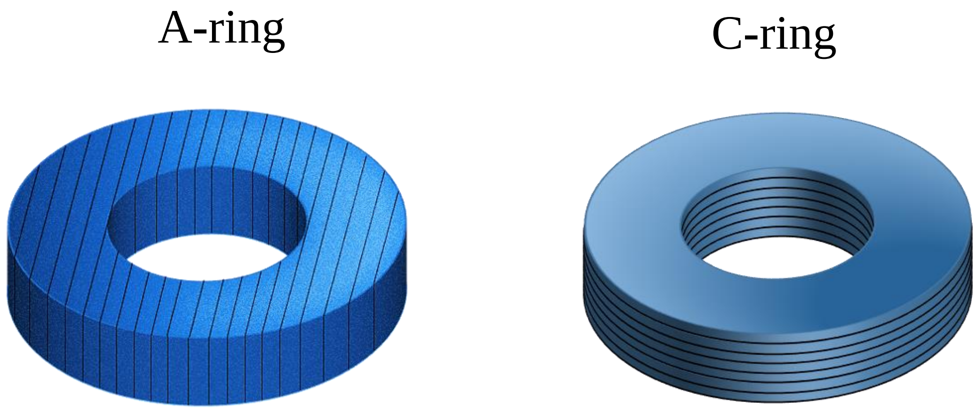
Temperature dependence – LSCO x=0.125





Two transitions in LSCO x=0.125





CuO_2 planes **parallel** to symmetry axis

CuO_2 planes **perpendicular** to symmetry axis

- Stiffness develops before current can flow in the **c** direction.
- No current dependence below 2mA.

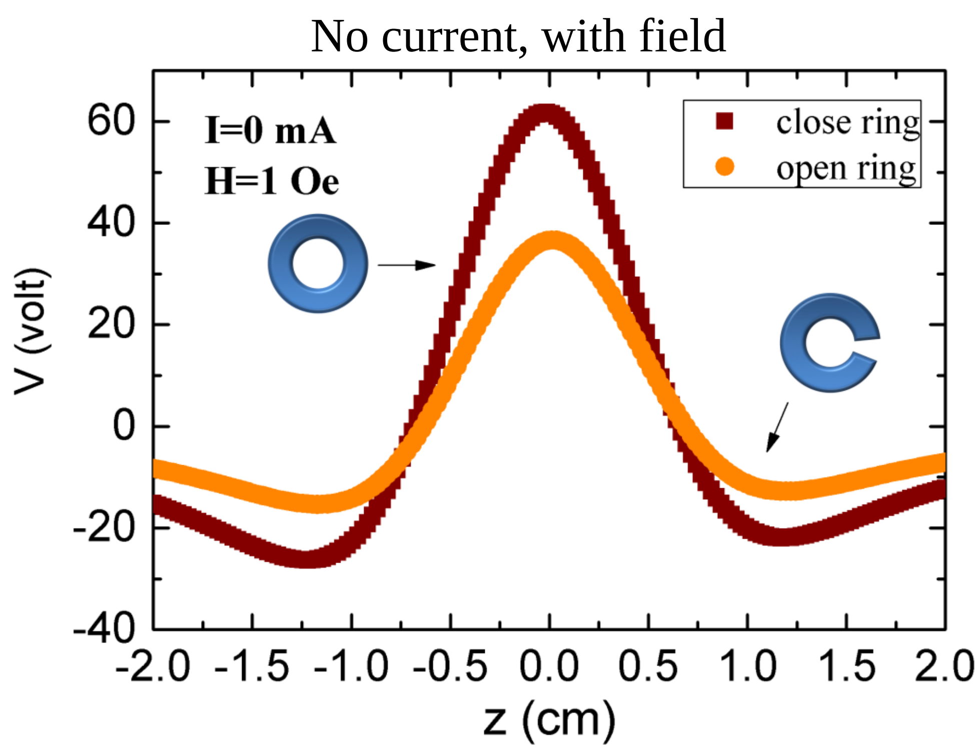
Intermediate conclusions

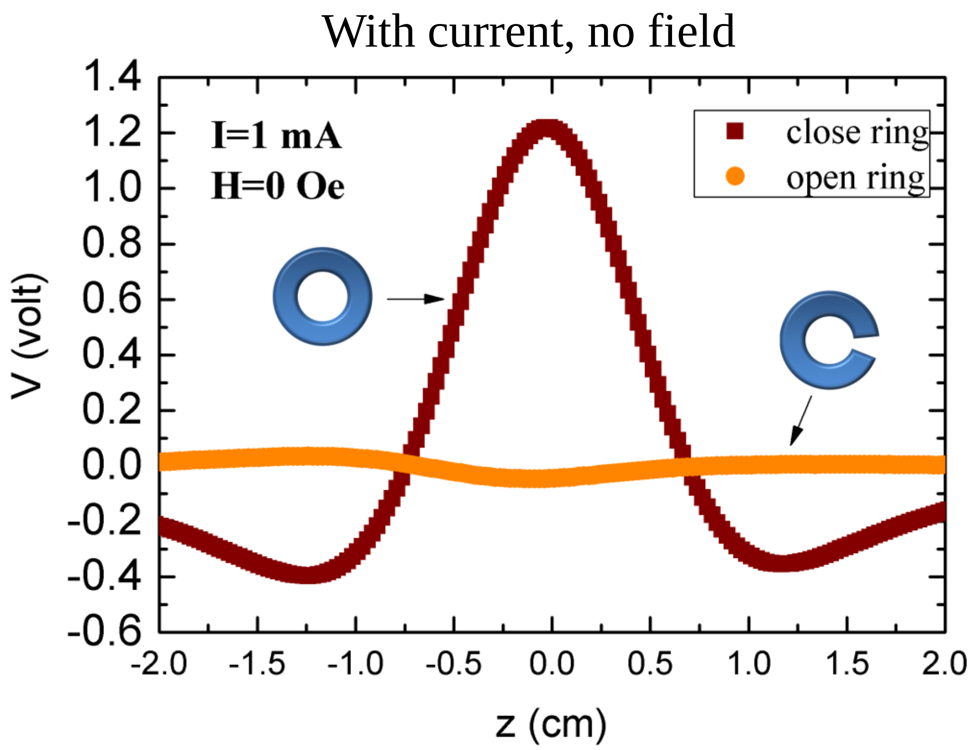
- We present a new technique to measure small stiffness, or large λ on the order of millimeters, without applying magnetic field.

- We find two superconducting phase transitions in LSCO 1/8.

Is our signal for real?

- Compare two Nb rings: one is closed and the other is disconnected (open).





- We use the open ring to determine the leakage of magnetic field, and use external coil to cancel it.

Extracting the stiffness

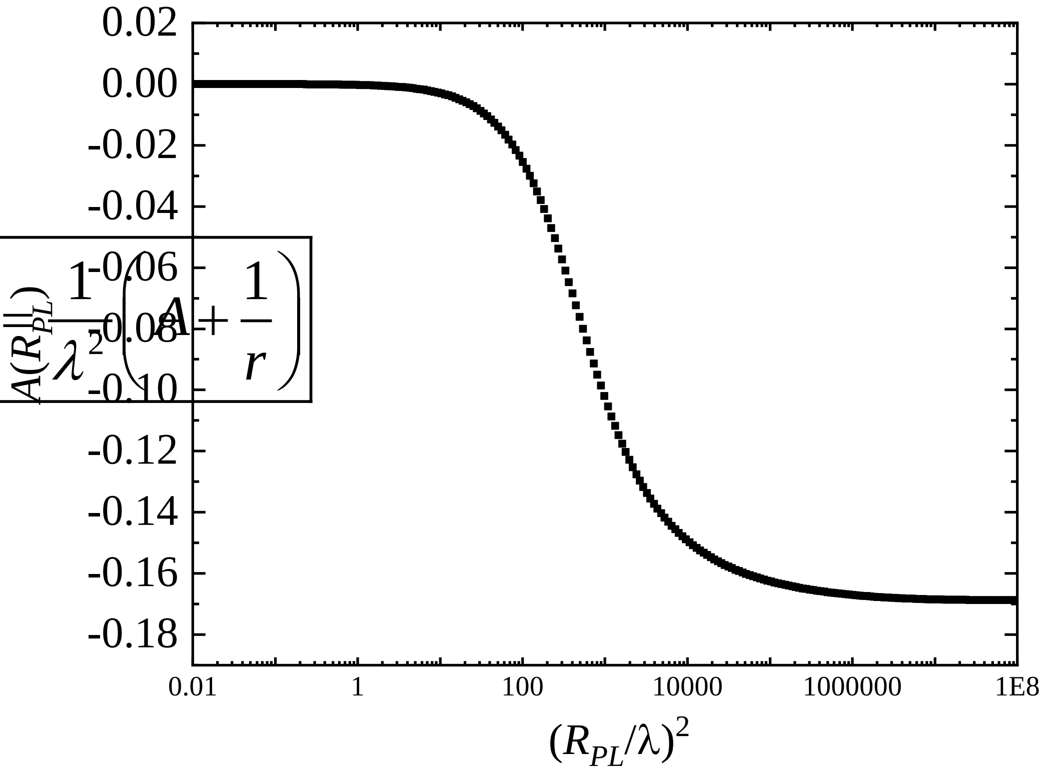
Maxwell: $\nabla \times \nabla \times \mathbf{A}_{ring} = -\mu_0 \mathbf{J}(\mathbf{r})$ **London**: $\mathbf{J}(\mathbf{r}) = -\rho_s \mathbf{A}_{tot} = -\frac{1}{\mu_o \lambda^2}\left(\mathbf{A}_{coil} + \mathbf{A}_{ring}\right)$

Combining the two equations, the built-in Coulomb gauge, and

$$\mathbf{A}(r,z) = \frac{A_{ring}(r,z)}{A_{coil}(R_{PL})}\hat{\theta}, \;\; r,\lambda \rightarrow r/R_{PL}, \lambda / R_{PL}$$

we get the equation:

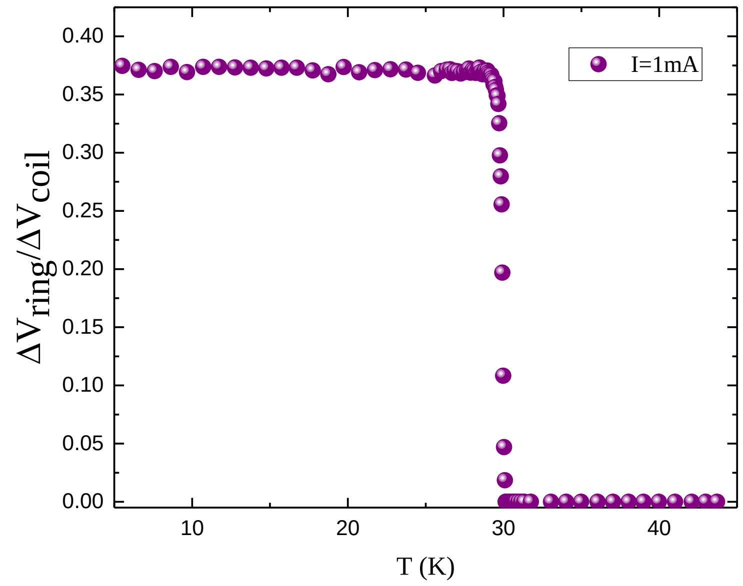
$$\boxed{\frac{\partial^2 A}{\partial z^2} + \frac{\partial^2 A}{\partial r^2} + \frac{1}{r}\frac{\partial A}{\partial r} - \frac{A}{r^2} = \frac{1}{\lambda^2}\left(A + \frac{1}{r}\right)}$$



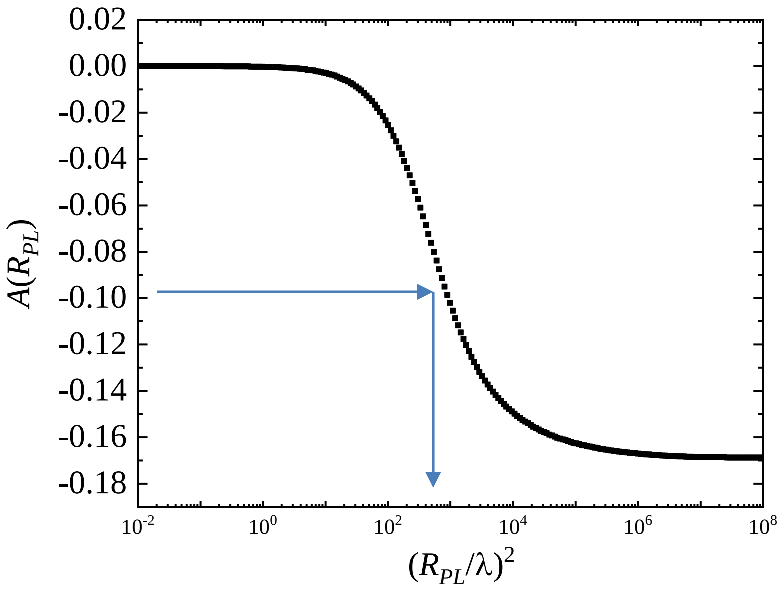
$$A(r=0,z) = A(r \rightarrow \infty, z) = A(r, z \rightarrow \pm\infty) = 0$$

Outside the ring $\lambda \rightarrow \infty$.

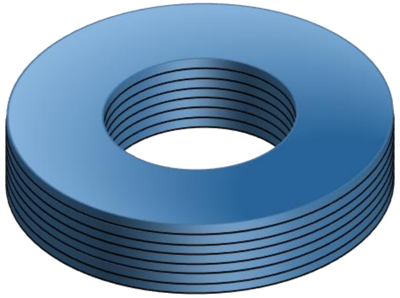
Stiffness of LSCO x=0.125



$$\frac{\Delta V_{ring}}{\Delta V_{coil}} = GA(R_{PL})$$



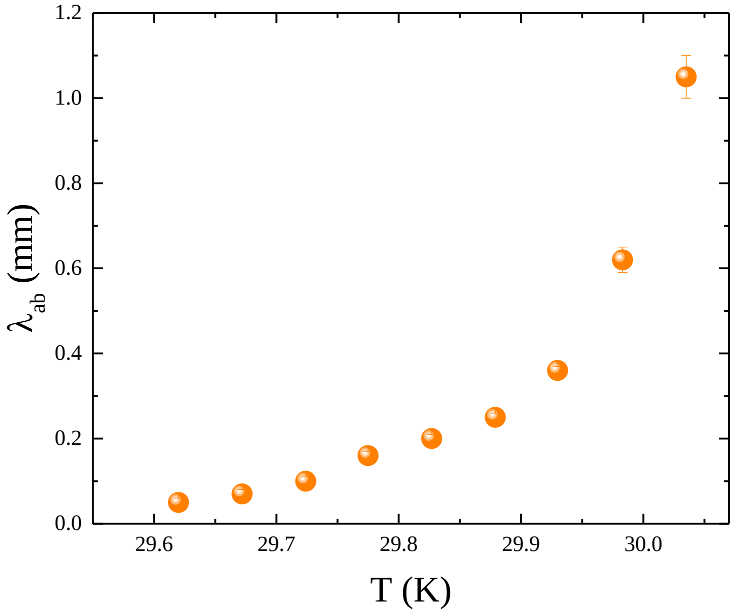
C-ring



CuO_2 planes **perpendicular** to symmetry axis

Fitting the data of LSCO x=0.125 at T=30.08K yields:

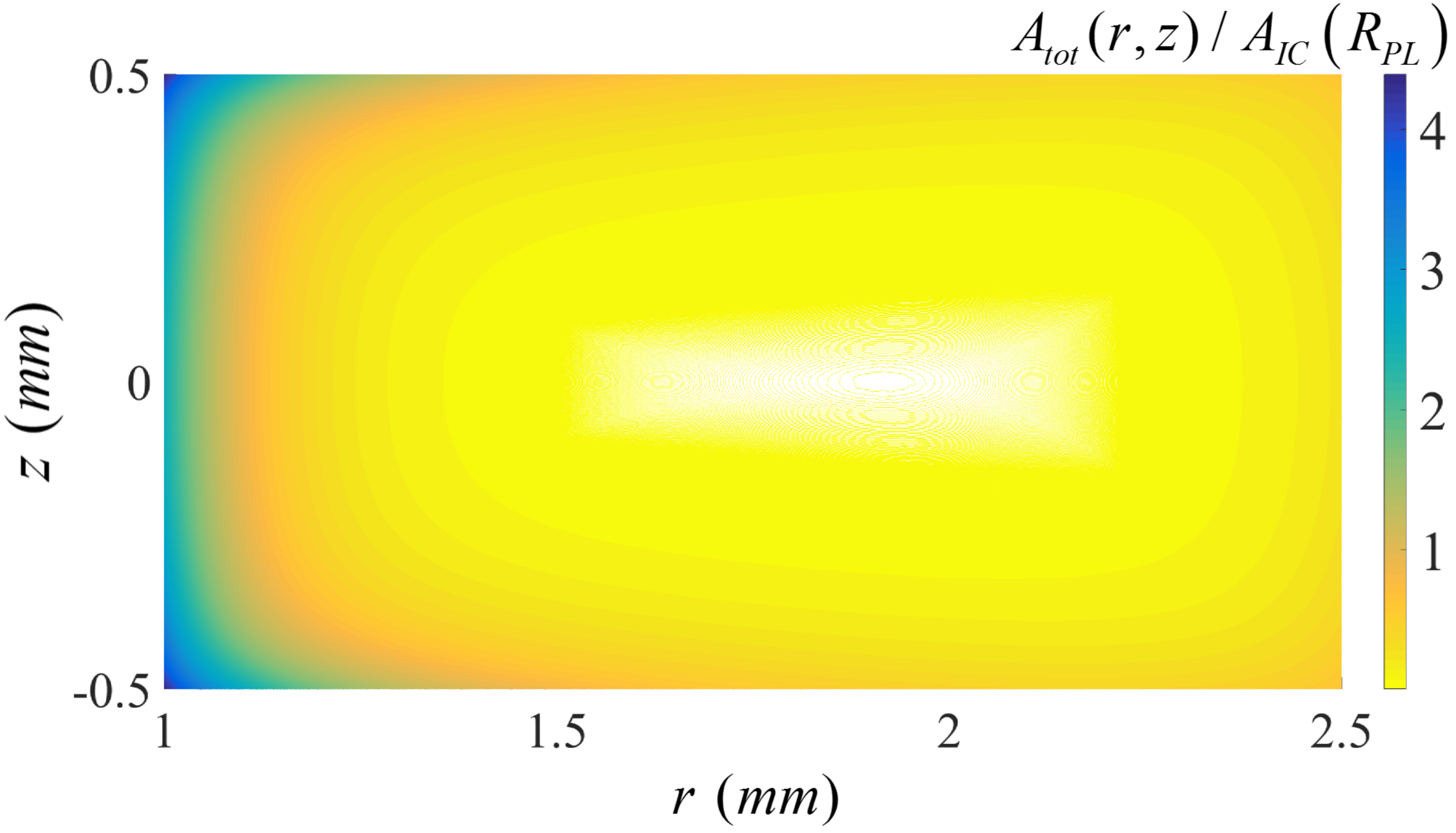
$$\boldsymbol{\lambda = 1.05 \pm 0.05\ mm}$$

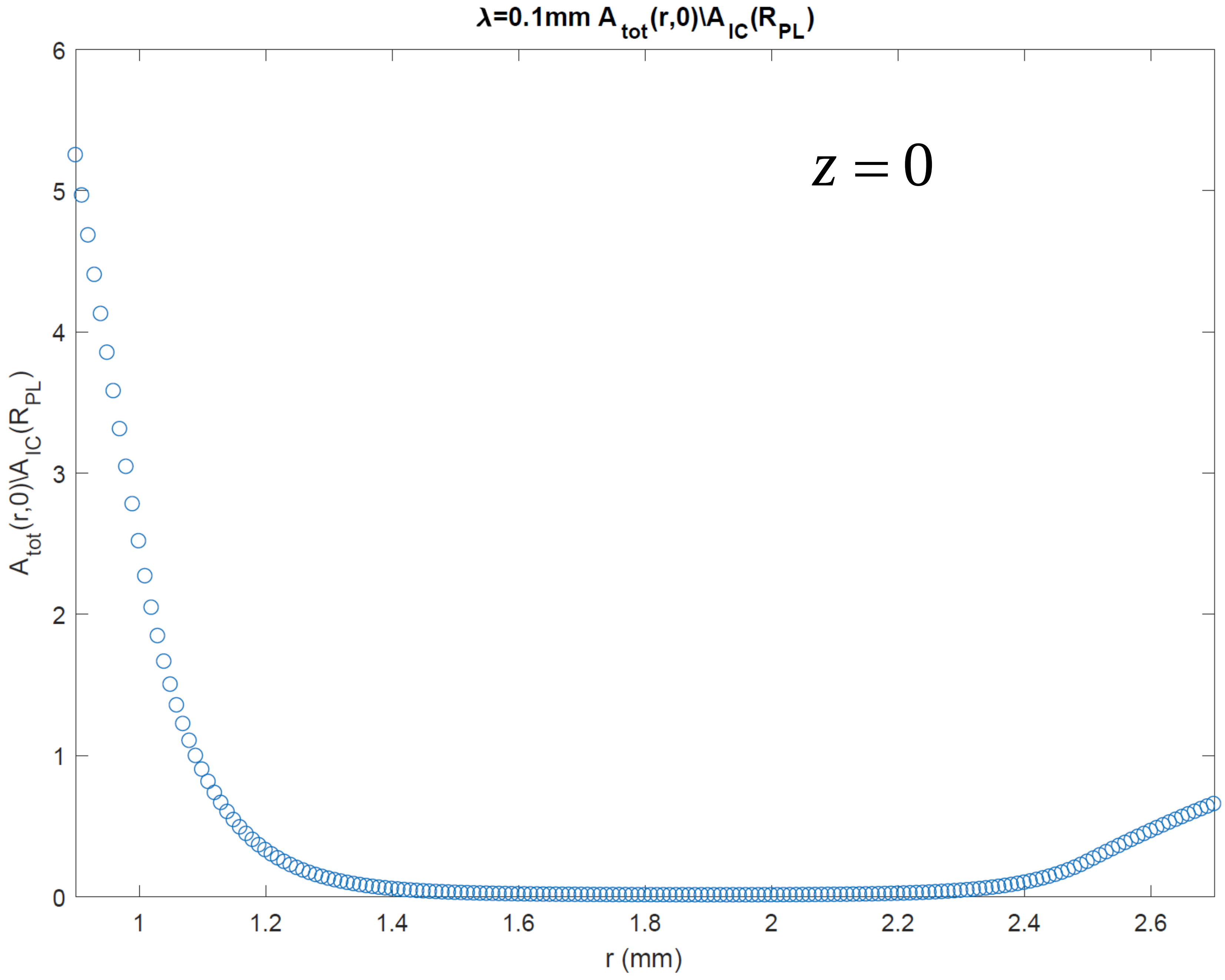


Numerical solution of the PDE

Isotropic case – cut at a fixed angle

$$\nabla \times \nabla \times \mathbf{A} = \frac{1}{\lambda^2}\left(\frac{1}{r}\hat{\boldsymbol{\theta}} + \mathbf{A}\right), \quad \lambda = 0.1\ \mathrm{mm}$$

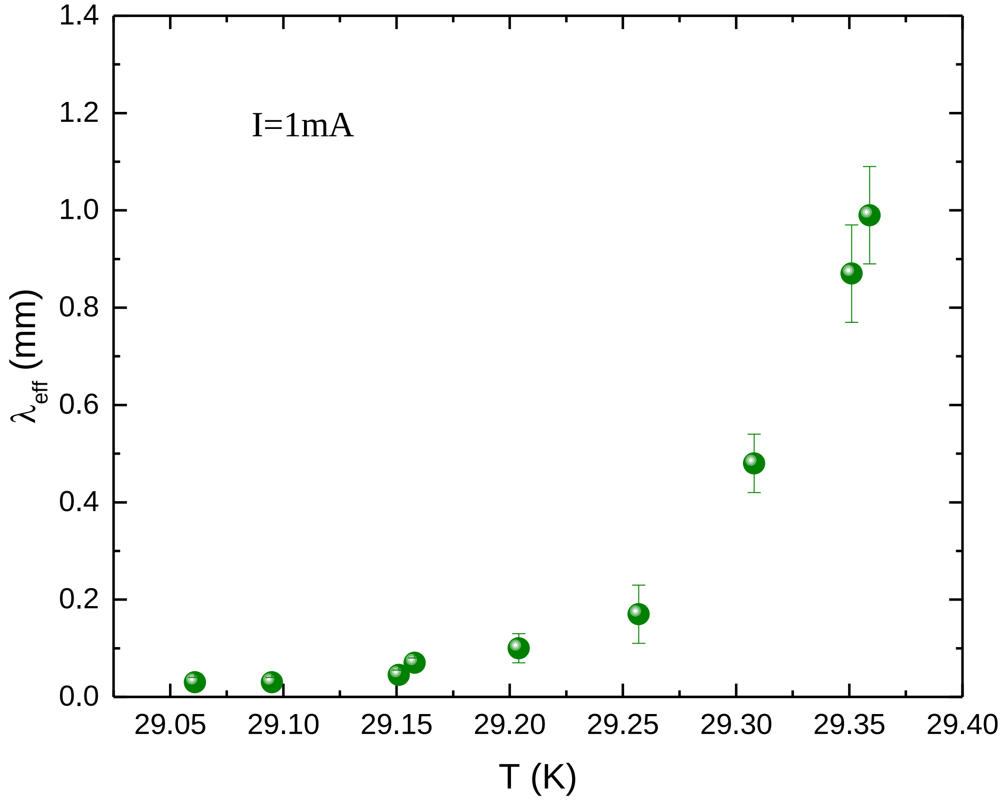




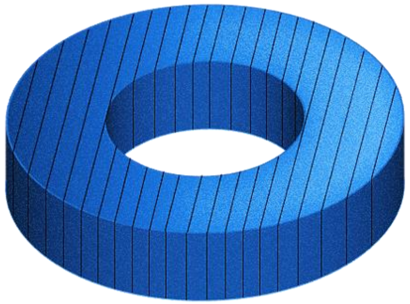
λ=0.1mm $A_{tot}(r,0)\backslash A_{IC}(R_{PL})$
$z = 0$
$A_{tot}(r,0)\backslash A_{IC}(R_{PL})$
r (mm)

Effective penetration depth for A-ring

Use the isotropic PDE solution for the anisotropic case and extract an effective penetration depth λ_{eff}.



A-ring



CuO_2 planes **parallel** to symmetry axis

Next we want to determine λ_c.

Extracting λ_c

Maxwell: $\nabla\times\nabla\times\mathbf{A}_{ring} = -\mu_0\mathbf{J}(\mathbf{r})$ **London**: $\mathbf{J}(\mathbf{r}) = -\bar{\rho}_s\mathbf{A}_{tot} = -\bar{\rho}_s\left(\mathbf{A}_{coil}+\mathbf{A}_{ring}\right)$ with

$$\bar{\rho}_s = \begin{bmatrix} \lambda_{ab}^{-2} & 0 & 0 \\ 0 & \lambda_{ab}^{-2} & 0 \\ 0 & 0 & \lambda_c^{-2} \end{bmatrix}$$

and using $\mathbf{A}_{coil} = \dfrac{Ba}{2\pi r}\hat{\boldsymbol{\theta}}$. Maxwell dictates $\nabla\cdot\left[\bar{\rho}_s\left(\mathbf{A}_{coil}+\mathbf{A}_{ring}\right)\right]=0$ only inside the ring.

We chose $\nabla\cdot\mathbf{A}_{ring}=0$ outside the ring without justification and solve

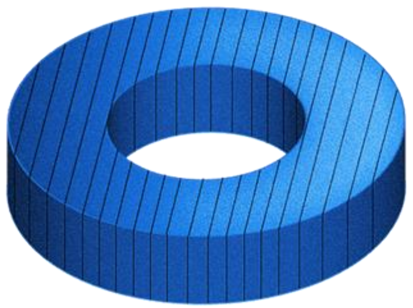
$$\boxed{\nabla\times\nabla\times\mathbf{A} = \bar{\rho}_s\left(\frac{1}{r}\hat{\boldsymbol{\theta}}+\mathbf{A}\right)}$$

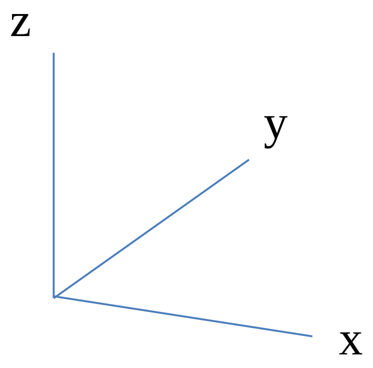
Jump conditions: $\mathbf{J}_\perp = \left[\bar{\rho}_s\left(\mathbf{A}_{coil}+\mathbf{A}_{ring}\right)\right]_\perp = 0,\ \Delta\mathbf{A}_{\parallel} = 0$

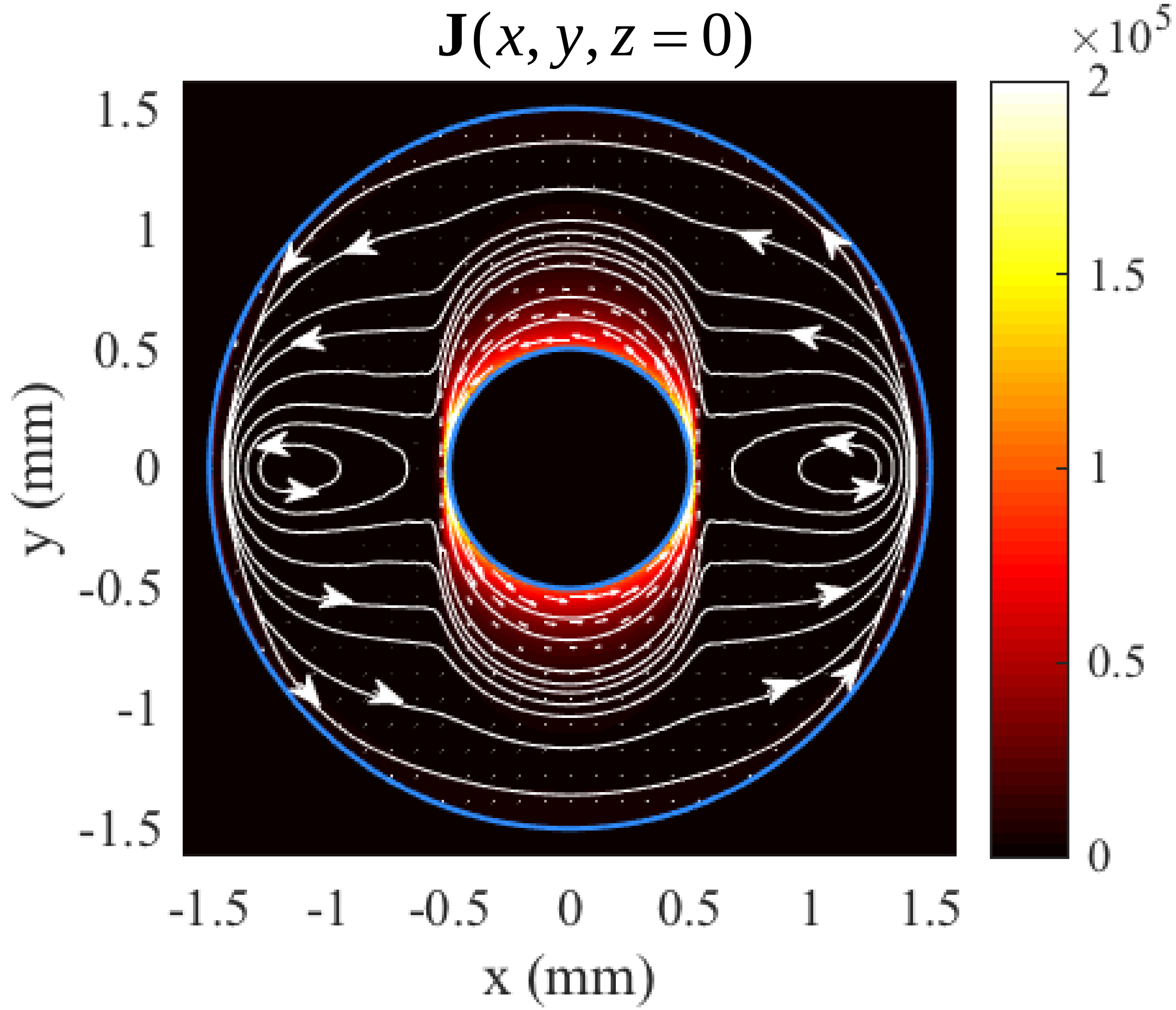
Boundary conditions $A(r\to\infty, z) = A(r, z\to\pm\infty) = 0$

Numerical solution of the anisotropic PDE

λ_c =145 μm and λ_{ab} = 13.9 μm







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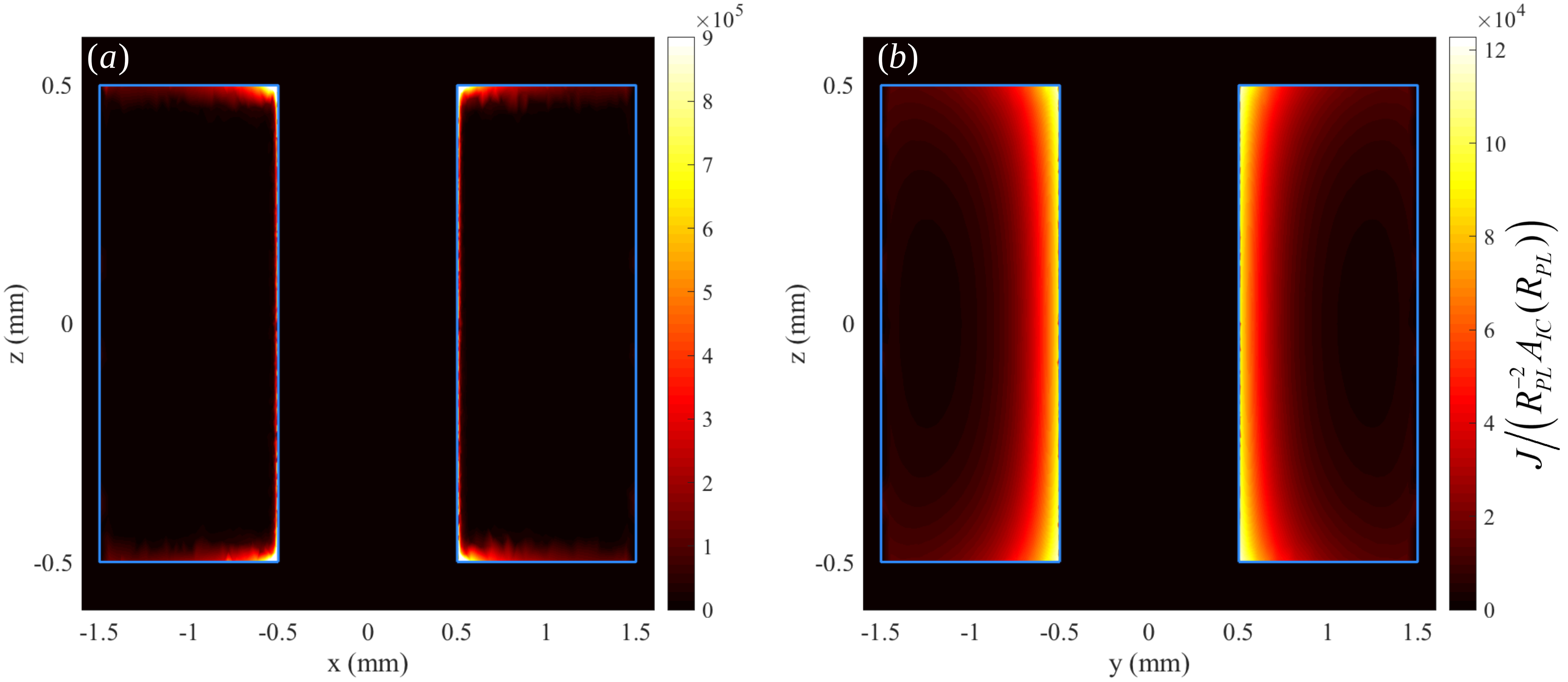
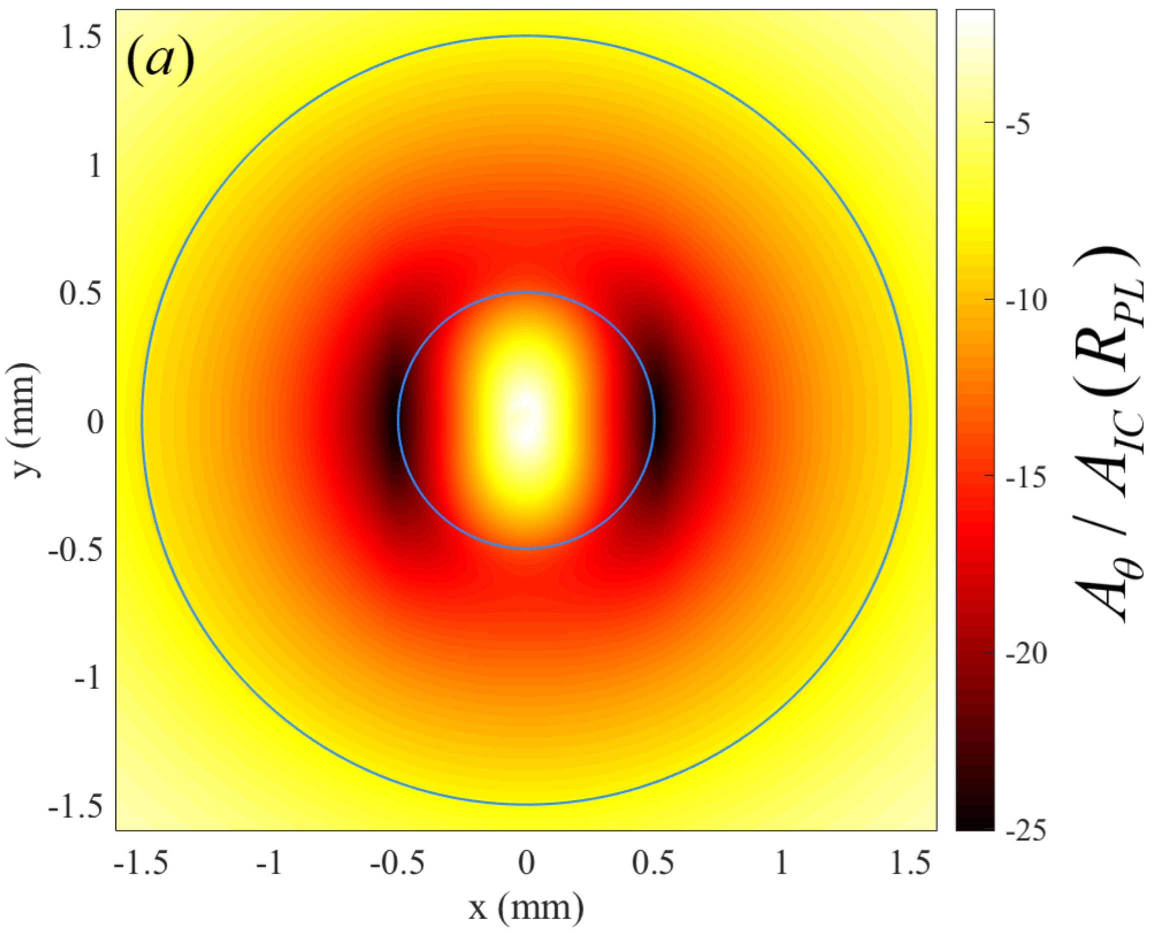
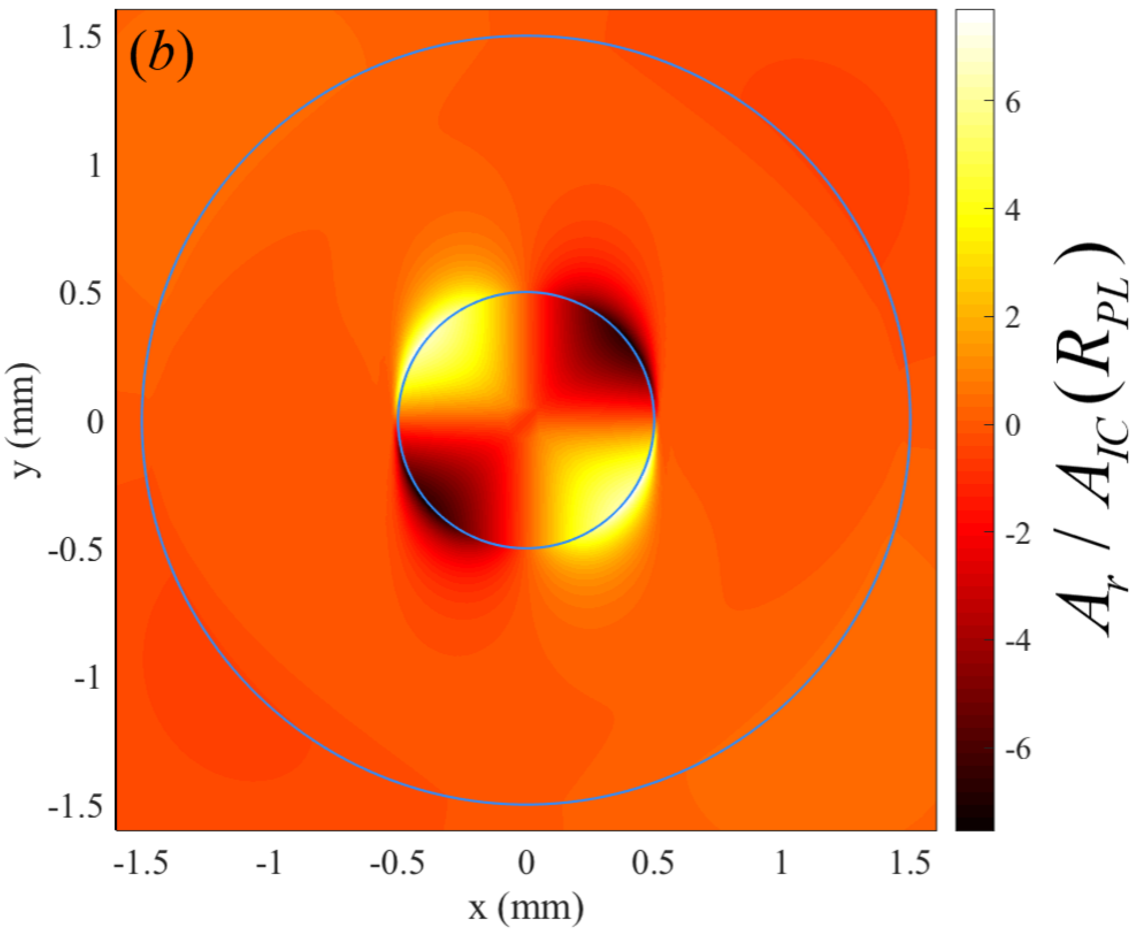


Current flows mainly on the inner radius of the ring

Vector potential anisotropic ring





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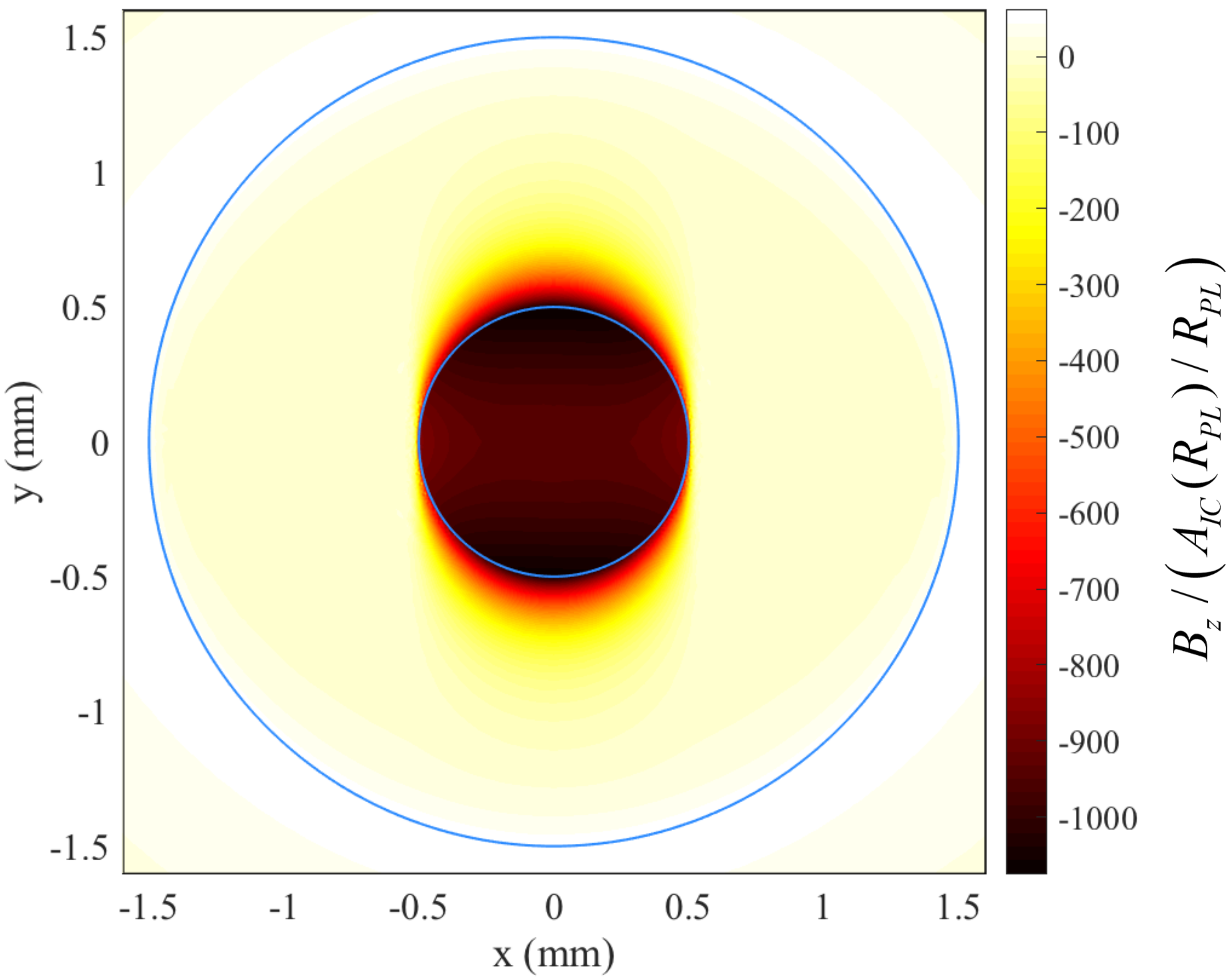
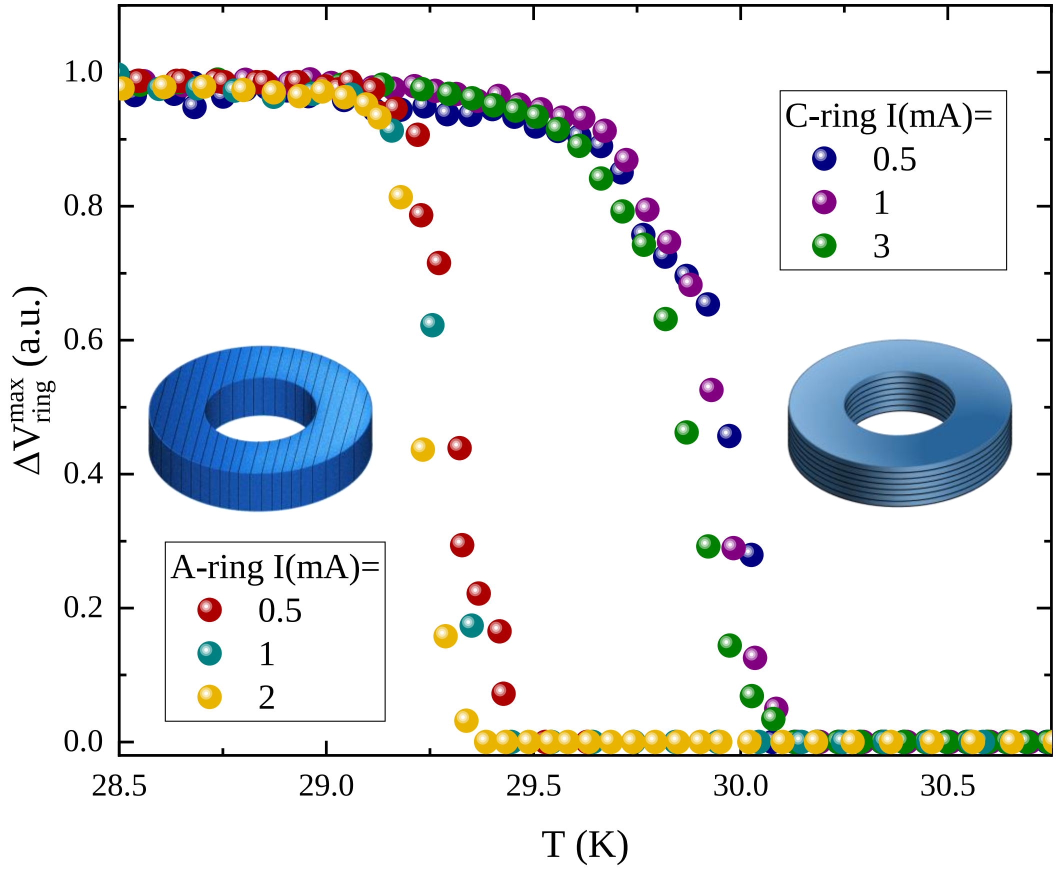
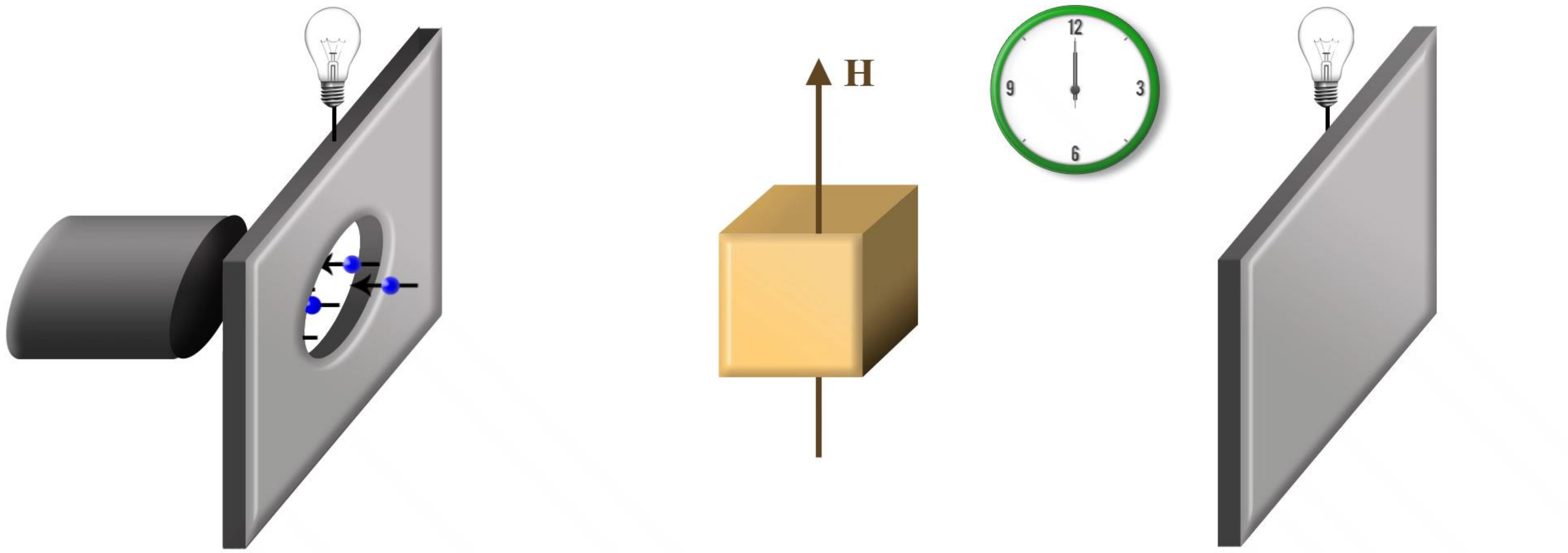


The problem



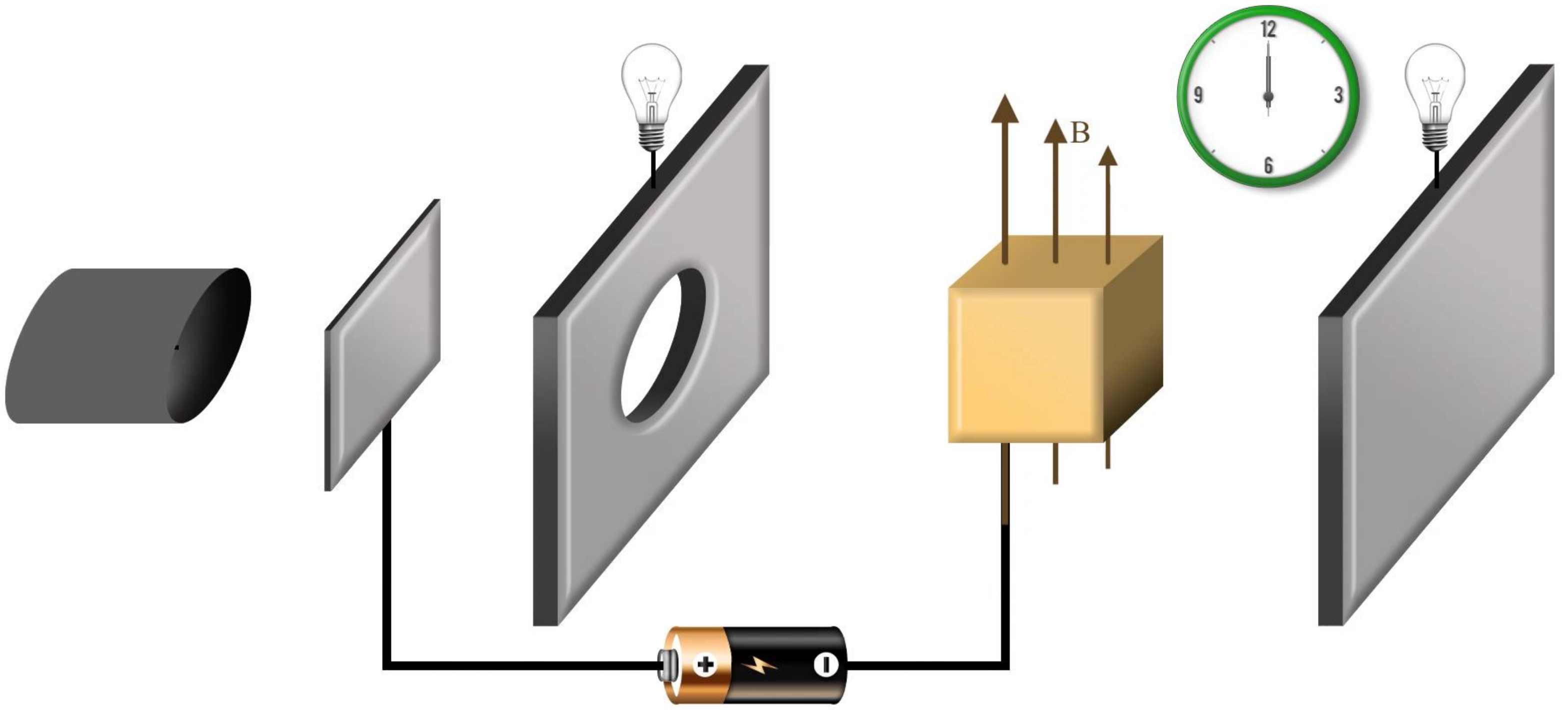
When we have signal from the a-ring, the c-ring is in saturation.
To find λ_c we need to find λ_{ab} at low T by some other technique.

Muon Spin Rotation (μSR)



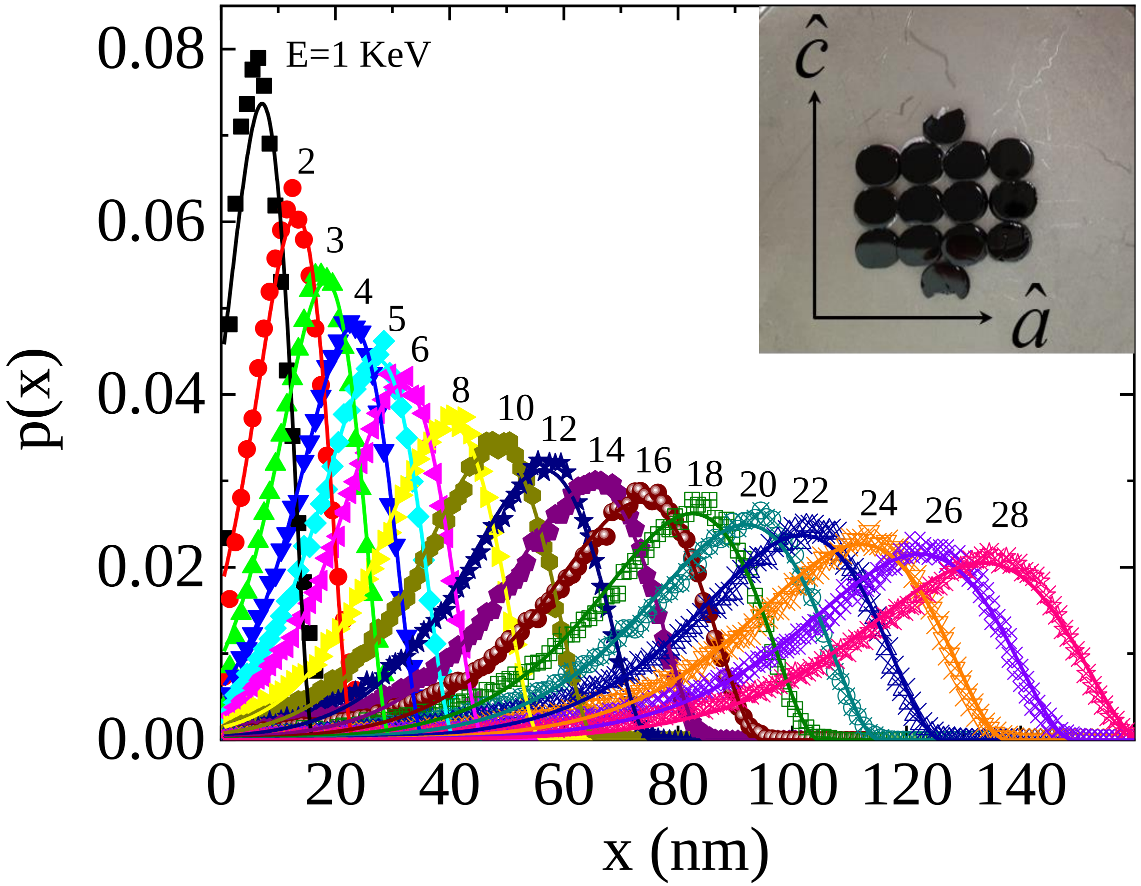
Animation by Omri Keren

Low Energy Muon Spin Rotation (LE-μSR)

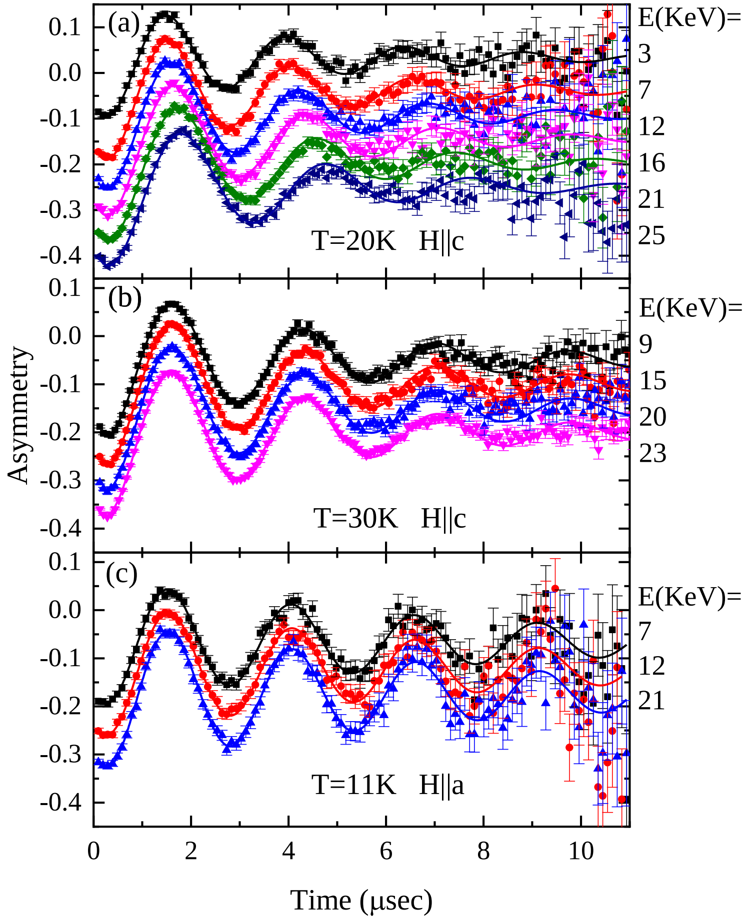


Animation by Omri Keren

Sample and stopping profile

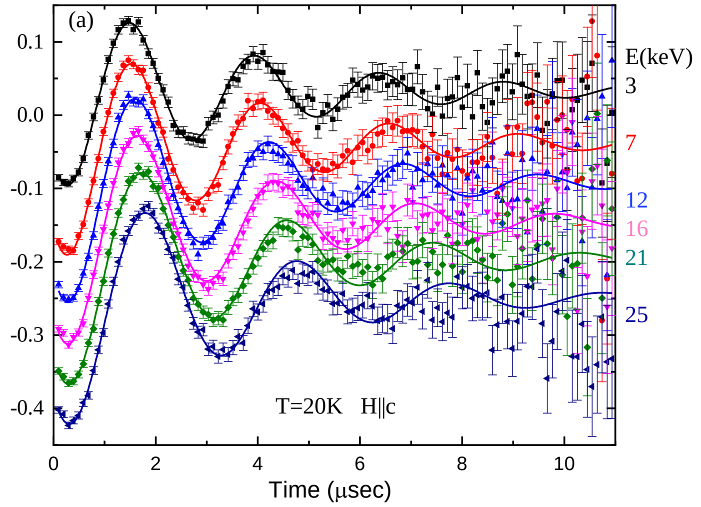


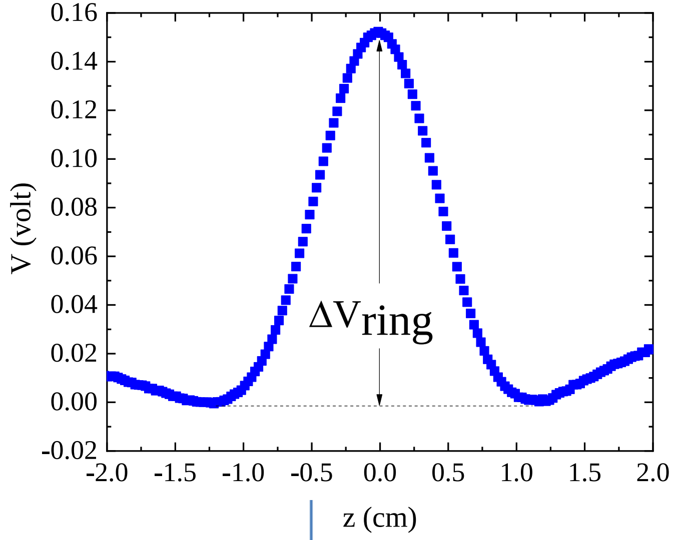
Raw data and analysis



$$A(E,t) = A_0 e^{-t/u} \int_0^\infty p(E,x) \cos\left(\gamma B_0 e^{-x/\lambda} t\right) dx$$

Extracting λ_c

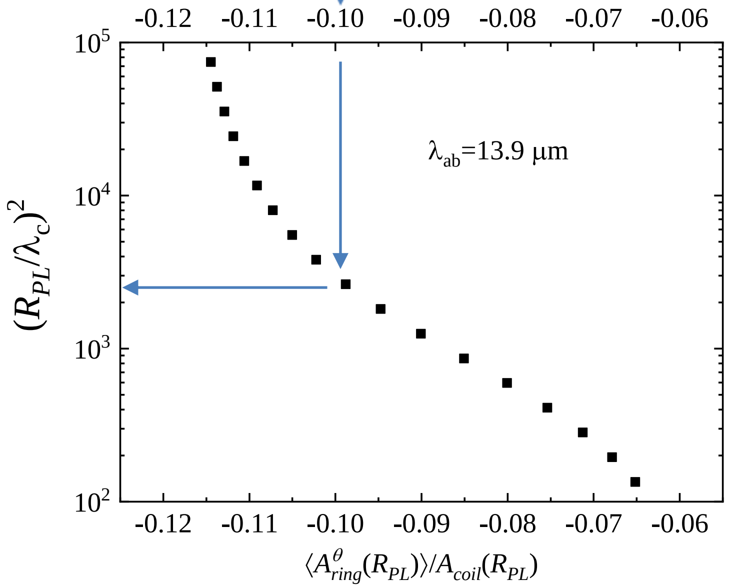




λ_{ab}

$$\boxed{\nabla \times \nabla \times \mathbf{A} = \bar{\rho}_s \left(\frac{1}{r} \hat{\boldsymbol{\theta}} + \mathbf{A} \right)}$$

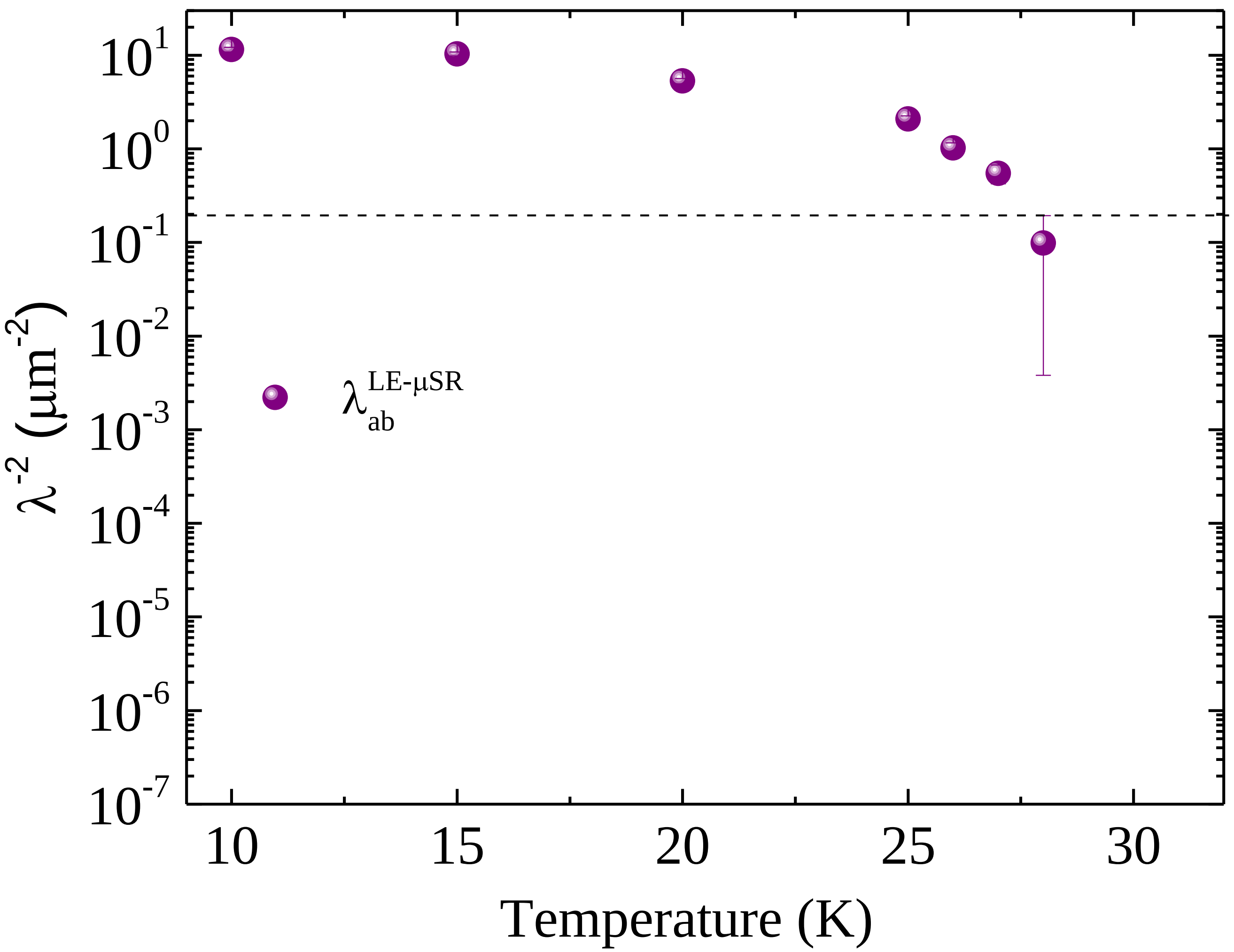
$$\bar{\rho}_s = \begin{bmatrix} \lambda_{ab}^{-2} & 0 & 0 \\ 0 & \lambda_{ab}^{-2} & 0 \\ 0 & 0 & \lambda_c^{-2} \end{bmatrix}$$



For a given λ_{ab} we run over all λ_c and calculate **A**.
Then, we convert $\Delta V_{ring} / \Delta V_{coil}$ to **A** to λ_c.

Combining results

- LE-μSR, sensitive to $\lambda < 10\mu m$, cannot detect two transitions.



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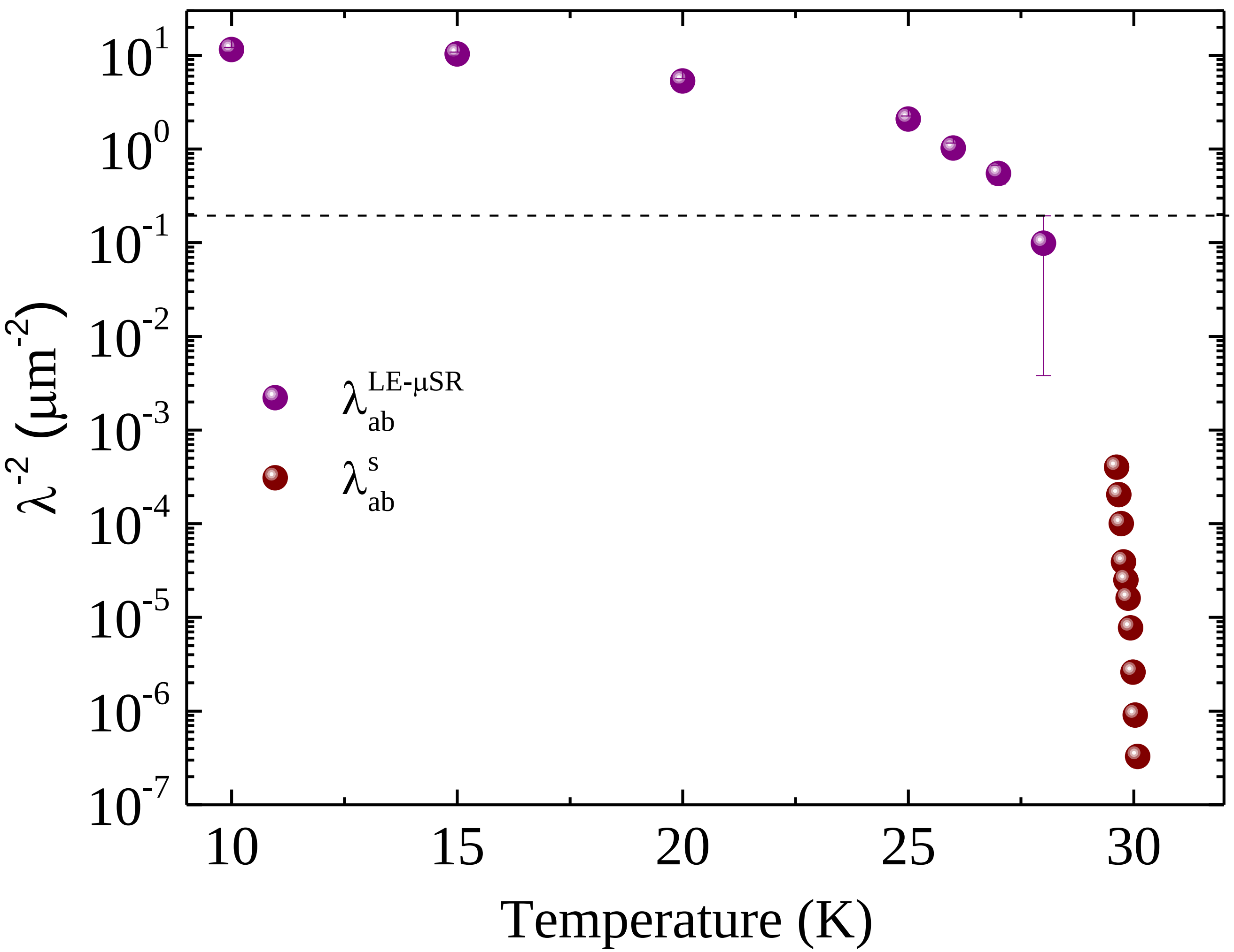
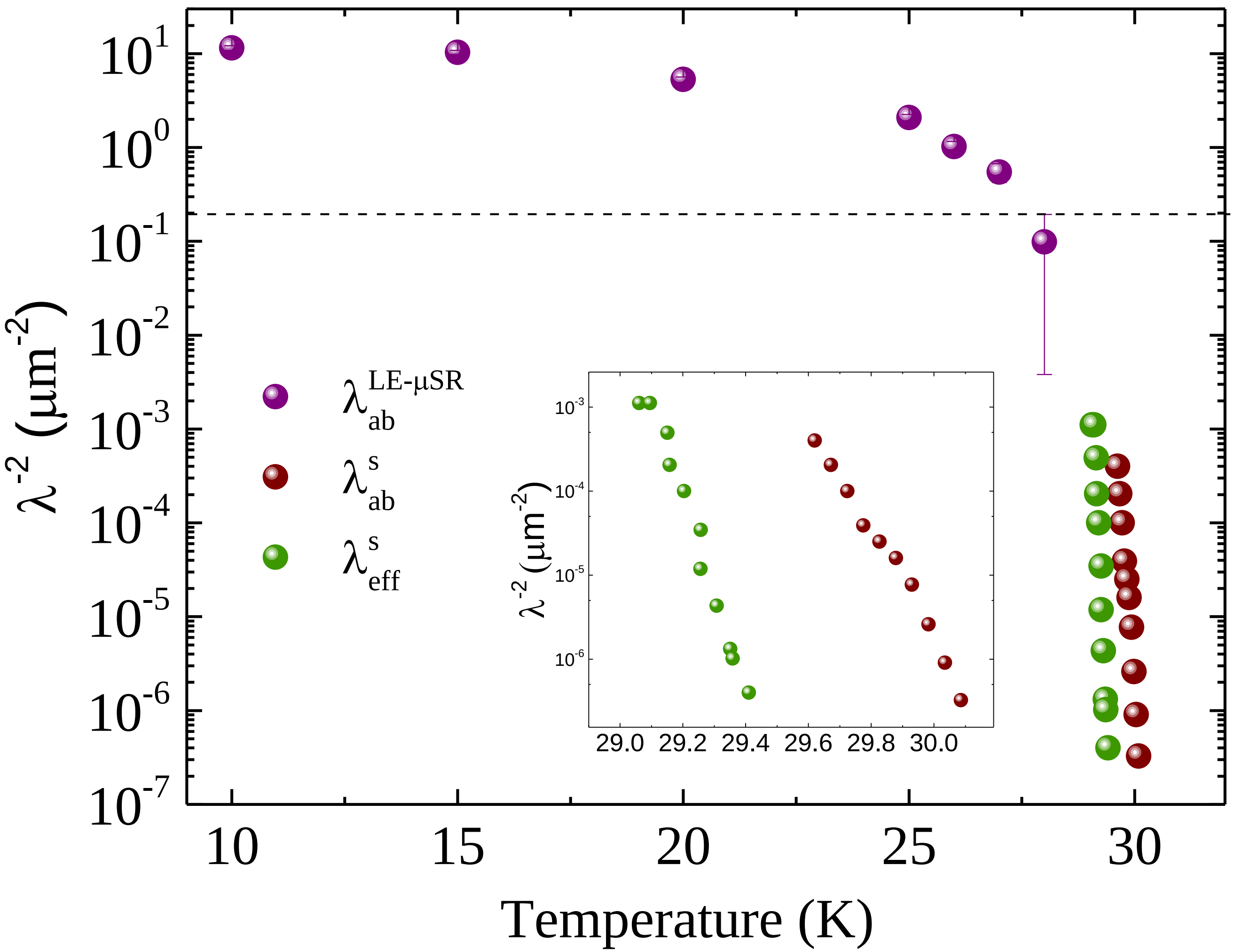


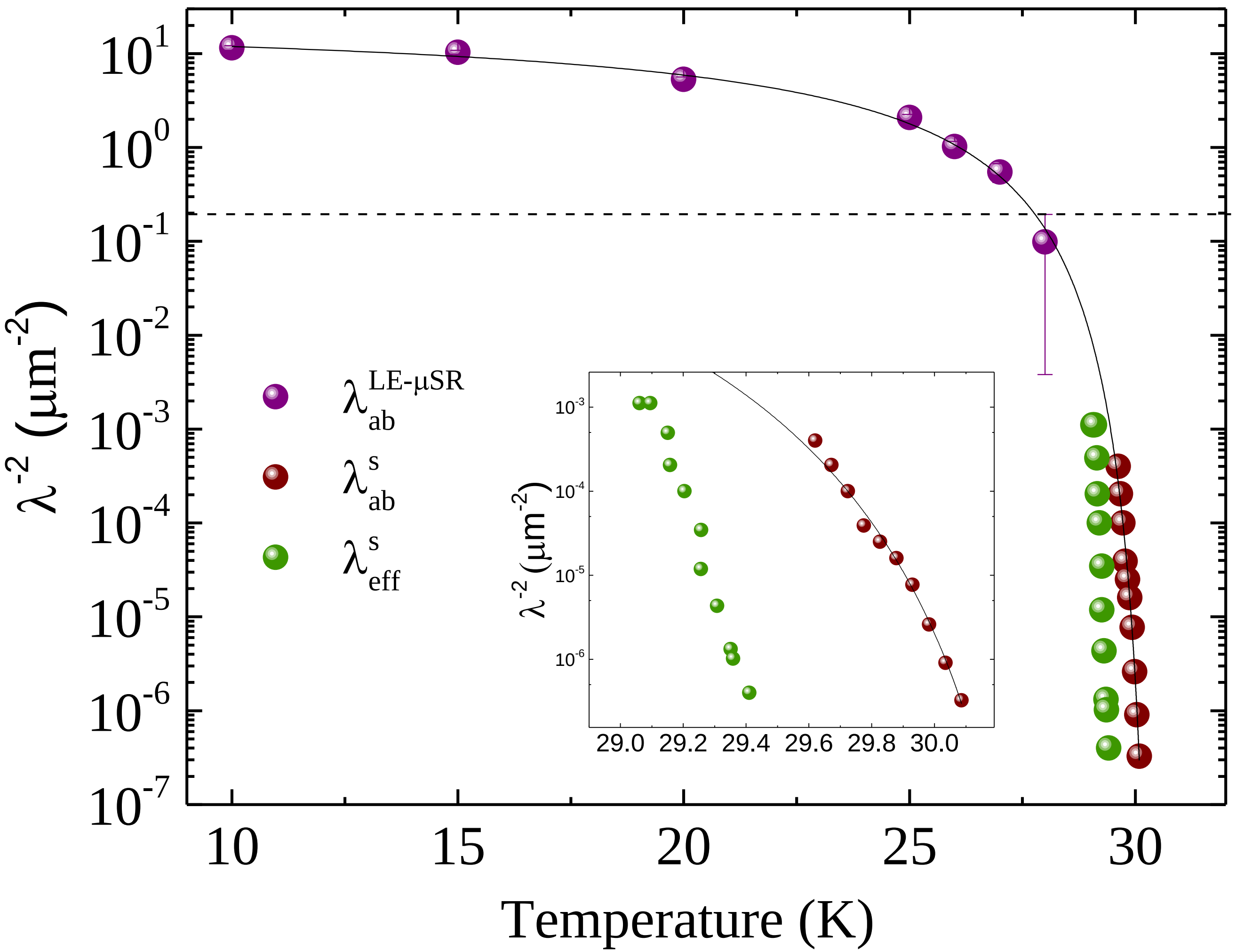
Combining results

- LE-μSR, sensitive to $\lambda < 10\mu m$, cannot detect two transitions.
- λ_{ab} and λ_{eff} start at different Tc.



Combining results

- LE-μSR, sensitive to $\lambda < 10\mu m$, cannot detect two transitions.
- λ_{ab} and λ_{eff} start at different Tc.
- $\lambda_{ab}^{-2} = C_0 \exp[C_1/(1 + C_3(1 - T/T_c)^{\delta})]$



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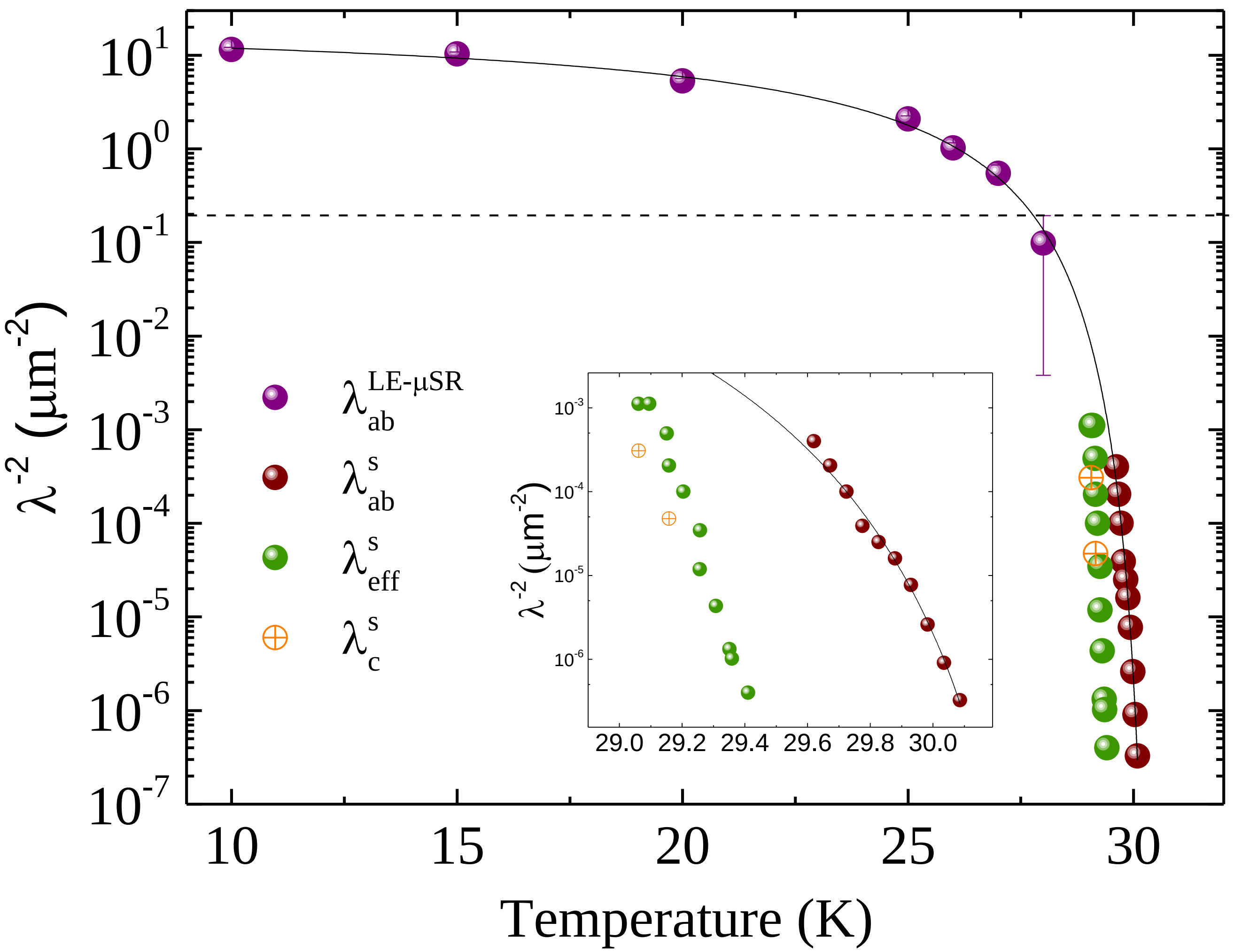
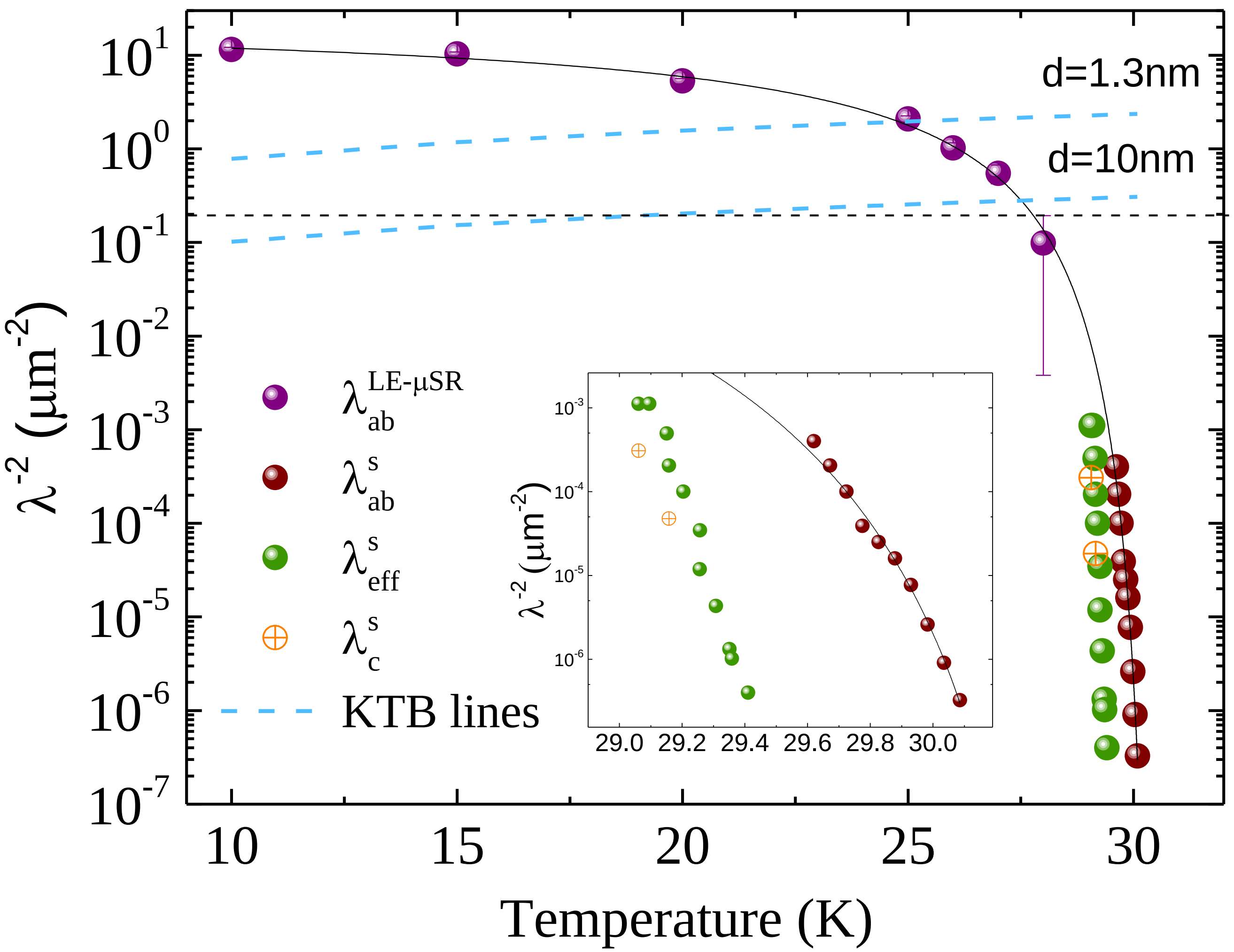
- LE-μSR, sensitive to $\lambda < 10\mu m$, cannot detect two transitions.
- λ_{ab} and λ_{eff} start at different Tc.
- $\lambda_{ab}^{-2} = C_0 \exp[C_1/(1 + C_3(1 - T/T_c)^{\delta})]$



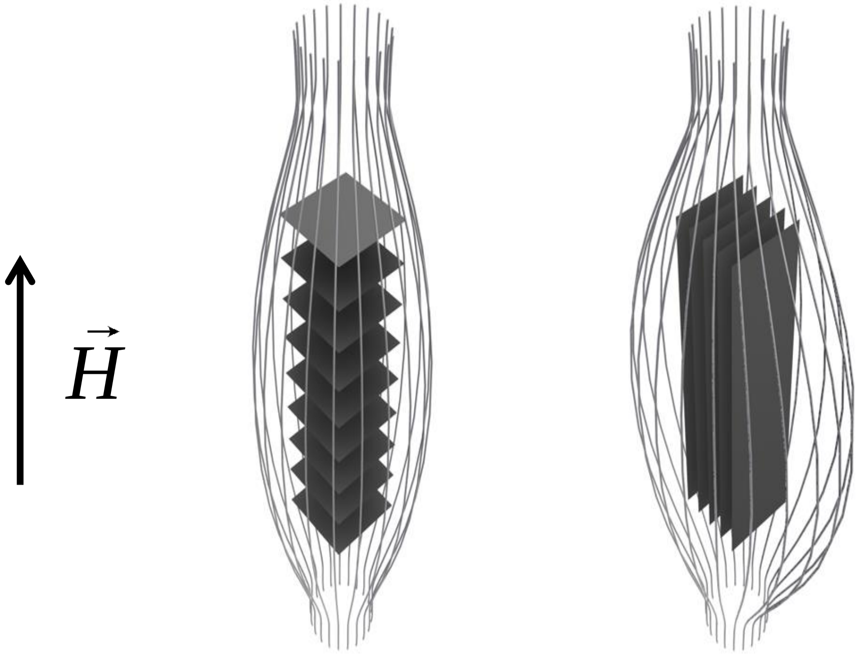
Combining results

- LE-μSR, sensitive to $\lambda < 10\mu m$, cannot detect two transitions.
- λ_{ab} and λ_{eff} start at different Tc.
- $\lambda_{ab}^{-2} = C_0 \exp\left[C_1/\left(1 + C_3(1 - T/T_c)^\delta\right)\right]$
- Berezinskii-Kosterlitz-Thouless transition $\lambda_{ab}^{-2} = \frac{8\pi\mu_0 k_B}{d\Phi_0^2} T_{BKT}$ requires d ~10 unit cells.
- Finite size effects are not responsible for the two T_c.



Other indication for two transitions

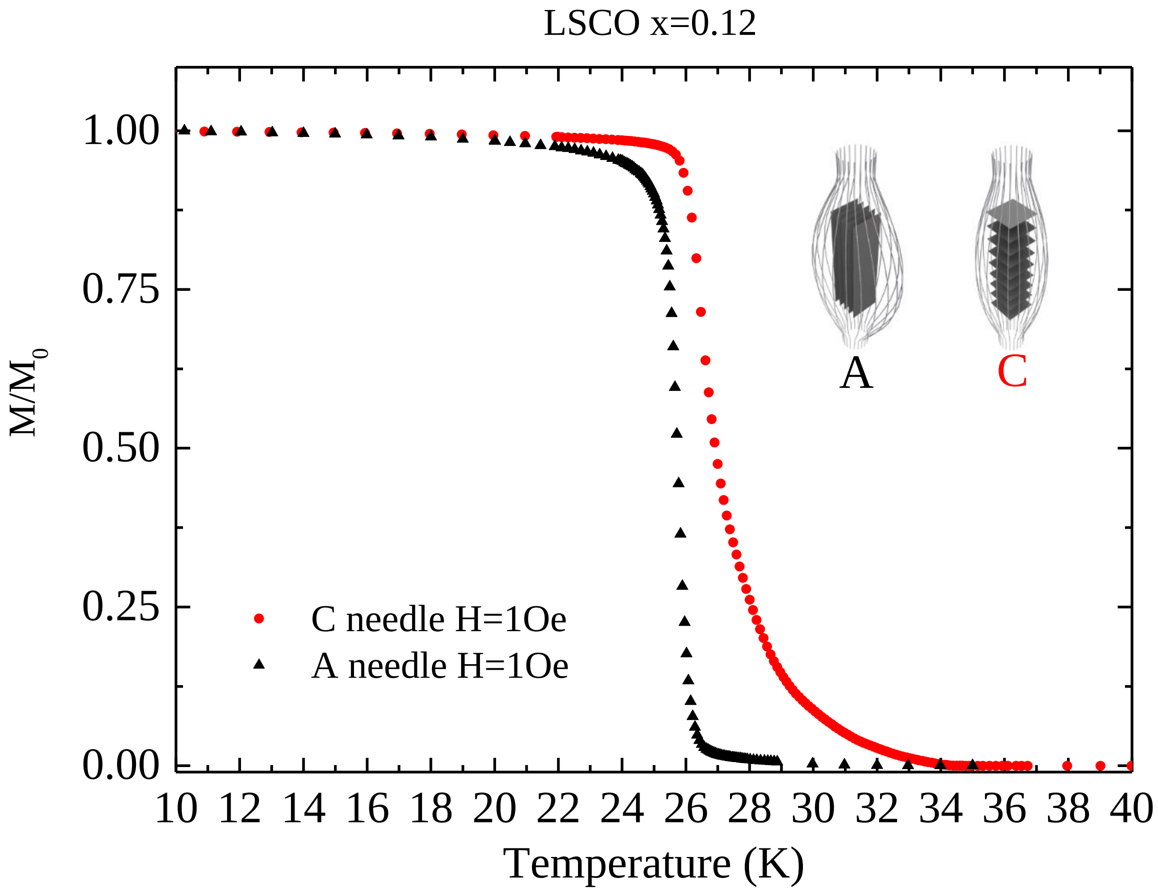
- We cut LSCO needles with the symmetry axis perpendicular or parallel to the CuO_2 planes.

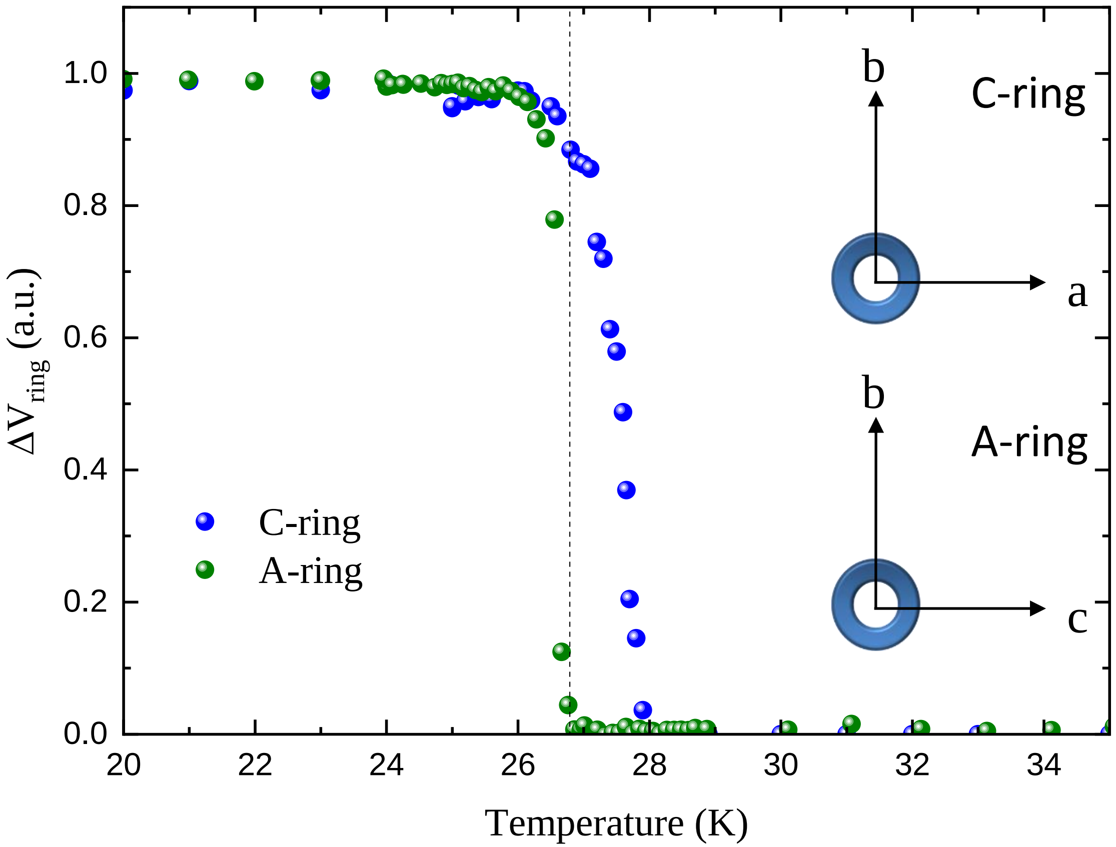


C-needle A-needle

- We measure the magnetization of the needles with H parallel to the symmetry axis.

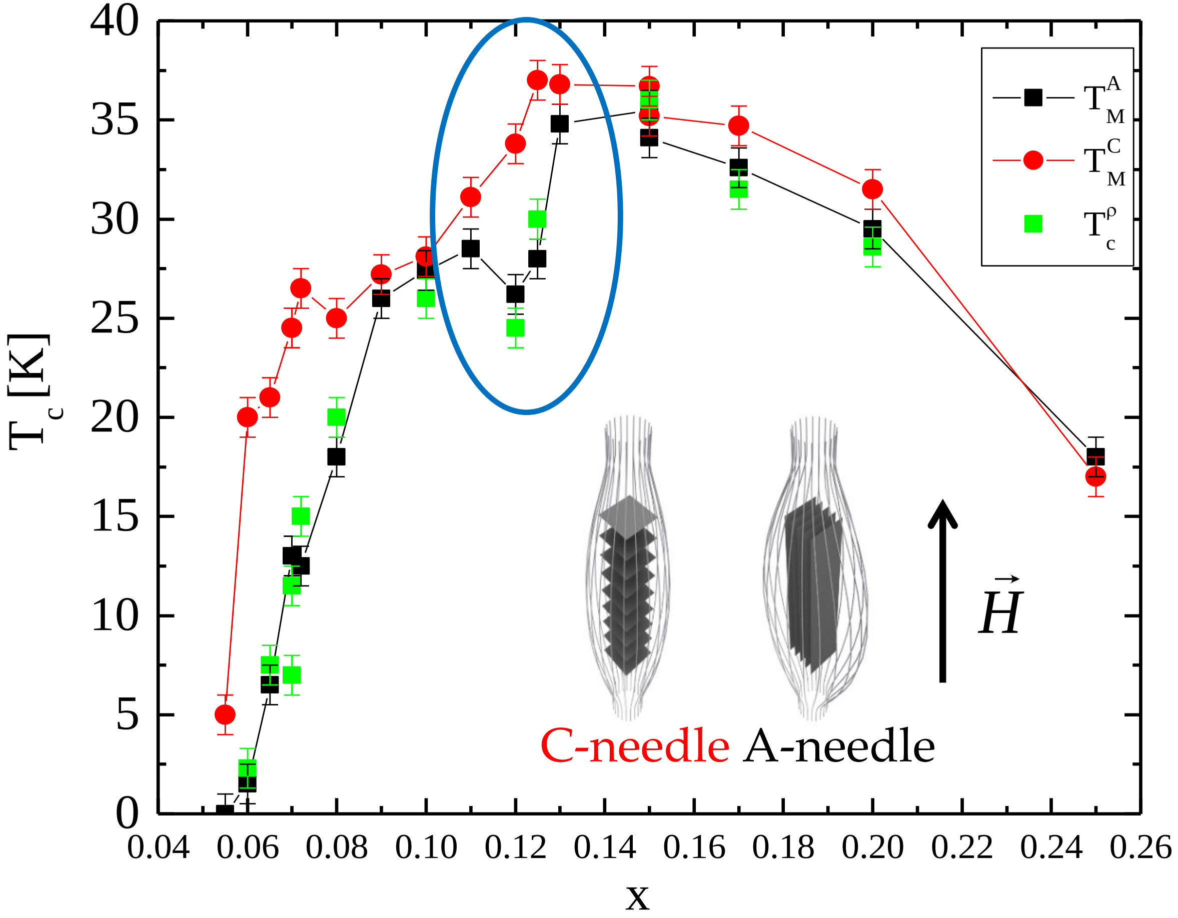
Stiffness vs. magnetization LSCO x=0.12





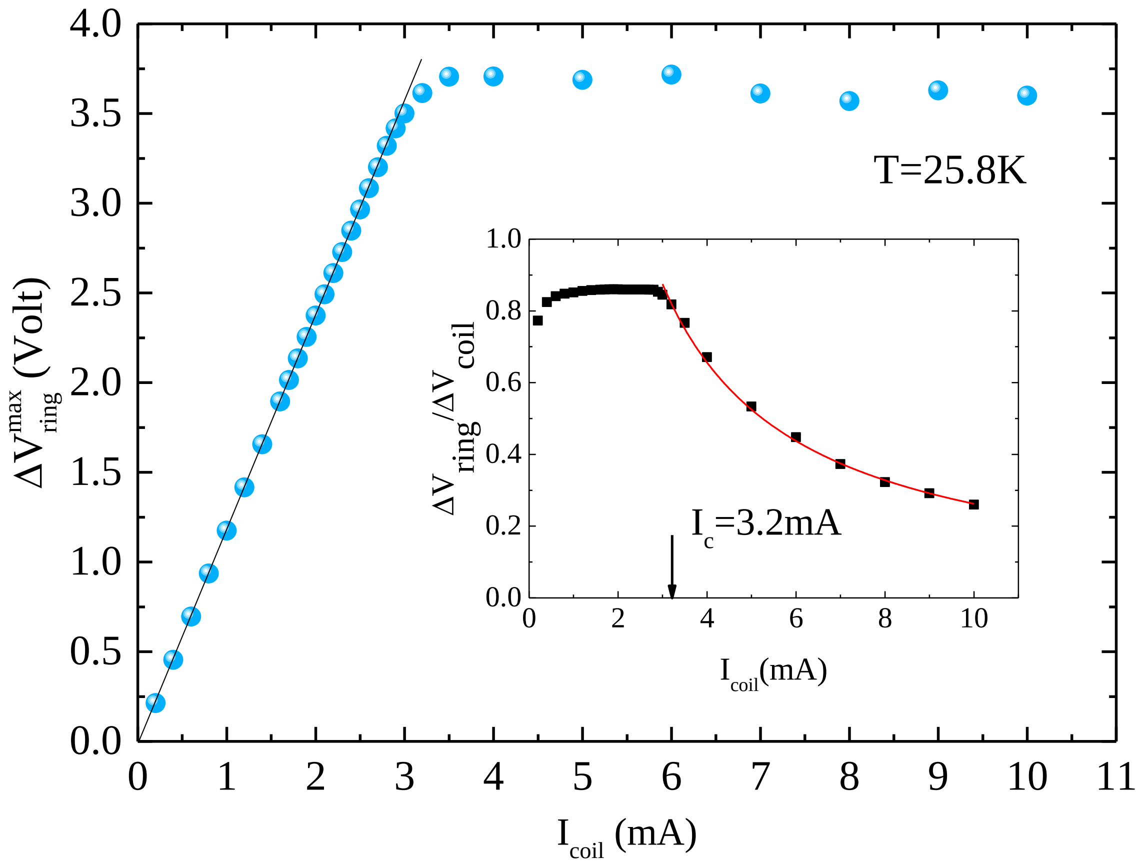
Magnetic response also develops before current can flow in the c direction.

New phase diagram



- The T_c difference is strongest at the 1/8 doping.
- The 1/8 anomaly is absent from c-needles.
- The 1/8 anomaly represents difficulty of current to flow in the c direction.
- Resistance T_c measurements agree with the low magnetization T_c.

Current dependence near T_c



- The voltage due to the ring increases linearly.
- The stiffness is *A* independent up to some critical *A* (some critical current).

Critical A at $T \to T_c$

Now we have to be more careful

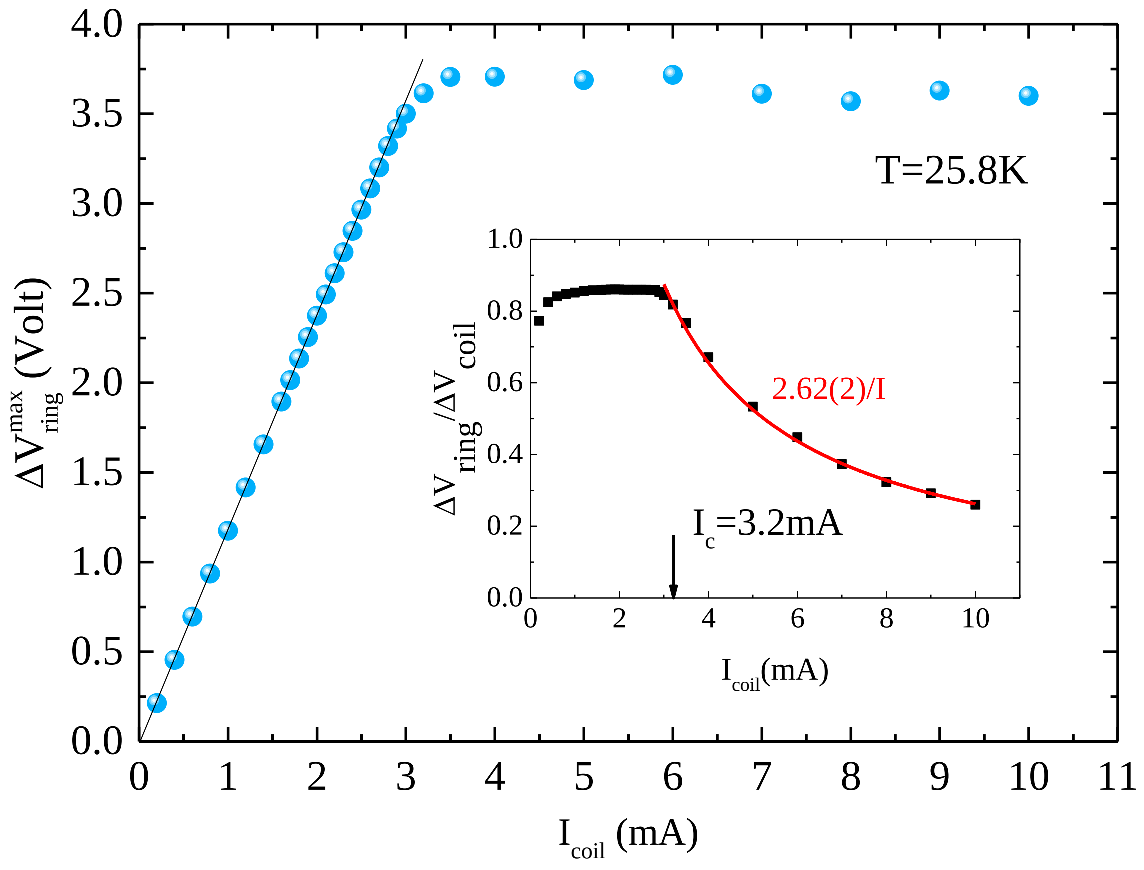
$$\nabla \times \nabla \times \mathbf{A}_{ring} = \frac{1}{\lambda^2}\left(\mathbf{A}_{coil} + \mathbf{A}_{ring} + \nabla\varphi\right)$$

$\nabla\varphi = \dfrac{n}{r}$, φ is the phase of the order parameter.

Up to a critical A_{tot}, $n=0$ since we cool first.
Once we cross the critical A_{tot}, n changes so that $A_{coil}+n/r=constant/r$.

At the critical current vortices cross the sample.

$J_c \sim 1\ \mathrm{Acm}^{-2}$



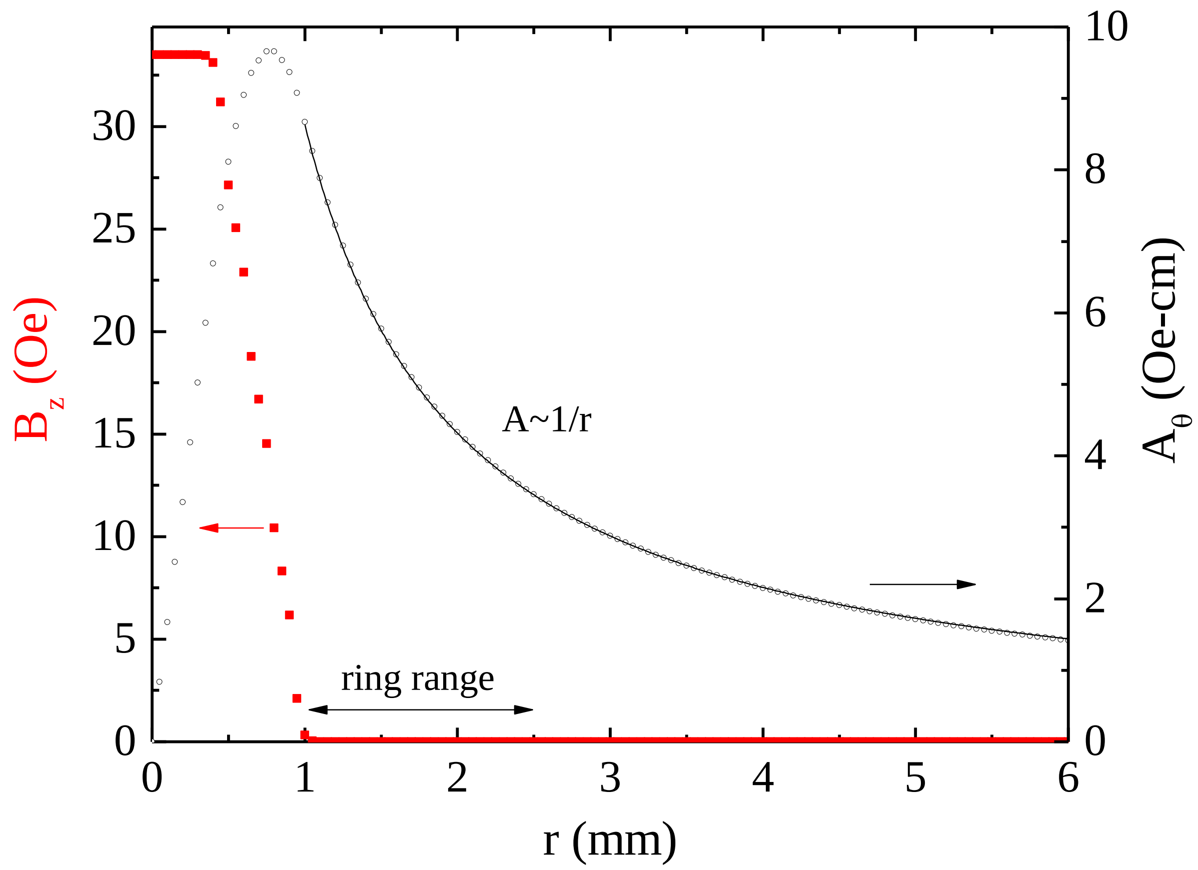
Conclusions

- Studying superconducting properties with the stiffnessometer leads to new results.

- Most intriguing result is two stiffness transition temperatures in the same sample.

Thank you!

Finite coil vector potential



Sample roughness is tens of nanometers