Transport properties of IMD-processed 100 m class 6-filament MgB_2 wire and solenoid coil

Dongliang Wang, Yanwei Ma, Xianping Zhang, Da Xu, Chao Yao

Institute of Electrical Engineering, Chinese Academy of Sciences

Outline

1. Introduction of internal Mg diffusion (IMD) processed MgB_2 wires
2. C-doped IMD-processed wires with crystalline boron powders
   - Purity of crystalline boron powders
   - Wire diameter
3. 100 m multifilament IMD-processed MgB_2 wires
   - Filament configuration
   - Wire diameter
   - *n* values
   - Uniformity of transport properties
4. IMD-processed MgB_2 solenoid coils
   - Specifications of solenoid coils
   - Superconducting properties
5. Summary

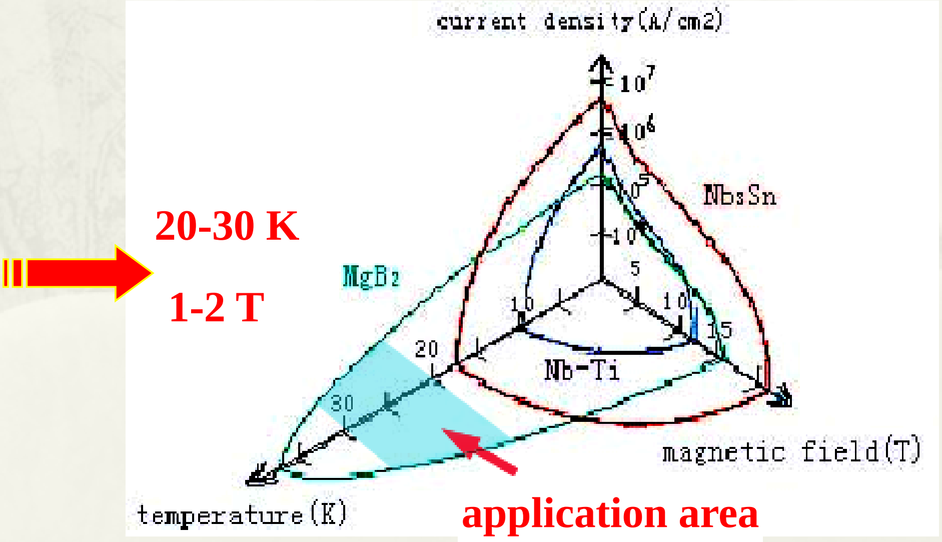
Superconductor-MgB_2

Superconducting Specifications of Practical superconductors

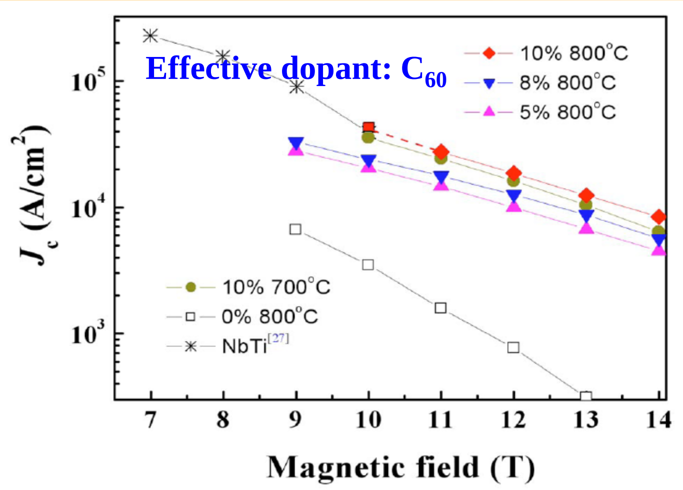
Material	T_c (K)	Anisotropy	B_{c2} at 4.2 K (T)	Coherence length ξ (0) (nm)	Penetration depth λ (0) (nm)
NbTi	9	Negligible	11-12	4-5	240
Nb_3Sn	18	Negligible	25-29	3	65
MgB_2	39	1.5-5	>30	10	50-100
Bi2223	110	50-200	>100	1.5	150
YBCO	93	5-7	>100	1.5	150
IBS-122	38	1-2	>100 (0K)	3	200

Advantages of MgB_2

- Highest T_c(~40K) among metallic superconductors
- No grain orientation required
  (Easy to fabricate long tape or wire)
- Low materials cost
- Good mechanical properties
- Light weight material



Transport properties of PIT wires or tapes (1G)



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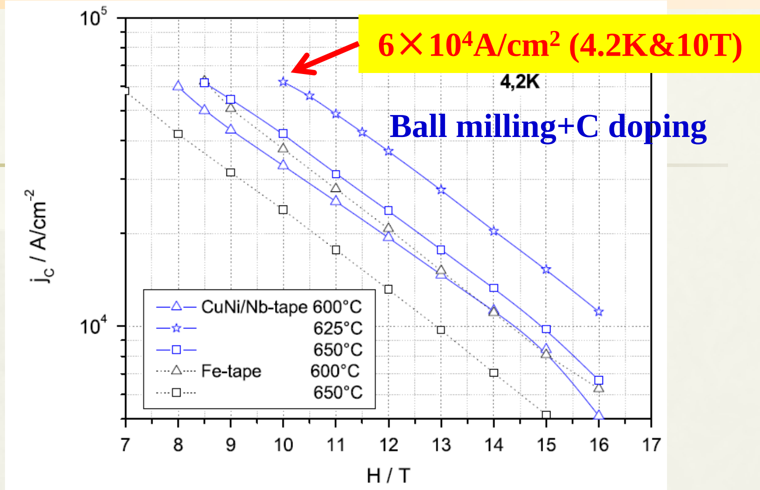

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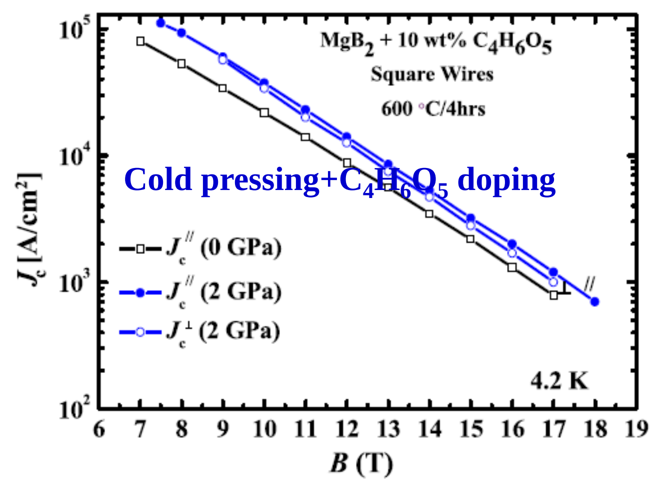

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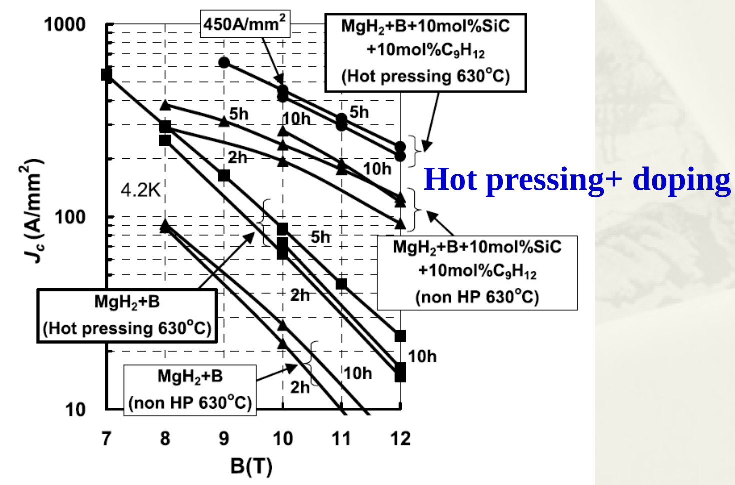

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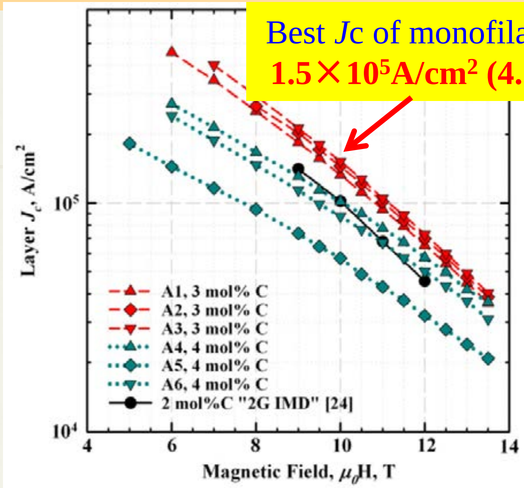
Grain connectivity problem?

*J*c properties of IMD (or AIMI) wires (2G)



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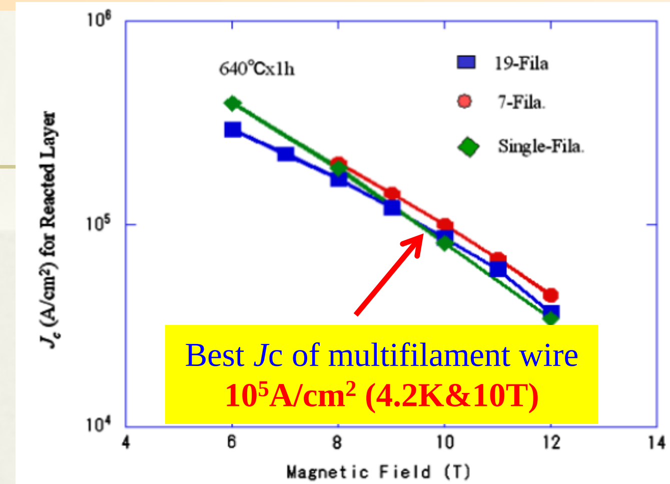

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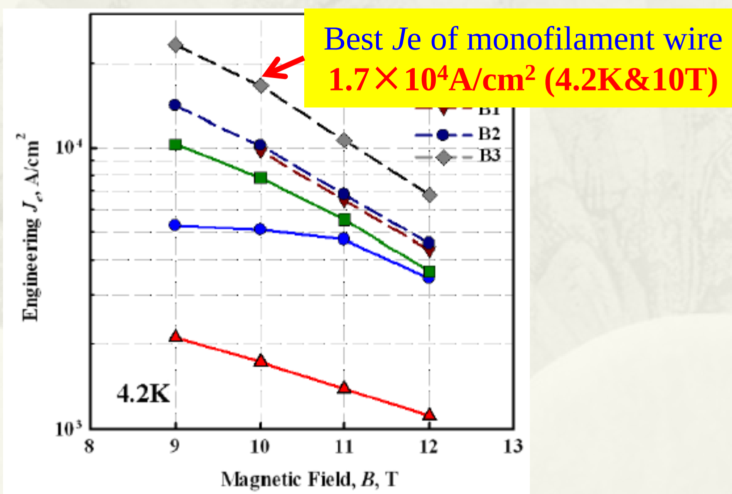

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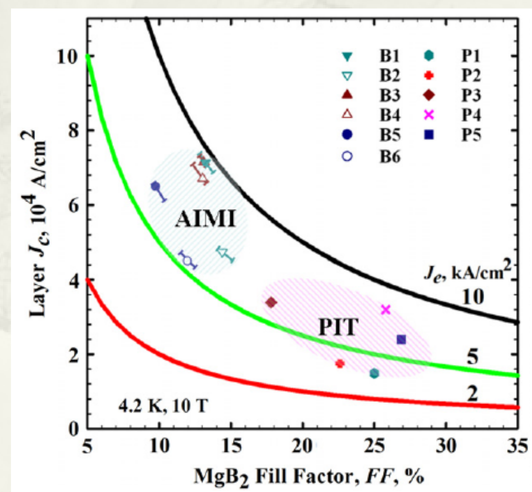

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Good grain connectivity!

IMD-processed wires with crystalline B

Motivation

The high J_c has been developed using amorphous nano B powders by *NIMS* and *OSU-HTR*.

Amorphous nano B： **expensive and hard to get**!

What about the **cheap crystalline** boron powders: 96% and 99.999% (5NB)?

Table 1. The specifications of all MgB_2 samples.

No.	Name	Boron	Process	Doped C (at.%)	Size (mm)	Reaction temperature (°C)	Reaction time (h)	I_c at 4.2 K & 10 T (A)
1	P1	96B	PIT	8	0.55 * 3.8	800	1	4.4
2	I1	96B	IMD	8	1.75	650	5	31
3	I2	96B	IMD	8	1.75	700	1	28
4	I3	96B	IMD	8	1.75	800	1	11.2
5	P2	5NB	PIT	8	0.55 * 3.8	850	1	113
6	I4	5NB	IMD	8	1.75	650	5	108
7	I5	5NB	IMD	8	1.75	700	1	96
8	I6	5NB	IMD	8	1.75	800	1	—
9	I7	5NB	IMD	8	1.105	650	3	38.4
10	I8	5NB	IMD	8	1.105	650	5	52.2
11	I9	5NB	IMD	8	1.105	700	1	57.6
12	I10	5NB	IMD	8	0.63	650	3	16.2
13	I11	5NB	IMD	8	0.63	650	5	16.8
14	I12	5NB	IMD	8	0.63	700	1	13.8

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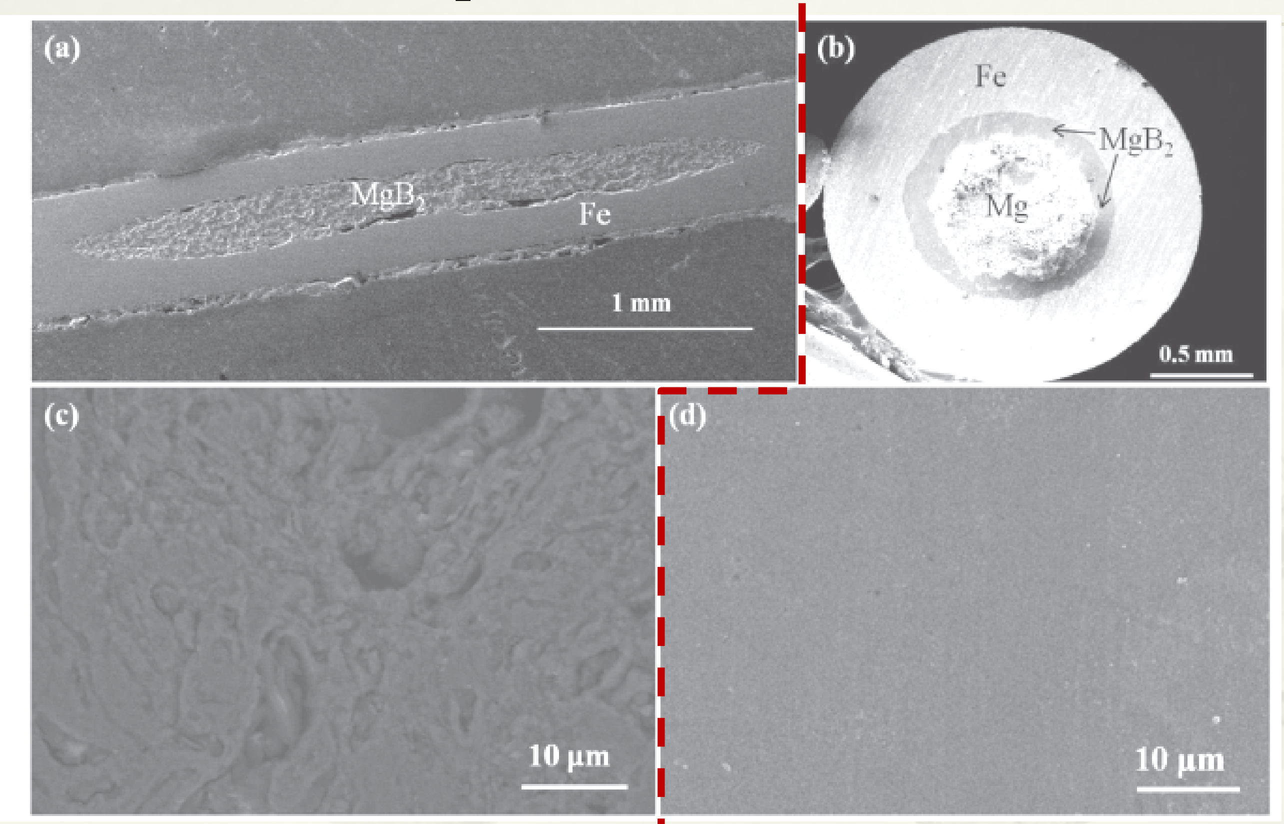
IMD wire: denser MgB_2 layer

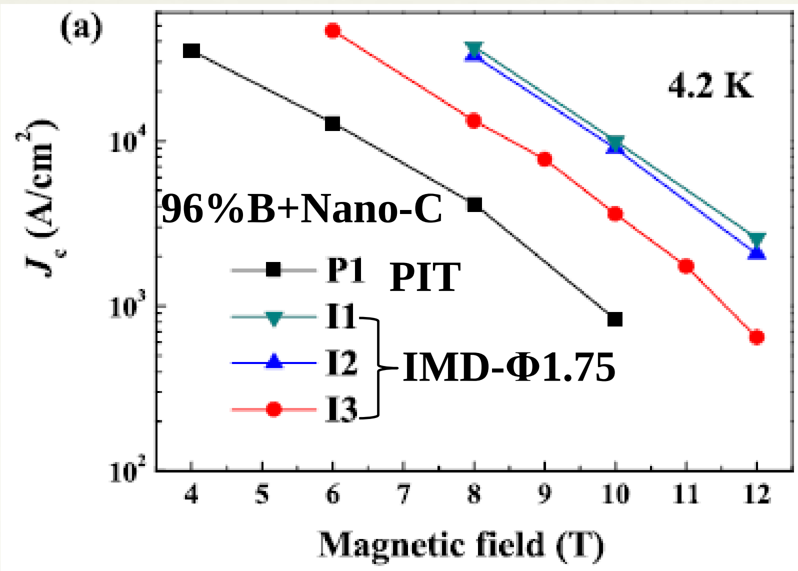
PIT tape | IMD wire

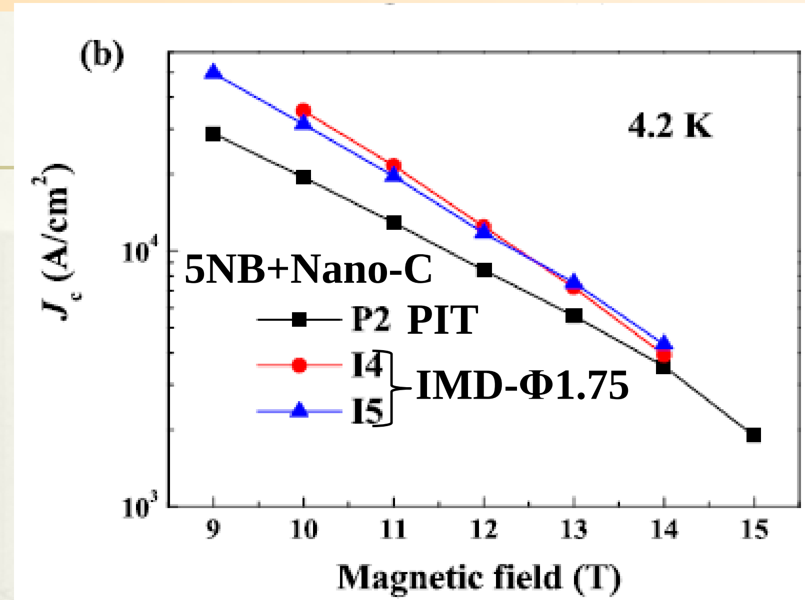


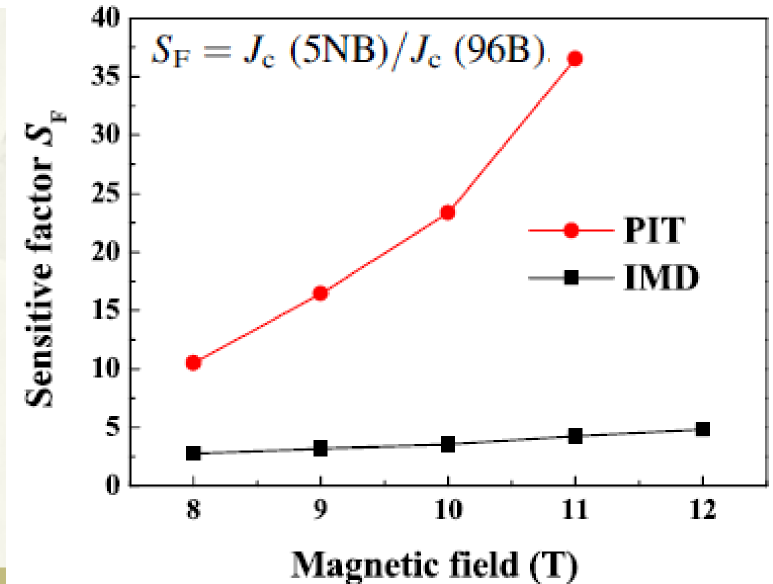
holes, cracks | dense

HV：252 | HV：630

IMD wire: larger *Jc* values

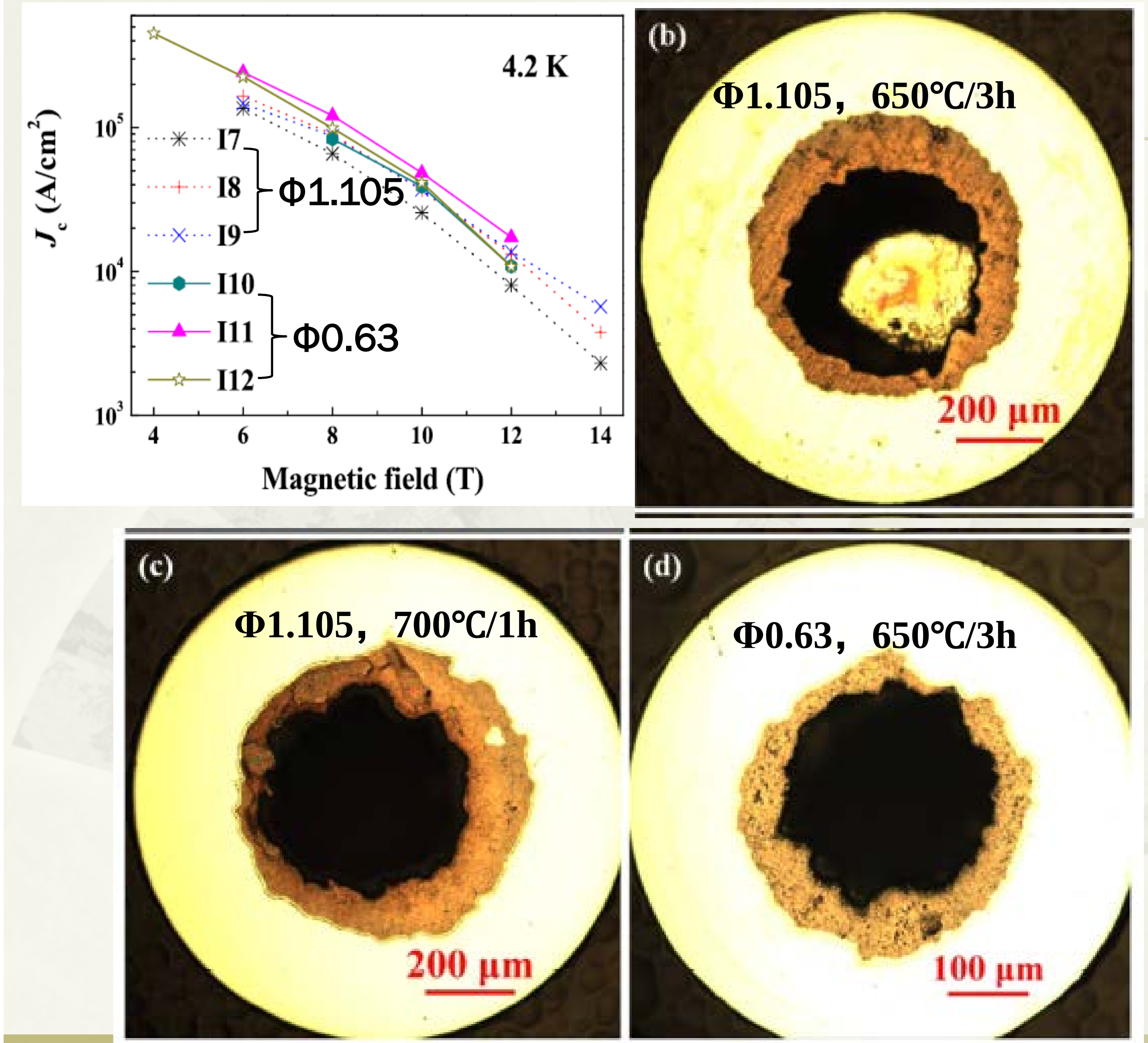






- ➢***Jc–B*** **properties of IMD wires are improved by using two kinds of boron powders, compared to PIT tapes.**
- ➢**The transport *Jc* values of the MgB_2 samples fabricated by the IMD method are less sensitive to the purity of the boron powder, compared with those fabricated by the PIT method.**

Smaller diameter, higher *J*c values

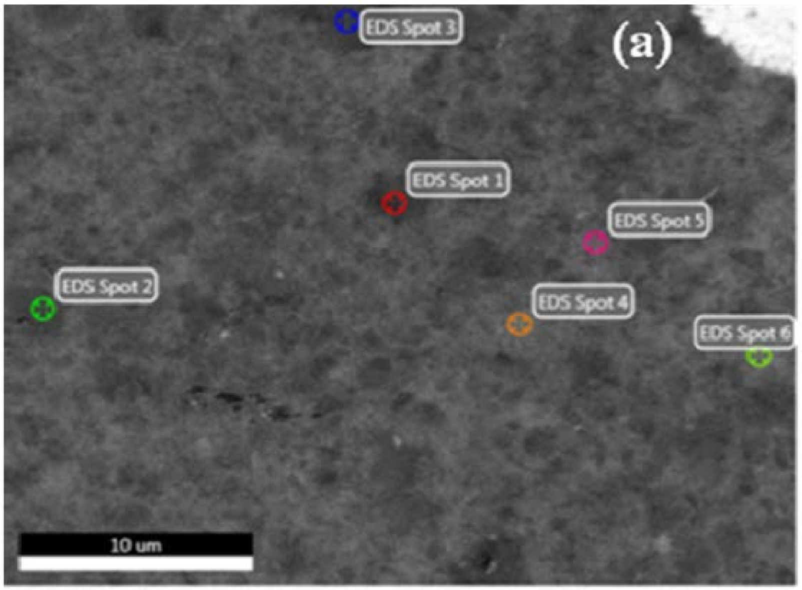


Small diameter

Thin B layer

Fully reacted MgB_2

Problem: B-rich particles



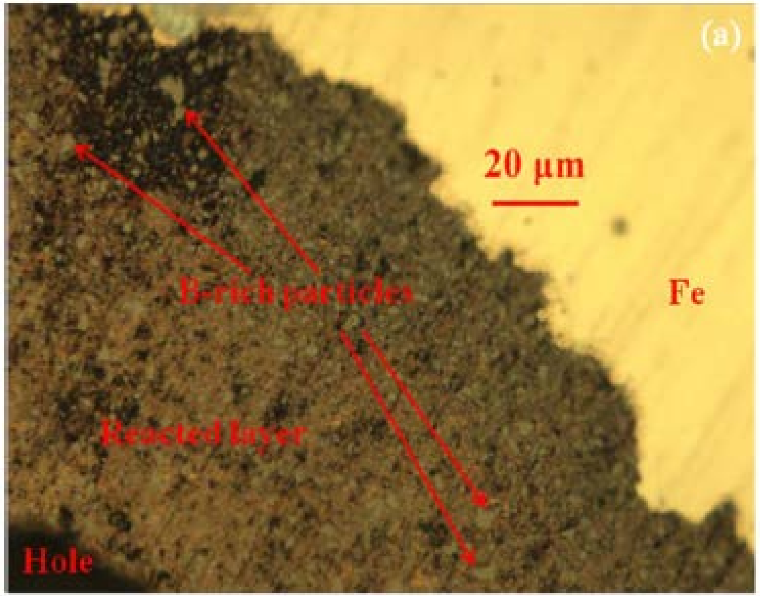
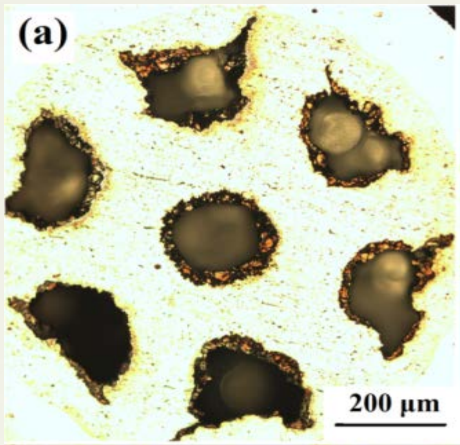


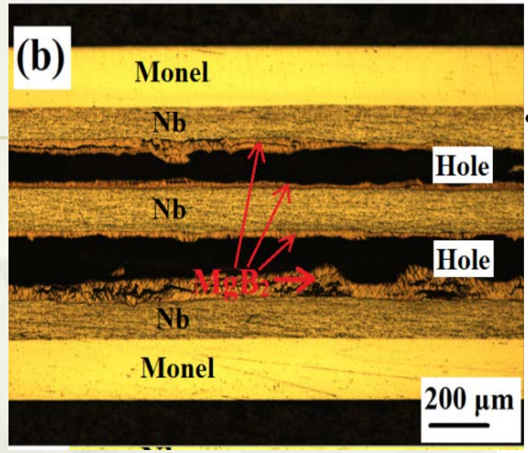
Table 2. The results of the elemental analysis of sample I8.

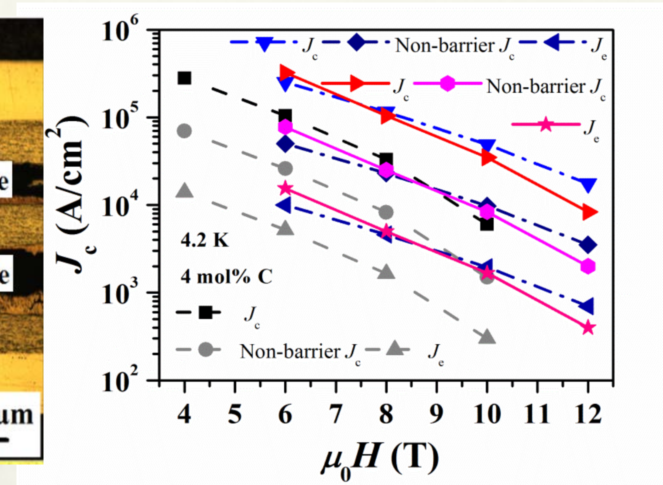
Element (at.%)	Spot 1	Spot 2	Spot 3	Spot 4	Spot 5	Spot 6
B K	82.11	85.27	85.65	15.03	60.63	74.06
C K	7.67	6.77	7.13	20.16	11.3	7.89
O K	2.13	1.39	0.59	25.98	8.57	3.61
Mg K	7.92	6.53	6.6	35.4	19.11	14.32
Fe L	0.17	0.04	0.03	3.43	0.39	0.12

- **Plenty of B-rich particles in the MgB_2 layer is due to the large size B powders (several μm).**
- **The *J*c of IMD wire will be further improved by using the nano-sized B powders.**

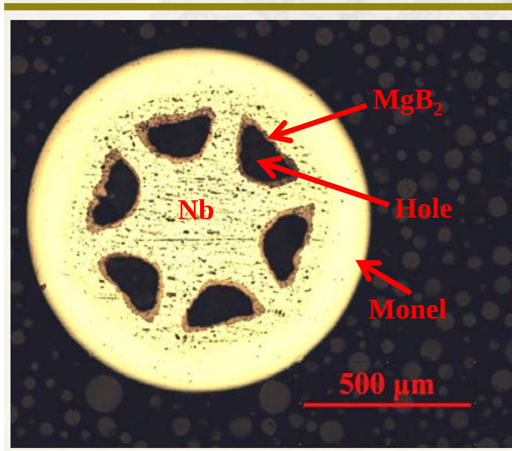
Filament configuration

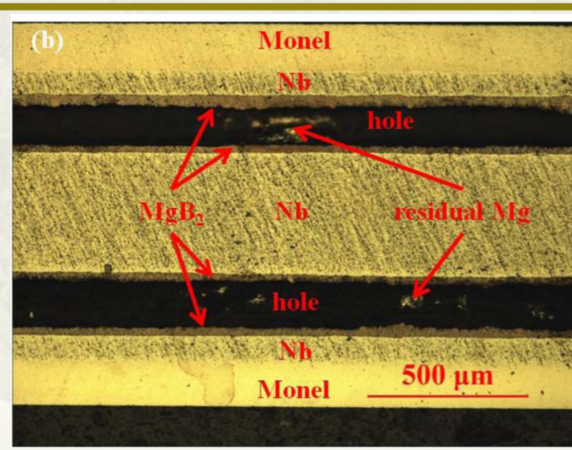






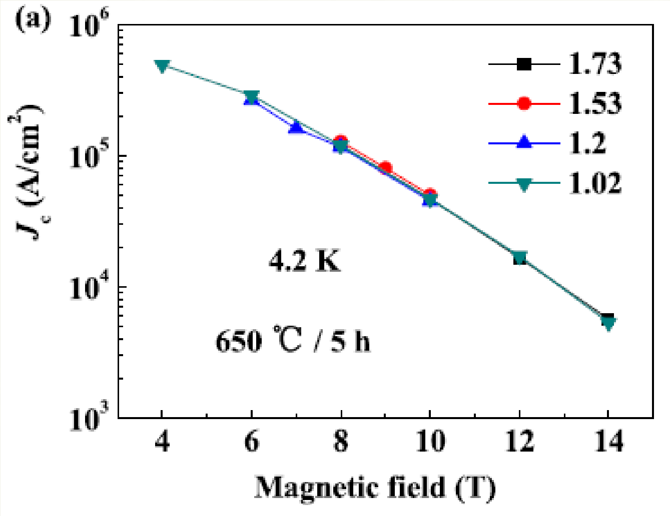
7-filament wire: longitudinal homogeneity is not good

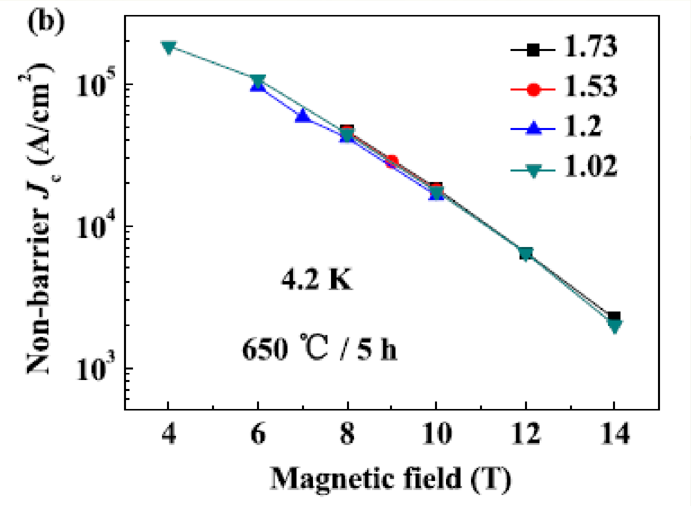


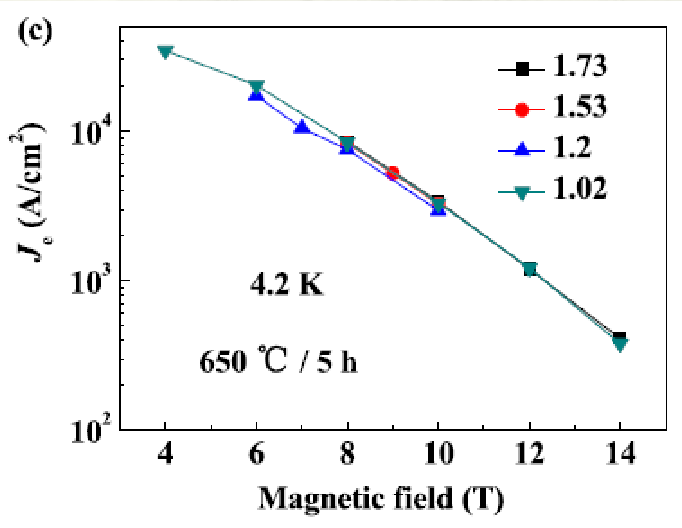


6-filament wire: good uniformity for 100 m wire

Transport properties of 100 m 6-filamentary wire



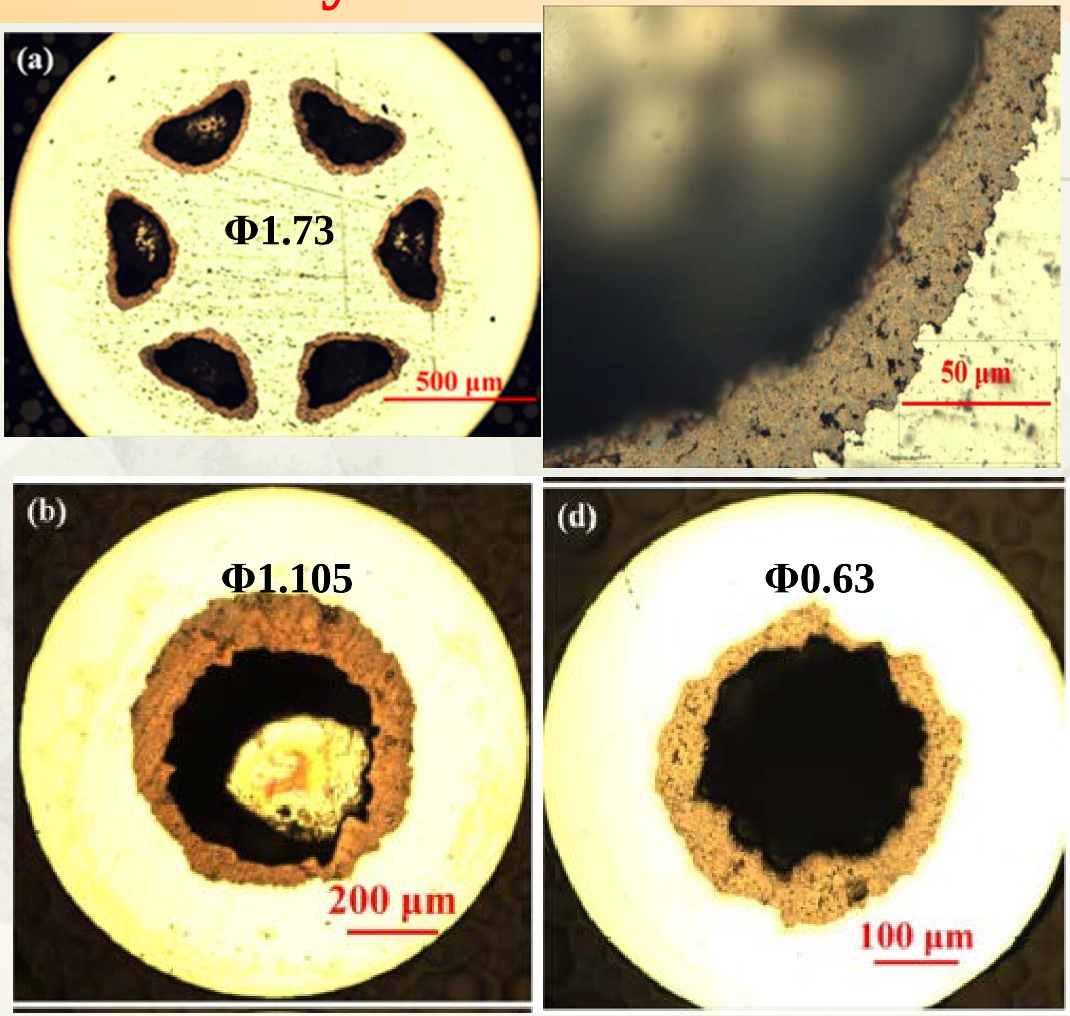




Fill factor：6.5%

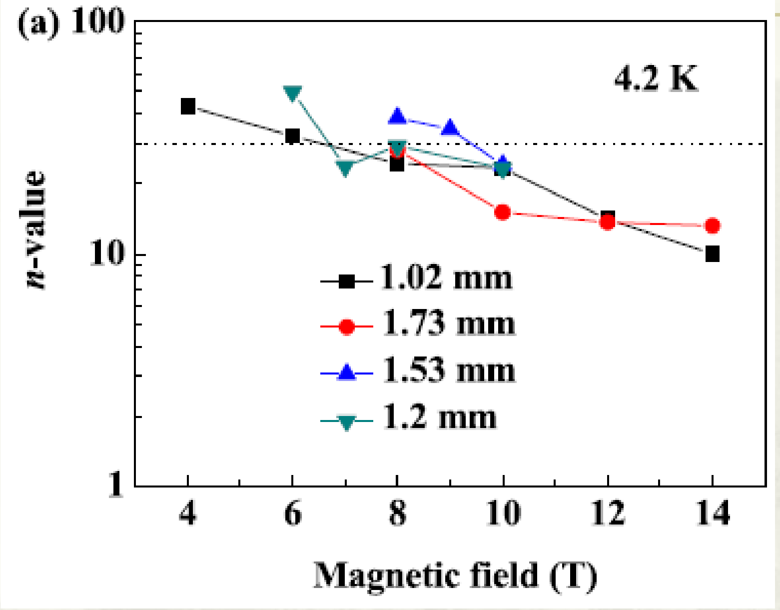
- **The *J*c of 100 m 6-filamentary IMD wire with 1.02 mm diameter was 4.6×10^4 A/cm² at 4.2 K and 10 T.**
- **The *J*c(*J*e) values of 6-filament IMD wire with different diameter were almost same.**

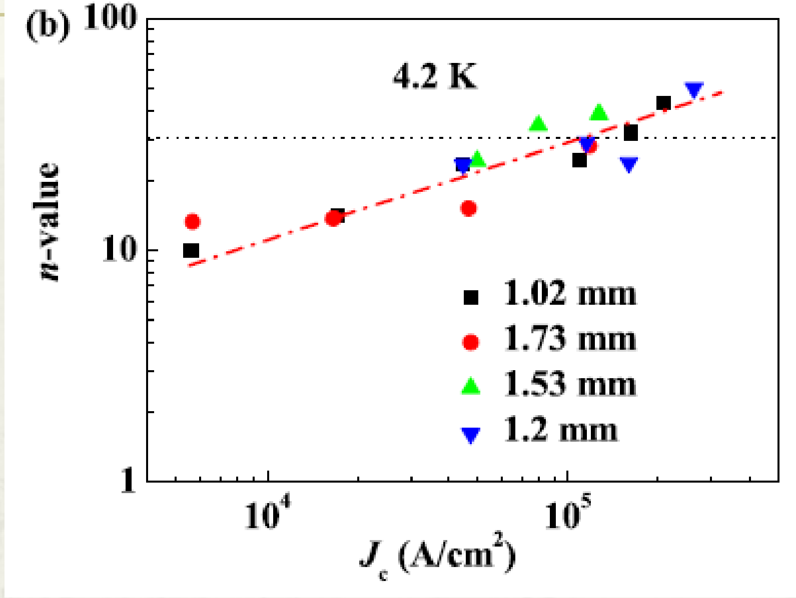
Thin B layer for multifilament wire



➢The thin B layer for multifilament wire is benefit for the full reaction between Mg and B, compared to the monofilament wire.

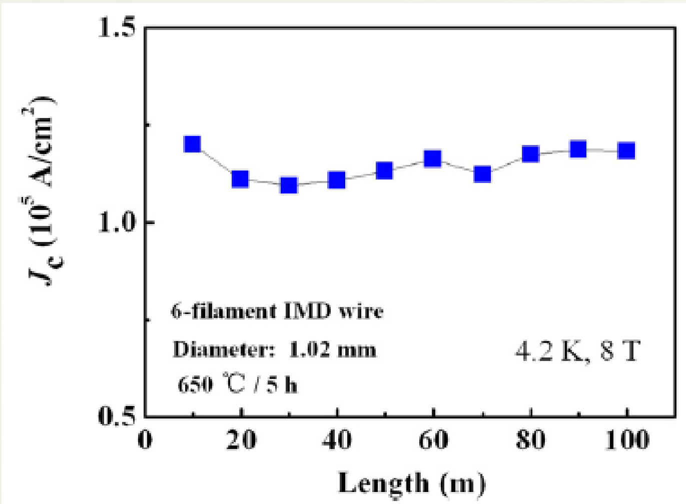
high *n* values

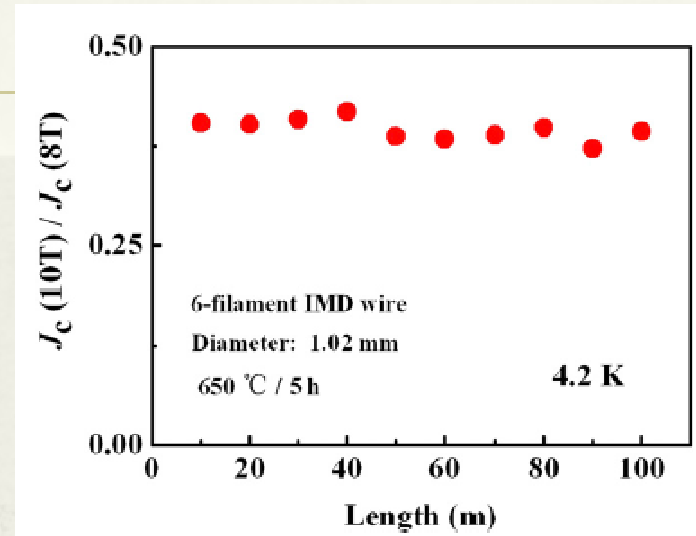




- The *n* values of IMD wires are around 30 at 4.2 K and 8 T.
- Larger *J*c led to a higher *n* value.

Uniformity of transport properties





D.L. Wang, ***SUST***. 29 (2016) 065003

➢**The ratio of the standard deviation to the average value is 3.3%, suggesting that the *J*c values have a fairly uniform distribution throughout the long wire.**

➢**The lowest *J*c value is 1.09×10^5 A cm^{-2} at 4.2 K and 8 T, which is close to the average value (1.15×10^5 A cm^{-2}), indicating that there were no serious defects along the length of the wire.**

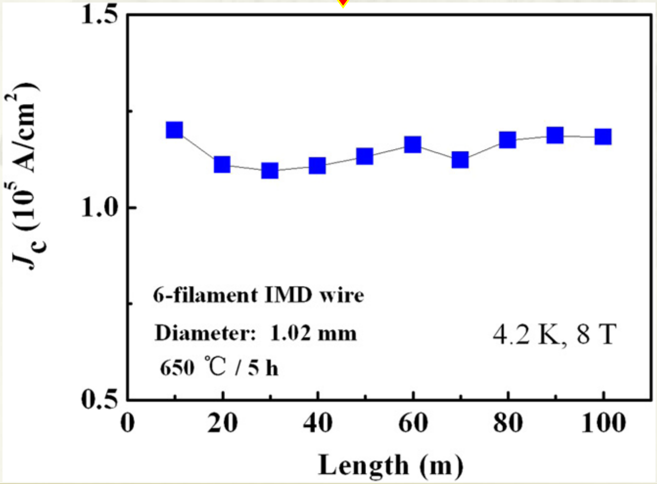
Longitudinal homogeneity evaluation

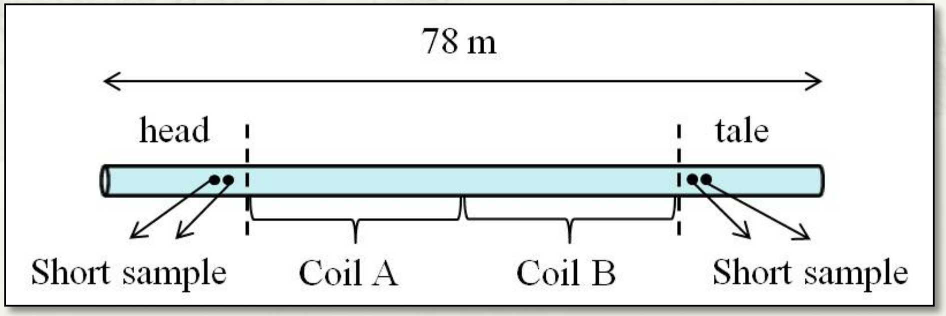
Direct

Challenge

- The lowest *Jc* value determined the *Jc* value of the whole wire.
- To wind wire into a coil without significant loss of *Jc*.

Indirect





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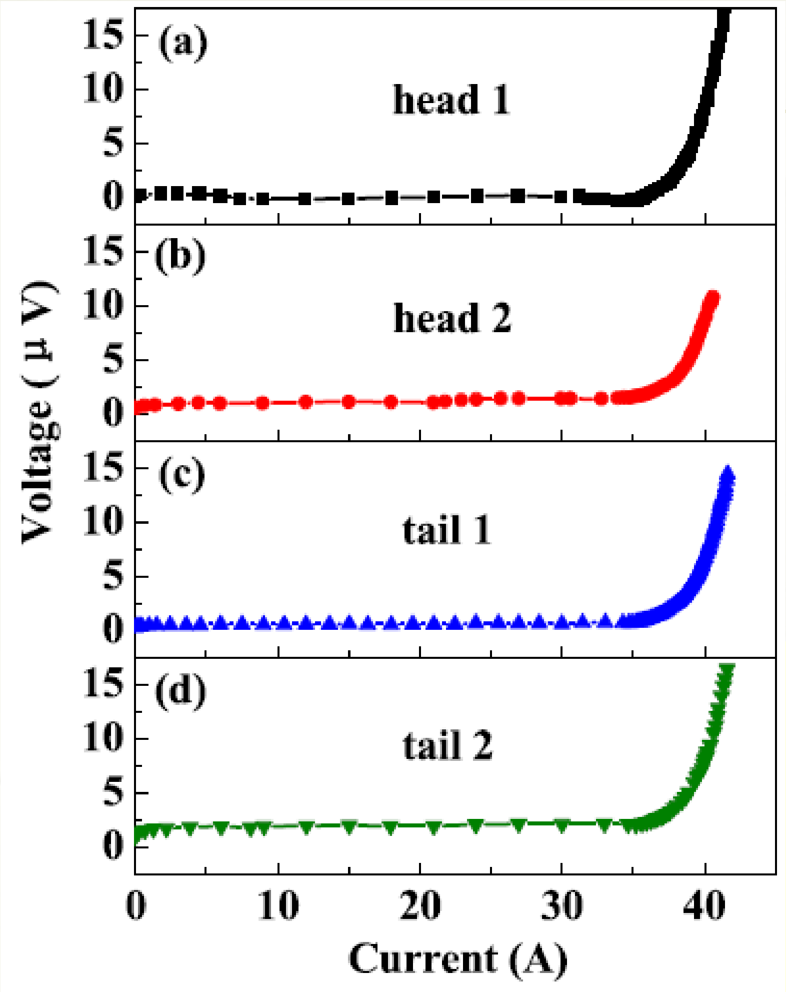
Short samples: I_c and *n* values

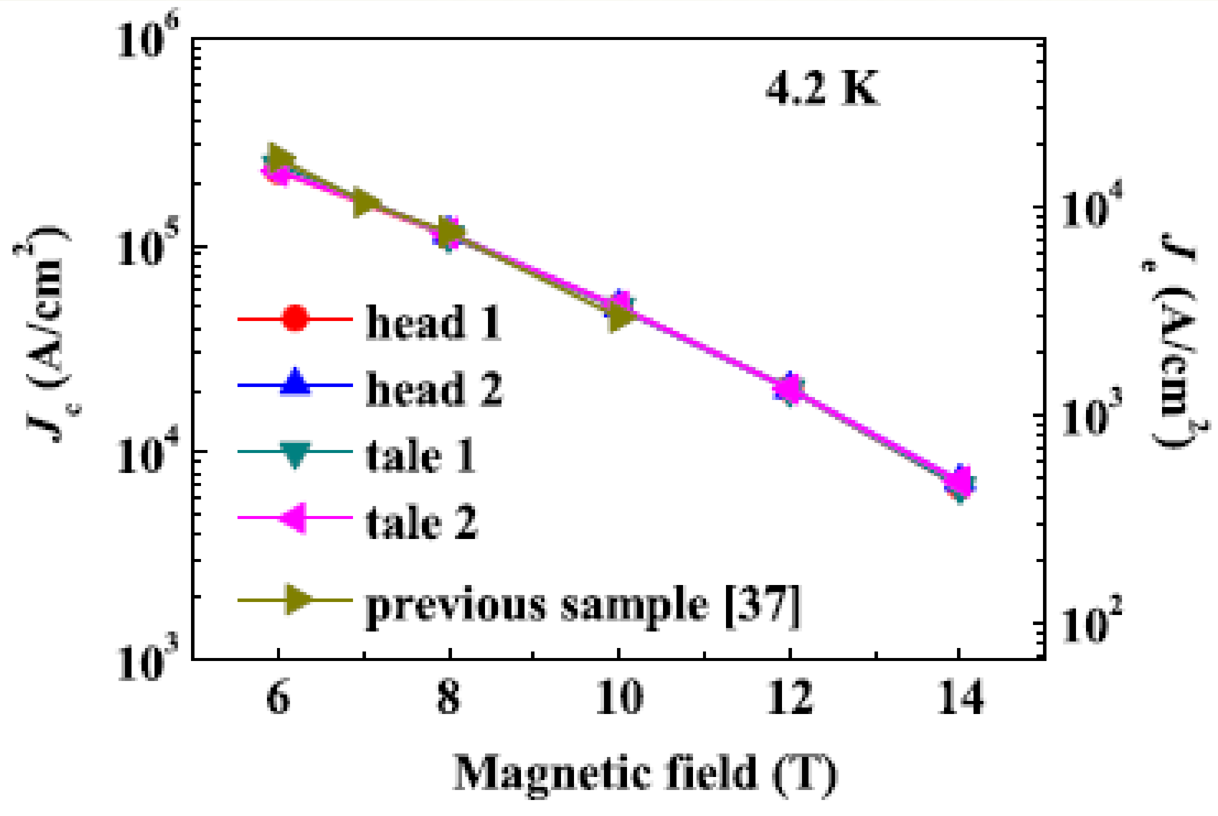


Fitting parameters of *I–V* curves for short samples at 10 T

Sample	I_c (A)	*n*-value
head 1	37	21.5
head 2	37.2	22.6
tale 1	37.2	21
tale 2	37.4	23.1
Average	37.2	22.1

- **Both *I*cs and *n*-values of four short IMD wires are close to each other, indicating that the long six-filament IMD-processed MgB_2 wire is uniform from head to tail.**

Short samples: J_c at 4.2 K



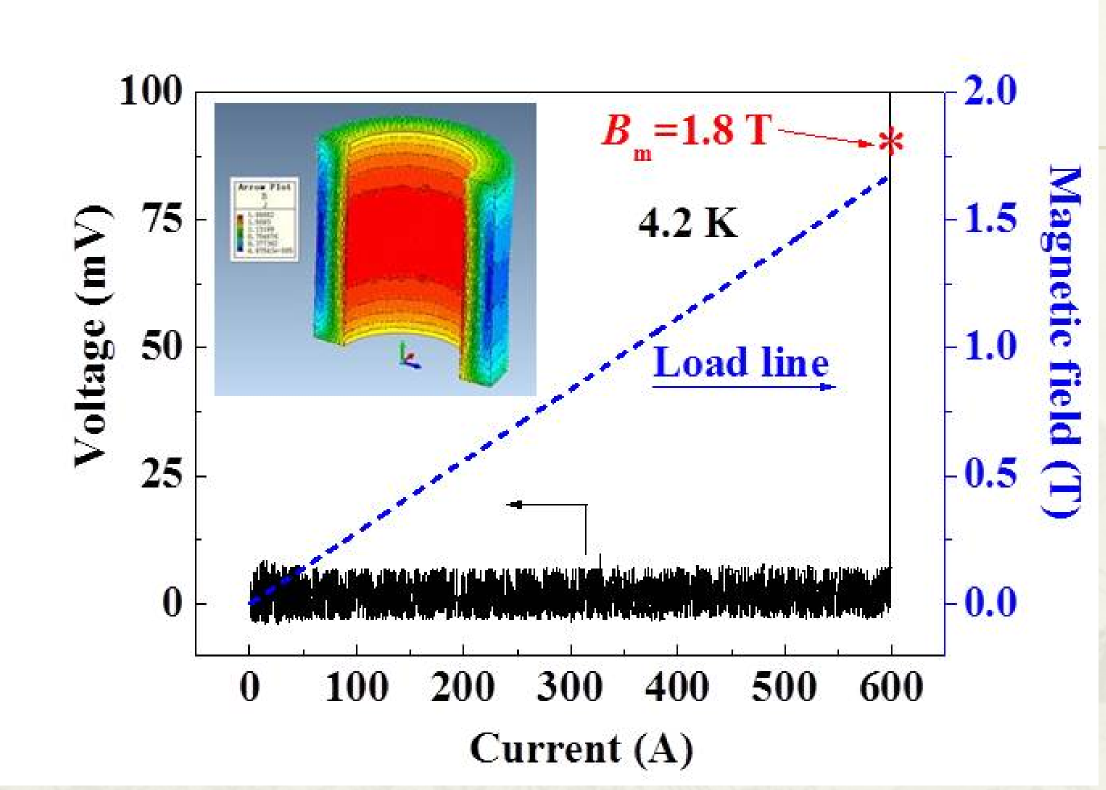
➢The *J*cs of four short IMD wires are close to each other and our previous 100 m IMD wires at 4.2 K.

MgB_2 solenoid coils

Specifications	Coil A	Coil B
Wire structure	MgB_2/(Nb /Monel)	MgB_2/(Nb/ Monel)
Number of filaments	6	6
Wire diameter (mm)	1.2	1.2
Winding inner diameter (mm)	38	38
Winding outer diameter (mm)	57.6	57.8
Winding height (mm)	60	60
Number of turns	178	174
Wire length (m)	26.7	26.1

Coil

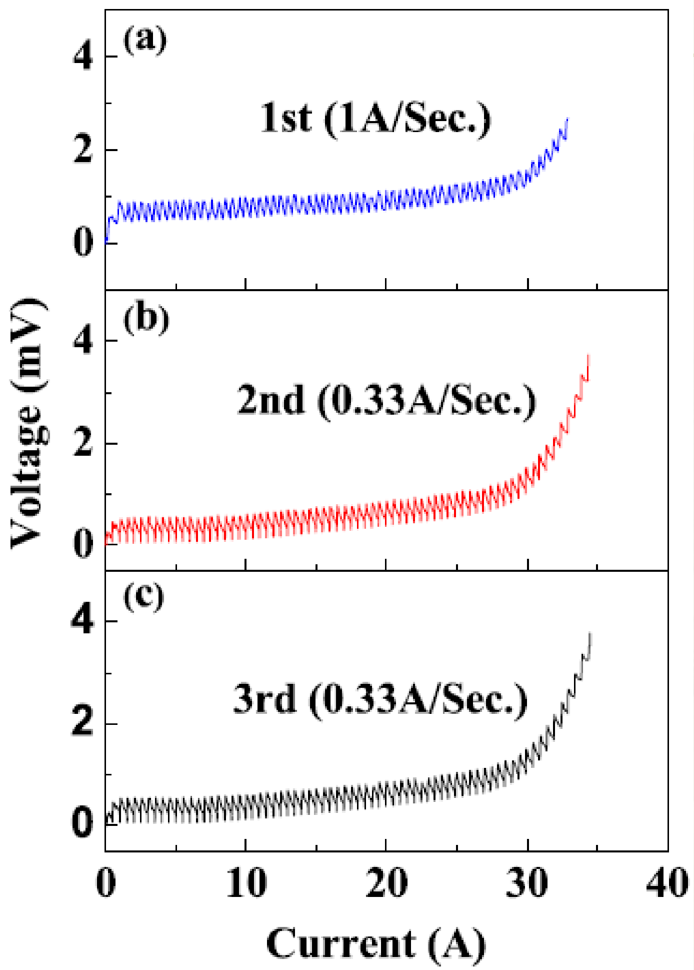
Transport properties of Coil A



- **The transport current of Coil A reached 599 A at 4.2 K.**
- **Coil A generated a self-field of 1.67 T at the coil center.**

Transport properties of Coil B

Three time excitation at 4.2 K and 10 T

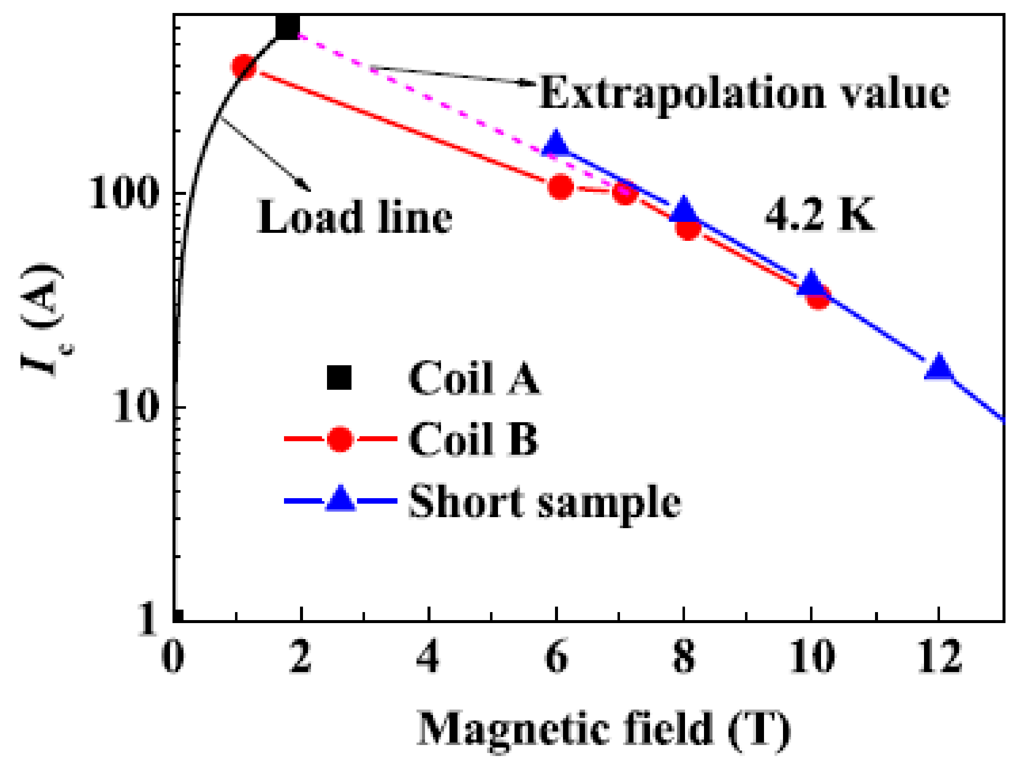


Fitting parameters of *I–V* curves for Coil B at 4.2 K and10T

No.	I_c (A)	*n*-value
1st	32.8	14.9
2nd	33	12.9
3rd	33.4	13.3
Average	33.1	13.7

- **No training effect.**
- ***Ic* (33.1 A) of Coil B is close to *Ic* (37.2 A) of short samples.**

Transport properties of Coil A and B



➢**Above 7 T, the *I–B* curve of Coil B was straight and in good agreement with that of the short sample.**

➢**Both the magnetic fields generated by two coils (H^{gen}) coincide with the same formula:** $H^{\mathrm{gen}} = (28\,\mathrm{Gs\,A^{-1}})\,I_{\mathrm{c}}$

Summary

1. The high *J*c of IMD wire is also achieved by using the crystalline boron powders. The best *J*c value of IMD wire is 6.2×10^4 A/cm^2 at 4.2 K&10 T. The *J*c can be further improved by decreasing the size of crystalline B powders.
2. We successfully fabricated a 100 m-level, Nb-reinforced, 6-filament MgB_2 wire by an IMD process. The highly uniform microstructure and transport performance are obtained for 100m long six-filament MgB_2 wire.
3. Two solenoid coils were made by a wind-and-react method using long wires. One coil exhibited *J*c of 4.5×10^4 A cm^{-2} at 10 T and 4.2 K, which is similar to the short samples. Another coil generated a central field of 1.67 T and a maximum magnetic field of 1.8 T at zero external field.

Collaborators:

Satoshi Awaji, Kazuo Watanabe

Institute for Materials Research, Tohoku University, Japan

Pavol Kovac

Institute of Electrical Engineering, Slovak Academy of Sciences, Slovakia

Liwei Jing, Fengyuan Zhang, Dong Zhang, Wanshuo Sun, Junsheng Cheng, Guoming Zhang, Qiuliang Wang, Liye Xiao, and Liangzhen Lin

Institute of Electrical Engineering, Chinese Academy of Sciences, China

Fang Liu, Lei Lei and Huajun Liu

Institute of Plasma Physics, Chinese Academy of Sciences, China

Thank you for your attention!