CCA2025
International Workshop on Coated Conductors for Applications
CERN | March 11-13, 2025

Delamination of REBCO tapes induced by electromagnetic forces: an experimental study

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Outline

- Degradation due to delamination
- The experiment
- Accompanying FEA

Speaker:
Gianluca VERNASSA

- Experimental results
- Forensic studies

Speaker:
Célia LUCAS ESPARSEIL

- Conclusions & perspectives

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- **Degradation due to delamination**
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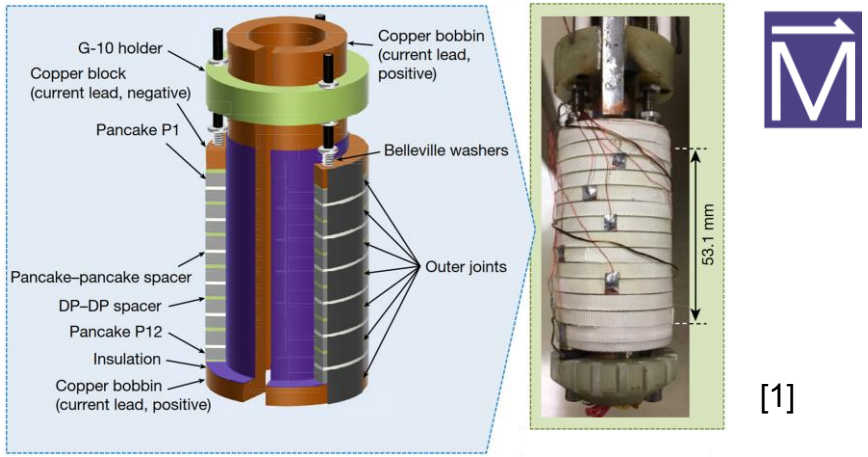
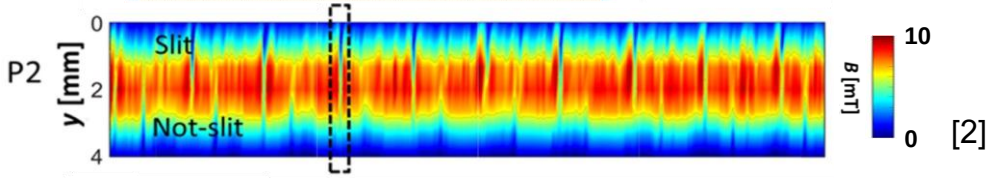
Delamination in UHF magnets

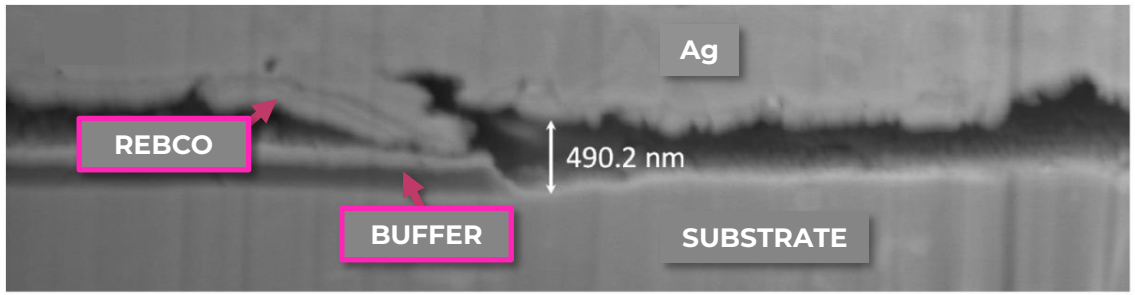
Little Big Coil 2 (42.5 T) at NHMFL - 2017



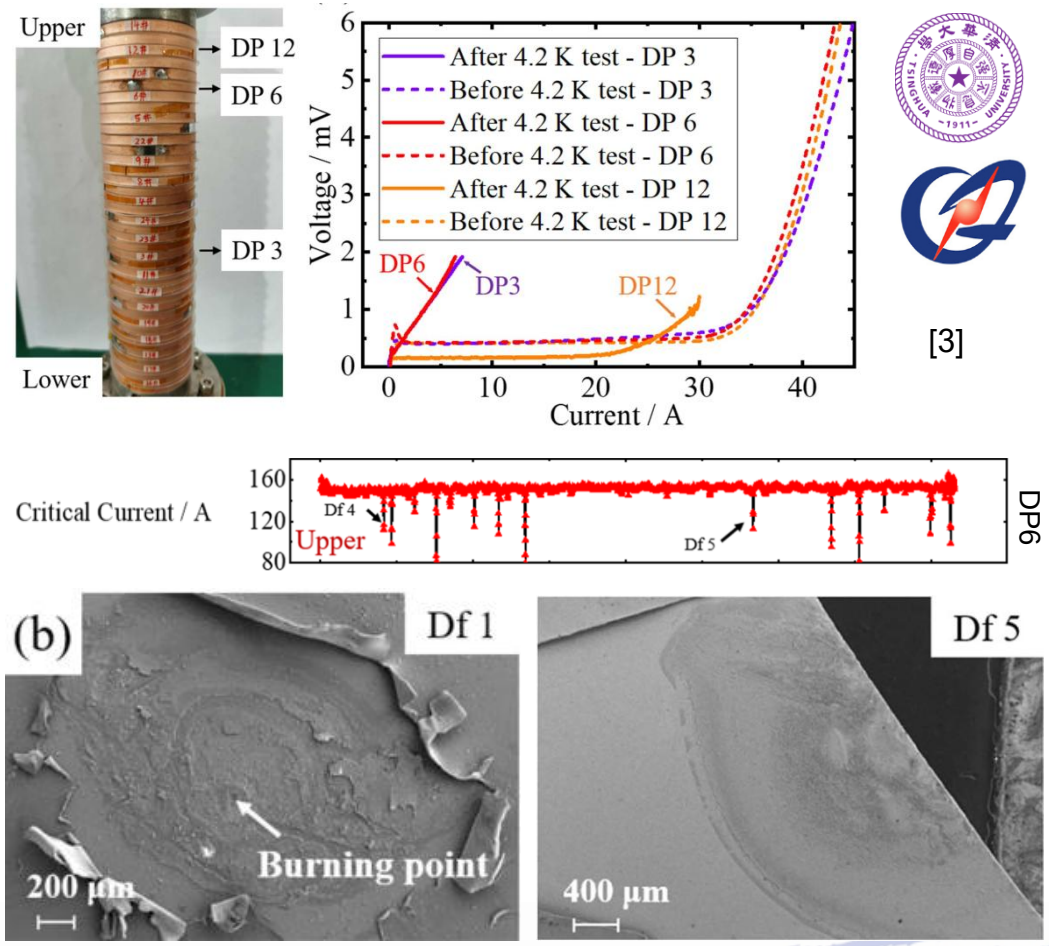
[1]



[2]



18.7 T insert for 35 T – ASIPP / Tsinghua - 2023

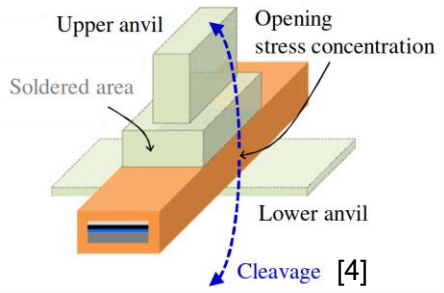


[3]

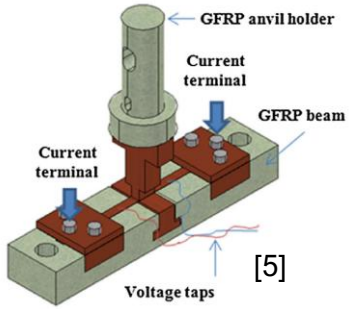
Images re-adapted from [1], [2], [3]

Mechanical measurement techniques

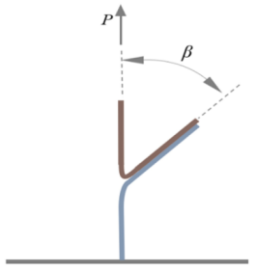
- Several mechanical testing methods have been proposed:
  - anvill / pin pull / bend peel;
  - peel off / cleavage test.



[4]



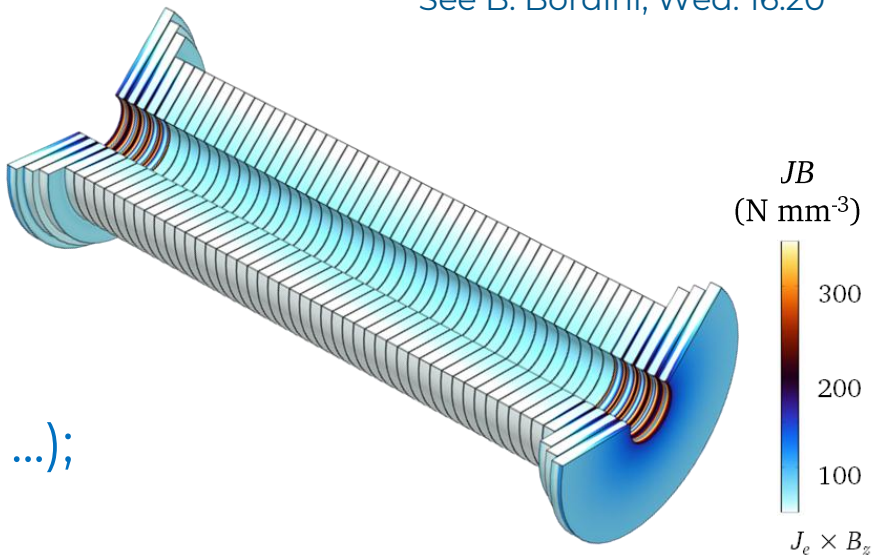
[5]



Schematic of a peel off test [6]

Example of Screening Currents Induced Lorentz forces in a 40 T Final Cooling Solenoid for the Muon Collider

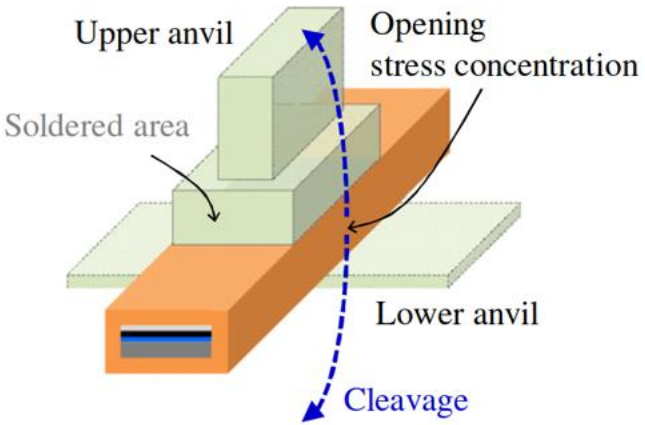
See B. Bordini, Wed. 16:20



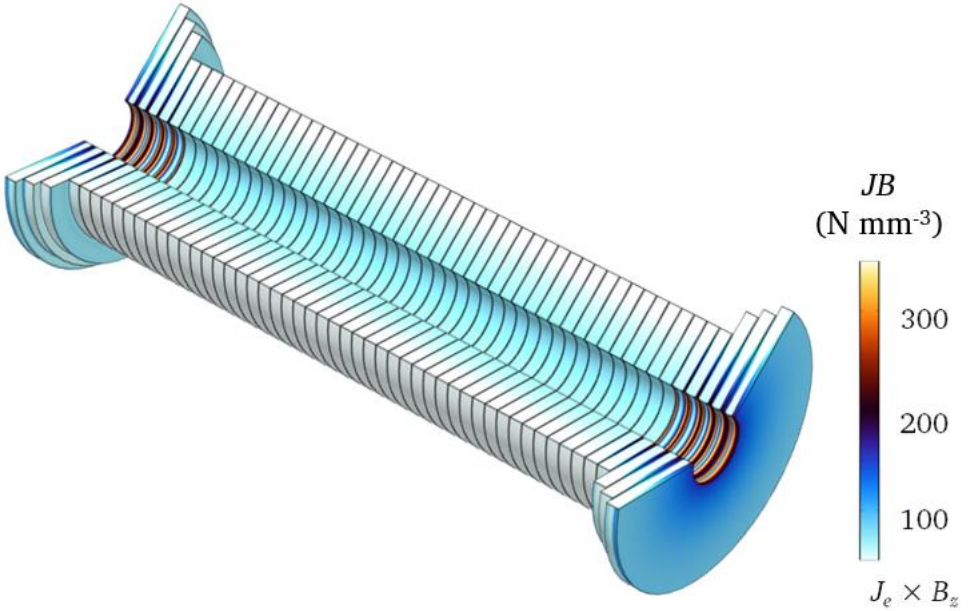
- Characteristics
  - → Different test protocols → data scattered;
  - → Composite effects (cracking/debonding, plasticity, …);
  - → Very **different conditions from UHF operation.**

Delamination under Lorentz forces : the experimental set-up

An experiment to characterize a property at the scale of the conductor…

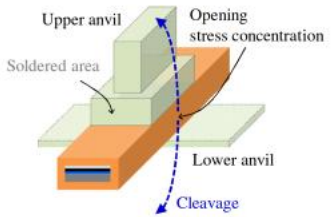


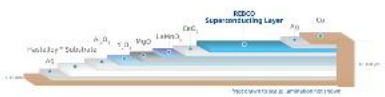
… though being representative of high field and forces conditions

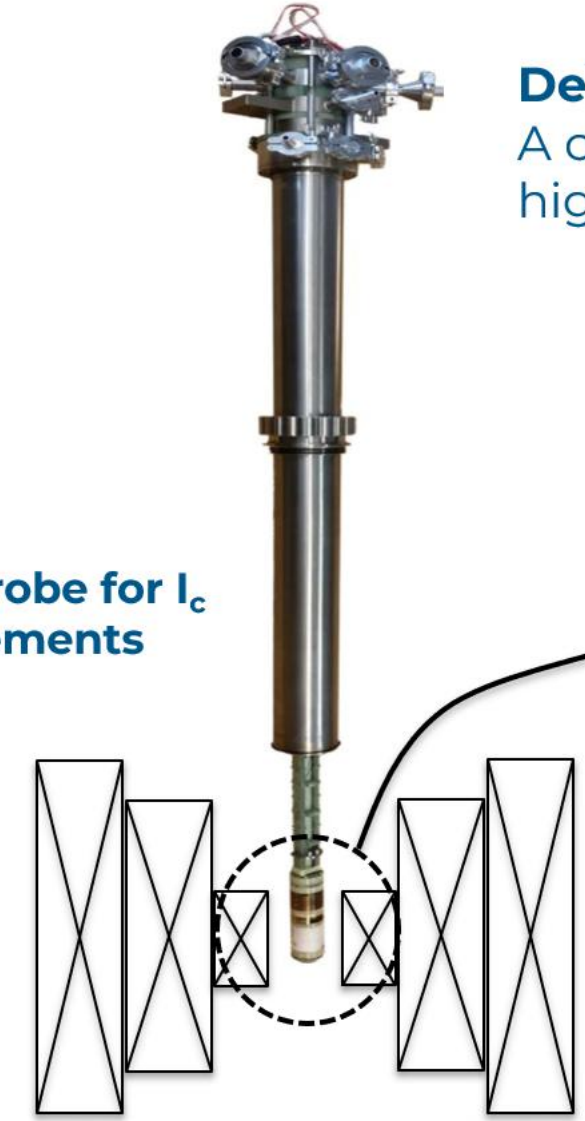


Images from [4] [8]

Delamination under Lorentz forces : the experimental set-up

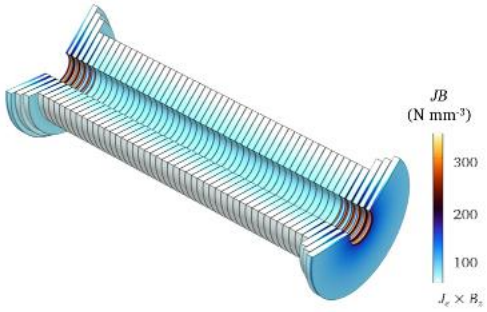




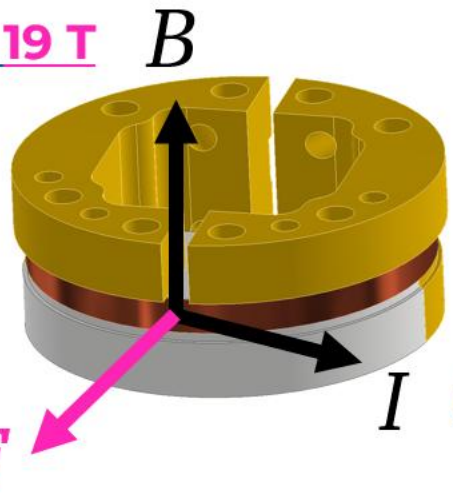


UniGE probe for I_c measurements

Delamination due to Lorentz forces:
A current running inside a tape in high field conditions



Field up to **19 T**



Current up to **2 kA**

Outwards, with REBCO layer on the outside

The average delamination stress

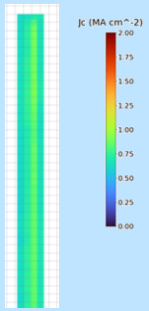
$$\bar{\sigma}_{\mathrm{D}} = \frac{I \times B}{w} = \frac{2000 \cdot 20}{0.004} = 10\ \mathrm{MPa}$$

Images from [4] [8]

Experimental procedure

1

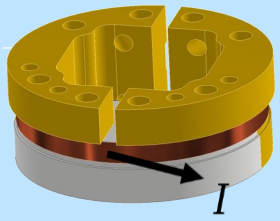
Cryoscan



- Ensuring homogeneity of J_c within length

2

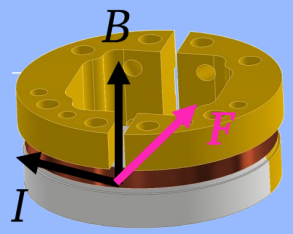
I_c (77 K, s.f.)



- Assess **performance** of the tape
- Assess **quality** of sample mounting

3a **3b**

I_c (4.2 K, 19 T)

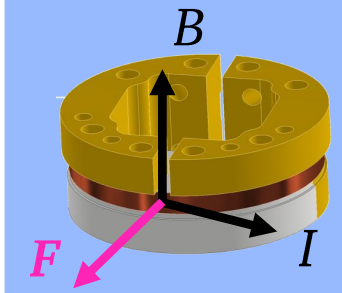


- Assess **performance** of the tape
- Settling to a lower energy state

repeated quenches

4a **4b**

Delamination (4.2 K, 19 T)



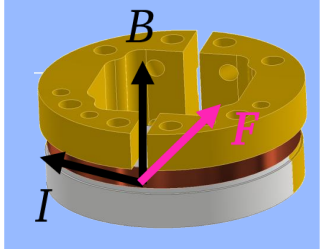
- Quench Concomitant to **Delamination (QCD)** occurs

repeated quenches

Quench current I_q

5

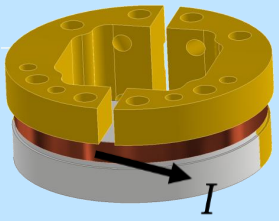
I_c (4.2 K, 19 T)



- Assess entity of degradation due to **QCD**

6

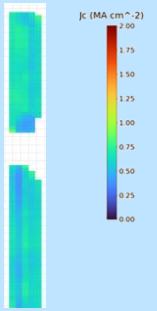
I_c (77 K, s.f.)



- Assess entity of degradation due to **QCD**

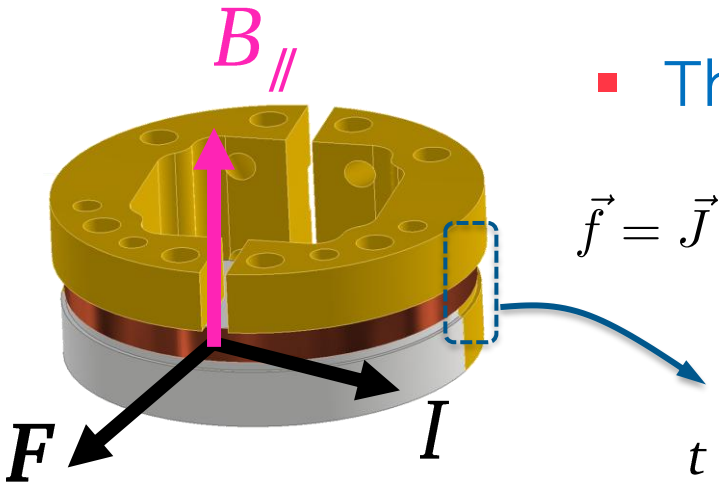
7

Cryoscan & imaging



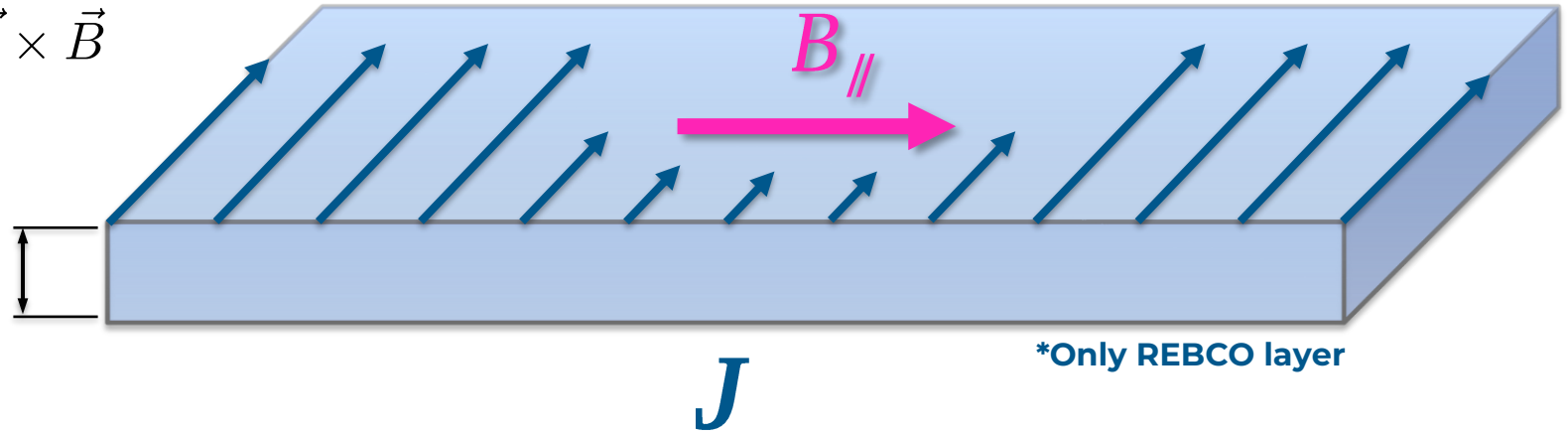
- Identify degraded regions

Current density map

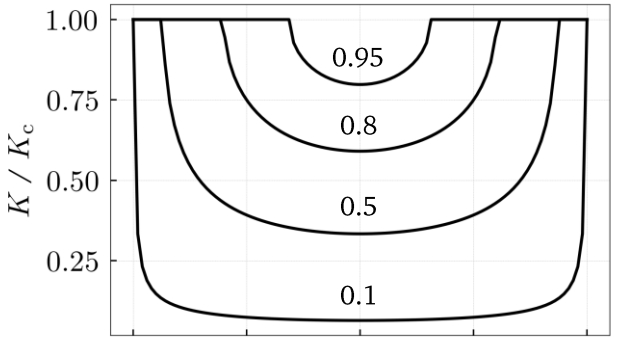


- The external field $B_{//}$ induces an initial **critical state**.

$$\vec{f} = \vec{J} \times \vec{B}$$

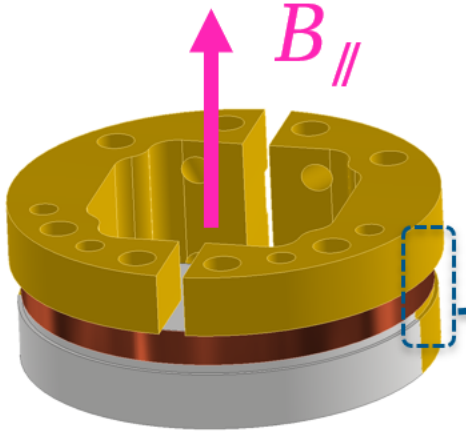


*Only REBCO layer



$$K = \int_t J \, dt$$

Current density map - FEA



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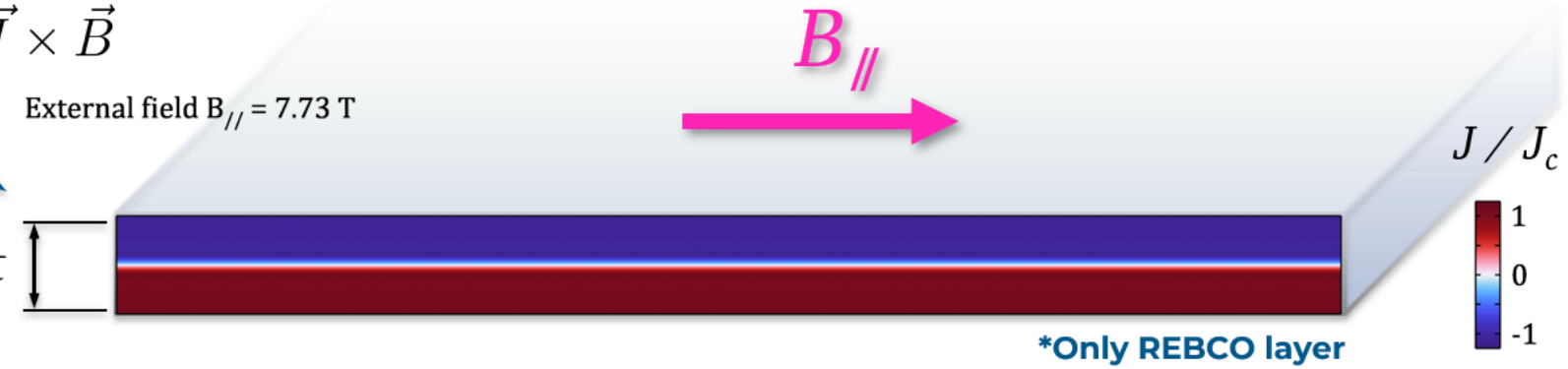

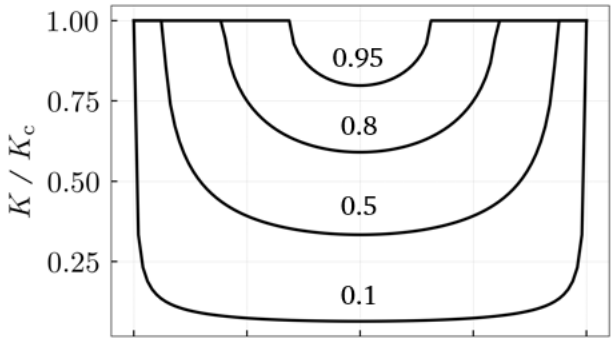

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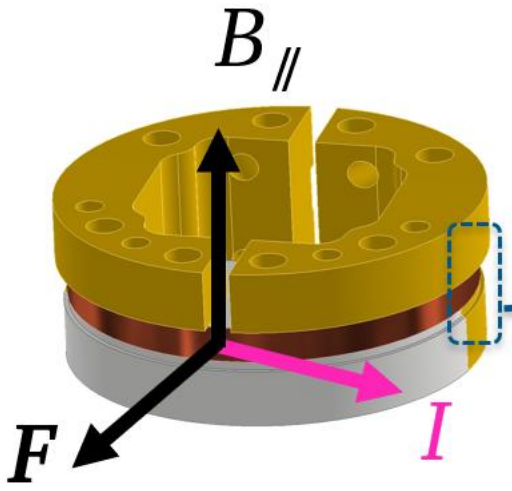
Current density map - FEA



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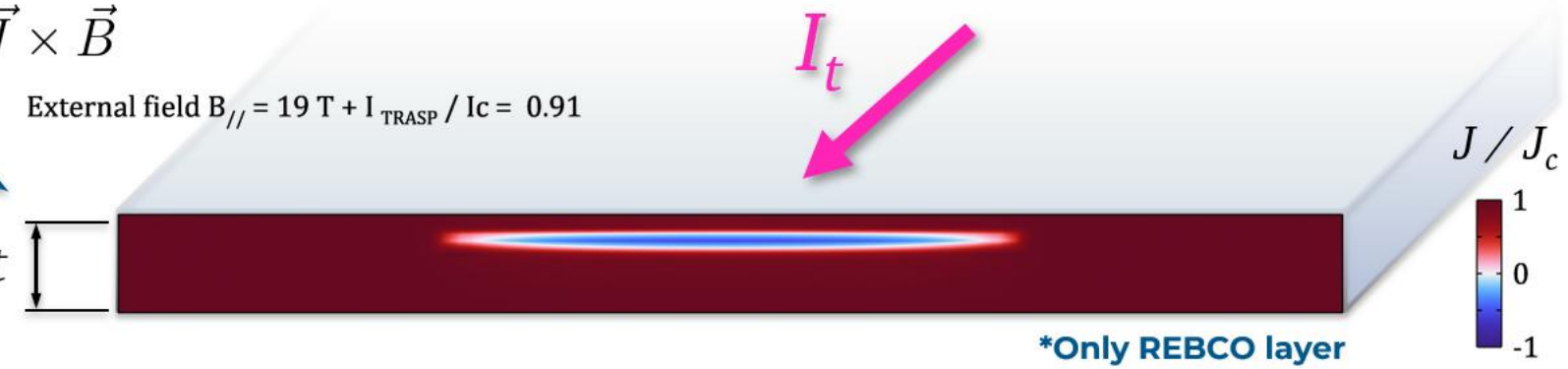
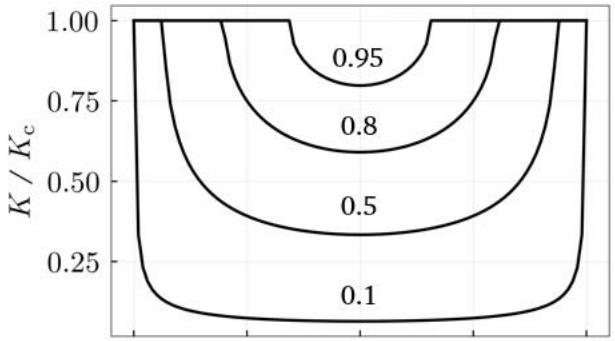
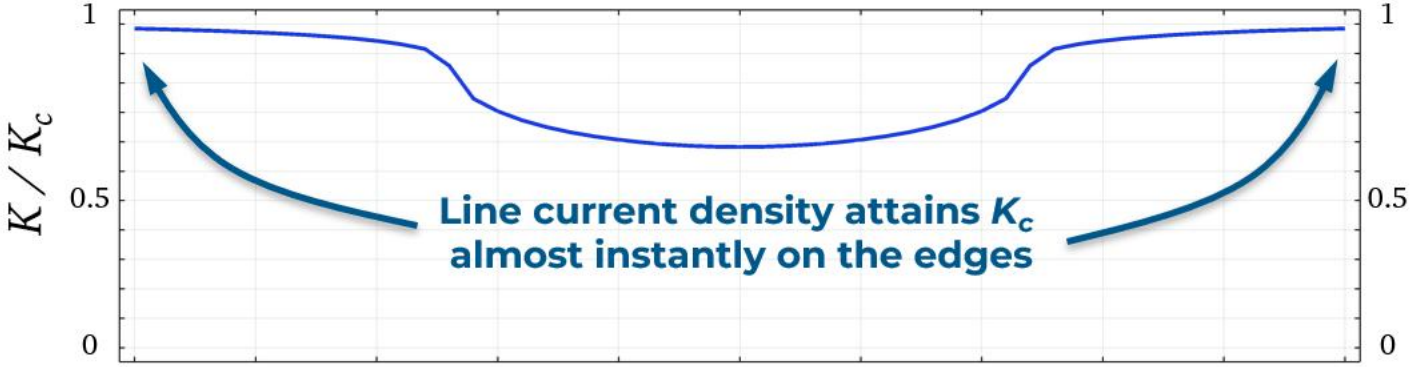






$$K = \int_t J \, dt$$

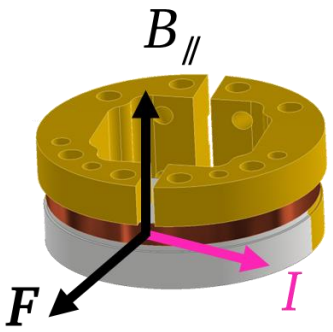
- The transport **current** injection restores the **thin-strip**-type ***J*-distribution**

Delamination force density - FEA

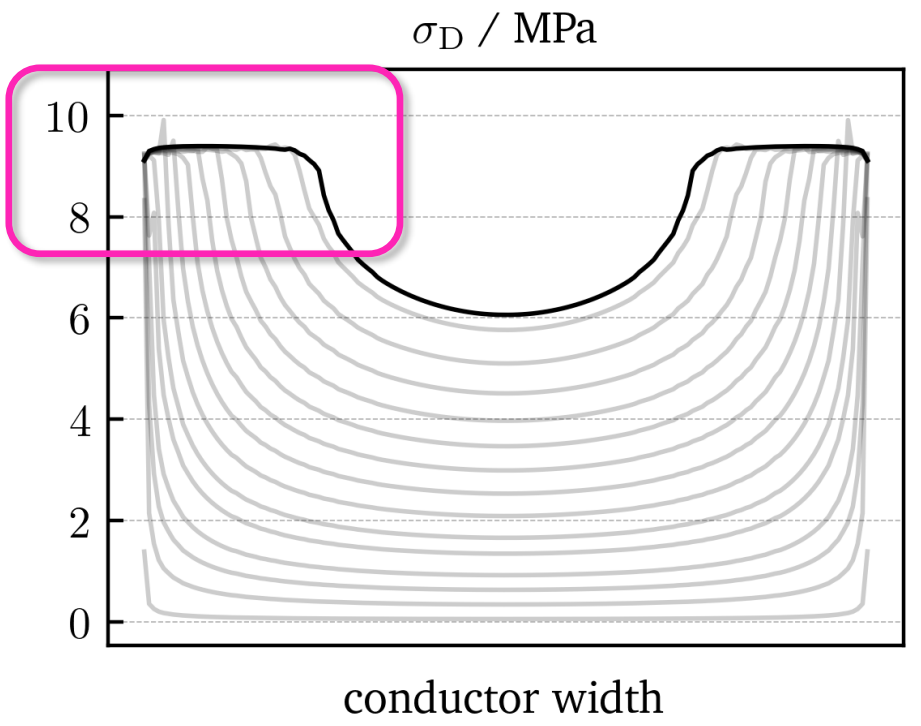
- Example of profiles for $I_q = 1700$ A , ~ 80 % of I_c

$$\sigma_D = \int_t \left(\vec{J} \times \vec{B}\right)_\perp dt$$

t : thickness of REBCO



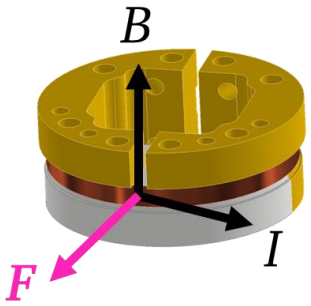
$$\vec{f} = \vec{J} \times \vec{B}$$



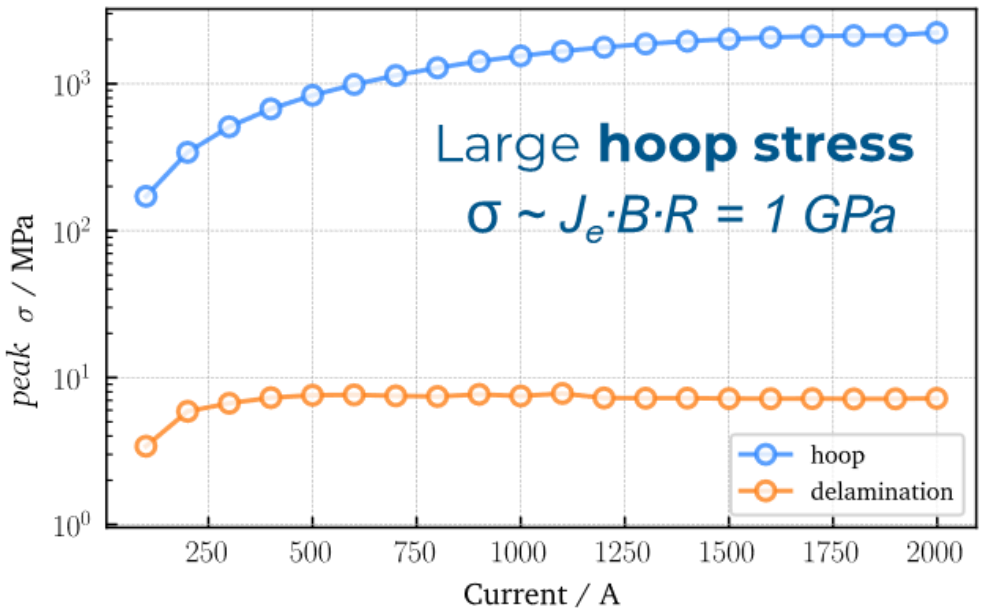
- **Peak delamination stress remains constant**
- **But the "*penetration*" depth increases**
- **Peak stress value function of $J_c \times B$**

$$\sigma_D = J_c \cdot B_{//} \cdot t \approx \frac{2\ \text{kA}}{4\ \text{mm}} \cdot 20\ \text{T} = 10\ \text{MPa}$$

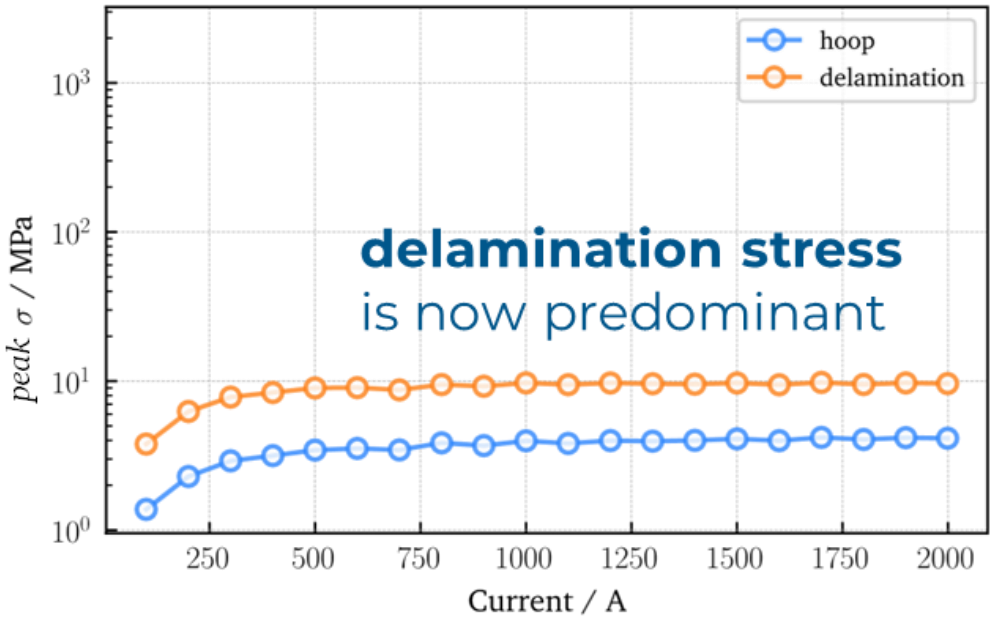
Mechanical Analyses



Soldering only at current injection



Soldering over the entire length



For more details on the **FE modeling** and the **evolution** of the **experiment** come to see our **poster** on Wednesday !

Outline

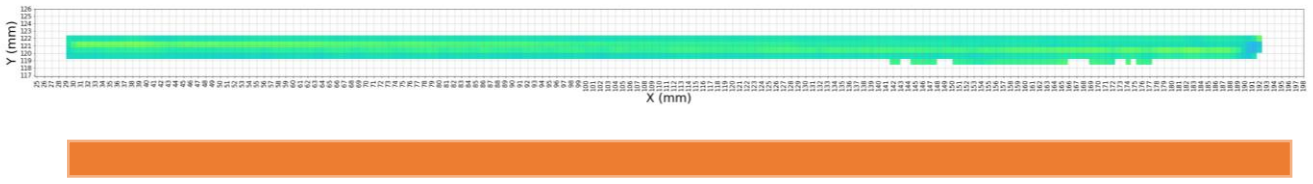
- Degradation due to delamination
- The experiment
- Accompanying FEA
- **Experimental results**
- **Forensic studies**
- **Conclusions & perspectives**

Speaker:
Célia LUCAS ESPARSEIL

Results: I_c measurements

The experimental testing starts by assessing the CC at 77 K through **mapping of critical current density** using a CryoScan (Theva), and measuring the I_c after it has been mounted on the support.

1) J_c (77 K) map before delamination

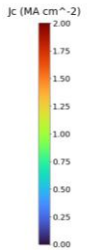


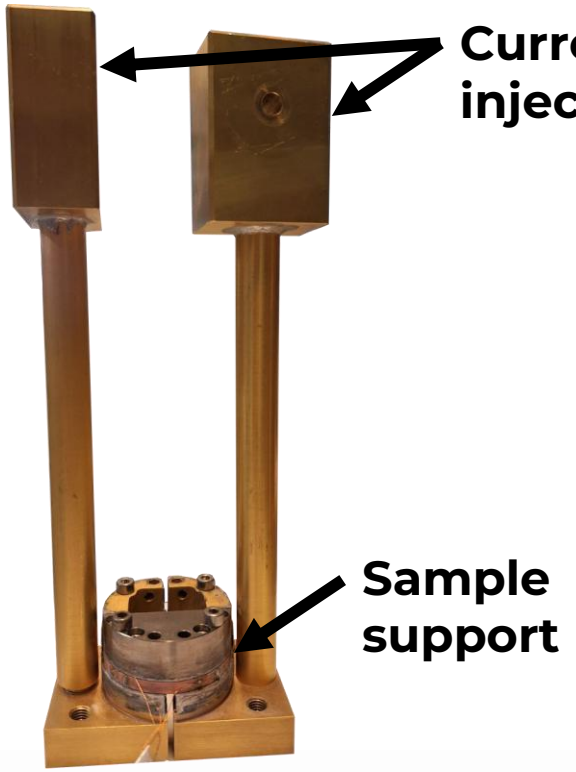
Current injection area

Area subjected to delamination

Current injection area

2) I_c measurement at 77 K





Current injectors

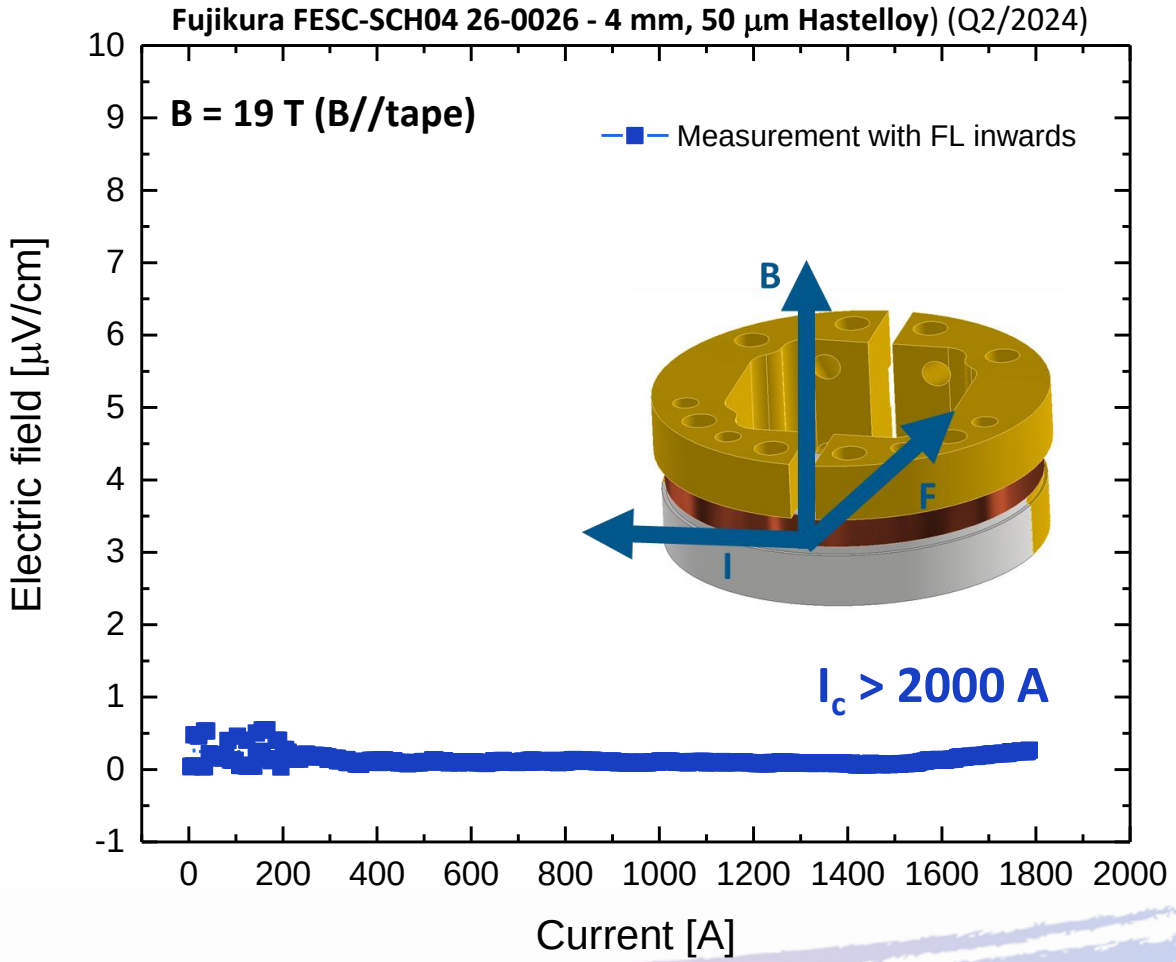
Sample support

Results: I_c measurements

The sample is then measured at **4.2 K and 19 T** to first evaluate its critical current and, secondly, to promote **delamination through Lorentz forces**.

3) Measurements at 4.2 K, 19 T: I_c

First, with the force inward, the I_c(4.2 K) is measured.



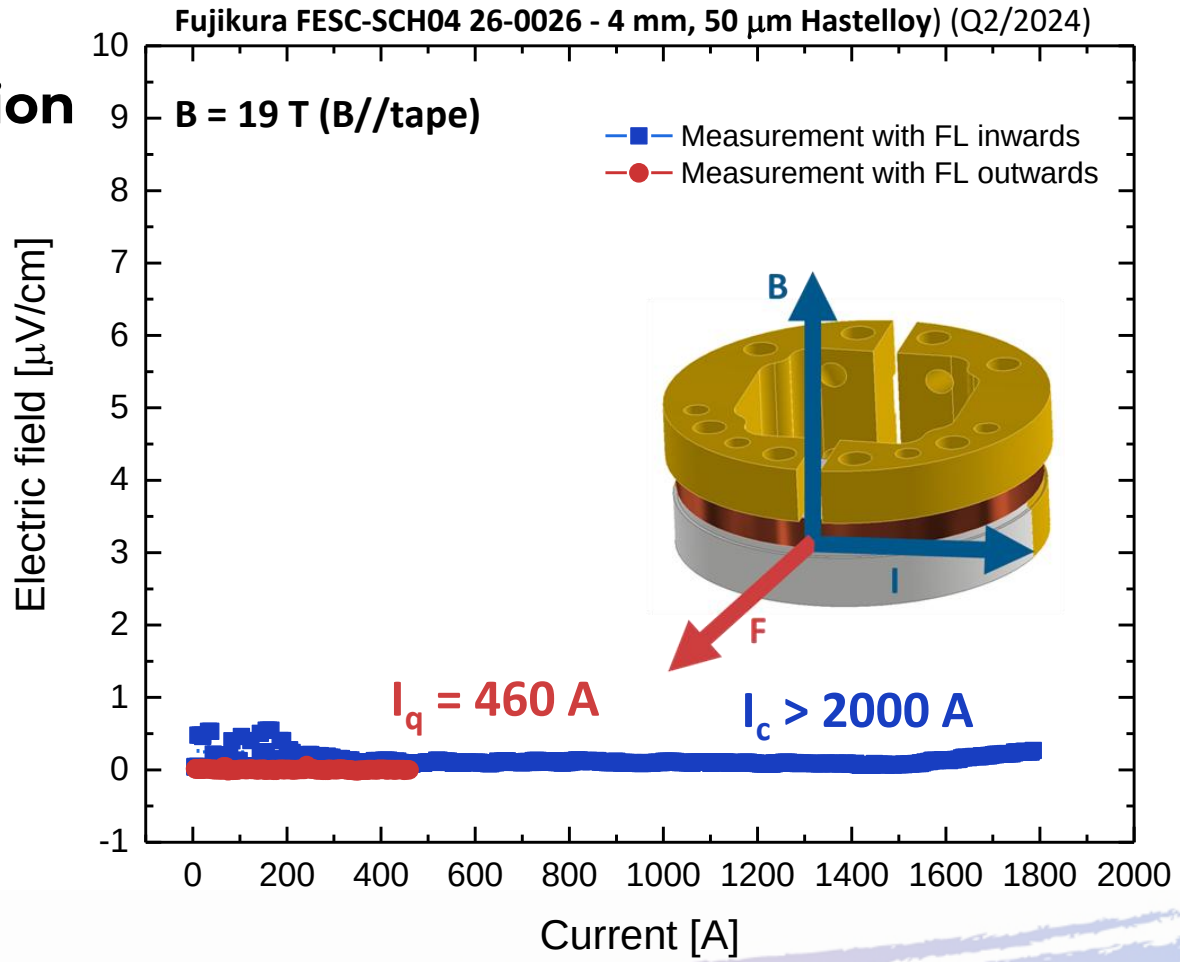
Results: I_c measurements

The sample is then measured at **4.2 K and 19 T** to first evaluate its critical current and, secondly, to promote **delamination through Lorentz forces**.

4) Measurements at 4.2 K, 19 T: Delamination

First, with the force inward, the I_c(4.2 K) is measured.

Then, the force is redirected outward by inverting the current.



Results: I_c measurements

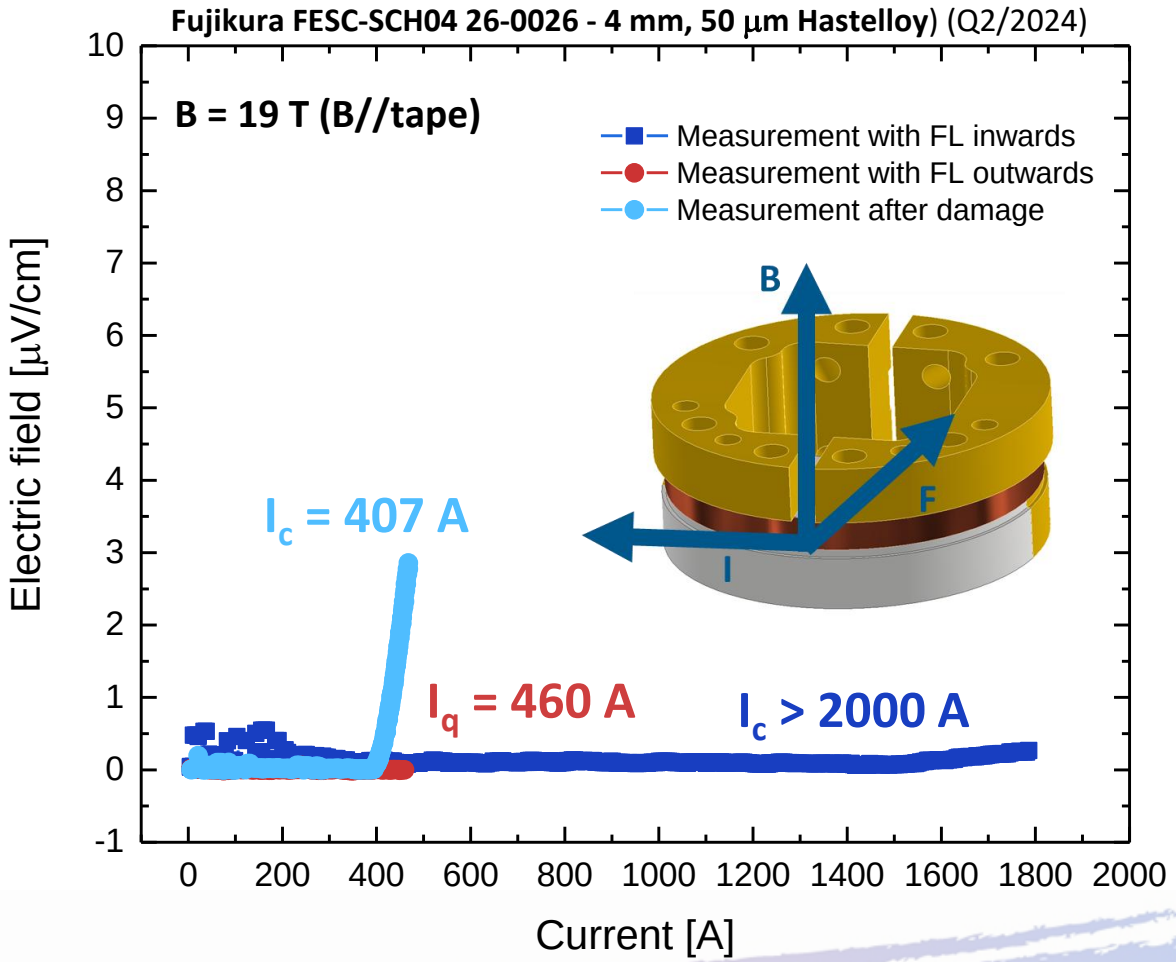
The sample is then measured at **4.2 K and 19 T** to first evaluate its critical current and, secondly, to promote **delamination through Lorentz forces**.

5) Measurements at 4.2 K, 19 T: I_c after delamination

First, with the force inward, the I_c(4.2 K) is measured.

Then, the force is redirected outward by inverting the current.

And lastly, the I_c is re-measured after the delamination.

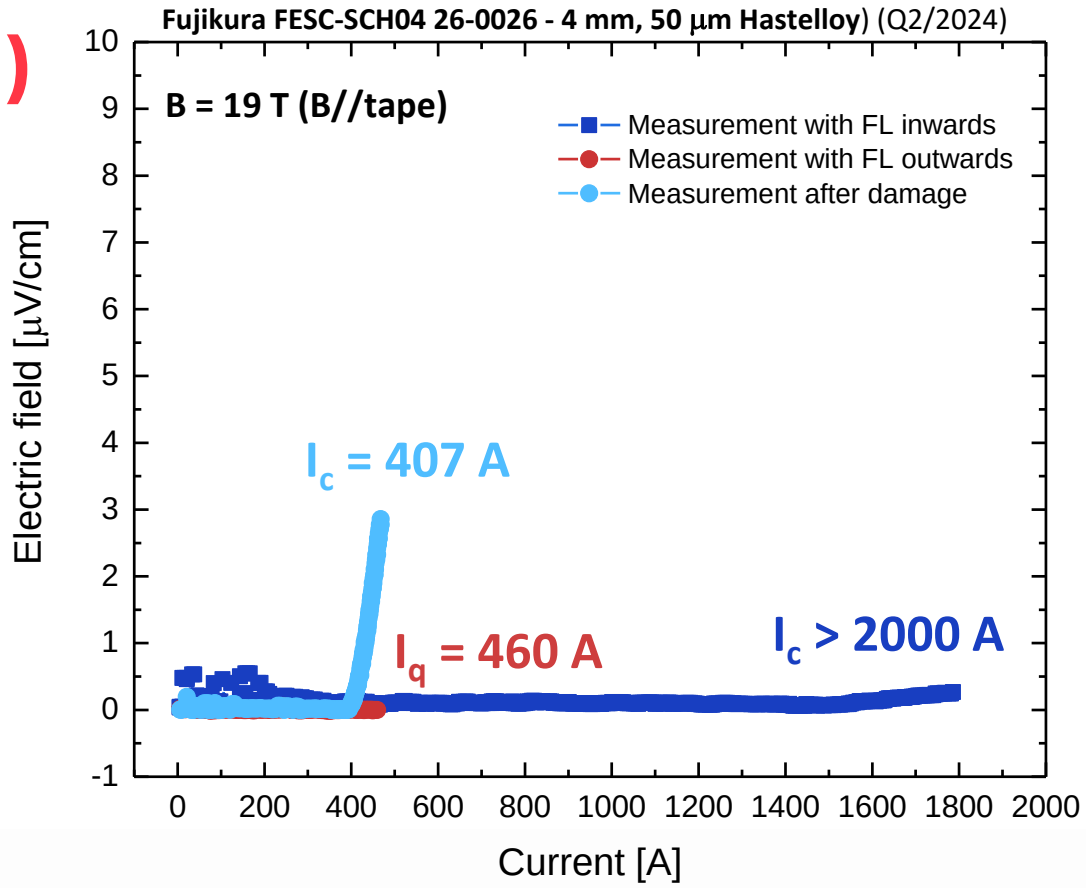


Results: I_c measurements

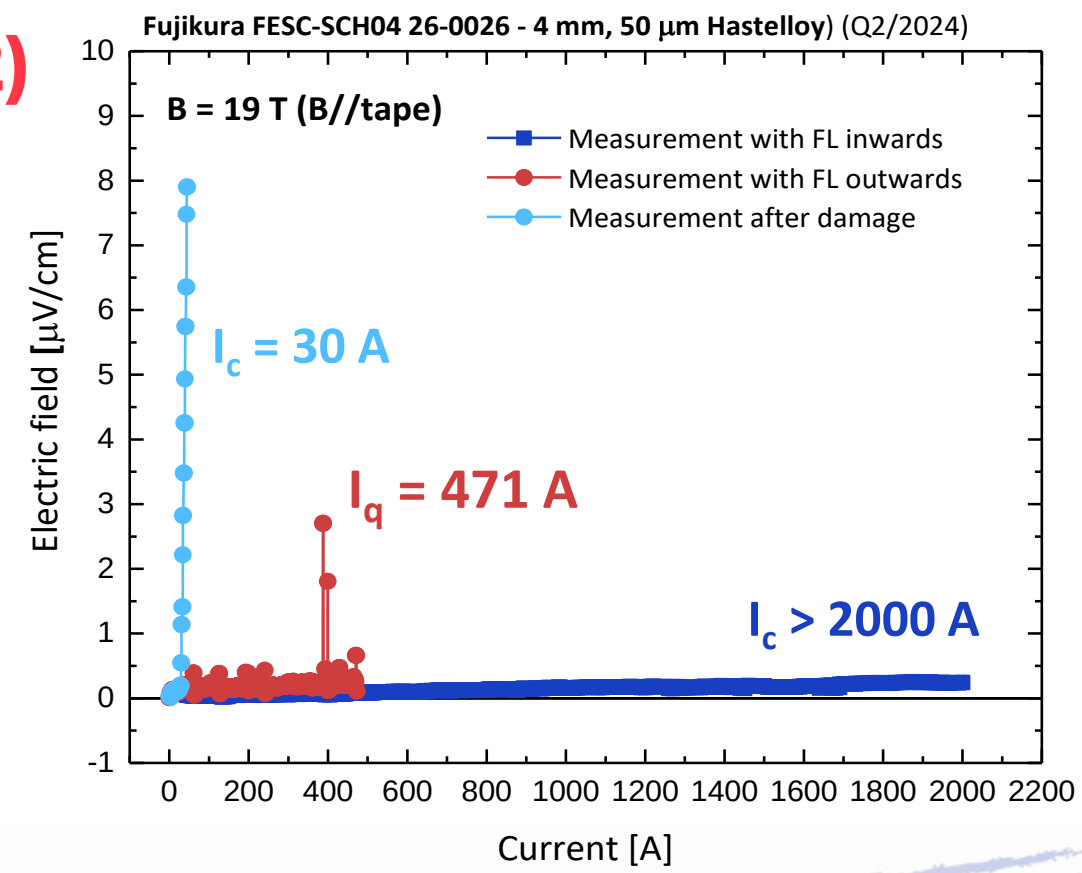
5) Measurements at 4.2 K, 19 T: I_c after delamination

Some **delamination events** can be more **catastrophic**, leading to higher I_c degradation.

1)



2)

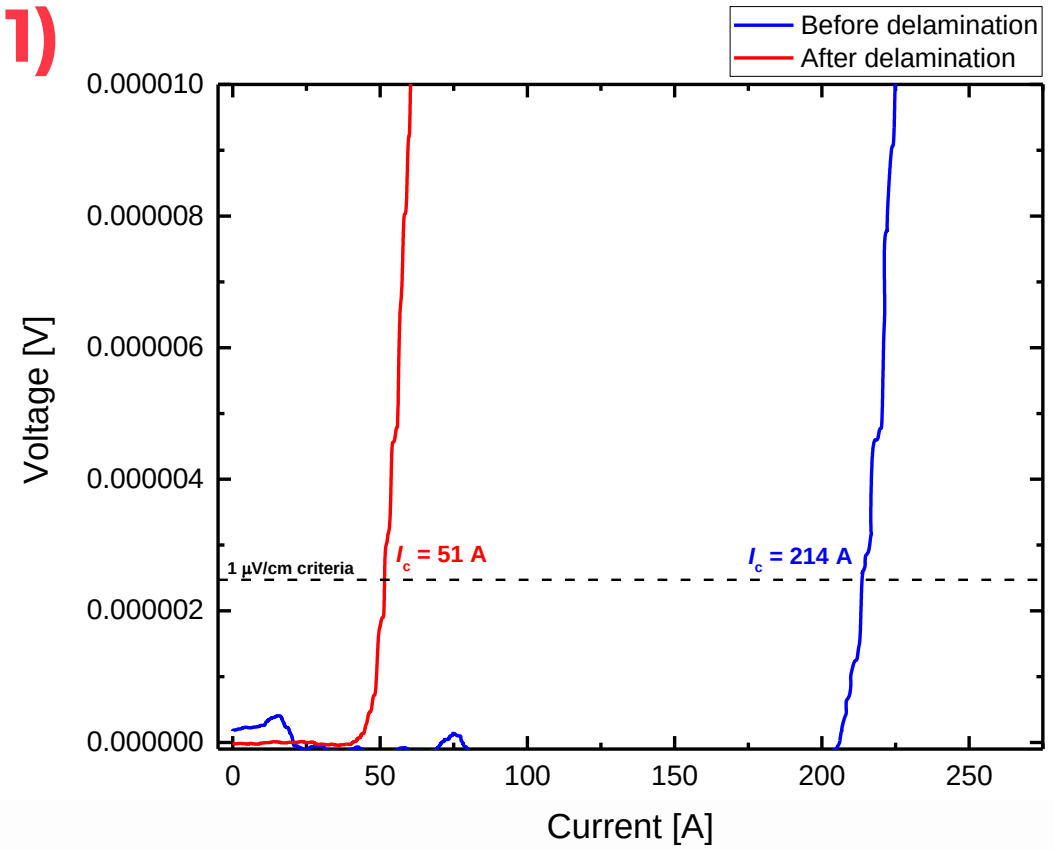


Results: I_c measurements

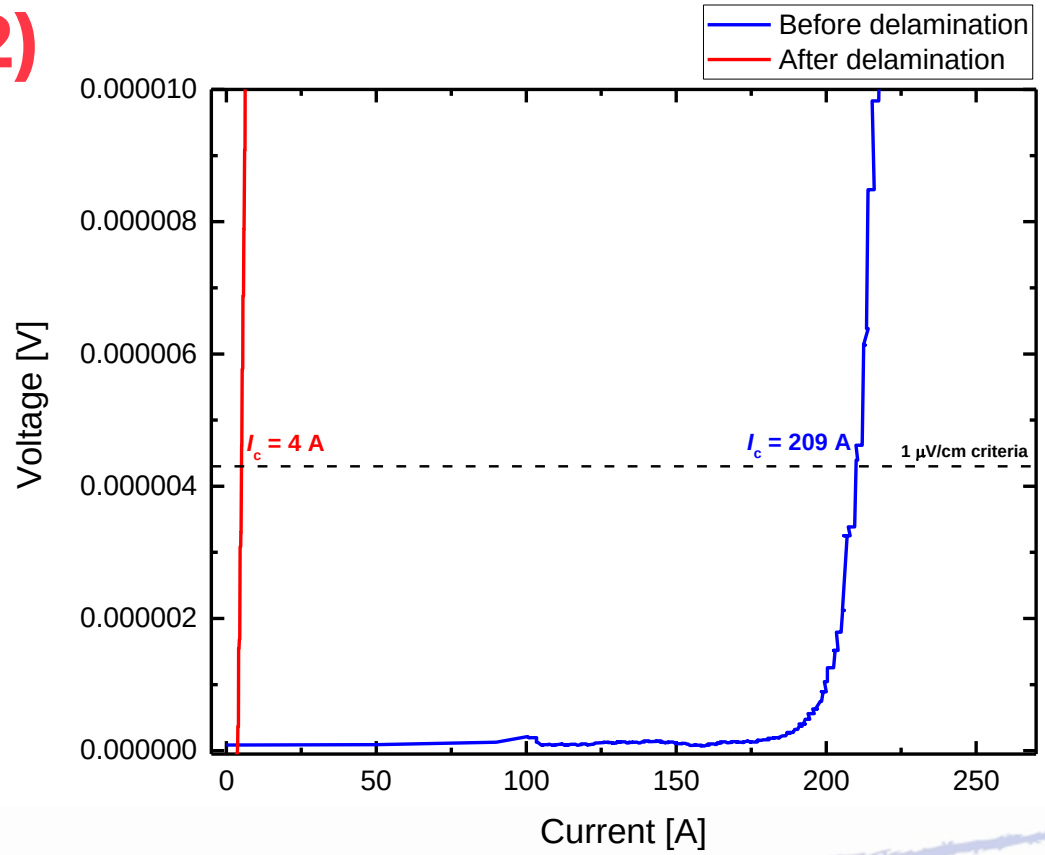
After delamination, the critical current degradation is evaluated at 77 K.

6) I_c measurement at 77 K after delamination

1)



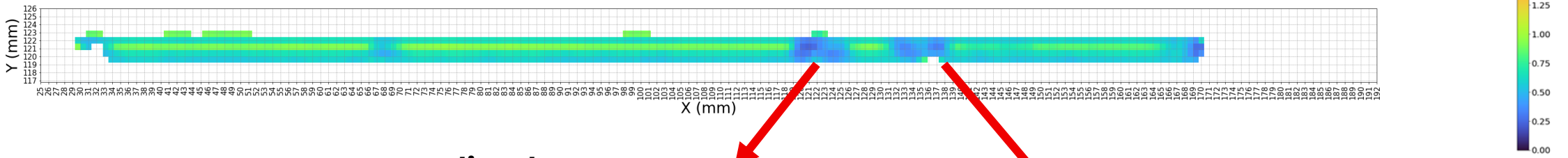
2)



Results: Forensic analysis

After completing the transport measurements, the sample is removed from the support and J_c and the damage induced is examined.

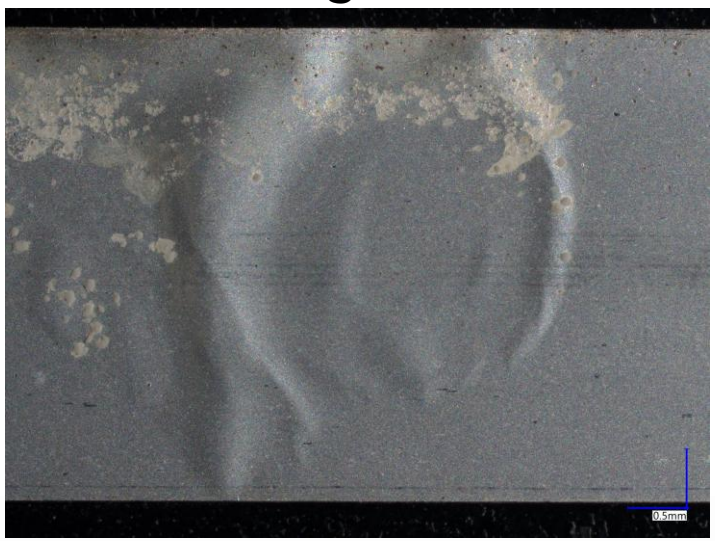
7) Forensic studies: J_c map after delamination, optical microscope



1)

With silver

Laser slit edge



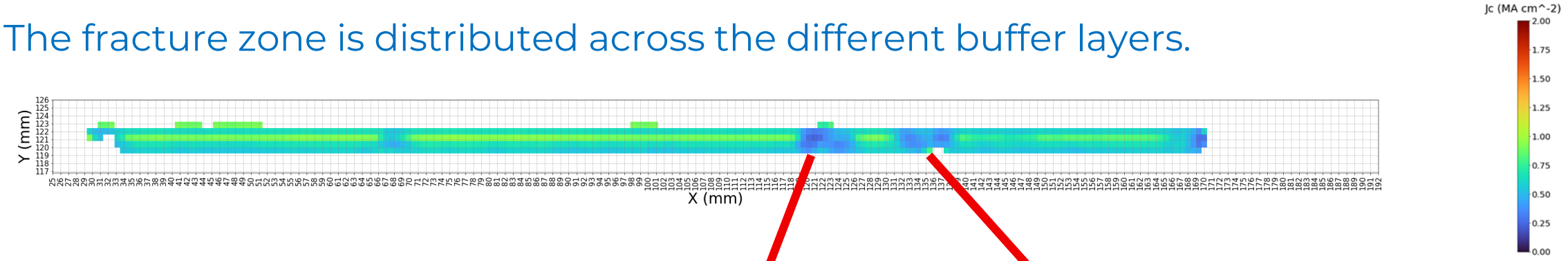
I_c (77 K) after delamination: 51 A

I_c (4.2 K) after delamination: 407 A

Results: Forensic analysis

7) Forensic studies: J_c map after delamination, optical microscope

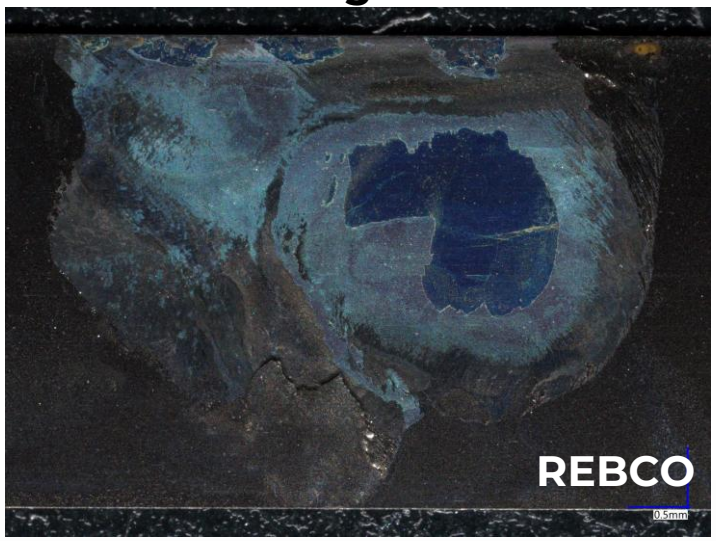
The fracture zone is distributed across the different buffer layers.

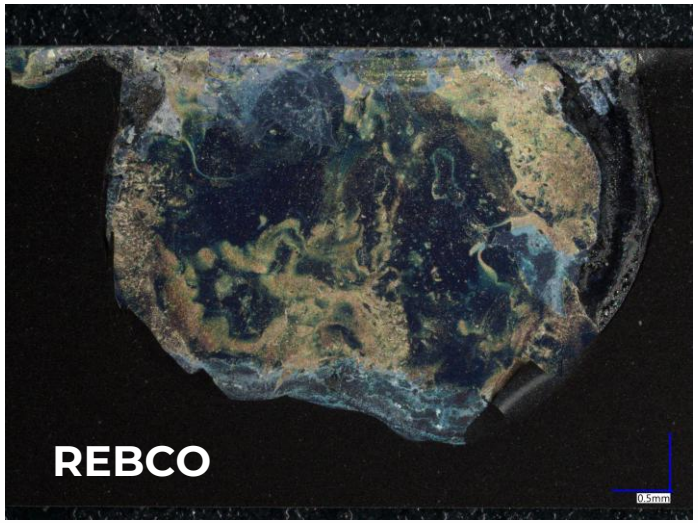


1)

After silver etching

Laser slit edge



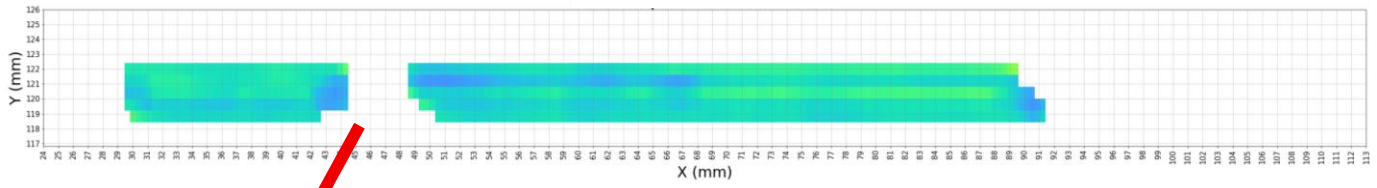


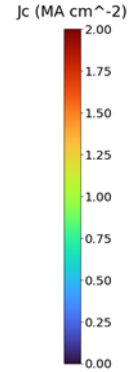
I_c (77 K) after delamination: 51 A

I_c (4.2 K) after delamination: 407 A

Results: Forensic analysis

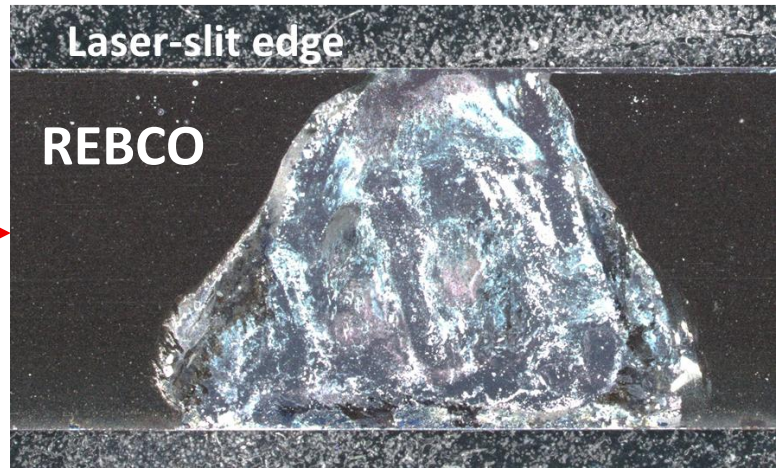
7) Forensic studies: J_c map after delamination, optical microscope





With silver

2)



After silver etching

I_c (77 K) after delamination: 4 A

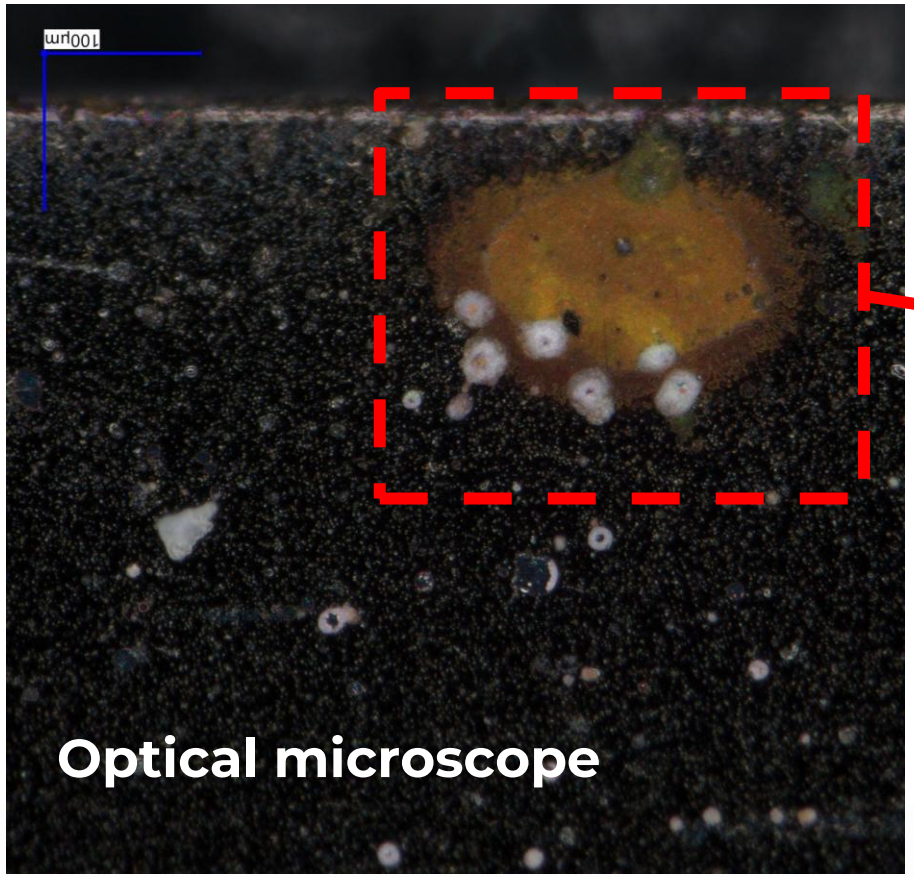
I_c (4.2 K) after delamination: 30 A

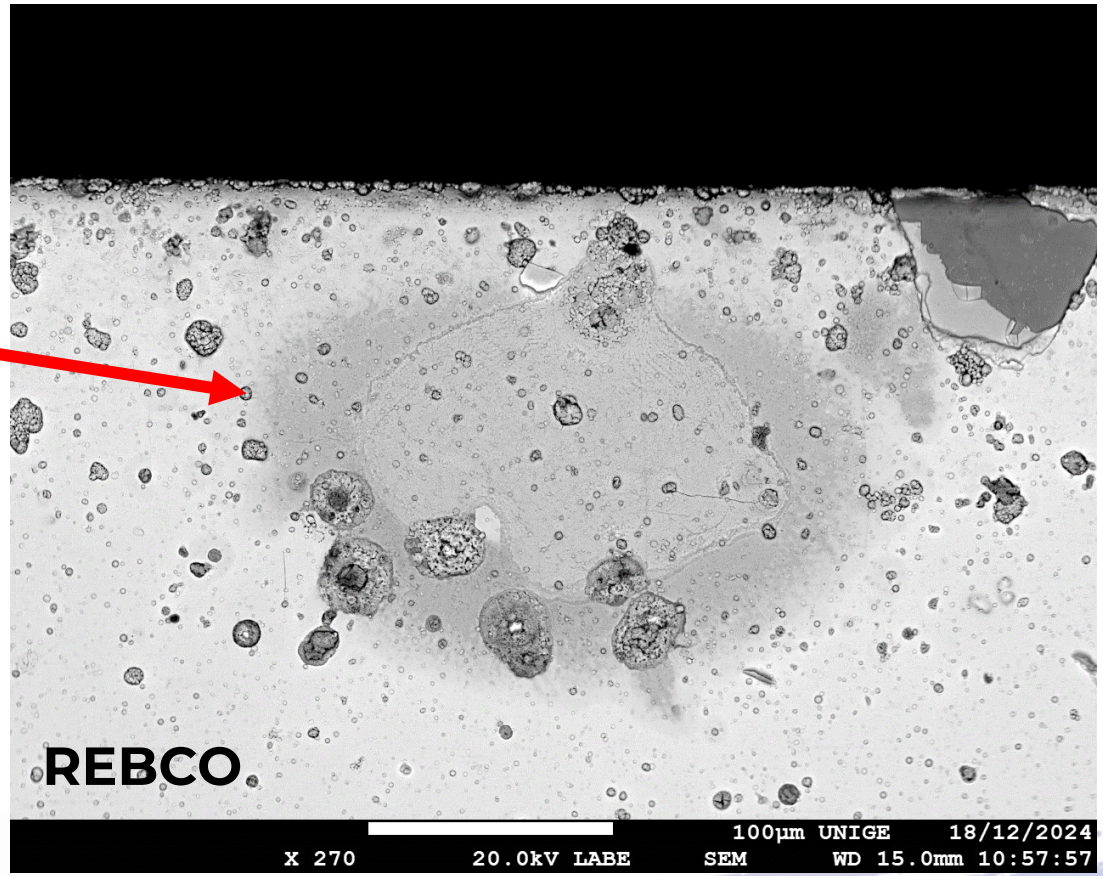
The appearance of “blisters" in the silver is **consistent** across samples and is a **clear indication** of areas where **delamination** has occurred.

Results: Forensic analysis

7) Forensic studies: SEM/EDX

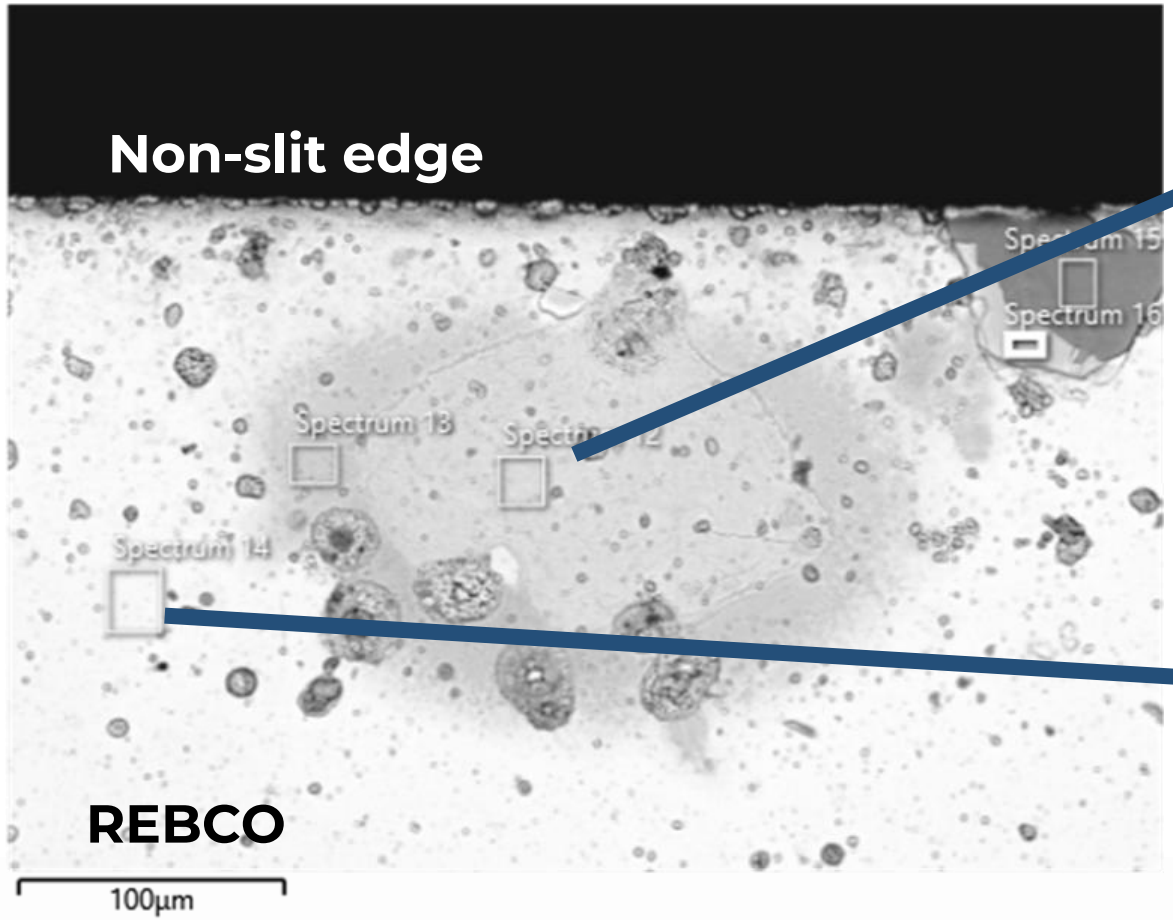
In addition to delamination, areas consistent with quench damage are observed near the edges.

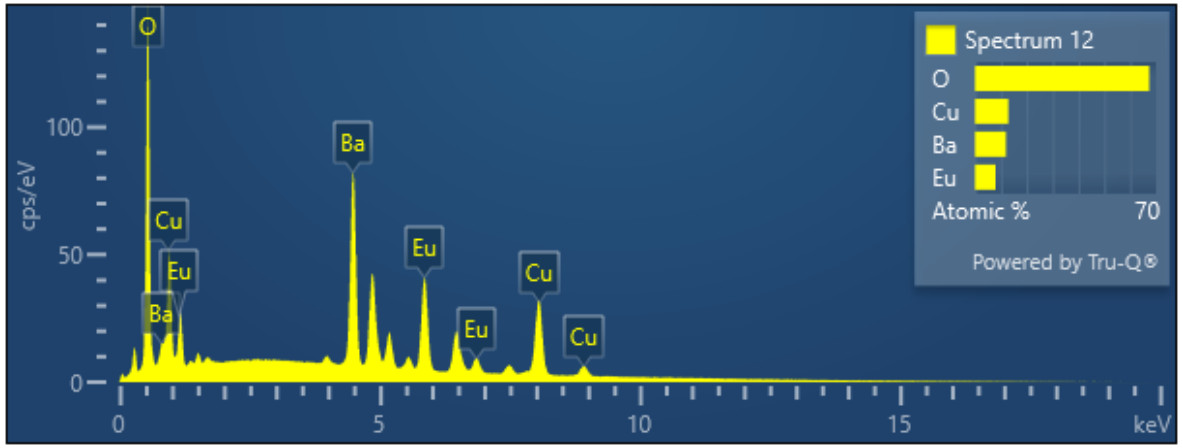


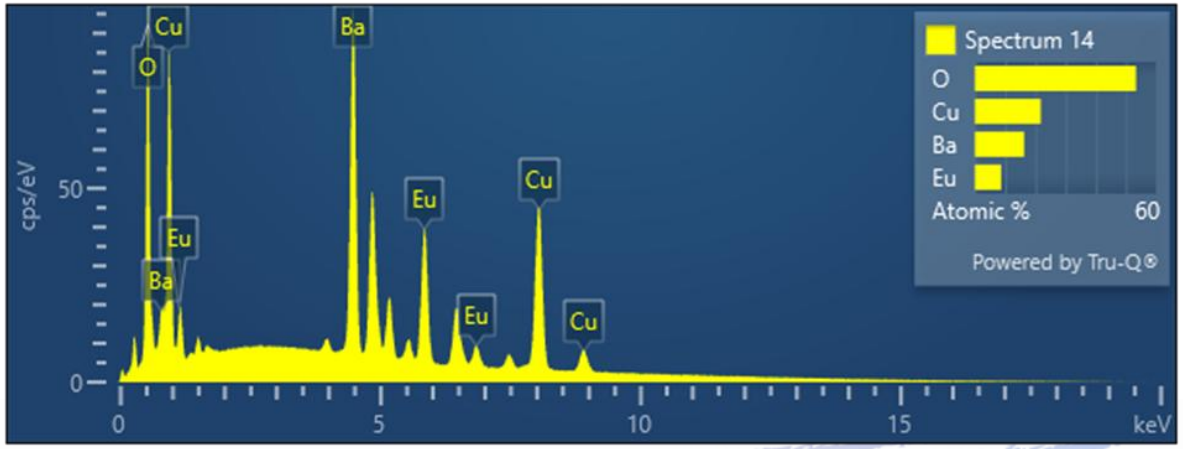


Results: Forensic analysis

7) Forensic studies: SEM/EDX



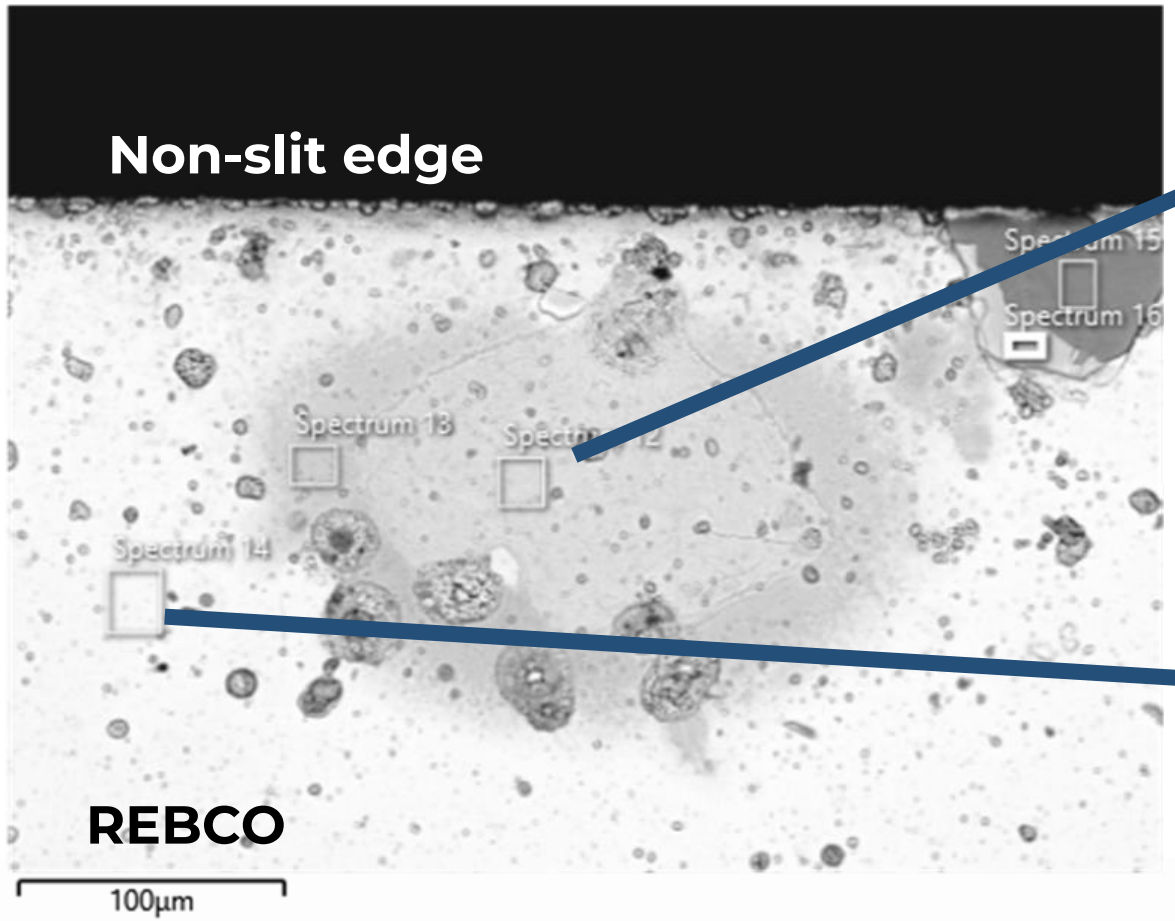


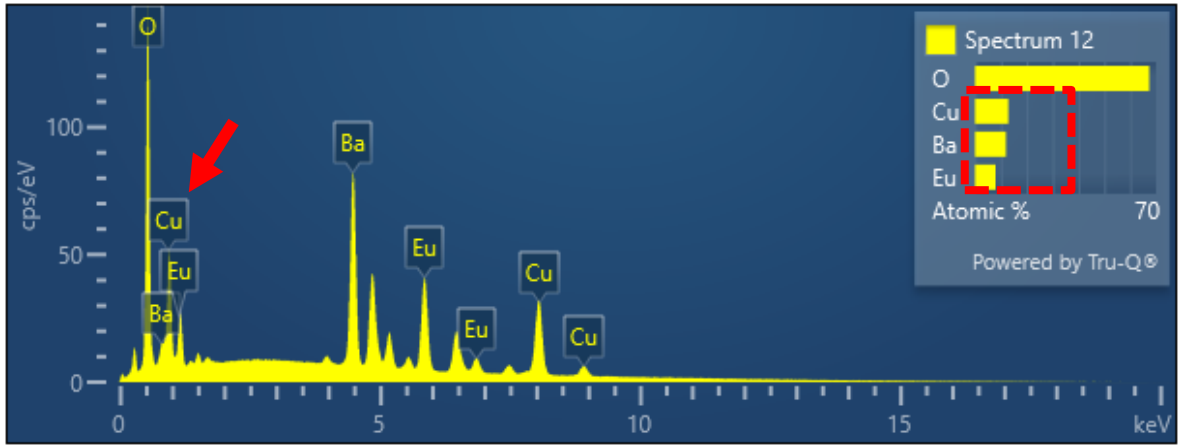


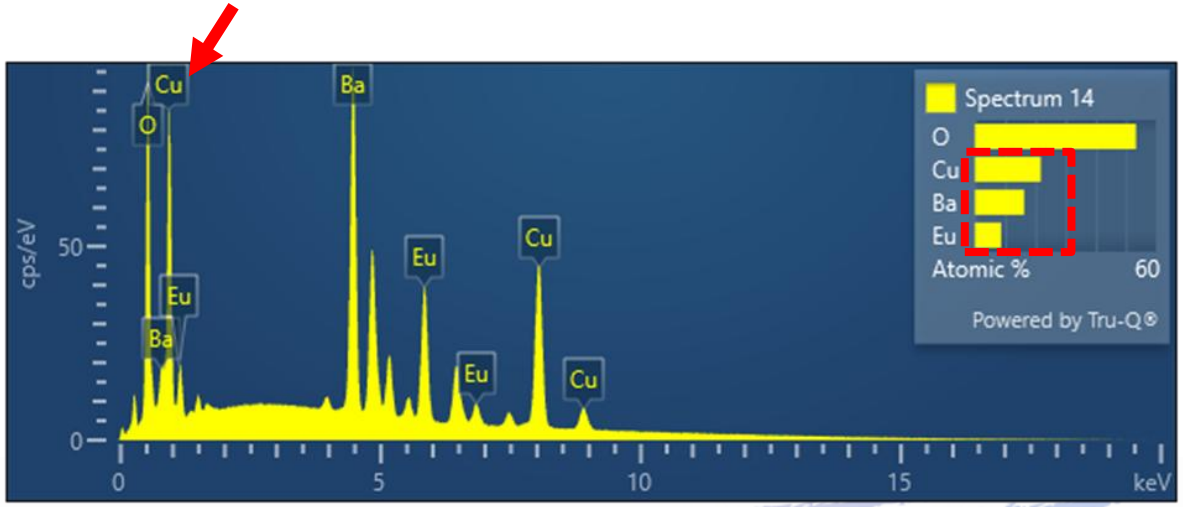
Results: Forensic analysis

7) Forensic studies: SEM/EDX

Compositional differences!







Conclusions

- Coils used in high magnetic field applications are subjected to significant electromagnetic stress. Due to their **multilayer structure**, REBCO CCs are highly sensitive to transverse tensile stress, which can promote conductor **delamination**.

- In this work, we demonstrate a novel method for determining delamination strength, which, unlike previously published approaches that rely on mechanical methods, utilizes the **Lorentz force to induce delamination**.

- The experiment evolved thanks to the input of **numerical simulations**, which also helped us gain a deeper **understanding of the underlying phenomena**.

- Upon examining the damage introduced in the samples via SEM/EDX, it was observed that the delamination occurs at the **interfaces** between the REBCO layer and the buffer layers.

Future works

- A more extensive measurement campaign must be carried out to **correlate the variability** on the results with the **defects** in the CCs introduced by the deposition and/or slitting.

- Given the hypothesis regarding the **importance of initial defects** and how they may arise due to the slitting methods used, measurements on CCs from **different manufacturers** are planned.

- Since the current penetration is dominated by J_C, other planned experiments include characterization at **different temperatures** (20 K, 40 K).

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Thank you for the attention !

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