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Performance of compact wind-and-react MgB_2 solenoid coil made with continuously produced cable

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C. Dhulst, J. Mestdagh - *NV Bekaert SA*

S. Atamert, M. Kutukcu - *Epoch Wires*

E. Young, J. Pelegrin, W. O. Bailey, Y. Yang - *University of Southampton*

MgB_2 background

Superconductivity at 39 K in magnesium diboride

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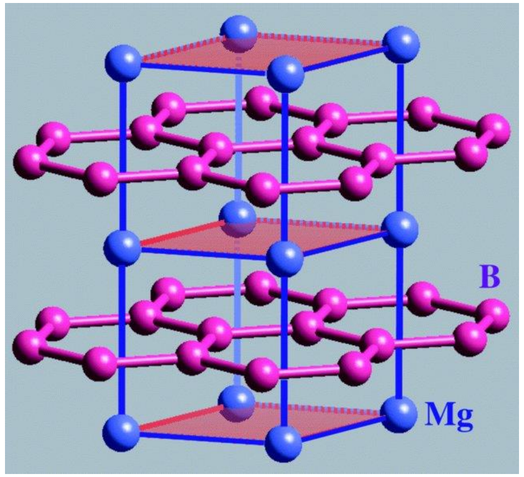
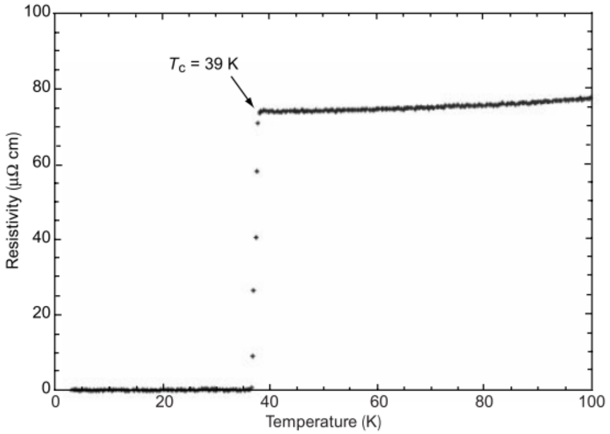
In the light of the tremendous progress that has been made in raising the transition temperature of the copper oxide superconductors (for a review, see ref. 1), it is natural to wonder how high the transition temperature, T_c, can be pushed in other classes of materials. At present, the highest reported values of T_c for non-copper-oxide bulk superconductivity are 33 K in electron-doped $Cs_xRb_yC_{60}$ (ref. 2), and 30 K in $Ba_{1-x}K_xBiO_3$ (ref. 3). (Hole-doped C_{60} was recently found[4] to be superconducting with a T_c as high as 52 K, although the nature of the experiment meant that the supercurrents were confined to the surface of the C_{60} crystal, rather than probing the bulk.) Here we report the discovery of bulk superconductivity in magnesium diboride, MgB_2. Magnetization and resistivity measurements establish a transition temperature of 39 K, which we believe to be the highest yet determined for a non-copper-oxide bulk superconductor.

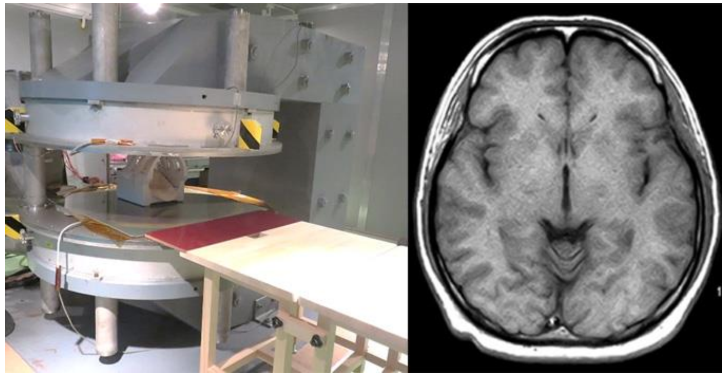




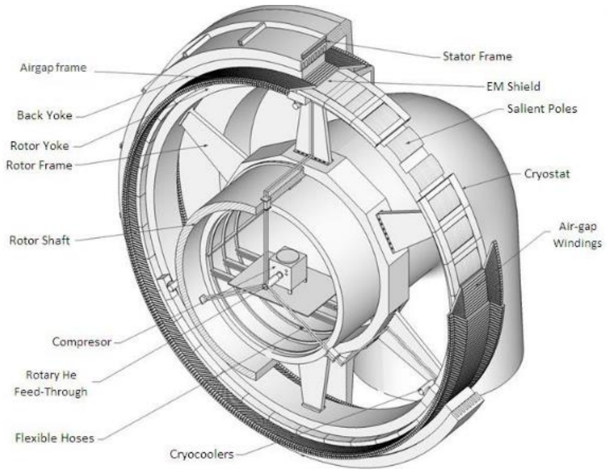
- Highest T_C of a binary compound
- Highest T_C of a 'conventional' BCS superconductor
- Mg and B are abundant, and processing into wire or tape is simpler than for REBCO
- Therefore: potential for higher-temperature operation than NbTi, but at lower cost than REBCO

MgB_2 applications

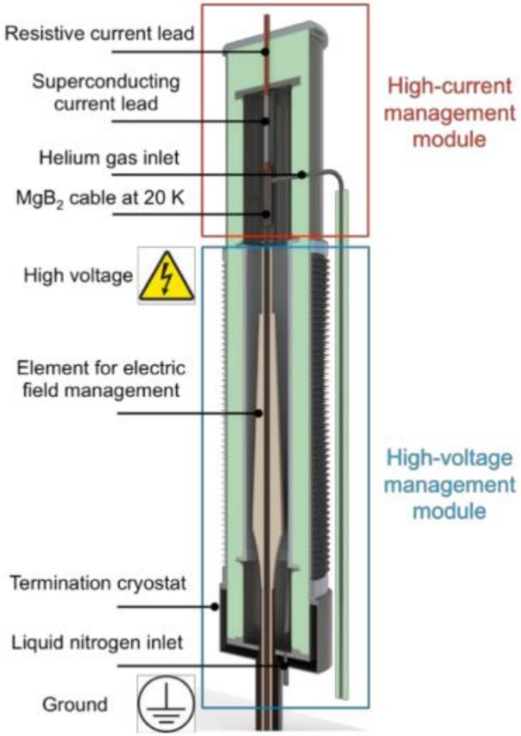
MRI (Hitachi)[1]



Wind turbine generators[3]



Power transmission[2]



- Highest T_C of a binary compound
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- Mg and B are abundant, and processing into wire or tape is simpler than for REBCO
- Therefore: potential for higher-temperature operation than NbTi, but at lower cost than REBCO

- **Lends itself well to large-scale, medium-field applications**

[1] www.hitachi.com/rd/news/topics/2021/0301.html
[2] C. Bruzek and A. Marian, "Superconducting links for very high power transmission based on MgB2 wires," in *2021 AEIT HVDC International Conference (AEIT HVDC)*, 2021, no. May, pp. 1–5.
[3] I. Marino *et al.*, "Lightweight MgB2 superconducting 10 MW wind generator," *Supercond. Sci. Technol.*, vol. 29, no. 2, p. 024005, Feb. 2016.

Epoch Wires & Bekaert

Who : Est. 2014 – Cambridge, UK

What : Continuous powder (Mg+B) feeding + laser seam welding

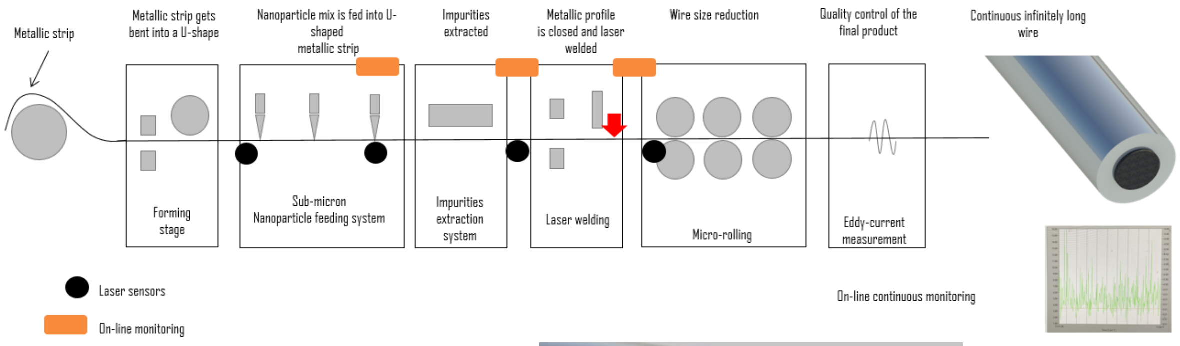
How : Industrialized high throughput production line

Who : Est. 1880 – Zwevegem, BE, operating in 120 countries

What : Steel wire transformation & coatings

How : Industrialized processes (drawing, cabling, heat treatment, metallic/non-metallic coatings…)

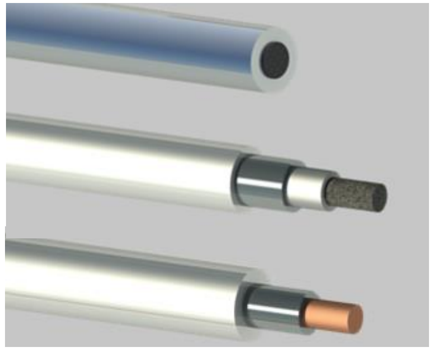
Continuous Material-In-Tube Wire



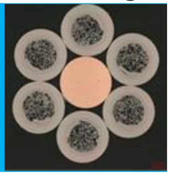
Modular product design

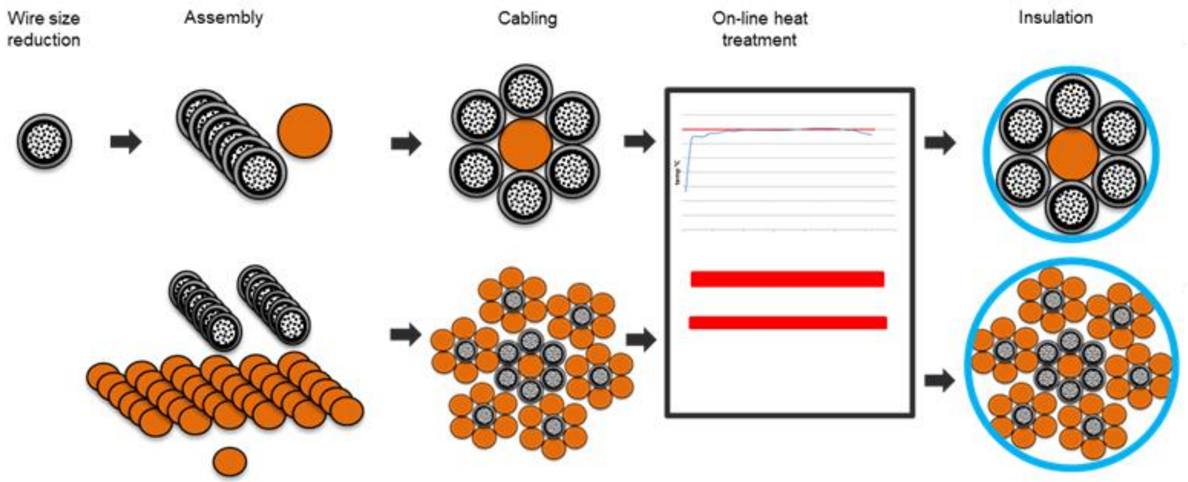
Long length consistency

> 30 km piece length



Continuous cabling, coating, insulation and heat treatment solutions





[1] S. Atamert, M. N. Kutukcu, J. L. Scandella, A. Baskys, Z. Zhong, and B. A. Glowacki, "Novel Superconducting MgB2 Wires Made by Continuous Process," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, pp. 5–8, 2016.

[2] M. N. Kutukcu *et al.*, "Composite Superconducting MgB2 Wires Made by Continuous Process," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, pp. 1–4, Jun. 2018.

[3] B. A. Glowacki *et al.*, "Comparative Study of the Continuous and Batch Thermal Processing of MgB2 Wires," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–4, Aug. 2019.

Experiment Objective

To demonstrate:

- Consistent performance of continuously-produced MgB_2 wire, by producing and testing a small solenoid coil
- That MgB_2 coils can be produced - wind, react, joint, epoxy impregnate - using similar equipment to ‘conventional’ LTS wire coils
- No significant degradation in I_C from wire to coil
- Safe quench
- Useful current densities

Test coil fabrication

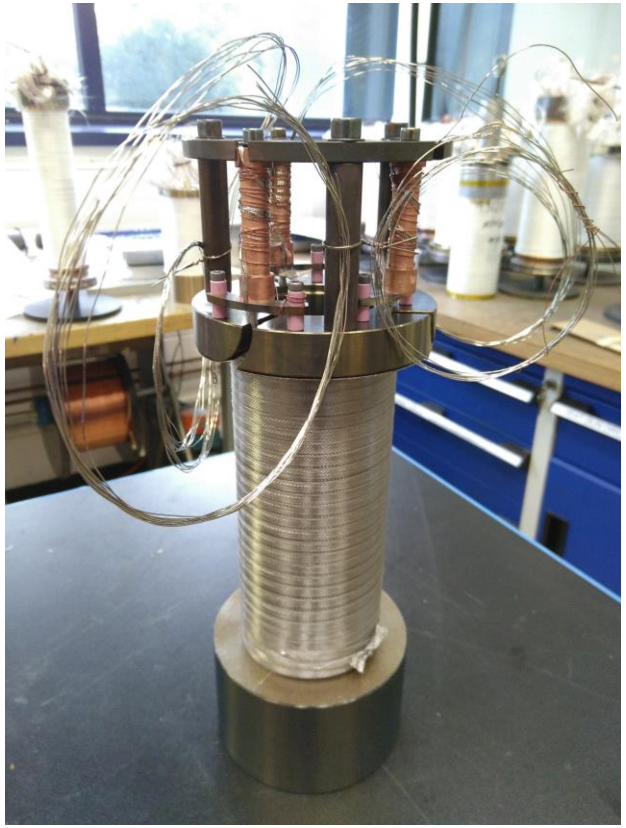
- Wind-and-react
- Wound onto a stainless steel former using a conventional round-wire winding machine
- 1.2 mm cable, 6 x 0.4 mm MgB_2 filament + 1 copper, S-glass insulated
- 148 m of cable; six layers
- ID 57 mm, OD 72 mm
- 160 mm long

- Reacted in vacuum furnace usually used for Nb_3Sn coils
- Rapid react schedule, 700° C for 25 mins, whole schedule complete in 48 hours.

- 200 mm long soldered joints wound around a copper joint post.

- Initially tested 'dry' (no epoxy impregnation)
- Later, vacuum epoxy impregnated and re-tested

Test coil after react, before jointing



Final condition – epoxy potted

Cryogenic test equipment

Left: coil set up for test rig

Right: Test rig at University of Southampton

Yifeng

Helium siphon

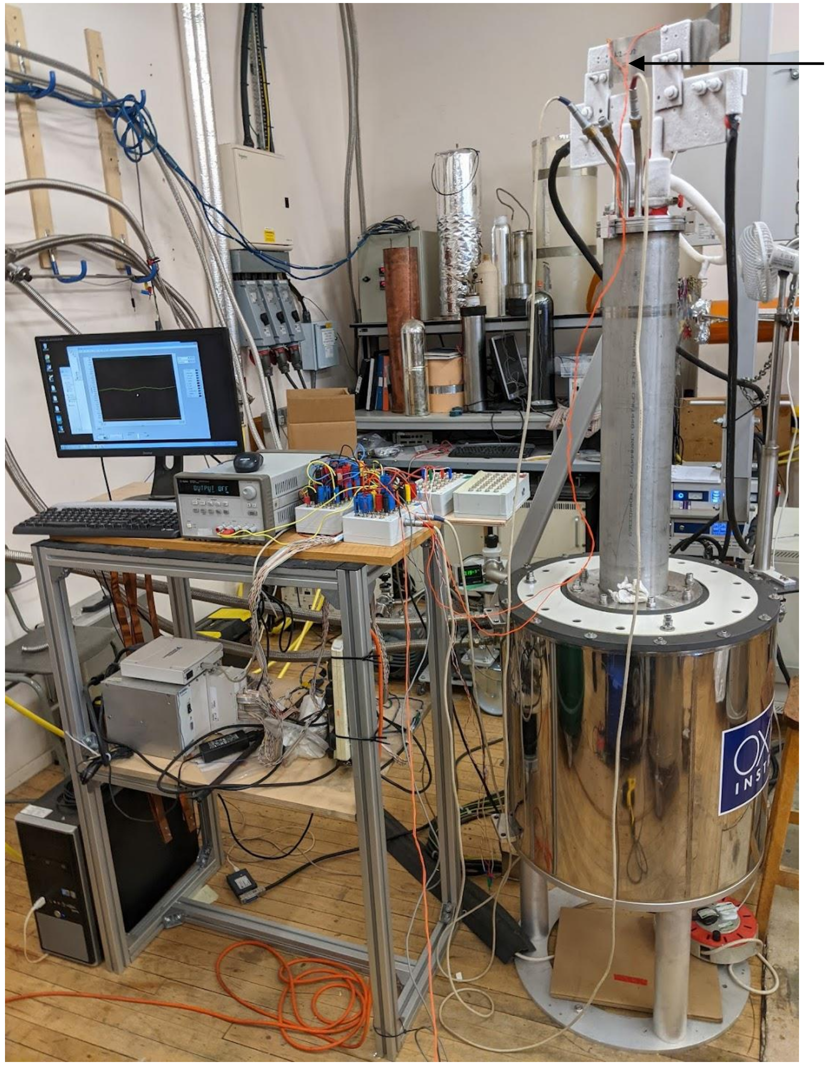
Gas flow VTI: 100 mm bore, 4 K to 70 K

OI 10 T Cryofree magnet

Cryogenic test equipment

Left: coil set up for test rig

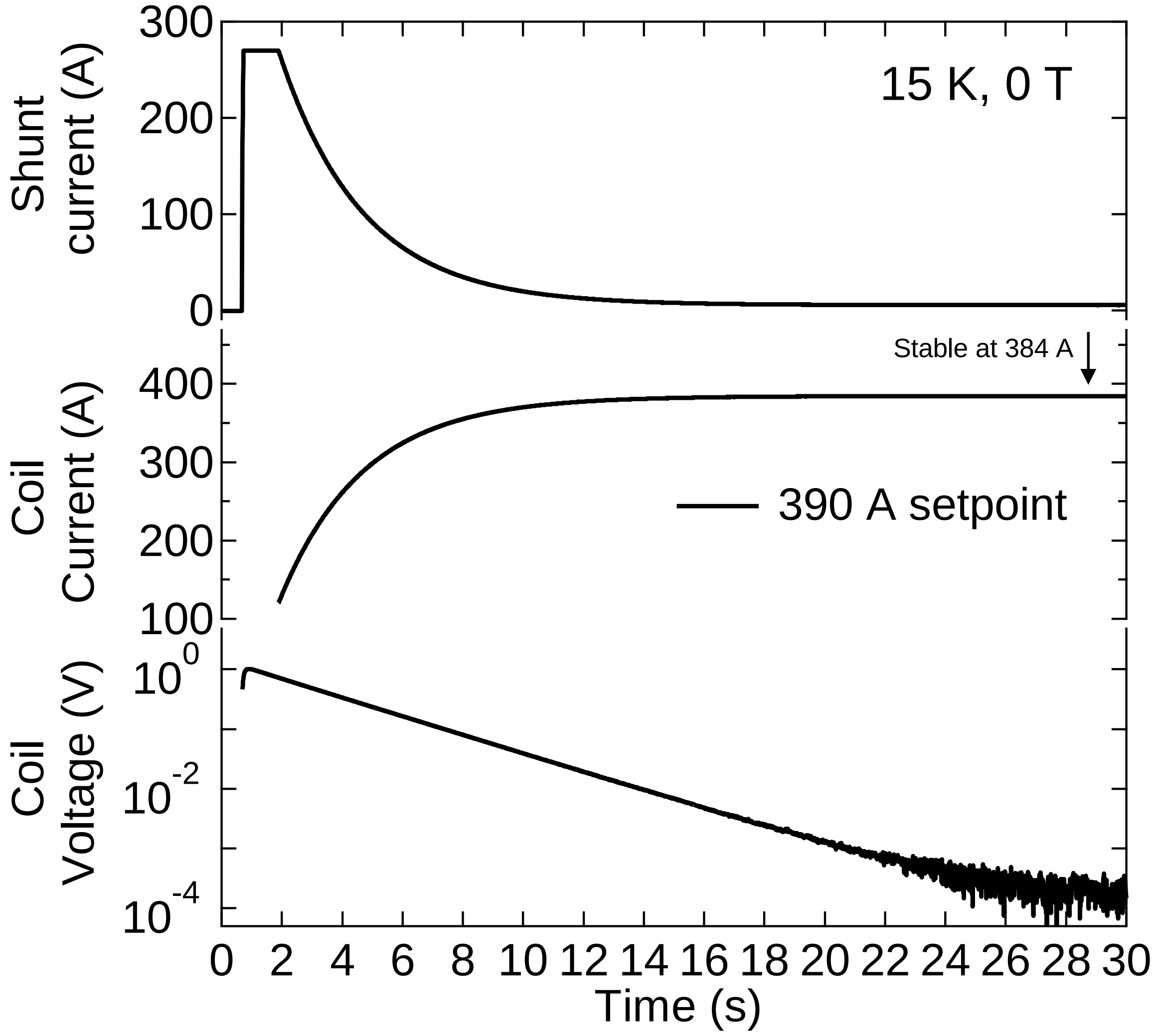
Right: Test rig at University of Southampton



mΩ shunt

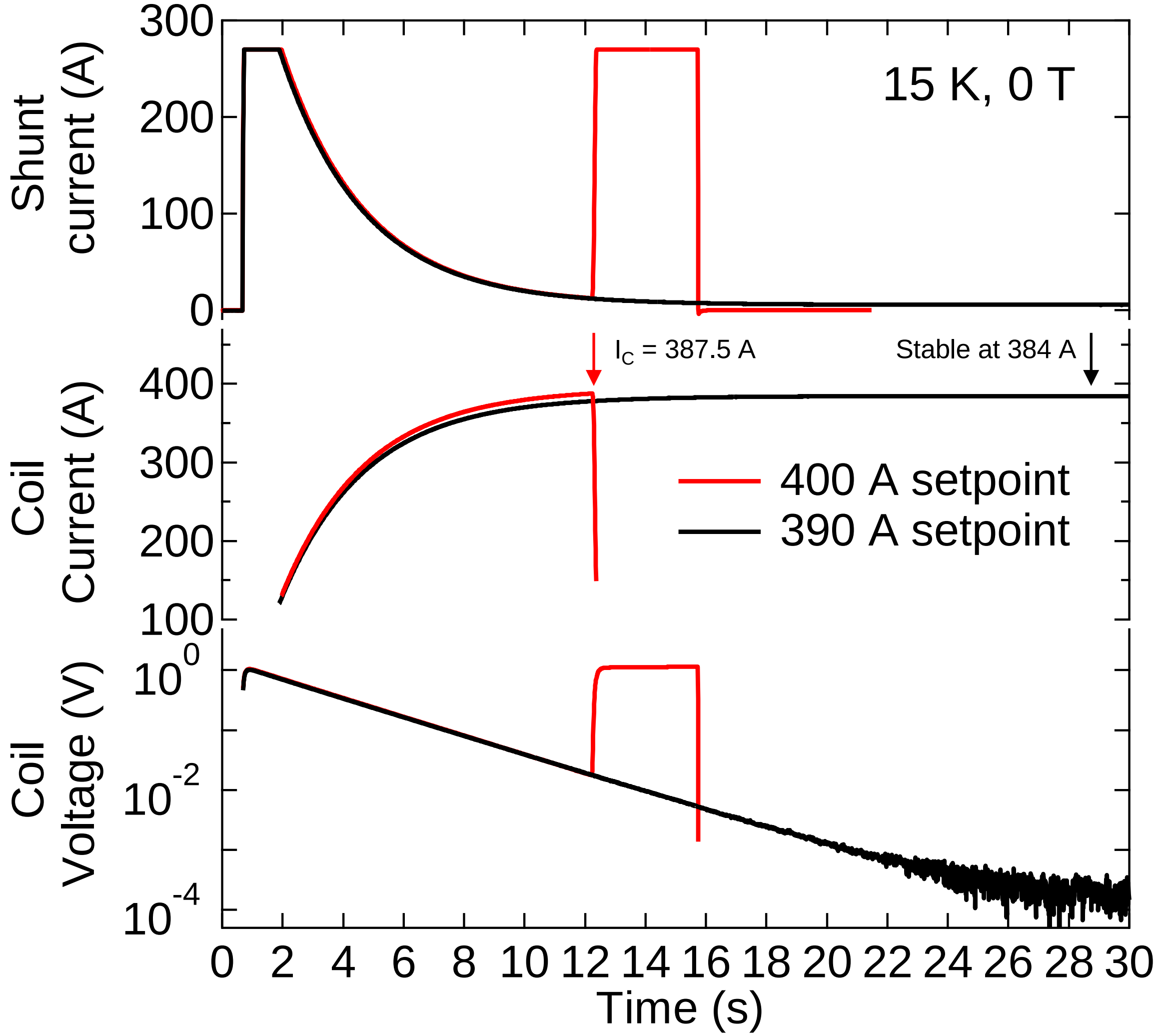
HP/Agilent 875 A power supply

Test method



- mΩ shunt in parallel with coil
- Power supply set directly to setpoint, not ramped
- RL time constant determines decay of shunt current and hence rate of current increase in coil
- Coil current calculated as power supply minus shunt current

Test method



- mΩ shunt in parallel with coil
- Power supply set directly to setpoint, not ramped
- RL time constant determines decay of shunt current and hence rate of current increase in coil
- Coil current calculated as power supply minus shunt current

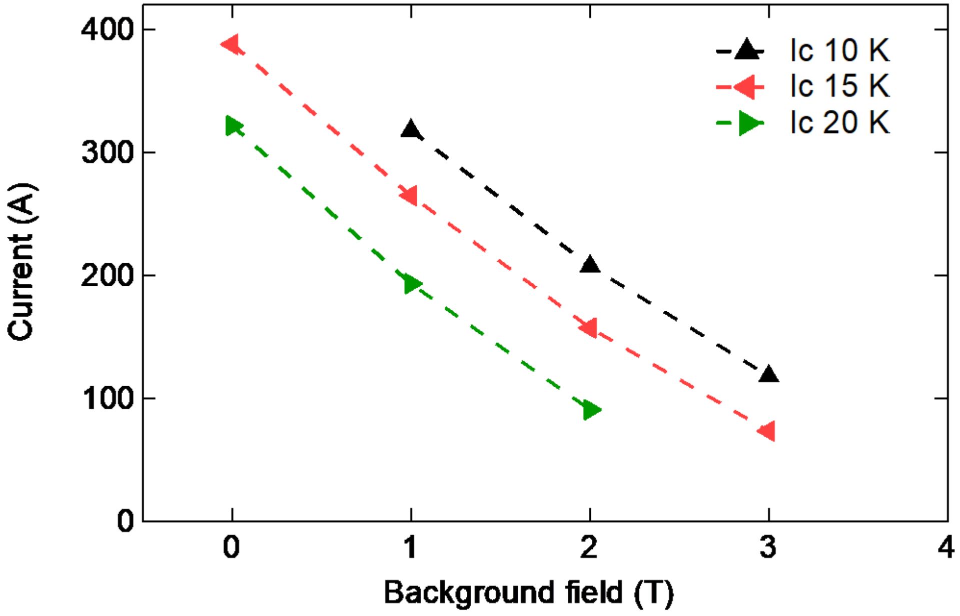
- Coil critical current measured as quench current
- Measured as a function of temperature (10, 15, 20 K) and background field (0 - 3 T)

- Highest central self-field: 384 A generates 1.88 T at 15 K

Results

Critical current vs field and temperature

Critical current vs. background field



Results

Critical current vs field and temperature

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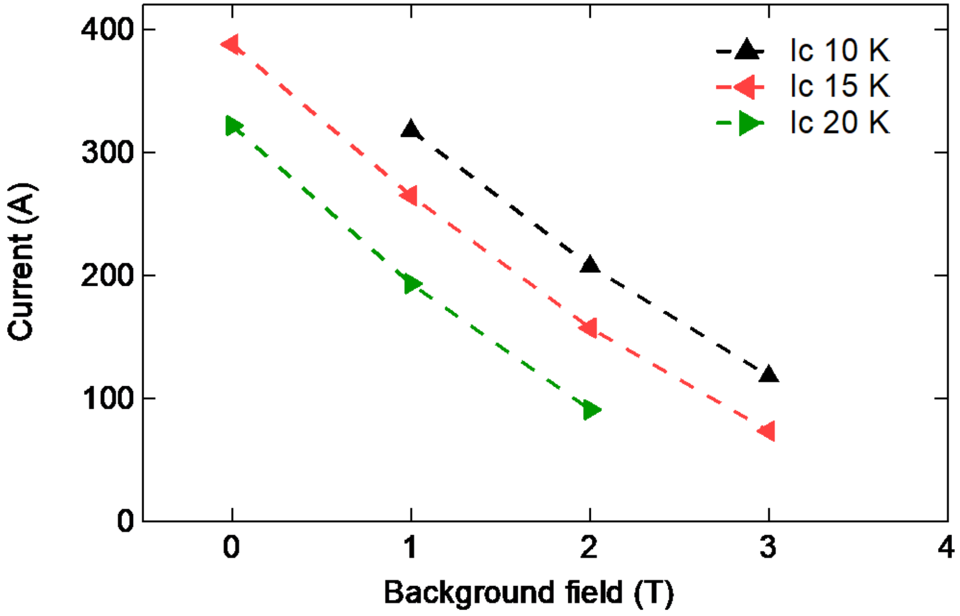
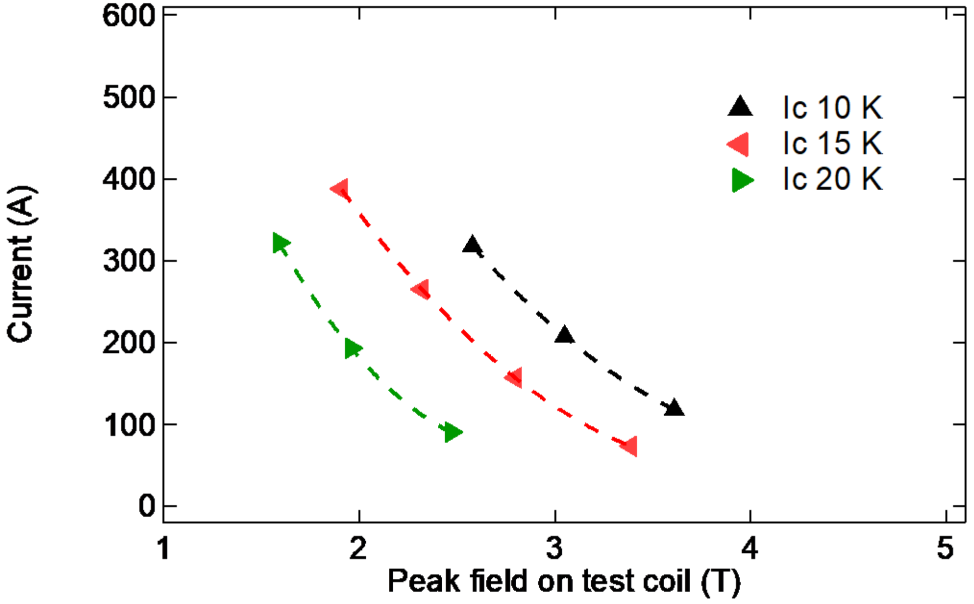


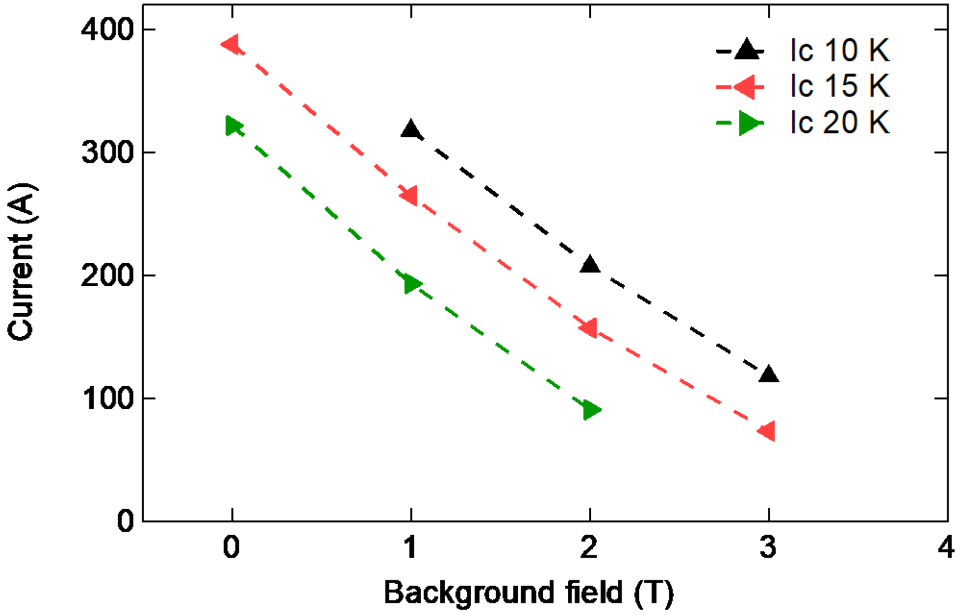
Critical current vs. max. total field at conductor



Results

Critical current vs field and temperature

Critical current vs. background field



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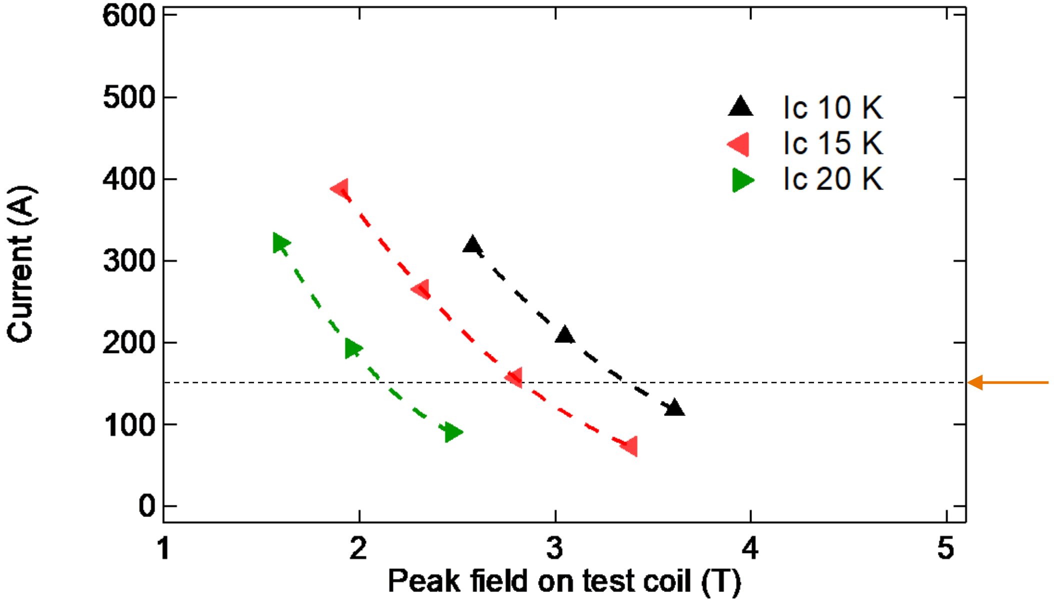


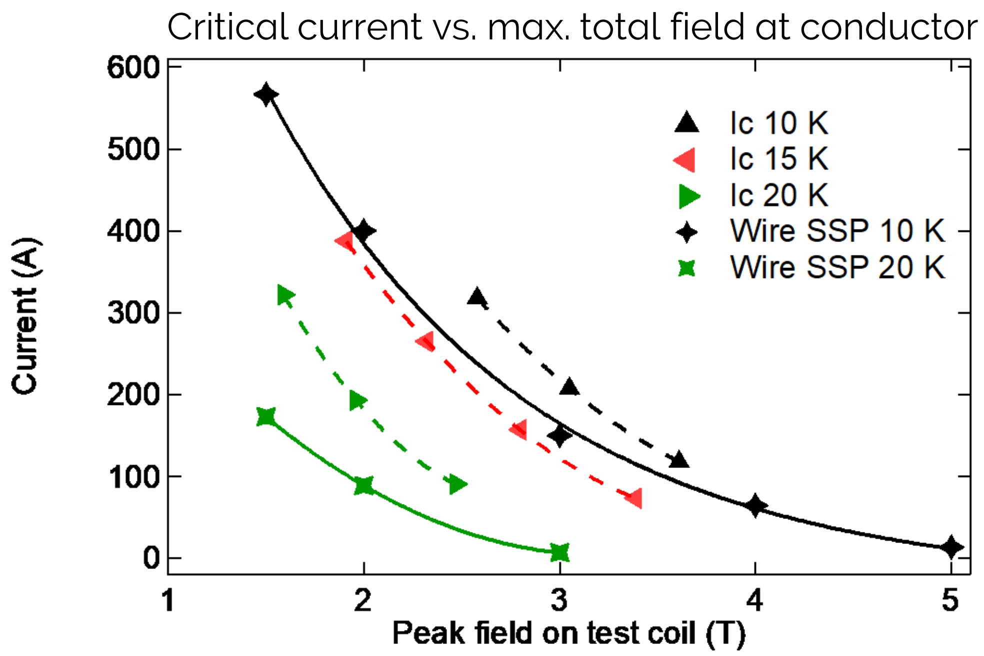
superconductor current density **1000 A/mm²**

superconductor current density J_C = **1000 A/mm²**
whole wire J_e = **133 A/mm²**
coil with insulation J_e = **90 A/mm²**

Results

Critical current vs field and temperature – comparison with wire short sample data

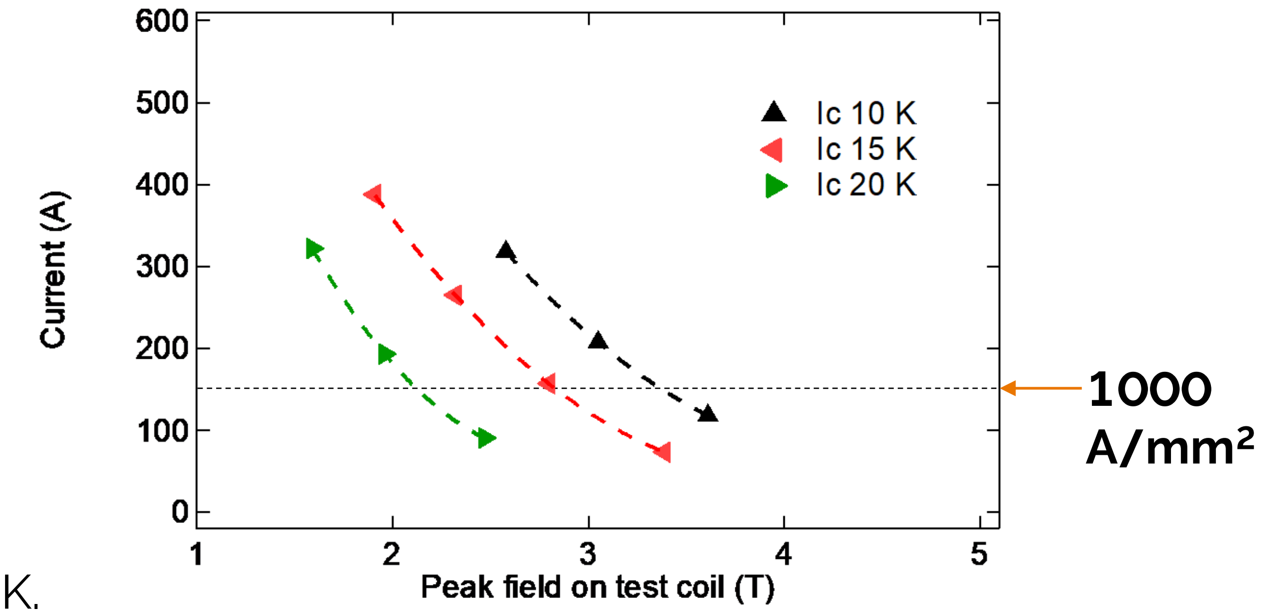
- Major discrepancy between coil I_C and wire short sample - 200 % of wire SSP at 20 K!
- However – wire I_C was measured using transport only at 4.2 K: higher temperature I_C data were obtained indirectly, by scaling based on magnetometry data
- Known that transport I_C can differ from magnetometry I_C [1]



[1] E. Martínez, L. A. Angurel, S. I. Schlachter, and P. Kováč, "Transport and magnetic critical currents of Cu-stabilized monofilamentary MgB2 conductors," *Supercond. Sci. Technol.*, vol. 22, no. 1, p. 015014, Jan. 2009.

Conclusions

- Demonstrates that a coil with practical current density can be fabricated using existing winding, react and epoxy impregnation equipment
- 20+ quenches with no degradation
- Presently commercially available MgB_2 wires achieve a superconductor current density of **1000 A/mm²** at 2.8 T at 20 K [1]
- This density is achieved in our coil at 2.1 T at 20 K.
- Coil was run stably at 99% I_C
- More work needed to investigate the discrepancy between transport I_C and magnetometry I_C



[1] M. Kodama *et al.*, "High-performance dense MgB2 superconducting wire fabricated from mechanically milled powder," *Supercond. Sci. Technol.*, vol. 30, no. 4, p. 044006, Apr. 2017.

Acknowledgments

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- Chris Dhulst - *Bekaert*
- Yifeng Yang, Ed Young, Jorge Pelegrin, Wendell Bailey - *University of Southampton*

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- Chris Watkins, Stuart Batts, Vicki Barnes, Kev Brett, Lisa Parke

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