IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

MuCol
International MUON Collider Collaboration

Tape performance specification and performance vs. production

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CERN
CERN, Switzerland

Outline

- A short introduction to the Muon Collider magnets
- MuCol procurement of REBCO coated conductors
  - Conductor specs for the HF and UHF solenoids
  - Transport I_c measurements and scaling relations
  - Results of the measurement campaign on the angular dependence of I_c
  - Delamination strength under I x B force
- Conclusions

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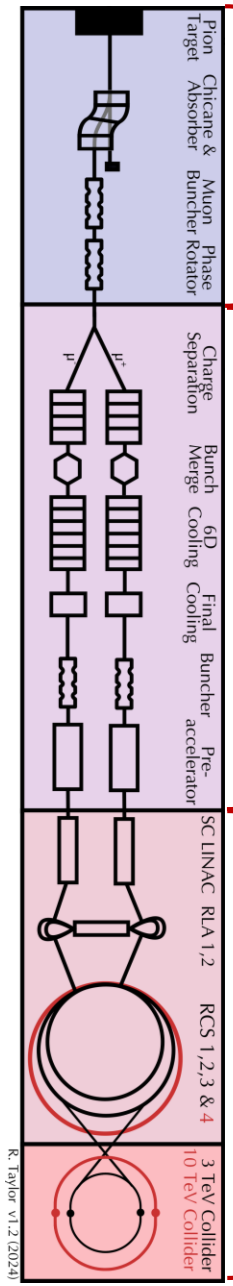
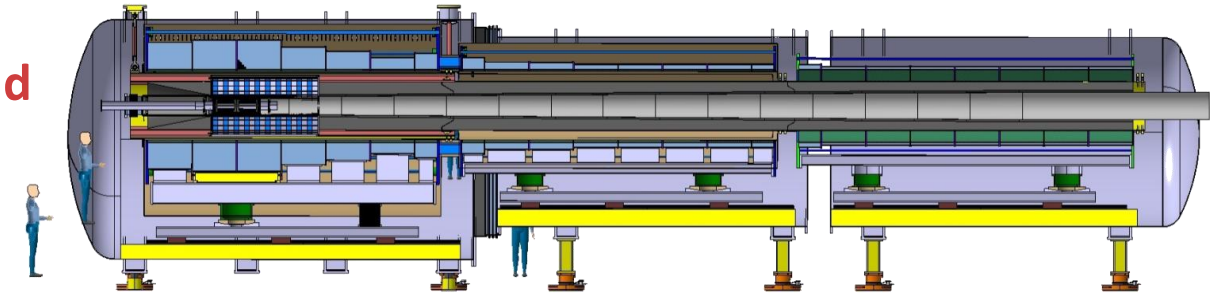
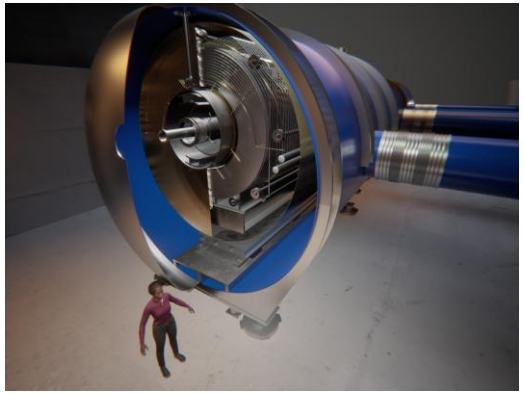
The zoo of REBCO magnets for a high-energy muon collider



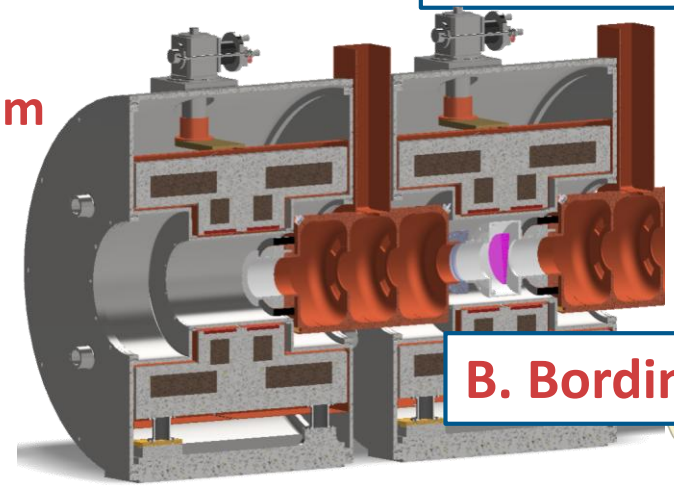
Target and capture solenoid



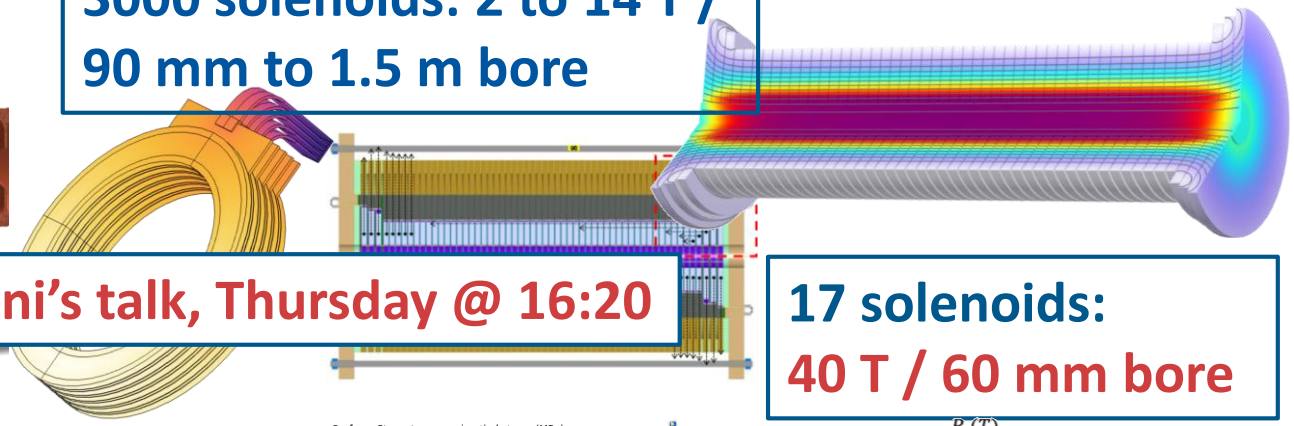


23 solenoids: 20 T / 1.4 m bore

Muon beam cooling solenoids



3000 solenoids: 2 to 14 T / 90 mm to 1.5 m bore



B. Bordini's talk, Thursday @ 16:20

17 solenoids: 40 T / 60 mm bore

Accelerator and collider magnets

And all this needs 300'000 km of REBCO tape

B. Caiffi's talk, Thursday @ 15:55

10 T, 30(V) x 100 mm (H) dipoles

14 T, 140 mm bore dipoles

L. Bottura, HFM meeting 2025

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HTS technical specs for MuCol solenoids R&D

European Organization for Nuclear Research
Organisation européenne p

EDMS No. 2960999

Price Enquiry

Technical Specification

Supply of REBCO Coated Conductor for Muon Collider Solenoids R&D

This Tec
REBCO
Delivery
Contract

modern REBCO tapes exceed these specs

Mechanics in UHF HTS solenoids is challenging. Few data on the conductors make hard to give good values for some specs

		Specification	Target
Minimum I_c/width (4.2 K, 20 T)	(A/cm)	600	1200
Benchmark I_c/width (4.2 K, 5 T)	(A/cm)	1440	
Minimum n value	(-)	15	
$\sigma(I_c(4.2\ K, 20\ T))$	(%)		5
Minimum $J_{non\text{-}Cu}$ (4.2 K, 20 T)	(A/mm^2)		3000
Minimum $J_{non\text{-}Cu}$ (20 K, 20 T)	(A/mm^2)		1200
Unit length UL	(m)	200	1000
Minimum bending radius	(mm)	10	5
Allowable non-Cu $\sigma_{longitudinal\ non\text{-}Cu}$ (4.2 K)	(MPa)	800	1000
Allowable compressive $\sigma_{transverse}$ (4.2 K)	(MPa)	300	600
Allowable tensile $\sigma_{transverse}$ (4.2 K)	(MPa)	> 5	50
Allowable shear $\tau_{transverse}$ (4.2 K)	(MPa)	> 5	50
Range of allowable $\varepsilon_{longitudinal}$	(%)	-0.1…0.4	-0.1…0.5
Internal specific resistance $\rho_{transverse}$	(nΩ/cm^2)		20

Procurement of 4 mm tape for R&D windings at FARADAY FACTORY JAPAN, 上海超导 SHANGHAI SUPERCONDUCTOR, Fujikura

Total 11 km of REBCO tape in house at CERN from 5 worldwide producers

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.)
Fujikura	4 mm	EuBCO	2.5 μm	IBAD/PLD	BHO columns (artificial)	50 μm	2 x 40 μm electroplated	420 A/cm
							2 x 20 μm electroplated	380 A/cm
							2 x 10 μm electroplated	▲650 A/cm
								558 A/cm
								515 A/cm
	2 mm						2 x 20 μm electroplated	555 A/cm
FARADAY FACTORY JAPAN	4 mm	YBCO	▲3.1 μm	IBAD/PLD	Y_2O_3 particles (native)	▲100 μm	2 x 20 μm electroplated	550 A/cm
			2.7 μm			40 μm	2 x 10 μm electroplated	490 A/cm
								467 A/cm
			2.5 μm					420 A/cm
								405 A/cm
上海超导™ SHANGHAI SUPERCONDUCTOR	3 mm	EuBCO	3 μm	IBAD/PLD	BHO columns (artificial)	▼30 μm	2 x 10 μm electroplated	590 A/cm
	4 mm		2 μm			50 μm		428 A/cm
								645 A/cm
								632 A/cm
SuperPower Inc. A Furukawa Company SCS4050-HM	4 mm	YBCO	▼1.5 μm	IBAD/MOCVD	BZO columns (artificial)	50 μm	2 x 5 μm electroplated	▼148 A/cm

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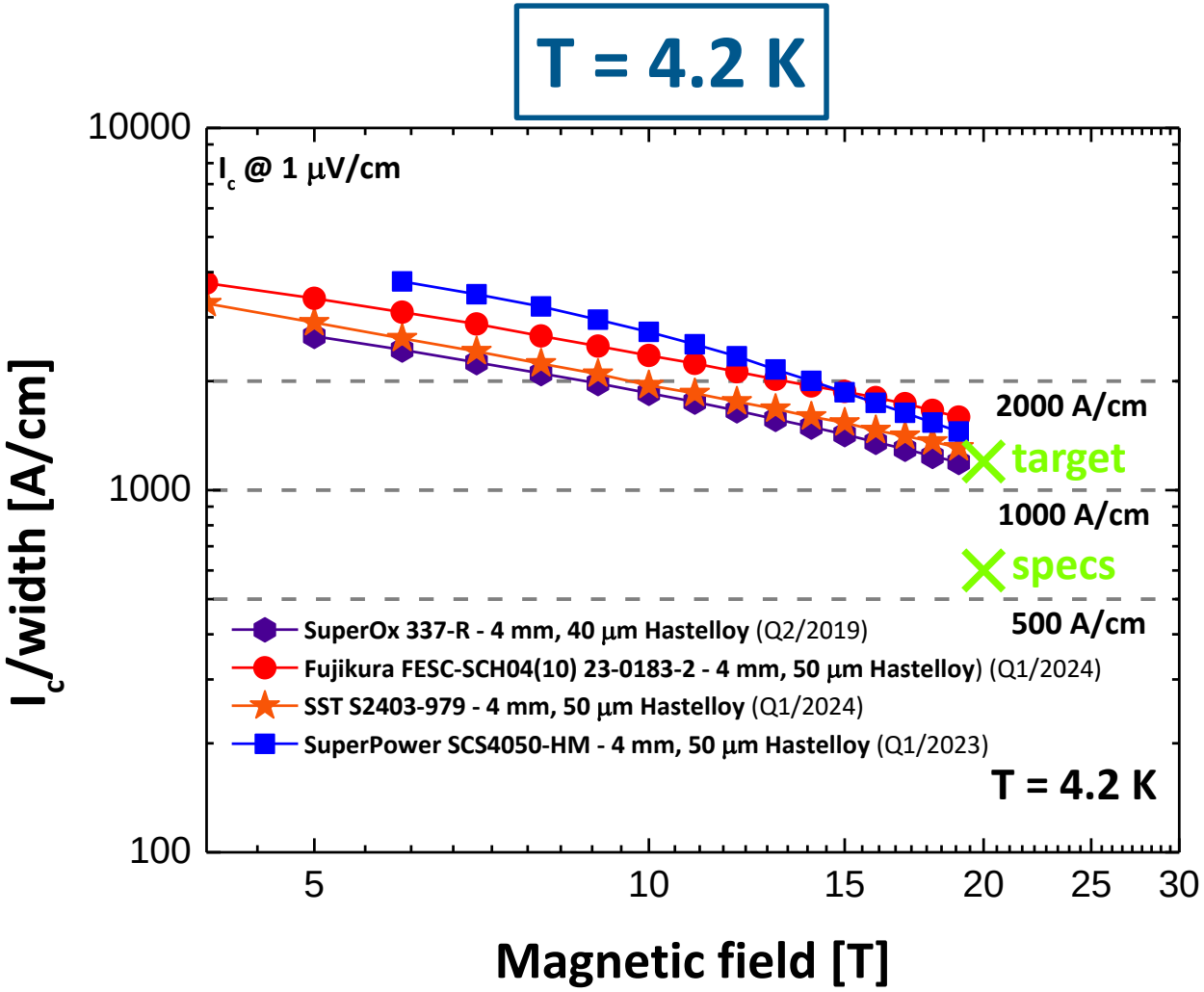
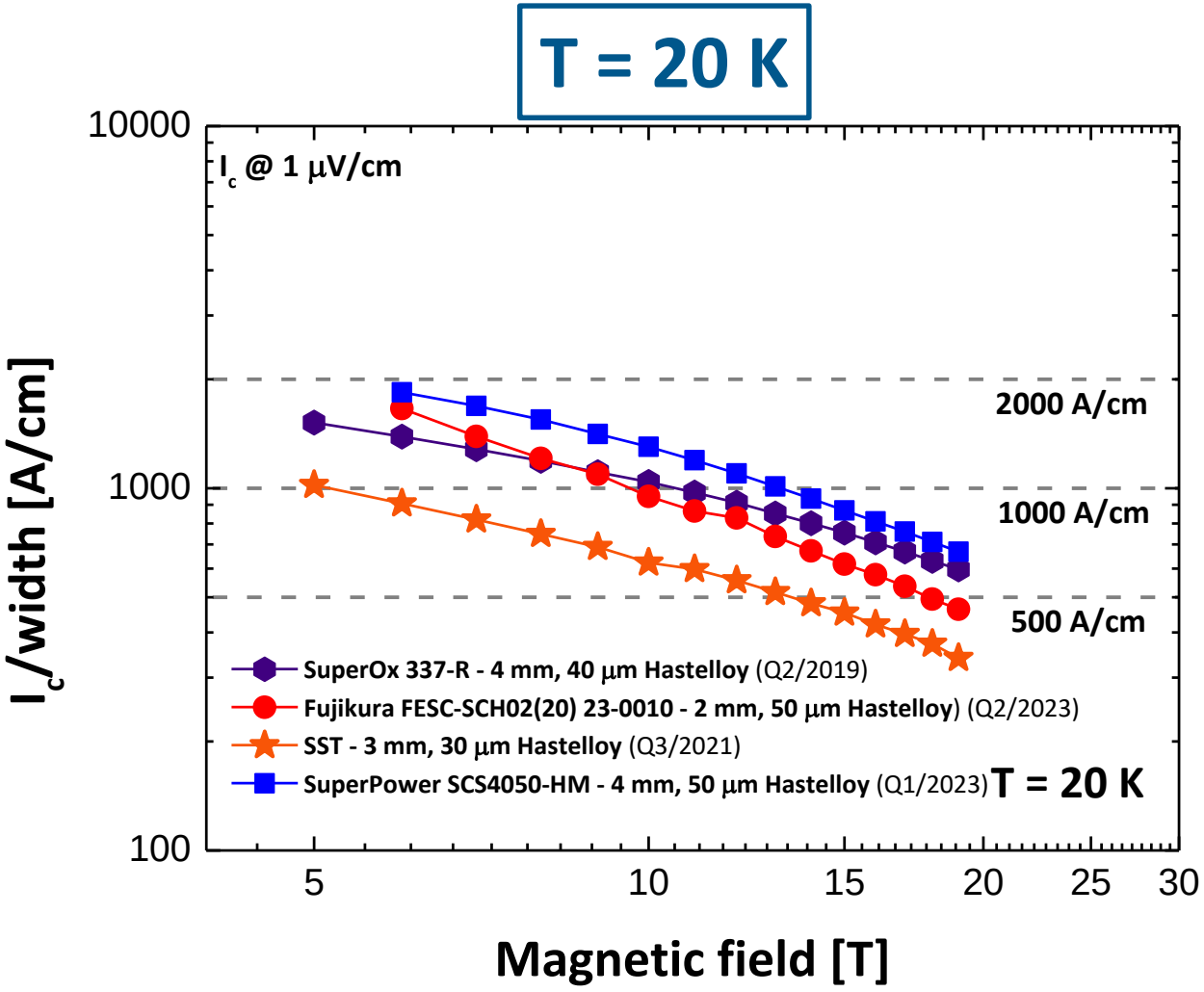
Comparison of the performance: I_c / width

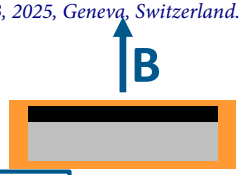
The best performing tapes from each manufacturer





The highest I_c at 4.2 K, 19 T is reached with the tapes having the highest and the lowest I_c(77 K, s.f.)

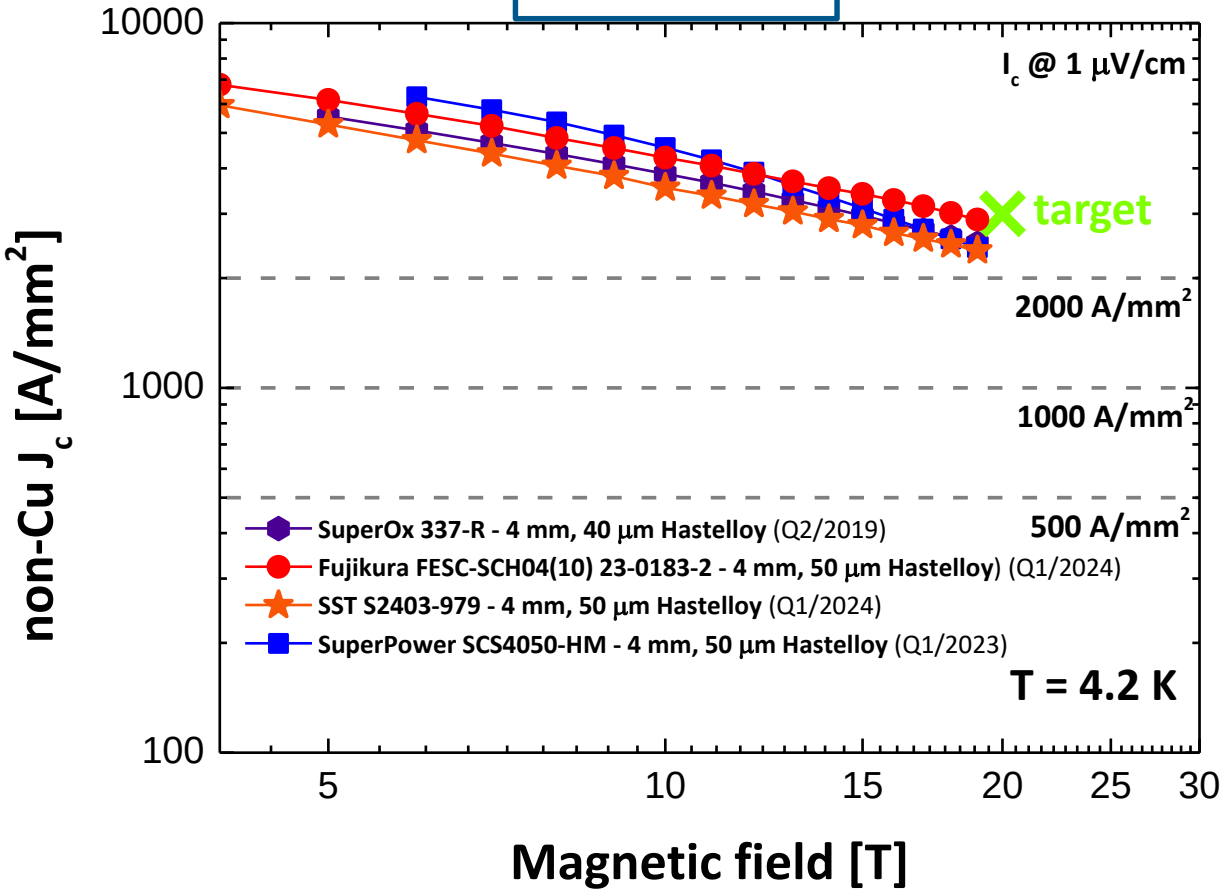
Comparison of the performance: non-Cu J_c



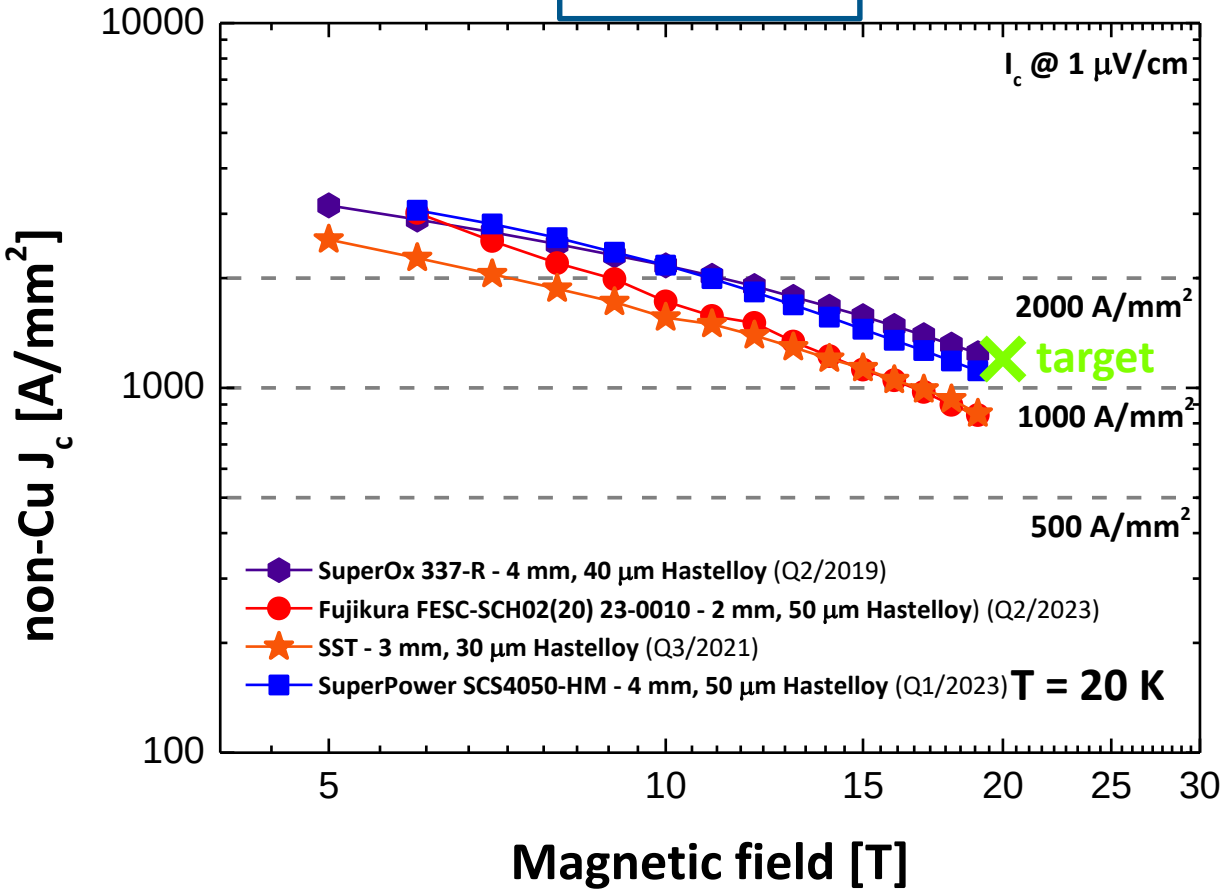
The non-Cu J_c corresponds to the critical current divided by the tape cross-section area minus the Cu area

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

T = 4.2 K

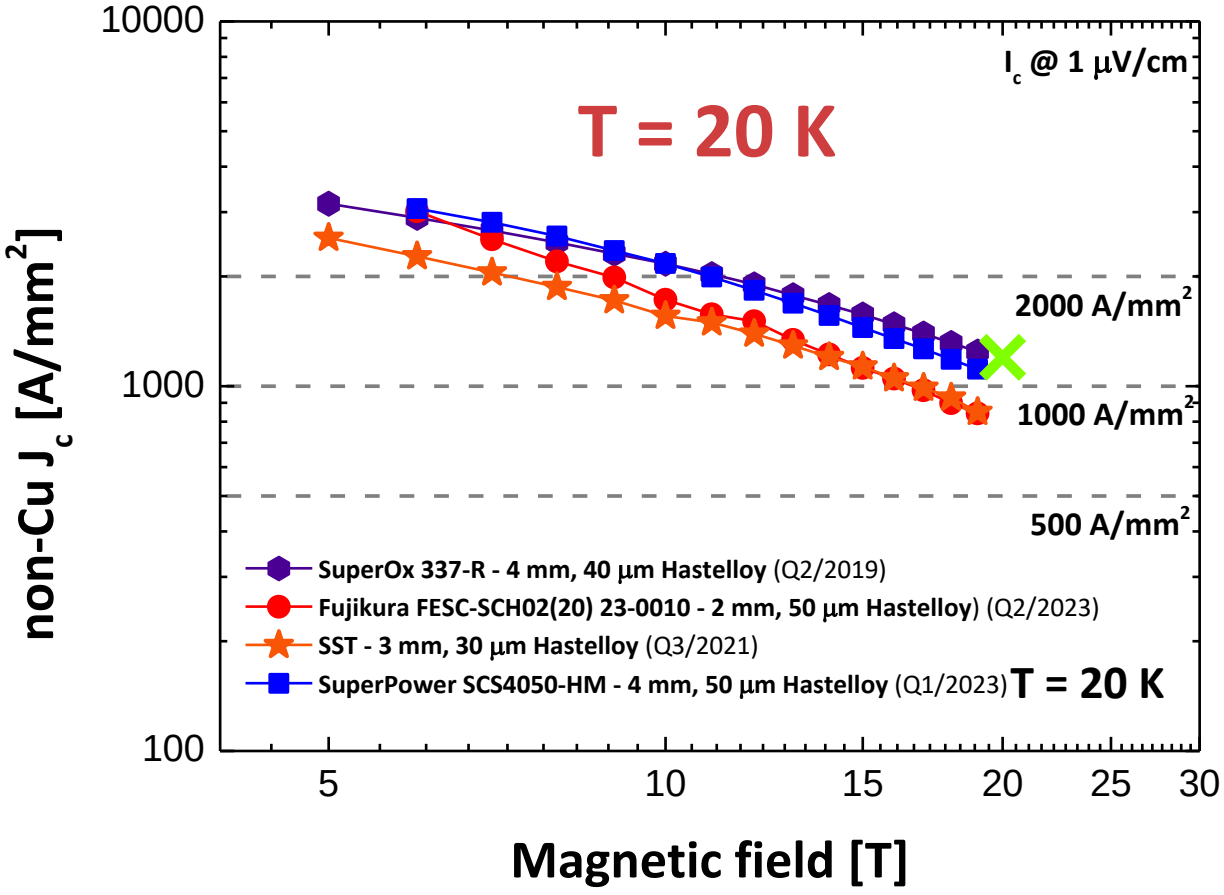


T = 20 K

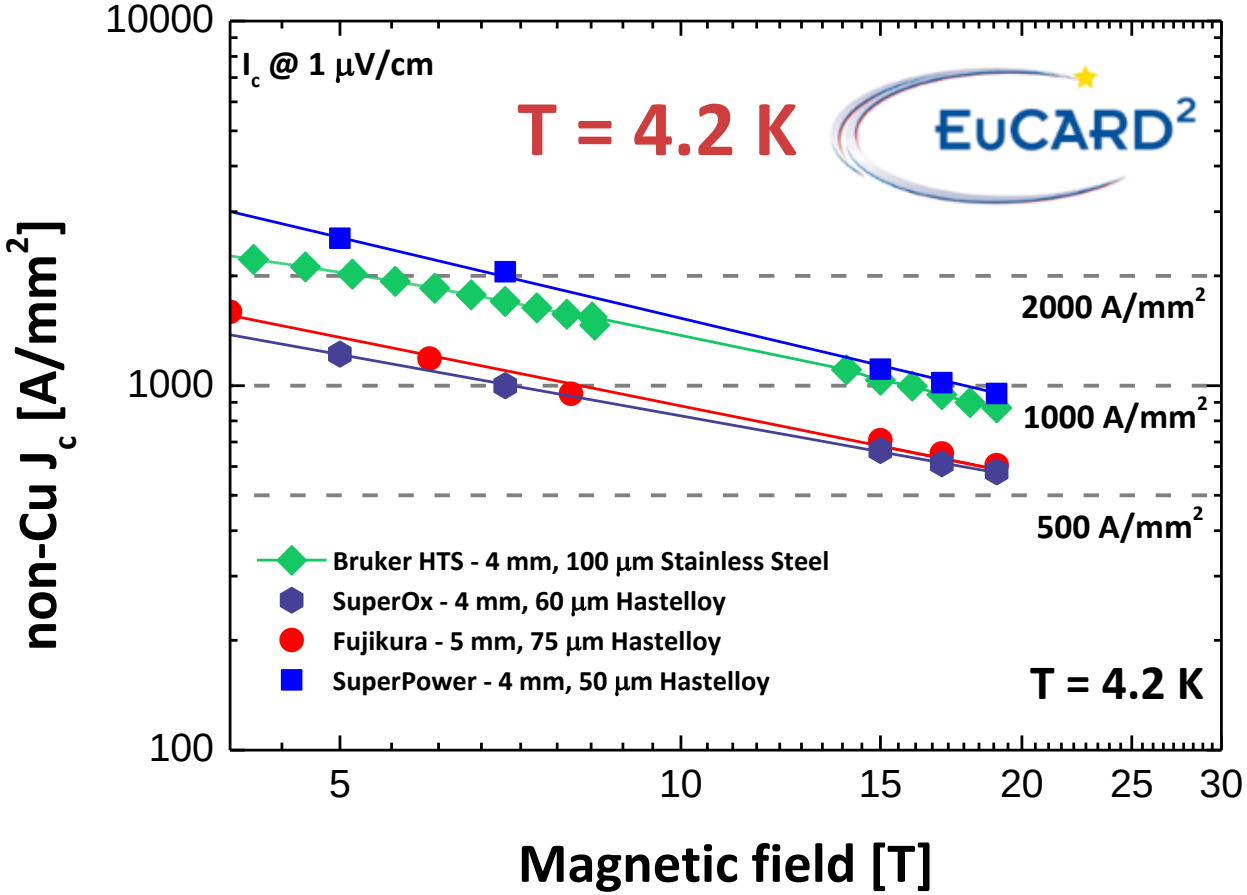


Evolution of the performance: non-Cu J_c

Tapes procured between 2019 and 2023



Tapes procured between 2013 and 2017



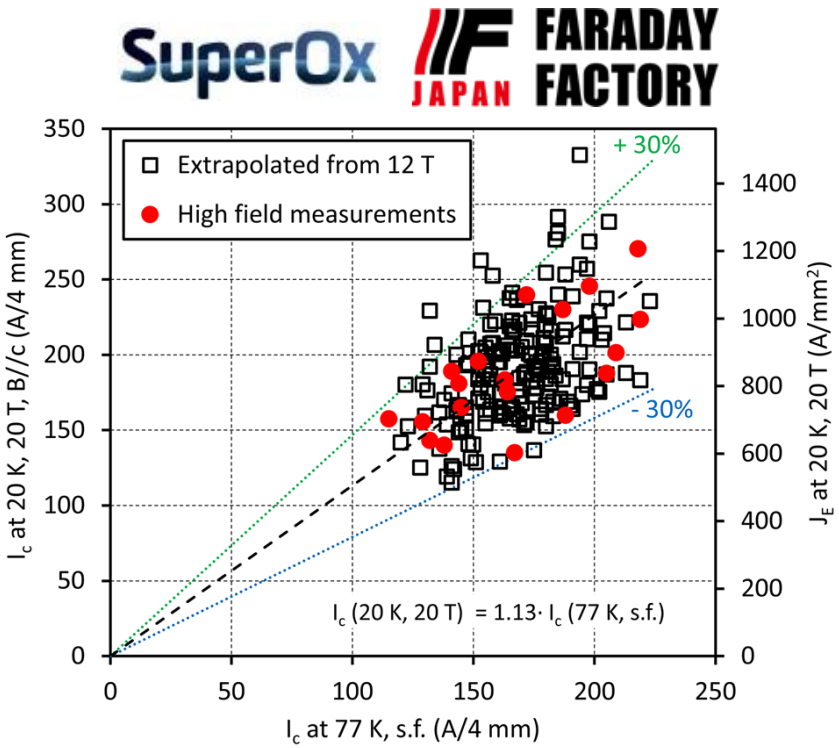
The performance at 4.2 K of the tapes procured during EuCARD² (2013-2017) is achieved and surpassed in modern tapes at 20 K !!

CS , WAMHTS-2

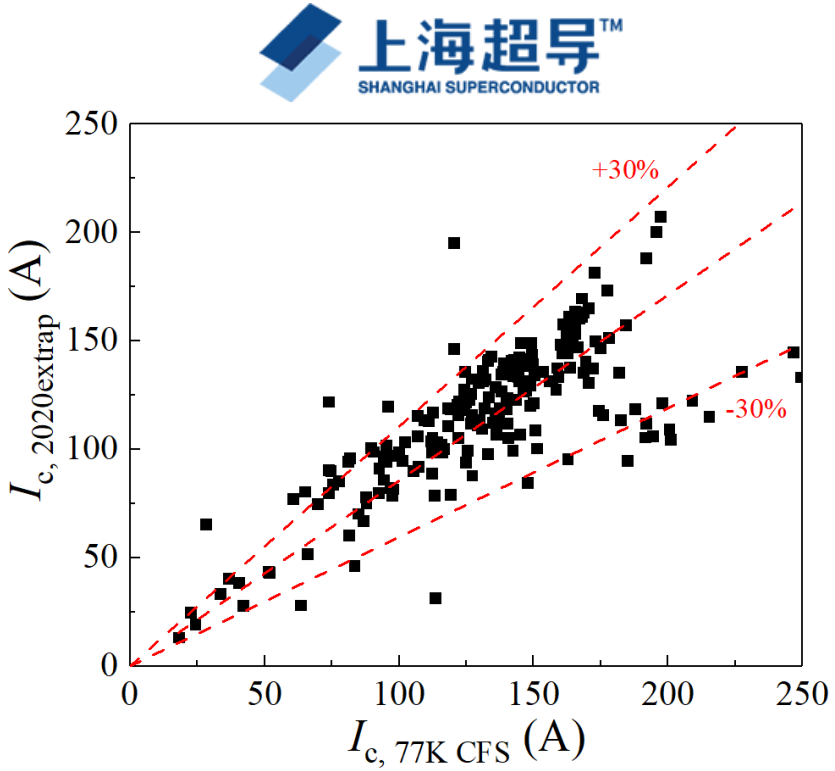
L. Rossi and CS, Instruments, 5 (2021) 8
DOI: 10.3390/instruments5010008

Batch-to-batch variability of REBCO performance

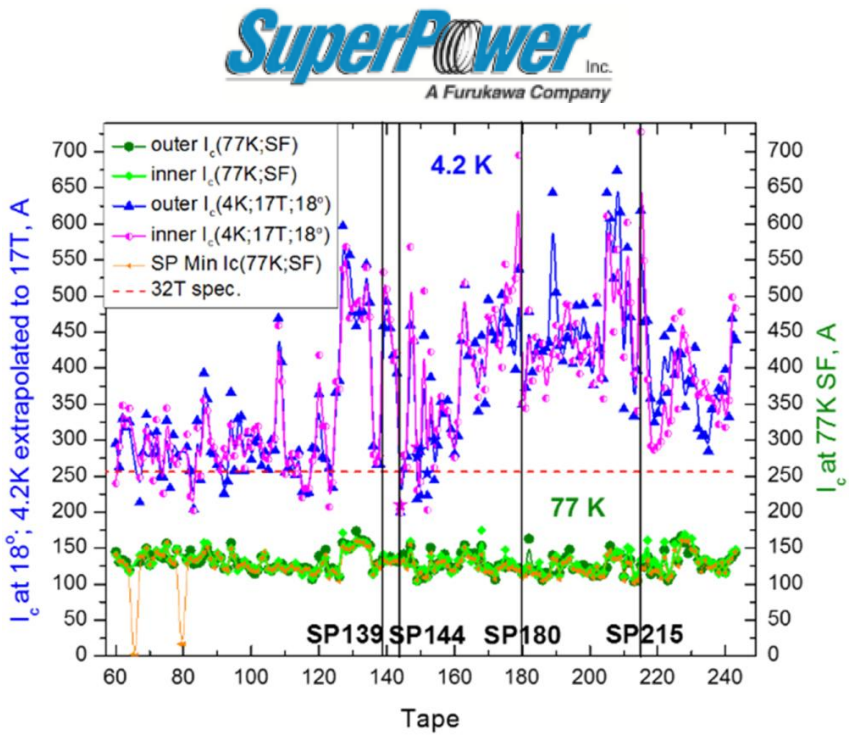
I_c distributions of tapes produced for fusion and for the 32 T magnet at MagLab



A. Molodyk, et al., Scientific Reports, 11 (2021) 2084
DOI: 10.1038/s41598-021-81559-z



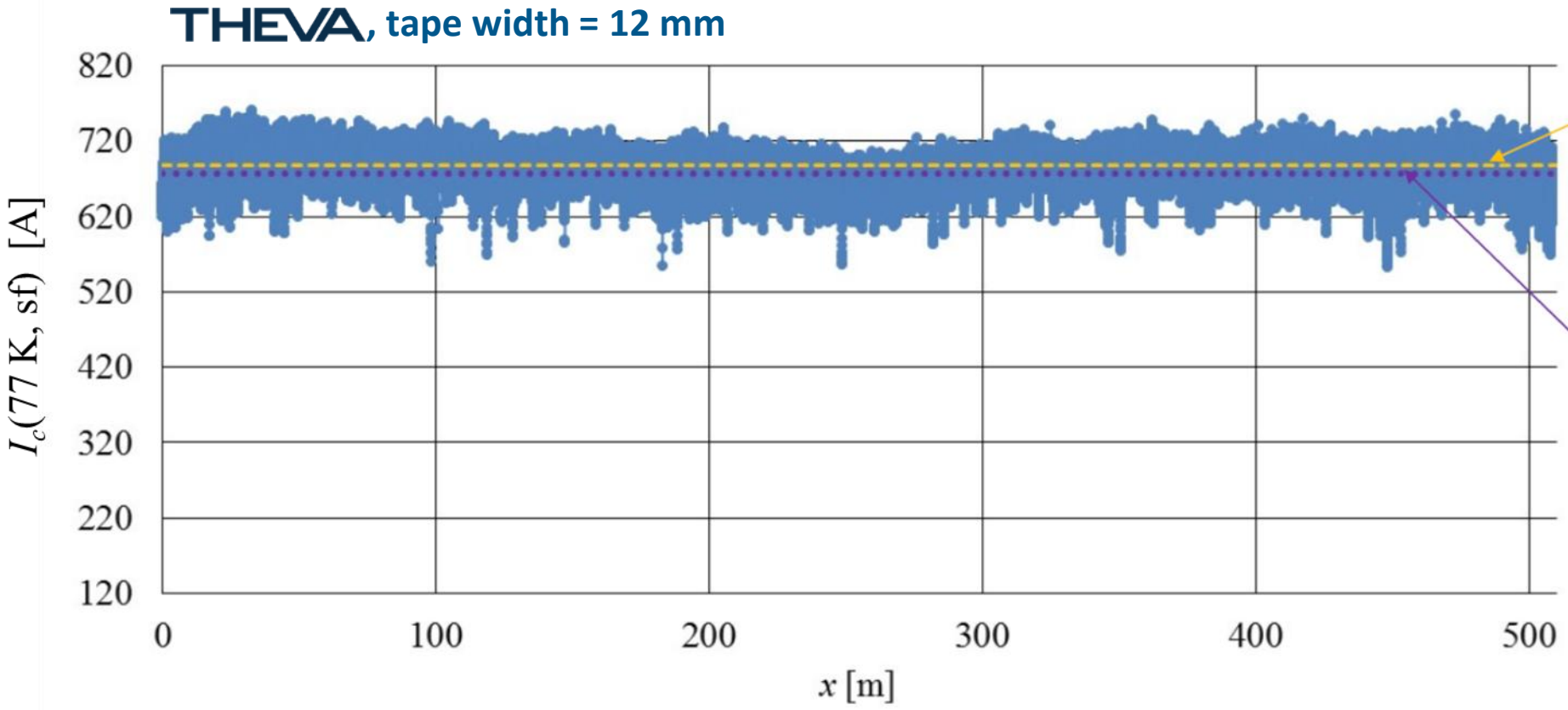
B. Song, private communication



A. Francis, et al., SuST 33 (2020) 044011
DOI: 10.1088/1361-6668/ab73ee

A large variability of the performance at low temperature/high field, about ± 30%, is observed for a given I_c at 77 K, self-field

(Non-)uniformity of I_c over the length



average value of critical current

$$I_{c,aver} = \frac{\sum_{i=1}^{N} I_{c,i}}{N} = 687 \text{ A}$$

$$\sigma = 19 \text{ A}$$

overall critical current generating 1 μV/cm on all the tape length

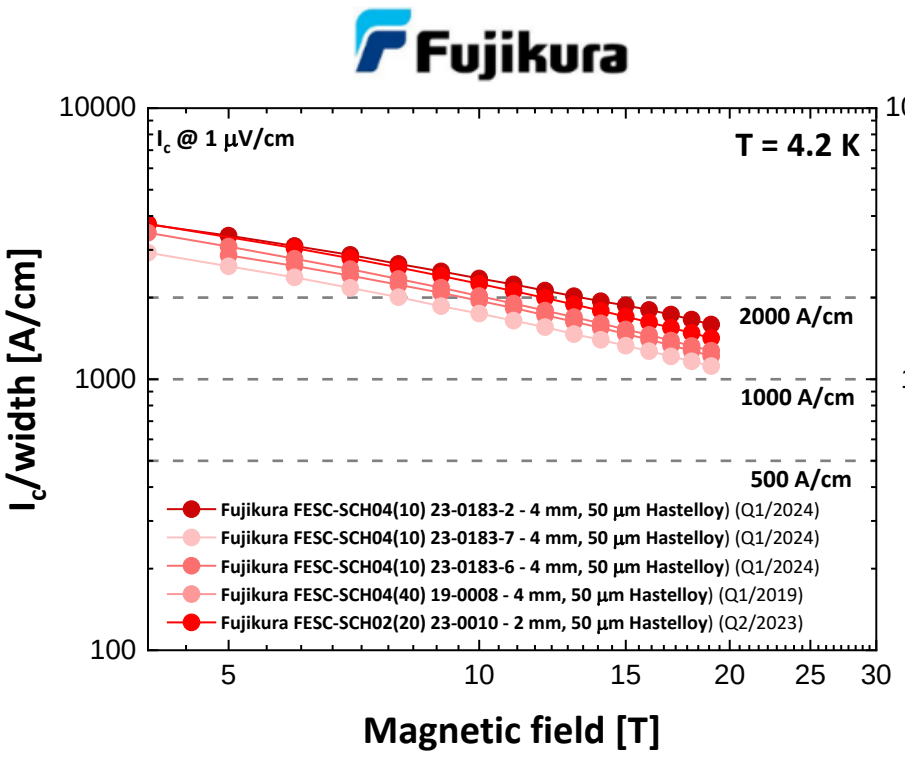
$$I_{c,ovrl} = \left[\frac{N}{\sum_{i=1}^{N}\left(\frac{1}{I_{c,i}}\right)^{n}}\right]^{\frac{1}{n}} = 678 \text{ A}$$

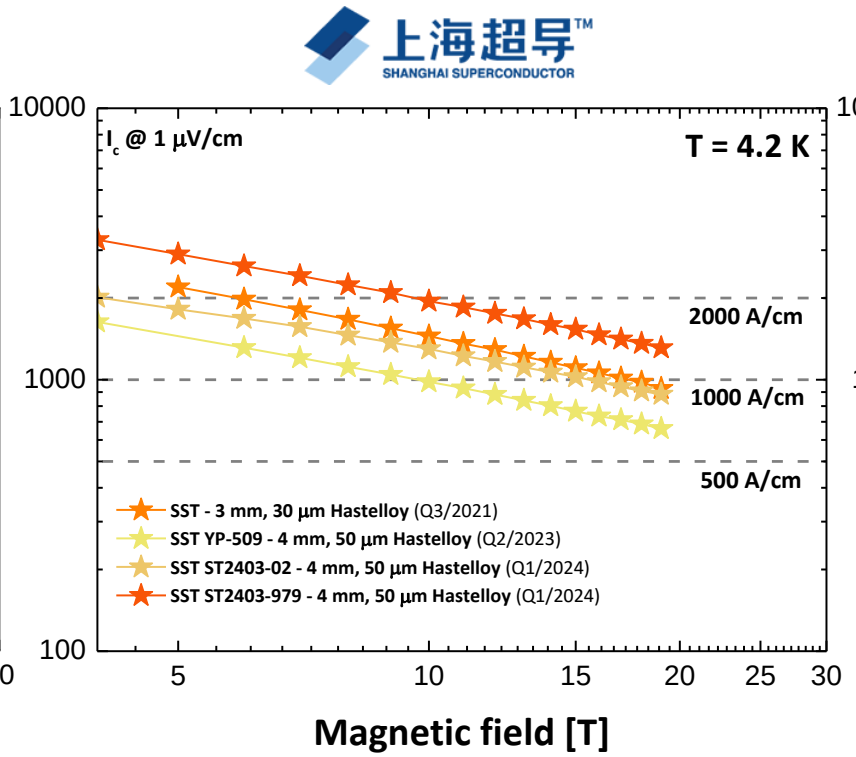
A variation of I_c(77 K,sf) by ± 10% along the length is common, but larger drops may occur locally

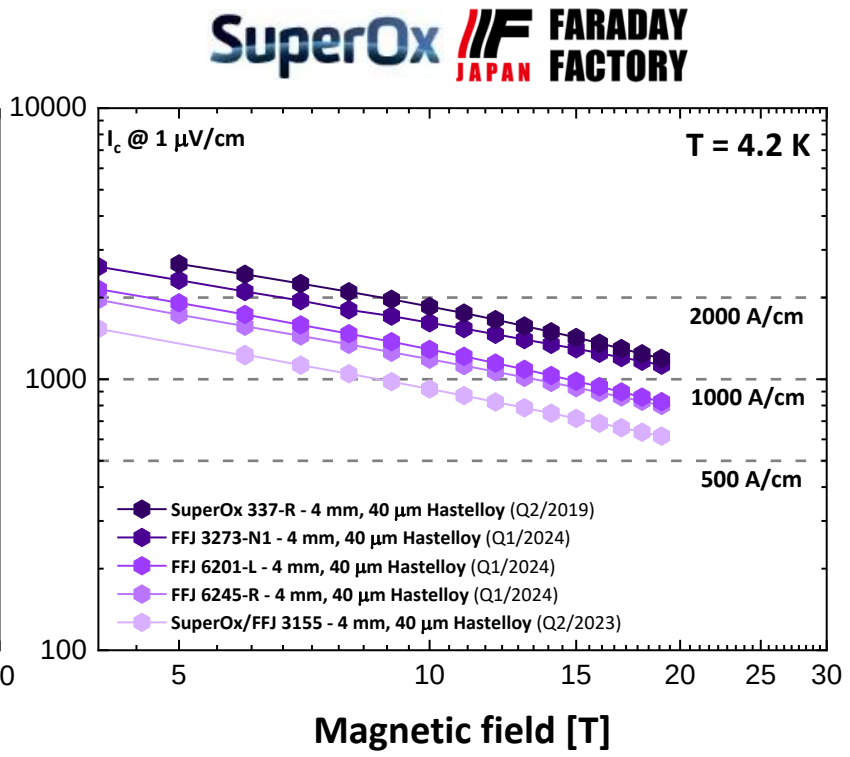
F. Gömöry, et al., SuST 36 (2023) 054001
DOI: 10.1088/1361-6668/acb73f

Comparison of the performance: I_c / width

Batch-to-batch variability in the material procured for MuCol







$I_c(4.2\ K, 19\ T)_{LOW} = 1100\ A/cm$

$I_c(4.2\ K, 19\ T)_{HIGH} = 1600\ A/cm$

$I_c(4.2\ K, 19\ T)_{LOW} = 660\ A/cm$

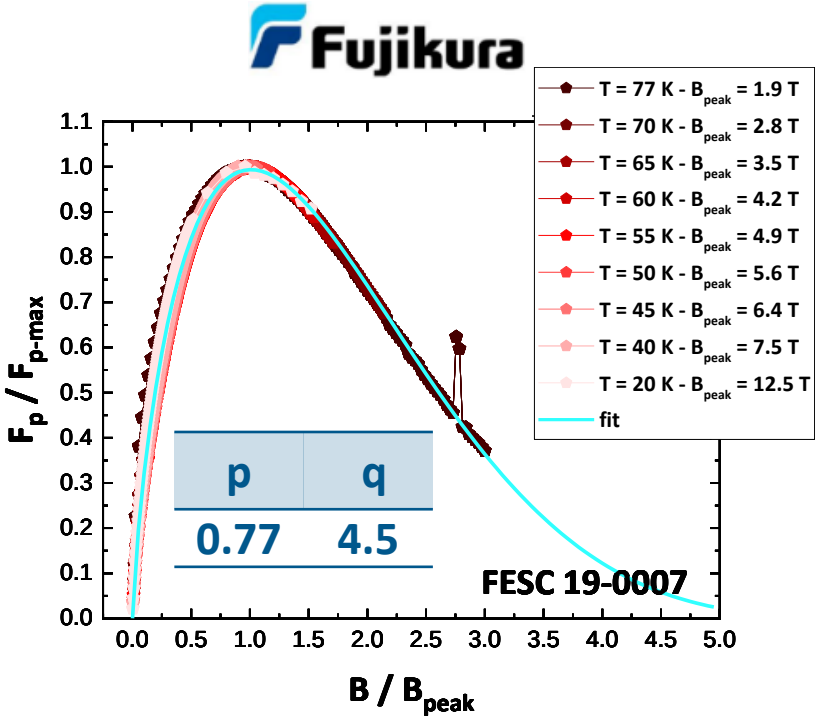
$I_c(4.2\ K, 19\ T)_{HIGH} = 1310\ A/cm$

$I_c(4.2\ K, 19\ T)_{LOW} = 620\ A/cm$

$I_c(4.2\ K, 19\ T)_{HIGH} = 1200\ A/cm$

Scaling of the pinning force: $f_p \propto b^p(1-b)^q$

Normalized pinning force vs B / B_{peak} from magnetic and transport measurements



Pinning: Artificial - BHO columns

CS *et al.*, Supercond. Sci. Tech. 37 (2024) 115013
DOI: 10.1088/1361-6668/ad7f95

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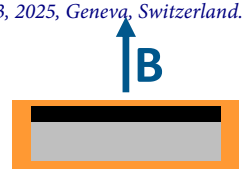

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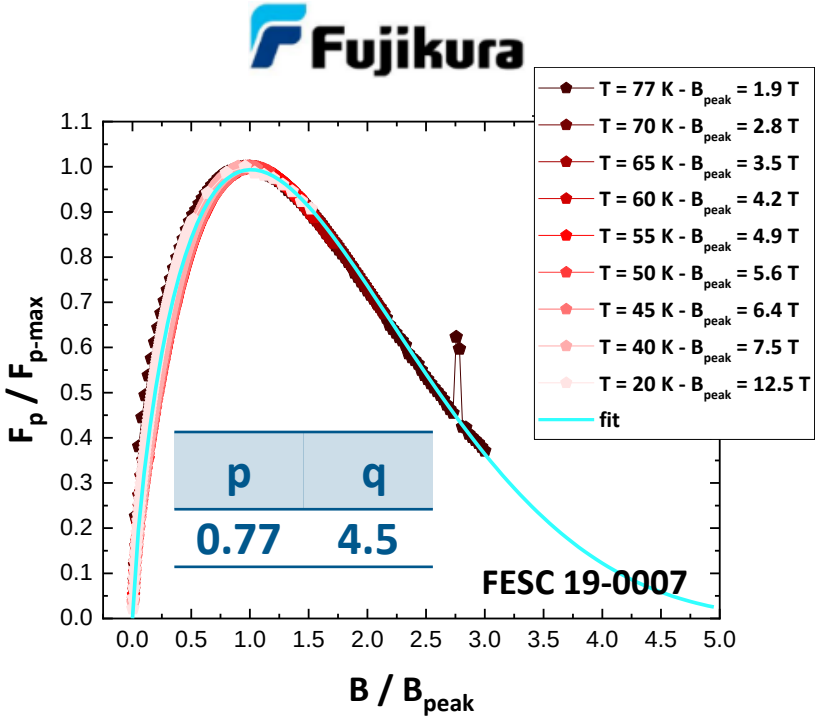

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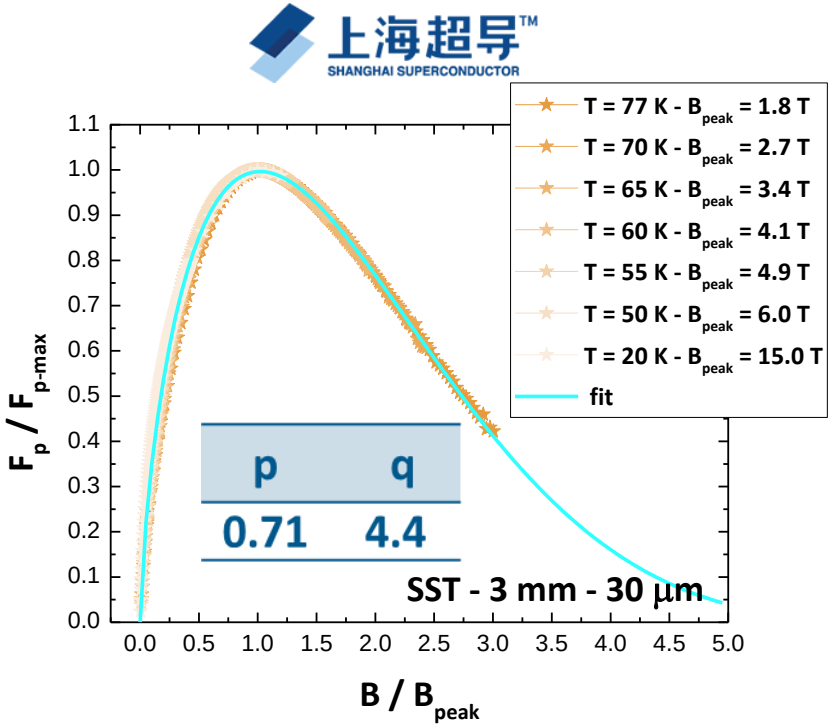

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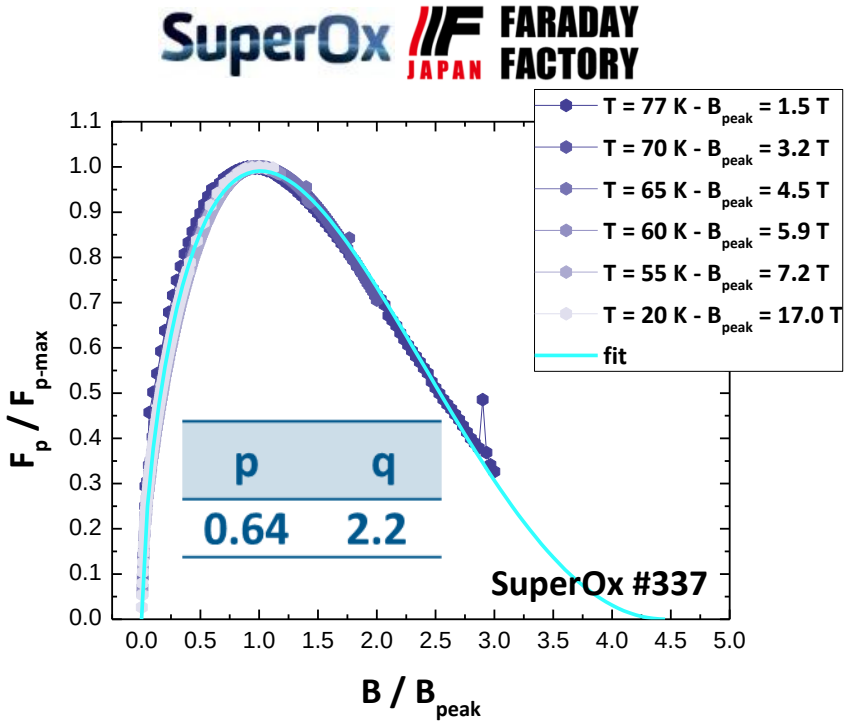
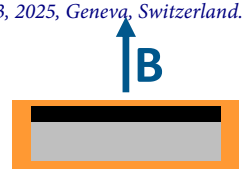
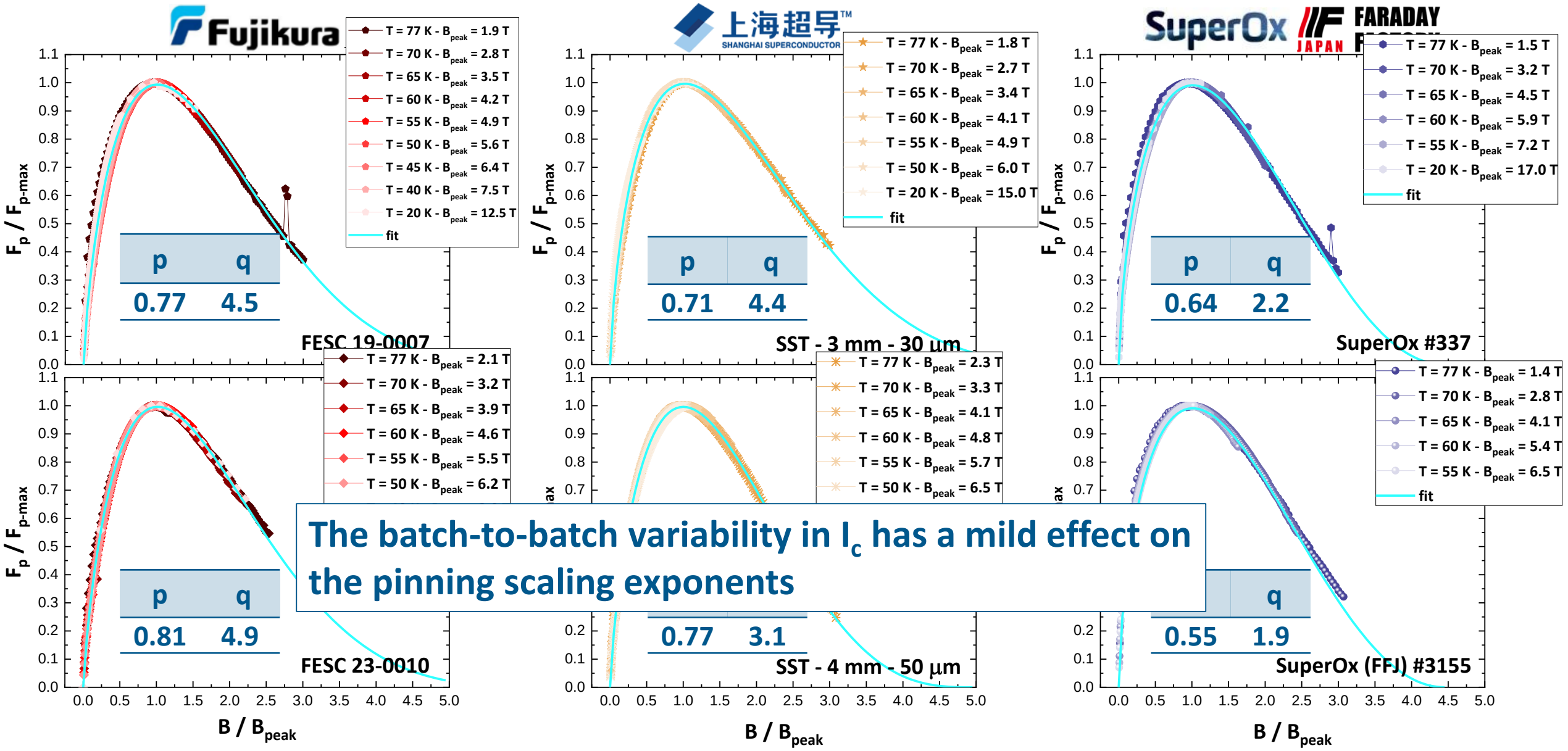


Pinning: Native – Y_2O_3 particles

CS *et al.*, Supercond. Sci. Tech. 37 (2024) 115013
DOI: 10.1088/1361-6668/ad7f95

Scaling of the pinning force: $f_p \propto b^p(1-b)^q$





The batch-to-batch variability in I_c has a mild effect on the pinning scaling exponents

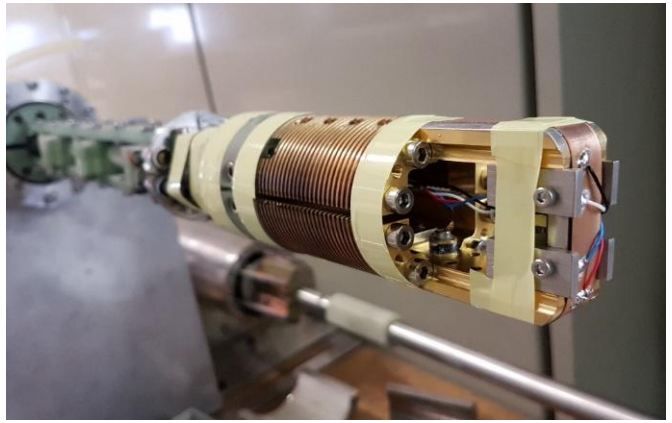
There is a robust scaling behavior in perpendicular field …

… but REBCO anisotropy adds a layer of complexity

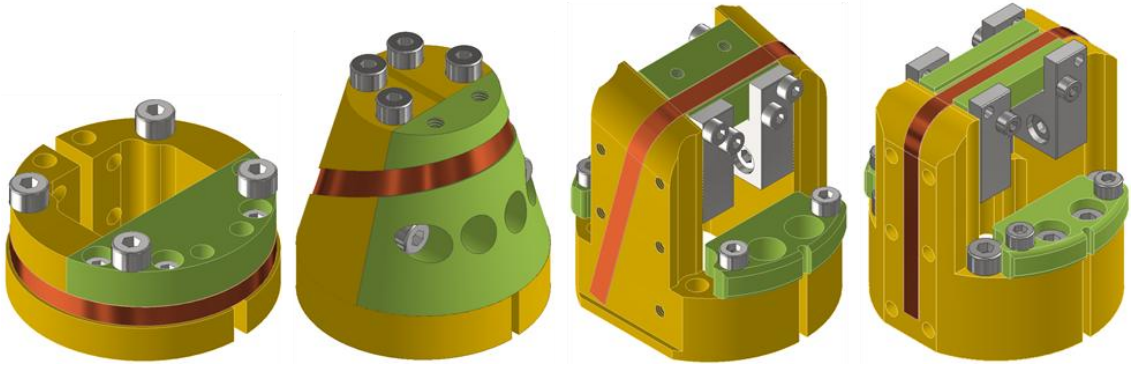
Measurement campaign on the angular dependence of I_c

Results on full-width tapes and microbridges

Setup at UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES



max current	2400 A
T range	4.2 – 40 K
B range	0 – 19 T (21 T)
Sample length	150 mm
Sample width	2 – 12 mm

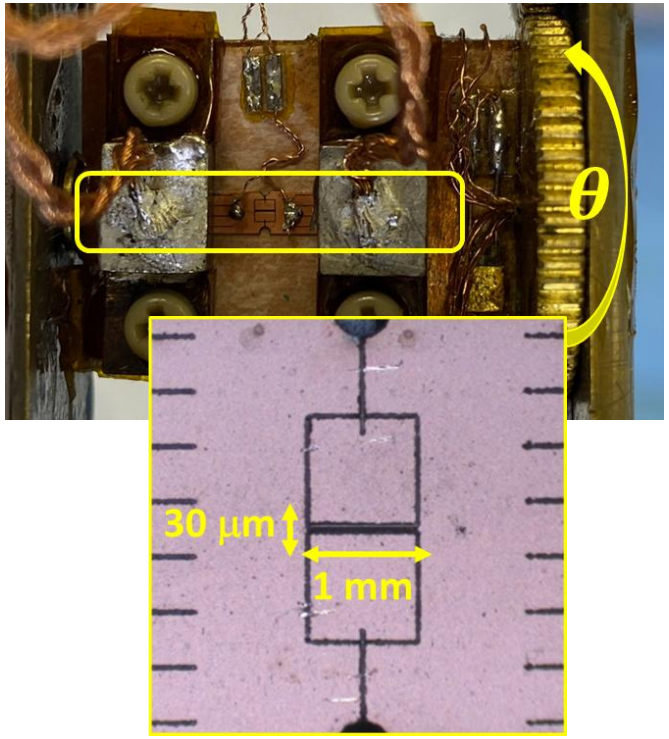


θ = 0° 5° - 15° 80° 90°

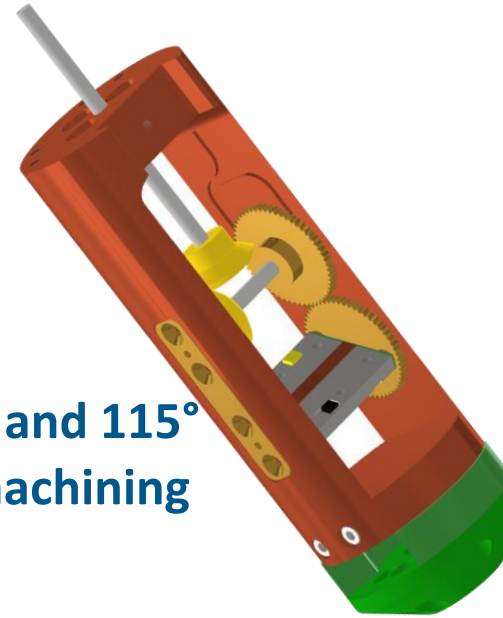
Adapters with fixed orientation

A fresh sample is tested at each angle

Experiments in Sendai at TOHOKU UNIVERSITY



max current	20 A
T range	5 – 77 K
B range	0 – 24 T (15 T)
Bridge length	1 mm
Bridge width	30 μm



Continuous rotation between -20° and 115°

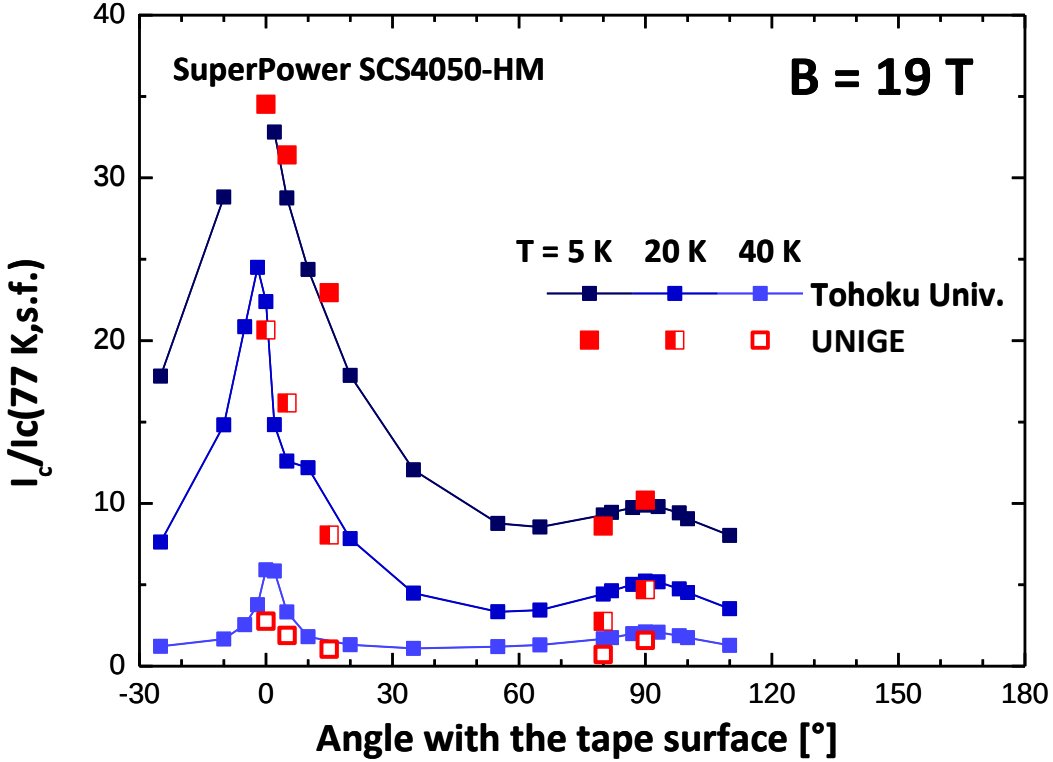
Microbridges patterned by laser machining

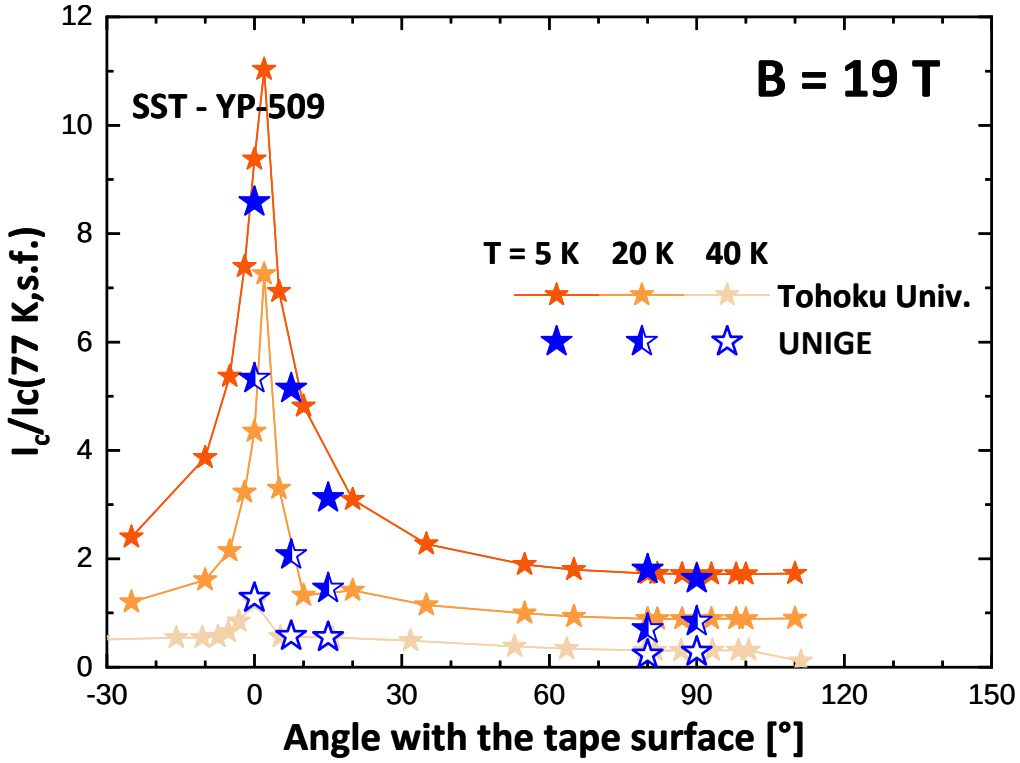
Measurement campaign on the angular dependence of I_c

Comparison of the results: TOHOKU UNIVERSITY vs UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES

SuperPower Inc. A Furukawa Company

上海超导™ SHANGHAI SUPERCONDUCTOR





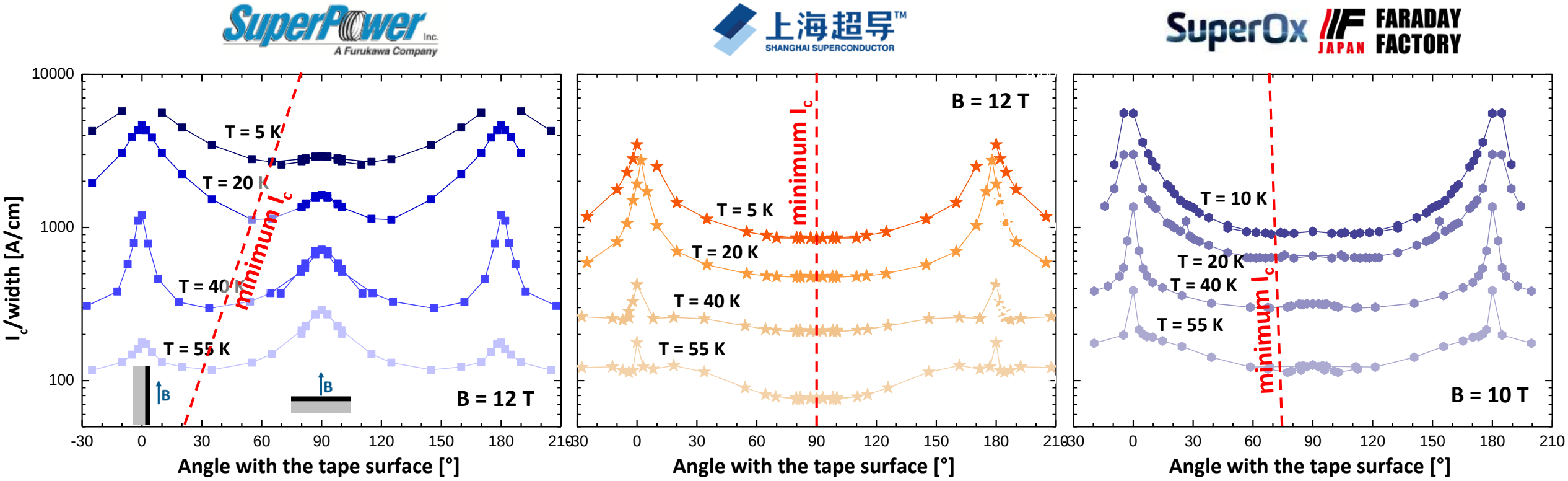
Good match of the results when comparing I_c/I_c(77 K, s.f.)

In both experiments I_c(77 K, s.f.) is measured on the actual sample mounted on the probe

R. Babouche's poster, Wednesday @ 12:30

$I_c(B,\theta,T)$ does not exhibit universal behaviour

Comparison of the results on tapes from three manufacturers



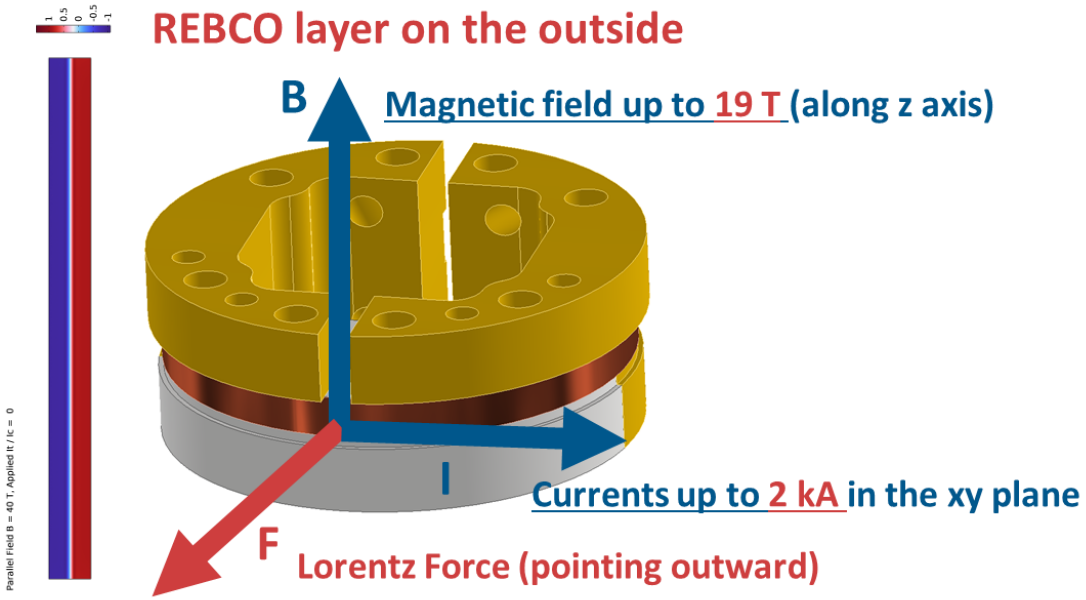
R. Babouche's poster, Wednesday @ 12:30

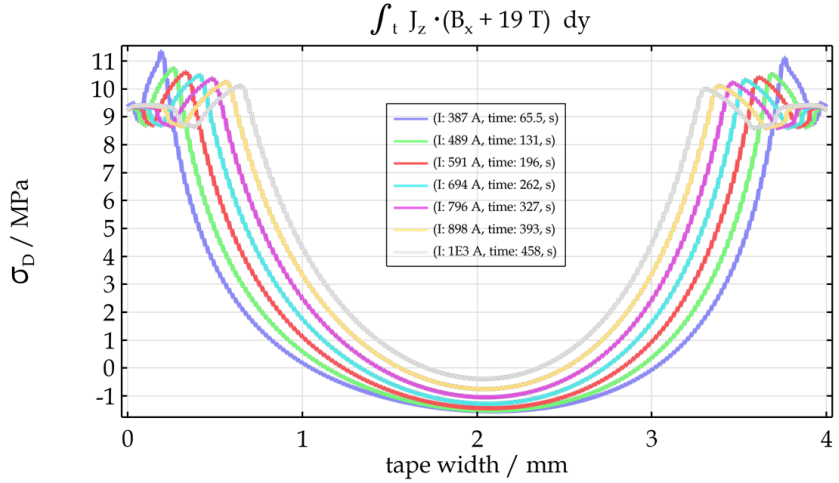
Outline

- A short introduction to the Muon Collider magnets
- **MuCol procurement of REBCO coated conductors**
  - Conductor specs for the HF and UHF solenoids
  - Transport I_c measurements and scaling relations
  - Results of the measurement campaign on the angular dependence of I_c
  - **Delamination strength under I x B force**
- Conclusions

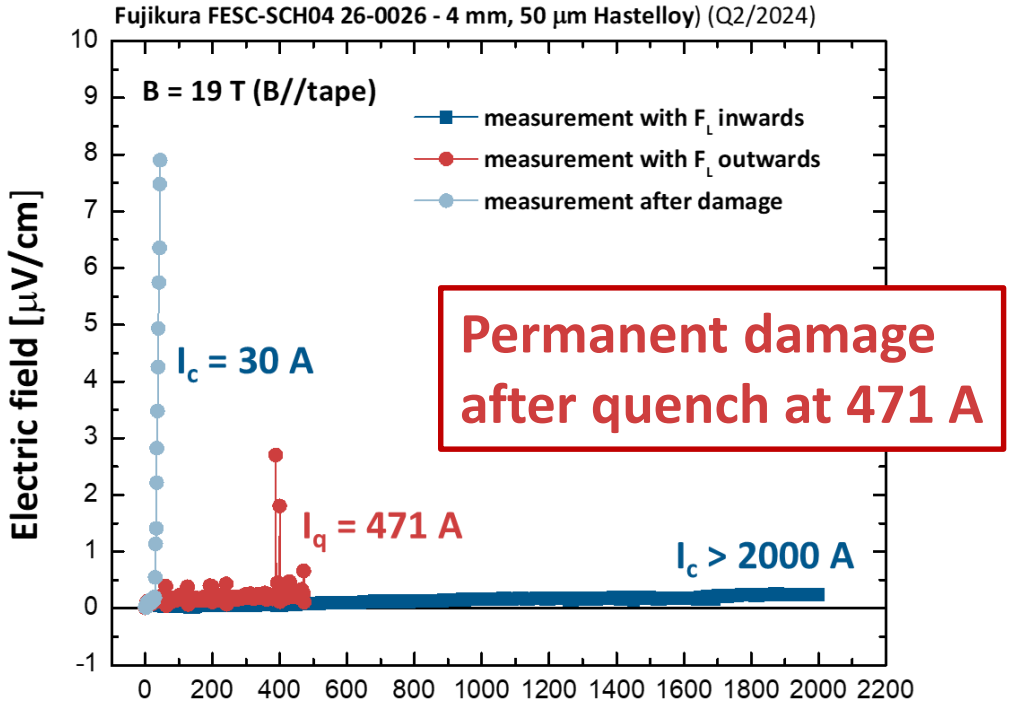
Delamination strength is very low…

A direct measurement of conductor degradation under I x B force



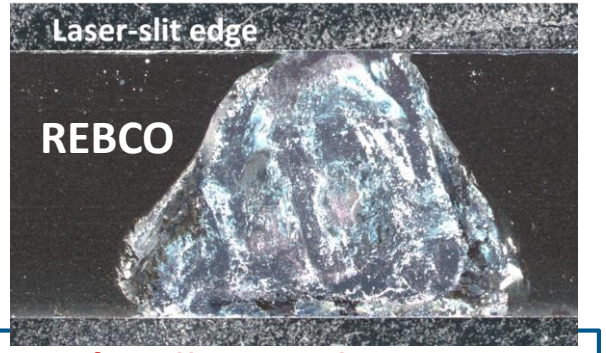


Stress profile within REBCO when current increases



after Cu etching

after Silver etching



C. Lucas & G. Vernassa's Talk, Tuesday @ 17:20

Conclusions

- The I_c values at low temperature/high field of commercial REBCO tapes in perpendicular orientation are quite close. And pinning forces scale reasonably well over a wide range of temperatures.
- Things change when we examine the angular dependence of I_c. It is strongly influenced by process, composition and pinning landscape.
- Electromagnetic Delamination Strength (EDS) experiments show that REBCO tapes cannot sustain transverse tensile tension. The procedure for EDS tests is being consolidated and more data will be shared soon.
- Unlike the traditional paradigm of round wires with transposed filaments, REBCO tapes bring challenges and opportunities. R&D efforts can mitigate some issues, but rather than waiting for the perfect material, we must continue to harness and capitalize on the strengths of current REBCO tapes and keep up the momentum in advancing the technology.
- In the case of MuCol, where high-performance magnets are crucial, efforts should be directed toward exploiting degrees of freedom in the other machine's subsystems to compensate for material limitations. This attitude should be embraced as a general approach.

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MuCol
International MUON Collider Collaboration

Thank you for the attention !

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