HTS 2020 Modelling

7th International Workshop on Numerical Modelling of High Temperature Superconductors
22nd – 23rd June 2021, Virtual (Nancy, France)

Utilising full angle-dependent critical current data in the electromagnetic modelling of HTS coils

Stuart C Wimbush

Nicholas M Strickland

Introduction

As the construction of real-world devices from HTS coated conductors becomes more prevalent, increasingly sophisticated modelling techniques are applied to the design process.

One aspect that remains relatively rarely touched upon in practical design methodologies is the incorporation of full anisotropic critical current data in electromagnetic modelling.

This has a number of reasons:

- Scarce availability / difficulty of acquiring such data.
- Perceived difficulty of modelling such complex behaviour.
- A possible underappreciation of the variability of this data and its impact on designs.

In this talk I will outline both a detailed methodology of incorporating this data into electromagnetic designs and illustrate by way of example the range of impacts it can have on the design process and the ultimate performance of the device.

The tools used here are chosen to be available to anyone who wishes to investigate this topic for themselves. The approaches outlined are applicable to any electromagnetic modelling package.

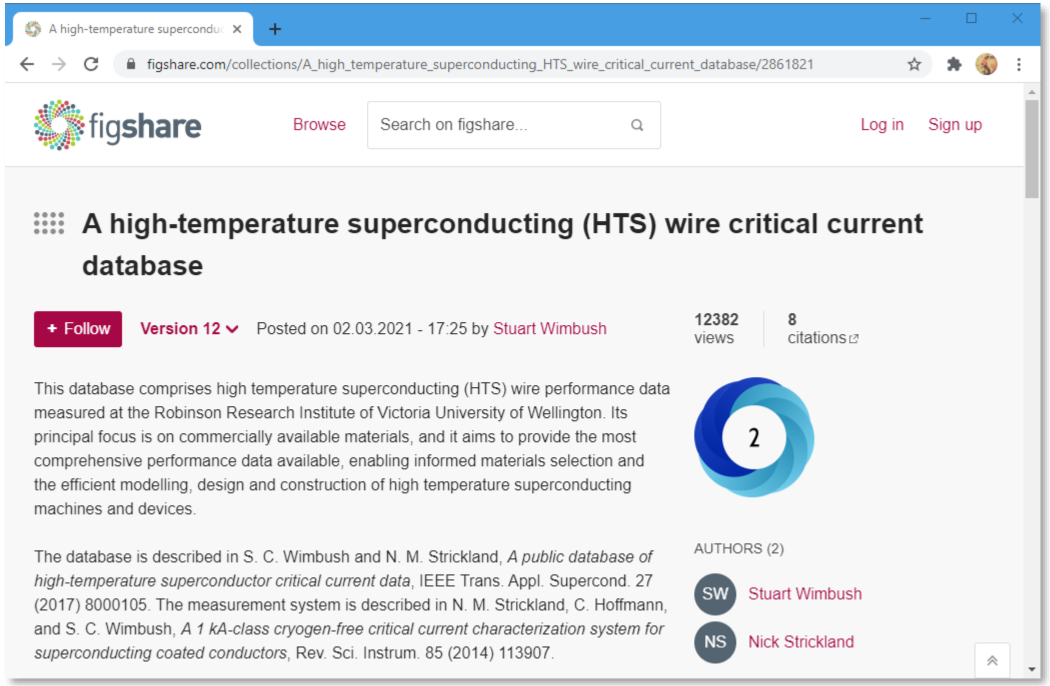
Data source

N. M. Strickland, C. Hoffmann and S. C. Wimbush.
A 1 kA-class cryogen-free critical current characterization system for superconducting coated conductors.
Rev. Sci. Instr. **85**, 113907 (2014).

SuperCurrent
I_c Measurement System

- Temperatures down to 15 K.
- Fields up to 8 T (12 T in some versions).
- Currents up to 1200 A (now 2400 A).
- **4,000 *IV* curves per day.**

Public wire I_c database https://www.robinson.ac.nz/hts-wire-database



A high-temperature superconducting (HTS) wire critical current database

Posted on 02.03.2021 - 17:25 by Stuart Wimbush

12382 views
8 citations

This database comprises high temperature superconducting (HTS) wire performance data measured at the Robinson Research Institute of Victoria University of Wellington. Its principal focus is on commercially available materials, and it aims to provide the most comprehensive performance data available, enabling informed materials selection and the efficient modelling, design and construction of high temperature superconducting machines and devices.

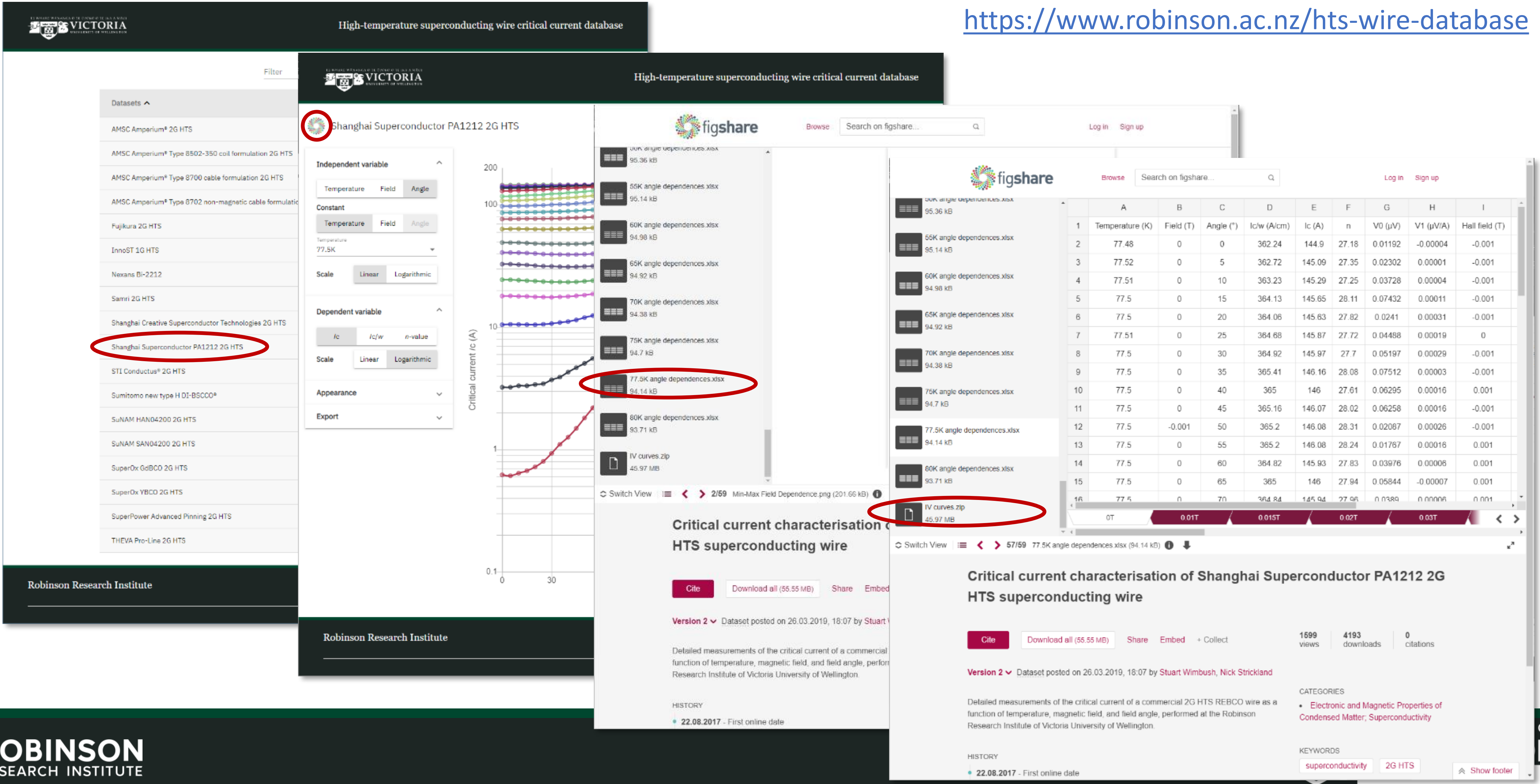
The database is described in S. C. Wimbush and N. M. Strickland, *A public database of high-temperature superconductor critical current data*, IEEE Trans. Appl. Supercond. 27 (2017) 8000105. The measurement system is described in N. M. Strickland, C. Hoffmann, and S. C. Wimbush, *A 1 kA-class cryogen-free critical current characterization system for superconducting coated conductors*, Rev. Sci. Instrum. 85 (2014) 113907.

Stuart Wimbush
Nick Strickland

Robinson public wire I_c database

S. C. Wimbush and N. M. Strickland.
A public database of high-temperature superconductor critical current data.
IEEE Trans. Appl. Supercond. **27**, 8000105 (2017).

https://www.robinson.ac.nz/hts-wire-database



High-temperature superconducting wire critical current database

Filter

Datasets

- AMSC Amperium® 2G HTS
- AMSC Amperium® Type 8502-350 coil formulation 2G HTS
- AMSC Amperium® Type 8700 cable formulation 2G HTS
- AMSC Amperium® Type 8702 non-magnetic cable formulatio
- Fujikura 2G HTS
- InnoST 1G HTS
- Nexans Bi-2212
- Samri 2G HTS
- Shanghai Creative Superconductor Technologies 2G HTS
- Shanghai Superconductor PA1212 2G HTS
- STI Conductus® 2G HTS
- Sumitomo new type H DI-BSCCO®
- SuNAM HAN04200 2G HTS
- SuNAM SAN04200 2G HTS
- SuperOx GdBCO 2G HTS
- SuperOx YBCO 2G HTS
- SuperPower Advanced Pinning 2G HTS
- THEVA Pro-Line 2G HTS

Robinson Research Institute

Shanghai Superconductor PA1212 2G HTS

Independent variable: Temperature Field **Angle**

Constant: **Temperature** Field Angle

Temperature: 77.5K

Scale: **Linear** Logarithmic

Dependent variable: **Ic** Ic/w n-value

Scale: Linear **Logarithmic**

Appearance

Export

Robinson Research Institute

- 55K angle dependences.xlsx 95.14 kB
- 60K angle dependences.xlsx 94.98 kB
- 65K angle dependences.xlsx 94.92 kB
- 70K angle dependences.xlsx 94.38 kB
- 75K angle dependences.xlsx 94.7 kB
- 77.5K angle dependences.xlsx 94.14 kB
- 80K angle dependences.xlsx 93.71 kB
- IV curves.zip 45.97 MB

Switch View 2/59 Min-Max Field Dependence.png (201.66 kB)

57/59 77.5K angle dependences.xlsx (94.14 kB)

	A	B	C	D	E	F	G	H	I
1	Temperature (K)	Field (T)	Angle (°)	Ic/w (A/cm)	Ic (A)	n	V0 (μV)	V1 (μV/A)	Hall field (T)
2	77.48	0	0	362.24	144.9	27.18	0.01192	-0.00004	-0.001
3	77.52	0	5	362.72	145.09	27.35	0.02302	0.00001	-0.001
4	77.51	0	10	363.23	145.29	27.25	0.03728	0.00004	-0.001
5	77.5	0	15	364.13	145.65	28.11	0.07432	0.00011	-0.001
6	77.5	0	20	364.06	145.63	27.82	0.0241	0.00031	-0.001
7	77.51	0	25	364.68	145.87	27.72	0.04488	0.00019	0
8	77.5	0	30	364.92	145.97	27.7	0.05197	0.00029	-0.001
9	77.5	0	35	365.41	146.16	28.08	0.07512	0.00003	-0.001
10	77.5	0	40	365	146	27.61	0.06295	0.00016	0.001
11	77.5	0	45	365.16	146.07	28.02	0.06258	0.00016	-0.001
12	77.5	-0.001	50	365.2	146.08	28.31	0.02087	0.00026	-0.001
13	77.5	0	55	365.2	146.08	28.24	0.01767	0.00016	0.001
14	77.5	0	60	364.82	145.93	27.83	0.03976	0.00006	0.001
15	77.5	0	65	365	146	27.94	0.05844	-0.00007	0.001
16	77.5	0	70	364.84	145.94	27.96	0.0389	0.00006	0.001

0T 0.01T 0.015T 0.02T 0.03T

Critical current characterisation of Shanghai Superconductor PA1212 2G HTS superconducting wire

Cite Download all (55.55 MB) Share Embed + Collect

1599 views 4193 downloads 0 citations

Version 2 Dataset posted on 26.03.2019, 18:07 by Stuart Wimbush, Nick Strickland

Detailed measurements of the critical current of a commercial 2G HTS REBCO wire as a function of temperature, magnetic field, and field angle, performed at the Robinson Research Institute of Victoria University of Wellington.

HISTORY

- 22.08.2017 - First online date

CATEGORIES

- Electronic and Magnetic Properties of Condensed Matter; Superconductivity

KEYWORDS

superconductivity 2G HTS

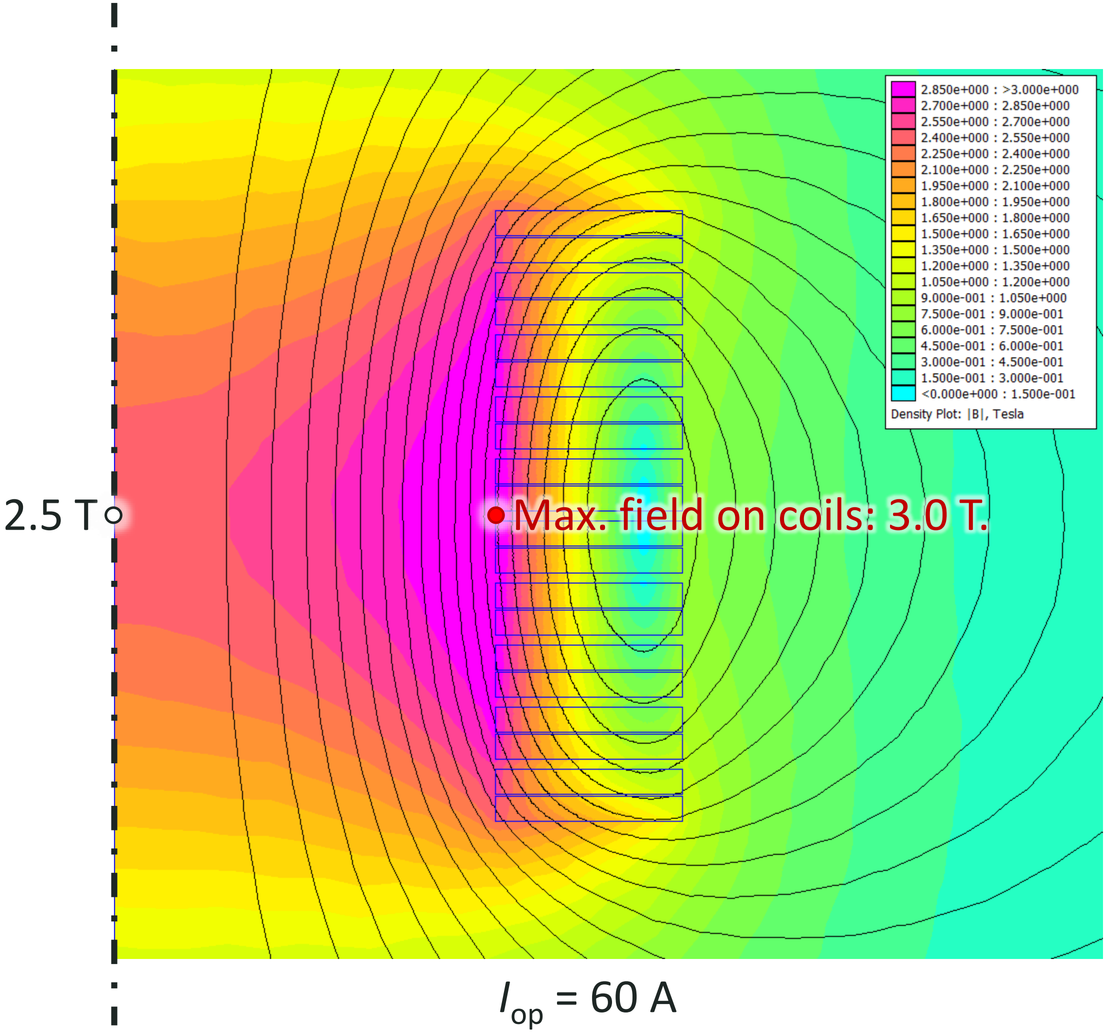
Show footer

ROBINSON
RESEARCH INSTITUTE

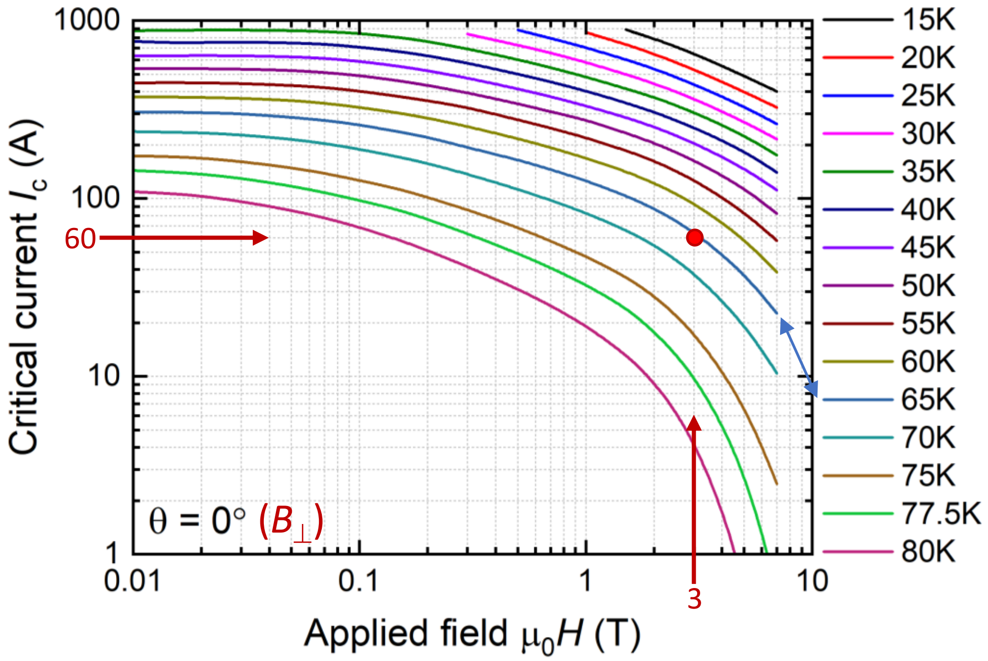
Electromagnetic modelling

D. C. Meeker.
Finite Element Method Magnetics, Version 4.2 (28Feb2018 Build).
https://www.femm.info.

Central field target: 2.5 T.

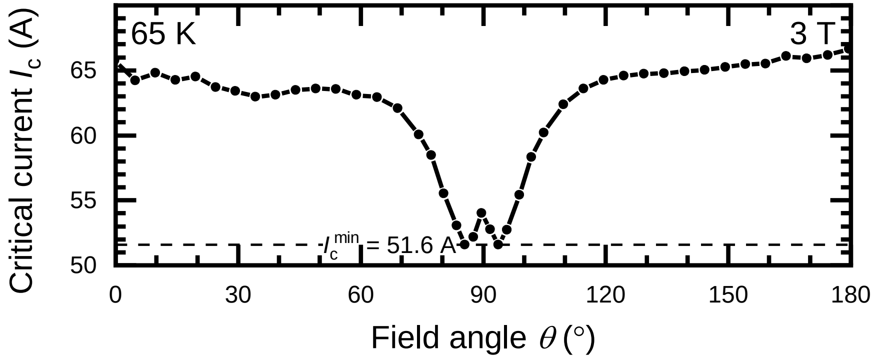


I_{op} = 60 A



Operating temperature < 65 K.

0° (field perpendicular) is **not** minimum I_c!



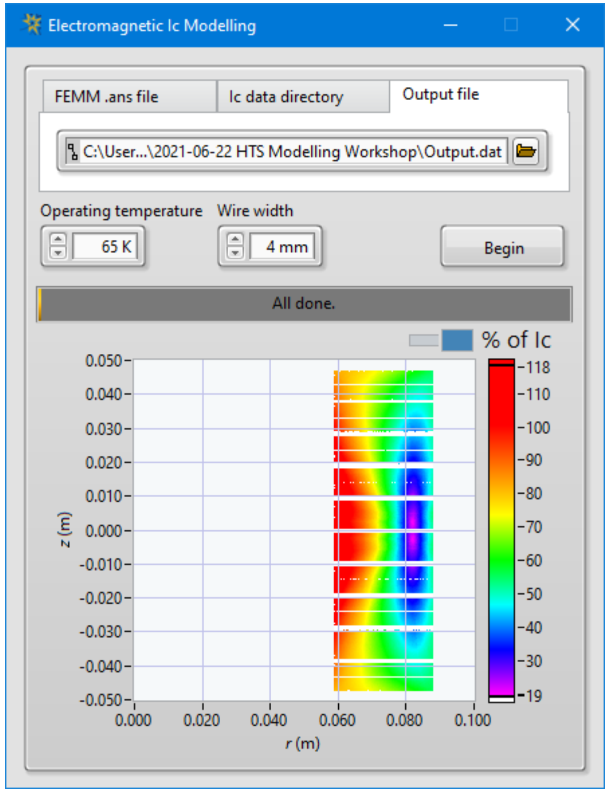
Utilise full angle-dependent I_c dataset

- Export (B,θ) values at each element in the mesh.
  - (In FEMM, you need to process the potentials to give **B**. Other packages may provide a direct export.)
  - For the 2D axisymmetric case, the components are B_r ($B_\perp$) and B_z ($B_{||}$), which is very convenient.
  - In 3D, need to process the three components of **B**, neglecting any in-plane variation in I_c.

- For a given operating temperature, we then have a {T,B,θ} triplet at each element of the mesh that can be used to lookup an interpolated $I_c(T,B,\theta)$ table to yield a local I_c value at each mesh element within the conductor.

- The operating current I_{op} as a percentage of this local I_c tells us what fraction of I_c we are operating each point in the coil at.

- A utility to perform this process for any FEMM model and SuperCurrent I_c dataset is available at https://github.com/scwimbush/Electromagnetic-Ic-Modelling.



Electromagnetic Ic Modelling

Output file: C:\User...\2021-06-22 HTS Modelling Workshop\Output.dat

Operating temperature: 65 K

Wire width: 4 mm

All done.

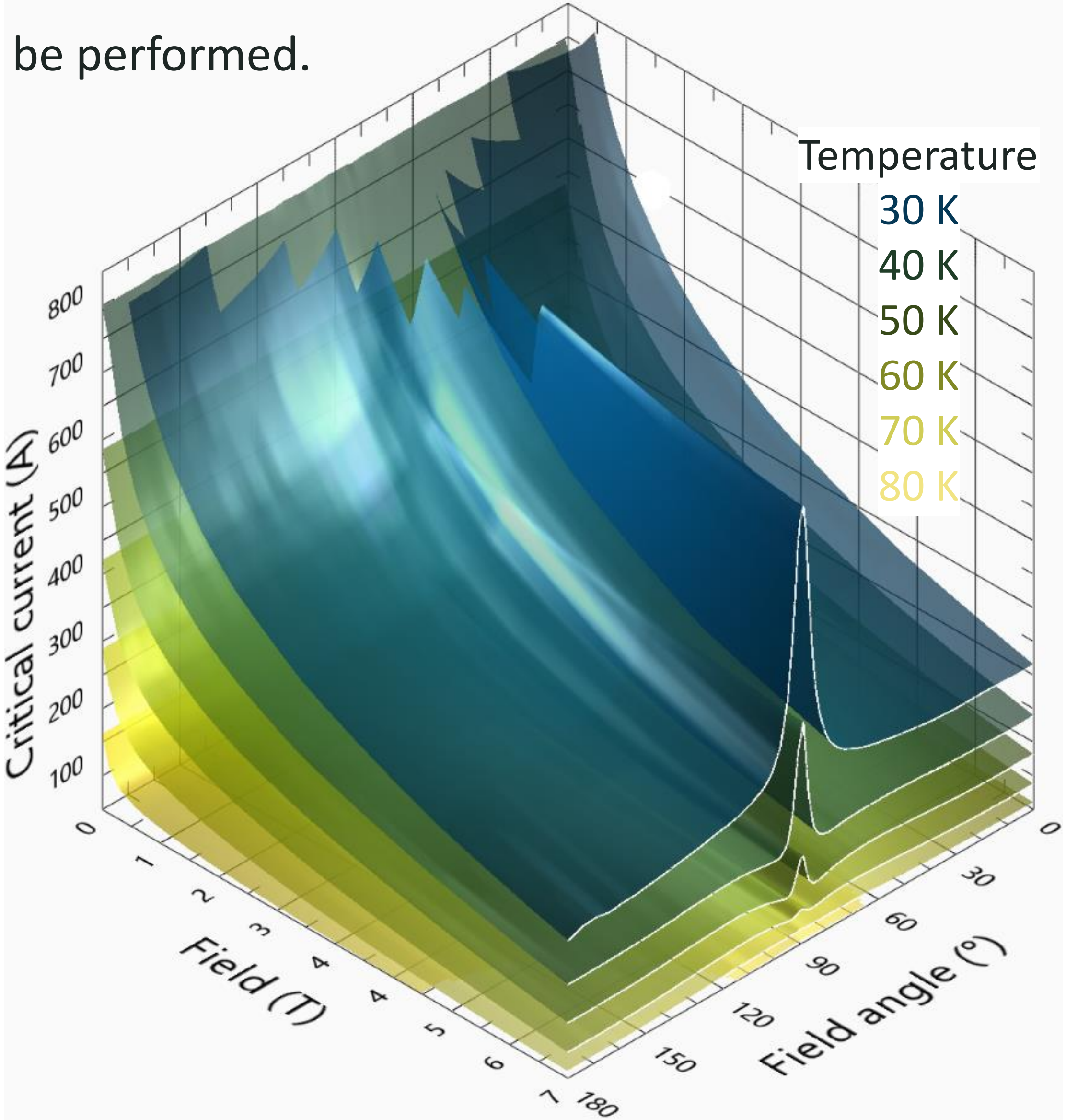
Interpolation of $I_c(T,B,\vartheta)$ datasets

With datasets of our density, extremely good interpolations can be performed.

Simple point-to-point interpolations, with a few tricks:

- First interpolate the angle dependences – smoothly varying.
- Then at each interpolated angle:
  - Interpolate the field dependences *logarithmically*.
  - Interpolate the temperature dependences linearly.

Doing these interpolations is the slowest part of the analysis.



Presently strictly an **inter**polation;
extrapolation is challenging to perform robustly and reliably.

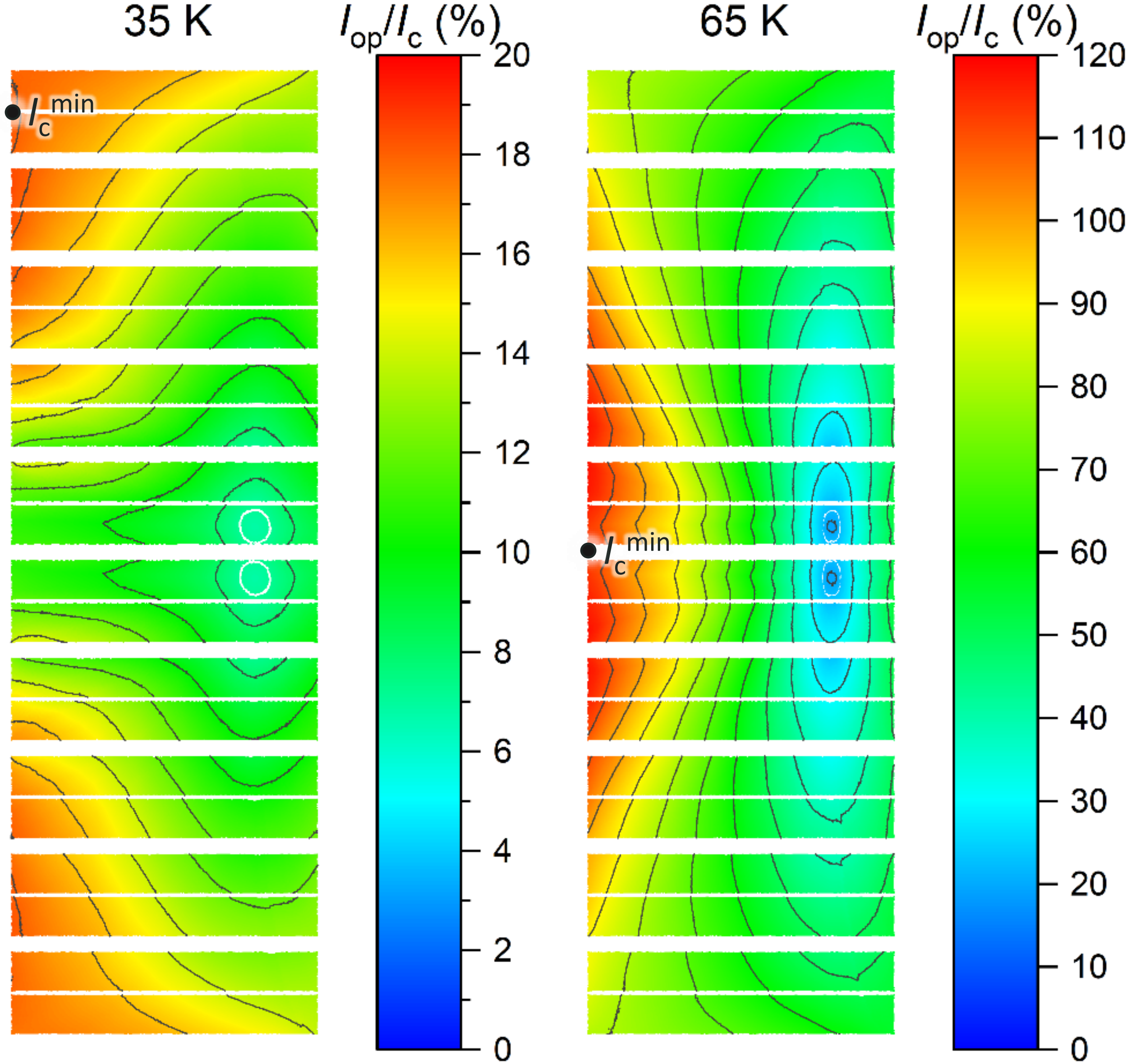
Results of I_c lookup

Looking at the I_c map across the conductor at our first proposed operating temperature of 65 K, we see:

- The critical point on the coils is the high field (fully in-plane!) region at the centre of the coil pack.
- We are 20% short of the performance required to operate.

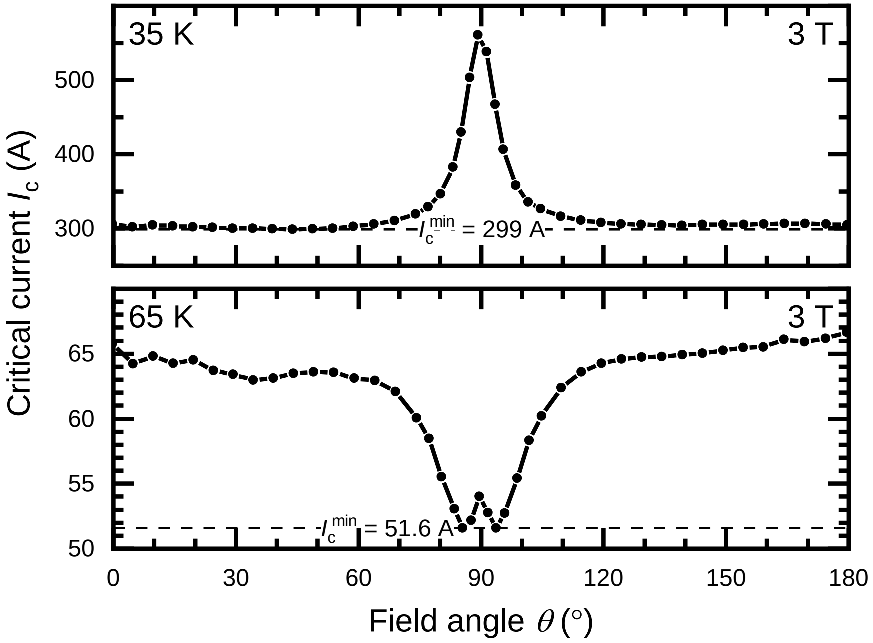
Refining the analysis at different temperatures shows we could expect to operate at 62 K, approximately as predicted by the (true) minimum I_c analysis. (This is the case because the field angle at the critical point coincides with the angle of minimum I_c.)

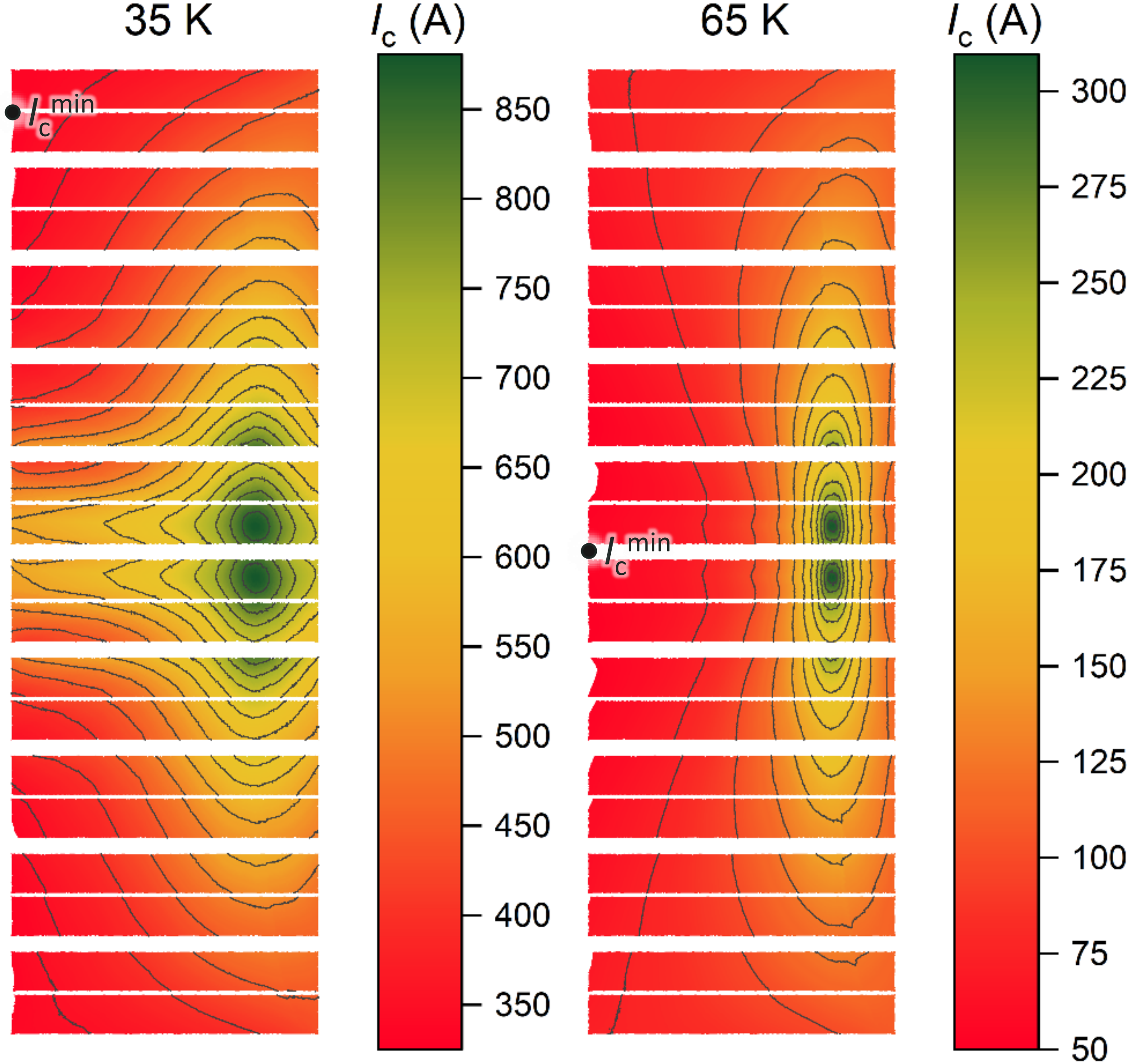
If we drop the operating temperature to 35 K, the critical point shifts to the more commonly observed inner edge of the end coils, where a moderate field strength and an unfavourable field direction combine. Here a minimum I_c analysis would underestimate the available I_c.



Results of I_c lookup

The reason for the shift in position of the critical point with temperature is evident upon comparison of the angle dependence of I_c under the different conditions.





This aspect of real wire behaviour cannot be captured by $I_c(B_{||}, B_{\perp})$ field dependences alone.

Applications

Hybrid windings

W. Song, Z. Jiang, M. Staines, S. C. Wimbush, R. A. Badcock and J. Fang.
AC loss calculation on a 6.5 MVA/25 kV HTS traction transformer with hybrid winding structure.
IEEE Trans. Appl. Supercond. **30**, 5500405 (2020).

Now we know exactly where in the coil pack the critical region occurs, we can replace selected coils with higher performance wire, or simply stack the coils we have on hand in an appropriate order.

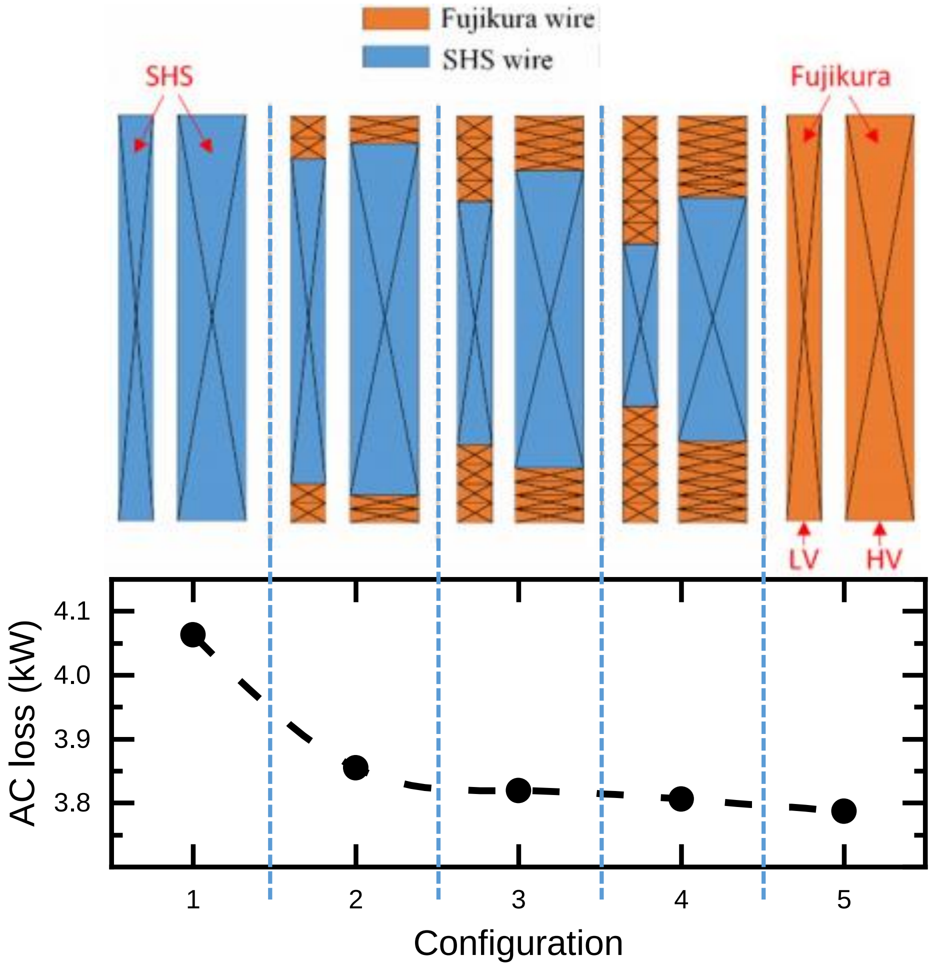
In the example presented so far, at 65 K:

- End coils I_{op}/I_c = 90%.
- Mid coils I_{op}/I_c = 120%. → Substitute better wire for these coils (only).

Many manufacturers provide wire with different performance specifications or we can select the most appropriate wire from multiple manufacturers.

This extends beyond operating current to other performance metrics.

In the real-world example of our traction transformer design, we can lower the overall ac loss by 5–10% by incorporating relatively small quantities of high-performance wire in the right places.



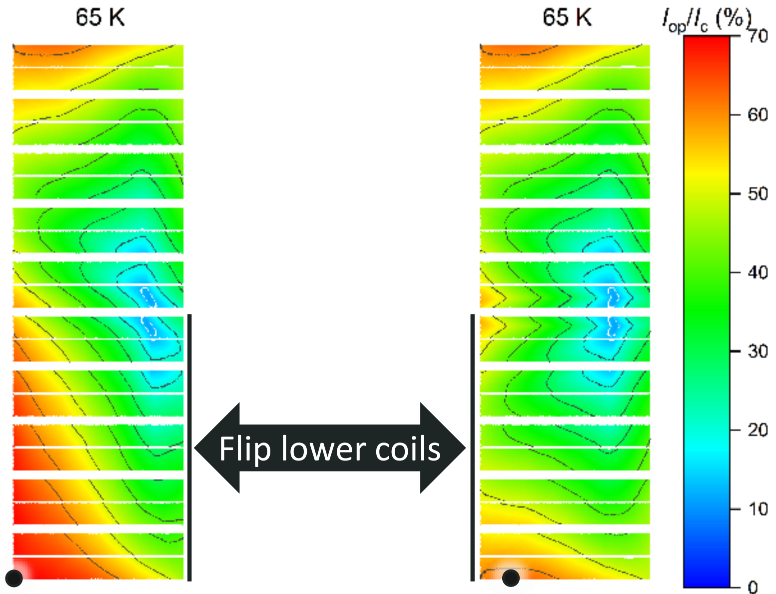
Flipped coils

Z. Jiang, W. Song, X. Pei, J. Fang, R. A. Badcock and S. C. Wimbush.
15% reduction in AC loss of a 3-phase 1 MVA HTS transformer by exploiting asymmetric conductor critical current.
J. Phys. Commun. **5**, 025003 (2021).

Now that we explicitly take account of the real anisotropy of the conductors, not an approximate functional form, we can exploit detailed characteristics such as asymmetry either side of the in-plane peak.

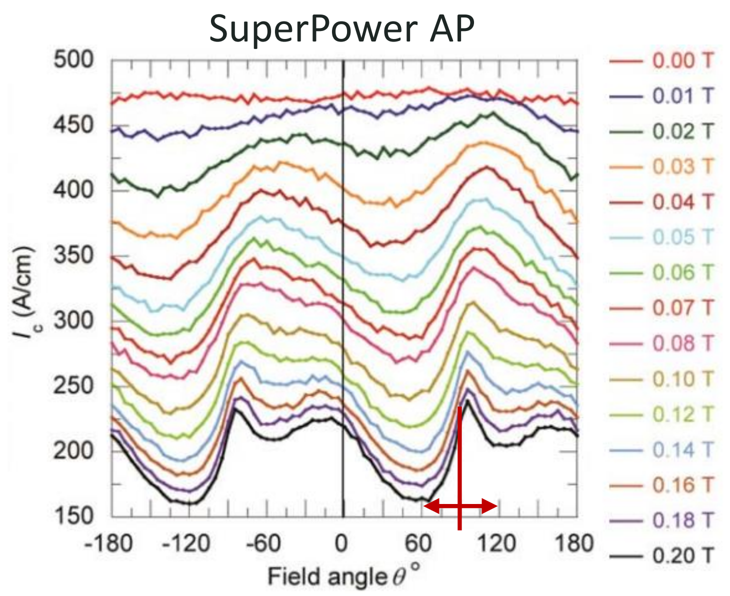
For some conductors, this is not strongly evident, but for some it is.

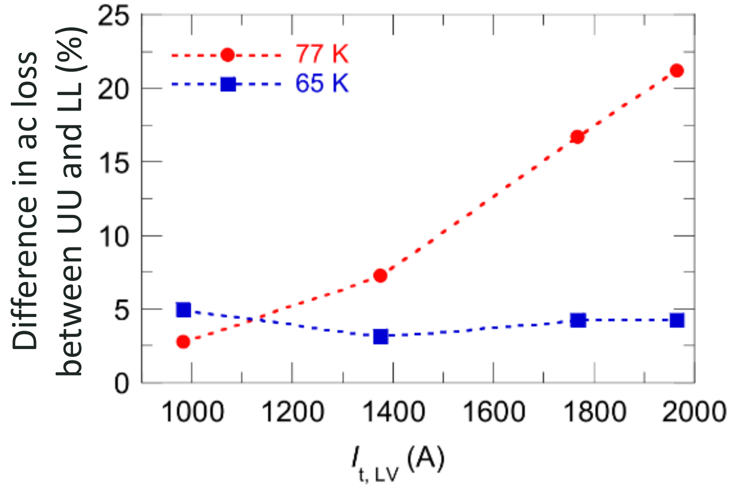
Taking advantage of this is as easy as ensuring the "correct" orientation of the coils when they are stacked.



I_{op}/I_c max.
70%

I_{op}/I_c max.
63%

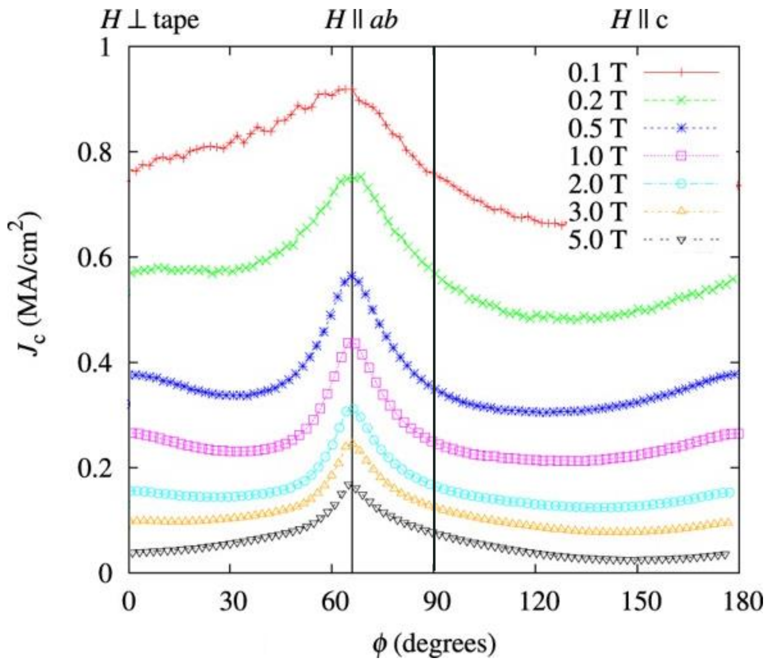




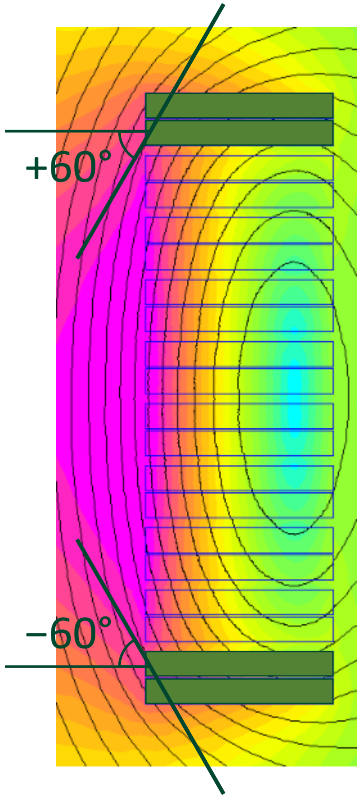
Inclined planarity coated conductors

M. Lao, J. Bernardi, M. Bauer and M. Eisterer.
Critical current anisotropy of GdBCO tapes grown on ISD-MgO buffered substrate.
Supercond. Sci. Technol. **28**, 124002 (2015).

Inherent asymmetry tends to be evident only at relatively low fields. But we can intentionally select a conductor (e.g. one produced by inclined substrate deposition) that is particularly appropriate to the required operating conditions. In this case, we must ensure correct orientation and we would also only utilise such a conductor in the relevant locations in the coil pack.



THEVA



To our knowledge, no such demonstrator has yet been produced.

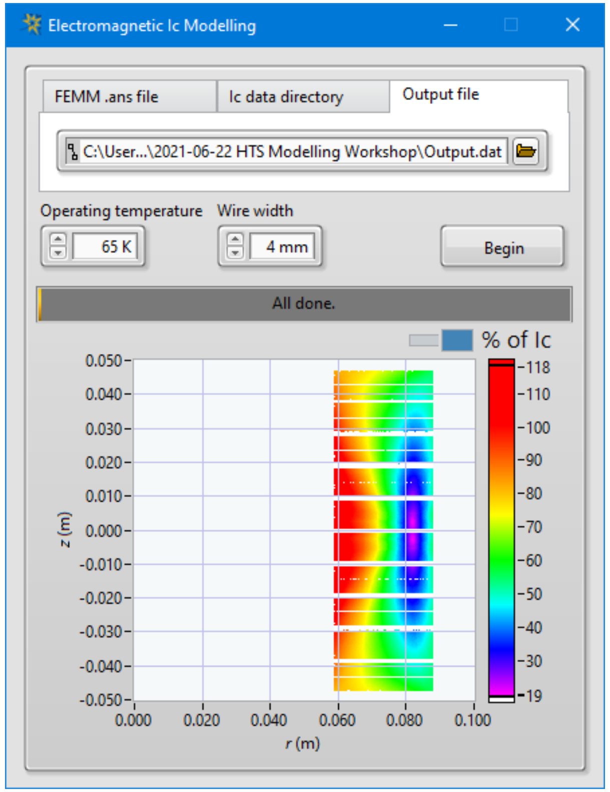
Summary

Summary

- Electromagnetic modelling utilising full angle-dependent I_c data is tractable.
- Exemplary I_c datasets are available to trial and refine techniques.
- Targeted data acquisition for specific projects is feasible.

- Such modelling reveals features of device design that could otherwise lead to failure.
- Optimisation of real-world devices offers a 10–20% enhancement in performance leading to real benefits.

- These analyses lead to novel design features such as:
  - Hybrid windings.
  - Flipped coils.
  - Inclined planarity conductors.



Electromagnetic Ic Modelling

FEMM .ans file | Ic data directory | Output file

C:\User...\2021-06-22 HTS Modelling Workshop\Output.dat

Operating temperature: 65 K

Wire width: 4 mm

All done.

Thank you for your attention!

https://www.robinson.ac.nz/hts-wire-database

https://github.com/scwimbush/Electromagnetic-Ic-Modelling