IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2022.
This plenary presentation was given at the virtual EUCAS 2021, September 5-10, 2021.

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Bulk superconductors and their applications, present and future

John Durrell – University of Cambridge

EUCAS 2021 Plenary

Acknowledgements

For kindly providing material (not all of which I could include):

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- Prof. Zigang Deng – Southwest Jiaotong University
- Dr Frank Werfel – ATZ
- Mr Jan Plecháček – CAN Superconductors
- Prof. Phillipe Vanderbemden – University of Liège
- Prof. Susannah Speller – University of Oxford
- Prof. Muralidhar Miryala, SIT, Tokyo
- Dr Marco Calvi, PSI, Villigen

- And many other colleagues in the bulk superconductivity community!

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Acknowledgements

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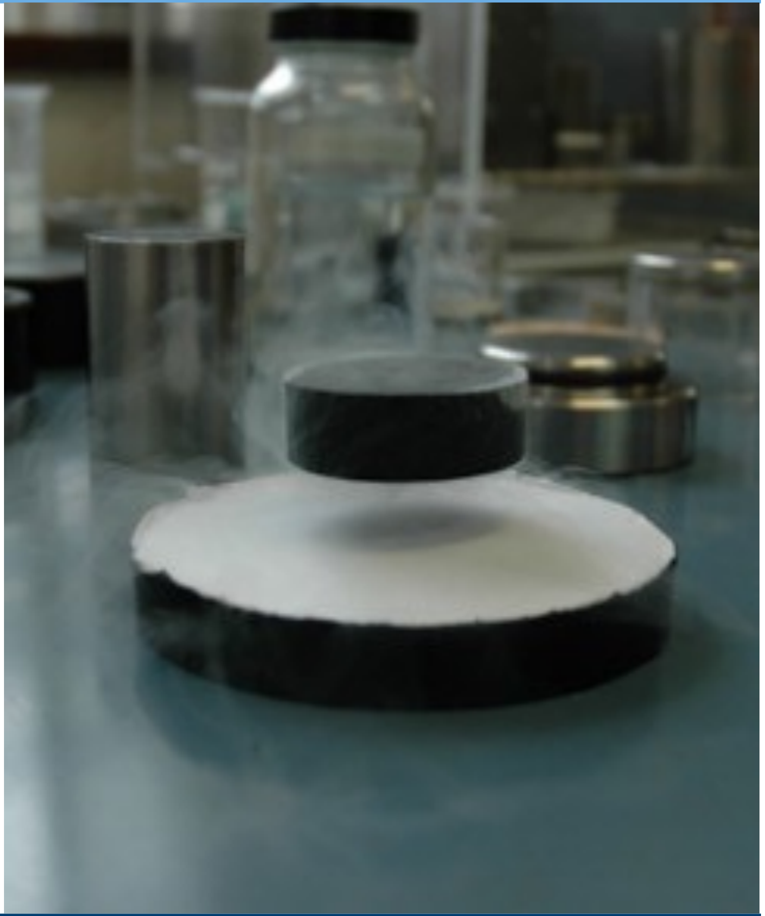
- Jan Srpčic
- Danny Huang
- Devendra Kumar Namburi
- Jasmin Congreve
- Harry Druiff
- Kysen Palmer

Overview

- Basics
- Materials
  - REBCO
  - MgB_2
- Applications
- Challenges
- Conclusion



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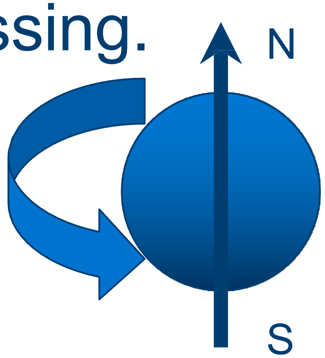
B|S|G

Limitations of Permanent Magnets

- Practical fields generated by permanent magnets limited to less than 2 T by the number of Bohr magnetons of iron.

- This is a fundamental limitation and cannot be increased
by processing.



$\mu_B = 9.27 \times 10^{-24}\ Am^2$

Magnetisation
independent of sample
volume

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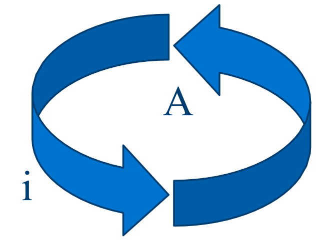
Bulk Superconductors

- Field generated by induced macroscopic currents rather than spins.

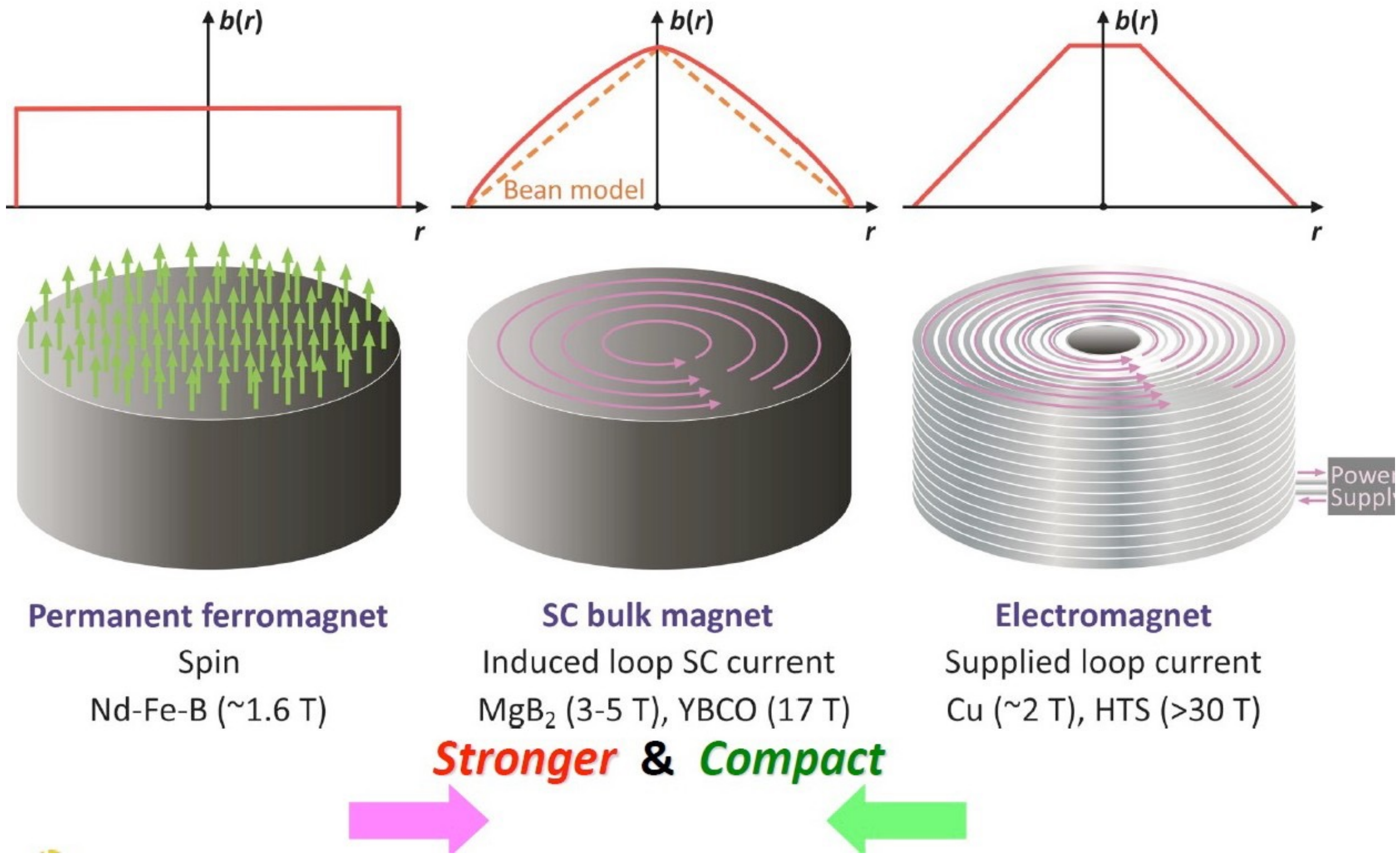
Magnetic moment= ! ! "# "#$



- The bigger the current loop, the bigger its magnetic moment

- Magnetisation *increases* with sample volume

Why Bulk?


b(r)
r
Bean model
Power
Supply
Permanent ferromagnet
Spin
Nd-Fe-B (~1.6 T)
SC bulk magnet
Induced loop SC current
MgB2 (3-5 T), YBCO (17 T)
Electromagnet
Supplied loop current
Cu (~2 T), HTS (>30 T)
Stronger & Compact

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And…..

- Changing the flux profile would require flux to move, hence a bulk resists changes in an external field.
- This is, strictly speaking, not the Meissner effect – the complete expulsion of flux.
- So in addition to acting as a high field magnets bulks offer stable levitation (and suspension!)

Upwards dripping….

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Image, Jan Srpčič

Upwards dripping….

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Video, Jan Srpčič

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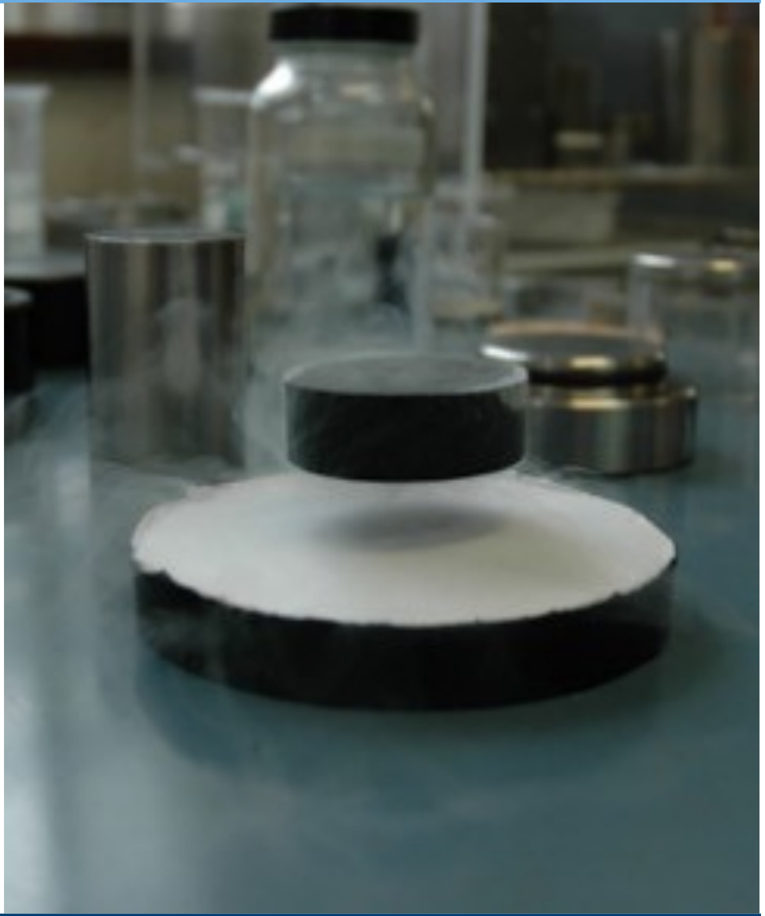

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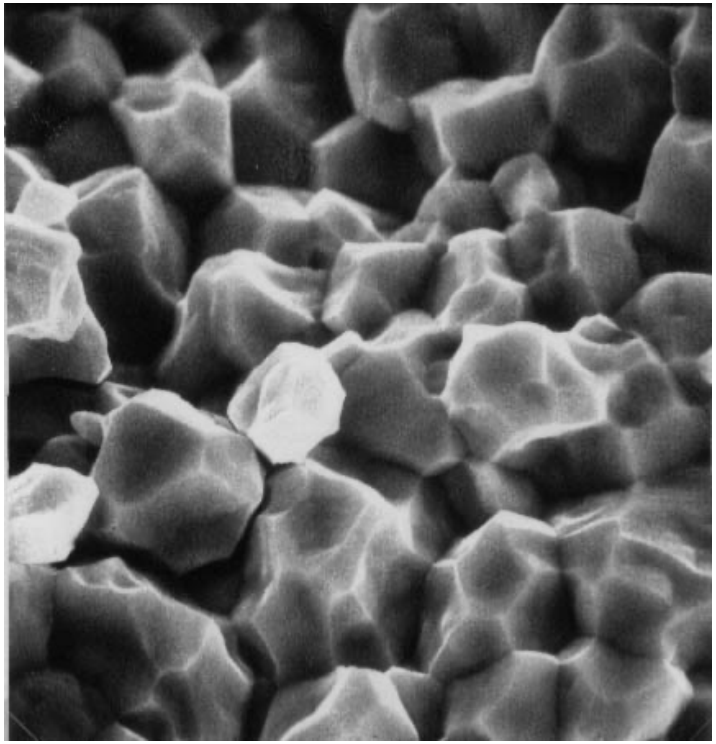
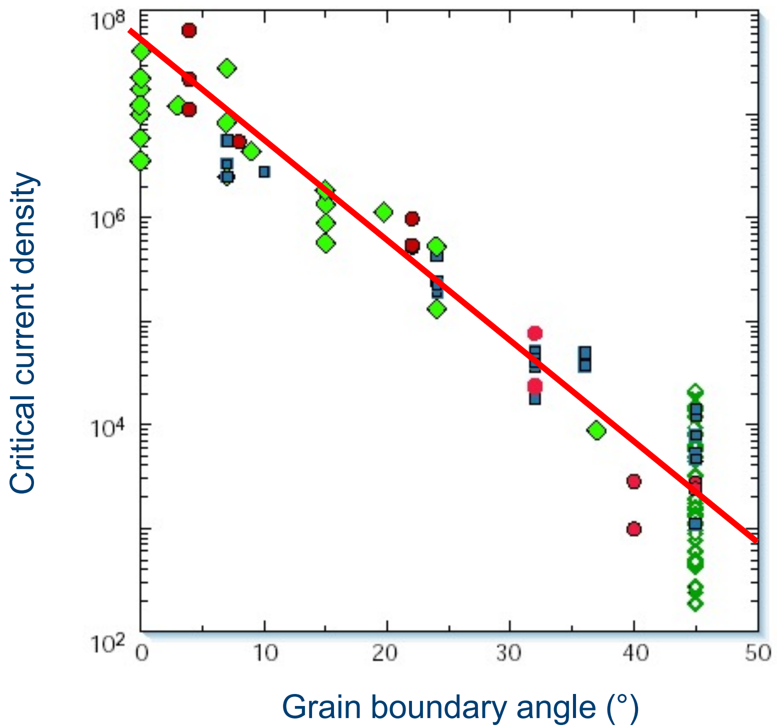
Granularity is a problem!



Sintered YBCO

- Simple sintering of (RE)BCO powder in bulks does not result in very good materials
- Early attempts at bulk material were… disappointing

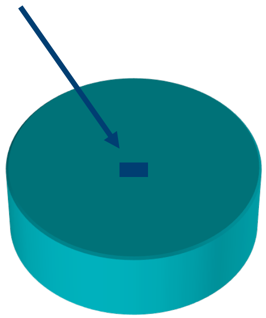
Grain Boundaries – An inconvenient truth……



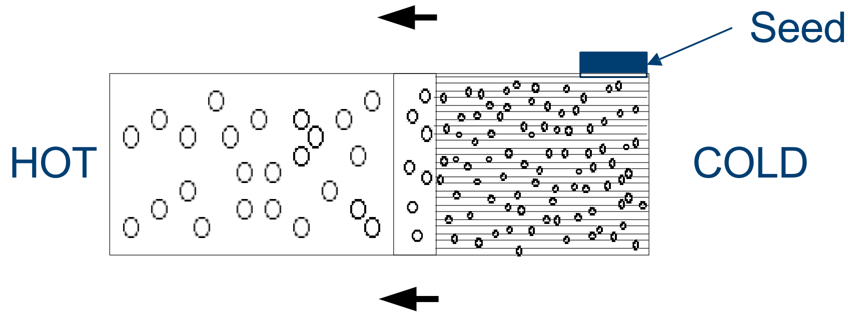
- Grain Boundaries must be avoided in REBCO materials, current carrying capacity drops exponentially with increasing mis-orientation

Melt Grown (RE)BCO Bulk Superconductors

Seed



Precursor pellet



$YBa_2Cu_3O_{7\text{-}8}$ + Y_2BaCuO_5 + Pt ® Y_2BaCuO_5 + L

- Avoid grain boundaries using a seeded peritectic growth process
- Use large excess of Y-211 (typically 40%)
- Sample require a subsequent anneal to optimise O_2 content

The (RE)BCO family

$YBa_2Cu_3O_{7-8}$	YBCO	92 K
$GdBa_2Cu_3O_{7-8}$	GdBCO	92 K
$Sm_{1+x}Ba_{2-x}Cu_3O_{7-8}$	SmBCO	92 K
$Nd_{1+x}Ba_{2-x}Cu_3O_{7-8}$	NdBCO	94 K

- Several different (RE)BCO materials can be used.

- Have differing melting points, need higher melting point seed

Commercial Scale Production

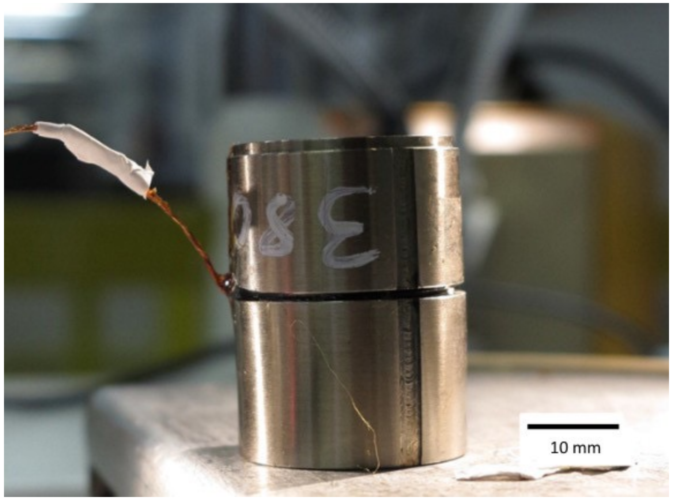
ATZ

- Companies are now providing commercial scale production of Bulk Superconductors

can superconductors

Bulk High Temperature Superconductors

- **Demonstrated trapped fields over 17 T**
  - 17.24 T at 29 K
    2 x 26.5 mm YBCO
    Tomita, Murakami *Nature* 2003
  - 17.6 T at 26 K
    2 x 25 mm GdBCO
    Durrell, Dennis, Jaroszynski, Ainslie et al. *Supercond. Sci. Technol.* 2014
- **Significant potential at 77 K**
  - J_c = up to 5 x 10^4 A/cm^2 at 1 T
  - B_{trap} up to 1 ~ 1.5 T for YBCO
  - B_{trap} > 2 T for (RE)-BCO
- **Record trapped field = 3 T at 77 K**
  - 1 x 65 mm GdBCO
  - Nariki, Sakai, Murakami *Supercond. Sci. Technol.* 2005



Stack of 2 x GdBCO samples that achieved 17.6 T at 26 K

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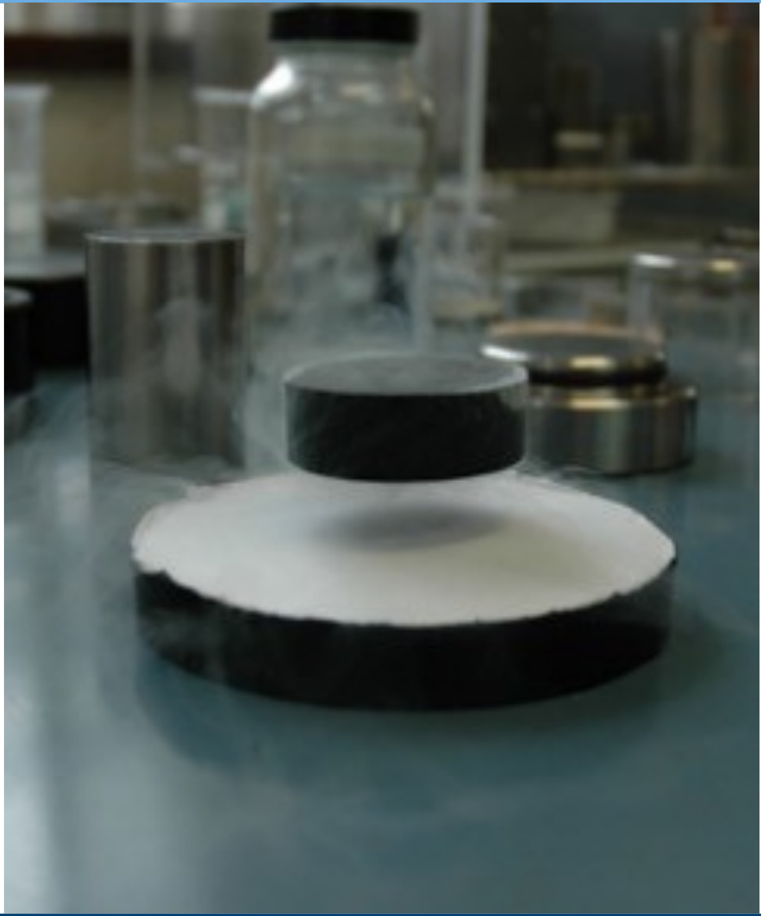

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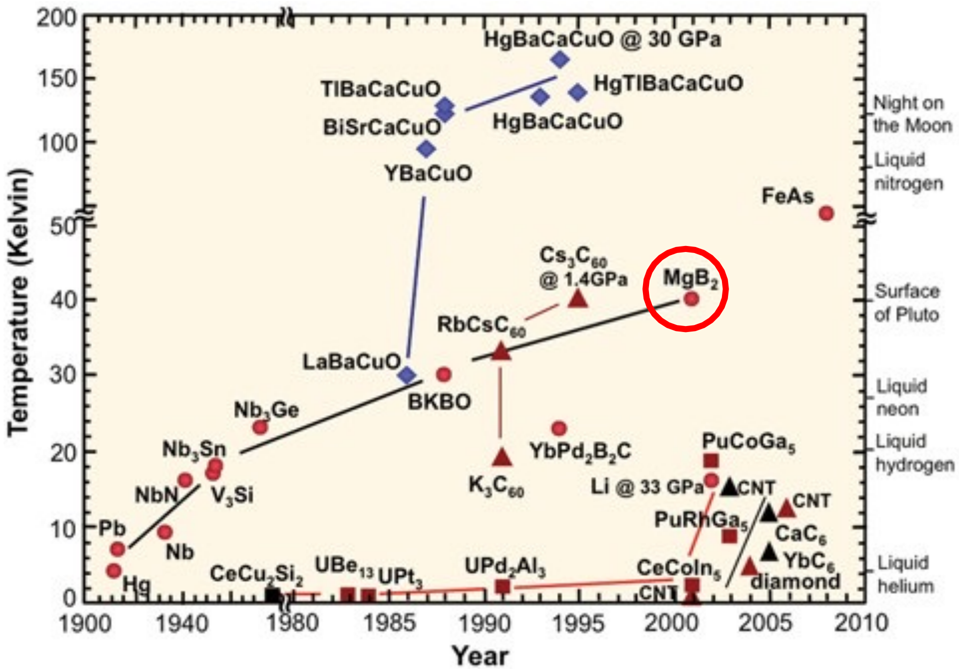
B|S|G

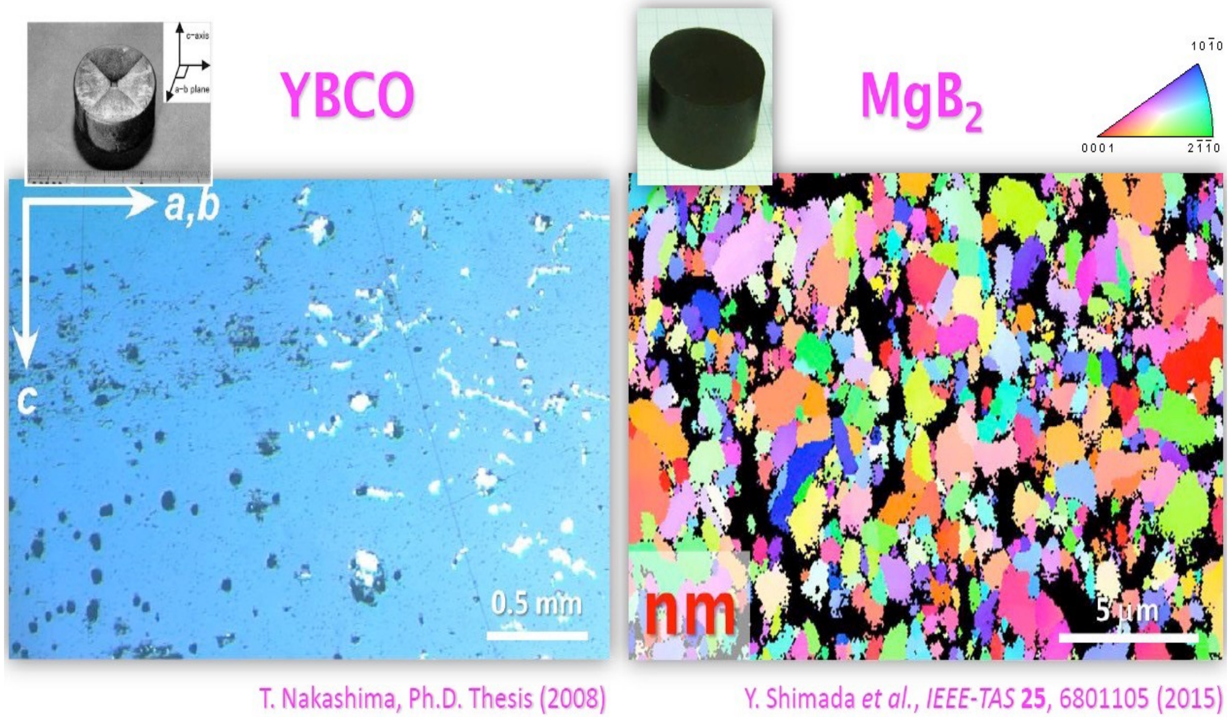
MgB_2

- Metallic nature, T_c 39 K
- Lightweight (2.624 g/cc), inexpensive
- Low anisotropy
- Large coherence length



Why MgB_2?

- No GB problem – simple to produce in large sizes
- Relatively cheap raw materials, no rare earths



Textured, single domain
Pinning by intragrain defects

Randomly oriented polycrystal
Pinning by grain boundaries

Hot Pressing at Element Six

Department of Materials
University of Oxford

- Industrial scale R & D presses at E6 Global Innovation Centre, Harwell.
- High Pressure - High Temperature (HPHT) processing of large bulk samples under extreme conditions.

Processing Conditions

Temperature	900-1500 °C (T1<T2<T3)
Pressure	4-8 GPa
Time	5-25 mins

R&D presses at E6 GIC, Harwell UK

elementsix™ a De Beers Group Company

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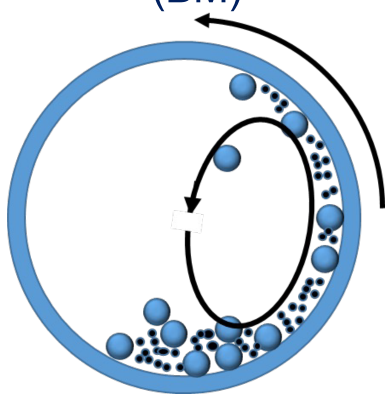
Powder Modifications

Department of Materials
University of Oxford

Commercial MgB_2 Powder

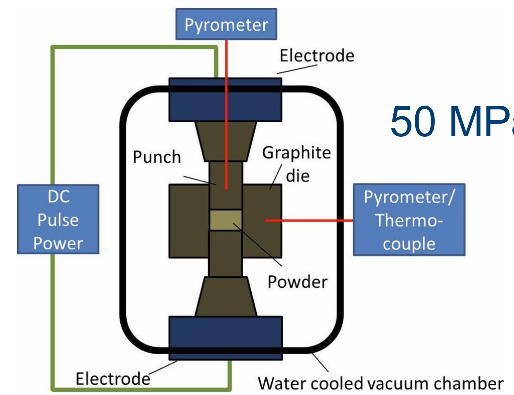
0.5-10 wt % Y_2O_3 powder additions

High energy Ball Milling (BM)



0-12 hours

Field-Assisted Sintering Technology (FAST)*



50 MPa

5, 30 mins, 950-1150 °C

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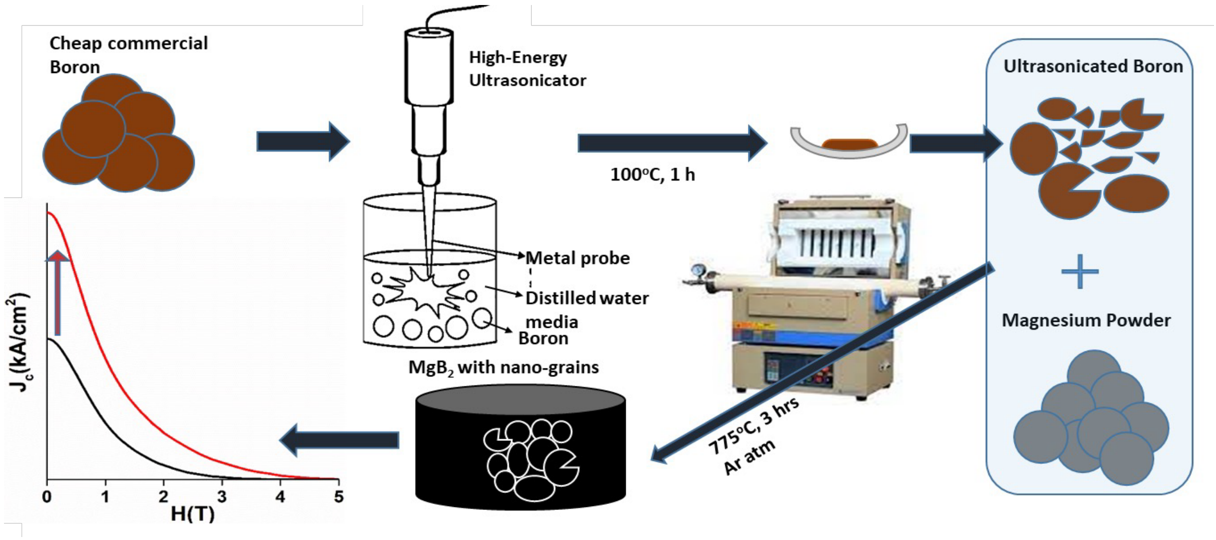
* Guillon et al, Adv. Eng. Mat. 2014, 16, 830

Cheap Precursors



- Key advantage of MgB_2 is that the precursor powders are comparatively cheap and abundant
- As an example: Work at SIT has shown that Ultrasound processing can be used to enable the use of cheap commercial grade boron

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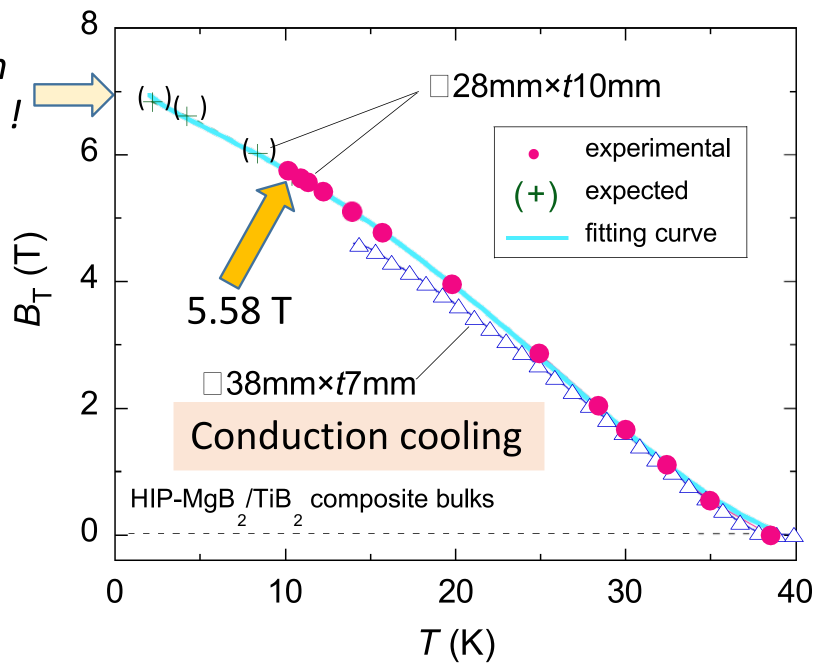
Arvapalli et al. (2021), Materials Science and Engineering B, 115030

State of the Art now ~ 5.5 T

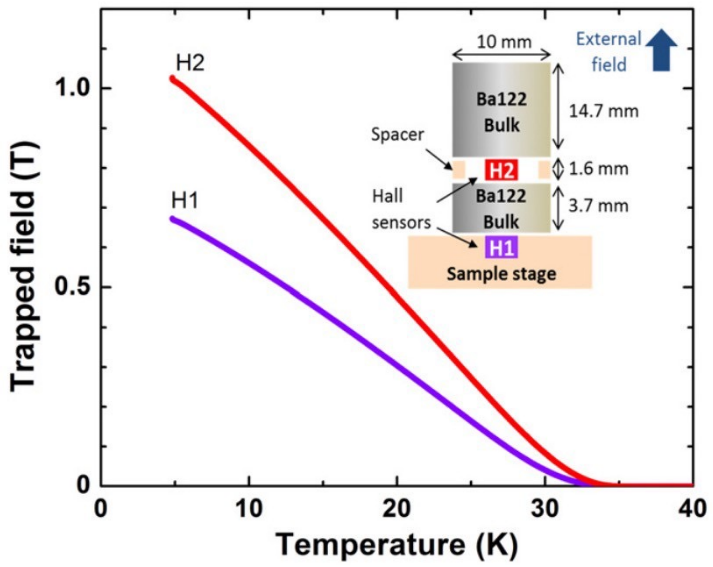
7 T-class can be obtained !

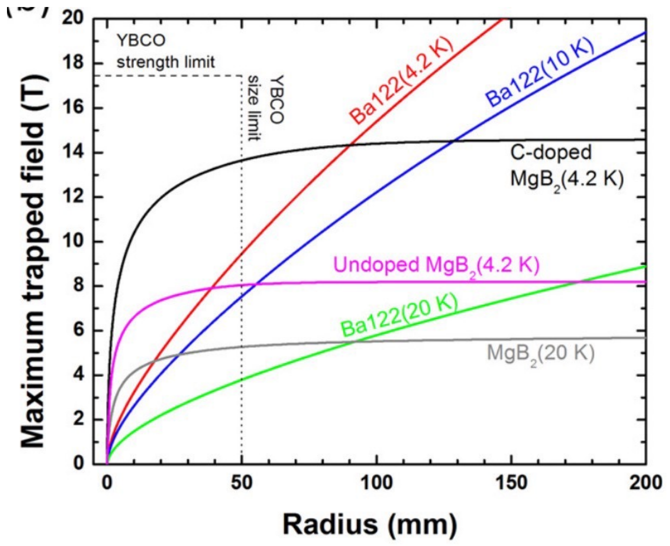


- Record: Naito *et al.* 5.58T at 11.3 K
- Yamamoto and colleagues reported 5 T at 7 K
- Fuchs *et. al* reported 5.4 T at 12 K

See Naito et al. SuST, Vol.33 (2020) 125004
Yamamoto et al. APL 105, 032601 (2014), Fuchs et al. SUST 2, 122002 (2013)

Other materials – Ba 122





- Weiss et al. have reported promising results on iron pnictide bulks (SUST 2015, 112011)
- Potential for good performance at high fields

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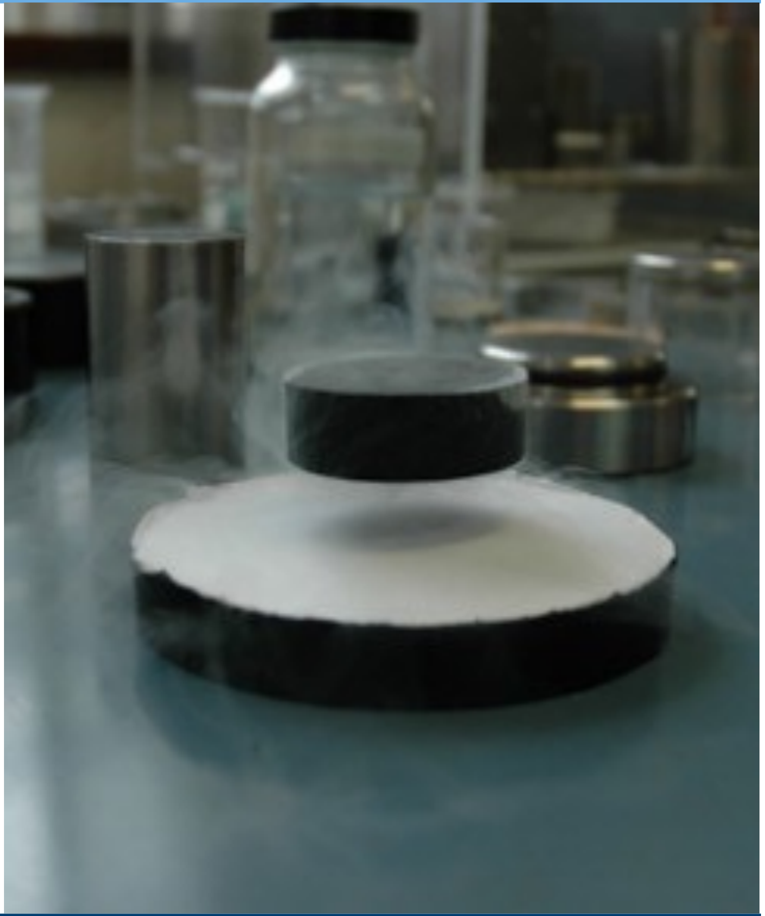
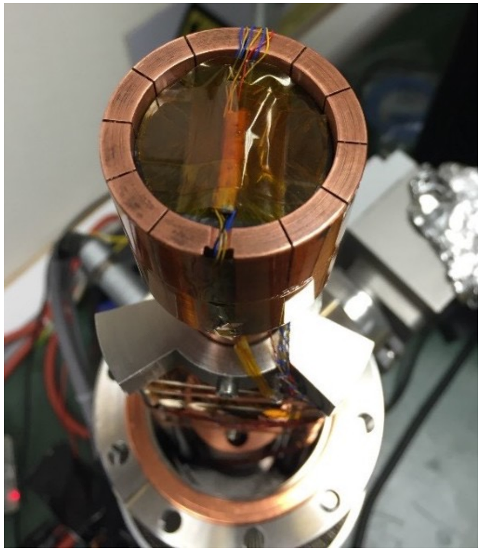


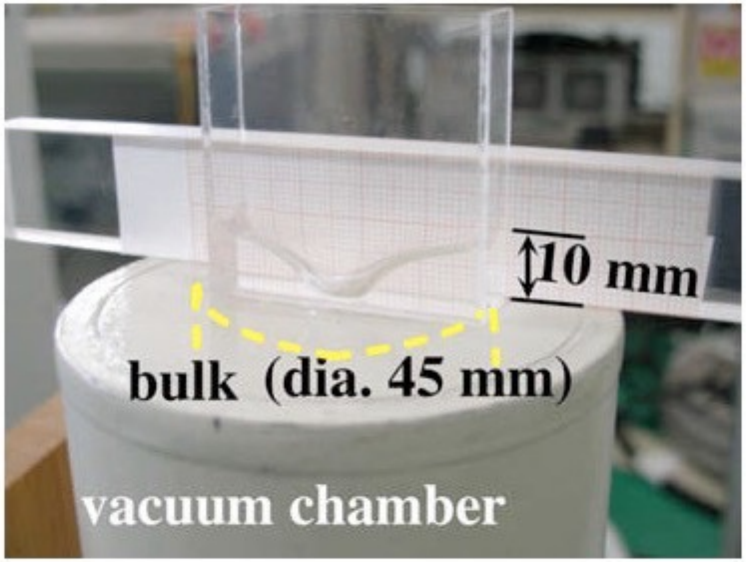
Accessible High Fields – for many applications



- "Bulk on a stick" allows easily accessible magnetic fields larger than those provided by permanent magnets.

Zhou et. al. Applied Physics Letters (2017) 110, 062601

Accessible High Fields



- Numerous potential applications for this kind of technology – EMAT, drug targeting, magnetic separation etc. etc.
- And you can part water ! “Moses Effect”

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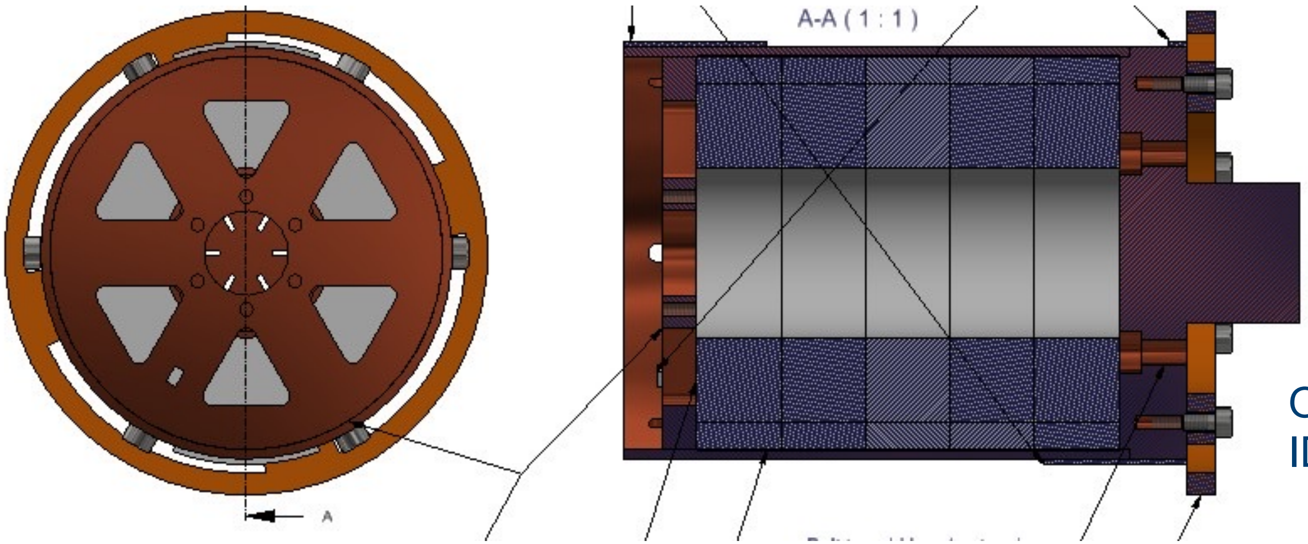
Image from Saho et al. Physica C 469, 15–20, (2009)

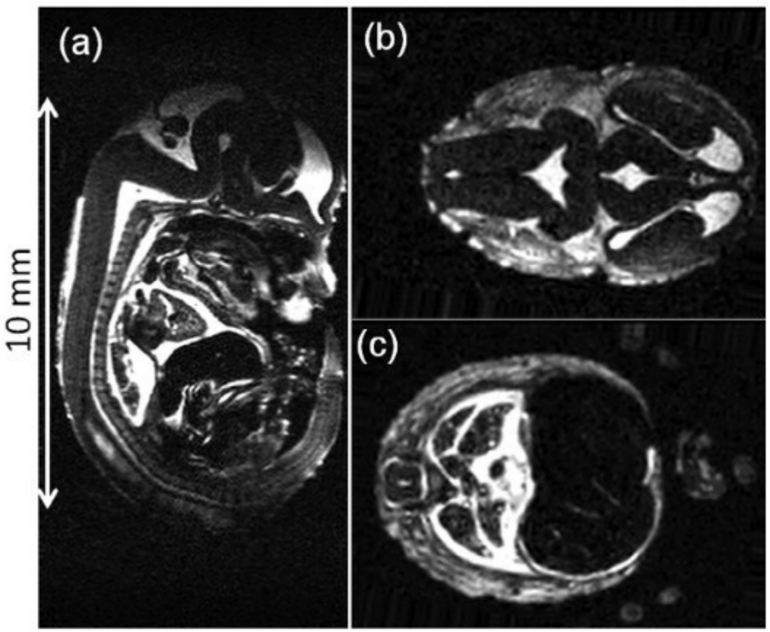
Bulk Superconductor Solenoids

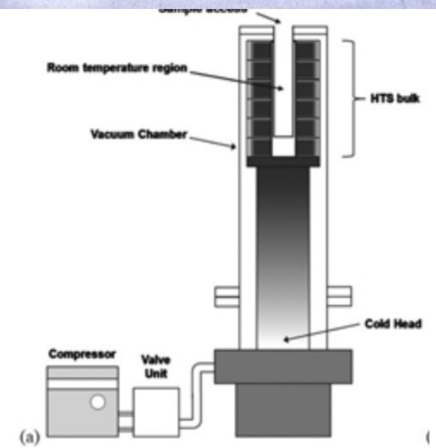


OD: 60 mm
ID: 28-36 mm

- Can, additionally, use ring shaped bulks to produce a solenoid style magnet.

NMR/MRI

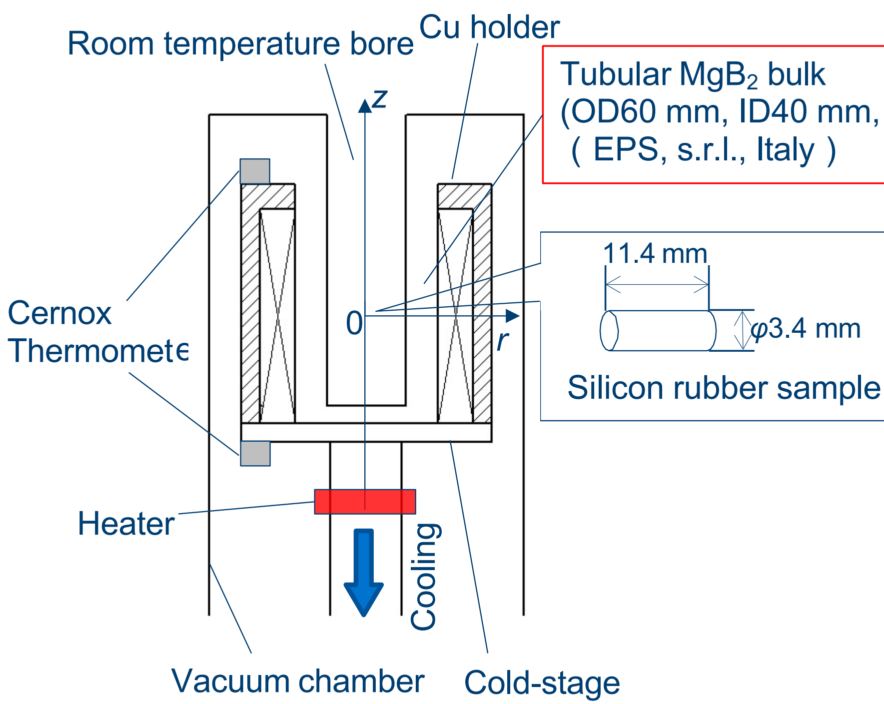


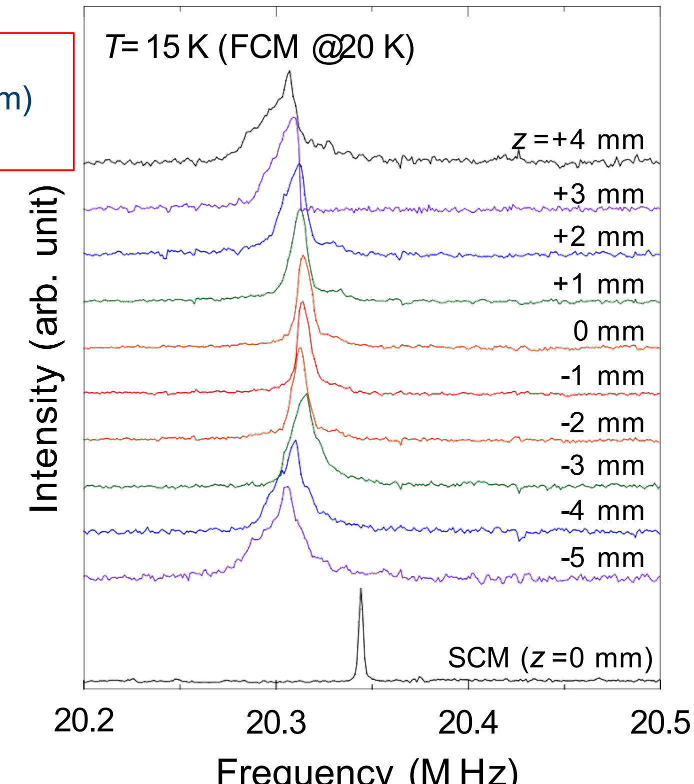


- Bulk solenoids have been shown to be usable in MRI imaging

T. Nakamura et al./Journal of Magnetic Resonance 259 (2015) 68–75

NMR/MRI – also MgB_2





- MgB_2 has been shown to be usable for NMR

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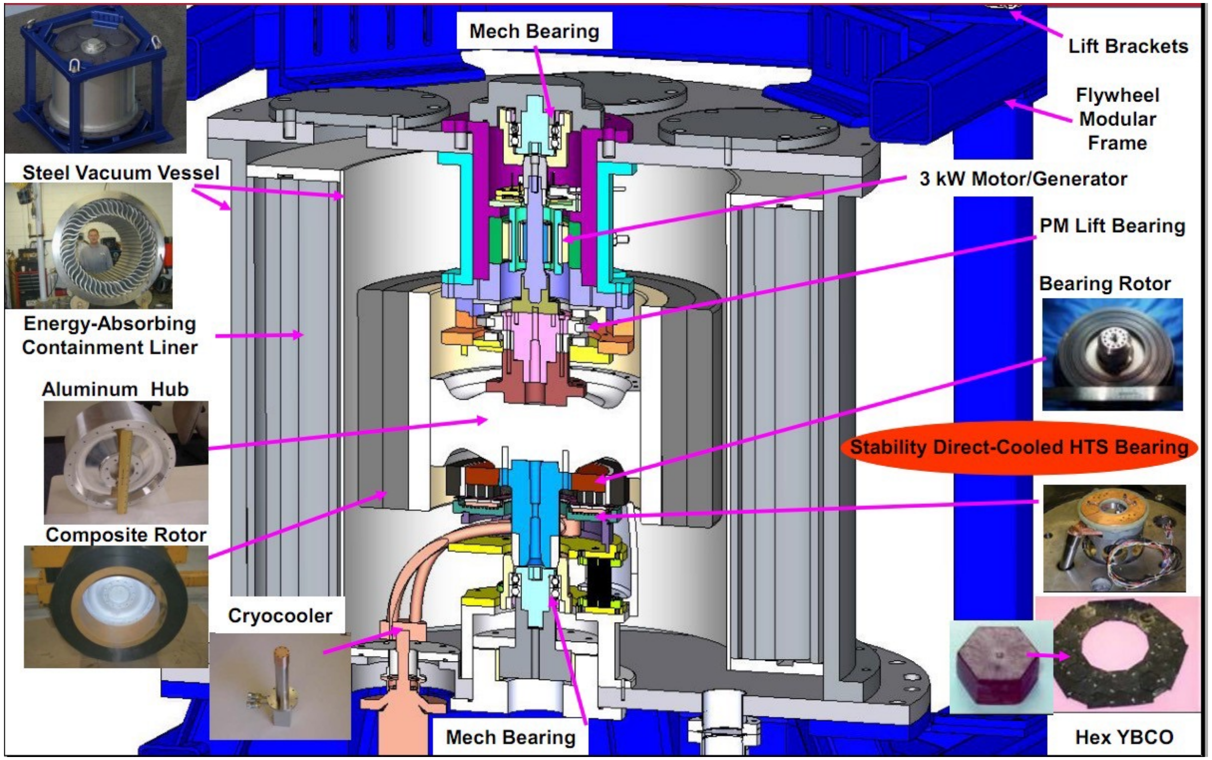
Naito et al. SuST, Vol.34 (2021) 06LT02

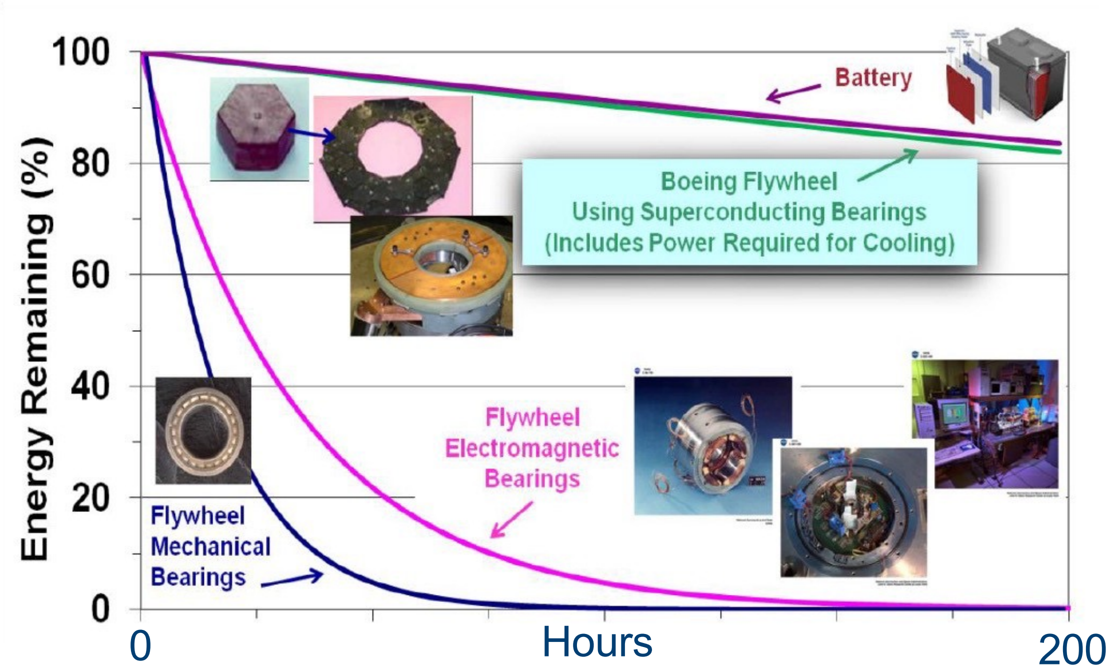
Superconducting Flywheel Bearings

- Flywheels offer unparalleled Specific Power Density ~5 kW/kg
- Specific Energy Density is slightly less than Li-Ion ~ 0.2 kWh/kg. Compare Petrol at 14 kWh/kg
- Key advantage is ability to discharge quickly (power).



http://www.sandia.gov/ess/docs/pr_conferences/2008/johnson_boeing.pdf

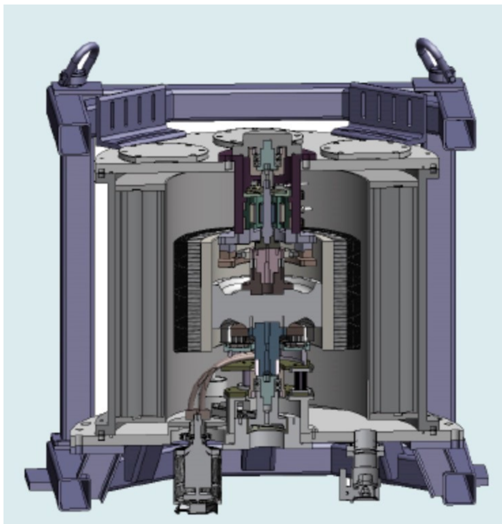
Applications - Superconducting Bearings

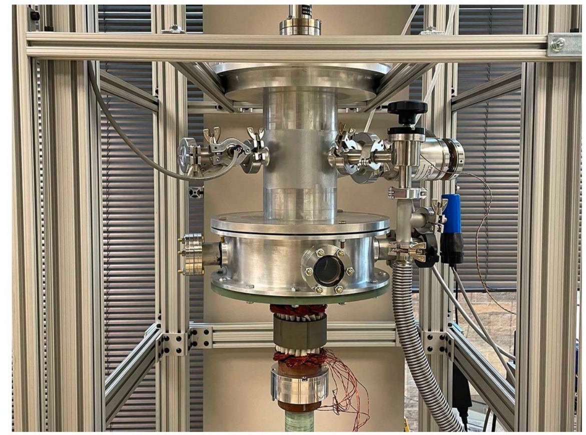


- Primary source of loss is friction. Superconducting bearings significantly extend useful energy storage time.

http://www.sandia.gov/ess/docs/pr_conferences/2008/johnson_boeing.pdf

Superconducting Flywheels



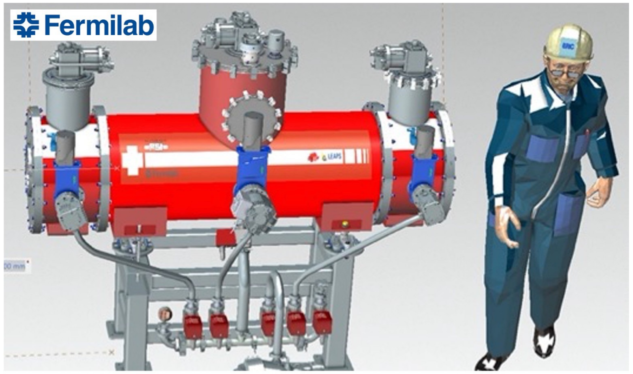


QuinteQ
energy storage

REVTERRA

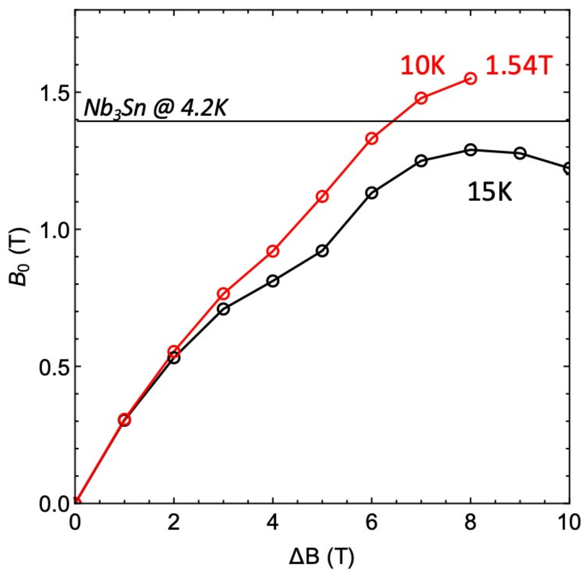
- Being pursued by multiple companies

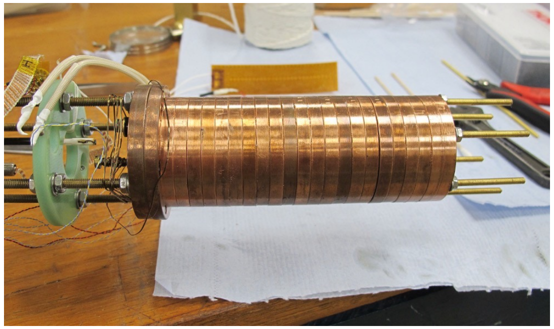
Undulators for Particle Physics

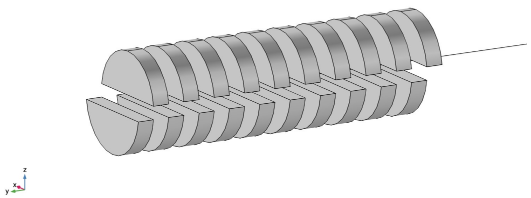


- Undulators are used in synchrotrons to produce more intense radiation than possible from simple beam bending
- May be able to replace large permanent magnet installations with bulk superconductor based systems

Bulk Undulator Performance







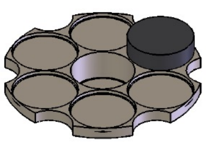
- With PSI we have demonstrated better performance in terms of undulator field than possible with LTS materials

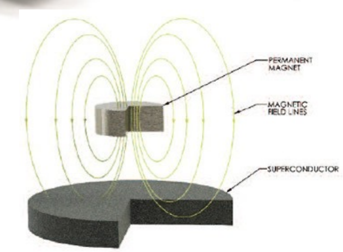
Superconducting Mixers

PALL

LevMixer®

- 1st Real Application of HTS used in LifeScience
- Made by PALL Corporation
- No shafts, no seals or bearings inside single-use mixer system
- Thousands of CAN bulks in use for more than 15 years, **more than 1,500 mixers made!**

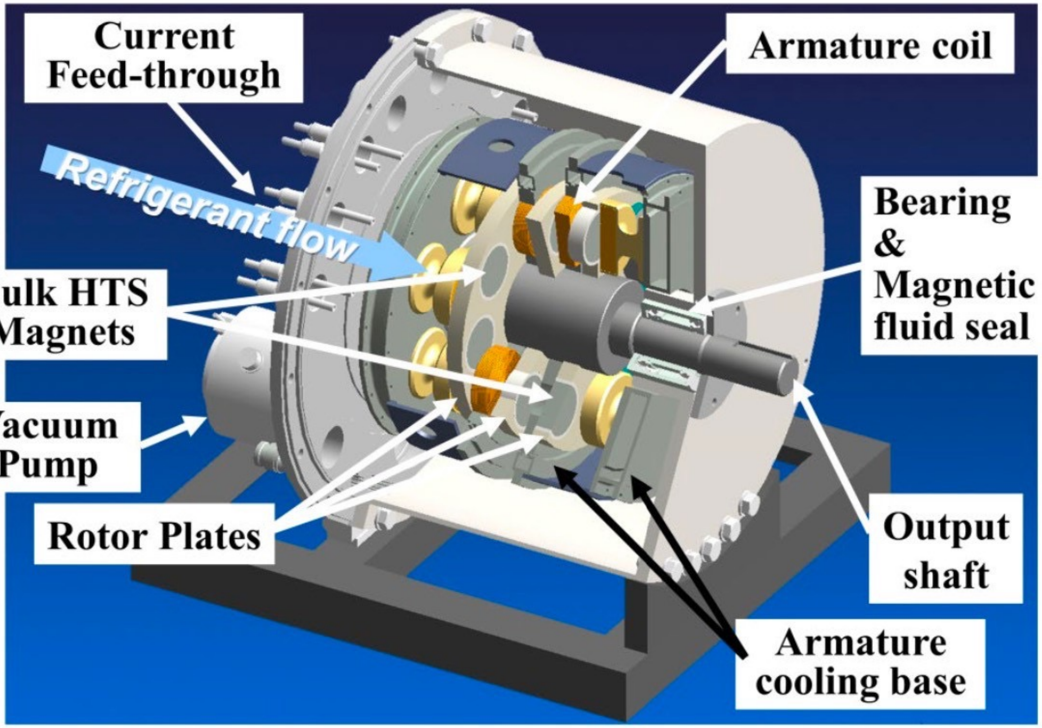




can superconductors

- Can also be used for mixing applications

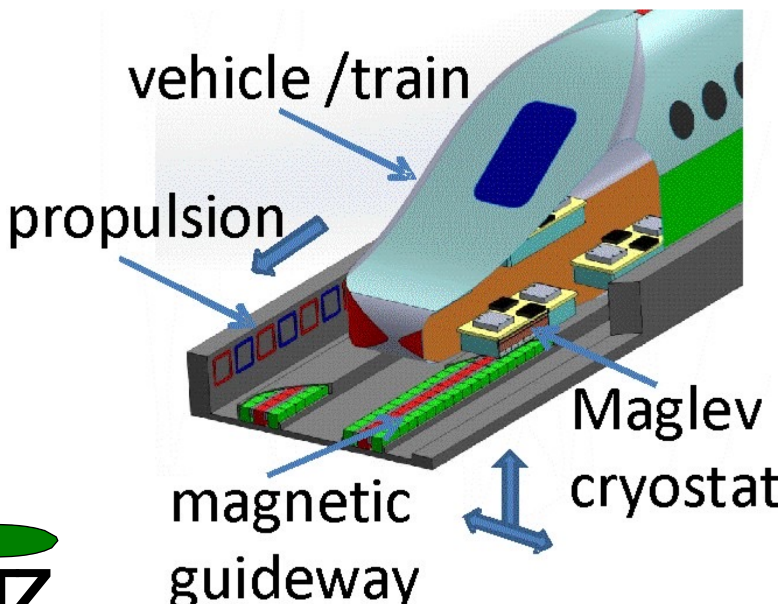
Bulk HTS Axial Flux Motor

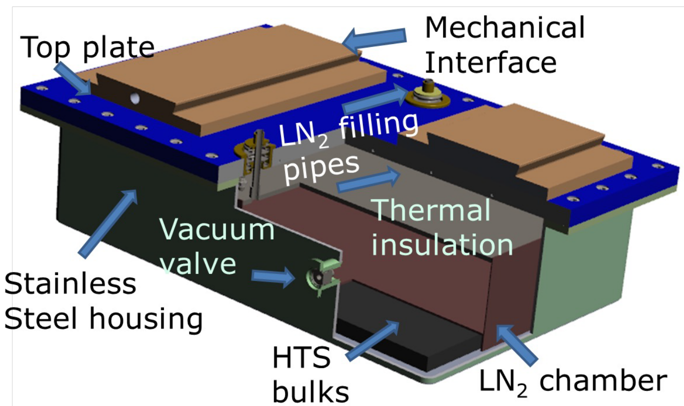


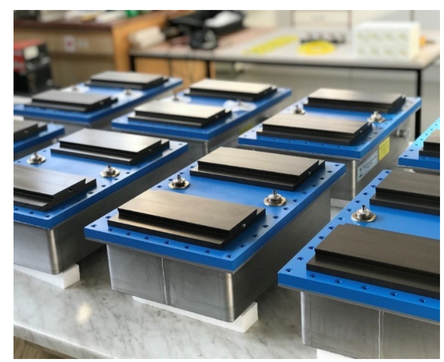
Axial-type bulk superconducting electric machine

Slide courtesy M. Izumi, TUMSAT

Maglev


vehicle /train
propulsion
Maglev
cryostat
magnetic
guideway

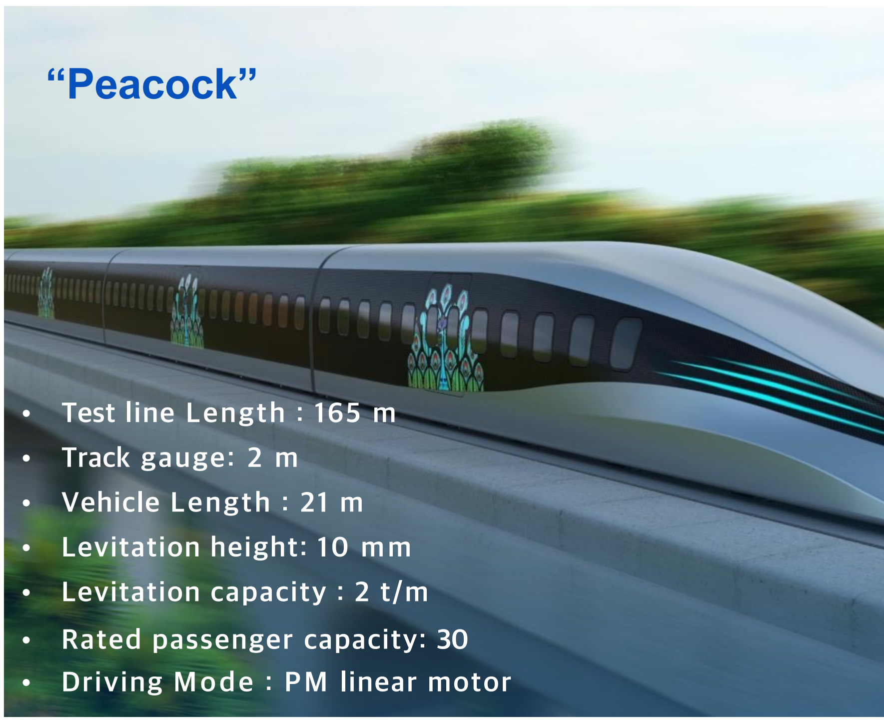

Top plate
Mechanical
Interface
LN_2 filling
pipes
Thermal
insulation
Vacuum
valve
Stainless
Steel housing
HTS
bulks
LN_2 chamber



ATZ

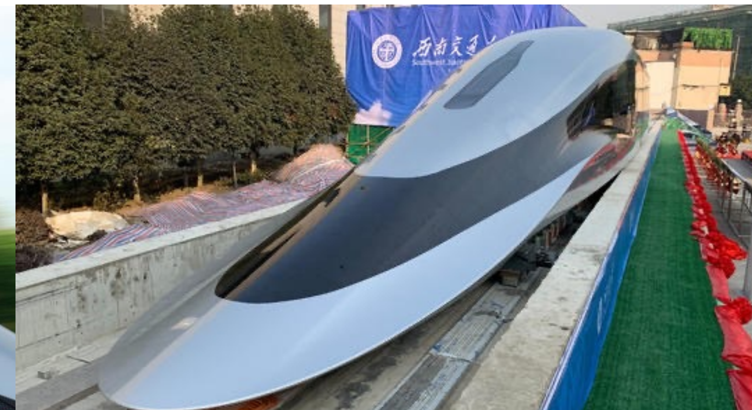
Maglev

♦ The First Prototype HTS Maglev Train, “Peacock”



“Peacock”

- Test line Length : 165 m
- Track gauge: 2 m
- Vehicle Length : 21 m
- Levitation height: 10 mm
- Levitation capacity : 2 t/m
- Rated passenger capacity: 30
- Driving Mode : PM linear motor



Jan.13, 2021

The first prototype HTS Maglev train was unveiled in Chengdu, China.

Expected top speed: 620 km/h.

Evacuated Tube Maglev

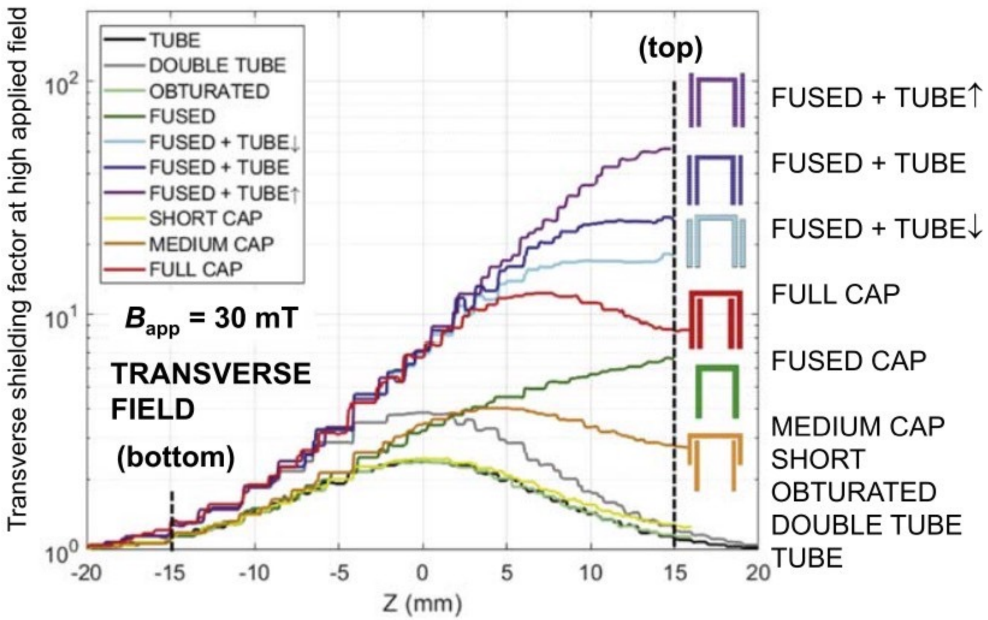
♦ Dynamic Model Test Platform for Multistate Coupled Rail Transit (1500 km/h)

Sichuan Provincial Reform Commission, Completion in 2023

- Model ratio：1:8~1:3
- Tube length: 1620 m
- Tube diameter：3 m
- Pressure：0.005 atm
- Top speed：1500 km/h

The construction site is in Chengdu. The total area of this platform is about 42,500 square meters.

Magnetic Shielding



- Bulk superconductors can be used to provide highly effective magnetic shielding in a number of geometries

Fagnard et al., *Supercond. Sci. Technol.* **32** (2019) 074007

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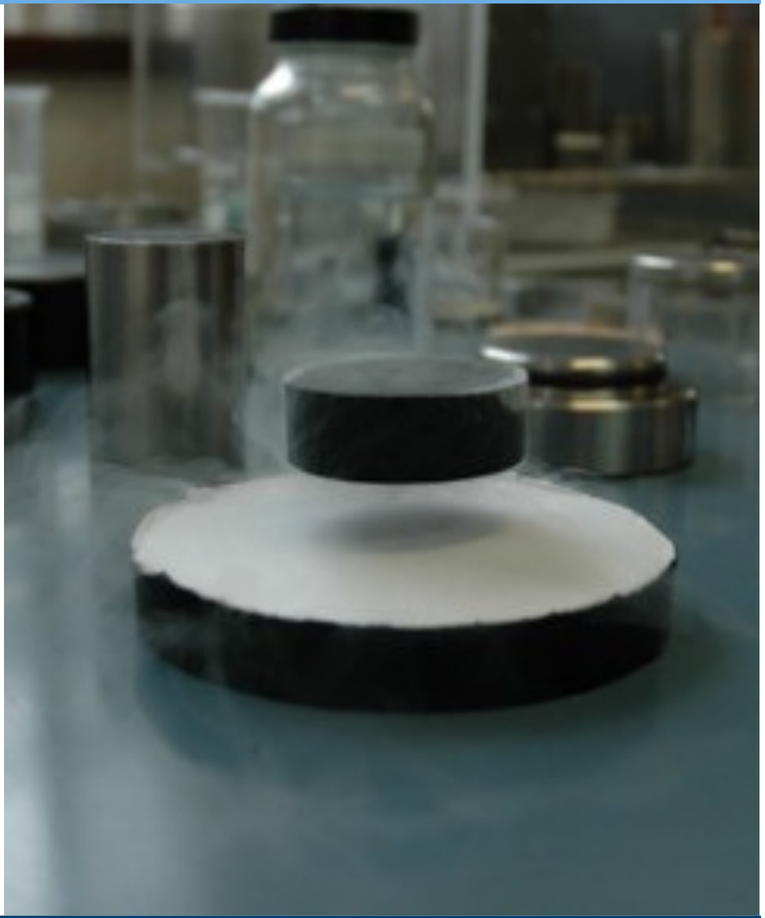
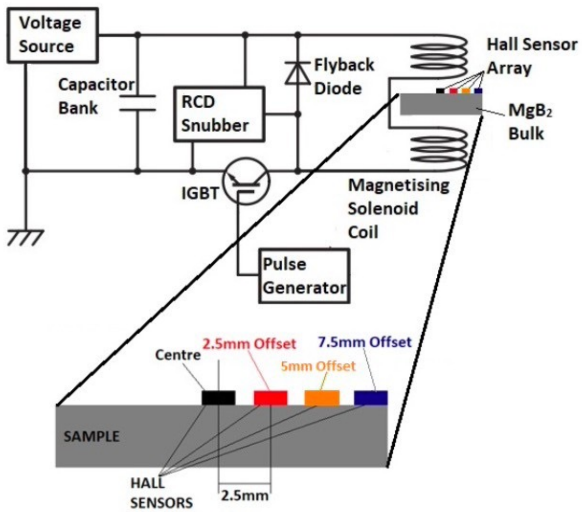
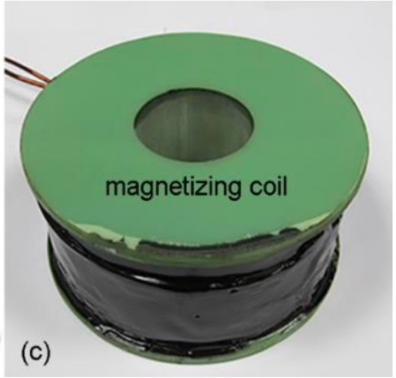


Charging





- Using a conventional superconducting magnet to charge bulks works – but isn't really the point
- Need a cheap and practical route to charge – pulse charging

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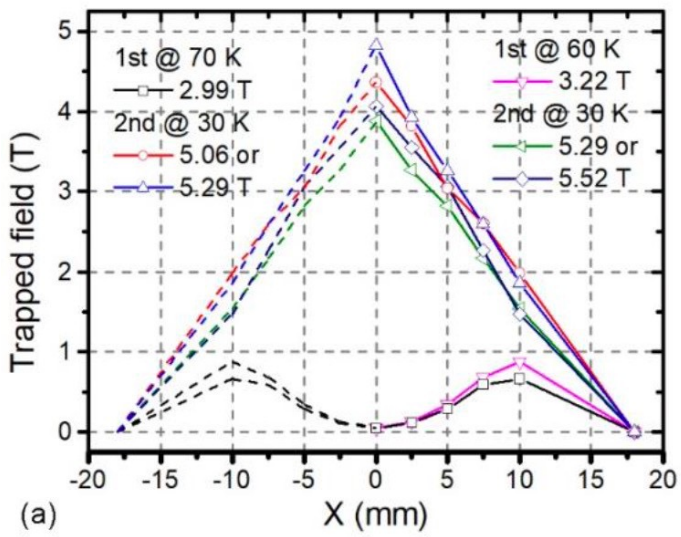
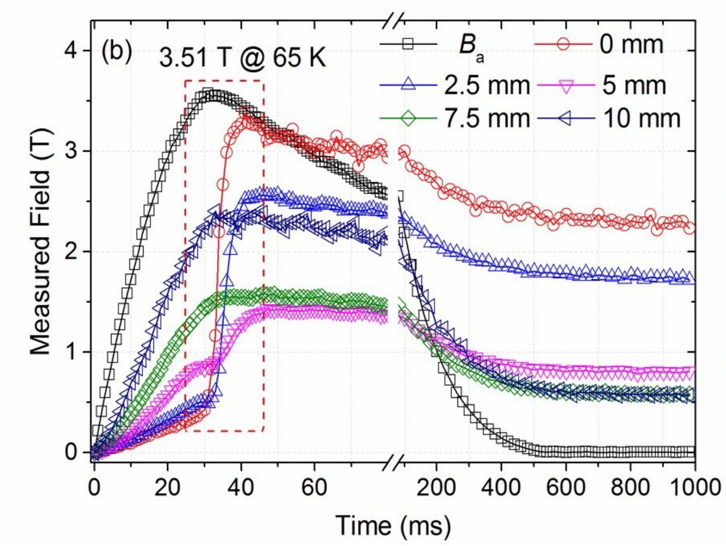
Charging





- However, process is complex and needs optimization, relies on “flux jumps”
- Especially stringent requirements in NMR and MRI
- Can achieve ~ 5T in REBCO materials

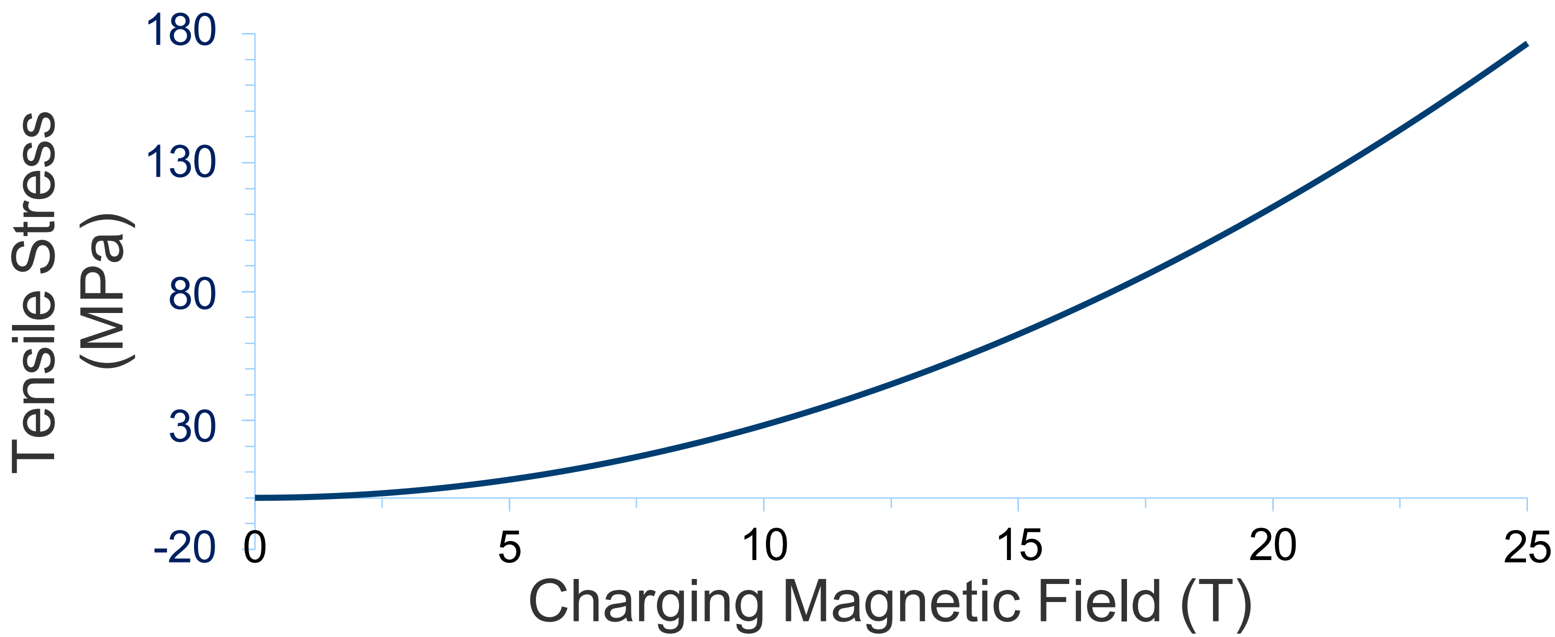
Zhou et. al. Applied Physics Letters (2017) 110, 062601
Zhou et. al. SUST (2020) 34, 034002

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2022.
This plenary presentation was given at the virtual EUCAS 2021, September 5-10, 2021.

Mechanical Strength

- J_C is important but not sufficient
- At ~17 T internal stresses are ~ 90 MPa
- Stress scales as the square of field ~ 0.282 B^2
- This leads to practical maximum of 7-9T in unreinforced samples as tensile strength is < 50 MPa
- Very variable performance – worst crack problem

Mechanical Stress during Charging

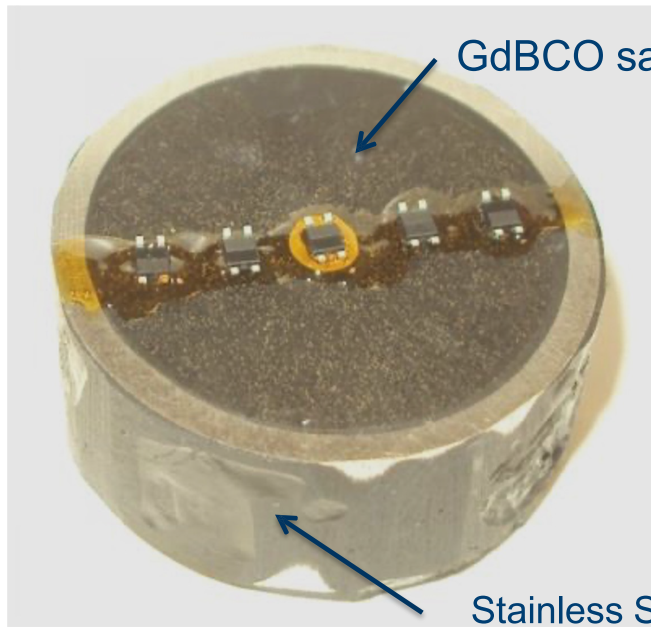


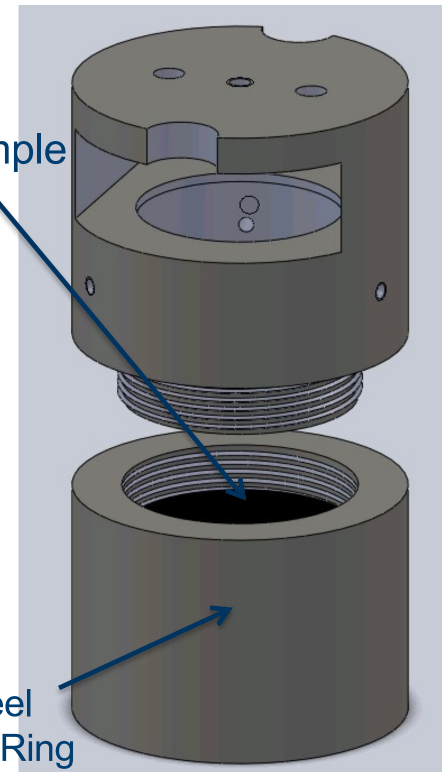
- During charging the maximum tensile stress increases as the square of the field.

Record trapped fields in (RE)BCO at Cambridge

2 samples combined with hall probes set in the centre.
Mounted top surface to top surface.

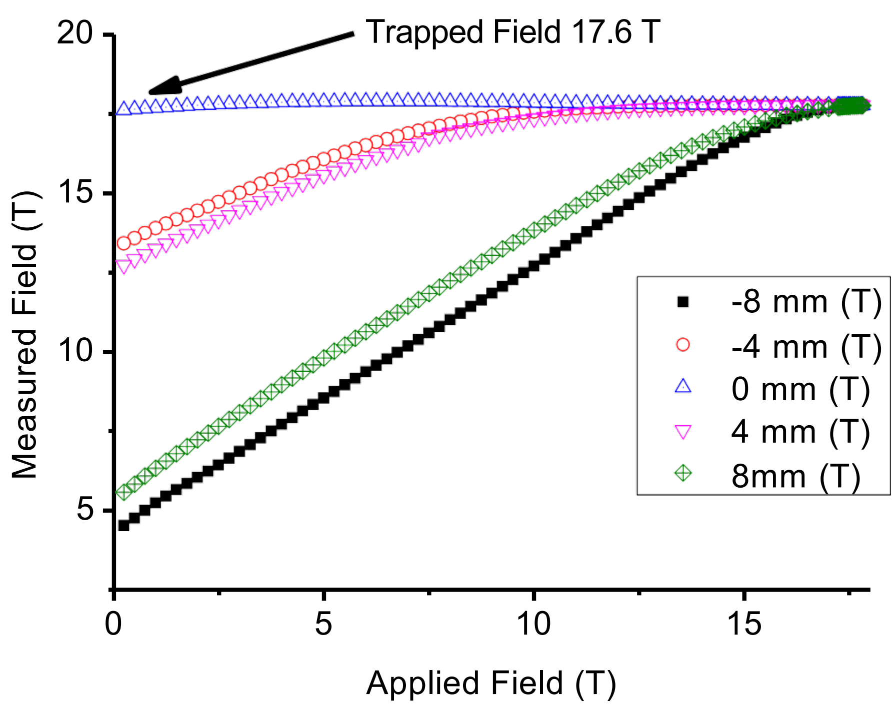
10 mm





Collaborative study with NHFML and Boeing

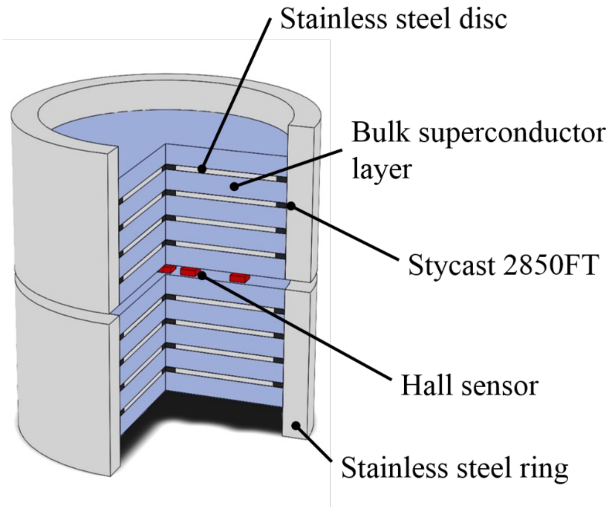
Record trapped fields in (RE)BCO at Cambridge



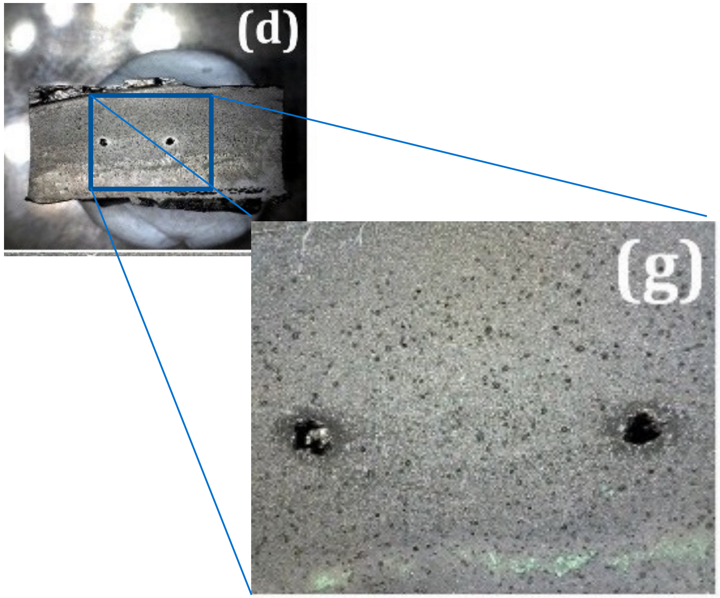
- Small sample (24 mm diameter)
- 26 K
- Energy density > 25 MJ/m^3
- Equivalent to 12% of energy density of TNT!

Superconductor Science and Technology, **27**, 082001, 2014

Mechanical Strength



Shrink fitting combined with layered steel



SiC fibre reinforcement

- Bulk superconductors are brittle materials – need reinforcement to achieve high fields and in-service robustness

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Namburi *et al* 2020 *Supercond. Sci. Technol.* **33** 054005
Huang *et al Supercond. Sci. Technol. 33 02LT01*

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2022.
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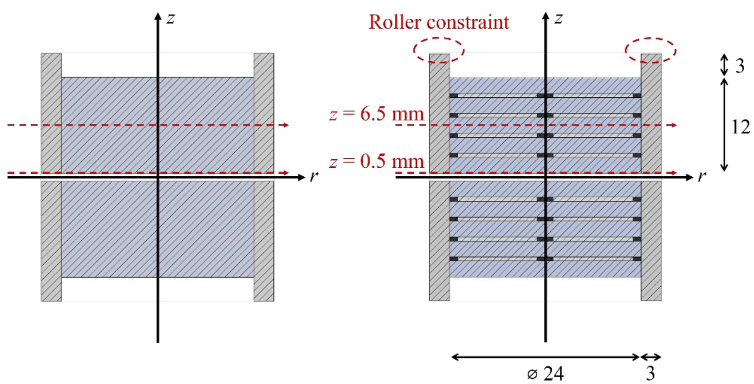
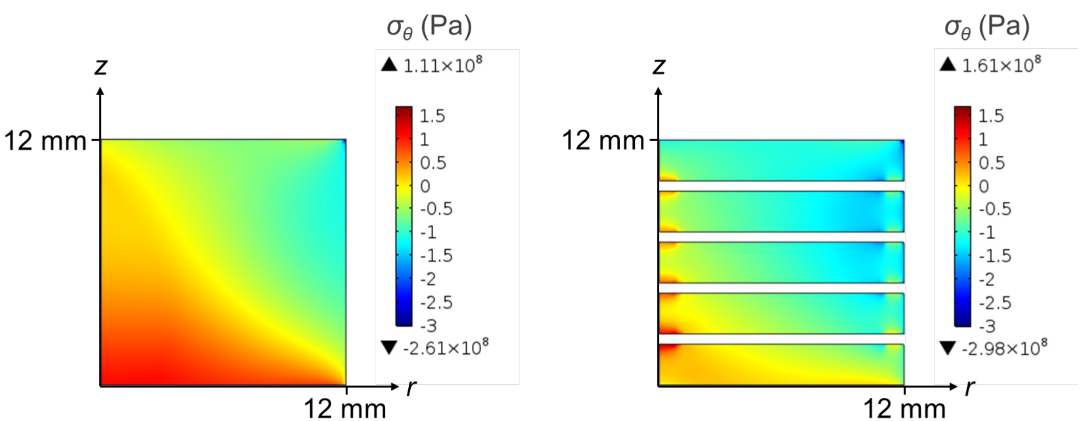
Composite bulk stack



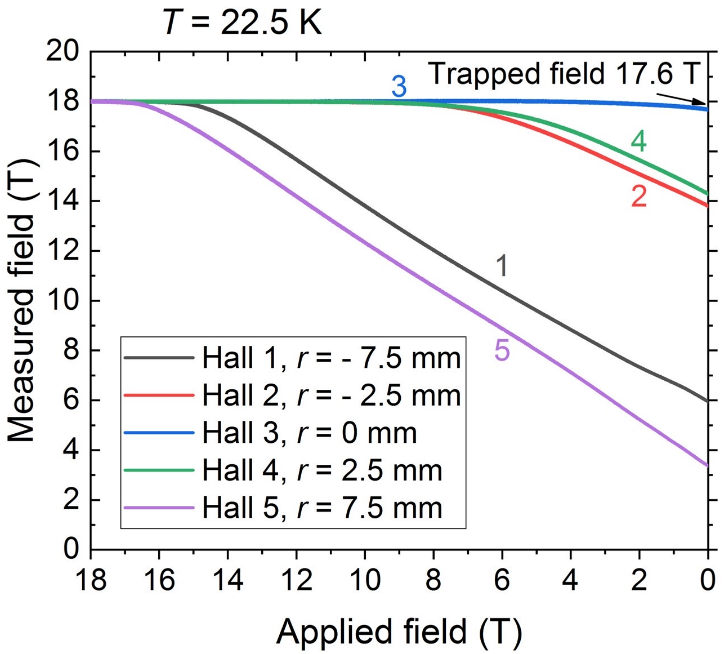


Comparison of the stress states in the bulk stacks after magnetization:

$$\sigma_!^{"\#"\$\%} = \sigma_!^{\&\#\#\%} + \sigma_!^{'\&(}$$

Trapped field of 17.6 T – again !

Run 2:



- Successfully trapped 17.6 T at 22.5 K
- Results are significant because:
  - This was achieved with the first stack made following this composite approach
  - Statistical nature of the failure mechanism means the best performance could not be attained reliably until now
  - High trapped fields ~ 17 T were reproduced in the same stack

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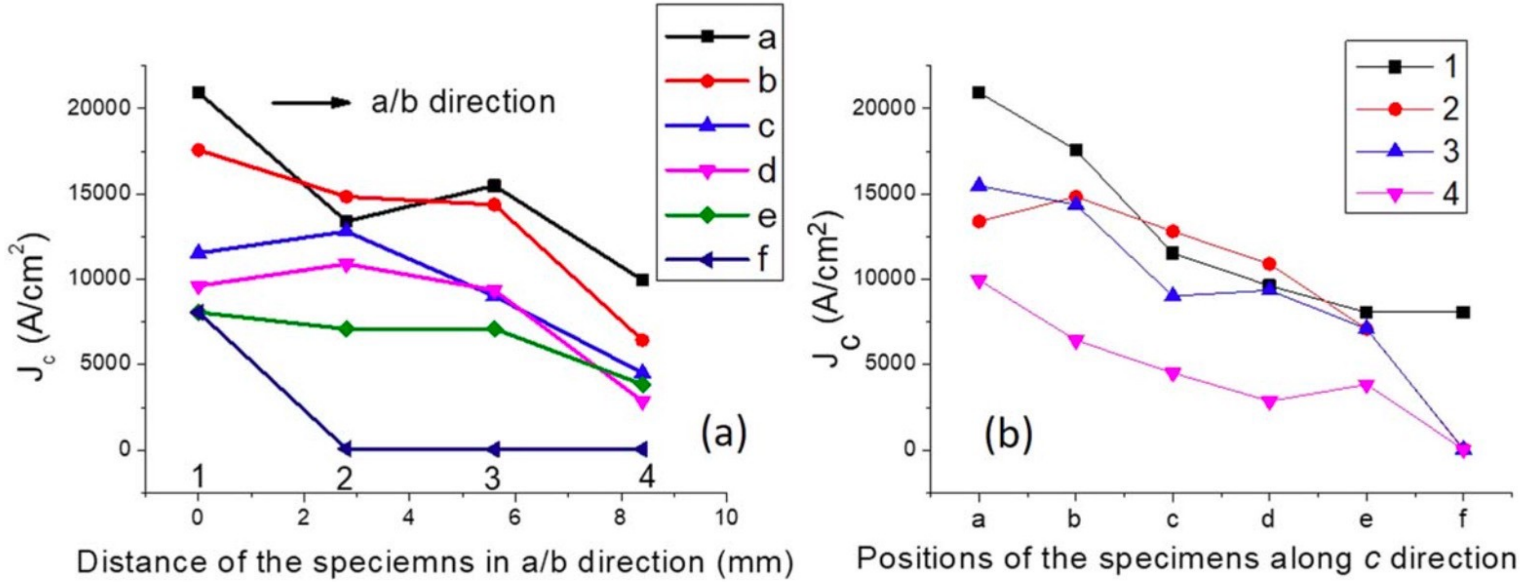
Huang et al Supercond. Sci. Technol. 33 02LT01

Sample Size limits

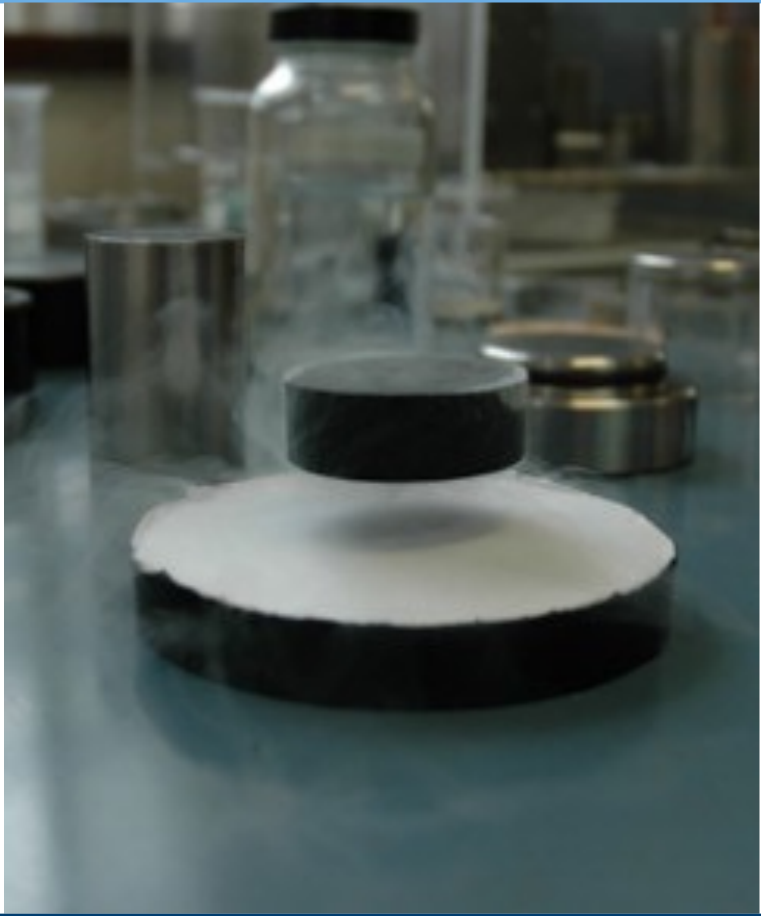


- Growing large bulks of (RE)BCO is challenging, properties can degrade at edges and process is intrinsically slow. Multi seeding is one potential route around this.
- MgB_2 scales well – no single grain issues – major advantage

Shi *et al* 2020 *Supercond. Sci. Technol.* **33** 044009

Overview

- Basics
- Materials
  - REBCO
  - MgB_2
- Applications
- Challenges
- Conclusion



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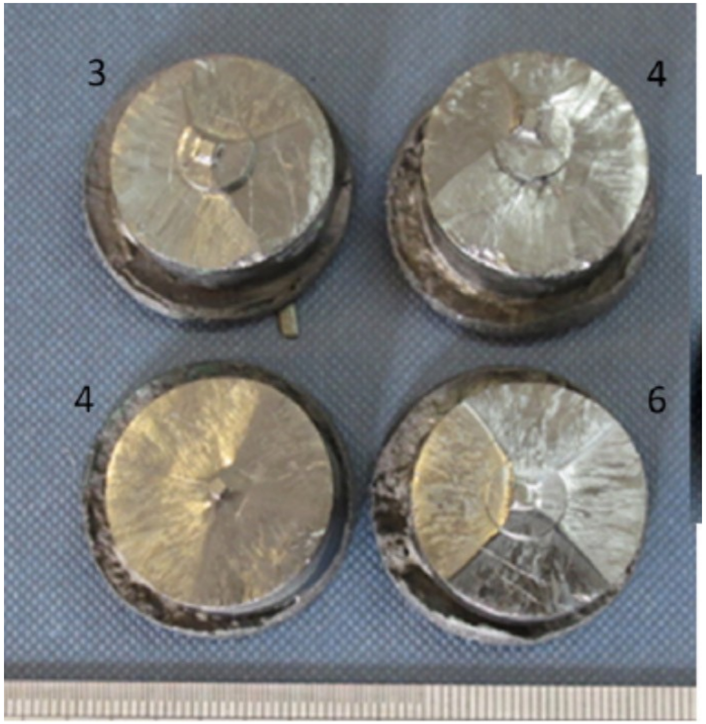
B|S|G

Sustainability?

- We are encouraged to think about recycling
- We can recycle bulk superconductors and obtain good performance
- Other research groups have also explored this problem – becomes more challenging with higher melting point materials.



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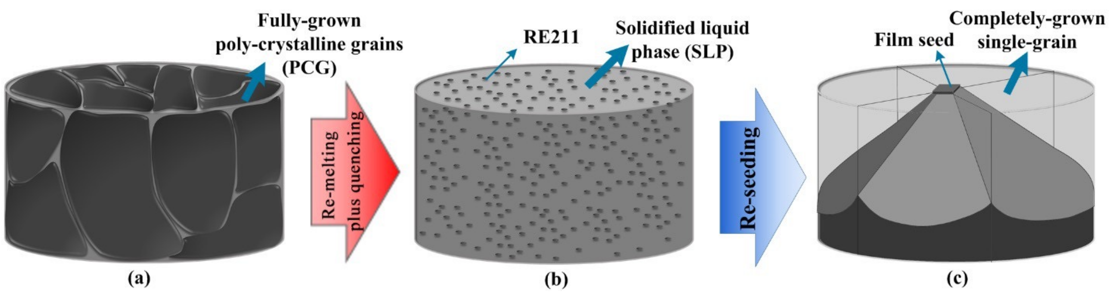
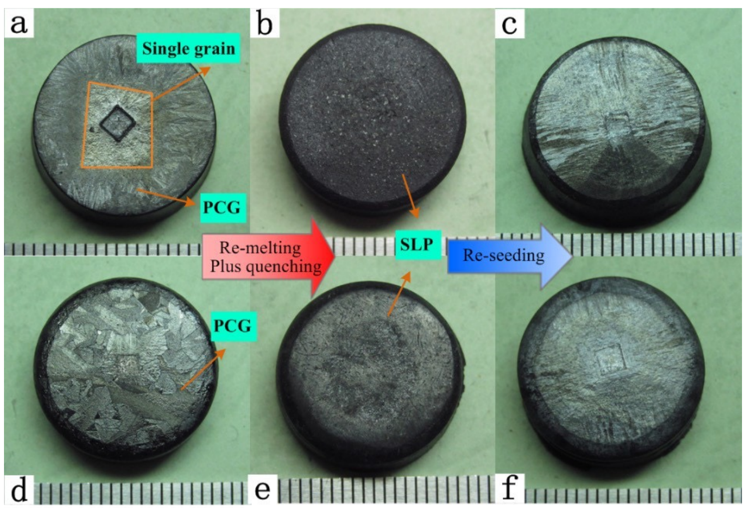
Shi, Y et al. (2015). J. Am. Ceram. Soc., 98: 2760-2766.

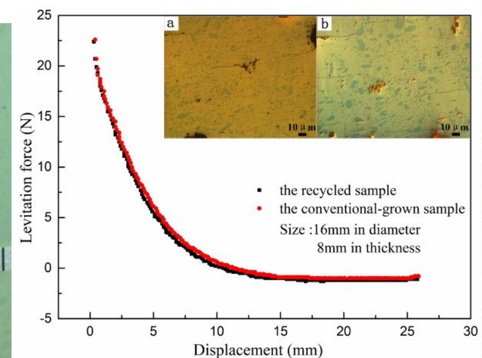
Two-step method: recycling hard-to-melt failed SmBCO bulks

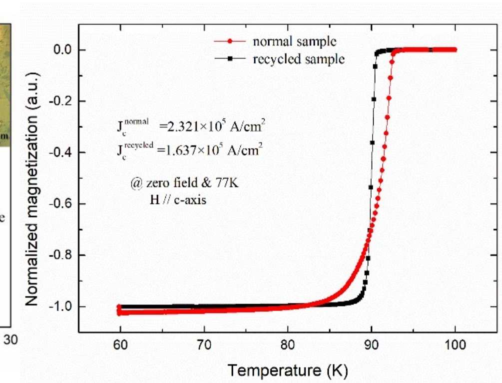
Yao et al., J. of . Amer. Cera. Soc. (2019)



Re-melting & quenching: Transforming PCG to SLP







Levitation force, J_c & T_c is comparable to primarily-grown sample

Difficulty level for recycling	Volume ratio of PCG†/SLP‡	T_p§	Meltability of sample	Failed-grown REBCO bulks	Melting for re-growing
Low	Low (Type I)	Low (YBCO)	High	YBCO (Type I, III, V)	Simply exploiting high T_{max} of 1120°C
Medium	Medium (Type III, V)	Medium (GdBCO)	Intermediate	Gd or SmBCO (Type I, III, V)	Using high T_{max} & liquid source at bottom
High	High (Type II, IV)	High (Sm or NdBCO)	Poor	All REBCO (Type II, IV)	Applying a re-melting plus quenching step at 1175°C

†. poly-crystalline grains; ‡. solidified liquid phase; §. peritectic temperature.

Slide – Prof. Xin Yao, Shanghai Jiao Tong University

Conclusions

- Bulk superconductors have been slower than coated conductors to find applications – slightly neglected
- Have some potentially important applications
- Potential to be cheap and practical as compared to complex coated conductor architectures
- Commercial applications are already there
- Best thought of as better permanent magnets