Practical considerations on the use of $J_c(B,\theta)$ in numerical models of the electromagnetic behavior of HTS

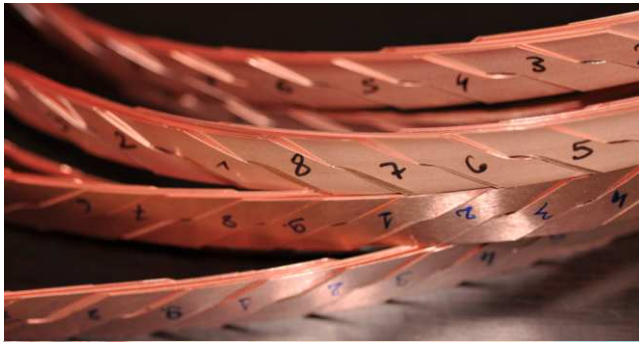
Francesco Grilli and Víctor M. R. Zermeño

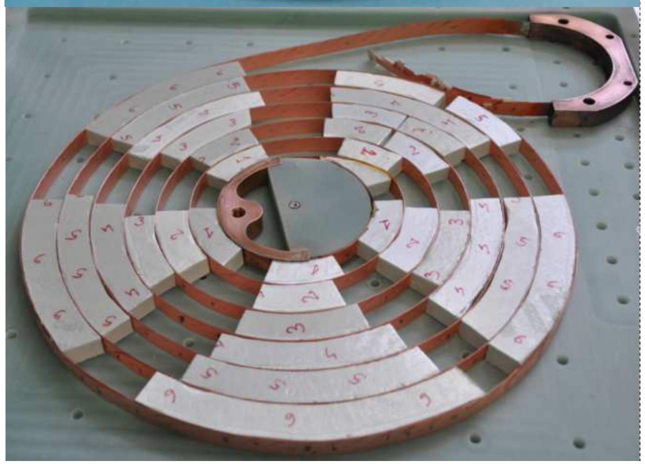
Karlsruhe Institute of Technology, Institute for Technical Physics, Germany

francesco.grilli@kit.edu

Motivation

Given a tape with known $I_c(B,\theta)$, how can we calculate the effective critical current of devices (cables, coils) made of that tape?



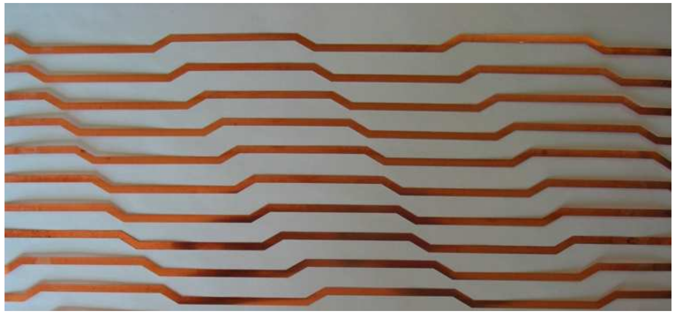


Picture sources:
Univ. Houston
Daibo et al. 10.1109/TASC.2011.2179691

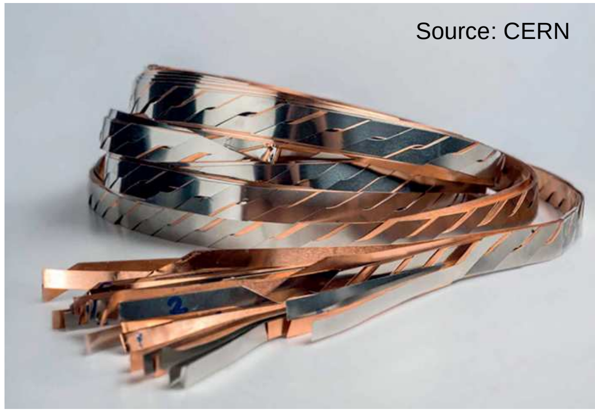
Example: Roebel cable

Tape, I_c=340 A

77 K, self-field



Strand, I_c=150 A



10-strand cable, I_c=?

10 x 150 = 1500 A?

No, 1000 A!

33 % self-field reduction

We need a tool to predict this value!

Let's start from the model for calculating I_C.

- The model solves Ampere's law in terms of **A**

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} = \mathbf{J}$$

- In the asymptotic limit t → ∞ from Faraday's equation

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla V \quad \Longrightarrow \quad \mathbf{E} = -\nabla V$$

- In the 2-D approximation, the scalar variable **E**
  - represents the voltage drop (per unit length)
  - must be constant in each conductor
- Superconductor simulated with power-law resistivity

$$E = E_c \frac{J}{J_c(\mathbf{B})} \left| \frac{J}{J_c(\mathbf{B})} \right|^{n-1}$$

Reference: Zermeno *et al.* 2015 SuST **28** 085004

How does the model work?

- Inversion of the *E*-*J* relationship

$$E = E_c \frac{J}{J_c(\mathbf{B})}\left|\frac{J}{J_c(\mathbf{B})}\right|^{n-1}$$

$$\begin{cases} J = J_c(\mathbf{B})P \\ P = \frac{E}{E_c}\left|\frac{E}{E_c}\right|^{\frac{1}{n}-1} \end{cases}$$

- If I_a is the transport current flowing in the i-th conductor, one has

$$I_a = \int_{\Omega_i} P_i J_c(\mathbf{B})\, d\Omega_i$$

$$P_i = I_a \Big/ \int_{\Omega_i} J_c(\mathbf{B})\, d\Omega_i$$

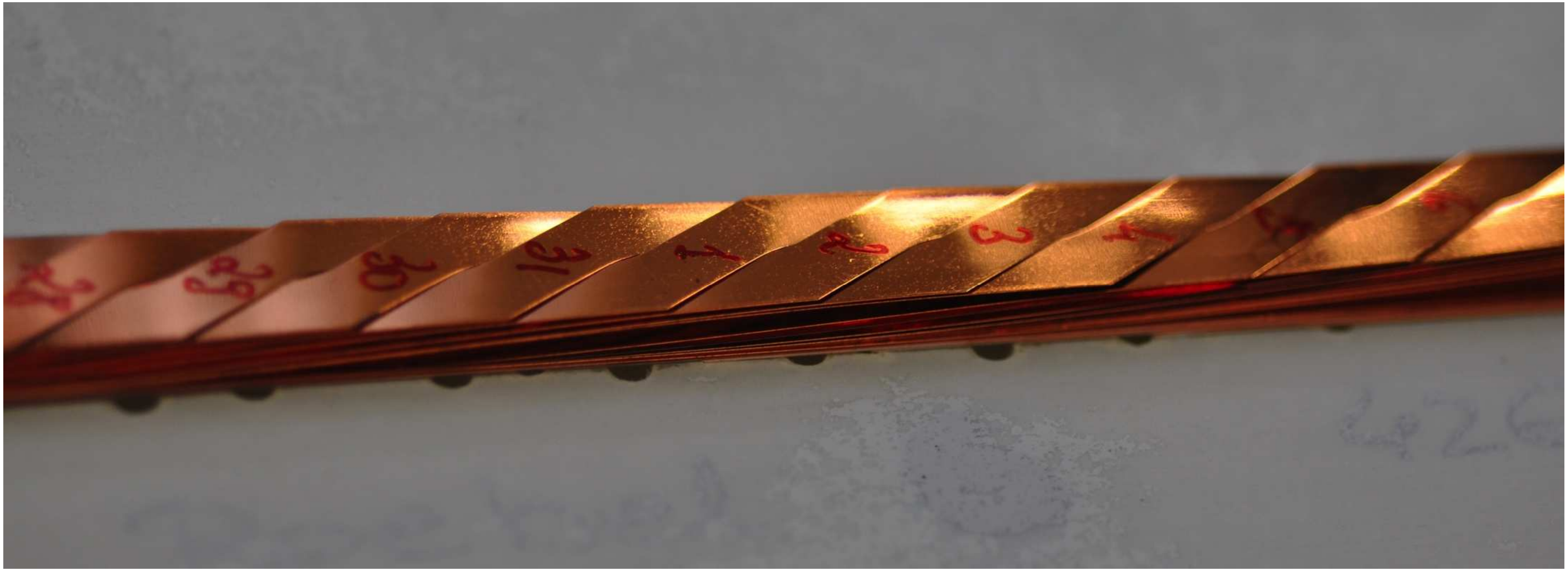
- And the voltage drop per unit length E_i in the i-th conductor

$$E_i = E_c P_i |P|^{n-1}$$

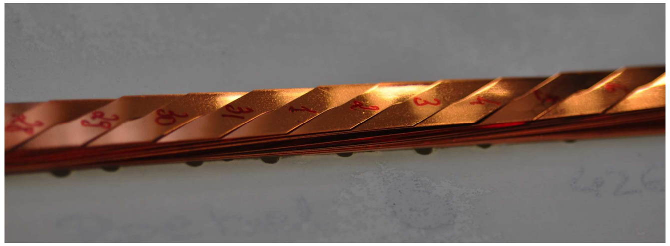
Test of the model against experimental data

Main features of the Roebel cables assembled at KIT

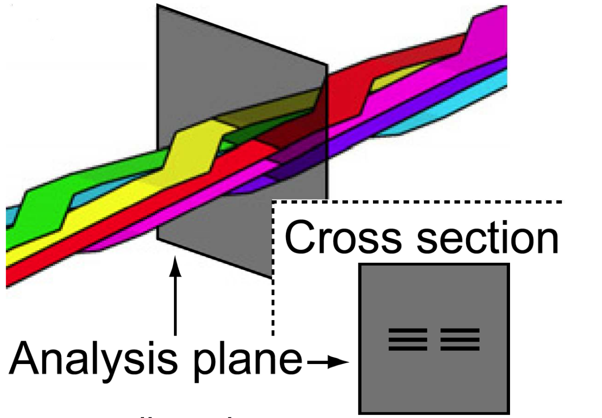
- 3 designs: 10, 17, 31 strands, transposition length 126, 226, 426 mm
- 12 mm tapes from two manufacturers: SuperOx and SuperPower
- 3 sizes x 2 manufacturers = 6 cables in total
- Length: 2.5 x transposition length



How to define the critical current of a Roebel cable?



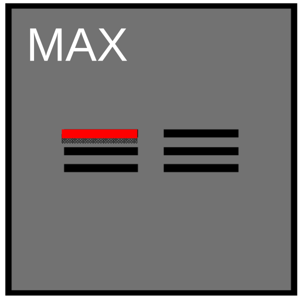
2-D calculation



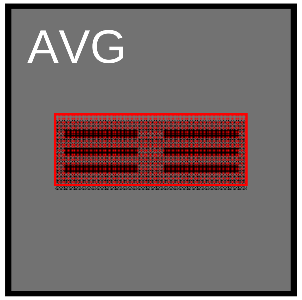
Source: Nii *et al.* 2012 SuST **25** 095011

Two possible criteria:

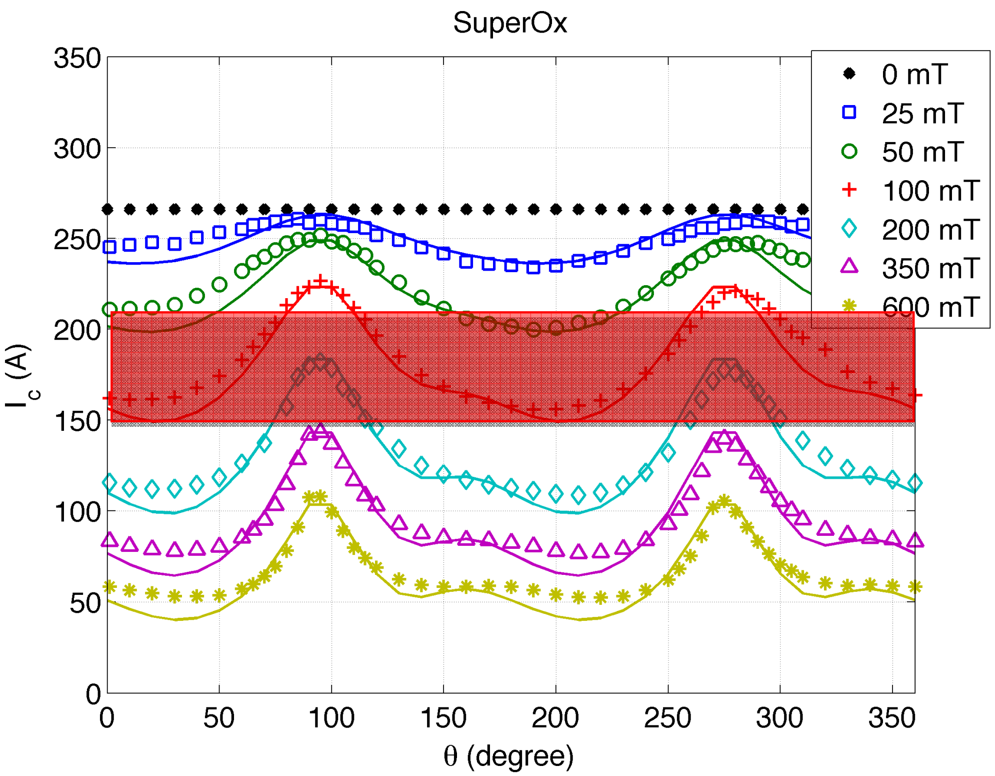
1. Current at which $E=E_c$ in at least one conductor (MAX criterion)

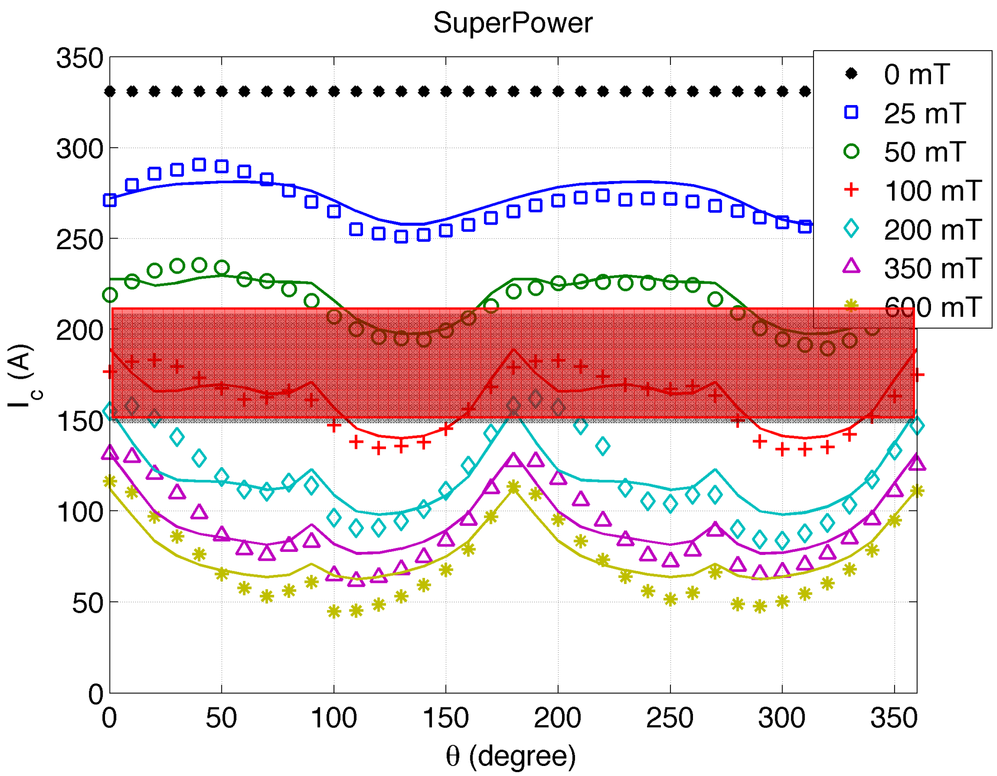


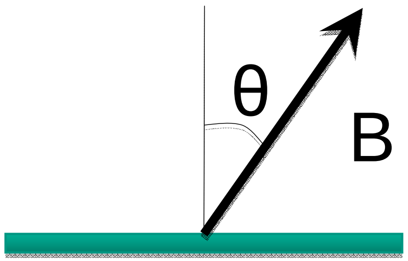
2. Current at which $E_{AVG}=E_{\mathrm{c}}$ (AVG criterion)



The starting tapes have very different $I_c(B,\theta)$.

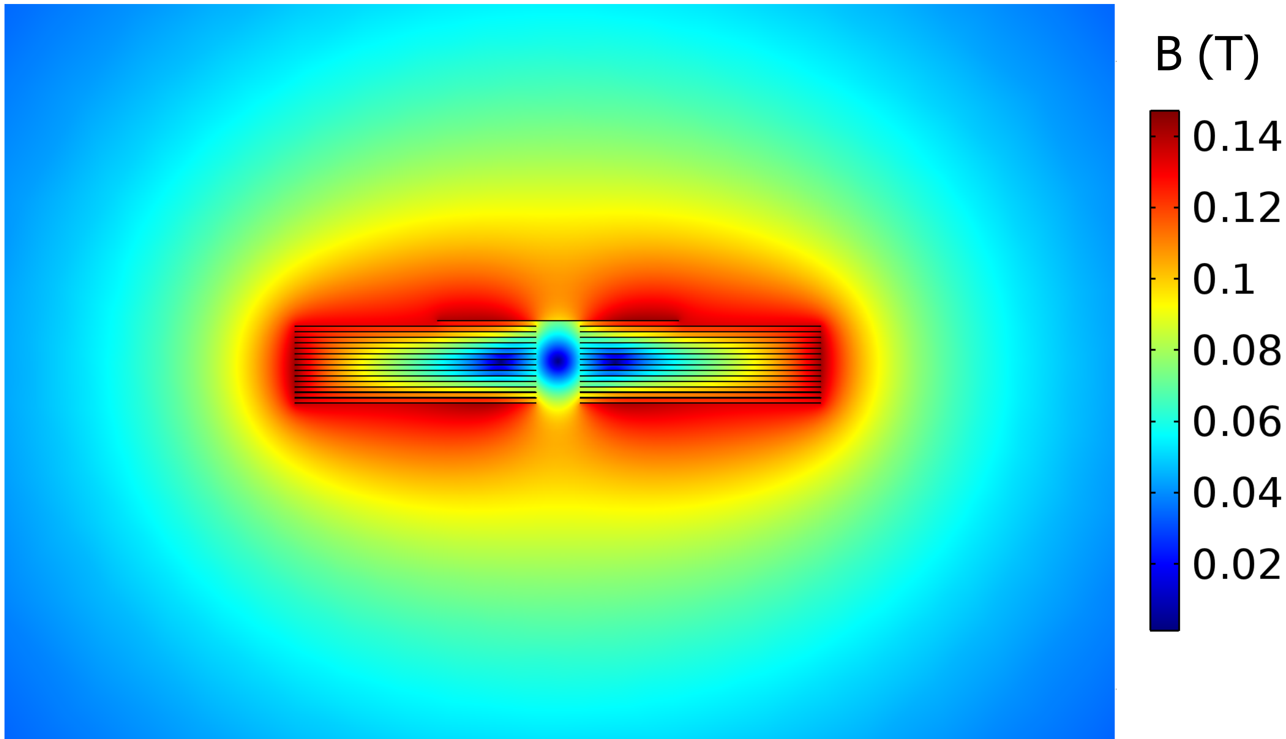




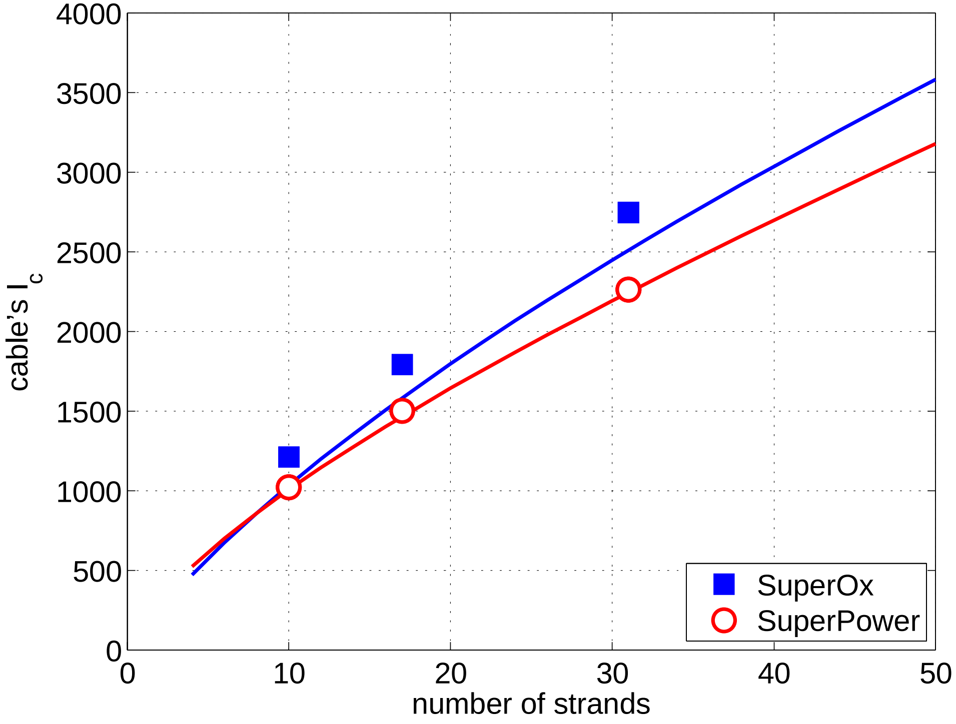


The in-field behavior determines the cable's I_c.

Sample (31 strands)	Measured I_c	(# of strands) x (I_c of the strands)
SuperOx	2747 A	3999 A
SuperPower	2264 A	4247 A



Measured and computed I_c values agree within 9 %



For SuperOx, the sample used for $J_c(B,\theta)$ was a below-average one.

For SuperPower, it was very close to average.

Statistics on I_c of 20 strands

SuperOx: mean=140 A, σ=10 A

SuperPower: mean=147 A, σ=7 A

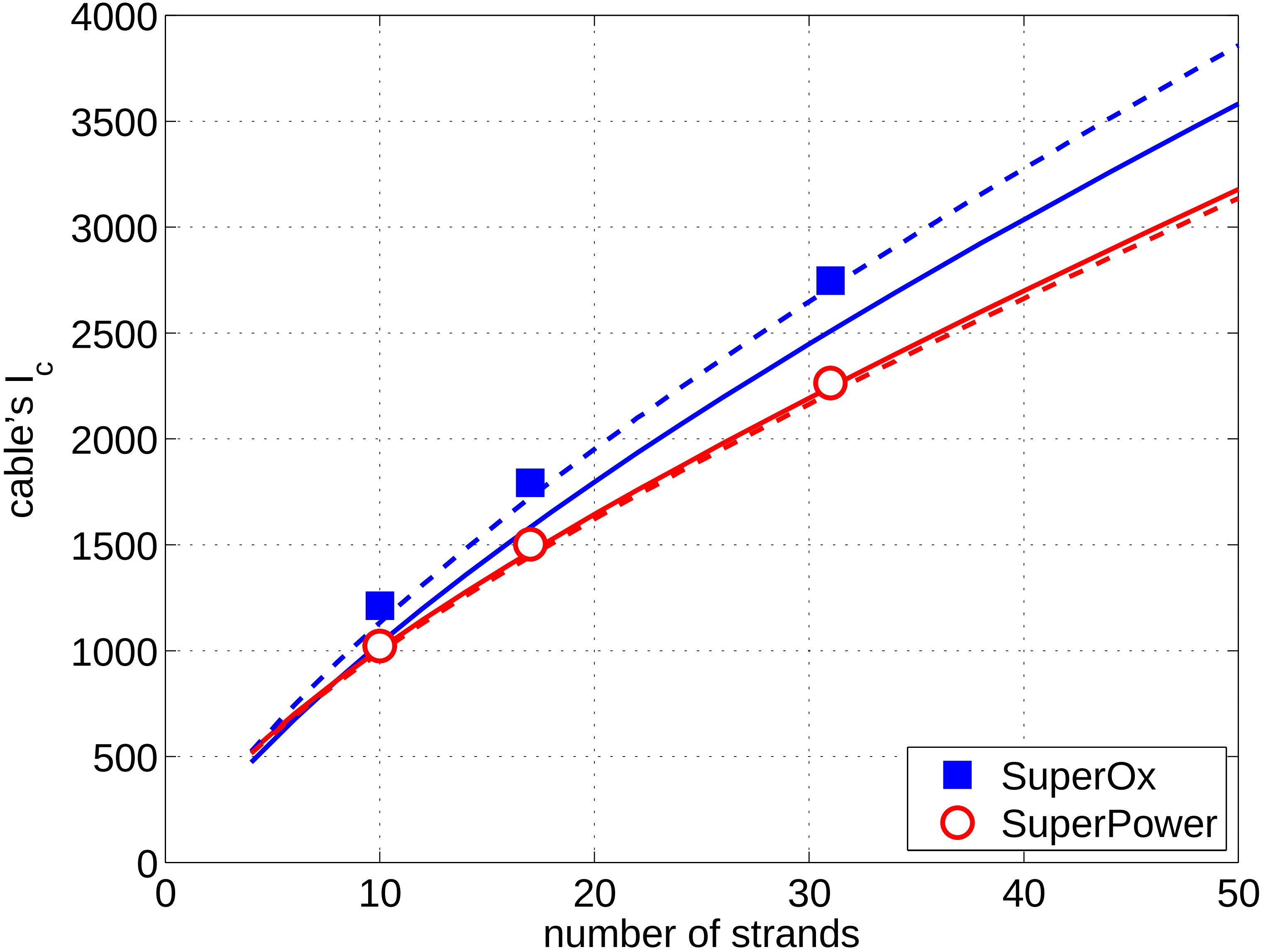
$J_c(B,\theta)$ measured on a tape.

The calculated I_c of the strand is:

SuperOx: 125.1 A

SuperPower: 146.0 A

With a correction factor 1.12 (dashed lines) the agreement for SOx is much better than before.



Considerations on cable design

What is the influence of the spacing between the superconducting layers?

Question #1:

Does a loose packing of the strands lead to higher I_c due to the reduction of self-field?

Example: SuperOx cable (31 strands)

Standard spacing: 125 µm → I_c= 2509 A

Increased spacing: 350 µm → I_c= 2700 A

+7.6 %

Supercond. Sci. Technol. **24** (2011) 065005 (9pp) doi:10.1088/0953-2048/24/6/065005

The dependence of AC loss characteristics on the spacing between strands in YBCO Roebel cables

Zhenan Jiang[1], K P Thakur[1], Mike Staines[1], R A Badcock[1], N J Long[1], R G Buckley[1], A D Caplin[2] and Naoyuki Amemiya[3]

4. Conclusion

Transport AC loss in a nine strand YBCO Roebel cable with 0.25 mm spacers between the strands was measured and compared with that in a nine strand YBCO Roebel cable without spacers. Critical current was increased by 6.8% by spacing, due to a reduced self-field effect. AC loss in

What is the influence of the distance between the superconducting layers?

Question #2:

Can we then increase J_e by pushing the superconducting layers closer to each other?

HTS coated conductors with 30 µm will be available soon

Example: SuperOx cable (31 strands)

Standard spacing: 125 µm → I_c= 2509 A

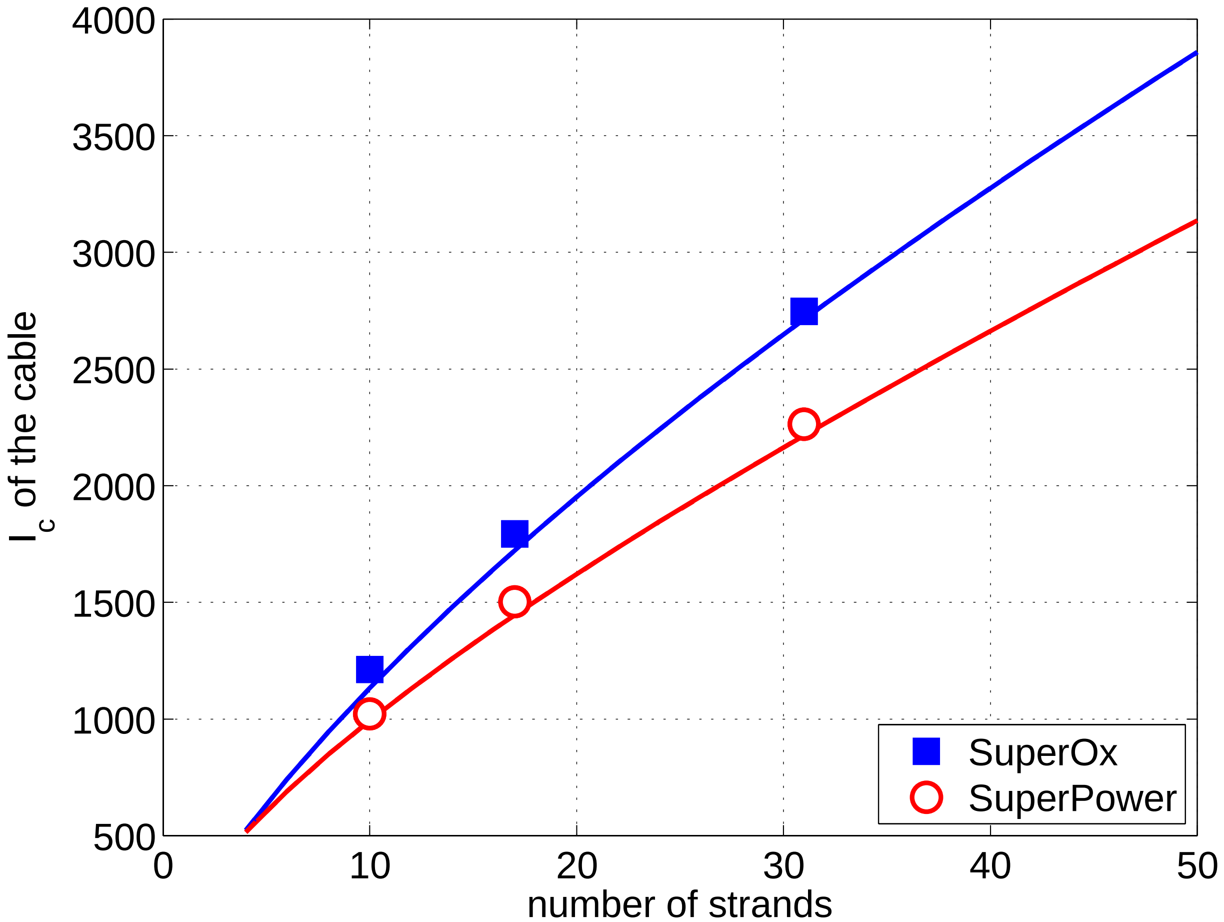
Reduced spacing: 75 µm → I_c= 2446 A

I_c down by 2.5 %

J_e up by 60 %

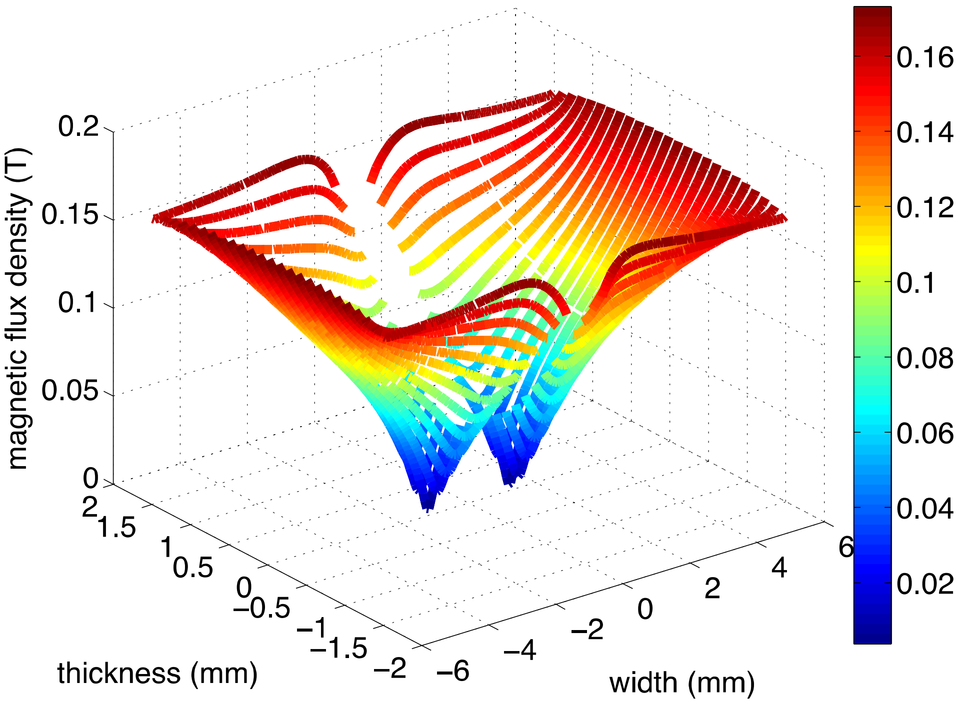
How does I_c increase with increasing number of strands?

- More strands → more self-field
- Important role of $J_c(B,\theta)$

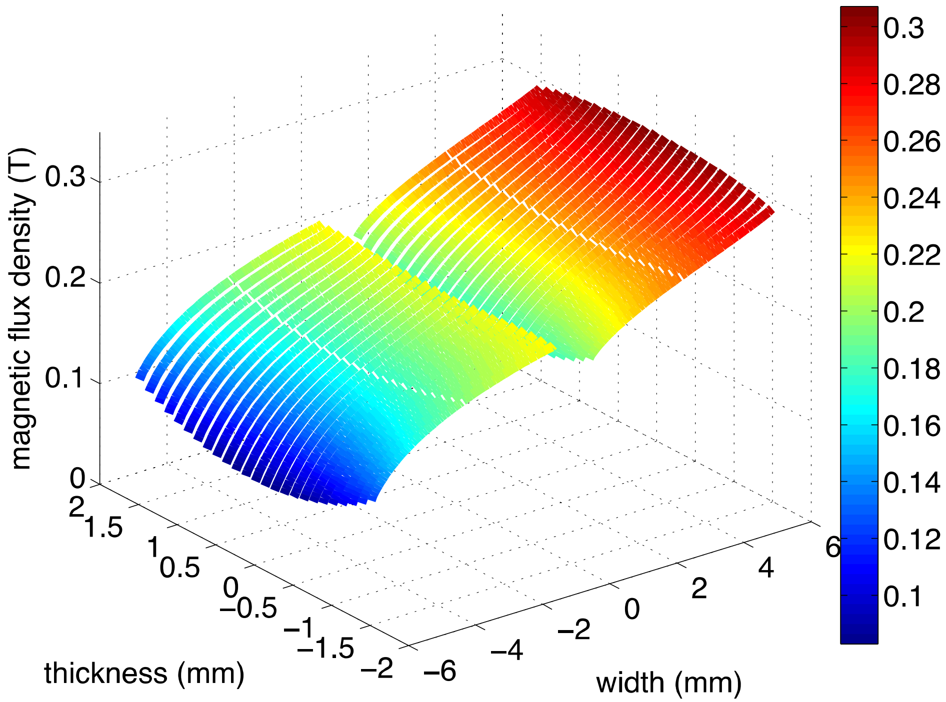


What is the influence of a background magnetic field?

50 strands
self-field

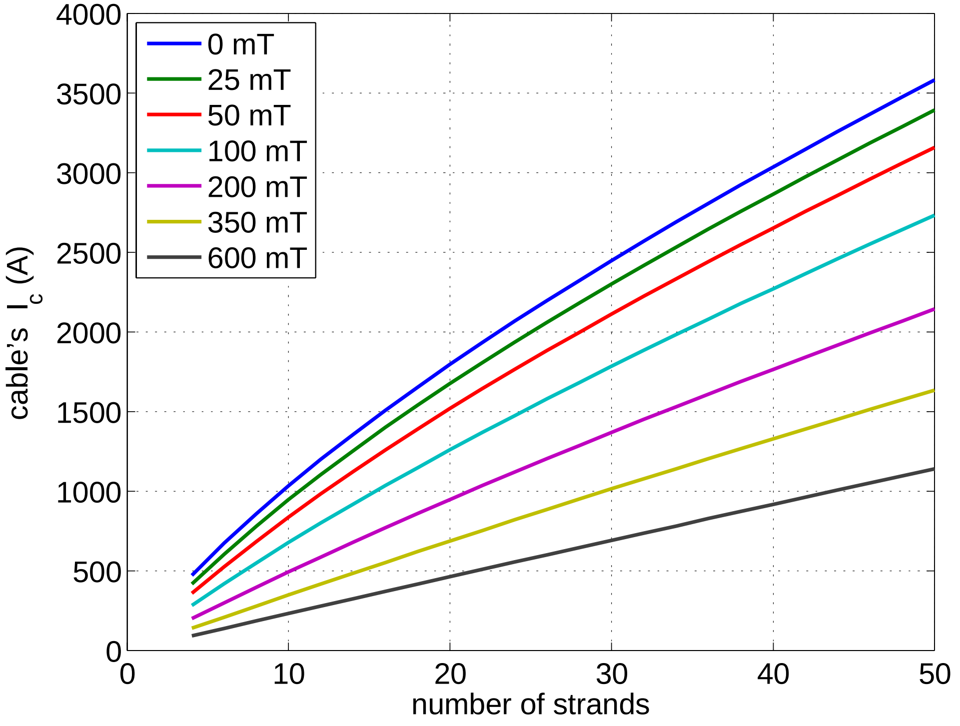


50 strands
background field 200 mT

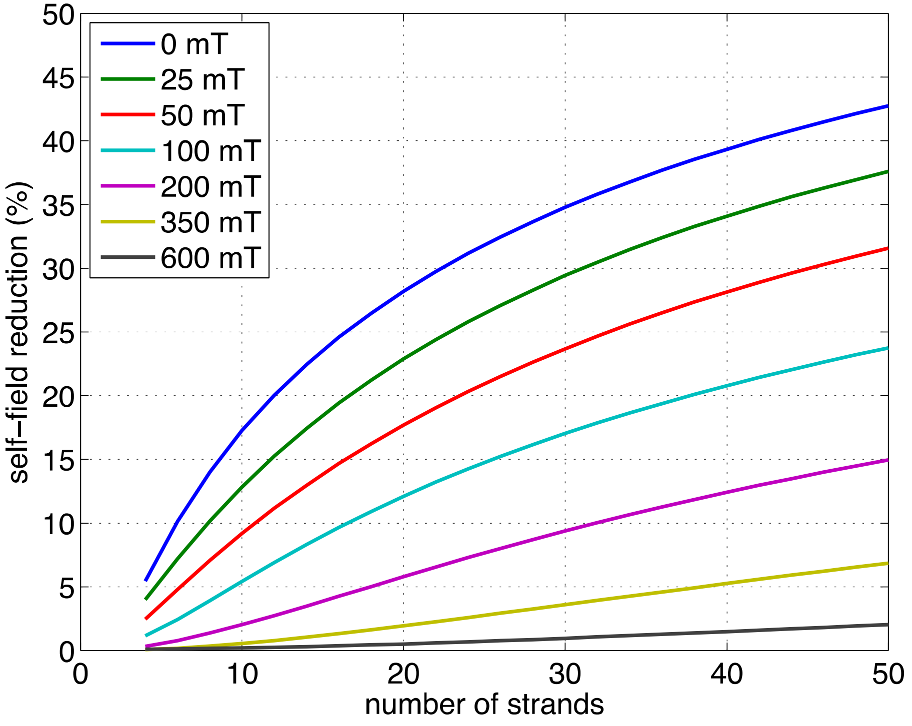


What is the influence of a background magnetic field?

cable's I_c



self-field reduction



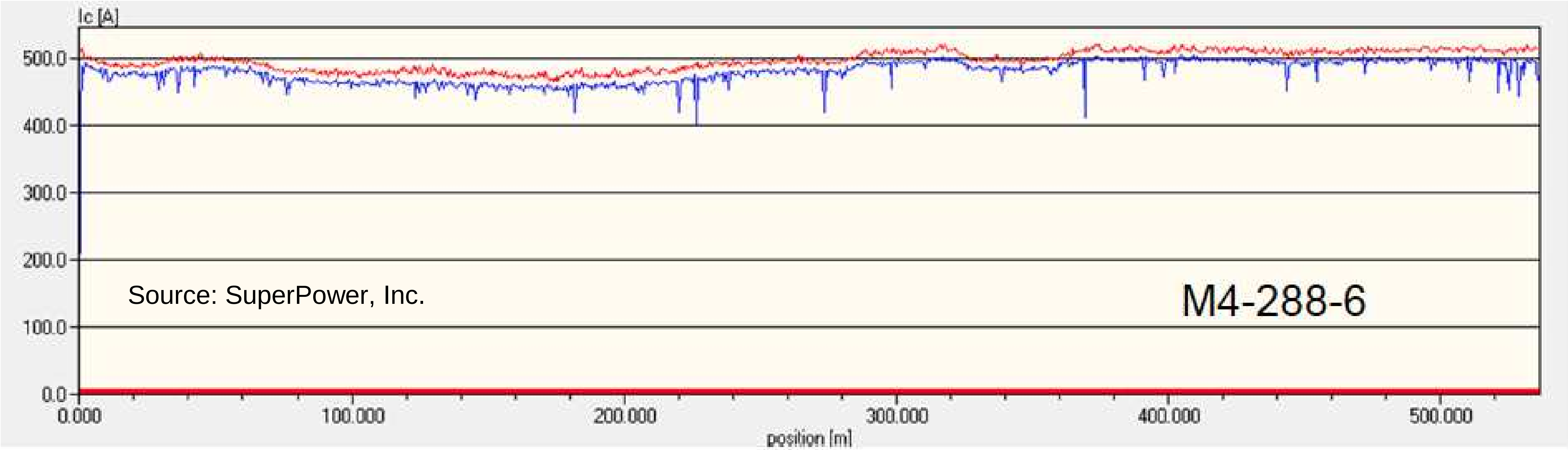
$$\eta = 1 - \frac{I_{CC}}{ns \times I_{CS}}$$

Conclusion (1)

- A DC model was used to evaluate critical current of Roebel cables for low-field applications.
- In-field performance of composing strands plays a major role on the effective I_c of the cable.
- Distance between superconducting layers has little influence → great potential for new tapes with thin substrate.
- With moderate fields (hundreds of mT), I_c can be simply calculated from the I_c of the strands.

How does $J_c(B,\theta)$ vary along the length of a tape?

- For modeling devices made of (hundreds of) meters of tape, we use a $J_c(B,\theta)$ model derived from data of a 15 cm long sample.
- We know that the self-field I_c varies along the length.



- How does $J_c(B,\theta)$ vary along the length? Simply a multiplicative factor? (e.g. 1.12 factor we used here)
- Recent work says "no".

Supercond. Sci. Technol. 29 (2016) 054006 (9pp) doi:10.1088/0953-2048/29/5/054006

Sample and length-dependent variability of 77 and 4.2 K properties in nominally identical RE123 coated conductors

L Rossi[1], X Hu, F Kametani, D Abraimov, A Polyanskii, J Jaroszynski and D C Larbalestier

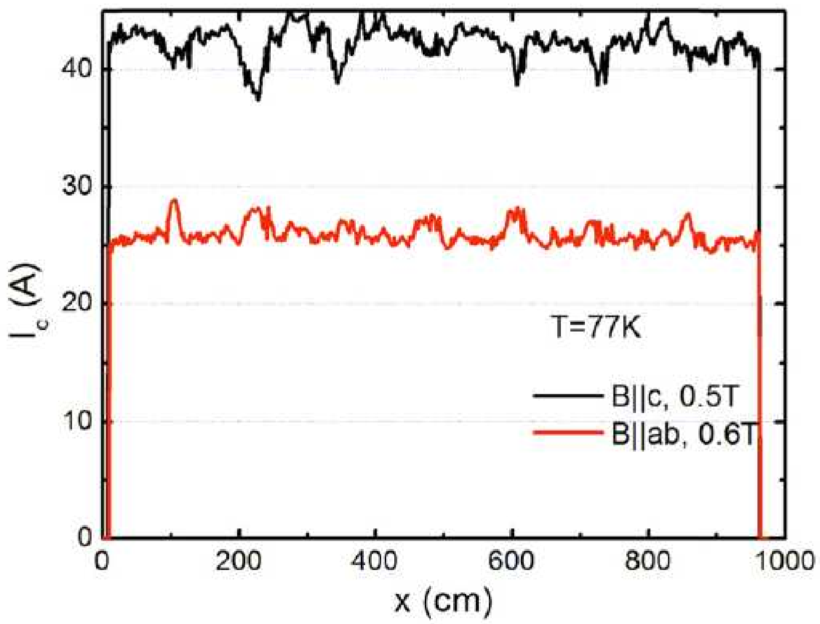


Figure 3. I_c as a function of position at $B||c = 0.5$ T and at $B||ab = 0.6$ T at 77 K in conductor S4 as a function of position. A tendency for I_c to drop for $H||c$ that correlates to I_c rising for $H||ab$ is evident.

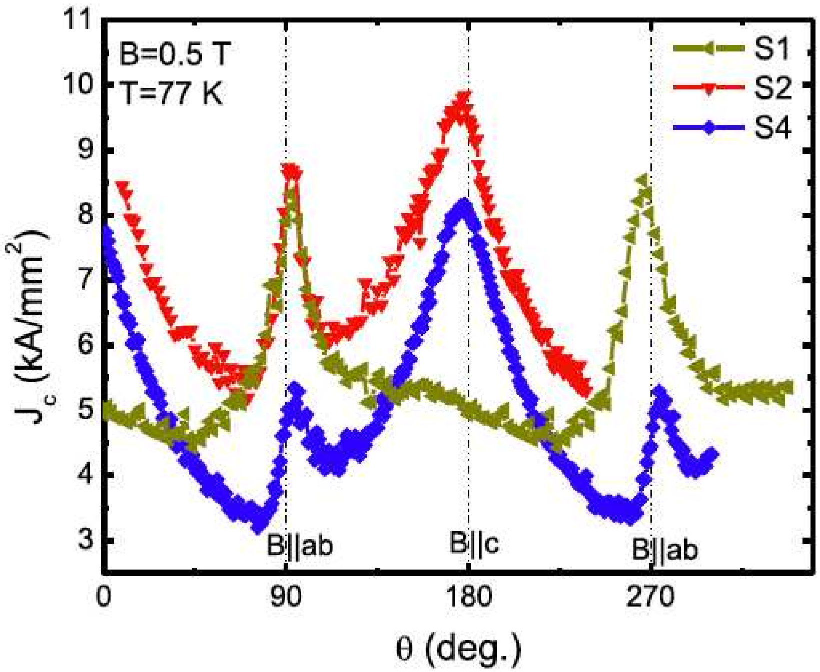
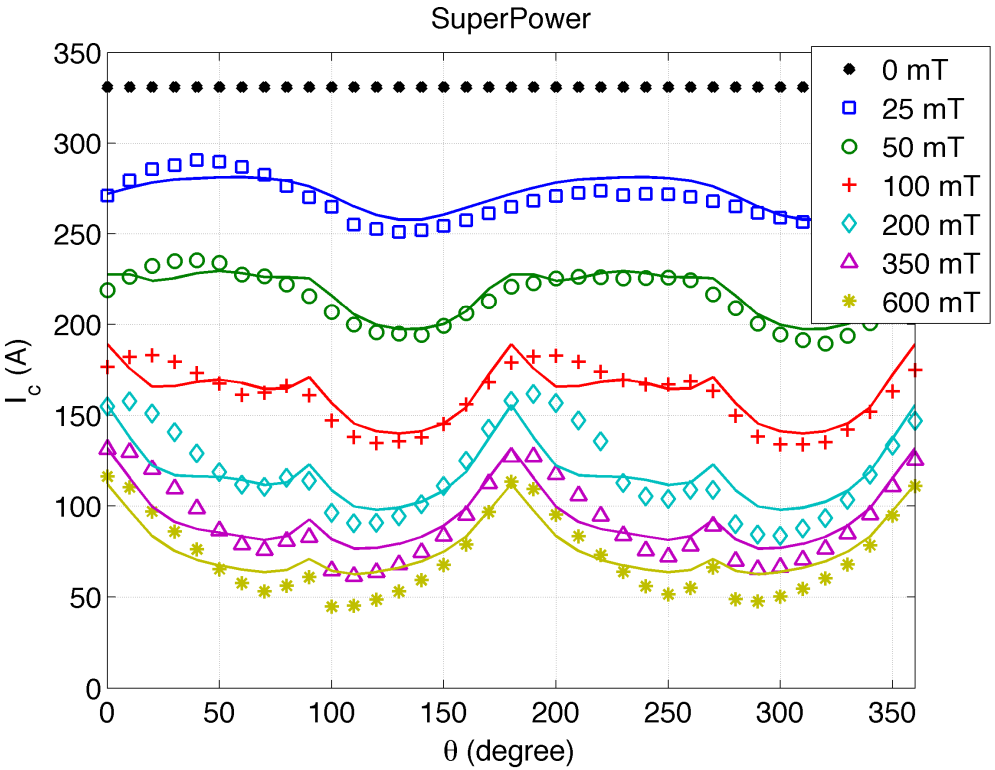
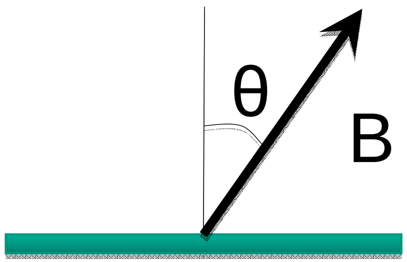


Figure 4. J_c angular dependence for tapes S1, S2, and S4.

A parameter-free approach





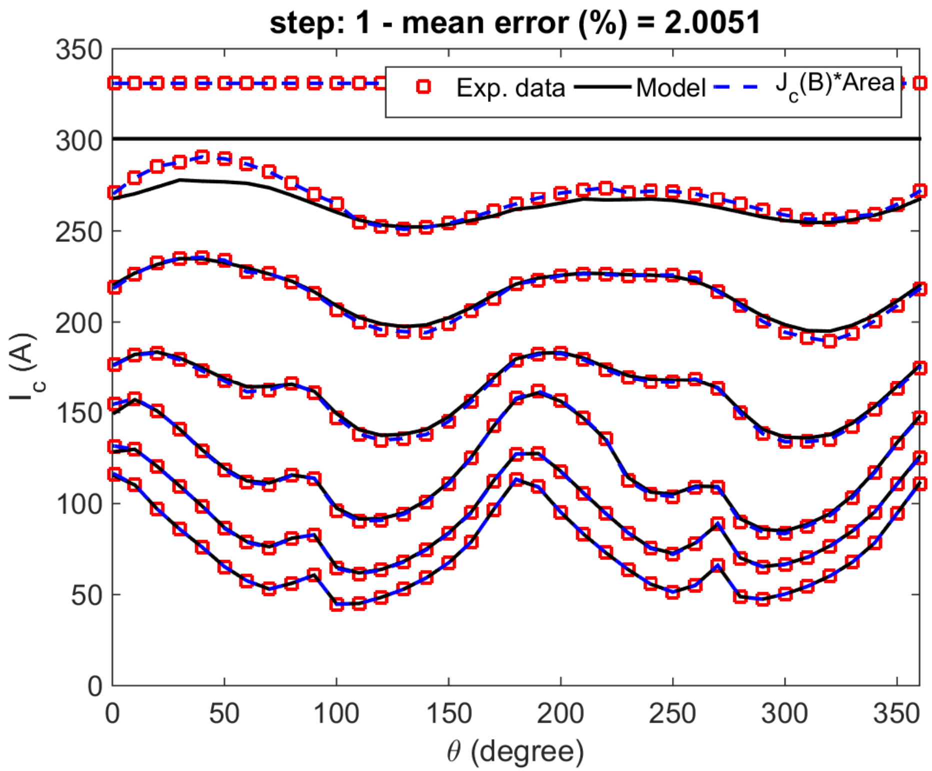
Extracting an analytic expression for $J_c(B,\theta)$ is a time consuming process:

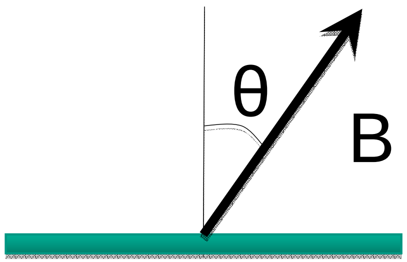
1. Find an analytic expression reproducing the angular dependence
2. Find the correct parameters that reproduce the data → calculation of effective I_c necessary for a large number of field/angle combinations!

In the example on the left:

1. the $J_c(B,\theta)$ has 11 parameters → brute force approach time-consuming → manual tweak
2. Still, the agreement is far from perfect.

A parameter-free approach





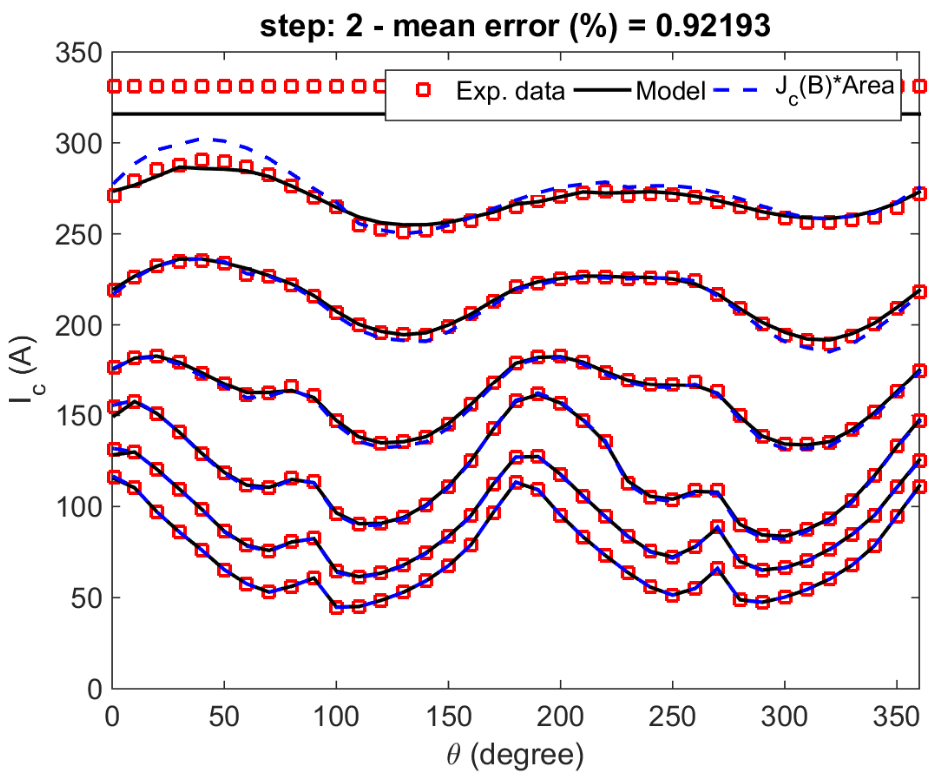
With the parameter-free approach (see Victor Zermeno's poster), we reach an excellent agreement with experimental data in just six steps.

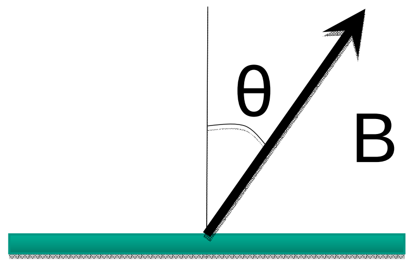
•No need of thinking about an analytic formula for $J_c(B,\theta)$.

•No need of manual or automatic tweaking of parameters.

•The interpolated $J_c(B,\theta)$ is ready to be used in successive simulations (e.g. calculation of I_c or AC losses in a device).

A parameter-free approach





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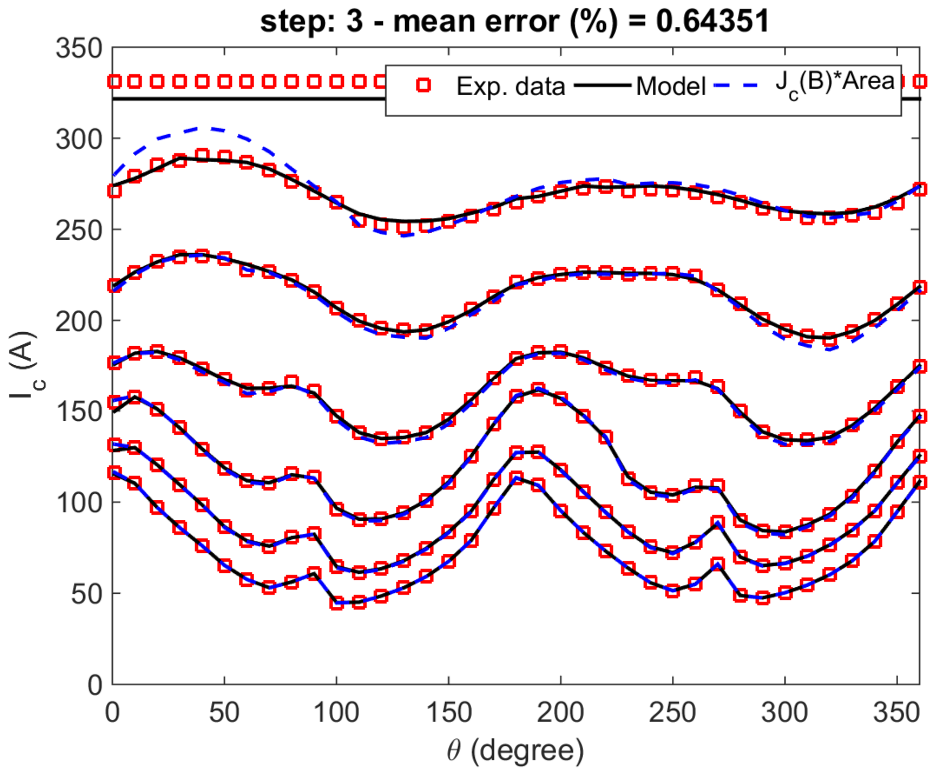

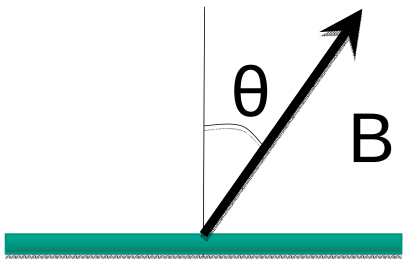

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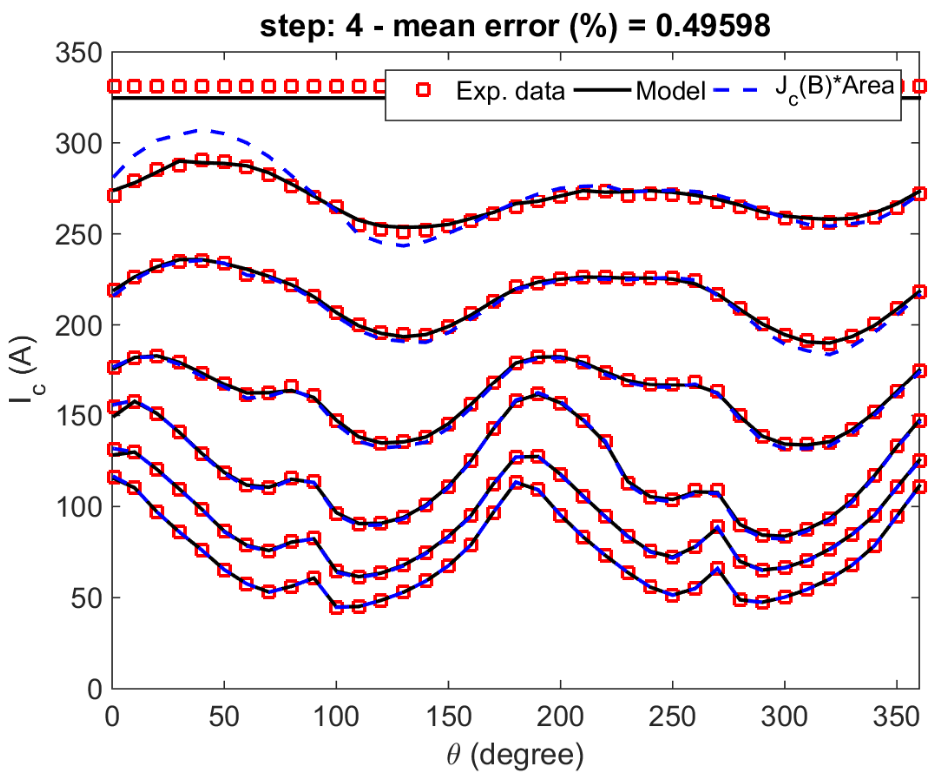

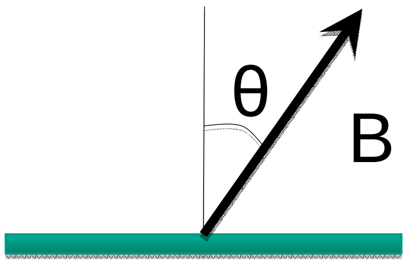

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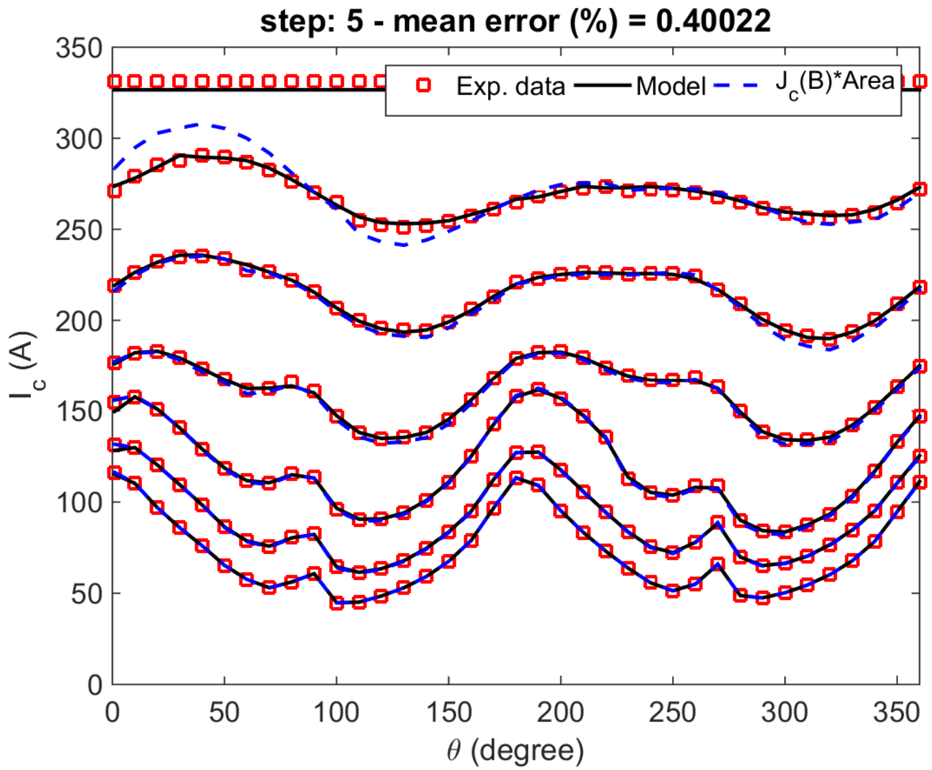

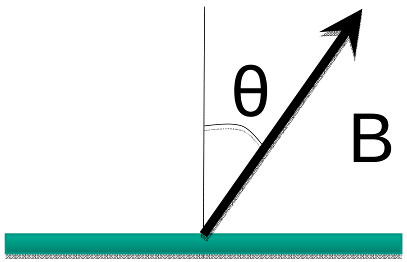

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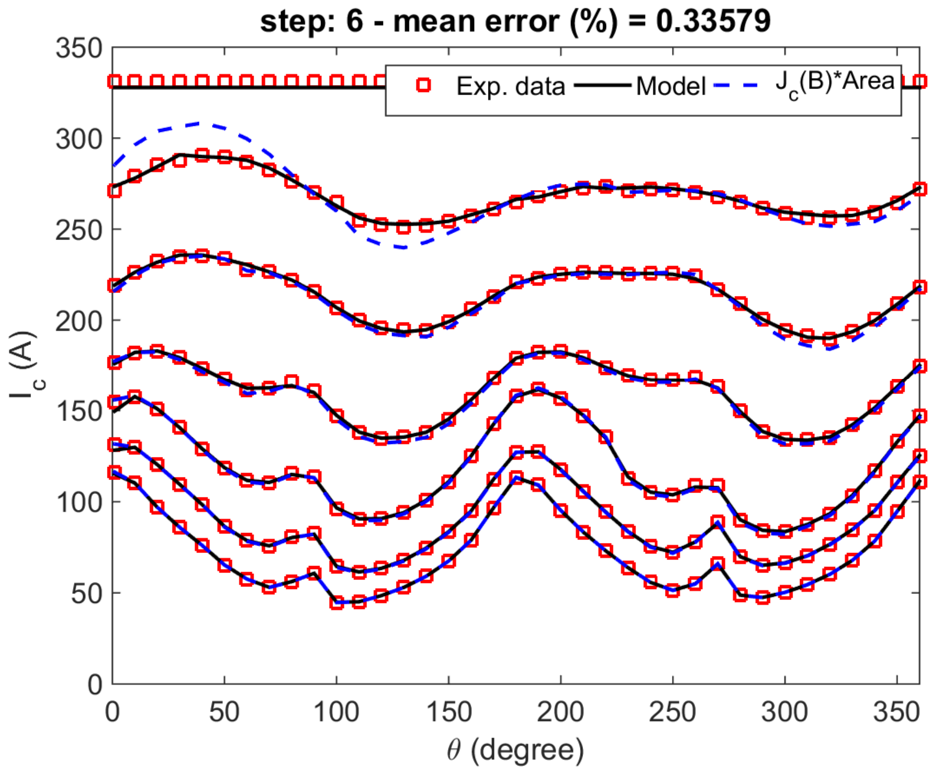

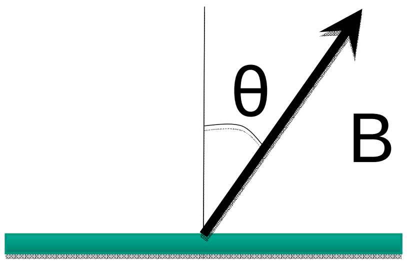

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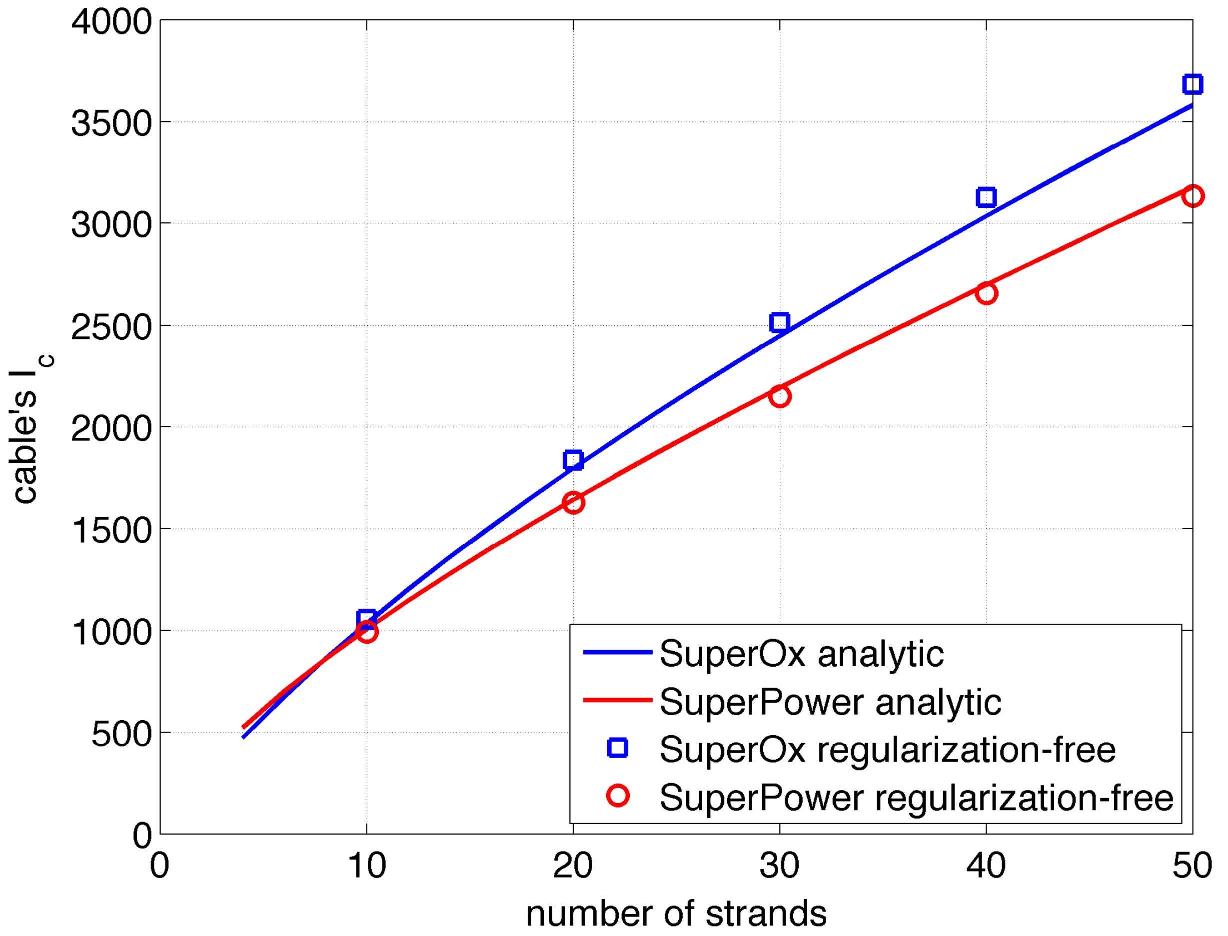
From experimental data to a ready-to-go model in 5 minutes!

I_c calculated with the parameter-free method and with analytic expressions agree well.



maximum difference <3 %

Conclusion (2)

- It is important to check how the short sample on which $I_c(B_{EXT},\theta)$ is measured is representative of the whole tape.
  - Recent work suggests variations of pinning center quality along the length.
- Parameter-free method allows going from experimental $I_c(B_{EXT},\theta)$ data to a ready-to-use local $J_c(B_{LOCAL},\theta)$ model in a few minutes.
  - No complex analytic expressions
  - No parameter tweaking

The codes for I_c calculation are available for free.
The one for extracting $J_c(B,\theta)$ will be soon.

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Open-Source Codes for Computing the Critical Current of Superconducting Devices

Víctor M. R. Zermeño, Salman Quaiyum, and Francesco Grilli

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Karlsruhe Institute of Technology, Institute for Technical Physics, Germany

francesco.grilli@kit.edu