2015
ICFA MINI-WORKSHOP
ON HIGH FIELD MAGNETS
FOR PP COLLIDERS

How can we control the formation of grain-boundaries (GBs) towards well connected, high field MgB_2?

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THE UNIVERSITY OF TOKYO

Outline

1. What can we expect for upcoming MgB_2 magnet ?

   Introduction to MgB_2

   Magnetic field produced by polycrystalline MgB_2 -
   - demonstration using SC bulk as prototype of coil -

2. Issues for high field magnet

3. Structural tuning of GBs (*ex situ* wire)

   Challenge for well-connected, mechanically tough GBs

4. Electromagnetic tuning of GBs (*in situ* bulk magnet)

   Improving trapped field by modification of GBs

5. Summary

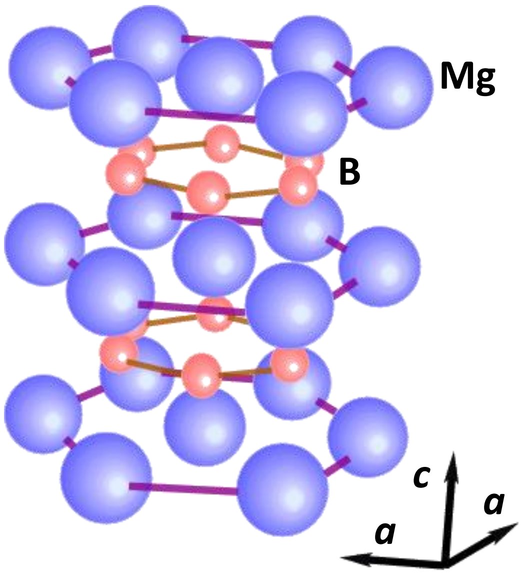
Introduction to MgB_2

MgB_2

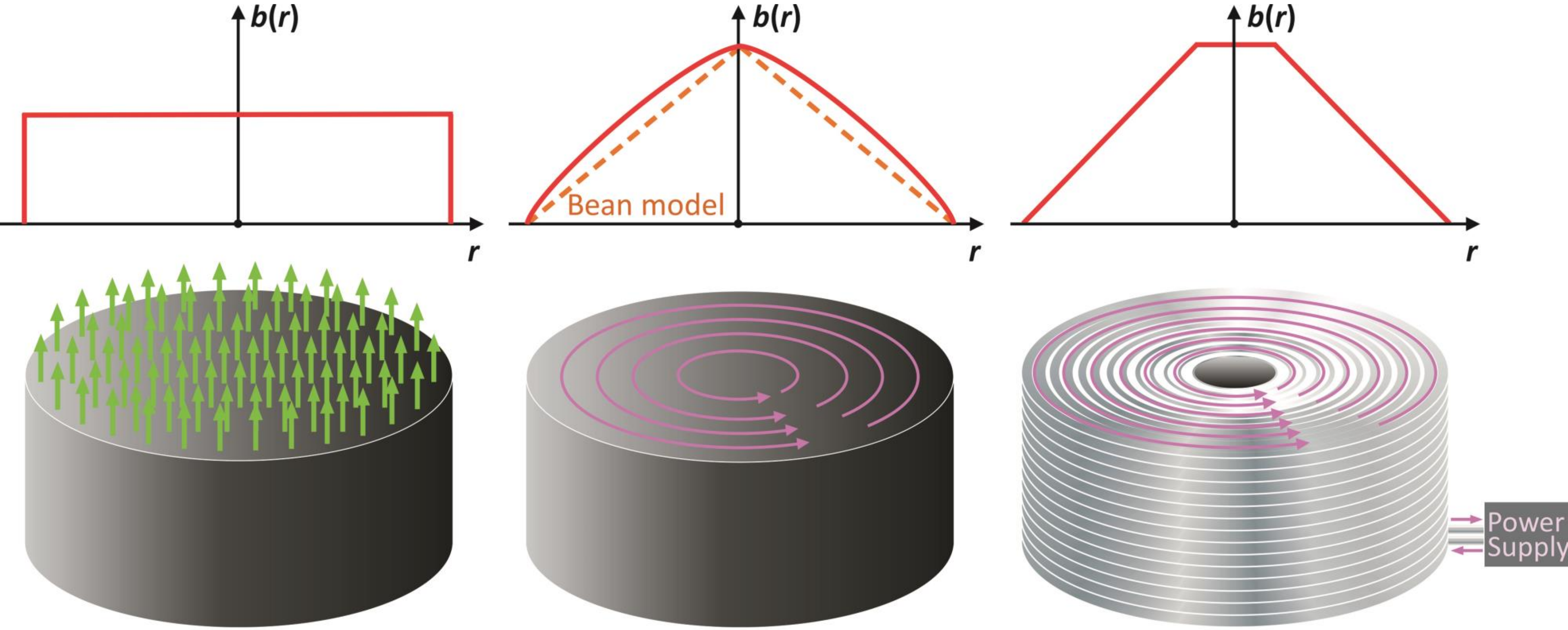
- metallic high-T_c superconductor (40 K)
- transparent GBs, high J_c current @~20 K in randomly oriented polycrystal

Good for applications

- easy wire fabrication
  >1 km multi-filamentary wires by PIT
- low cost for materials and processing
- liq.He-free operation by cryocooler



Bulk magnet as prototype of SC coil



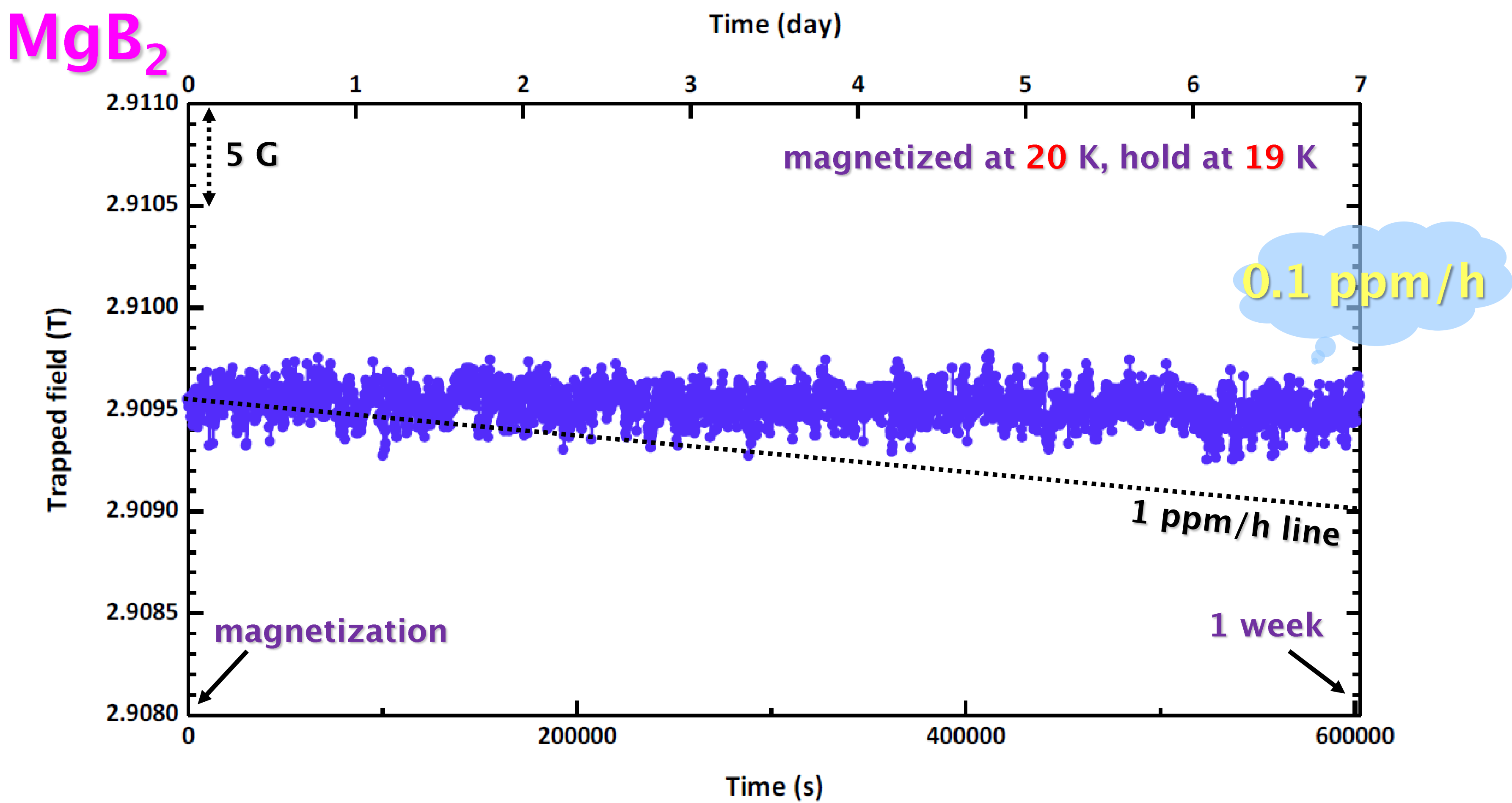
Permanent ferromagnet	SC bulk magnet	Electromagnet
Spin	Induced loop SC current	Supplied loop current
Nd-Fe-B (~1.6 T)	MgB_2 (3-5 T), YBCO (17 T)	Cu (~2 T), HTS (>30 T)

Local spin

Macroscopic SC current loop

(field produced by the same mechanism)

Temporal uniformity of field



Negligible decay of field (2.9 T at 19 K) over the first week!

Macroscopic SC current loop in polycrystalline MgB_2 can be very stable .

AY *et al., Appl. Phys. Lett.* 105, 032601 (2014).

MgB_2 : applicable for high field magnet?

MgB_2 could provide **high quality field** (spatial & temporal uniformity)

$H_{c2}^{//ab}$(0 K):	<u>wires ~30 T</u>	*vs*	<u>films >50 T</u>
			V. Braccini, A. Gurevich *et al.*, 2003
J_c(20 K):	<u>wires 10^5-10^6 A/cm^2</u>	*vs*	<u>films 10^7-10^8 A/cm^2</u>
			C. G. Zhuang, X. X. Xi *et al.*, M. Naito *et al.* 2008-

Very nice potential of MgB_2, demonstrated by thin film study, has not yet realized in polycrystalline wire forms, issues for high field magnets:

➔ **Higher H_{c2}**

➔ **Higher in-field J_c**

→ Connectivity

→ Flux pinning

→ Multi-band

➔ **Mechanical strength?**

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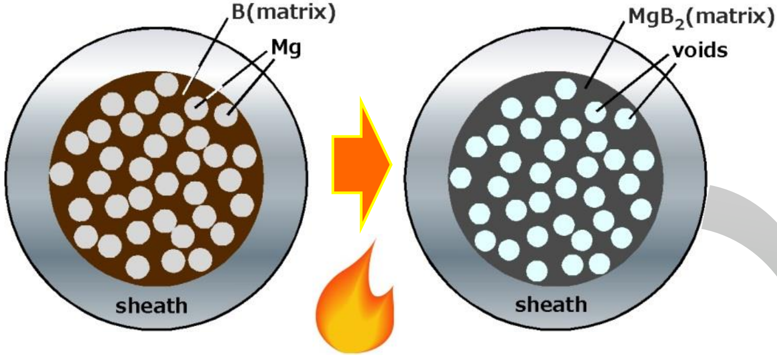
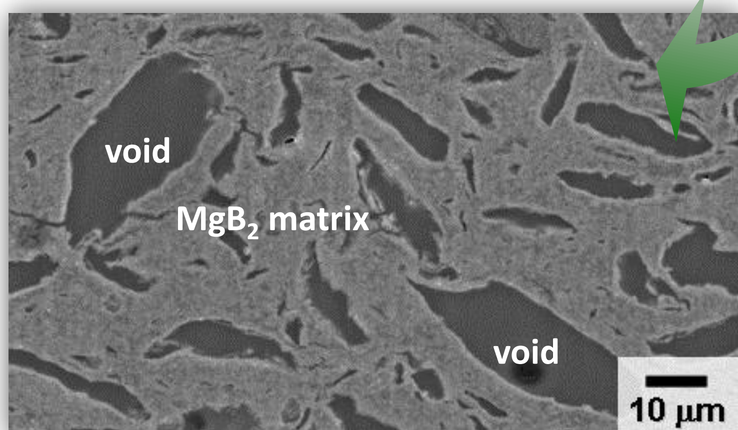
Standard MgB_2 wire fabrication techniques

in situ PIT



Mg + 2 B ⇒ MgB_2

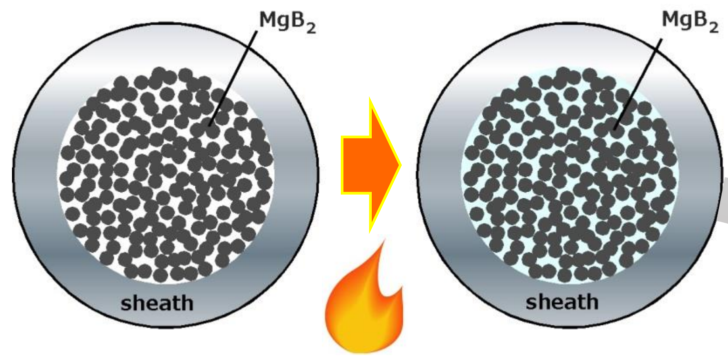


× **porous** (~50%)

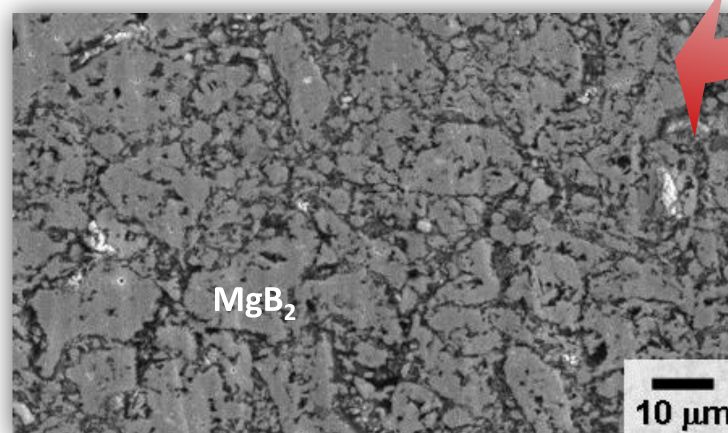
◎ **strong intergrain coupling**

○ **higher K, J_c**

ex situ PIT



MgB_2 ⇒ MgB_2

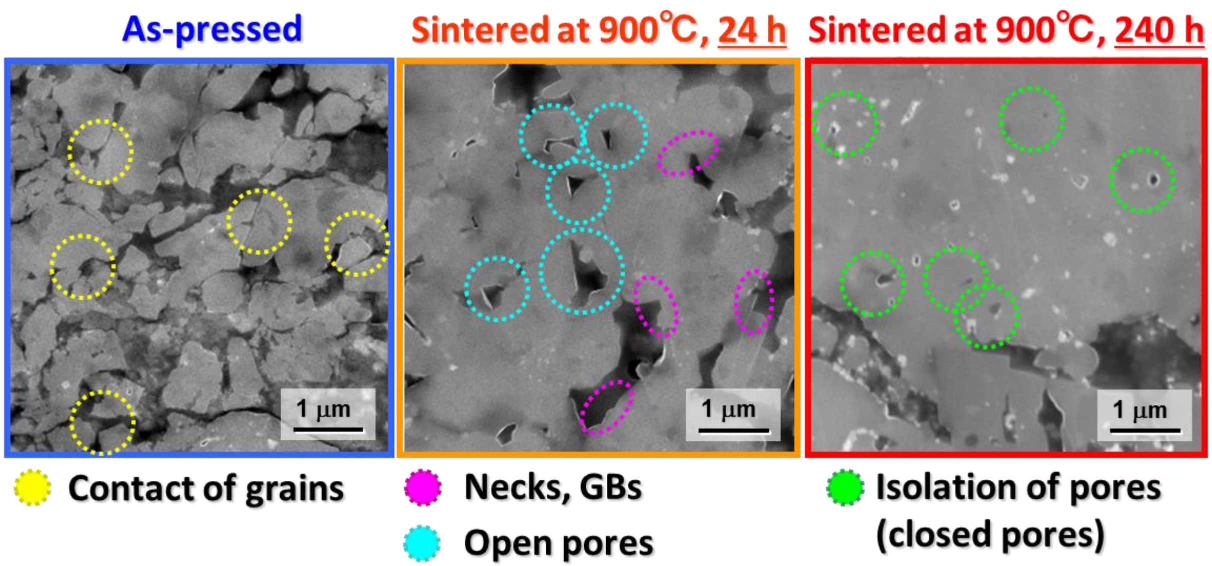


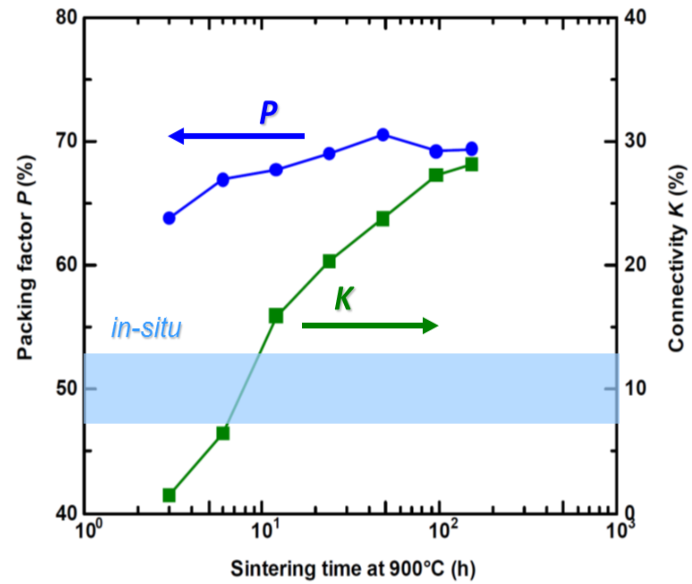
◎ **dense** (~75%), **uniform**

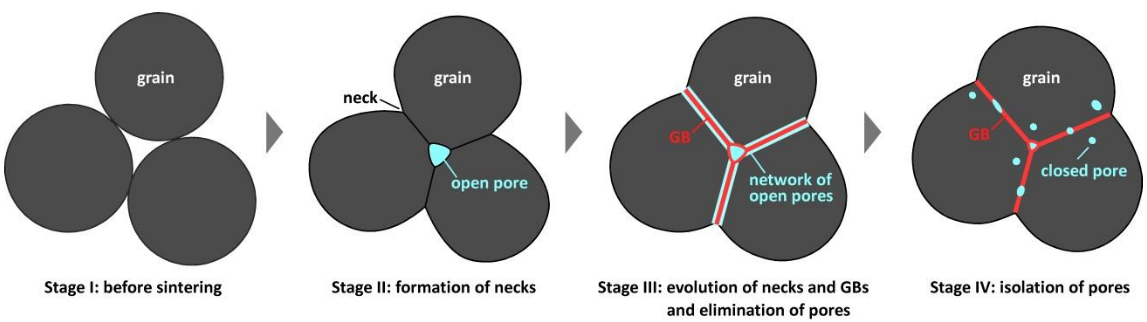
× **weak intergrain coupling**

Structural control of GBs

- ○ Pressure-less, low-temperature self-sintering of *ex situ* MgB_2
- ○ Connectivity largely increased x3







A. Yamamoto *et al., Jpn. J. Appl. Phys.* **51**, 010105 1-6 (2012); H. Tanaka *et al., SuST* **25**, 115022 1-7 (2012);
S. Mizutani *et al., Supercond. Sci. Technol.* **27**, 044012 1-7 (2014); *SuST* **27**, 114001 1-8 (2014).

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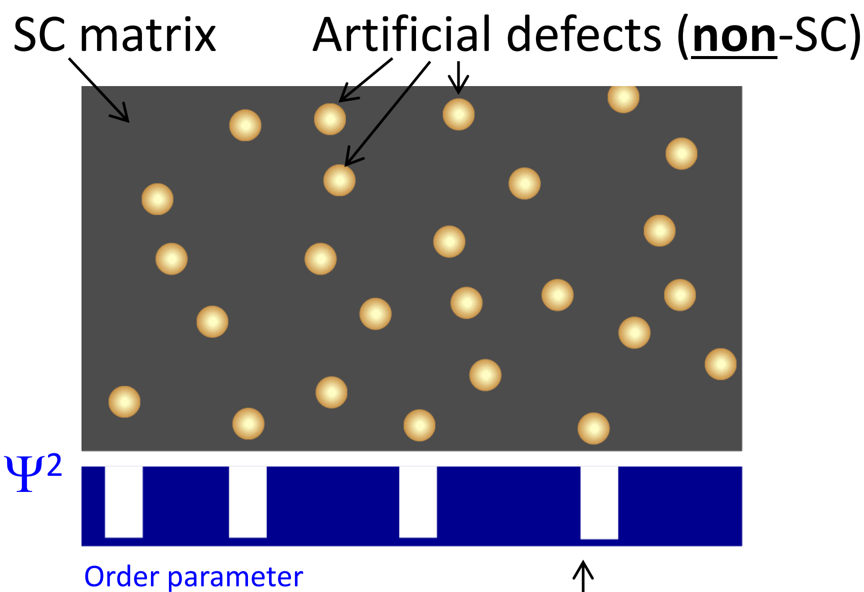
Electromagnetic modification of GBs for higher fields

Single-grain bulk

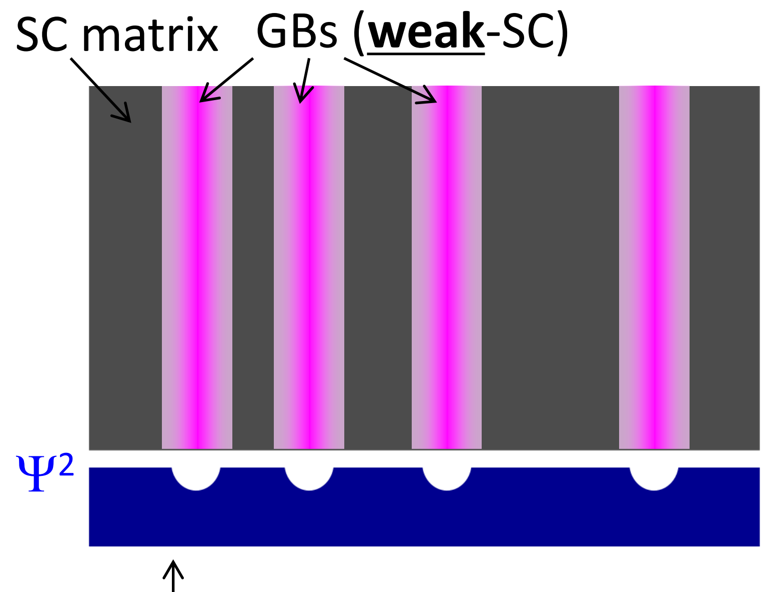
Introducing artificial defects



Flux pinning at non-SC precipitates by saving condensation energy

Polycrystalline bulk

Flux pinning at natural defects



Flux pinning at natural GBs by modulation of coherence length ξ due to electron scattering *

Our approach: Increase GB area (grain refinement) + Enhance e scattering near GBs

(*) T. Matsushita *et al., Supercond. Sci. Technol.* 21, 015008 (2008); A. Yamamoto *et al., Appl. Phys. Lett.* 88, 212505 (2005).
G. Zerweck, *Appl. Phys. Lett.* 42, 1 (1981); W. E. Yetter *et al., Philos. Mag. B* 46, 523 (1982).

Experimental procedure

Mg, B powder (*in situ*, Mg : B = 1 : 2)

↓

Planetary ball milling
(0-600rpm)

↓

Interface purification process

↓

Uniaxial pressing to form
disk shape (30 mmϕ, 10mm^{t})

↓

Heating 850℃, 3 h (pressureless, Ar)

↓

MgB_2 bulk

↓

Cutting & Evaluation
SEM, XRD, SQUID, PPMS

MgB_2 bulk →

Magnetization by field-cooling (FC)

↓

Trapped field measurements

Milling energy

$$E_t/m = c\beta(\omega_p r_p)^3 t/r_v$$

- E_t/m : 原料粉末単位質量あたりに加えられるエネルギー
- c : 定数
- β : ボールと原料粉末の質量比
- $\omega_p r_p$: ボールミルの公転角速度
- t : ボールミル時間
- r_v: ボールミル容器の半径

W. Häßler *et al.*,
Supercond. Sci. Technol. **26** (2013) 025005.

Magnetization and trapped field measurement

MgB_2 bulk

↓

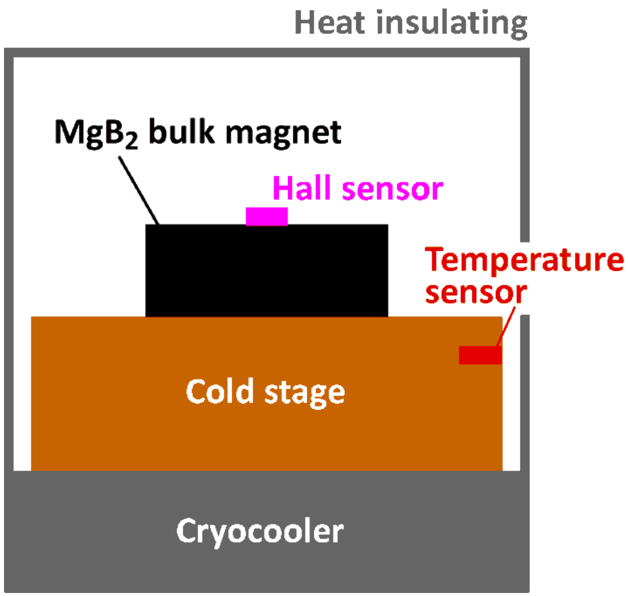
Field-cooling (FC)
to 5–20 K by a cryocooler under 6 T

↓

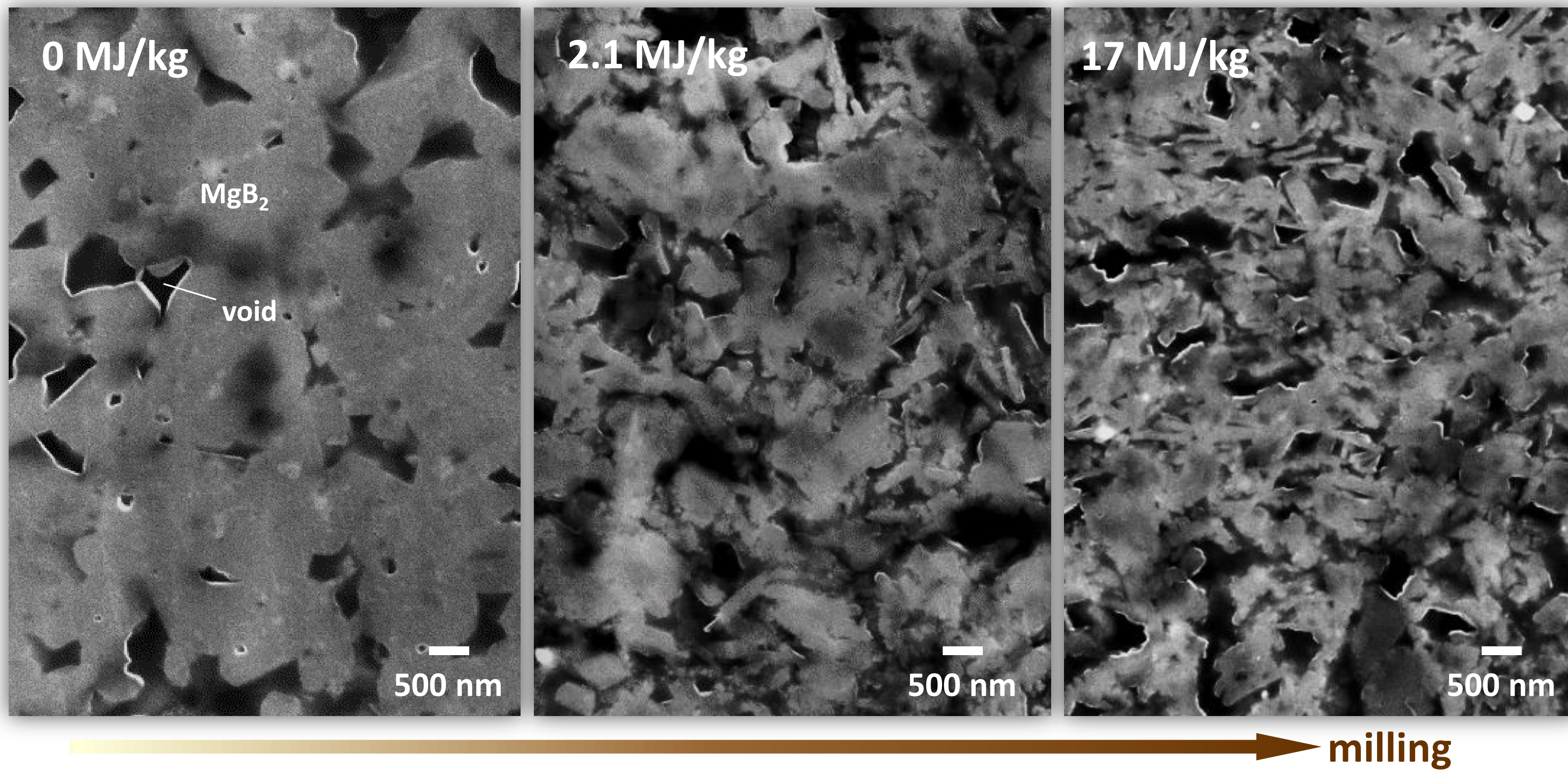
Magnetizing
by a superconducting magnet (6→0 T)

↓

Trapped field measurement
by a hall sensor at center of surface
from 5 to 40 K



Influence of milling on grain size & microstructure

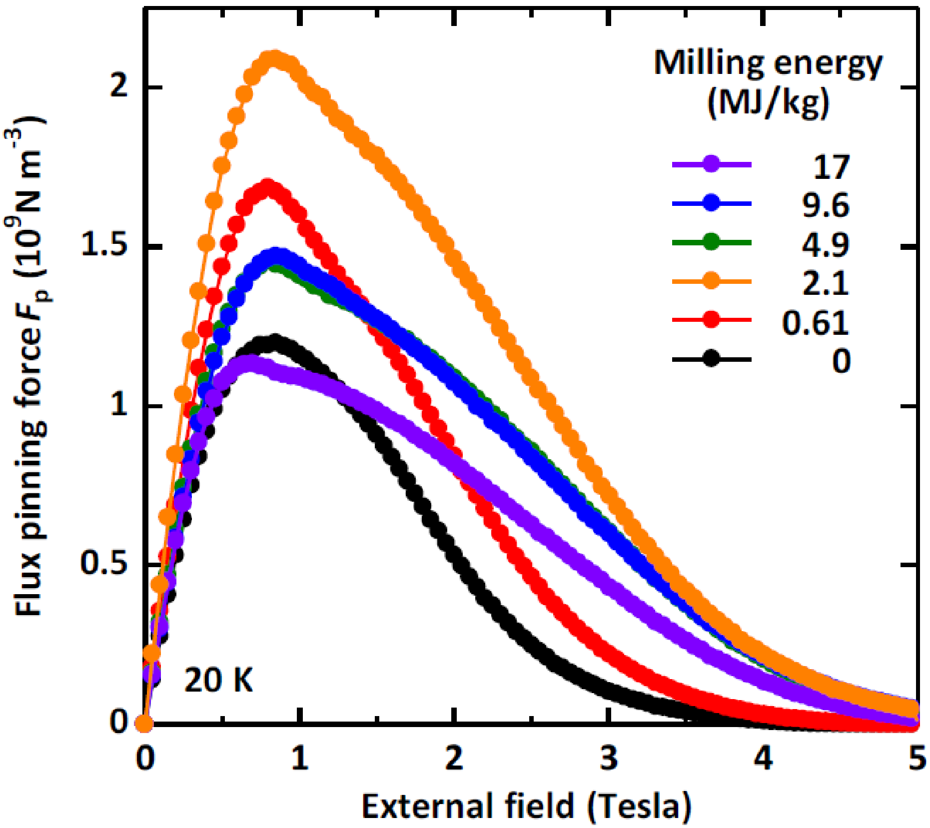


D_G ~1400 nm | ~400 nm | ~300 nm

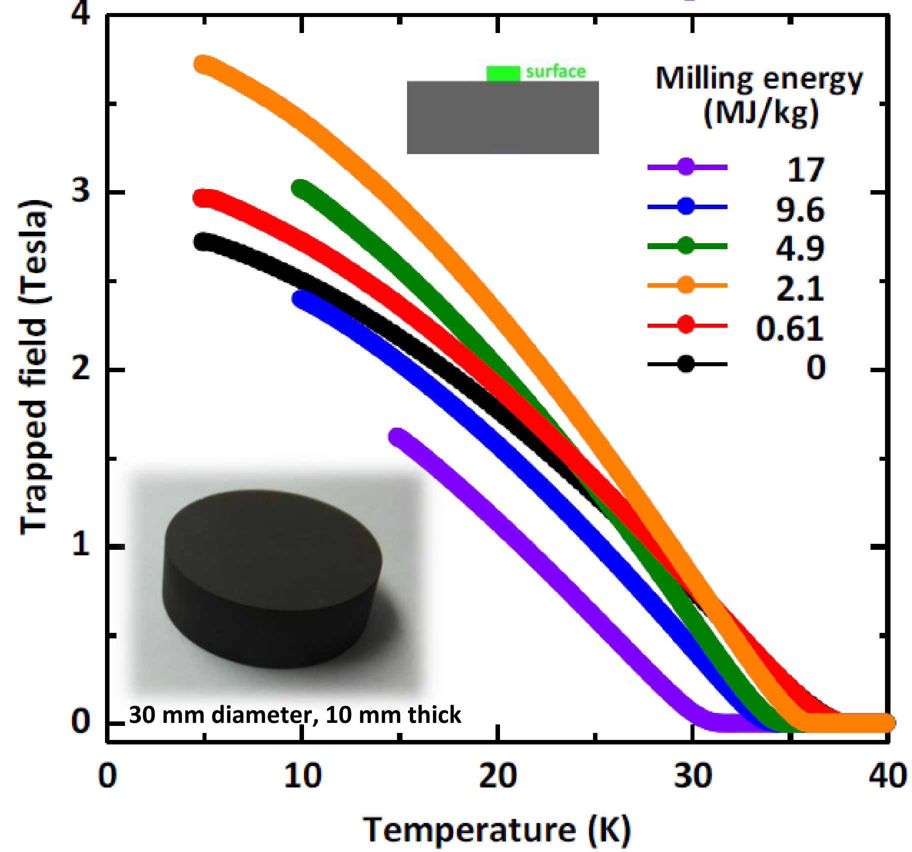
S. Sugino *et al.*, *Supercond. Sci. Technol.* **28** (2015) 055016.

Flux pinning strength & trapped field

Macroscopic pinning strength vs. external field



Trapped field vs. temperature for MgB_2 bulk magnets



Flux pinning enhancement: x2 in low field, >x10 under high field

30% increase in trapped field (3.72 Tesla at 5 K)

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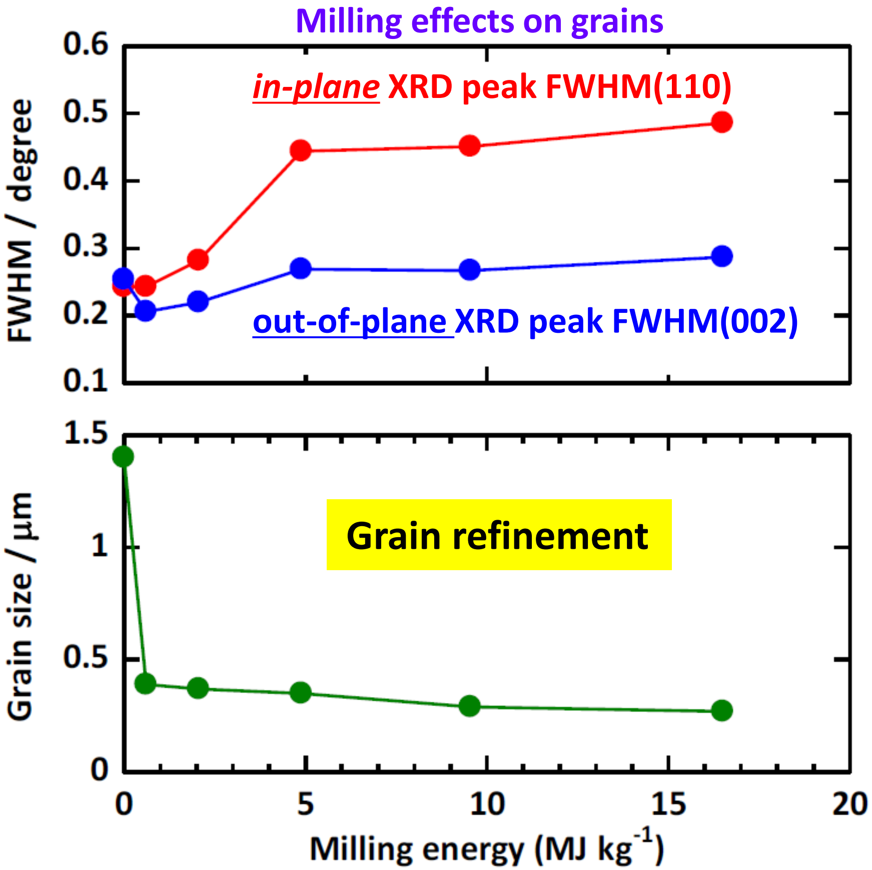
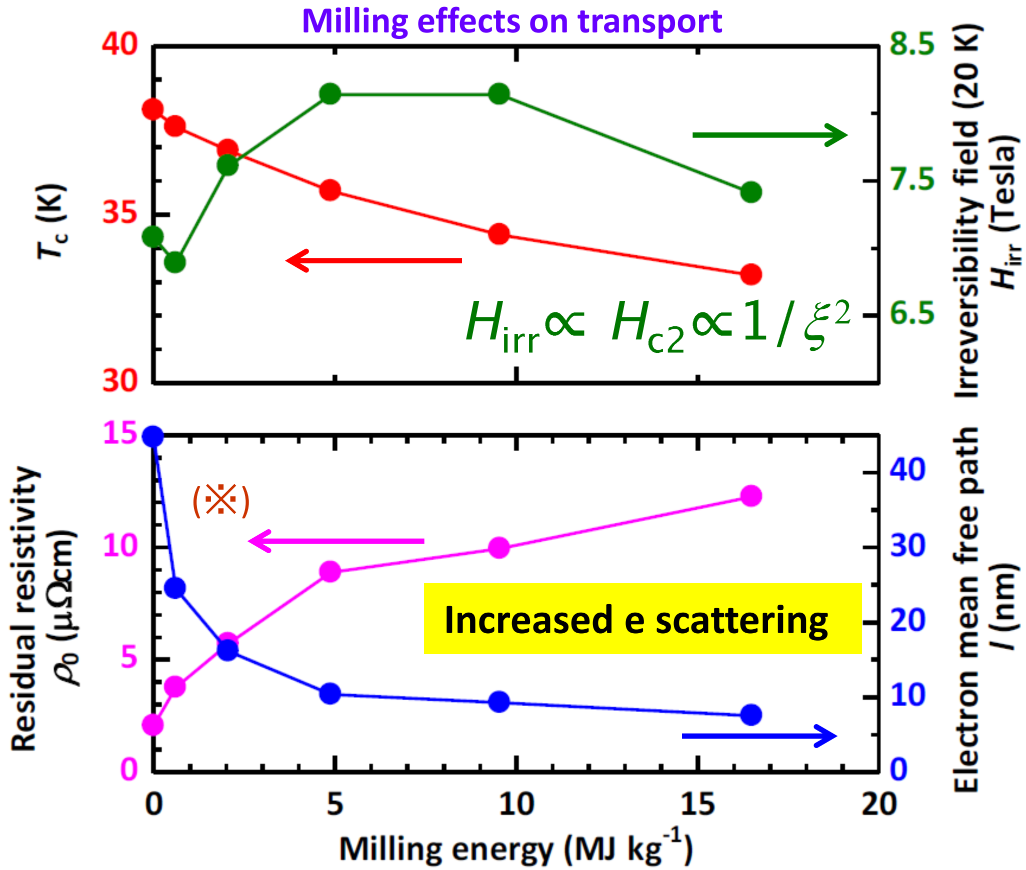
S. Sugino *et al.*, *Supercond. Sci. Technol.* **28** (2015) 055016.

Discussion: grain size, disorder & scattering





Density of pinning centers $N_p \propto$ (grain size)$^{-1}$

Elementary pinning strength $f_p \propto \Delta\xi_{\text{near GB}}$

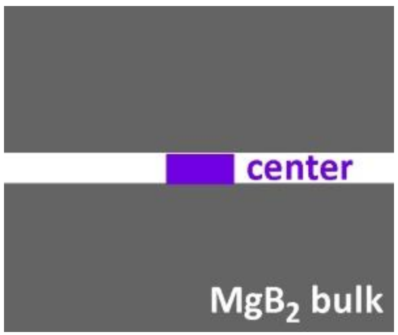
Macroscopic pinning force $F_p^{global} \propto N_p \times f_p$

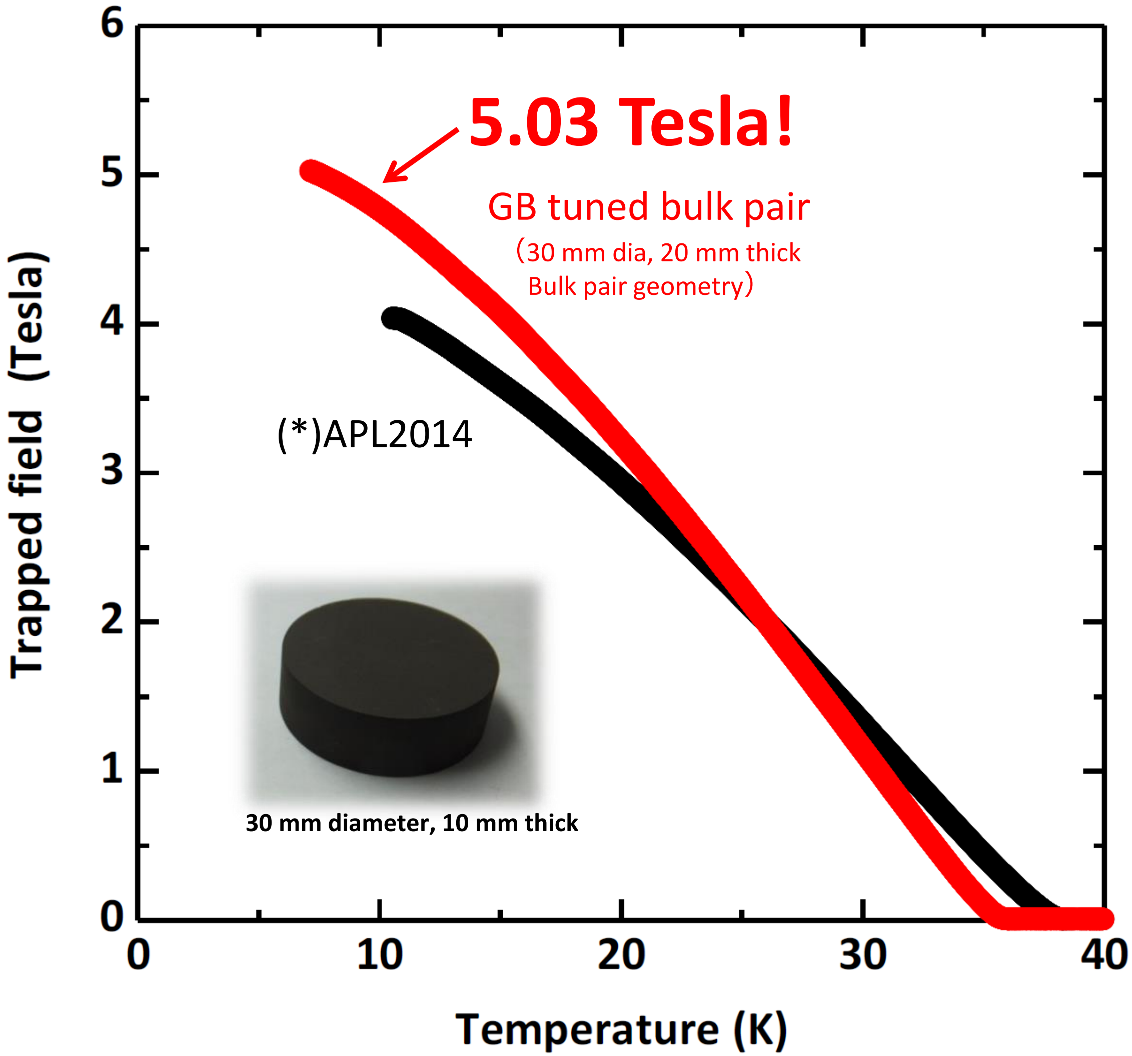
⇒ Quantitative and qualitative increase of GB pinning

(※) M. Kodama *et al., Supercond. Sci. Technol.* 27, 055003 (2014); T. Matsushita *et al., SuST* 21, 015008 (2008).

S. Sugino *et al., Supercond. Sci. Technol.* **28** (2015) 055016.

Trapped field of bulk pair MgB_2





5 Tesla at 7 K. The highest field among pressureless bulk MgB_2

(*) AY *et al., Appl. Phys. Lett.* 105, 032601 (2014).

Summary

Polycrystalline MgB_2 could produce high quality field with…

- ✔ 5 Tesla
- ✔ uniform field distribution
- ✔ excellent magnet stability up to ~20 K

owing to natural/nano-scale flux pinning centers (GBs).

More works needed:

- ✔ processing needs to be improved for dense, better Jc(B).

Thank you for your attentions!

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