U.S. MAGNET DEVELOPMENT PROGRAM

Jax 2018

Long length properties before and after test of REBCO coated conductors

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Many thanks to:

H. W. Weijers , W. D. Markiewicz et al. (NHMFL)

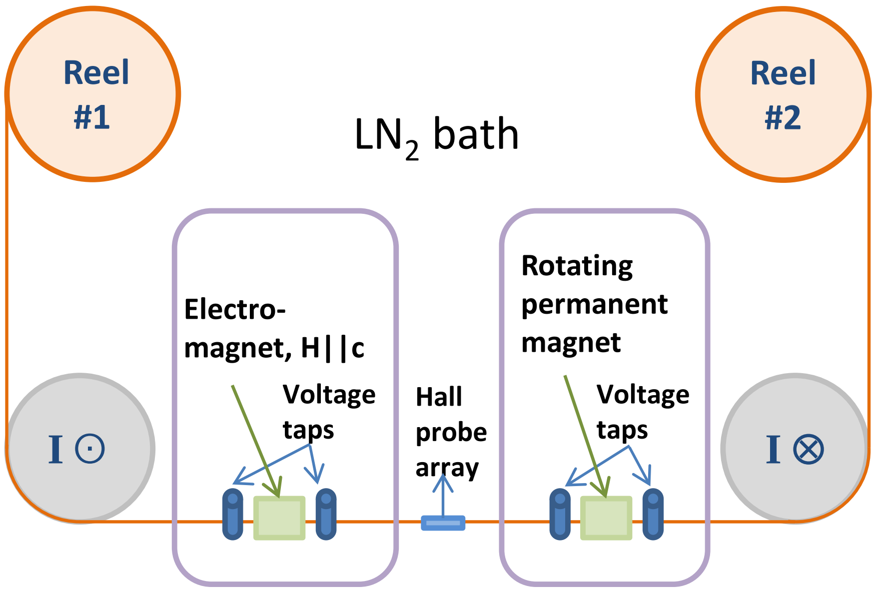
D.C. van der Laan, J. D. Weiss (Advanced Conductor Technologies)

S. Hahn et al. (NHMFL, University of Seoul)

NSF/DMR-1644779

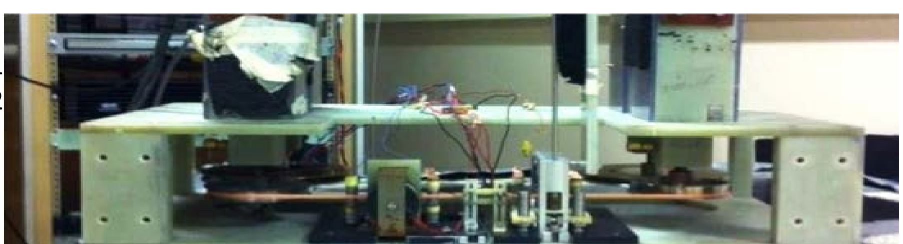
Reel-to-reel current and magnetization measurement

- Transport device invented by Yates Coulter, LANL, NHMFL
- Further developed with magnetization at ASC, NHMFL



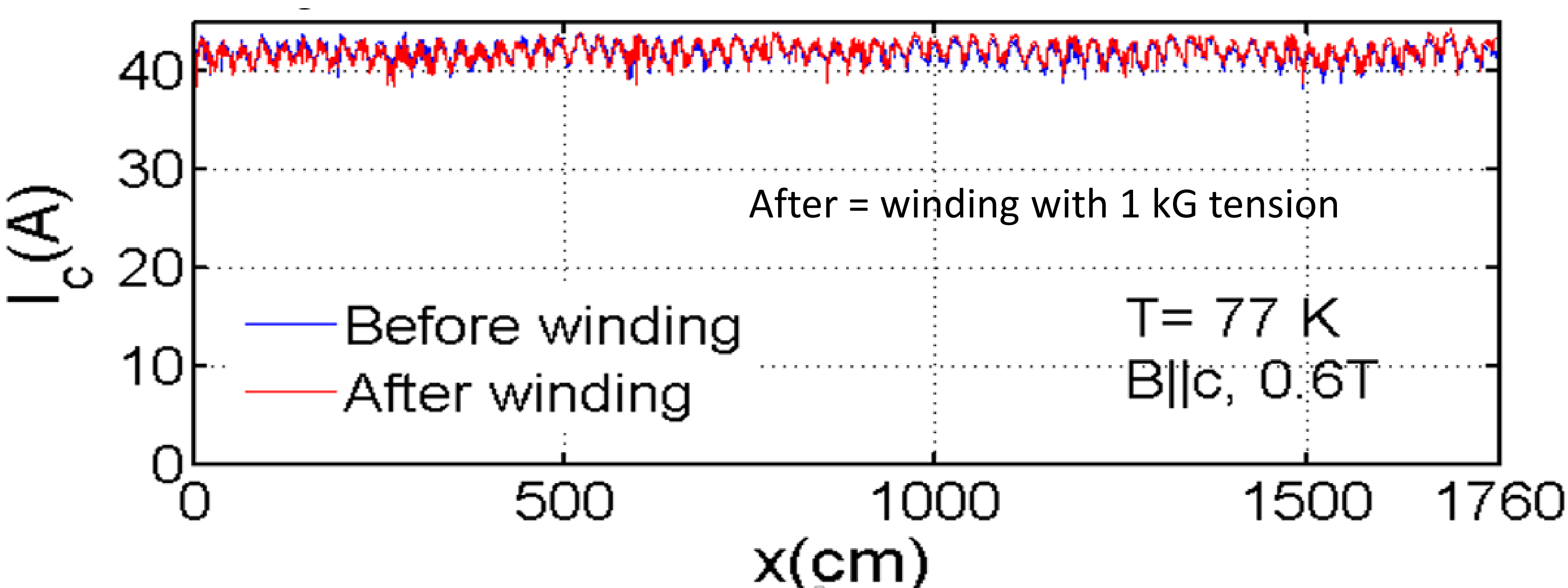
- ❑ Transport
  - Current goes from one pulley to the other
  - biangular vs. position
  - or vs. angle, field
- ❑ Magnetization
  - Remnant field
  - Hall probe array with 7 sensors
- Transport sensitivity with ~2 cm resolution with B parallel and perpendicular
- Magnetization sensitivity with mm resolution in remanent field

[1
[2

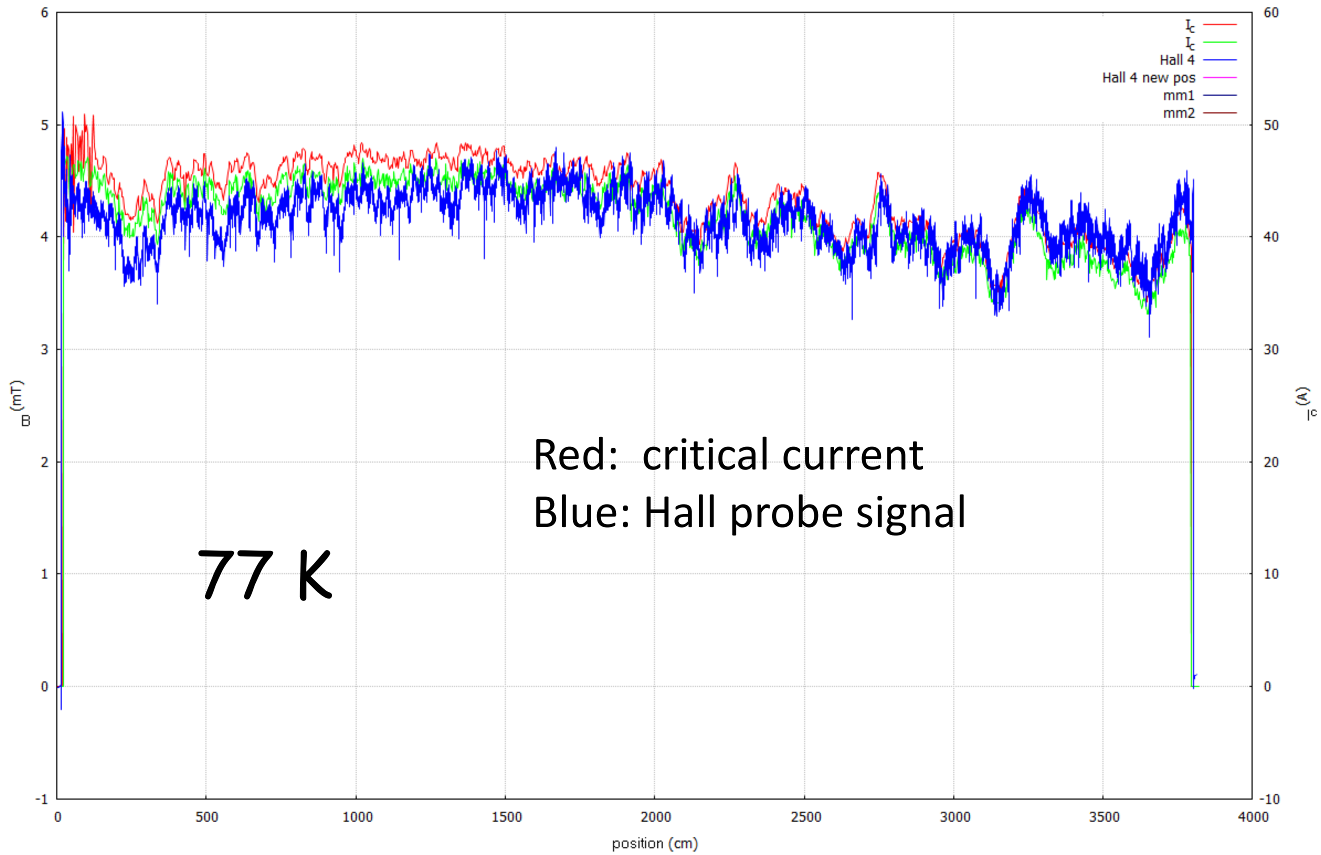


YateStar does not degrade tapes

30 µm substrate from NI



Good correlation Ic and M



YateStar mission is to explore:

1) Ic variability in virgin REBCO CC tapes: trends and origin

Question: cross section or vortex pinning variations responsible ?

2) signatures of degradation in CC tapes from deconstructed test coils and CORC cables

Question: are they degradations of cross-section or of the vortex pinning?

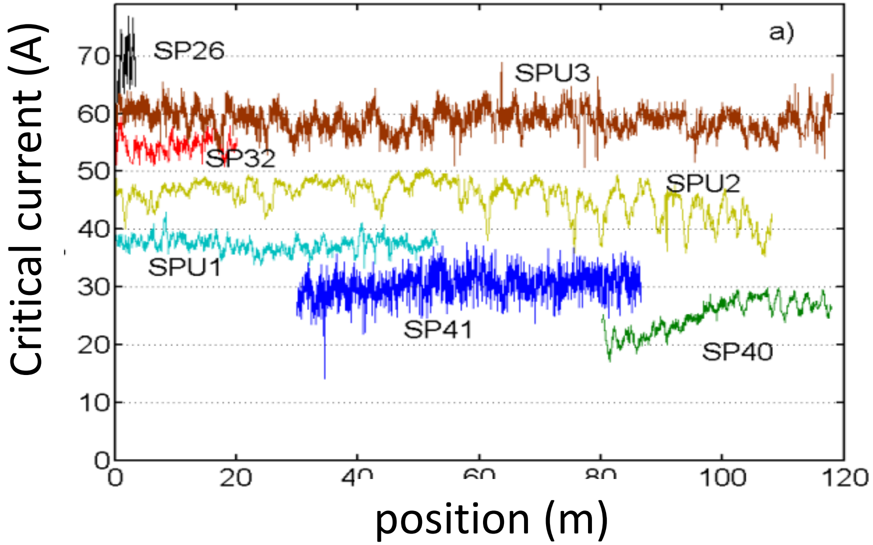
5

5

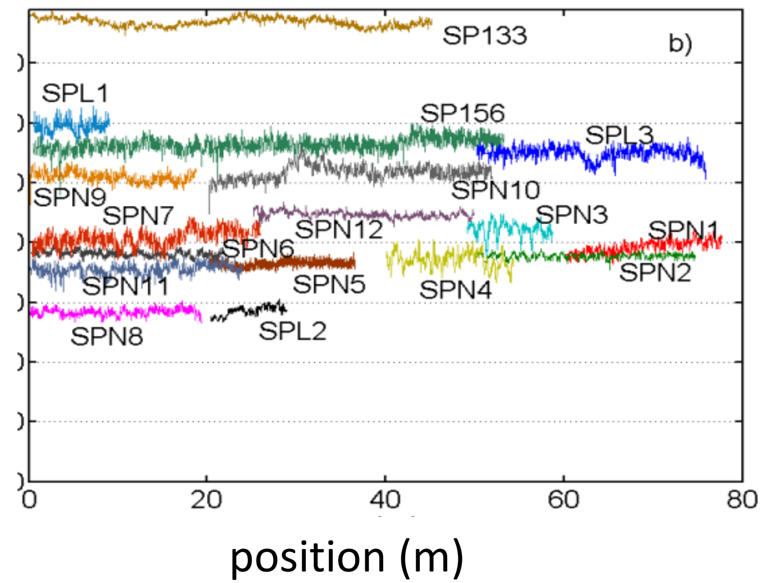
Recent production shows substantial improvement

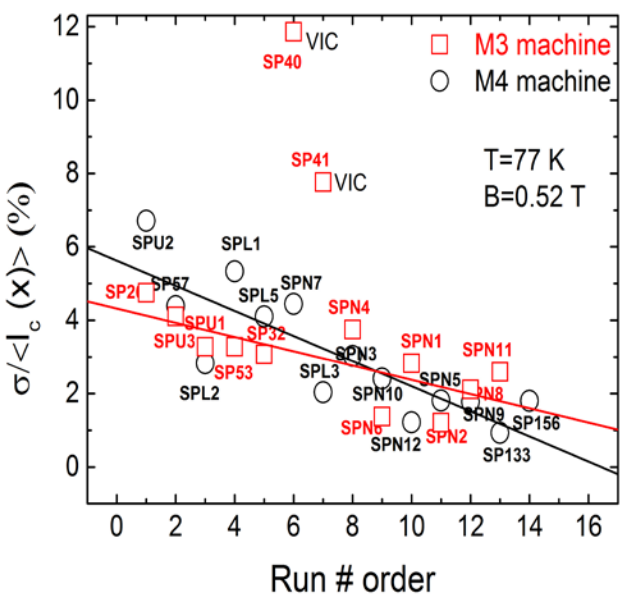
Critical current vs. position on tape

5-6 years ago



3-5 years ago





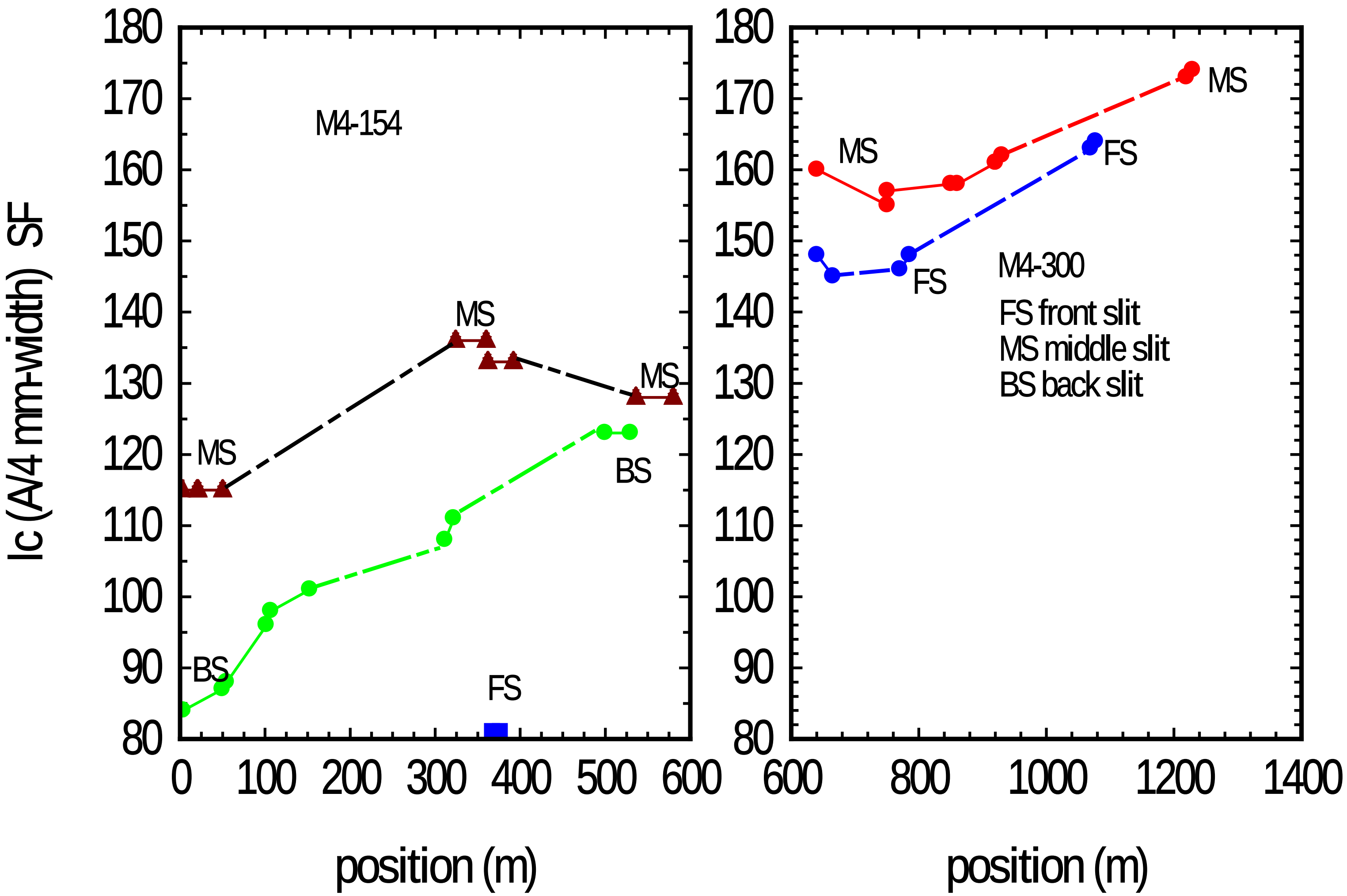
Standard deviation decreased from 5 % to 1-2%

But variation between tapes still present

SuperPower Inc.
A Furukawa Company

X. Hu et al IEEE Trans. Appl. Supercon. 2017

Recent production shows substantial improvement

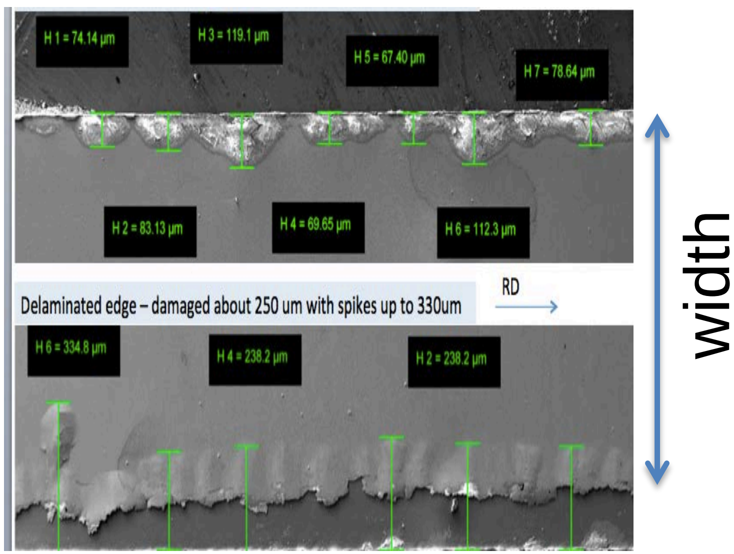


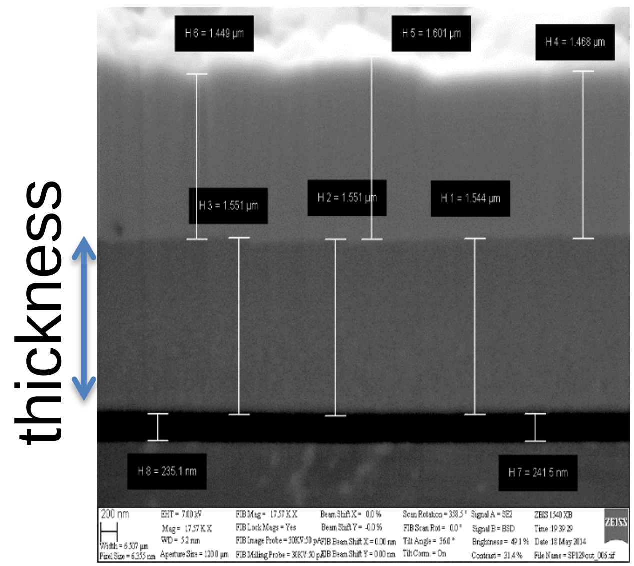
What is the nature of Ic variations: cross section or pinning?

$$I_c(x) = A(x)\ J_c(x)$$

It is impossible to measure cross section along the tape!

Tedious SEM imaging shows width and thickness but not necessarily distinguishes conducting and non-conducting regions

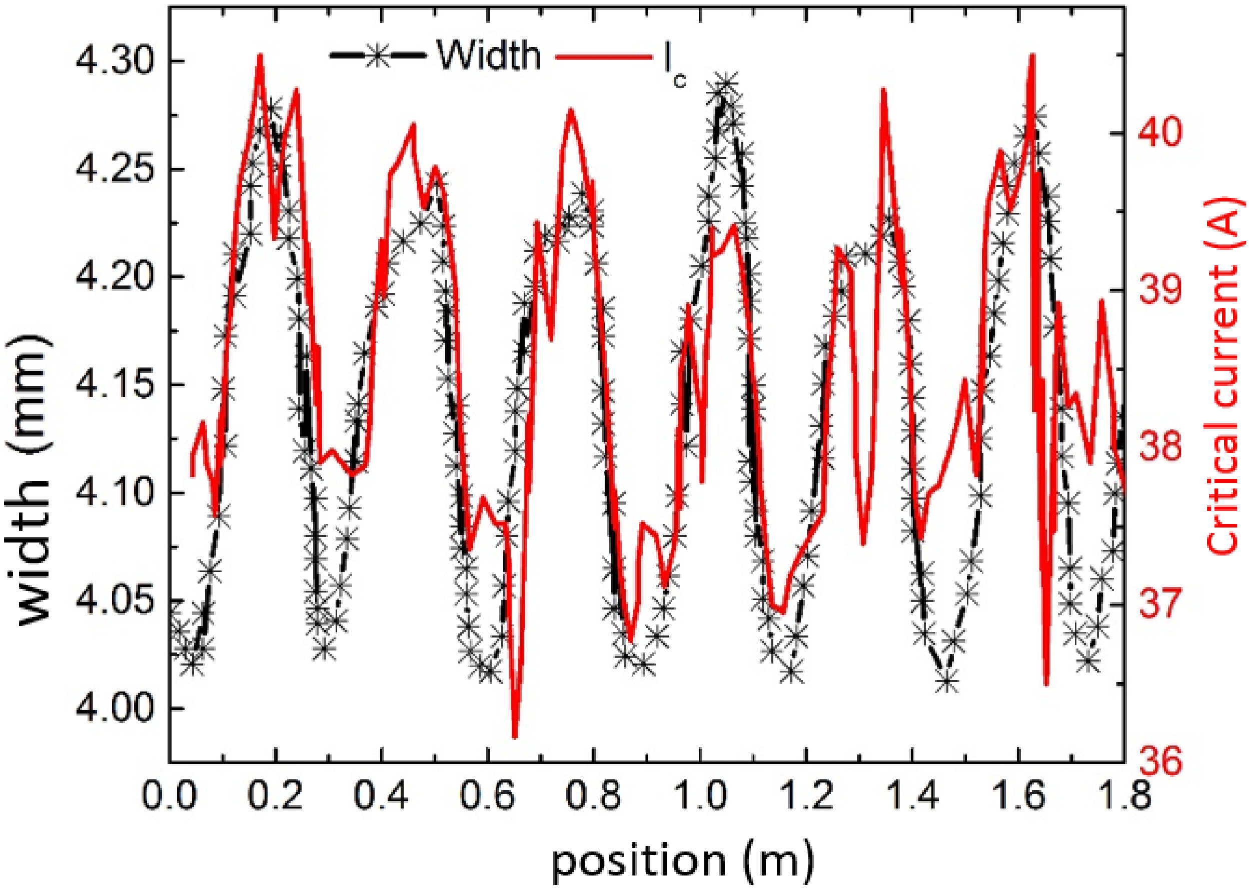




D. Abraimov, unpublished

However, A(x) does not depend on *B*, angle and temperature, while J_c (x) does! D. Abraimov, unpublished

Periodic Ic oscillations because of width variation (trivial)



12 mm

-slitting process

-residual in recent production

-recently because of HTS film width

variation, not the whole tape width changes

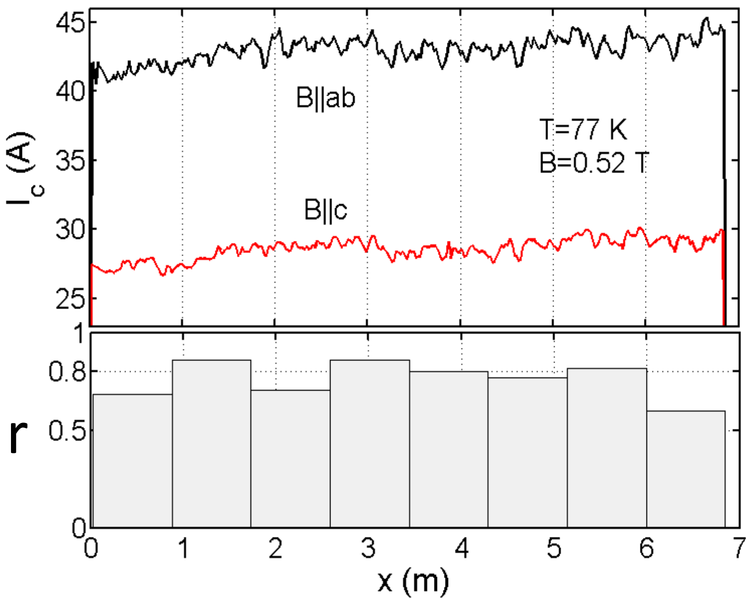
Denis Markiewicz et al.

In most cases pinning variations responsible

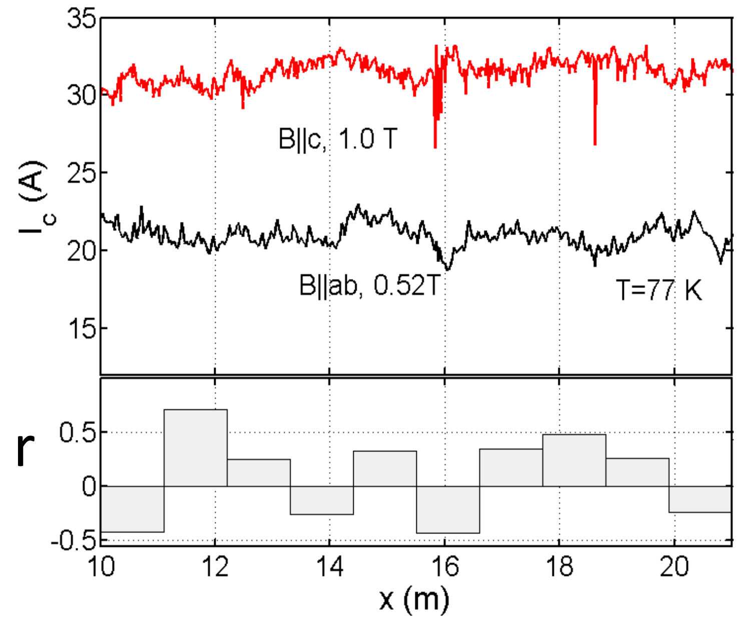
Ic biangular measurement in magnetic field

Correction coefficient between B||c and B||ab Ic traces

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$



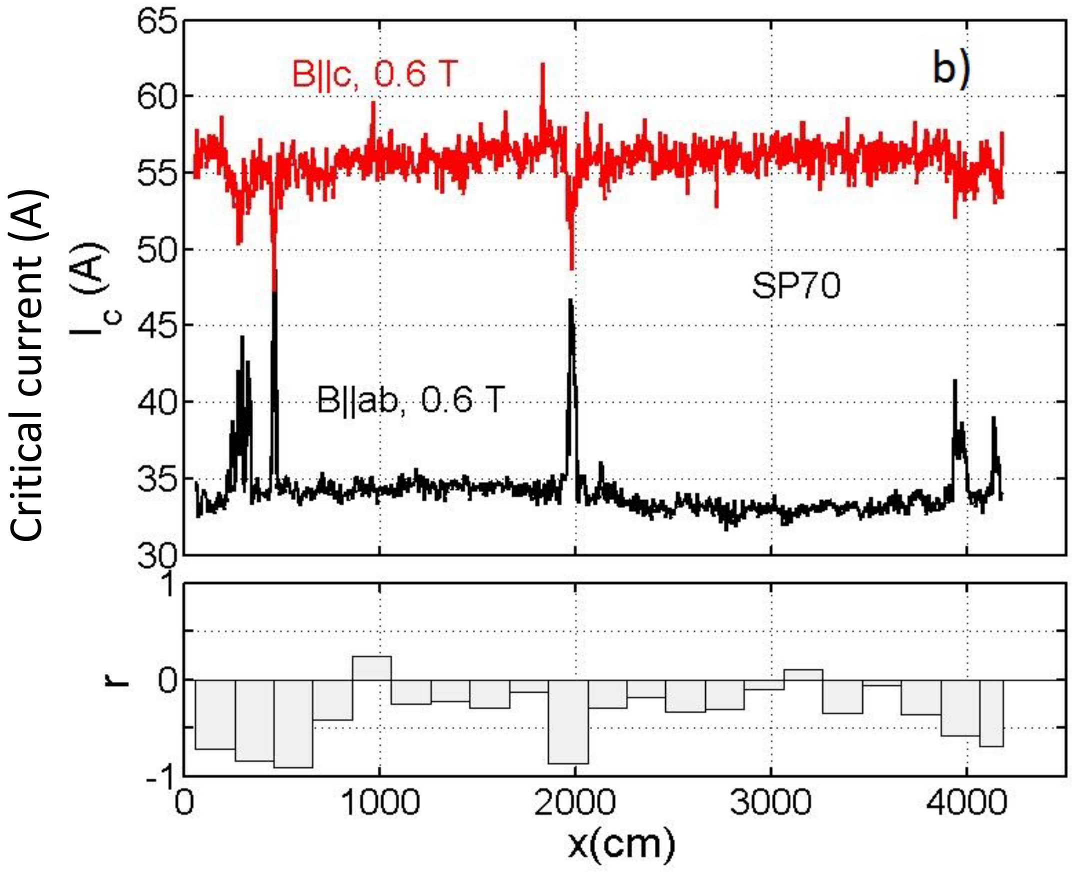
Well correlated (rare)
=> Ic ~ cross section variations

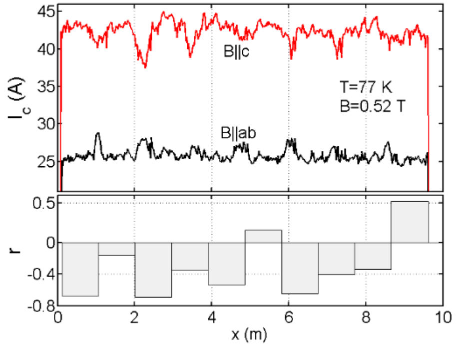


Not correlated (most cases)
=> Ic ~ pinning variations (Jc)

The origin of $I_C(x)$ variation: mostly pinning variation,
Lidia Rossi *et al* 2016 *Supercond. Sci. Technol.* 29 054006

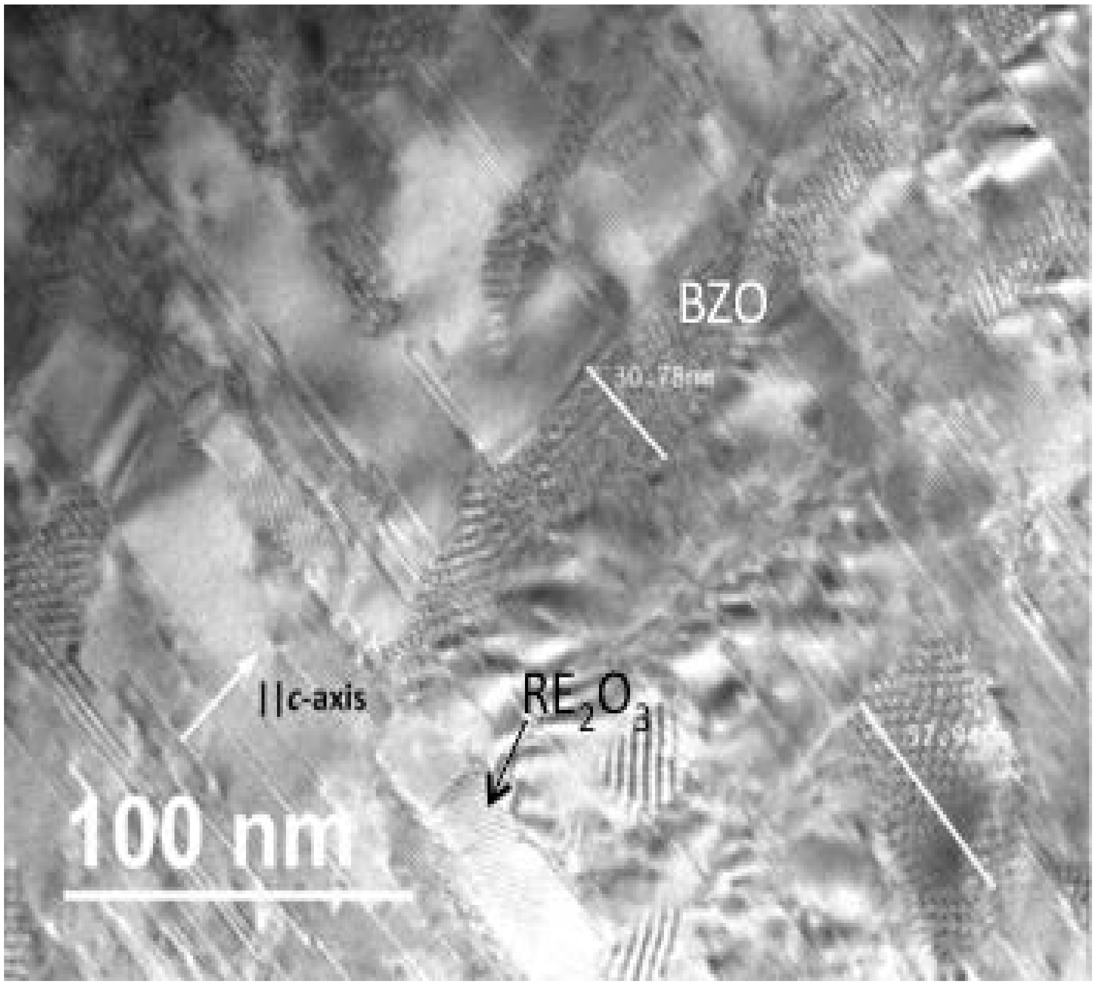
Anti-correlation - obvious result of pinning variations

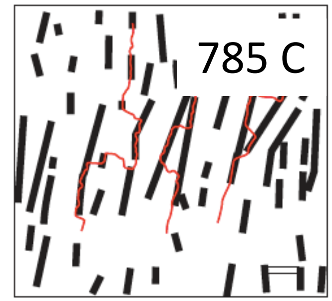


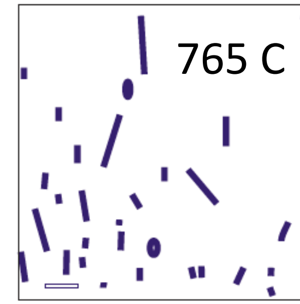


TEM study reveals that here BZO forms thick BZO column promoting ab-peaks rather then c-peaks

These anomalies may originate from temperature changes during growth



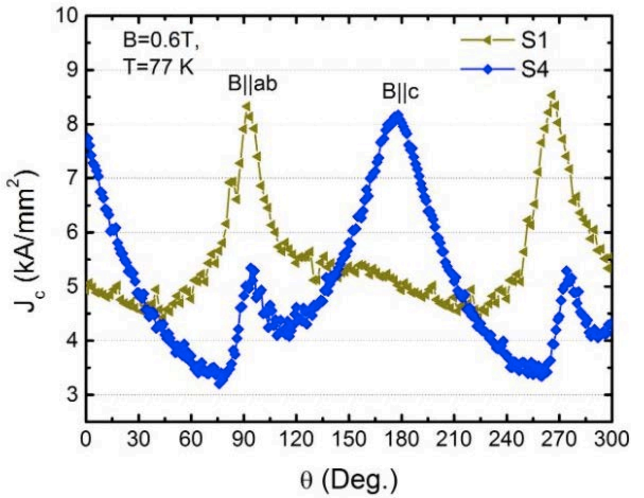




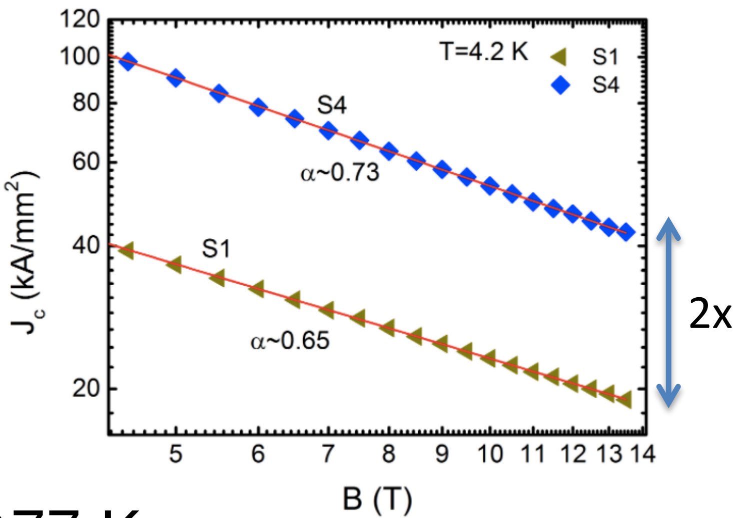
B. Maiorov et al. Nat. Mat. 2009, Y. Yoshida CCA 2016

TEM: Xinbo Hu under supervision of Fumitake Kametani

Some Ic variations: precursors of degradation??



Less BZO => twice lower performance at low temperatures



Less c-pinning looks innocent @77 K
=> twice lower performance
at low temperatures, precursor of troubles

Lidia Rossi *et al* 2016 *Supercond. Sci. Technol.* 29 054006

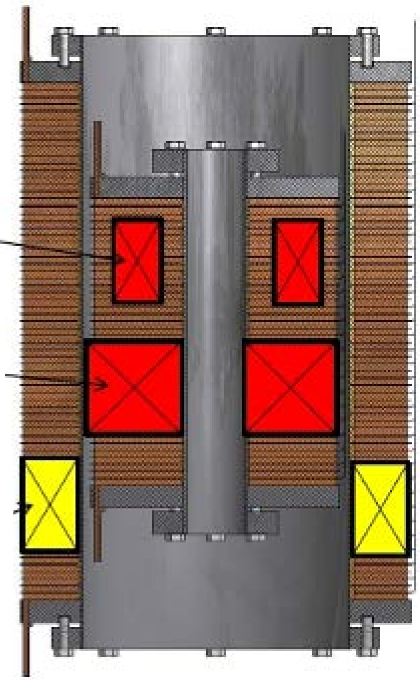
Post mortem examination:
Tapes deconstructed from 32 T and NI coils

YateStar can localize bad spot in tapes deconstructed from underperformed coils

2018

YBCO coils for 32 T

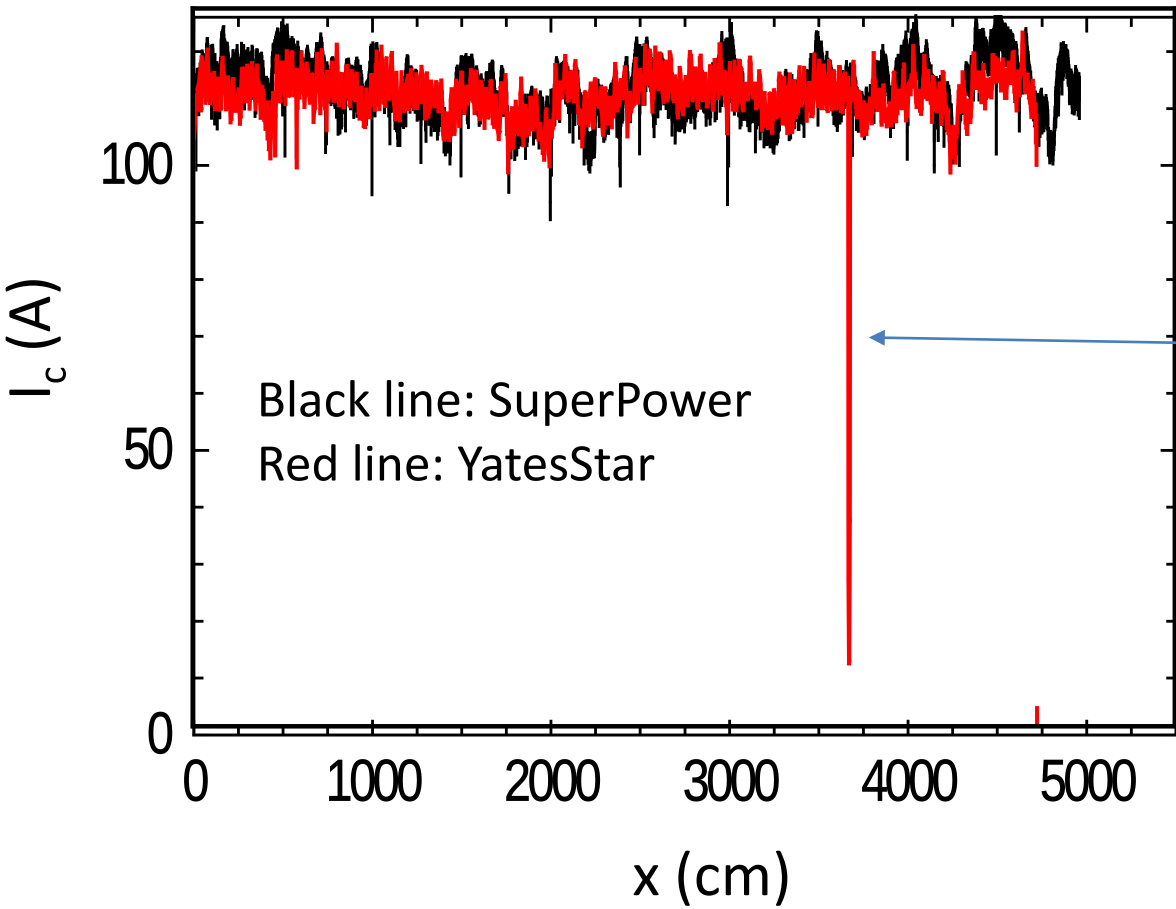
20/70 test coil puzzle:
low critical current Ic = 208 A
in module # 6 : SP 53, 57, 59

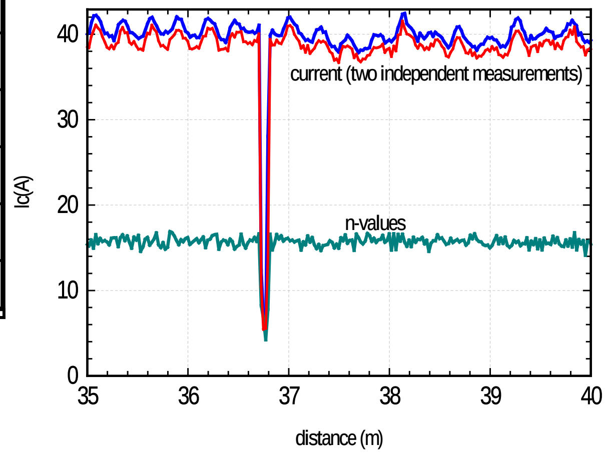


Markiewicz, Weijers et al.

32 T 24/7/365 costs ~ M$ 5 for energy in resistive magnet

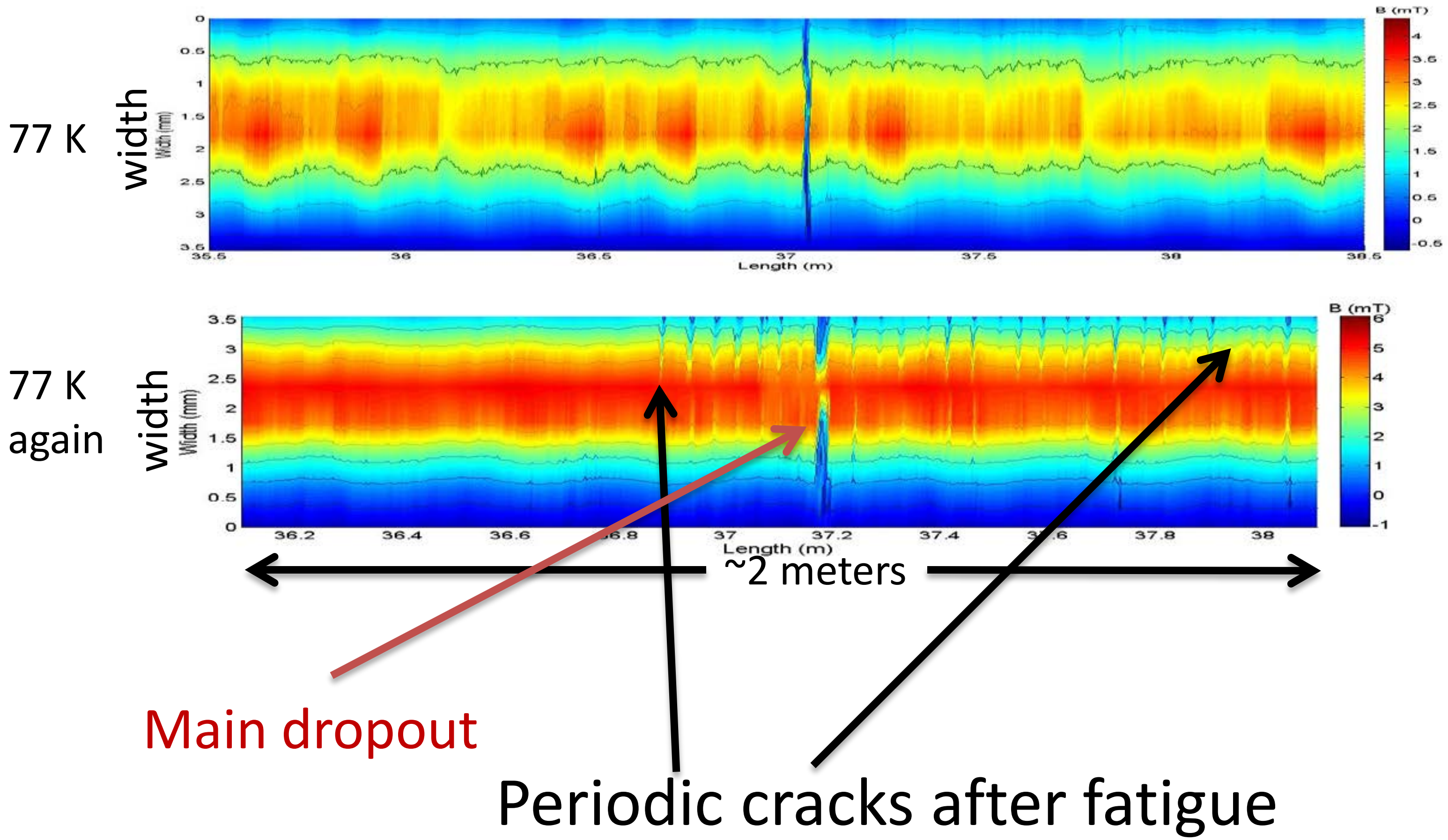
Comparison of Ic results from SuperPower and YatesStar





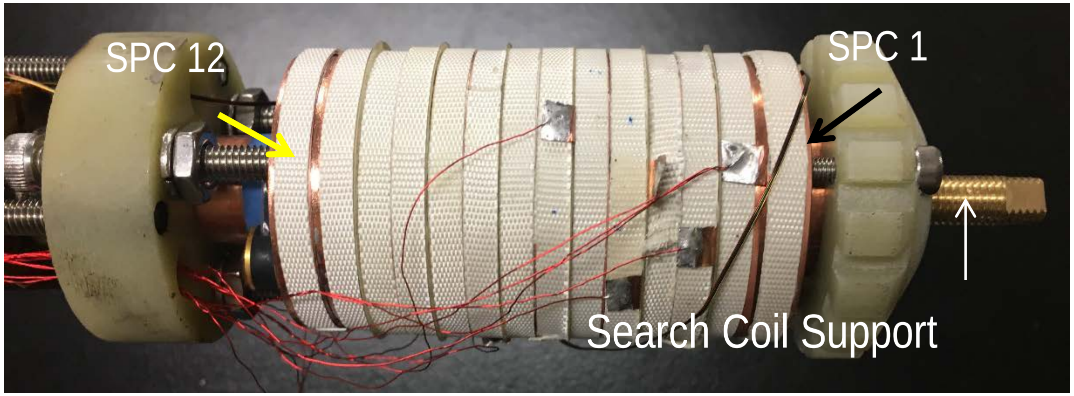
Our measurement is comparable to SuperPower's , except for the big drop. What happened?

Cracks responsible for underperformance



45.5 T Record High Field from All-REBCO NI Insert

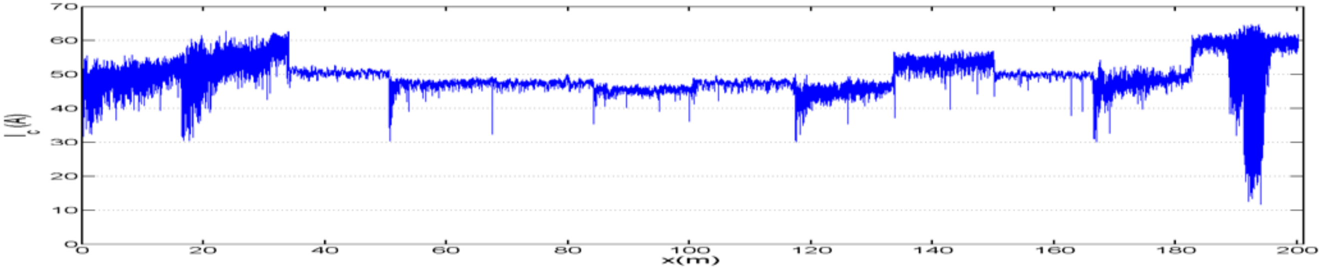
- All-REBCO NI Insert
  - Consisted of 12 single pancake coils
  - Wound with the latest 30 μm substrate REBCO tapes manufactured by <u>SuperPower Inc.</u>



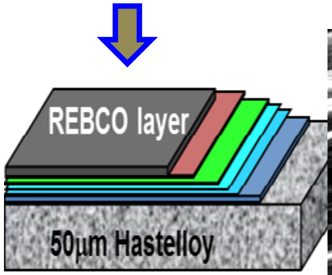
6.5 cm long, 3.8 cm DIA, 31.2 T + 14.3 T !

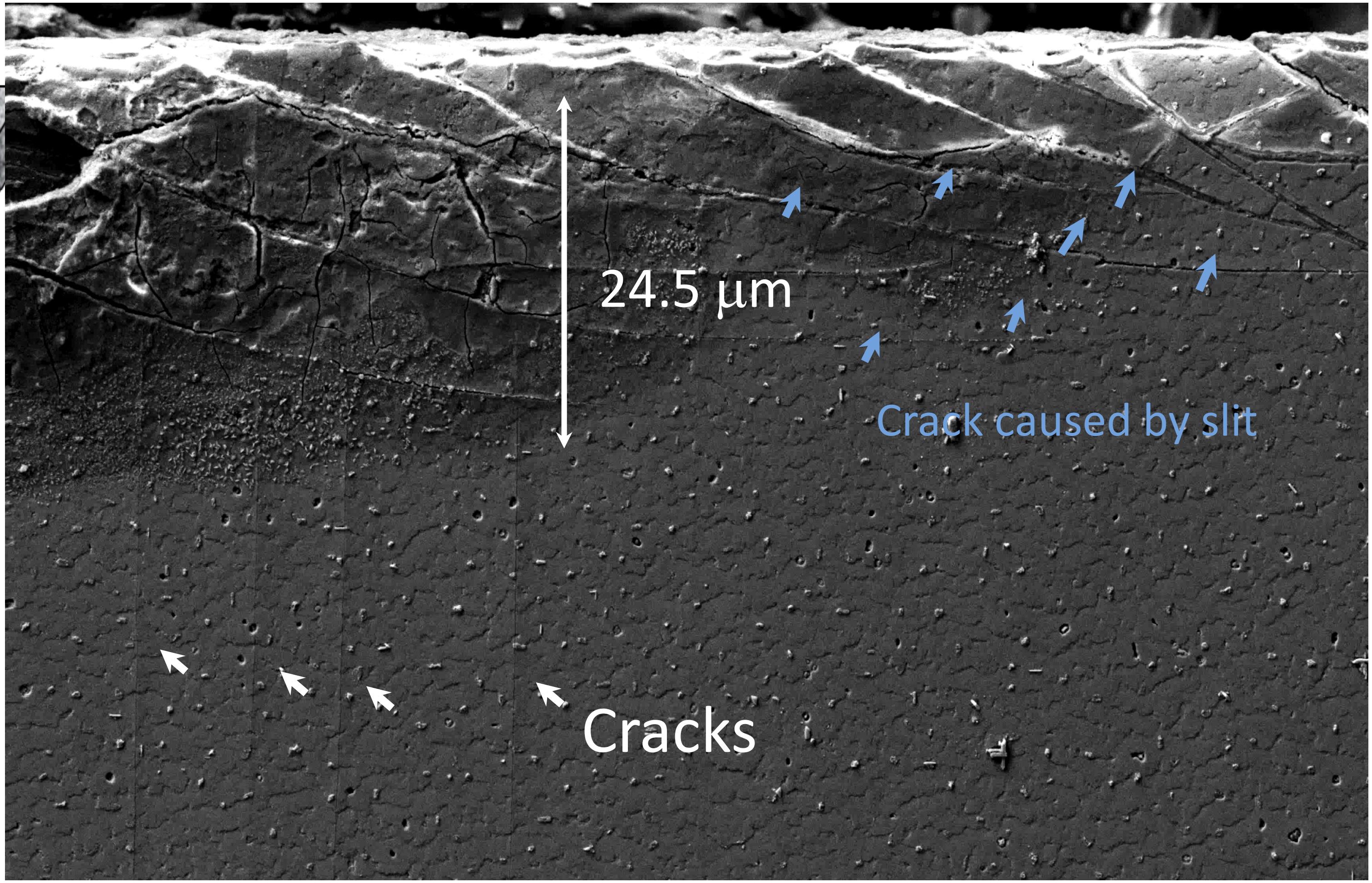
2 m x 1 m DIA
18 MW

YateStar after quench:



The major defects are caused by transverse cracks

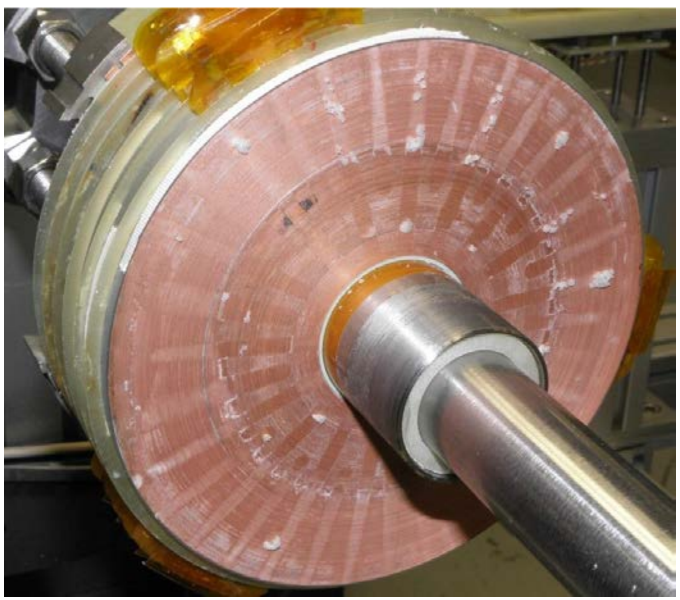


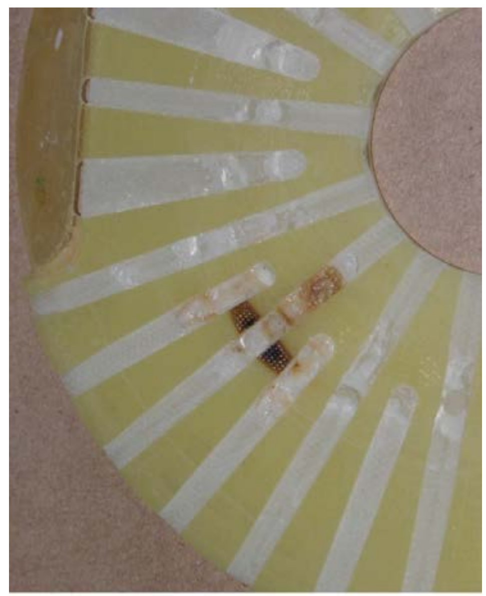


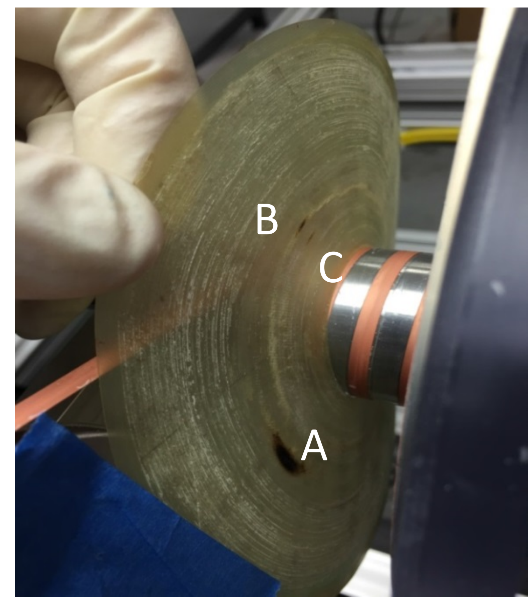
- Transverse cracks are not related to slit cracks.

Quenches in 32 T prototype possibly triggered by pinning variations

Three spontaneous quenches caused degradation, after more than 100 safe triggered quenches

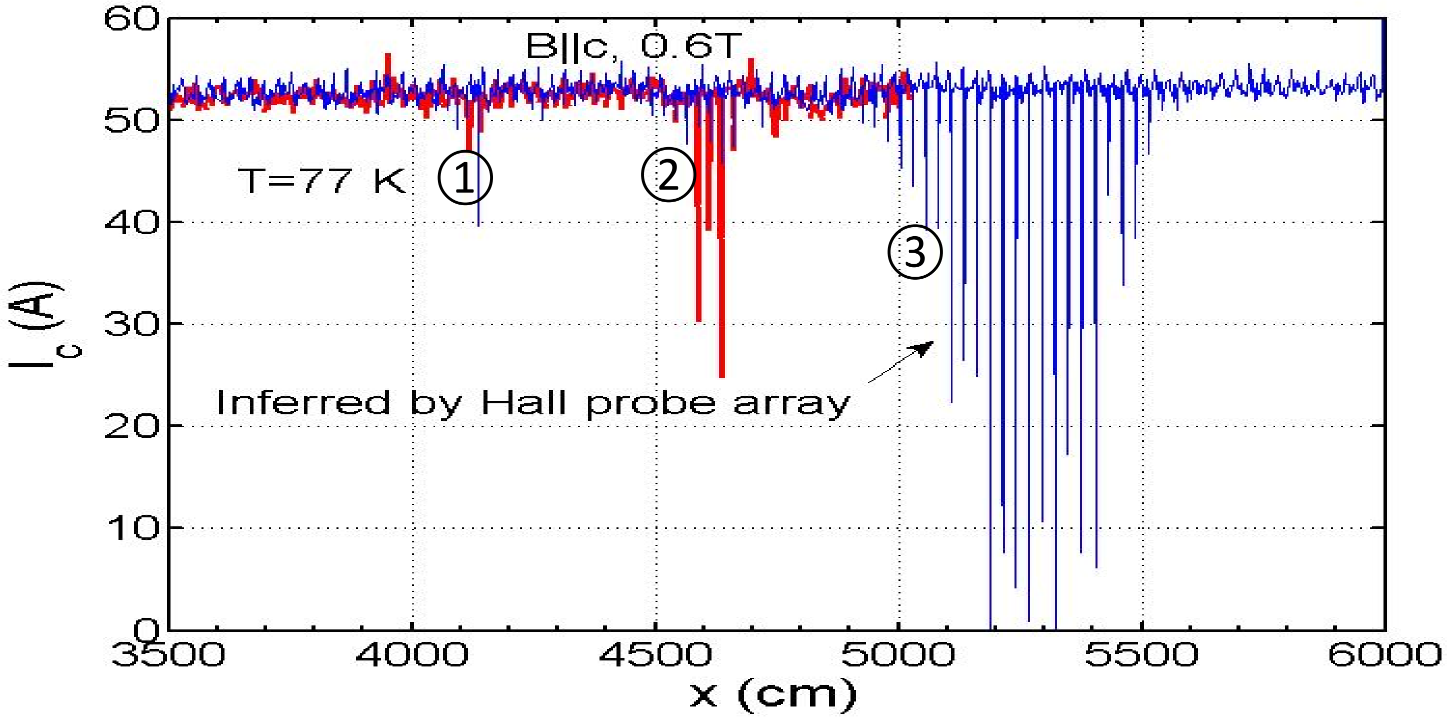






Weijers *et al*.

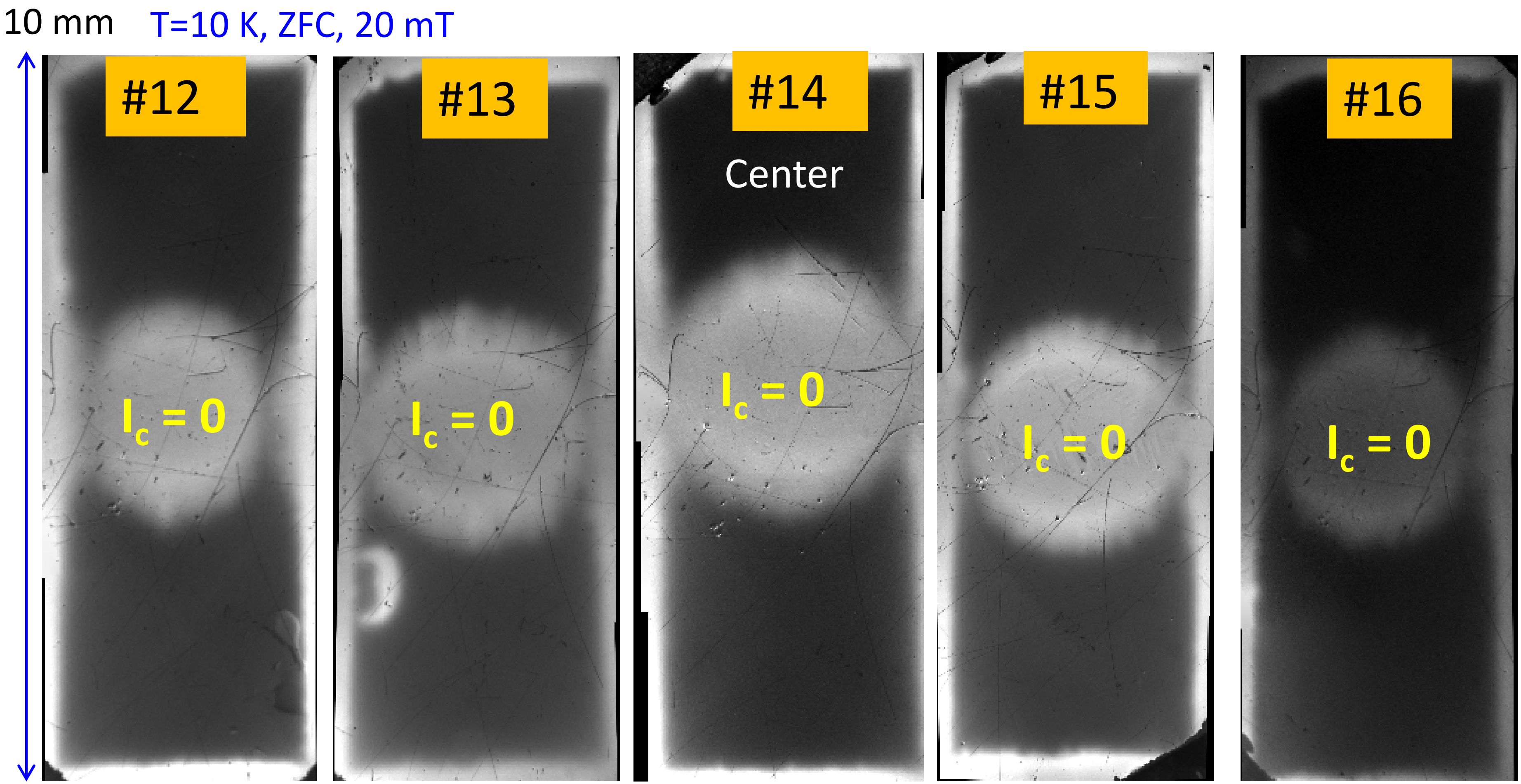
Post mortem transport and magnetization, pancake 6 of 32 T prototype



Pancake radii, 20/70 mm

Note that the damage occurred during accelerated fatigue testing at many times the high operational sweep rate

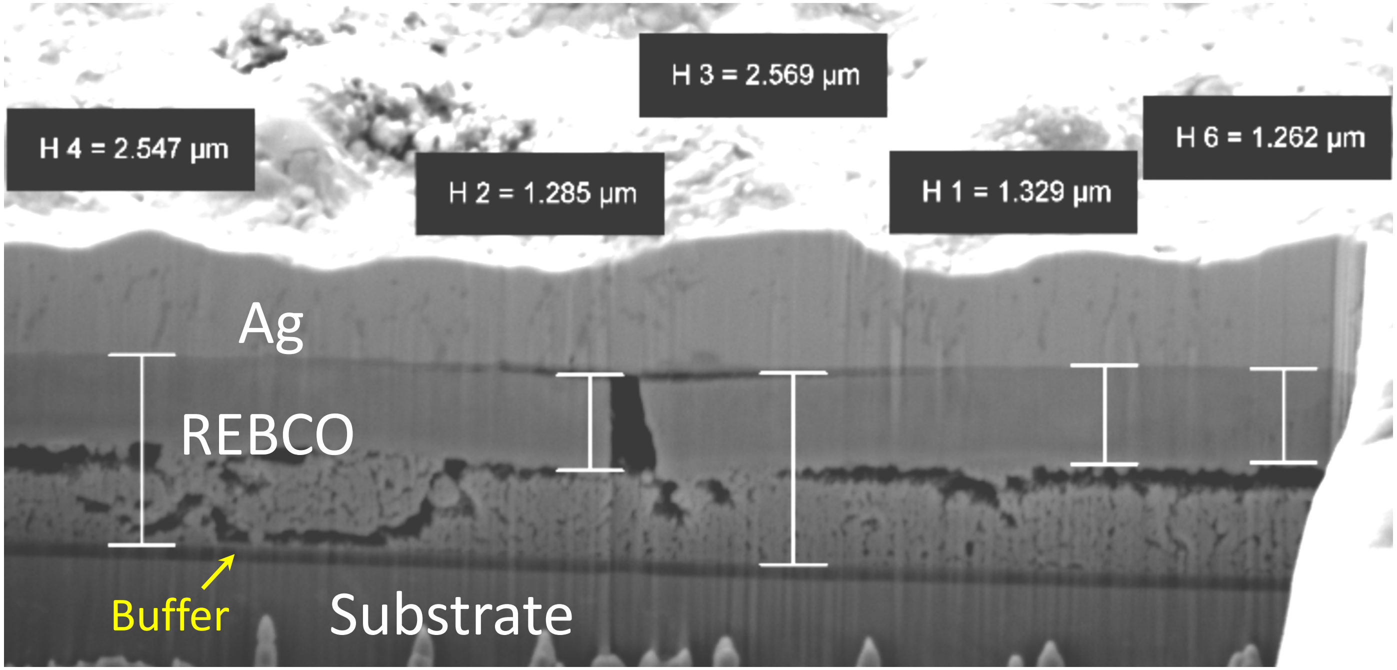
Magneto-optical imaging (MOI) at zone A show turn #14 is the zone center



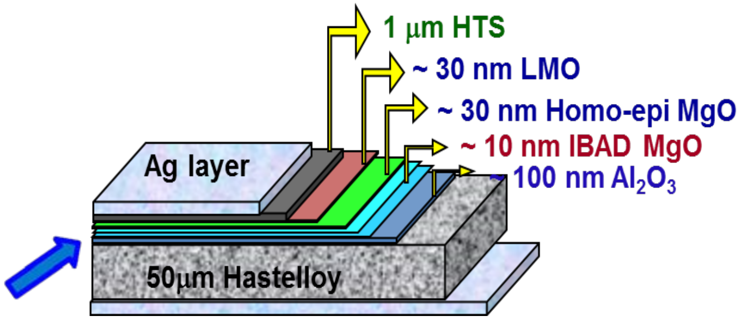
A. Polyanskii

- Quench center is determined by the size of the damaged zone.

Localized heat blew apart the REBCO layer and introduced planar defects



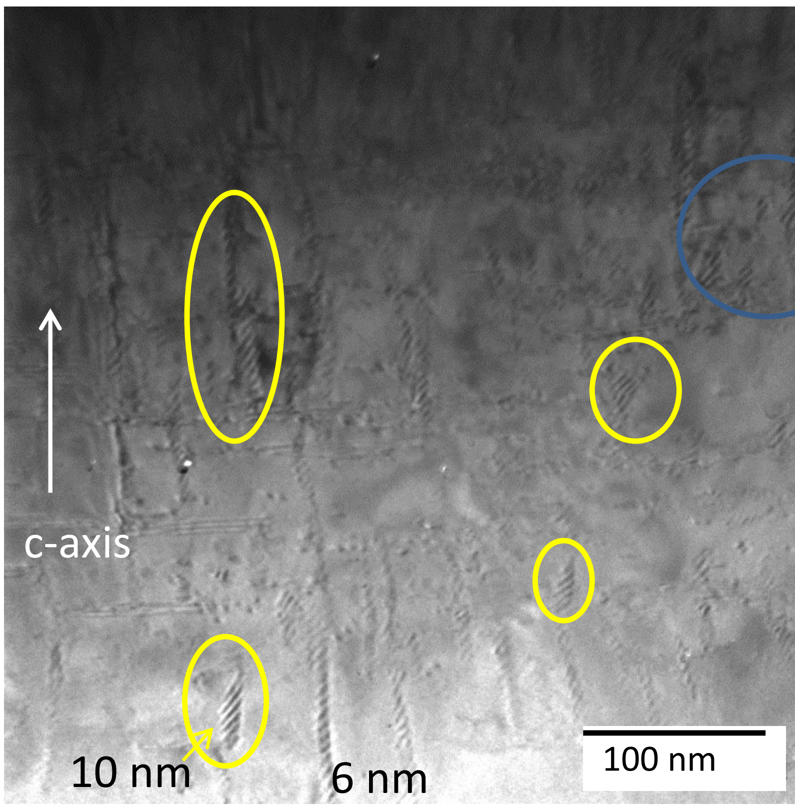
D. Abraimov

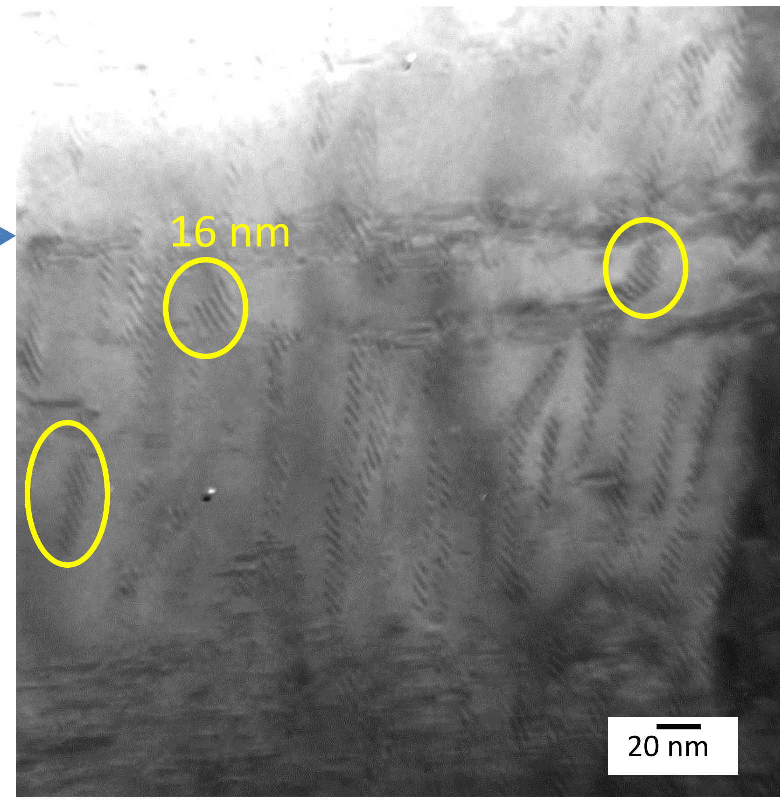


- REBCO is normally ~1 µm thick.
- REBCO thickness is more than tripled on the edge of the black spot.

Vortex pinning variations might be one of the reasons for the initiation of the quench

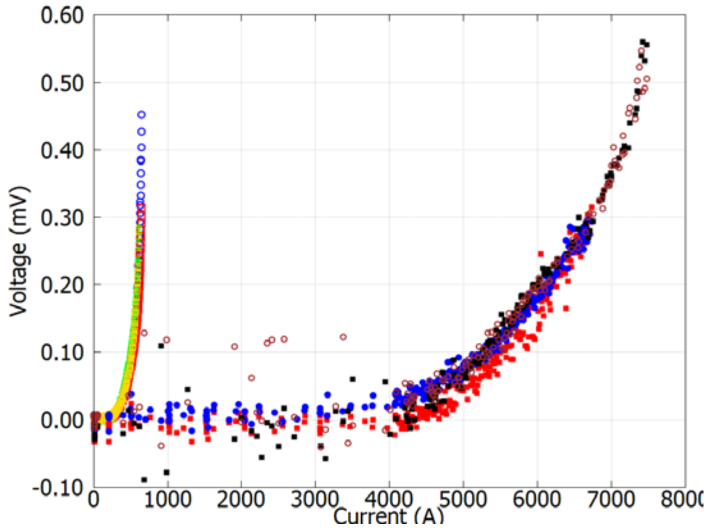
Thicker BZO nanorods found ~4 mm away from the hot spot edge of quench A



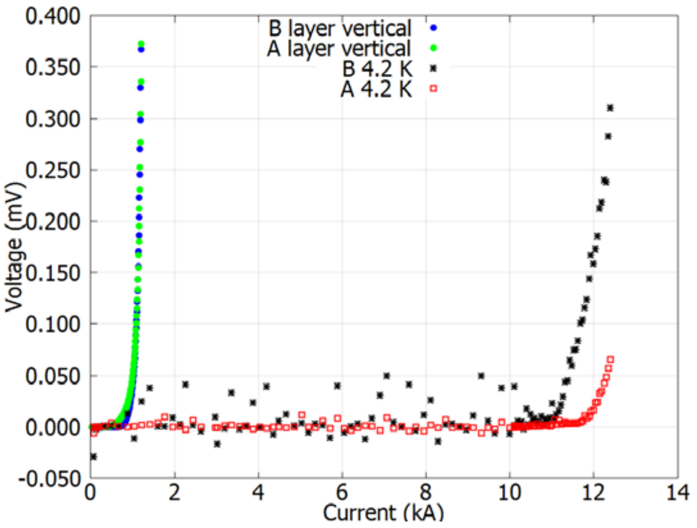


Post mortem examination of deconstructed CORC

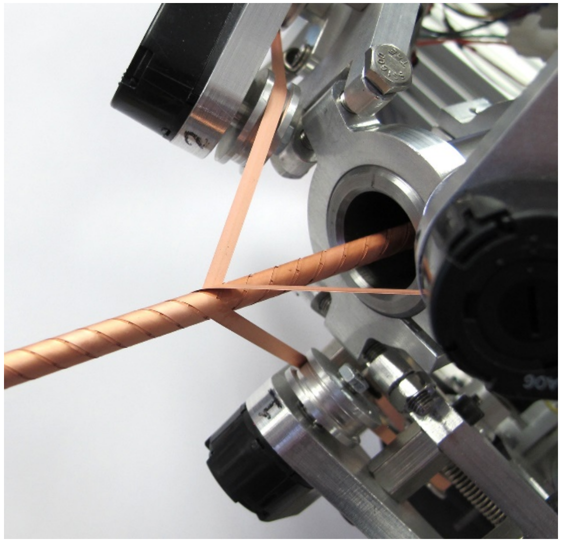
old



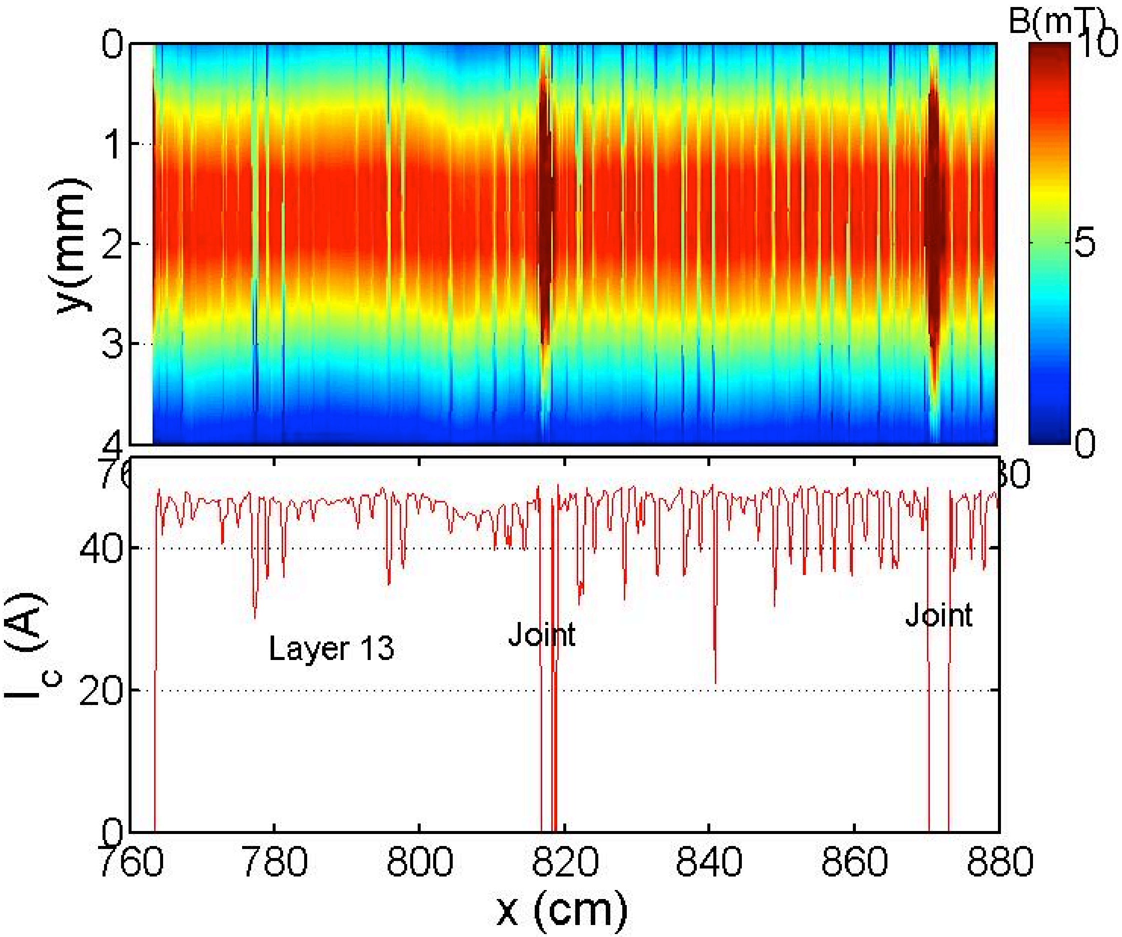
recent



High retention now
It was not always observed



Damage seen in CORC® cables after bending



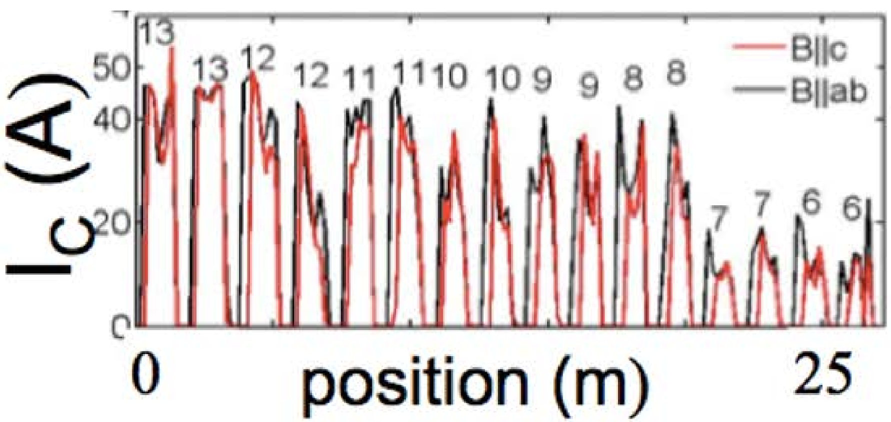
Period of Ic dropouts
well correspond
to cable circumference
After these tests production
protocol improved

[1] D C van der Laan 2009 *Supercond. Sci. Technol.* **22** 065013
[2] D C van der Laan et al. 2013 *Supercond. Sci. Technol.* **26** 045005
[3] D C van der Laan et al. 2015 *Supercond. Sci. Technol.* **28** 124001

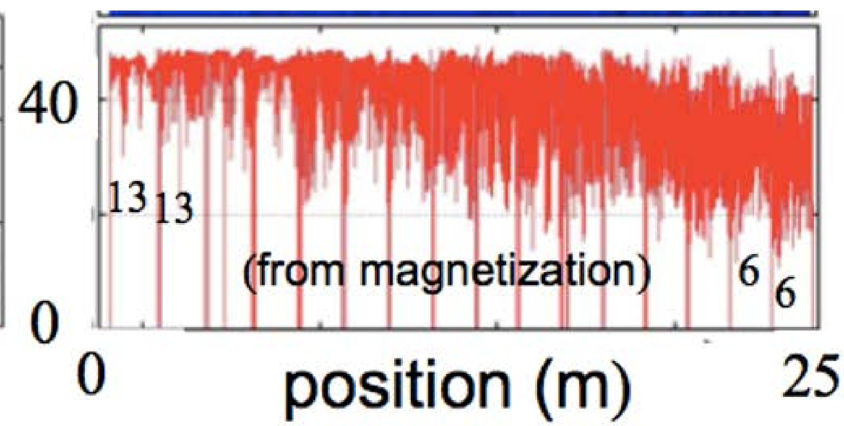
Winding degrades inner layers, quenching at 4.2 K 16 T degrades further

Damage increases from outer to inner layers

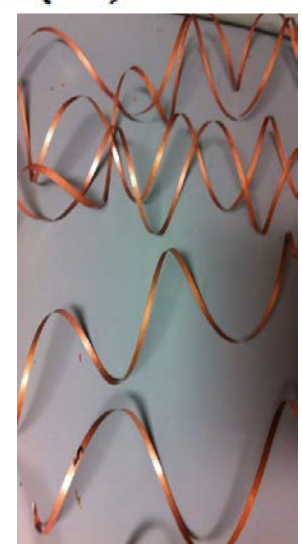
after winding



after quenching 4.2 K 16 T

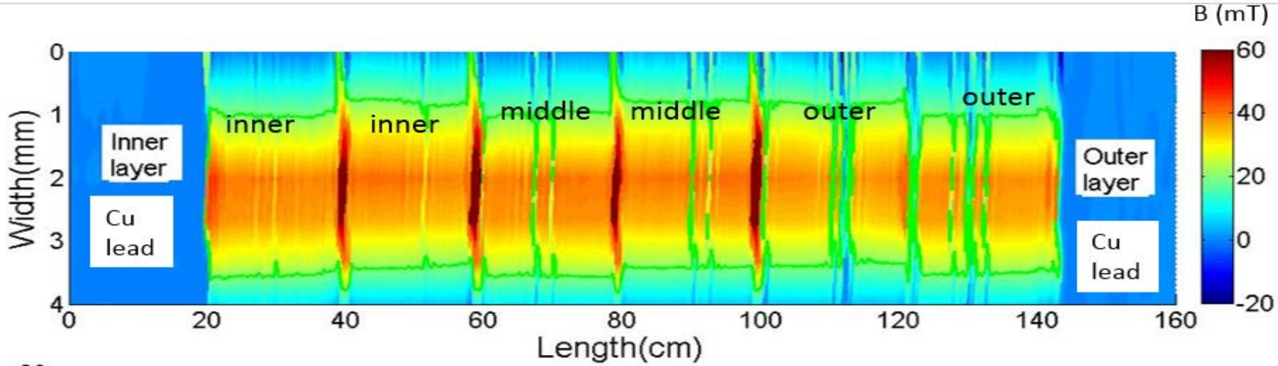


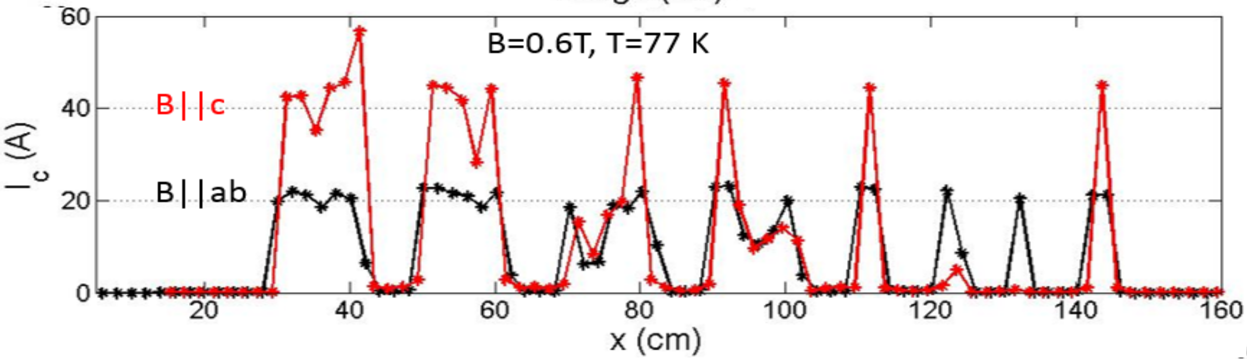
Layers	1-5 (inner)	6-13 (middle)	14-20 (outer)
# of tapes each layer	2	2	3
Tape width	3mm	4mm	3mm
Substrate thickness(μm)	50	50	50
Cu thickness each side (μm)	5	5	5

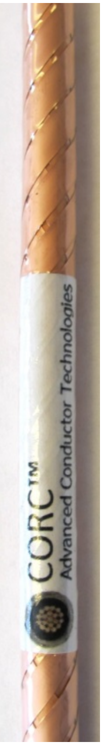


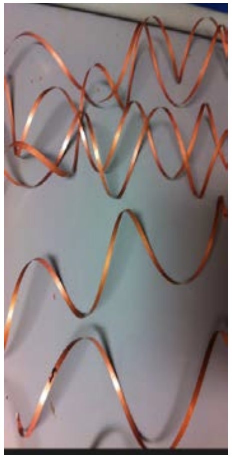
Quite generally, in degenerated regions, vortex pinning changes

• CORC deliberately compressed 3 layers, 2 tapes for each layer.





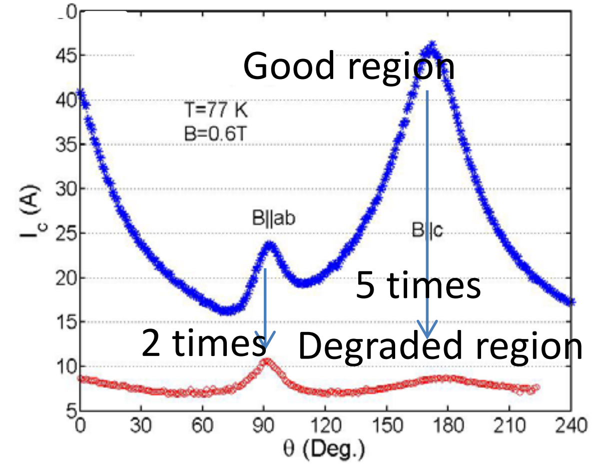




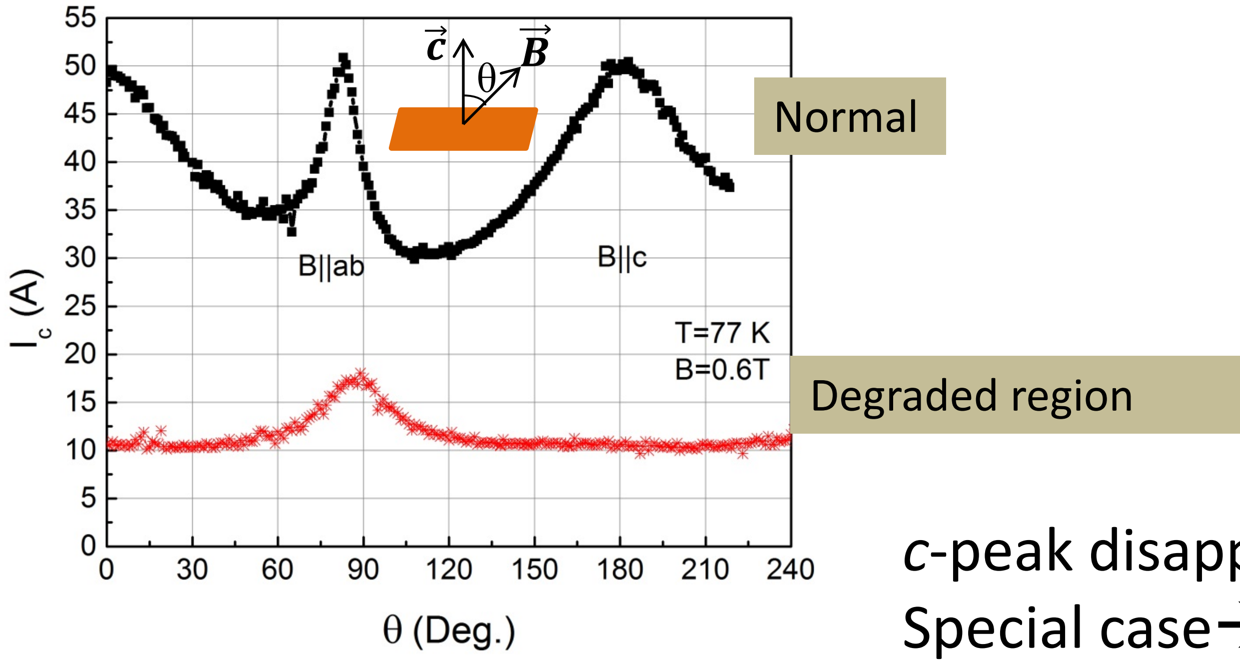
•The strongest damage in the outer layers

•c-peak is strongly depressed, ab – no change

• apparent change of vortex pinning



Pinning changes seen in cables after being quenched in high-field (17 T) tests



c-peak disappears totally!

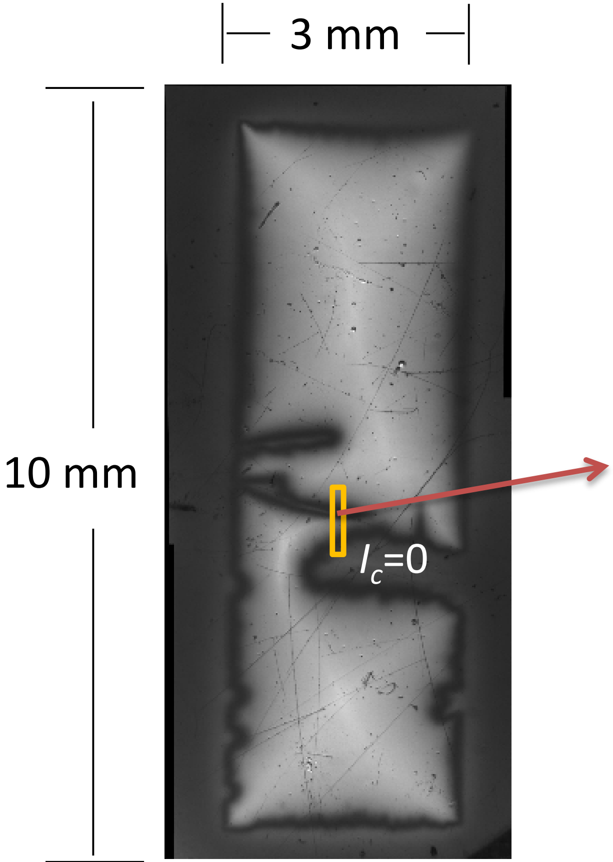
Special case→ TEM

[1] D C van der Laan 2009 *Supercond. Sci. Technol.* **22** 065013

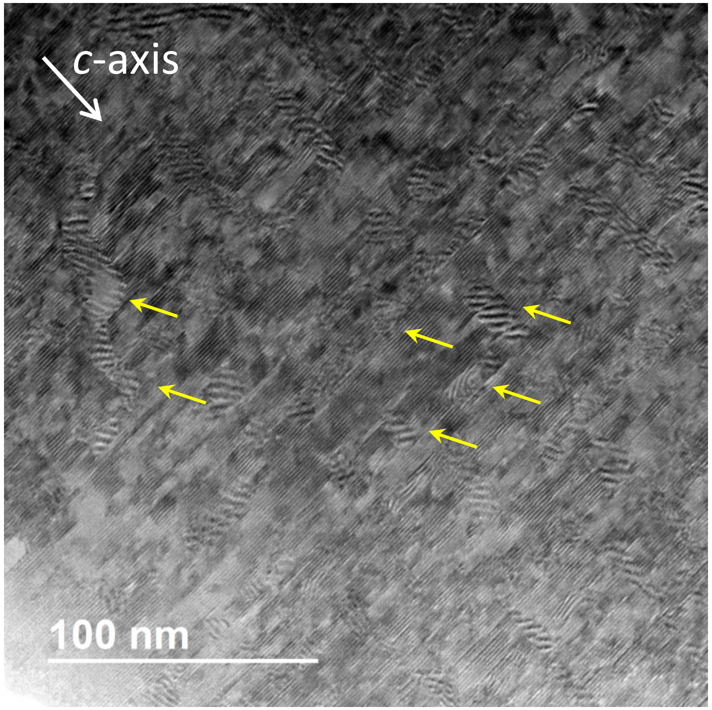
[2] D C van der Laan et al. 2013 *Supercond. Sci. Technol.* **26** 045005

[3] D C van der Laan et al. 2015 *Supercond. Sci. Technol.* **28** 124001

In this region of anomalous pinning TEM shows abnormal microstructure



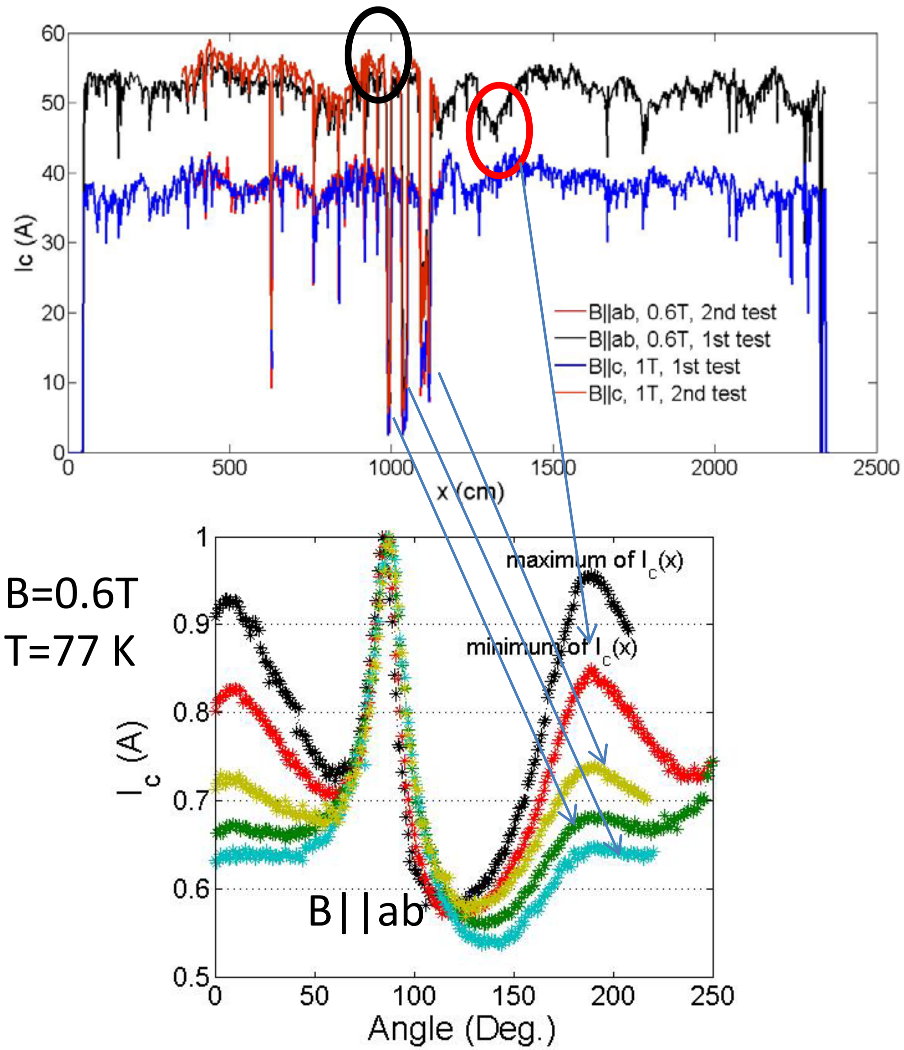
Degraded region



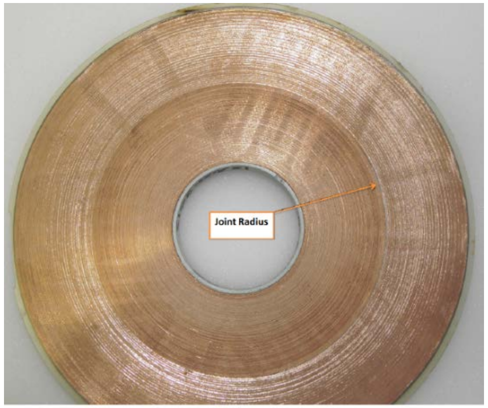
- BZO nanorods random, short
- High density of stacking faults.
- PREEXISTING!

MOI by A. Polyanskii

Similar c-peak suppression observed in conductor from deconstructed coils



- The $\mathbf{I_{ab}/I_c}$ peak ratio at the maximum and minimum of $I_c(x)$ are 0.95 and 0.84, which could be a result of chemical variation.
- However, the $\mathbf{I_{ab}/I_c}$ peak ratio at defects drops even to 0.64.



What are possible reasons for pinning changes?

- Temperature
  - High temperature attained during quench modifies BZO columns responsible for c-axis pinning.
- BZO inhomogeneity on the microscopic scale
  - Some regions are rich in BZO while some regions are poor; are the rich regions weaker?
- less effective pinning
  - Small cracks relax strain around BZO columns or crack them, lowering their contribution to pinning.

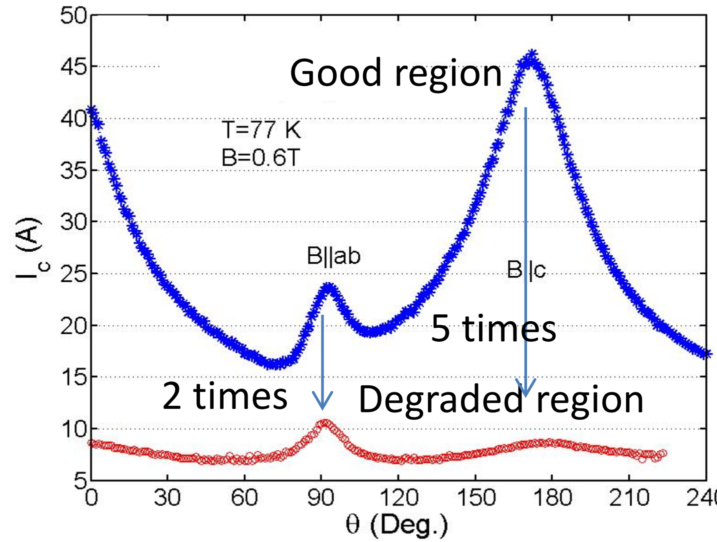
Summary

- REBCO coated conductors from SuperPower substantially enhanced their homogeneity over past years
- Ic variation along CC tapes and between tapes is due to pinning changes in most cases
- c-axis peak degrades more than the ab-plane I_c peak at degraded regions measured at 77K.
- Both cracks and pinning cause underperformance of REBCO CC in coils and cables

Thanks

Pinning changes seen in CORC® cables after compression tests

- CORC® cables: Conductor On Round Core[1,2]
- Stress dependence of I_c in LN_2 was tested by cable compression between two anvils.
- Cable deconstructed after test and individual tapes run through YateStar



$I_c(B||c)/I_c(B||ab)$ drops from 2.0 to 0.8

- Dominant pinning peak changes from c-axis to ab-plane in degraded regions

[1] D C van der Laan 2009 *Supercond. Sci. Technol.* **22** 065013
[2] D C van der Laan et al. 2013 *Supercond. Sci. Technol.* **26** 045005
[3] D C van der Laan et al. 2015 *Supercond. Sci. Technol.* **28** 124001

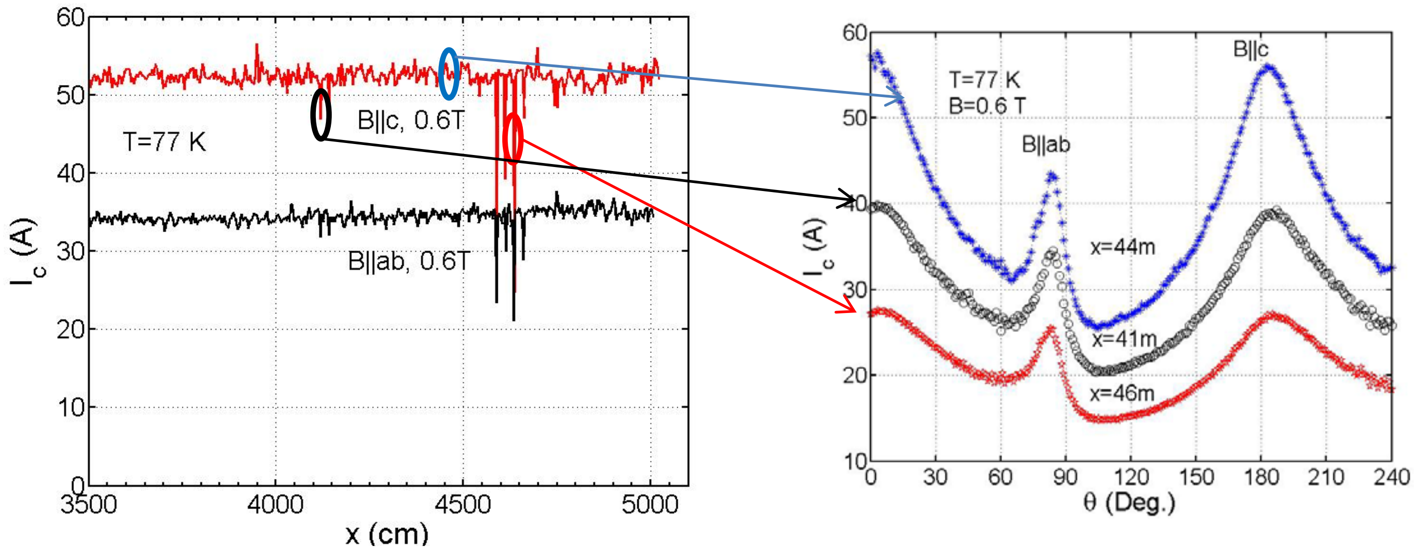
Summary

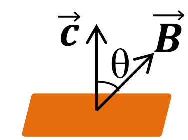
- REBCO coated conductors from SuperPower substantially enhanced their homogeneity over past few years
- Still existing Ic variation along CC tapes and between tapes is due to pinning changes in most cases
- Reasons for degeneration:

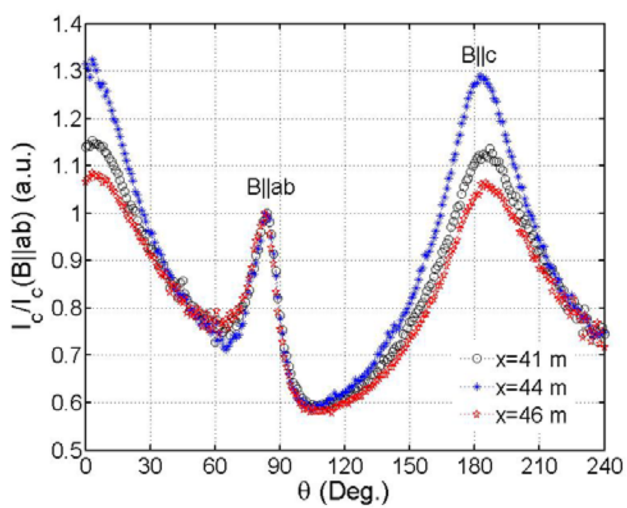
  - secondary: high temperature introduces stacking faults and cracks, but reason for quench unknown

  - preexisting, e.g. ‘anti-correlated’ region with low Ic triggers quench
- All the above mechanisms lead to anomalous angular current with strongly suppressed c-peak

What is the anomaly? Degradation of I_c is cross-section AND pinning related!







- In good regions, $I_c(B\|c)/I_c(B\|ab)=1.3$
- In degraded region, $I_c(B\|c)/I_c(B\|ab)=1.1$

Unexpected loss of *c*-axis pinning in degraded regions.

It Is not clear to me what caused this degradation – is it a CORC or single filament – maybe say that at least as for next slide?

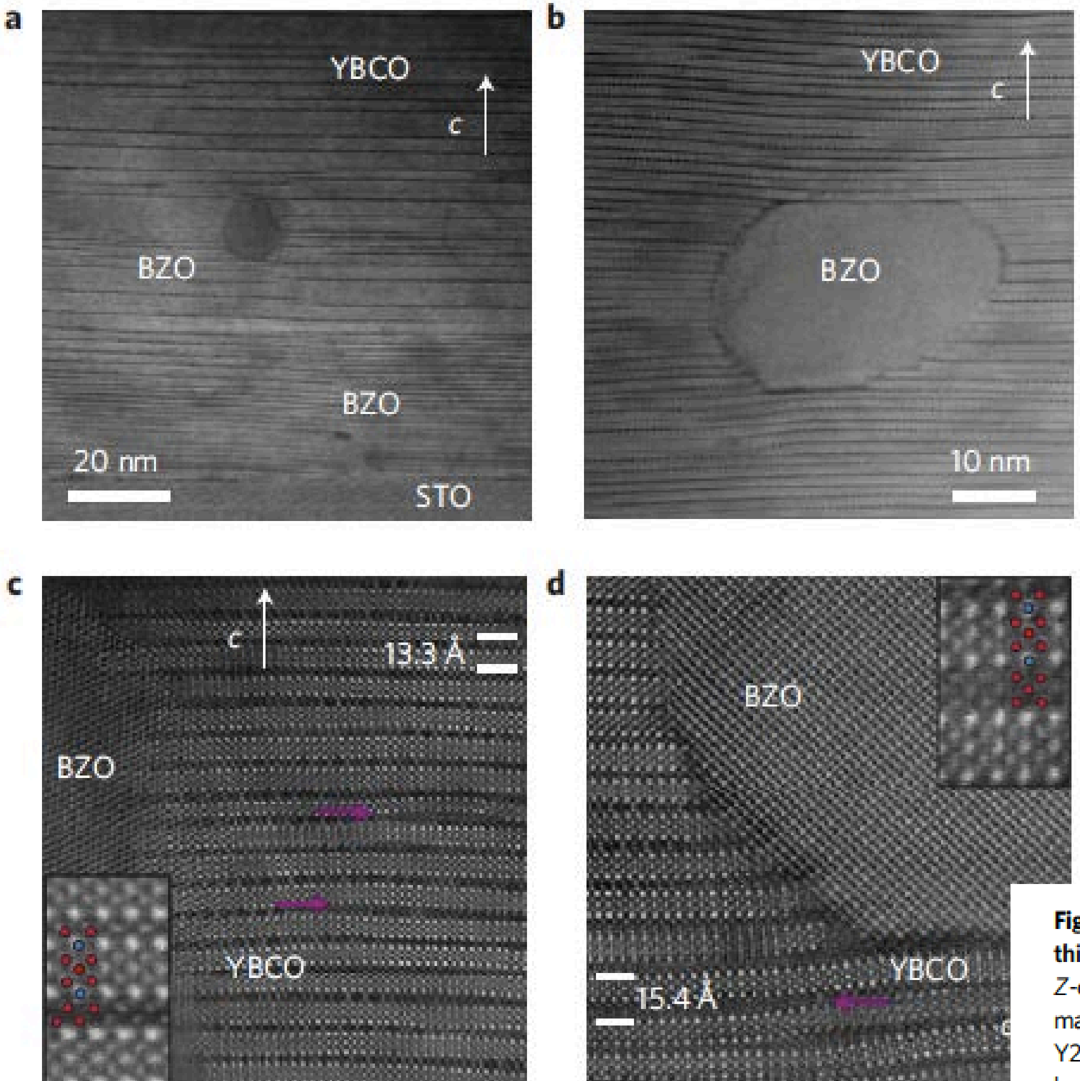
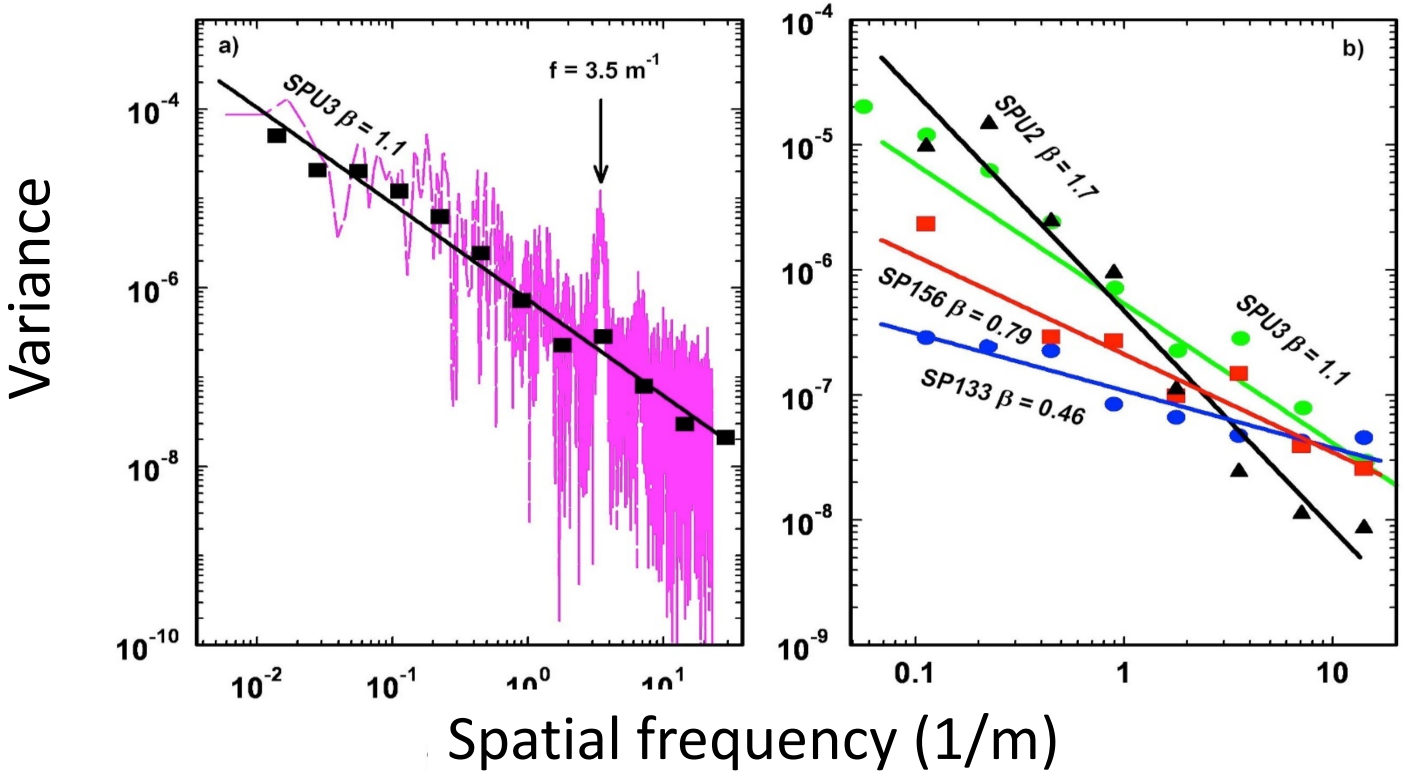


Figure 3 | Cross-sectional STEM micrograph of a YBCO nanocomposite thin film grown on STO along the [010] zone axis. a, Low-magnification *Z*-contrast images showing embedded BZO nanoparticles in the YBCO matrix. The horizontal dark stripes that cross the image are due to the Y248 intergrowths. **b**, Higher-magnification *Z*-contrast image showing the bending of the YBCO planes around the BZO nanoparticles. **c**,**d**, High-resolution *Z*-contrast images showing the interface between two different BZO nanoparticles with two different orientations and the YBCO matrix ($\langle 111 \rangle_{BZO} \parallel [100]_{YBCO}$ and $\langle 110 \rangle_{BZO} \parallel [010]_{YBCO}$ in **c** and $\langle 110 \rangle_{BZO} \parallel [001]_{YBCO}$ and $\langle 110 \rangle_{BZO} \parallel [100]_{YBCO}$ in **d**). These interfaces present a high density of Y248 intergrowths and cause a major distortion of the YBCO matrix. Purple arrows point to an intergrowth with two extra Cu–O chains added. The inset in **c** shows in detail the Y248 intergrowth, whereas the inset in **d** shows an intergrowth consisting of three Cu–O chains.

Recent production shows substantial improvement

Fourier analysis: fluctuation variation vs. spatial frequency



-residual periodic

-1/f aperiodic

-the slope much lower in recent production => less long wave fluctuations => longer pieces can be cut from production tapes

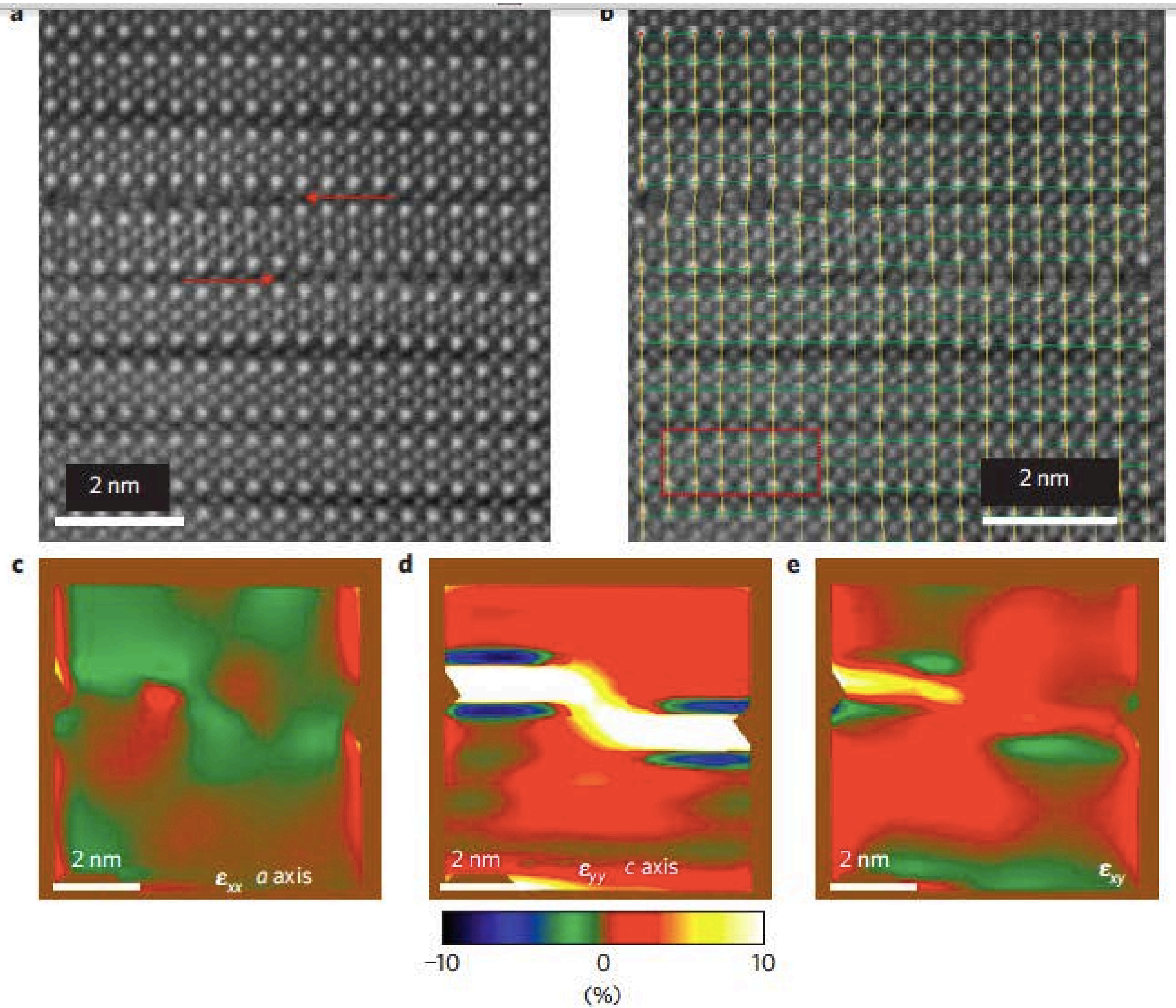
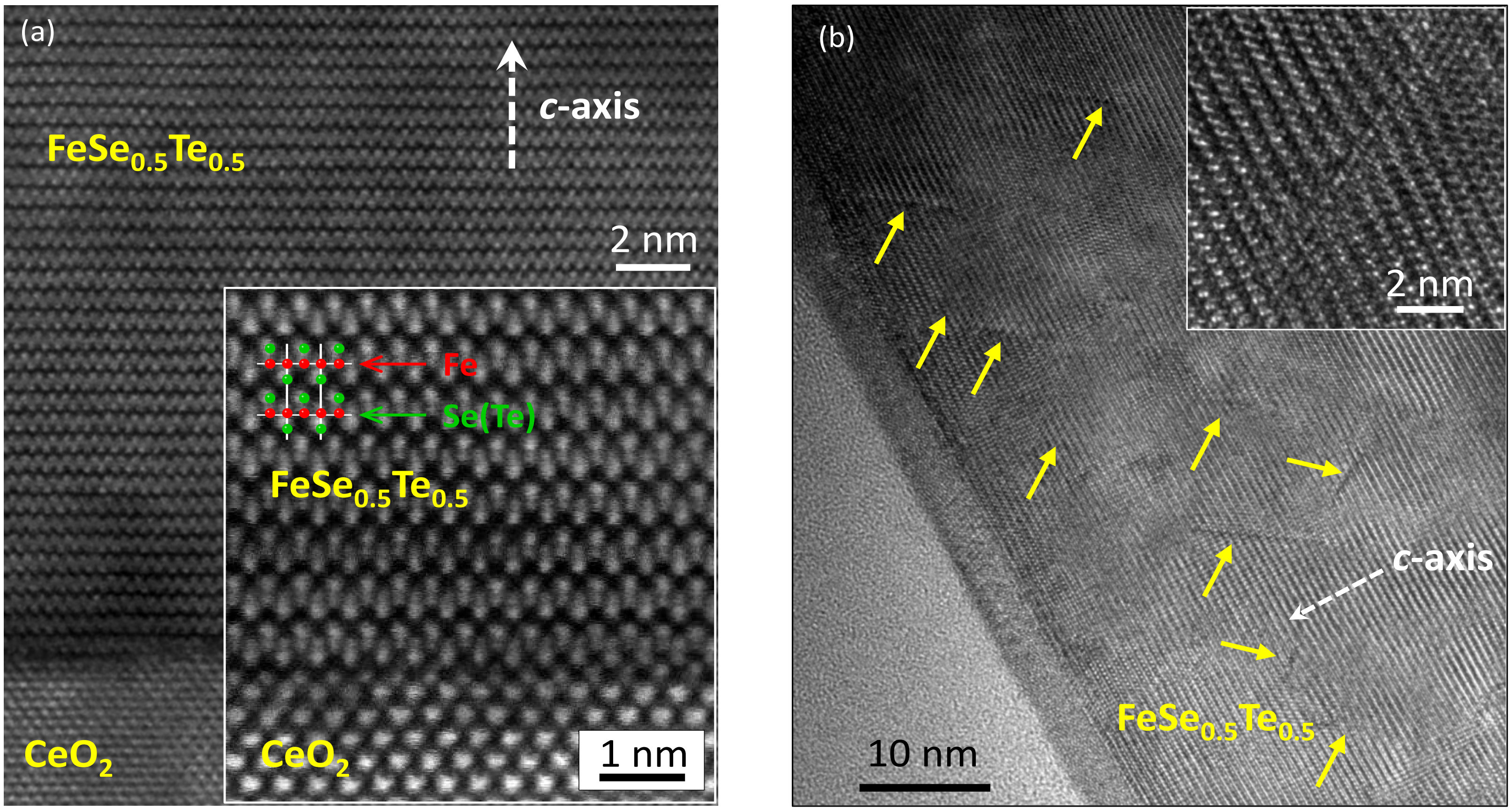


Figure 4 | Strain maps determined by Peak Pairs Analysis of cross-sectional STEM images showing intergrowths. a, *Z*-contrast image from which the strain maps were generated. The red arrows indicate two close intergrowths. **b**, Grid obtained by Peak Pairs Analysis from the image shown in **a**. The dotted red rectangle indicates the region of the image taken as reference. **c–e**, ε_{xx}, ε_{yy} and ε_{xy} maps, respectively.

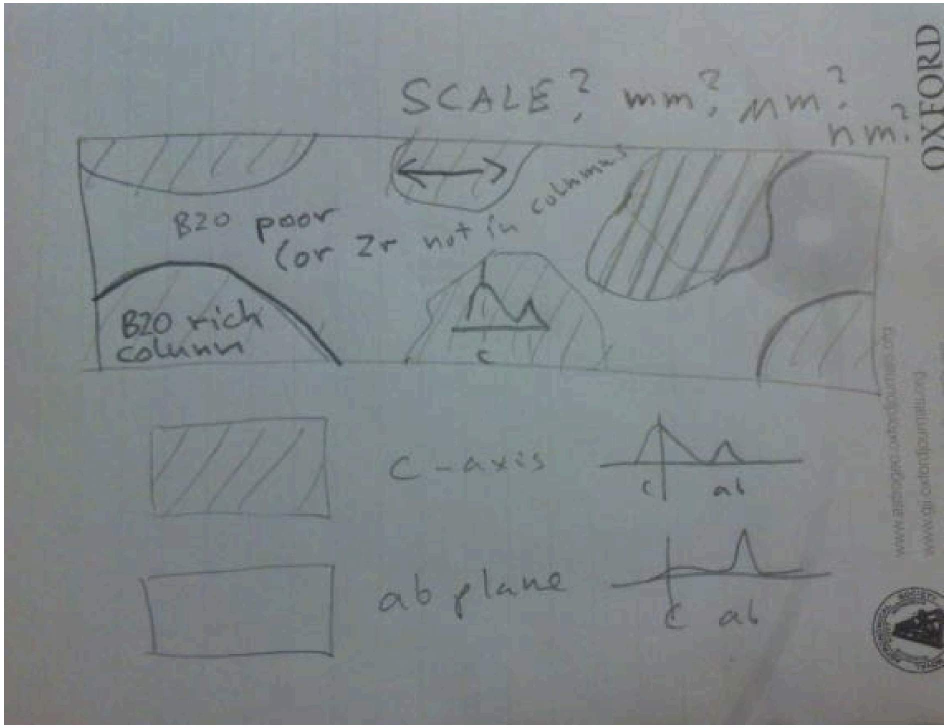
Fig.2 Microstructure of $FeSe_{0.5}Te_{0.5}$ films. **a** ADF STEM images of the representative FST film on the CeO_2 buffer layer. Inset: high-resolution image at the interface between CeO_2 and $FeSe_{0.5}Te_{0.5}$. **b** HRTEM image of $FeSe_{0.5}Te_{0.5}$ film irradiated with 1×10^{15} p/cm^2 dose of 190 keV proton. Inset: high resolution image of splayed cascade defect and strain field produced by 190 keV proton irradiation.

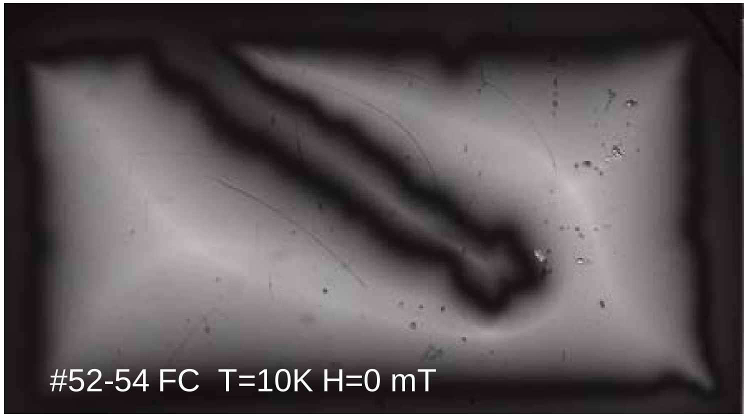


➢BZO inhomogeneity on some scale microscopic scale

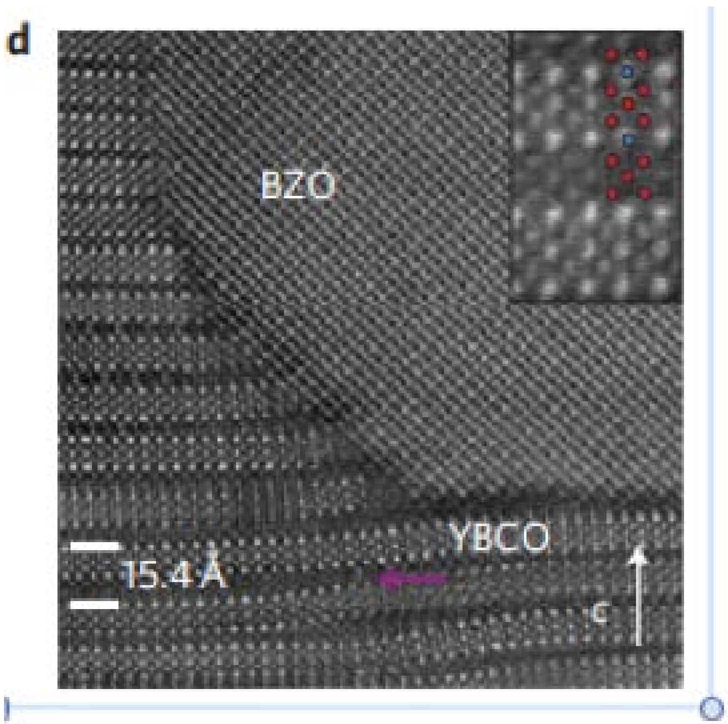
- Some regions are rich in BZO while some regions are poor; are the rich regions weaker?

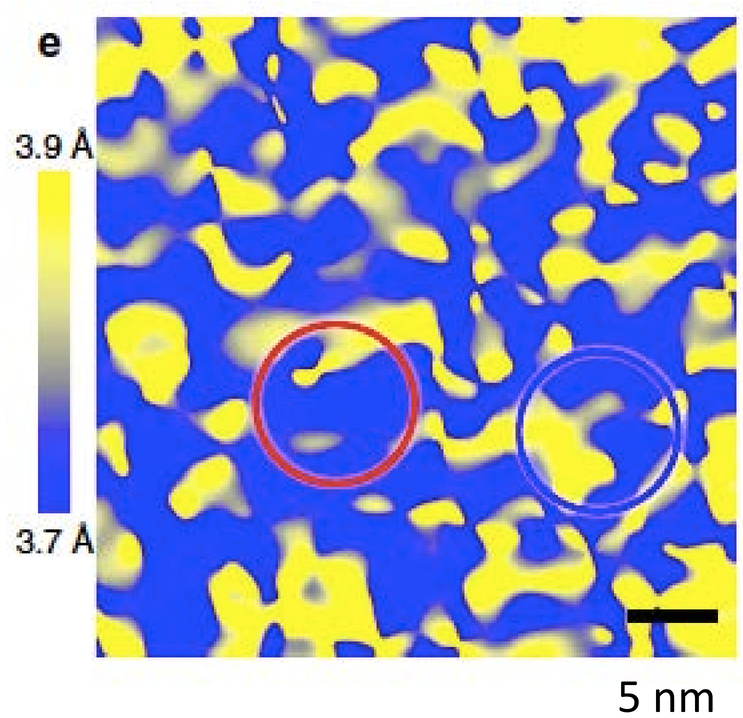
I think you can add an illustration
To this 'percolation' model
And also MOI (the latest you have)





Nano-cracks relax strain around BZO columns and/or crack them, lowering their contribution to c-pinning???





A. Llordės et al Nat. Mat 2012, T. Ozaki at al. Nat. Comm. 2016, in press,
Q. Li, ASC 2016 Denver, Co, V. Selvamanickam CCA 2016

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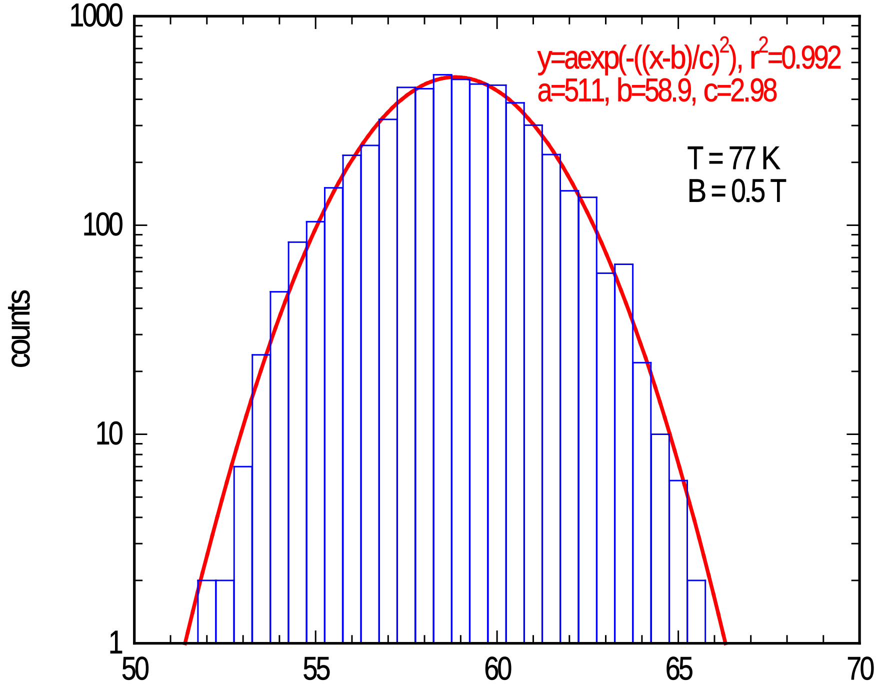
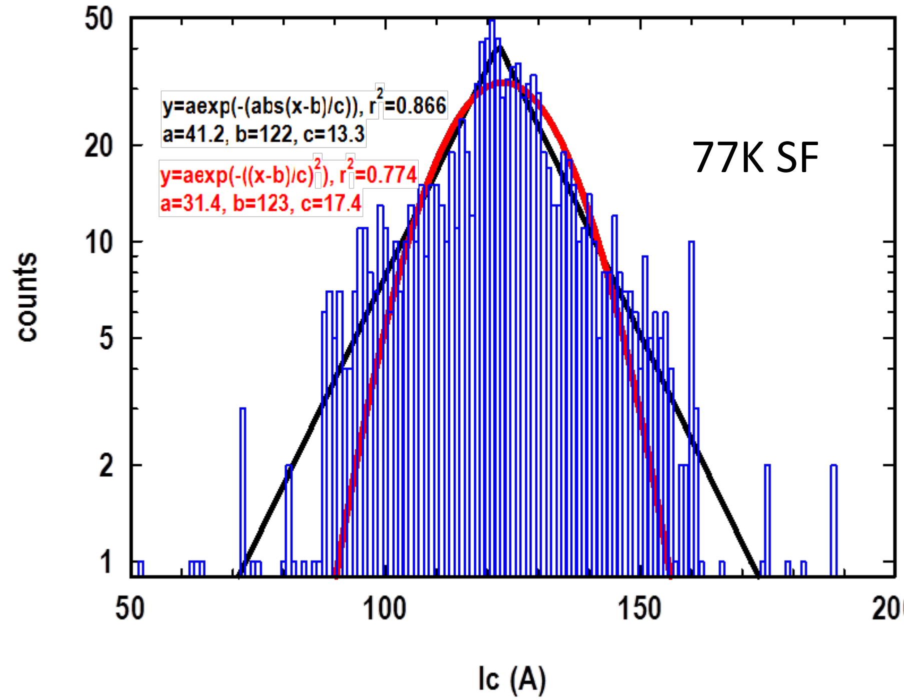
Ic distribution in REBCO CC

Gaussian in one tape (good)



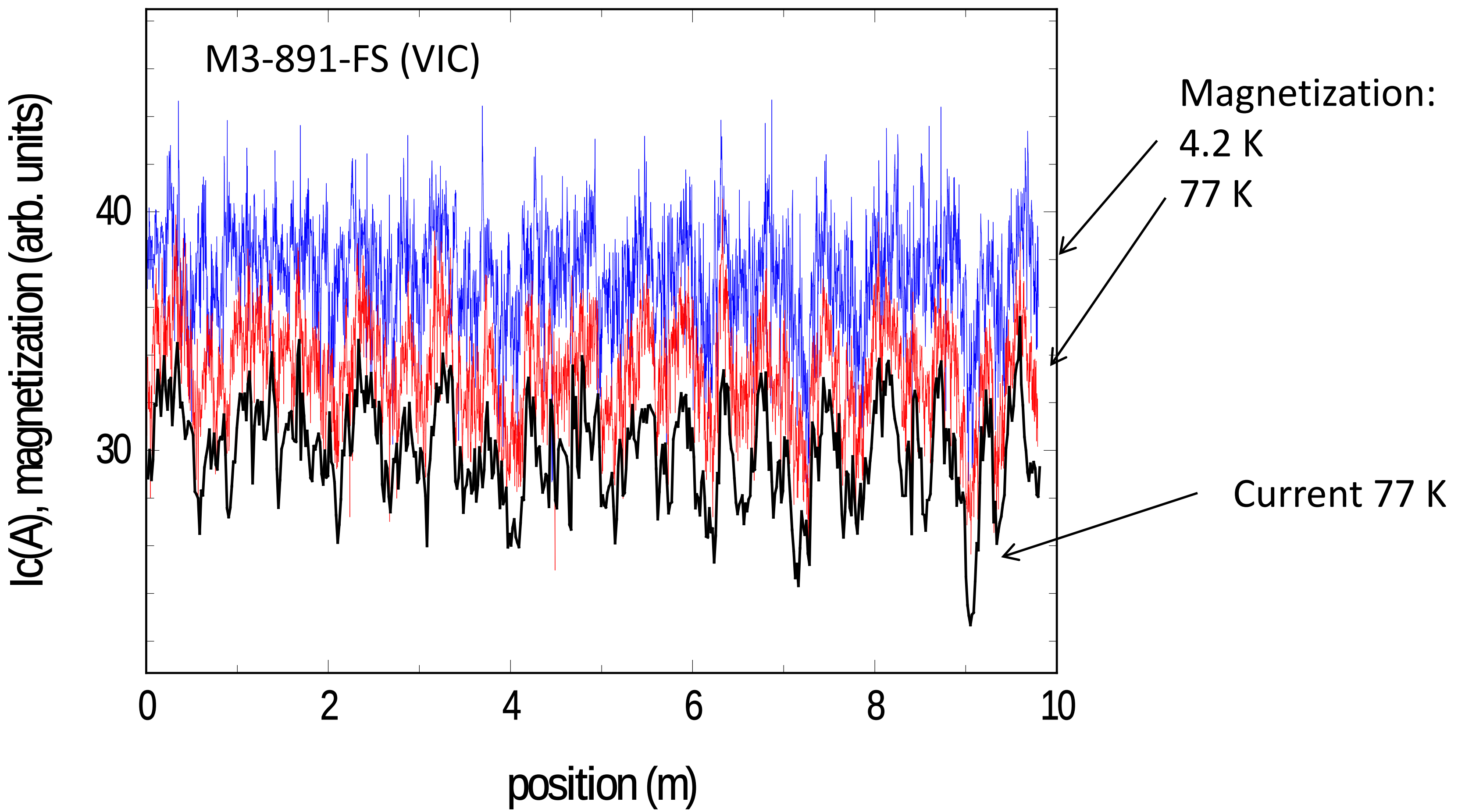
Critical current (A)

Exponential between different tapes (bad)



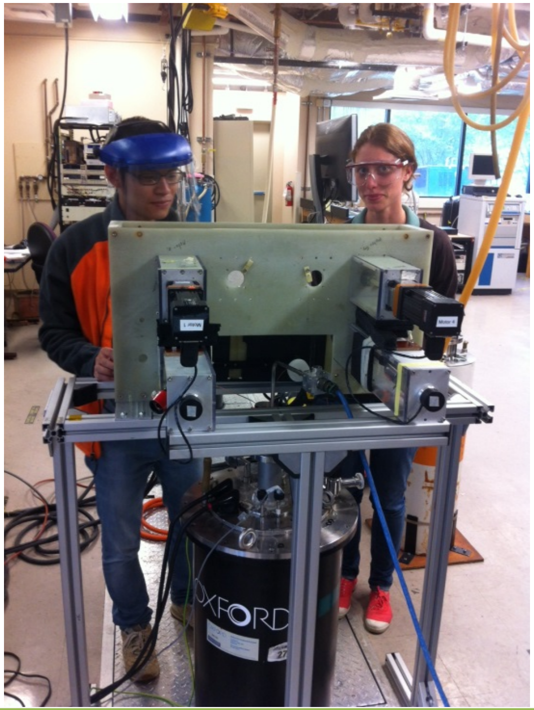
Ic distribution in several short samples (~1200 measurements) taken from many different production runs of the same AP process

Reasons for Ic variations along the length: cross section variations?

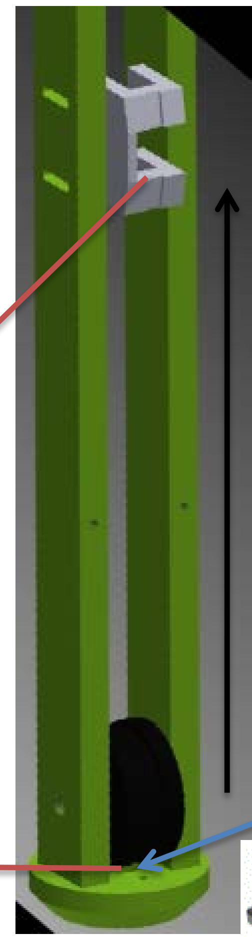


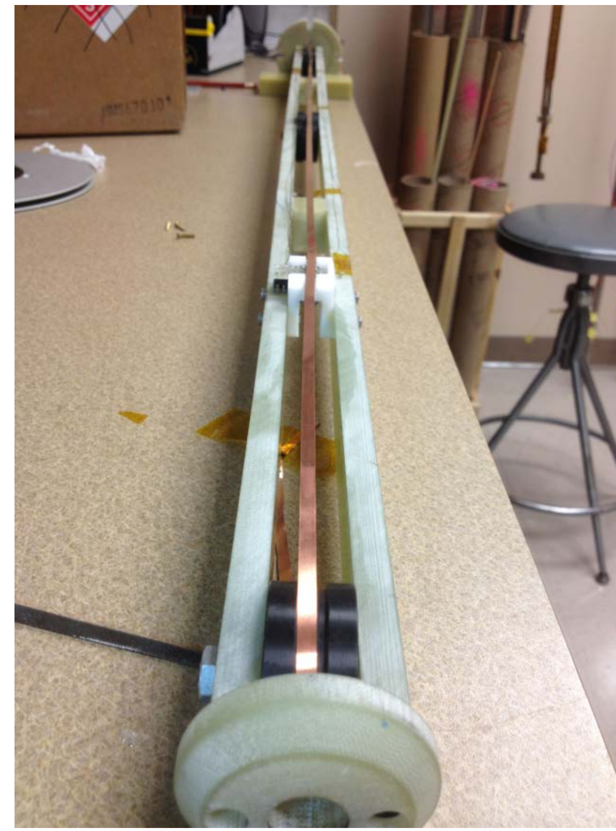
Ic fluctuations along the tape are well correlated between 77 and 4.2 K
This is unusual and probably due to cross section variations
in this VIC tape

Magnetization reel-to-reel measurement in LHe



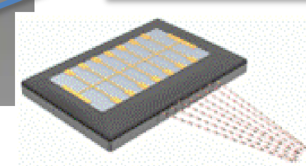
Position of 1st Hall probe array; measuring remanent magnetization



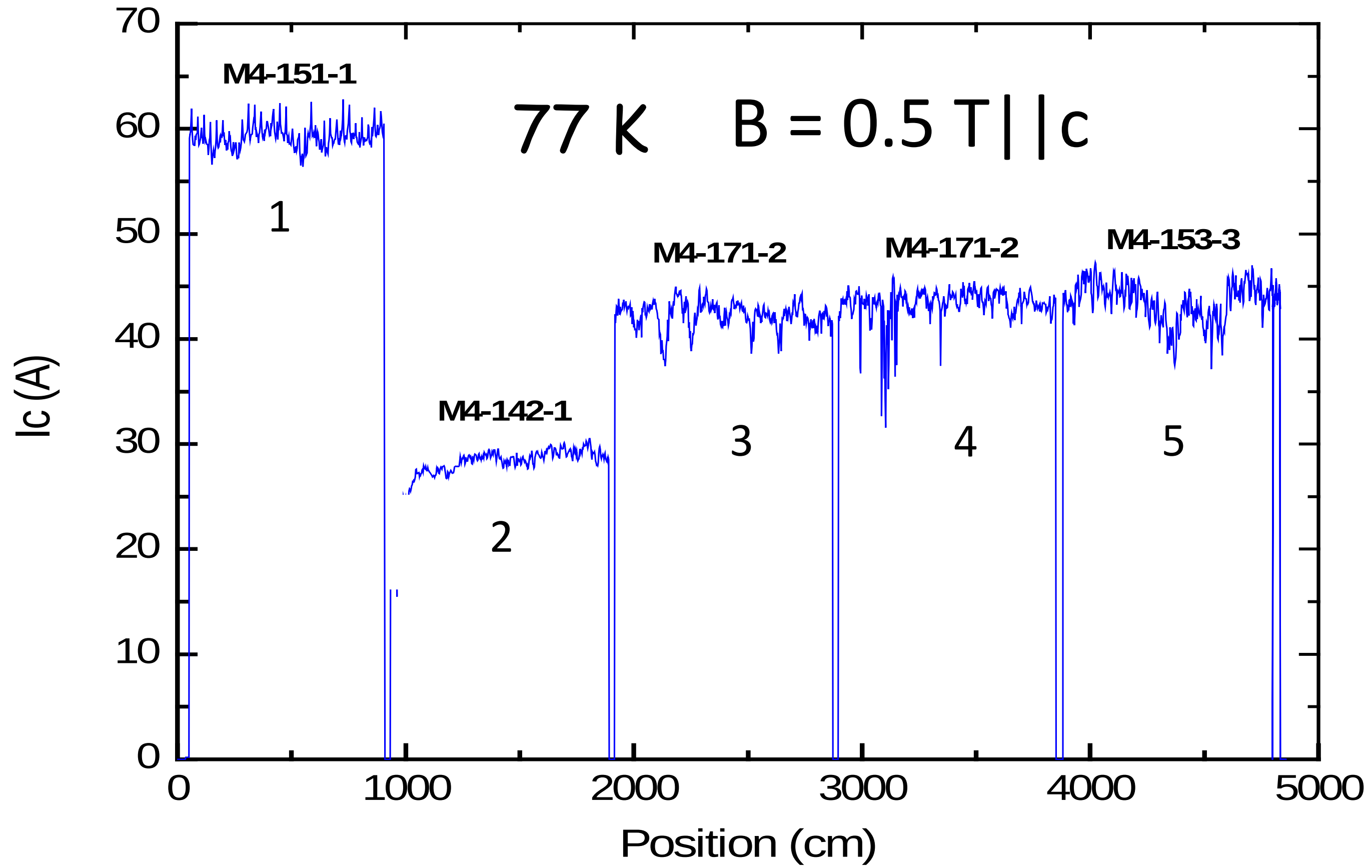


Center of field (B_{max})

Position of 2nd Hall probe array; measuring in field magnetization



5 recent REBCO tapes: Ic vs position:



Again: variations in different tapes:

Tape 1 very high Ic

Tape 2 very low Ic

Slide from quick sales