Bulk Superconducting Materials – Ready for Applications?

Dr J. H Durrell


Department of Engineering – University of Cambridge
Acknowledgements

- Group Leader: Prof. David Cardwell
- SRA: Dr Yunhua Shi; RAs: Dr Devendra Kumar, Dr Difan Zhou
- Professor Archie Campbell (Emeritus)
- Royal Academy of Engineering Fellow: Dr Mark Ainslie
- PhD Students: Wei Zhai, Jin Zou, Di Hu, Kysen Palmer, Wen Zhao, Jordan Rush
- Technical Officer: Tony Dennis
- Technician: Danny Huang
- Funding: EPSRC, Boeing, KACST
- Facilities: NHMFL

Acknowledgements

Eric Hellstrom, Jan Jaroszynski, David Larbalestier – FSU/NHMFL
John Hull and Mike Strasik – The Boeing Company
Susannah Speller, Chris Grovenor – University of Oxford
A. Yamamoto – University of Tokyo
M. Izumi – TUMSAT
A. Patel – University of Cambridge
Outline

• Basics

• Practical Bulk Materials
  • (RE)BCO
  • MgB$_2$

• Advanced Materials

• Applications
Outline

• Basics

• Practical Bulk Materials
  • (RE)BCO
  • MgB$_2$

• Advanced Materials

• Applications
Superconductivity

- Discovered in Mercury by Kammerling Onnes shortly after he had succeeded in liquefying Helium.
- Sharp decrease of resistivity to zero at a critical temperature $T_c$.
- Small magnetic fields destroyed effect – limited practical application.
Useful Superconductors

• Fortunately in a few elements and many alloys and compounds superconductivity and magnetism can co-exist.

• This occurs because the sign of the free energy at the Normal-Superconducting boundary changes in “Type-II” superconductors.

• Superconductivity can then persist to several Tesla

Flux lines in NbSe$_2$, University of Oslo

See http://www.mn.uio.no/fysikk/english/research/groups/amks/superconductivity/sv/ for more details of this groups really
What Limits Current Flow?

- Flux lines are pinned by defects
- Pinning is crucial

Slope is given by $\rho_s = (H/H_{c2})\rho_n$

$F_p = J_c \times B$

$F_p$ = Maximum Pinning Force Density
$J_c$ = Critical Current
$B$ = Magnetic Flux Density
Families of Superconductors
Forms of superconductor

• Bulk
  4 cm
  High field permanent magnets
  Self stabilized levitation

• Wires and Tapes
  Power cables and high field solenoids (e.g. MRI)

• Thin Films
  High speed electronics,
  GHz frequency generators
  Single Photon Detectors
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.

\[ \mu_B = 9.27 \times 10^{-24} \text{ Am}^2 \]

Magnetisation independent of sample volume
Bulk Superconductors

• Field generated by induced macroscopic currents rather than spins.

\[
\text{Magnetic moment} = \int_{r = 0}^{R} iA
\]

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

• Magnetisation *increases* with sample volume
Why Bulk?

- **Permanent ferromagnet**: Spin Nd-Fe-B (~1.6 T)
- **SC bulk magnet**: Induced loop SC current MgB$_2$ (3-5 T), YBCO (17 T)
- **Electromagnet**: Supplied loop current Cu (~2 T), HTS (>30 T)

**Stronger & Compact**

*Slide courtesy A. Yamamoto, University of Tokyo*
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!)
A (Simple) Superconducting Bearing
Outline

• Basics

• Practical Bulk Materials
  • (RE)BCO
  • MgB$_2$

• Advanced Materials

• Applications
Granularity is a problem!

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

Sintered YBCO

2 µm
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

- 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

YBa$_2$Cu$_3$O$_{7-\delta}$ + Y$_2$BaCuO$_5$ + Pt $\rightarrow$ Y$_2$BaCuO$_5$ + L
The (RE)BCO family

<table>
<thead>
<tr>
<th>Formula</th>
<th>Material</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>YBa$_2$Cu$<em>3$O$</em>{7-\delta}$</td>
<td>YBCO</td>
<td>92 K</td>
</tr>
<tr>
<td>GdBa$_2$Cu$<em>3$O$</em>{7-\delta}$</td>
<td>GdBCO</td>
<td>92 K</td>
</tr>
<tr>
<td>Sm$<em>{1+x}$Ba$</em>{2-x}$Cu$<em>3$O$</em>{7-\delta}$</td>
<td>SmBCO</td>
<td>92 K</td>
</tr>
<tr>
<td>Nd$<em>{1+x}$Ba$</em>{2-x}$Cu$<em>3$O$</em>{7-\delta}$</td>
<td>NdBCO</td>
<td>94 K</td>
</tr>
</tbody>
</table>

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

- Have differing melting points, need higher melting point seed.
Outline

• Basics

• Practical Bulk Materials
  • (RE)BCO
  • MgB$_2$

• Advanced Materials

• Applications
MgB$_2$

- Metallic nature, $T_c$ 39 K
- Lightweight (2.624 g/cc), inexpensive
- Low anisotropy
- Large coherence length
Why MgB2?

- 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

Slide courtesy A. Yamamoto
Oxford MgB$_2$ measured in Cambridge

- Density of final sample was 91% of theoretical maximum (taking into account MgO). 25mm diameter.
- ‘Ex-situ’ Uniaxial Hot Press
- Trapped 3T measured in stack
State of the Art now ~ 5 T

- Yamamoto and colleagues report 5 T at 7 K
- Samples produced using sintering only – no pressure
- Fuchs et. al report 5.4 T at 12 K

See Yamamoto et al. APL 105, 032601 (2014)
Fuchs et al. SUST 2, 122002 (2013)
Outline

• Basics

• Practical Bulk Materials
  • (RE)BCO
  • MgB$_2$

• Advanced Materials

• Applications
What’s ‘New’ in Bulk?

• Pinning enhancement
• New Seeding Techniques
• Multi Seeding
• Reinforcement for High Fields
• Composite Bulks from Tape
Pinning Enhancement

• The Y-211 particles that are essentially part of the production process of bulks do give good pinning

• Nonetheless critical current in bulks is at least an order of magnitude less than coated conductors

• Clear scope for improvement in performance
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
Flux pinning - YBCO containing Y-2411 (Nb)

- 2411 content has a significant effect on $J_c$
- 6 wt % of Y-2411 gives optimum performance
Pt/U pinning

- Houston group have shown that the combination of \((\text{Pt}_{0.4}\text{U}_{0.6})/\text{YBa}_2\text{O}_6\) pinning centres and subsequent neutron induced of the U can achieve spectacular pinning - 2 T trapped field at 77K

- Sawh et al. have demonstrated a batch of 60 samples which reliably exhibit such high performance

# Advanced Seeds

<table>
<thead>
<tr>
<th>RE in (RE)Ba$_2$Cu$_3$O$_7$</th>
<th>Mg-NdBCO</th>
<th>La</th>
<th>Nd</th>
<th>Sm</th>
<th>Eu</th>
<th>Gd</th>
<th>Dy</th>
<th>Ho</th>
<th>Y</th>
<th>Er</th>
<th>Yb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point (± 5 °C)</td>
<td>1088</td>
<td>1068</td>
<td>1068</td>
<td>1054</td>
<td>1046</td>
<td>1030</td>
<td>1010</td>
<td>1005</td>
<td>1005</td>
<td>990</td>
<td>960</td>
</tr>
</tbody>
</table>

**Requirements:**

- Higher melting point
- Chemical compatibility
- Structural compatibility
Generic seeds – higher melting point

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

Multi-seeding

- The TSMG growth process is slow
- Ability to grow large samples quickly would be advantageous
- One approach is to use multiple nucleation points with seeds that are aligned – avoiding grain boundary problems
Multi Seeded Samples

#265
0.68 T

#263
0.74 T

#268
0.78 T

32mm
Growth sector between seeds

- Sub-grain morphology indicates that growth occurs first from seed 1.
- Where the growth front from seed 1 meets the growth front from seed 2, the subgrains stop abruptly.
- At interface there is a build up in Y-211 particles, as seen in EDX maps.

Note the buildup of Y-211 at the growth region boundary.

Images: S. Speller – University of Oxford
Low magnification backscattered electron images

- Channelling contrast showing subgrain structures in a-axis growth sectors.
- No chemical composition variation corresponding to subgrains.

Images: S. Speller – University of Oxford
Multi-seeding – oriented seed growth in YBCO


Trapped particles at GB – length depends on seed separation

Growth fronts meet at angle – particles ejected.
Materials for High Fields

- $J_C$ is important but not sufficient
- At ~17T 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
During charging the maximum tensile stress increases as the square of the field.
Previous High Field Measurements

- Tomita et al. used CF/Epoxy and a sample soaked in woods metal -17.2 T


- Fuchs *et al.* used a SS reinforcement band. – 15 T

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

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

Main advantages are

- Flexibility of geometry
- Consistency of superconducting properties of 2G HTS tape

Fabrication

- Simple cutting and stacking
- Can use solder plated tape to create self-supporting slabs/builds by compression and heating
- Can create large slabs by overlapping layers

Trapped field results

- Stacks respond very well to pulsed field magnetization
- Current records for stacks set using commercial 12mm tape
- Limited by tape width and engineering $J_c$
- Higher fields expected with new tape

Slide courtesy Anup Patel – University of Cambridge
Potential Applications of Stacked Tapes

- **NMR magnets**
  - **40mm wide**
  - Stable, uniform trapped fields for potential desktop NMR
  - 0.7T @ 77K, ≈ 3T @ 4.2K

- **Motor field poles**
  - Motor field poles, flexible shapes
  - Efforts to try pulse magnetization of curved poles

- **High field PMs**
  - Latest test on coil like stacks acting like bulk cylinders show similar forces possible compared to bulks
  - May be advantageous for some geometries

- **Patterned field PMs**
  - Stable, uniform trapped fields for potential desktop NMR
  - 0.7T @ 77K, ≈ 3T @ 4.2K

**Potential Applications**

- Motor field poles, flexible shapes
- Latest tests on coil-like stacks acting like bulk cylinders show similar forces possible compared to bulks
- May be advantageous for some geometries

**References**

- Selva K et al. 2013 *Supercond Sci Tech*, 26 115006
- Patel A et al. 2015 *SUST*, (submitted)
- Patel A et al. 2014 J *Supercond Nov Magn*, 28 397-401

**Slide courtesy Anup Patel – University of Cambridge**
Outline

• Basics

• Practical Bulk Materials
  • (RE)BCO
  • MgB$_2$

• Advanced Materials

• Applications
Applications

- Two main classes:
  - High field “permanent” magnet
  - Self stabilised levitation
- Challenges to practical applications are:
  - Cooling
  - Charging

Pulse charging system

Cryotel Cryo-Cooler for Bulk Application
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).

Applications - Superconducting Bearings

- Primary source of loss is friction. Superconducting bearings significantly extend useful energy storage time.
Portable High Fields – for many applications

- Modern cryocoolers allow bulks to be charged in a solenoid and then moved around in a portable system.

- Hitachi have demonstrated such a system with an eye on medical applications

Portable High Fields

• Numerous potential applications for this kind of technology

• And you can part water! “Moses Effect”

Bulk HTS Applications – Motors

• Considerable work on superconducting motors using tape

• Greatly improved power to weight ratio

• Bulks can be used to substitute permanent magnets
Bulk HTS Applications – Motors

• Axial gap, trapped flux-type motor

• Advantages:
  • Higher torque/power density
  • Compact ‘pancake’ shape
  • Better heat removal
  • Adjustable air gap
  • Multi-stage machines possible

Axial gap, trapped-flux motor

Slide courtesy Mark Ainslie - Cambridge
Bulk HTS Axial Flux Motor

- Uses stator coils to magnetise HTS bulks with pulsed field
  - Cooled using liquid nitrogen
  - Dual purpose: magnetising coils, then armature winding
- Closed cycle neon thermosyphon system
  - Includes cryo-rotary joint
  - Cryogen from static condenser to rotating rotor plate with bulk HTS
  - Allows cooling of bulks HTS down to below 40 K

Schematic diagram of TUMSAT prototype motor

Slide courtesy M. Izumi, TUMSAT
Maglev

• Evico/ IfW Dresden MagLev demonstrator using bulk superconductors.

• Bulks provide a simple levitation system as compare to conventional or superconducting coils

See: IFW Dresden / evico.de
And more….

• Drug targeting
• Compact MRI/NMR
• High fields for non-destructive testing (EMAT)
• Spacecraft docking
• Generators
• Process Transport
Summary

• Yes!

• Bearing/Levitation applications straightforward – as cooling technology improves should become very competitive.

• “Permanent” magnet applications still require an effective route to magnetisation – exciting developments in pulse magnetisation are happening!
Visit Cambridge!