

# Self-field critical currents of practical superconductors

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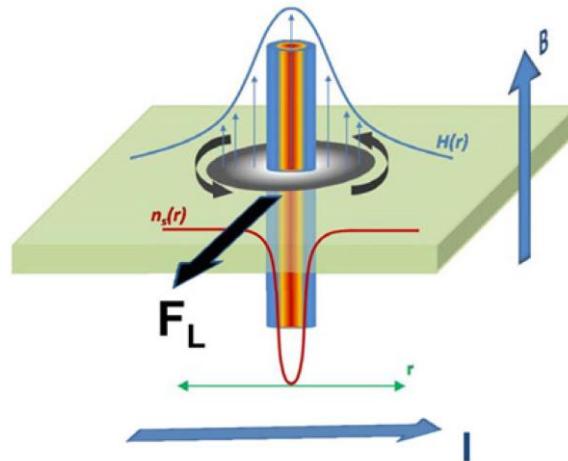
# Wanted: as large as possible dissipation-free current

## Key questions:

- What is the maximum dissipation-free current for given superconductor?
- Is it an engineering property? And if so, how to increase it?
- Is it fundamentally limited? And if so, what is the limit?

## For last several decades answers were:

- Critical current is engineering property, depending on ability of superconductor microstructure to pin Abrikosov vortexes vs Lorentz force/thermal depinning/etc.
- Critical currents fundamentally limited by Ginzburg-Landau “depairing current density”,  $J_{c,d}$ . Best type II superconductors can reach 10%-15% of “depairing current density”.

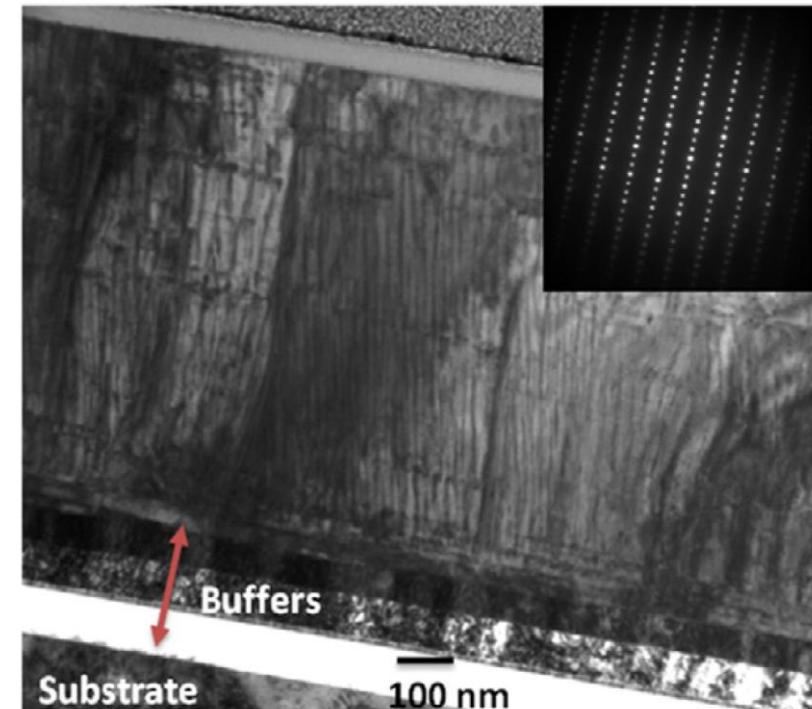
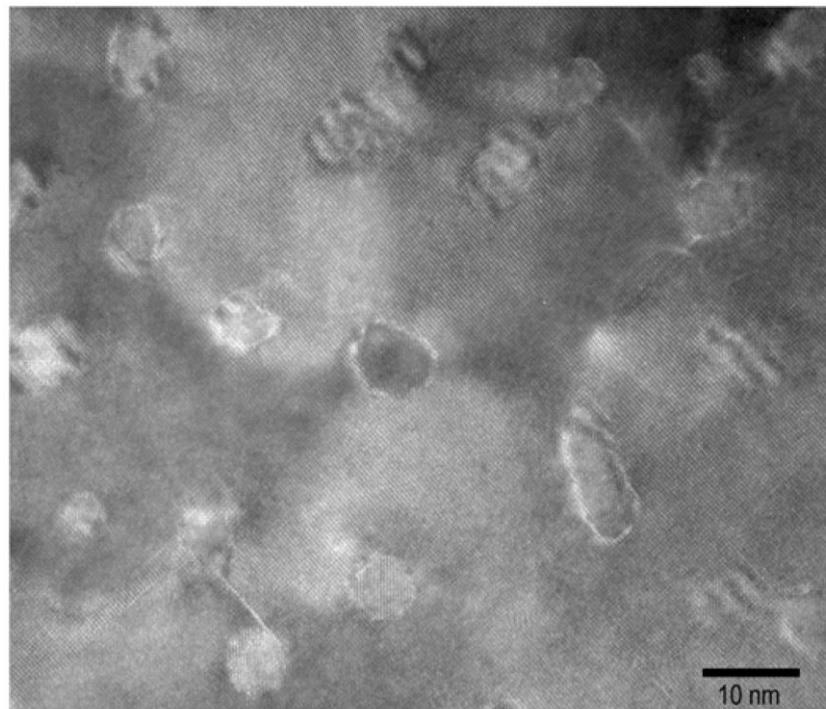


$$J_{c,d} = \frac{B_c}{\mu_0 \lambda} = \frac{\phi_0}{2\sqrt{2}\pi\mu_0\xi(T)\lambda^2(T)}$$

# Wanted: nanostructured superconductor

Main R&D focus in the field for last few decades:

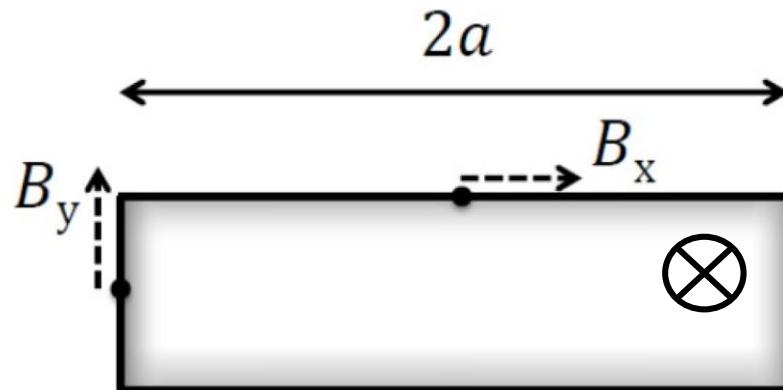
- To modify vortex pinning landscape to create nano-scaled structures of secondary phases in superconductors to pin Abrikosov vortices.
- There are more than **10,000** peer-reviewed papers, claiming there was an increase in critical currents through nano-structural modification. Typical example: introduction of  $\text{BaZrO}_3$  nanorods in YBCO films (Selvamanickam, *SUST* **26**, 035006 (2013)).



# Wanted: quantitative description

**Unavoidable big problem of vortex approach:  
quantitative description of self-field critical current**

- For thin films and nanowires surface fields  $B_x$  and  $B_y$  at self-field critical current,  $I_c(sf, T)$ , are much smaller than lower critical field,  $B_{c1}$ , and vortices do not yet exist. Ampere's law equations for  $B_x$  and  $B_y$  are below.



$$J_c = \frac{I_c}{4ab}$$

$$B_x = \mu_0 b J_c$$

$$B_{c1} = \frac{\phi_0 \left( \ln \left( \frac{\lambda}{\xi} \right) + 0.5 \right)}{4\pi\lambda^2(T)}$$

$$B_y = \frac{\mu_0 b J_c}{\pi} \left[ \ln \left( \frac{2a}{b} \right) + 1 \right]$$

# Wanted: quantitative description for 2D SCs

**FeSe single monoatomic layer [1]**

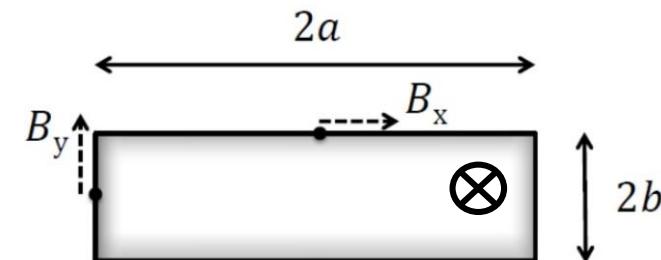
**TaS<sub>2</sub> several monoatomic layers [2]**

**Ga triple monoatomic layer [3]**

[1]. W.-H. Zhang et al., *Chin. Phys. Lett.* **31**, 017401 (2014).

[2]. E. Navarro-Moratalla, et al., *Nature Comms.* **7**, 11043 (2016).

[3]. Y. Xing, et al., *Science* **350**, 542 (2015).



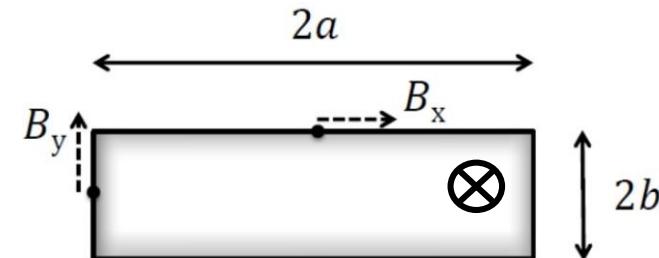
Parameters	FeSe	TaS <sub>2</sub>	TaS <sub>2</sub>	Ga
$2a$ ( $\mu\text{m}$ )	1,450	0.45	1.0	2,000
$2b$ (nm)	0.55	4.2	3.5	0.828
$T_{\text{meas}}$ (K)	2.0	0.02	0.02	2.0
$I_c$ (mA)	13.7	0.012	0.0034	4.6
$J_c$ (MA/cm <sup>2</sup> )	1.72	0.63	0.098	0.28
$B_x$ (mT)	0.006	0.017	0.002	0.0015
$B_y$ (mT)	0.031	0.034	0.005	0.0076
$B_{c1}$ (mT)	7.5	2.98	2.98	2.2

# Wanted: quantitative description: 2G wires

**(Nd,Eu,Gd)BCO film [1]**

**SuperPower tape (our data)**

**STI tape nanoparticle-free (our data)**



Parameters	(NEG)BCO	SP	SP	STI
$2a$ ( $\mu\text{m}$ )	50	50	250	500
$2b$ (nm)	50	1,000	1,000	4,500
$T_{\text{meas}}$ (K)	19	18	18	23
$I_c$ (A)	0.61	11	56	240
$J_c$ (MA/cm <sup>2</sup> )	24.3	21.5	22.4	10.6
$B_x$ (mT)	7.6	135	141	300
$B_y$ (mT)	20.9	241	354	603
$B_{c1}$ (mT)	42.7	41.5	42.7	42.7

[1]. C. Cai, et al., *Appl. Phys. Lett.* **84**, 377 (2004).

# Flux pinning is irrelevant for $J_c(sf, T)$ limitation

## Key conclusion:

- Limitation mechanism for  $J_c(sf, T)$  is not vortex pinning/depinning.
- Supported by large number of studies of pinning on  $J_c(sf, T)$

## Is there any way to describe experimental $J_c(sf, T)$ data?

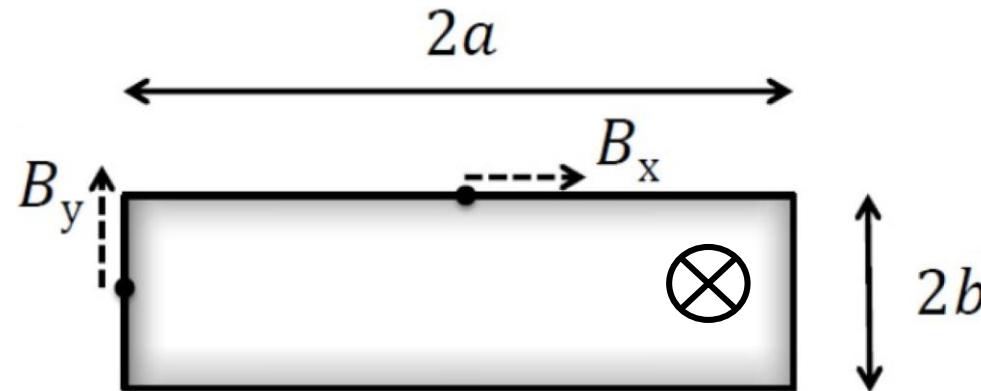
- Yes, in 2015 we found universal equation that quantitatively described self-field critical current density in (all, in total > 50) thin films ( $2b < \lambda(0)$ ) [1]:

$$J_c(sf, T) = \frac{\phi_0 \left[ \ln \left( \frac{\lambda}{\xi} \right) + 0.5 \right]}{4\pi\mu_0\lambda^3(T)}$$

[1]. E.F. Talantsev and J.L. Tallon, *Nature Communications* **6**, 7820 (2015).

# Basic equations for $J_c(sf, T)$

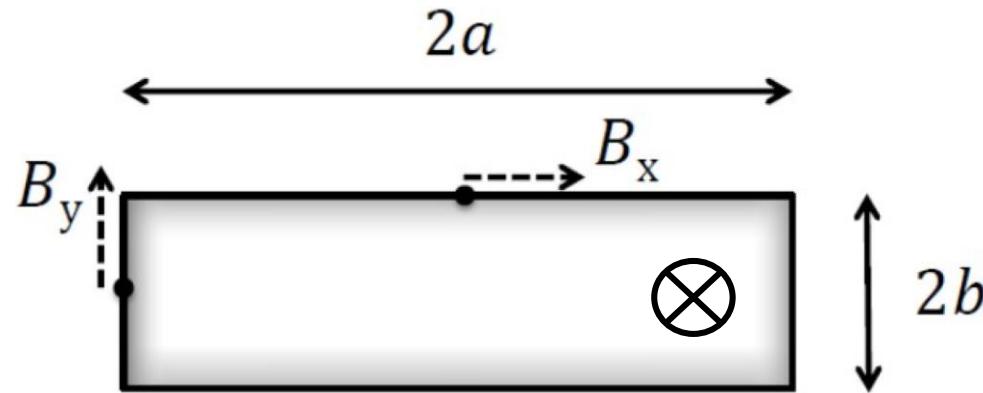
**Key equation for rectangular isotropic SCs of any dimensions:**



$$J_c(sf, T) = \frac{\phi_0 \left[ \ln\left(\frac{\lambda}{\xi}\right) + 0.5 \right]}{4\pi\mu_0\lambda^3(T)} \left( \frac{\lambda}{a} \tanh \frac{a}{\lambda} + \frac{\lambda}{b} \tanh \frac{b}{\lambda} \right)$$

# Basic equations for $J_c(sf, T)$

**Key equation for rectangular anisotropic SCs of any dimensions:**



$$\begin{aligned}
 J_c(sf, T) = & \frac{\phi_0}{4\pi\mu_0} \cdot \frac{(\ln(\kappa_c) + 0.5)}{\lambda_{ab}^3(T)} \cdot \left( \frac{\lambda_c(T)}{b} \cdot \tanh\left(\frac{b}{\lambda_c(T)}\right) \right) + \\
 & + \frac{\phi_0}{4\pi\mu_0} \cdot \frac{(\ln(\kappa_{ab}) + 0.5)}{\lambda_{ab}^2(T) \cdot \lambda_c(T)} \cdot \left( \frac{\lambda_{ab}(T)}{a} \cdot \tanh\left(\frac{a}{\lambda_{ab}(T)}\right) \right)
 \end{aligned}$$

➤ For **simplicity**, in all fits below we assumed  $\lambda_c(0) = 1,000$  nm

Talantsev, Crump, Tallon, *Annalen der Physik* **529**, 1700197 (2017).

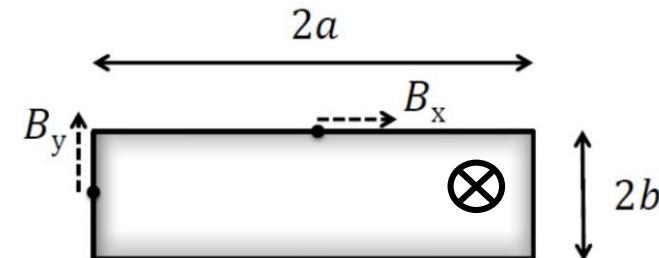
# Wanted: quantitative description

(Nd,Eu,Gd)BCO film [1]

SuperPower tape: (Y,Gd)BCO+BZO

STI tape nanoparticle-free: SmBCO

Sample thickness is varied by factor of 90



Parameters	(NEG)BCO	SP	SP	STI
$2a$ ( $\mu\text{m}$ )	50	50	250	500
$2b$ (nm)	50	1,000	1,000	4,500
$T_{\text{meas}}$ (K)	19	18	18	23
$I_c$ (A)	0.61	11	56	240
$J_c$ (MA/cm <sup>2</sup> )	24.3	21.5	22.4	10.6
$B_x$ (mT)	7.6	135	141	300
$B_y$ (mT)	20.9	241	354	603
$\lambda_{ab}(T \approx 20\text{K})$ (nm)	140	142	140	140

$$J_c(\text{sf}, T) = \frac{\phi_0}{4\pi\mu_0} \cdot \frac{(\ln(\kappa_c) + 0.5)}{\lambda_{ab}^3(T)} \cdot \left( \frac{\lambda_c(T)}{b} \cdot \tanh\left(\frac{b}{\lambda_c(T)}\right) \right) + \frac{\phi_0}{4\pi\mu_0} \cdot \frac{(\ln(\kappa_{ab}) + 0.5)}{\lambda_{ab}^2(T) \cdot \lambda_c(T)} \cdot \left( \frac{\lambda_{ab}(T)}{a} \cdot \tanh\left(\frac{a}{\lambda_{ab}(T)}\right) \right)$$

# Bardeen-Cooper-Schrieffer theory approach

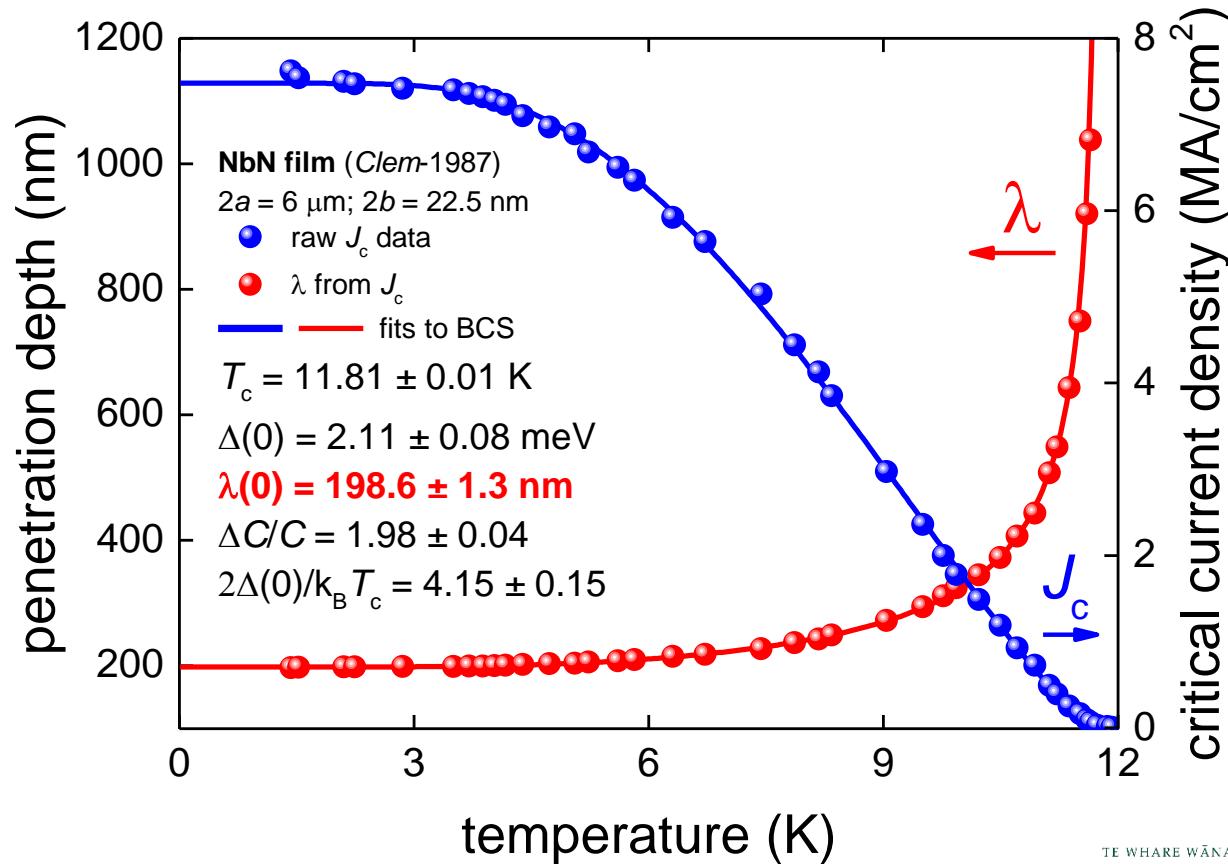
$$J_c(sf, T) = \frac{\phi_0 \left[ \ln \left( \frac{\lambda}{\xi} \right) + 0.5 \right]}{4\pi\mu_0\lambda^3(T)} \left( \frac{\lambda(T)}{a} \tanh \frac{a}{\lambda(T)} + \frac{\lambda(T)}{b} \tanh \frac{b}{\lambda(T)} \right)$$

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1 - \frac{1}{2k_B T} \cdot \int_0^\infty \frac{d\varepsilon}{\cosh^2 \left( \frac{\sqrt{\varepsilon^2 + \Delta^2(T)}}{2k_B T} \right)}}}$$

$$\Delta(T) = \Delta(0) \tanh \left( \frac{\pi k_B T_c}{\Delta(0)} \sqrt{a \frac{\Delta C}{C} \left( \frac{T_c}{T} - 1 \right)} \right)$$

# Key approach: to derive thermodynamic parameters from $J_c(sf, T)$ for practical SCs

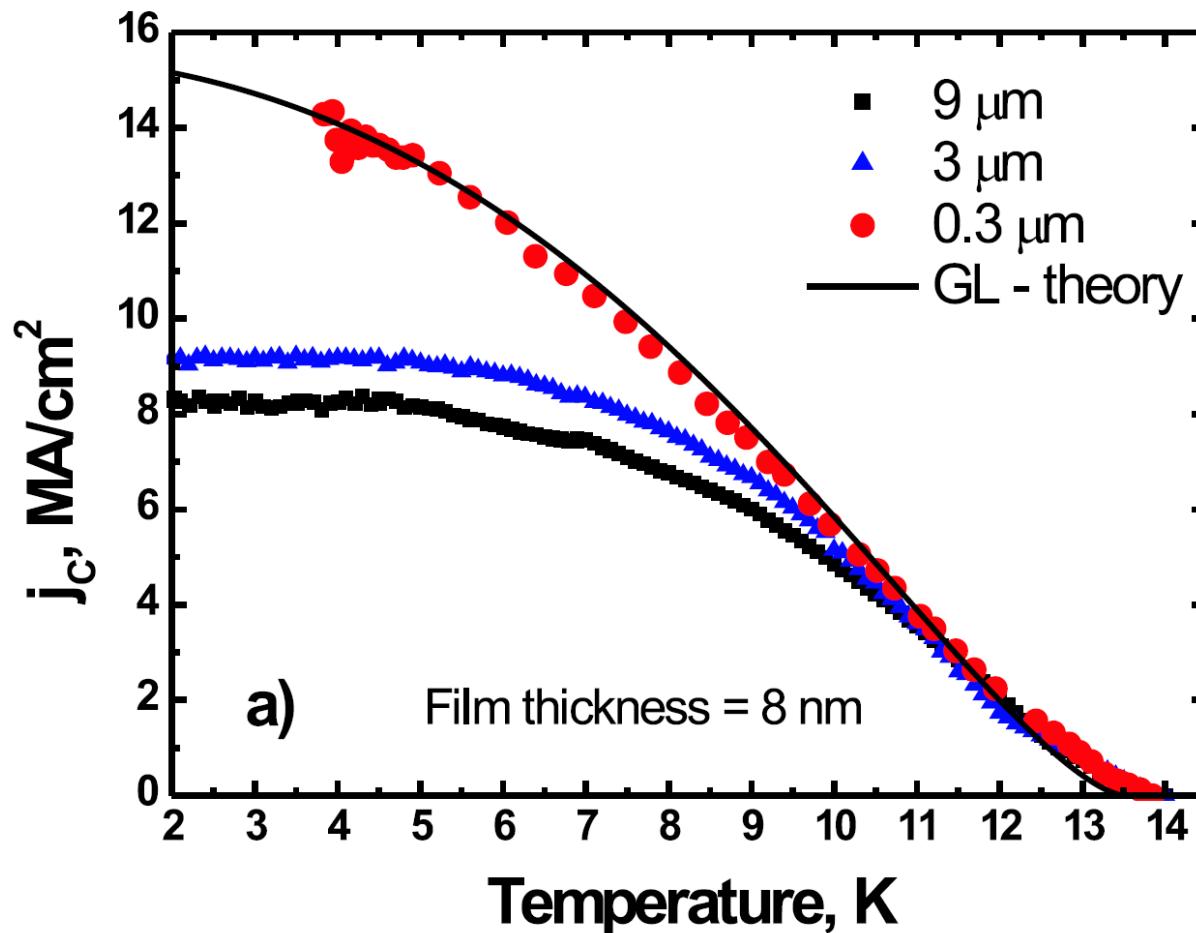
- To derive  $\lambda(0)$ ,  $\Delta(0)$ ,  $\Delta C/\gamma T_c$  and  $T_c$ .
- NbN is the material for superconducting nanowire single photon detectors (SNSPD)
- NbN is *s*-wave superconductor with  $\lambda(0) = 200 \text{ nm}$  (Poole, et. al., 2<sup>nd</sup> Edition, 2007)



[1]. J.R. Clem et al, Phys. Rev. B 35, 6637 (1987).

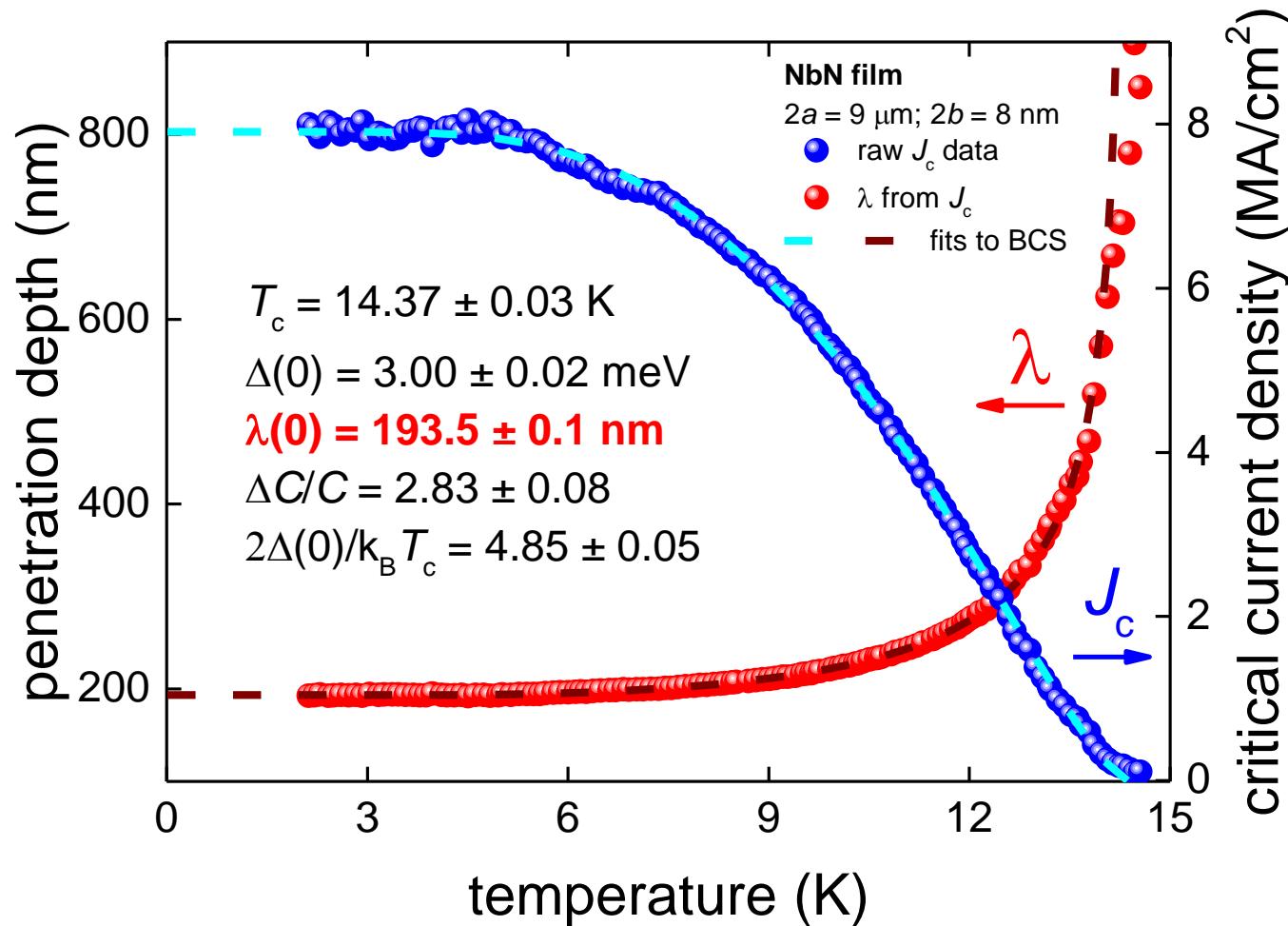
# Is there a problem for our approach?

➤ NbN (material for SNSPD)



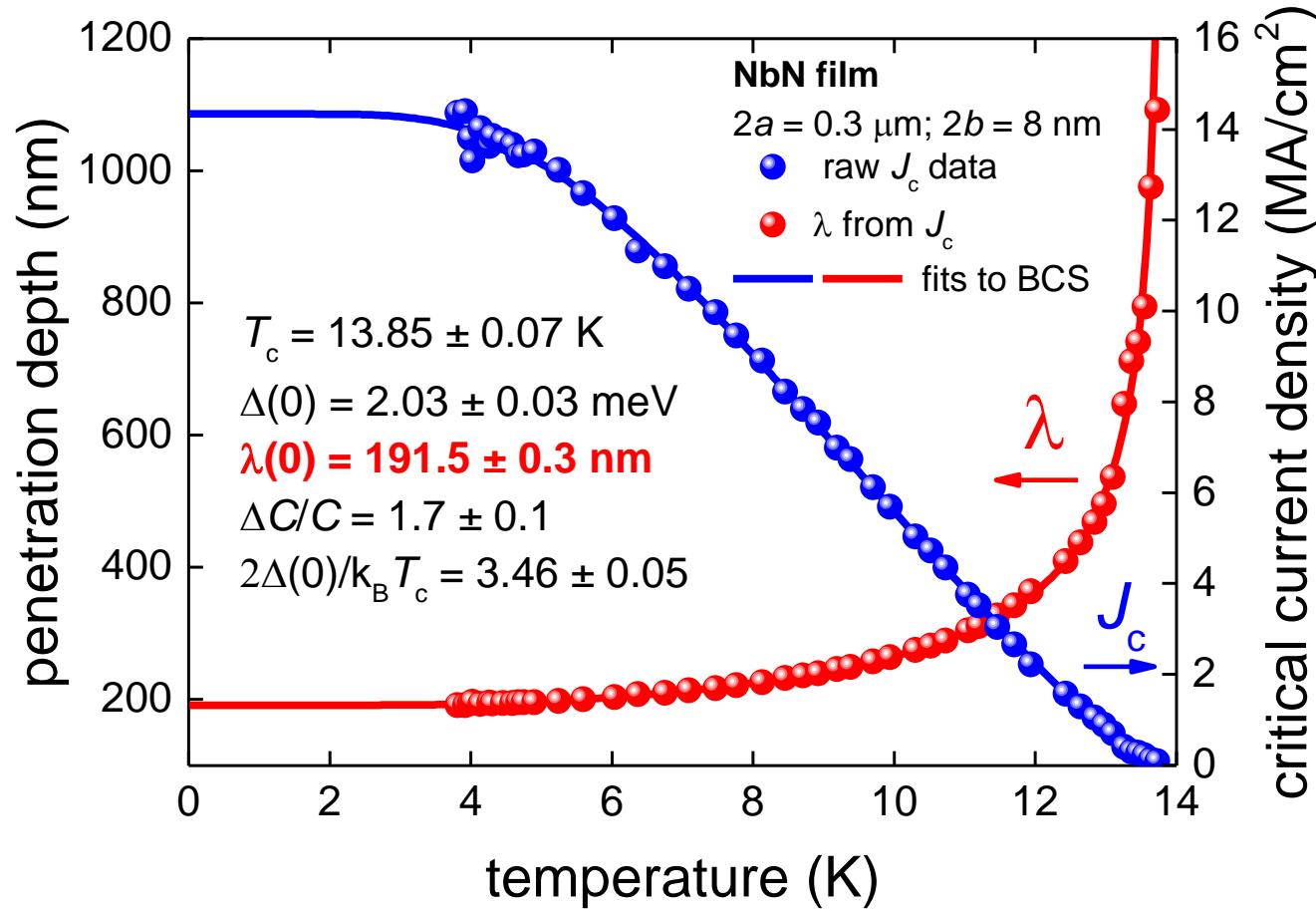
K. Il'in *et al*, *J. Low Temp. Phys.* **151**, 585 (2008).

# All fine for wide film ( $2a = 9 \mu\text{m}$ )



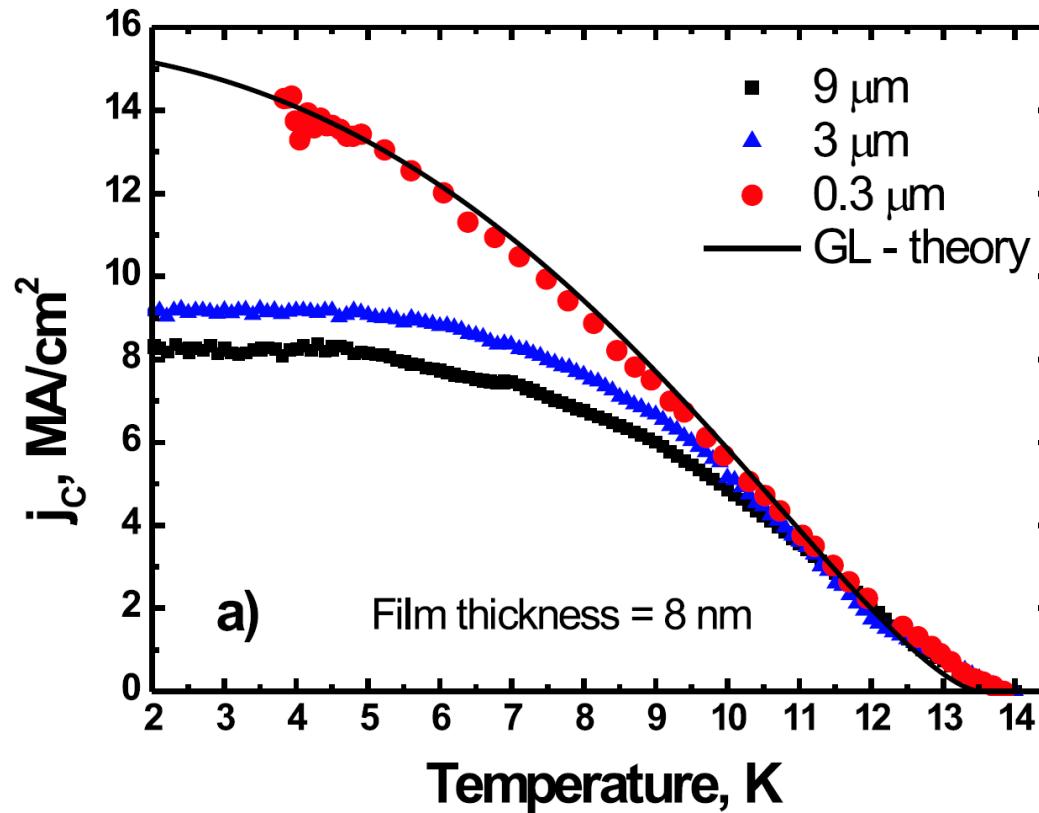
$$J_c(\text{sf}, T) = \frac{\phi_0}{4\pi\mu_0} \cdot \frac{(\ln(\kappa) + 0.5)}{\lambda^3(T)} \cdot \left( \frac{\lambda(T)}{b} \cdot \tanh\left(\frac{b}{\lambda(T)}\right) + \frac{\lambda(T)}{a} \cdot \tanh\left(\frac{a}{\lambda(T)}\right) \right)$$

# All fine for narrow film ( $2a = 300$ nm)



$$J_c(\text{sf}, T) = \frac{\phi_0}{4\pi\mu_0} \cdot \frac{(\ln(\kappa) + 0.5)}{\lambda^3(T)} \cdot \left( \frac{\lambda(T)}{b} \cdot \tanh\left(\frac{b}{\lambda(T)}\right) + \frac{\lambda(T)}{a} \cdot \tanh\left(\frac{a}{\lambda(T)}\right) \right)$$

# All fine for NbN (and other s-wave SCs)



$$J_c(\text{sf}, T) = \frac{\phi_0}{4\pi\mu_0} \cdot \frac{(\ln(\kappa) + 0.5)}{\lambda^3(T)} \cdot \left( \frac{\lambda(T)}{b} \cdot \tanh\left(\frac{b}{\lambda(T)}\right) + \frac{\lambda(T)}{a} \cdot \tanh\left(\frac{a}{\lambda(T)}\right) \right)$$

K. Il'in *et al*, *J. Low Temp. Phys.* **151**, 585 (2008).

# 2G-wires: thermodynamic parameters from $J_c(sf, T)$

- What is expected  $\lambda_{ab}(0)$  for 2G-wires?
- $\lambda_{ab}(0) = 118 \text{ nm}$  for YBCO from  $\mu\text{SR}$  data

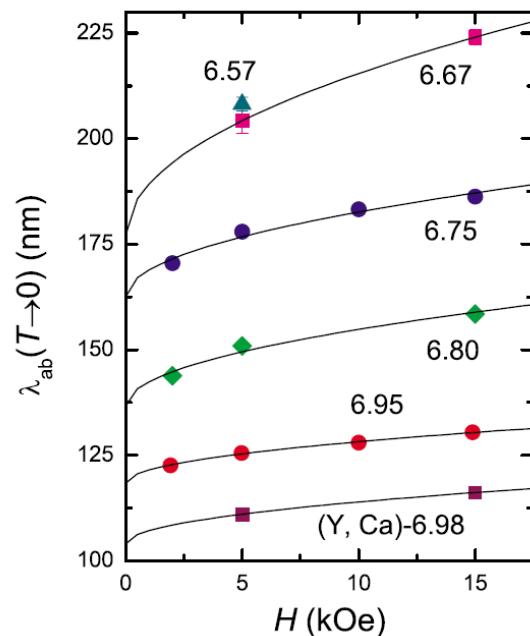
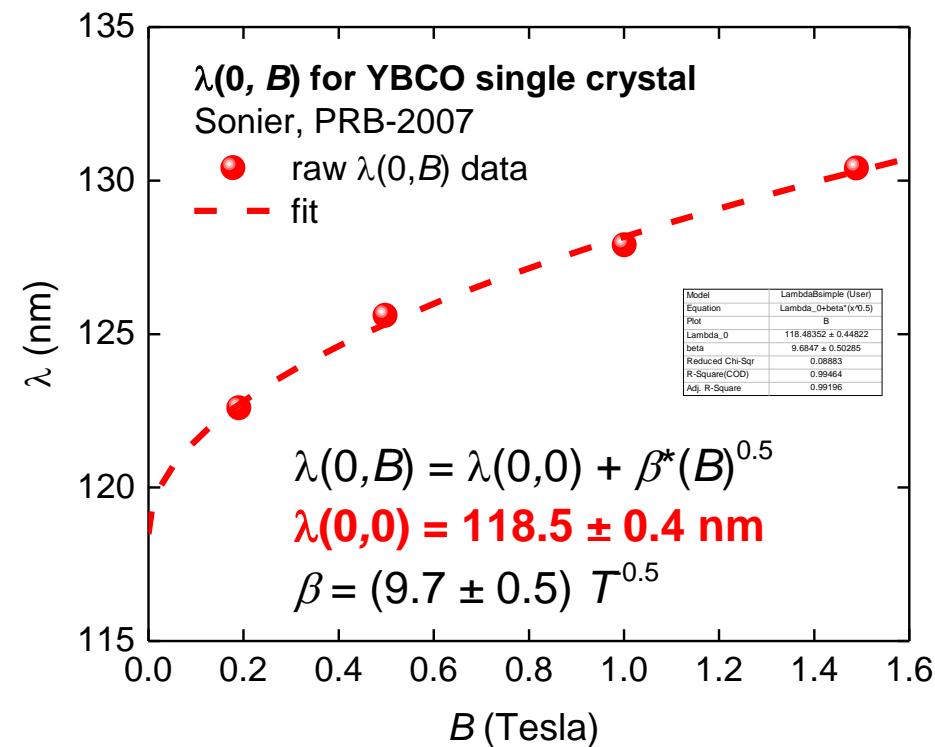


FIG. 6. (Color online) Magnetic field dependence of the extrapolated zero-temperature value of  $\lambda_{ab}$ . The solid curves are fits to  $\lambda_{ab}(0, H) = \lambda_{ab}(0, 0) + \beta\sqrt{H}$ , where the coefficient  $\beta$  decreases with increasing hole doping.

J.E. Sonier, et. al., PRB 76, 134518 (2007).



# 2G-wires: thermodynamic parameters from $J_c(sf, T)$

- What is expected  $\lambda_{ab}(0)$  for 2G-wires?
- $\lambda_{ab}(0) = 107 \text{ nm}$  for YBCO from the magnetization data
- For simplicity, in all fits below we assumed  $\lambda_c(0) = 1,000 \text{ nm}$

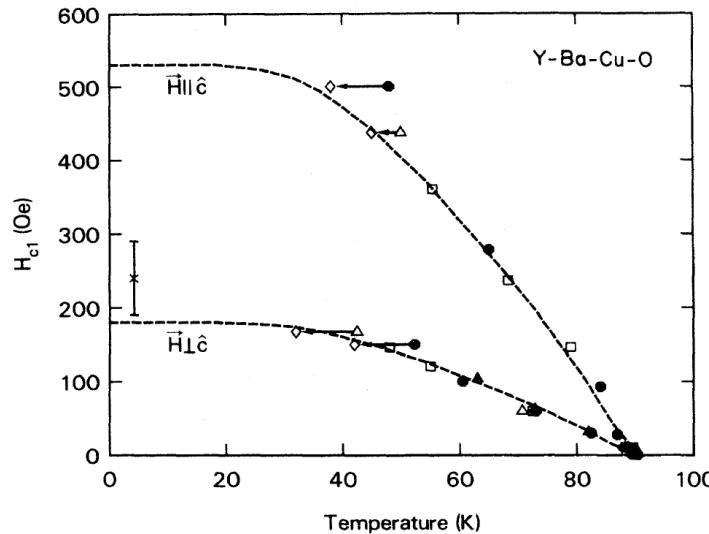
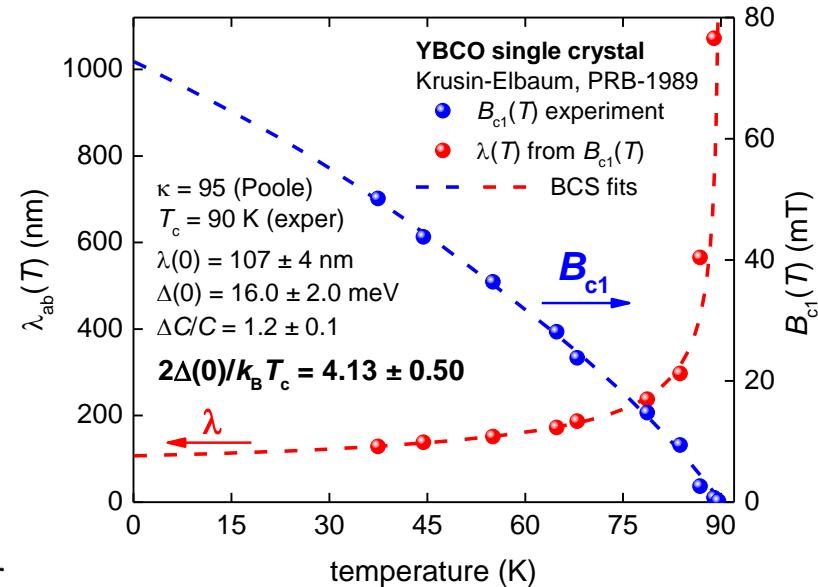


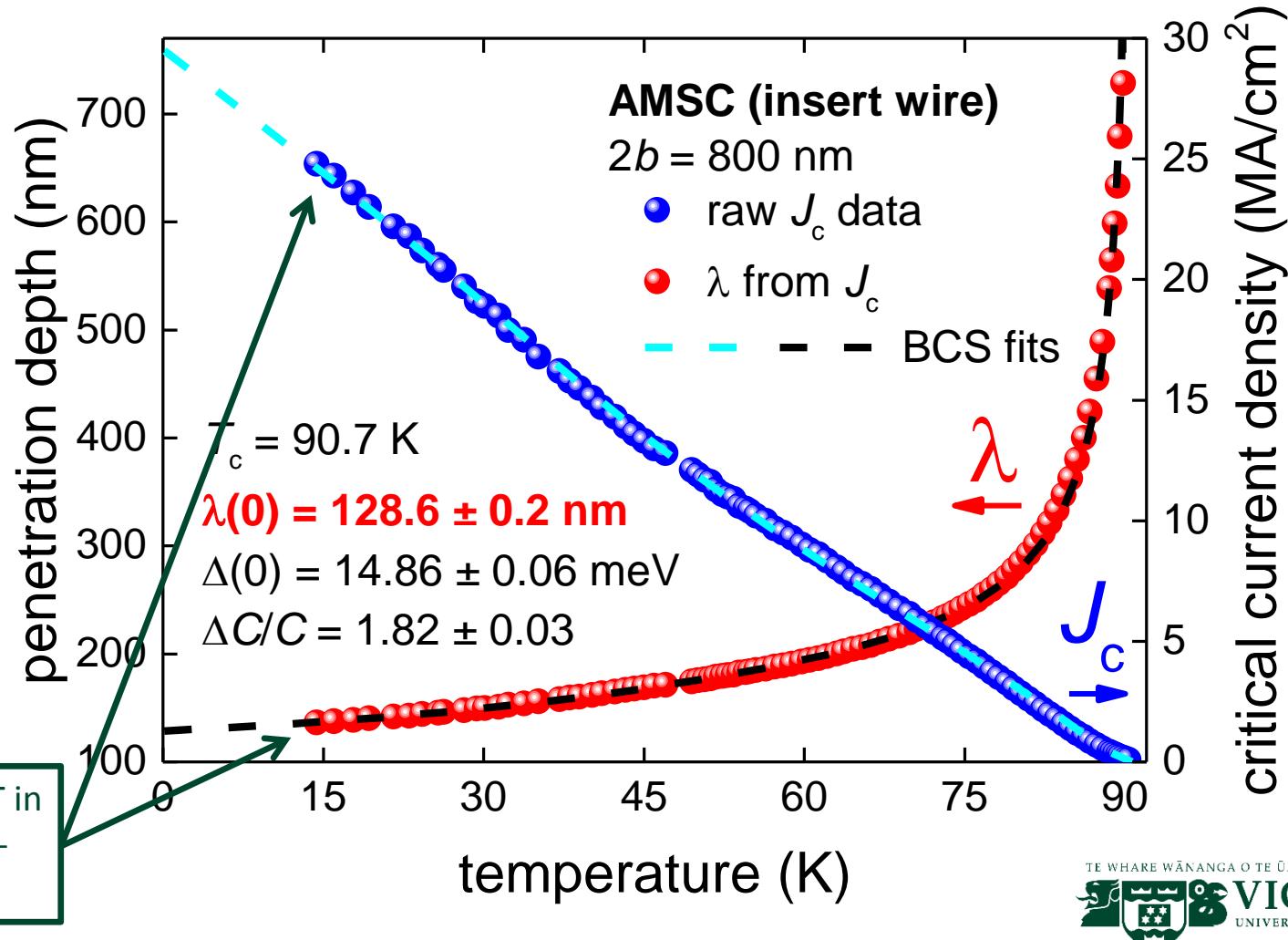
FIG. 3.  $H_{c1}$  for  $H$  applied parallel to the  $c$  axis and perpendicular to the  $c$  axis for several Y-Ba-Cu-O crystals. The  $T_{c1}$  corrections described in the text are indicated by the horizontal arrows. Low-temperature value for  $H_{c1\perp\hat{c}} = 250 \pm 50$  Oe from Yeshurun *et al.* (Ref. 7) is shown as a cross (their value for  $H_{c1\parallel\hat{c}}$  is  $900 \pm 100$  Oe). The dashed line represents to the clean-local-limit weak-coupling BCS prediction.

Krusin-Elbaum, *et. al.*, PRB 39, 2936 (1989).



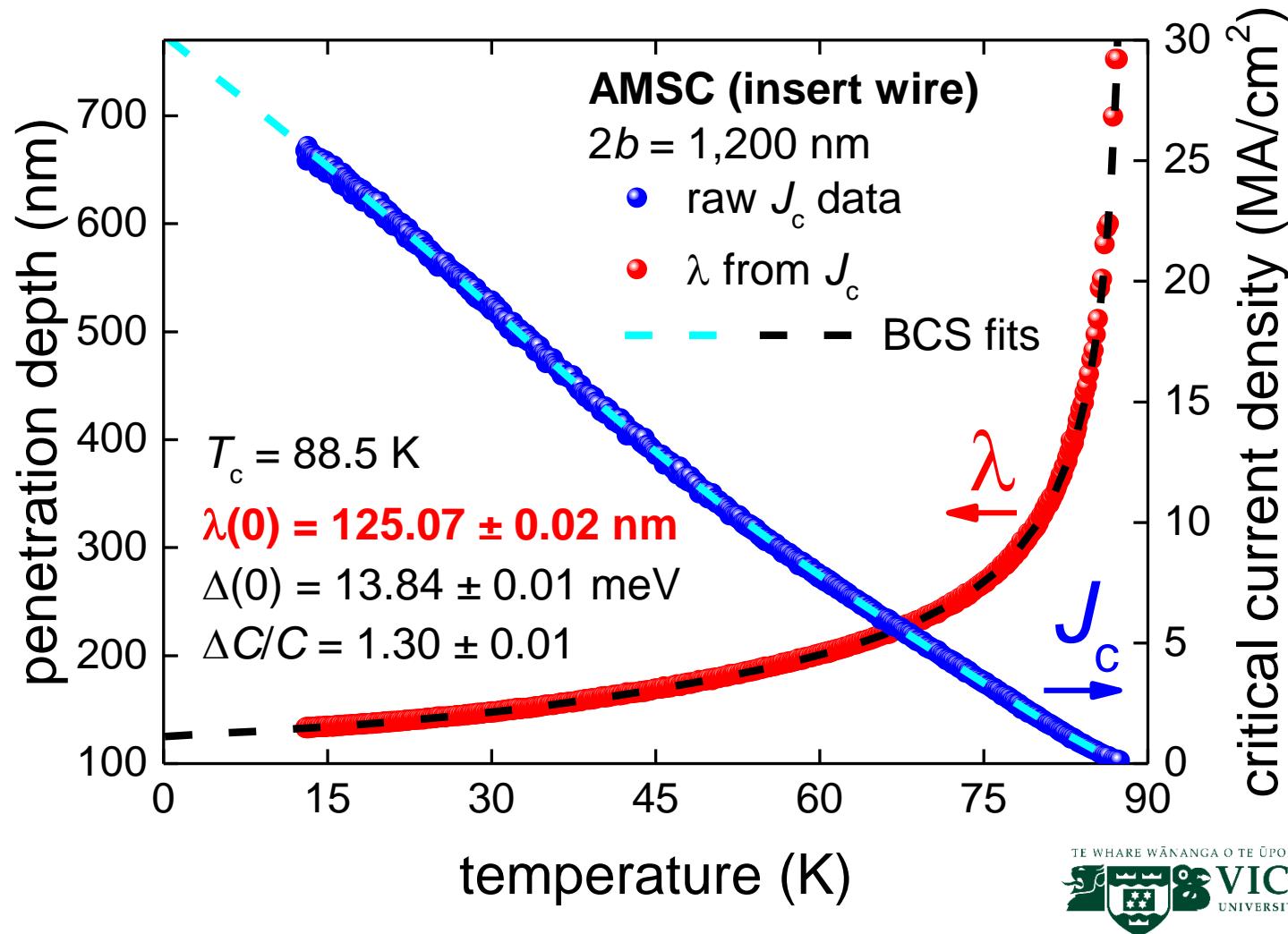
# 2G-wires: to derive thermodynamic parameters from $J_c(sf, T)$

- AMSC insert tape (our data). Thickness  $2b = 800$  nm



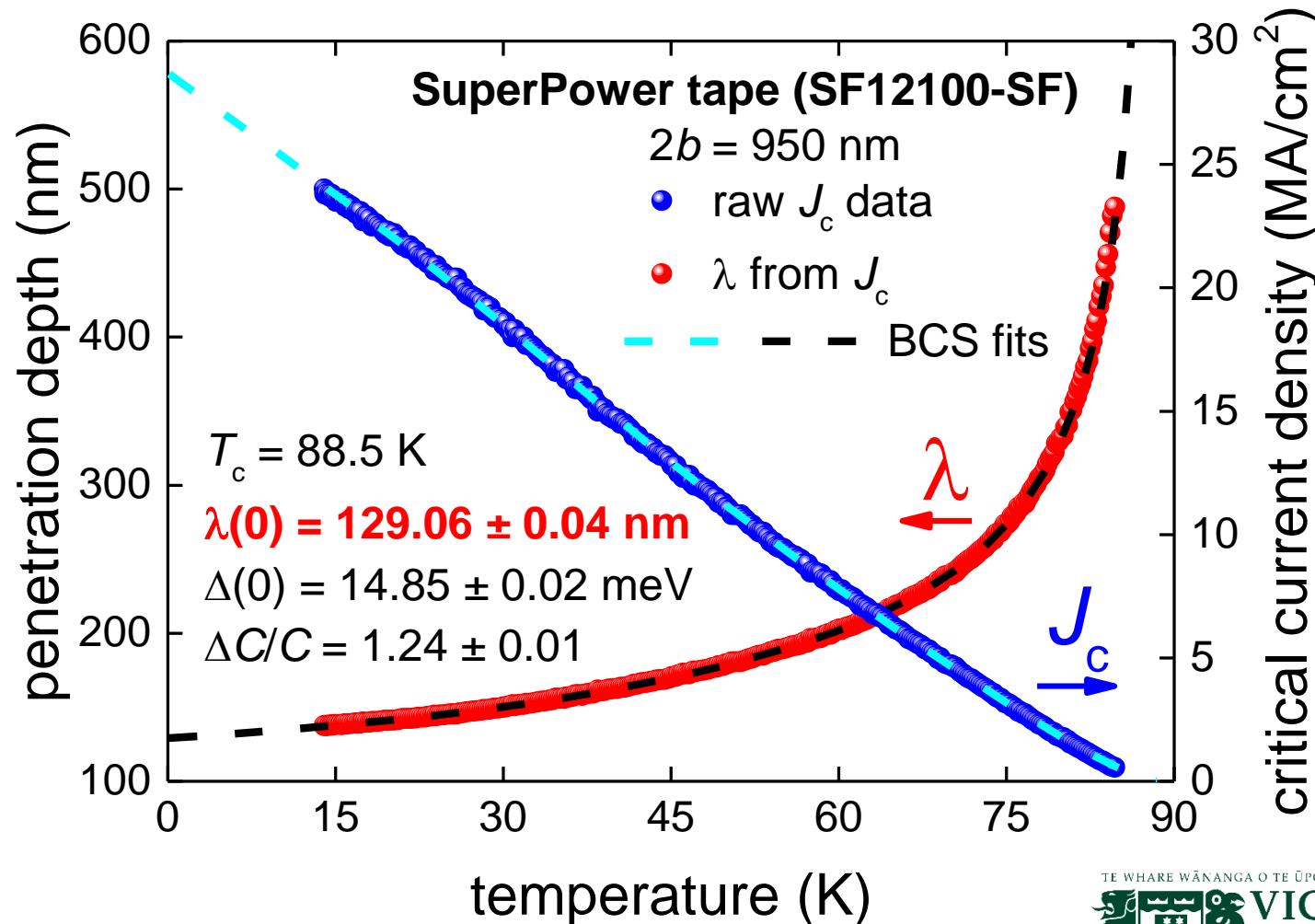
# 2G-wires: to derive thermodynamic parameters from $J_c(sf, T)$

- AMSC insert tape (our data). Thickness  $2b = 1,200$  nm



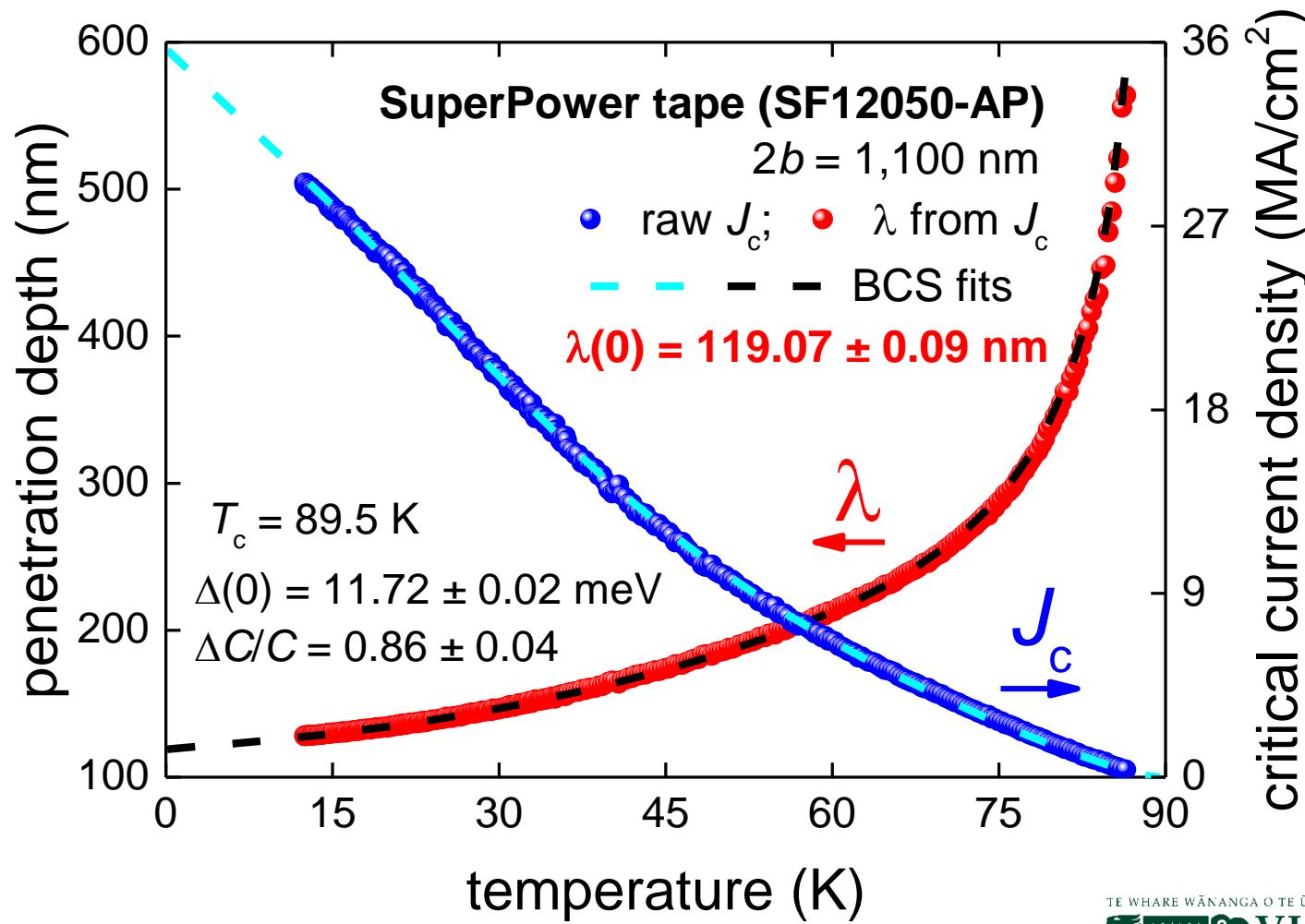
# 2G-wires: to derive thermodynamic parameters from $J_c(sf, T)$

- SuperPower commercial tape (our data)



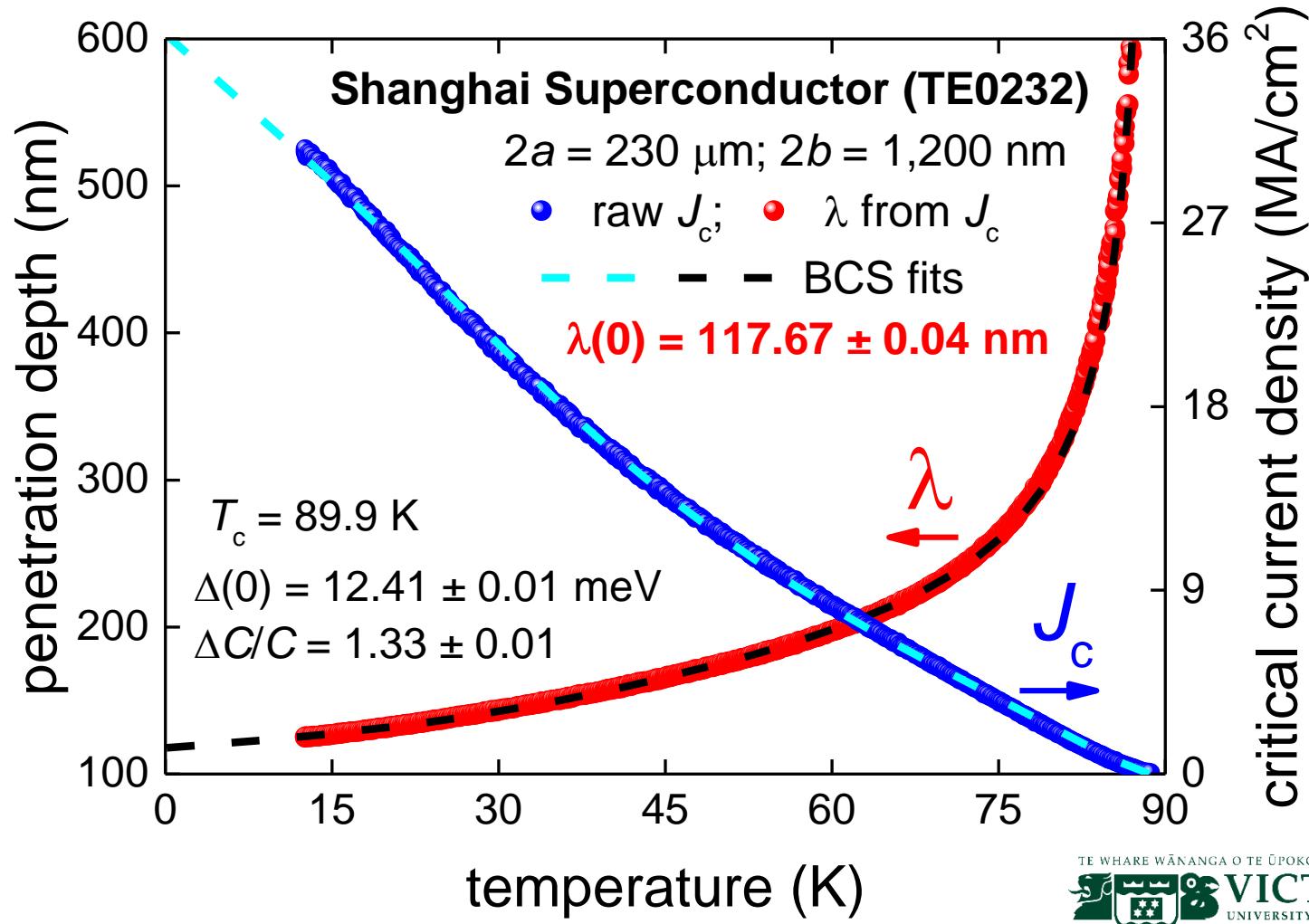
# 2G-wires: to derive thermodynamic parameters from $J_c(sf, T)$

- SuperPower commercial tape (our data)



# 2G-wires: to derive thermodynamic parameters from $J_c(sf, T)$

- Shanghai Superconductor commercial tape (our data)



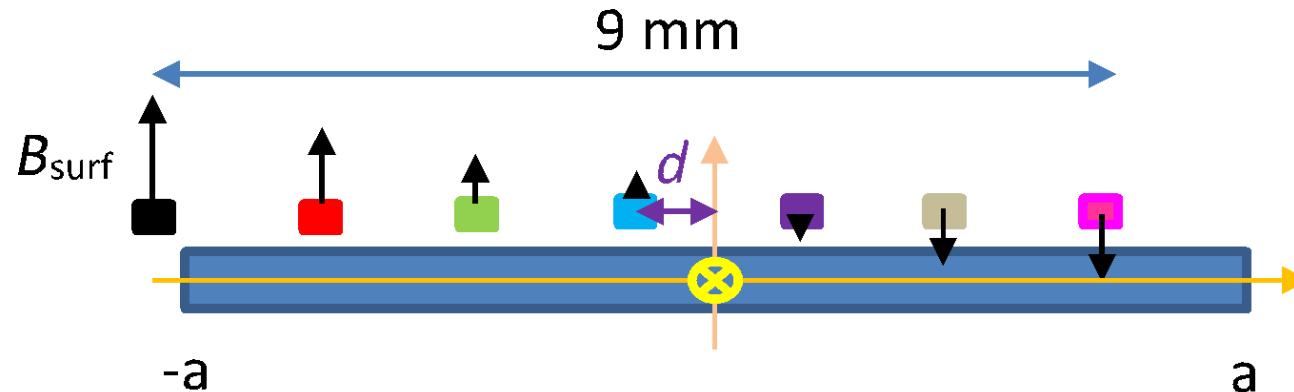
# Wanted: experimental flux density at the superconductor surface

## Key question:

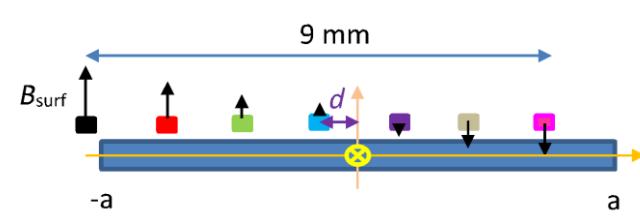
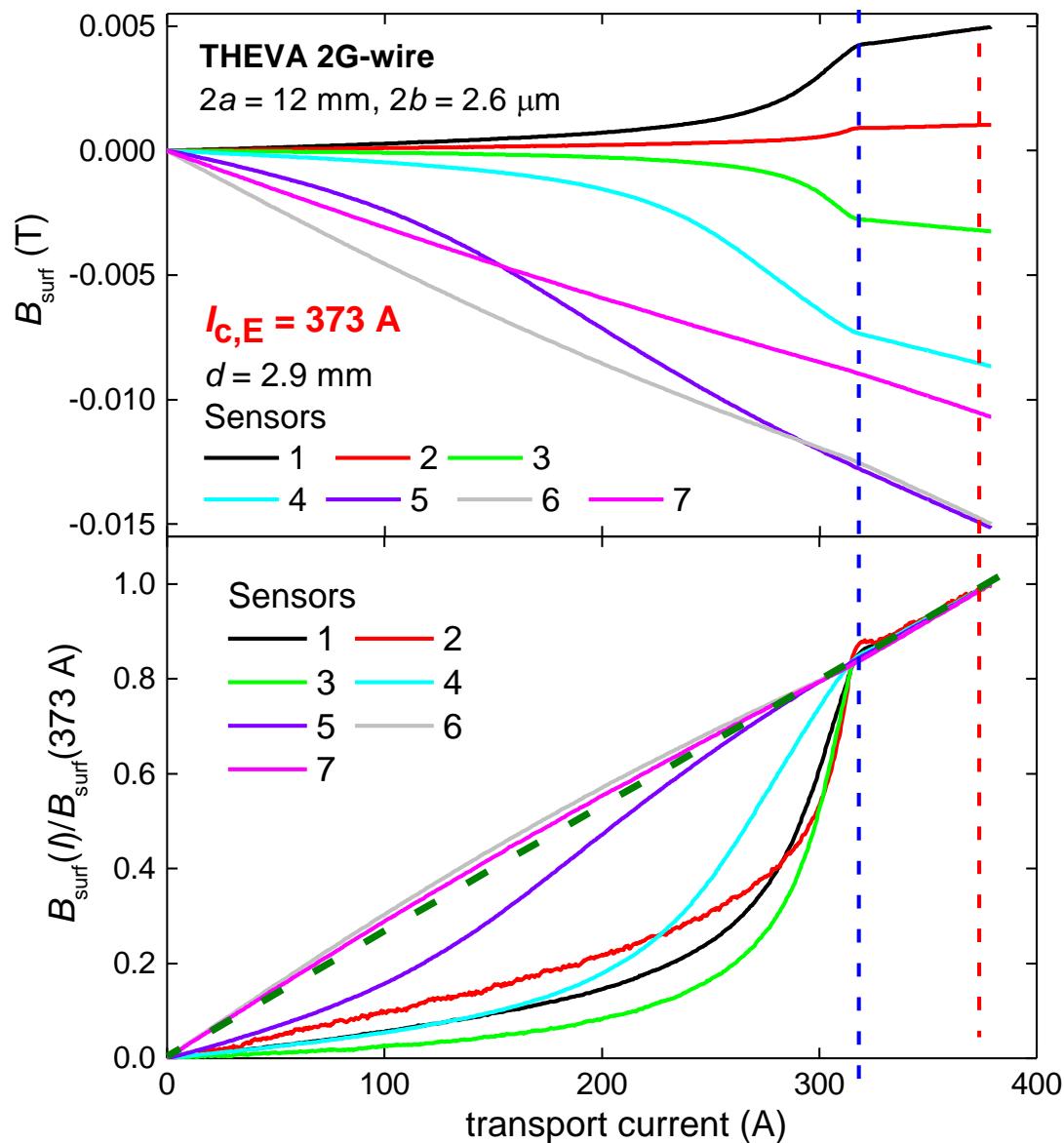
- If there is no correlation between  $B_x$ ,  $B_y$  and  $B_{c1}$ , what is the actual field within superconductor surface?

## Our recent experimental findings toward the answer:

- Field profile measurements of  $B_{\text{surf}}$  for 2G-wires.

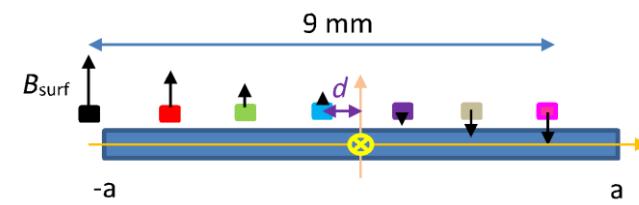
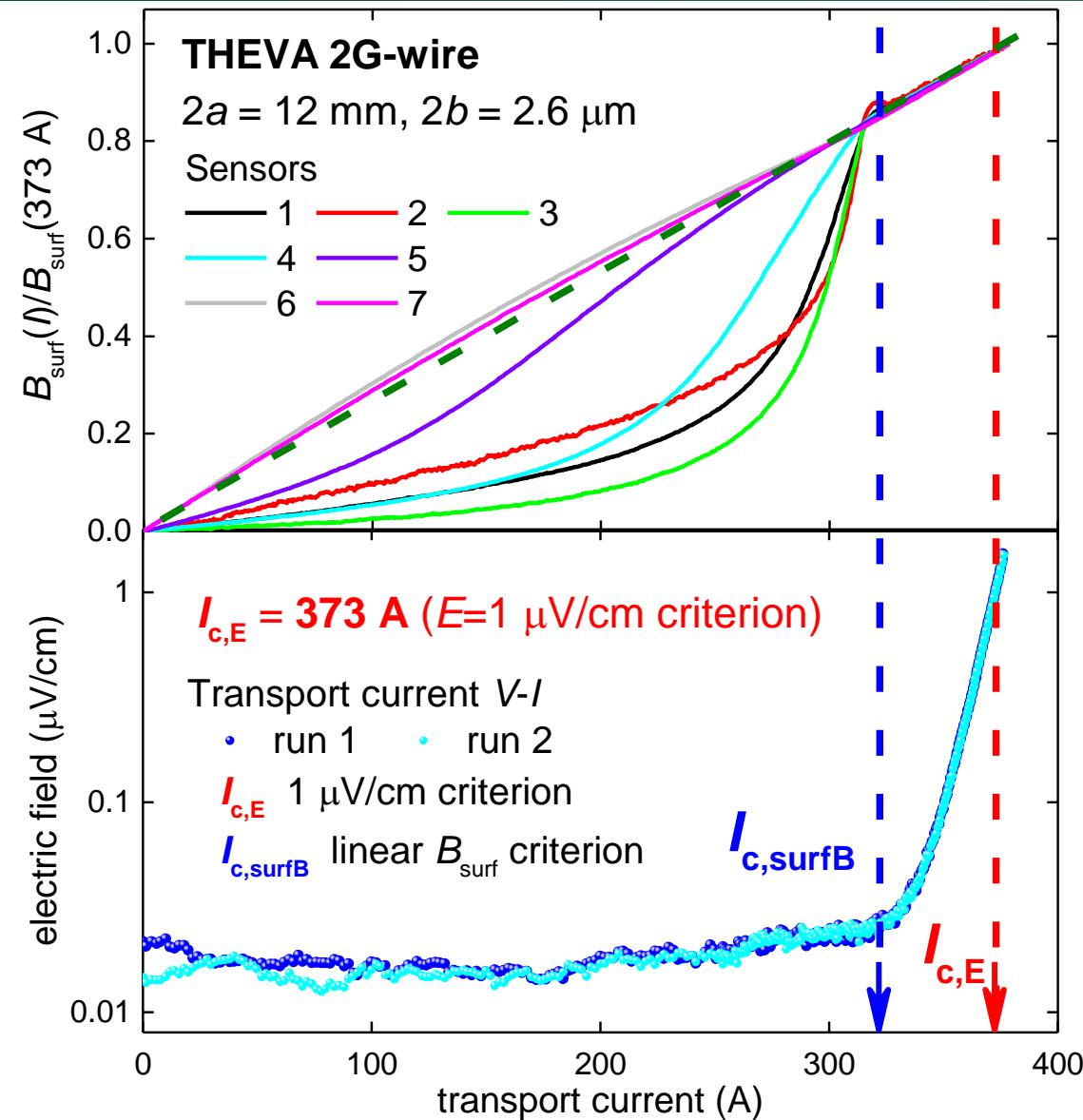


# Wanted: magnetic fields



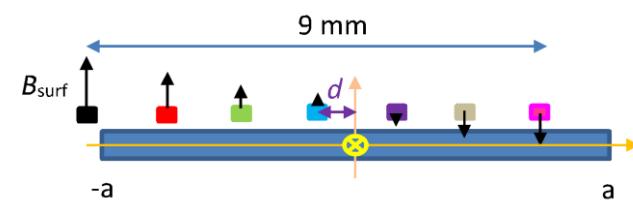
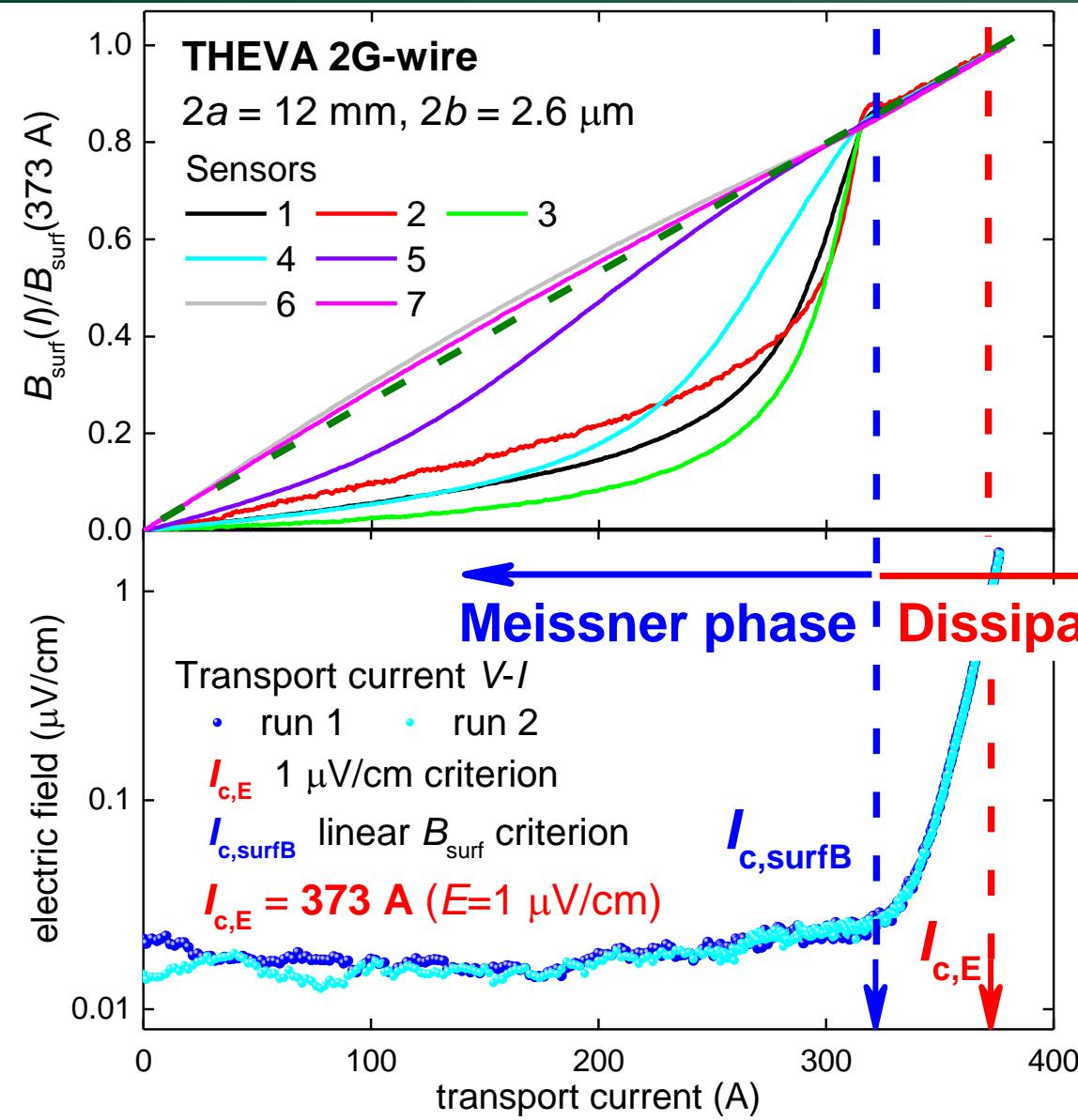
Talantsev, *arXiv: 1707.07395* (2017).

# Wanted: dissipation mechanism

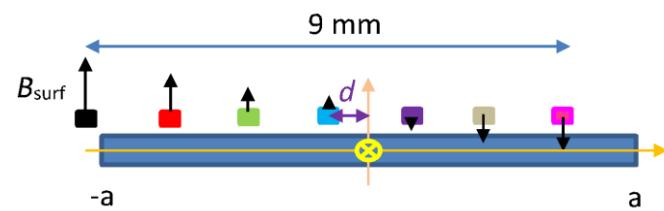
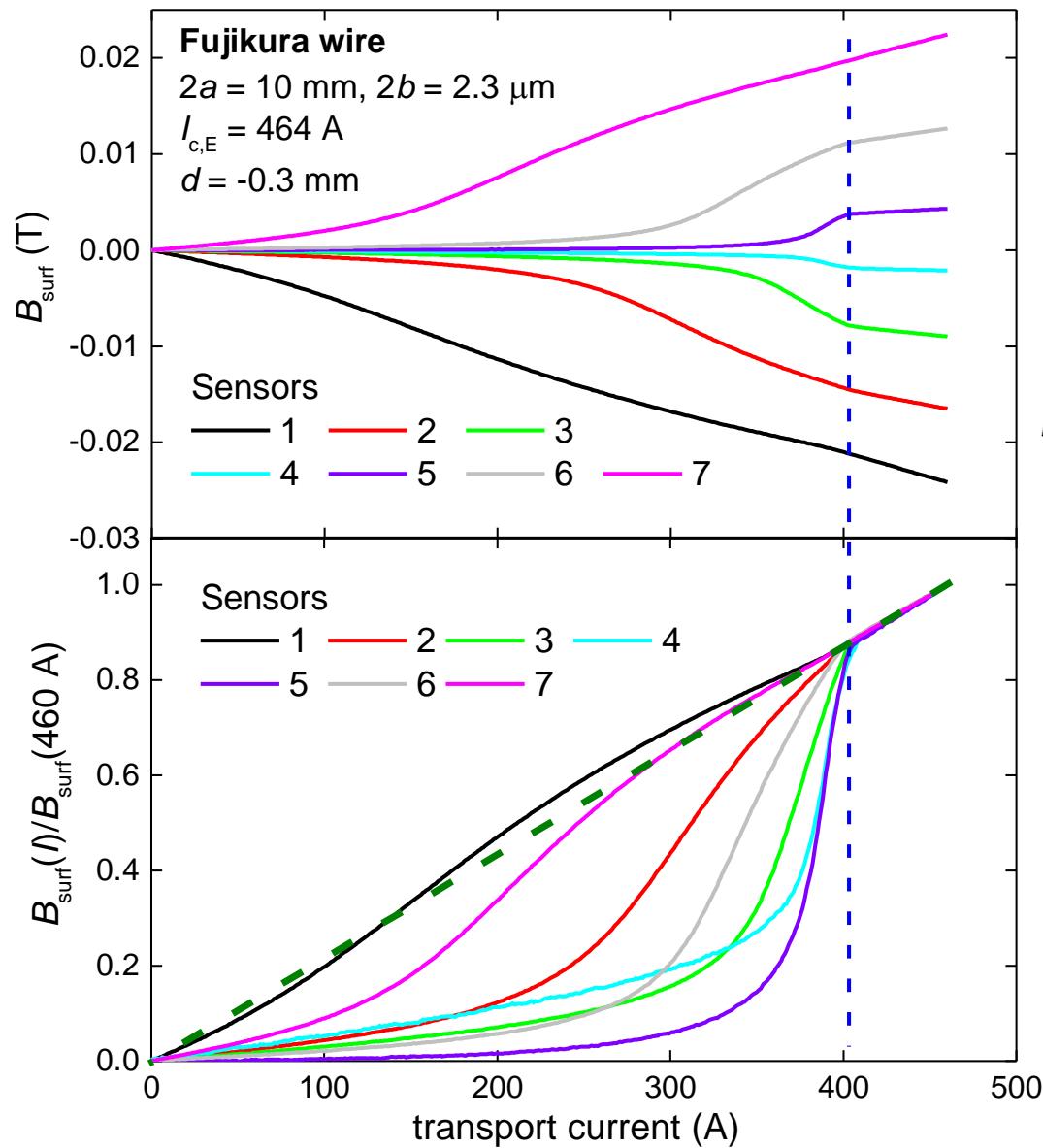


Talantsev, *arXiv*: 1707.07395 (2017).

# Dissipation starting point

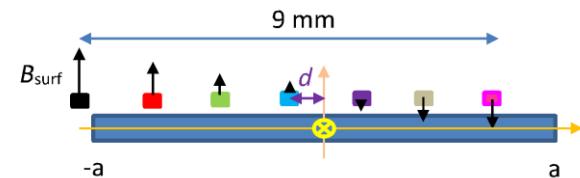
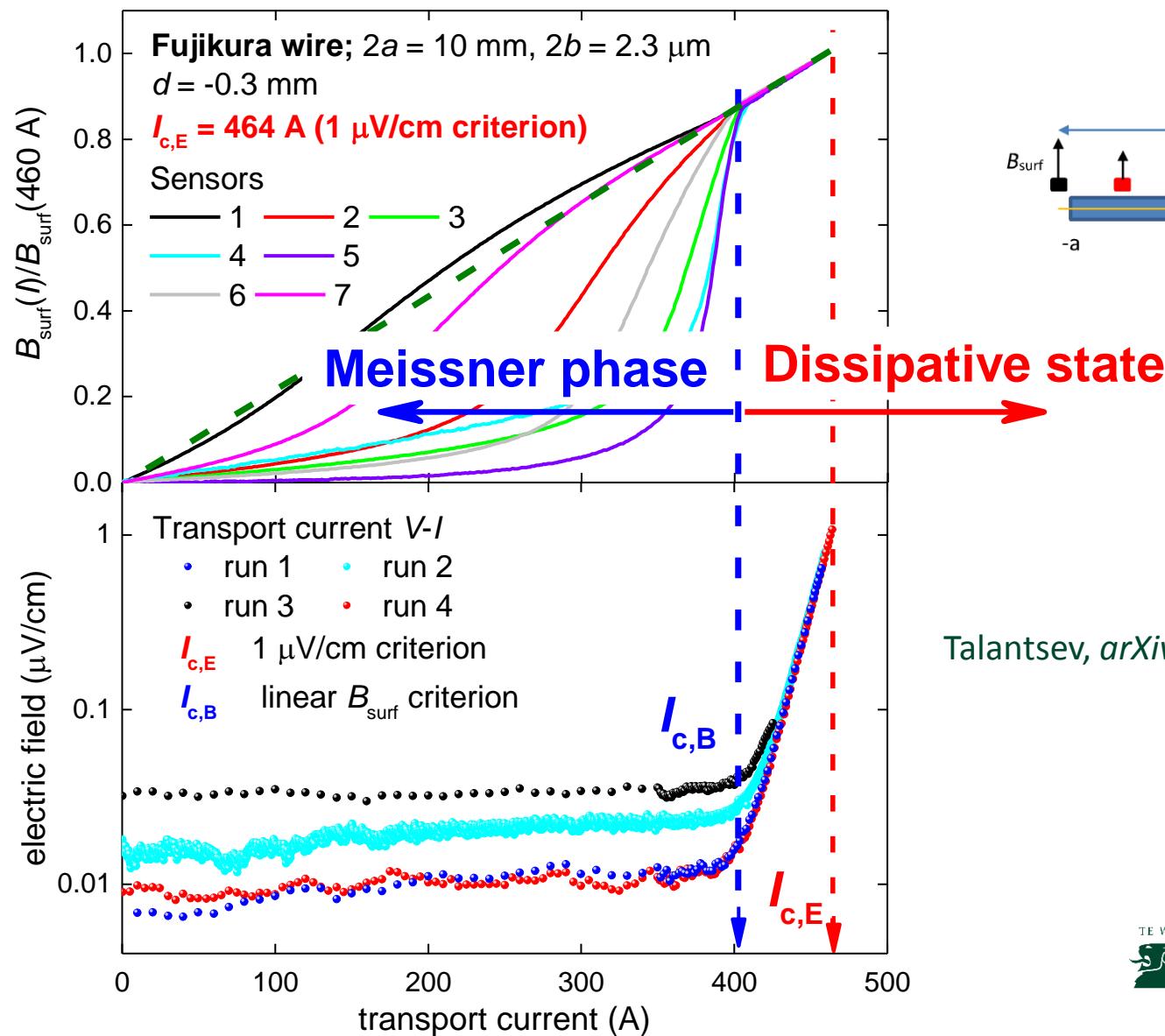


# Identical behaviour for other 2G-wires

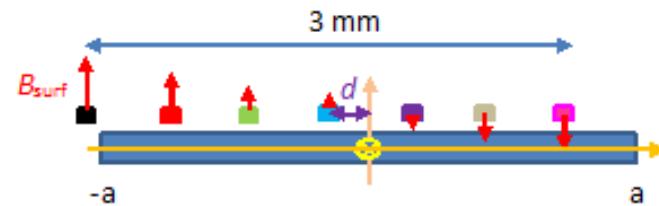
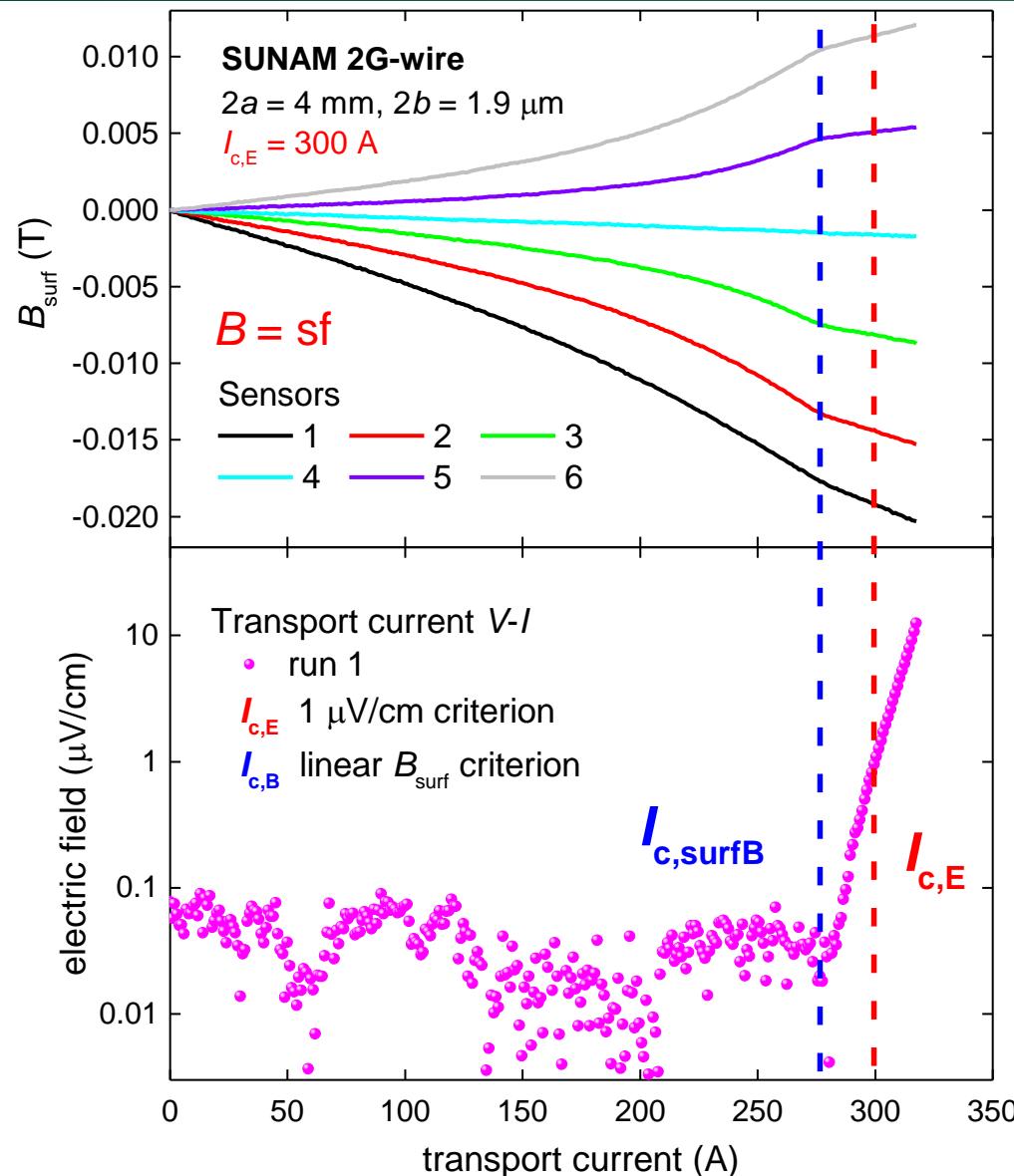


Talantsev, *arXiv: 1707.07395* (2017).

# Dissipation starting point: self-field regime

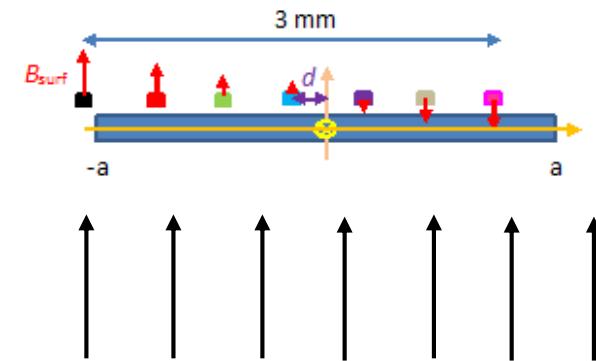
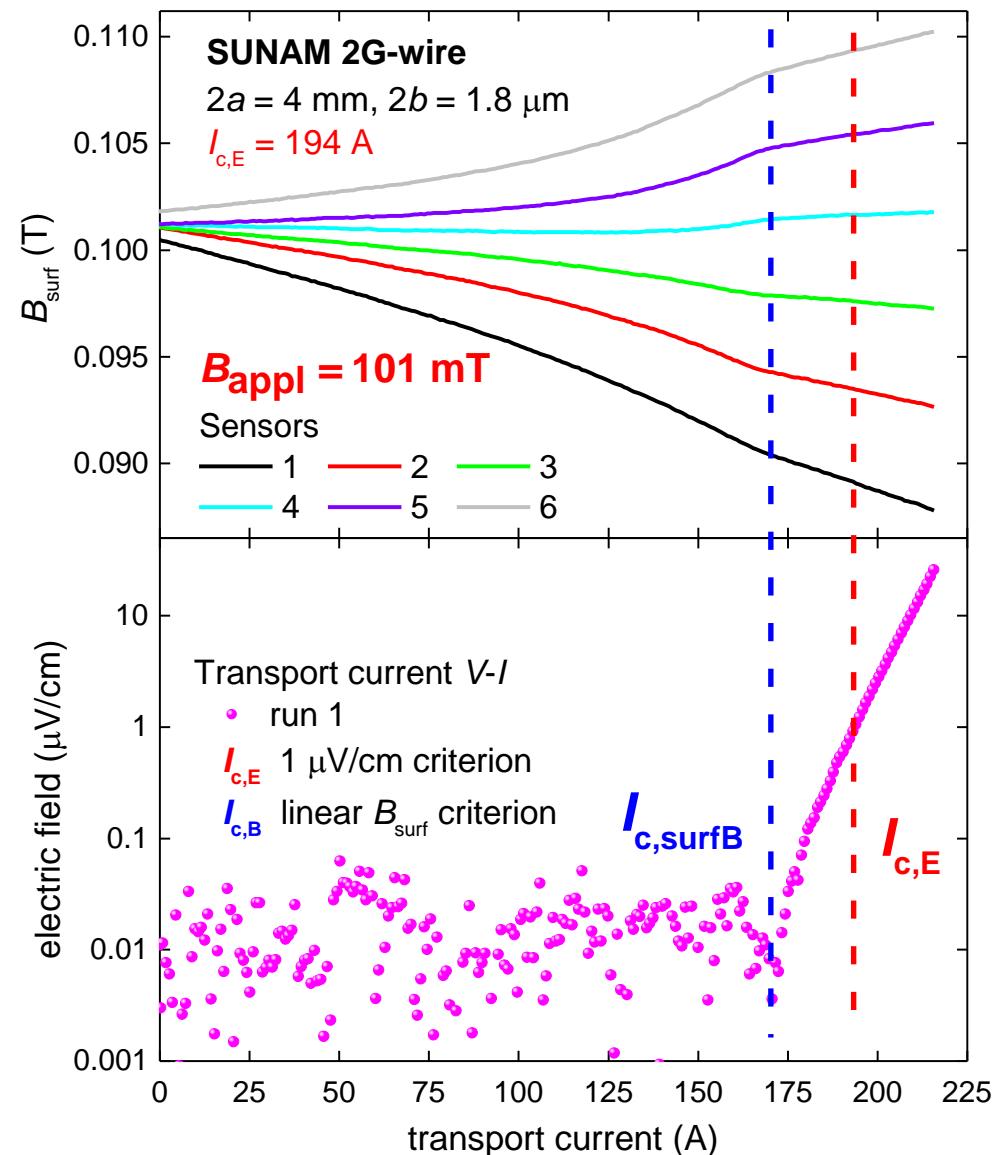


# Dissipation starting point: in-field experiments



E.F. Talantsev, N.M. Strickland, S.C. Wimbush,  
*paper is under preparation.*

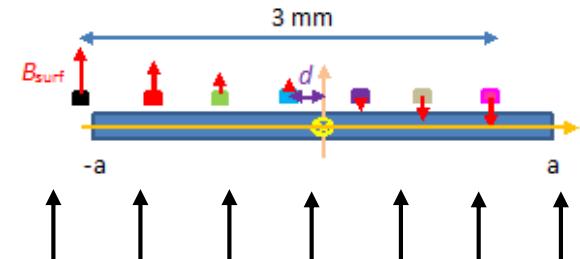
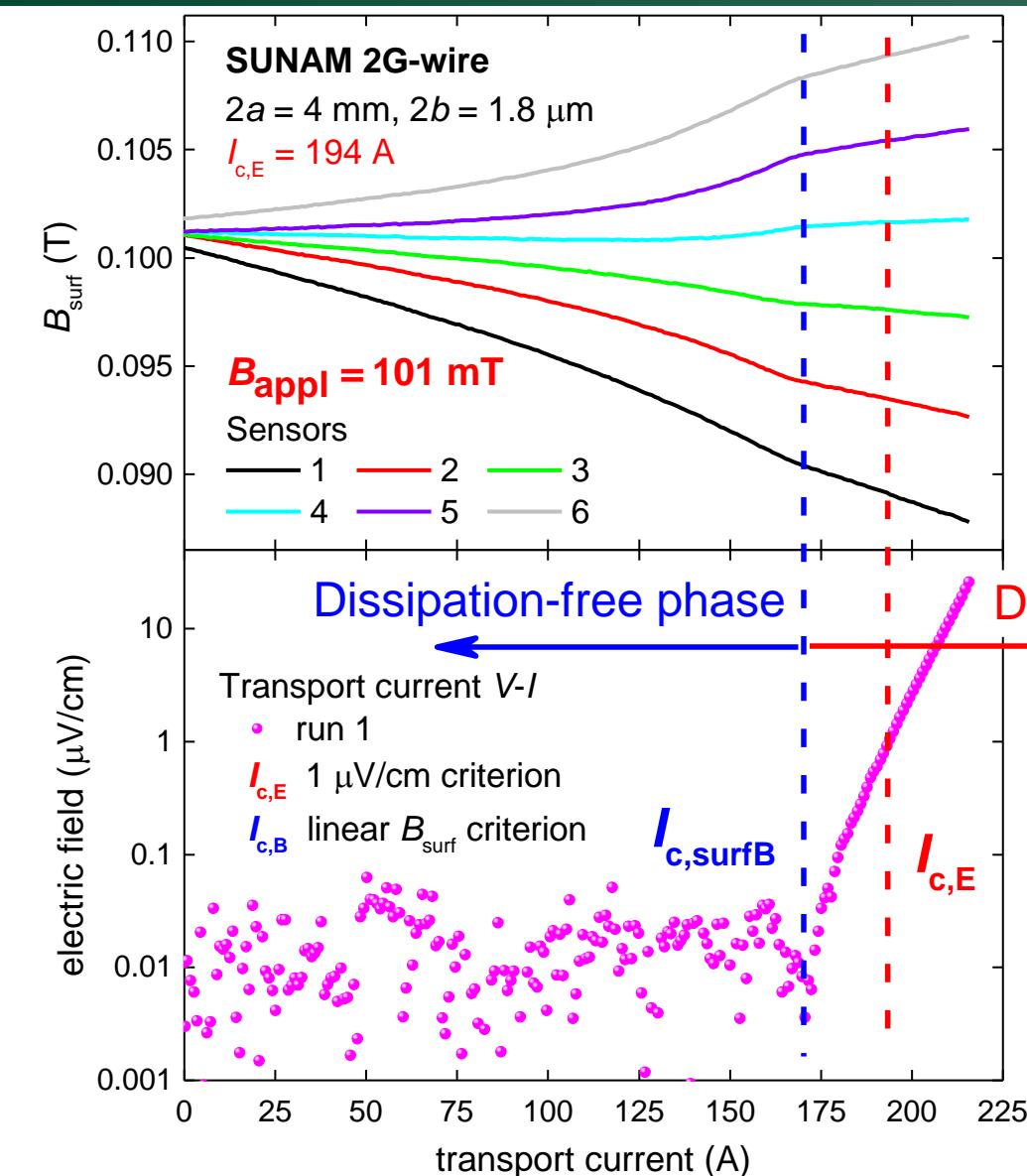
# Dissipation starting point: in-field experiments



$B = 101 \text{ mT} \gg B_{c1}(77\text{K})$   
 $B_{c1}(77\text{K}) \approx 10 \text{ mT}$

E.F. Talantsev, N.M. Strickland, S.C. Wimbush,  
*paper is under preparation.*

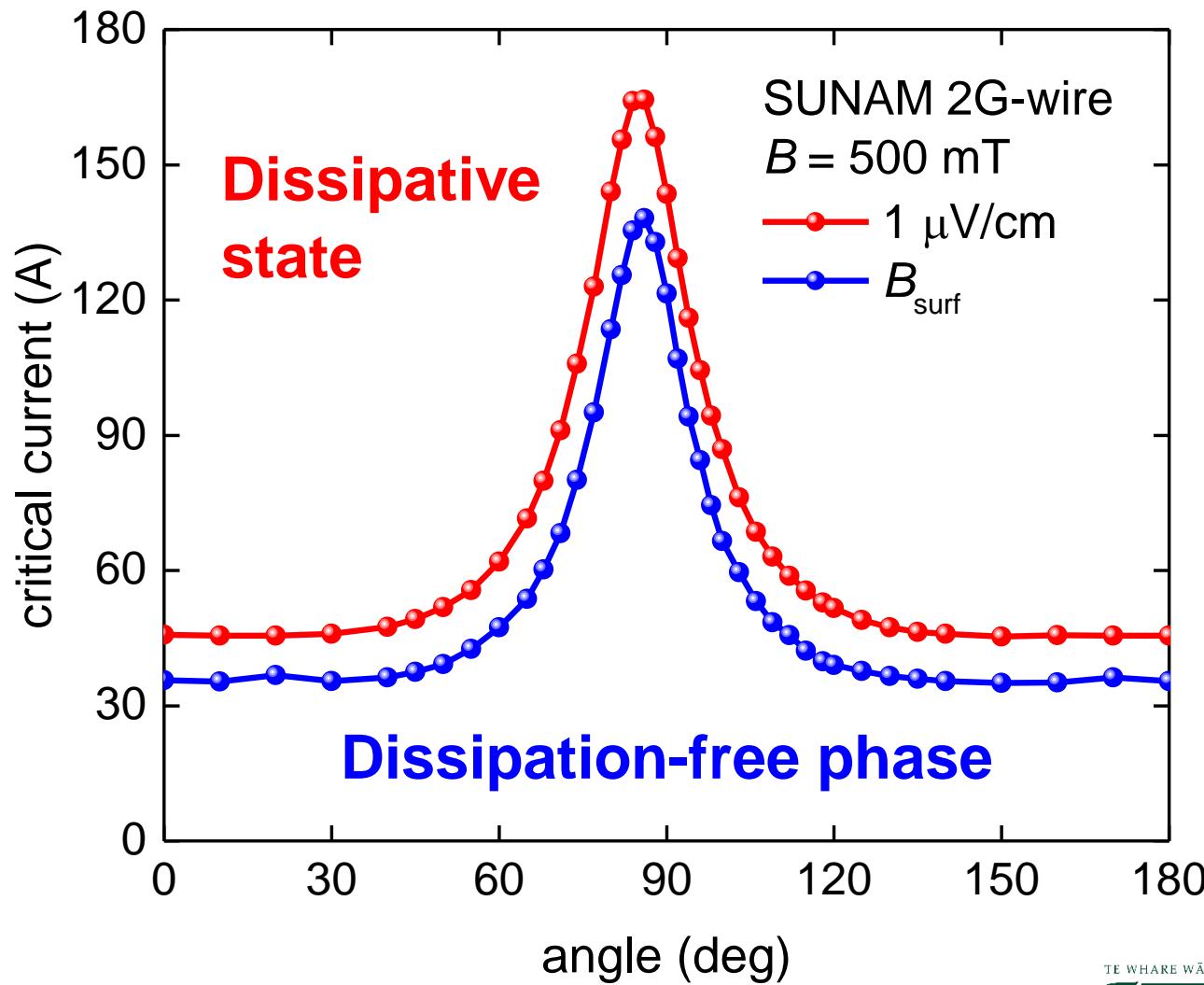
# Dissipation starting point: in-field experiments



$B = 101 \text{ mT} \gg B_{c1}(77\text{K})$   
 $B_{c1}(77\text{K}) \approx 10 \text{ mT}$

E.F. Talantsev, N.M. Strickland, S.C. Wimbush,  
*paper is under preparation.*

# Dissipation starting point: perp-field, para-field, and angular dependence experiments



# Summary

## Summary

- The **self-field critical current density** is therefore a **fundamental property** of superconductors and it is a window into the key thermodynamic parameters in all superconductors (2D and 3D) and represents a very simple technique for extracting their values.
- Dissipation mechanism in Type-II superconductors at self-field regime **is not governed by vortex pinning/depinning and it should be established.**
- See also our posters:
  - 3MP1-14:** 20<sup>th</sup> Sep 2017, 13:30-15:30
  - 4MP3-07:** 21<sup>st</sup> Sep 2017, 10:15-12:15

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