Angular dependence of the critical current of high performance HTS tapes from various manufacturers

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High Field Laboratory for Superconducting Materials, University of Tohoku, Japan

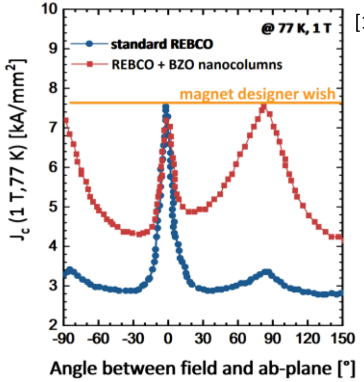
Outline

1. **Context**
2. **Measurement and samples overview**
3. **Comparison of the performances with angular dependence from various manufacturers**
4. **Next steps and conclusions**

1 – Context

Anisotropy of tape design ⟺ tape orientation with respect to $\vec{B}$

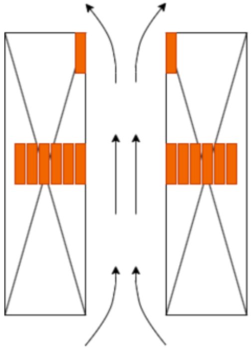
↳ need for a comprehensive dataset of $I_c(B,T,\theta)$ for manufacturers, magnet designers and simulation inputs



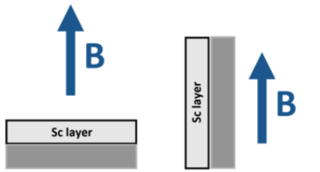
[1]

Pinning (intrinsic and/or artificial) is a way to improve tape performances.

Nowadays, magnet designs are based on the worst $B(\theta)$ configuration near coil ends



All following measurements using this convention



I_c performances of current HTS (especially $\vec{B}$ //) ask for setup and/or sample adaptations

↳ microbridge fabrication

Sample as measured in Geneva

[1] V. Selvamanickam et al, IEEE TAS **21** (2011) 3
10.1109/TASC.2011.2107310

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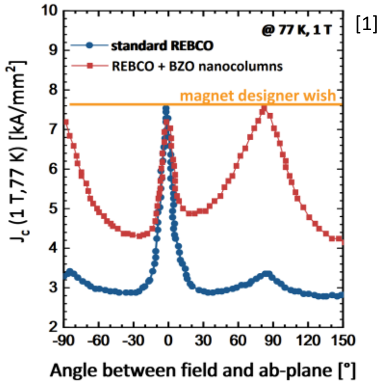

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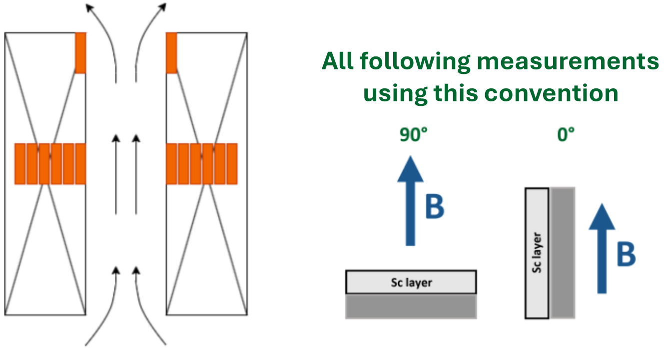

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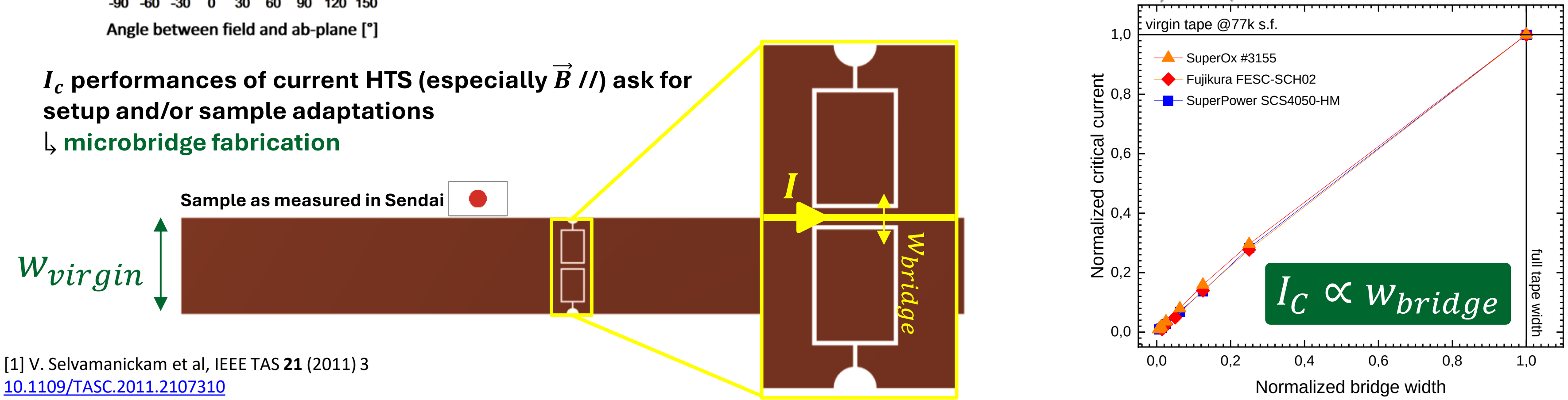

[1] V. Selvamanickam et al, IEEE TAS **21** (2011) 3
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1. Context

2. **Measurement and samples overview**

3. Comparison of the performances with angular dependence from various manufacturers

4. Next steps and conclusions

2 – Measurement and samples overview

2 experimental campaigns conducted in 2024

In Geneva: $I_c(B, \theta, T)$ at specific angles

- **~6+ hours of measurement per sample**
- **1 magnet used: 21T *(measurements limited at 19T)***
- **At 3 temperatures (40K, 20K, 4.2K)**
- **Current up to 2000 A**

+ High input current
+ Fixed angle
- New sample length at each angle

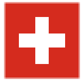
In Sendai: full $I_c(B, \theta, T)$ over -20° ; 115°

- **~15+ hours of measurement per sample**
- **2 magnets used: 15T CSM and 25T CSM *(measurements limited at 24T)***
- **At 6 temperatures (77K, 55K, 40K, 20K, 10K, 5K)**
- **Current up to 20 A**

+ Same sample length along the measurement
+ Wide range of temperatures and fields
- Low input current

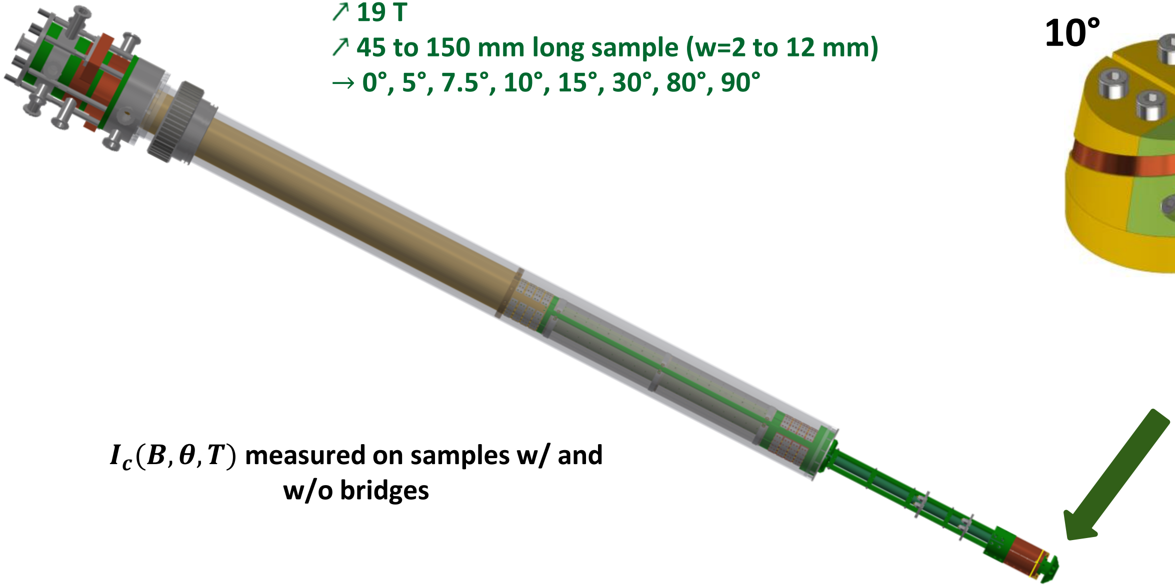
2 – Measurement and samples overview

In Geneva

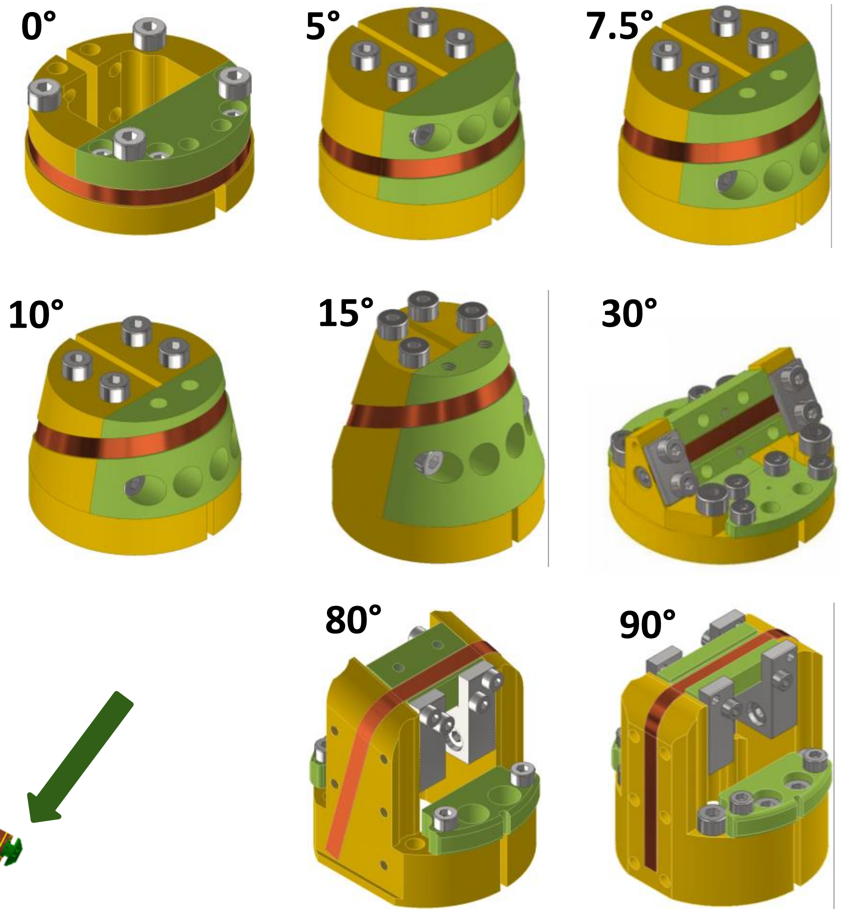


$I_c(B, \theta, T)$ measured at specific angles with dedicated adaptors

↗ 2000 A
↗ 40 K
↗ 19 T
↗ 45 to 150 mm long sample (w=2 to 12 mm)
→ 0°, 5°, 7.5°, 10°, 15°, 30°, 80°, 90°



$I_c(B, \theta, T)$ measured on samples w/ and w/o bridges



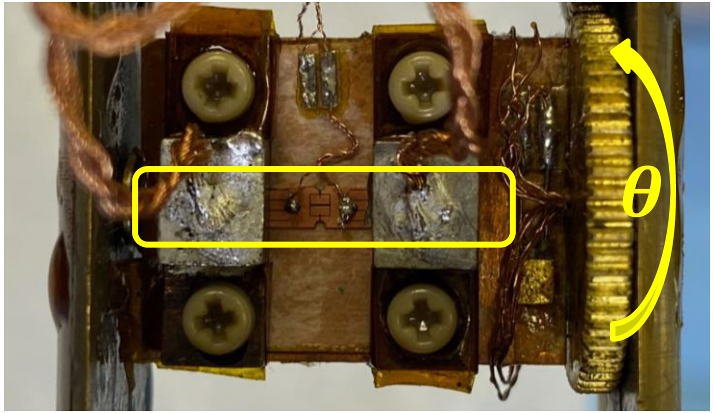
C.Barth et al, IEEE TAS **28** (2018) 4
10.1109/TASC.2018.2794199

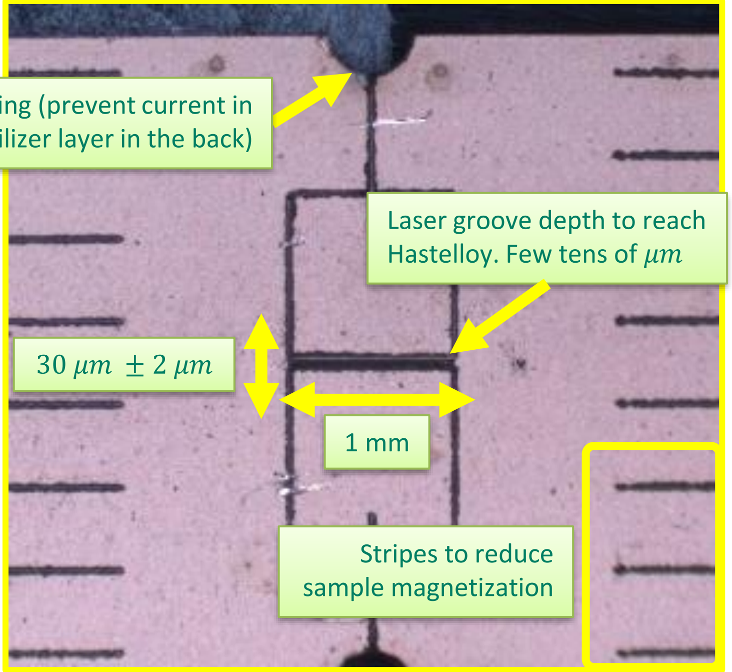
2 – Measurement and samples overview

In Sendai

$I_c(B, \theta, T)$ continuously measured at desired angle and step

- ↗ 20 A
- ↗ 77 K
- ↗ 15 T/24 T
- ↗ 12 mm long sample (w=2 to 4 mm)
- → 20 angles over -20° ; 115°
- → on patterned tapes





Bridges manufactured in Sendai by Yuji Tsuchiya using laser ablation method

Following I_c are expressed in I_c/width

Tohoku University, HFLSM. 25T CSM, 15T CSM superconducting magnets

2 – Measurement and samples overview

Samples procured for Muon Collider collaboration
Characterizations on other samples published in [1]

	Sample width	REBCO + pinning centers	REBCO thickness	Hastelloy thickness	Cu stabilizer (per side)	Nom. bridge width	Nom. bridge length	I_c(77K,s.f.)
Fujikura FESC SCH04	$4\ mm$	EuBCO + BHO nanocolumns	$2.5\ \mu m$	$50\ \mu m$	$10\ \mu m$	$30\ \mu m$	$1\ mm$	$585\ A/cm$
Faraday / SuperOx #3155	$4\ mm$	YBCO + Y_2O_3 particles	$2.5\ \mu m$	$38\ \mu m$	$5\ \mu m$	$30\ \mu m$	$1\ mm$	$420\ A/cm$
SuperPower SCS4050 HM	$4\ mm$	YBCO + BZO nanocolumns	$1.6\ \mu m$	$50\ \mu m$	$10\ \mu m$	$30\ \mu m$	$1\ mm$	$148\ A/cm$
Shanghai Superconductor Technology YP-506	$4\ mm$	EuBCO + BHO nanocolumns	$2\ \mu m$	$50\ \mu m$	$10\ \mu m$	$30\ \mu m$	$1\ mm$	$428\ A/cm$

[1] C. Senatore et al, SuST **37** (2024) 115013
10.1088/1361-6668/ad7f95

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Layer thicknesses

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Various pinning centers

Optimized for HF applications

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Same microbridges prepared

[1] C. Senatore et al, SuST **37** (2024) 115013
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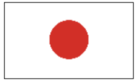
2 – Measurement and samples overview

Angular dependence measured over -20° ; 115° in 

		T = 77K	T = 55K	T = 40K	T = 20K	T = 10K	T = 5K
24 T CSM magnet	**Fujikura** FESC SCH04 **Shanghai Superconductor Technology** YP-506 **SuperPower** SCS4050 HM	1 T 5 T 10 T	1 T 5 T 10 T 12 T 16 T	1 T 5 T 10 T 12 T 16 T 19 T	5 T 10 T 12 T 16 T 19 T 24 T	7 T 10 T 12 T 16 T 19 T 24 T	10 T 12 T 16 T 19 T 24 T
15 T CSM magnet	**Faraday / SuperOx** #3155	1 T 5 T 10 T	1 T 5 T 10 T 15 T	1 T 5 T 10 T 12 T 15 T	5 T 8 T 10 T 12 T 15 T	5 T 8 T 10 T 12 T 15 T	5 T 8 T 10 T 12 T 15 T

2 – Measurement and samples overview

Angular dependence measured over -20° ; 115° in (Japan) **and** (Switzerland)

40K, 20K, 5K at UNIGE up to 19 T

		T = 77K	T = 55K	T = 40K	T = 20K	T = 10K	T = 5K
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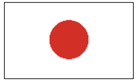
Angular dependence measured over -20° ; 115° in  **and** 

Focus on 40K, 20K, 5K

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15 T CSM magnet	**Faraday / SuperOx** #3155	1 T 5 T 10 T	1 T 5 T 10 T 15 T	1 T 5 T 10 T 12 T 15 T	5 T 8 T 10 T 12 T 15 T	5 T 8 T 10 T 12 T 15 T	5 T 8 T 10 T 12 T 15 T

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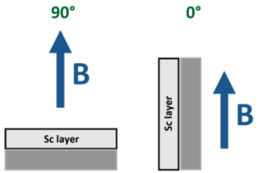
3 – Angular dependence of I_c

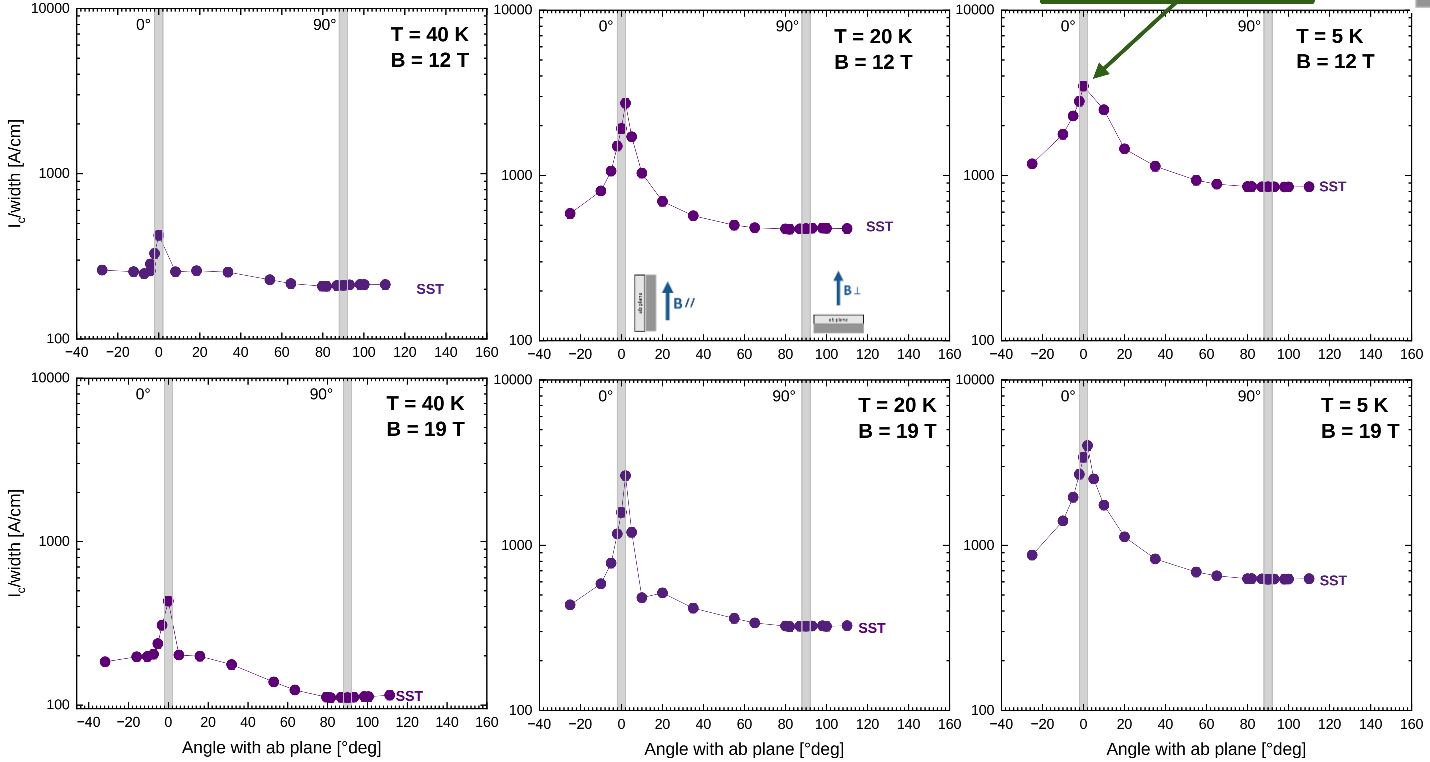
Full angular dependence over -20° ; 115° measured in Sendai



$I_{c\ peak}$ missed due to 20A limitation

T = 40 K

T = 20 K



B = 12 T

B = 19 T

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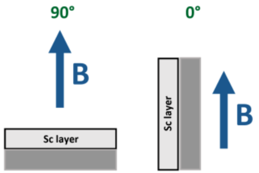

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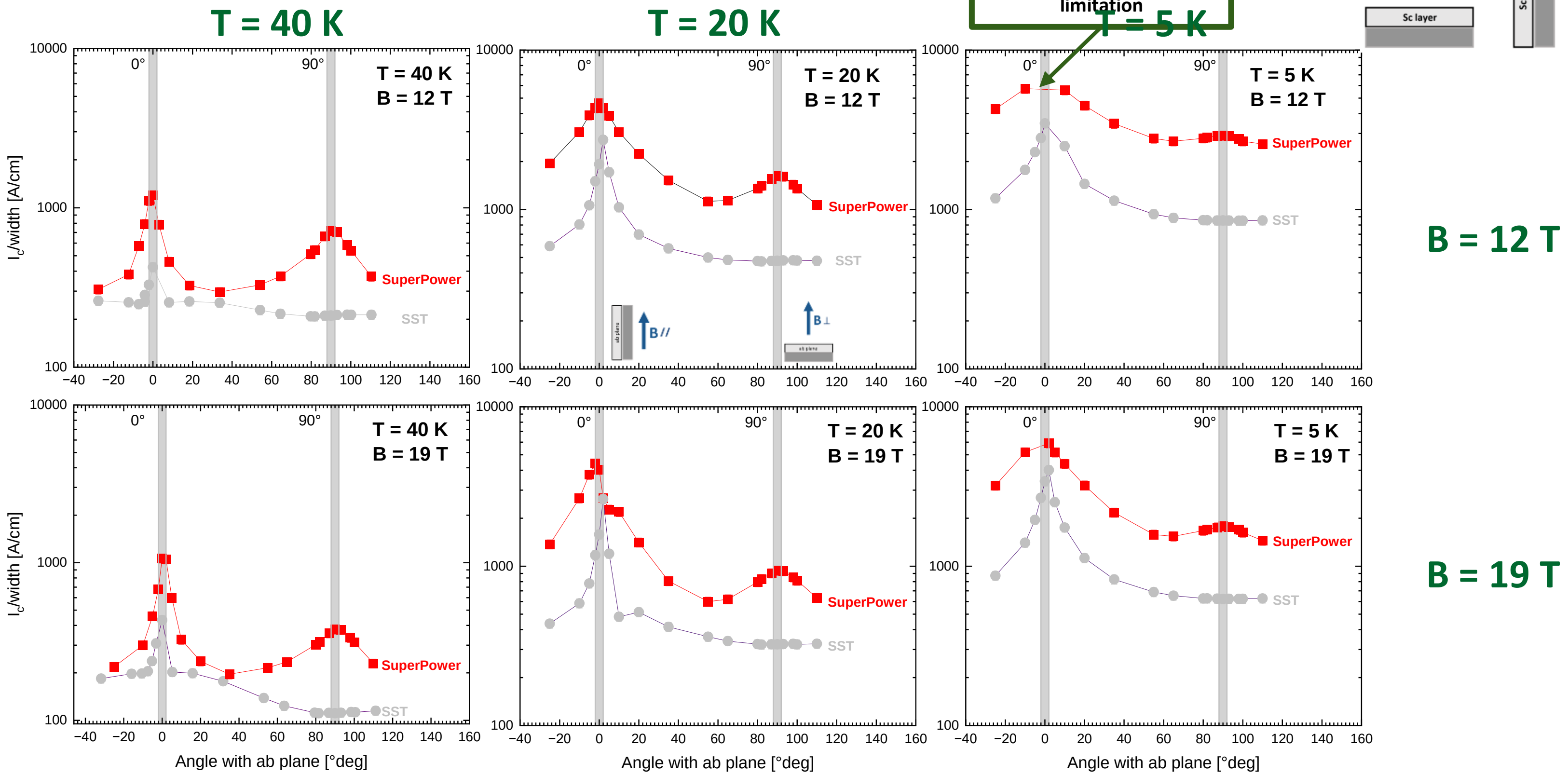

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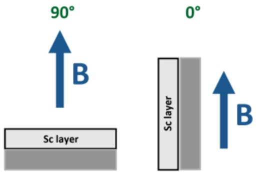

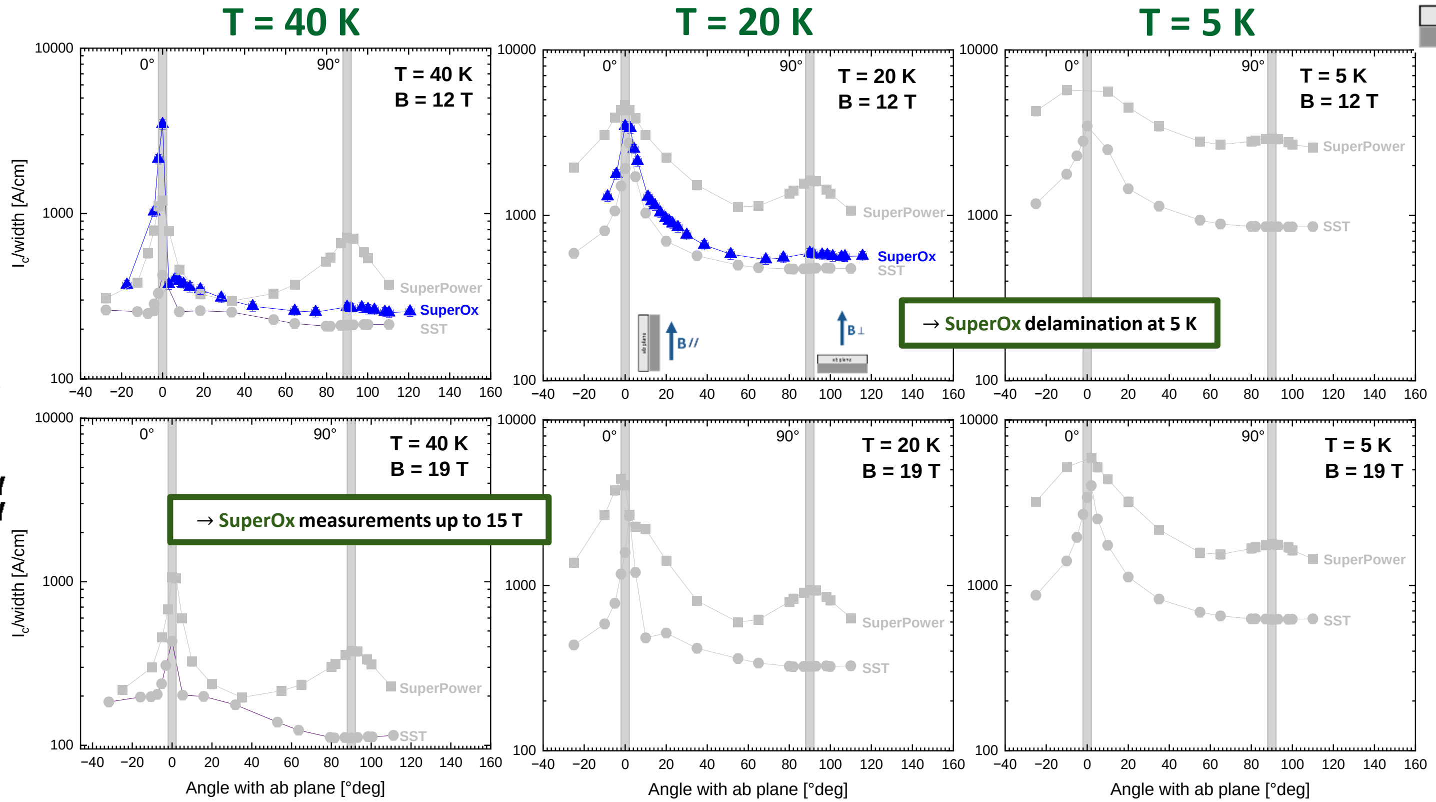

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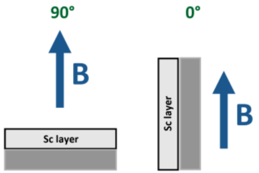
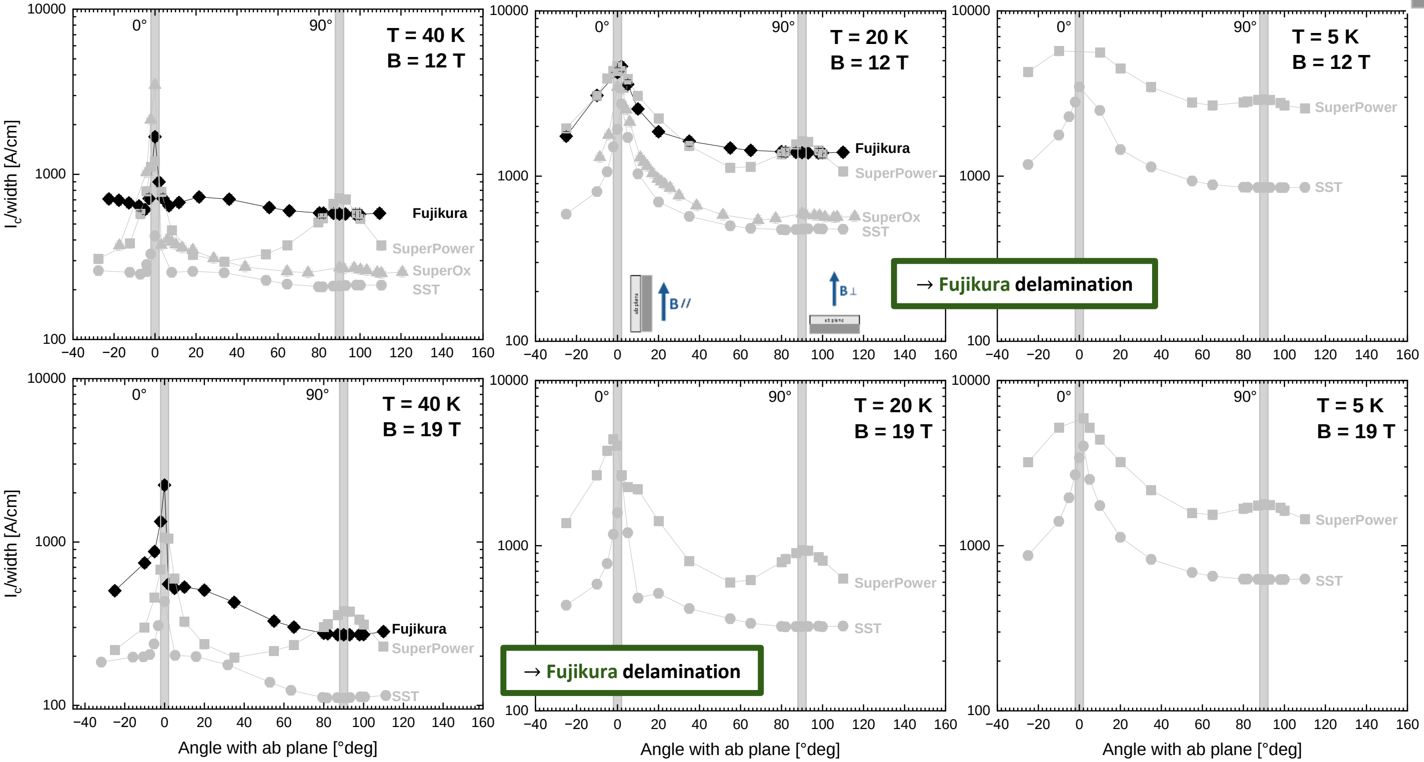


T = 40 K   T = 20 K   T = 5 K



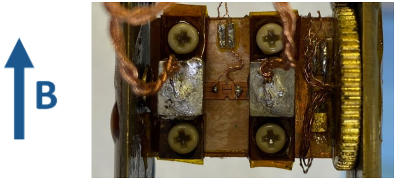
B = 12 T

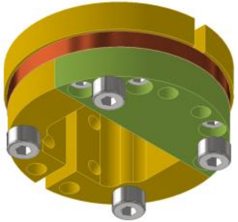
B = 19 T

3 – Angular dependence of I_c

Comparison of the angular dependence measured from fixed angles and in-field rotating angles

Example: $\theta = 0°$ **setup configurations in** 🇯🇵 **vs in** 🇨🇭

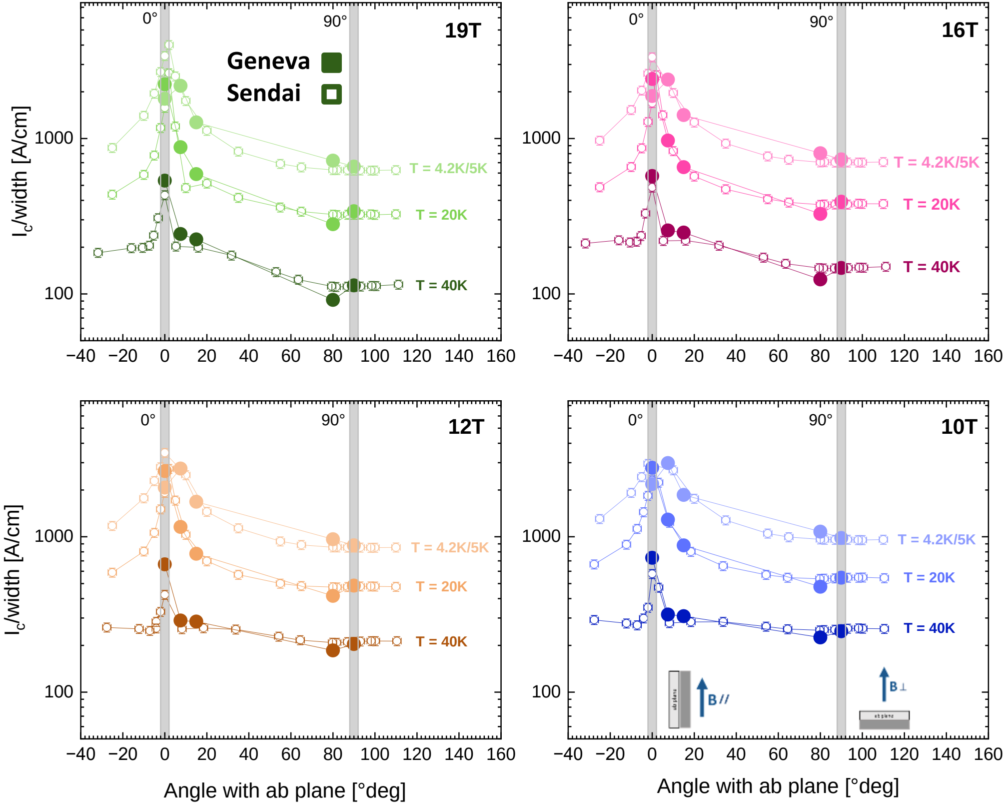




Good agreement between I_c measured in **Geneva** and **Sendai**

Seems to validate
→ **the microbridge approach**
→ **the benefic crosscheck between fixed and in-field rotating angles**

Shanghai Superconductor Technology YP-506



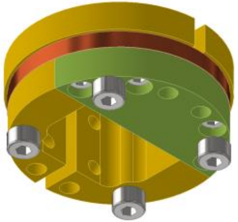
3 – Angular dependence of I_c

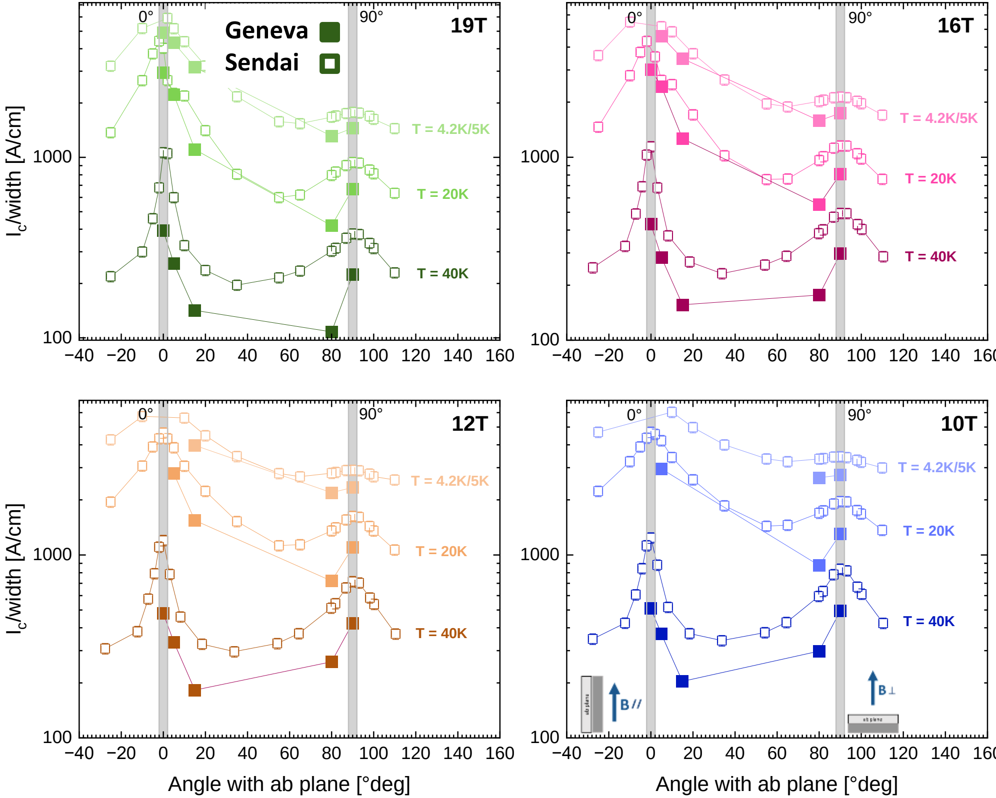
SuperPower SCS4050 HM

Comparison of the angular dependence measured from fixed angles and in-field rotating angles

Example: $\theta = 0°$ setup configurations in vs in

B





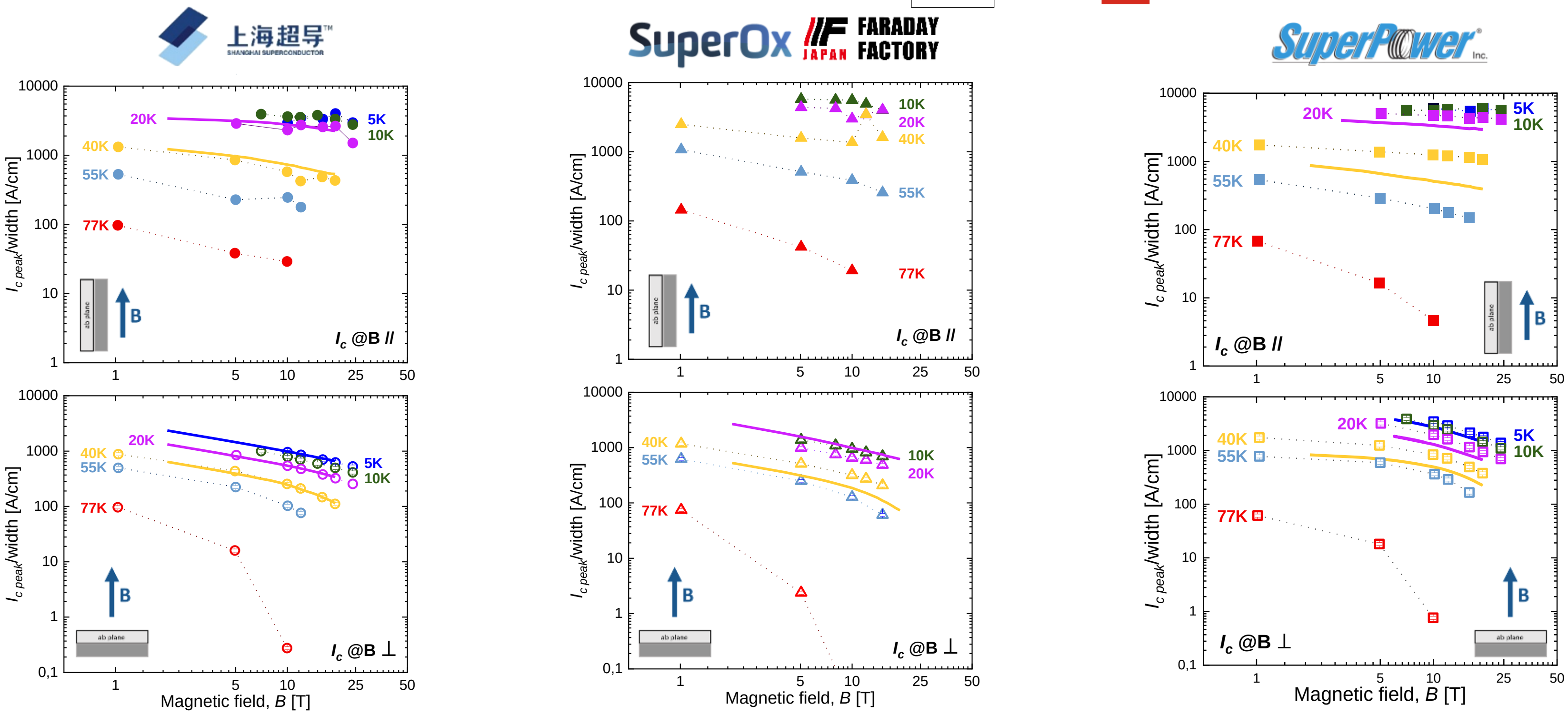
Discrepancies between I_c measured in **Geneva** and **Sendai**

Raise questions about
→ **measurements on full width tapes vs patterned tapes**

3 – Angular dependence of I_c

$I_c(B,T)$ measured at B // and $B\perp$

Comparison of the measurements from (■) and (—)

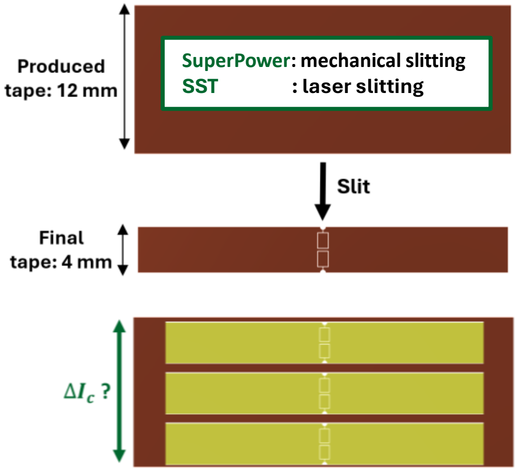


Differences exist and may be related to I_c distribution across tape width (SuperPower and SuperOx)

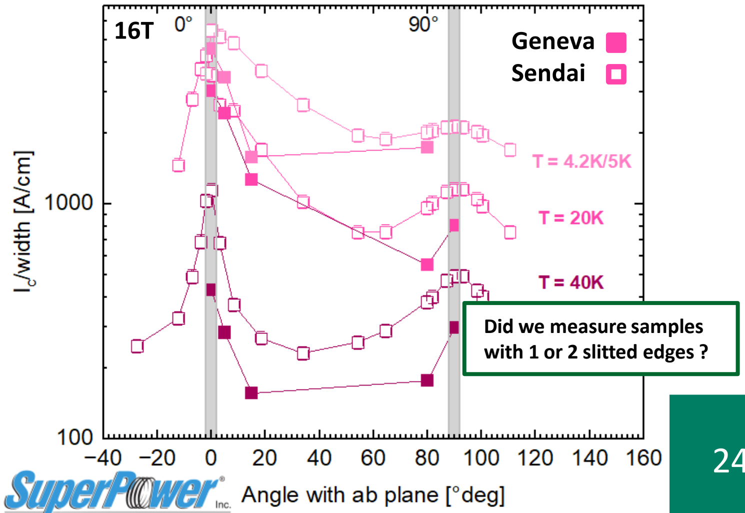
3 – Challenges

Some limitations and challenges remain with the current methods /

- Only specific angles in Geneva
- Sample magnetization → angle uncertainty in Sendai
- Current limited to 20 A in Sendai
  - → micro-bridges fabrication $\sim 30\ \mu m$ → tape delamination
- Slit location from 12 mm to 4 mm



How much $I_c(B,\theta,T)$ varies accross the tape width ?



SuperOx FARADAY FACTORY JAPAN #3155

Critical delamination: (10K, 15T) – (5K, 15T)

Fujikura FESC SCH04

Critical delamination: (20K, 19T) – (10K, 12T)

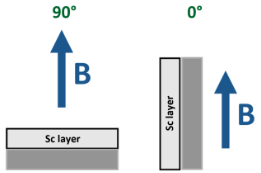
SuperPower SCS4050 HM

Non-critical delamination

3 – Angular dependence of I_c

Anisotropy factor is defined as $\Gamma = I_c^{//}/I_c^{\perp}$ [1]

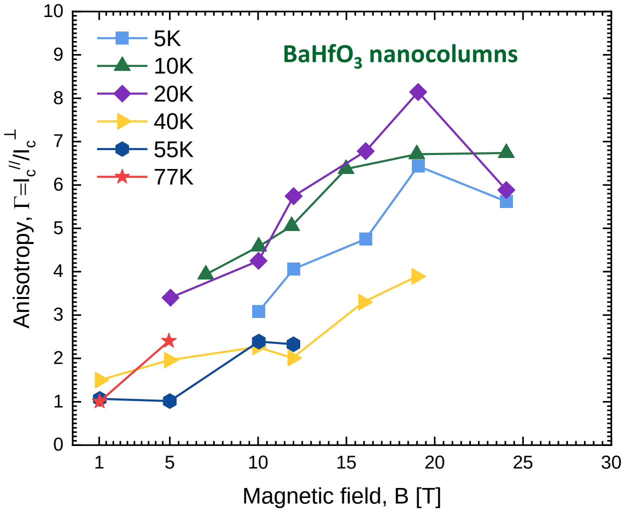
$I_c^{//}$ **not necessary** $I_{c\,max}$
$I_c^{\perp}$ **not necessary** $I_{c\,min}$

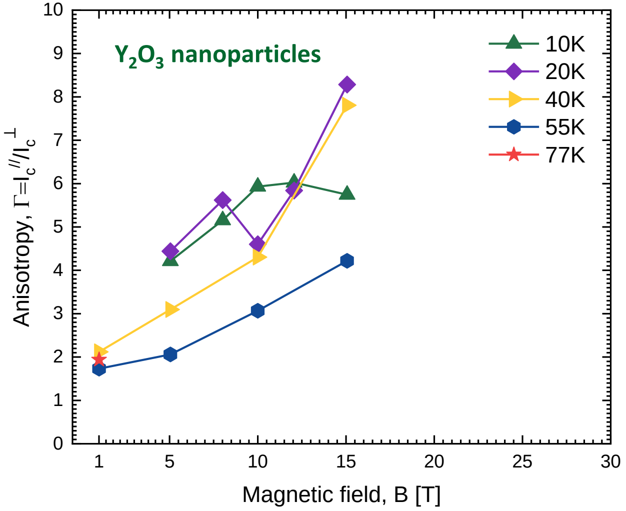


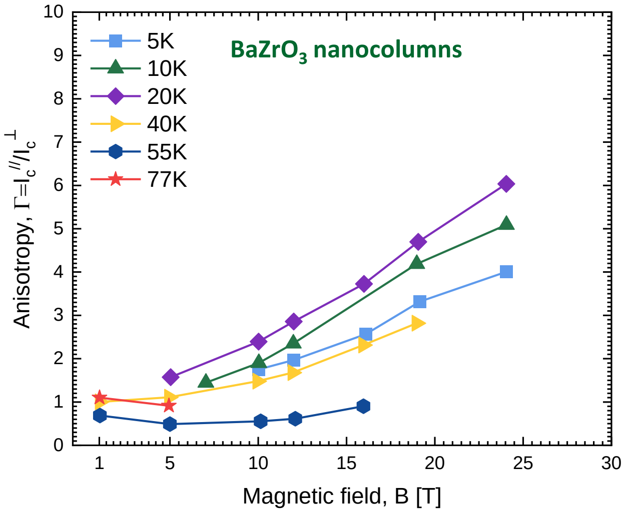
上海超导™ SHANGHAI SUPERCONDUCTOR

SuperOx FARADAY FACTORY JAPAN

SuperPower Inc.







$\Gamma \propto B$
$\Gamma \propto 1/T$
Various Γ values ⇔ various pinning landscapes

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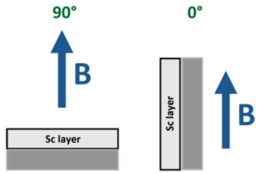
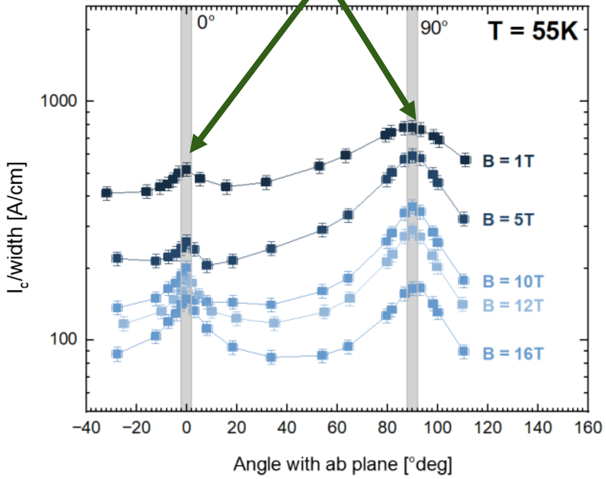
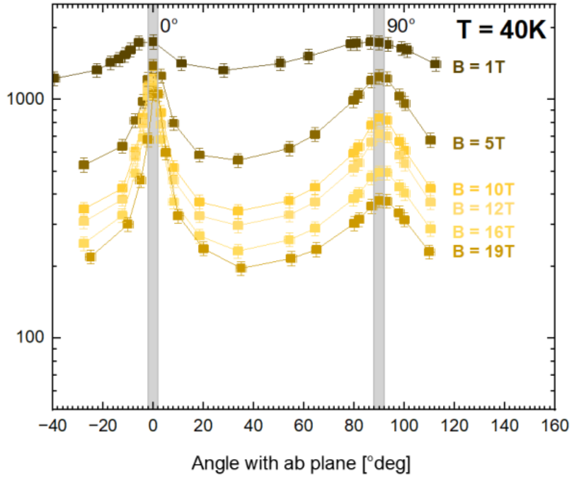
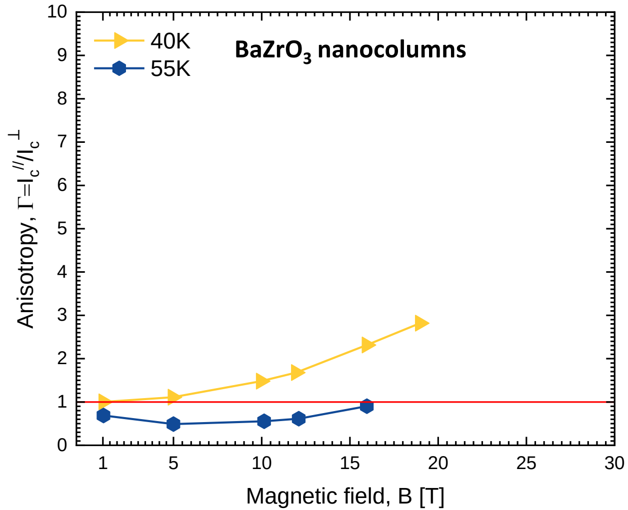


SuperPower Inc.

$I_c^{//} < I_c^{\perp}$



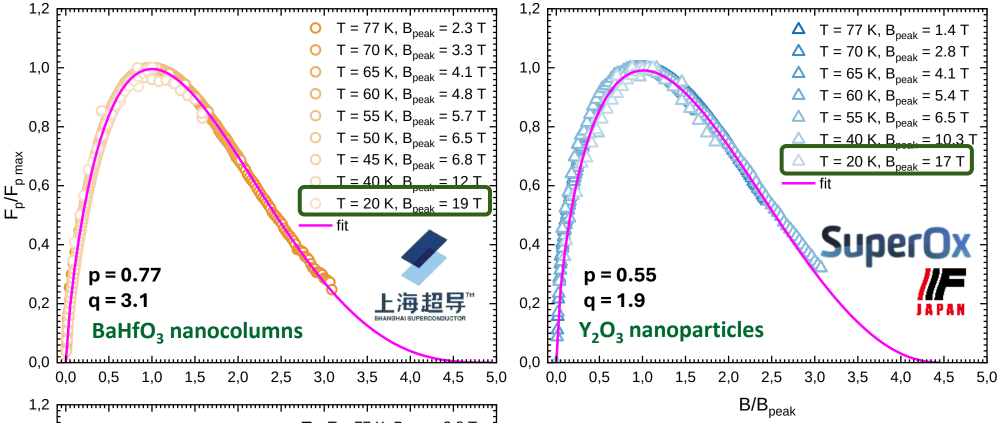


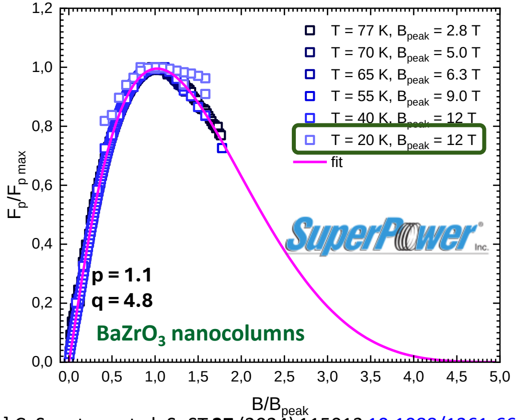


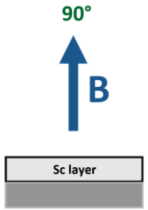
→ **lower** $\Gamma(B)$ **slope due to the two peaks at 0° and 90°**

[1] C. Senatore et al, SuST **37** (2024) 115013
10.1088/1361-6668/ad7f95

3 – Pinning force







Combination of transport and magnetic measurements

The pinning force is defined as

$$F_p(B,T) = I_c(B,T) \times B$$

and fitted using Dew-Hughes scaling [2]

$$F_p(B,T) \propto \left(\frac{B}{B_{peak}}\right)^p \left(1 - \frac{B}{B_{peak}}\right)^q$$

Various B_{peak} values at a given T ⇔ various pinning landscapes

The observed scaling behavior (when $B\perp$) of the pinning force implies that there is an analytical description of $I_c(B,T)$ holding over a wide range of temperatures and fields [1]

[1] C. Senatore et al, SuST **37** (2024) 115013 10.1088/1361-6668/ad7f95
[2] Dew-Hughes, Phil Mag 30 (1974) 293-305 10.1080/14786439808206556

3 – Comparison of the performance: non-Cu J_c

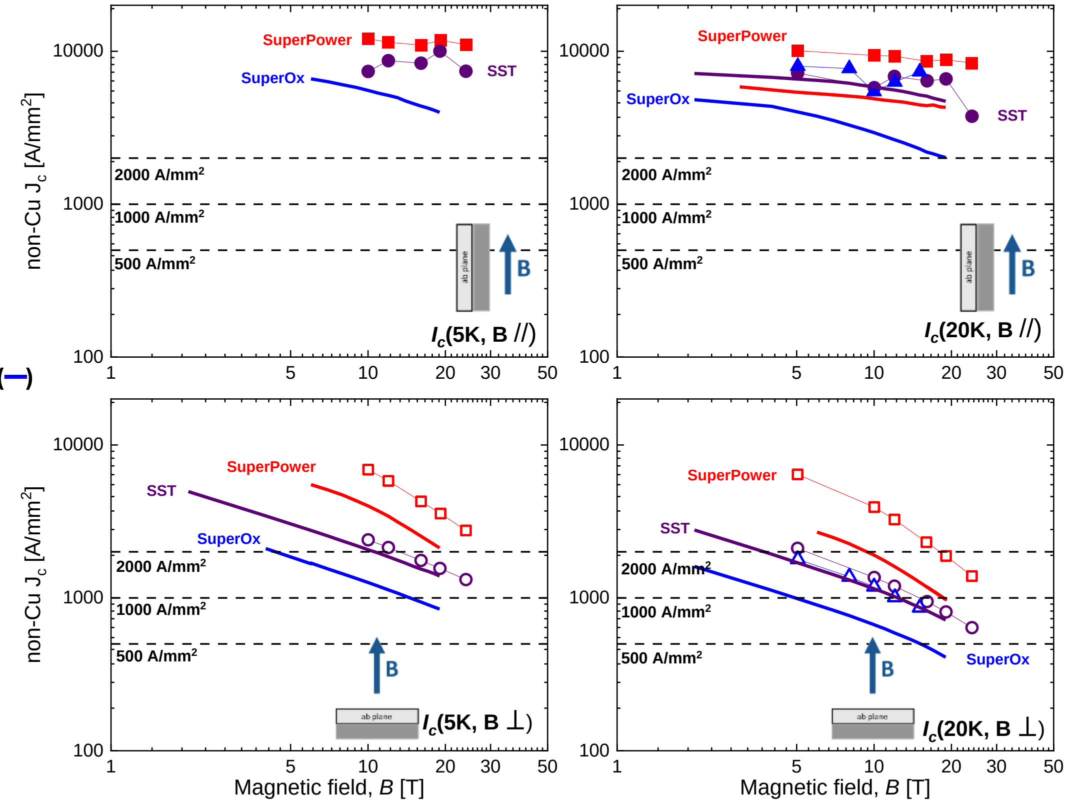
The non-Cu J_c is defined over the total tape cross-section (Hastelloy, buffer, Ag, Sc) minus the Cu

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

Comparison of the measurements from [Japanese flag] (■,□) and [Swiss flag] (—)

Differences exist and may be related to I_c distribution accross tape width (SuperPower) and in coming delamination at 10K (SuperOx)

non-Cu J_c	T = 5 K	T = 20 K
B //	$> 5\,000\ A/mm^2$	$> 2\,000\ A/mm^2$
$B \perp$	$> 1\,000\ A/mm^2$	$> 500\ A/mm^2$



1. Context
2. Measurement and samples overview
3. Comparison of the performances with angular dependence from various manufacturers
4. **Next steps and conclusions**

4 – New $I_c(B, \theta, T)$ probe development

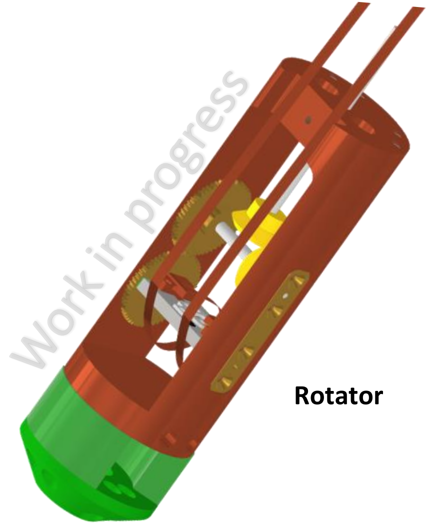
Objective: combine the best of current setups
combine fixed and in-field rotating angles measurements

UNIGE aimed performances

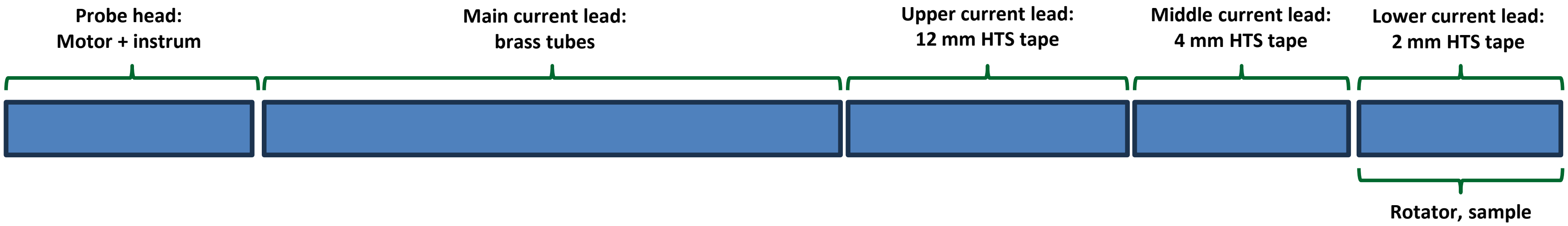
↗ ~200 A
↗ 40 K (4.2K, 10K, 20K, 40K)
↗ 19 T/21 T
↗ 32.5 mm long sample (w=2 to 4 mm)
→ n angles over 180°
→ on patterned tapes

Tohoku University current performances

↗ 20 A
↗ 77 K (5K, 10K, 20K, 40K , 55K , 77K)
↗ 25 T
↗ 12 mm long sample (w=2 to 4 mm)
→ n angles over 180°
→ on patterned tapes



Block schematic of the probe:
→ Easy mounting w/o soldering
→ Hall probe sensor for calibration



4 – Conclusion

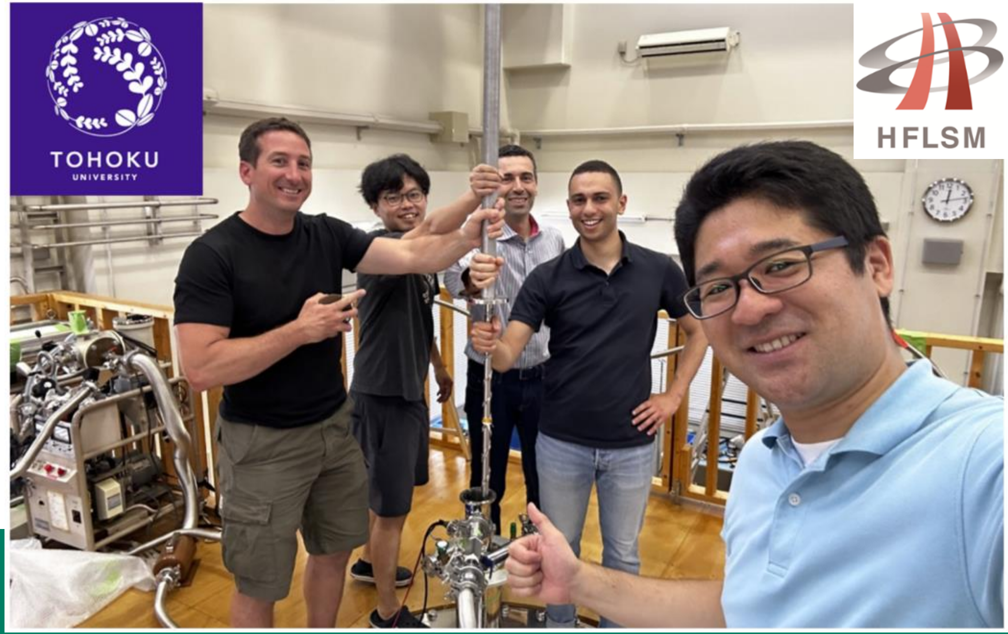
- **Strong performance variations over the -20° ; 115° range between the different manufacturers.**
  → Is it possible to link these variations to the pinning landscape ?

- **These measurements may offer a valuable dataset of $I_c(B,\theta,T)$ from various high performance HTS for magnet designers and manufacturers.**

- **Relevancy of measuring $I_c(B,\theta,T)$ with different setups and methods**
  → However, how much $I_c(B,\theta,T)$ varies across the tape width ?
  → How to mitigate delamination ?

- **New $I_c(B,\theta,T)$ probe under development at the University of Geneva to measure patterned HTS tapes up to 200 A with sample width from 2 to 4 mm.**

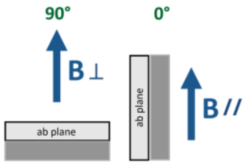
Thank you for your attention



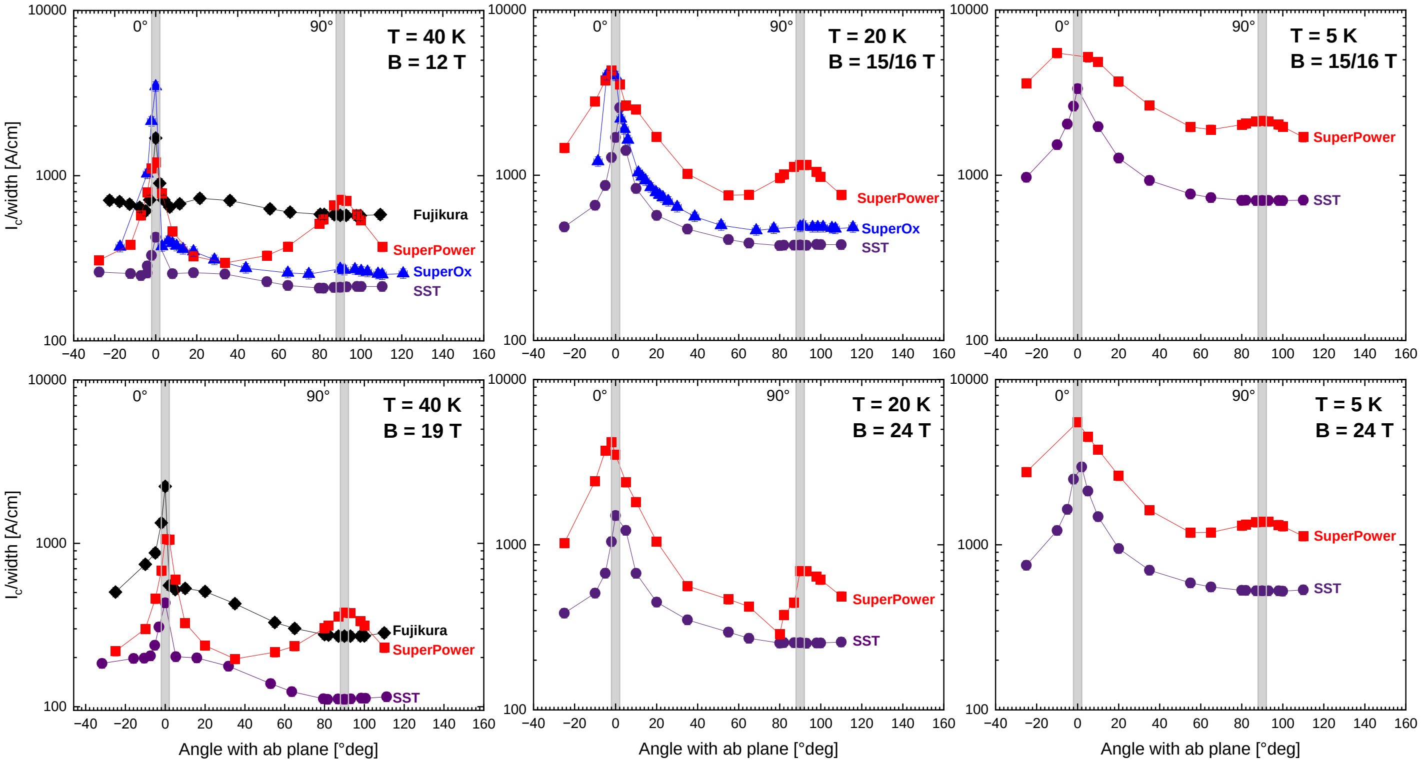
Appendix

3 – Angular dependence

Full angular dependence over -20° ; 115° measured in Sendai



T = 40 K | T = 20 K | T = 5 K

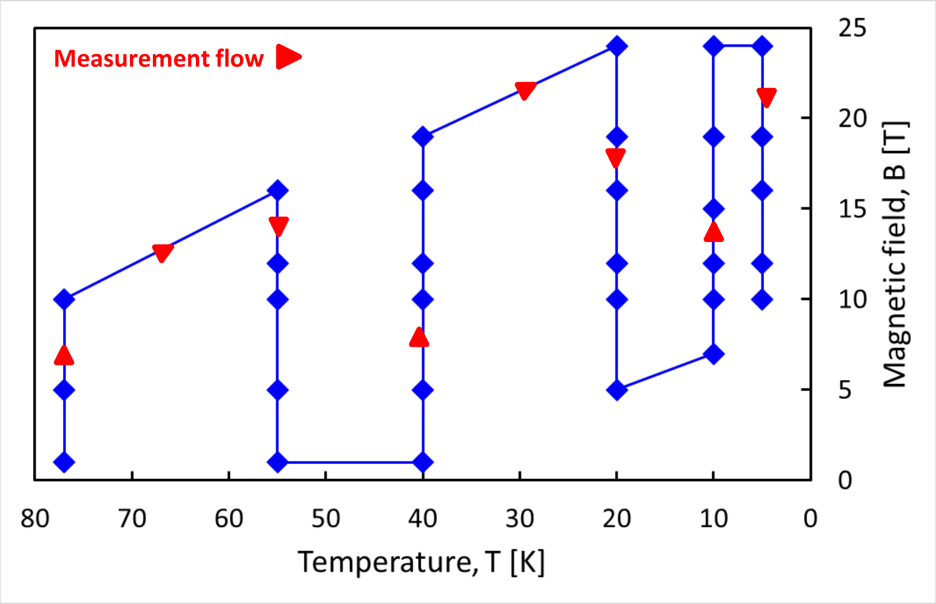


B = 12 T

B = 19 T

3 – Angular dependence

On the 25 T CSM magnet



On the 15 T CSM magnet