IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2015.
Plenary presentation M1PL given at CEC-ICMC 2015, Tucson, USA, June 28 – July 2, 2015.

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# Bulk Superconducting Materials – Ready for Applications ?

*Dr J. H Durrell*

*Post Conference Annotated Version – July 2015*

**Department of Engineering – University of Cambridge**

BSG

# 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

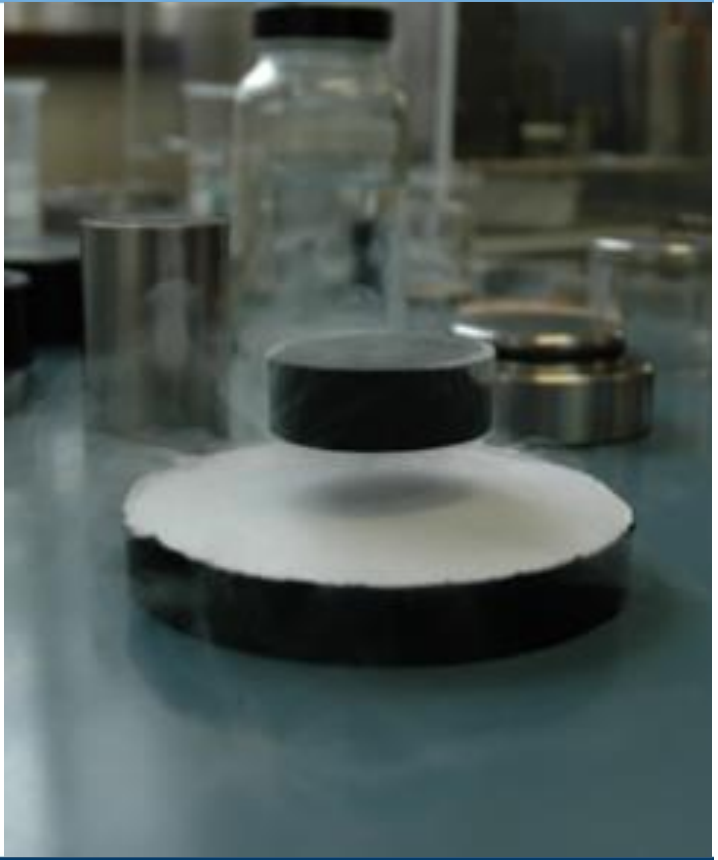
A. Yamamoto – University of Tokyo

M. Izumi – TUMSAT

A. Patel – University of Cambridge

# Outline

- Basics
- Practical Bulk Materials
  - (RE)BCO
  - $MgB_2$
- Advanced Materials
- Applications



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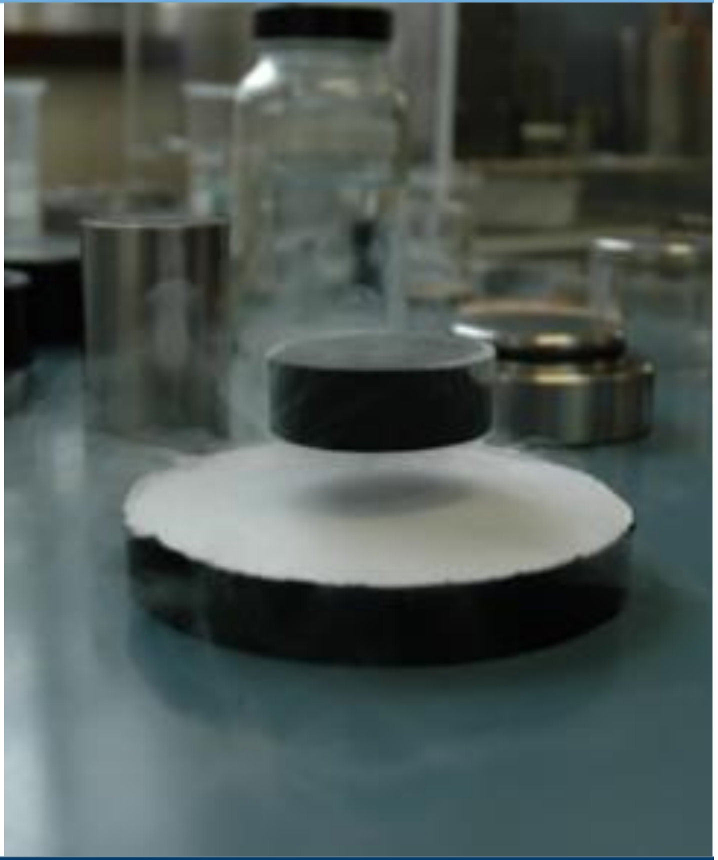

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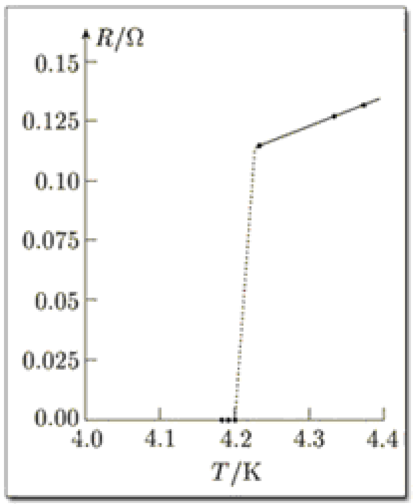
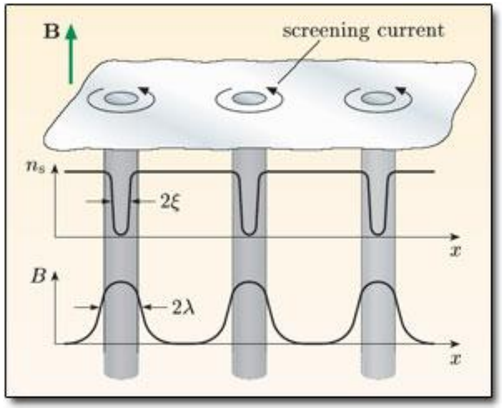
# Superconductivity

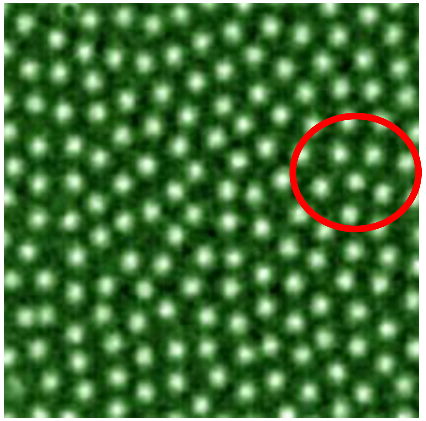



- Discovered in Mercury by Kammerling Onnes shortly after he had succeeded in liquefying Helium
- Sharp decrease of resistivity to zero at a critical temperature $T_c$.
- Small magnetic fields destroyed effect – limited practical application

# 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

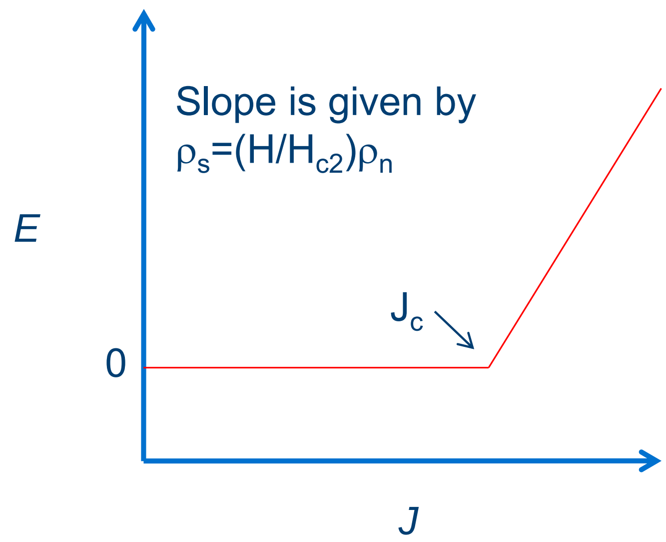


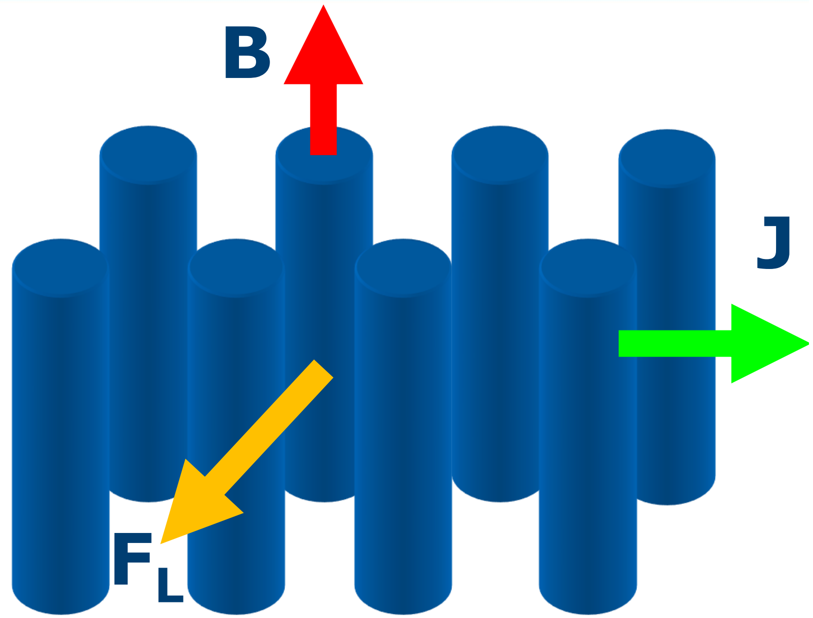



Flux lines in $NbSe_2$, University of Oslo

See http://www.mn.uio.no/fysikk/english/research/groups/amks/superconductivity/sv/ for more

# What Limits Current Flow?




- Flux lines are pinned by defects
- Pinning is crucial

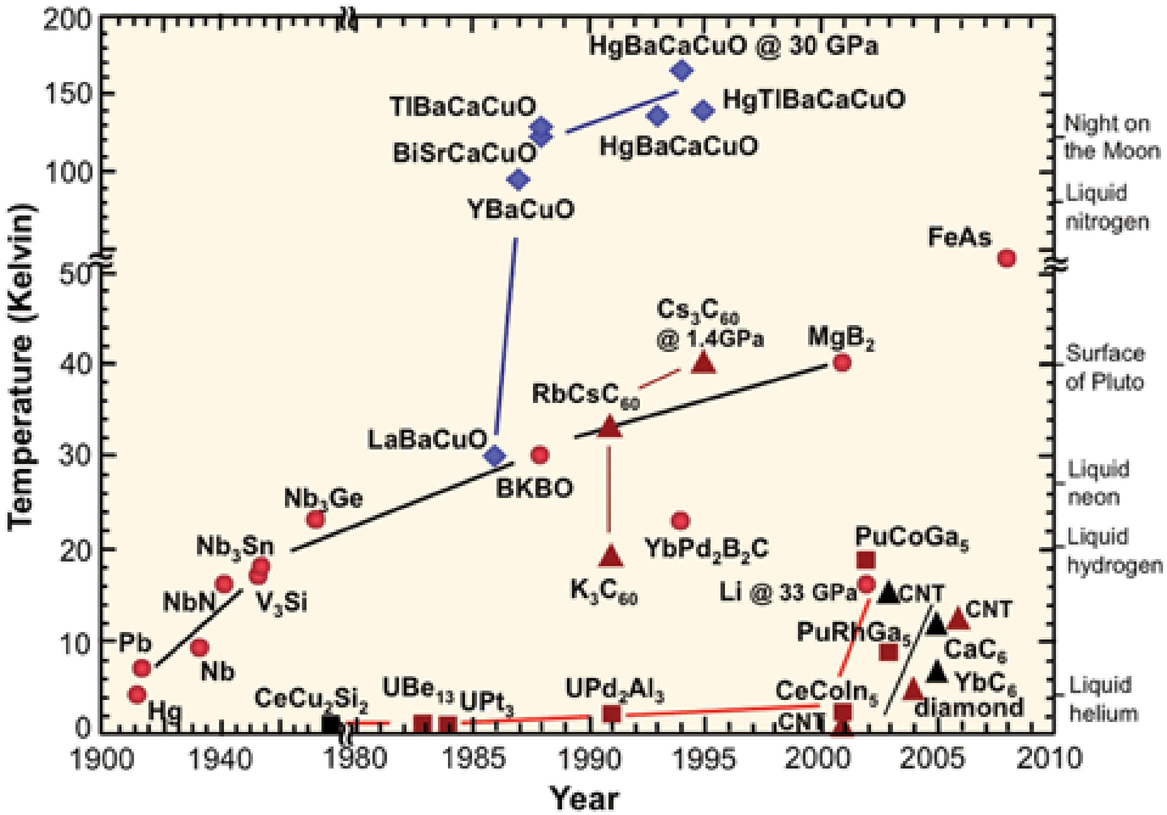
Critical Current

$$\mathbf{F_p} = \mathbf{J_c} \times \mathbf{B}$$

Maximum Pinning Force Density

Magnetic Flux Density

# Families of Superconductors



# Forms of superconductor

- **Bulk**

4 cm

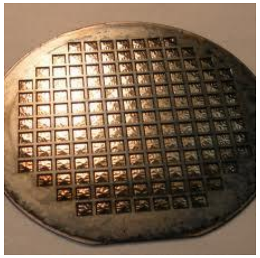
High field permanent magnets

Self stabilized levitation

- **Wires and Tapes**

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

- **Thin Films**

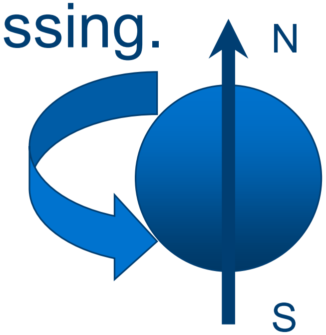


High speed electronics,
GHz frequency generators
Single Photon Detectors

# 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.



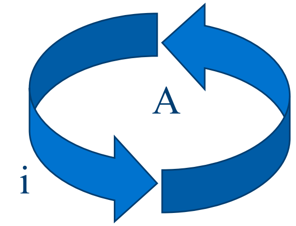

$\mu_B = 9.27 \times 10^{-24}$ Am$^2$

Magnetisation independent of sample volume

# Bulk Superconductors

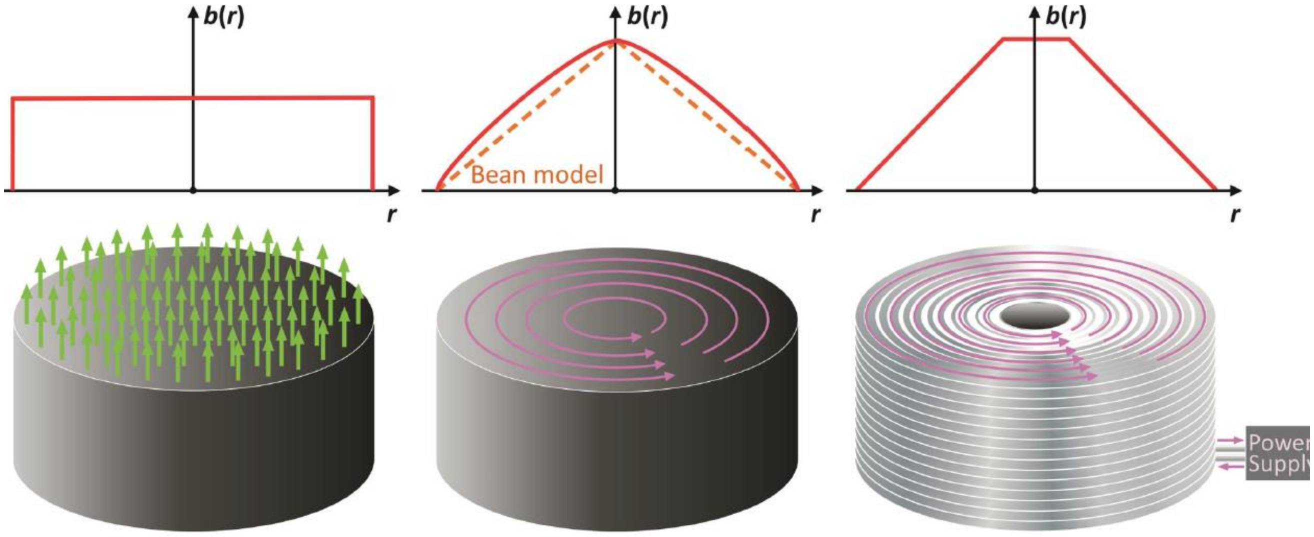
- Field generated by induced macroscopic currents rather than spins.

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




- 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

If video not embedded see http://bulk-sucon.eng.cam.ac.uk/platform.php

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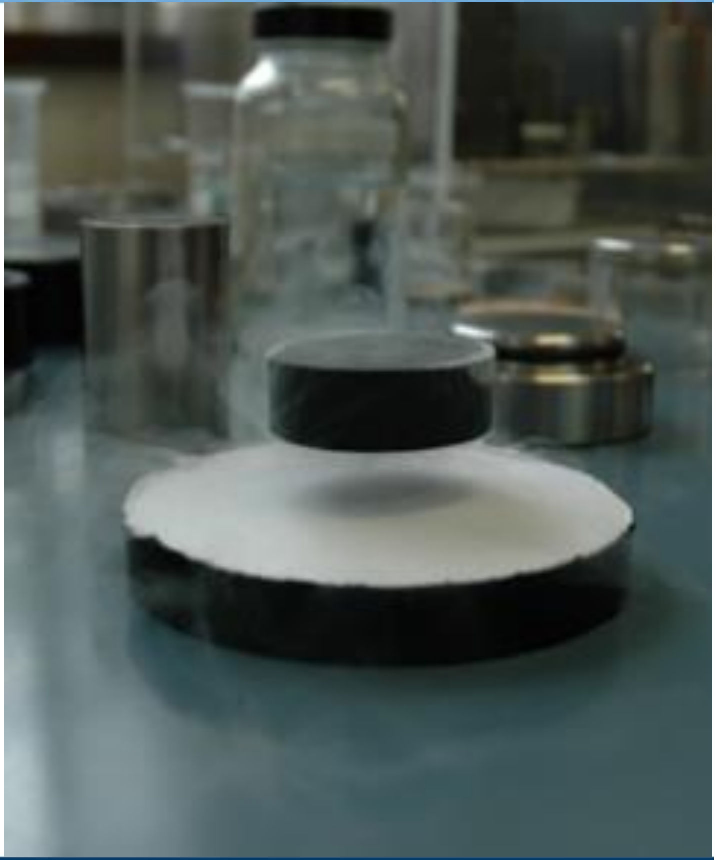

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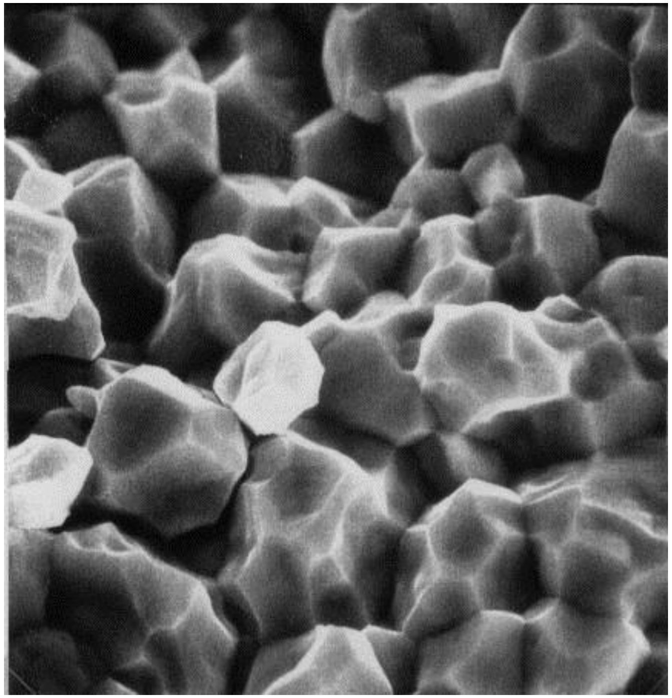
# Granularity is a problem!

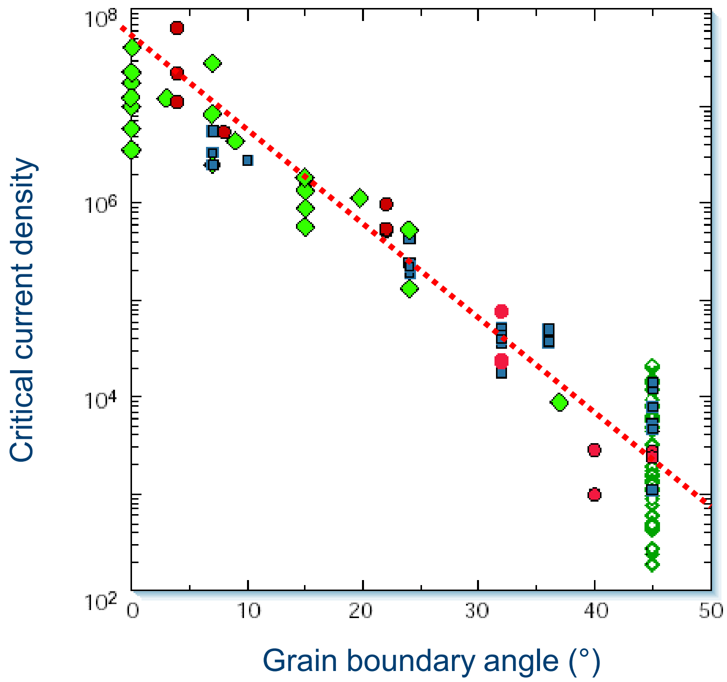


Sintered YBCO



- 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

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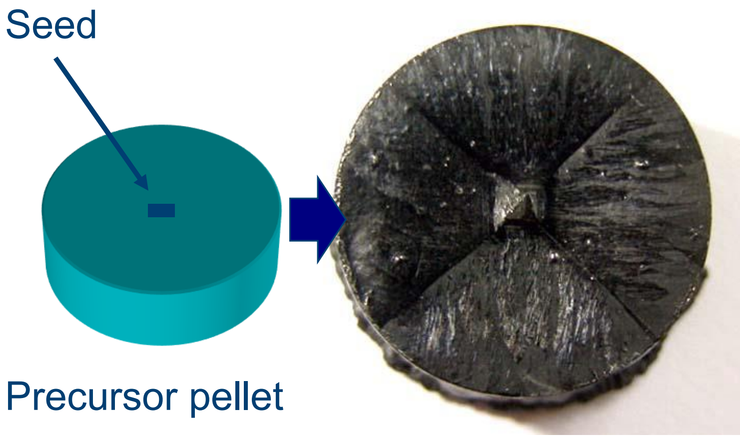
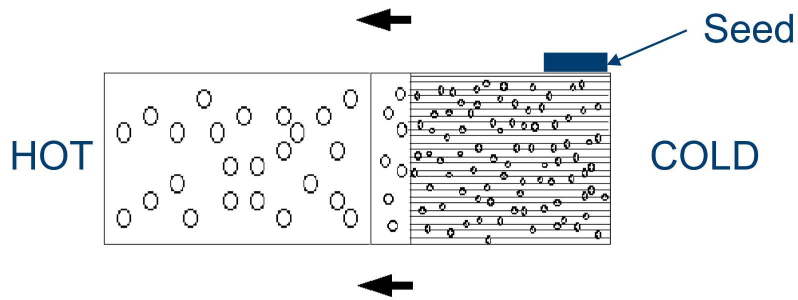
# Melt Grown (RE)BCO Bulk Superconductors




$$YBa_2Cu_3O_{7-\delta} + Y_2BaCuO_5 + Pt \rightarrow Y_2BaCuO_5 + L$$

- 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

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# The (RE)BCO family

| | | |
|---|---|---|
| $YBa_2Cu_3O_{7-\delta}$ | 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 |

- Several different (RE)BCO materials can be used.
- Have differing melting points, need higher melting point seed

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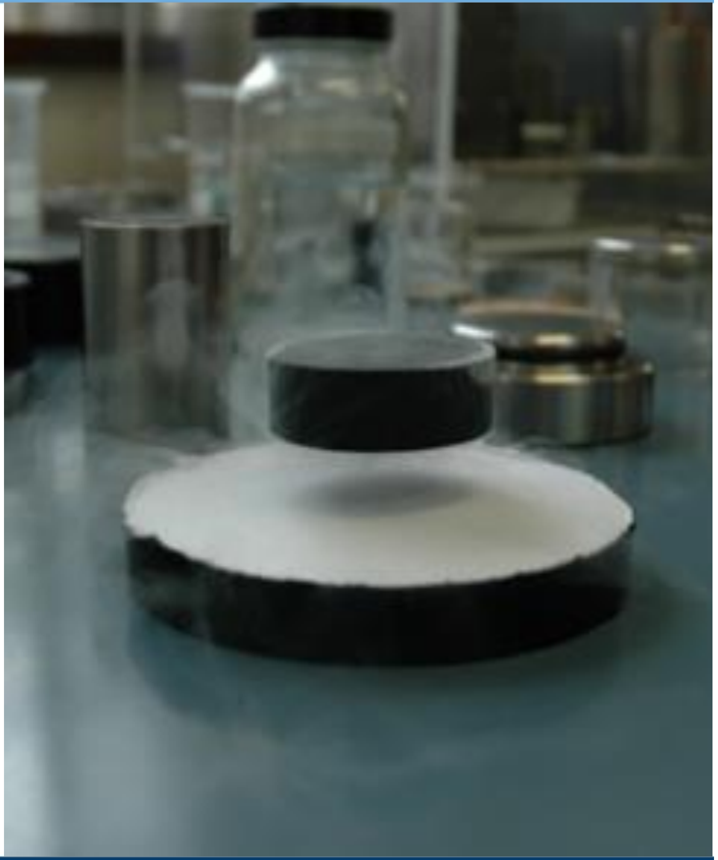

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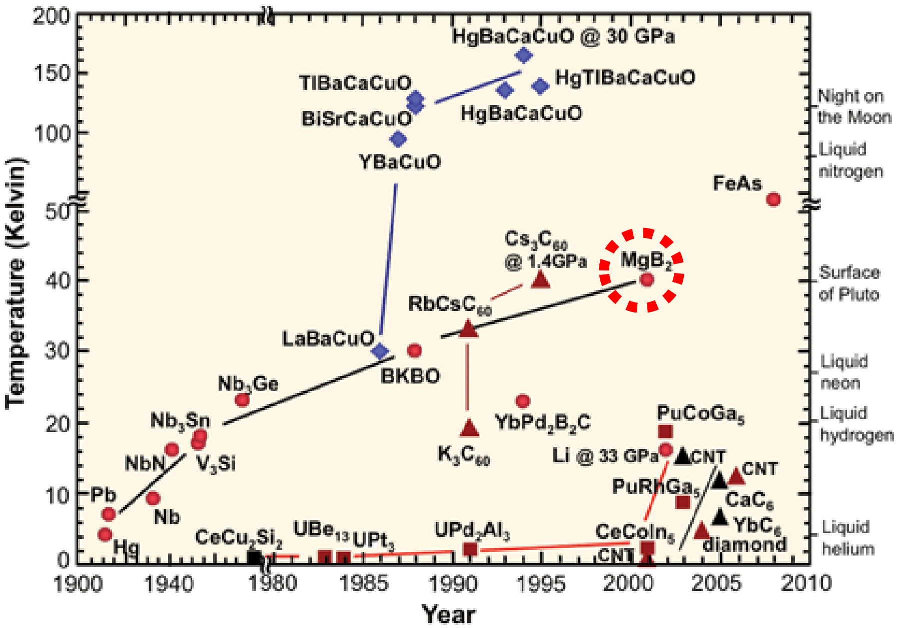
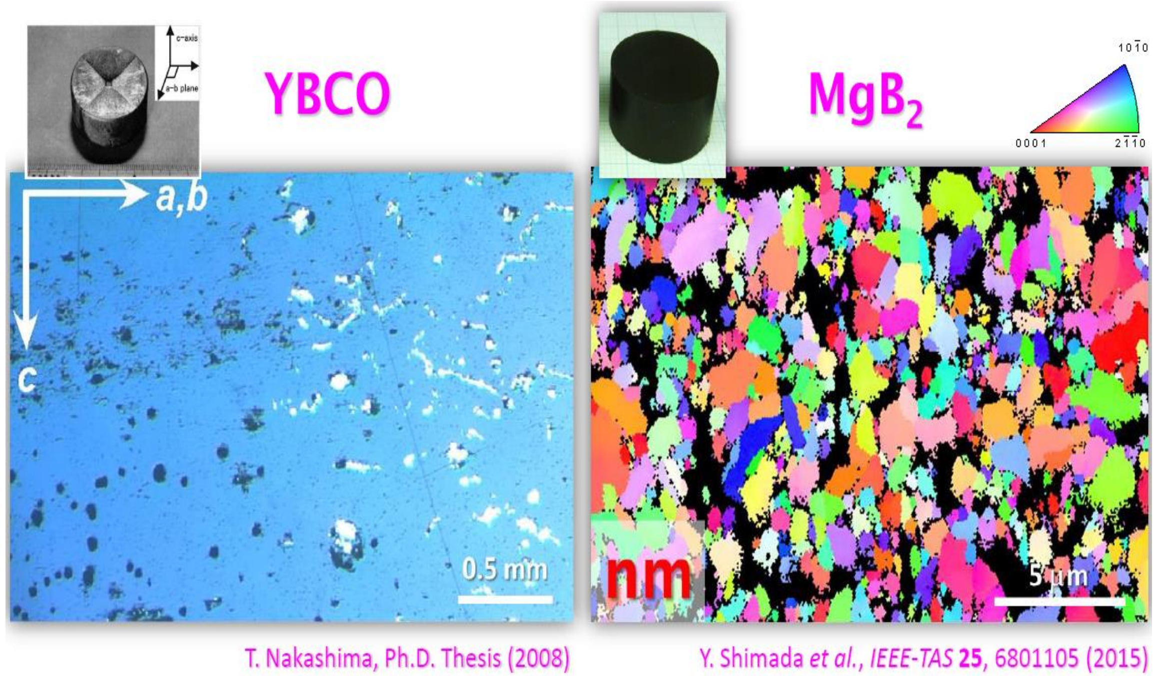
# $MgB_2$

- 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

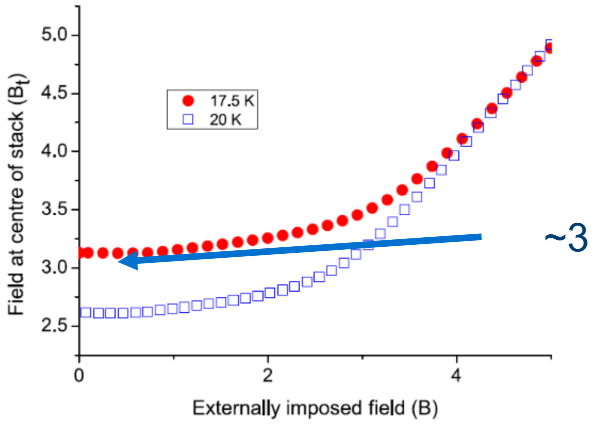
Randomly oriented polycrystal
Pinning by grain boundaries



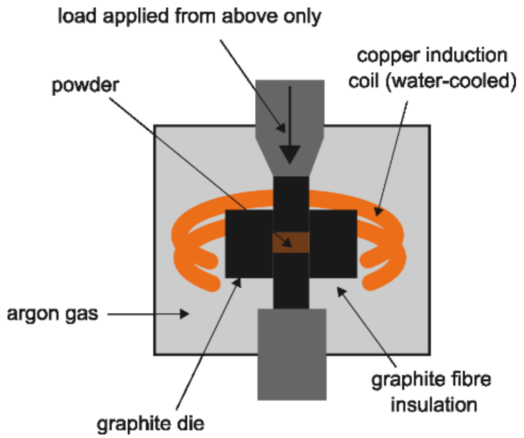
*Slide courtesy A. Yamamoto*

# 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









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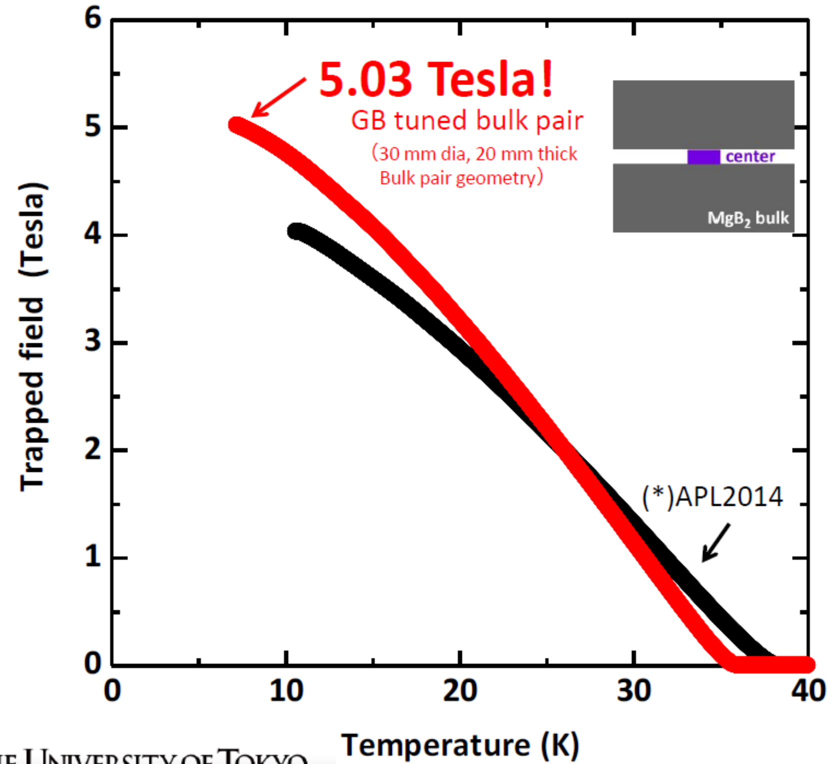
*Durrell et al. Supercond. Sci. Technol. 25 (2012) 112002*

# 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

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

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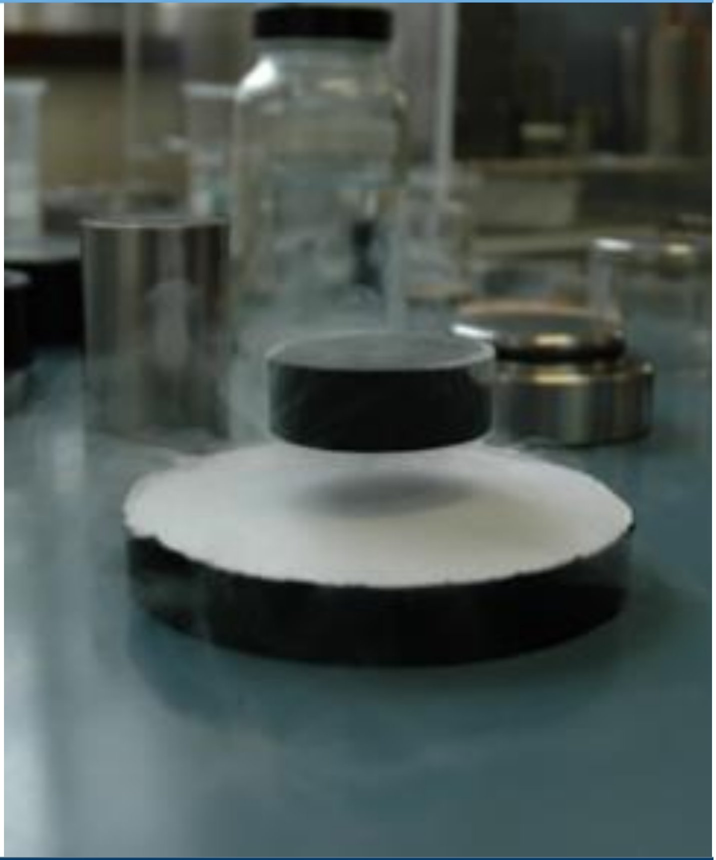

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# What's 'New' in Bulk?

- 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

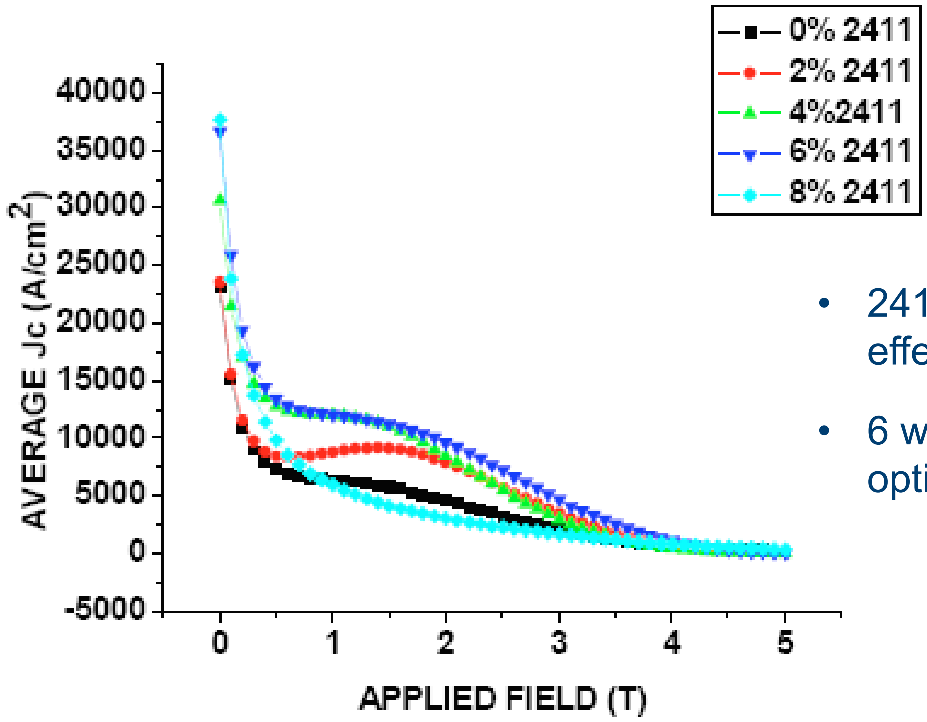
$$(RE)_2Ba_4CuMO_y$$

RE = Sm, Gd, Nd, Y

M = Nb, Zr, Hf, W, Bi, Ag, U …etc.

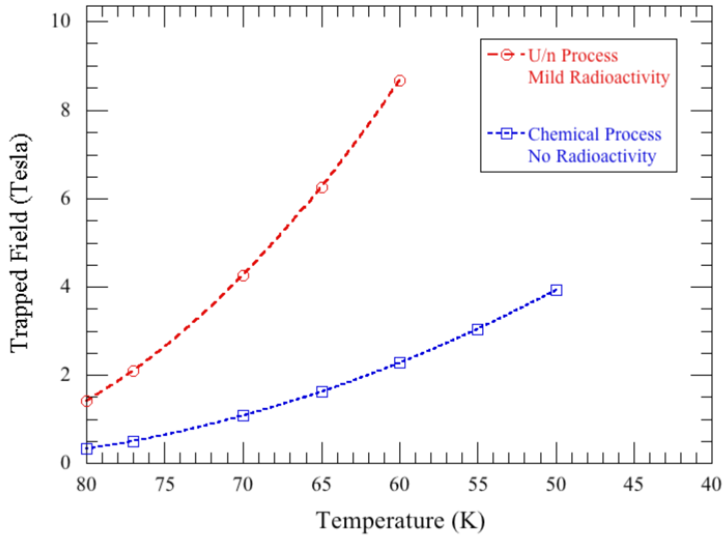
- All paramagnetic and non-superconducting down to 5 K

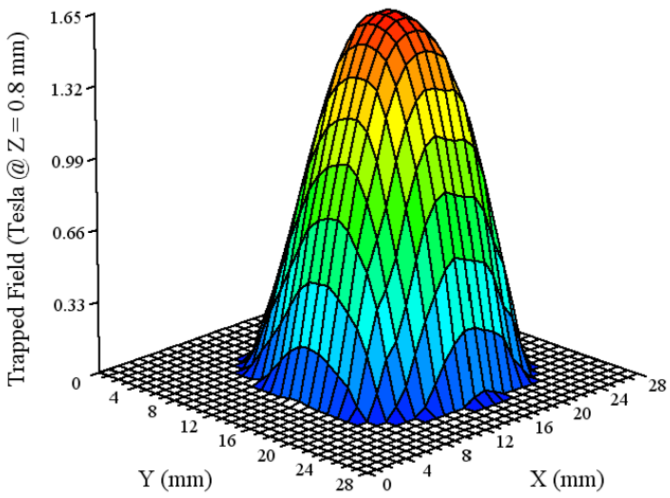
# Flux pinning - YBCO containing Y-2411 (Nb)




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

# Pt/U pinning




- Houston group have shown that the combination of $(Pt_{0.4}U_{0.6})/YBa_2O_6$ 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



*Sawh et al. Supercond. Sci. Technol. 26 (2013) 105014*

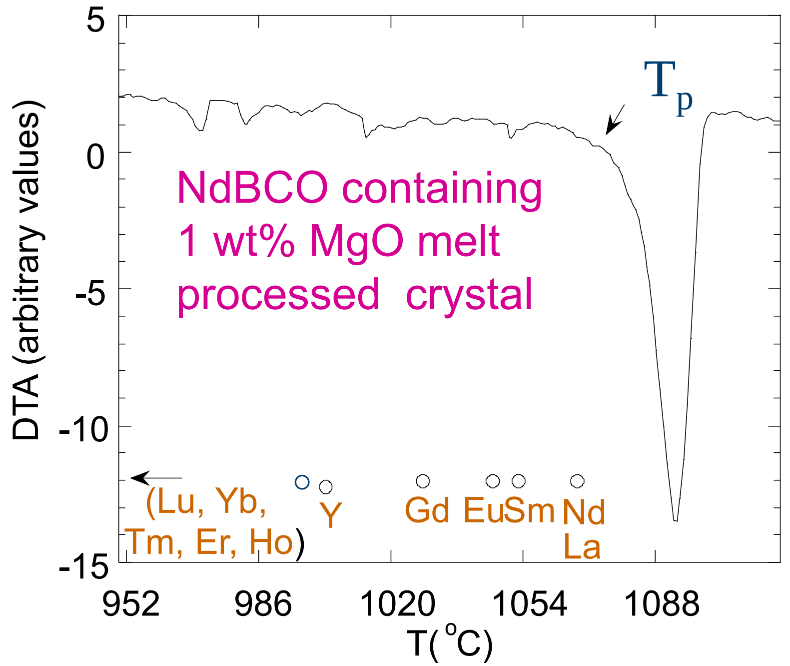
# Advanced Seeds

| 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;

- 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.

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

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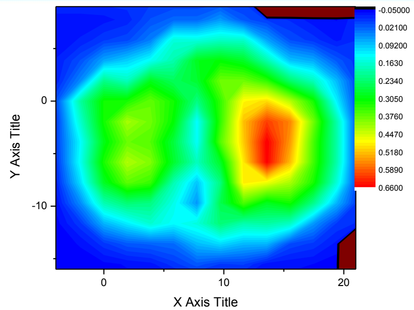
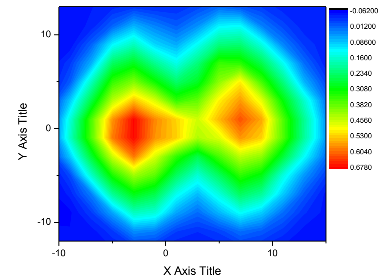
# Multi-seeding

- 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

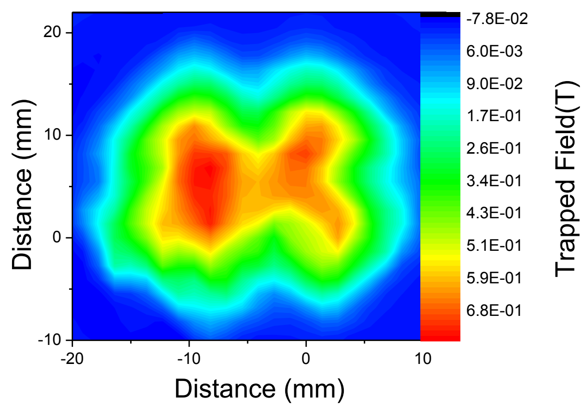



**#265**
**0.68 T**

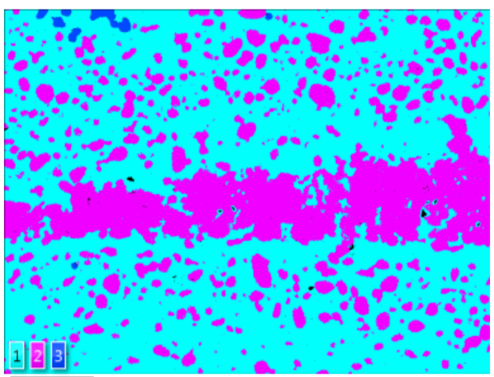
**#263**
**0.74 T**


**#268**
**0.78T**

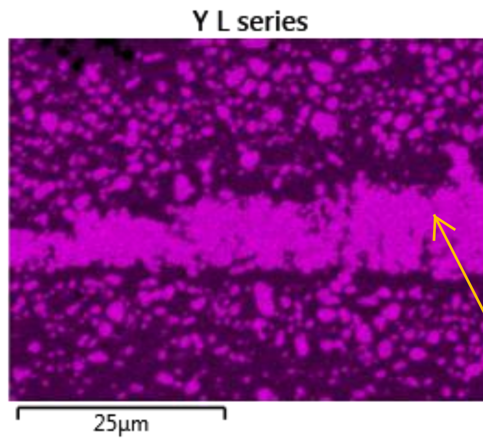



# Growth sector between seeds

- 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.

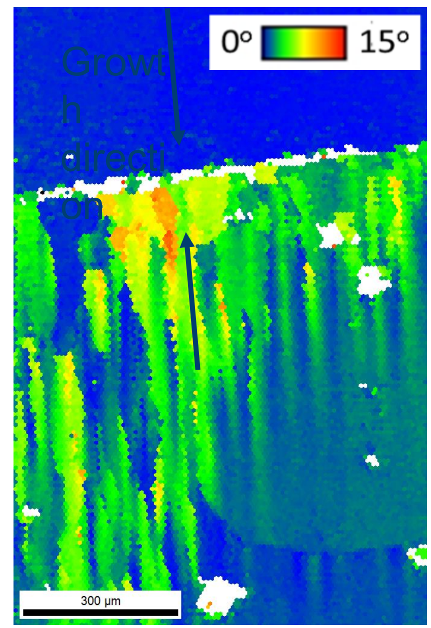



Y-123 Y-211 $BaCeO_3$




Phase map

Seed 2




Seed 1

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

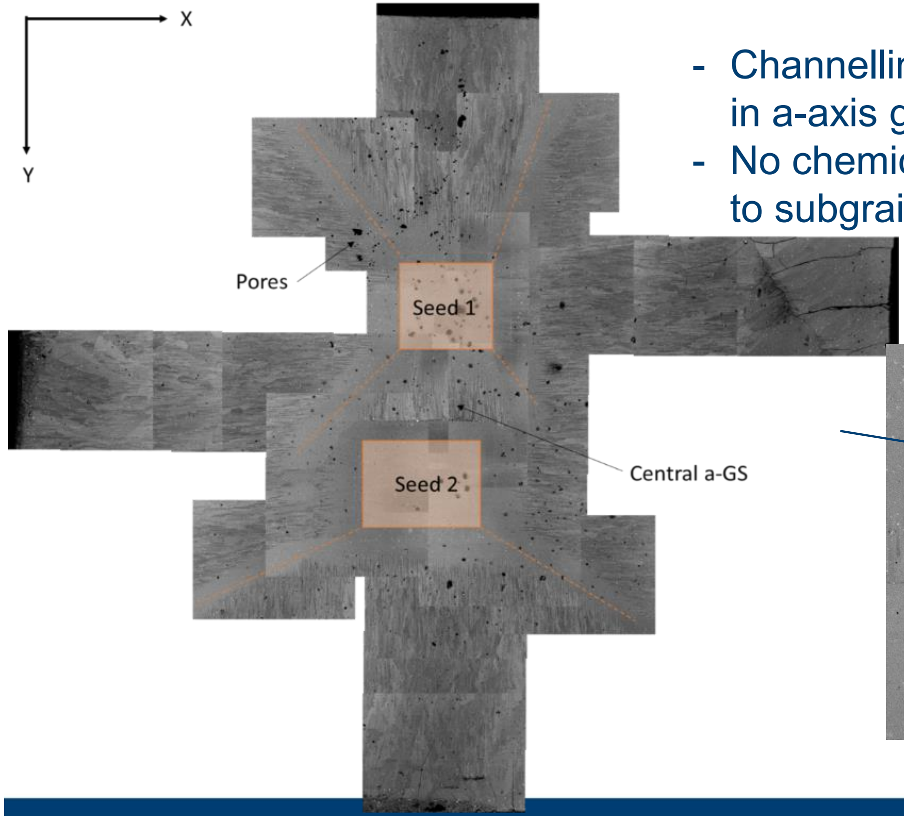


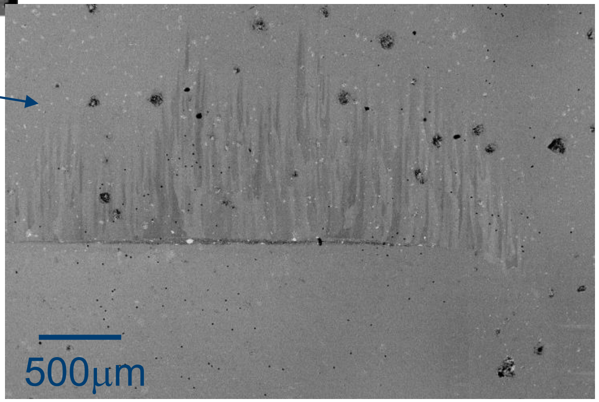
*Images: S. Speller – University of Oxford*

# SEM images of seed interface

Low magnification backscattered electron images

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

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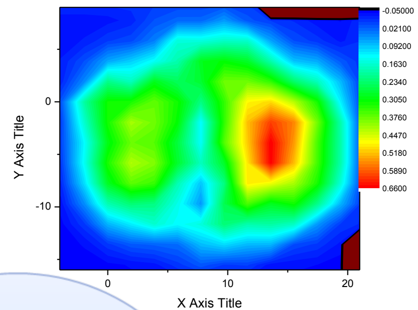
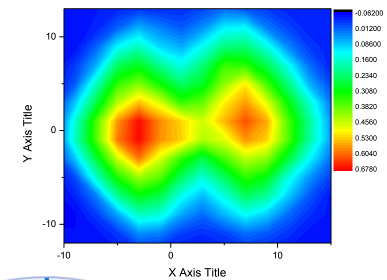
*Images: S. Speller – University of Oxford*

# Multi-seeding – oriented seed growth in YBCO

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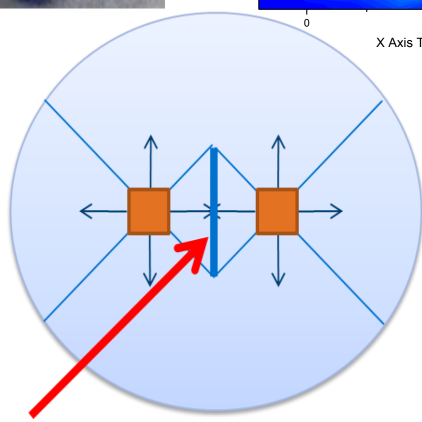
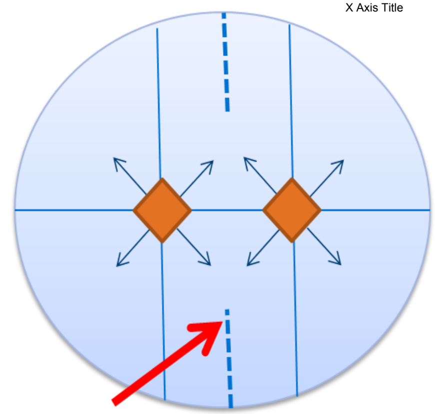


Shi et al, *Supercond. Sci. Technol.*, **26**, 015012. 2013.



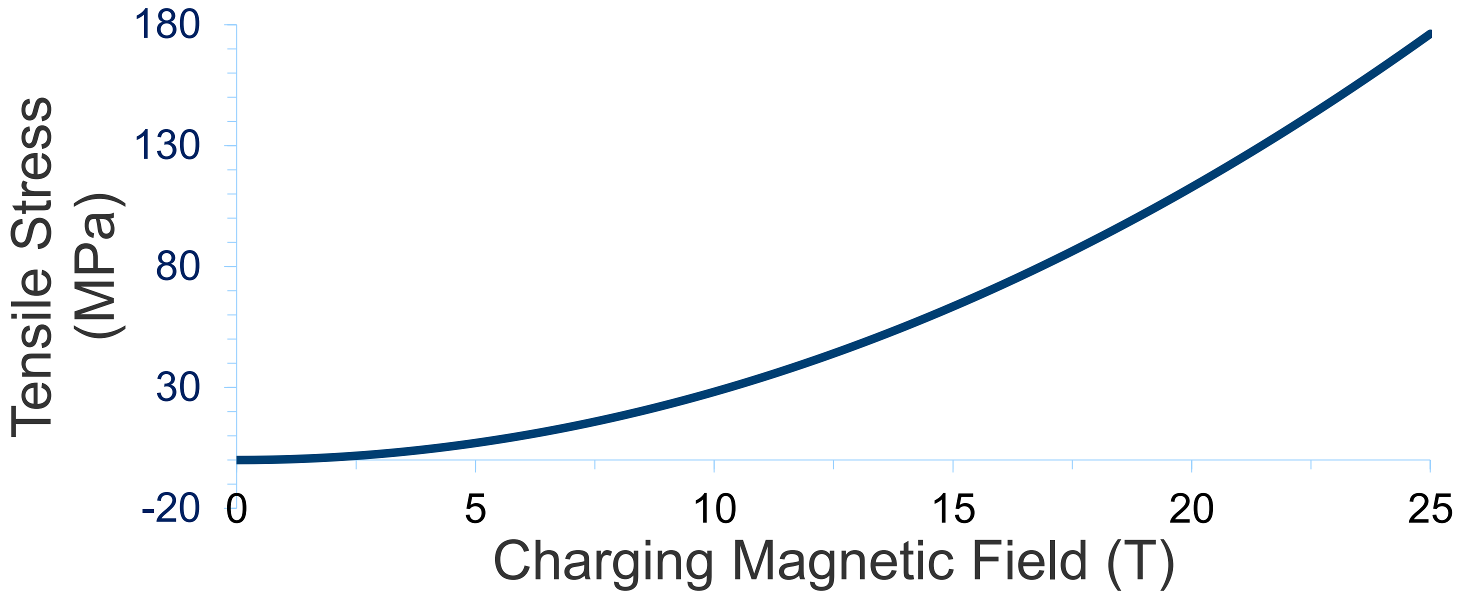
Trapped particles at GB – length depends on seed separation

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

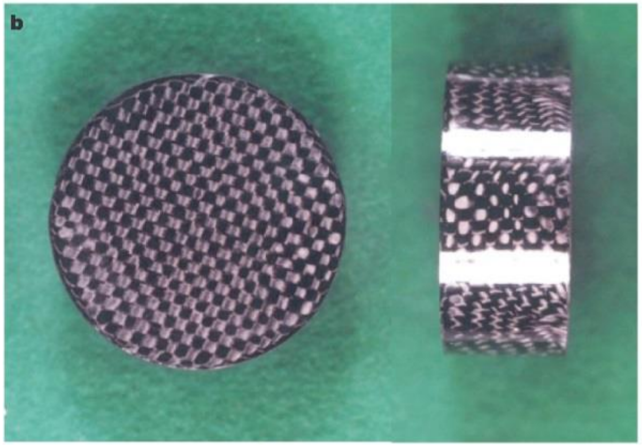
# Tensile Stress during Charging




- 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



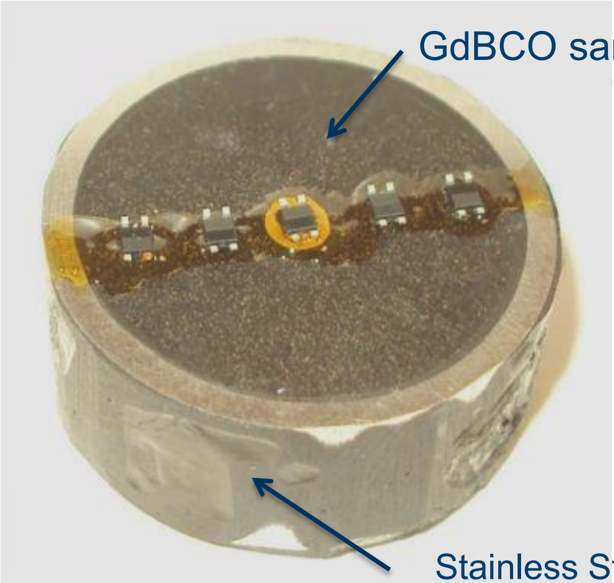

Tomita *et al.*, *Nature* 421, 517-520 (2003)

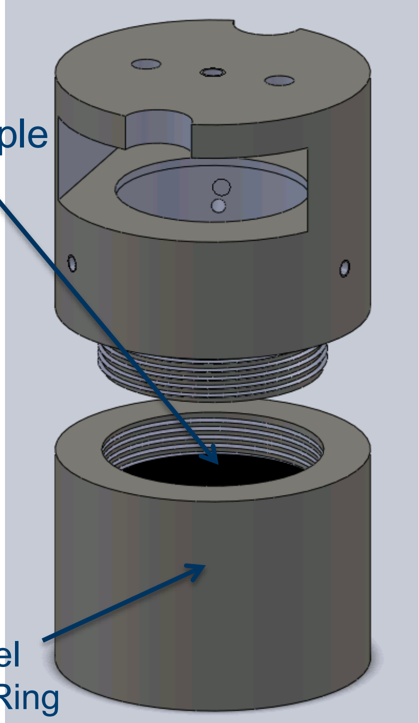
- Fuchs *et al.* used a SS reinforcement band. – 15 T

Appl. Phys. Lett. **76**, 2107 (2000)

# 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

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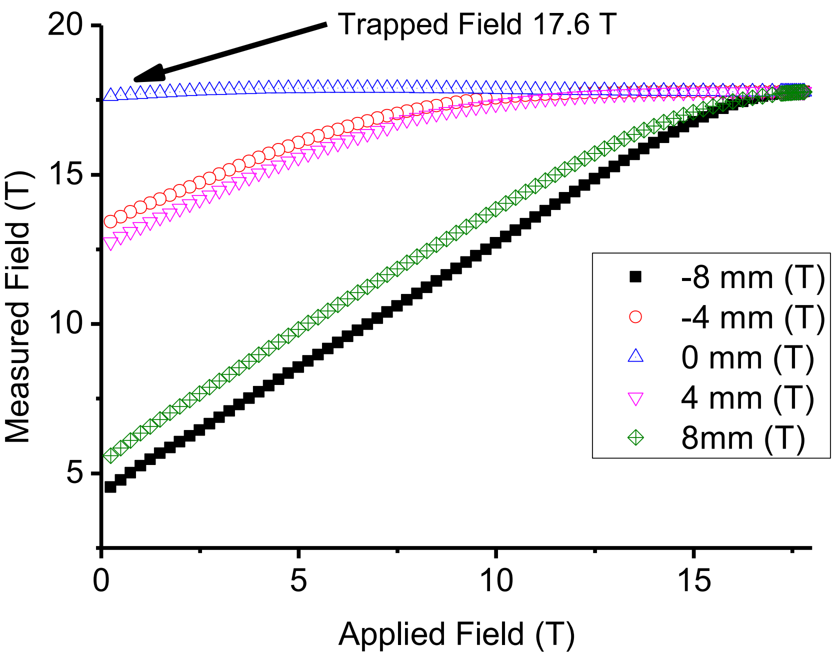
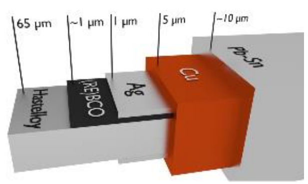


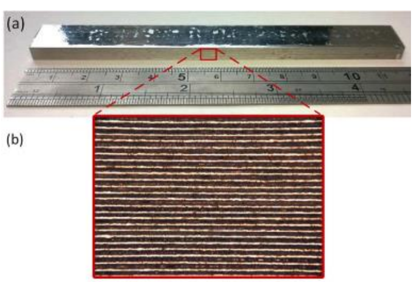

- Small sample (24 mm diameter)
- 26 K
- Energy density > 25 $MJ/m^3$
- Equivalent to 12% of energy density of TNT!

# Pseudo-Bulks – Stacked Tapes

## Fabrication




Baskys A et al. 2015, *IEEE Trans. Appl. Supercond.*, **25** 6600304




**Main advantages are**

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

**Fabrication**

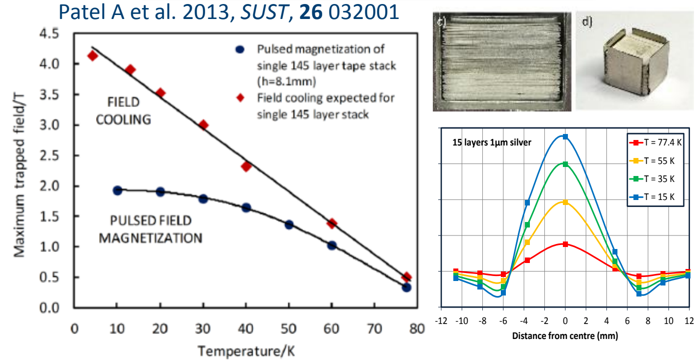
- Simple cutting and stacking
- Can use solder plated tape to create self-supporting slabs/blocks by compression and heating
- Can create large slabs by overlapping layers

**Trapped field results**

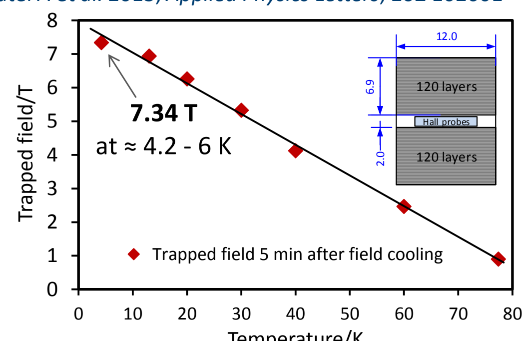
- Stacks respond very well to pulsed field magnetization
- Current records for stacks set using commercial 12mm tape
- Limited by tape width and engineering Jc
- Higher fields expected with new tape

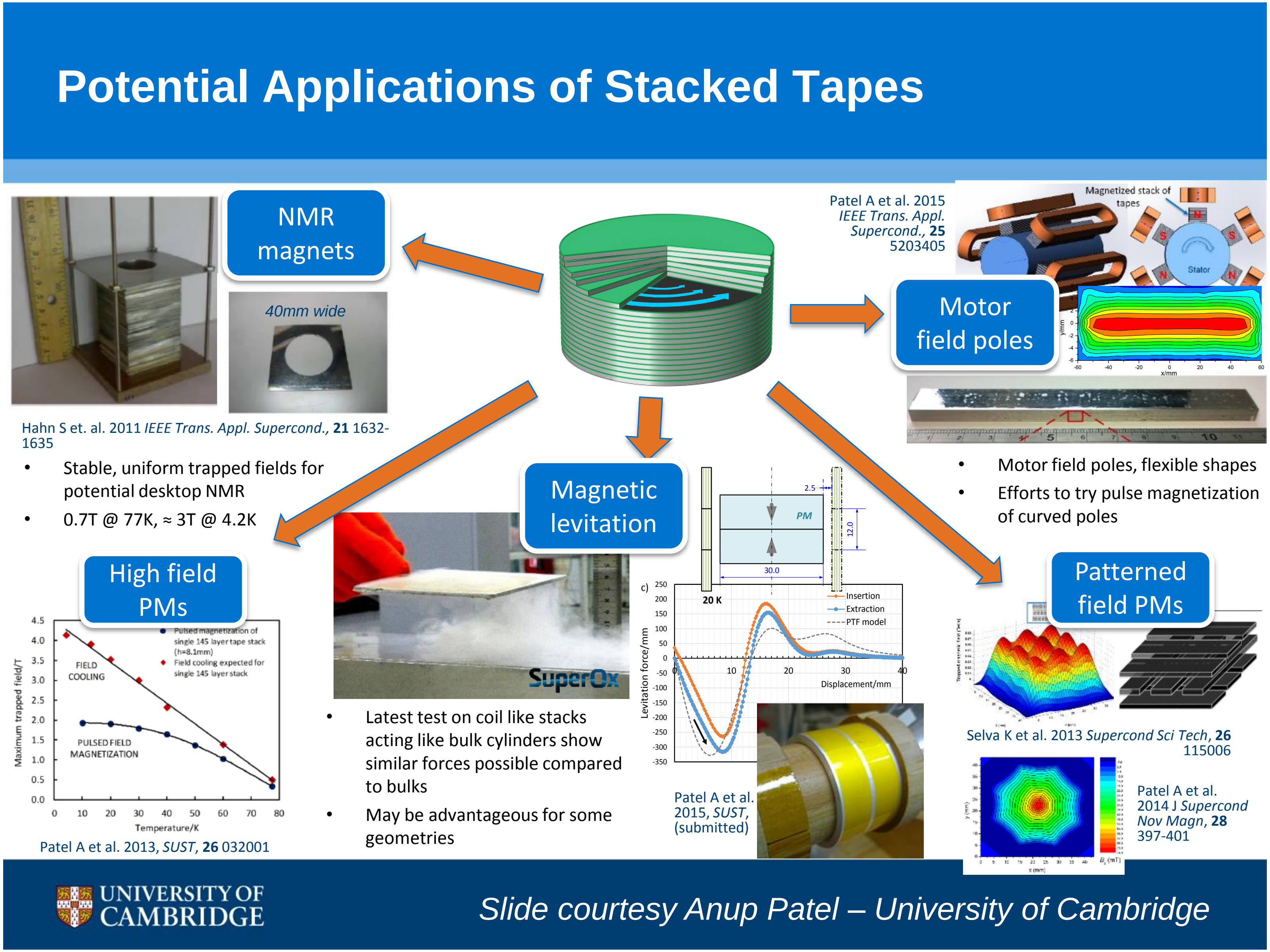
## Trapped field measurements 12mm square stacks

Patel A et al. 2013, *SUST*, **26** 032001




Patel A et al. 2013, *Applied Physics Letters*, **102** 102601




Potential Applications of Stacked Tapes
NMR magnets
40mm wide
Hahn S et. al. 2011 IEEE Trans. Appl. Supercond., 21 1632-1635
• Stable, uniform trapped fields for potential desktop NMR
• 0.7T @ 77K, ≈ 3T @ 4.2K
High field PMs
Maximum trapped field/T
Temperature/K
FIELD COOLING
PULSED FIELD MAGNETIZATION
Pulsed magnetization of single 145 layer tape stack (h=8.1mm)
Field cooling expected for single 145 layer stack
Patel A et al. 2013, SUST, 26 032001
Magnetic levitation
SuperOx
• Latest test on coil like stacks acting like bulk cylinders show similar forces possible compared to bulks
• May be advantageous for some geometries
PM
30.0
12.0
2.5
20 K
Insertion
Extraction
PTF model
Levitation force/mm
Displacement/mm
Patel A et al. 2015, SUST, (submitted)
Patel A et al. 2015 IEEE Trans. Appl. Supercond., 25 5203405
Magnetized stack of tapes
Stator
Motor field poles
x/mm
y/mm
• Motor field poles, flexible shapes
• Efforts to try pulse magnetization of curved poles
Patterned field PMs
Selva K et al. 2013 Supercond Sci Tech, 26 115006
Patel A et al. 2014 J Supercond Nov Magn, 28 397-401
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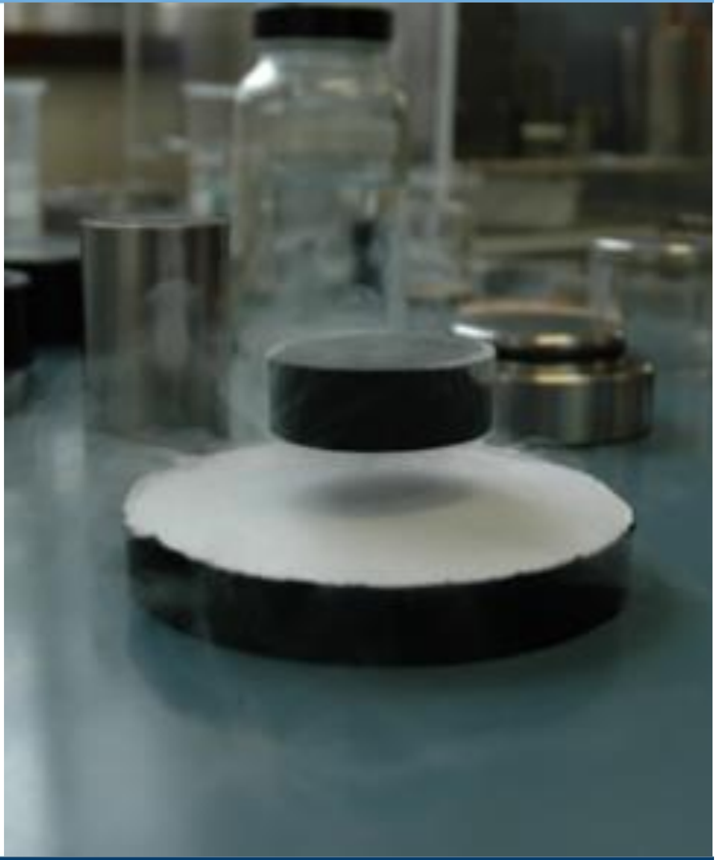
Slide courtesy Anup Patel – University of Cambridge

# Outline

- Basics
- Practical Bulk Materials
  - (RE)BCO
  - $MgB_2$
- Advanced Materials
- Applications



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# Applications

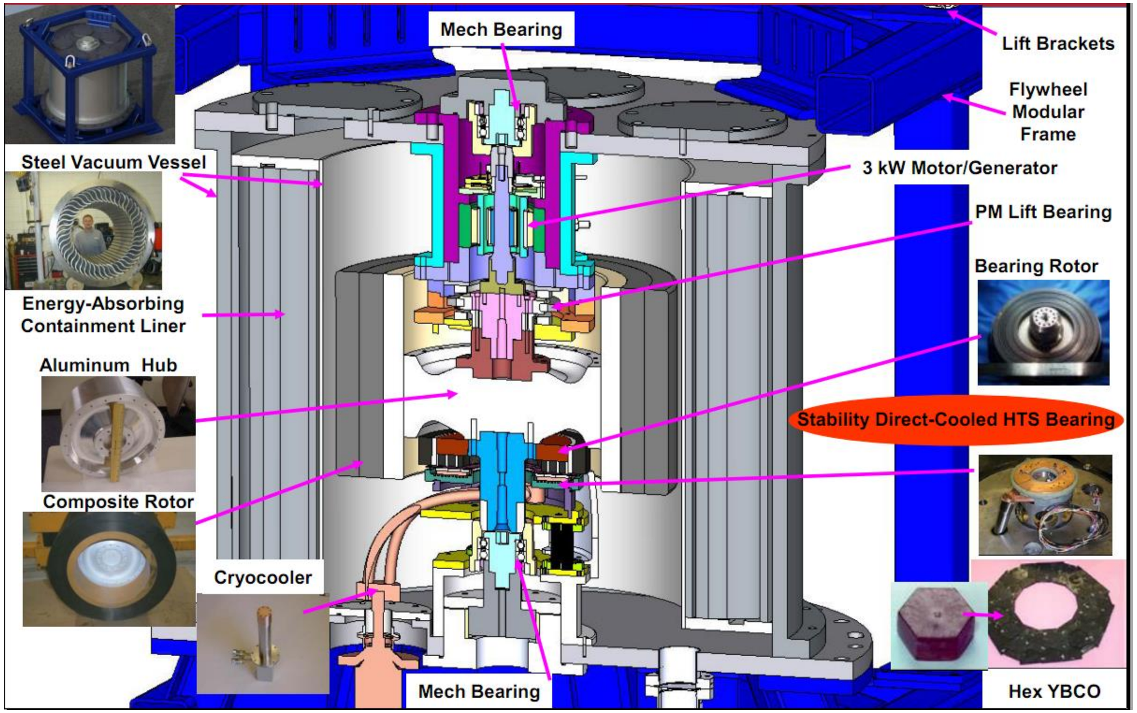
- Two main classes:
  - High field "permanent" magnet
  - Self stabilised levitation
- Challenges to practical applications are:
  - Cooling
  - Charging

Pulse charging system


Cryotel Cryo-Cooler for Bulk Application

# Superconducting Flywheel Bearings

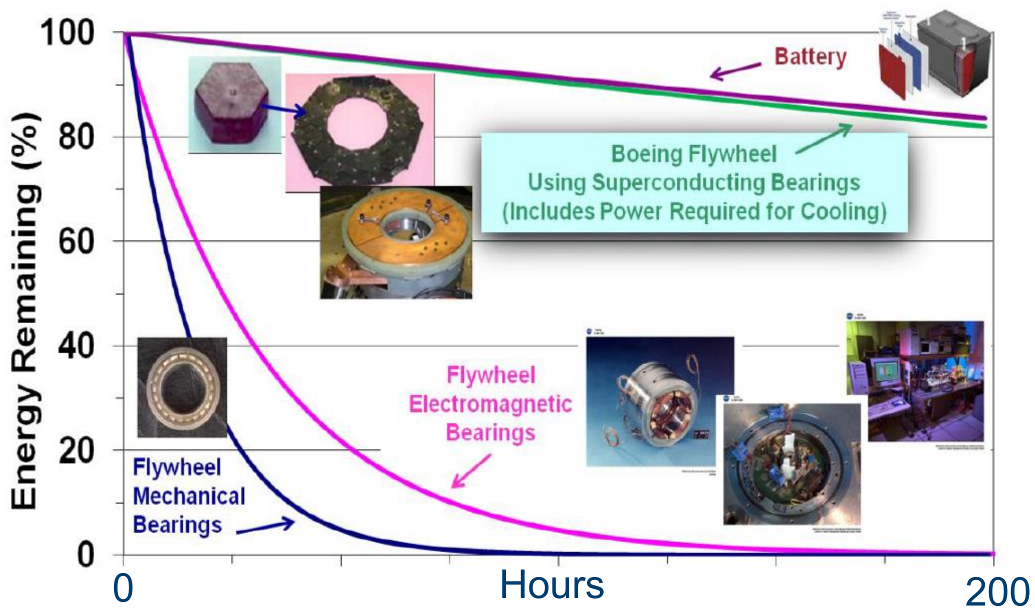
- Flywheels offer unparalleled Specific Power Density ~5 kW/kg
- Specific Energy Density is slightly less than Li-Ion ~ 0.2 kWh/kg. Compare Petrol at 14 kWh/kg
- Key advantage is ability to discharge quickly (power).






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

# Applications - Superconducting Bearings

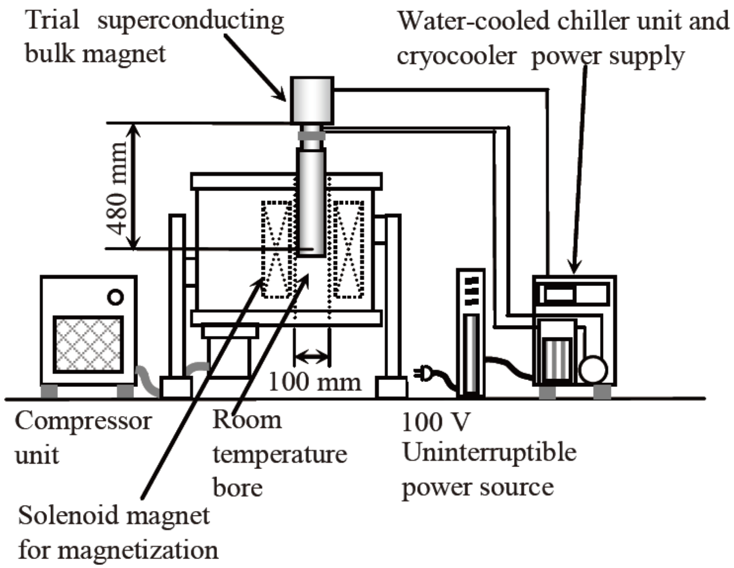


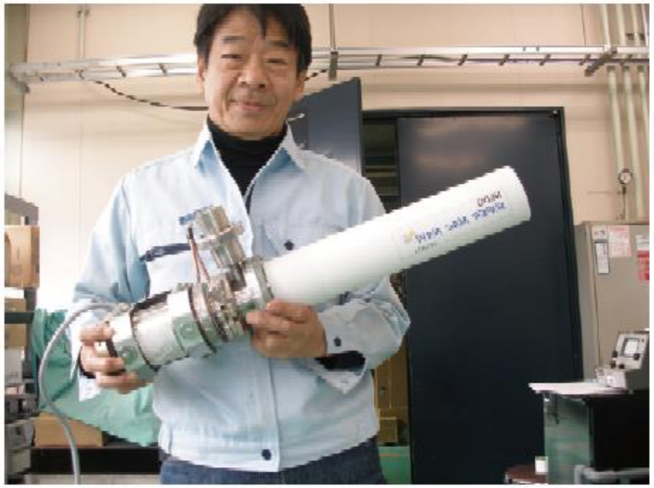

- Primary source of loss is friction. Superconducting bearings significantly extend useful energy storage time.



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

# Portable High Fields – for many applications



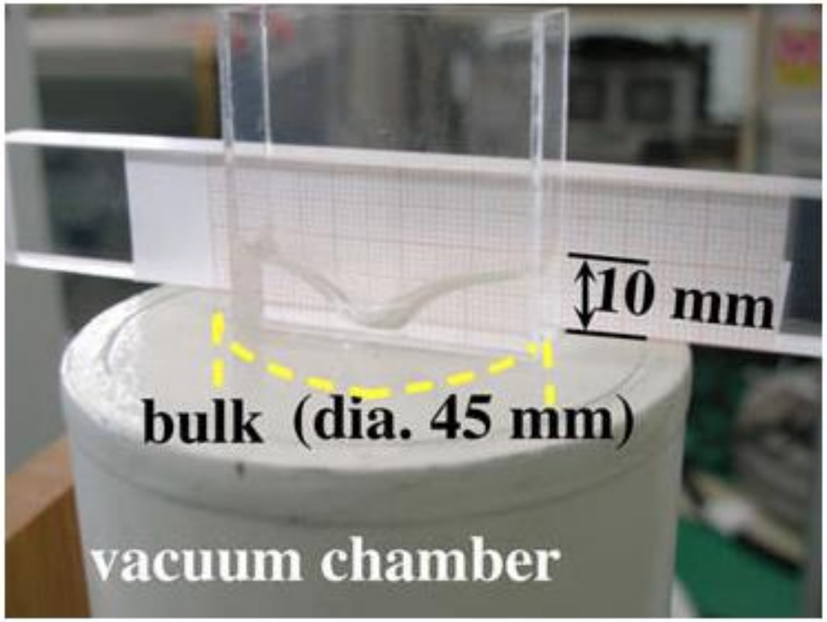



- Modern cryocoolers allow bulks to be charged in a solenoid and then moved around in a portable system.
- Hitachi have demonstrated such a system with an eye on medical applications



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

# Portable High Fields




- Numerous potential applications for this kind of technology
- And you can part water ! "Moses Effect"



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

# 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

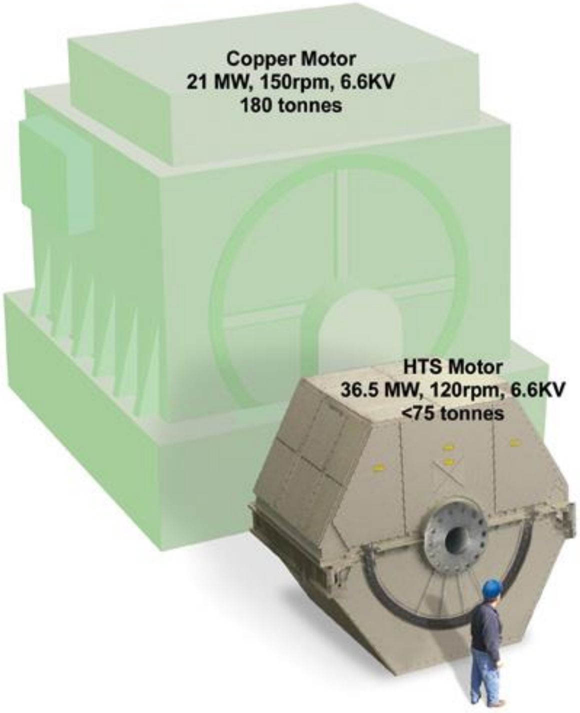



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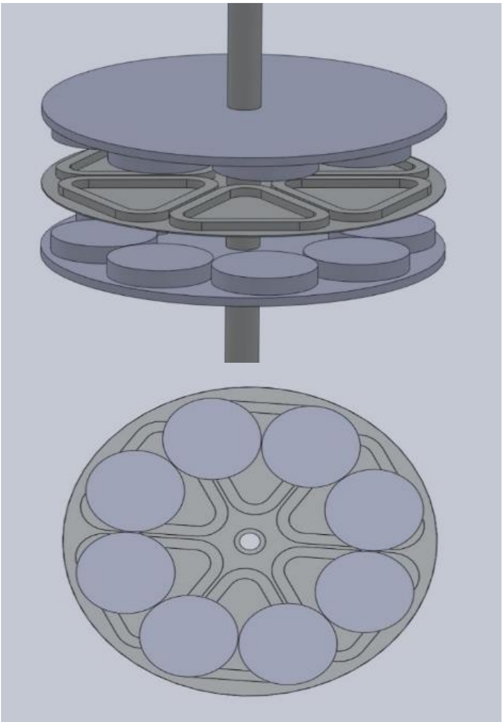
*Image – AMSC website*

# Bulk HTS Applications – Motors

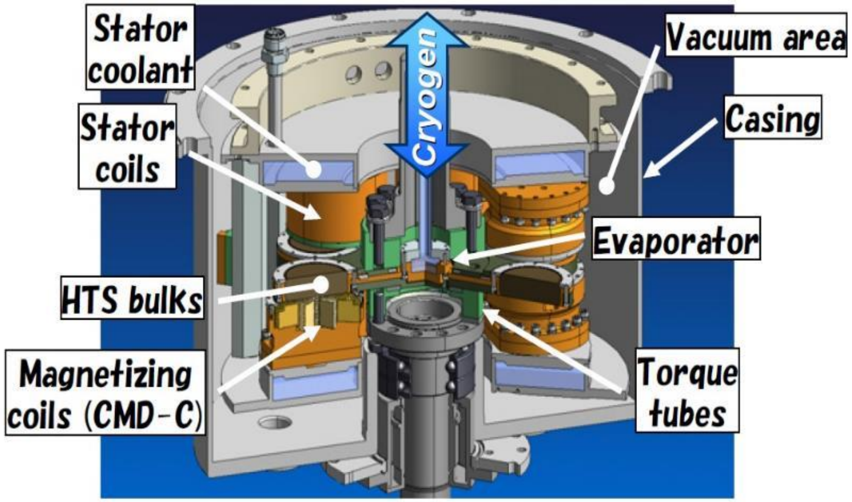
- **Axial gap, trapped flux-type motor**
- **Advantages:**
  - Higher torque/power density
  - Compact 'pancake' shape
  - Better heat removal
  - Adjustable air gap
  - Multi-stage machines possible



**Axial gap, trapped-flux motor**

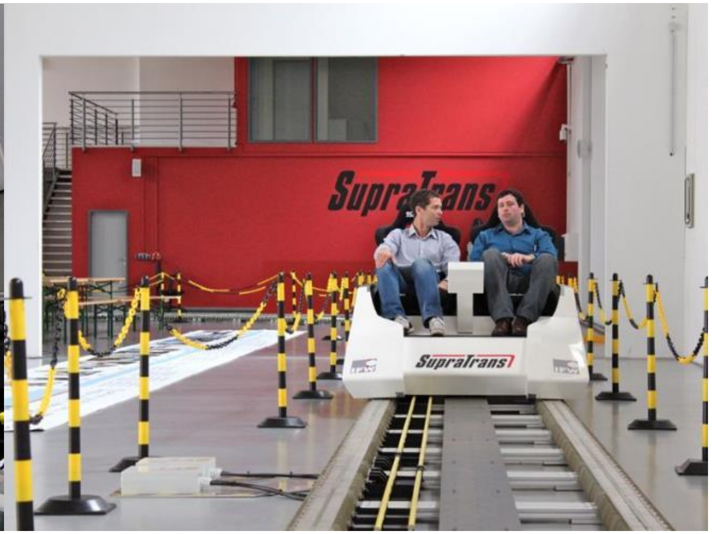
# Bulk HTS Axial Flux Motor

- **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**

# 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 a effective route to magnetisation – exciting developments in pulse magnetisation are happening!

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