IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) January 2015.
Invited Presentation PC-16-INV given at ISS 2014, Tokyo, November 25 - 27, 2014.

UNIVERSITY OF CAMBRIDGE

Recent Developments in the Processing of Bulk HTS for High Field Applications

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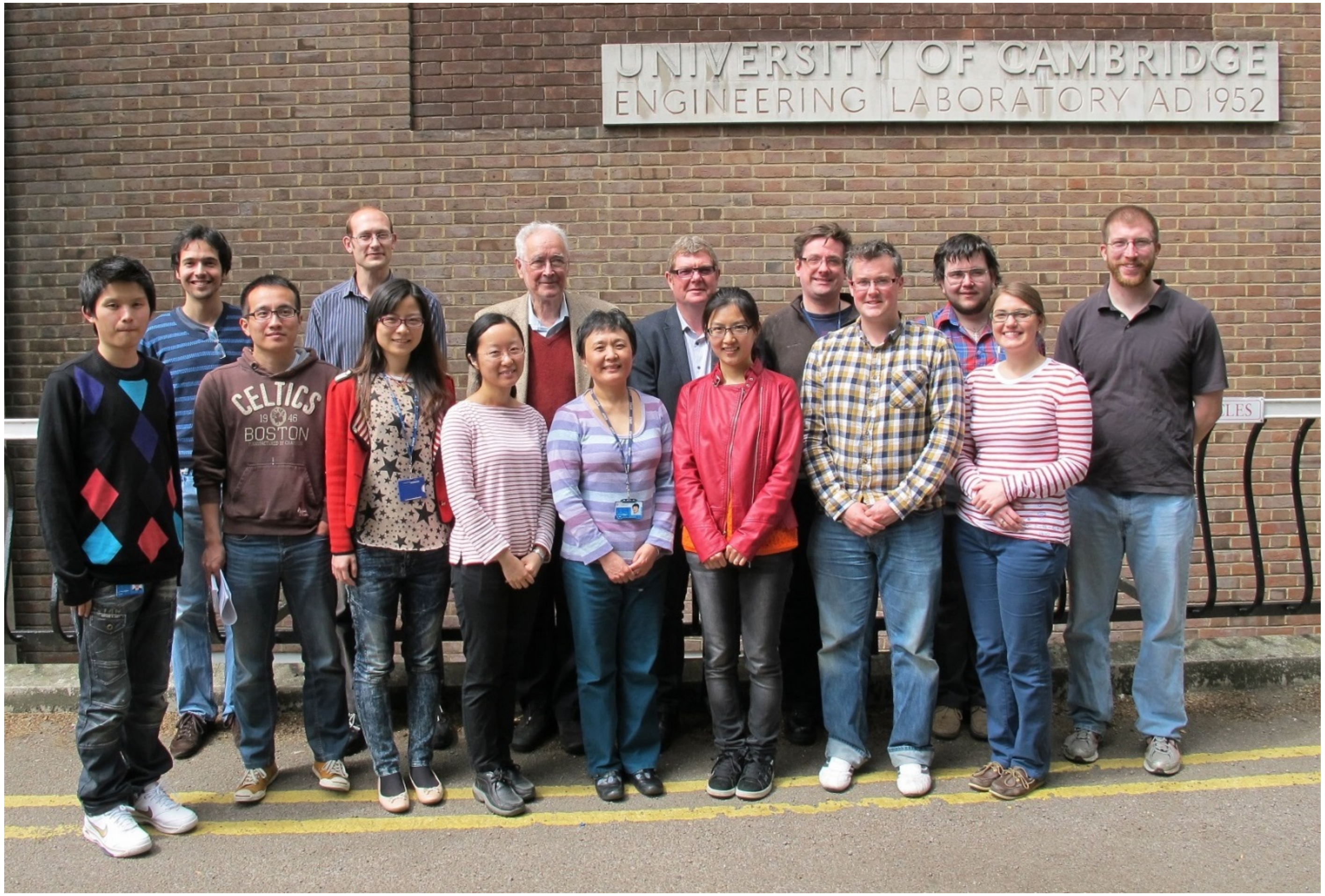
27th International Superconductivity Symposium, Tokyo, November, 2014

Bulk Superconductivity Group

Group Members:

- SRAs; Dr Hua Shi, Dr John Durrell
- RA; Dr Devendra Kumar
- Professor Archie Campbell (Emeritus)
- Royal Academy of Engineering Fellow; Dr Mark Ainslie
- PhD Students; Zhiwei Zhang, Wei Zhai, Jin Zou, Di Hu
  Kysen Palmer, Wen Zhao, Jordan Rush
- Visitors; Konstantina Konstantopoulous, Zejun Shen, Miao Wang
- Technical Officer; Tony Dennis
- Plus Masters and 4th year project students

Cambridge Bulk Superconductivity Group



Bulk Superconductivity Group

Principle Collaborators:

- Atomic Institute, TU Vienna
- IFW, Dresden
- University of Oxford
- University of Liege
- Shanghai Jiatong, Beijing and Shannxi Universities
- Boeing
- Siemens
- KACST (Riyadh)
- Florida State University (NHFML)

Overview

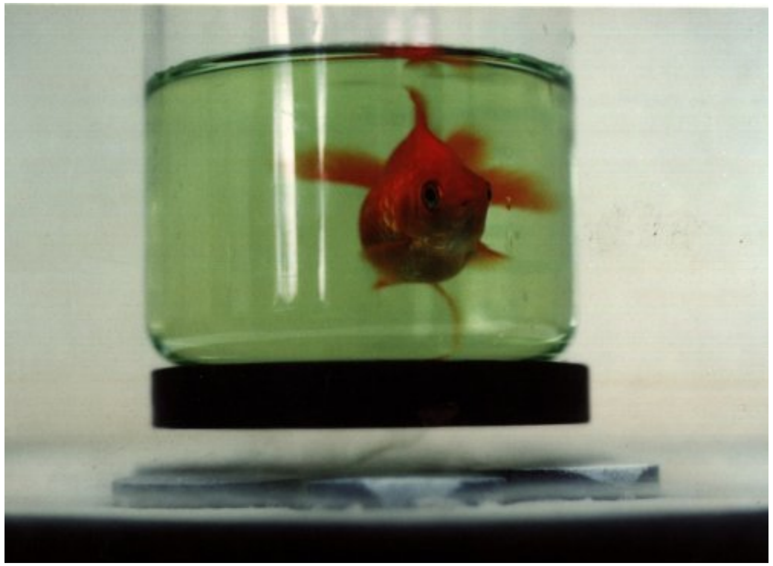
- Introduction
  - General properties of bulk superconductors

- Practical TSMG processing method for bulk (RE)BCO
  - Nano-scale second phase inclusions
  - Generic seed
  - Multi-seeding
  - Record fields

- Conclusions and summary

General properties of bulk superconductors

- Bulk Type II high temperature superconductors have significant potential for high magnetic field applications at 77 K



M. Murakami, *SUST*, 1992

1996

General properties of bulk superconductors

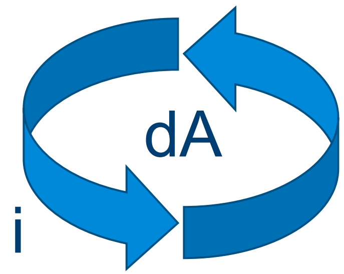
- Potential for high magnetic field applications at 77 K is based on their ability to trap significantly greater magnetic fields than can be generated by permanent magnets (limited to < 1.8 T in iron)

- Candidate materials must pin magnetic flux effectively and hence be able to carry high critical current densities, J_c's, over large length scales and be insensitive to the application of magnetic fields

General properties of bulk superconductors

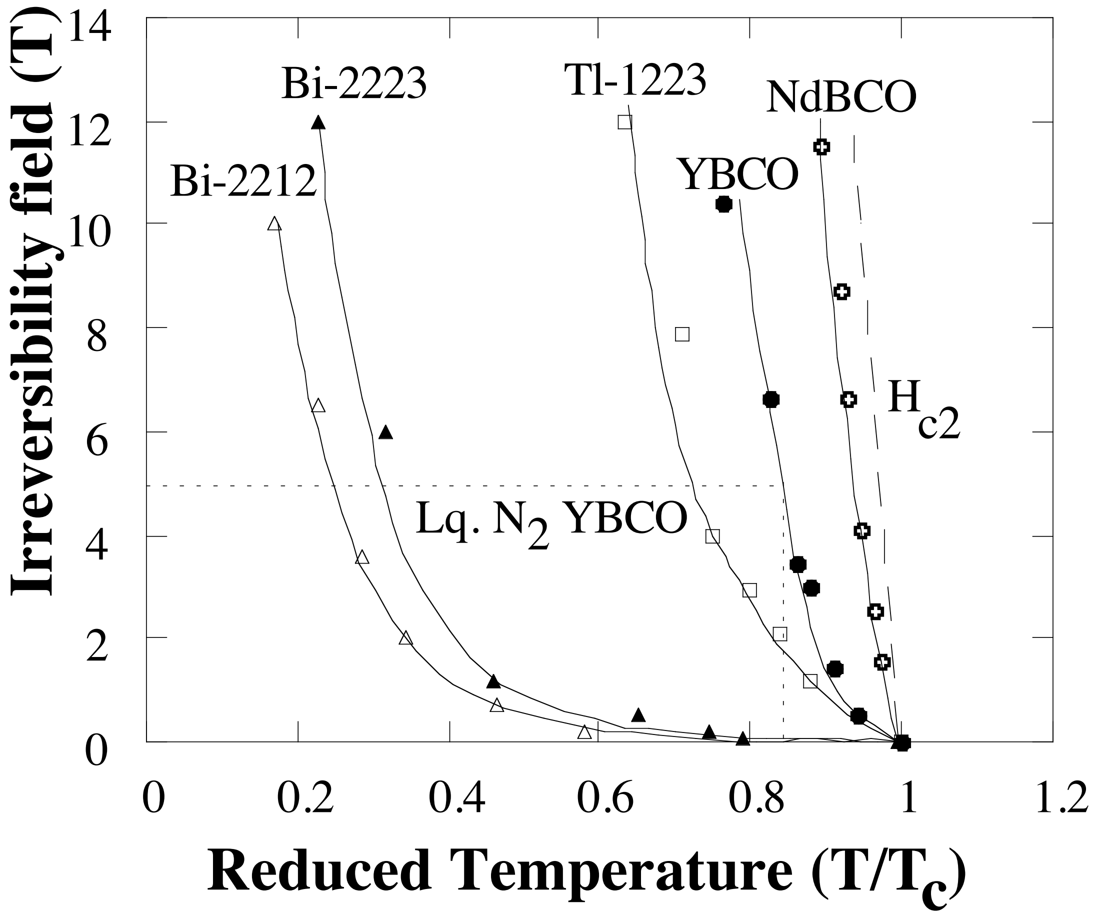
- Field generated by induced macroscopic currents rather than spins.

Magnetic moment $= \int i \, dA$

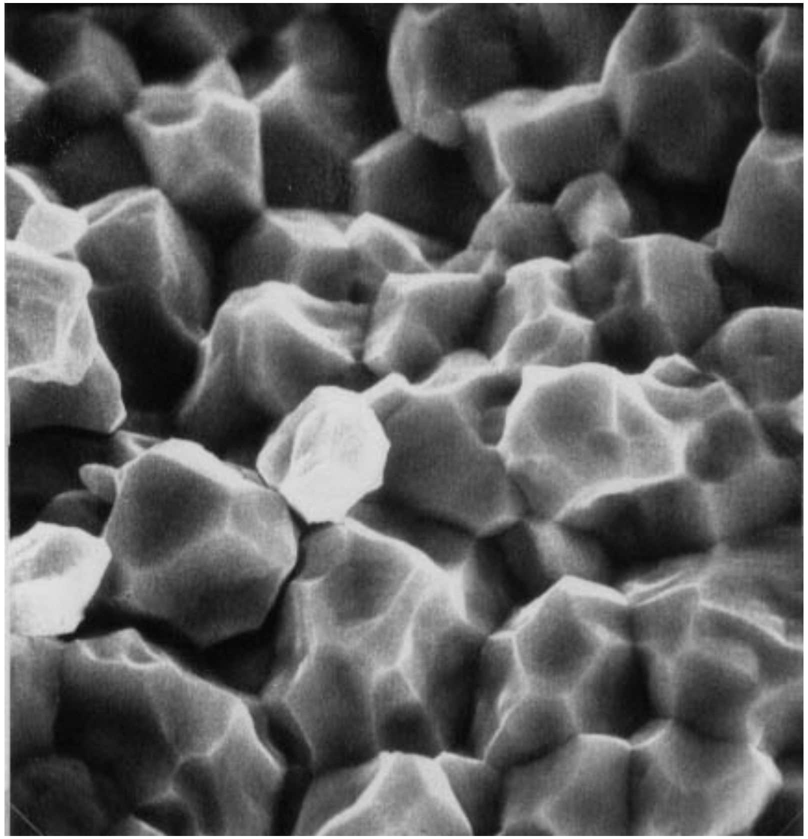


- The bigger the current loop, the bigger its magnetic moment
- Magnetisation *increases* with sample volume
- BIG samples carrying large currents = BIG fields

Irreversibility



Granularity is a problem!



Sintered YBCO

$2\ \mu m$

Candidate Materials

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

- YBCO has greatest short-term potential for applications, provided in can be made grain boundary free
- GdBCO looking good for large scale applications

Seeded melt growth

- All (RE)BCO melt processes are based on the following peritectic reaction that occurs around 1015 °C:

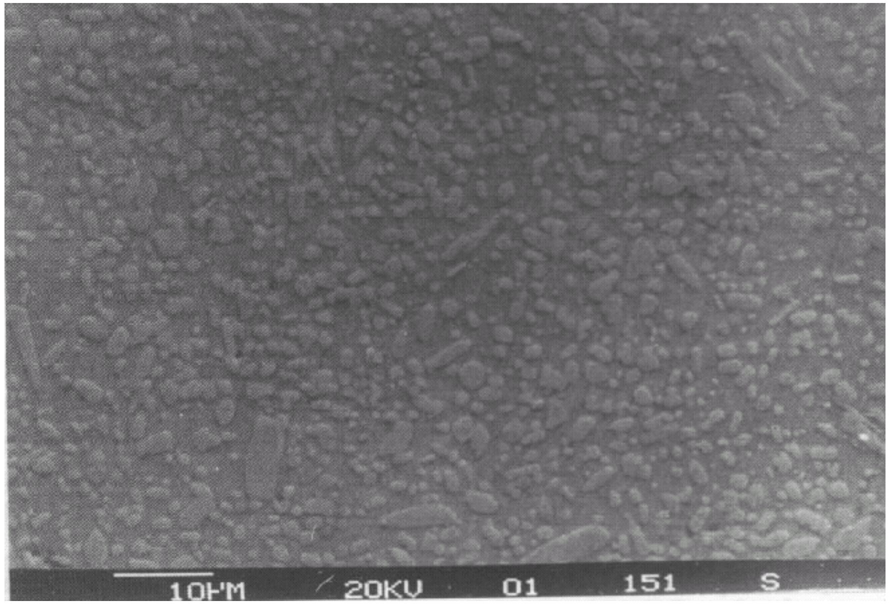
$$2(RE)Ba_2Cu_3O_{7-\delta} \rightarrow (RE)_2BaCuO_5 + (Ba_3Cu_5O_8)$$

(123) → (211/422) + Liquid

- Structurally compatible seed with higher melting point usually used to seed large grain growth in top seeded melt growth process (TSMG).

E.g. T_p(SmBCO) ~ 1070 °C, T_p(YBCO) 1015 °C

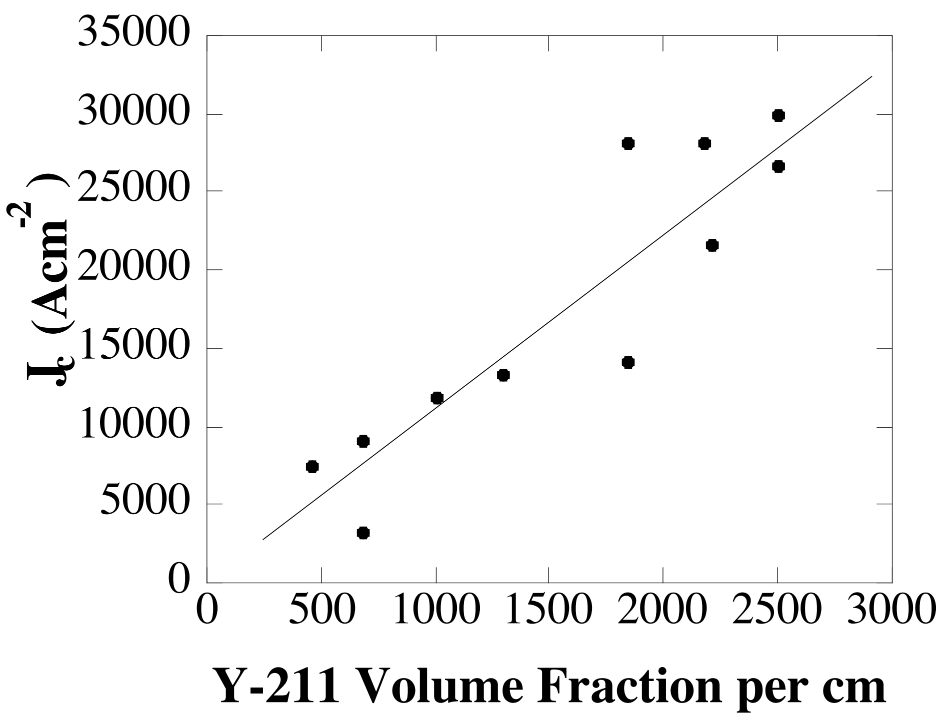
(RE)BCO Bulk Microstructure



- Discrete Y-211 particles, typically of size around 1 μm embedded in a bulk superconducting Y-123 matrix

(RE)BCO Bulk Microstructure

- Homogeneous distribution of fine, second phase particles correlates with increased flux pinning and hence increased J_c

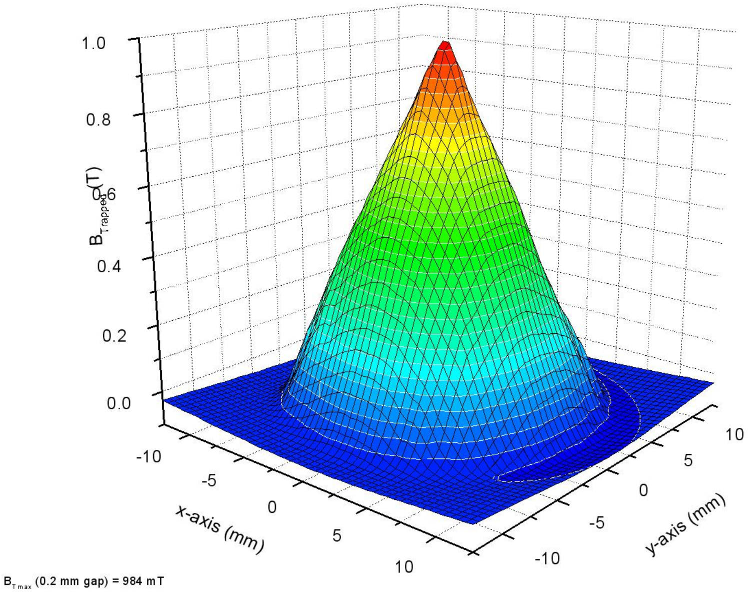


Murakami, *Supercond. Sci. Technol.*, 1992

Y-211 inclusions not necessarily optimum for flux pinning

The challenge

- To fabricate large, single grain, (RE)BCO bulk superconductors by a practical process with efficient flux pinning, high critical current density and high trapped fields.



Novel pinning centres – the 2411 phase

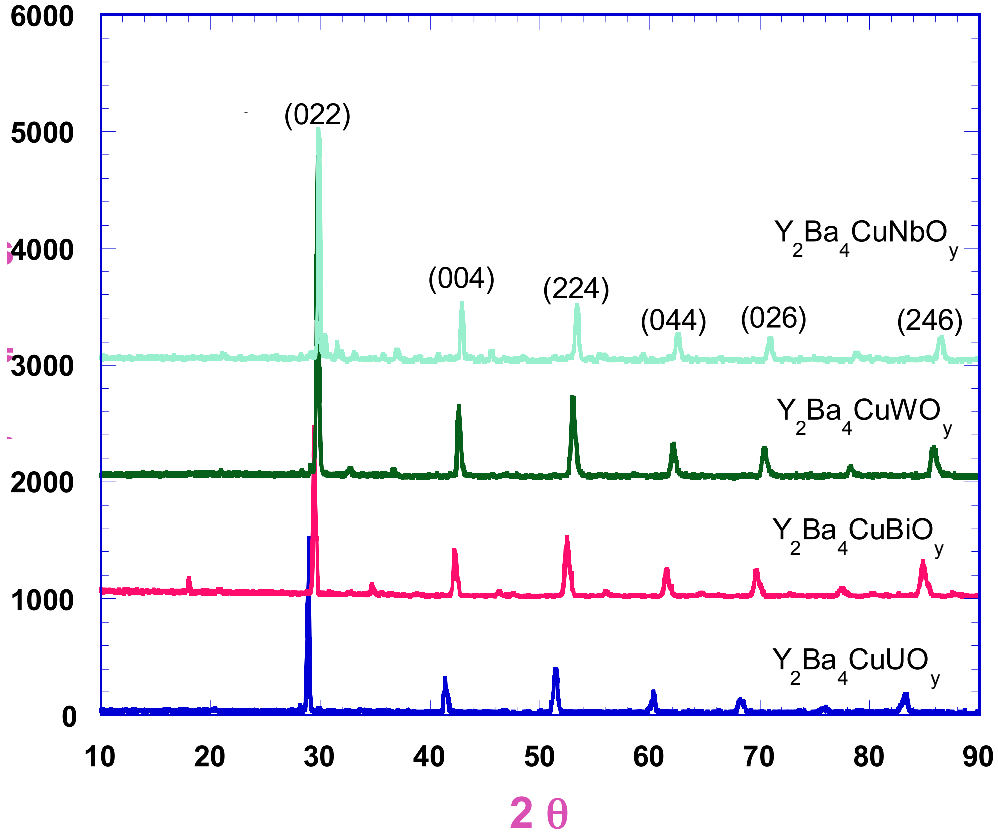
$$(RE)_2Ba_4CuMO_y$$

RE = Sm, Gd, Nd, Y

M = Nb, Zr, Hf, W, Bi, Ag, U …etc.

- All paramagnetic and non-superconducting down to 5 K

Novel pinning centres – the 2411 phase

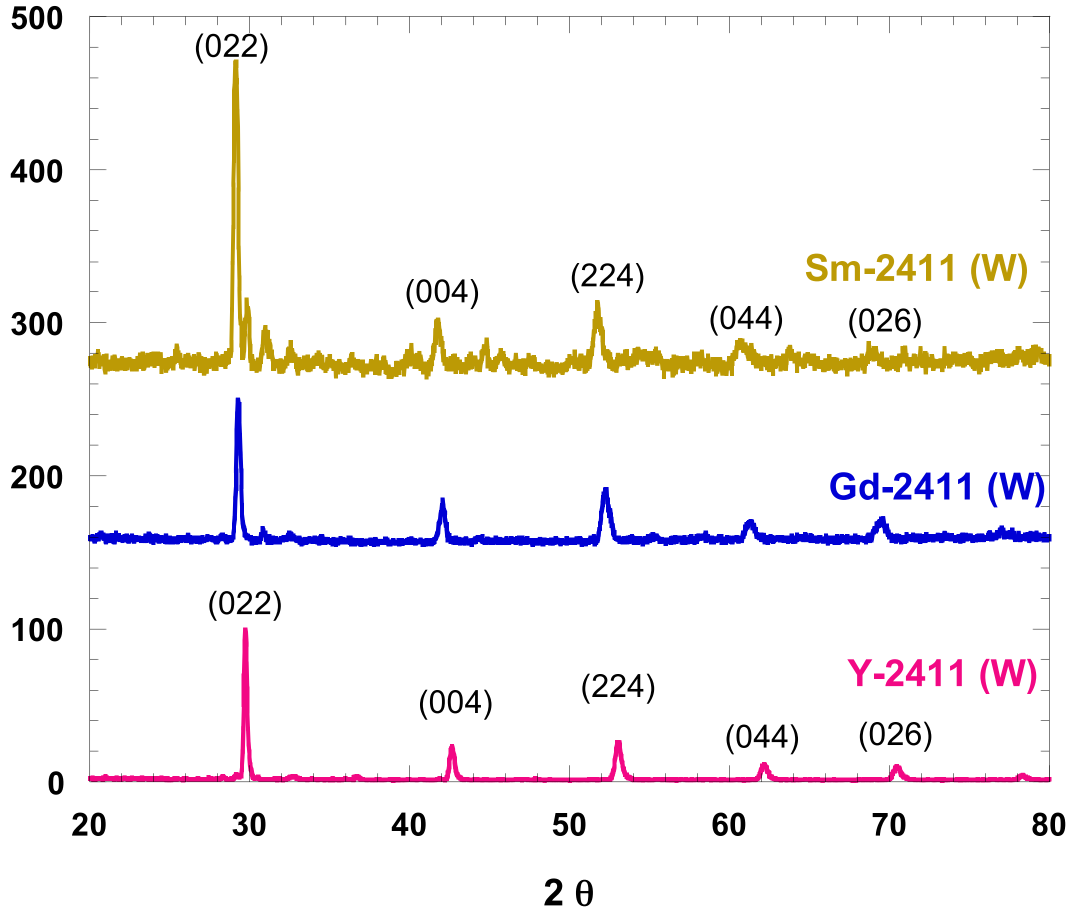


Unit cell volume

- $Y_2Ba_4CuZrO_y$
- $Y_2Ba_4CuNbO_y$
- $Y_2Ba_4CuMoO_y$
- $Y_2Ba_4CuRuO_y$
- $Y_2Ba_4CuAgO_y$
- $Y_2Ba_4CuSnO_y$
- $Y_2Ba_4CuSbO_y$
- $Y_2Ba_4CuHfO_y$
- $Y_2Ba_4CuTaO_y$
- $Y_2Ba_4CuWO_y$
- $Y_2Ba_4CuBiO_y$
- $Y_2Ba_4CuUO_y$

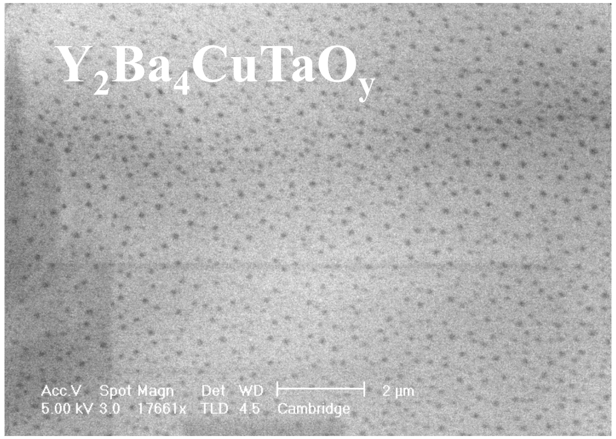
Cubic, iso-structural double perovskite $Y_2Ba_4CuMO_y$ phases with a ~ 8.43 Å to 8.71 Å

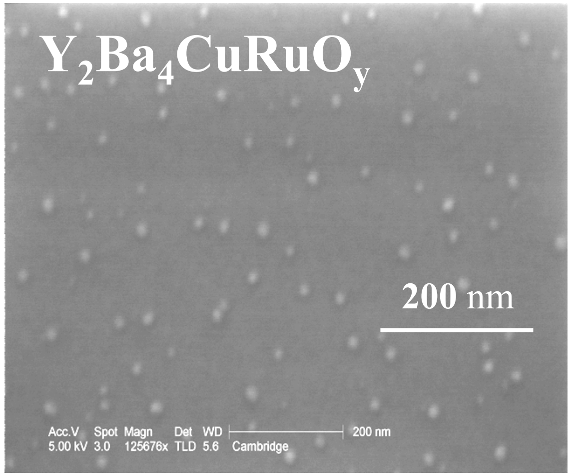
Novel pinning centres – the 2411 phase

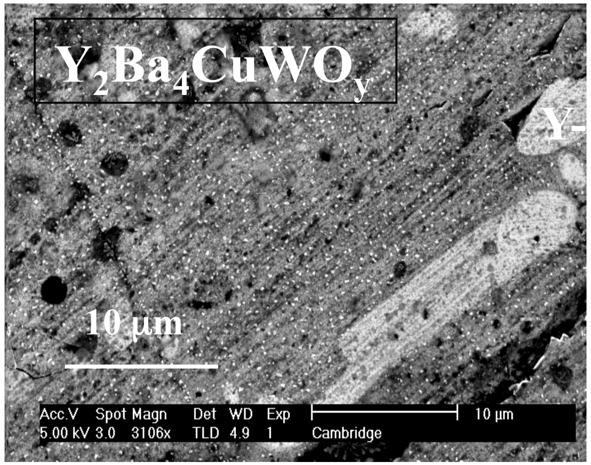


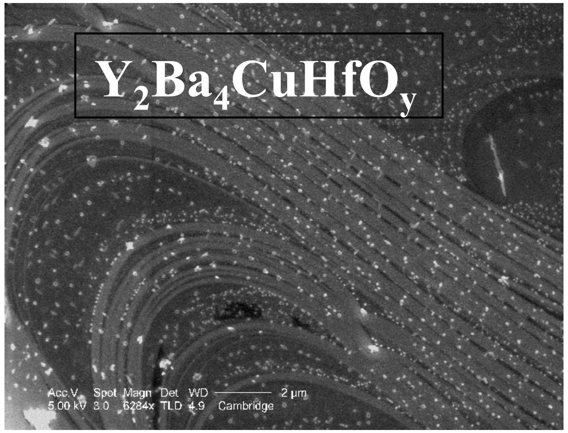
> 30 known 2411 compositions

2411-123-211 nanocomposites

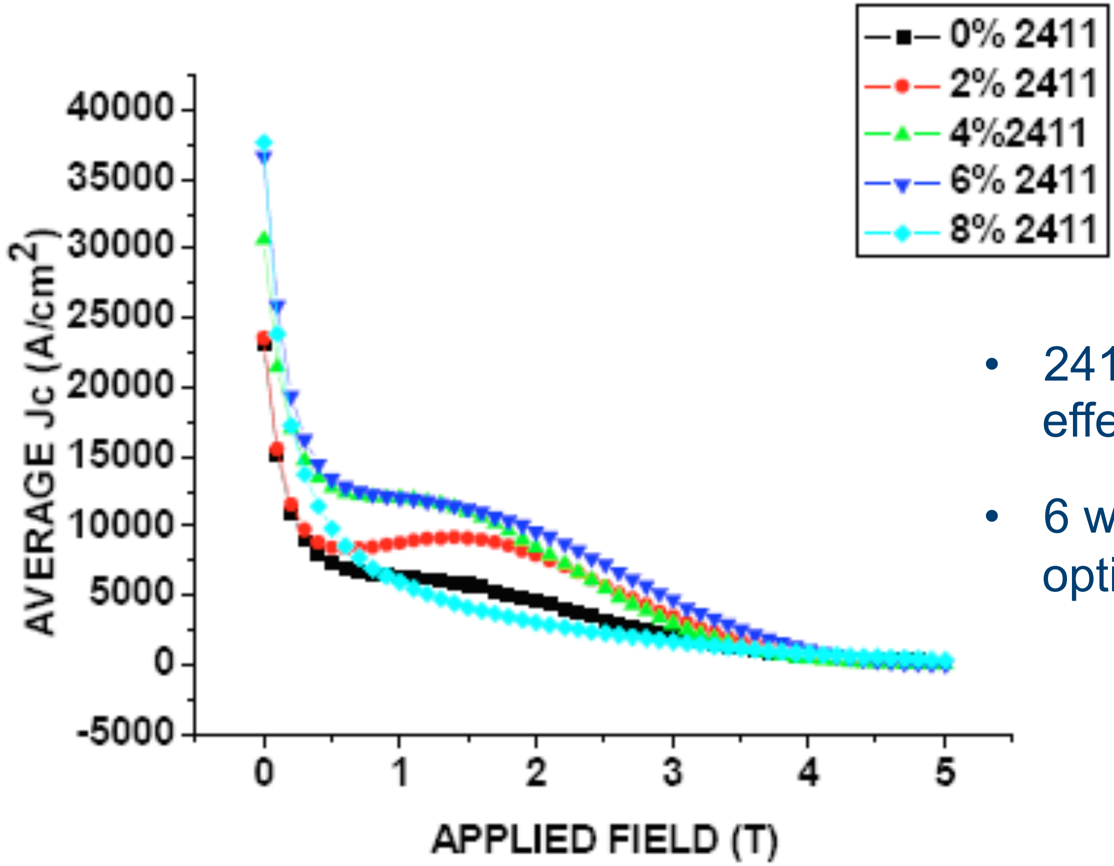








Flux pinning - YBCO containing Y-2411 (Nb)



- 2411 content has a significant effect on J_c
- 6 wt % of Y-2411gives optimum performance

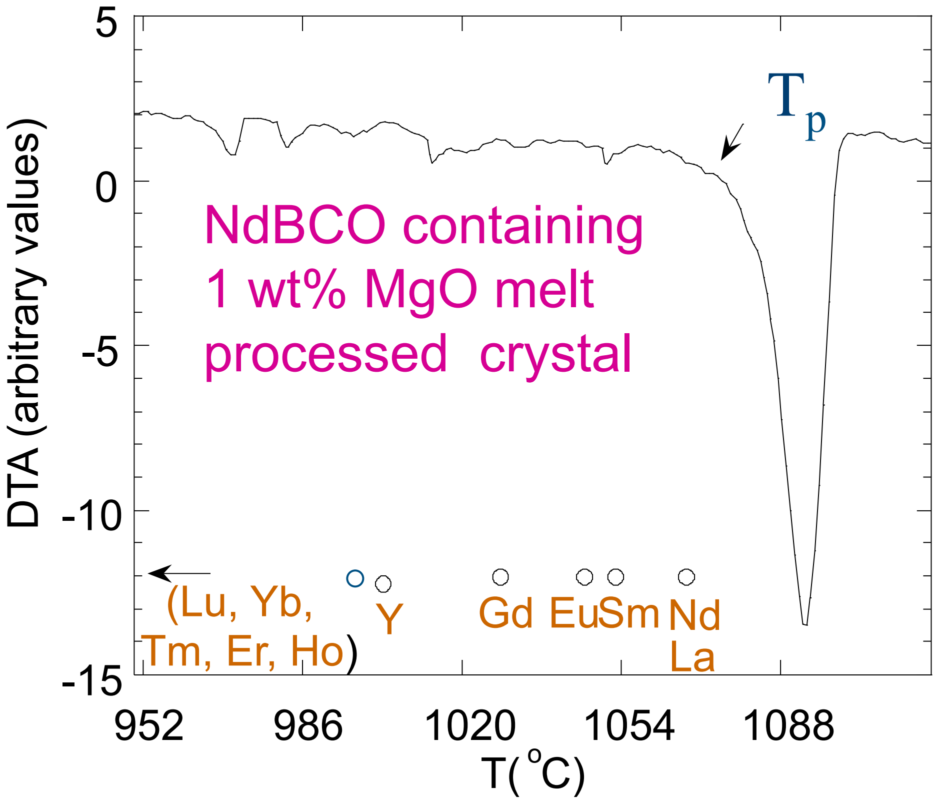
Generic seeds

RE in (RE)$Ba_2Cu_3O_7$	**Mg-NdBCO**	La	Nd	Sm	Eu	Gd	Dy	Ho	Y	Er	Yb
Melting point (±5 ^oC)	**1088**	1068	1068	1054	1046	1030	1010	1005	1005	990	960

Requirements;

1. Higher melting point
2. Chemical compatibility
3. Structural compatibility

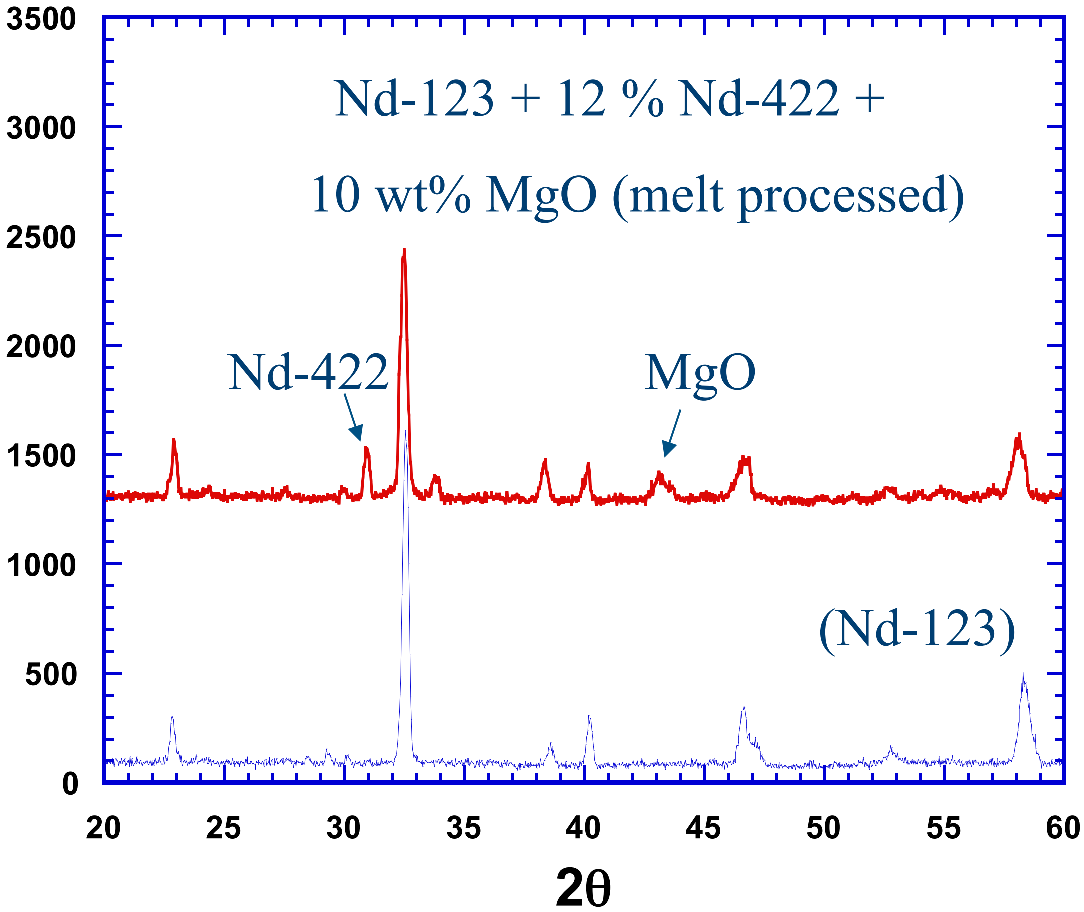
Generic seeds – higher melting point



- Mg-doped NdBCO has at least 15 °C higher melting point than any other (RE)BCO.

Shi et al,
Supercond. Sci. Technol., 2005

Generic seeds – lattice matching

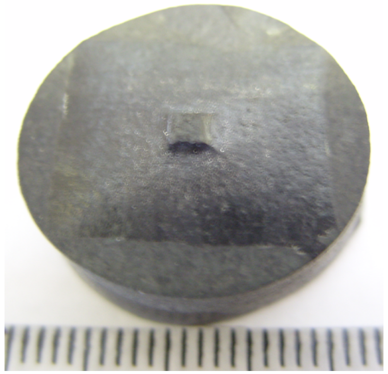


- Mg-doped NdBCO crystal structure is similar to that of NdBCO
- Lattice mismatch is negligible (~ 0.7%)

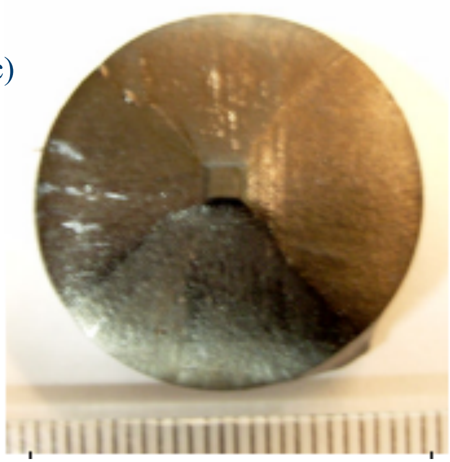
Generic seeds – versatility

(a)

(b)



(c)



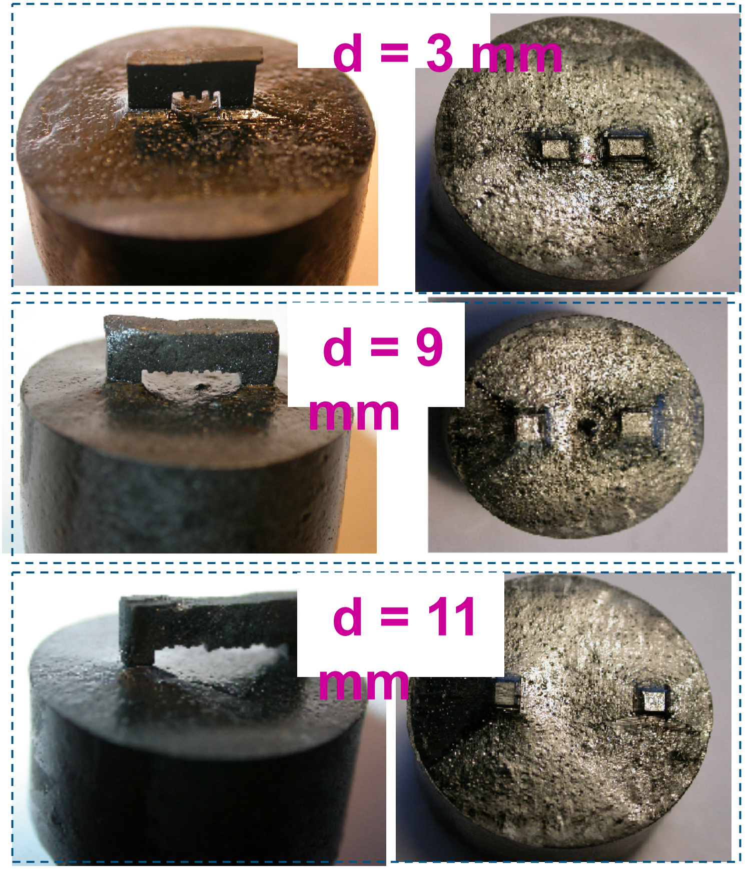
Photographs of (a) YBCO single grain (20 mm dia without 2411) (b) YBCO with 2411 and (c) GdBCO single grain (26 mm dia) with 2411. All samples were grown in air using the generic seed.

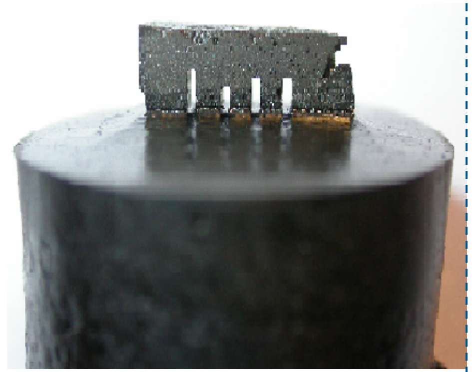
Multi-seeeding

Multi-seeding has the potential to;

1. Increase overall grain size
2. Enable the fabrication of conformal geometries
3. Yield strongly-connected grain boundaries
4. Reduce the level of impurities

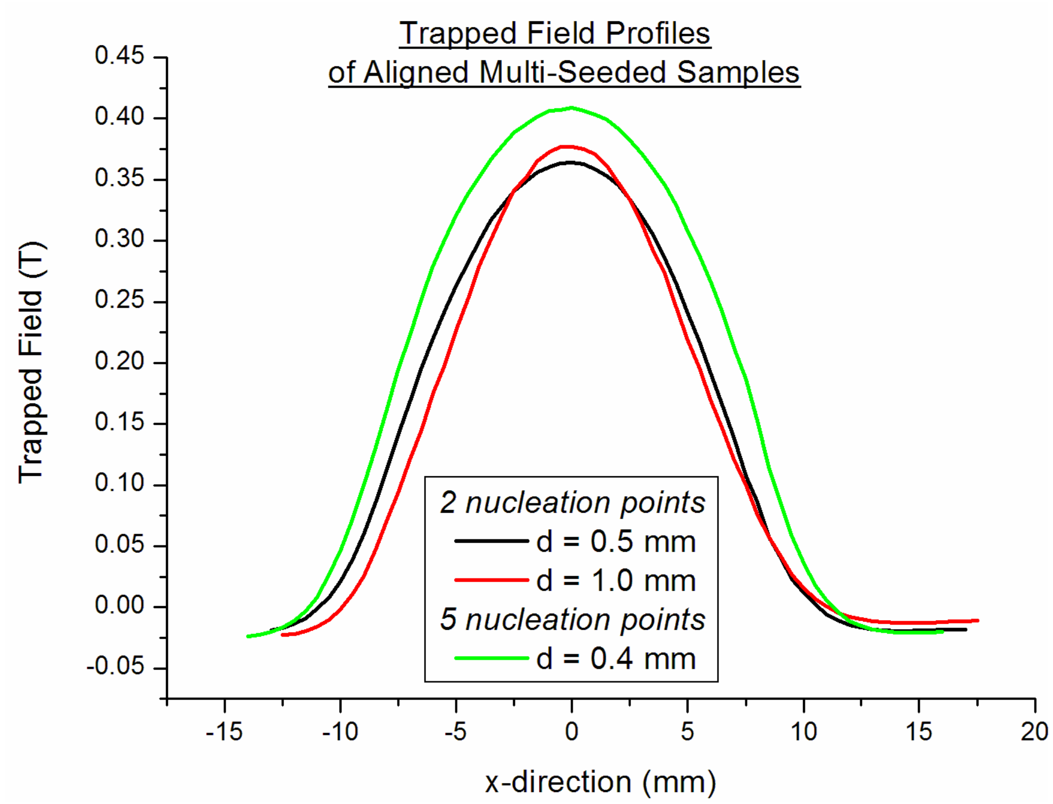
Multi-seeding – bridge seeds

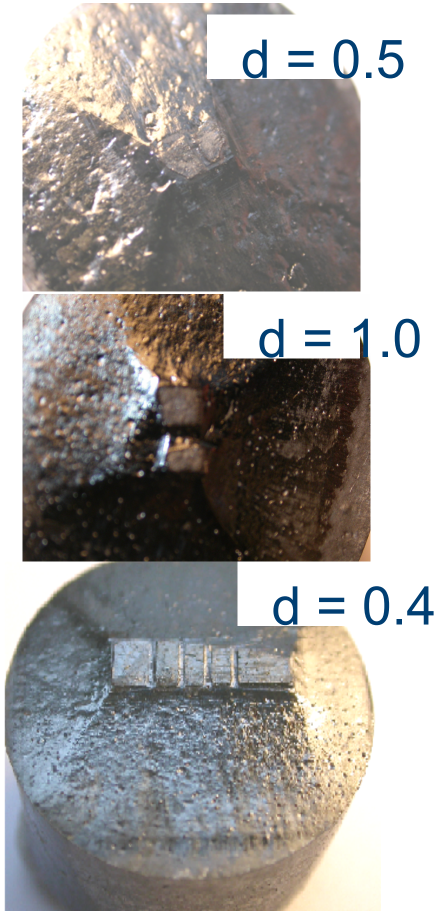




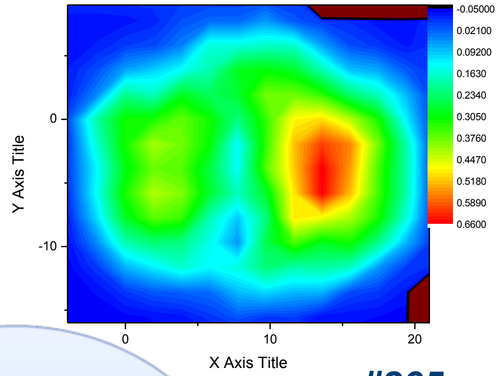
4 GBs with 5 nuclei

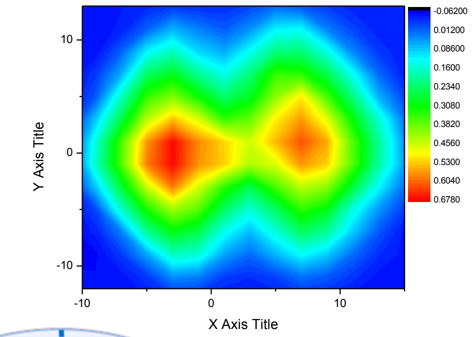
Multi-seeding – bridge seeds

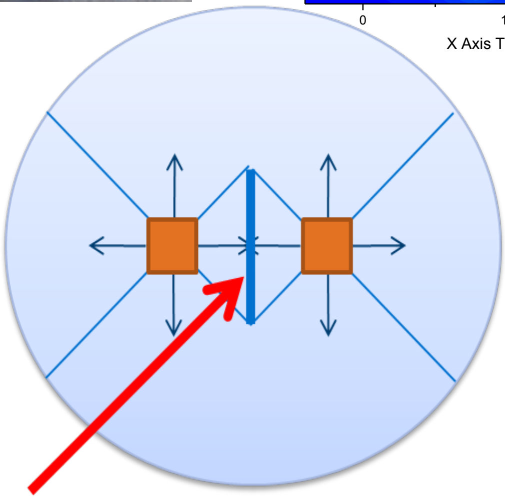




Multi-seeding – oriented seed growth in YBCO



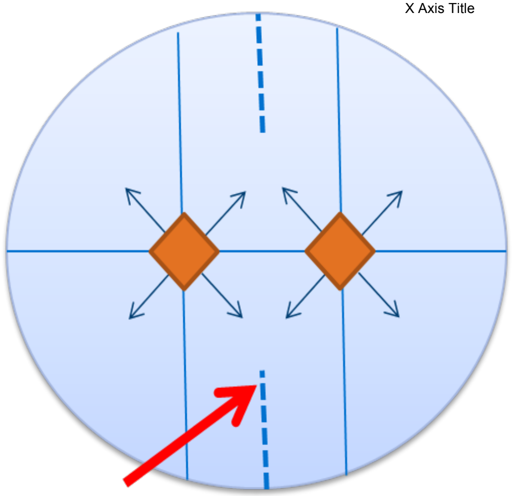




#265
0.68 T

Shi et al, *Supercond. Sci. Technol.*, **26**, 015012. 2013.

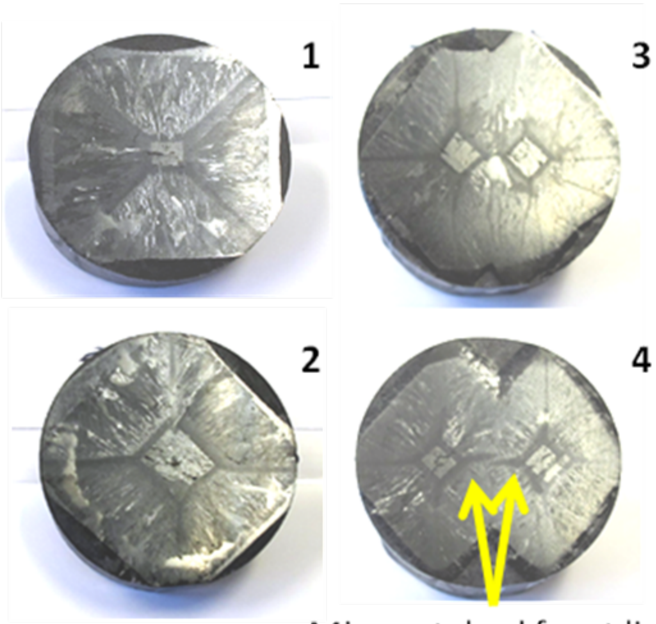
Trapped particles at GB – length depends on seed separation



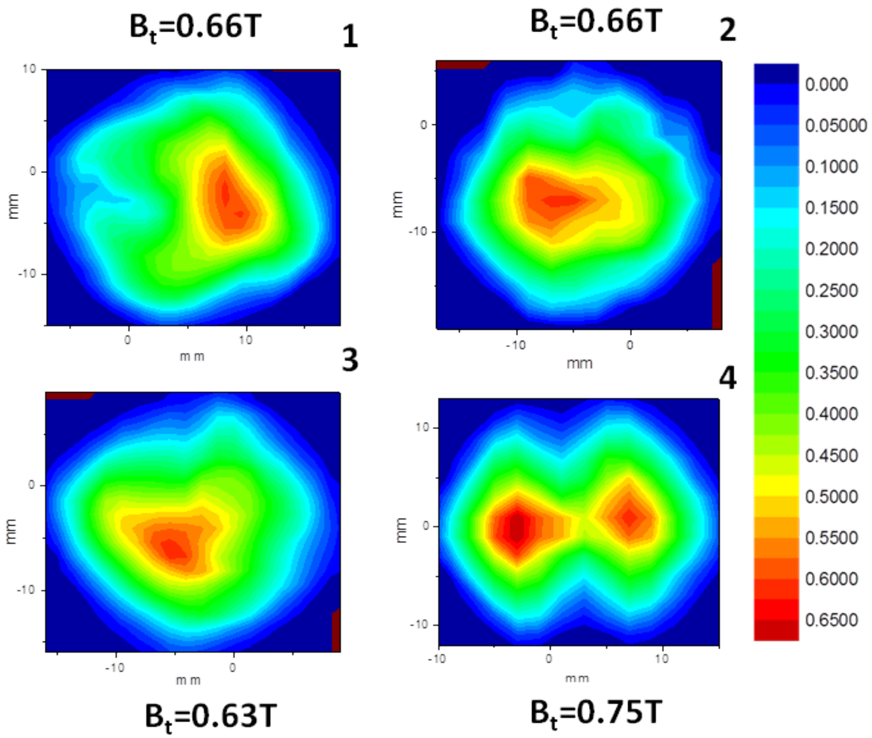
#263
0.74 T

Growth fronts meet at angle – particles ejected.

Multi-seeding – oriented seed growth in YBCO



Mis-matched facet lines



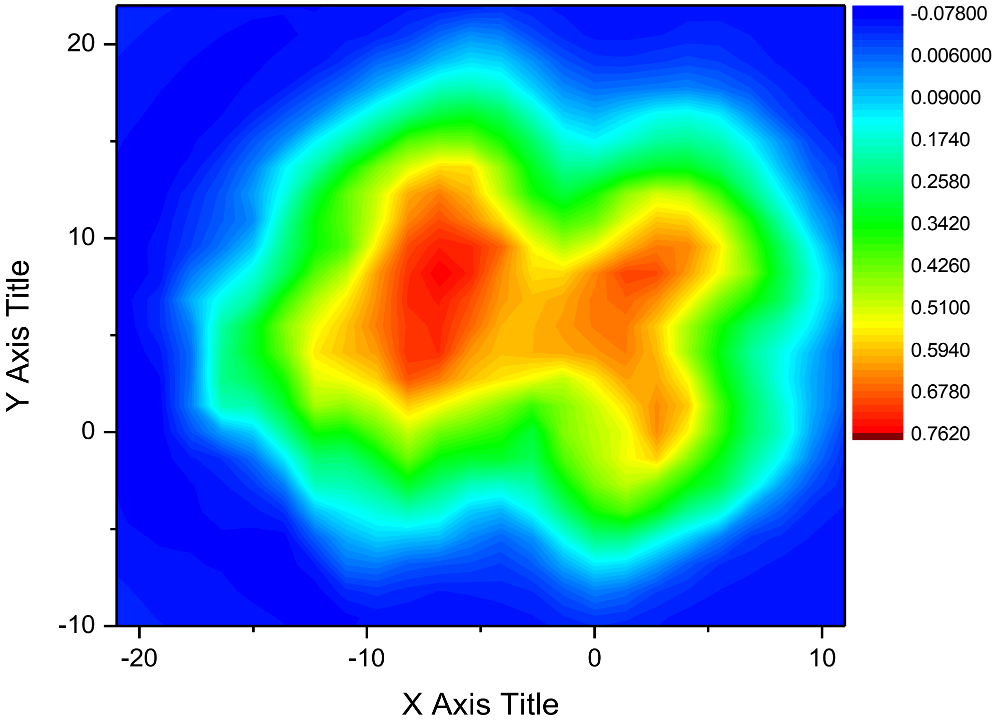
45-45 bridges

Shi et al, *Supercond. Sci. Technol.*, **26**, 015012. 2013.

Multi-seeding – oriented 4 seed growth in YBCO

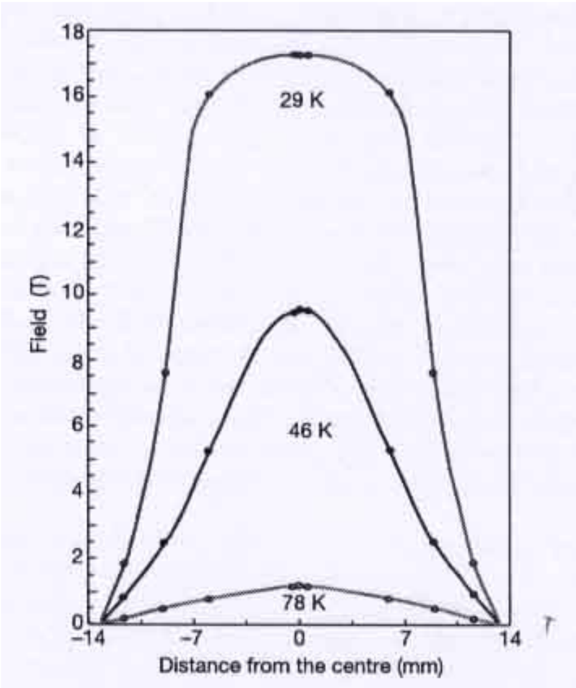
20120606-TF

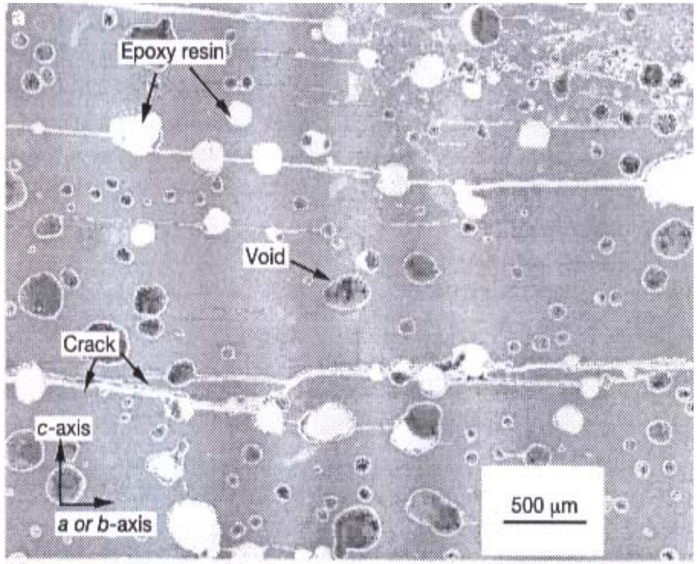
45-45-9 mm Pair



#268
0.78 T

Record trapped fields (RE)BCO





Tomita and Murakami, *Nature,* **421**, 517, 2003

YBCO
Double sample arrangement

Record until recently was 17 T at 29 K

High Field Measurements on Cambridge Samples

- Collaboration with FSU to use NHMFL facilities – 20 T SC Magnet
- Can our Bulk Superconductors trap record fields?

They can!!

Fast Track Communications
IOP Publishing
Superconductor Science and Technology
Supercond. Sci. Technol. **27** (2014) 082001 (5pp)
doi:10.1088/0953-2048/27/8/082001

Fast Track Communication

A trapped field of 17.6T in melt-processed, bulk Gd-Ba-Cu-O reinforced with shrink-fit steel

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Abstract
The ability of large-grain (RE)$Ba_2Cu_3O_{7-\delta}$ ((RE)BCO; RE = rare earth) bulk superconductors to trap magnetic fields is determined by their critical current. With high trapped fields, however, bulk samples are subject to a relatively large Lorentz force, and their performance is limited primarily by their tensile strength. Consequently, sample reinforcement is the key to performance improvement in these technologically important materials. In this work, we report a trapped field of 17.6 T, the largest reported to date, in a stack of two silver-doped GdBCO superconducting bulk samples, each 25 mm in diameter, fabricated by top-seeded melt growth and reinforced with shrink-fit stainless steel. This sample preparation technique has the advantage of being relatively straightforward and inexpensive to implement, and offers the prospect of easy access to portable, high magnetic fields without any requirement for a sustaining current source.

Keywords: bulk superconductor, high magnetic field, critical current, top-seeded melt growth

(Some figures may appear in colour only in the online journal)

Introduction

It has long been known that, in addition to fabricating solenoids from wire or tape, type-II superconducting materials can be used to trap magnetic fields when fabricated in the form of well-connected bulks [1, 2]. Top-seeded melt growth (TSMG) has emerged over the past 25 years as a practical route for fabricating large, single grains of the rare earth (RE) cuprate family of high-temperature superconductors (HTS) of composition (RE)$Ba_2Cu_3O_{7-\delta}$ ((RE)BCO). As a result, these materials have significant potential for application, effectively, as high-field permanent magnets [3]. The performance of these magnets at 77 K is limited by the critical current carrying capacity of the bulk superconductor. Nevertheless, fields of up to 2 T have been achieved in 20 mm diameter superconducting bulk samples [4] and up to 3 T in samples of 65 mm diameter [5] at 77 K.

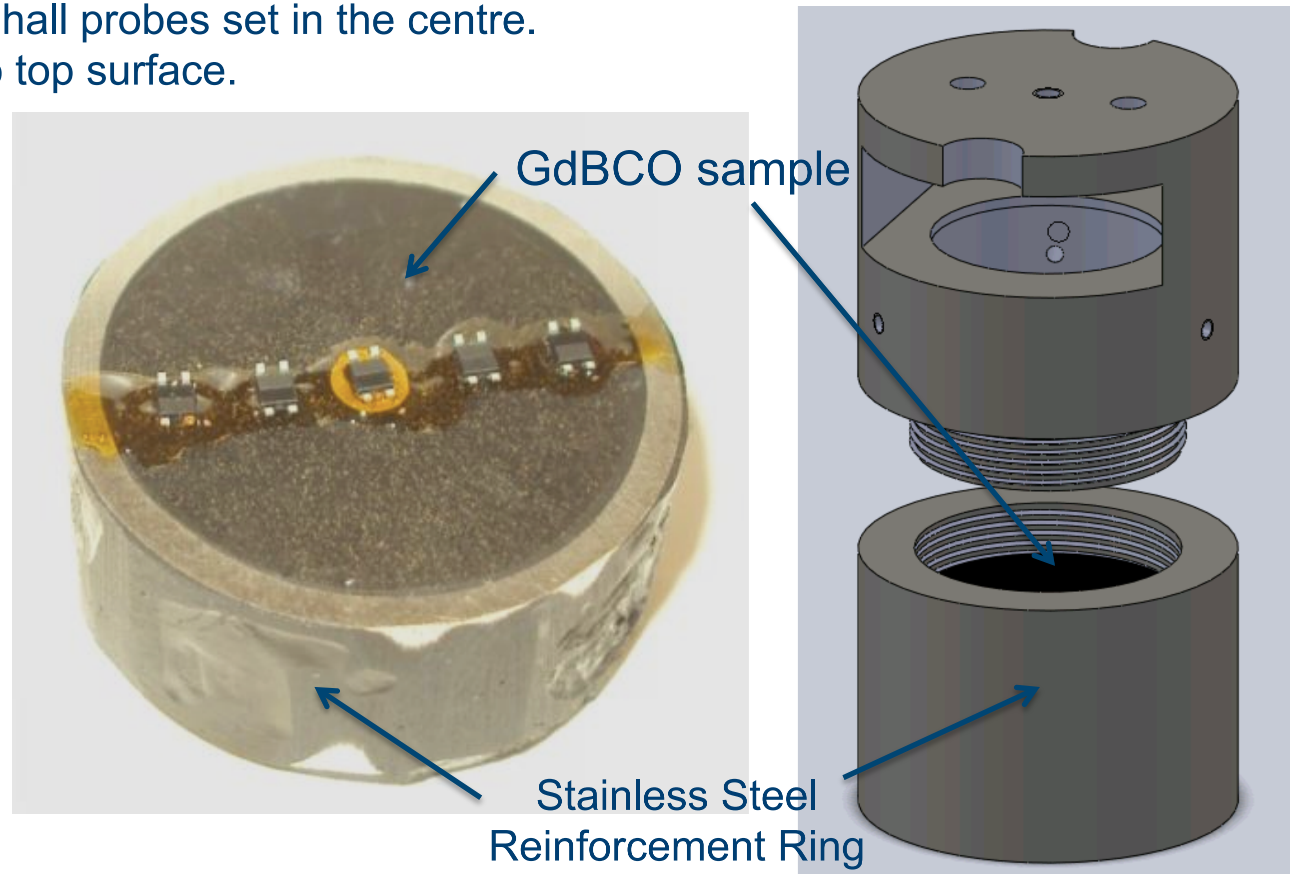
The critical current density (J_c) of HTS is enhanced at temperatures lower than 77 K, and significantly larger magnetic fields can be trapped. Notably, Tomita and Murakami reported a trapped field of 17.24 T at 29 K in an arrangement of two $YBa_2Cu_3O_{7-\delta}$ (YBCO) samples of 26 mm diameter impregnated with Wood's metal and resin and reinforced with carbon fibre [6]. Fuchs *et al* also reported a trapped field of 16 T at 24 K in a Zr-doped and Ag-impregnated YBCO sample of 25 mm diameter placed inside a reinforcing stainless-steel tube [7]. The prospect of generating portable high fields that are available outside the bore of a superconducting solenoid is now a distinct possibility, given that considerable

0953-2048/14/082001+05$33.00 1

IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) January 2015.
Invited Presentation PC-16-INV given at ISS 2014, Tokyo, November 25 - 27, 2014.

Record trapped fields in (RE)BCO at Cambridge

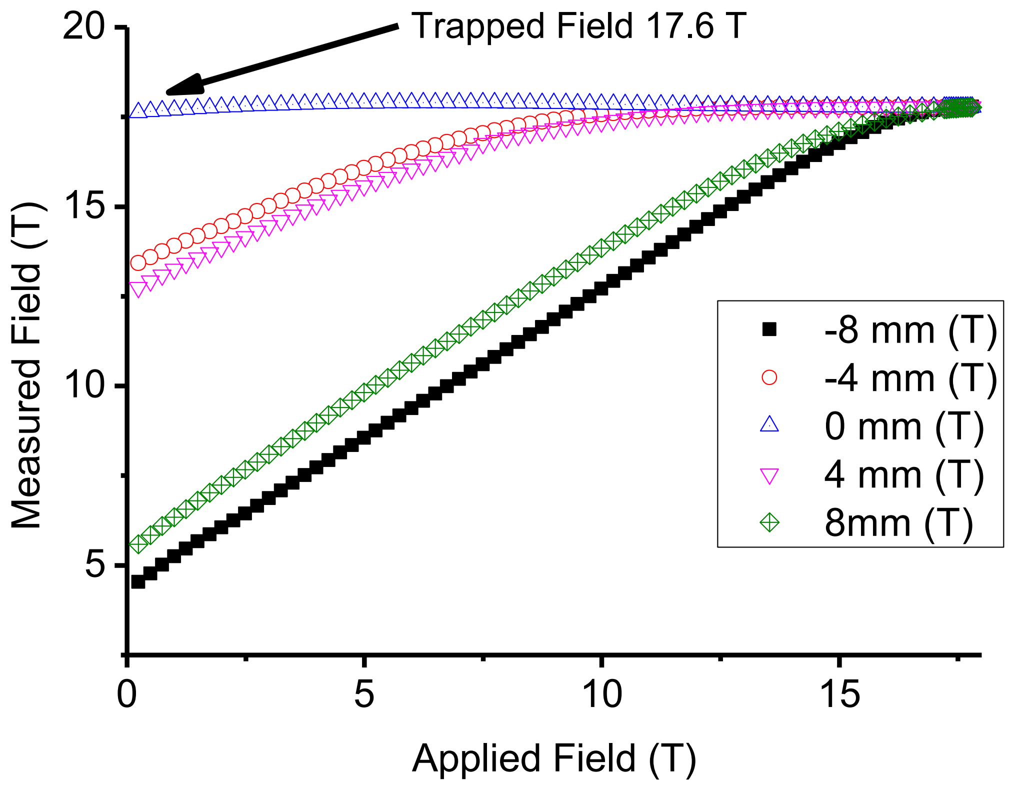
2 samples combined with hall probes set in the centre.
Mounted top surface to top surface.



Collaborative study with NHFML and Boeing

Record trapped fields in (RE)BCO at Cambridge

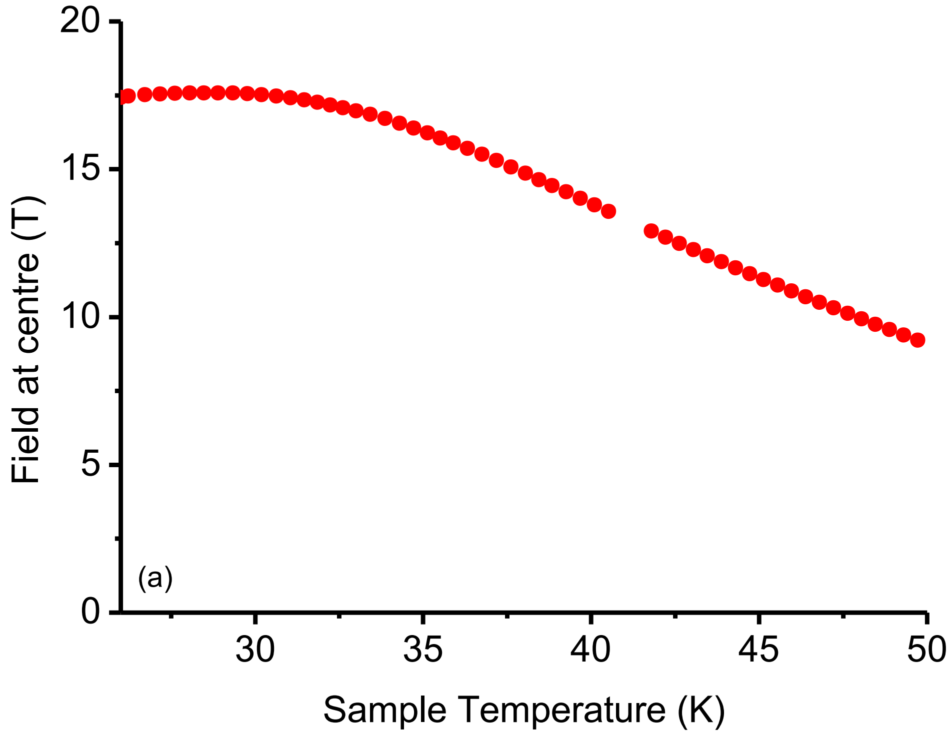
Durrell et al, *Superconductor Science and Technology*, **27**, 082001, 2014



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

Record trapped fields in (RE)BCO at Cambridge

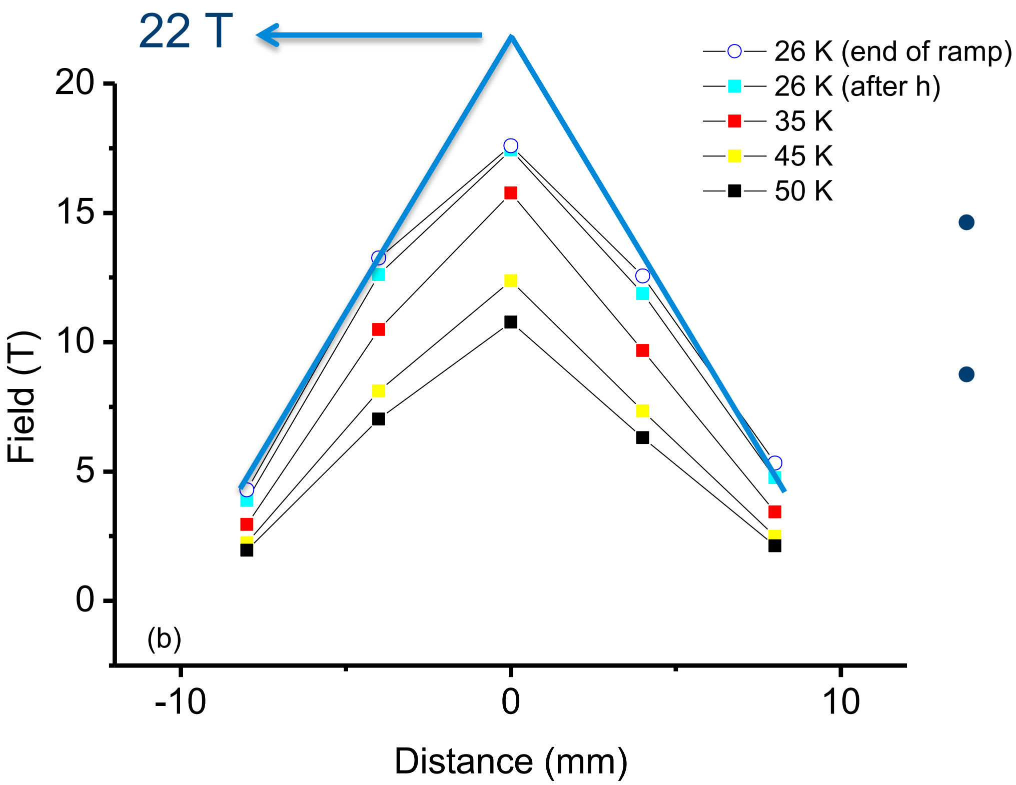
Durrell et al, *Superconductor Science and Technology*, **27**, 082001, 2014



- Field of almost 10 T at centre of sample at 50 K

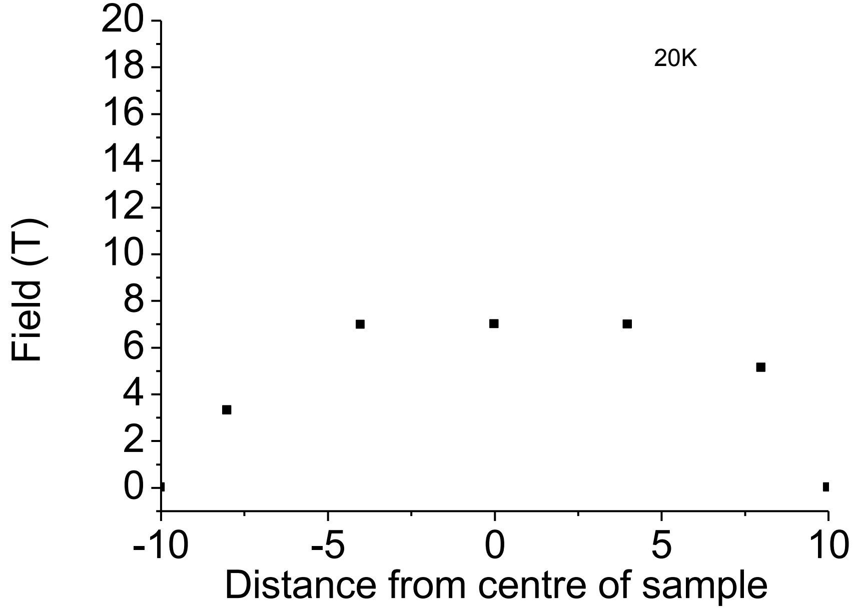
Record trapped fields in (RE)BCO at Cambridge

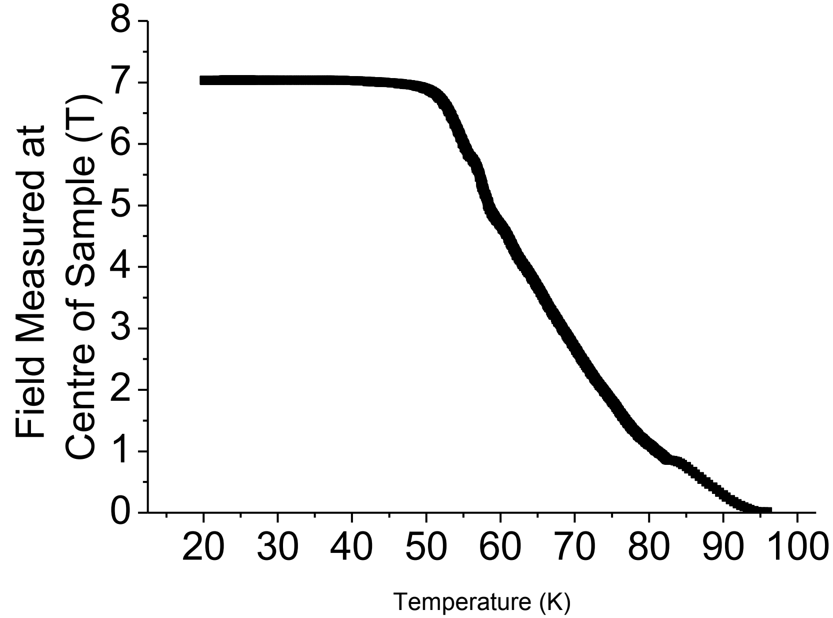
Durrell et al, *Superconductor Science and Technology*, **27**, 082001, 2014



- Field flattens-off at low temperature
- Suggests not sample limited

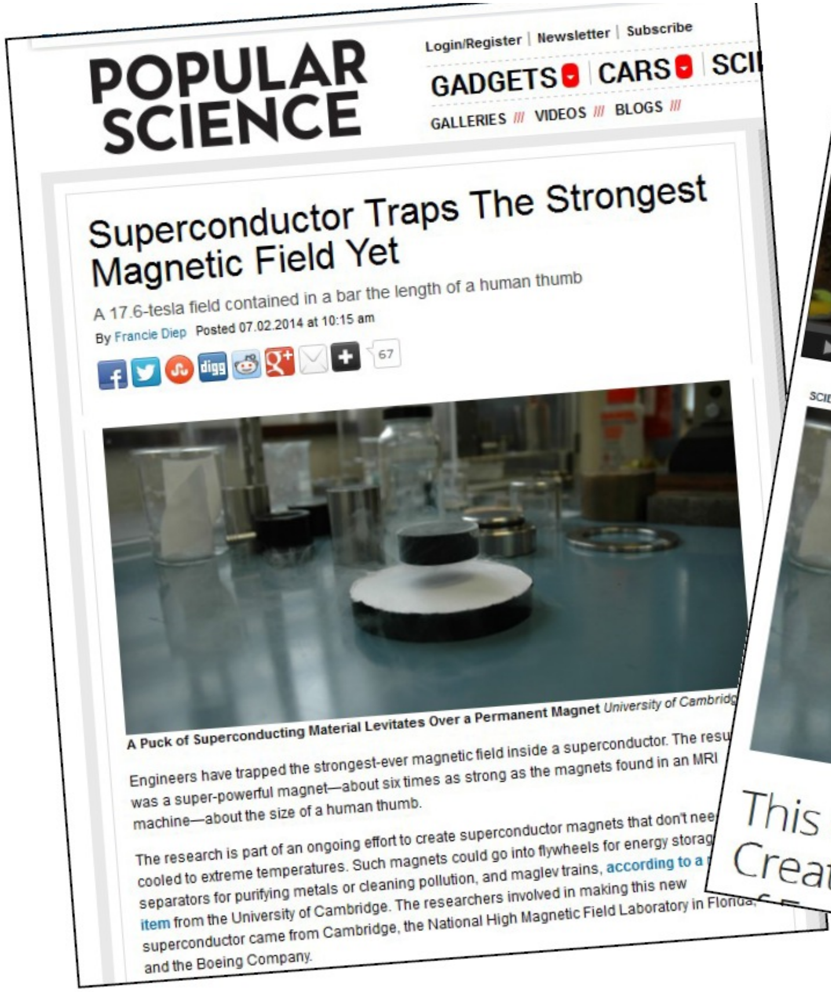
Practical trapped field in (RE)BCO Single sample





- Unreinforced GdBCO 20 mm diameter traps ~7 T
- Has to be warmed to 50 K before reduction in trapped field is seen
- Can reproducibly achieve 7 T performance at 50 K

Press Coverage



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Superconductor Traps The Strongest Magnetic Field Yet

A 17.6-tesla field contained in a bar the length of a human thumb

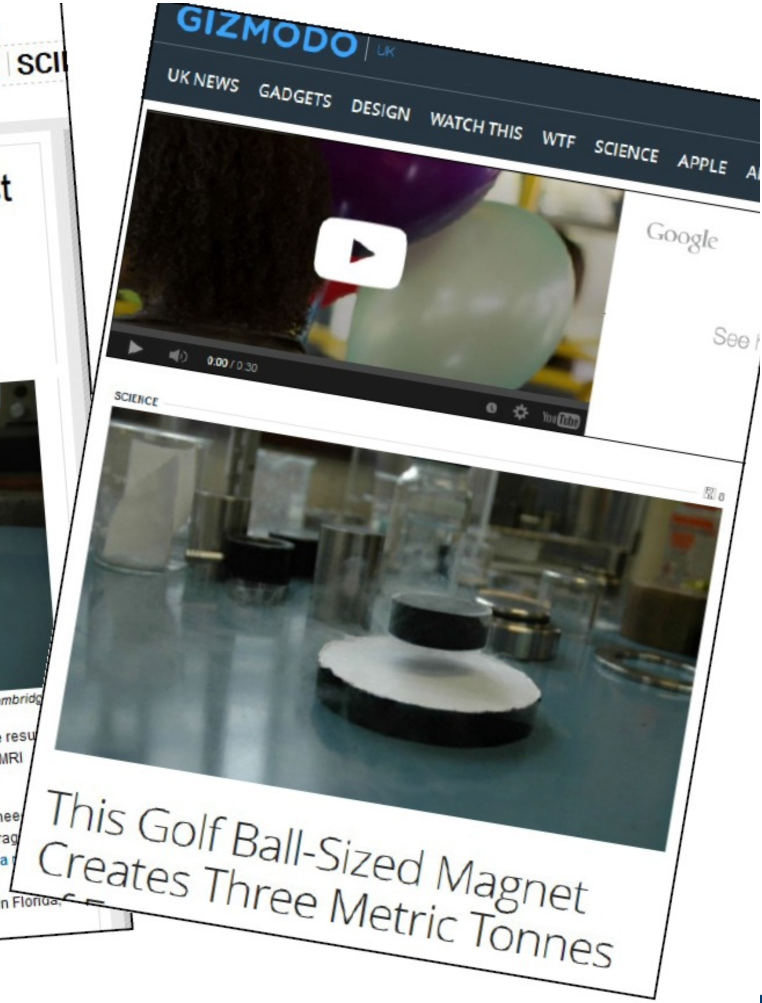
By Francie Diep Posted 07.02.2014 at 10:15 am

67

A Puck of Superconducting Material Levitates Over a Permanent Magnet *University of Cambridg*

Engineers have trapped the strongest-ever magnetic field inside a superconductor. The resu was a super-powerful magnet—about six times as strong as the magnets found in an MRI machine—about the size of a human thumb.

The research is part of an ongoing effort to create superconductor magnets that don't nee cooled to extreme temperatures. Such magnets could go into flywheels for energy storag separators for purifying metals or cleaning pollution, and maglev trains, according to a item from the University of Cambridge. The researchers involved in making this new superconductor came from Cambridge, the National High Magnetic Field Laboratory in Florida, and the Boeing Company.



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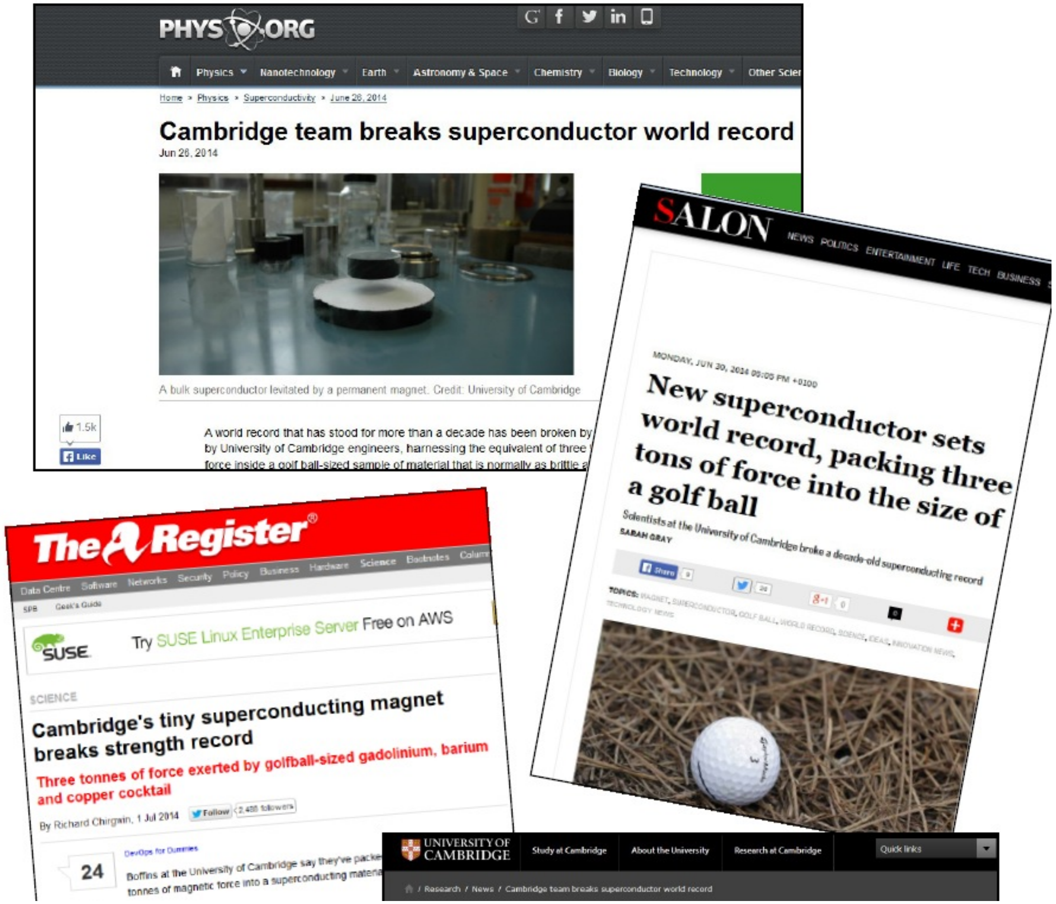
SCIENCE

This Golf Ball-Sized Magnet Creates Three Metric Tonnes

Press Coverage

- Paper has been downloaded > 3000 times since July
- Article made “open access” with HEFCE funds, free for all to download
- Significant traffic to UCAM website



Applications of Bulk Superconductors

1. Magnetic bearings
   - Maglev
   - Flywheel energy storage

2. Motors and generators
   - Higher efficiency, lower loss, smaller machines

3. Medical device applications
   - Drug delivery, MRI

4. Other applications

Conclusions and Summary

- There have been significant developments in the processing of bulk superconductor at Cambridge over the past 10 years;
- Flux pinning in bulk YBCO has been improved by engineering effective nano-scale flux pinning sites within the bulk microstructure;
- Average bulk J_c and trapped has been observed to increase with the addition of nano-scale $Y_2Ba_4CuMO_x$ phase particles in large grain Y-Ba-Cu-O;
- Development of generic seed crystal enabled the fabrication of GdBCO large, single grains using TSMG and shown to trap record magnetic flux densities of 17.6 T at 26 K;
- Multi-seeding is being developed and has significant potential for the manufacture of materials of practical geometry;
- Record trapped field samples fabricated by a relatively straight forward process.

Conclusions and Summary

Thank you for your attention