1st High Temperature superconductors for Accelerator Technology (HiTAT) workshop

UNIVERSITÉ DE GENÈVE

FACULTÉ DES SCIENCES

Critical current surface of commercial REBCO tapes and search for a scaling law

Carmine SENATORE, Marco BONURA, Tommaso BAGNI, Damien ZURMUEHLE

Department of Quantum Matter Physics, University of Geneva, Switzerland

Department of Nuclear and Particle Physics, University of Geneva, Switzerland

Outline

- Motivation of the work
  - The call for HTS from High Energy Physics, Fusion and High Field Science
  - Critical current characterization: needs and limitations
- Results of the measurement campaign on REBCO tapes from various manufacturers
  - Transport I_c measurements up to 2 kA in variable temperature and at various orientations
  - Magnetization measurements and pinning force analysis
- Comparison of the critical current performance and pinning force scaling
- Conclusions

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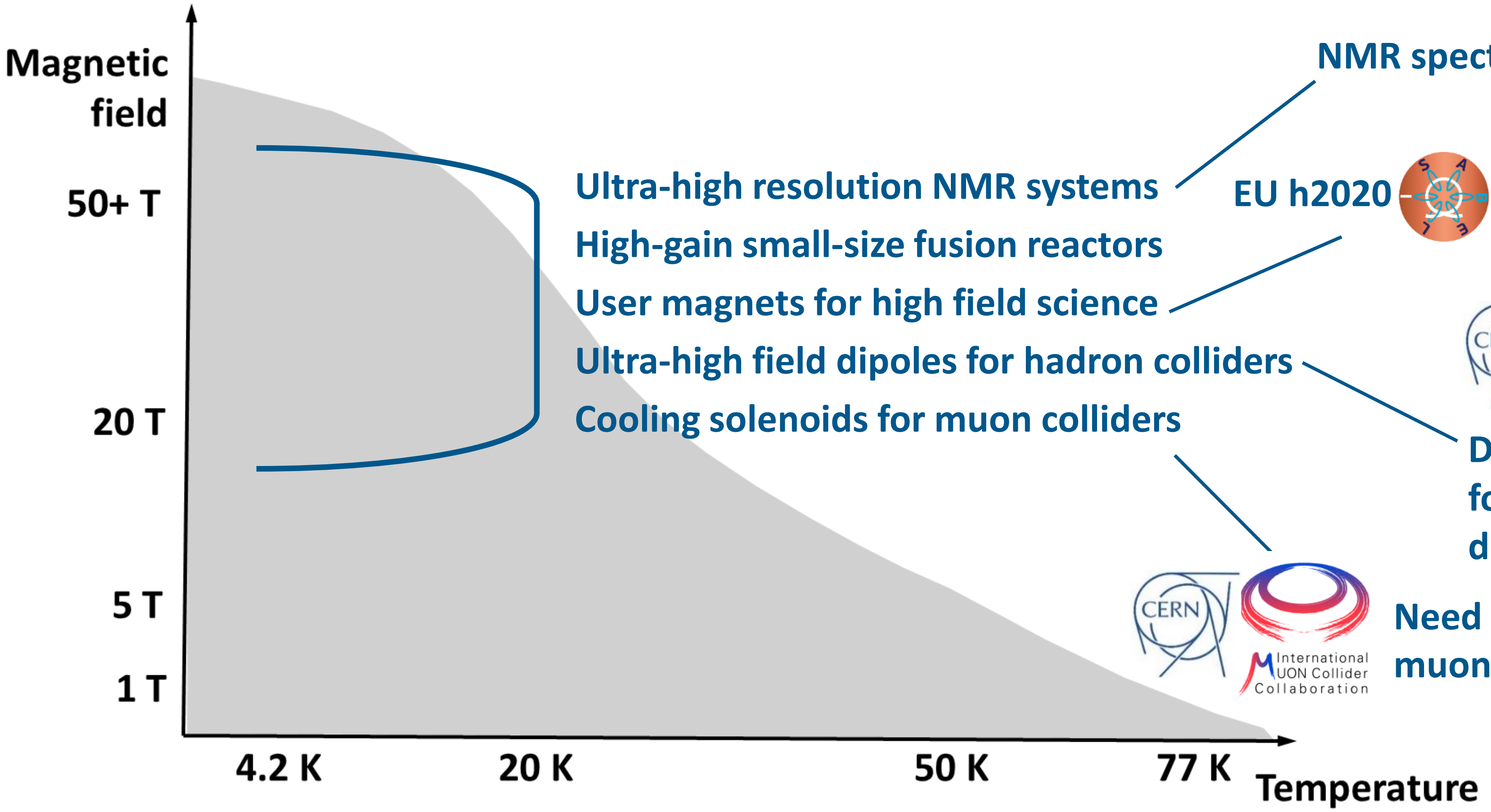
Applications of HTS in ultra-high magnetic field



NMR spectrometers at frequency ≥ 1.3 GHz (B = 30.5 T)

EU h2020 and Super EMFL coordinated by LNCMI

CERN FUTURE CIRCULAR COLLIDER HFM High Field Magnets

Demonstrate the suitability of HTS for accelerator magnets, aiming at dipole fields of at least 20 T

CERN International MUON Collider Collaboration

Need for solenoids ≥ 40 T for cooling the muon beams

What are the needs and what we can do

- **Need for high fidelity $I_c(B,\theta,T)$ characterization** (but also electromechanical and thermophysical studies)
  - Angular dependence at high field / low temperature for magnet design
  - Temperature dependence for quench protection calculation

- **Limited availability of complete datasets and limited experimental capacity**
  - I_c vs θ at Robinson Research Institute (NZ): up to 8 T, 1 kA, variable temperature

    Strickland, Hoffmann & Wimbush, Rev. Sci. Instrum. 85 (2014) 113907
    DOI: 10.1063/1.4902139
  - I_c vs θ at HFLSM IRM Tohoku Univ. (Japan): up to 25 T, only microbridges, variable temperature

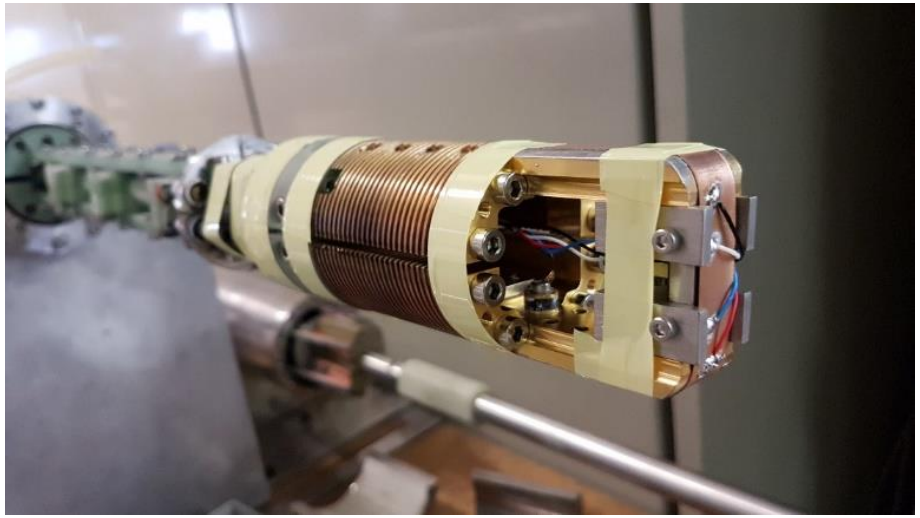
    Awaji, et al., SuST 30 (2017) 065001
    DOI: 10.1088/1361-6668/aa6676
  - τ vs θ at NHMFL (US): up to 30 T, only 4 K (?), needs a transport I_c reference

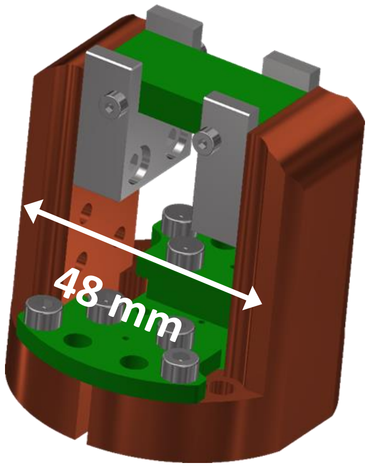
    Jaroszynski, et al., SuST 35 (2022) 095009
    DOI: 10.1088/1361-6668/ac8318

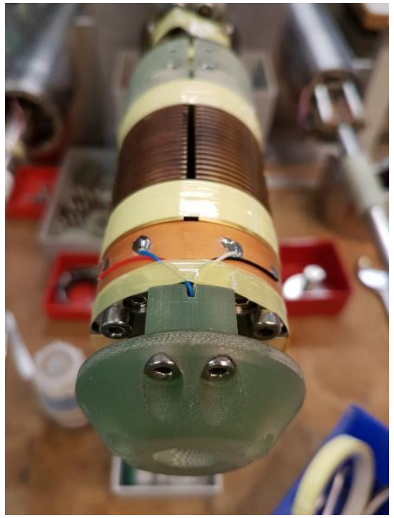
- **Lack of universal scaling laws covering the entire ranges of B, θ and T**

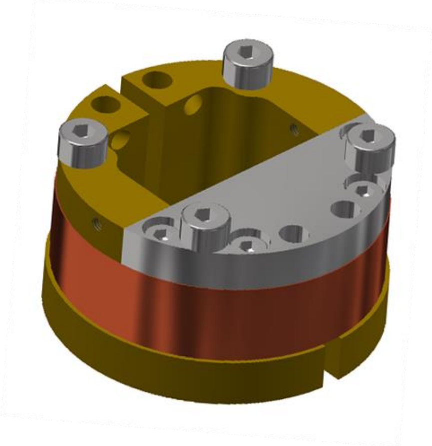
What we can do at UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES :Critical current tests up to 2 kA

Magnetic fields up to 19 T/21 T and temperatures up to 50 K in a 50 mm VTI

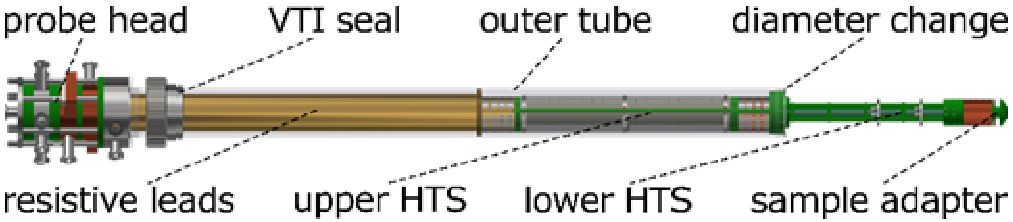


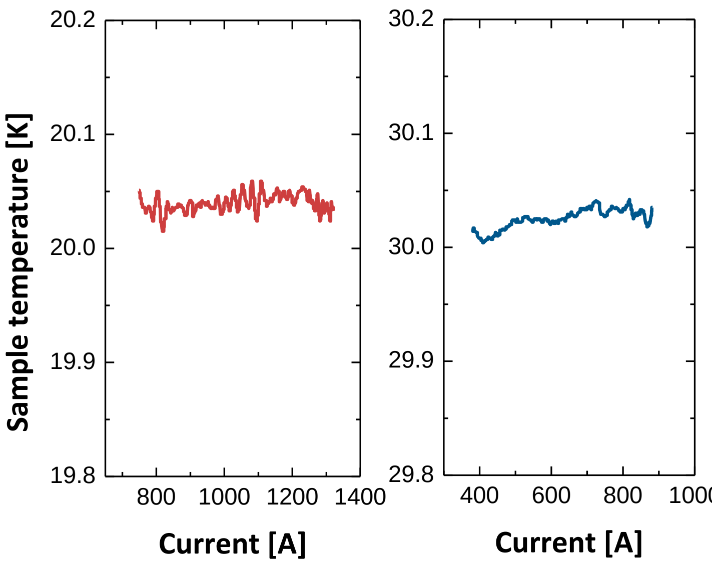


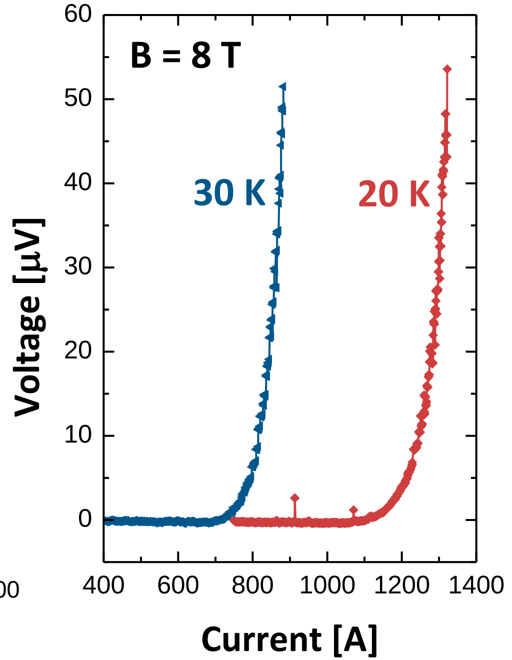




- Possible to test long samples (> 120 mm) at various angles: θ = 0°, 5°, 7.5°, 10°, 15° and 90°
- **Active stabilization** of the sample temperature







Barth, Bonura, and CS, IEEE Trans. Appl. Supercond., 28 (2018) 9500206
DOI: 10.1109/TASC.2018.2794199

What has been tested – Catalogue of the Tapes

	Width	REBCO Type	REBCO Thickness	Deposition Method	Pinning Type	Substrate	Cu Stabilizer
Fujikura	4 mm	EuBCO	2.5 μm	IBAD/PLD	BHO columns (artificial)	50 μm/Hastelloy	2 x 40 μm electroplated
							2 x 20 μm electroplated
SuperOx	4 mm	YBCO	3.1 μm	IBAD/PLD	Y_2O_3 particles (native)	100 μm/Hastelloy	2 x 20 μm electroplated
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上海超导™ SHANGHAI SUPERCONDUCTOR	3 mm	EuBCO	3 μm	IBAD/PLD	BHO columns (artificial)	30 μm/Hastelloy	2 x 10 μm electroplated
THEVA	4 mm	GdBCO	3 μm	ISD/EB-PVD	Gd_2O_3 particles (native)	100 μm/Hastelloy	2 x 20 μm electroplated
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Fujikura tapes courtesy of S. Richardson and M. Daibo, SuperOx tapes courtesy of A. Molodyk, 上海超导 SHANGHAI SUPERCONDUCTOR tapes courtesy of Y. Zhao and B. Song, THEVA tapes courtesy of M. Bauer and M. Bendele

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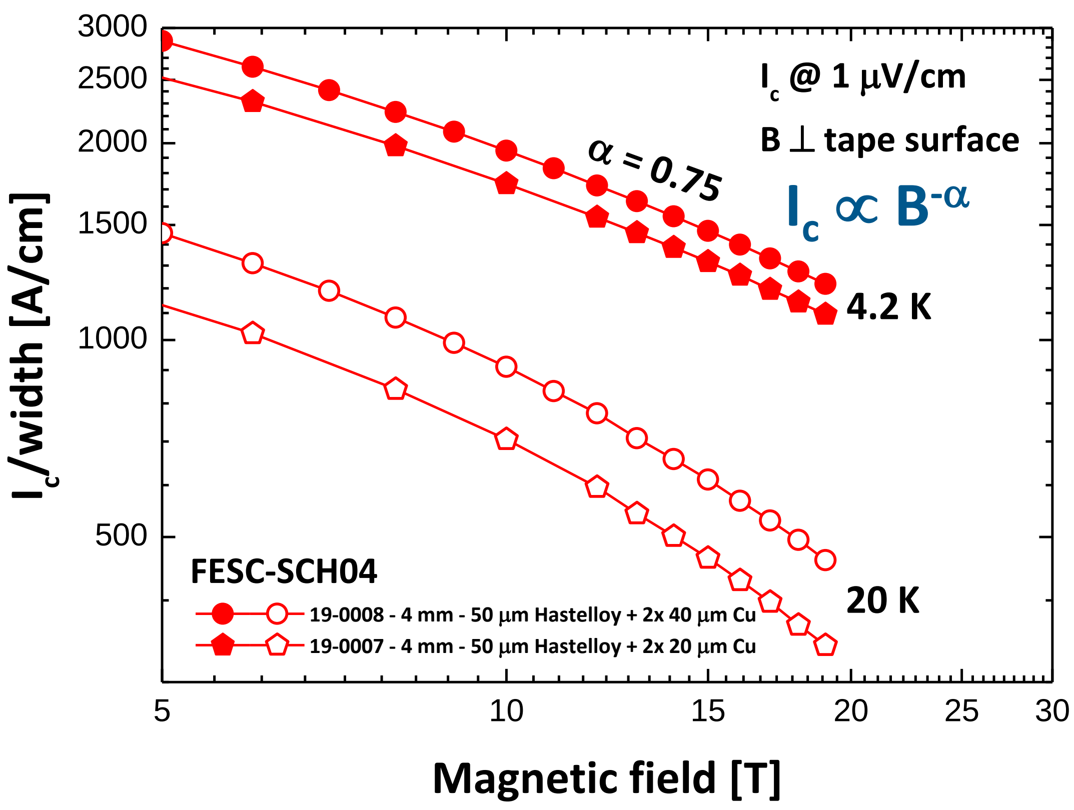
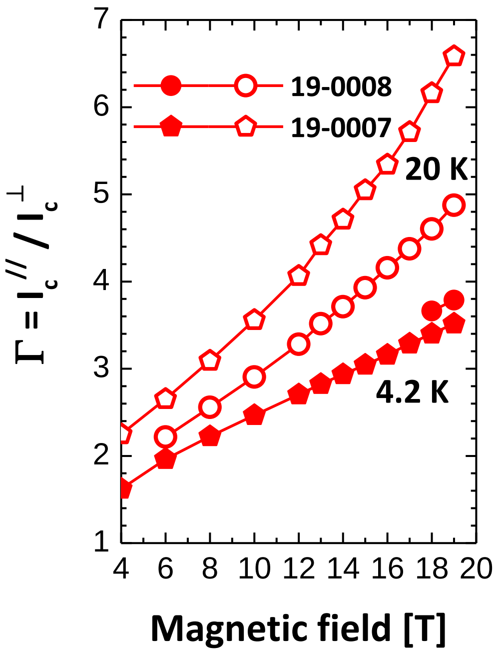
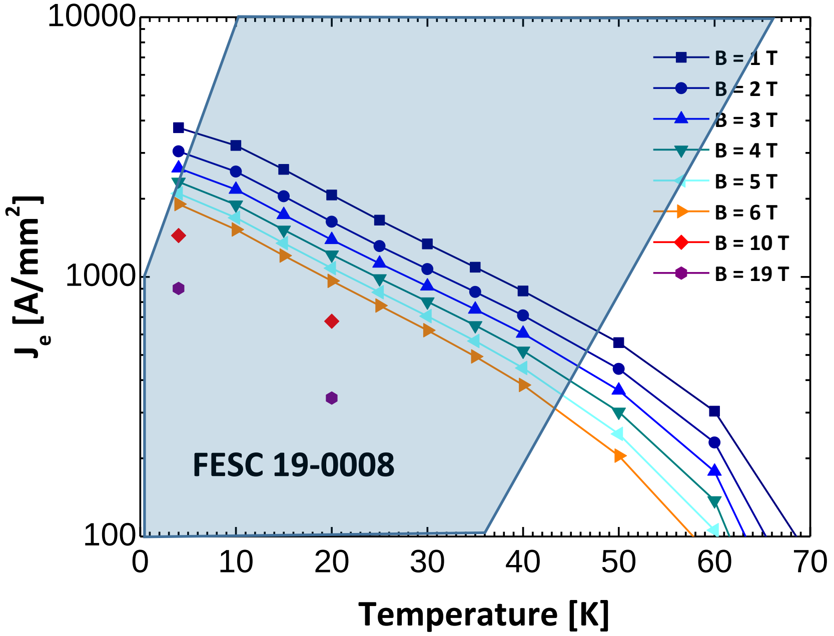
Fujikura tapes: Overview of the $I_c(B,T)$ properties

Material received in Q1/2019







$$J_e(B,T) = J_e(B,T=0)\exp\left[-\frac{T}{T^*}\right]$$

Temperature scaling

I_c/width (4.2K, 19T)	I_c/width (20K, 19T)	α (4.2K) @ B > 10 T
1094-1218 A/cm	341-460 A/cm	0.75

Fujikura tapes: Pinning force scaling

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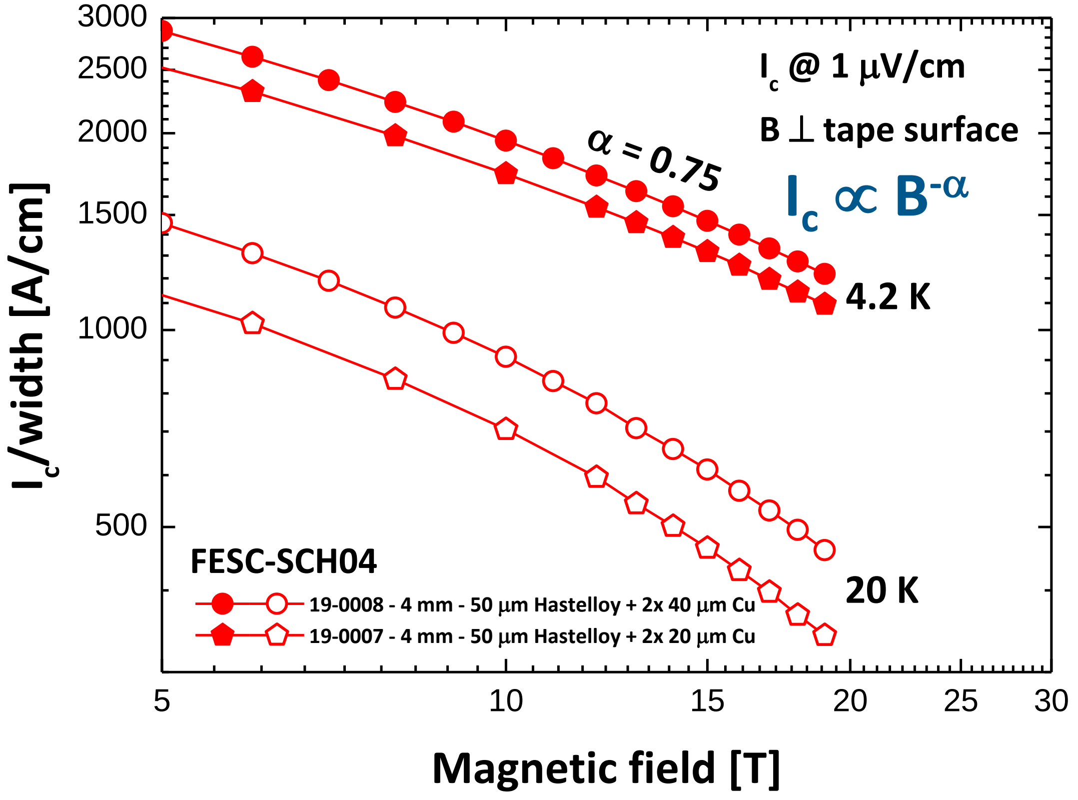

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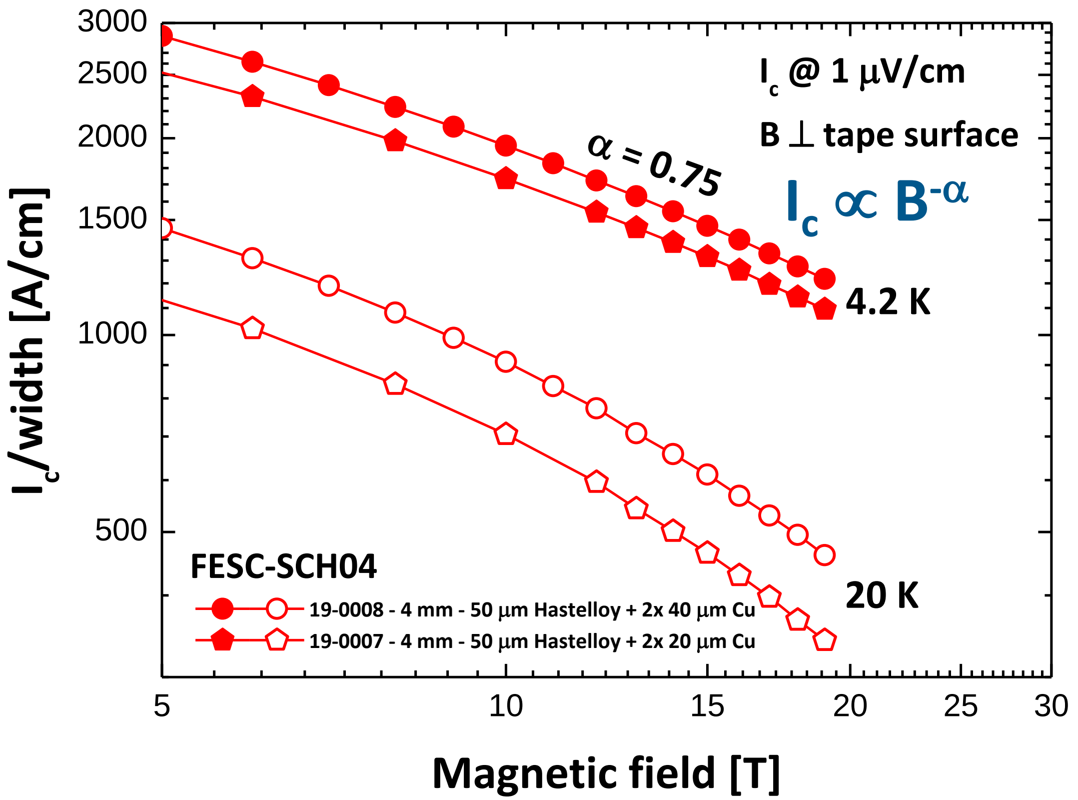
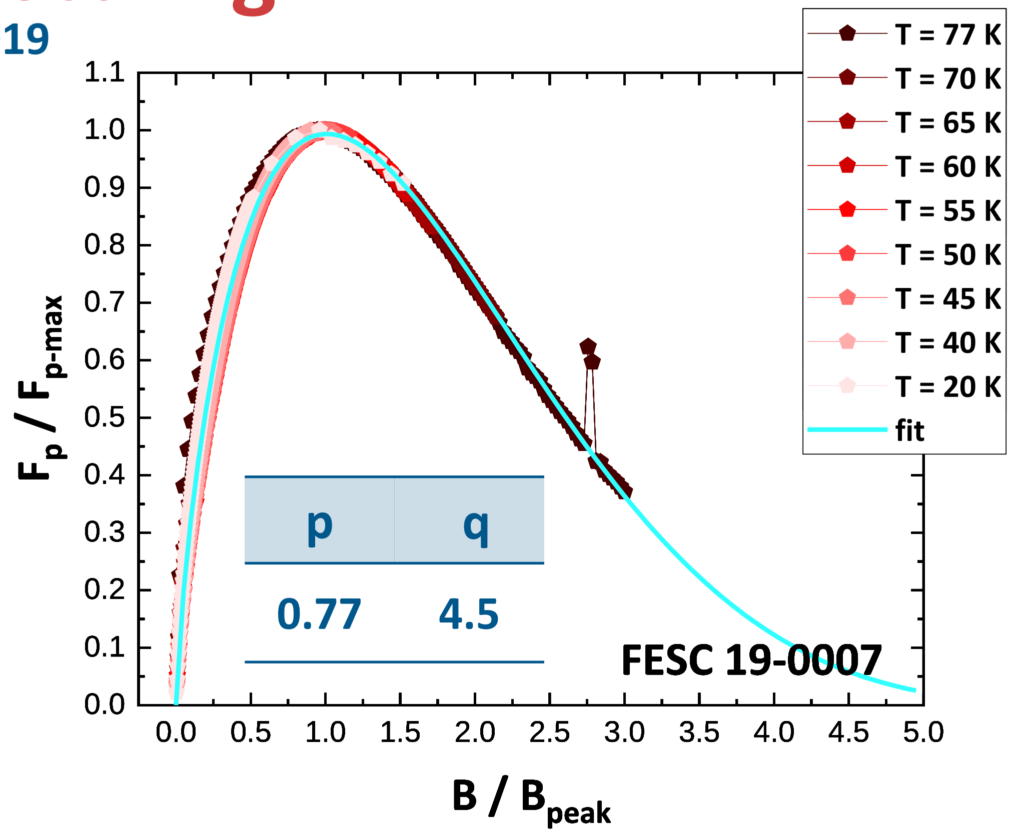




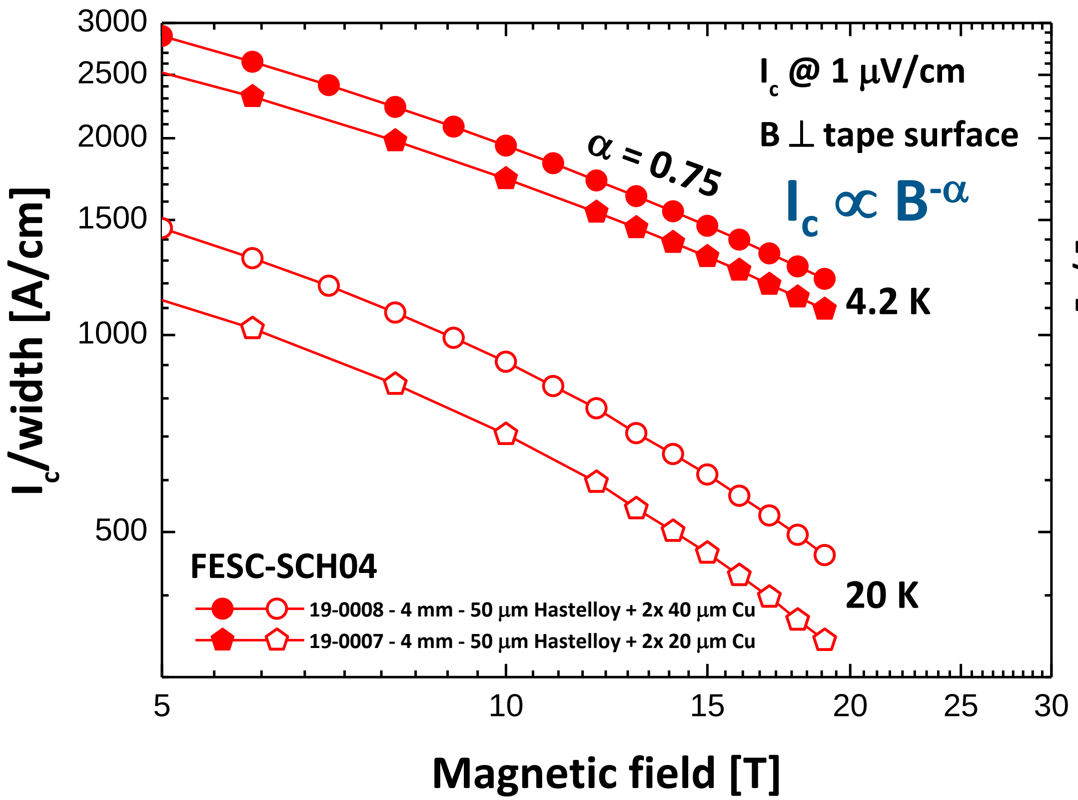
I_c/width (4.2K, 19T)	I_c/width (20K, 19T)
1094-1218 A/cm	341-460 A/cm

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 $f_p \propto b^p (1-b)^q$

Fujikura tapes: Pinning force scaling

Material received in Q1/2019



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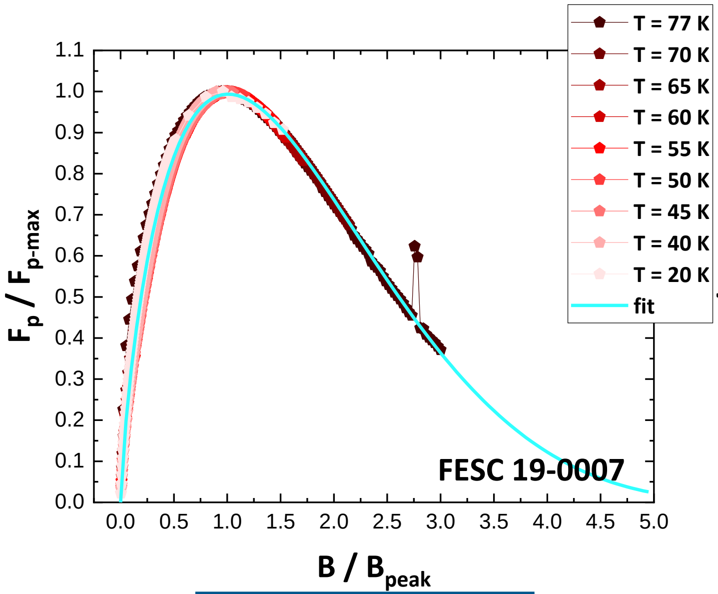
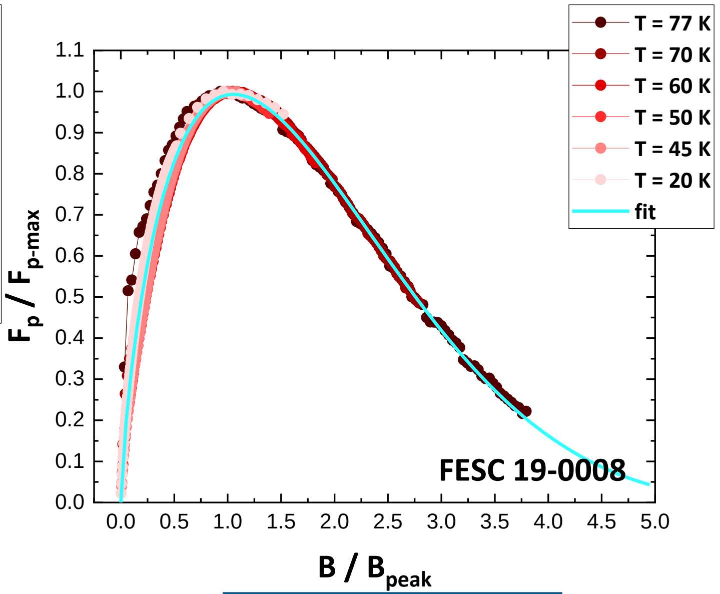


p	q
0.77	4.5



p	q
0.74	4.4

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 $f_p \propto b^p (1-b)^q$

What has been tested – Catalogue of the Tapes

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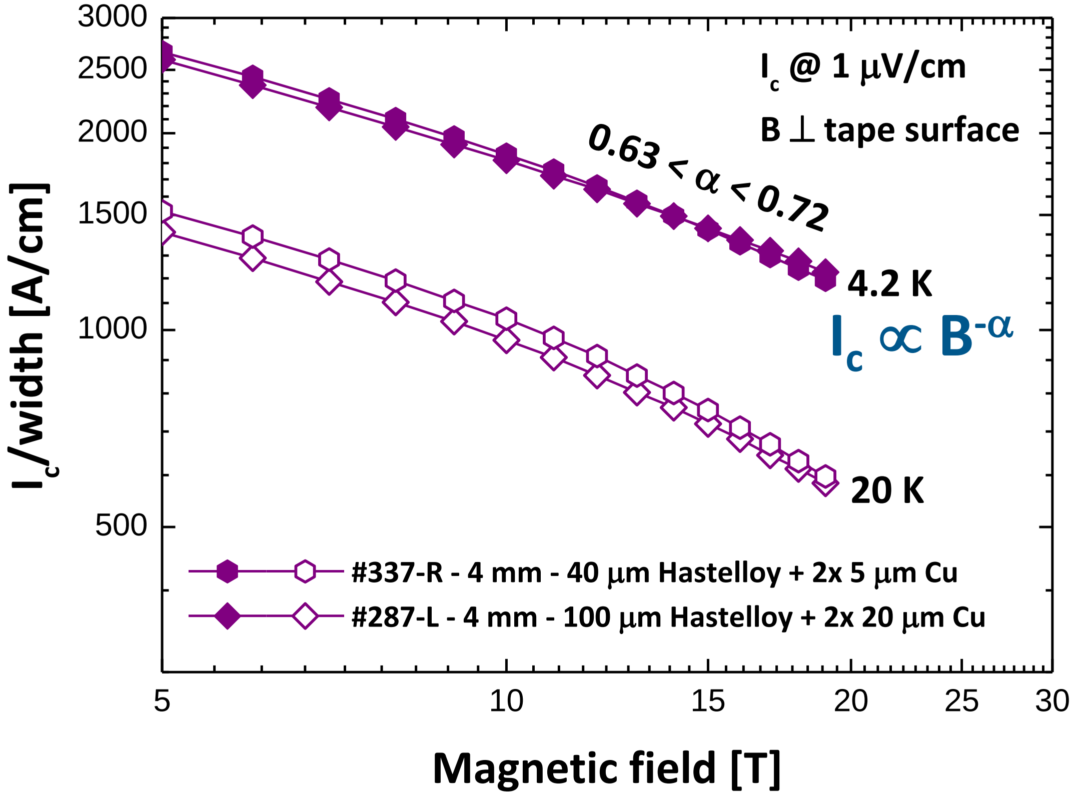
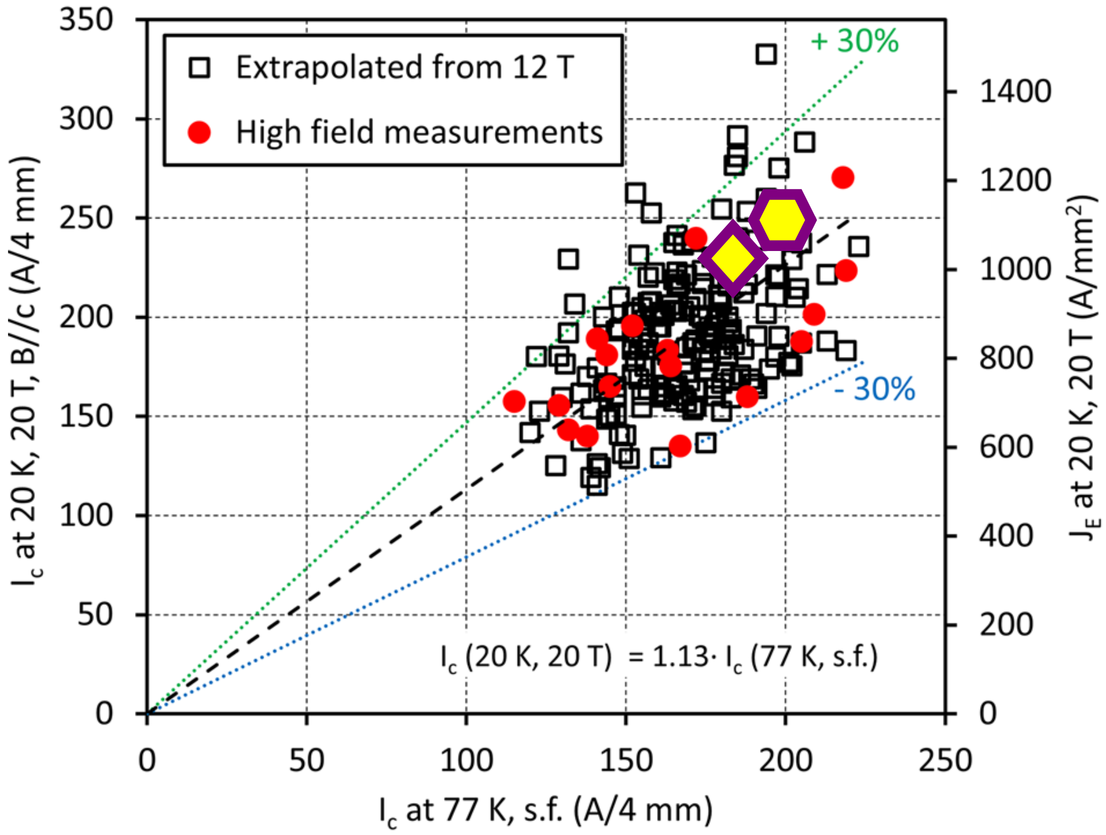
THEVA	4 mm	GdBCO	3 μm	ISD/EB-PVD	Gd_2O_3 particles (native) / Gd_2O_3 particles (native) BHO particles (artificial)	100 μm/Hastelloy / 40 μm/Hastelloy	2 x 20 μm electroplated / 2 x 10 μm PVD-plated

Fujikura tapes courtesy of S. Richardson and M. Daibo, SuperOx tapes courtesy of A. Molodyk, 上海超导 SHANGHAI SUPERCONDUCTOR tapes courtesy of Y. Zhao and B. Song, THEVA tapes courtesy of M. Bauer and M. Bendele

SuperOx tapes: Overview of the $I_c(B,T)$ properties

Tapes from a large-volume production





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

I_c/width (4.2K, 19T)	I_c/width (20K, 19T)	α (4.2K) @ B > 10 T	Γ (4.2K, 19T)
1200 A/cm	590 A/cm	0.63-0.72	n/a

Material received in Q2/2019

SuperOx tapes: Overview of the $I_c(B,T)$ properties

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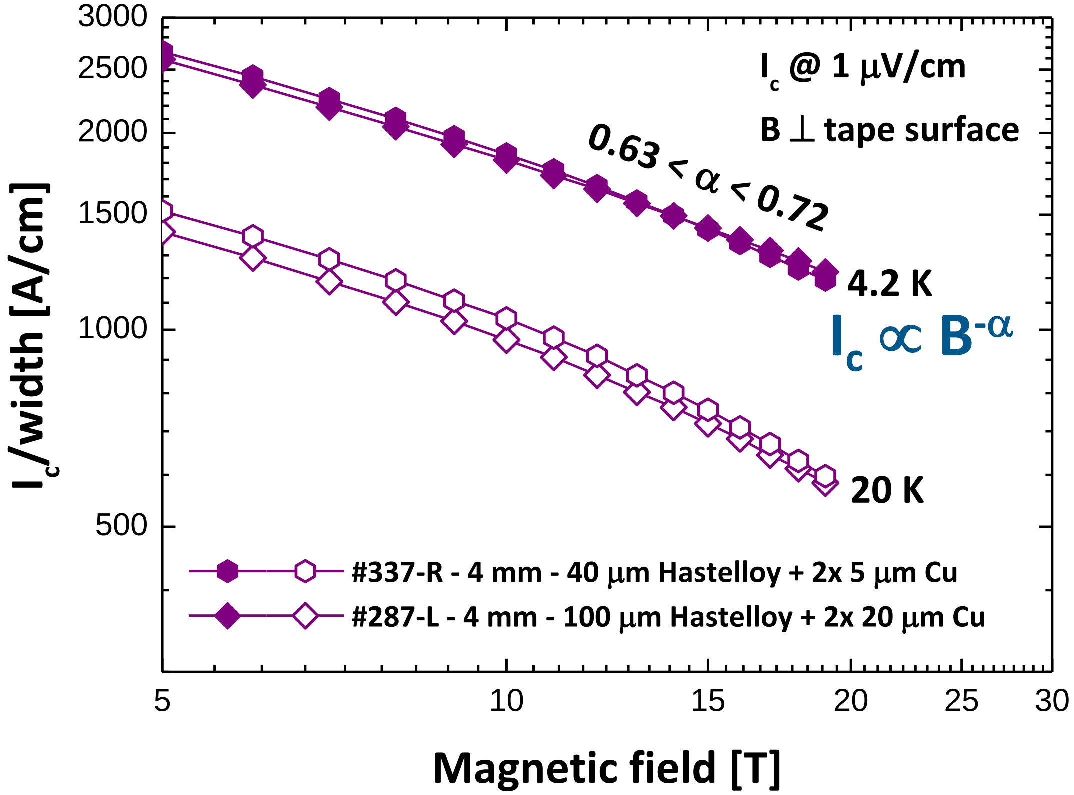
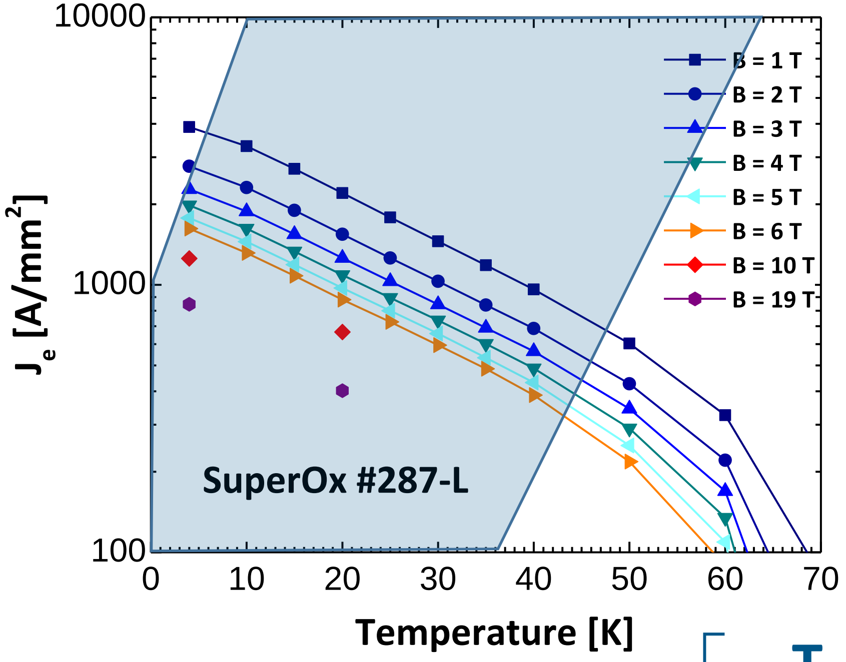




$$J_e(B,T) = J_e(B,T=0)\exp\left[-\frac{T}{T^*}\right]$$

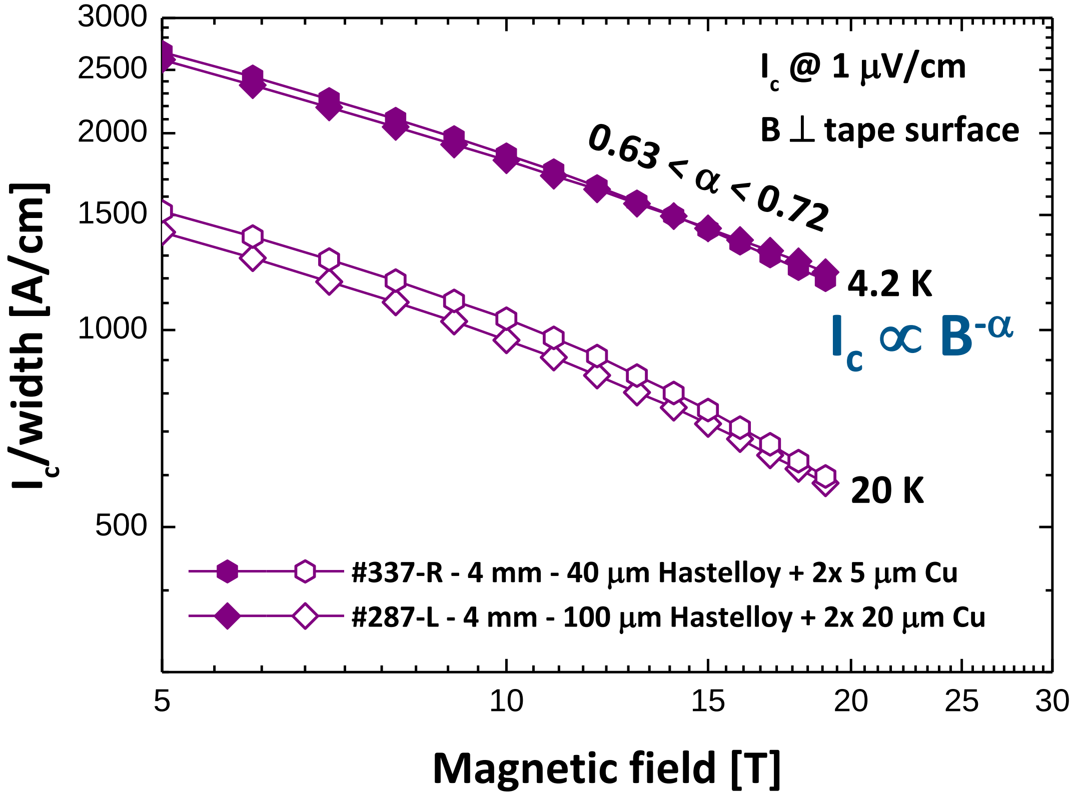
Temperature scaling

I_c/width (4.2K, 19T)	I_c/width (20K, 19T)	α (4.2K) @ B > 10 T	Γ (4.2K, 19T)	T* @ T < 40 K
1200 A/cm	590 A/cm	0.63-0.72	n/a	24-26 K

Material received in Q2/2019

SuperOx tapes: Pinning force scaling

Tapes from a large-volume production



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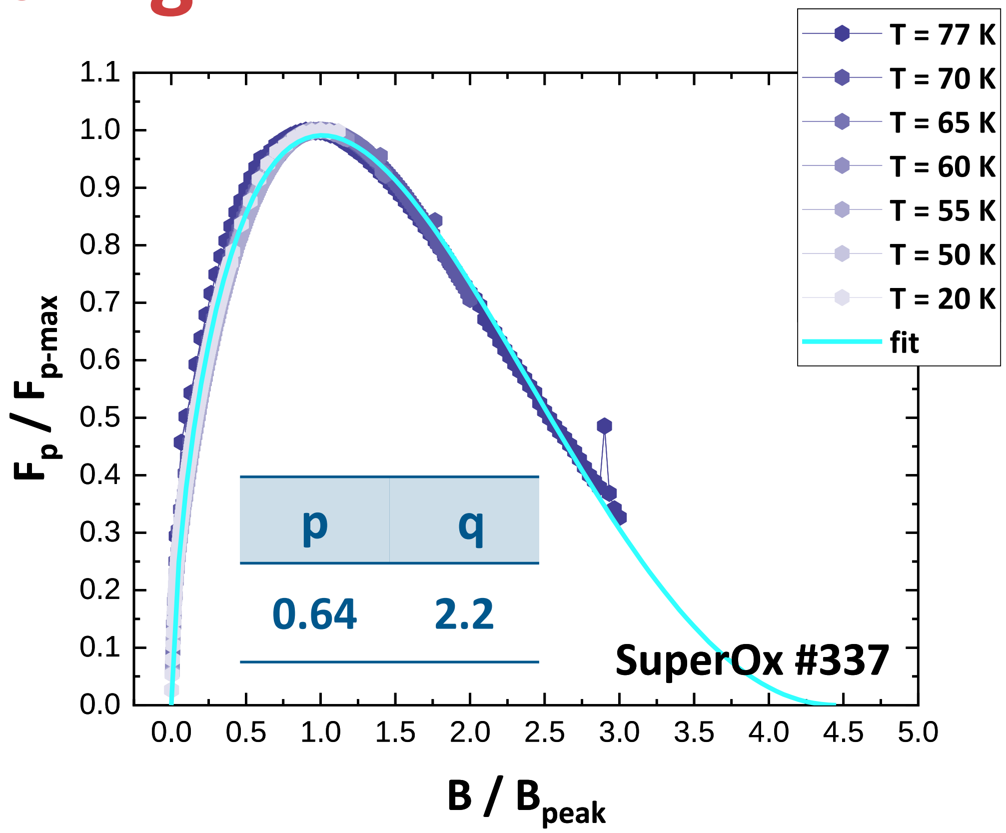

Normalized pinning force vs B / B_{peak} , from M(B) curves up to 7 T with some points from transport I_c

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

Material received in Q2/2019

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上海超导™ SHANGHAI SUPERCONDUCTOR	3 mm	EuBCO	3 μm	IBAD/PLD	BHO columns (artificial)	30 μm/Hastelloy	2 x 10 μm electroplated
THEVA	4 mm	GdBCO	3 μm	ISD/EB-PVD	Gd_2O_3 particles (native) / Gd_2O_3 particles (native) BHO particles (artificial)	100 μm/Hastelloy / 40 μm/Hastelloy	2 x 20 μm electroplated / 2 x 10 μm PVD-plated

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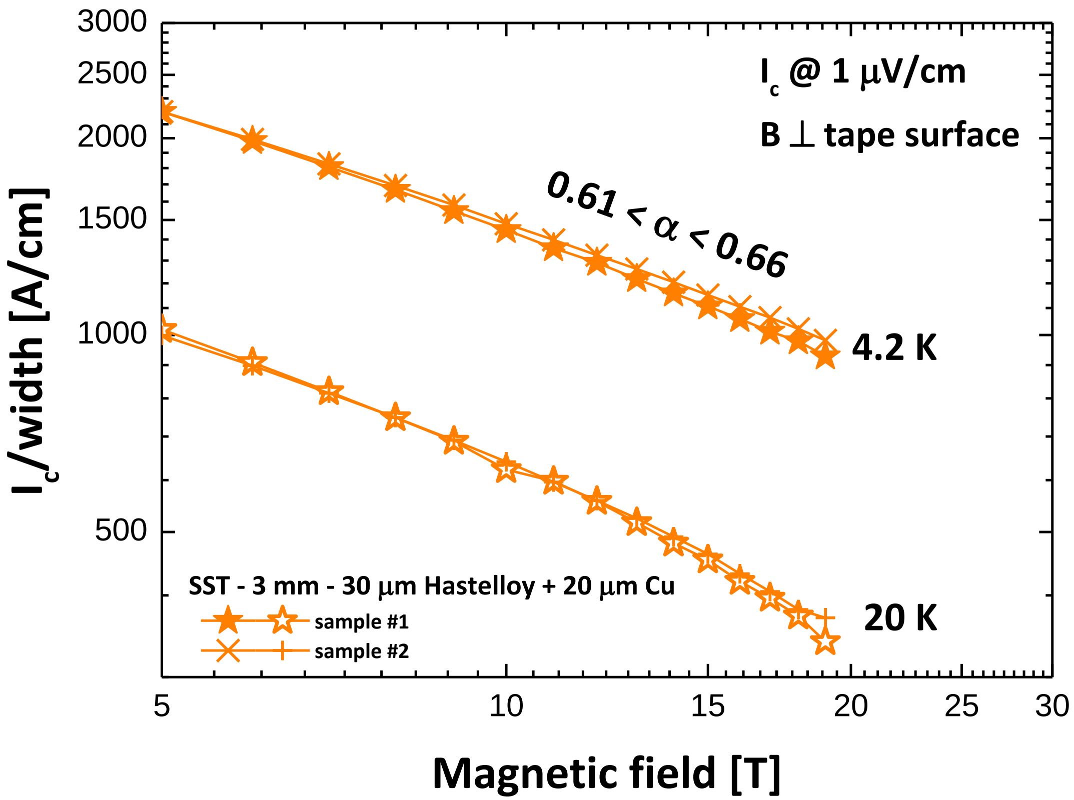
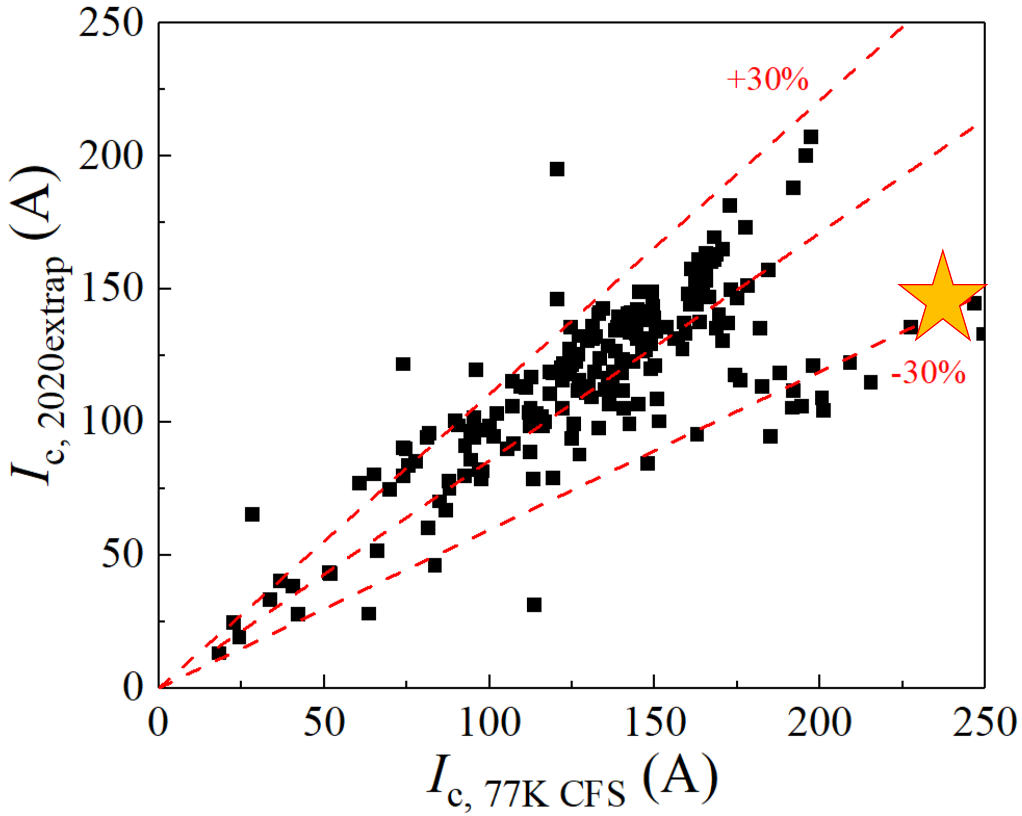
上海超导™ tapes: Overview of the $I_c(B,T)$ properties

SHANGHAI SUPERCONDUCTOR

Material received in Q3/2021





Courtesy of Bai Song - SST

I_c/width (4.2K, 19T)	I_c/width (20K, 19T)	α (4.2K) @ B > 10 T
930-980 A/cm	340-370 A/cm	0.61-0.66

上海超导™ tapes: Overview of the $I_c(B,T)$ properties

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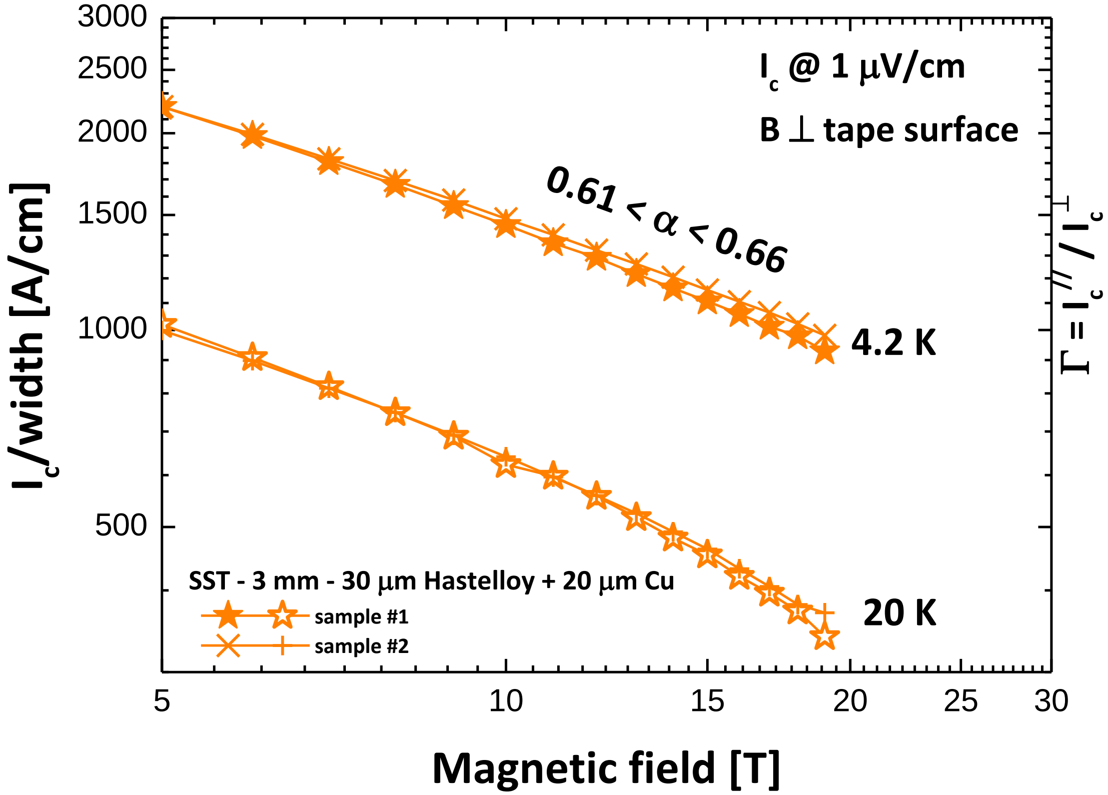
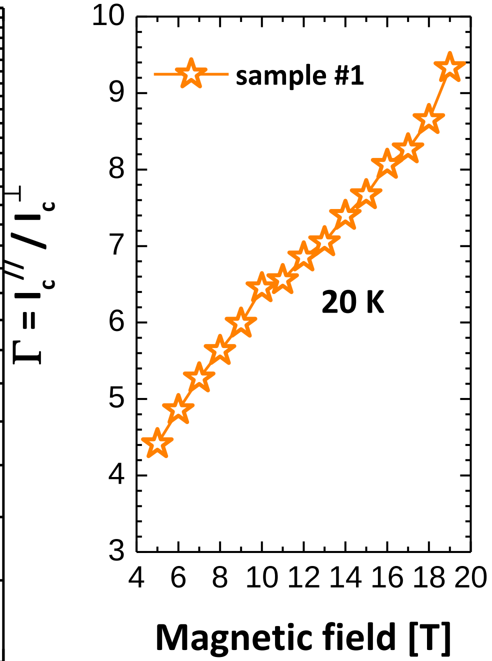
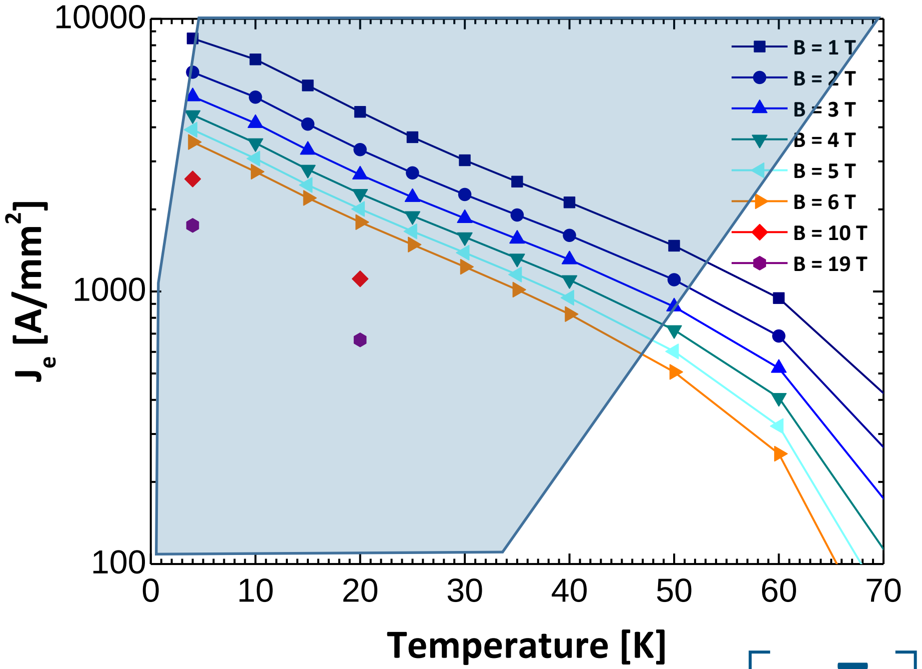






$$J_e(B,T) = J_e(B,T=0)\exp\left[-\frac{T}{T^*}\right]$$

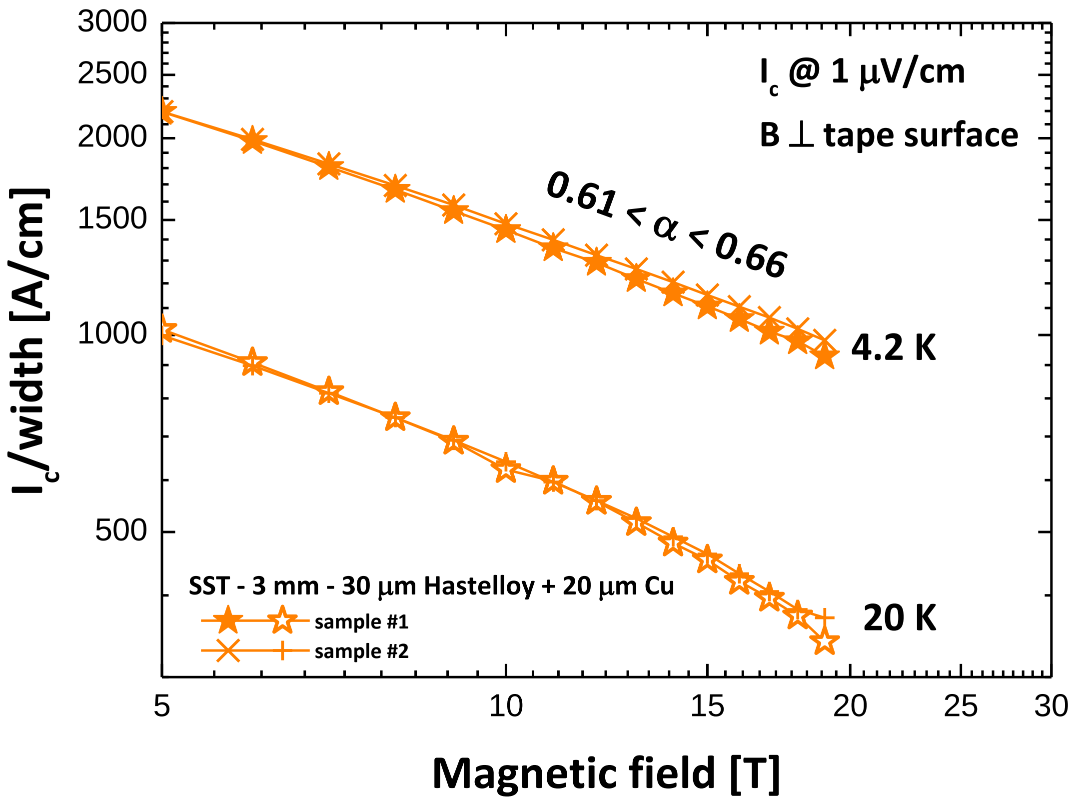
Temperature scaling

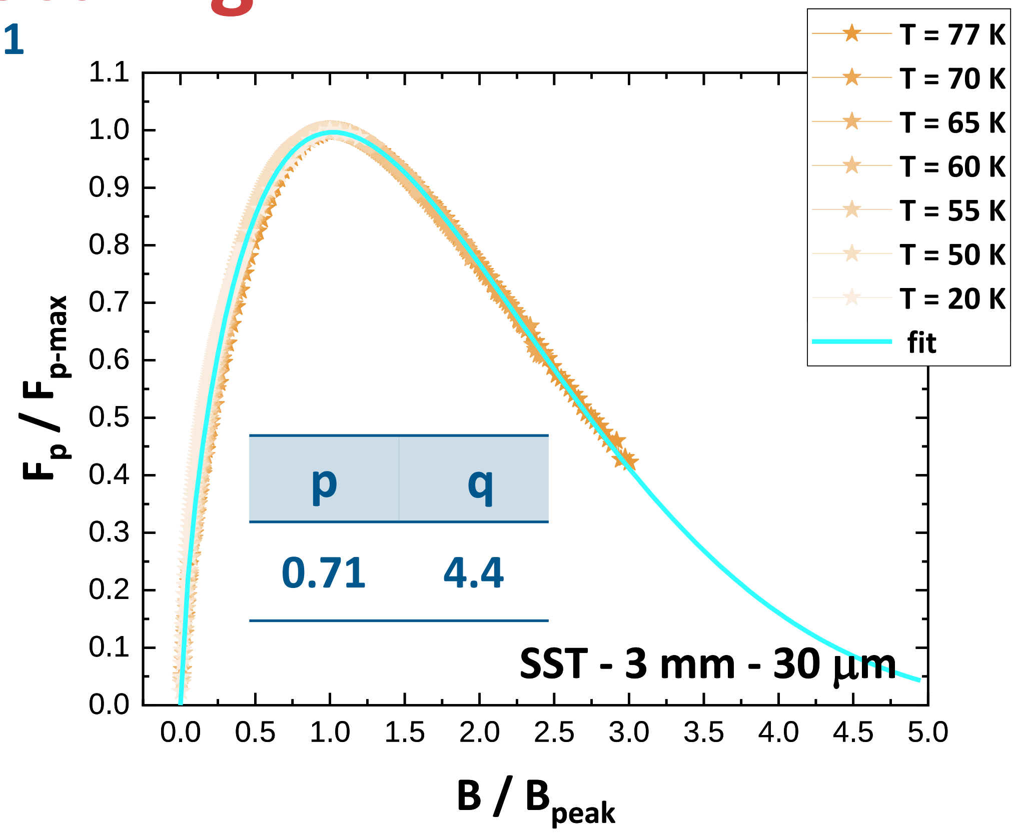
I_c/width (4.2K, 19T)	I_c/width (20K, 19T)	α (4.2K) @ B > 10 T	Γ (20K, 10T)
930-980 A/cm	340-370 A/cm	0.61-0.66	6.3

上海超导™ tapes: Pinning force scaling

SHANGHAI SUPERCONDUCTOR

Material received in Q3/2021





I_c/width (4.2K, 19T)	I_c/width (20K, 19T)
930-980 A/cm	340-370 A/cm

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

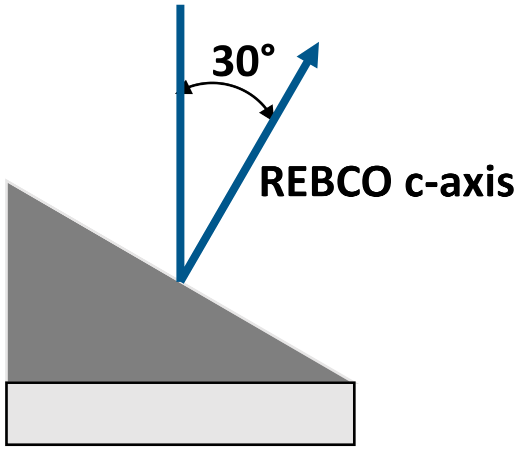
Concatenated fit of the type $f_p \propto b^p (1-b)^q$

What has been tested – Catalogue of the Tapes

	Width	REBCO Type	REBCO Thickness	Deposition Method	Pinning Type	Substrate	Cu Stabilizer
Fujikura	4 mm	EuBCO	2.5 μm	IBAD/PLD	BHO columns (artificial)	50 μm/Hastelloy	2 x 40 μm electroplated
							2 x 20 μm electroplated
SuperOx	4 mm	YBCO	3.1 μm	IBAD/PLD	Y_2O_3 particles (native)	100 μm/Hastelloy	2 x 20 μm electroplated
			2.7 μm			40 μm/Hastelloy	2 x 5 μm electroplated
上海超导™ SHANGHAI SUPERCONDUCTOR	3 mm	EuBCO	3 μm	IBAD/PLD	BHO columns (artificial)	30 μm/Hastelloy	2 x 10 μm electroplated
THEVA	4 mm	GdBCO	3 μm	ISD/EB-PVD	Gd_2O_3 particles (native)	100 μm/Hastelloy	2 x 20 μm electroplated
					Gd_2O_3 particles (native) BHO particles (artificial)	40 μm/Hastelloy	2 x 10 μm PVD-plated

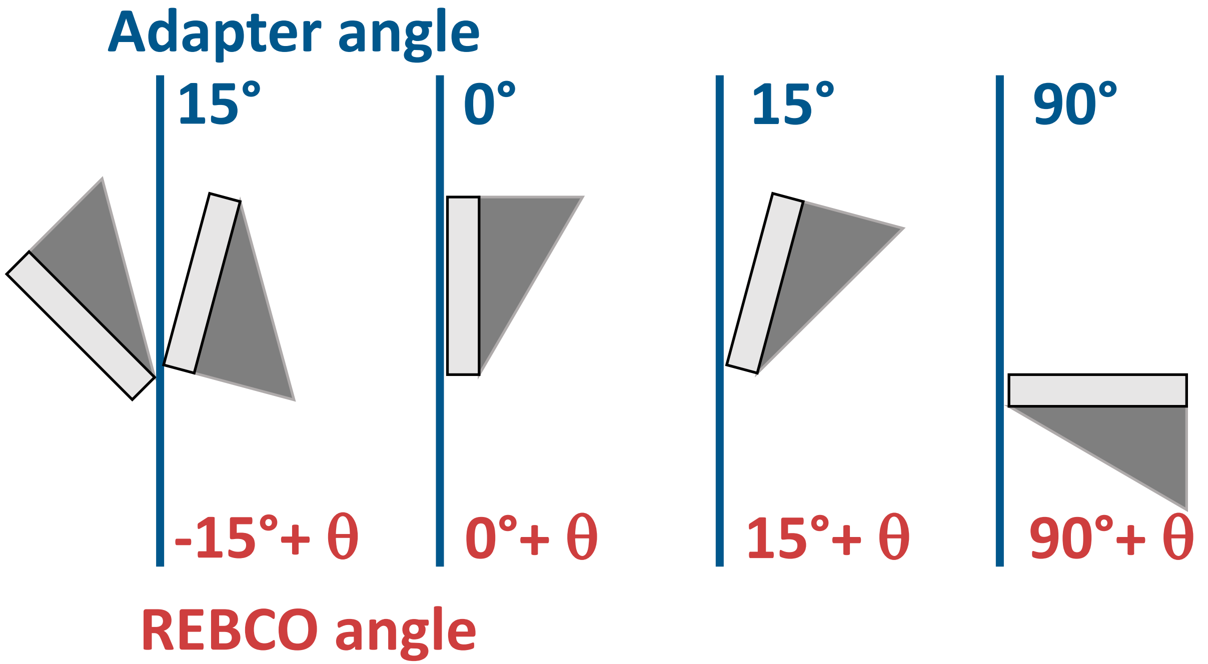
Fujikura tapes courtesy of S. Richardson and M. Daibo, SuperOx tapes courtesy of A. Molodyk, 上海超导 SHANGHAI SUPERCONDUCTOR tapes courtesy of Y. Zhao and B. Song, THEVA tapes courtesy of M. Bauer and M. Bendele

Peculiarity of the REBCO tapes from THEVA



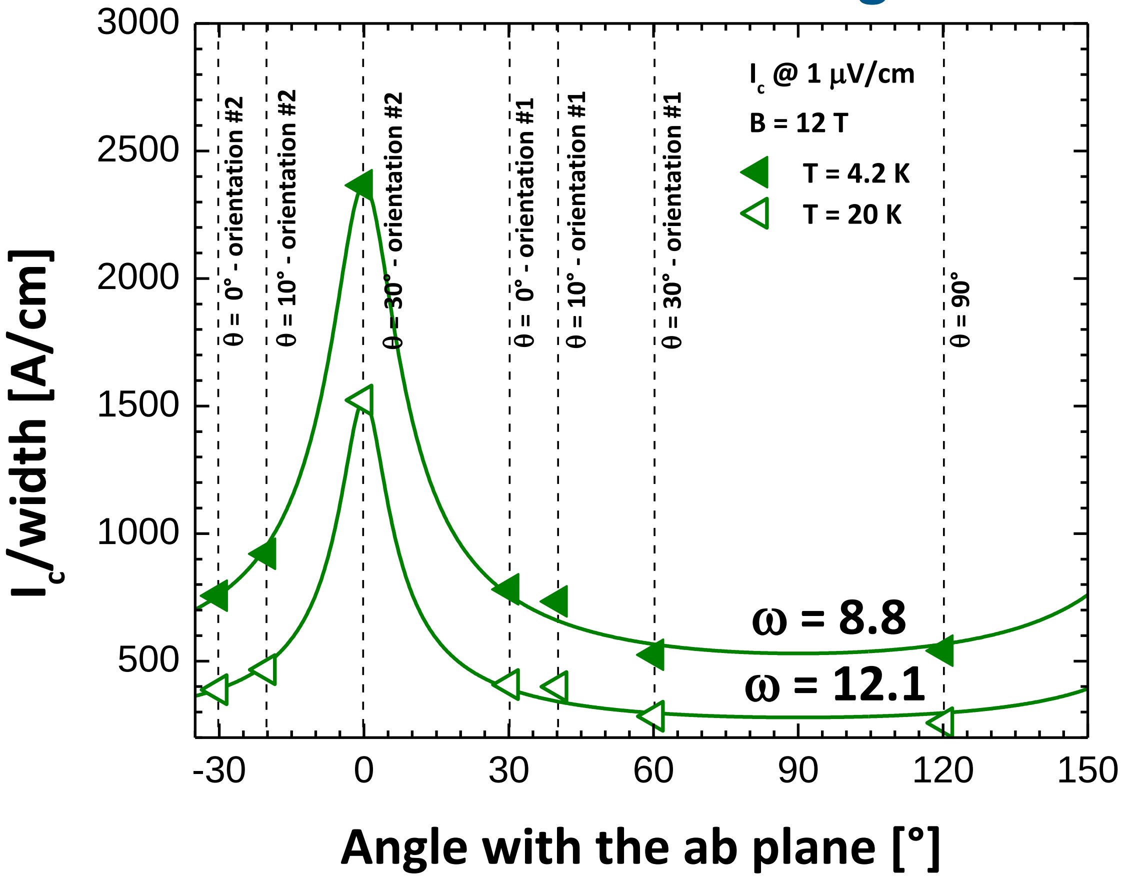
The ISD-MgO buffer layer grows tilted by 30° with respect to the substrate. REBCO grows biaxially textured on the top of the MgO layer

We extracted the angular dependence of I_c and estimated I_c^{max} and I_c^{min} from a limited number of measurements at fixed orientation

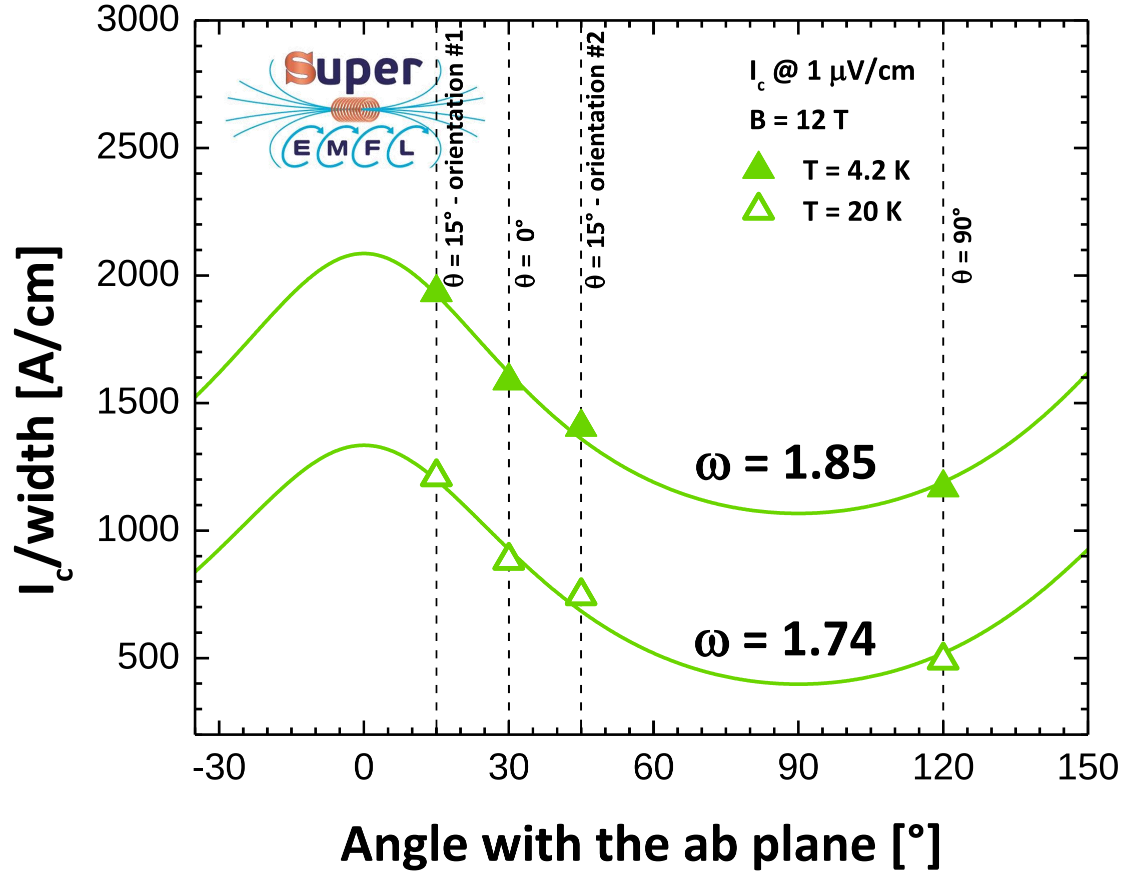


THEVA tapes: Angular dependence of I_c

Without Artificial Pinning – 2018



With Artificial Pinning – Q4/2021



Fit performed according to the Hilton model

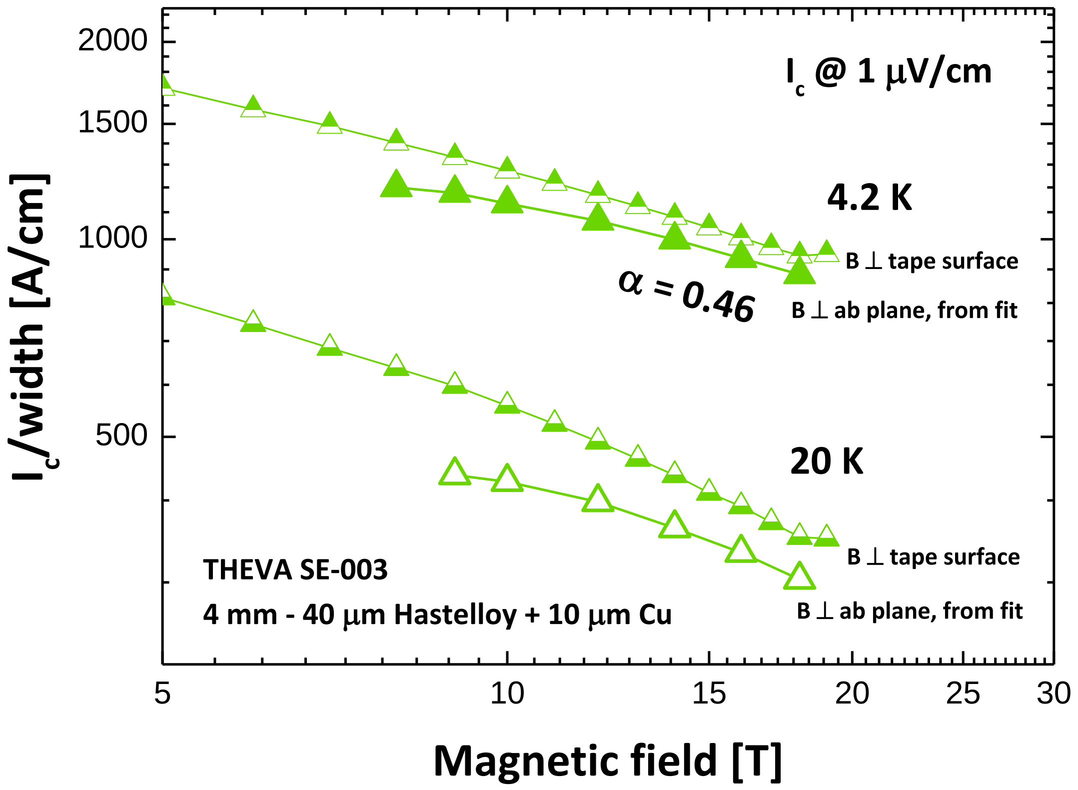
$$I_c(B,\theta)=I_c(B,90^\circ)+\left[I_c(B,0^\circ)-I_c(B,90^\circ)\right]\frac{\omega\, f(\omega,\theta)-1}{\omega-1}$$

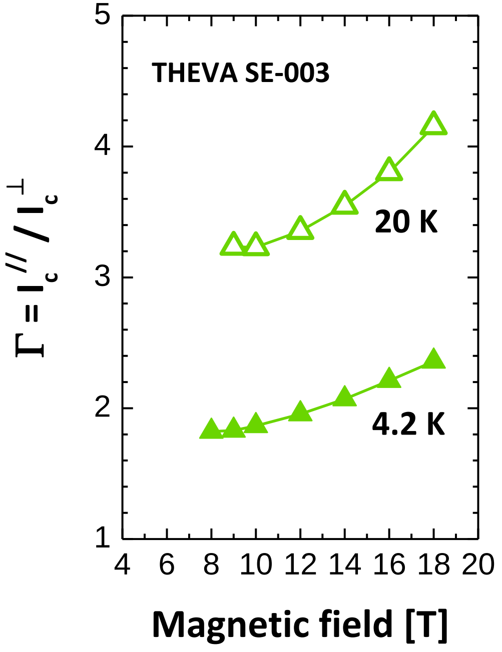
$$f(\omega,\theta)=\left[\omega^2\sin^2\theta+\cos^2\theta\right]^{-\frac{1}{2}}$$

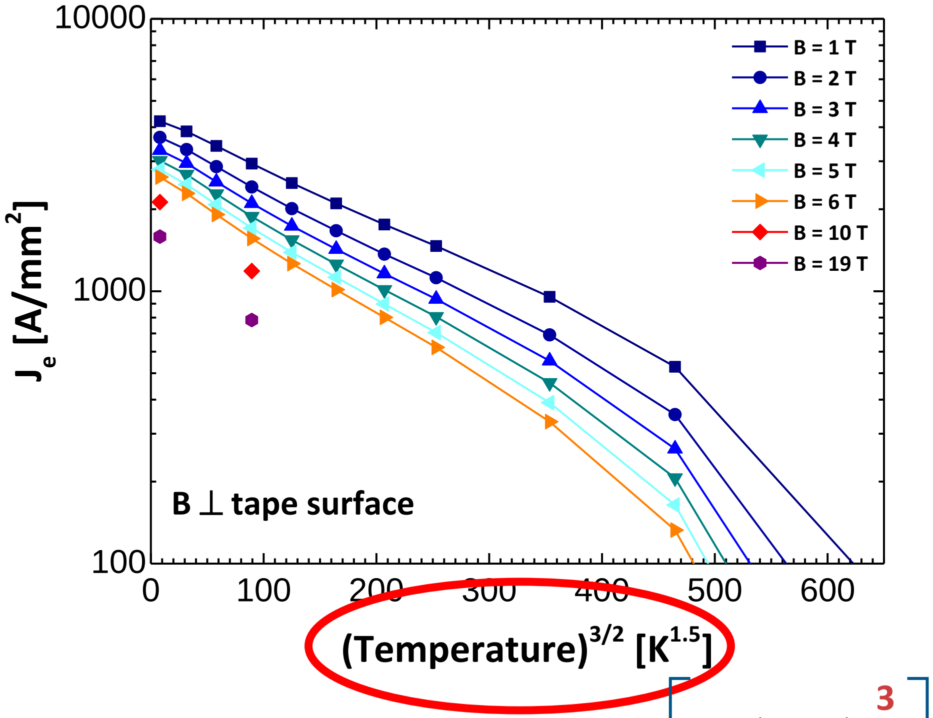
Hilton, Gavrilin & Trociewitz, SuST 28 (2015) 074002
DOI: 10.1088/0953-2048/28/7/074002

THEVA tapes: Overview of the $I_c(B,T)$ properties

Material received in Q4/2021







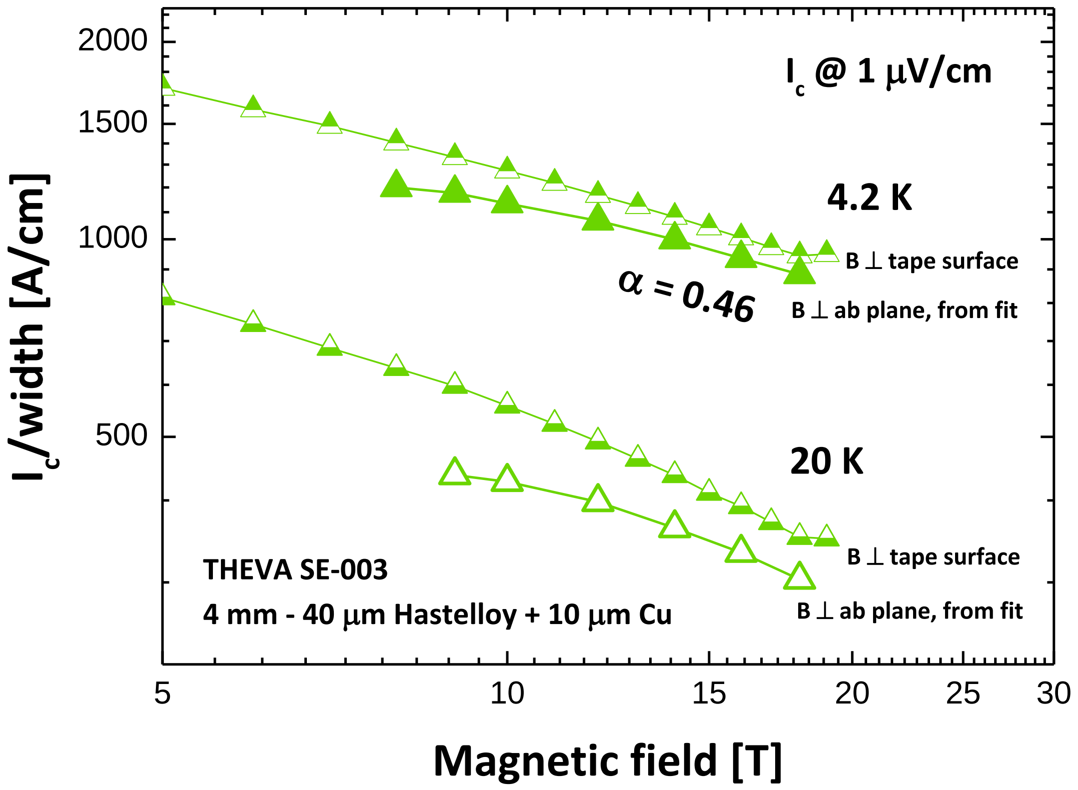
$$J_e(B,T) = J_e(B,T=0)\exp\left[-\left(\frac{T}{T^*}\right)^{\frac{3}{2}}\right]$$

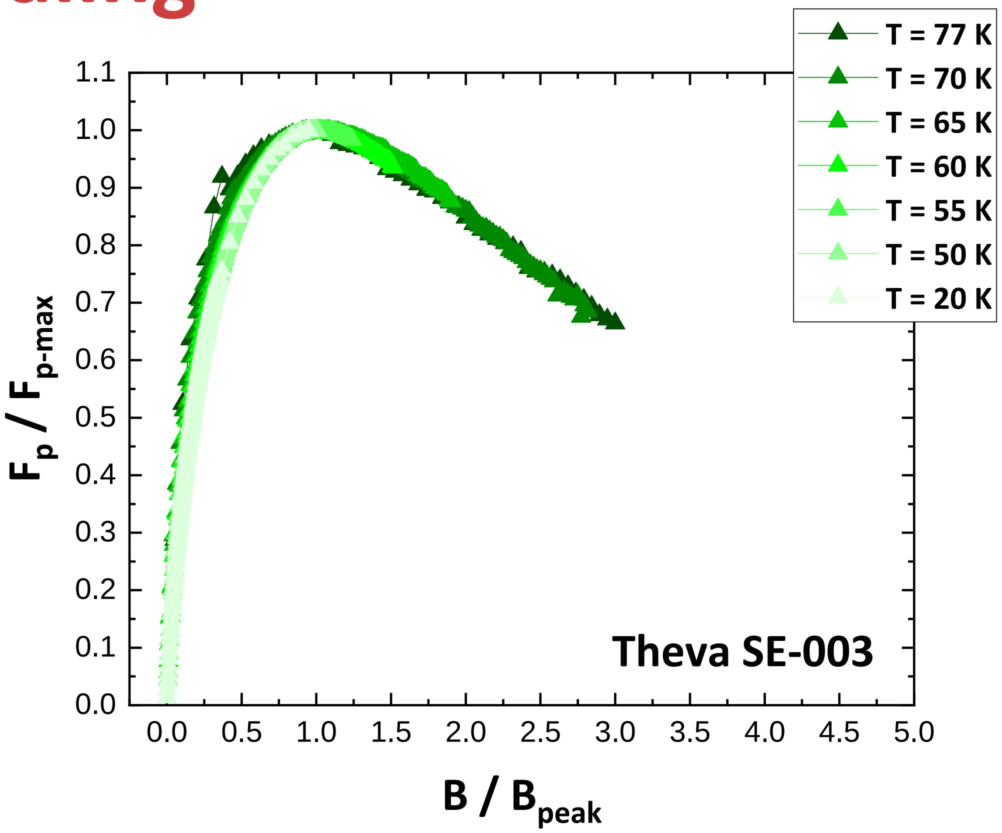
Temperature scaling

I_c/width (4.2K, 18T)	I_c/width (20K, 18T)	α (4.2K) @ B > 10 T	Γ (4K, 18T)
884 A/cm	303 A/cm	0.46	2.3

THEVA tapes: Pinning force scaling

Material received in Q4/2021





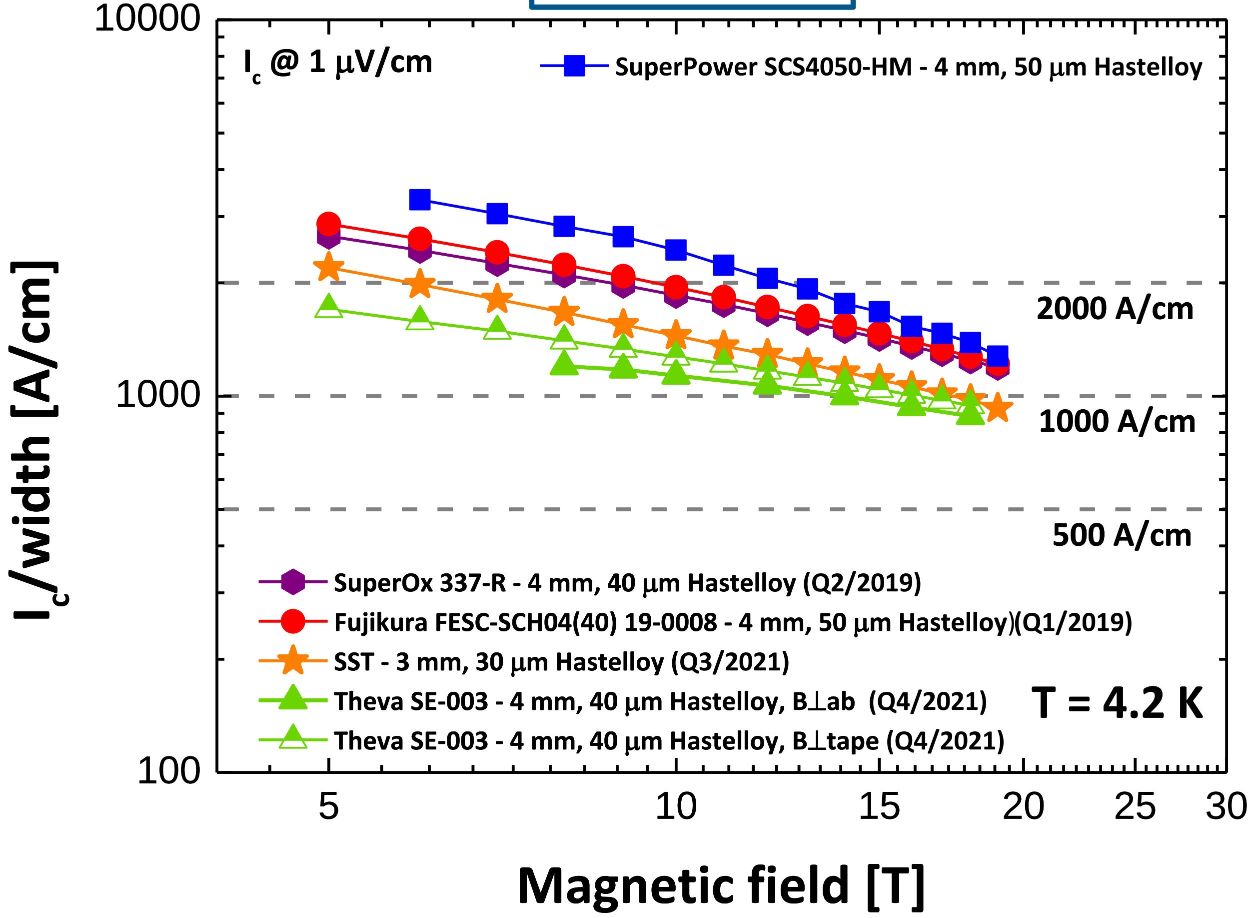
I_c /width (4.2K, 18T)	I_c /width (20K, 18T)
884 A/cm	303 A/cm

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

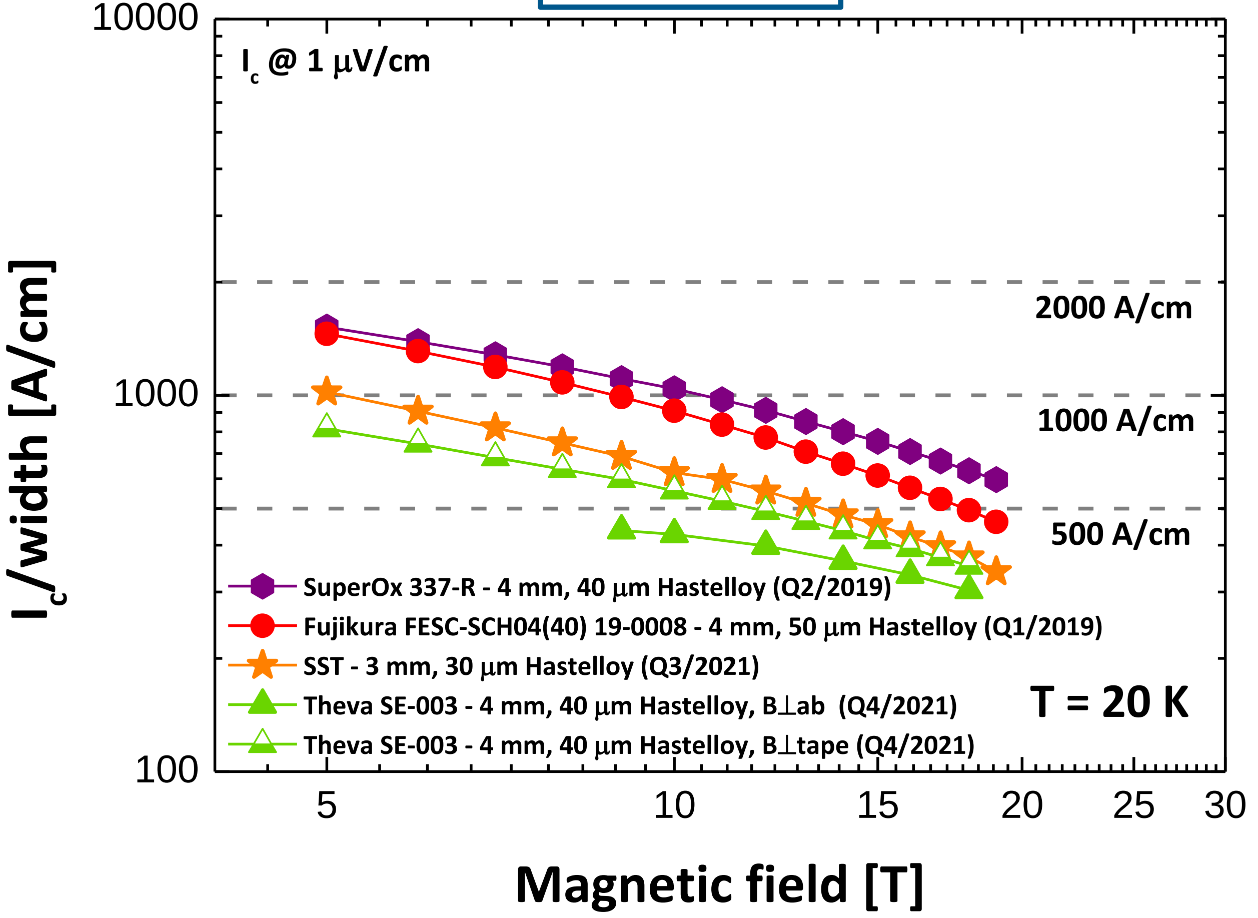
Not possible to fit the data with $f_p \propto b^p (1-b)^q$

Comparison of the performance: I_c / width

T = 4.2 K



T = 20 K

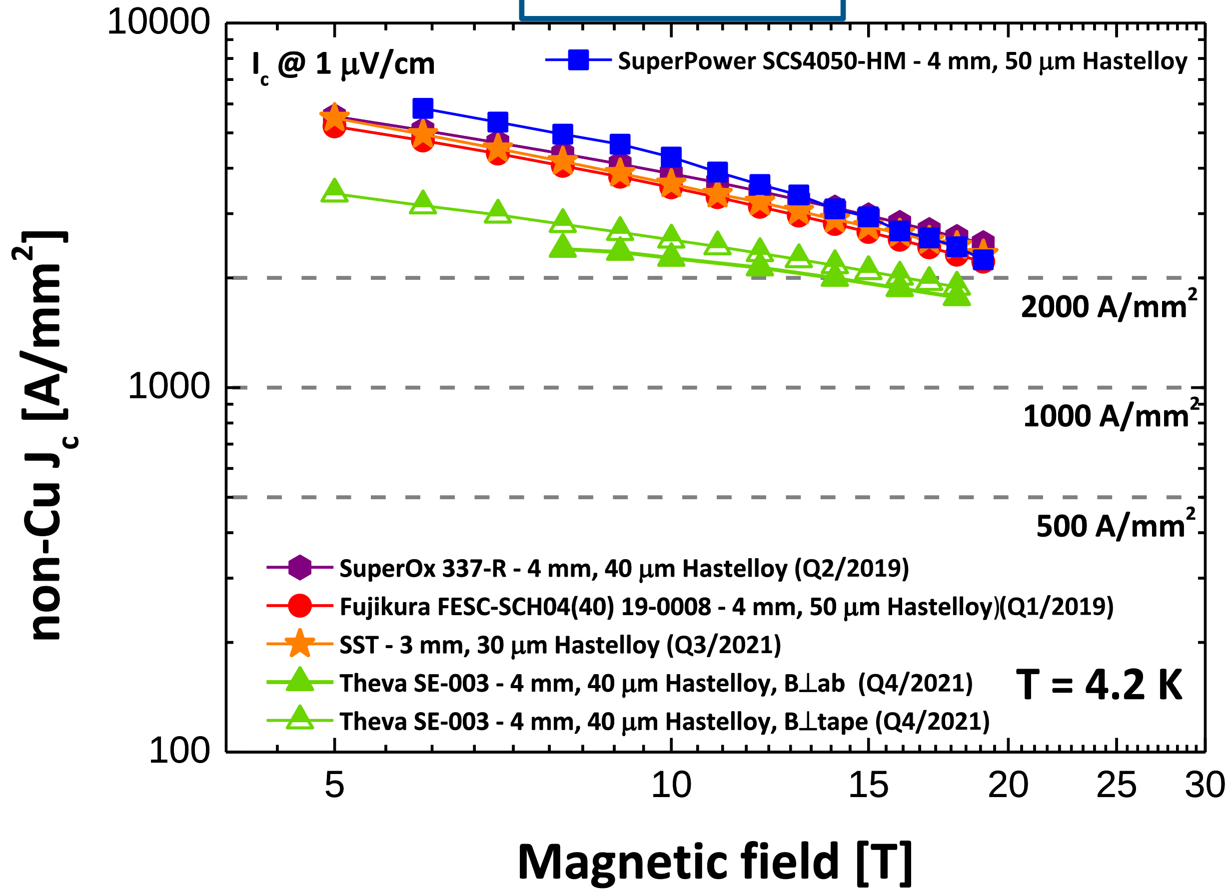


Comparison of the performance: non-Cu J_c

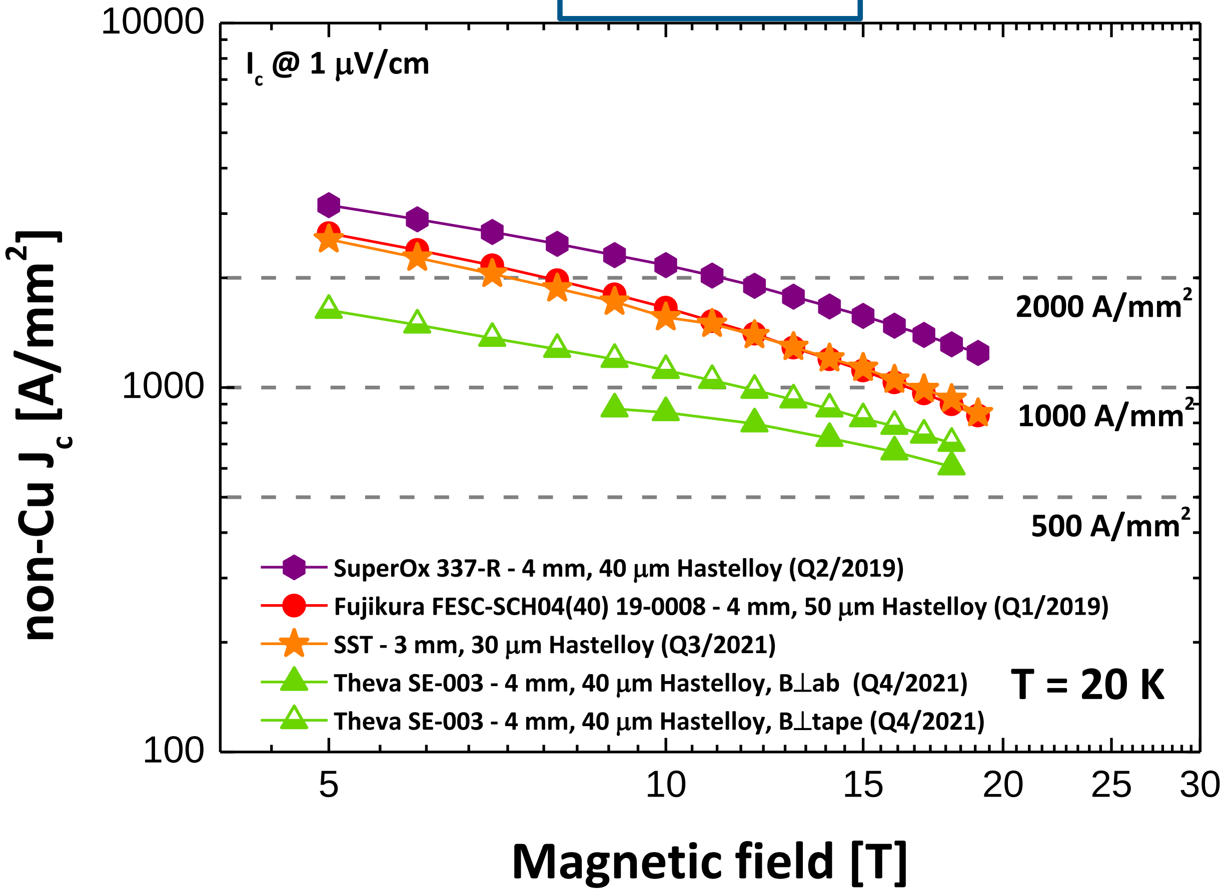
The non-Cu J_c corresponds to the critical current divided by the tape cross-section area minus the Cu area

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

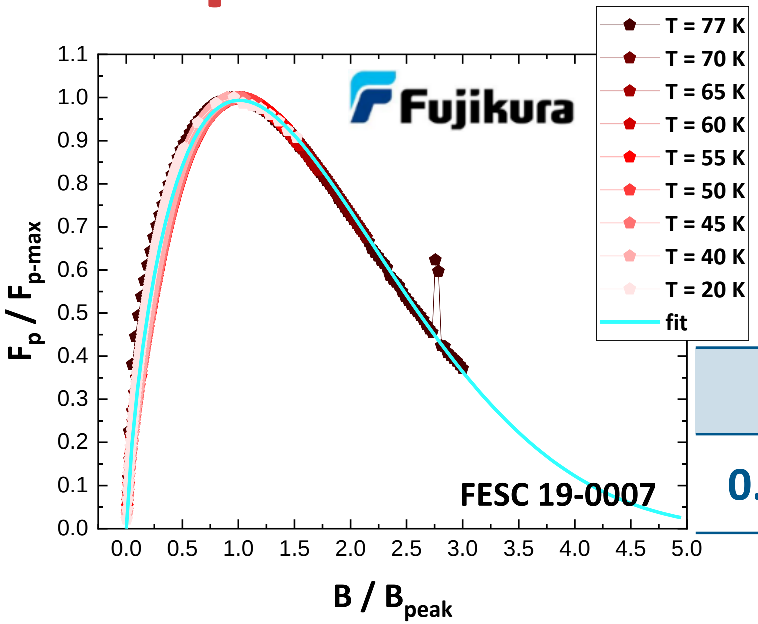
T = 4.2 K



T = 20 K

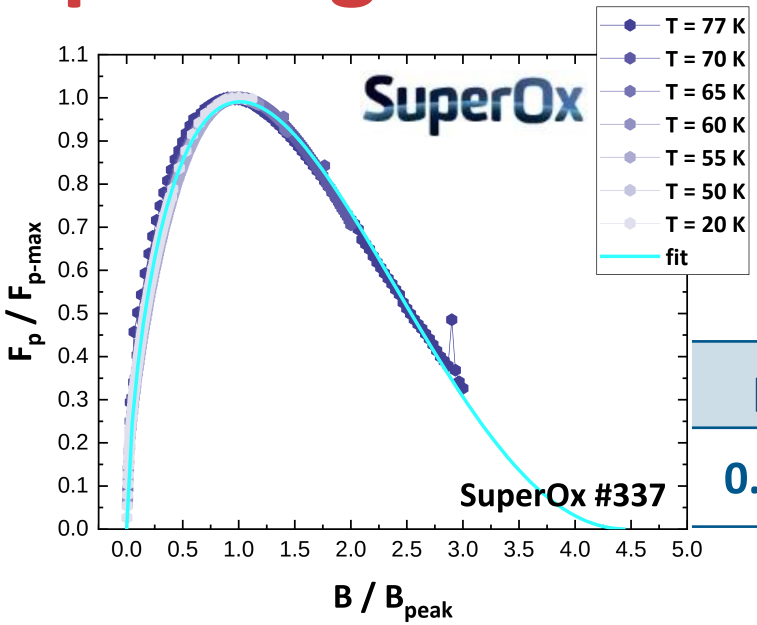


Comparison of the normalized pinning force



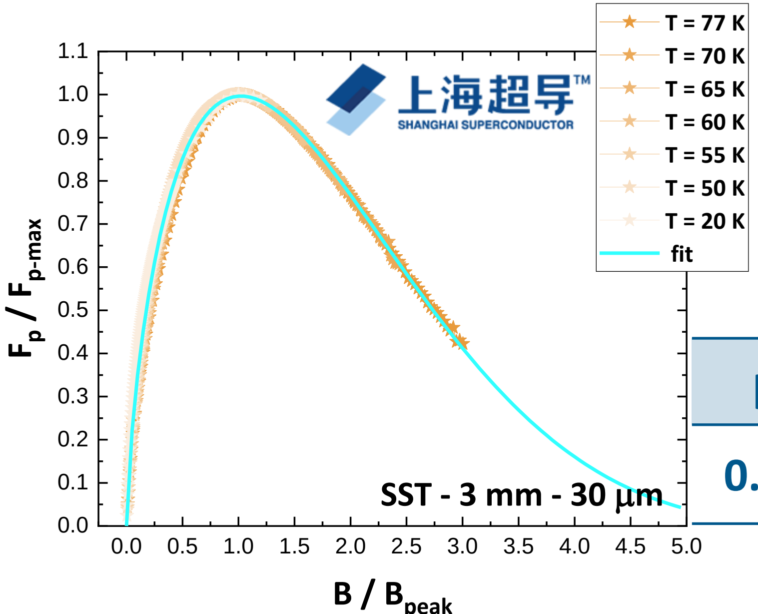
Pinning:
Artificial - BHO columns

p	q
0.77	4.5



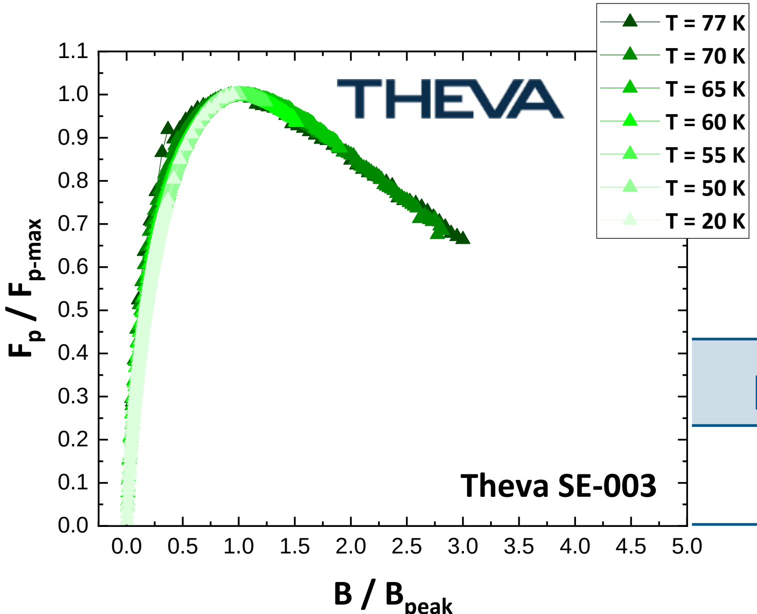
Pinning:
Native – Y_2O_3 particles

p	q
0.64	2.2



Pinning:
Artificial - BHO columns

p	q
0.71	4.4



Pinning:
Native – Gd_2O_3 particles
Artificial – BHO particles

p	q
n/a	

Conclusions

REBCO manufactures are taking on the challenge and the most recent coated conductors are setting the grounds for compact fusion reactors, ultra-high field solenoids and higher field accelerator magnets for future particle physics experiments

In the comparison shown here, the performance gap between various manufacturers is relatively small in spite of the differences in composition and pinning landscape

A temperature scaling of the pinning force is observed but the scaling parameters change substantially from one manufacturer to another. Is it possible to link these variations to the pinning landscape?

Complete datasets covering the entire parameter space are needed to build robust – but probably not universal – scaling laws

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Thank you for the attention !

Carmine SENATORE

carmine.senatore@unige.ch

http://supra.unige.ch

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Comparison of the performance

	I_c/width (4.2K, 19T)	I_c/width (20K, 19T)	α (4.2K) @ B > 10 T	Γ (4.2K, 19T)	T* @ T < 40 K
Fujikura	1094-1218 A/cm	341-460 A/cm	0.75	3.5-3.8	21-23 K
SuperOx	1200 A/cm	590 A/cm	0.63-0.72	n/a	24-26 K
上海超导™ SHANGHAI SUPERCONDUCTOR	930-980 A/cm	340-370 A/cm	0.61-0.66	6.3*	24-26 K
THEVA	884 A/cm**	303 A/cm**	0.46	2.3	30-37 K

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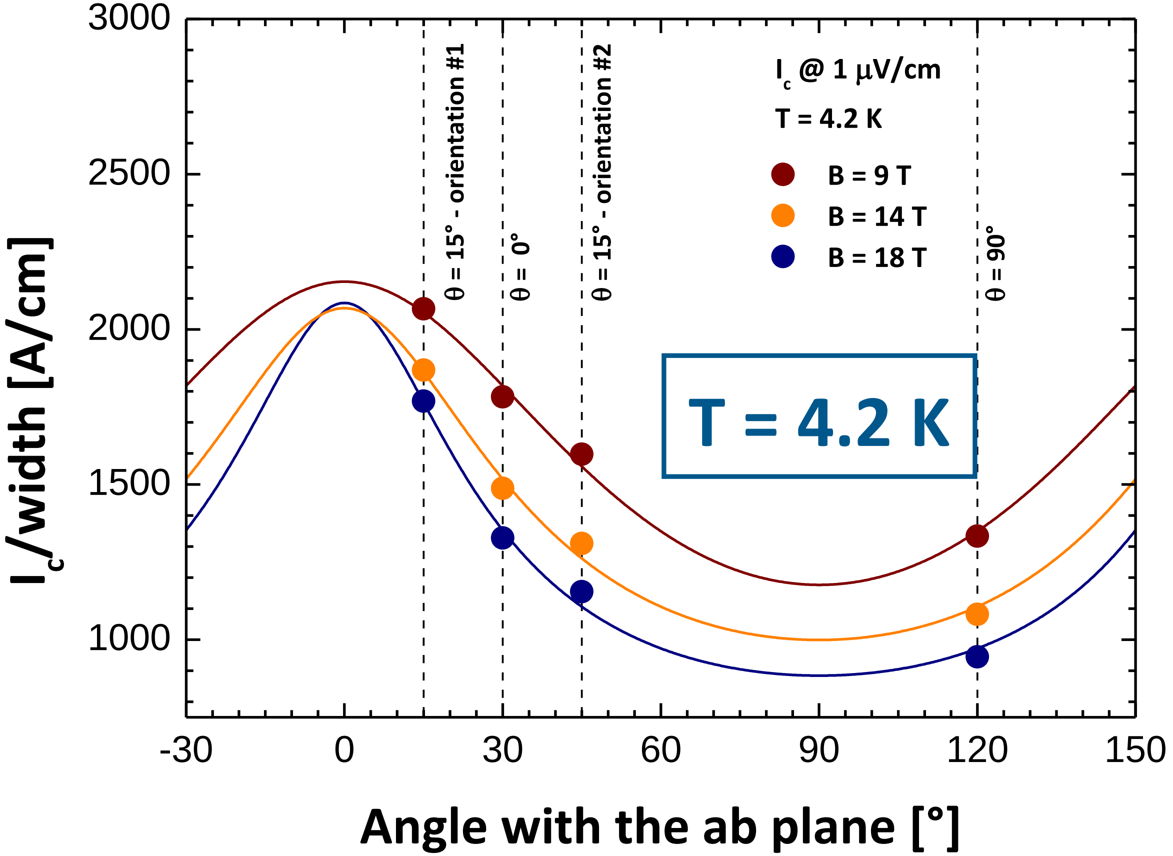
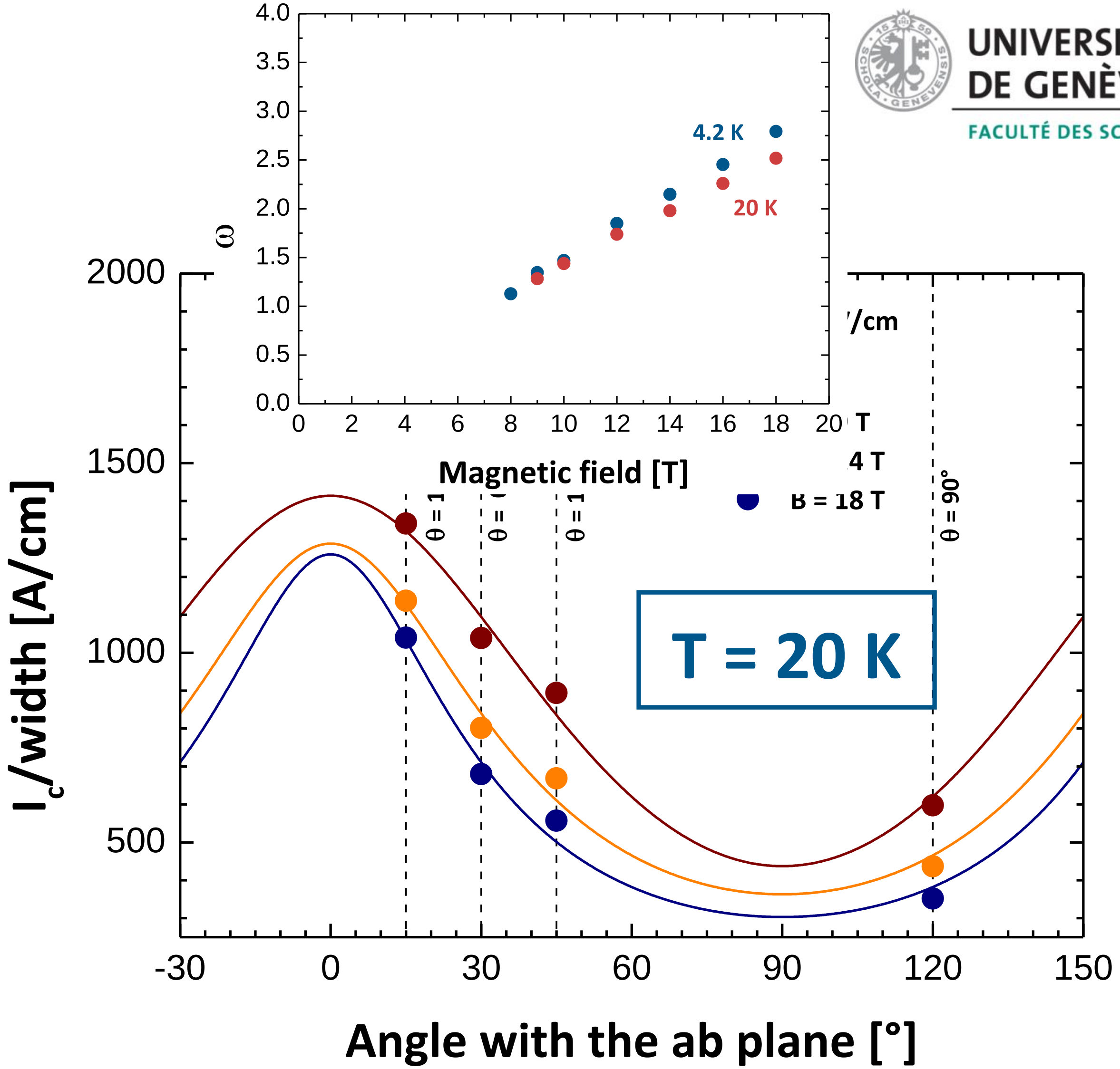
Angular dependence of I_c

Fit performed according to the Hilton model



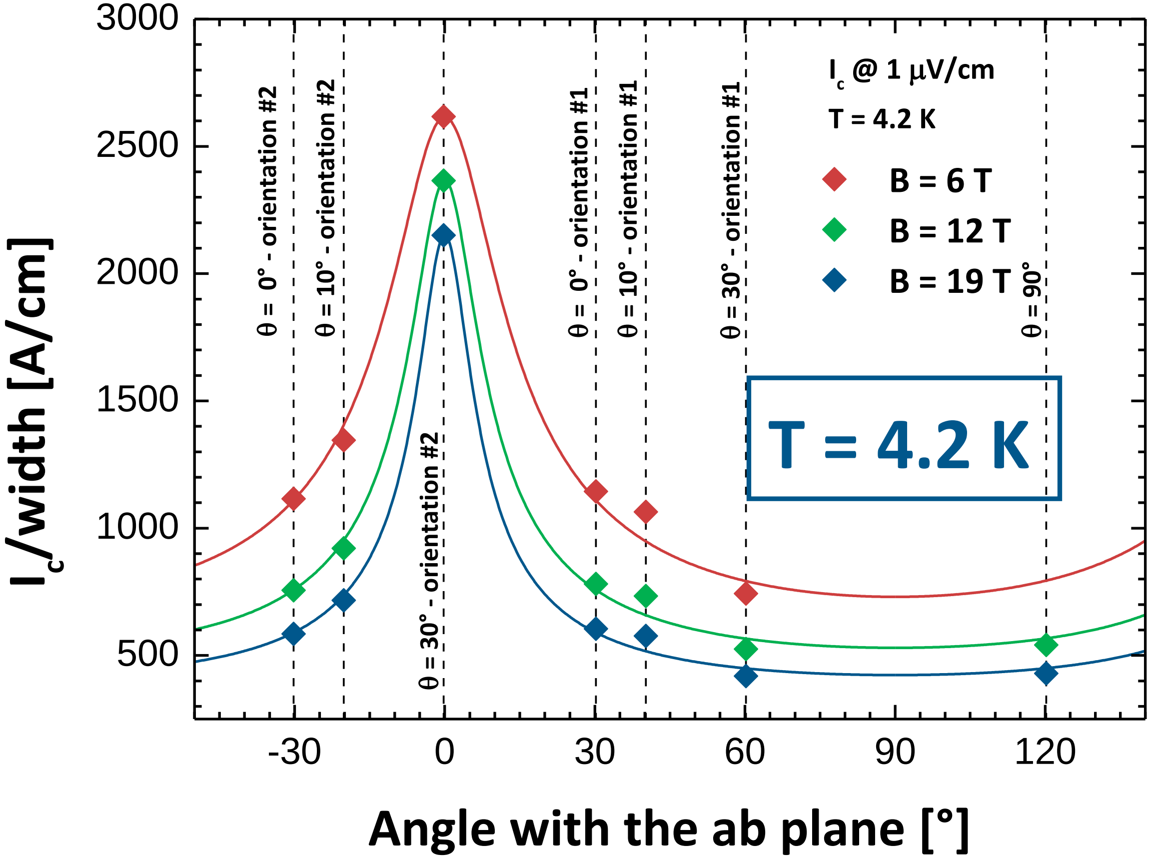


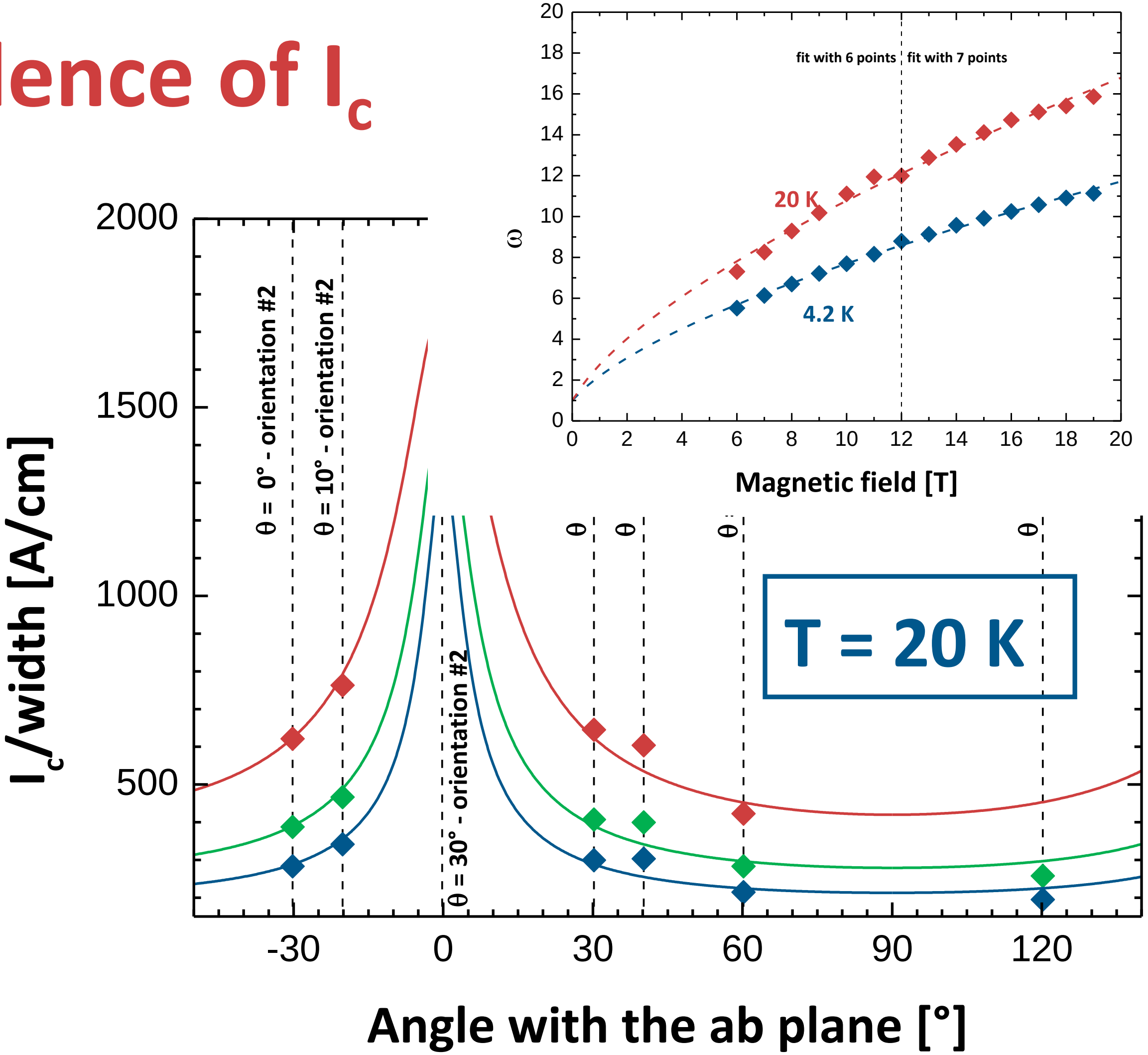
$$I_c(B,\theta) = I_c(B,90^\circ) + \left[I_c(B,0^\circ) - I_c(B,90^\circ)\right]\frac{\omega f(\omega,\theta) - 1}{\omega - 1}$$

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

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

THEVA tapes: Angular dependence of I_c





Maximum at θ_{tape} = 30.2°±0.2°, fit performed according to the Hilton model

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