Paihau—Robinson Research Institute

VICTORIA UNIVERSITY OF WELLINGTON
TE HERENGA WAKA

Design of a Bifilar HTS Switching Element Using Iron-Core Field Coils

J.H.P. Rice[1], J. Geng[1], R.A. Badcock[1], D.A. Moseley[1], H. Zhang[2] and S. Wray[2].

[1]Robinson Research Institute, Victoria University of Wellington, New Zealand

[2]UK Atomic Energy Authority, Culham, Oxfordshire, United Kingdom

Paihau—Robinson Research Institute
VICTORIA UNIVERSITY OF WELLINGTON TE HERENGA WAKA

Outline

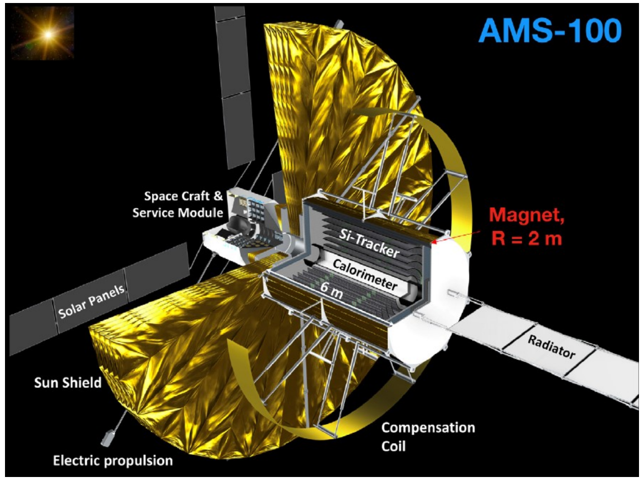
- HTS Flux Pumps for Low Inductance Magnets
- Design of an HTS Switching Element
- Testing of the HTS Switch
  - Critical Current Measurements
  - Finite-Element Modelling
- Conclusions

Background

<u>Low-inductance (<1 H) superconducting magnets</u>

- low-power, high-field magnets
- Useful for space, fusion energy applications

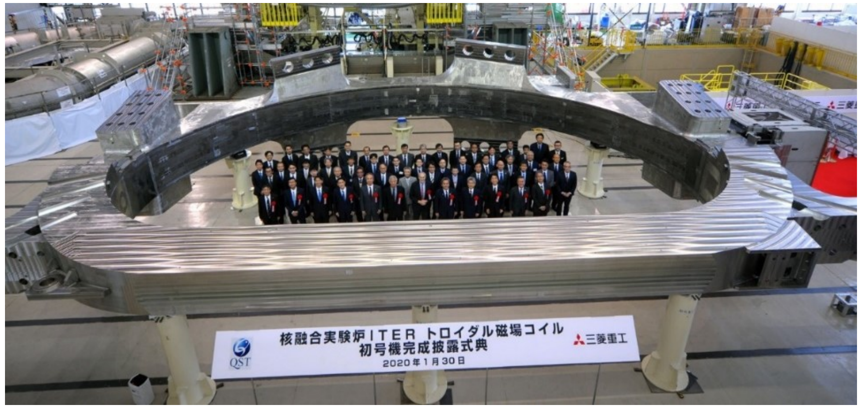
AMS-100 Spectrometer
(13.5 kA – 1.0 T - REBCO) [2]
[AMS-100 Whitepaper]



However,

- High current required (>10 kA)
- Solid-state current supplies:
  - size, weight limitations
- Light-weight, cheaper alternative needed…

CFS – SPARC Test coil
(~40 kA – ~12 T – REBCO) [1]
[MIT News]



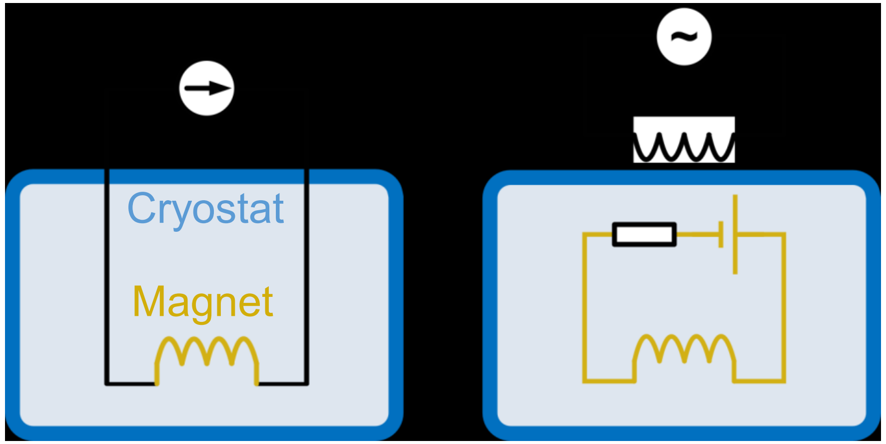
ITER – 1st Toroidal Field Coil
(68 kA – 5.3 T – Nb_3Sn) [3]
https://www.iter.org/newsline/-/3393

[1] A. J. Creely *et al.*, *J. of Plasma Phys.*, 86 5 (2020).
[2] S. Schael *et al.*, *Nucl. Instr. and Methods in Phys. Res. A*, 944 162561 (2019).
[3] C. Sborchia *et al.*, *IEEE Trans. Appl. Supercond.*, 18 2, 463–466 (2008).

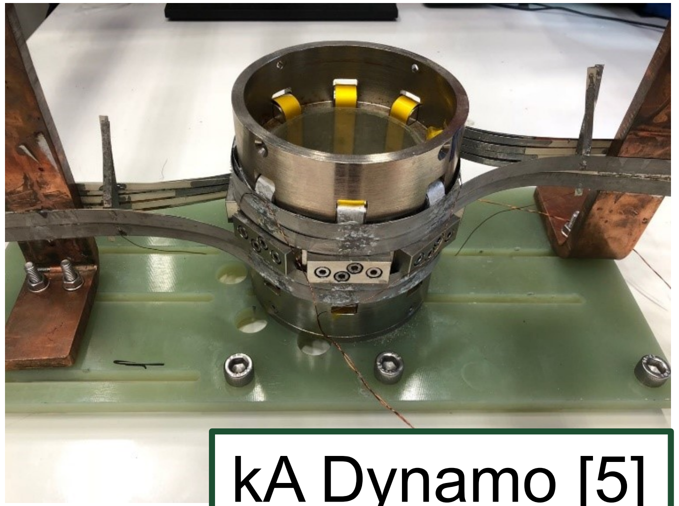
HTS Flux Pumps

Superconducting (SC) current supplies

- Intra-cryostat operation **– no feedthrough** [4]
  - Reduced cryogenic heat load
- Demonstrated **kA current output** [5, 6]
- *Low-power, high-current* supply systems
  - Well suited to **powering low-L magnets**!

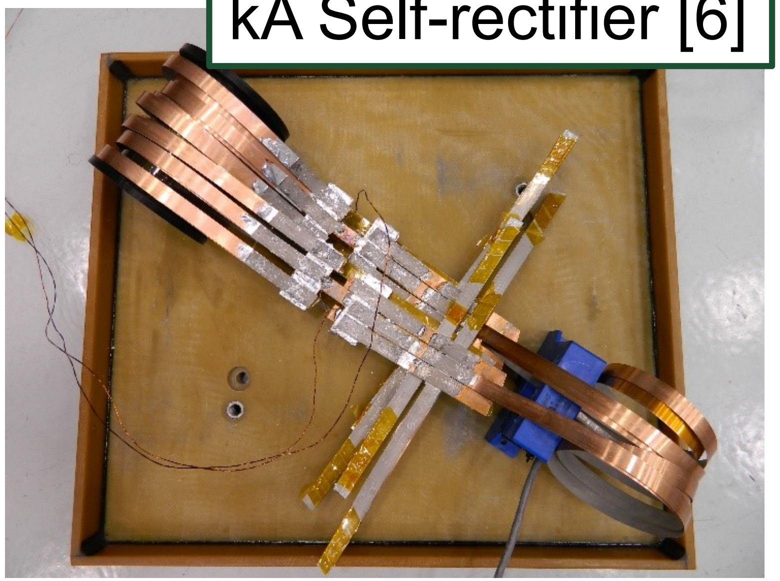


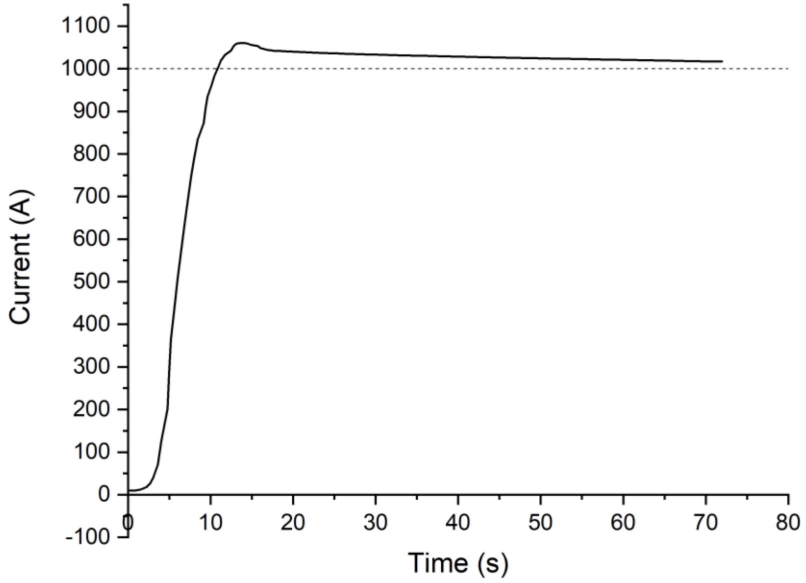
Current Leads Flux Pump



kA Dynamo [5]

kA Self-rectifier [6]



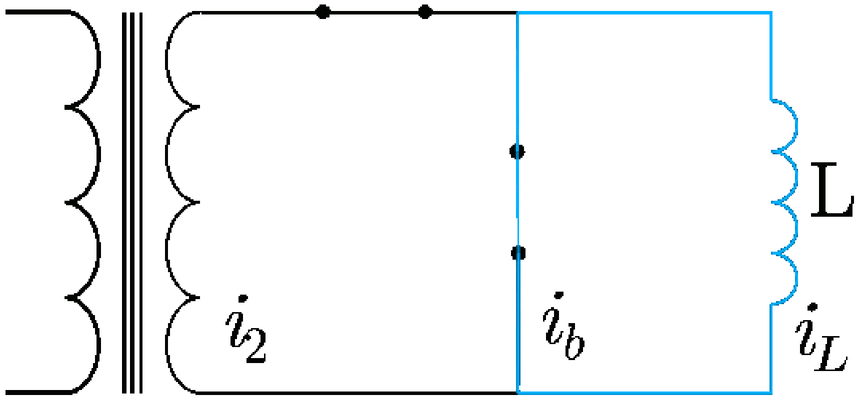


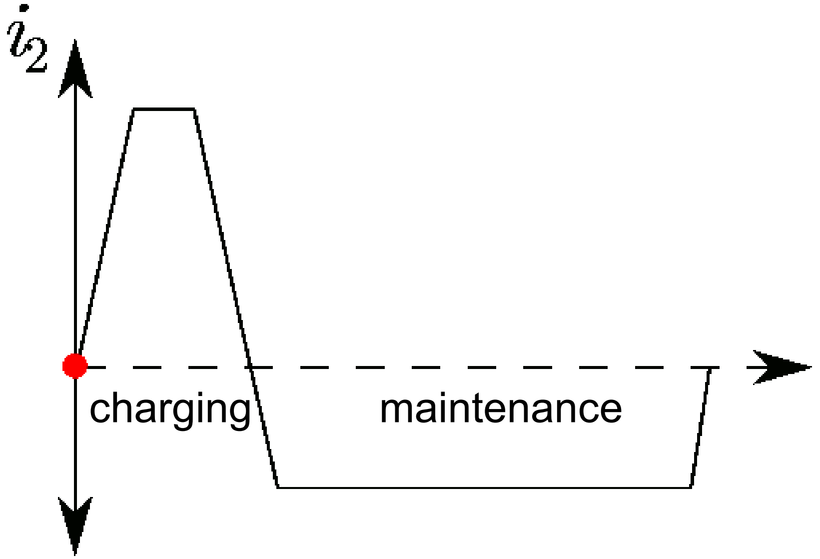
[4] C. W. Bumby *et al*, *IEEE Trans. Appl. Supercond.* **26** (4), 1–5 (2016).
[5] J. Geng *et al*, *Supercond. Sci. Technol.*, **33** (4), 045005 (2020).
[6] K. Hamilton *et al*, *IEEE Trans. Appl. Supercond.*, **28** (4), 1–5 (2018).

HTS Flux Pump – Transformer-Rectifier

- Controllable resistance → active switching
  - Similar operation to solid-state rectifier
- AC current → DC voltage rectifier
  - Current induced in SC by transformer
  - Switching by variable bridge resistance [7]
  - Transformer→rectifier
- "Closed"-state bridge short circuits load
  - Maintains load current with minimal loss [8]

→ *Superconducting switch required*





[7] J. Geng *et al*, *Appl. Phys. Lett.*, **108** (26), 262601 (2016).
[8] S. Lee *et al.*, *IEEE Trans. Appl. Supercond.*, **26** (4), 1–4 (2016).

HTS Switch Element

Practical switch topology [9]:

- applied magnetic field $B_{a,\perp}$ actuates switch
- *Actively controllable resistivity*

"$J_c(B)$-switching" [10]:

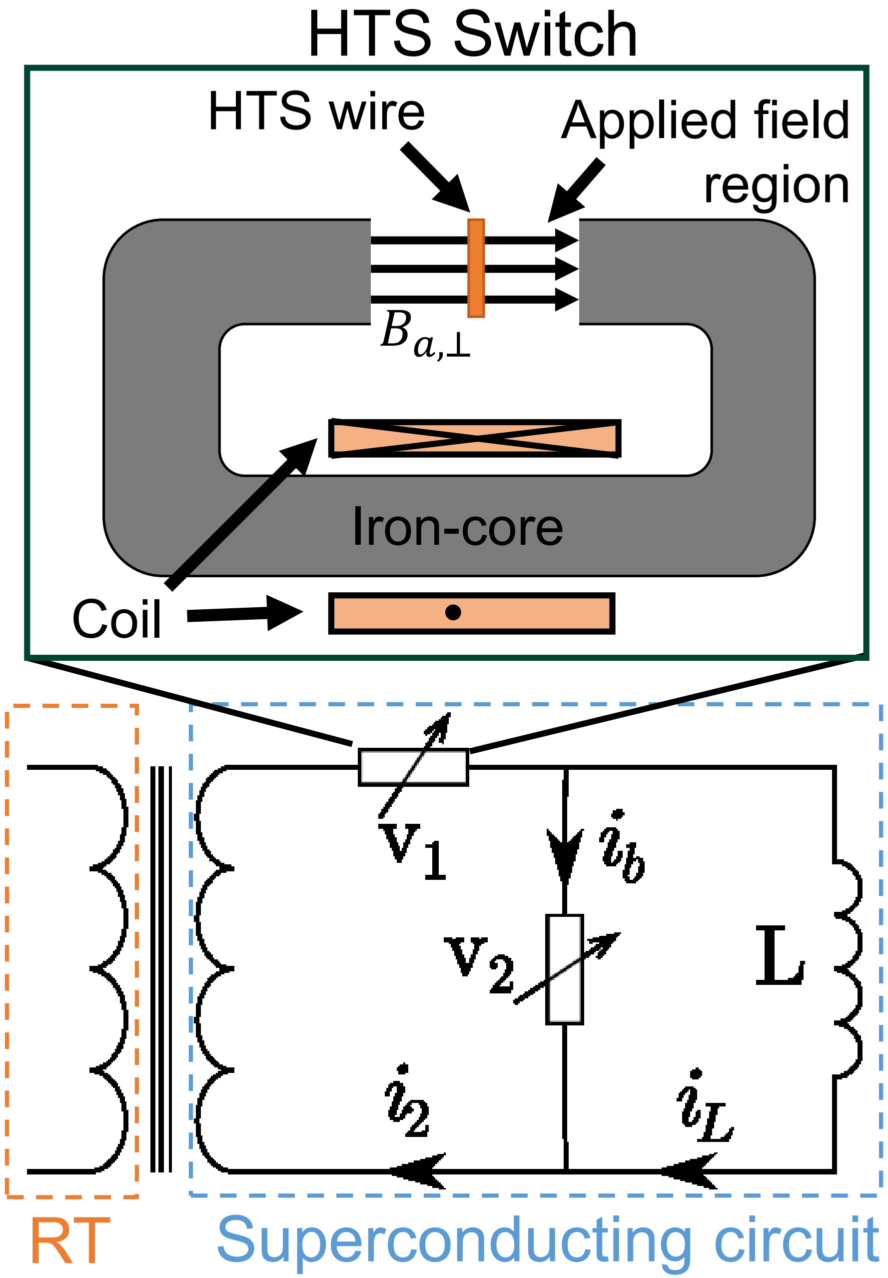
- Non-linear resistivity – E-J power law [11]

$$V(I) = E_0 l \left(\frac{I}{I_c(B_{a,\perp})}\right)^n \qquad E_0 = 1\,\mu V/cm$$

  - Voltage produced when $I_t \gtrsim I_c(B_{a,\perp})$

- Better switching from more I_c modulation [12]

$$\rightarrow \text{Switching ratio } \kappa = \frac{\text{self field}}{\text{applied field}} = \frac{I_c(0)}{I_c(B_{a,\perp})}$$



[9] J. Geng and T. A. Coombs, *Appl. Phys. Lett.*, **107** (14), 142601, (2015).
[10] B. Leuw *et al.*, Submitted Manuscript (2021).
[11] E. H. Brandt, *Phys. Rev. B*, **54** (6), 4246–4264 (1996).
[12] J. H.P. Rice *et al.*, accepted manuscript (2021).

Motivation

- Explore physics of switch behaviour
- Investigate ex situ (outside flux pump)

Unknowns in switch behaviour/design:

- Critical current? ← switching mechanism
- Inductance? ← circuit behaviour
- Use of cables? ← necessary for >10 kA
- Field screening? ← reduced applied field

Initially focus on critical current, as it limits flux pump output [13]

[13] J. Geng *et al*, *Supercond. Sci. Technol.*, **33** (4), 045005, (2020).

Switch Testing – Critical Current

HTS switch element – SuNAM SCN06300 – (GdBCuO, 1.3 μm, $I_{c,77\,\mathrm{K}}$ = 357±5 A)

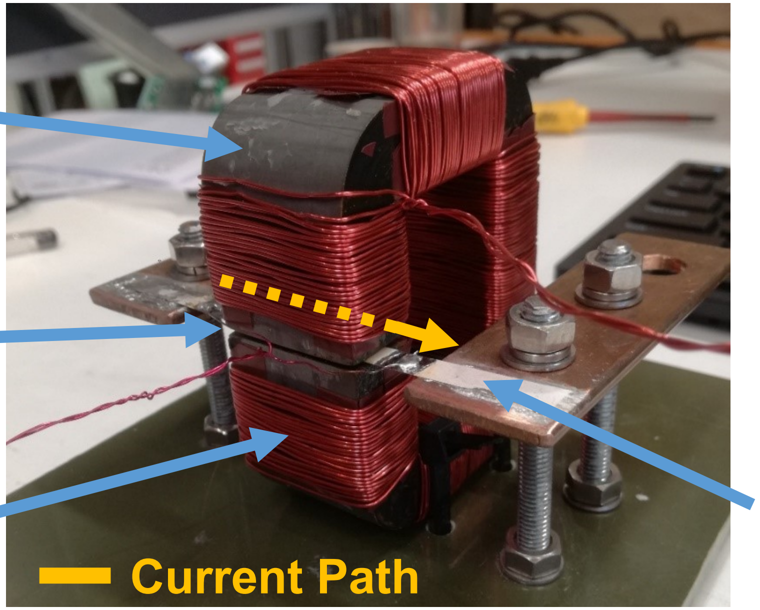
- Ex situ critical current measurements < 800 A
- Calibrated $J_c(B)$-switch electromagnet – linear field < 1.1 T
- Applied field in iron-core 1 mm air-gap – switch-element location
- Setups:

"unifilar" (single pass)

Soft iron core

1 mm Air gap

405 turns



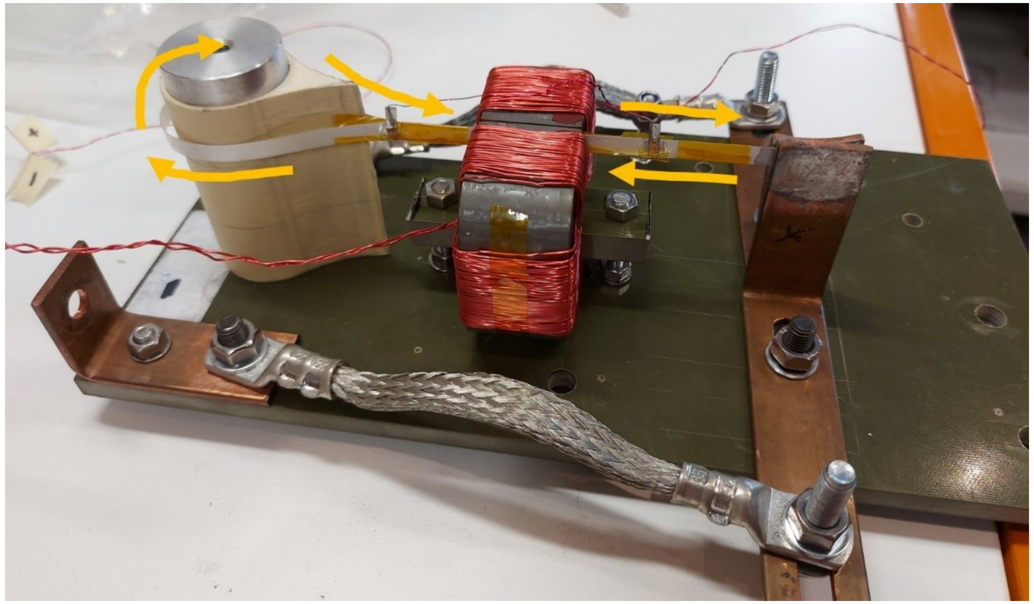
6 mm 2G HTS

Single Tape "Unifilar"

>

Inductance

"bifilar" (return pass)



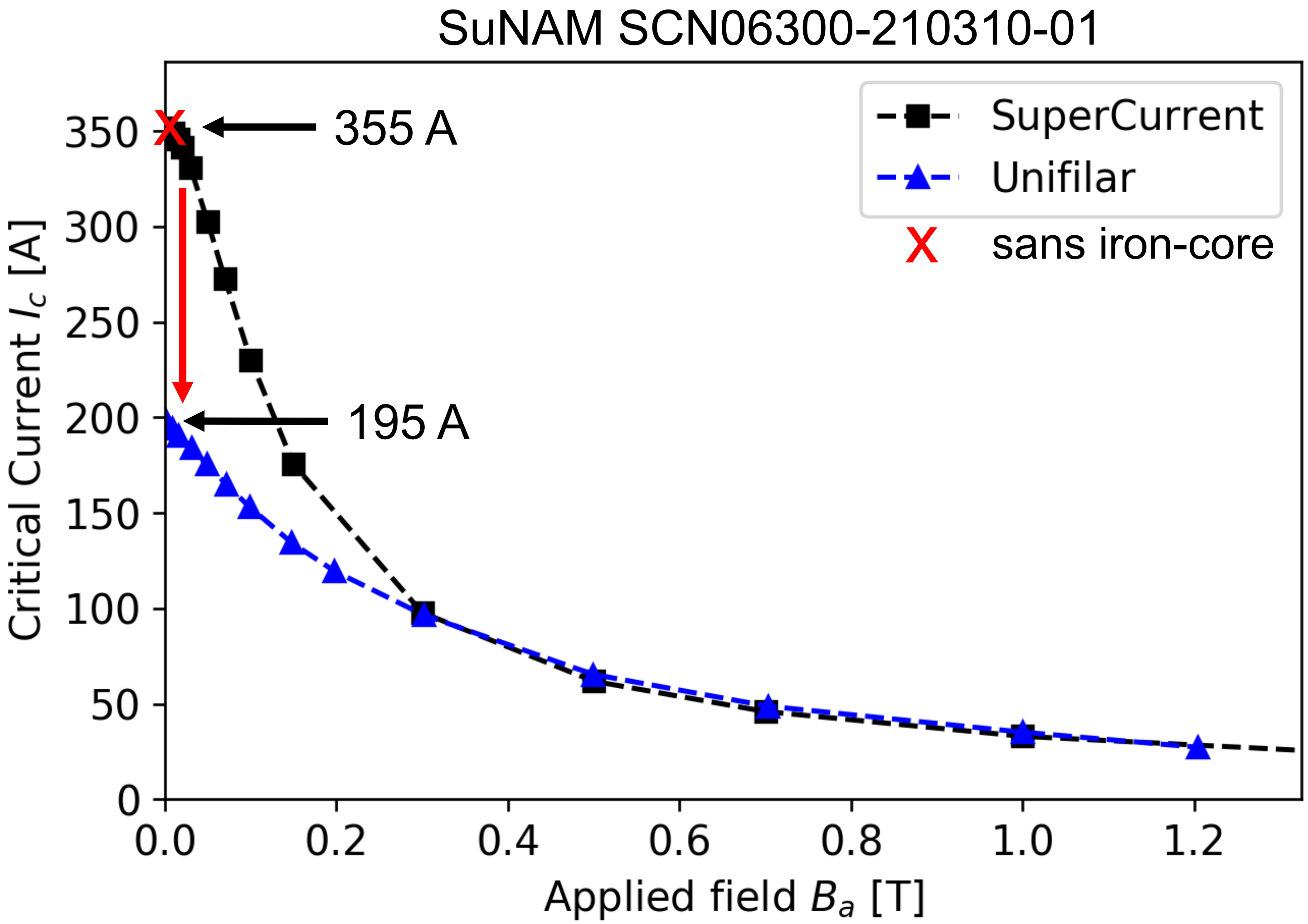
Return Loop "Bifilar"

Experimental Results – Iron-core Switch

- Switch I_c compared to SuperCurrent HTS wire database [13,14]
- **Self-field I_c reduced 45%** in iron-core switching element
- Converges at higher applied field above 0.3 T

Hypothesis:

- **Iron-core electromagnet limits current capacity of switching element**



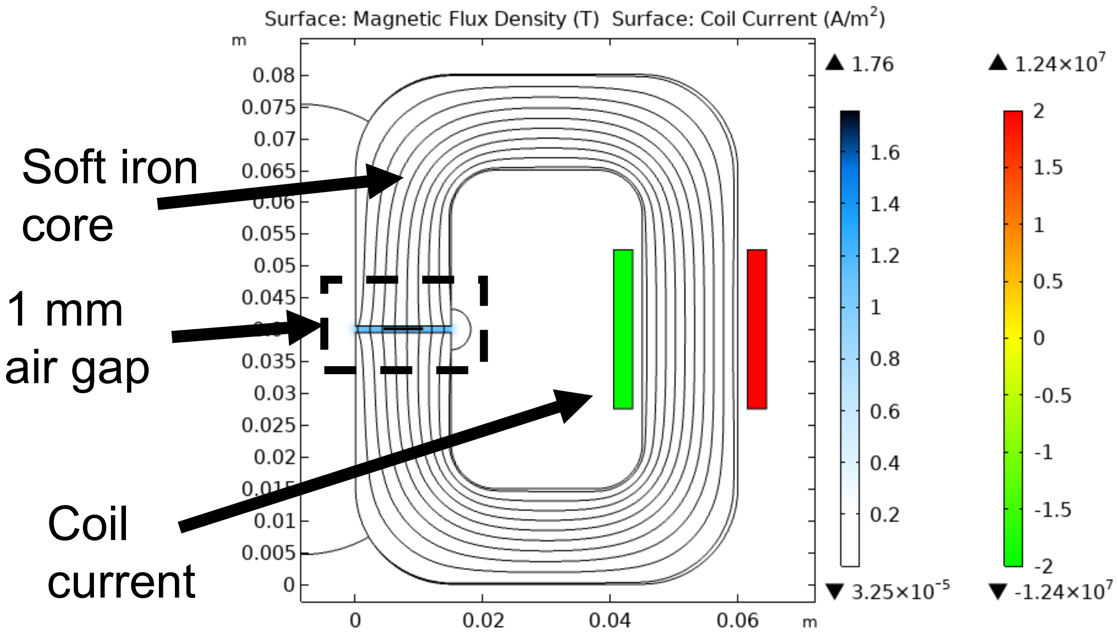
[13] N. M. Strickland, C. Hoffmann, and S. C. Wimbush, Rev. Sci. Instr., 85 11, 113907 (2014).
[14] S. C. Wimbush and N. M. Strickland, IEEE Trans. Appl. Supercond., 27 4, 1–5 (2013).

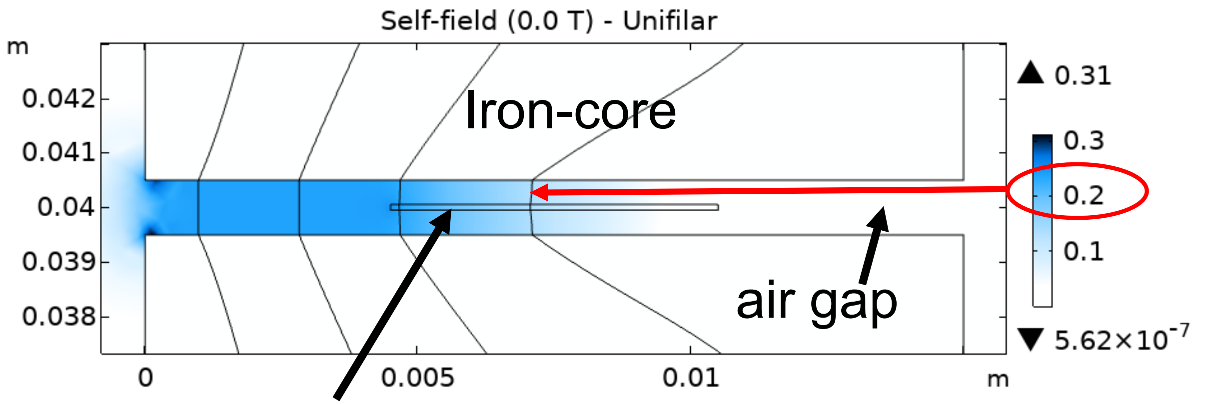
Vector Field Model

- Switch element geometry replicated
- Iron-core gives low reluctance return path
  - Spreads, increases self-field across tape

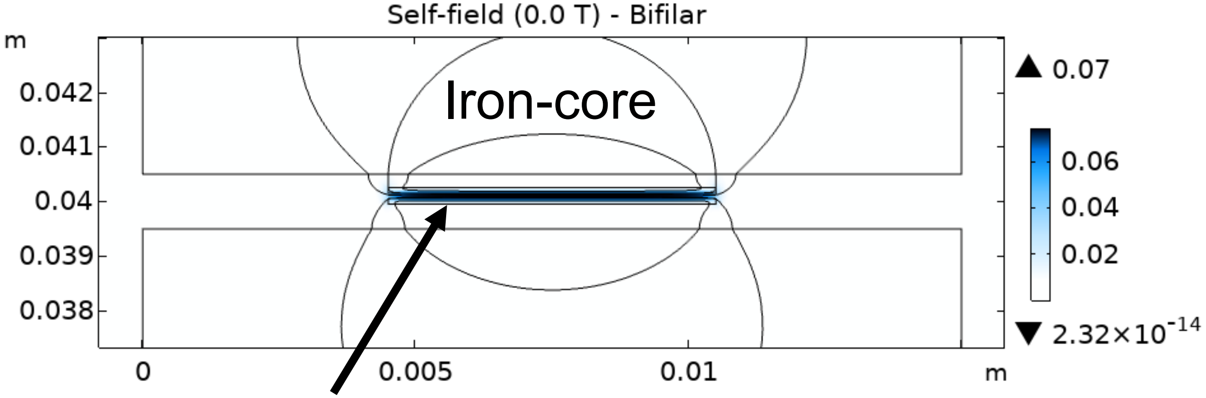
→ *Self-field I_c suppressed by iron-core*

- Bifilar topology limits iron-core interaction





single tape carrying
195 A transport current



bifilar tape carrying
355 A transport current

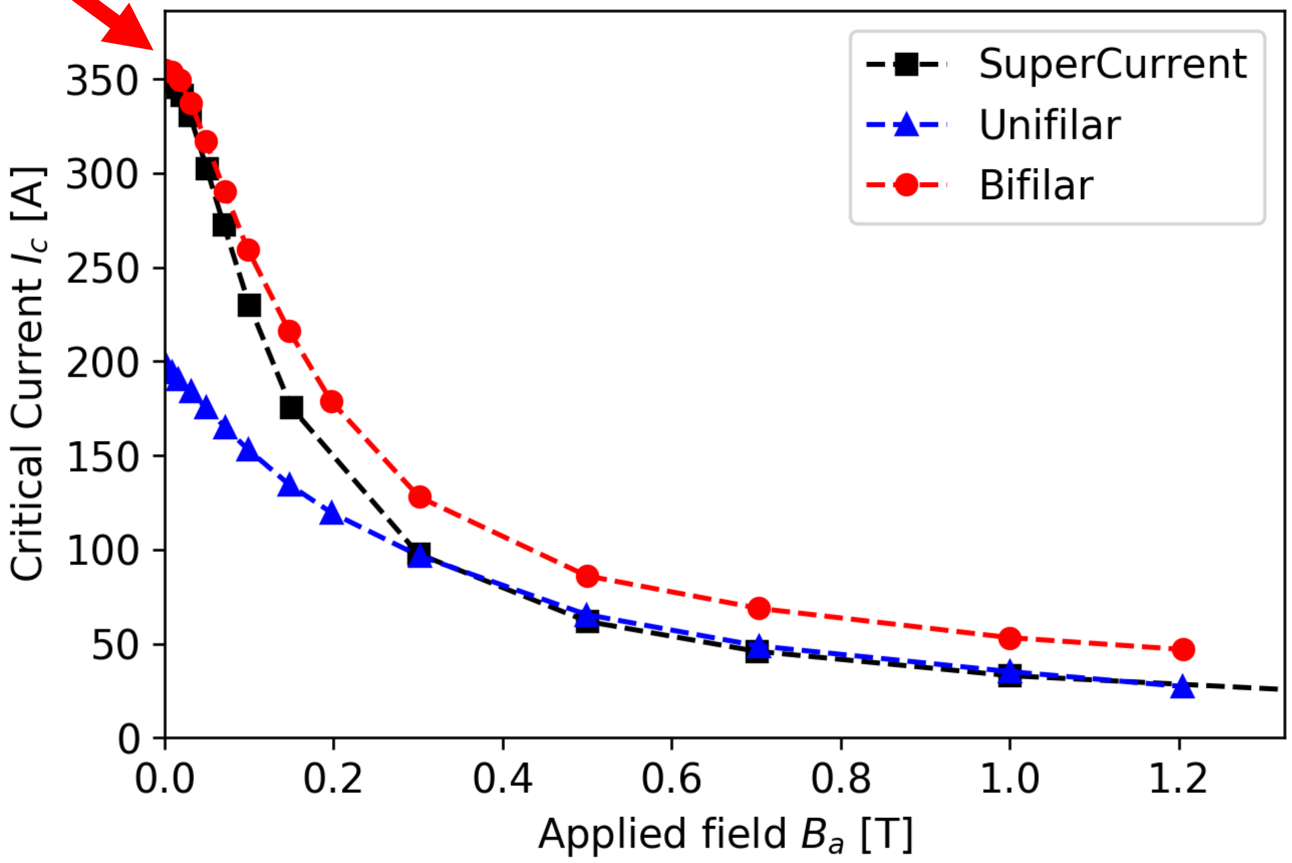
Experimental Results – Bifilar Switch

- Bifilar self-field I_c agrees with database
- improved switching in bifilar element
  - switching ratio $\kappa = \frac{\text{self field}}{\text{applied field}} = \frac{I_c(0)}{I_c(B_a)}$

Additionally:

- Bifilar $I_c(B_a)$ not fully suppressed at higher fields > 0.1 T (B_{pen} ~ 116 mT)
- **Tape stack screens applied field**
- May limit switching of cable elements
  → Necessary to increase output beyond I_c

SCN06300-210310-01



Summary

- Iron-core HTS switching element tested ex situ
- Self-field critical current suppressed by presence of iron-core
- Physics modelled using vector-field
- Bifilar switch element avoids self-field critical current suppression
- Introduces some screening of applied field

Acknowledgements

This work was supported by the New Zealand Ministry of Business, Innovation and Employment (MBIE Grant: RTVU1916).

This work has also been part-funded by *STEP*, a UKAEA programme to design and build a prototype fusion energy plant and a path to commercial fusion.

Additional thanks to Mr. R. Mataira and Dr. A. Petrov for their time and helpful discussion.