2nd High Temperature Superconductors for Accelerator Technology (HiTAT-2) Workshop

International MUON Collider Collaboration

Exploring the critical current scaling and electromechanical limits of REBCO tapes How far have we come?

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CERN, Switzerland

Outline

- REBCO specifications for the magnets R&D of the Muon Collider
- Results of the measurement campaign on the angular dependence of I_c
  - Transport I_c measurements on full-width tapes at UNIGE
  - Continuous angular dependence tested on microbridges at Tohoku Univ.
  - Scaling relations for the $I_c(B,\theta,T)$
- Delamination strength under I x B force
- Conclusions

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REBCO technical specs for MuCol magnets R&D

Ongoing R&D on the 40 T/60 mm bore solenoids for the muon beam final cooling

MuCol

HFM High Field Magnets

CERN

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 Te
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-Cu} (4.2 K, 20 T)	(A/mm²)		3000
Minimum J_{non-Cu} (20 K, 20 T)	(A/mm²)		1200
Unit length UL	(m)	200	1000
Minimum bending radius	(mm)	10	5
Allowable non-Cu $\sigma_{longitudinal\ non-Cu}$ (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/cm²)		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

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What has been tested – Catalogue of the Tapes

	REBCO Type	REBCO Thickness	Deposition Method	Pinning Type	I_c(77K,s.f.)
Fujikura	EuBCO	2.5 μm	IBAD/PLD	BHO columns (artificial)	380-650 A/cm▲
FARADAY FACTORY JAPAN	YBCO	2.5 - 3.1 μm ▲	IBAD/PLD	Y_2O_3 particles (native)	405-550 A/cm
上海超导™ SHANGHAI SUPERCONDUCTOR	EuBCO	2 - 3 μm	IBAD/PLD	BHO columns (artificial)	428-645 A/cm
SuperPower Inc. A Furukawa Company SCS4050-HM	YBCO	1.5 μm ▼	IBAD/MOCVD	BZO columns (artificial)	148 A/cm ▼
SuNAM Zero to Infinity	YBCO	2.2 μm	IBAD/PLD	Y_2O_3 particles (native)	410 A/cm
SuperMag	YBCO	< 2 μm	IBAD/PLD	BHO columns (artificial)	373 A/cm

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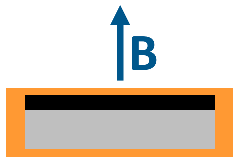
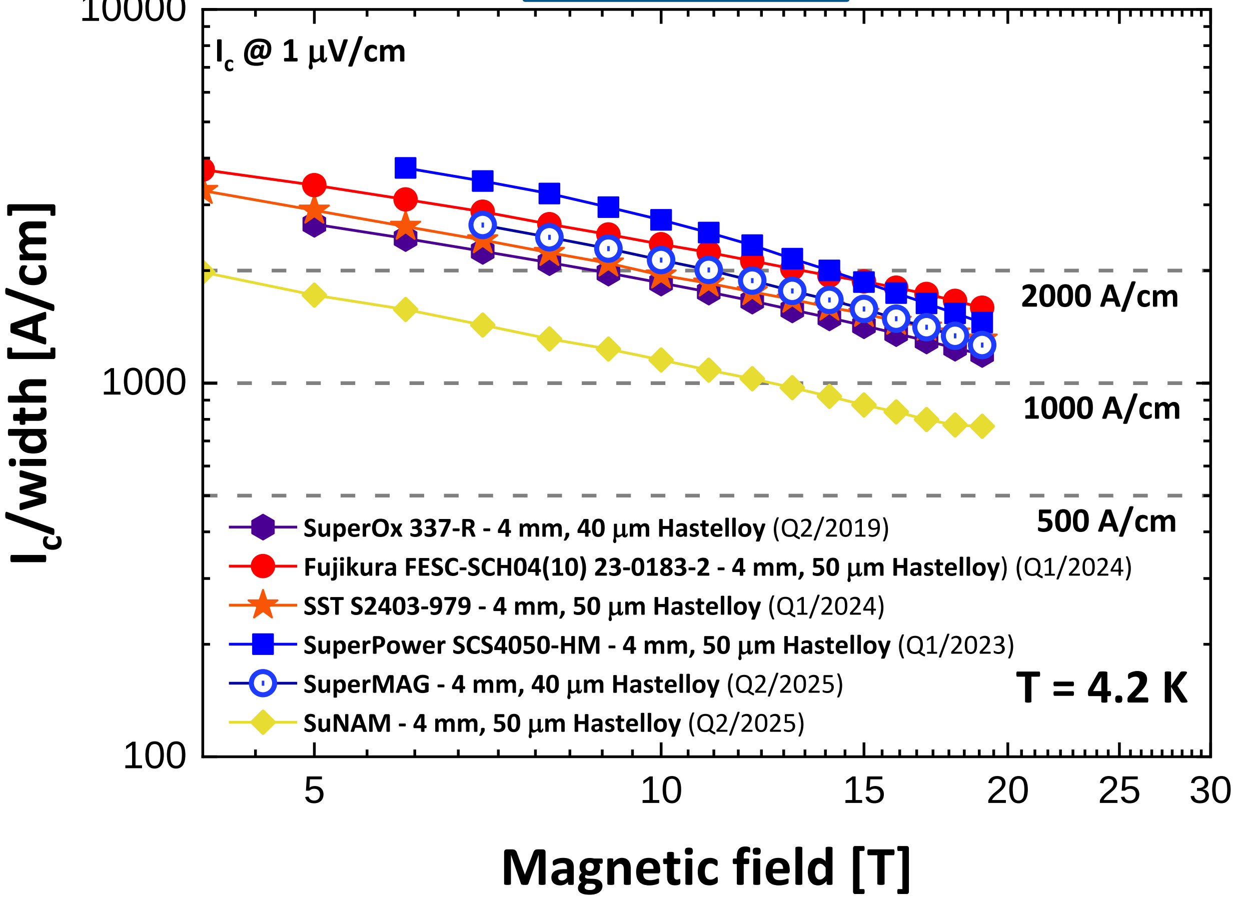
Comparison of the performance: I_c / width

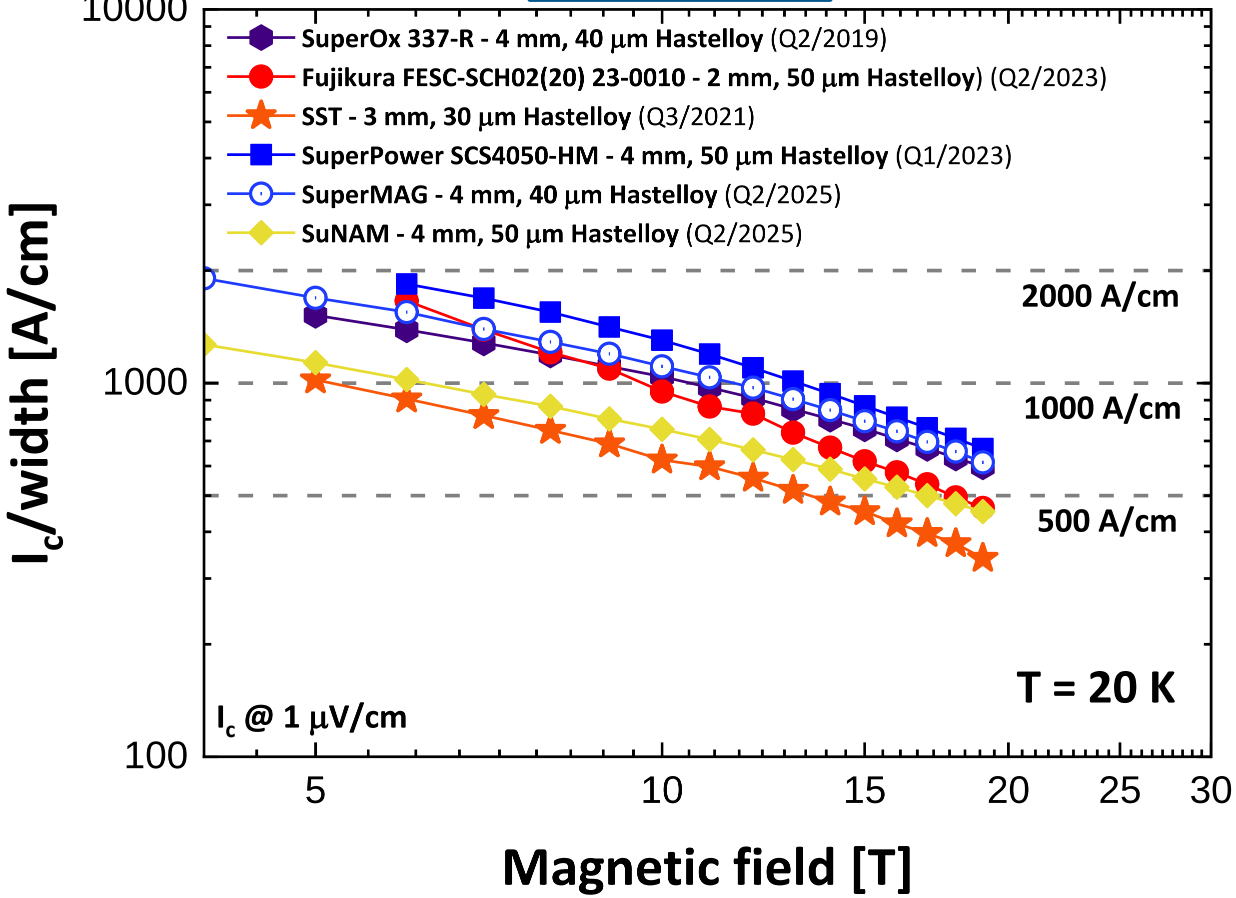


The best performing tapes from each manufacturer

T = 4.2 K



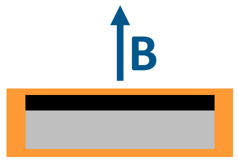
T = 20 K

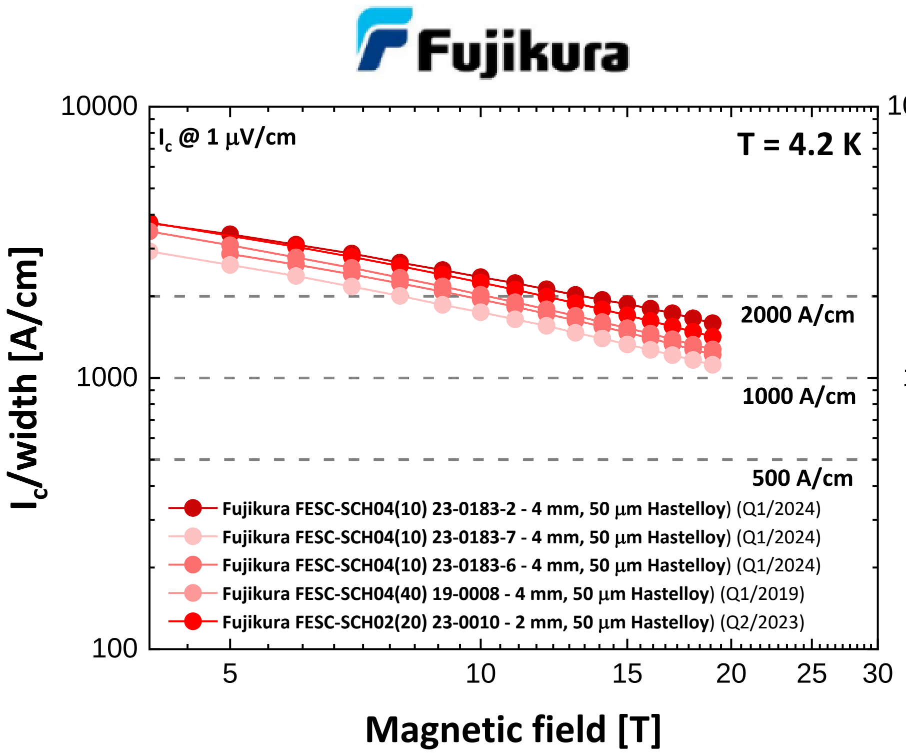


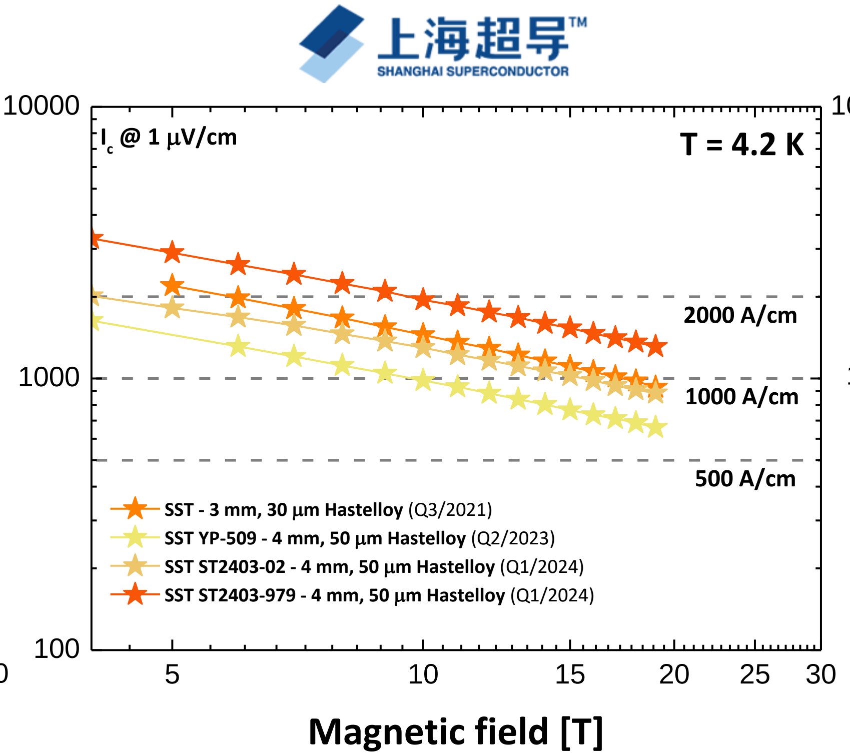
The highest I_c at 4.2 K, 19 T is reached with the tapes having the highest and the lowest I_c(77 K, s.f.)

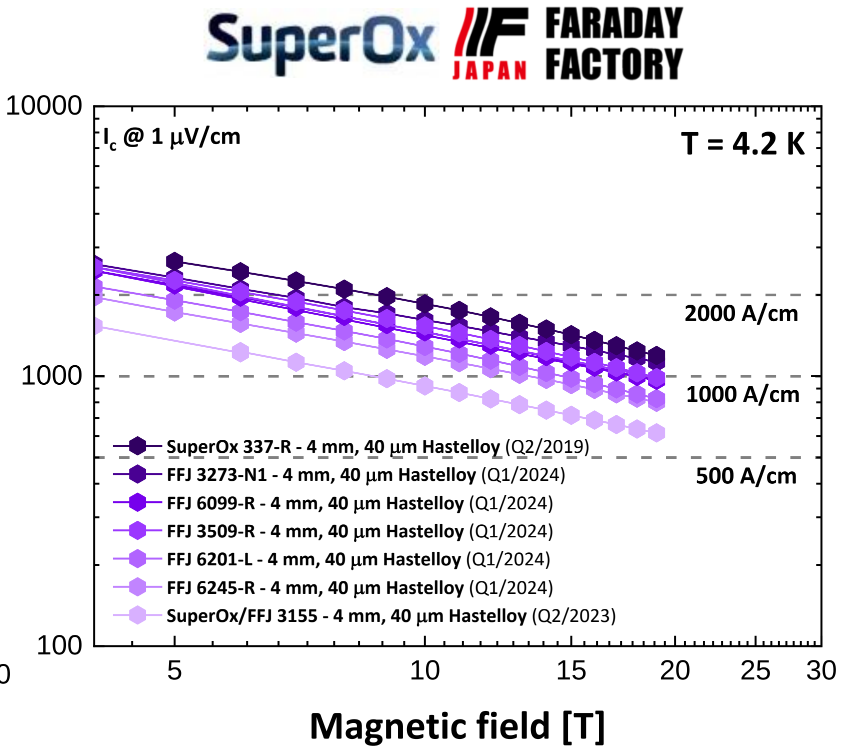
Comparison of the performance: I_c / width

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

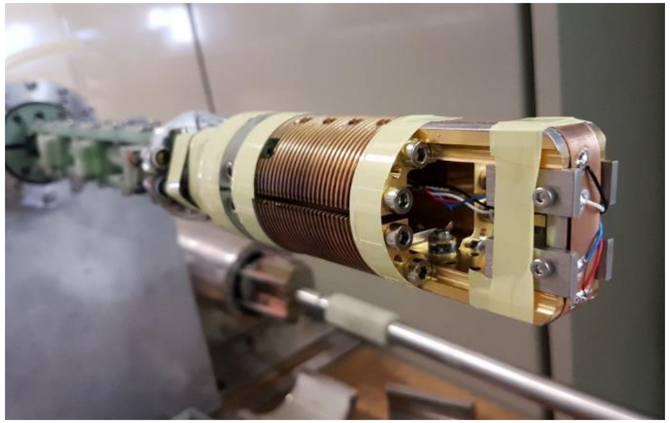
This is what we get with the field perpendicular to the tape…

… but things get more complicated with the angular dependence

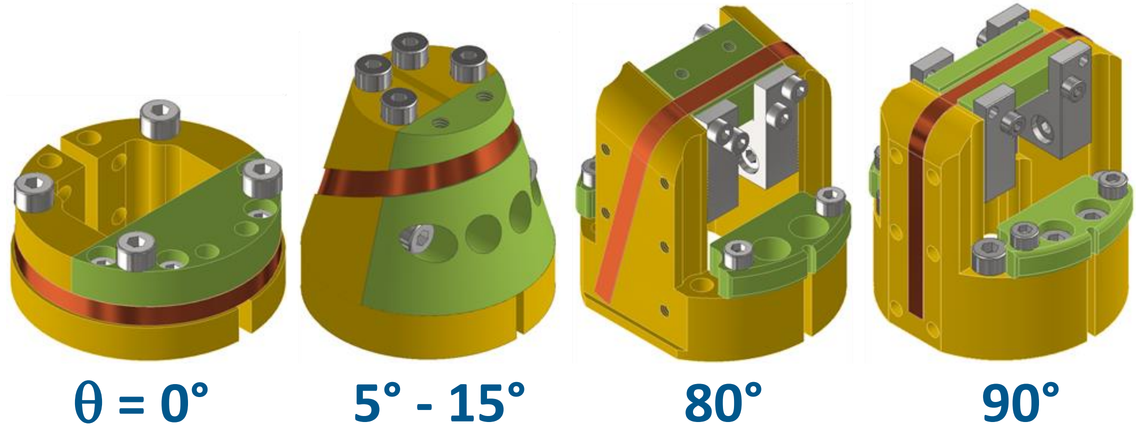
Measurement campaign on the angular dependence of I_c

Results on full-width tapes and microbridges

Setup at Université de Genève – Faculté des Sciences



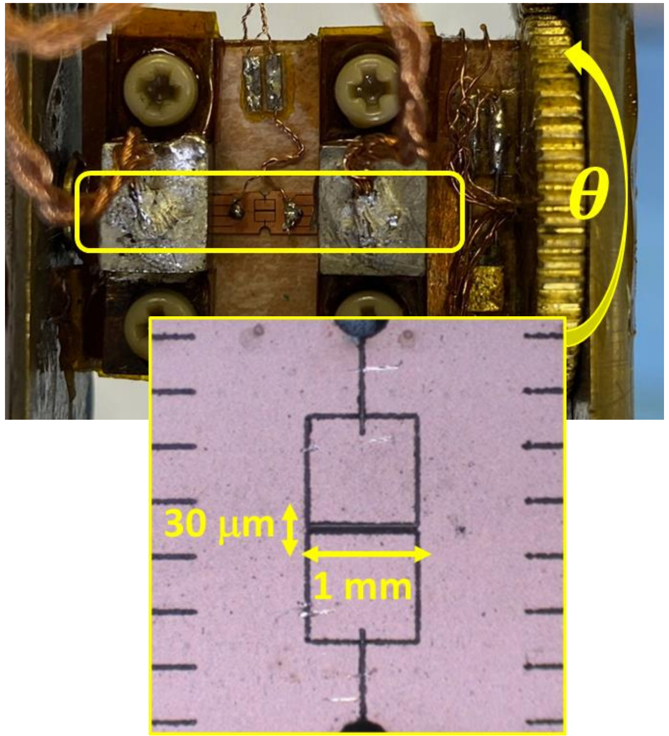
max current	2400 A
T range	4.2 – 40 K
B range	0 – 19 T (21 T)
Sample length	150 mm
Sample width	2 – 12 mm



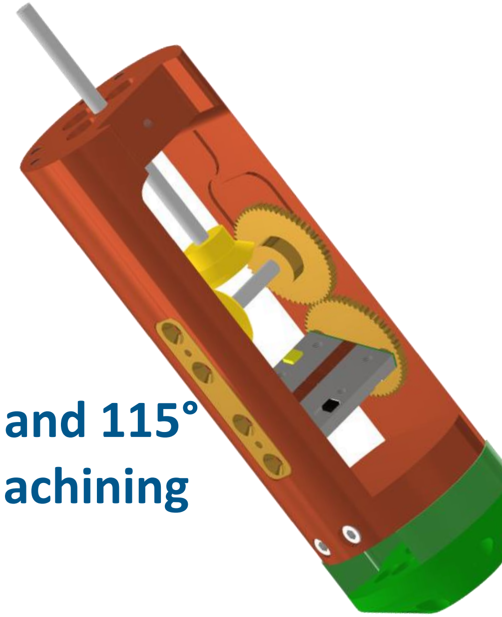
Adapters with fixed orientation

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

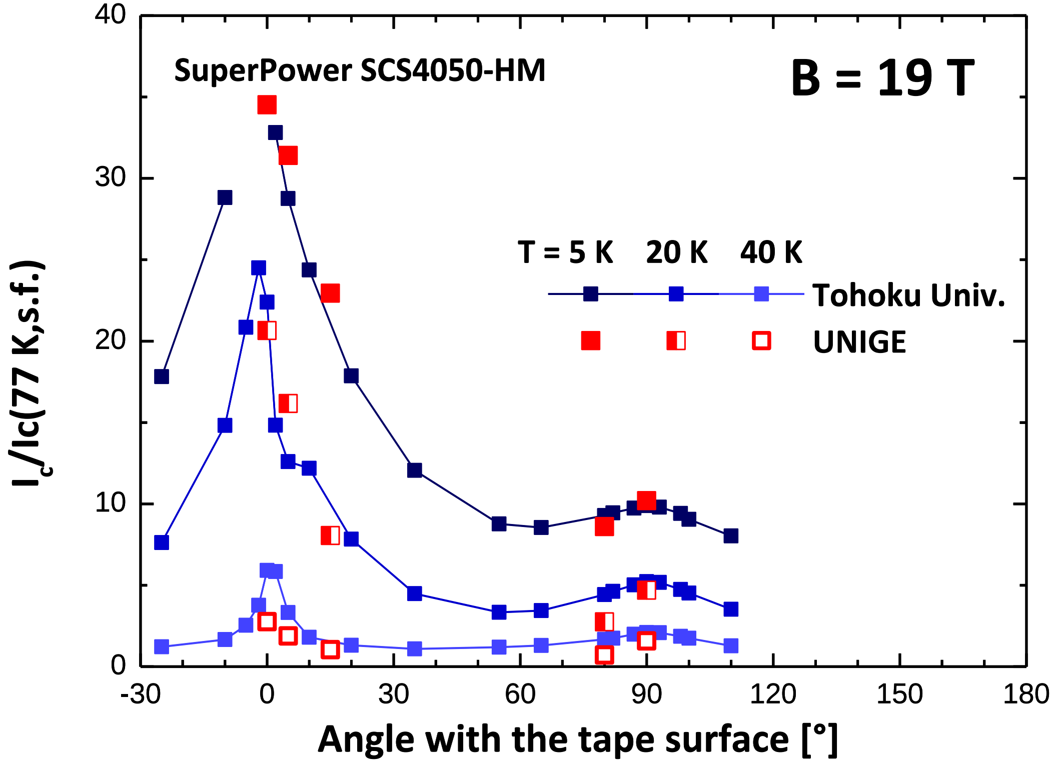


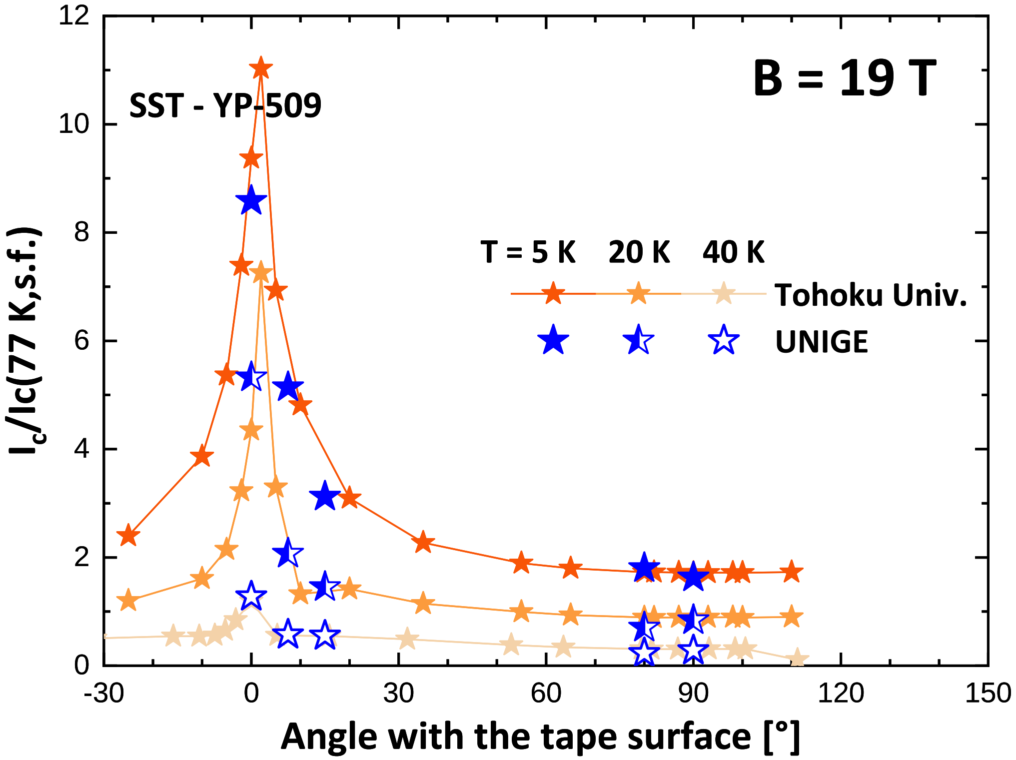
Continuous rotation between -20° and 115°

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





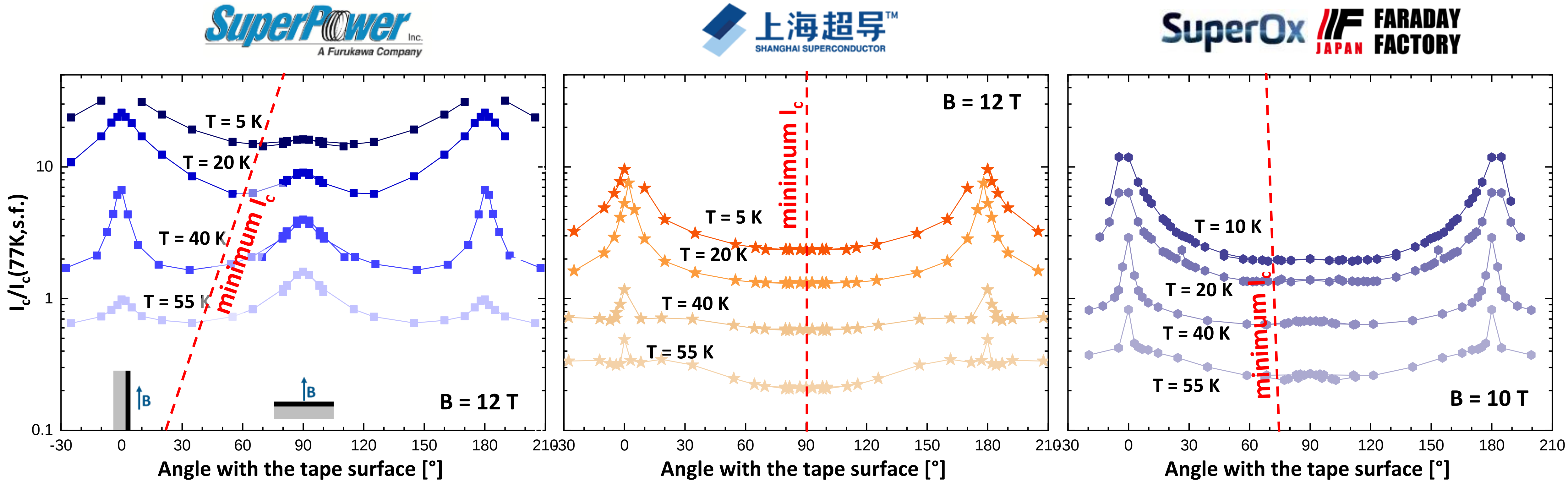
Good match of the results when comparing I_c/I_c(77 K, s.f.)

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

R. Babouche, et al., IEEE TASC 36 (2025) 6600206
DOI: 10.1109/TASC.2025.3617455

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

Comparison of the results on tapes from three manufacturers



R. Babouche, et al., IEEE TASC 36 (2025) 6600206
DOI: 10.1109/TASC.2025.3617455

Scaling laws for the critical surface of practical superconductors

A practical fit for the critical surface of Nb-Ti – *field and temperature dependences*

$$J_c = \frac{C_0}{B} b^{\alpha} (1-b)^{\beta} (1-t^n)^{\gamma}$$ **with** $$t = \frac{T}{T_{c0}}$$ **and** $$b = \frac{B}{B_{c2}(T)}$$

L. Bottura, IEEE TASC 10 (2000) 1054-1057
DOI: 10.1109/77.828413

Unified Scaling Law for flux pinning in Nb_3Sn – *field, temperature and strain dependences*

$$I_c(B, T, \varepsilon)B = C[b_{c2}(\varepsilon)]^s (1 - t^{1.5})^{\eta-\mu} (1 - t^2)^{\mu} b^p (1-b)^q$$ **with** $b \equiv B/B_{c2}{}^*(T,\varepsilon)$ **and** $t \equiv T/T_c{}^*(\varepsilon)$

where $B_{c2}{}^*(T,\varepsilon) = B_{c2}{}^*(0,0)(1 - t^{1.5})b_{c2}(\varepsilon)$ **and** $T_c{}^*(\varepsilon) = T_c{}^*(0)[b_{c2}(\varepsilon)]^{1/3}$

J. Ekin *et al.*, SuST 29 (2016) 123002
DOI: 10.1088/0953-2048/29/12/123002

Parameterization of the critical surface of REBCO conductors from Fujikura – *field intensity, orientation and temperature dependences*

$$J_c(B,T,\theta) = J_{c,c}(B,T) + \frac{J_{c,ab}(B,T) - J_{c,c}(B,T)}{1 + \left(\frac{\theta - \pi/2}{g(B,T)}\right)^{v}}$$

$$J_{c,c} = \frac{\alpha_c}{B} b_c{}^{p_c}(1-b_c)^{q_c}(1-t^n)^{\gamma_c}$$

$$B_{i,c} = B_{i0,c}(1-t^n)$$

$$g(B,T) = g_0 + g_1 \exp(-[g_2 \exp(g_3 T)]B)$$

$$J_{c,ab} = \frac{\alpha_{ab}}{B} b_{ab}{}^{p_{ab}}(1-b_{ab})^{q_{ab}}[(1-t^{n1})^{n2} + a(1-t^n)]^{\gamma_{ab}}$$

$$B_{i,ab} = B_{i0,ab}((1-t^{n1})^{n2} + a(1-t^n))$$

J. Fleiter and A. Ballarino, Internal Note 2014-24
EDMS Nr: 1426239

Fitting the $I_c(B,\theta,T)$ surface with the Maximum Entropy Method

An empirical description of the $I_c(B,\theta,T)$ surface as a sum of Lorentzian and Gaussian functions

$$I_c(\theta) = \sum_{i=1,2,\ldots} I_{Li}(\theta) + I_{Gi}(\theta)$$

Lorentzian

$$I_L(\theta) = \frac{I_{L0}}{\pi\Gamma} \frac{1}{\cos^2(\theta-\theta_L) + (1/\Gamma_L{}^2)\sin^2(\theta-\theta_L)}$$

- I_{L0} : peak amplitude
- Γ_L : peak sharpness, $0 < \Gamma_L \leq 1$
- θ_L : center angle

Gaussian

$$I_G(\theta) = \frac{I_{G0}}{\sqrt{2\pi}\Gamma_G} \frac{1}{\cos^2(\theta-\theta_G)} \exp\left(-\frac{\tan^2(\theta-\theta_G)}{2\Gamma_G{}^2}\right)$$

- I_{G0} : peak amplitude
- Γ_G : peak sharpness
- θ_G : center angle

Entropy **2013**, *15*, 2585-2605; doi:10.3390/e15072585
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Article

Maximum Entropy Distributions Describing Critical Currents in Superconductors

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journal homepage: www.elsevier.com/locate/supcon

Onset temperature of intrinsic pinning in a REBCO coated conductor from critical current anisotropy

Nicholas M. Strickland [a,*], Arya Ambadiyil Soman [a], Martin W. Rupich [b], Stuart C. Wimbush [a]

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[b] American Superconductor Corporation, Ayer, MA 01432, USA

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https://doi.org/10.1088/1361-6668/acbac6

Near-isotropic enhancement of the 20 K critical current of $REBa_2Cu_3O_7$ coated conductors from columnar defects

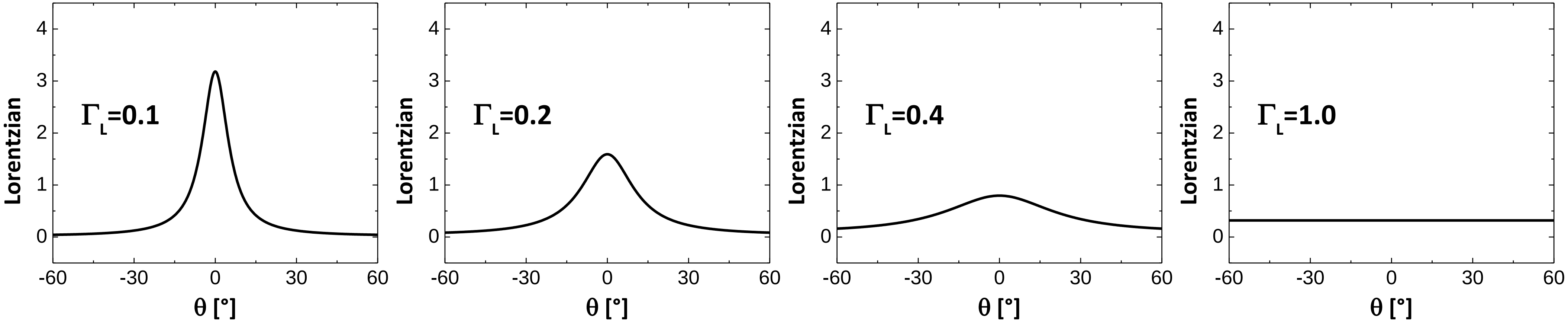
Nicholas M Strickland[1,*], Stuart C Wimbush[1], Arya Ambadiyil Soman[1], Nicholas J Long[1], Martin W Rupich[2], Ruth Knibbe[3], Ming Li[3], Christian Notthoff[4] and Patrick Kluth[4]

[1] Robinson Research Institute, Victoria University of Wellington, Lower Hutt 5010, New Zealand
[2] American Superconductor Corporation, Ayer, MA 01432, United States of America
[3] School of Mechanical and Mining Engineering, University of Queensland, Brisbane, QLD 4072, Australia
[4] Research School of Physics, Australian National University, Canberra, ACT 2601, Australia

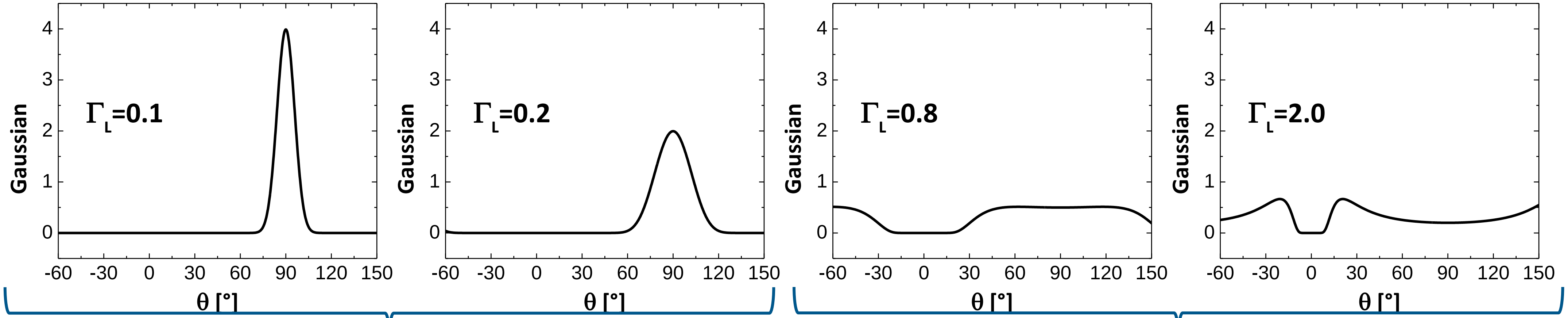
N. Long *et al.*, Entropy 15 (2013) 2585-2605
DOI: 10.3390/e15072585
N. Strickland *et al.*, SuST 36 (2023) 055001
DOI: 10.1088/1361-6668/acbac6
N. Strickland *et al.*, Superconductivity 4 (2022) 100025
DOI: 10.1016/j.supcon.2022.100025

Fitting the $I_c(B,\theta,T)$ surface with the Maximum Entropy Method

Lorentzian at $\theta_L = 0°$



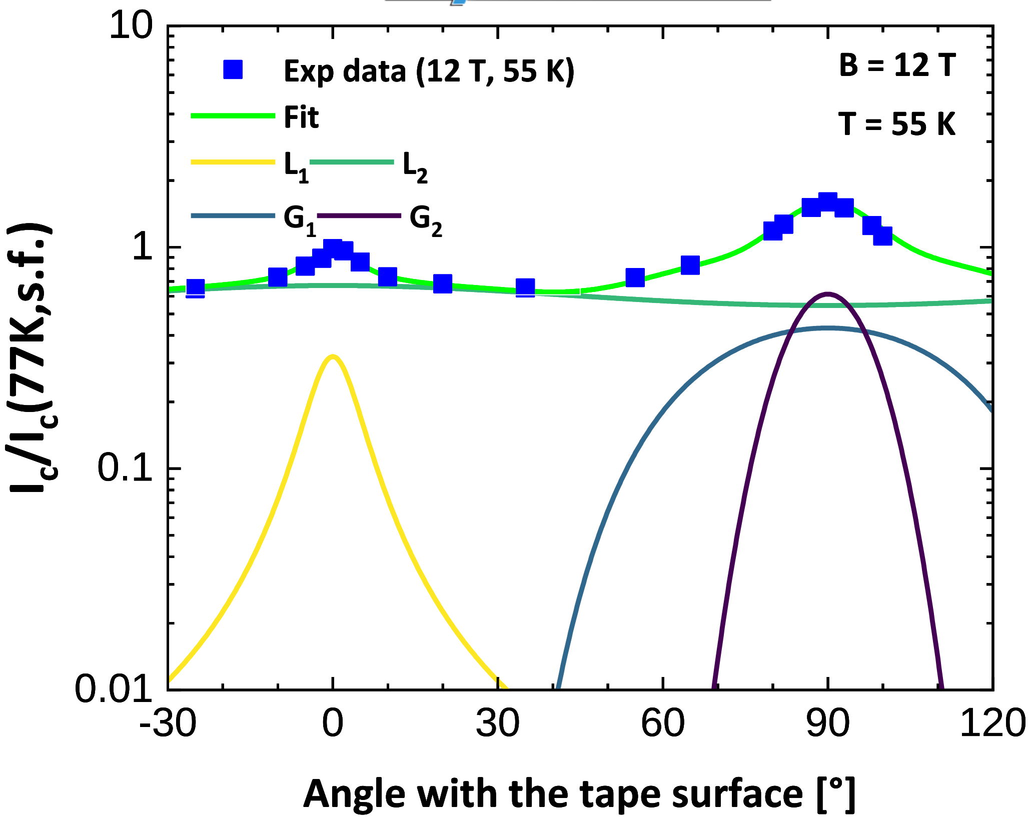
Gaussian at $\theta_G = 90°$



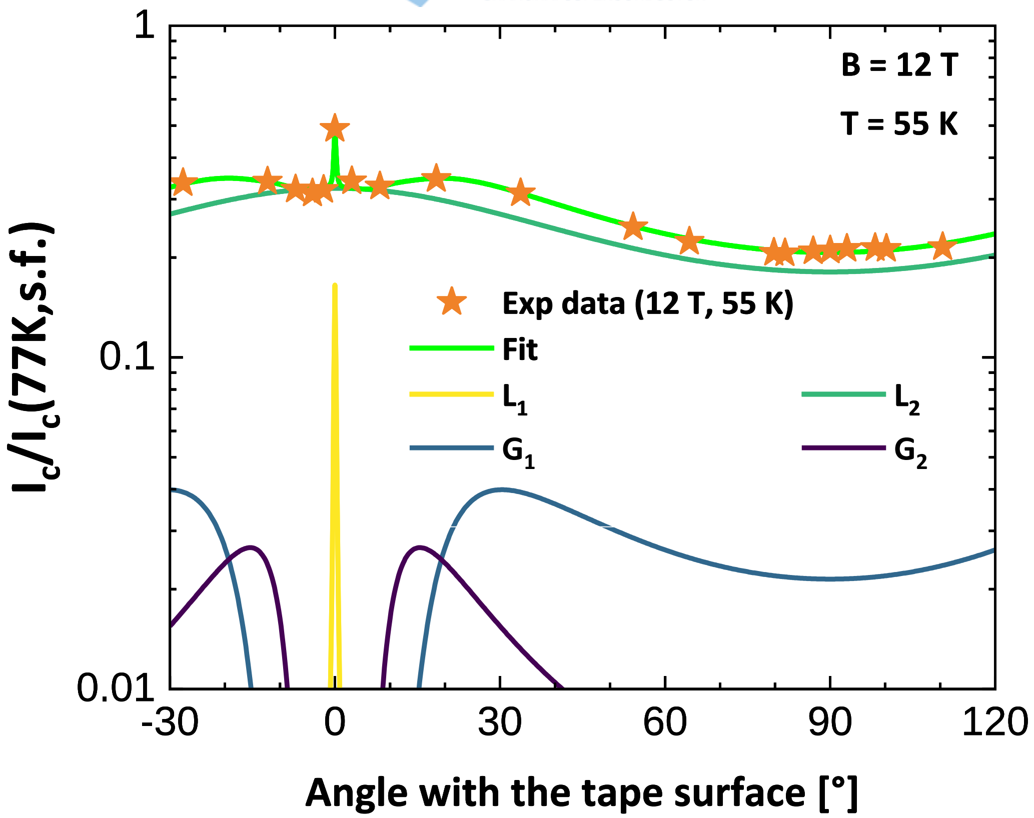
$\Gamma_L \leq \frac{1}{\sqrt{2}}$

$\Gamma_L > \frac{1}{\sqrt{2}}$

Two examples of decomposition of the fit

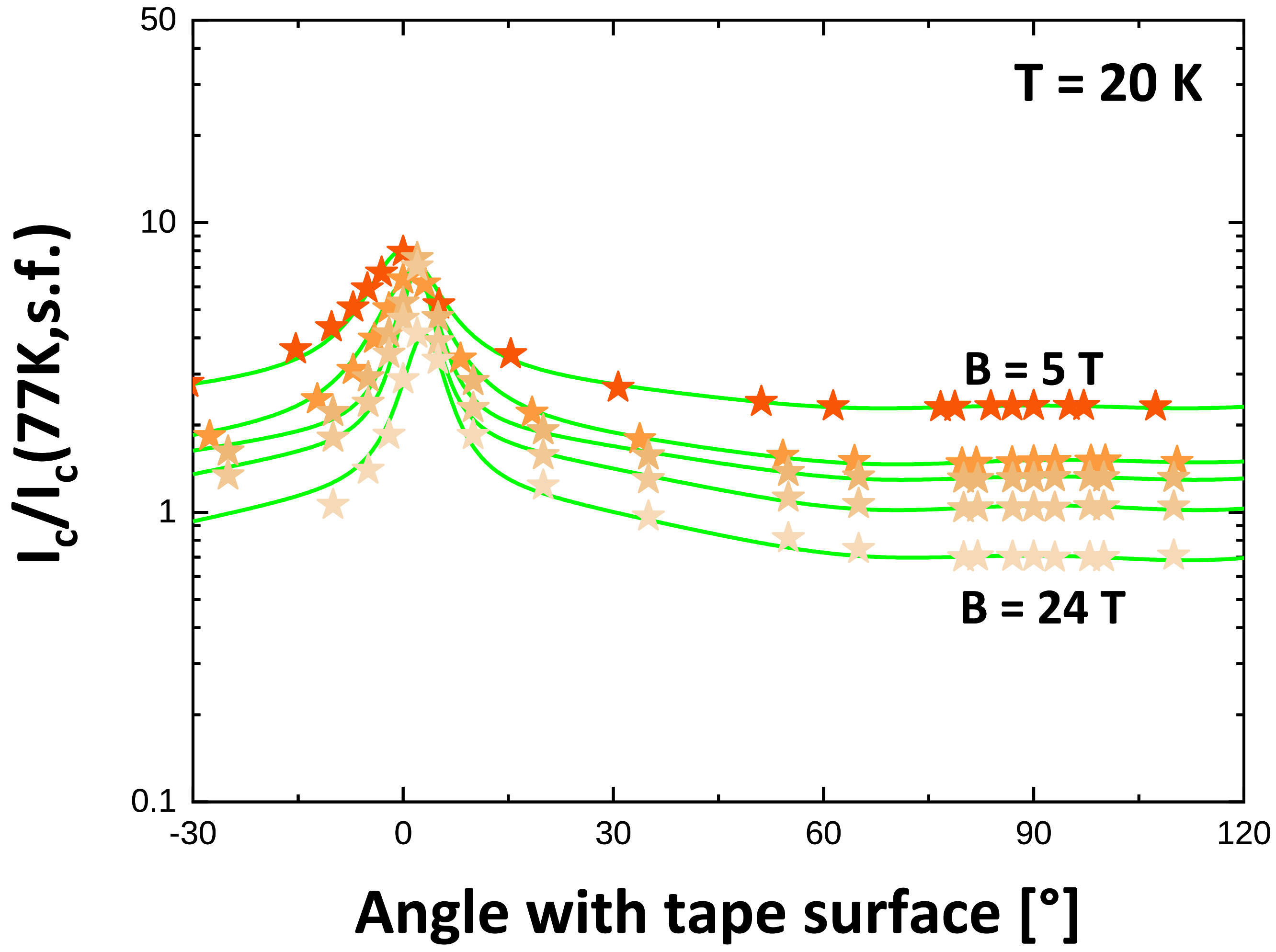


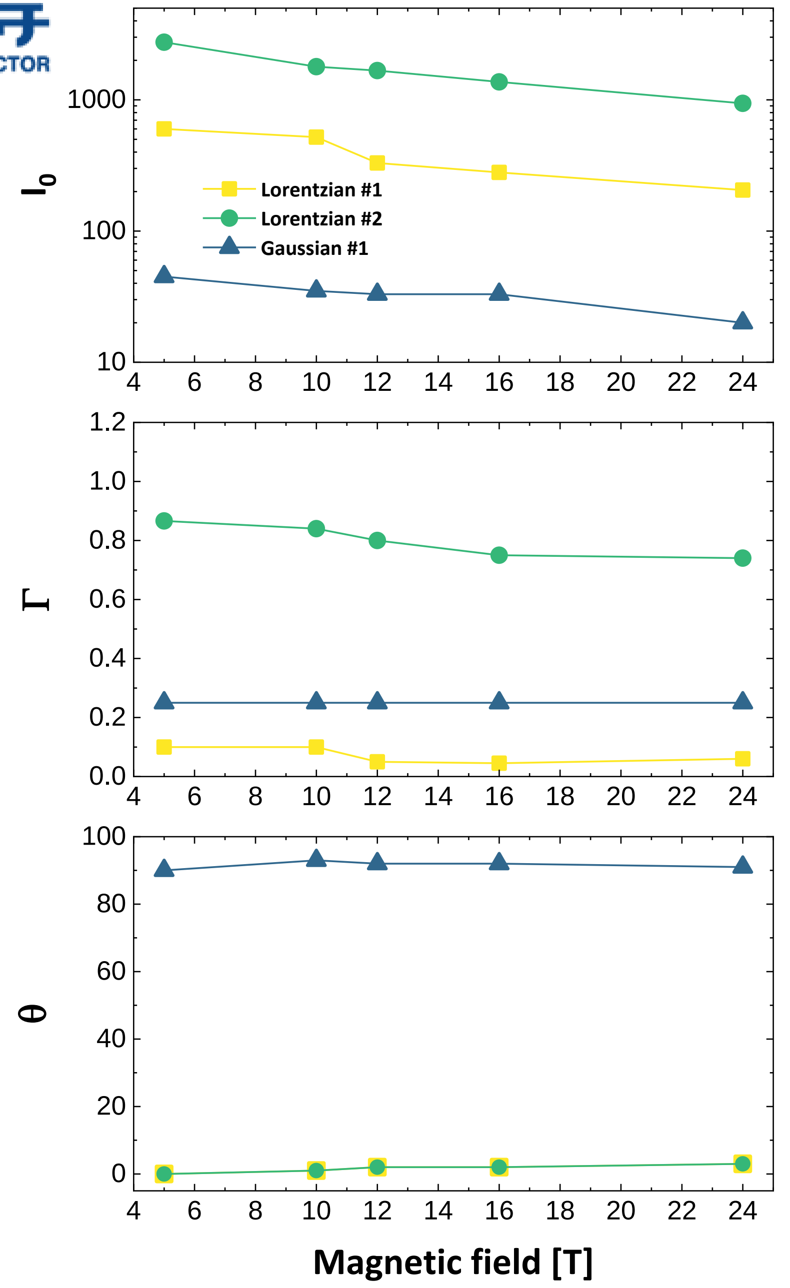
	$I_{0L;G}$ [A]	$\Gamma_{L;G}$	$\theta_{0,L;G}$
L1	17	0.09377	0
L2	342	0.90147	0
G1	74	0.38	90
G2	36	0.13	90



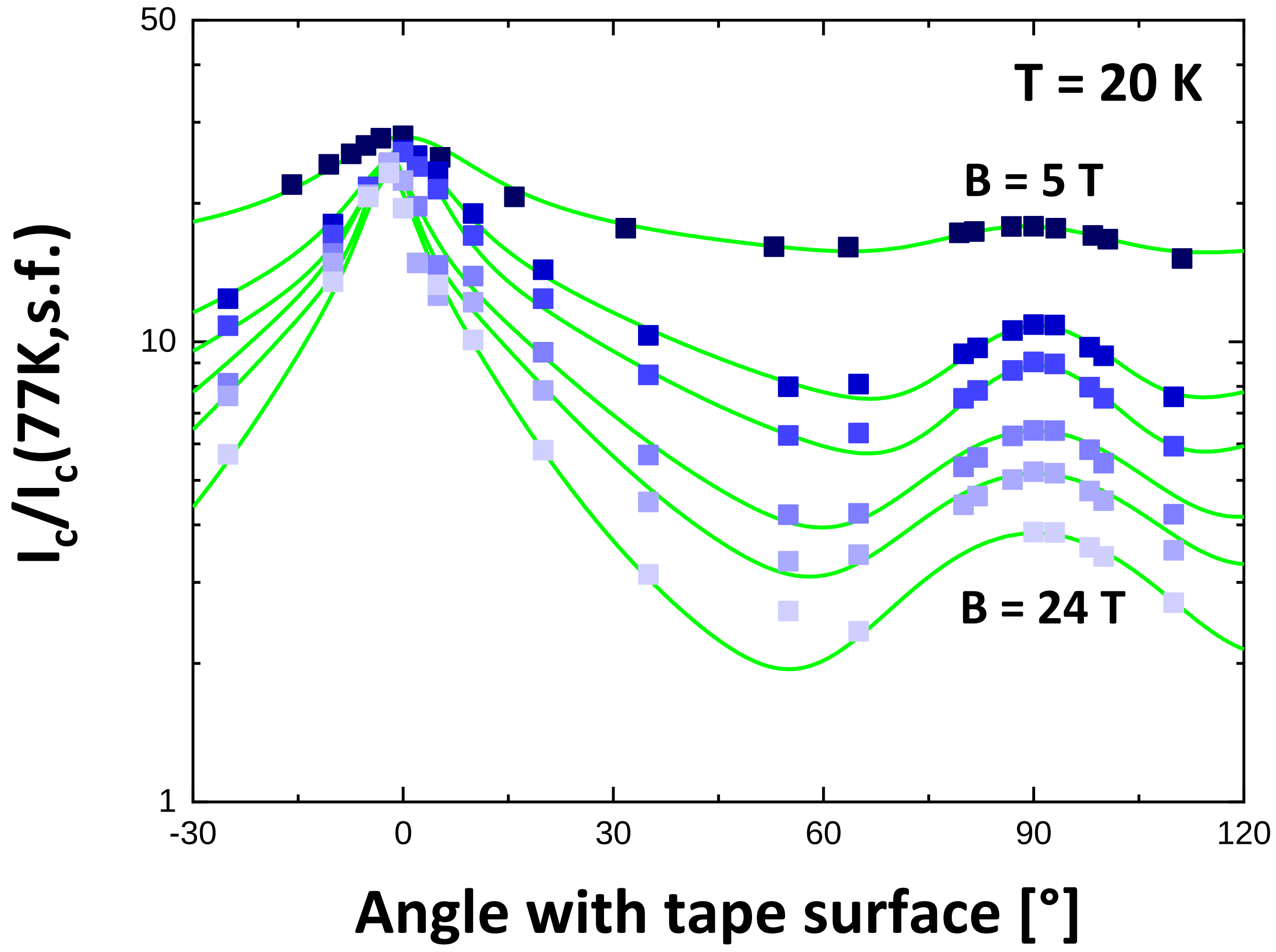
	$I_{0L;G}$ [A]	$\Gamma_{L;G}$	$\theta_{0,L;G}$
L1	0.7	0.0037	0
L2	276	0.7479	0
G1	27	1.3995	90
G2	12	2.6592	90

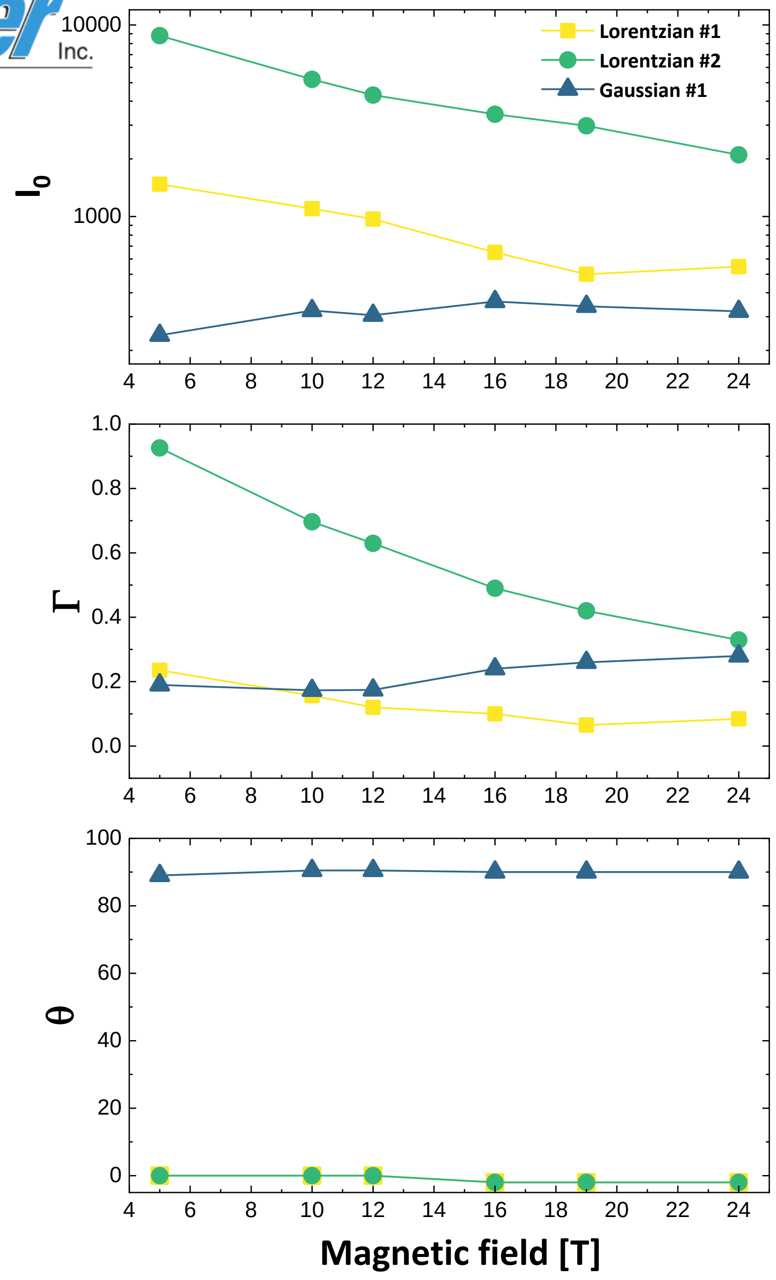
Calculated fits at T = 20 K for 上海超导™ SHANGHAI SUPERCONDUCTOR





Calculated fits at T = 20 K for SuperPower Inc.





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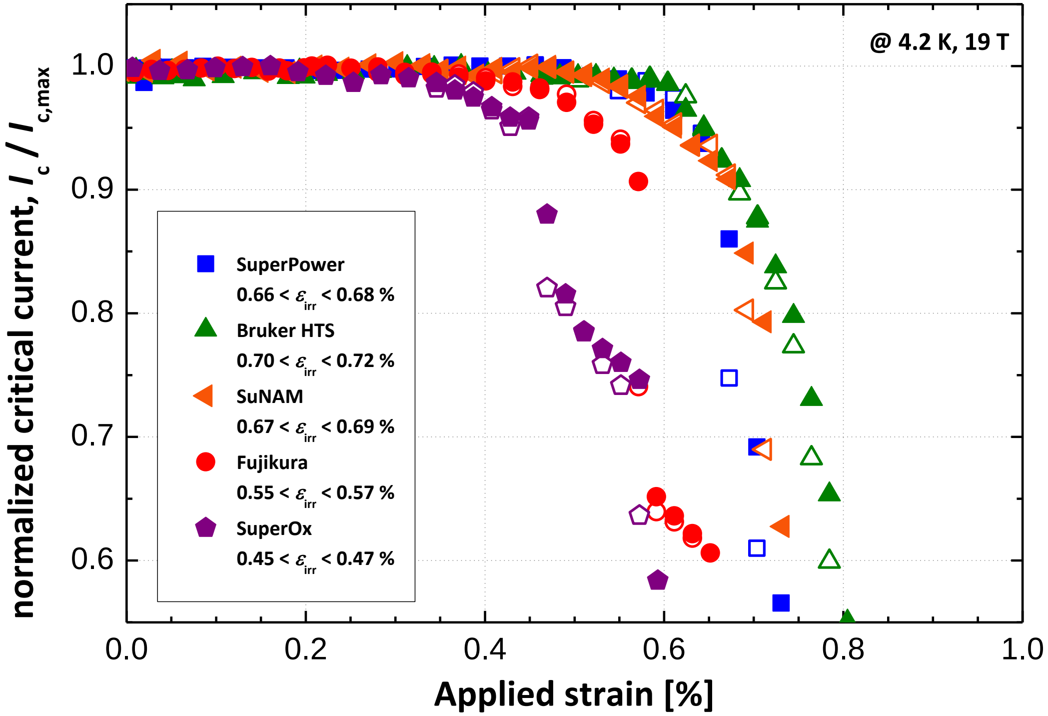
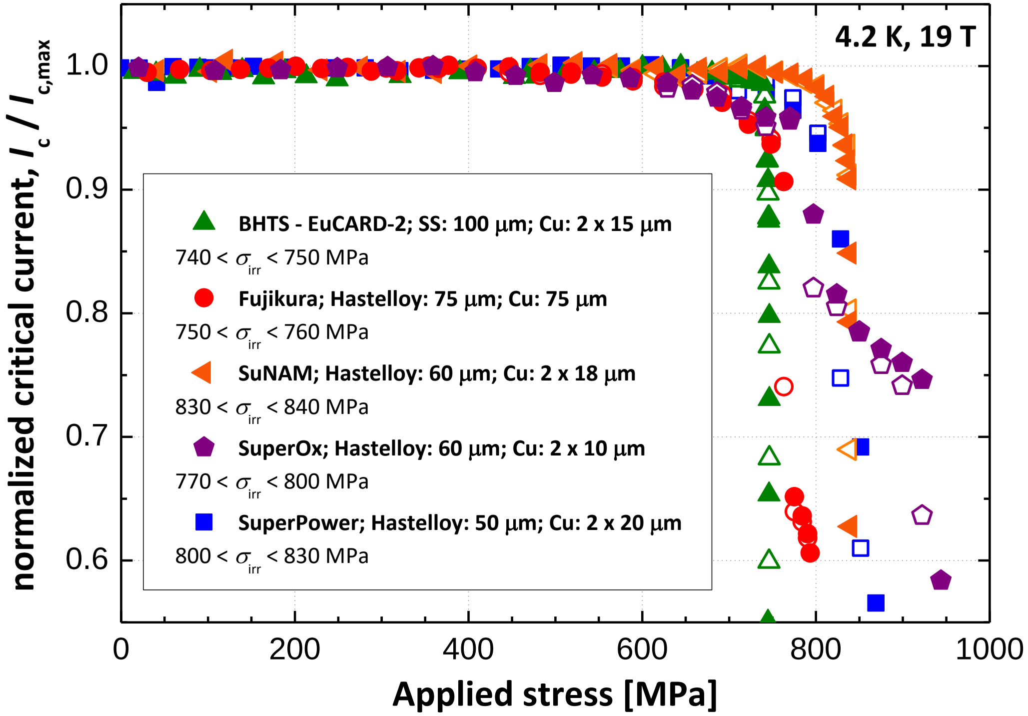
REBCO tapes are robust against longitudinal tension

Results of the measurement campaign from 2015

I_c vs. longitudinal strain



I_c vs. longitudinal stress



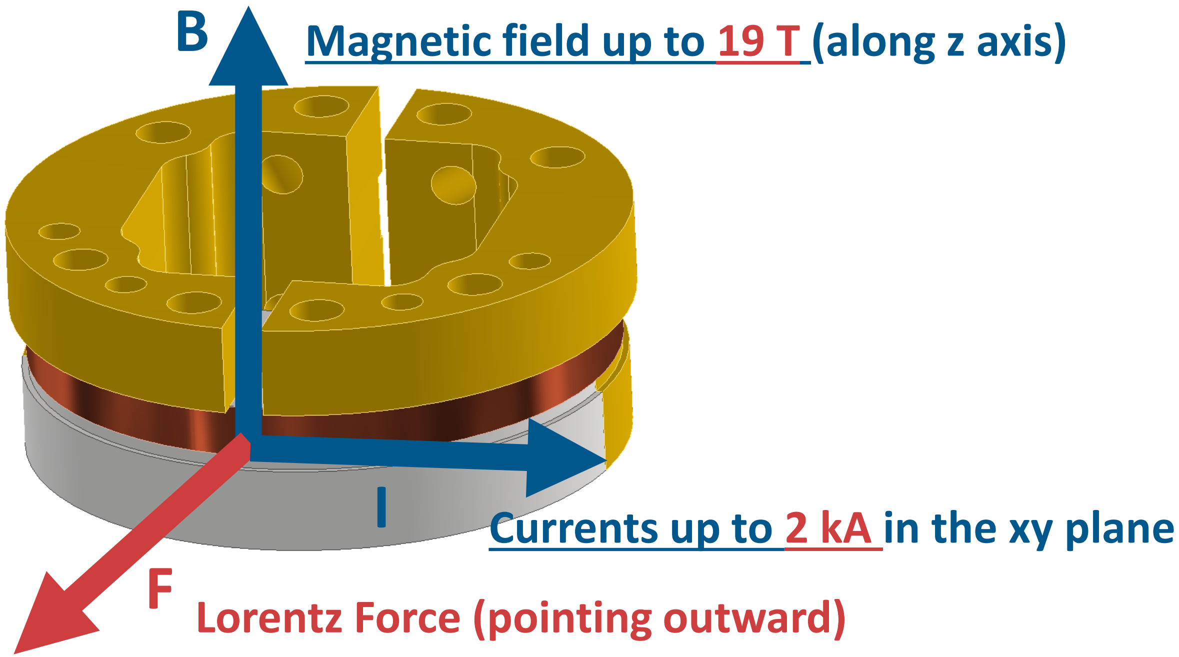
- REBCO tapes are inherently strong, ~50% is a high strength alloy
- Very low stress effect and irreversible stress limit well above 500 MPa
- But mechanical properties are very ANISOTROPIC, tapes are inherently prone to delamination

C. Barth *et al.*, SuST 28 (2015) 045011
DOI: 10.1088/0953-2048/28/4/045011

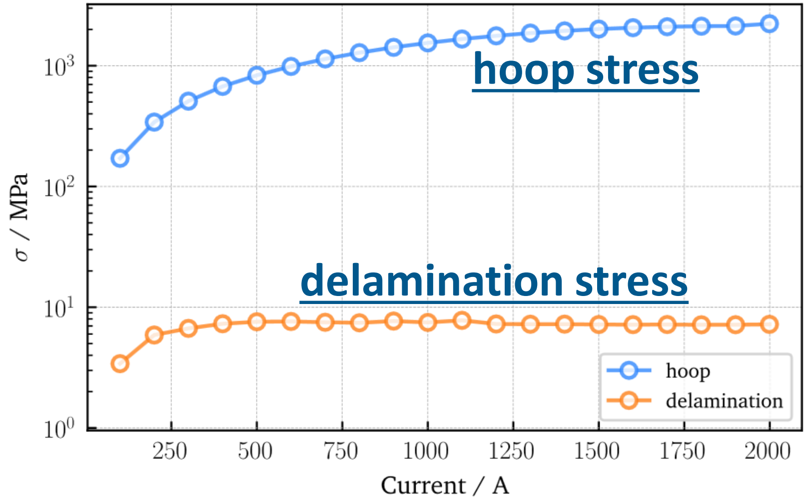
Electromagnetic Delamination Strength measurement

A direct measurement of conductor degradation under I x B force

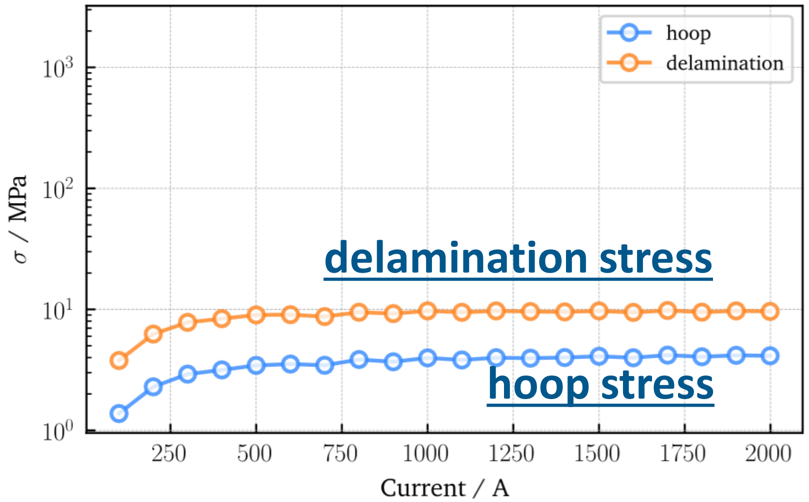
REBCO layer on the outside



Tape soldered only at the current injection



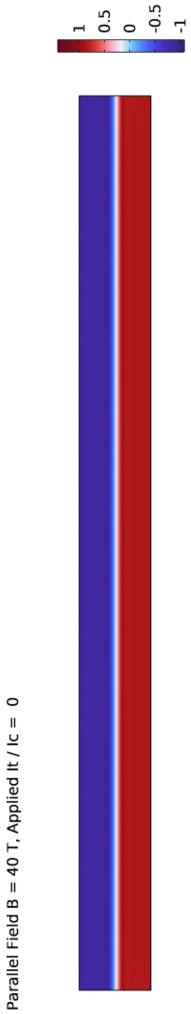
Tape soldered on the entire length



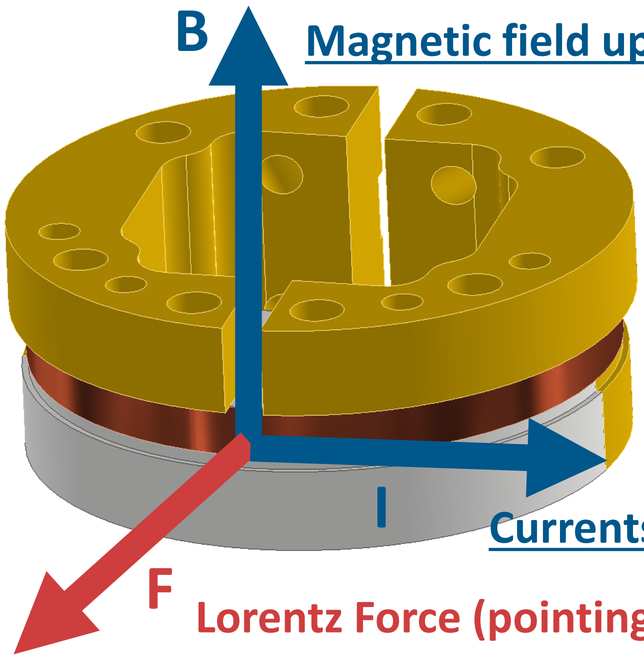
Simulations from Gianluca Vernassa, CERN

Electromagnetic Delamination Strength measurement

A direct measurement of conductor degradation under I x B force



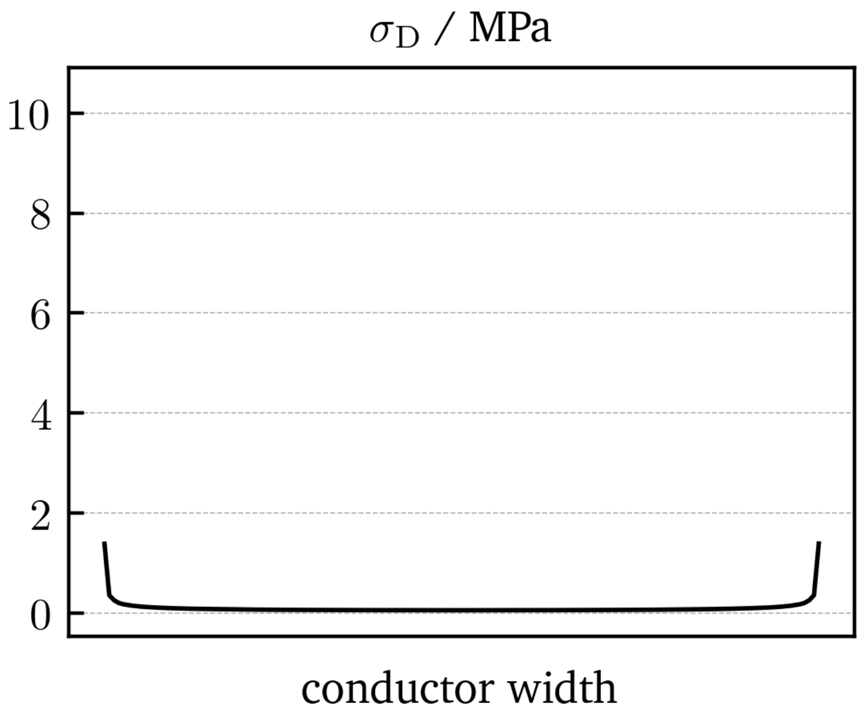
REBCO layer on the outside



Magnetic field up to 19 T (along z axis)

Currents up to 2 kA in the xy plane

Lorentz Force (pointing outward)

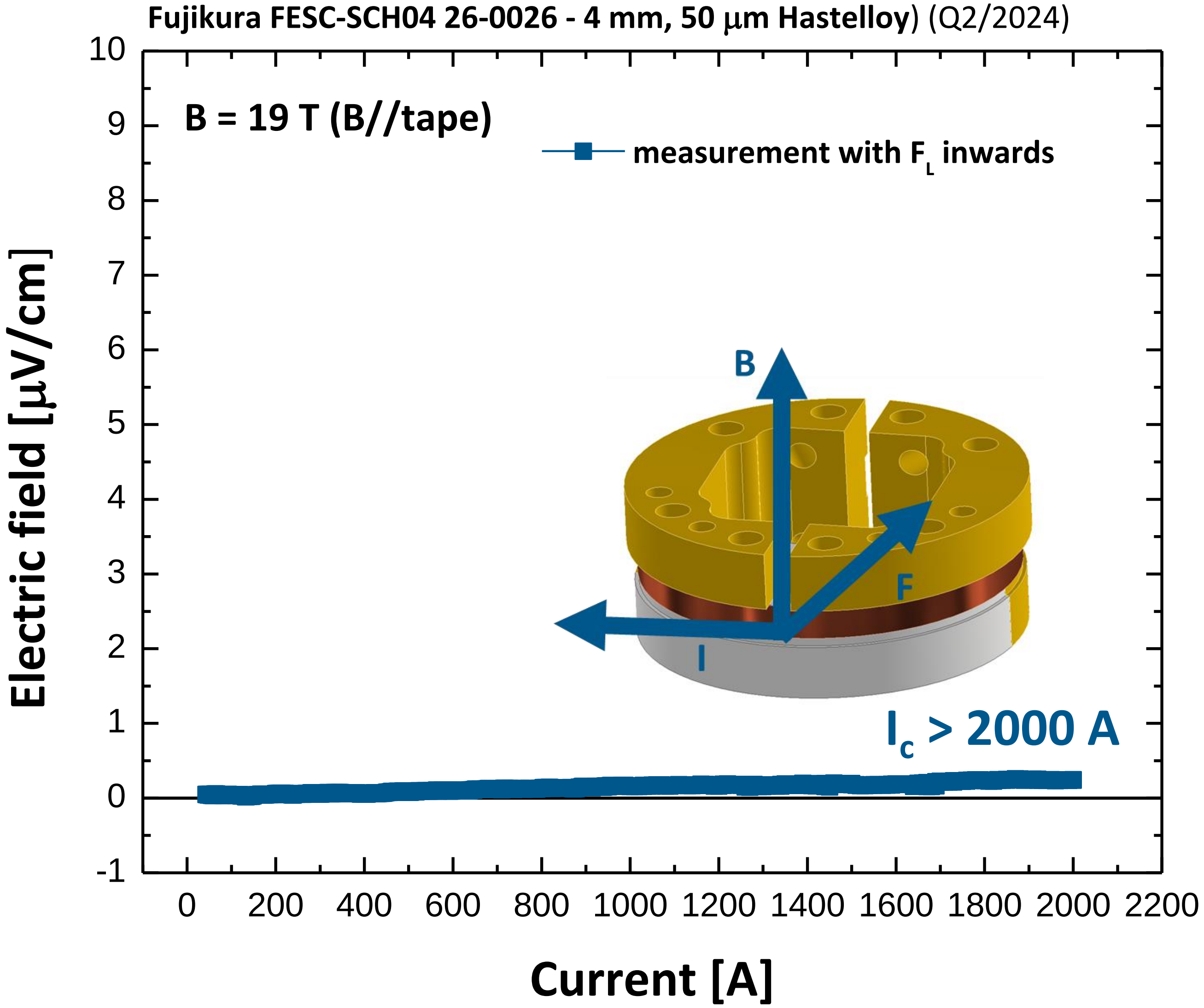


The delamination stress is $\sigma_D = J_c \cdot B_{//} \cdot t \approx \frac{2\text{ kA}}{4\text{ mm}} \cdot 20\text{ T} \approx 10\text{ MPa}$

Simulations from Gianluca Vernassa, CERN

Electromagnetic Delamination Strength measurement

First measurement campaign on Fujikura FESC tape



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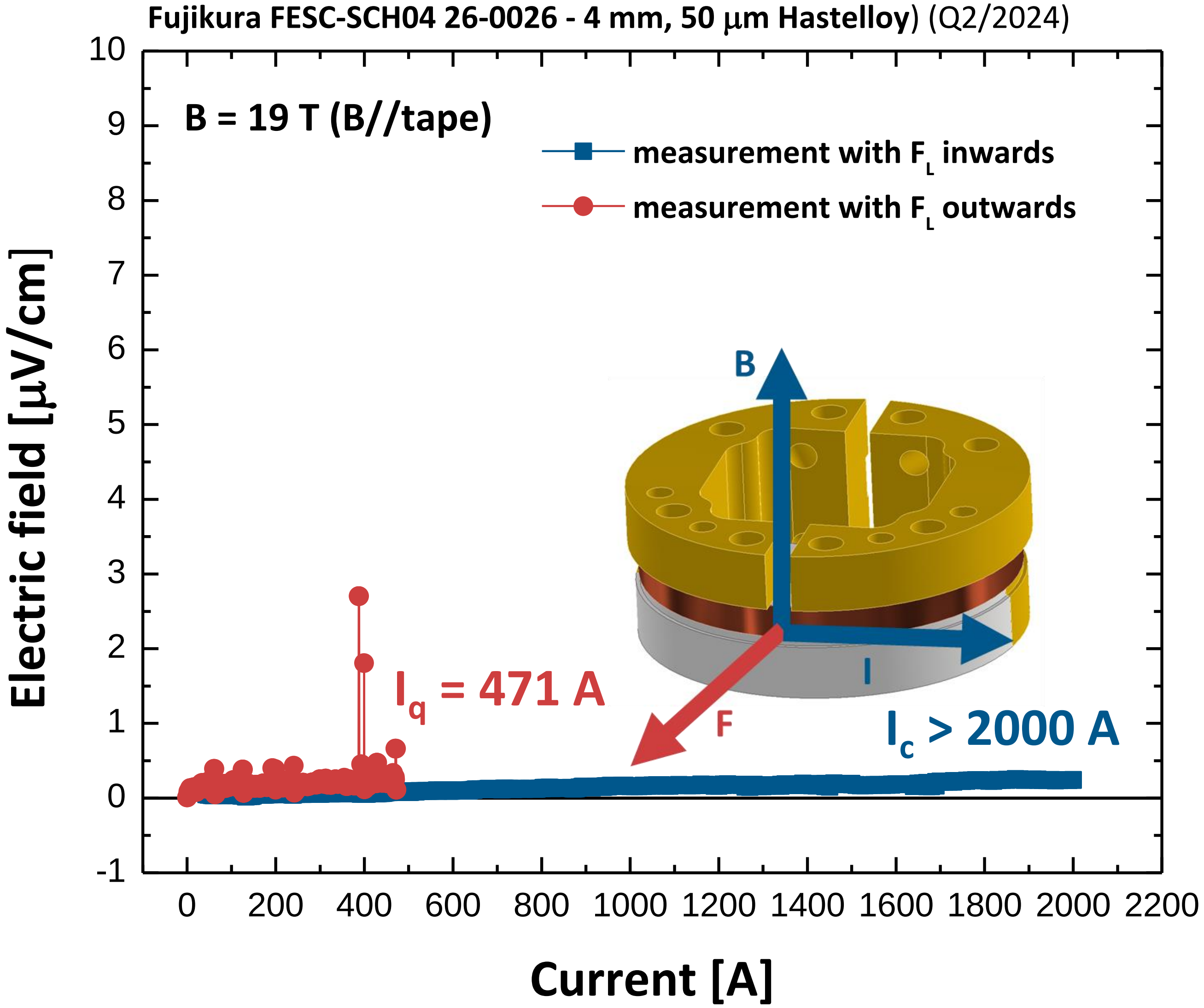
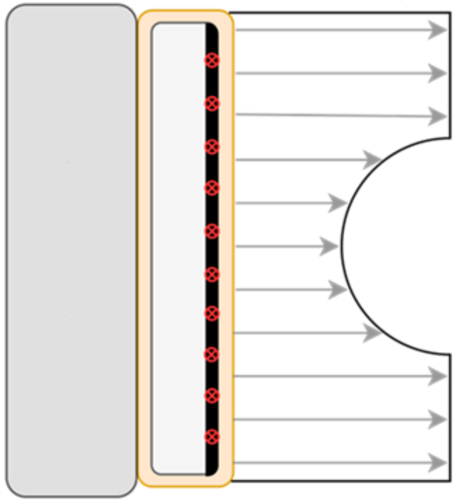
Electromagnetic Delamination Strength measurement

First measurement campaign on Fujikura FESC tape





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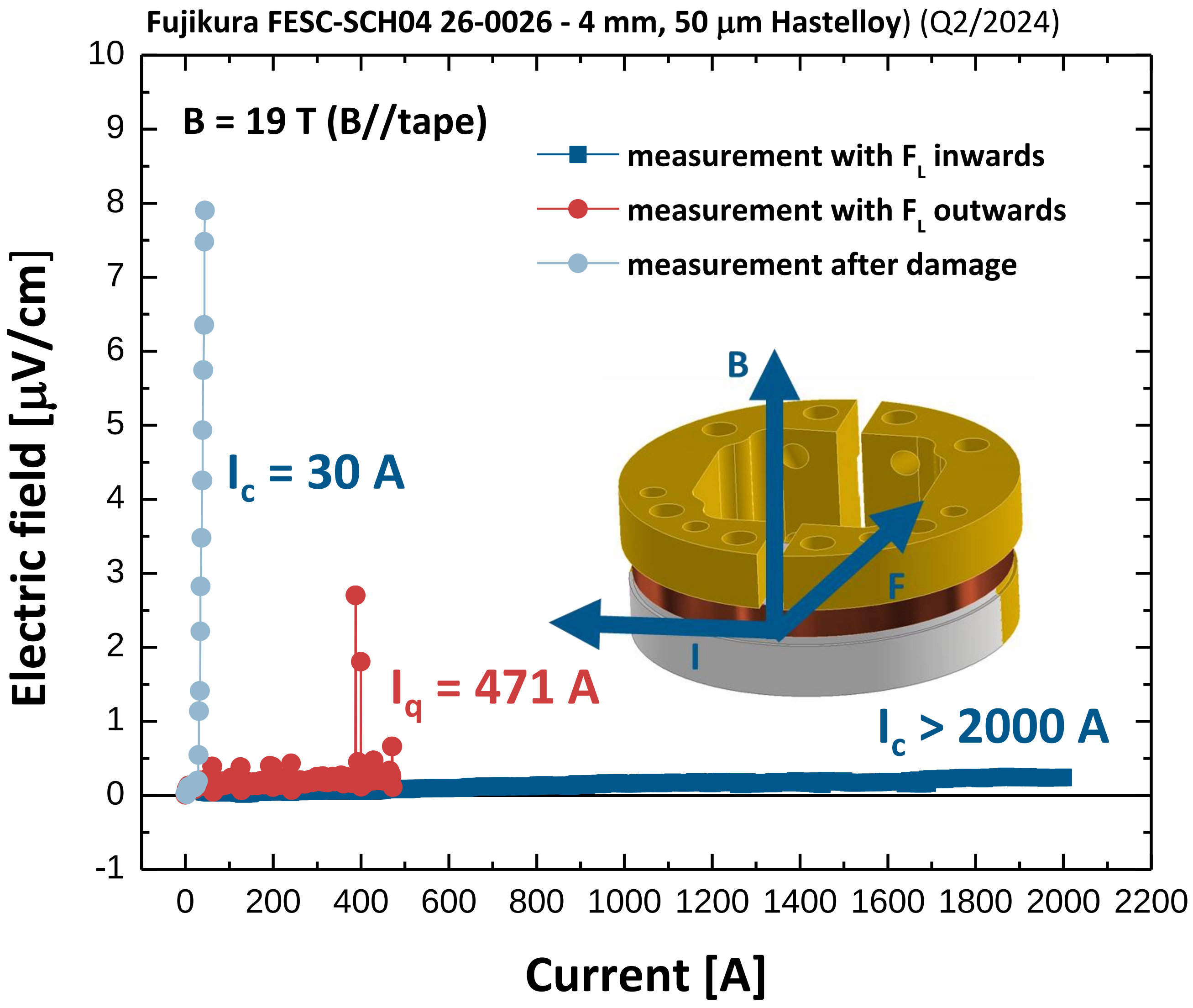
Electromagnetic Delamination Strength measurement

First measurement campaign on Fujikura FESC tape



- This phenomenology was reproduced over a large number of experiments with a certain variability in I_q and extension of the damage
- I_q ranges between 380 A and 1750 A
- I_c after damage ranges between 30 A and 930 A

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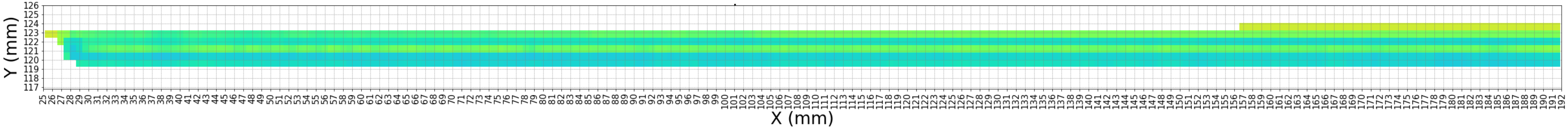
Electromagnetic Delamination Strength measurement

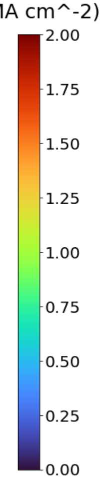
Forensic analyses

J_c(77K) map of the sample before delamination experiment

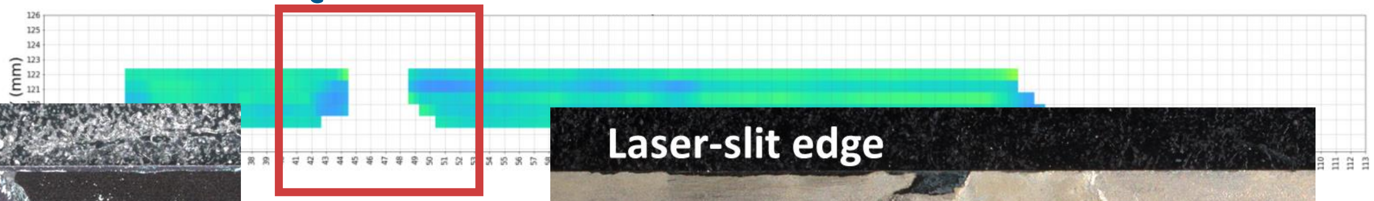


current injection

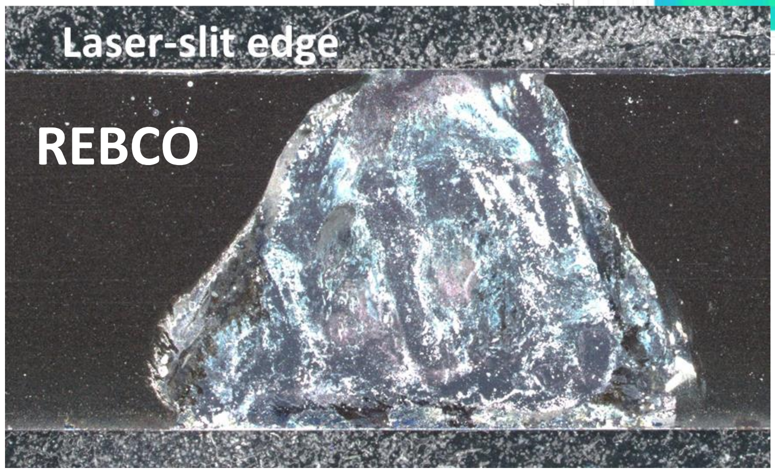
current injection



J_c(77K) map after delamination



after Silver etching



after Cu etching

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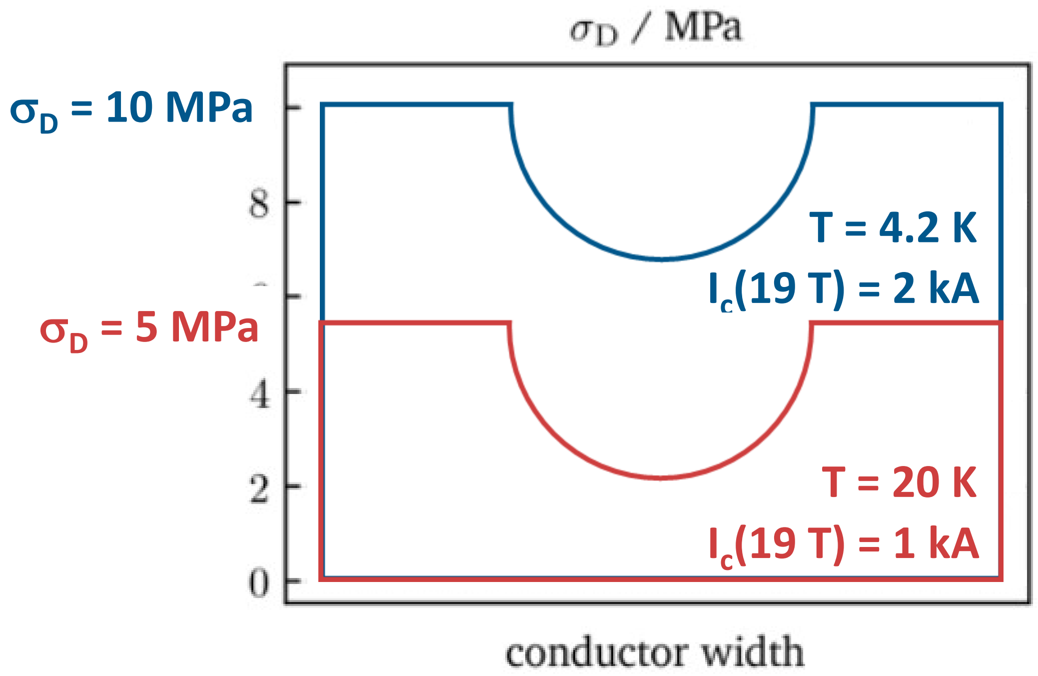
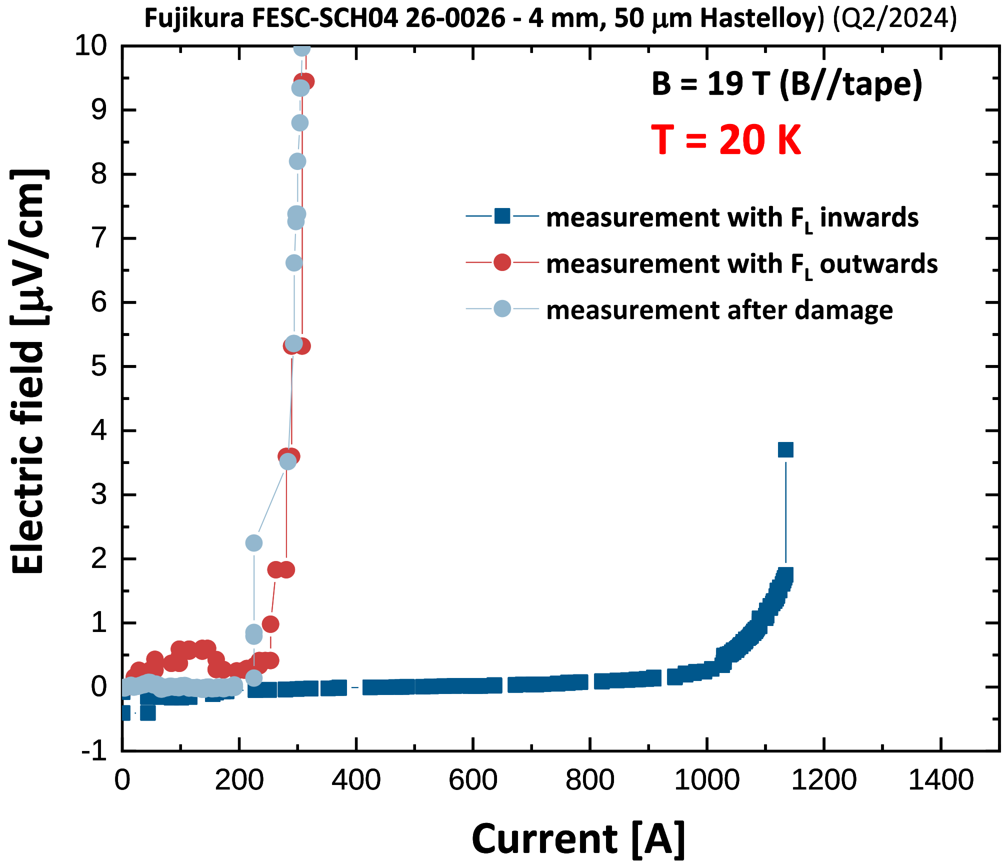
A transverse stress of 10 MPa is sufficient to delaminate…

… is this the value of the delamination strength?

Electromagnetic Delamination Strength measurement

A method to tune the applied stress by varying the temperature





$$\sigma_D(4.2\ K) = J_c(4.2\ K) \cdot B_{//} \cdot t \approx \frac{2\ kA}{4\ mm} \cdot 19\ T \approx 10\ MPa$$

$$\sigma_D(20\ K) = J_c(20\ K) \cdot B_{//} \cdot t \approx \frac{1\ kA}{4\ mm} \cdot 19\ T \approx 5\ MPa$$

Delamination occurs also at ~ 5 MPa !!!

Conclusions

- The performance gap between various manufacturers in perpendicular orientation is relatively small in spite of the differences in process, composition and pinning landscape. But...
- There is still an important batch-to-batch variability of the properties.
- The angular dependence of I_c is strongly influenced by process, composition and pinning landscape.
- An effective description of the $I_c(B,\theta,T)$ surface can be produced with the empirical Maximum Entropy Model
- Investigations are ongoing on the correlation between the model parameters and the pinning landscape
- Electromagnetic Delamination Strength (EDS) experiments show that REBCO tapes cannot sustain transverse tension.
- The procedure for EDS tests is now consolidated and tests will be performed also on tapes from other manufacturers.

Thank you for the attention !

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State Secretariat for Education, Research and Innovation SERI

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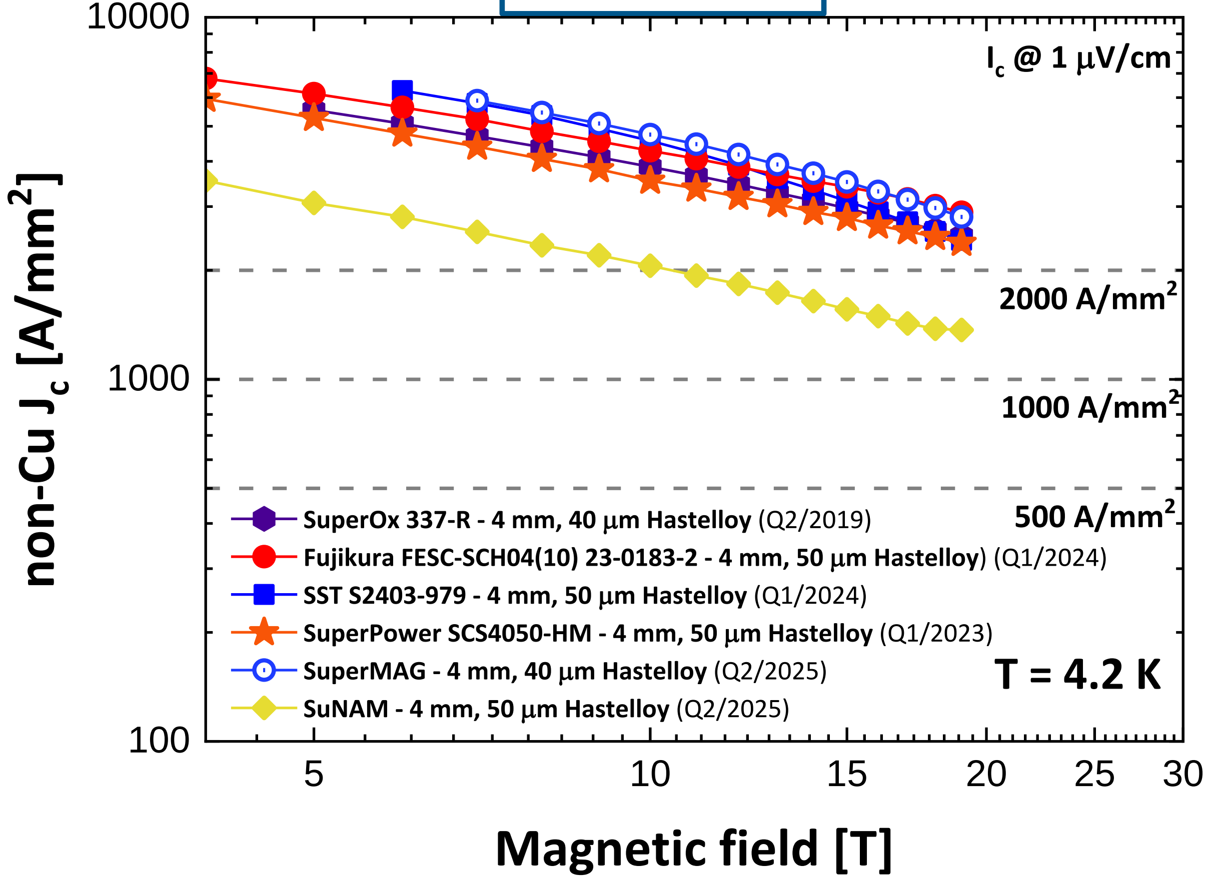
Comparison of the performance: non-Cu J_c

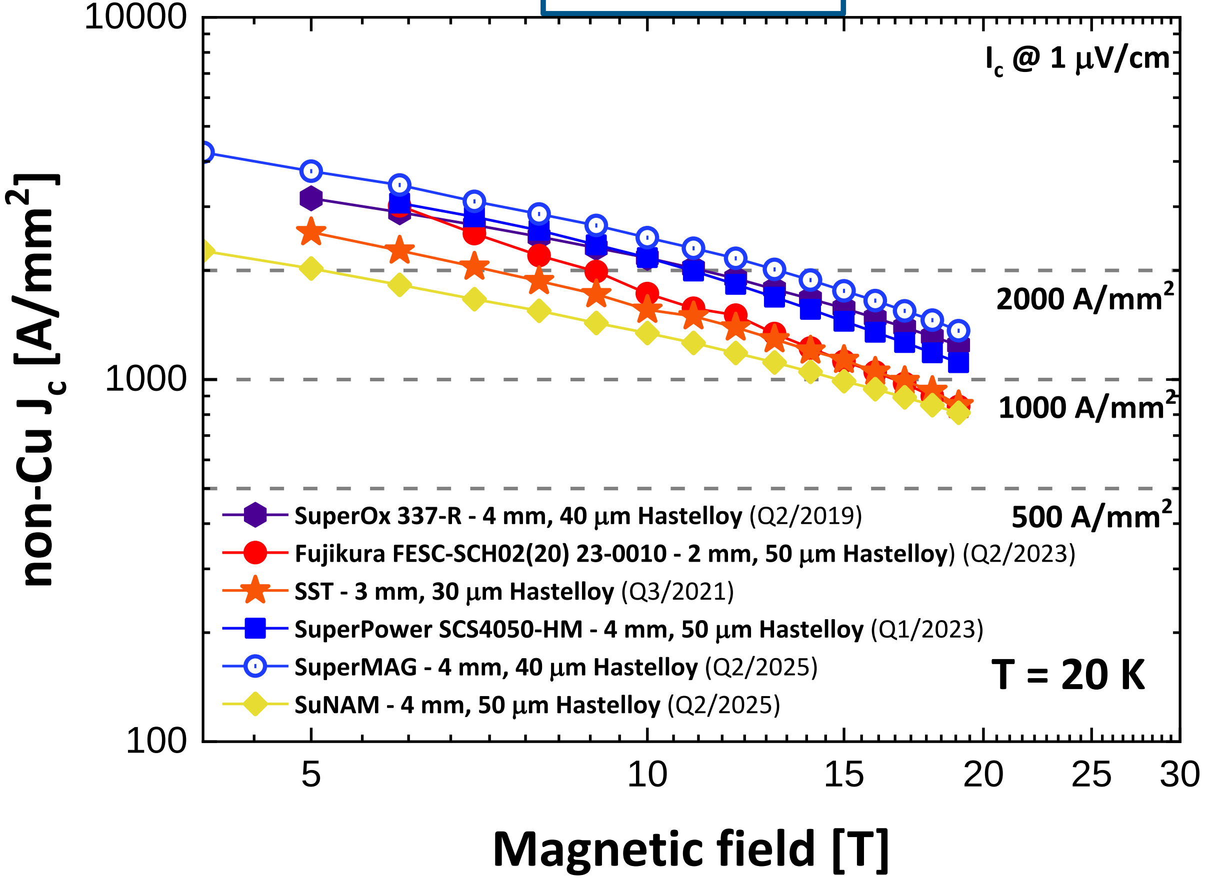
The non-Cu J_c corresponds to the critical current divided by the tape cross-section area minus the Cu area

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

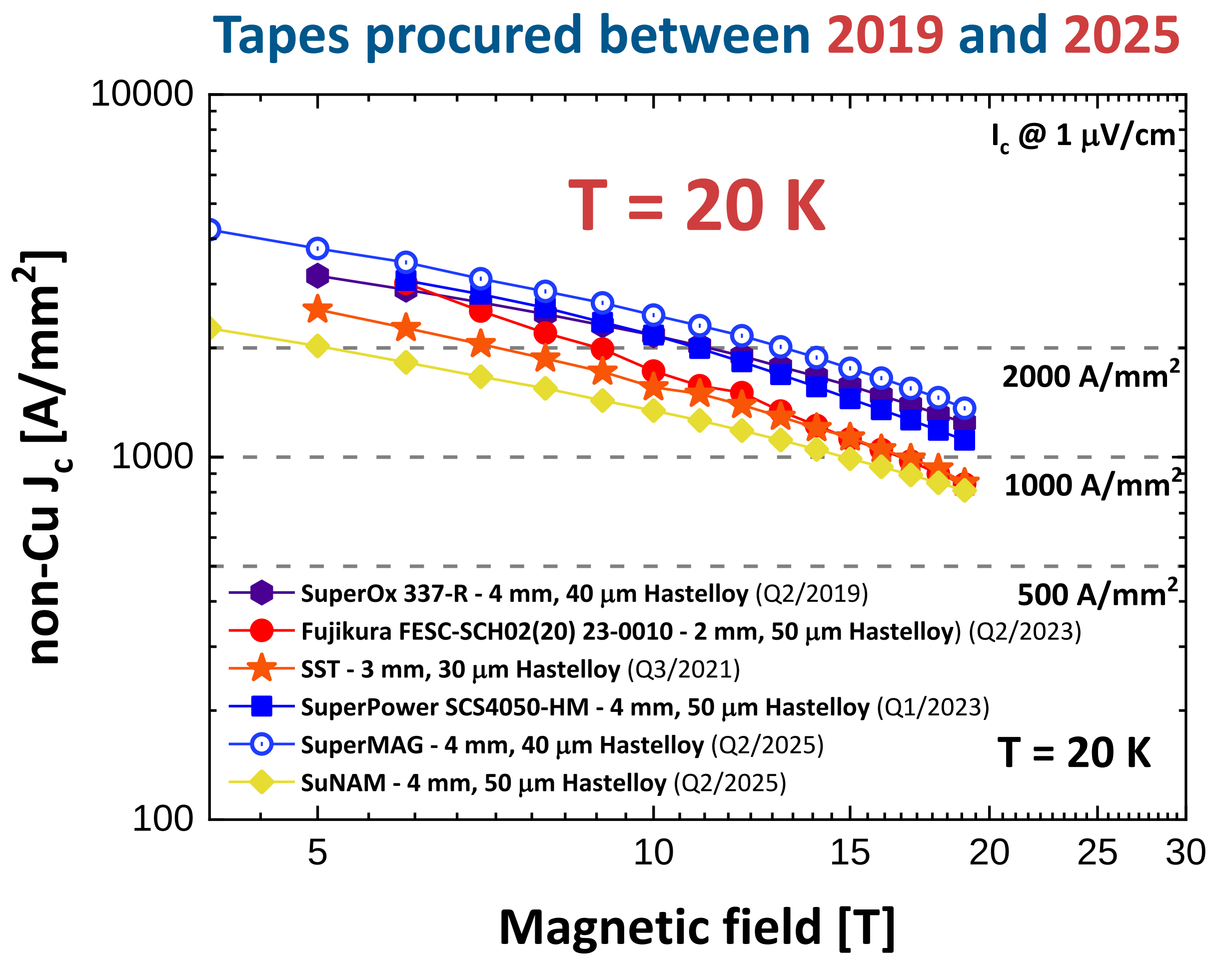
T = 4.2 K

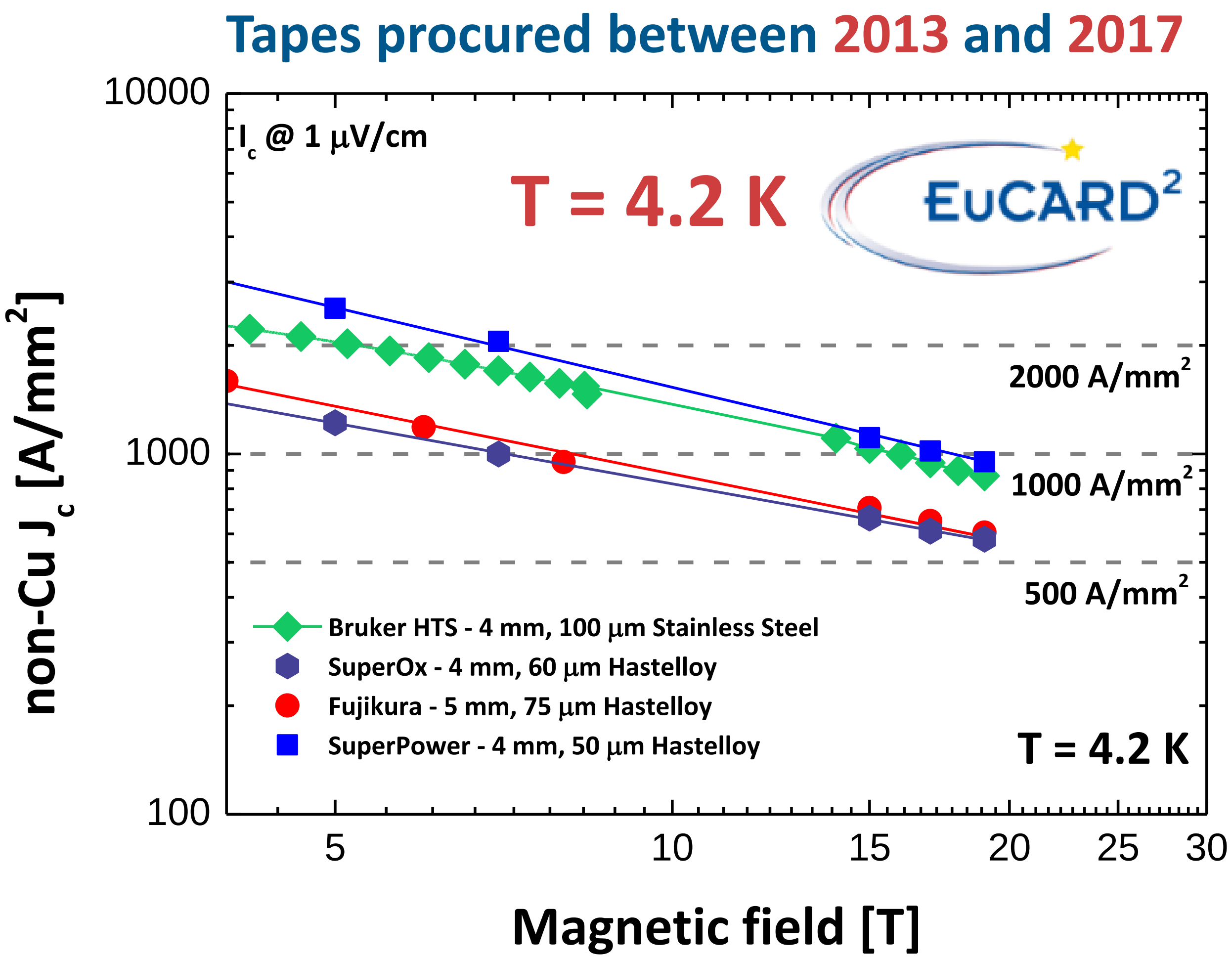


T = 20 K



Evolution of the performance: non-Cu J_c





The performance at 4.2 K of the tapes procured during EuCARD^2 (2013-2017) is achieved and surpassed in modern tapes at 20 K !!

CS , WAMHTS-2

L. Rossi and CS, Instruments, 5 (2021) 8

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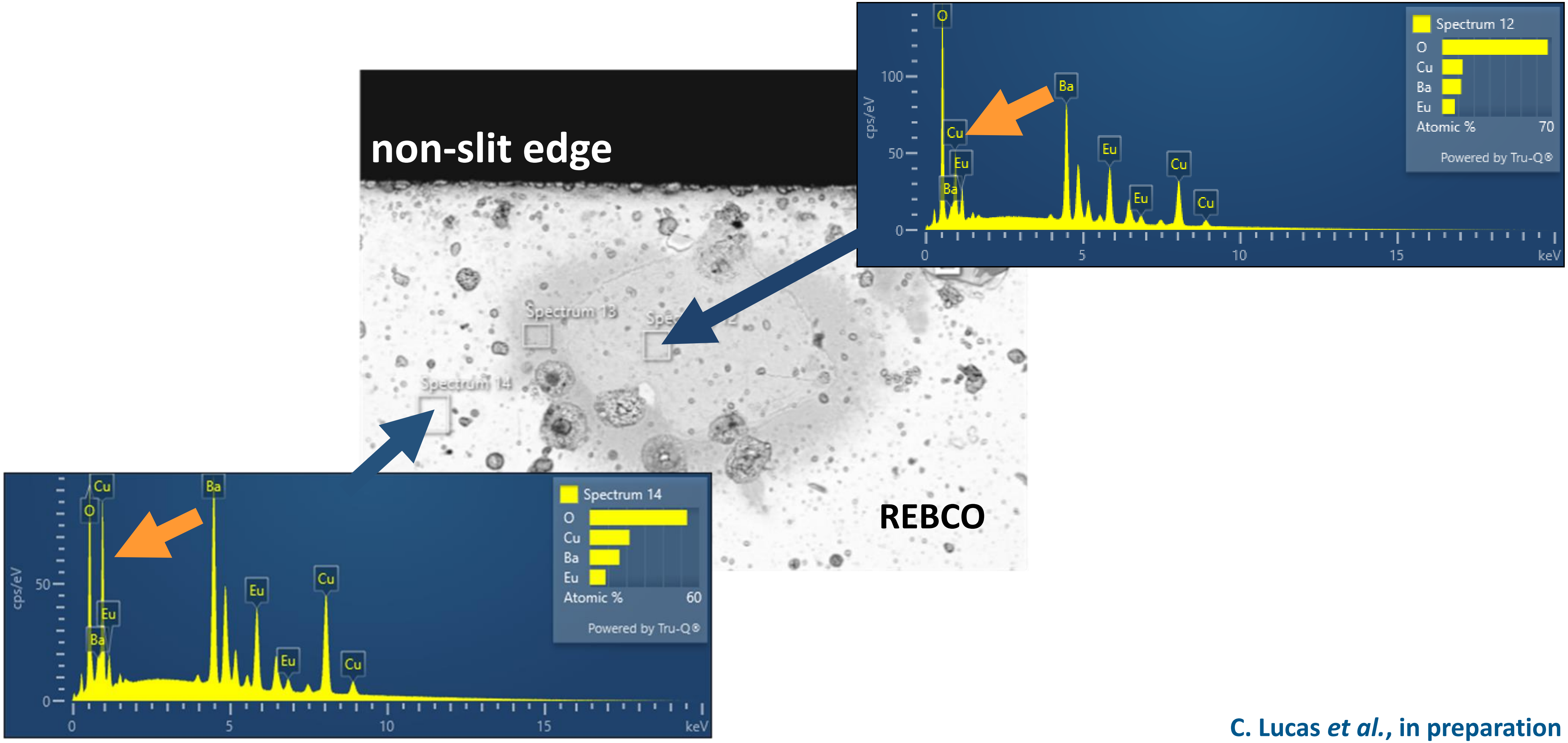
Electromagnetic Delamination Strength measurement

Forensic studies



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