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Invited presentation M2OrE-02 given at CEC-ICMC 2017, July 09-13, 2017, Madison, WI (USA).

Targeted high-temperature superconductor wire characterization and selection for electric propulsion applications

Stuart C Wimbush

Robinson Research Institute, Victoria University of Wellington

VICTORIA
UNIVERSITY OF WELLINGTON
TE WHARE WĀNANGA
O TE ŪPOKO O TE IKA A MĀUI

Robinson Research Institute

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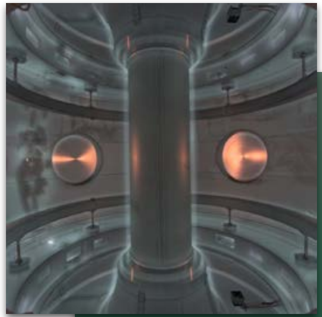
Example targeted applications of HTS

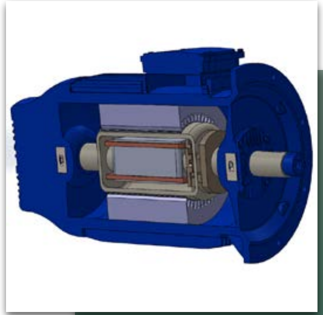


Fusion reactor

20 K
22 T

Ma[illegible] resonance imaging

20 K
1–5 T



Motor / generator

50 K
3 T

✓

Aircraft

Transformer

65–77 K
< 0.2 T

✓

Railway

Roebel cable

77 K
~ 0 T

✓

ac loss

4.2 K, 18 T

30 K, 3 T

77 K, 0 T

eurotapes

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Critical current measurement system

- Fully automated $I_c(T,B,\theta)$ measurement:

$$\begin{aligned} 0.1\text{ A} \le\ & \boldsymbol{I_c} \le 1000\text{ A} \\ 12.5\text{ K} \le\ & \boldsymbol{T} \\ & \boldsymbol{B} \le 8\text{ T} \\ -360^\circ \le\ & \boldsymbol{\vartheta} \le 360^\circ \end{aligned}$$

  - 8 T HTS (cryocooled) magnet.
  - Closed-cycle cryocooled helium gas circulation system to cool the sample and current leads.

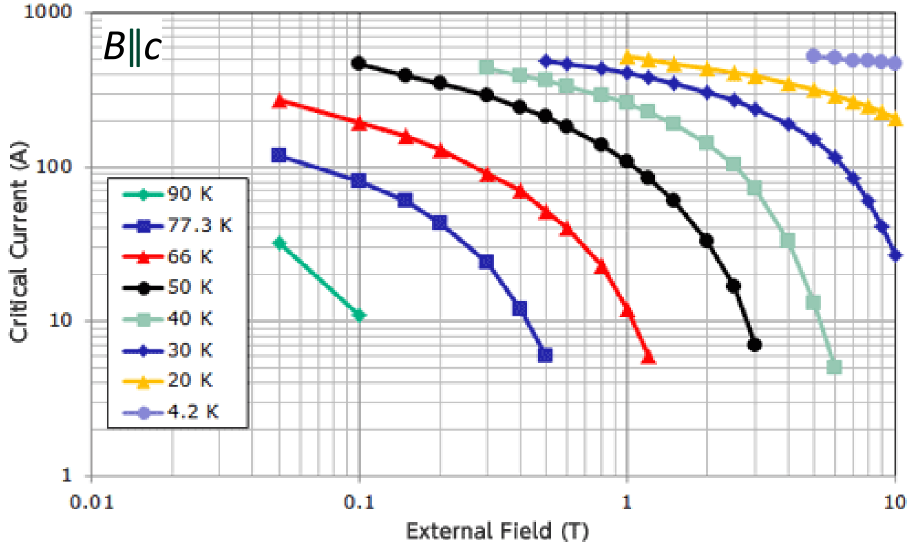
- 100 full *IV* curve measurements per hour with automated analysis and I_c determination.

- Typically ~48 hour sample characterisation – 4800 discrete I_c data points.

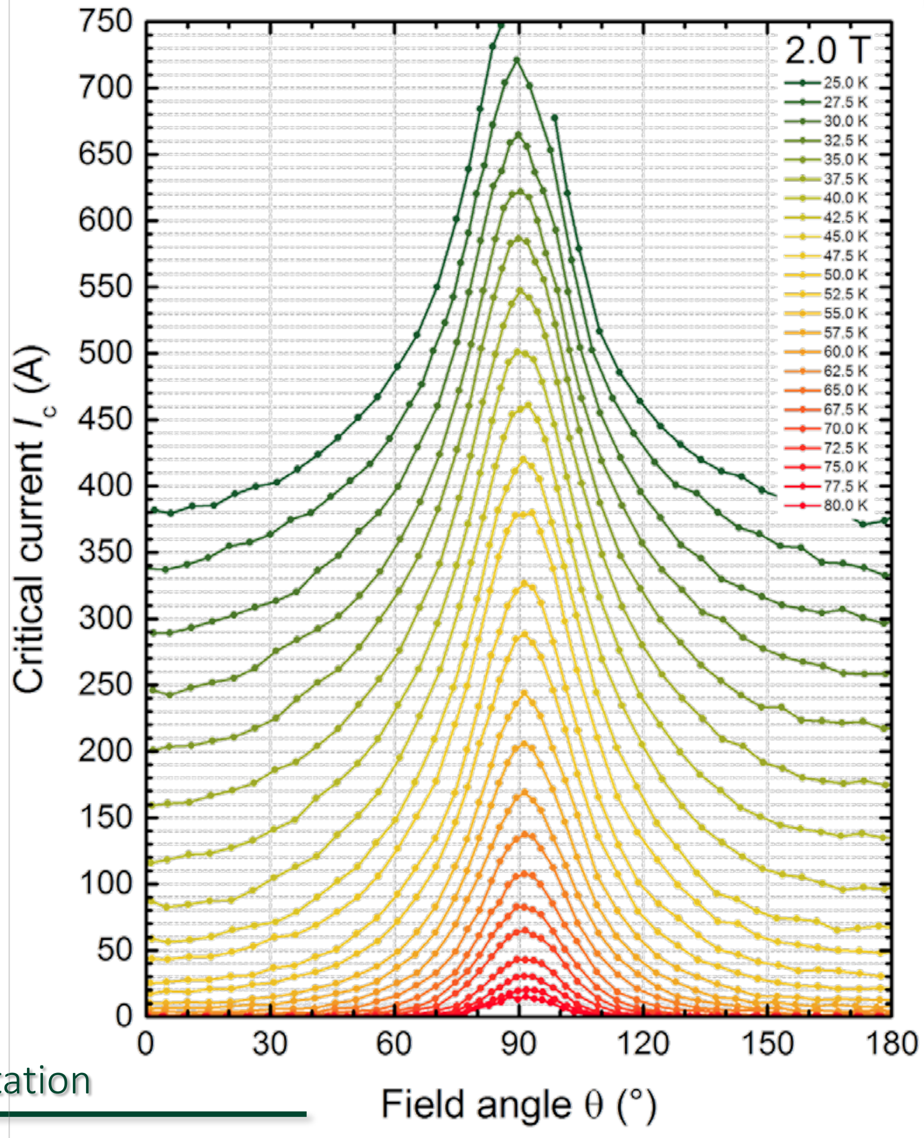
Strickland, Hoffmann, Wimbush, *Rev. Sci. Instr.* 85 (2014) 113907.

What do $I_c(B)$ plots tell us?

Sumitomo Type H DI-BSCCO® Wire



Source: Sumitomo (http://global-sei.com/super/hts_e/type_h.html).



- $I_c(B\|c)$ measurements on 1G BSCCO wires are informative and meaningful because they accurately represent the **minimum I_c value** of the wire under a given set of T,B operating conditions.

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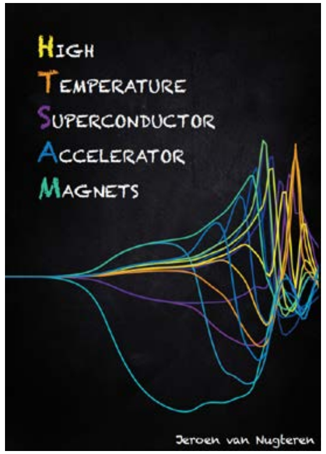
tokamak energy
a faster way to fusion

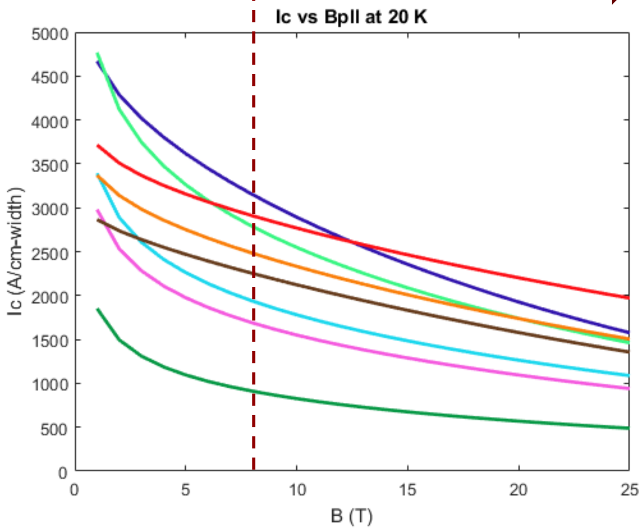
Fusion reactors

Jeroen van Nugteren, *PhD Thesis*, University of Twente (2016).

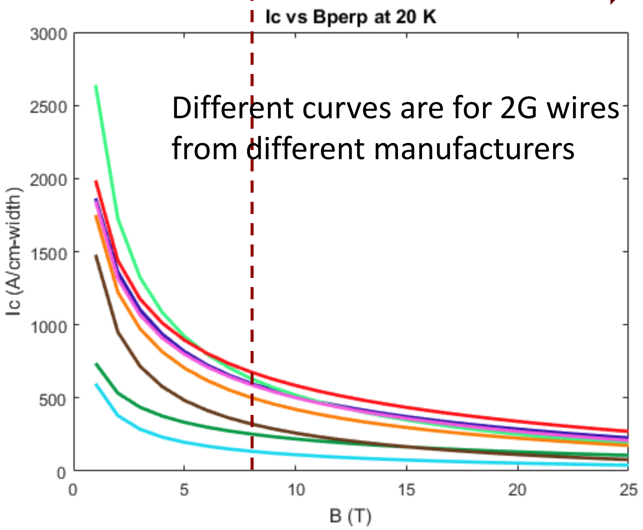


- Extrapolations of available data sets to higher fields and lower temperatures.
- Reliability achieved through modelling high density of data in accessible regime.
- Accuracy of extrapolated results to be verified by additional targeted measurements.

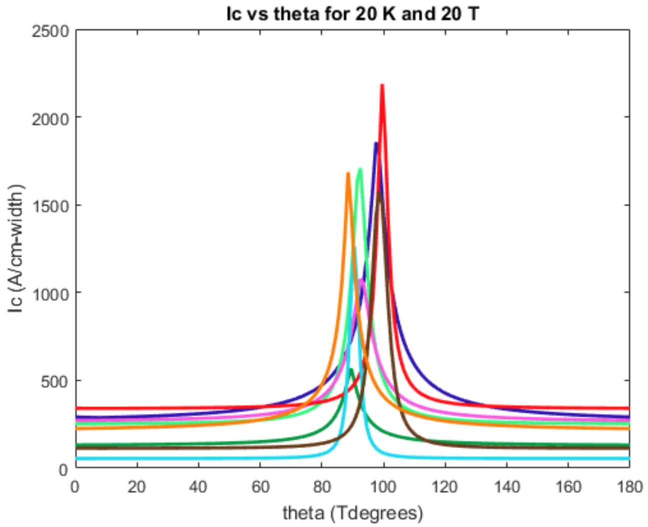
Modelling of existing data | Extrapolation to higher *B*



Modelling of existing data | Extrapolation to higher *B*



Angle dependences also extrapolated in *B*



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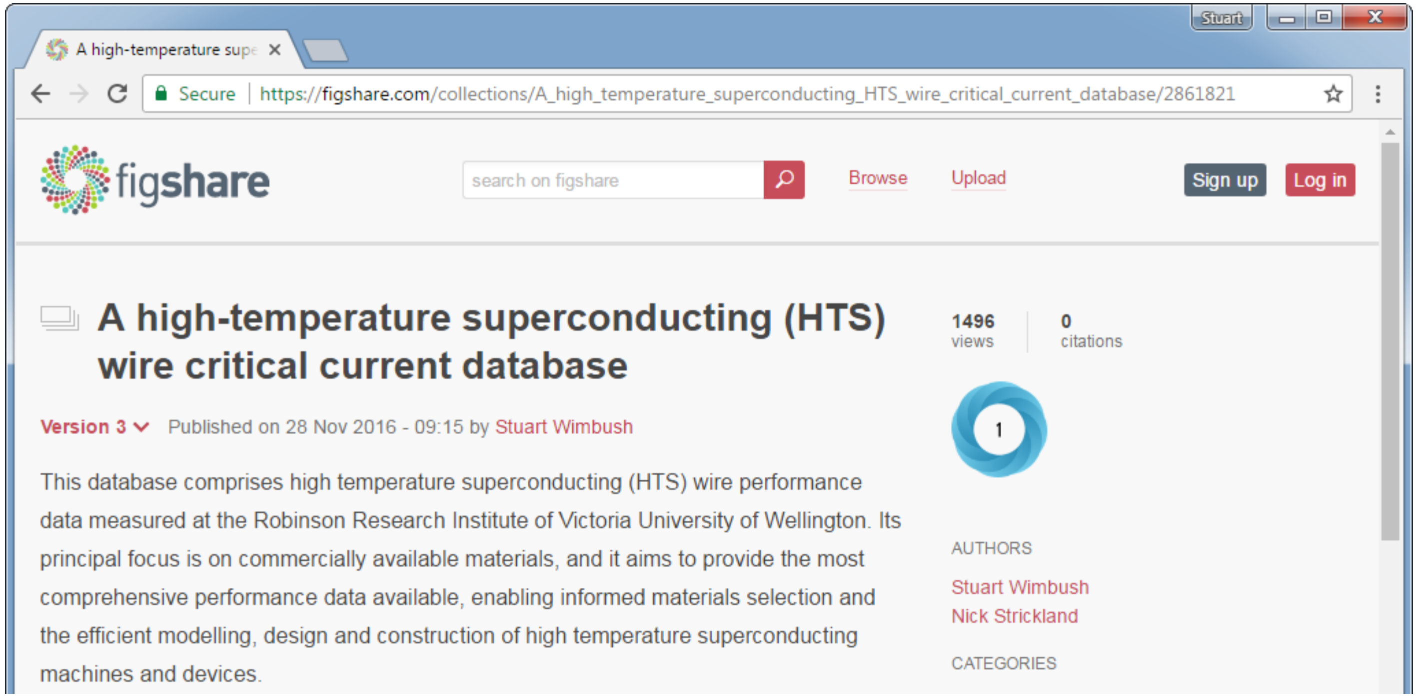
Public HTS wire critical current database

As high temperature superconducting technologies edge closer and closer to industrial breakthrough, the need for *detailed* wire critical current characterisation becomes greater and greater.



http://www.victoria.ac.nz/robinson/hts-wire-database

Wimbush and Strickland, *IEEE Trans. Appl. Supercond.* 27 (2017) 8000105.

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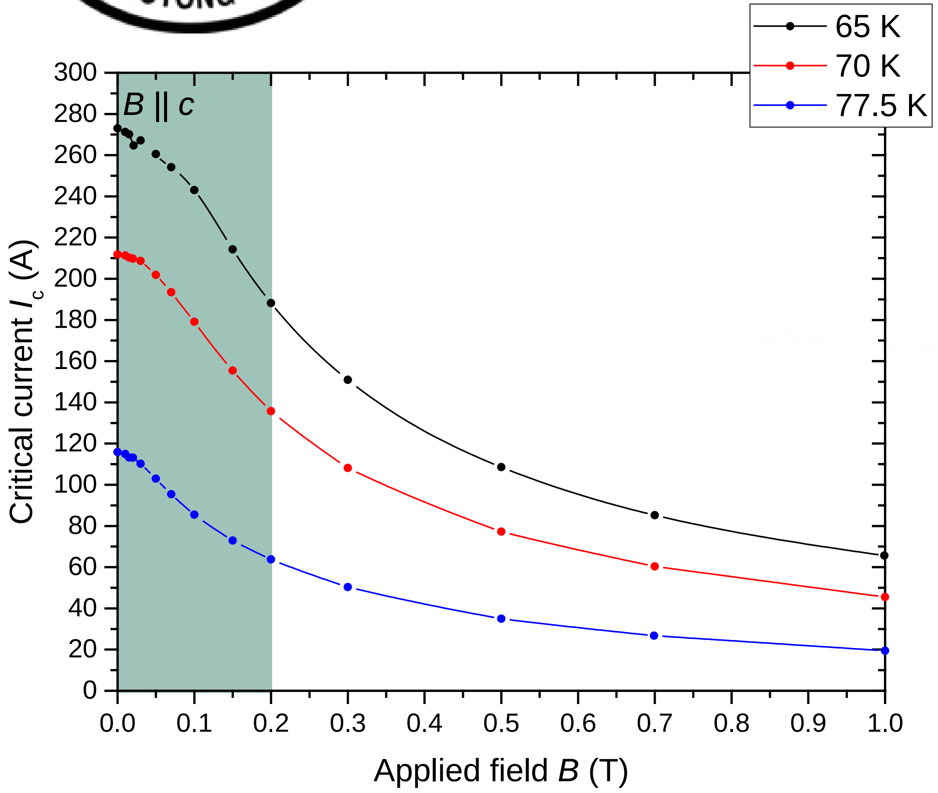
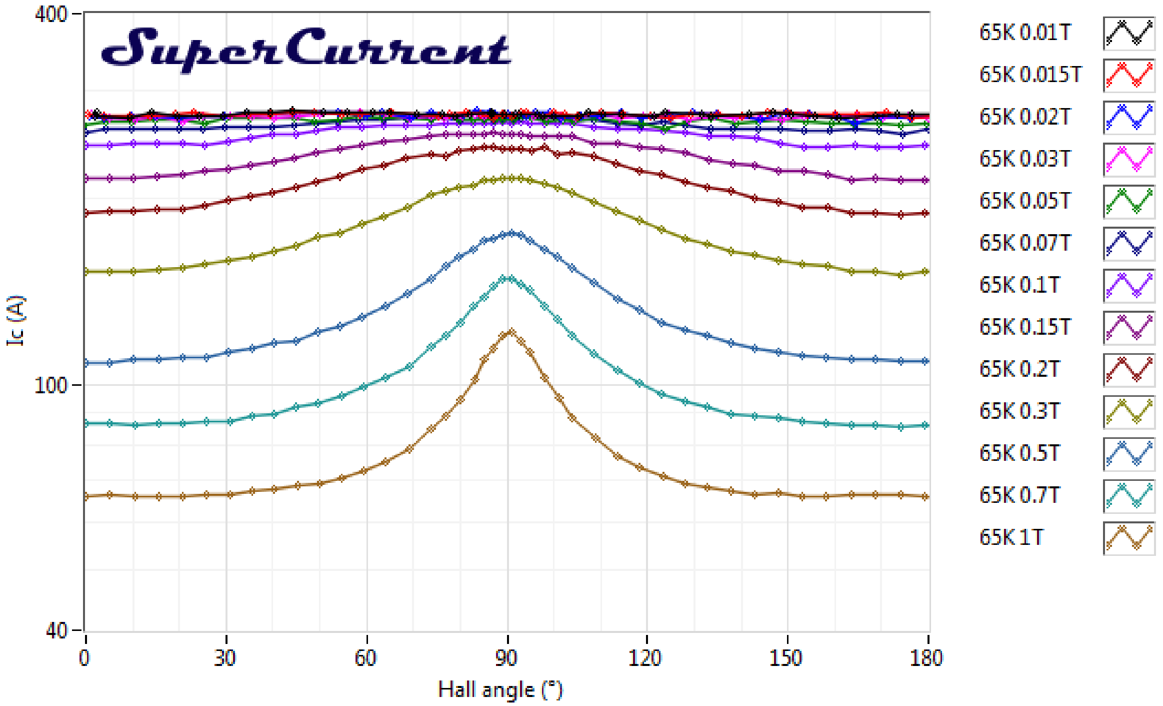
Transformers

- Design of a 6.4 MVA single phase HTS traction transformer as a drop-in replacement for the 3 MVA conventional transformer in the CRH high-speed train.
- Accurate ac loss modelling in the liquid nitrogen (65 K – 77 K) regime.
- Models based on real data for perpendicular fields significantly below 1 T.



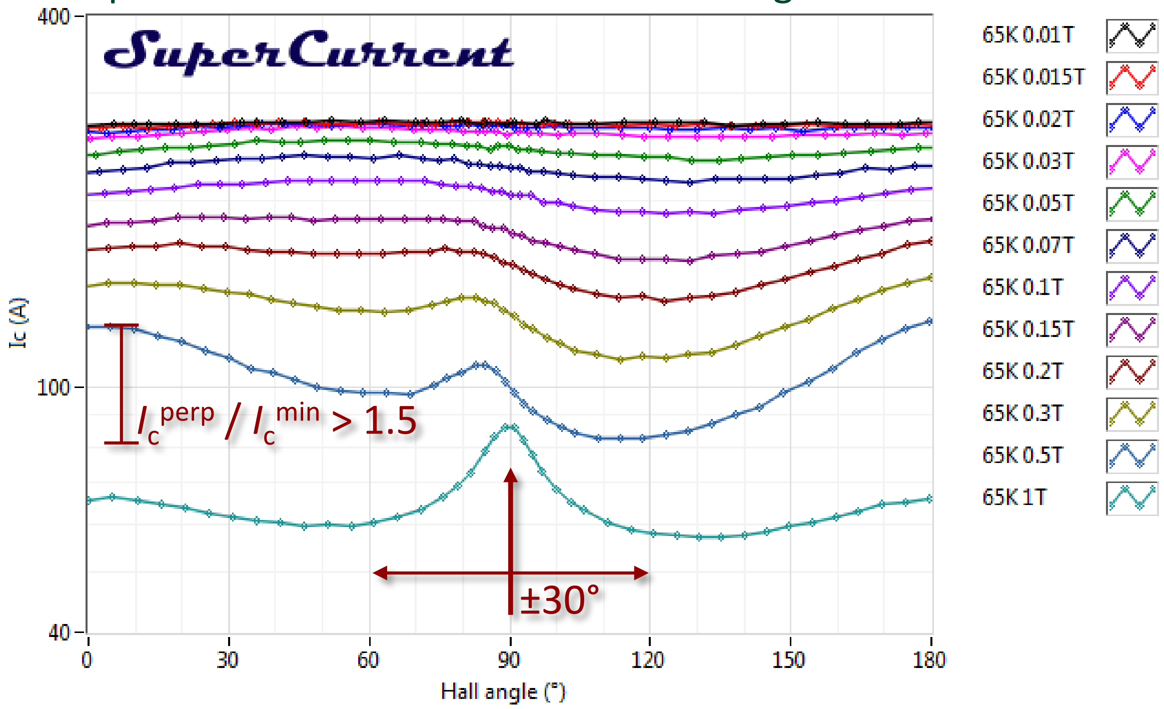
AMSC Amperium® Type 8700 Wire



Hybrid coils for reducing ac loss

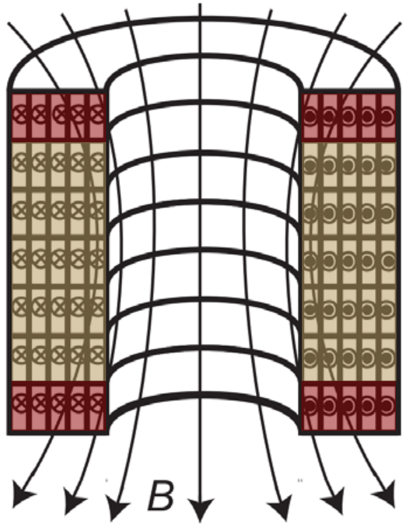
- AC loss modelling of **hybrid** coils targeting ac machines such as motors / generators.
- Primarily the radial field component in the end turns determines the coil I_c.
- AC loss determined by ratio of operating current to I_c.

SuperPower® SCS4050 Advanced Pinning M3 Wire

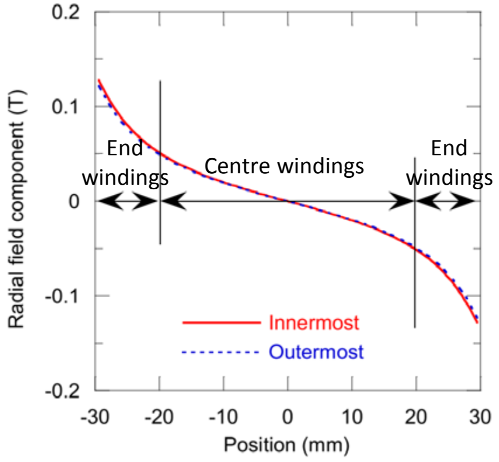


REBCO ac loss $\propto \left(\frac{I}{I_c}\right)^{3-4}$

BSCCO ac loss $\propto \left(\frac{I}{I_c}\right)^{2-3}$



Jiang *et al.*, *Supercond. Sci. Technol.* 29 (2016) 095011.



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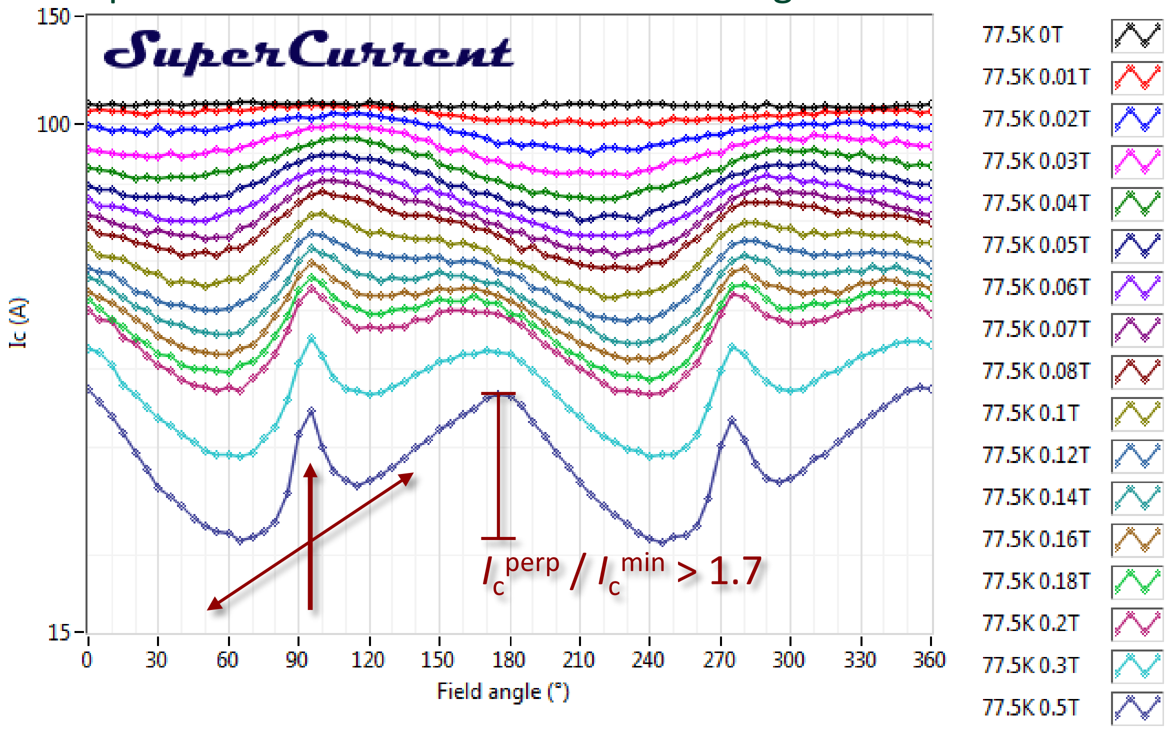
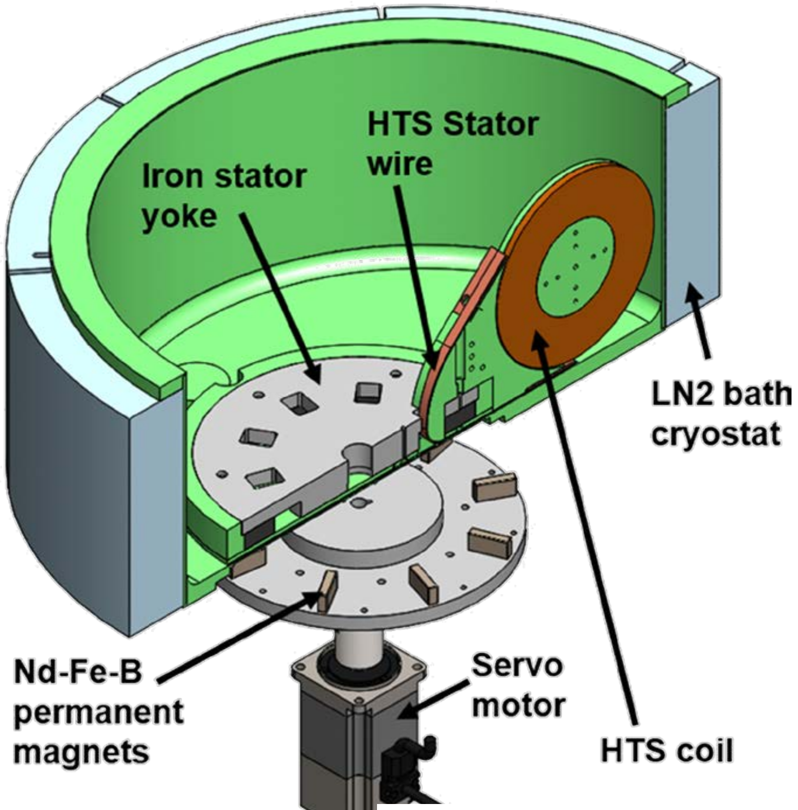
Flux pumps

- Flux pumps can be used as an efficient (contactless) power source for HTS rotating machines.
- The "dynamic resistance" of the flux pump determines the maximum current pumped into the coil.
- Want to move from experimental determination of dynamic loss to a prediction based on wire properties.

SuperPower® SCS4050 Advanced Pinning M3 Wire



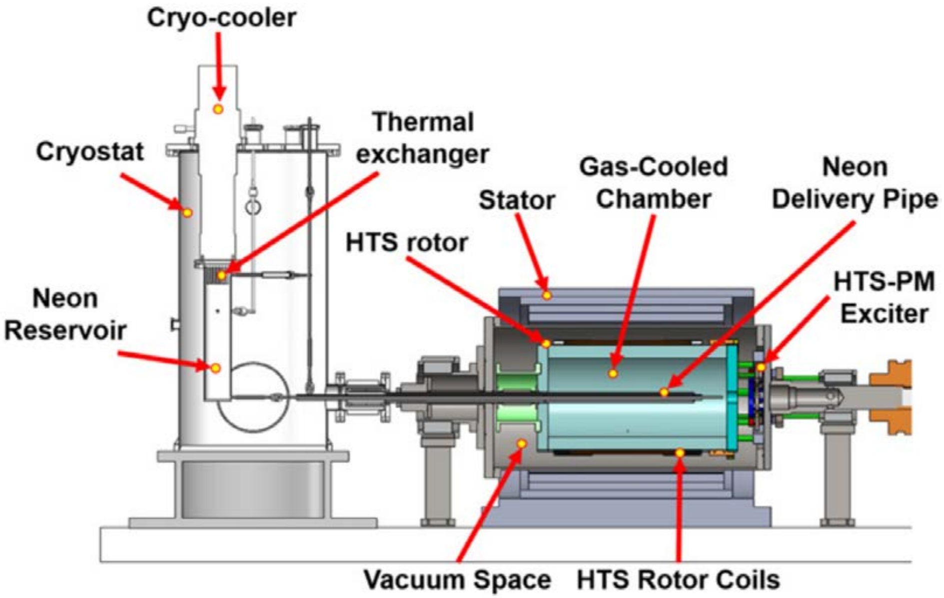


Bumby *et al., IEEE Trans. Appl. Supercond.* 26 (2016) 0500505.

Motors / generators

창원대학교
CHANGWON NATIONAL UNIVERSITY

- Design and construction of a 10 kW HTS generator as a precursor to a 12 MW wind power generator.



Courtesy of Hae-Jin Sung, Center for Advanced Power Technology Applications

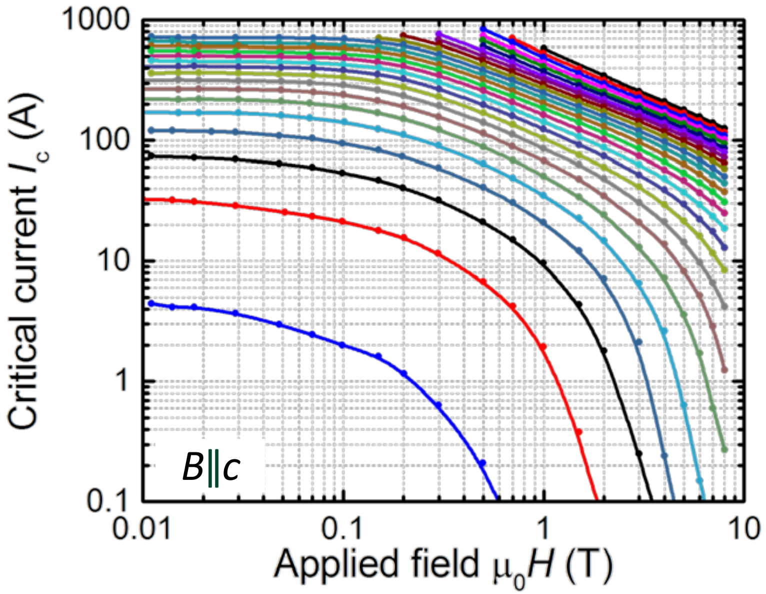
		Existing design	Refined data
Design parameters	Rotational speed	300 rpm	
	Operating temperature	30 K	
	Insulation thickness of coil layers	1 mm	
	Width of coil bobbin	25 mm	
HTS coil	Total width of HTS coil	95.53 mm	68.53 mm
	Effective length of HTS coil	170 mm	200 mm
	Turns of HTS coil/layer/pole	235	145
	Operating current	91 A	336 A
	Current margin	60% of I_c	
	Number of poles	6	
	Number of HTS coil layers/pole	4	2
	Total length of HTS wire required	3 km	1 km
Results	Inductance	0.15 H	0.02 H
	Total diameter	453.3 mm	183.5 mm
	Frequency	15 Hz	
	Maximum magnetic field	2.2 T	5.8 T
	Perpendicular magnetic field	1.1 T	2 T

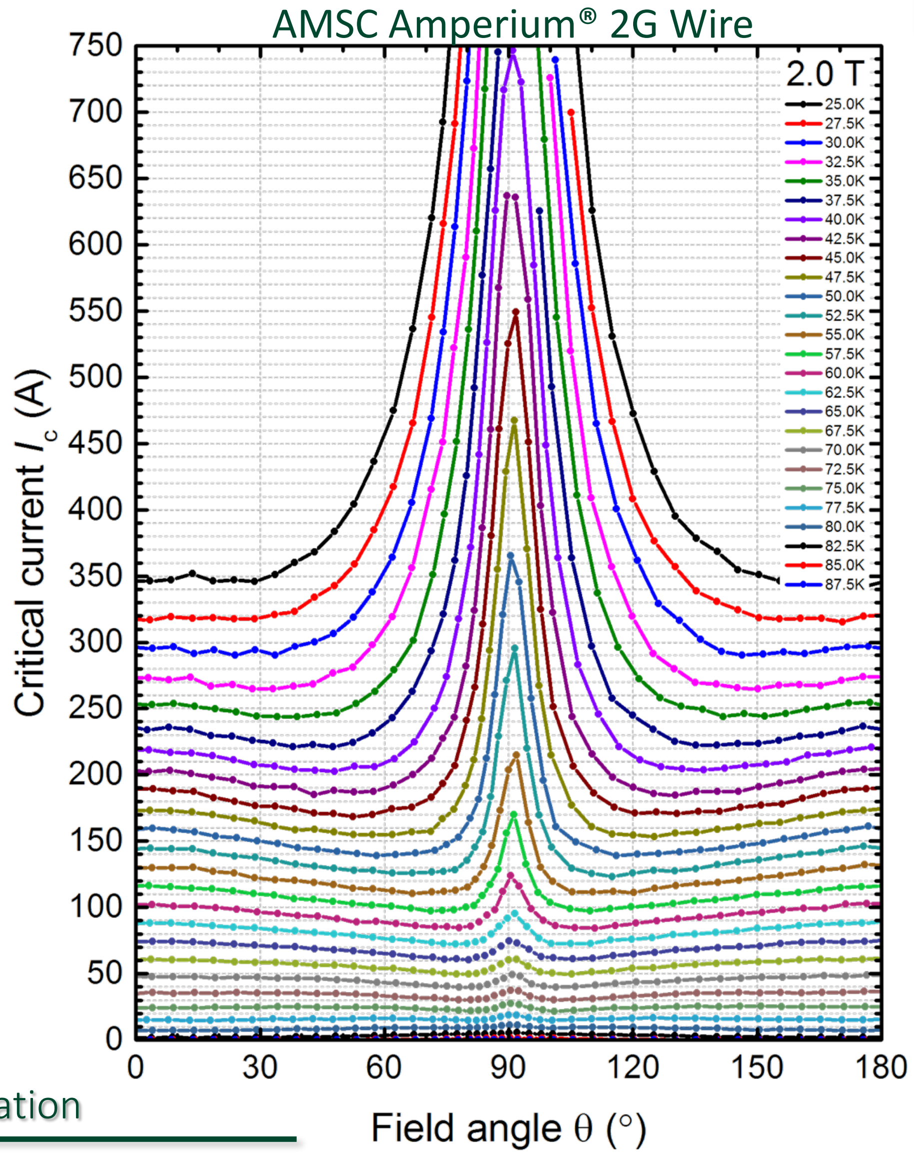
- Wire selection can greatly influence the design parameters of an HTS machine.

H.-J. Sung *et al.*, *IEEE Trans. Appl. Supercond.* 27 (2017) 5202305.

Common understanding of the situation for 2G wires

- Where flux pinning in 2G REBCO wires is dominated by **random pinning** or **planar defects** then we broadly expect a similar form of $I_c(\theta)$ to that in the case of BSCCO wires – a strong *ab* peak leading to a close-to-minimum value for $B \| c$.
- In this case, $I_c(B \| c)$ data remains meaningful, with only a small (~20%) margin of error being introduced by the fact that the $B \| c$ data point is not the true minimum.
- This is commonly the case for AMSC and Fujikura wires.

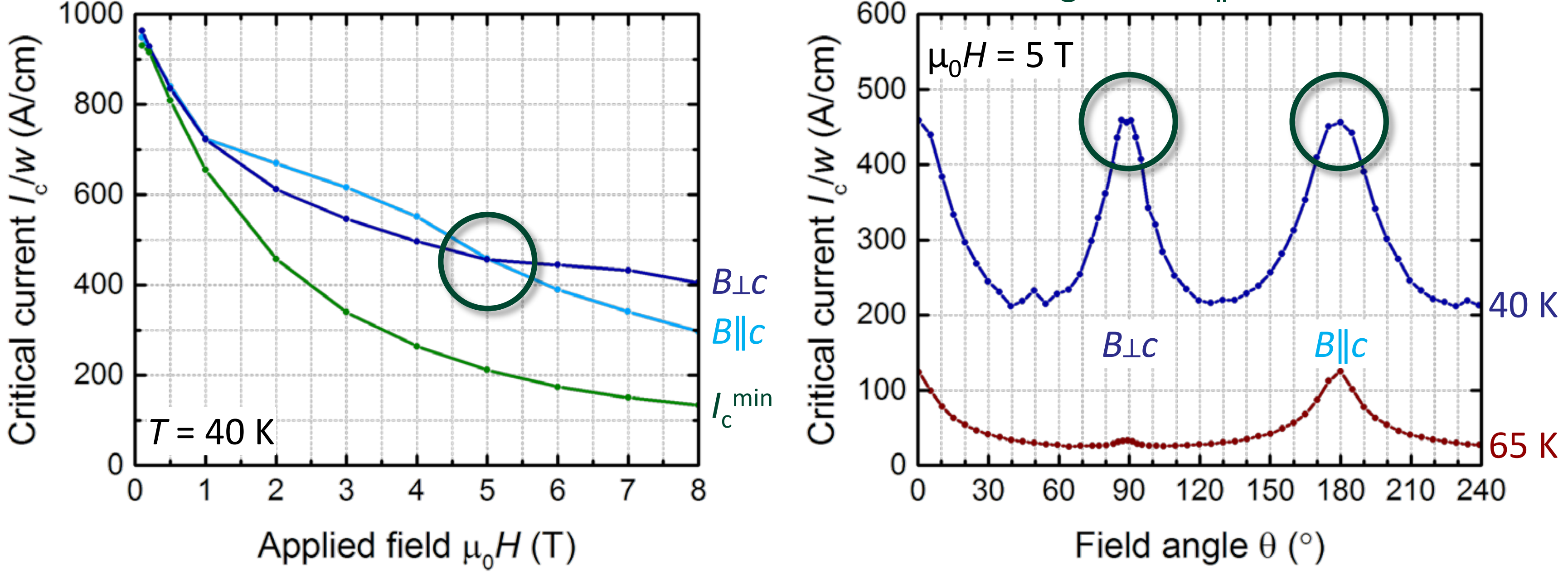




Isotropic wires?

- Nowadays, it is increasingly common for wire manufacturers to seek to introduce **correlated pinning centres** to push up $I_c(B\|c)$ with the aim of increasing the minimum I_c overall.
- The archetypal method of generating such defects is via ion irradiation to produce damage tracks in the superconductor (now being investigated for production).

AMSC 2G wire insert irradiated with 185 MeV gold ions ∥*c*

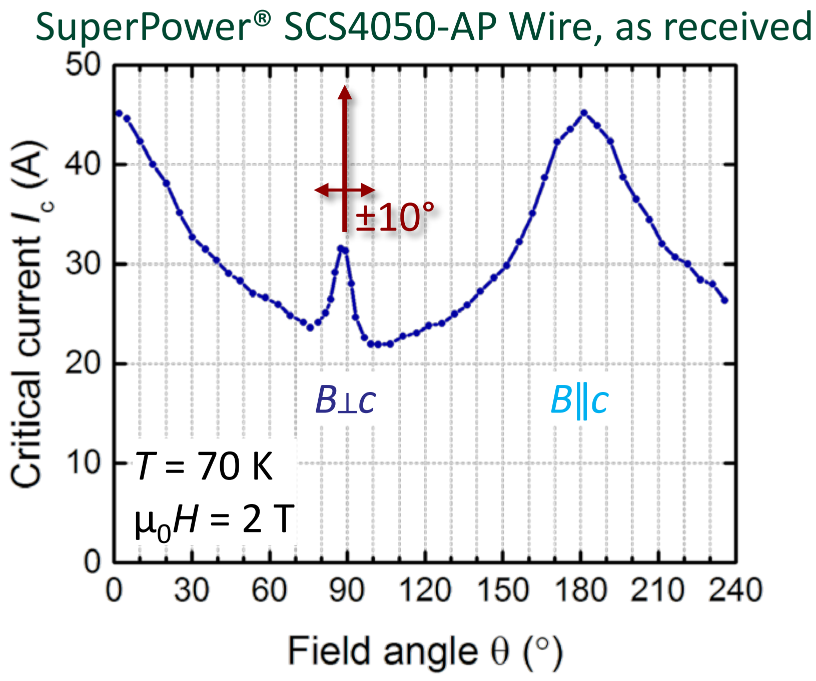


- This $B\|c$ value, taken as the minimum I_c, overestimates the true value by a factor 2 (40 K) or 5 (65 K).

Strickland and Wimbush, *IEEE Trans. Appl. Supercond.* 27 (2017) 8000505.

Comparison with real wires

- Actual production wires from many manufacturers (most notably SuperPower "Advanced Pinning" formulation) now incorporate artificial columnar pinning centres (e.g. $BaZrO_3$) that have a similar effect.



- $I_c(B \| c)$ again overestimates I_c^{min} by a factor 2 under these conditions.
- This effect is strongest to higher temperatures.

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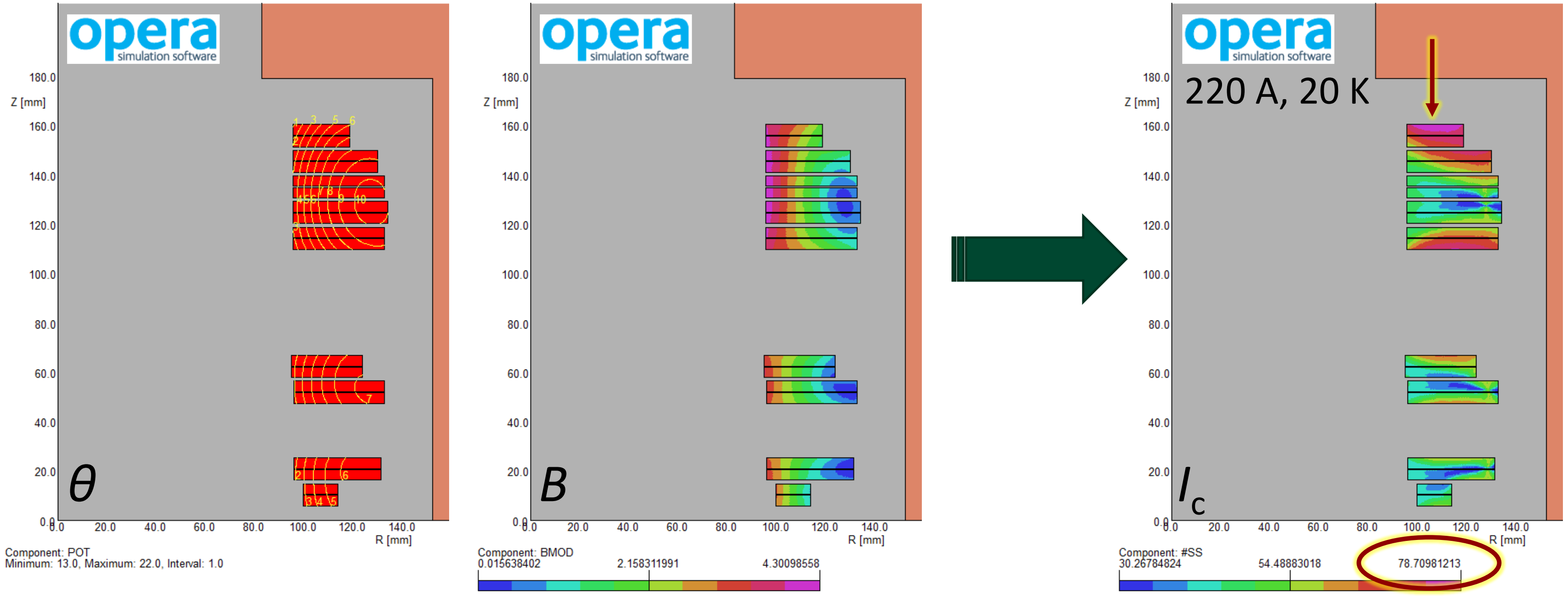
Benefits of utilising a full I_c dataset

- There are benefits of utilising a full $I_c(T,B,\theta)$ dataset in preference to a minimum I_c value.
- At the present time, the cost of wire is most often cited as the greatest impediment to the uptake of HTS technologies.
- Finite-element modelling incorporating the full $I_c(T,B,\theta)$ datasets described here can lead to significant reductions in the amount of wire required for a robust, cost-effective design.



Flux lines indicate field angle. **Colour map shows field magnitude.** **Properties are combined to show tape current as a percentage of I_c.**

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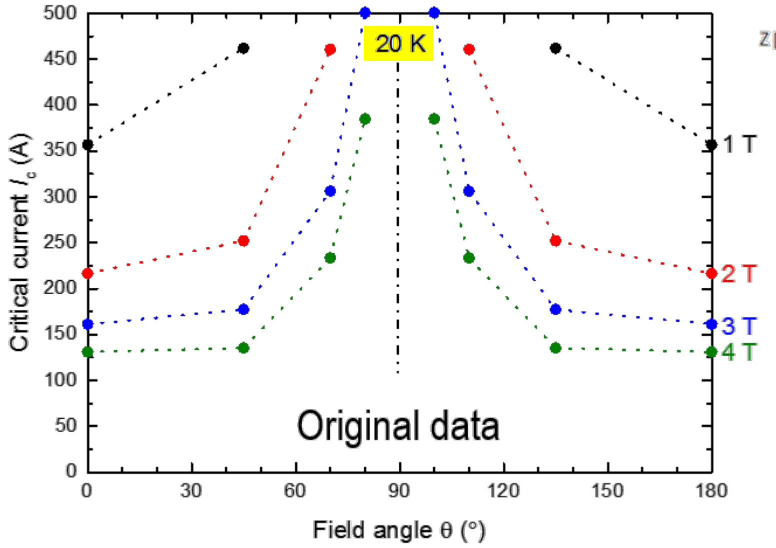
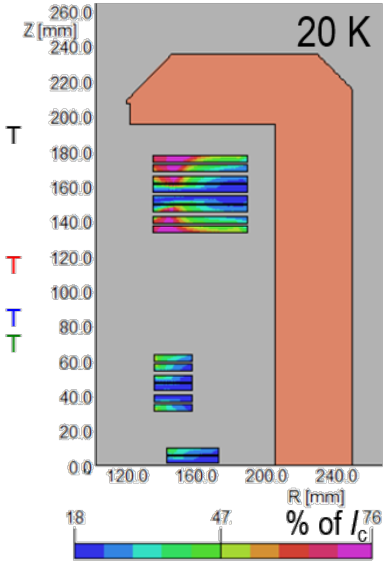
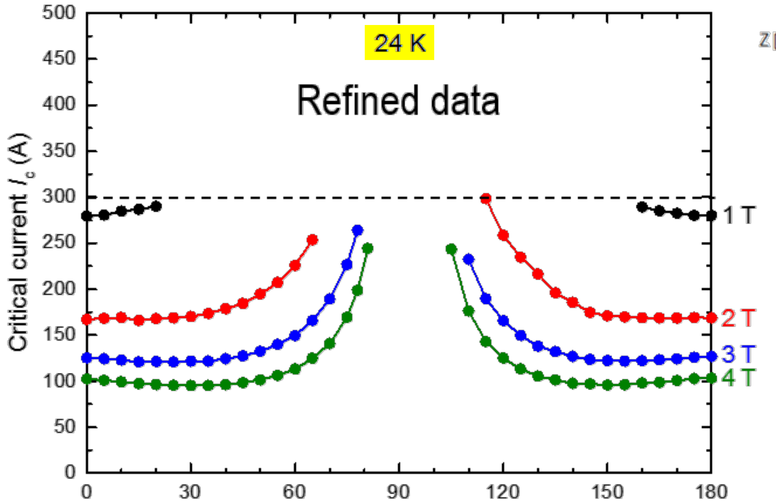
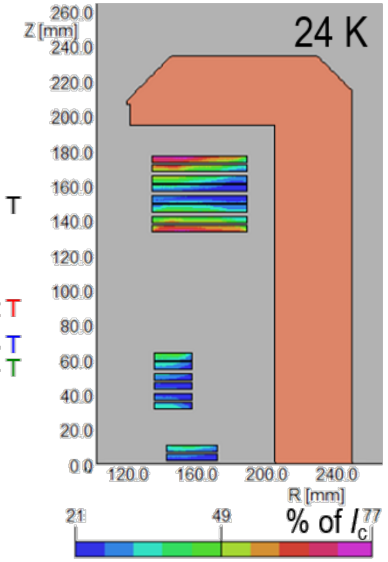
Benefits of utilising a full dataset

- Case study: **1.5 T HTS MRI design**.
  - Original design specification was for 20 K operation at a worst-case utilisation of 76% of I_c.
  - Using refined characterisation of the same wire, we were able to indicate safe operation at 24 K with approximately the same I_c utilisation.
- In this case, detailed characterisation enabled device operation at a significantly higher temperature.
- Equally, at design time, a lesser amount of wire could have been specified for 20 K operation.
- Consider the benefit over an I_c^{min}-based design!









Conclusion

- **Detailed** wire characterisation covering the full $I_c(T,B,\theta)$ parameter space is **urgently and routinely required** if efficient machines and devices are to be constructed using 2G wire.
    - Datasets acquired by the Robinson Research Institute are freely available to download from our public wire database located at http://www.victoria.ac.nz/robinson/hts-wire-database.
- Selection of 2G wire based on partial information is unlikely to be meaningful.
- Reliance on $I_c(B)$ curves for pinning-enhanced 2G wires is similarly misleading, unless those are true $I_c^{min}(B)$ curves, which anyway require full $I_c(B,\theta)$ acquisition.
    - Careful use of this data can greatly increase the efficiency of 2G device designs.