High Trapped Fields in C-doped MgB_2 Bulk Superconductors Fabricated by Infiltration and Growth

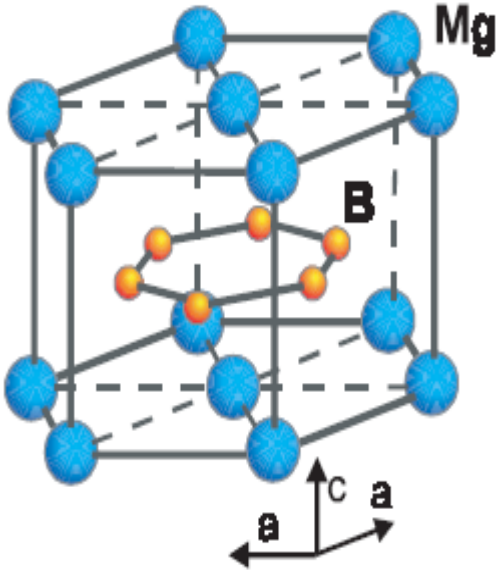
A. Bhagurkar & N. Hari Babu
BCAST, Brunel University London, UK

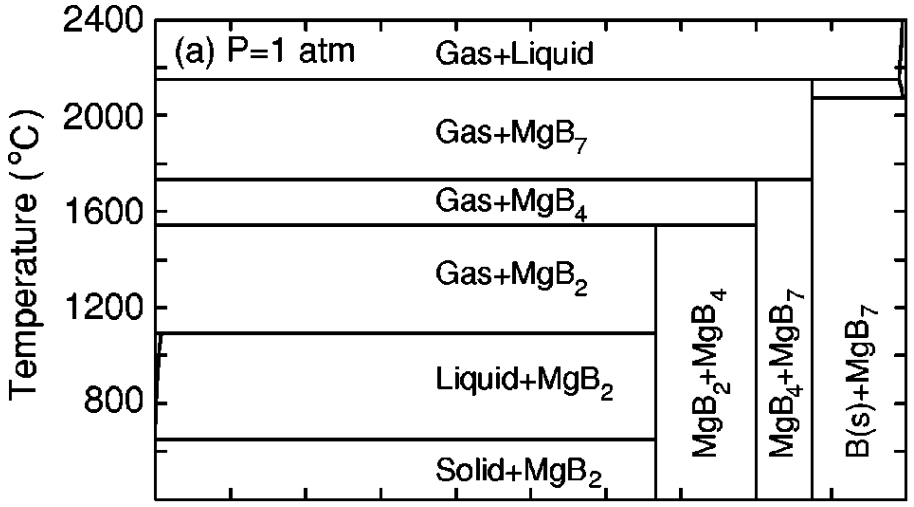
A R Dennis, J H Durrell, D. A. Cardwell
Department of Engineering, University of Cambridge, Cambridge, UK

A. Yamamoto
Dept. of Applied Physics, Tokyo University of Agriculture and Technology, Tokyo, Japan

Magnesium Diboride

- Superconductivity discovered in 2001
- Conventional superconductor (Phonon mediated superconductivity)
- T_c = 39 K (Highest amongst intermetallics)
- Larger coherence length
- Strongly linked current flow in polycrystals makes fabrication easier
- Relatively inexpensive
- Light weight





Applied Phy. Let. 78, 2678 (2001)

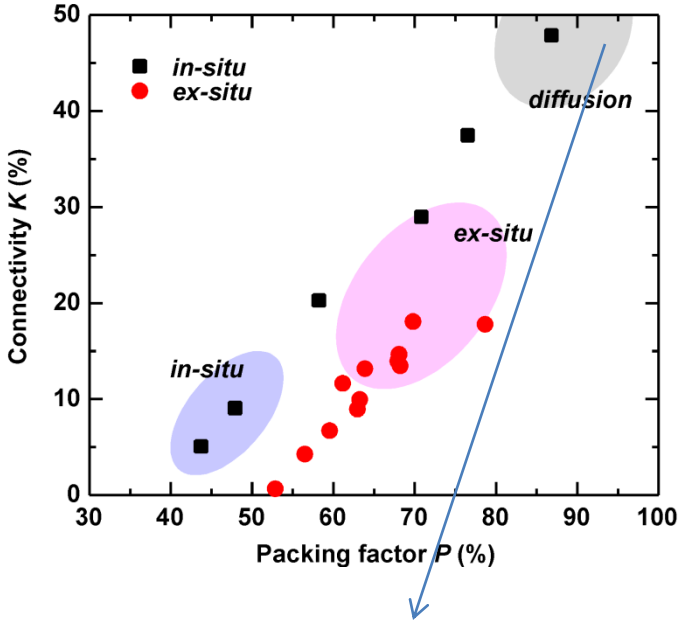
Sintering

Sintering *(Ex-situ)*

- Low sinterability
- High Temperature
- High pressure
- Poor intergrain coupling
- Poor connectivity

Sintering *(In-situ)*

- High Mg vapor pressure
- Large porosities (upto 50%)
- Brittle
- High pressure
- Dense structure possible by diffusion route, But small cross section

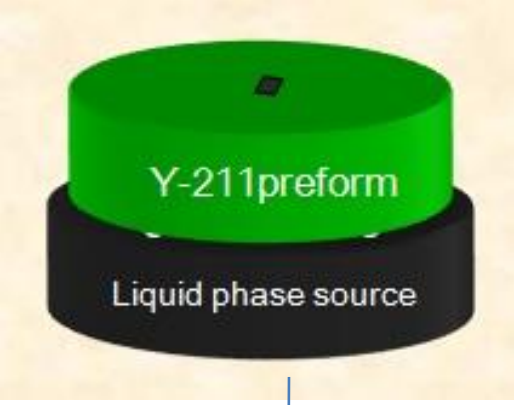


Scope to improve connectivity and coupling.

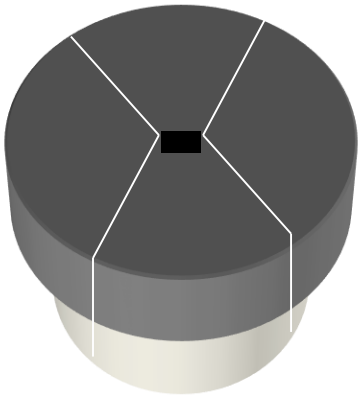
Yamamoto et al Jpn. J. Appl. Phys. 51 (2012) 010105

Infiltration and Growth

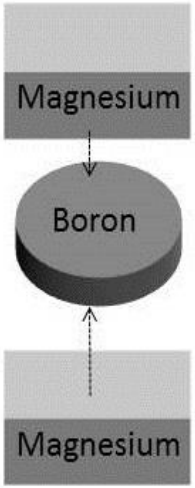
- Simple method to obtain near-net shaped bulk
- Ba-Cu-O liquid phase infiltration in to Y_2BaCuO_5 preform and then growth of $YBa_2Cu_3O_7$ phase
- Ambient pressure, No requirement of high pressure apparatus.
- Scaling up is much easier.
- Complex shapes (other than cylindrical shape) are possible
- Final product has significantly reduced porosity

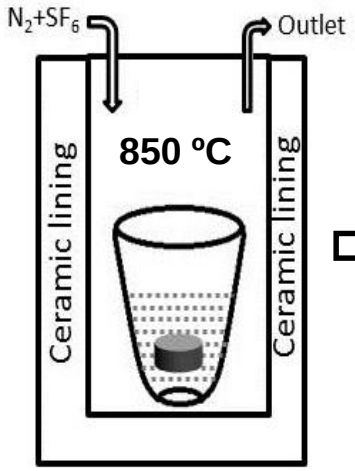


Y-211+ Ba-Cu-O →Y123



Infiltration and Growth Process

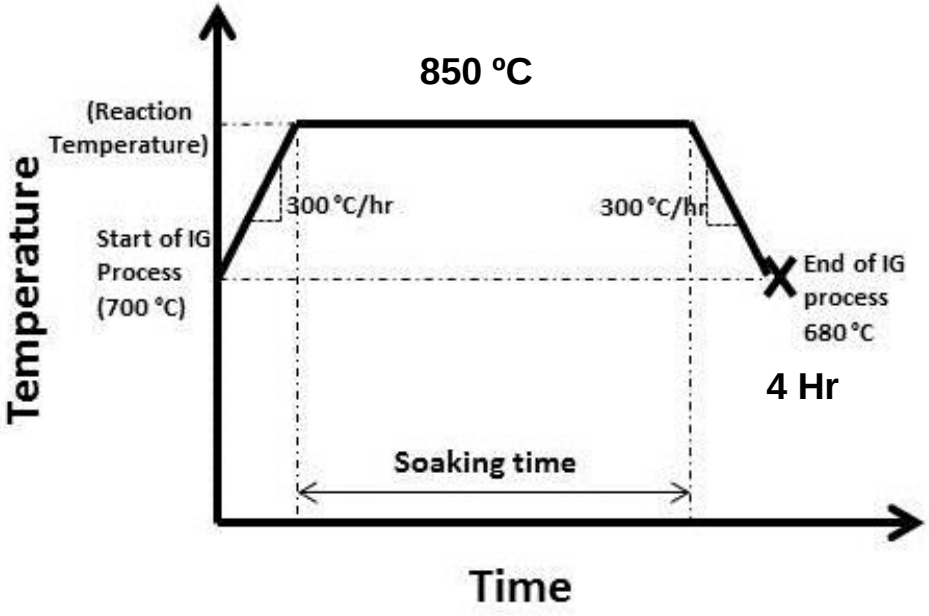




SF_6 helps form a continuous MgF_2 layer

Mg + 2B → MgB_2

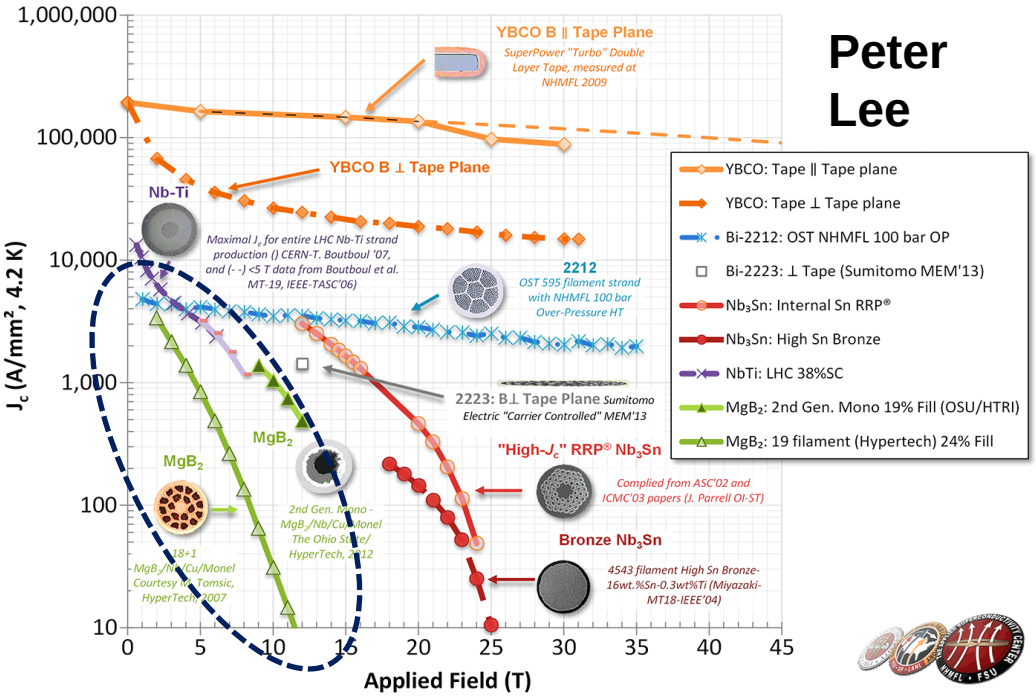
(density ≈ 2.45 g/cc)



*A. G. Bhagurkar et al SuST **28** 015012, 2015*

*A. G. Bhagurkar et al IEEE TAS **25** 6801504,2015*

Challenge



Peter Lee

http://fs.magnet.fsu.edu/~lee/plot/plotarchive.htm

High Anisotropy

↓

Rapid drop in J_c with external field!

In-field performance of bulk MgB_2 must be enhanced if LTS are to be replaced.

Solution?

- **Grain refinement → Pinning**
  (Increased Grain Boundary Density)
- **Irradiation → Pinning**
  (Vacancy, dislocations, stacking faults)

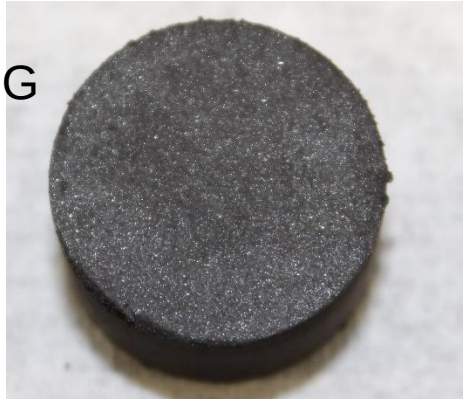
C-Doping → Impurity Scattering → H_{c2}

→ Reduced Anisotropy

→ Lattice strains → Pinning

SiC and B_4C

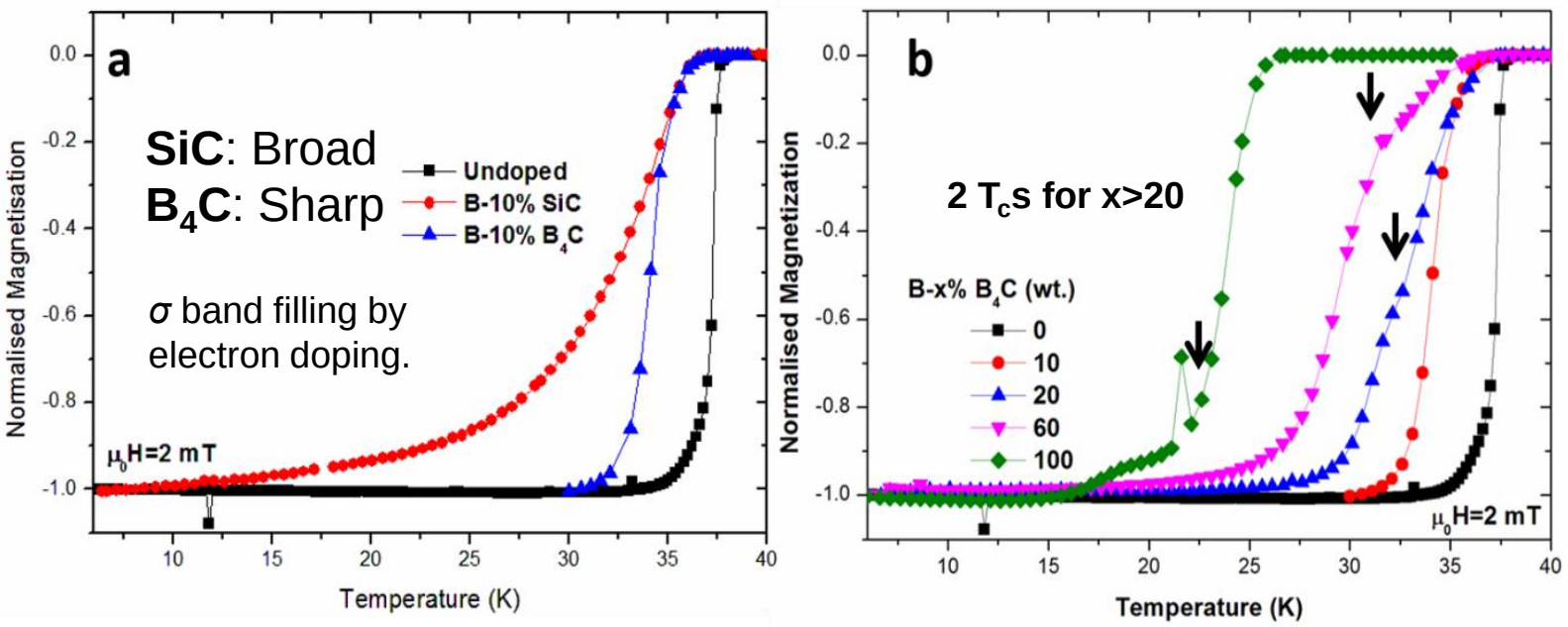
Subject to IG process



(100-*x*)%B + *x*% B_4C/SiC
x in weight proportion

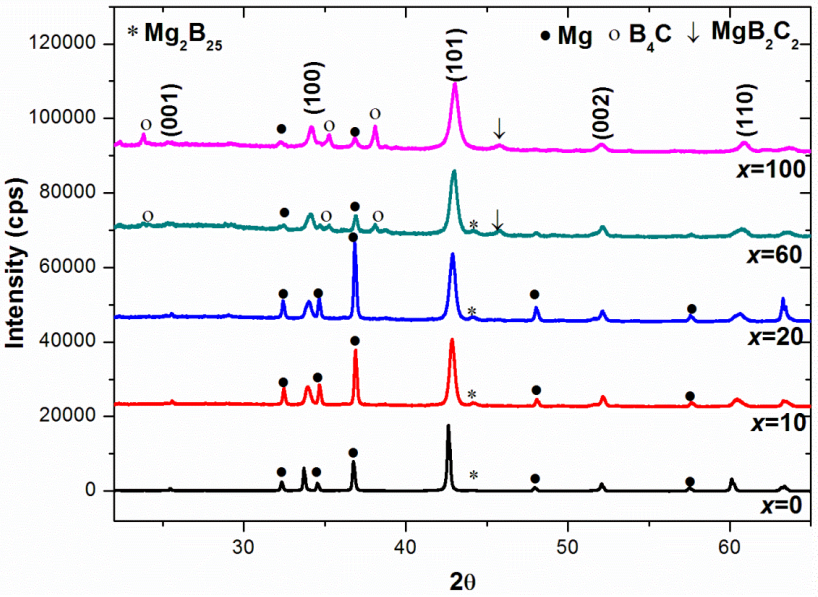
x_i: Actual doping in $Mg(B_{1-xi}C_{xi})_2$

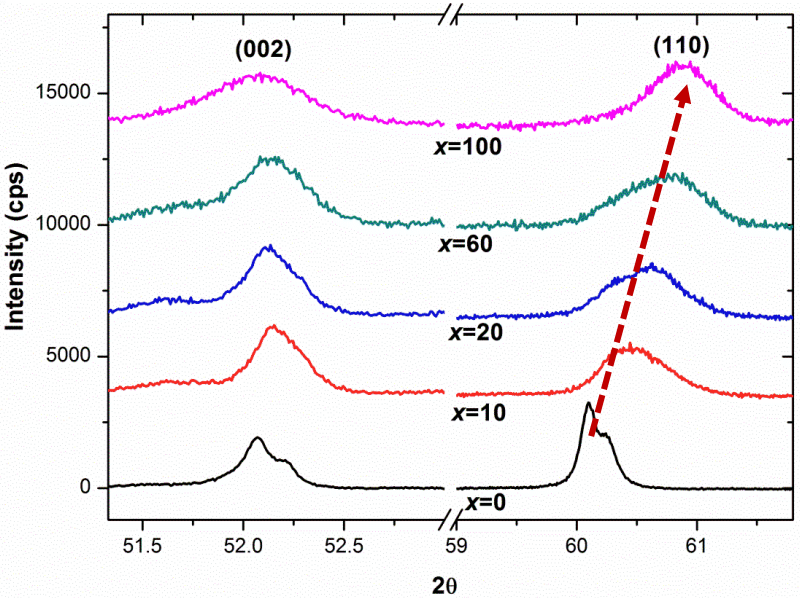
M-T



B_4C: Homogeneous distribution of C at the atomic scale

Phase Analysis

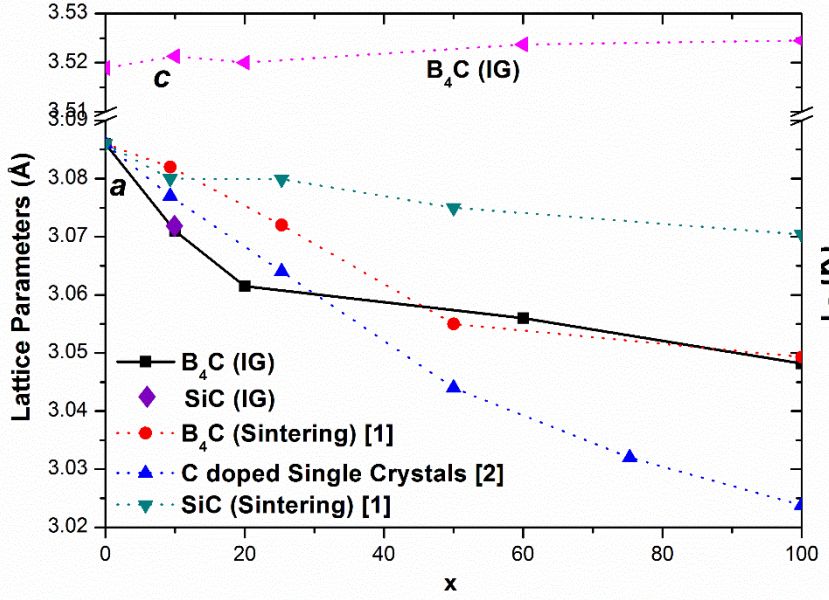


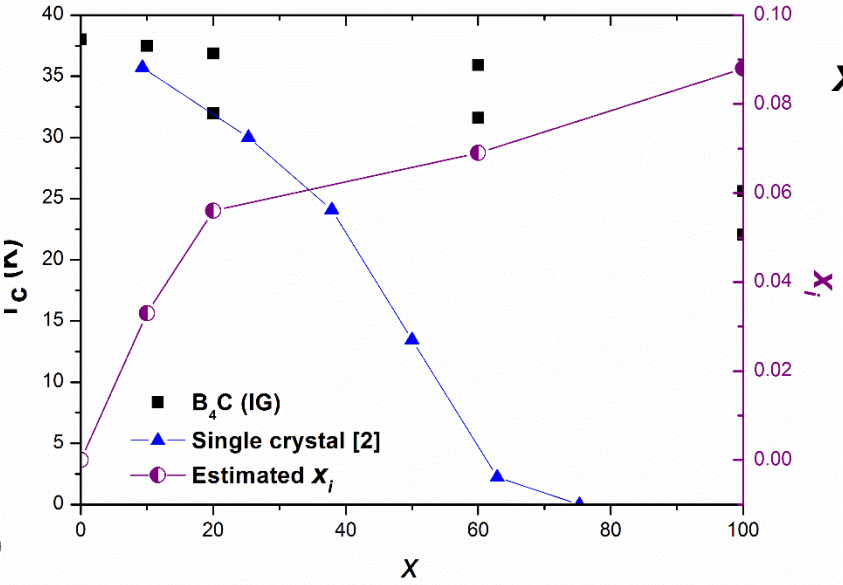


Maximum x_i=0.15

MgB_2C_2: C Precipitation

Strain: *a-b* plane only



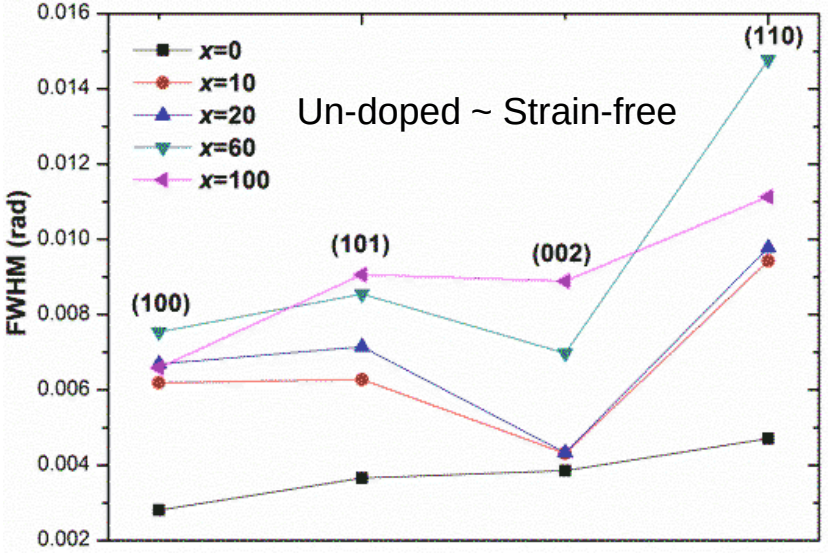


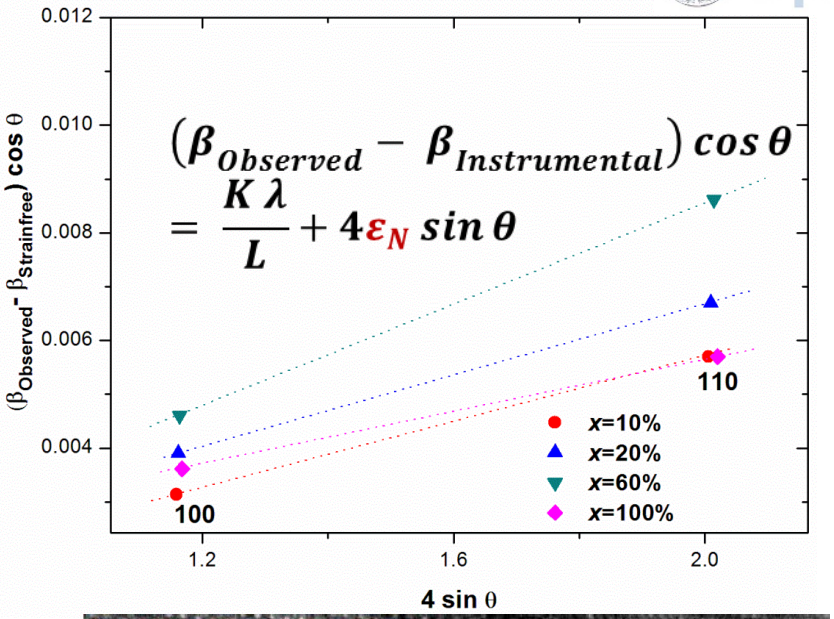
x_i=9%

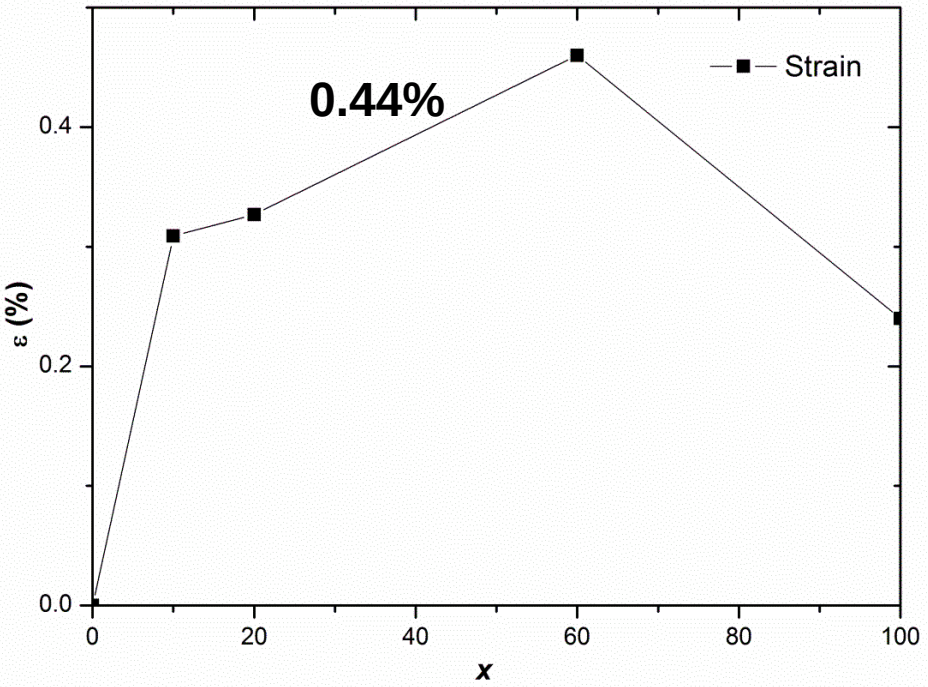
[1] Yamamoto *et al.Supercond. Sci. Technol.* **18** 1323 (2005).

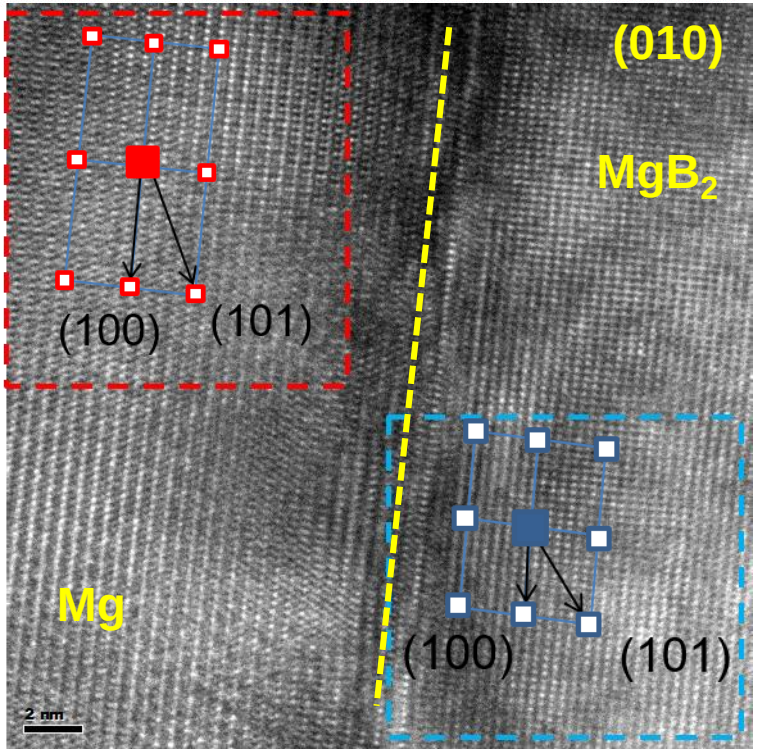
[2] Lee *et al*. *Physica* C **397** 7 (2003).

Strain Analysis: Williamson-Hall Method



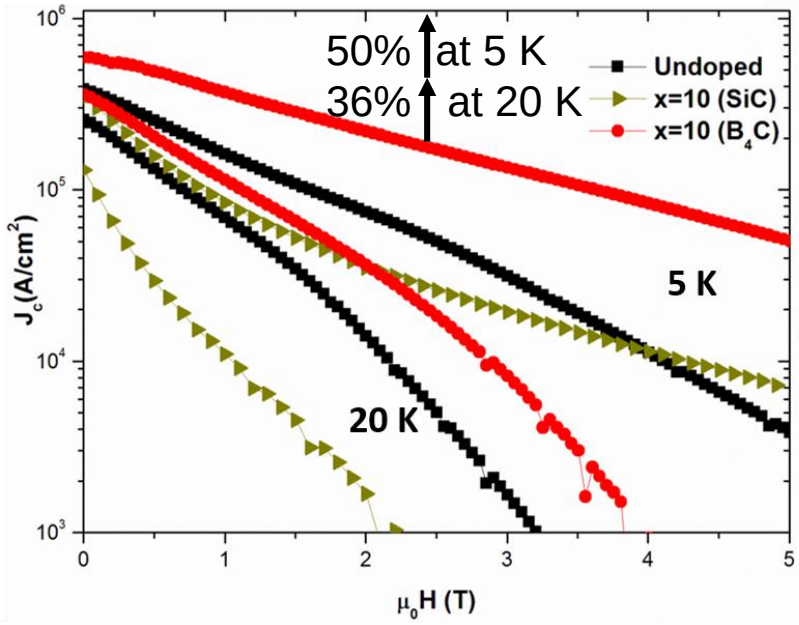


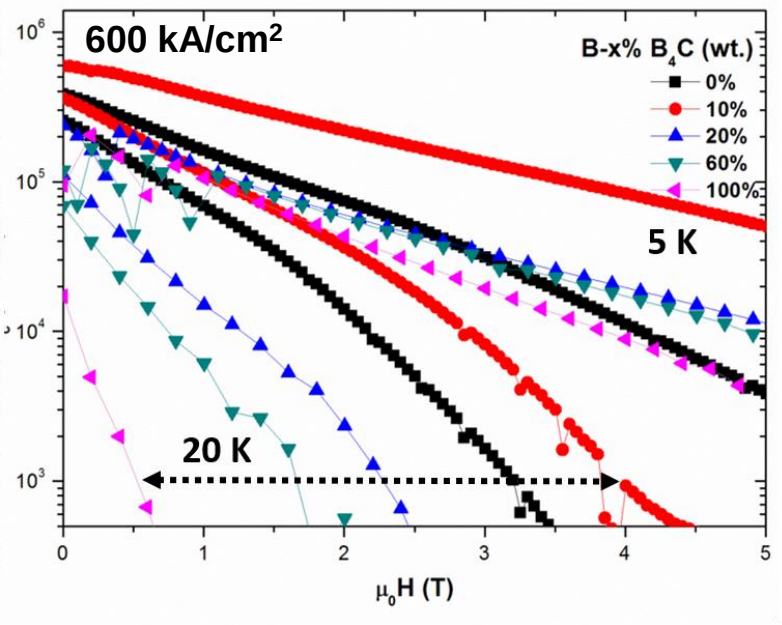




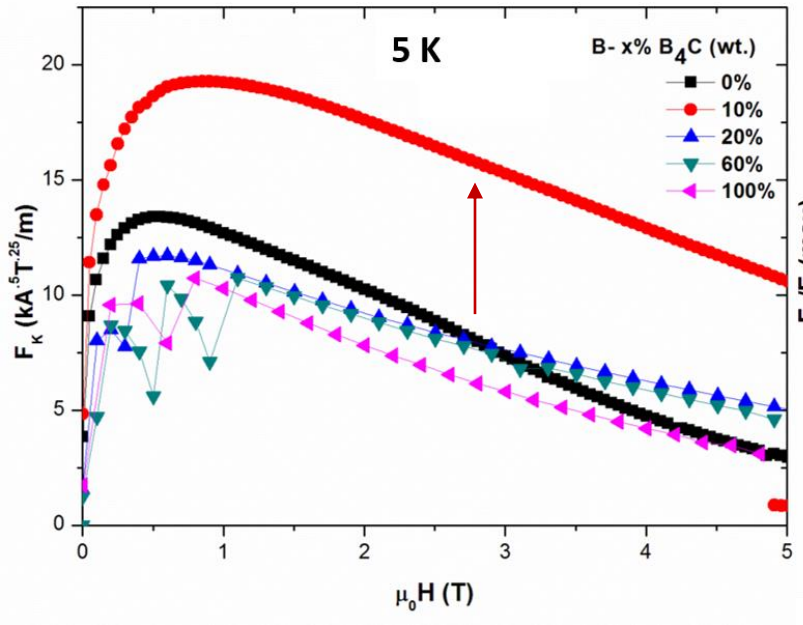
Williamson and Hall *Acta metallurg.* **1** 22(1953)

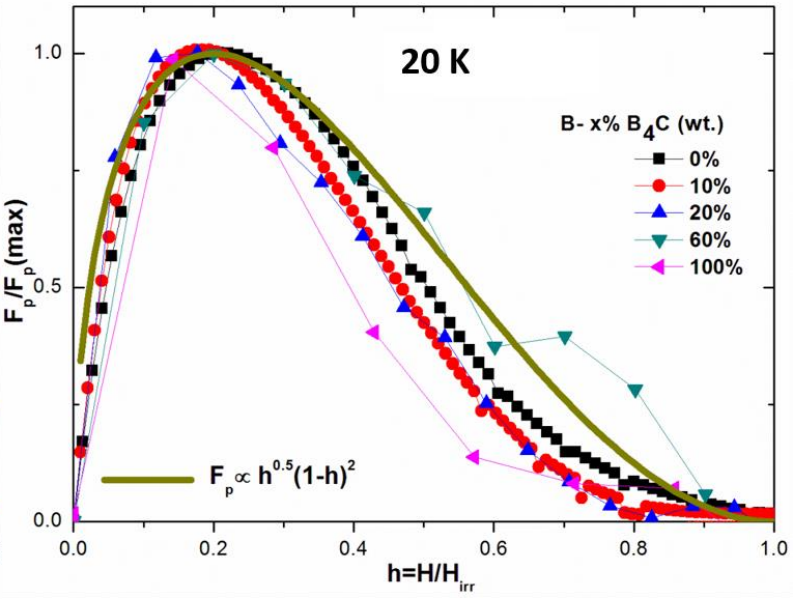
J_c and Pinning Force





Trade off between enhancement in J_c and reduction in T_c.



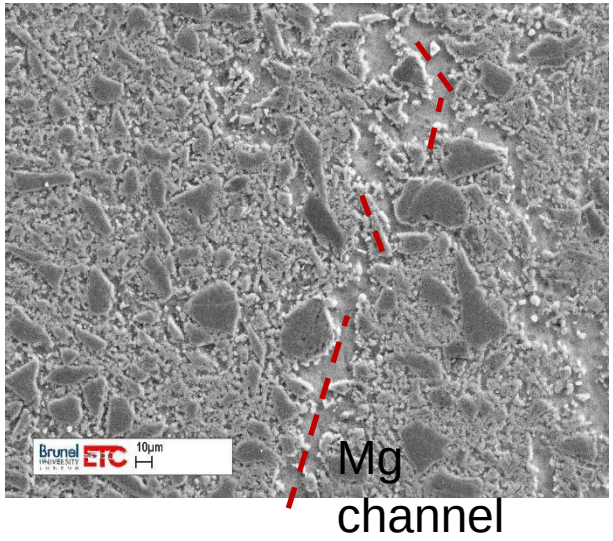


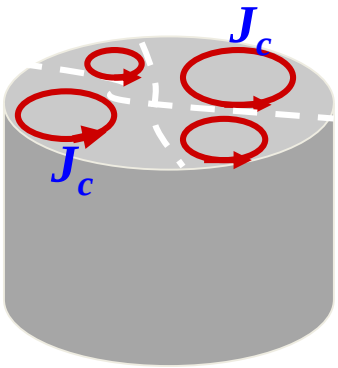
h: 0.2→ 0.15

Volume Pinning?

Gradient of F_k correlates with strain

Eliminating Mg channels

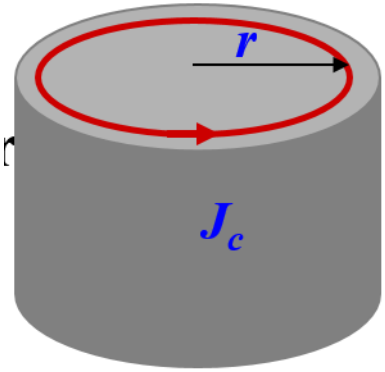


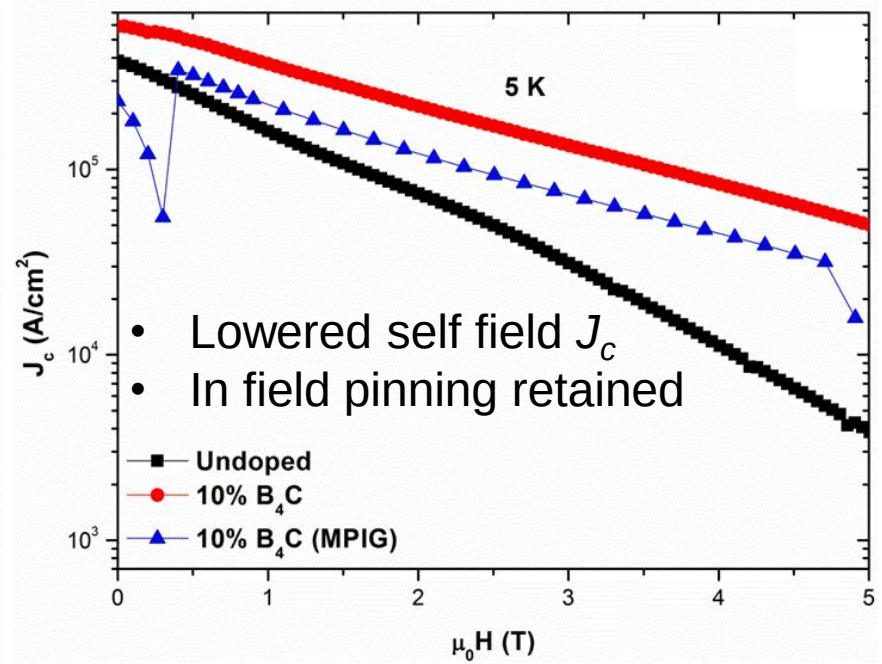


Presence of residual Mg, especially in the form of <u>continuous channels</u>, may have an adverse effect on bulk properties such as the trapped field, despite superior local J_c

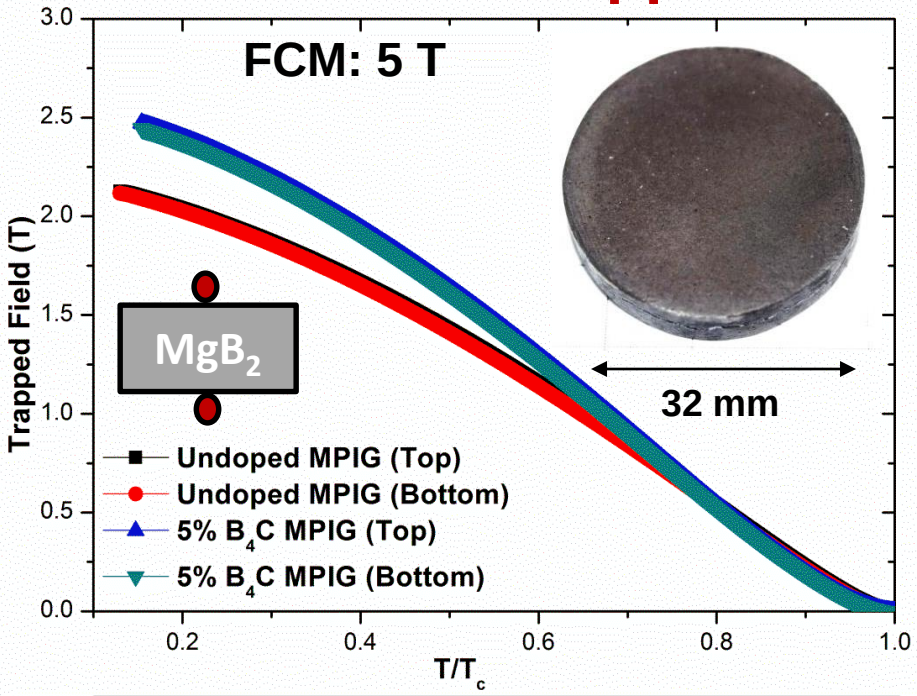
Modified Precursor IG Method

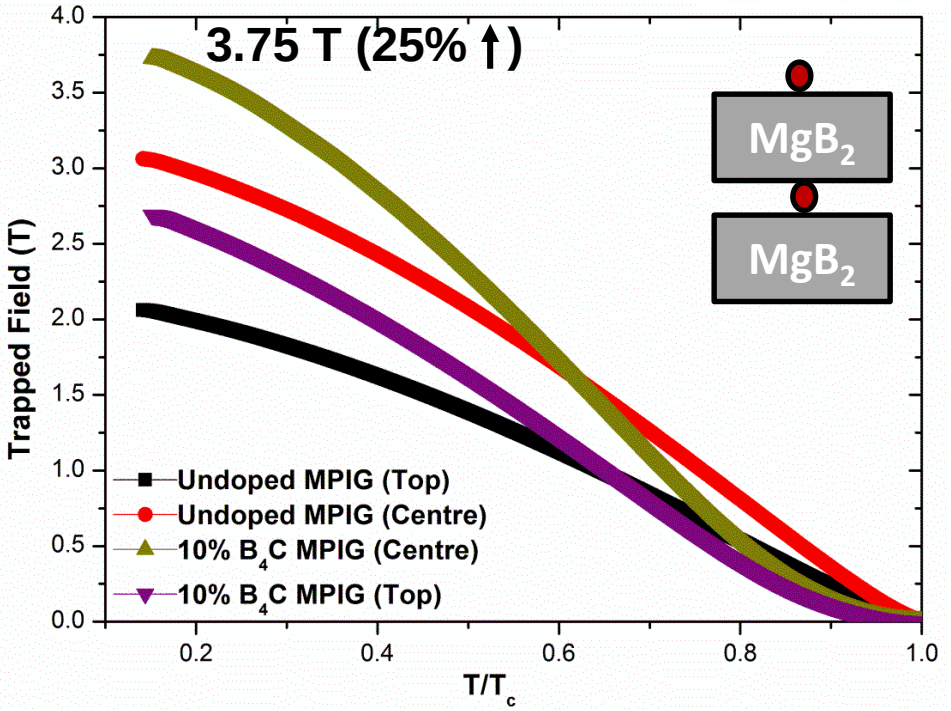
→Incorporated (10% mole) MgB_2

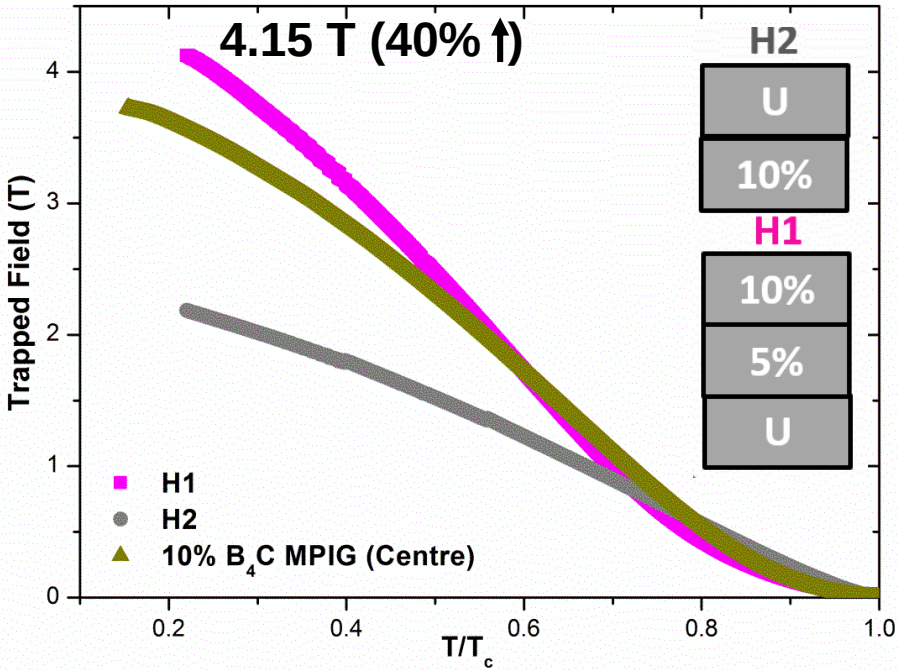




Trapped Field measurements



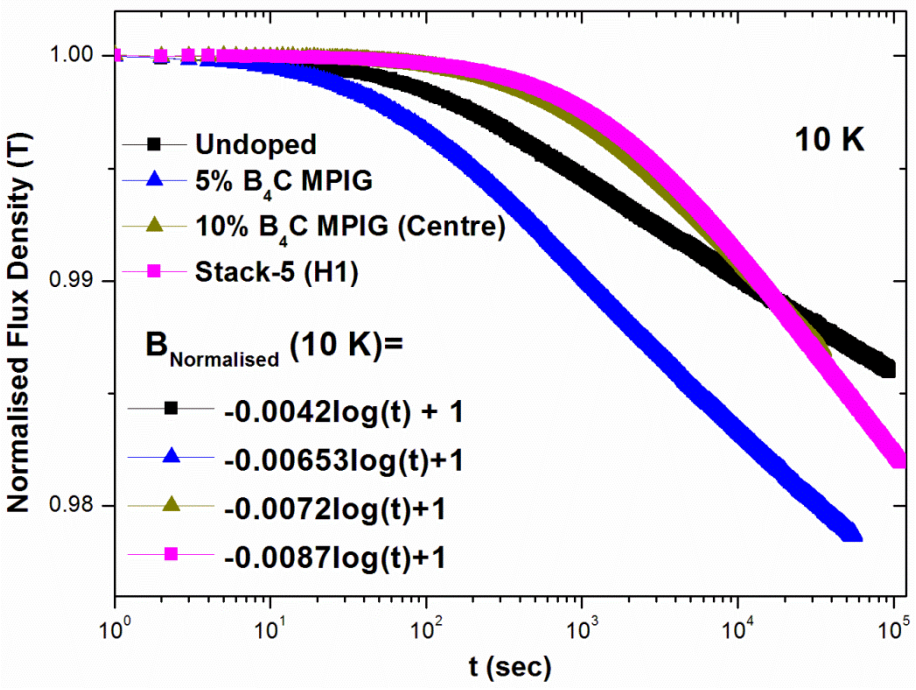


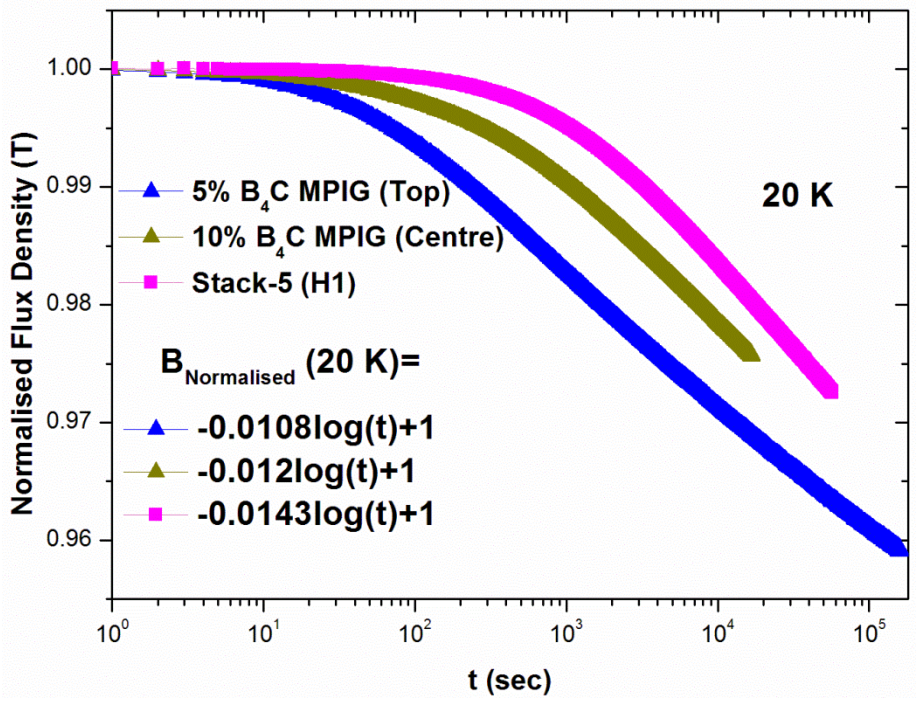


- **C doping→** Enhanced trapped field
- **Less than 1% difference** in trapped field recorded on top and bottom.

- **Trapped field of 4.15 T**, highest amongst samples under ambient pressure.
- Increase achieved by simple B_4C addition, without using expensive techniques.
- Flux distribution needs further attention

Field Decay





- **Logarithmic** decay with time
- Faster decay with C-doping
- $U = U_0\left(1 - \frac{T}{T_c}\right)^{\alpha_c}$ U: Height of potential well

Flux lines can overcome pinning barrier and migrate relatively easily

$$\nu = \nu_0 e^{\frac{-U_0}{k_B T}}$$

ν: Jump Frequency

flux jump frequency increases with temperature

Summary

- B_4C helped achieve a more **homogeneous** C distribution. Due to higher reactivity of B_4C with Mg and an atomically uniform distribution of C in the bulk microstructure.
- **Enhancement in J_c**, particularly at lower temperature and higher fields. Generation of lattice disorder in the MgB_2 phase accompanied by the effects of C-doping. Analysis of the pinning force also suggested the possibility of a contribution to enhanced J_c from volume pinning.
- A significant increase in trapped field was observed in C-doped MgB_2 bulk superconductors. The trapped field obtained (4.15 T) is the **highest reported to date** for MgB_2 bulk superconductors synthesized under **ambient pressure** conditions
- **Finer particle size of B_4C** is likely to yield more efficient and uniform C-doping, without the formation of MgB_2C_2 and leaving residual B_4C. This, together with nano-sized boron powder, would potentially yield an optimum combination of enhanced grain boundary pinning and increased H_{c2}.