UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

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Swiss Accelerator Research and Technology

# Activities of the WP2.3 at UNIGE

## Focus on REBCO coated conductors

HFM
High Field Magnets

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International MUON Collider Collaboration

# Outline

- **Results of the measurement campaign on REBCO coated conductors from various manufacturers**
  - Main characteristics of the examined tapes
  - Transport $I_c$ measurements up to 2 kA in variable temperature and at various orientations
  - Magnetization measurements and pinning force analysis
- **A new experiment to test the delamination strength of REBCO coated conductors**
- **Summary and conclusions**

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# What has been tested – Catalogue of the Tapes

| | Width | REBCO Type | REBCO Thickness | Deposition Method | Pinning Type | Hastelloy Thickness | Cu Stabilizer | $I_c$(77K,s.f.) |
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| Fujikura Q1/2019 | 4 mm | EuBCO | 2.5 µm | IBAD/PLD | BHO columns (artificial) | 50 µm | 2 x 40 µm electroplated | n/a |
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| SuperOx Q2/2019 | 4 mm | YBCO | 3.1 µm<br>2.7 µm | IBAD/PLD | $Y_2O_3$ particles (native) | ▲ 100 µm<br>40 µm | 2 x 20 µm electroplated<br>2 x 5 µm electroplated | 550 A/cm<br>n/a |
| 上海超导 SHANGHAI SUPERCONDUCTOR Q3/2021 | 3 mm | EuBCO | 3 µm | IBAD/PLD | BHO columns (artificial) | ▼ 30 µm | 2 x 10 µm electroplated | ▲ 590 A/cm |
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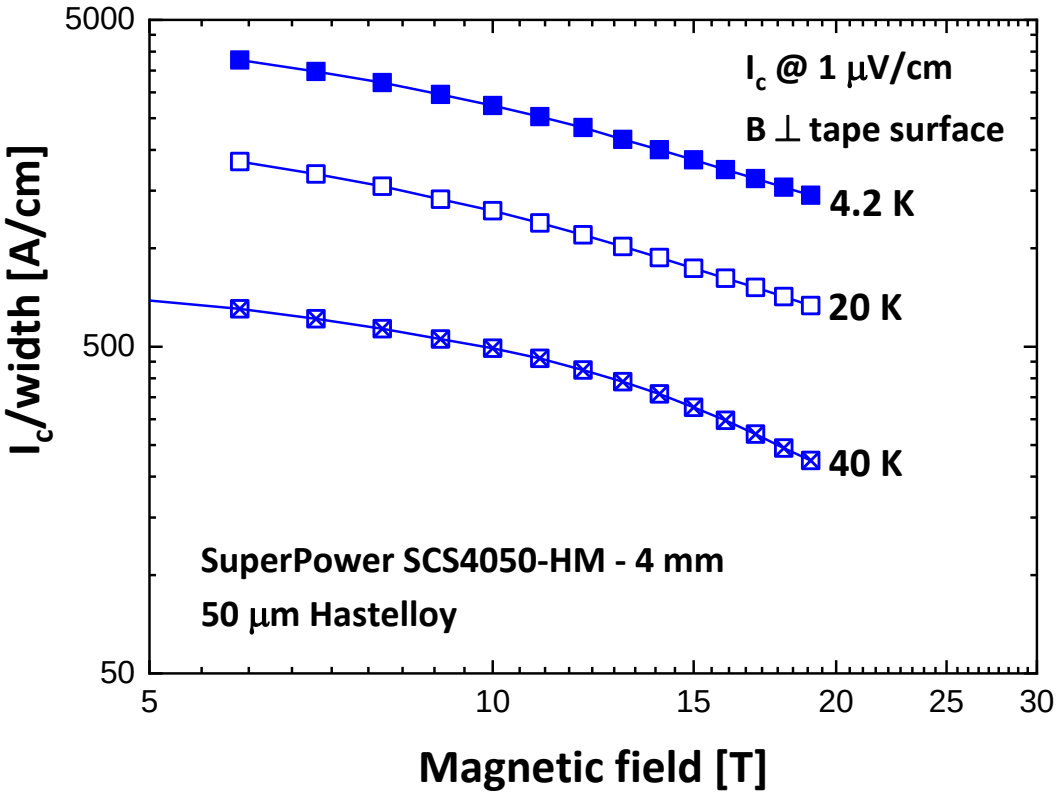
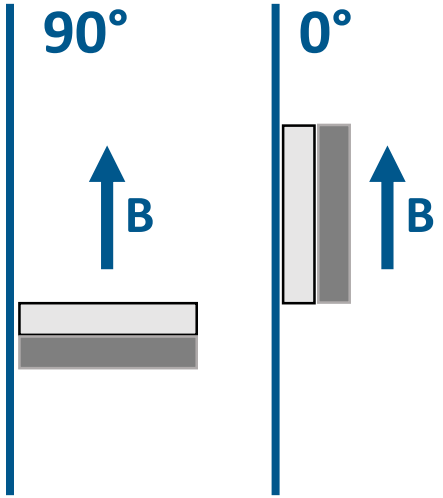
# Characterization protocol

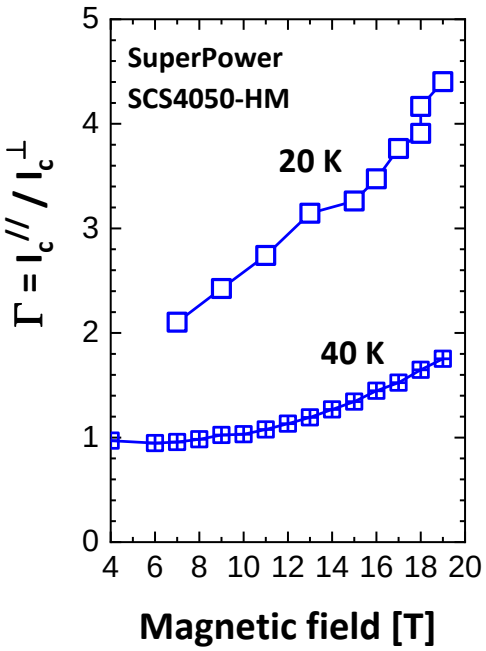
- Transport $I_c$ at 4.2 K, 20 K and 40 K up to 19 T
  - $I_c$ at $\theta$ = 90° and 0° wrt the tape surface + some intermediate angles
  - Currents up to 2 kA (4.2 K) or 1 kA (> 4.2 K) were the upper limits of the experiments
  - Measurements performed on full width tapes
- Magnetization loops up to 77 K and 7 T
- Scaling analysis of the pinning force, from magnetization and transport data

# SuperPower Inc. A Furukawa Company tapes: minimum and maximum $I_c$ at 4.2 K and 20 K

## Material received in Q1/2023

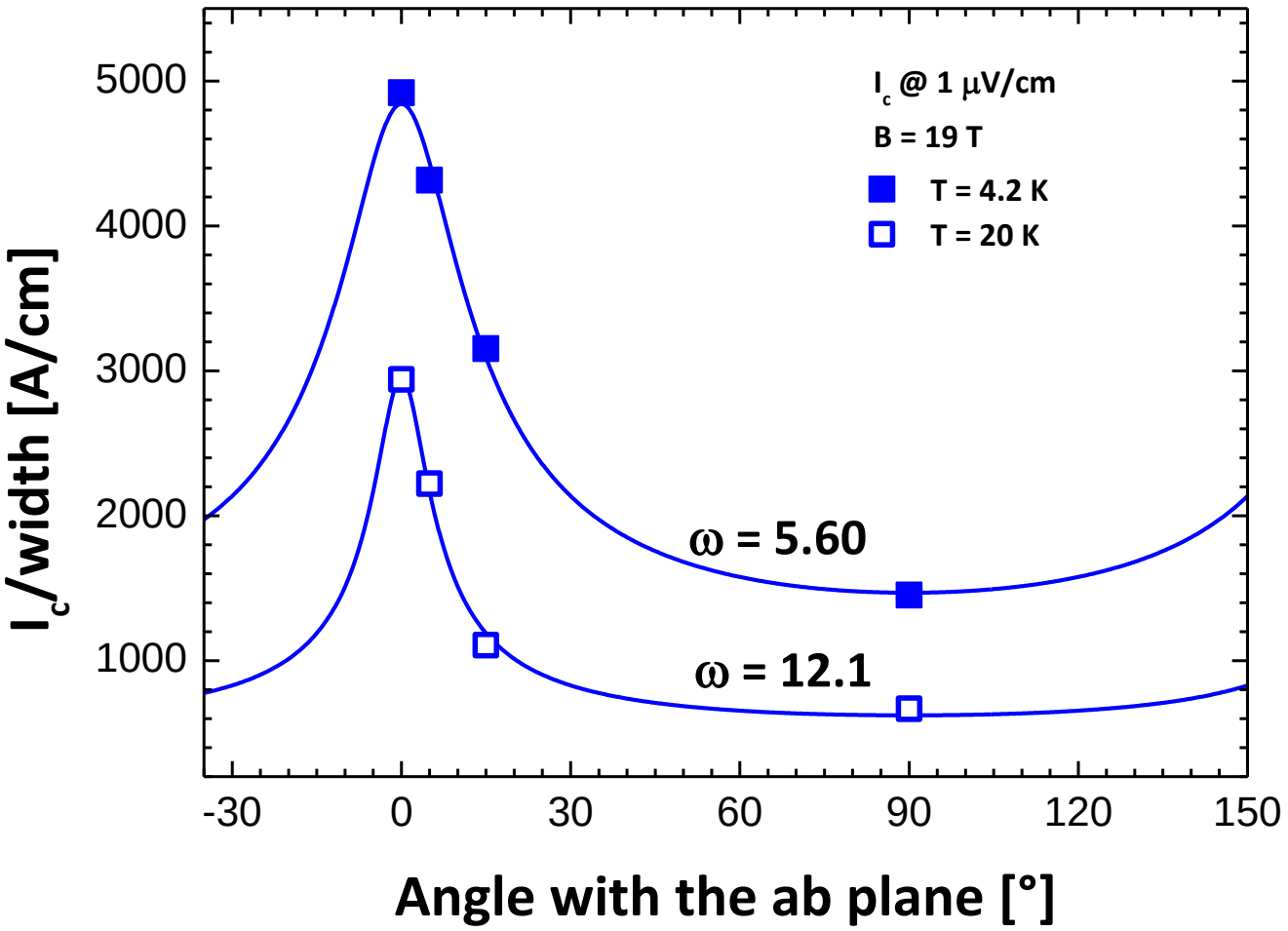



| $I_c$/width (4.2K, 19T) | $I_c$/width (20K, 19T) | $I_c$/width (40K, 19T) |
|---|---|---|
| 1450 A/cm | 670 A/cm | 220 A/cm |

# SuperPower Inc. A Furukawa Company tapes: Angular dependence of $I_c$



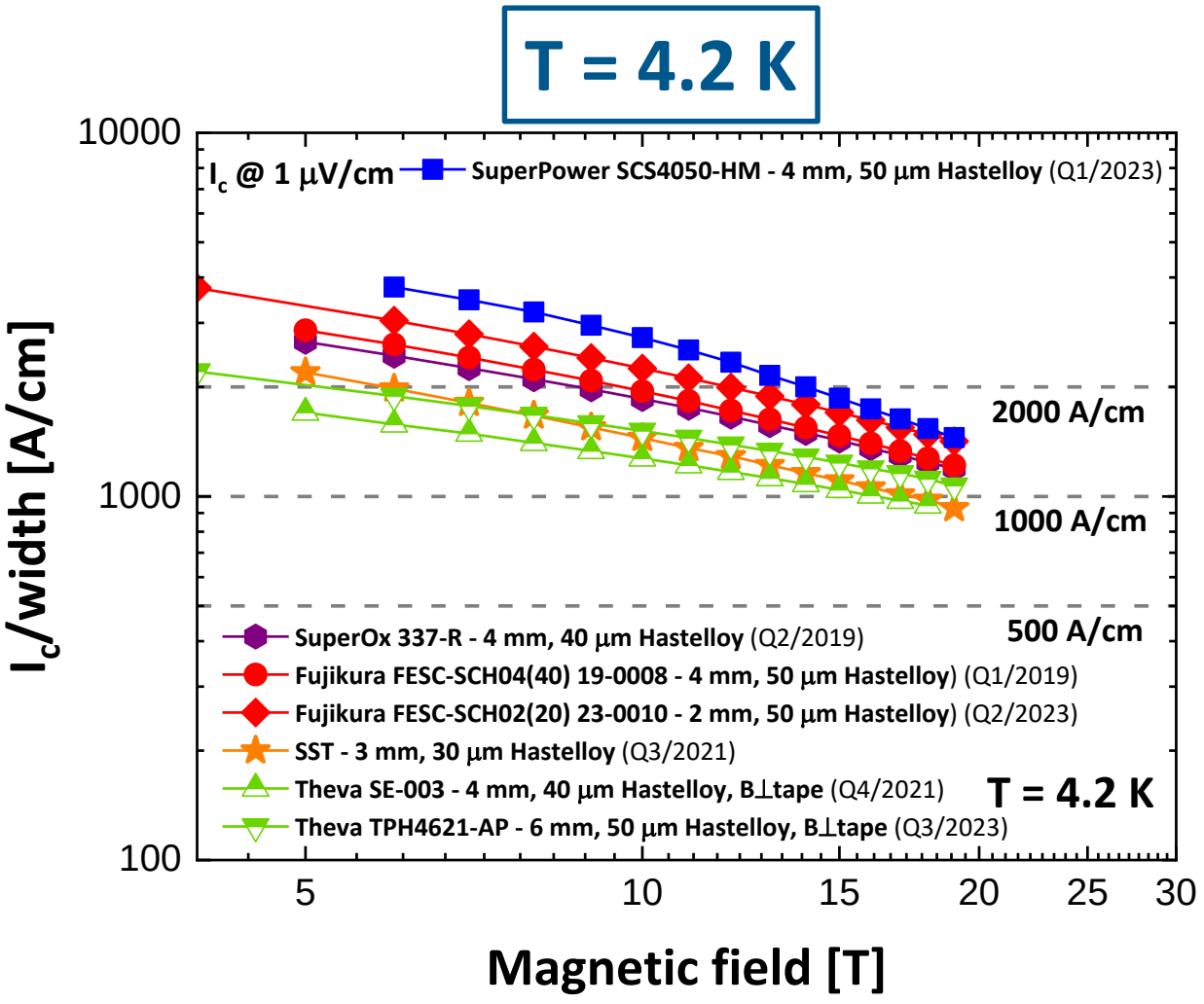

**Fit performed according to the Hilton model**

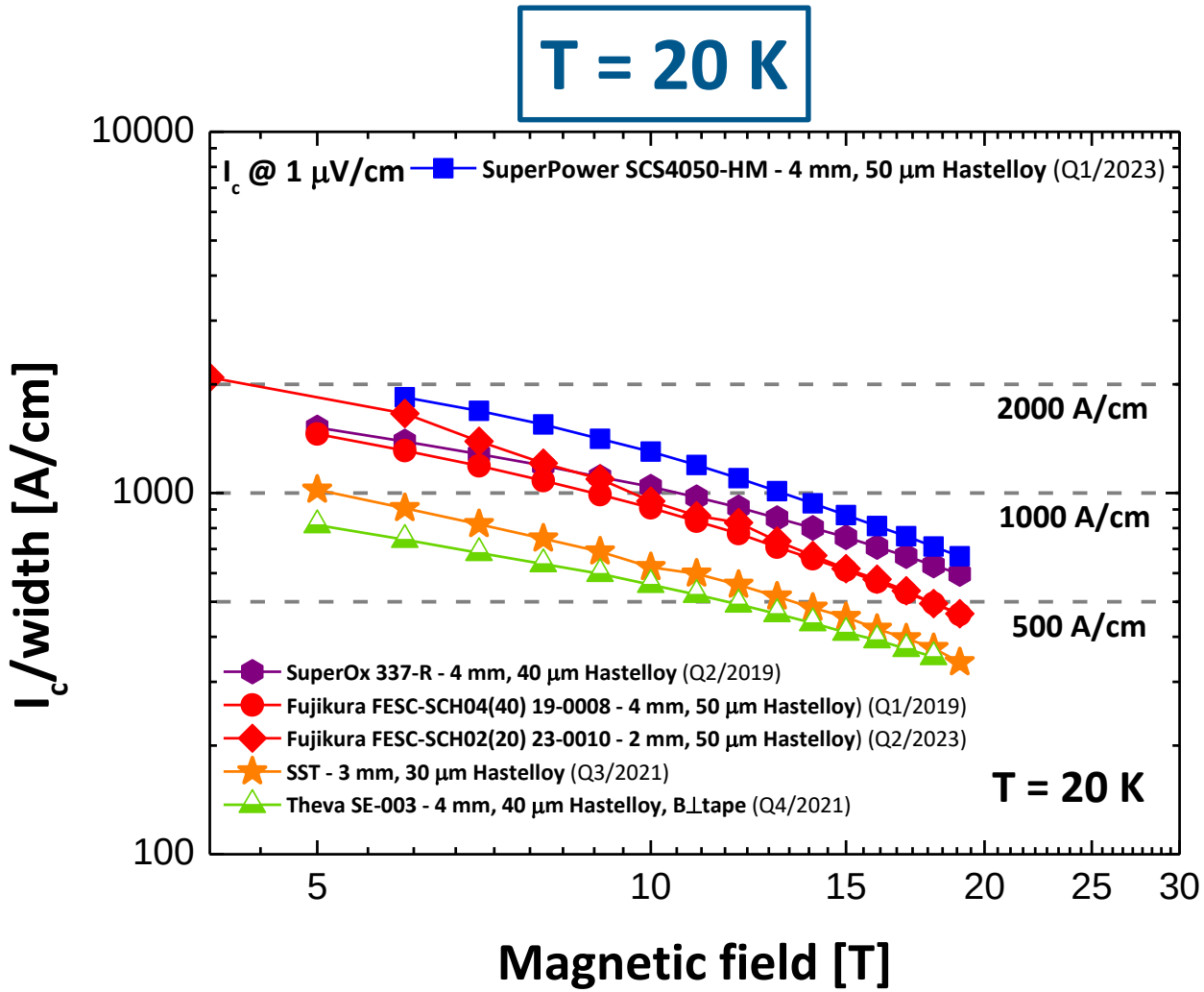
$$I_c(B,\theta) = I_c(B,90°) + \left[I_c(B,0°) - I_c(B,90°)\right]\frac{\omega\, f(\omega,\theta) - 1}{\omega - 1}$$

$$f(\omega,\theta) = \left[\omega^2 \sin^2\theta + \cos^2\theta\right]^{-\frac{1}{2}}$$

Hilton, Gavrilin & Trociewitz, SuST 28 (2015) 074002
DOI: 10.1088/0953-2048/28/7/074002

# Comparison of the performance: $I_c$ / width

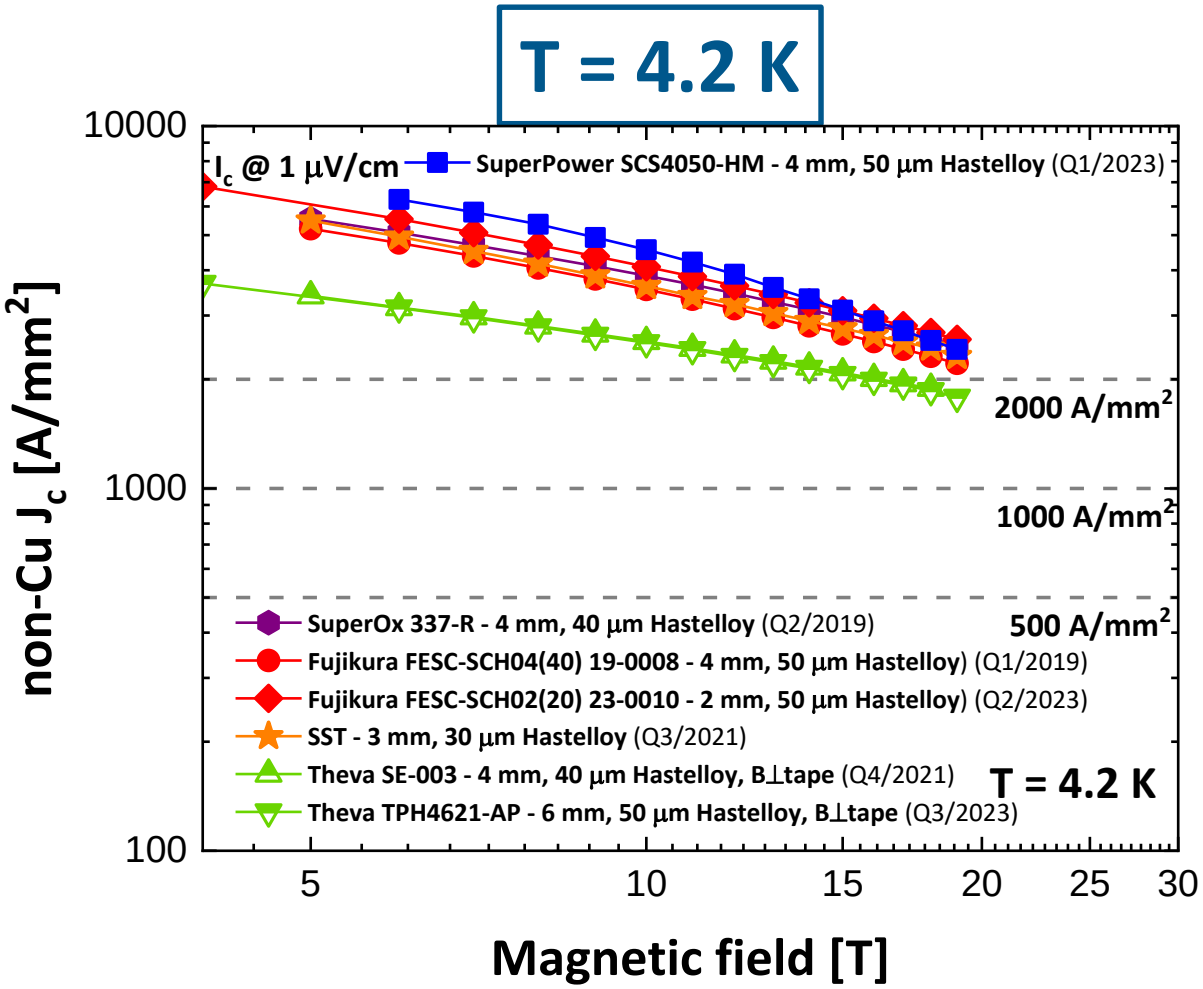


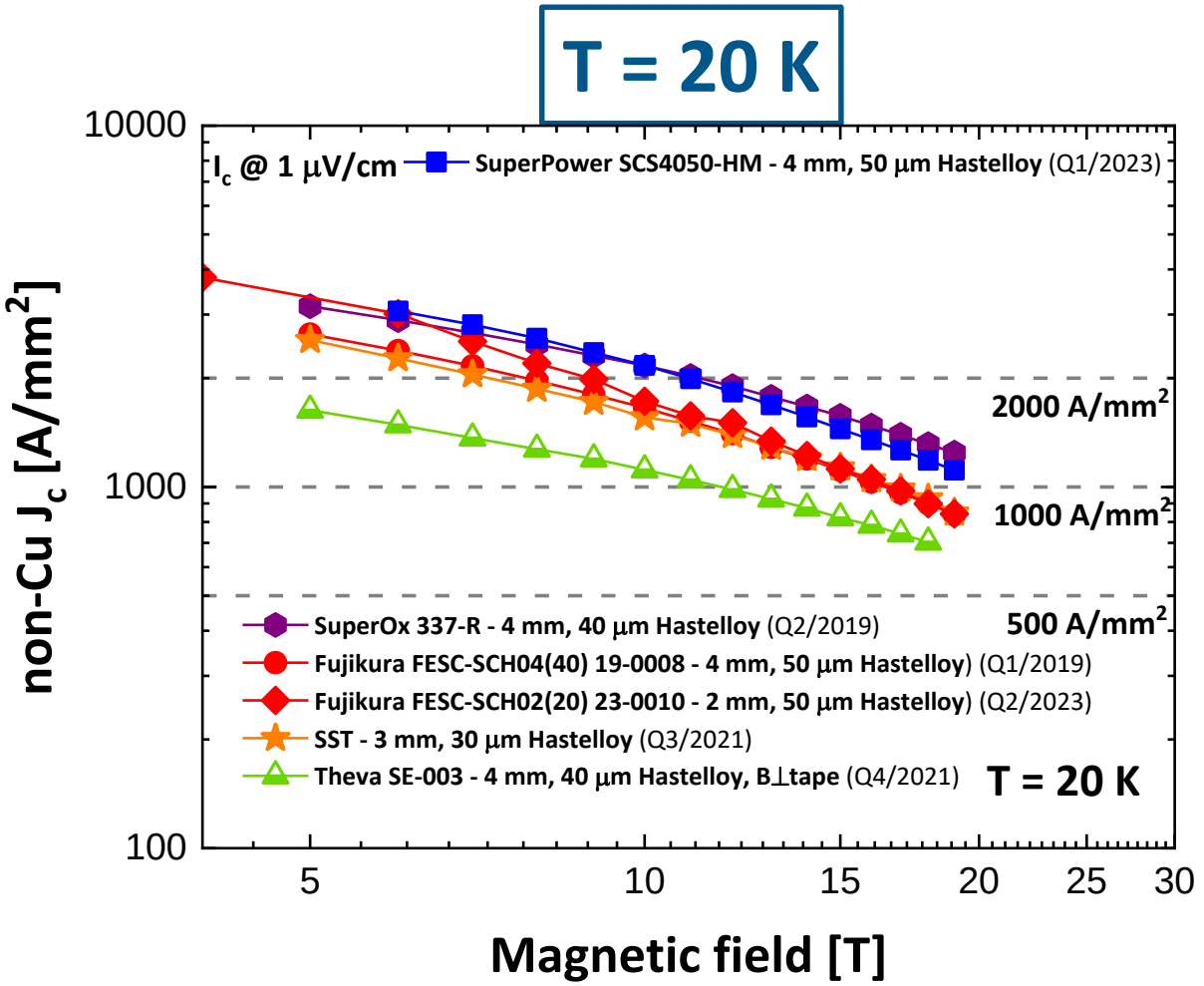



# Comparison of the performance: non-Cu $J_c$

**The non-Cu $J_c$ corresponds to the critical current divided by the tape cross-section area minus the Cu area**

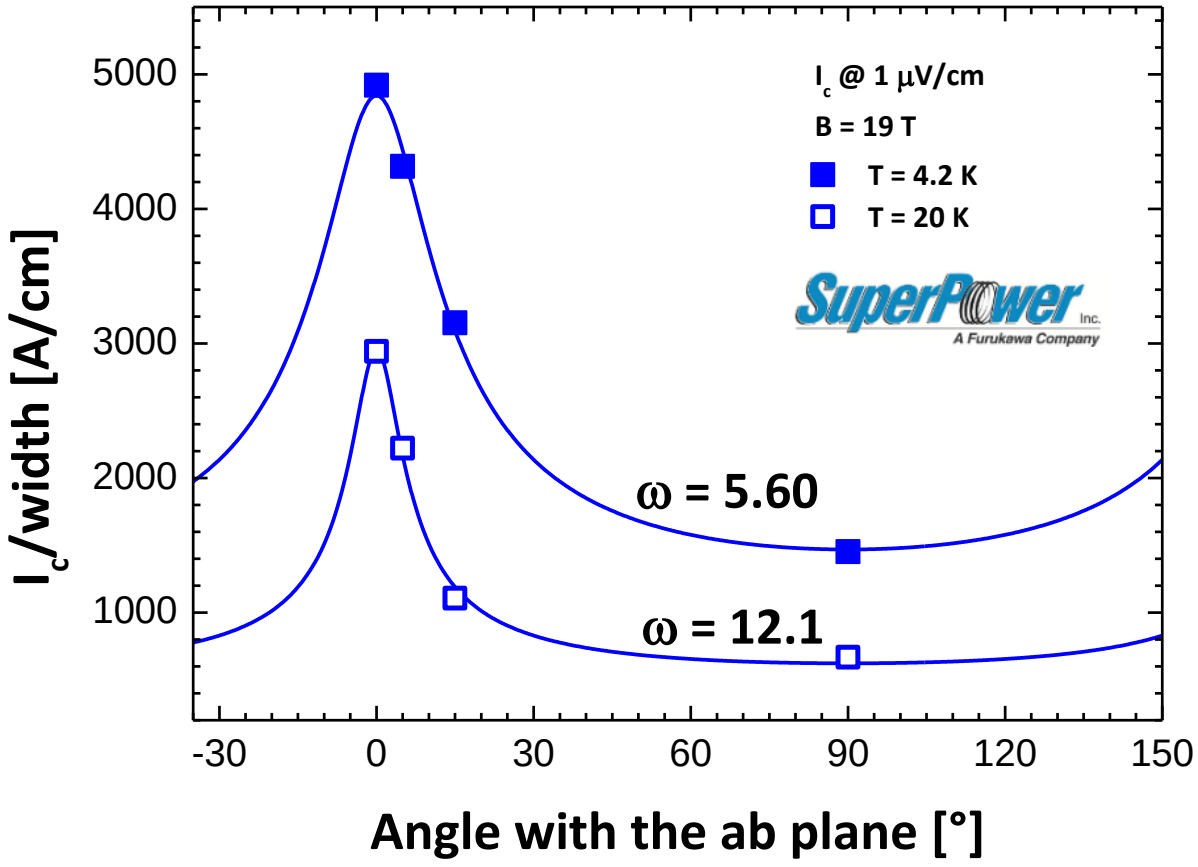
$$\text{non-Cu } J_c = \frac{I_c}{A_{tot} - A_{Cu}}$$



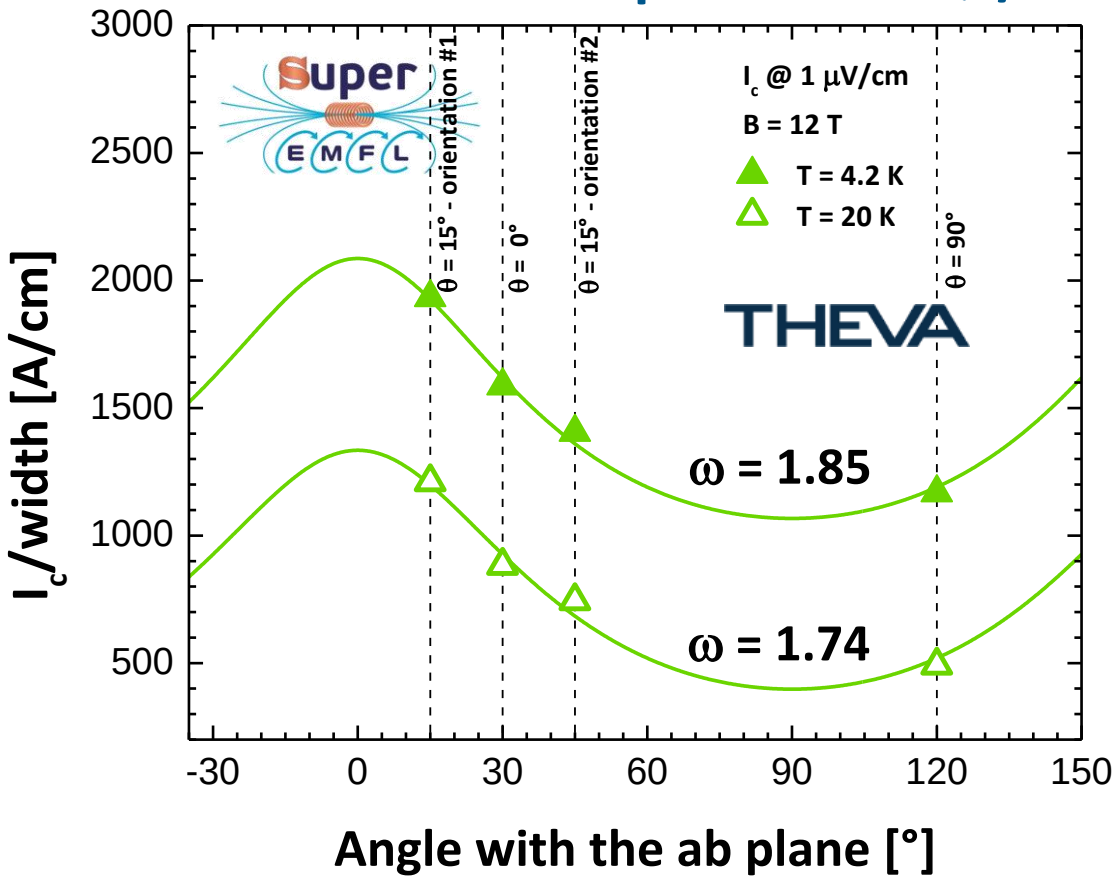



# Angular dependence of $I_c$ : two examples

## Without artificial nanocolumns – Q1/2023




## With artificial nanoparticles – Q4/2021

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Hilton, Gavrilin & Trociewitz, SuST 28 (2015) 074002
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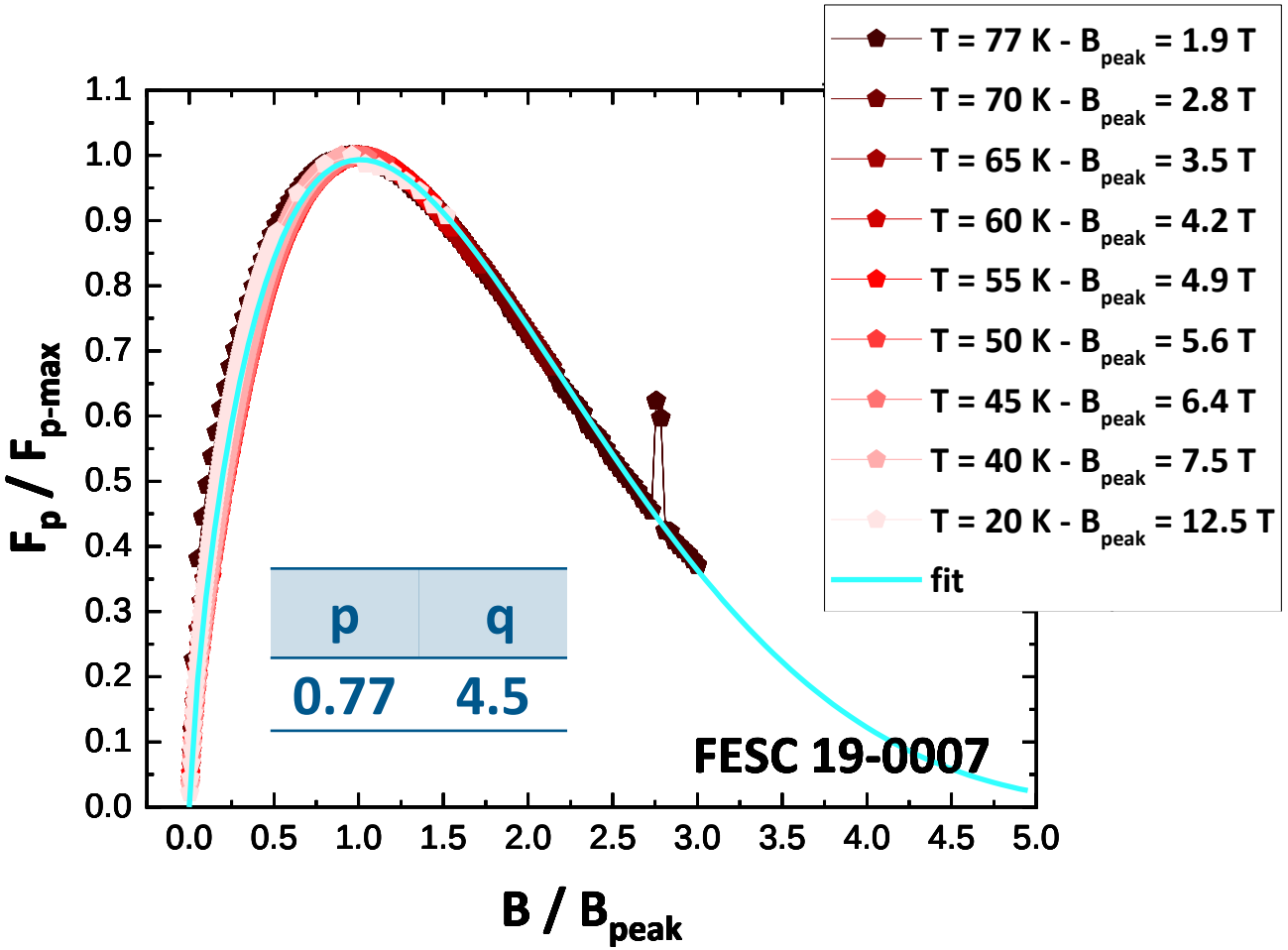
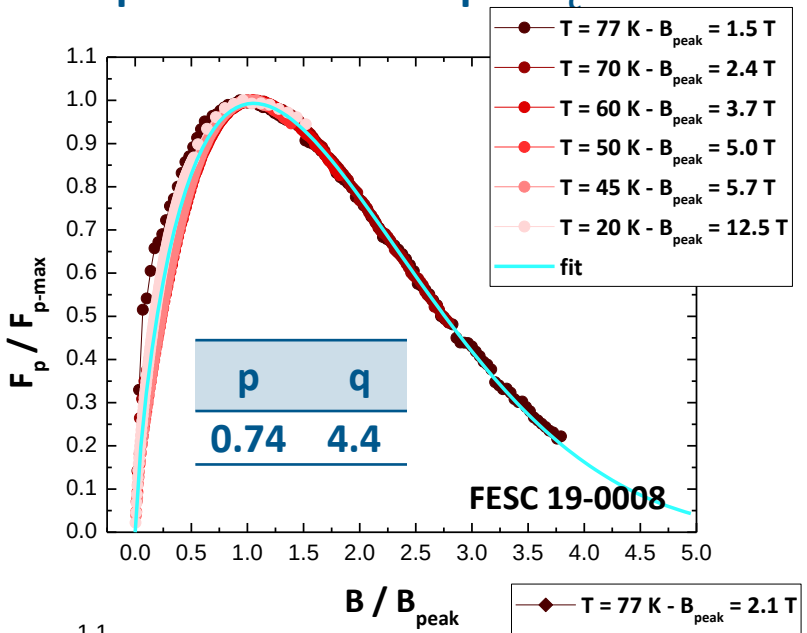
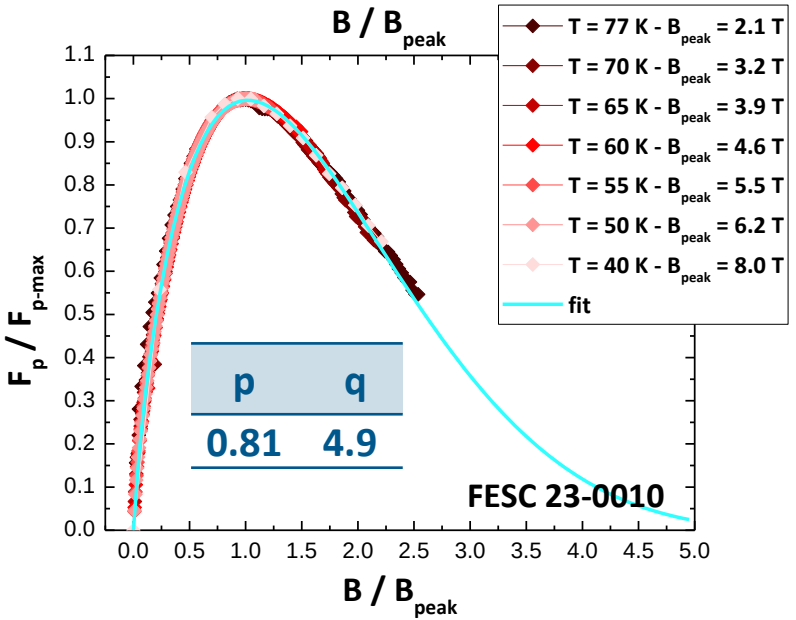
# Fujikura tapes: Pinning force scaling

## Normalized pinning force vs B / $B_{peak}$ , from M(B) curves up to 7 T with some points from transport $I_c$



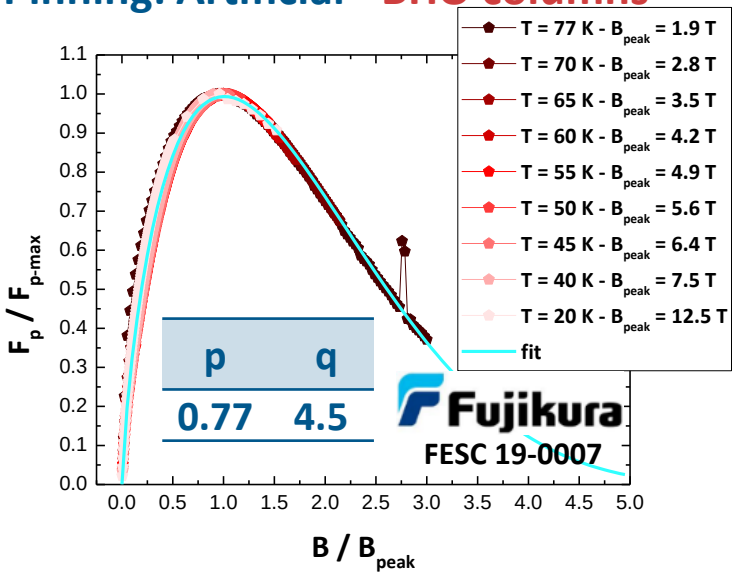




## Concatenated fit of the type $f_p \propto b^p (1-b)^q$

# Pinning force scaling, B ⊥ tape: Comparison

## Pinning: Artificial - BHO columns

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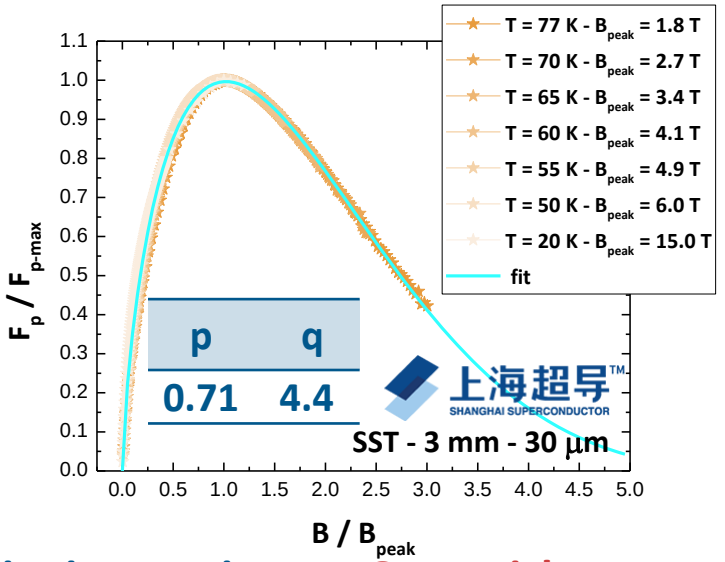
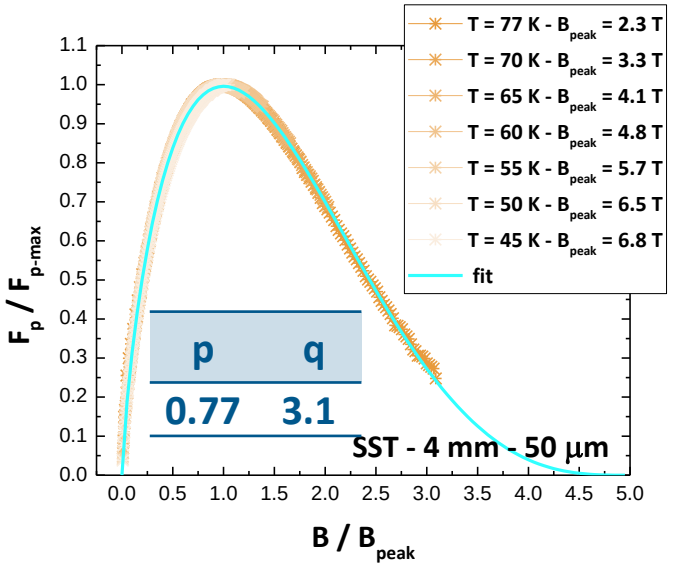
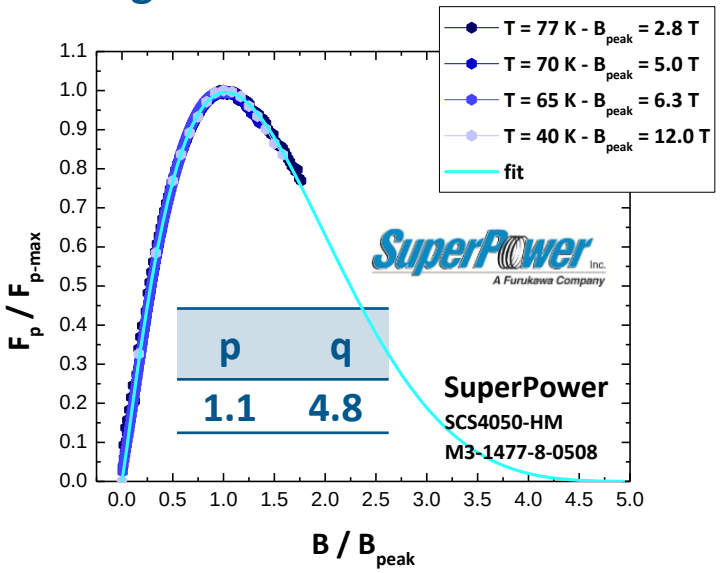
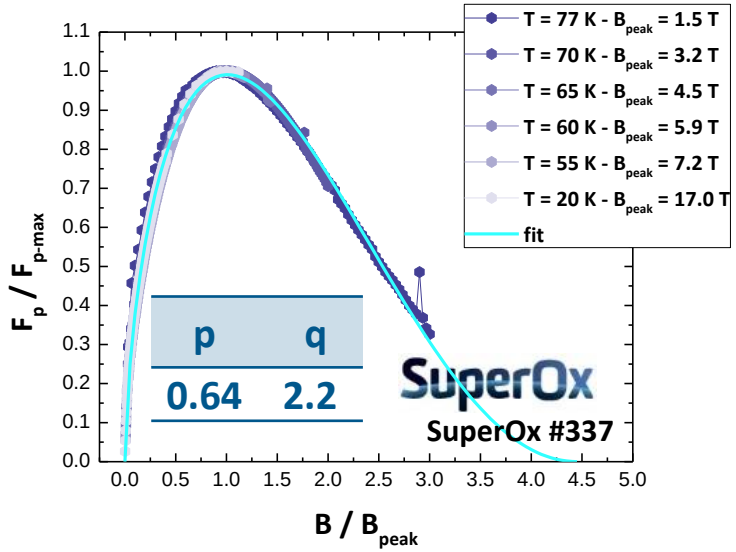


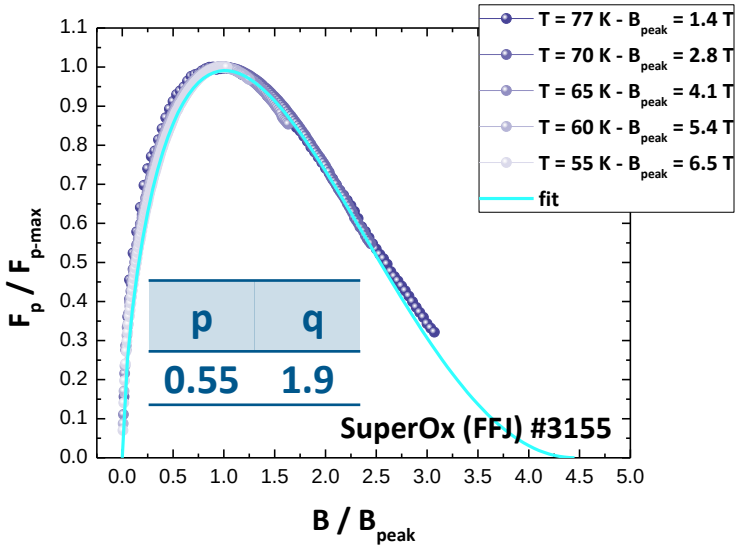




## Pinning: Artificial – BZO columns




## Pinning: Native – $Y_2O_3$ particles



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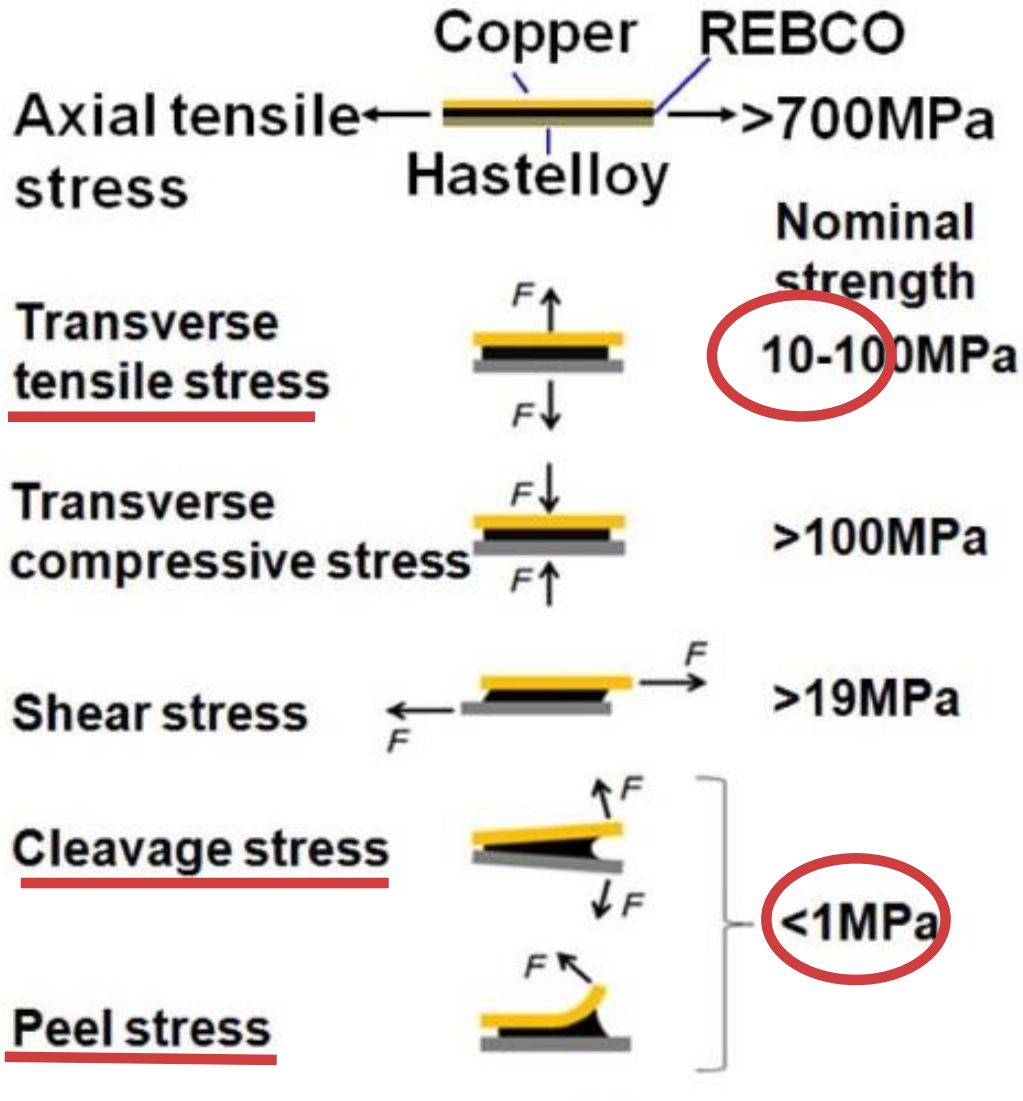
# High in-field $J_c$ is not sufficient for UHF magnets

## A short note on the mechanical properties

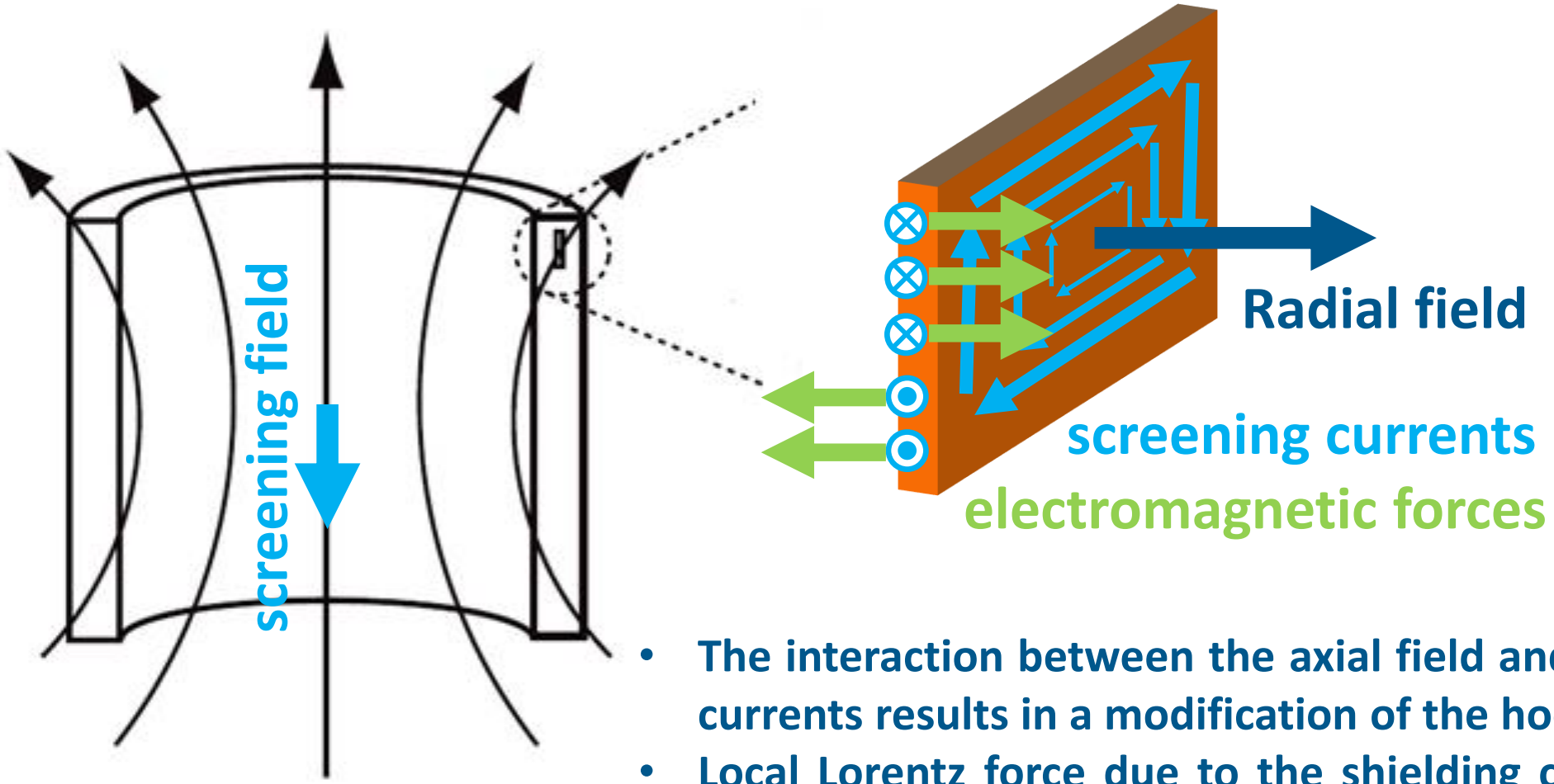



- REBCO tapes are inherently prone to delamination
- Adhesion between layers seems to be process dependent
- A standardized process to determine the properties of the tapes is missing

H. Maeda, and Y. Yanagisawa, IEEE Trans. Appl. Supercond., 24 (2014) 4602412
DOI: 10.1109/TASC.2013.2287707

# High in-field $J_c$ is not sufficient for UHF magnets

## Conductor degradation/delamination due the screening currents

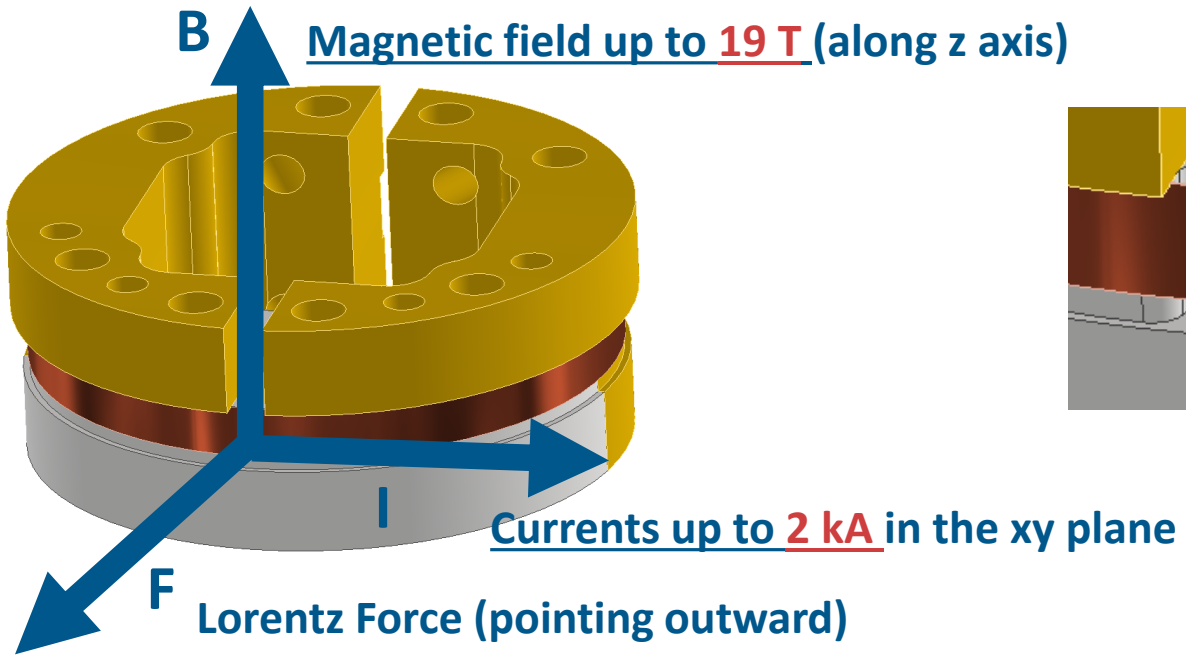



- The interaction between the axial field and the screening currents results in a modification of the hoop stress
- Local Lorentz force due to the shielding currents can be source of delamination force

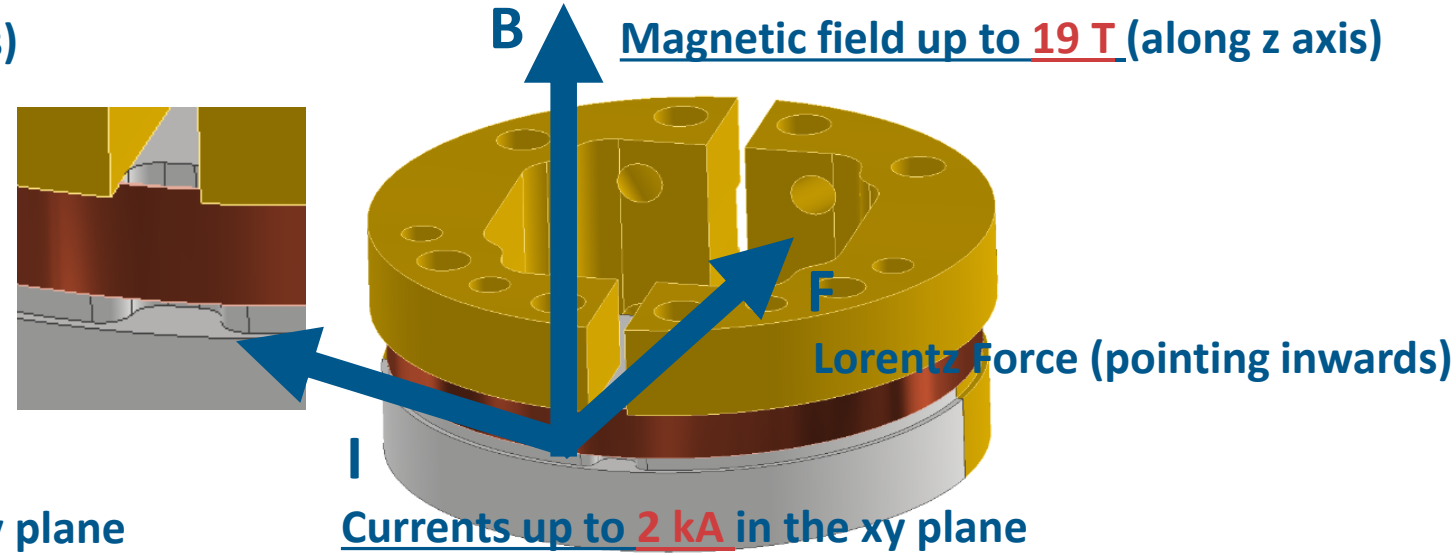
# Delamination strength measurements under I x B force

## A novel experiment for a direct measurement of the conductor degradation

### REBCO layer on the outside

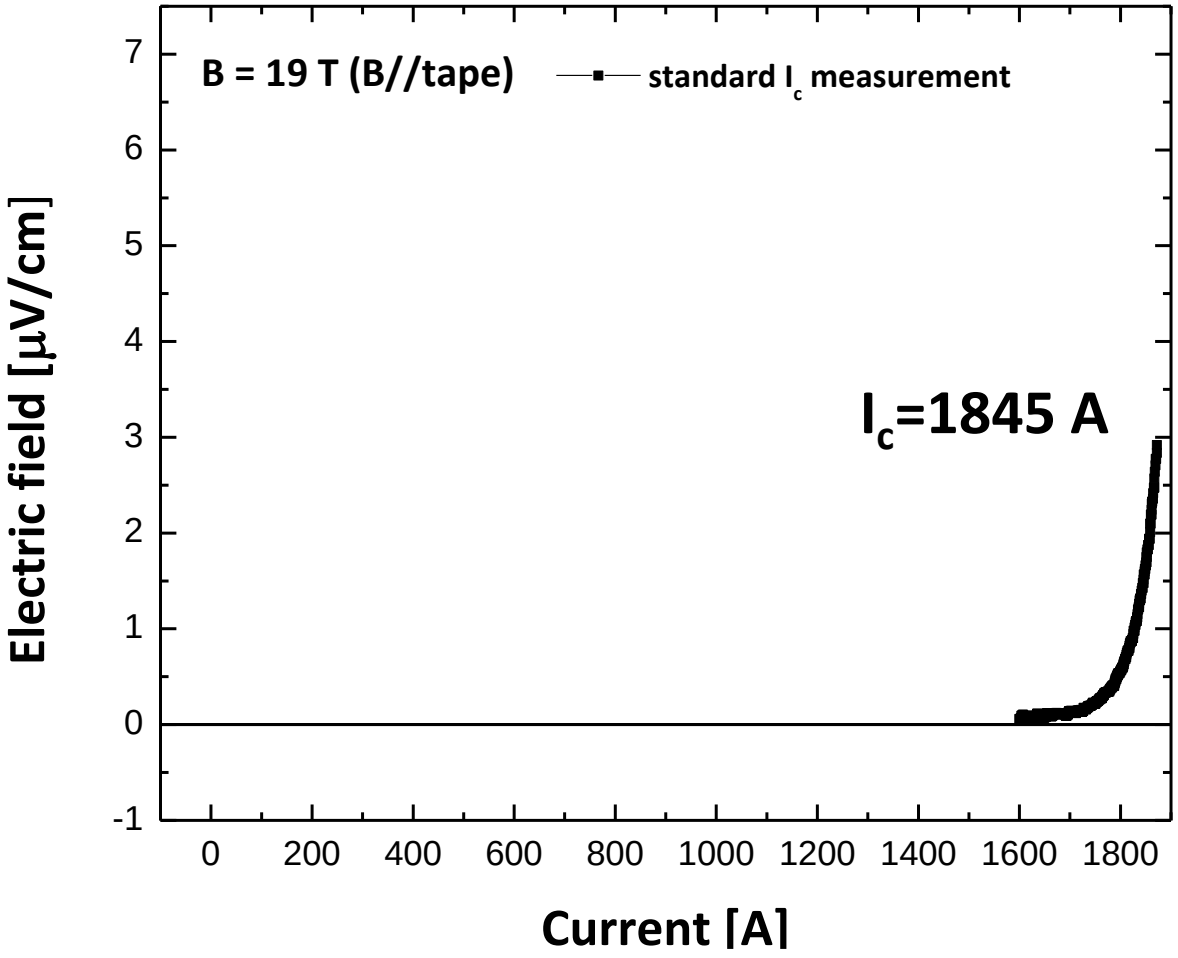



### REBCO layer on the inside

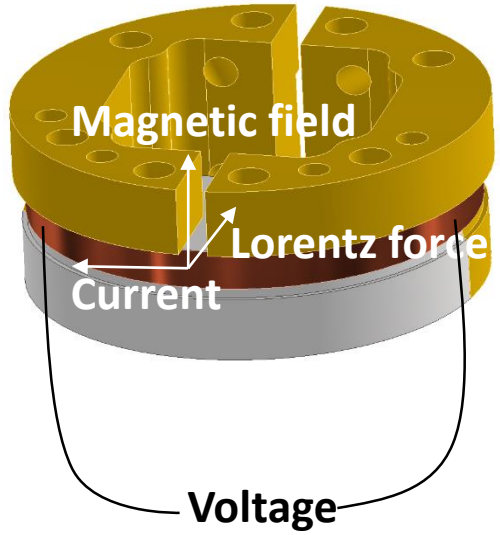



The average stress due to the Lorentz force is $\bar{\sigma}_T = \frac{F_R}{S} = \frac{I\,B}{w}$

# Results of the experiment #1 on Fujikura FESC SCH04




**Reference $I_c$ measurement**
**Force inwards**
**REBCO layer inside**




**Quench protection threshold ~ 10 μΩ/cm**

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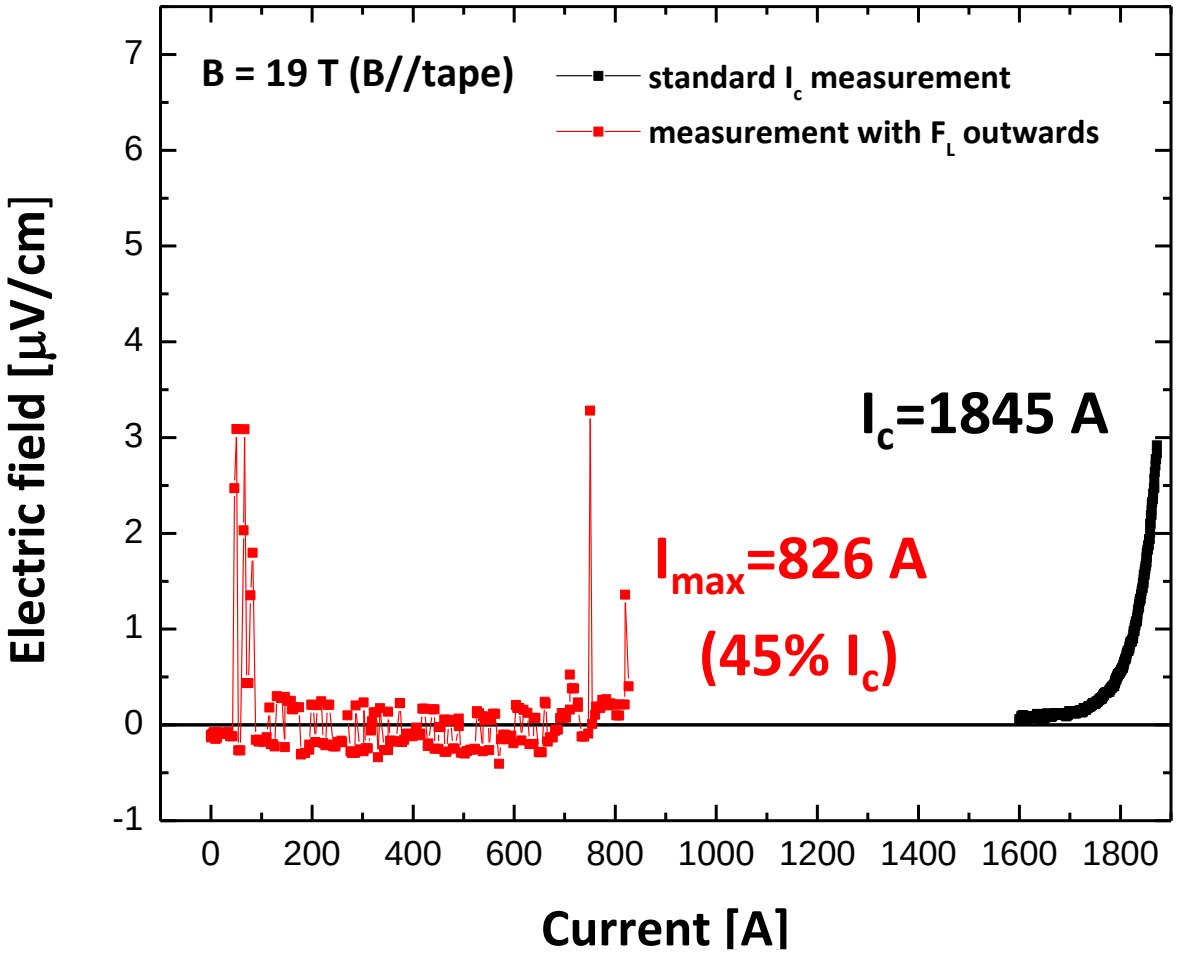
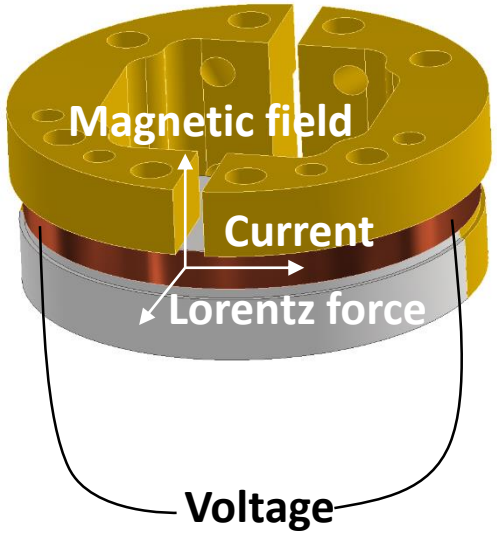



**Delamination test - configuration #1**

**Force outwards**

**REBCO layer outside**

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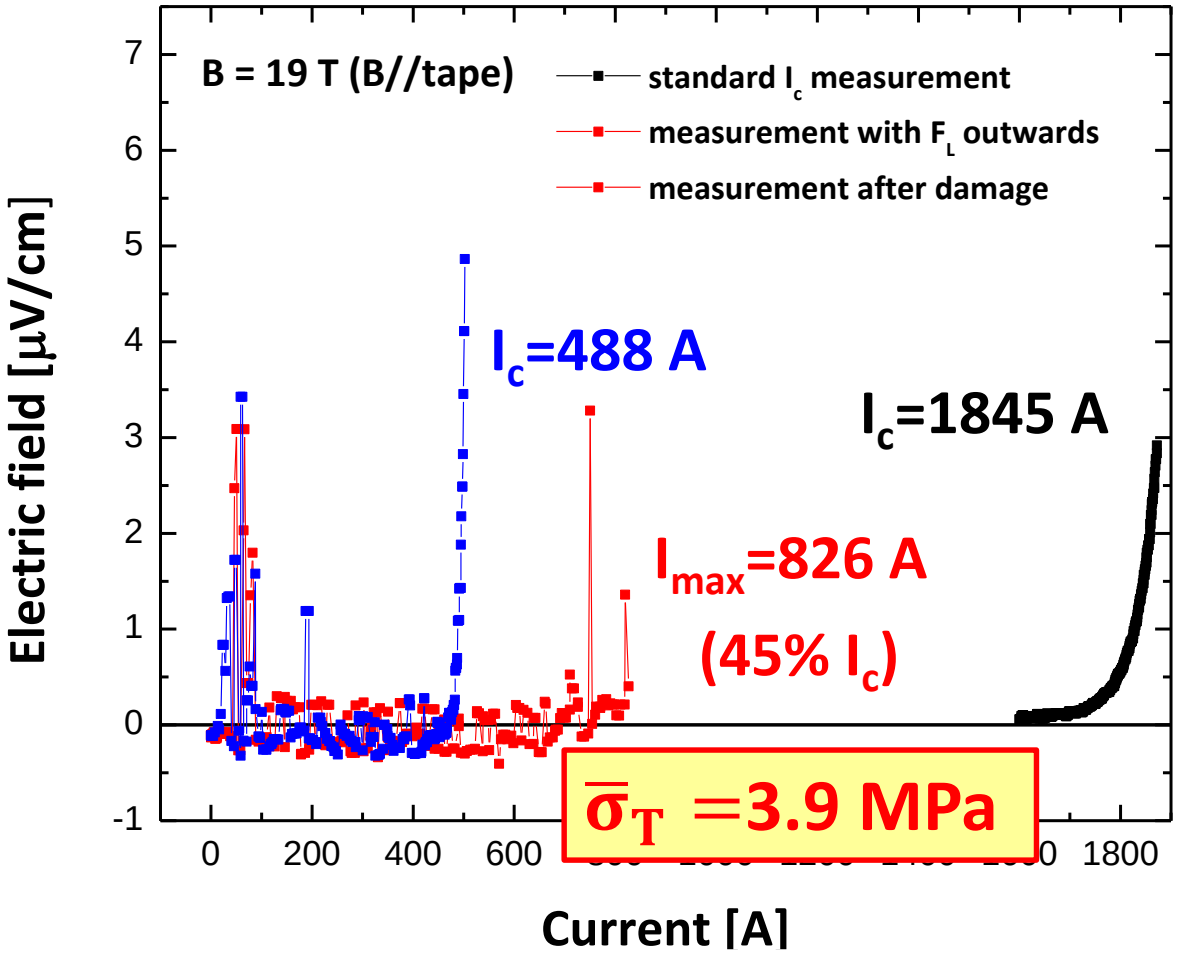


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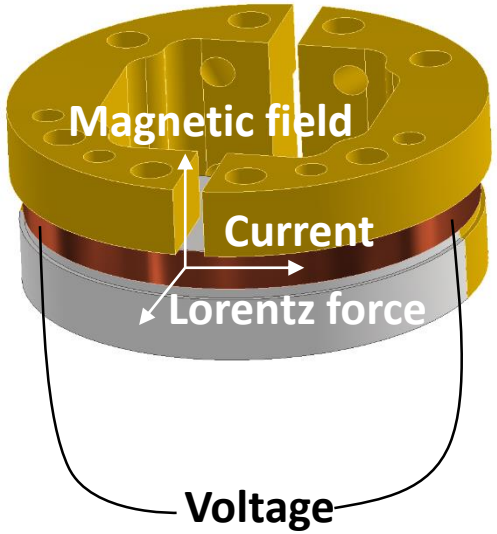
**REBCO layer outside**




**Quench protection threshold ~ 10 μΩ/cm**

# What has been tested so far

Fujikura

Type: FESC SCH04
Tape ID: 19-0008

Delamination strength ~ 4 MPa
(45% $I_c$)

$\bar{\sigma}_T$ =3.9 MPa $F_L$ outward

$\bar{\sigma}_T$ =4.1 MPa $F_L$ inward

Fujikura

Type: FESC SCH02
Tape ID: 23-0010

Delamination strength ~ 4.3 MPa
(39% $I_c$)

$\bar{\sigma}_T$ =4.3 MPa $F_L$ inward

SuperPower Inc.

Type: SCS4050-AP
Tape ID: M3-1464-7

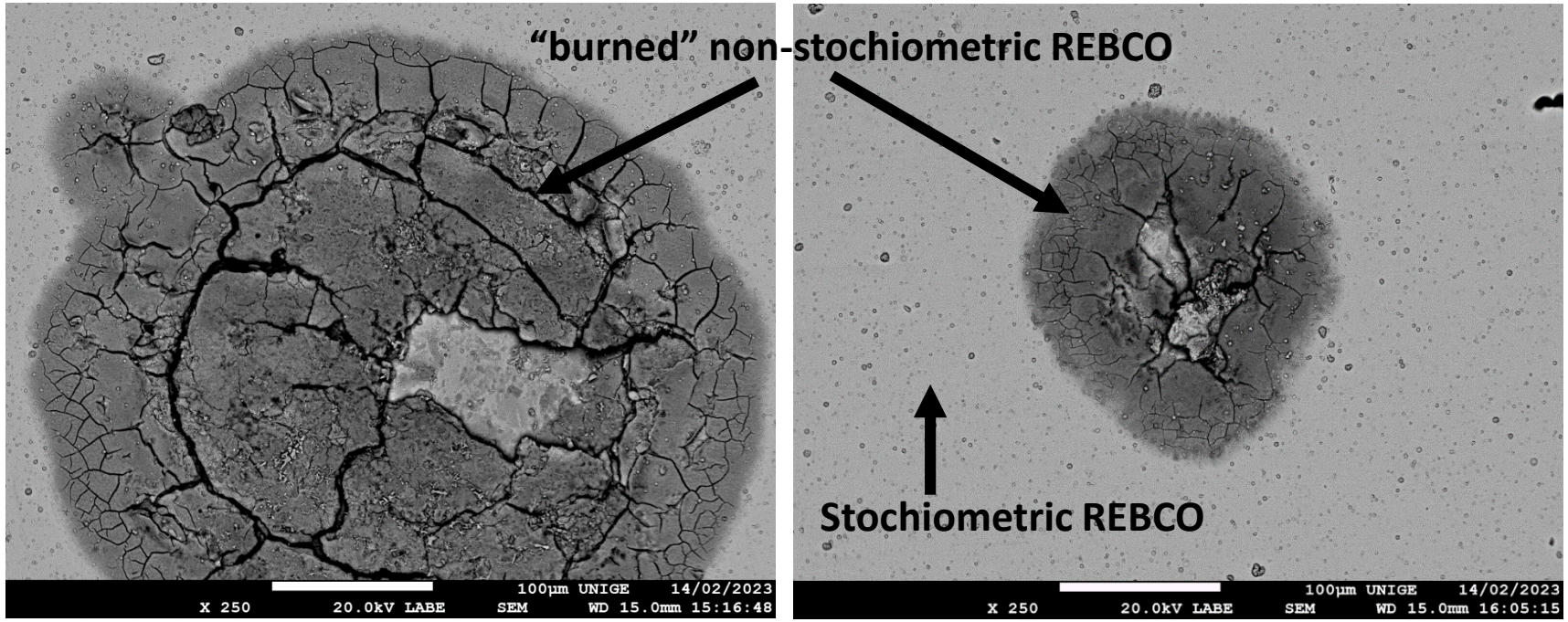
Delamination strength ~ 5.5 MPa
(82% $I_c$)

$\bar{\sigma}_T$ =5.5 MPa $F_L$ inward

# Delamination strength and forensic microscopy

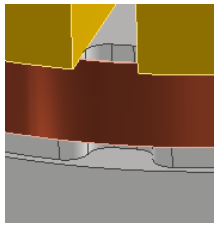
## SEM-EDX and 3D Optical microscopy

**Delamination → Quench → Local heating → Blistering**



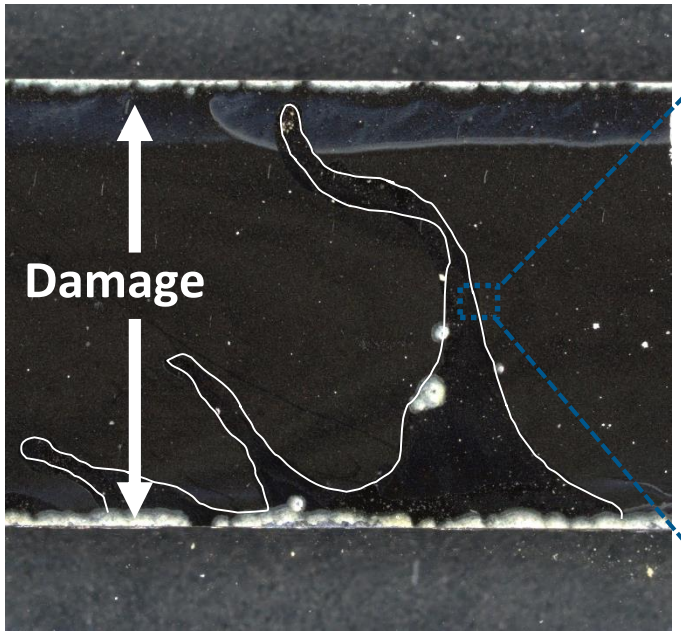
# Delamination strength and forensic microscopy

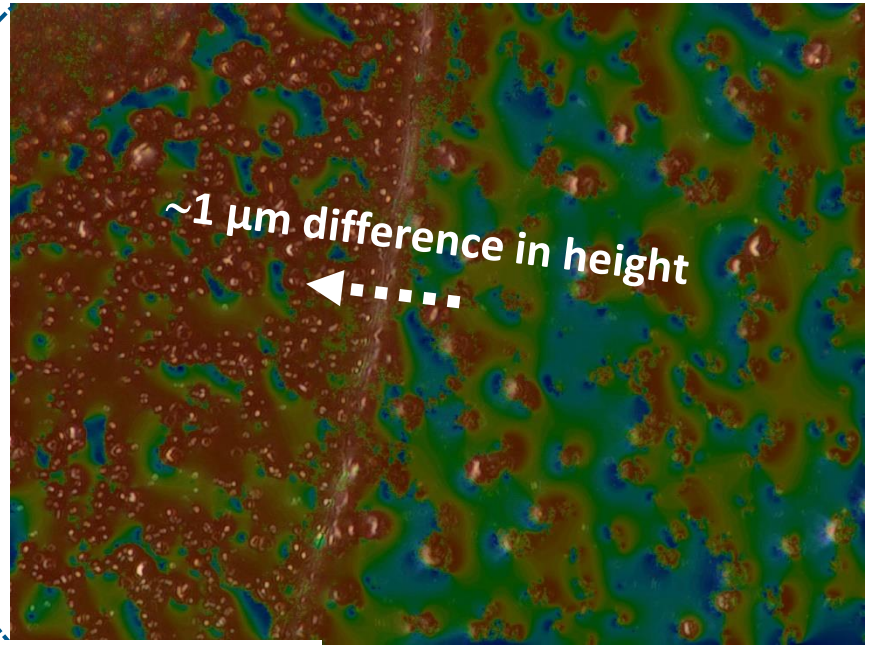
## SEM-EDX and 3D Optical microscopy



Evidence of delaminated area where the tape was not supported

3D optical microscope analysis




z-axis color code

97% of $I_c$ was lost after the delamination experiment

# What has been tested so far

Fujikura

Type: FESC SCH04
Tape ID: 19-0008

Delamination strength ~ 4 MPa
(45% $I_c$)

$\bar{\sigma}_T$ =3.9 MPa  $F_L$ outward

$\bar{\sigma}_T$ =4.1 MPa  $F_L$ inward

Longitudinal damage on both edges of the CC + Blisters

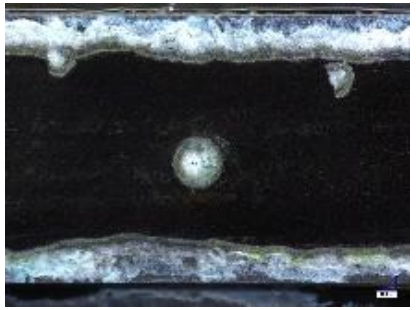
Fujikura

Type: FESC SCH02
Tape ID: 23-0010

Delamination strength ~ 4.3 MPa
(39% $I_c$)

$\bar{\sigma}_T$ =4.3 MPa  $F_L$ inward

Longitudinal damage on both edges of the CC + Blisters



SuperPower Inc.

Type: SCS4050-AP
Tape ID: M3-1464-7

Delamination strength ~ 5.5 MPa
(82% $I_c$)

$\bar{\sigma}_T$ =5.5 MPa  $F_L$ inward

Longitudinal damage on 1 edge of the CC + Blisters

# Conclusions

The performance gap at low temperatures, high fields between various manufacturers is relatively small in spite of the differences in process, composition and pinning landscape

Magnet designers need high performance tapes but also high fidelity $I_c(B,\theta,T)$ characterization. However, it is difficult to produce complete datasets

The new experiment to measure the delamination strength of REBCO tapes aims to produce robust data with a reproducible process. The ongoing activities involve:

- Systematic study about the role of the CC edges on the delamination strength (Laser vs mechanical slitting; Slitting on 1 or 2 edges)
- FEM study in collaboration with CERN to determine the local stress distribution in our experiment
- Correlation between visual damage (optical microscopy) and local $I_c$ values from magnetic scans

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

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# Thank you for the attention !

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HFM
High Field Magnets

International MUON Collider Collaboration