CEC-ICMC2015, Jun. 29-Jul. 2, Tucson

Development of *kilometer-grade* MgB_2 superconducting wires at NIN

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2015, 07/01

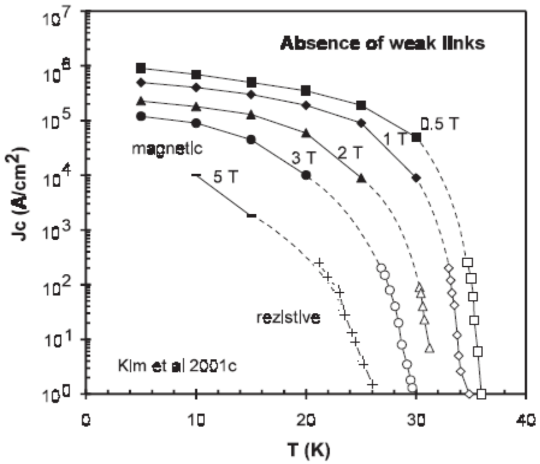
Outline

- Introduction
- Fabrication of *km*-grade MgB_2 wires by *in-situ* PIT method
  - Preparation of precursor powders
  - Conductor structure design
  - Fabrication of km-grade MgB_2 wires and their superconducting properties
- Conclusions

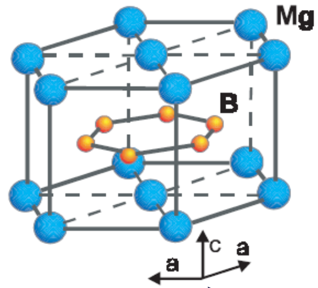
Introduction

Advantages of MgB_2 superconductor

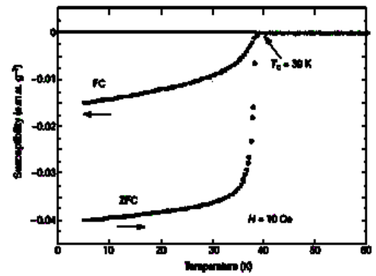
Absence of weak links



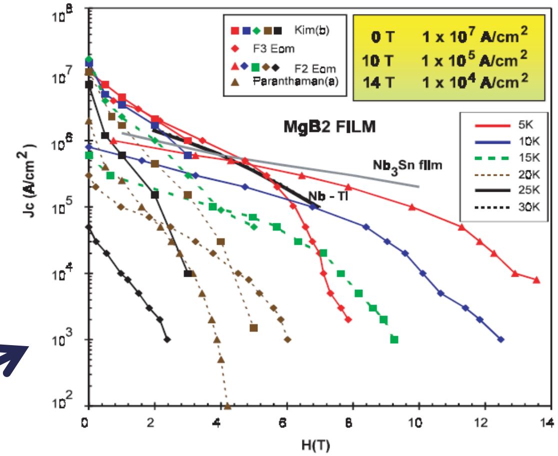
Simple crystal structure



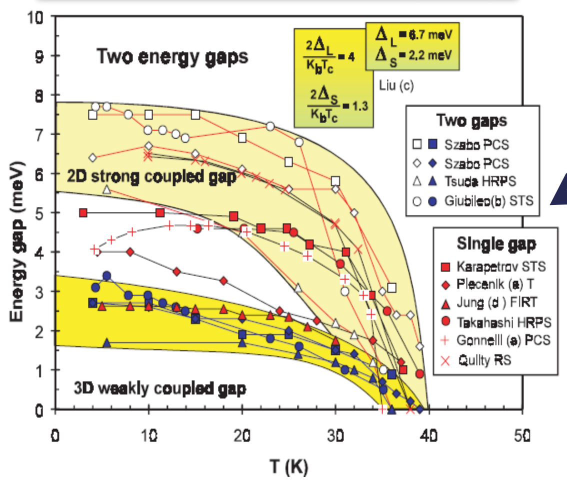
Moderately high T_c



High current densities



Two energy gaps



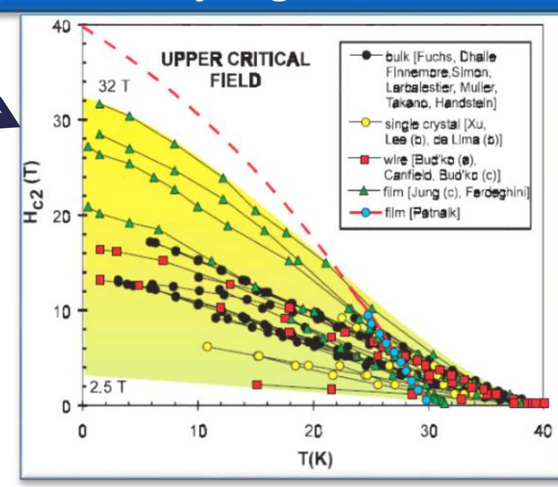
MgB_2

Low cost – low weight

precursors price: 150 €/Kg

Density: 2.5 kg/dm^3

Potentially high critical field

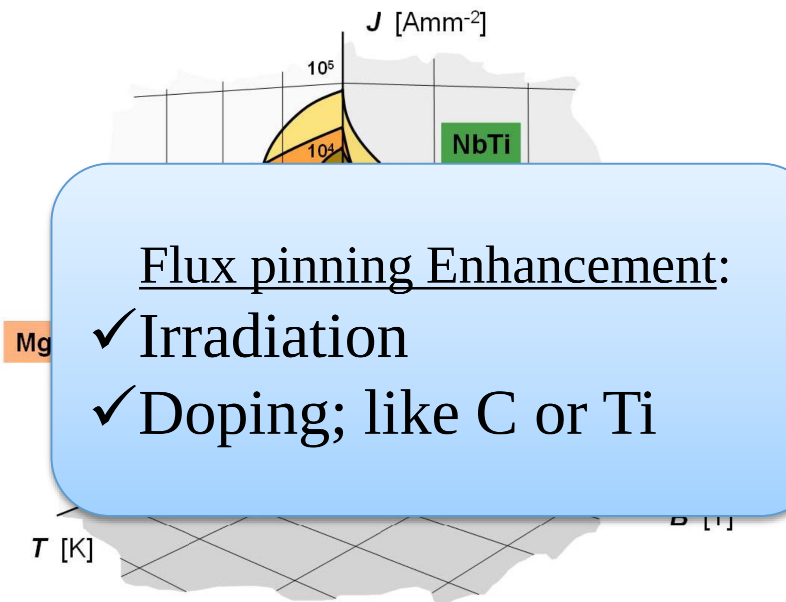


Nagamatsu *et al*. *Nature* 410, 63 (2001)

C. Buzea, T. Yamashita. *Supercond. Sci. Technol*. 14 (2001) R115

Disadvantages of MgB_2 superconductor

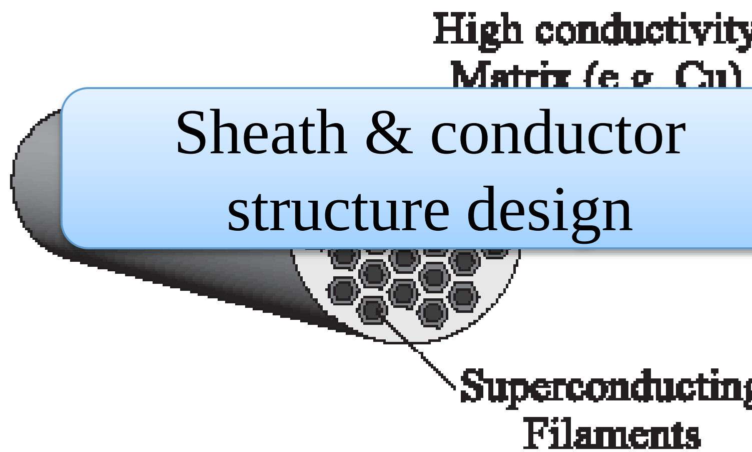
J_c decrease with increasing field quickly



Flux pinning Enhancement:

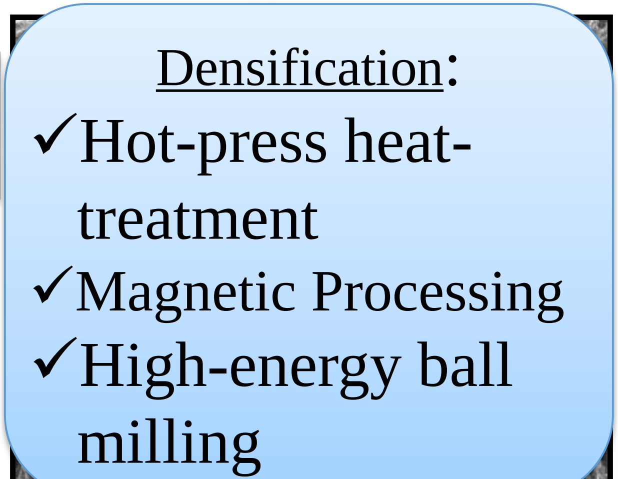
- ✓Irradiation
- ✓Doping; like C or Ti

Fragile → Difficult to making wires and tapes directly



Sheath & conductor structure design

Porosity structure



Densification:

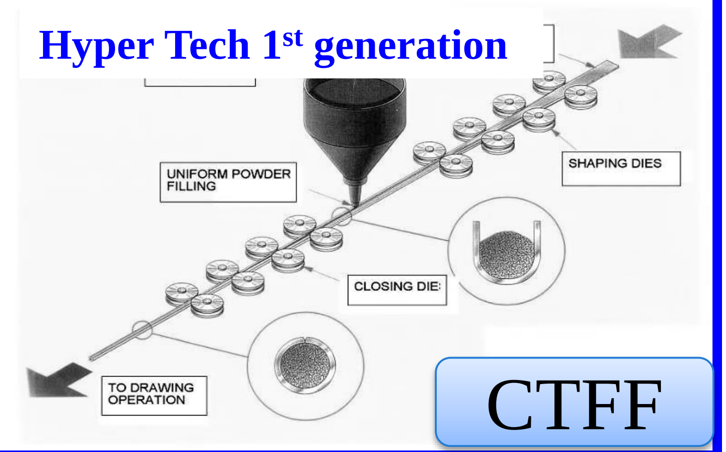
- ✓Hot-press heat-treatment
- ✓Magnetic Processing
- ✓High-energy ball milling

Homogeneous deformation for the powders is not easy.

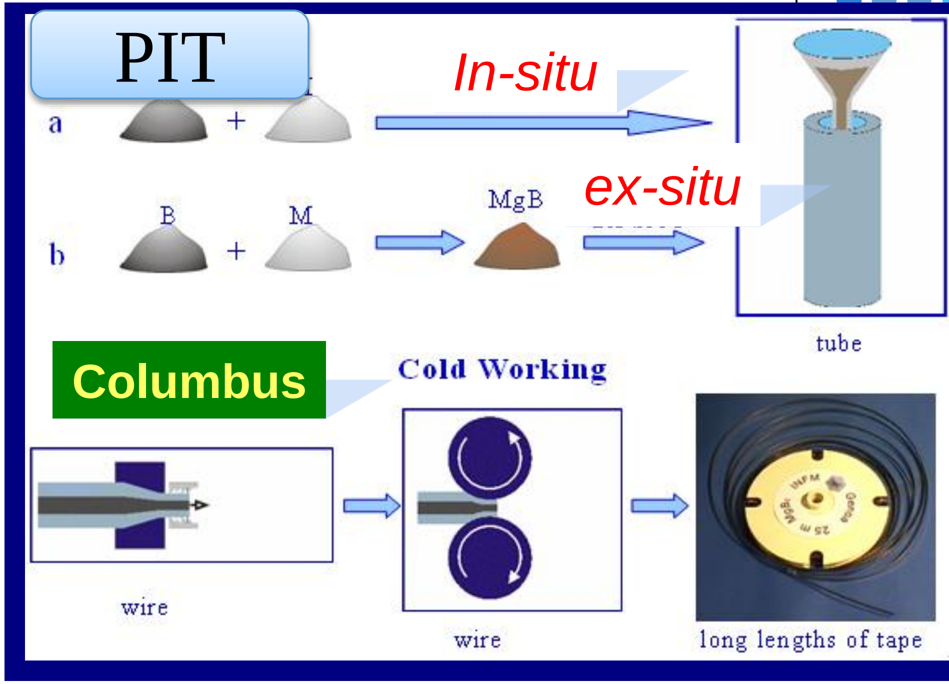
Fabrication Technique for MgB_2 wires and tapes

Hyper Tech 1st generation

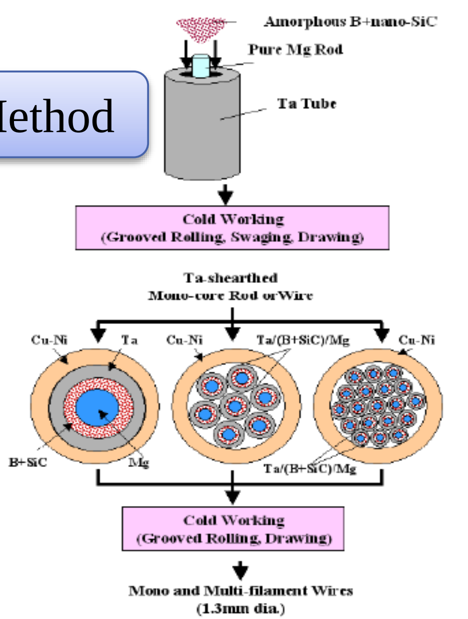
CTFF



PIT



IMD Method



NIMS & Hyper Tech-2nd generation

Advantages of *in-situ* PIT:

- **Simple fabrication process**
- **Easy to introduce doping**

Disadvantages of *in-situ* PIT:

- **Reaction between precursor and sheath**

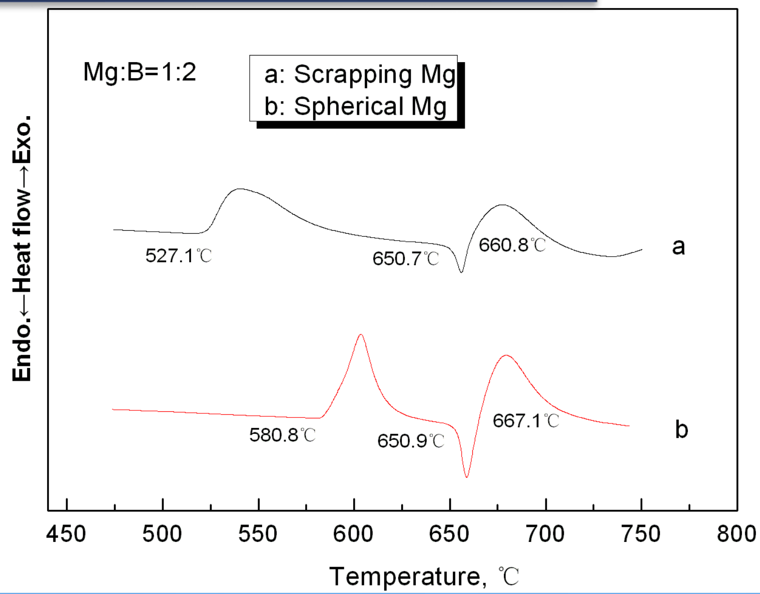
K Togano, *et al. Supercond. Sci. Technol*. 23 (2010) 085002

In-situ PIT method for *km*-grade MgB_2 wires

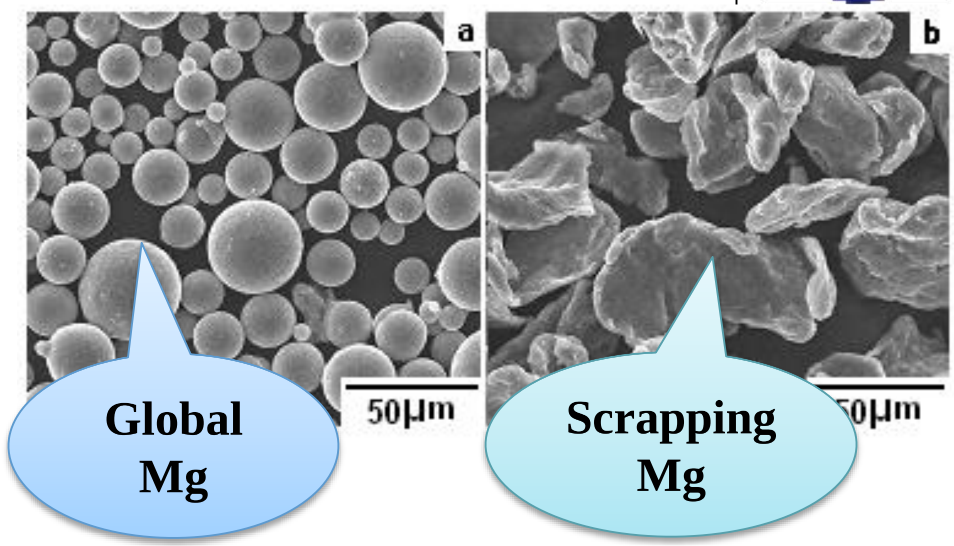
- ✓ Preparation of Precursor powders
- ✓ Conductor structure design
- ✓ Fabrication of km-grade MgB_2 wires and their superconducting properties

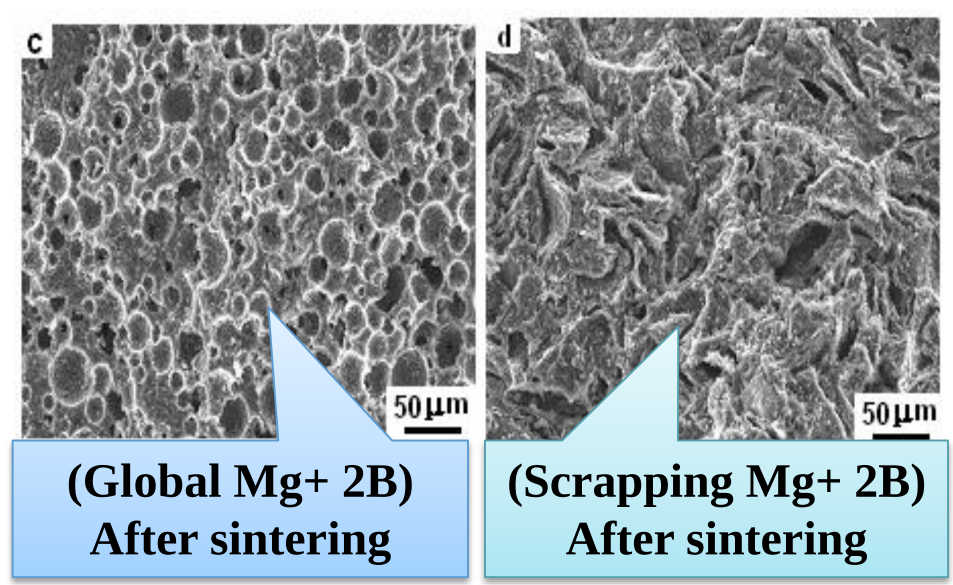
Preparation of Precursor powders

Shape of Mg powders



- **Scrapping Mg:**
  - ✓Higher specific surface area;
  - ✓Larger surface energy;
  - ✓Lower solid-solid starting reaction temperature.
- The shape and size of holes depend on the shape and size of raw Mg powder.



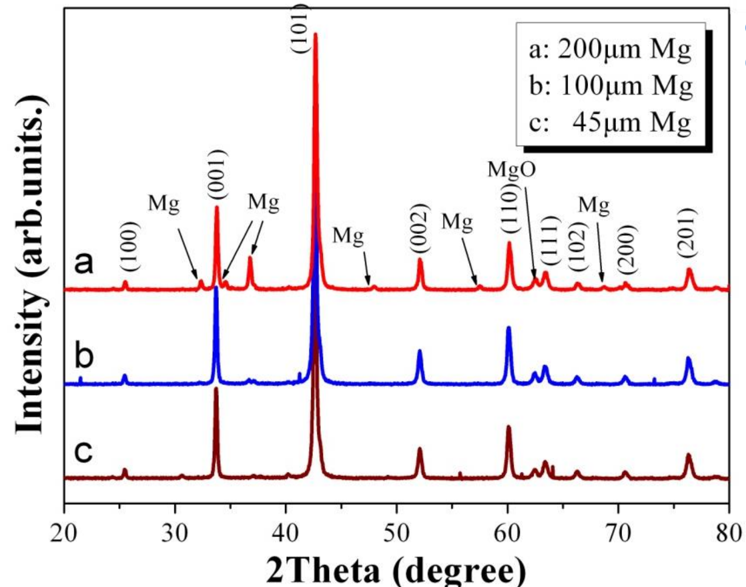


S.C. Yan *et al. Acta metallurgica* sinica,43(2007)358-362

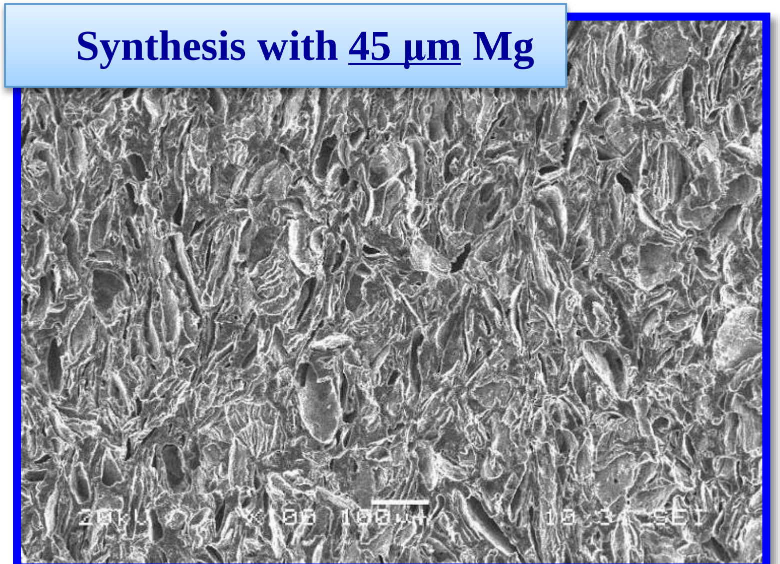
Preparation of Precursor powders

Size of Mg powders

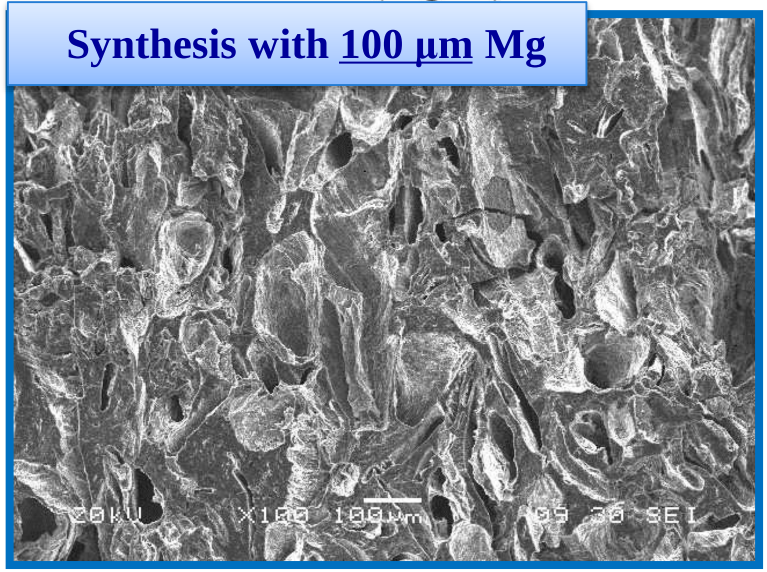
Complete Reaction, higher density and higher phase purity can be acquired using <u>scrapping</u> **Mg powder with the size of <u>45 µm</u> as the precursor powder**



Synthesis with <u>45 µm</u> Mg



Synthesis with <u>100 µm</u> Mg



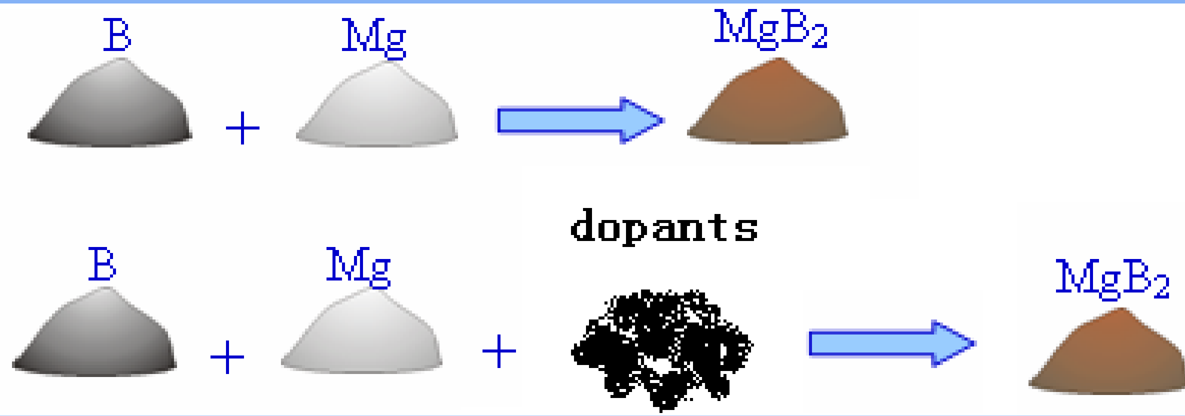
S.C. Yan *et al. Rare metal mat. Eng.* 36(2007)1260-1262

Preparation of Precursor powders

Two-step reaction method

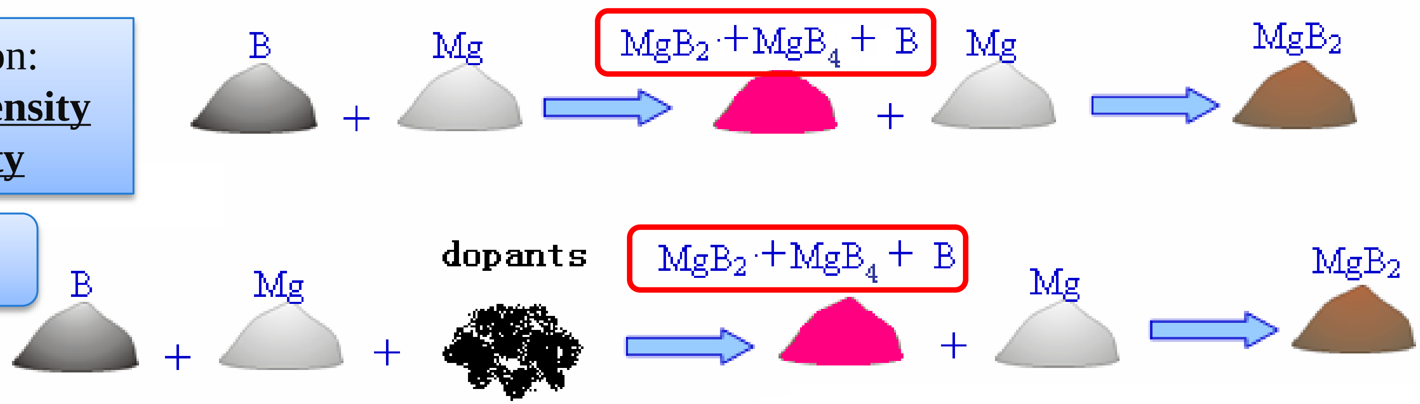
Single-step reaction:
Mass hole formed!

Mg:B=1: 2



Two-step reaction:
Improved the **density**
and **homogeneity**

Mg:B=1: 4

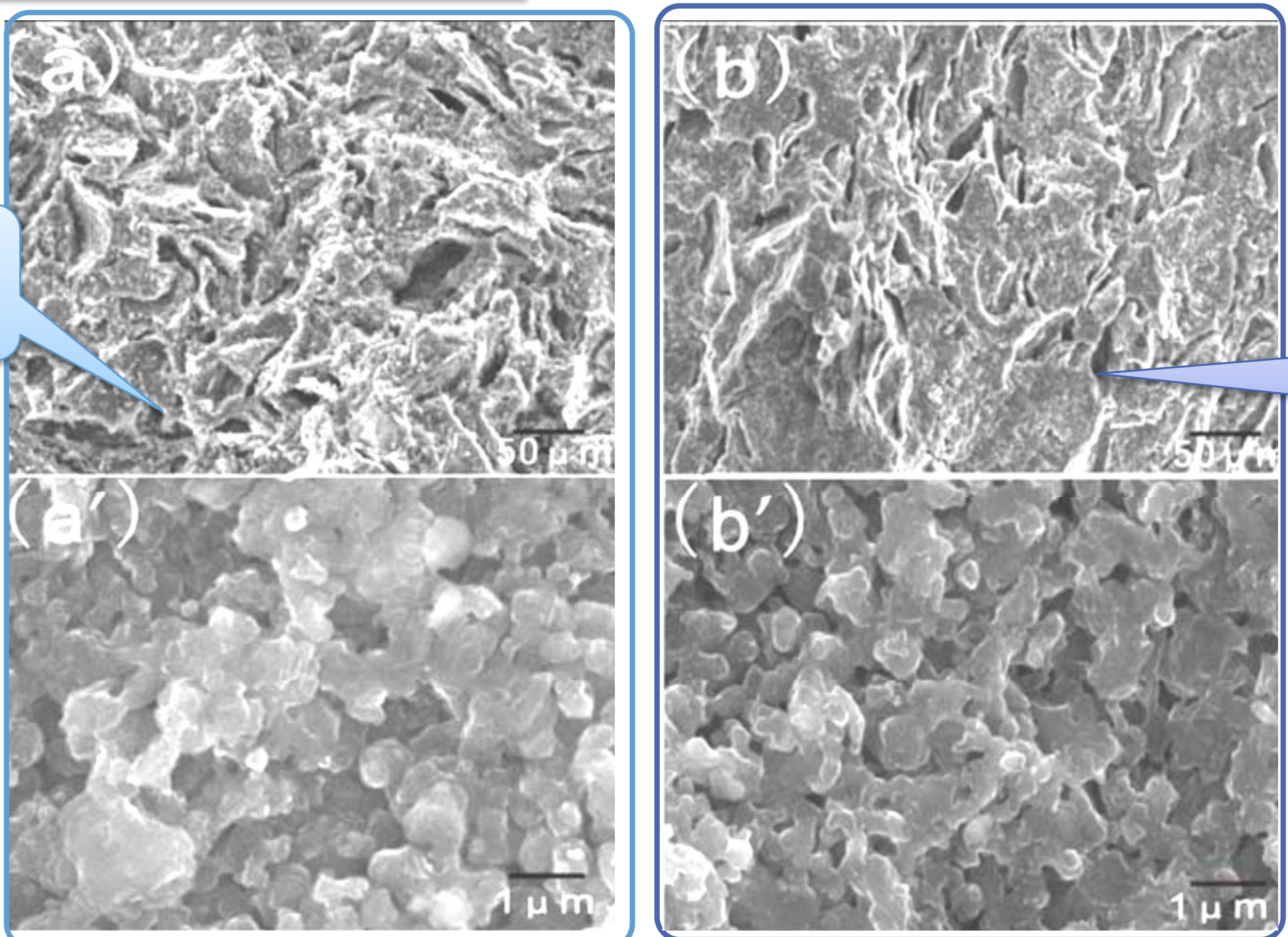


S.C. Yan *et al. Rare metal mat. Eng.* 36(2007)1260-1262

The hole in MgB_2 is depending on the size of magnesium. The two-step method could decrease the initial Mg ratio and thus improve the density.

Preparation of Precursor powders

Two-step reaction method



One-step reaction

Two-step reaction

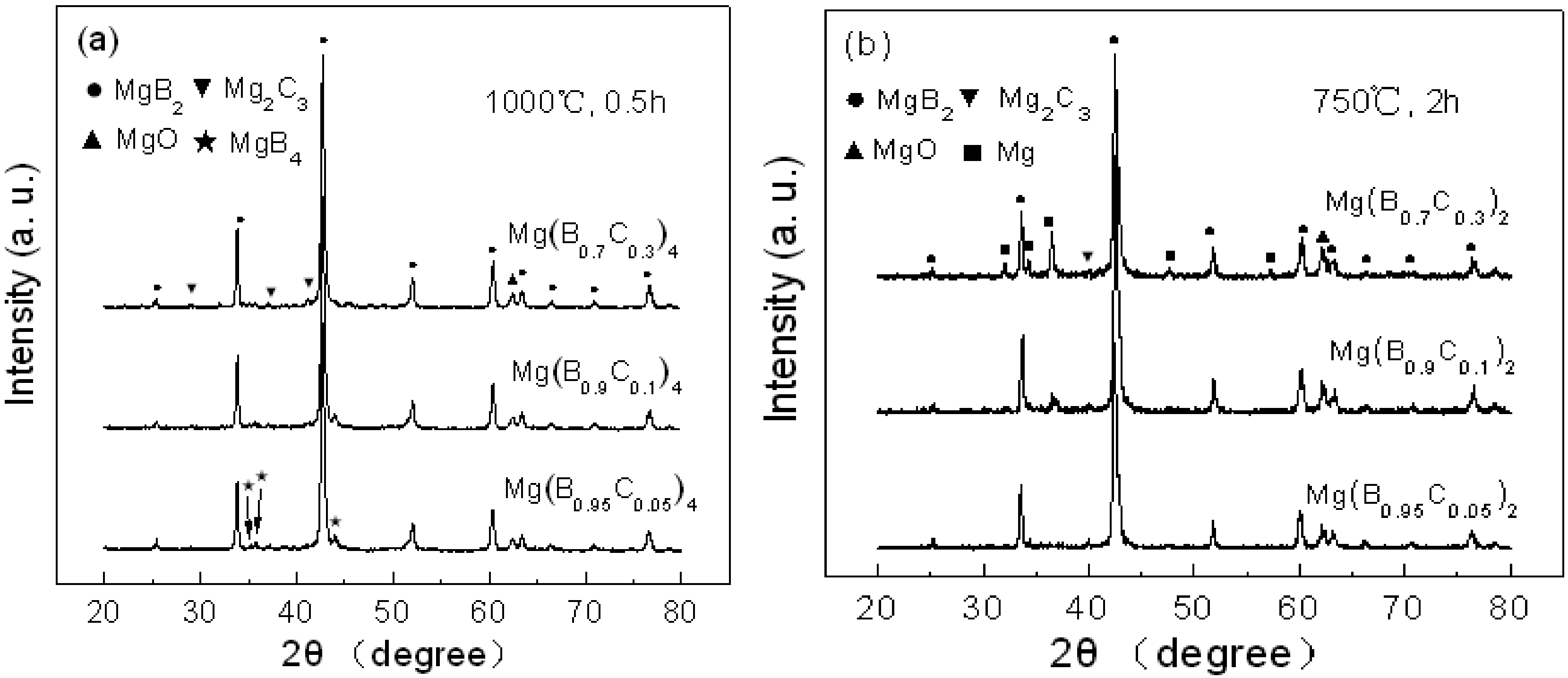
- ✓ Porosity decrease obviously, the density increased from 1.5 to 1.9 g/cm^3
- ✓ The Grains are still with very small size.

Preparation of Precursor powders

Two-step reaction method

First step sintering with C doping

Second step sintering with C doping



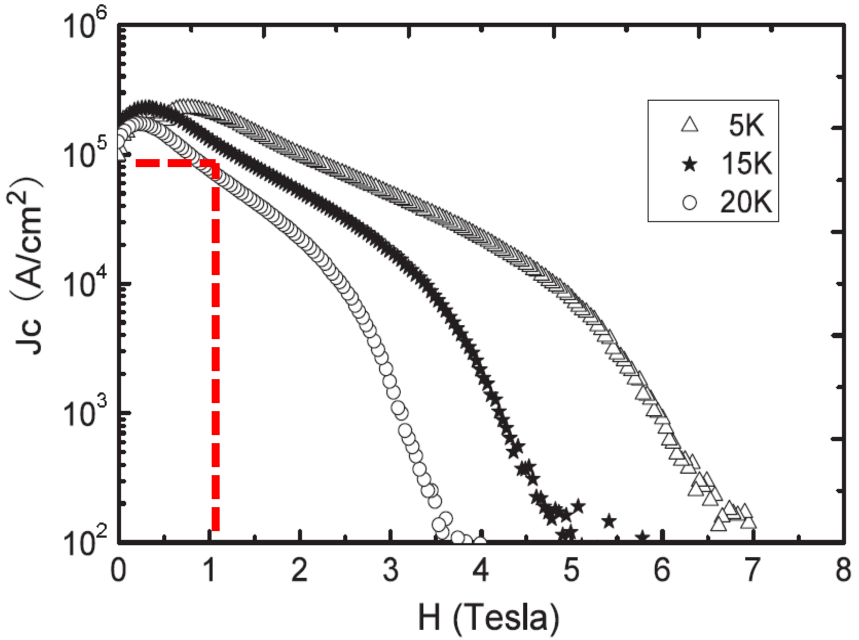
S.C. Yan *et al. J. Alloys Compd.* 459(2008)452-456

Two-step reaction method is beneficial for carbon substitution at B sites.

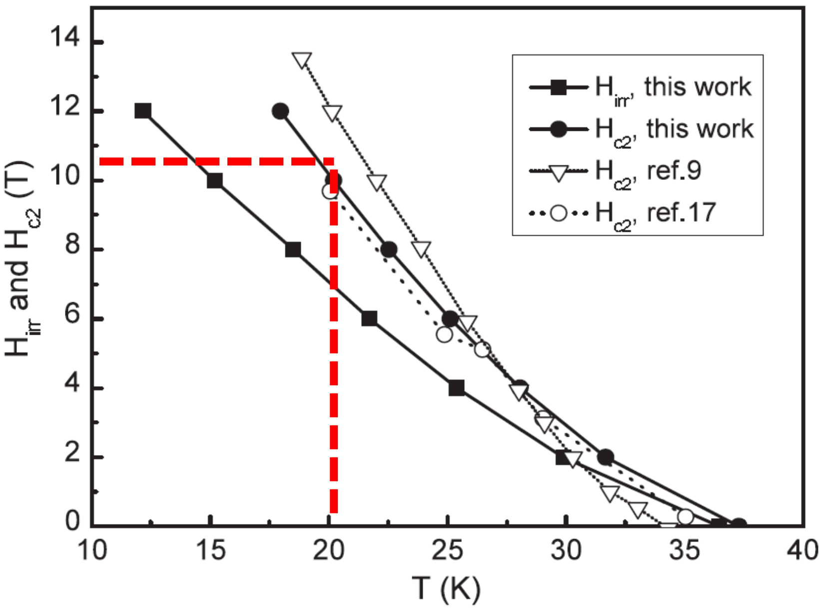
Preparation of Precursor powders

Two-step reaction method

J_c of $Mg(B_{0.95}C_{0.05})_2$



H_c and H_{irr} of $Mg(B_{0.95}C_{0.05})_2$



S.C. Yan *et al. Supercond. Sci. Technol* 20(2007)377-380

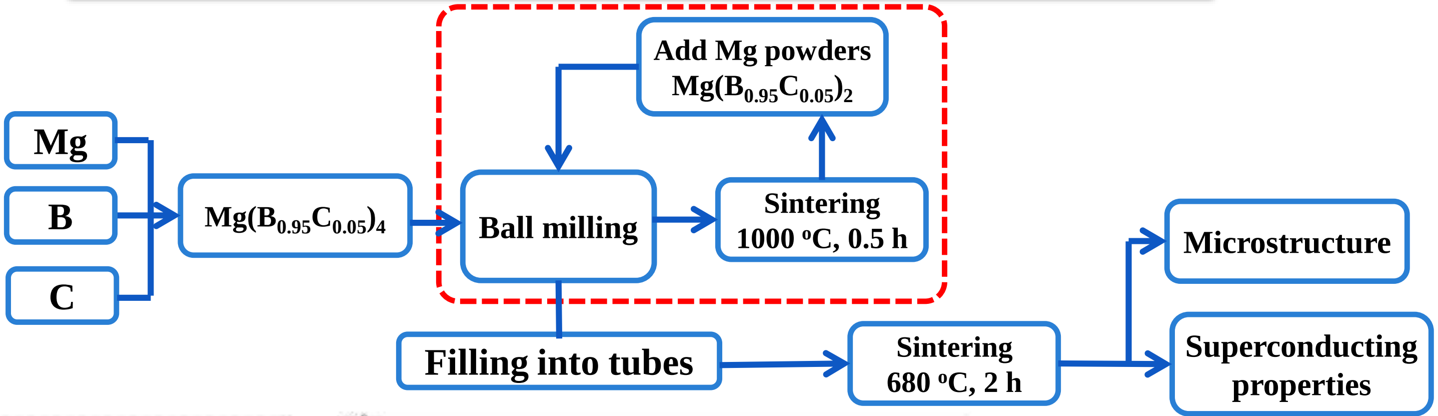
For the sub-micron carbon-doped MgB_2 by a two-step reaction:

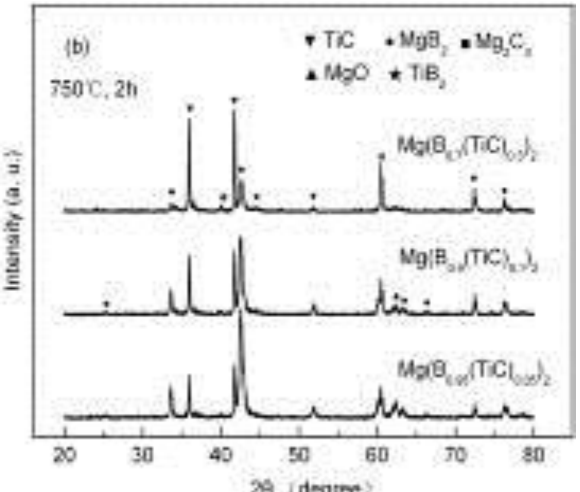
- ✓ The upper critical field H_{c2} reached 10.5 T at 20 K.
- ✓ The critical current density J_c is 7.8×10^4 A cm^{-2} at 20 K and 1 T.

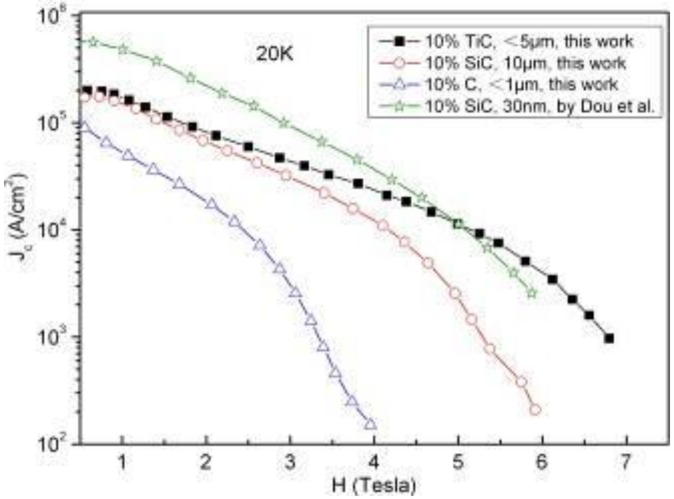
Preparation of Precursor powders

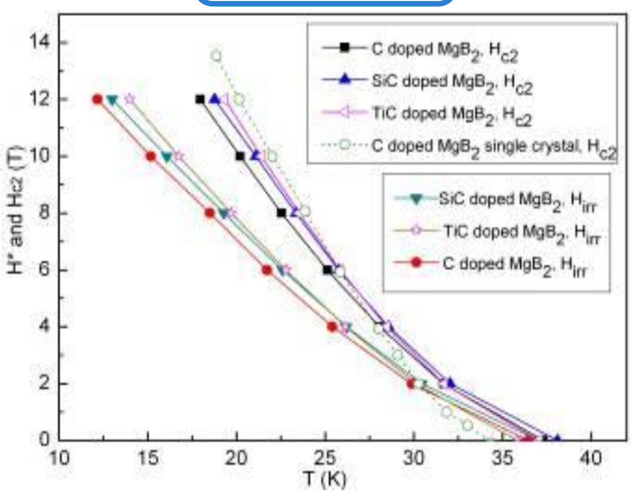
Two-step reaction method

Synthesis flow chart of the two-step reaction method







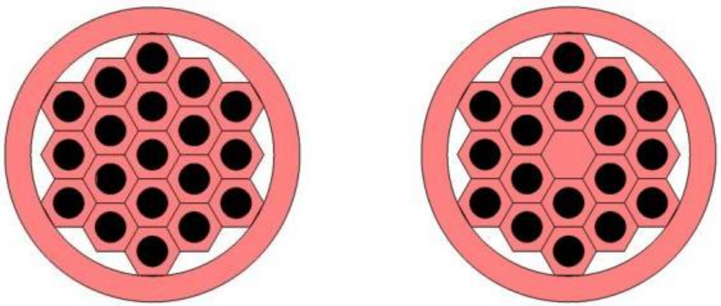


The two-step reaction method is beneficial to the preparation of chemical doped MgB_2 superconducting materials with high density.

Conductor structure design

Conductor structure design

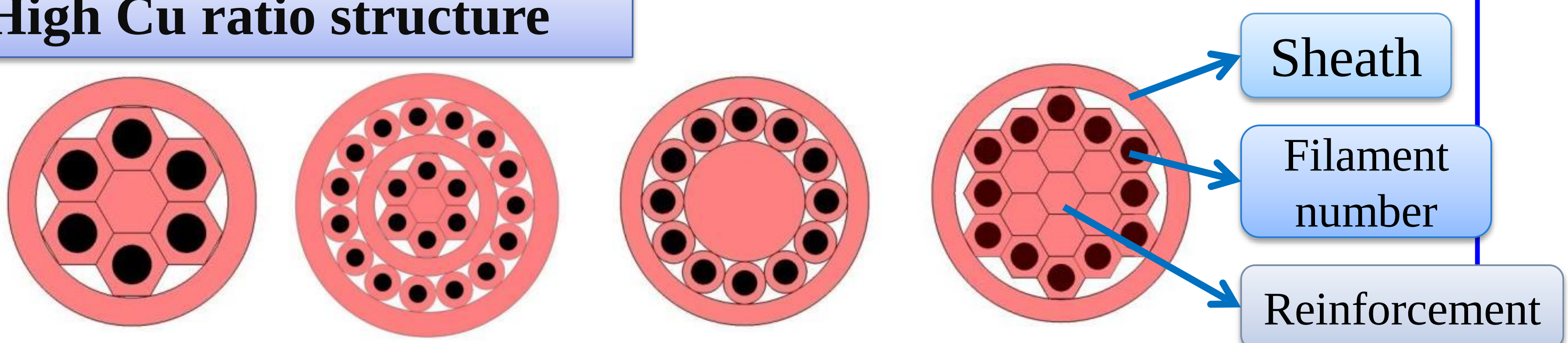
Low Cu ratio structure



Principle:

- ➢ Stabilization
- ➢ Workability
- ➢ Critical current density
- ➢ Satisfaction for various application required

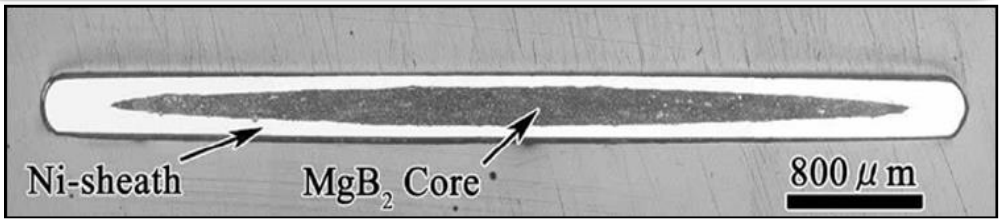
High Cu ratio structure



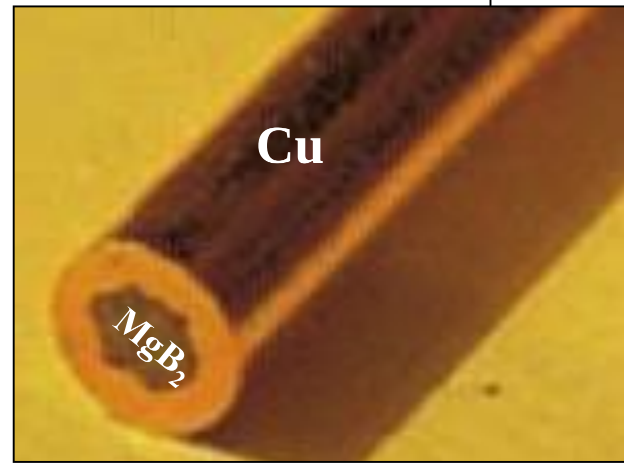
Conductor structure design

Sheath materials

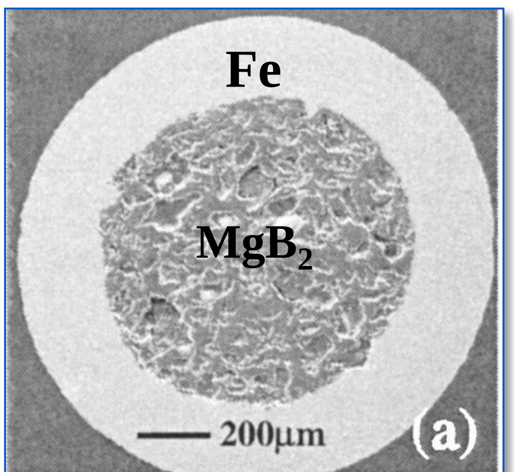
Sheath: Ni, Fe, Cu, Ti, Al, SS…
Barrier: Nb, Fe



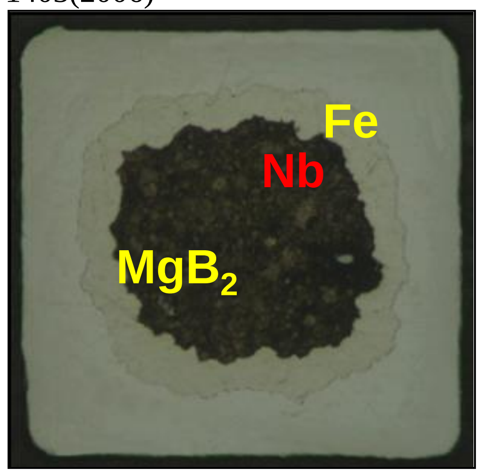
Murase *et al. IEEE Trans. Appl. Supercond.*, 16, 1403(2006)



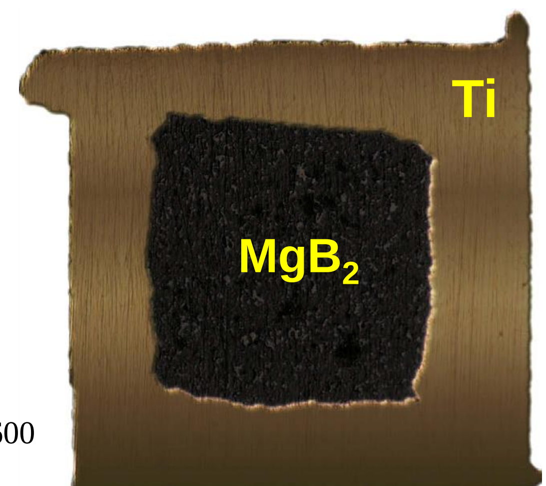
Eisterer *et al.*, *Supercond. Sci. Technol.* 15 (2002) 1088–1091



Pan *et al.*, *J. Appl. Phys.* 96(2004)1150



P Kovac *et al.*, *Supercond. Sci. Technol.* 19 (2006) 600



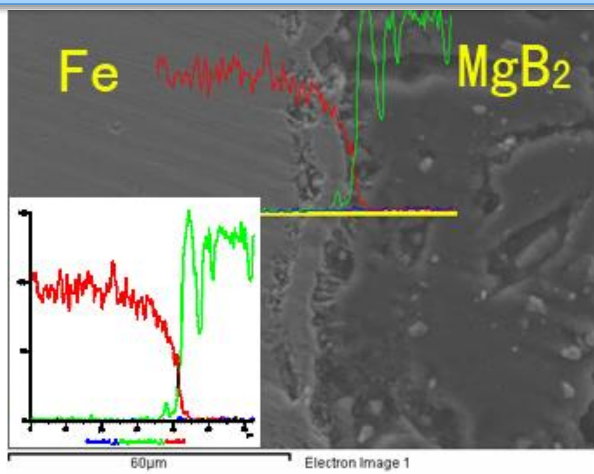
M. Kulich *et al.* *Physica C* 469 (2009) 827–831

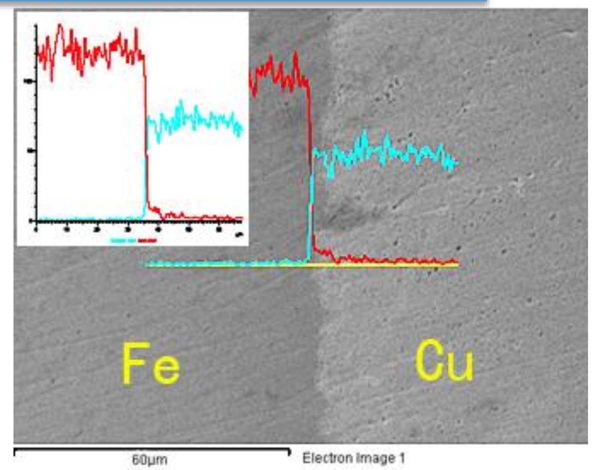
In our study: MgB_2/Nb/Cu

Conductor structure design

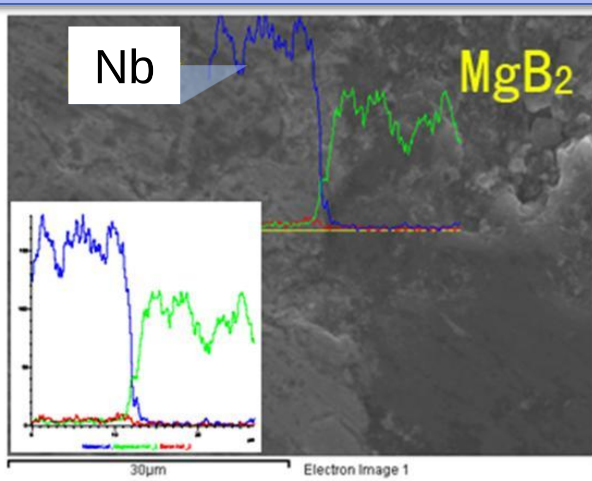
Choice of sheath/barrier materials

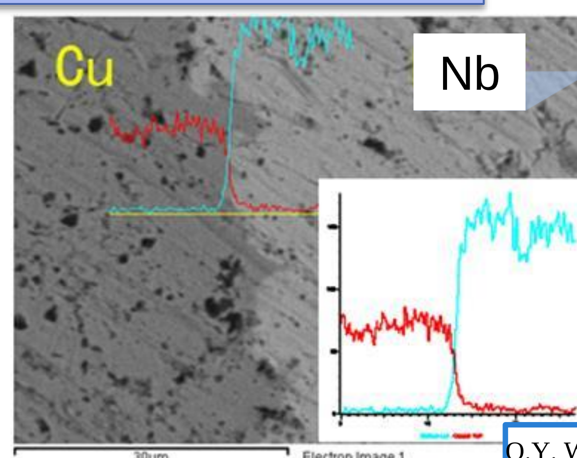
Interface of MgB_2/Fe/Cu after sintering





Interface of MgB_2/Nb/Cu after sintering



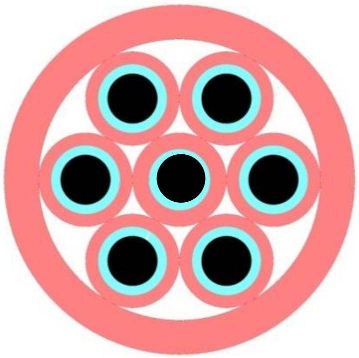


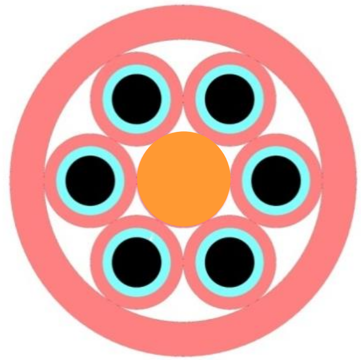
- Diffusion layer appeared between sheath and SC core and obstacled the current transport
- Thinner diffusion layer was obtained, with Nb sheath.

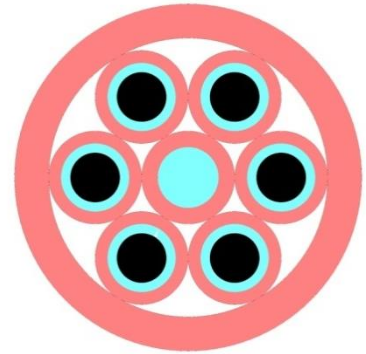
Q.Y. Wang *et al. Rare Metal Mat. Eng.*, 2013, 42(5): 0881-0884

Conductor structure design

Central reinforcement Materials





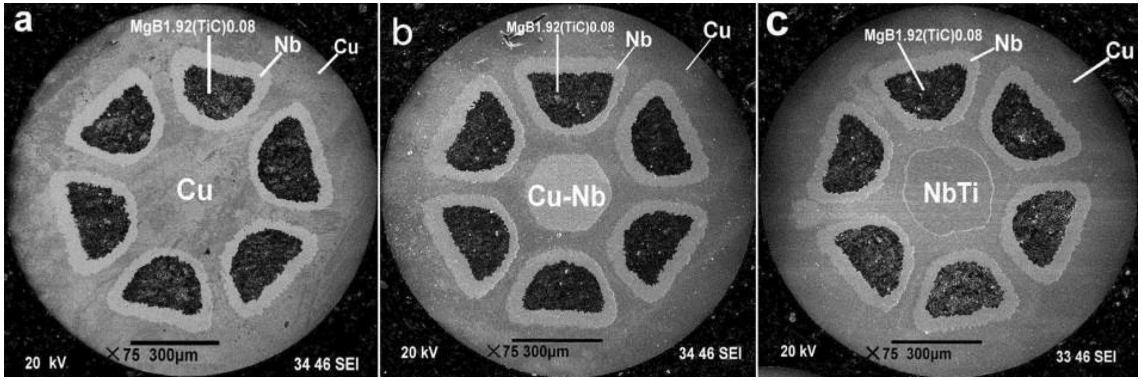


7-MgB_2 filaments

Central filament
easily be broken

6-MgB_2 filaments
+Cu reinforcement

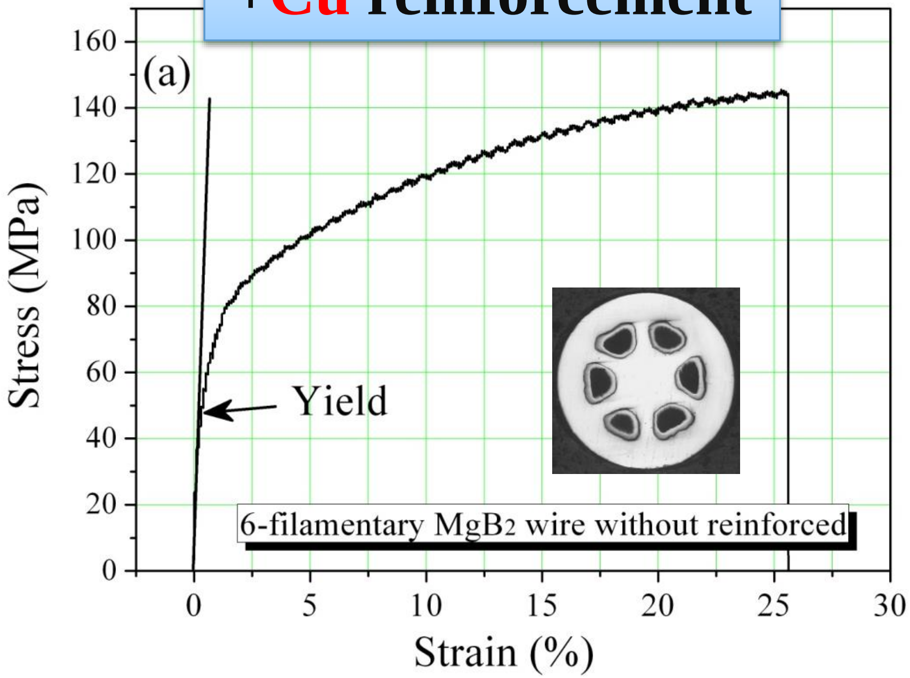
6-MgB_2 filaments
+ Nb or NbTi
reinforcement



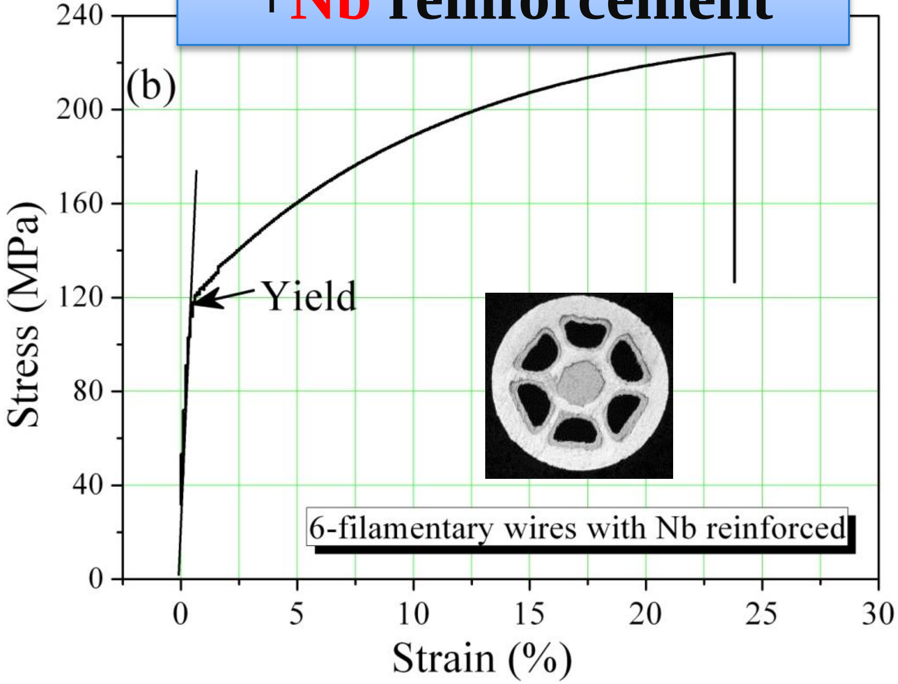
Conductor structure design

Mechanical Properties

6-MgB_2 filaments +Cu reinforcement



6-MgB_2 filaments +Nb reinforcement



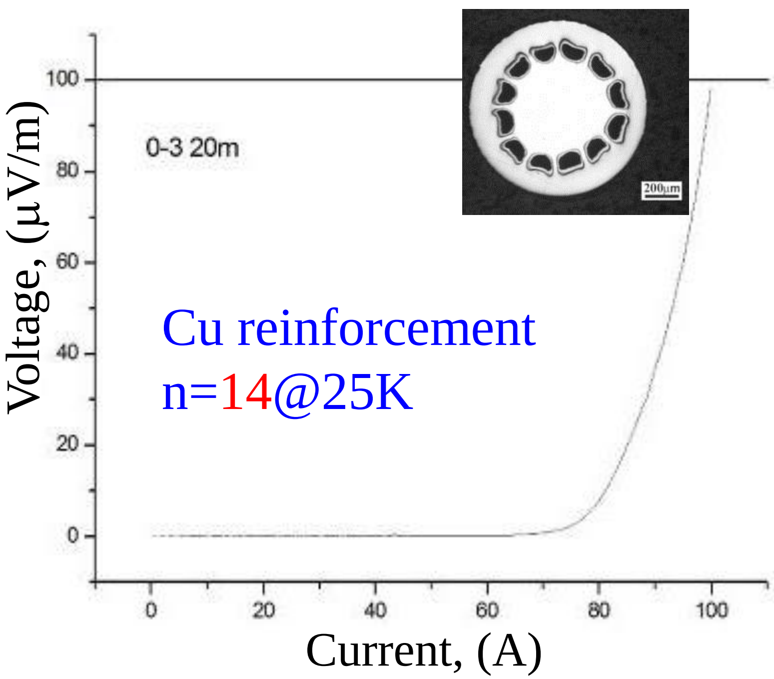
- Nb reinforced wire exhibits higher mechanical properties. The yield strength of the Nb reinforced wire is about **120 MPa** and only **50 MPa** for the wires with Cu reinforced.
- The Nb reinforcement could remarkably enhance the mechanical property of the 6 filaments MgB_2 wires.

C.S. Li *et al. Physica C* 494 (2013) 177–180

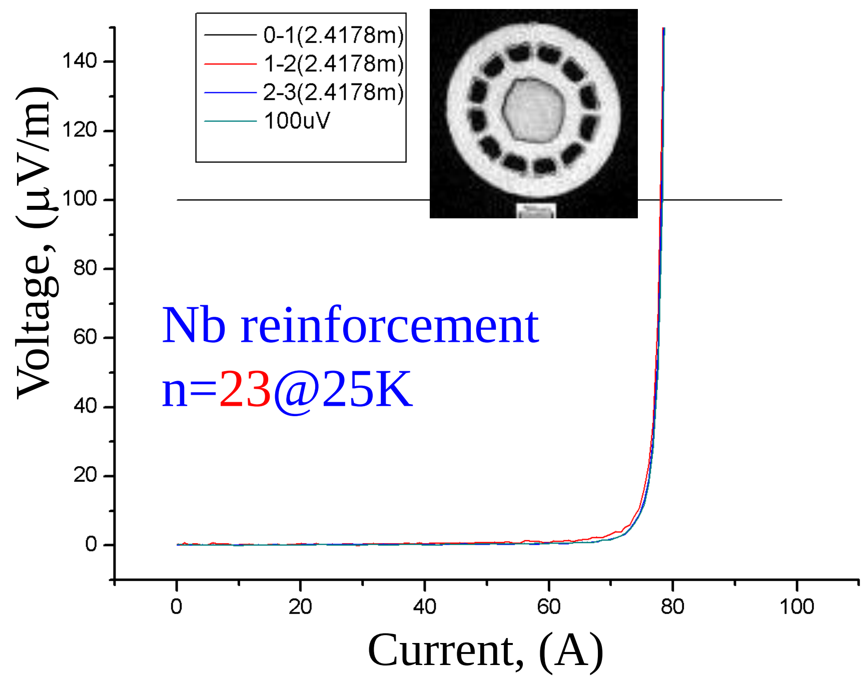
Conductor structure design

Thermal stability

12-core MgB_2 +Cu reinforcement



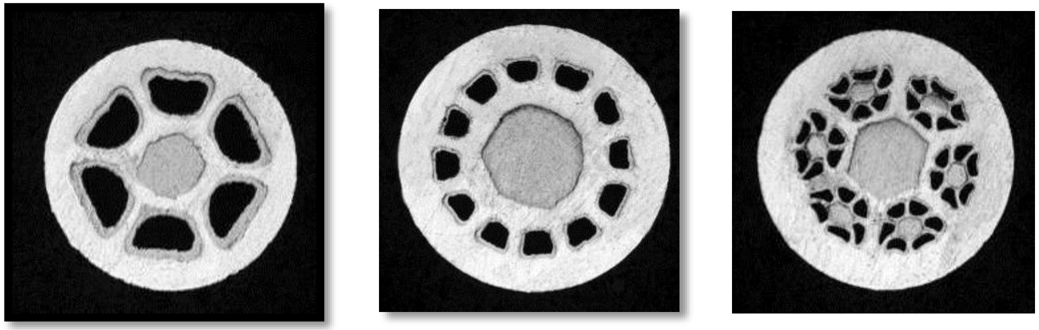
12-core MgB_2 + Nb reinforcement



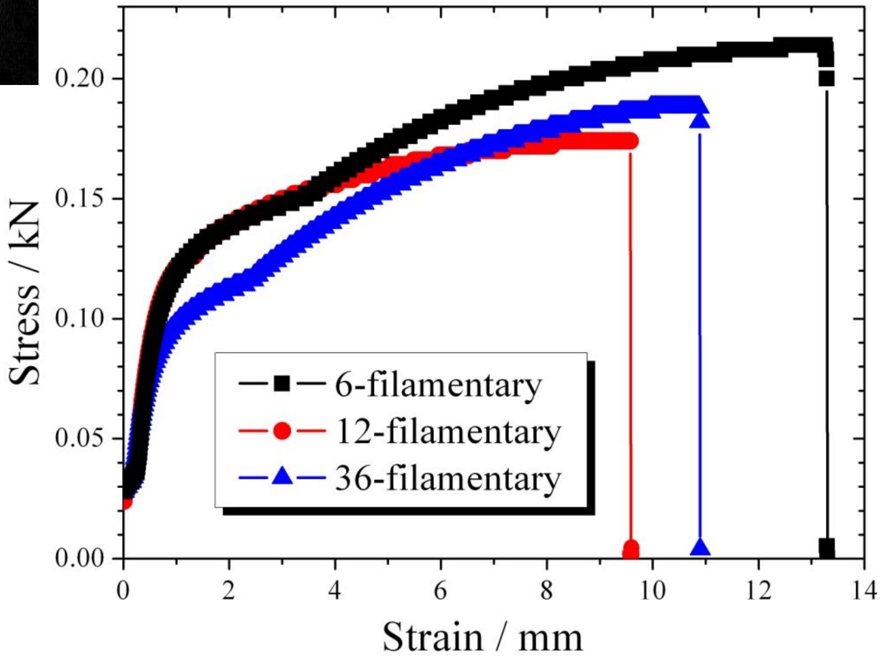
Nb reinforcement is also prone to improve the ***n* value** and **homogeneity** of superconducting wires.

Conductor structure design

Different Filament Numbers



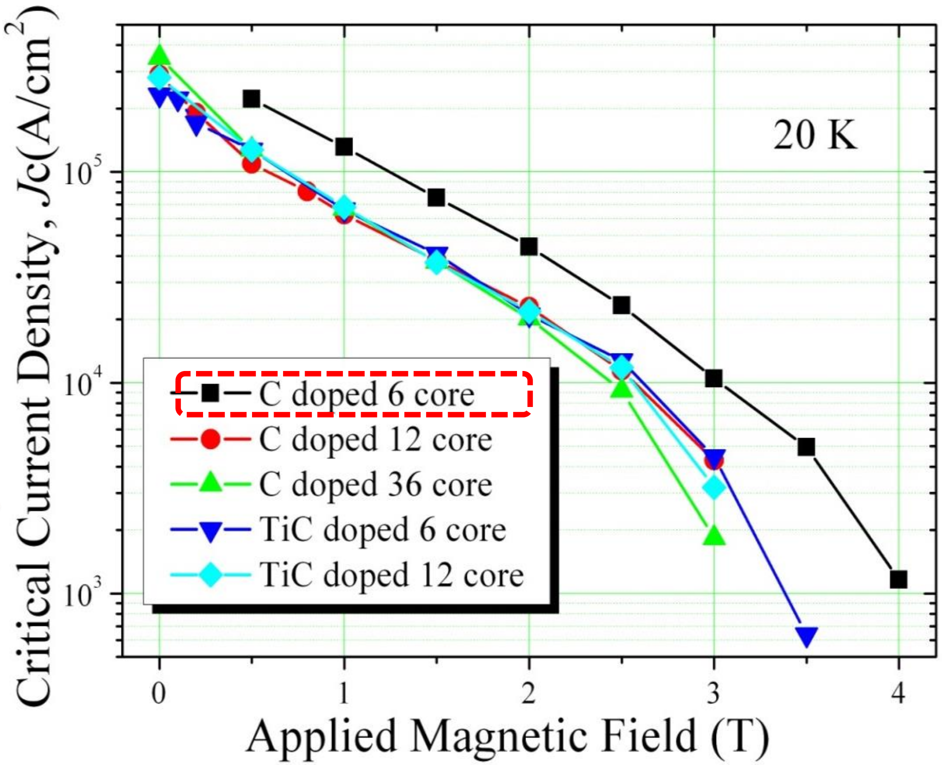
Filament	6	12	36
MgB_2	21.89	14.14	13.95
Nb	23.61	21.88	20.97
Cu	54.50	63.98	65.08



The intensity of 6 filaments wire is higher than that of other wires due to much higher Nb content.

Conductor structure design

Transport properties

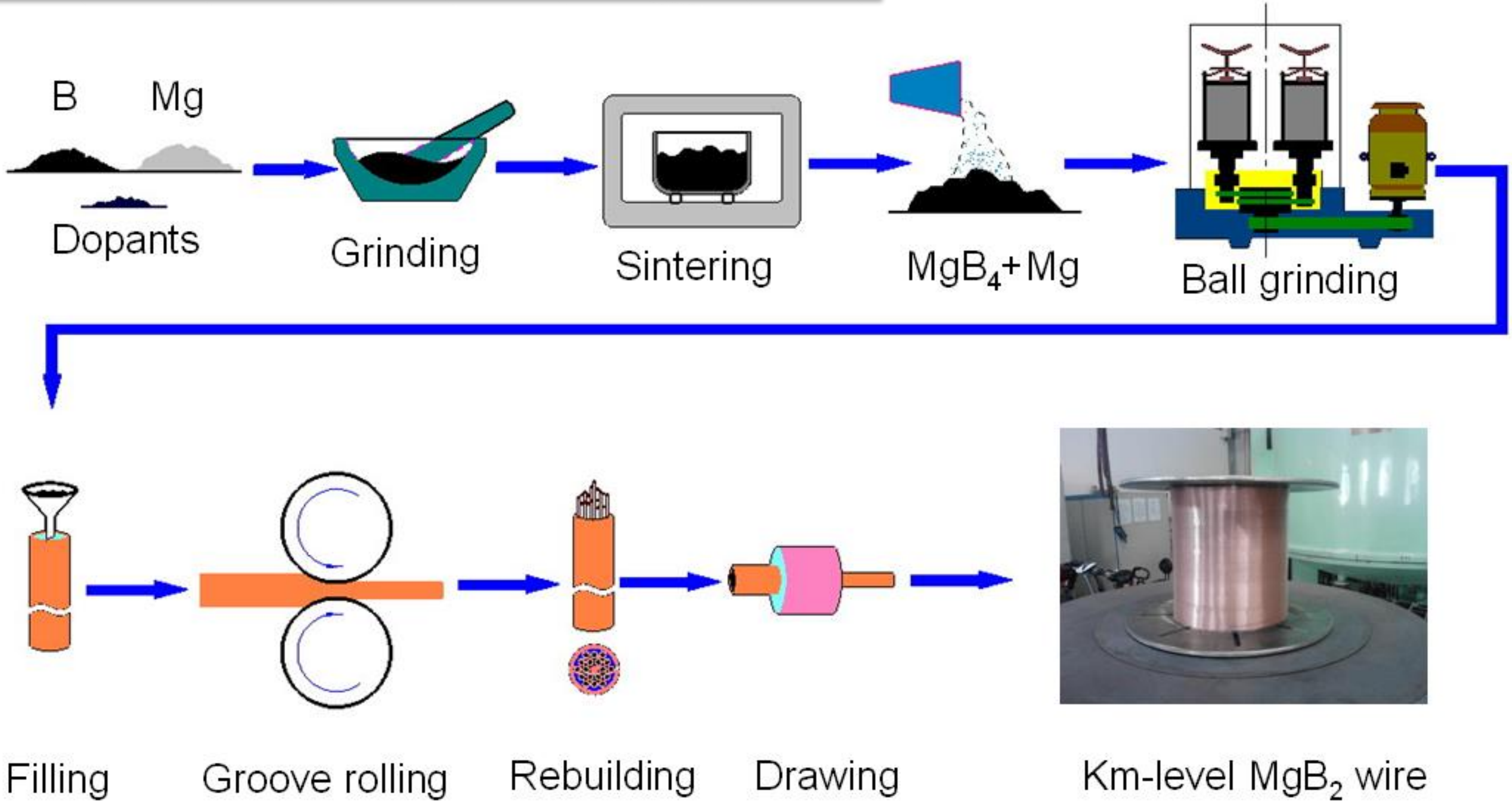


✓ J_c is influenced by filament number;

✓ The optimal filament number is 6-filament.

Fabrication of *km*-grade MgB_2 wires

In-situ PIT process for MgB_2 long wires

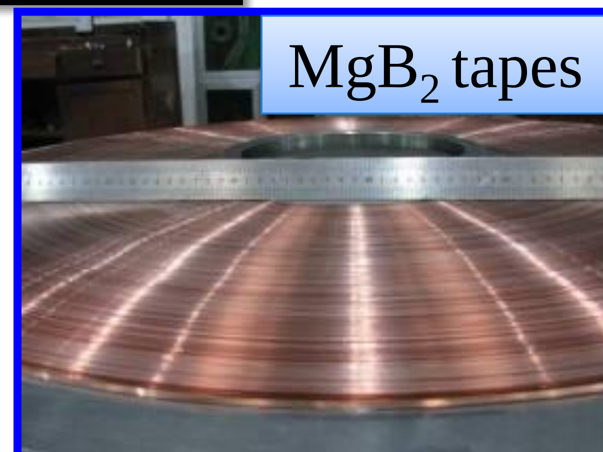


Fabrication of *km*-grade MgB_2 wires

Production of **1500 m** MgB_2 wires/tapes

MgB_2 wires

MgB_2 wires

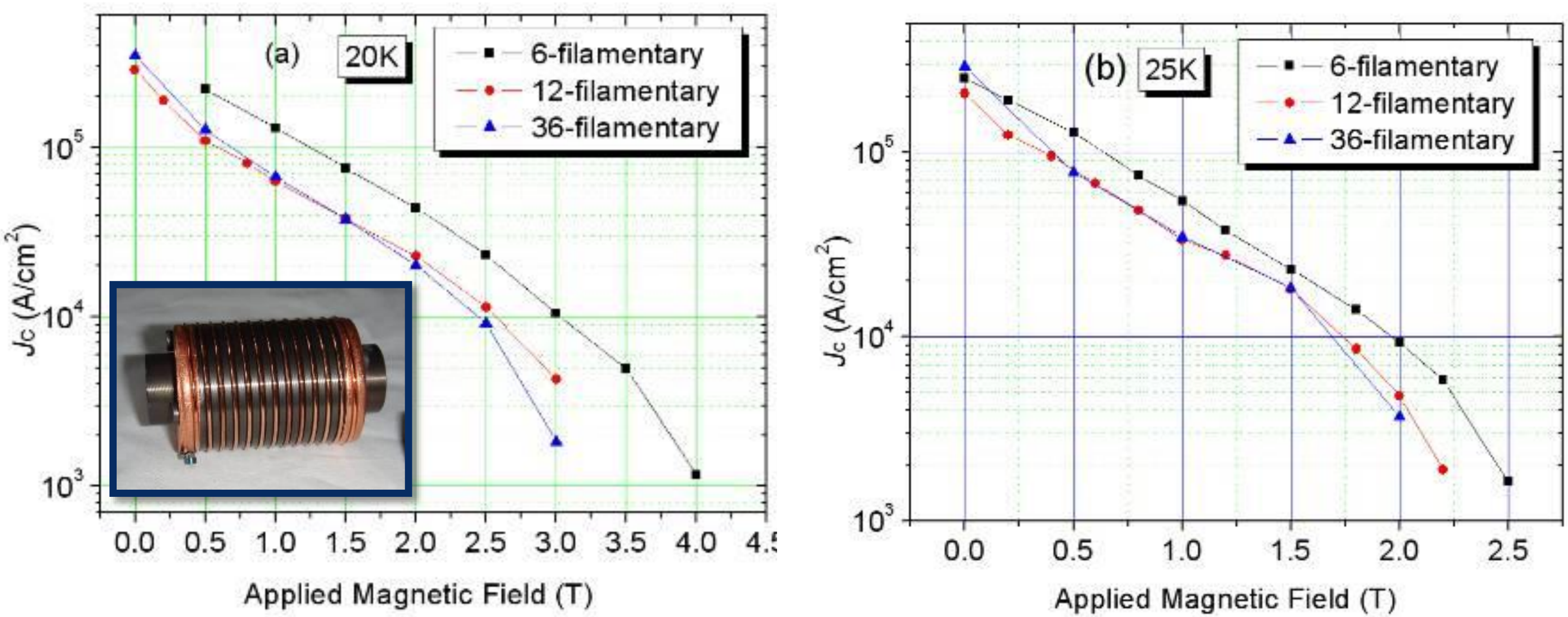


MgB_2 tapes

The preparation technology of kilometer MgB_2 wire is stable, we have prepared **20 kilometers** MgB_2 superconducting wires.

Fabrication of *km*-grade MgB_2 wires

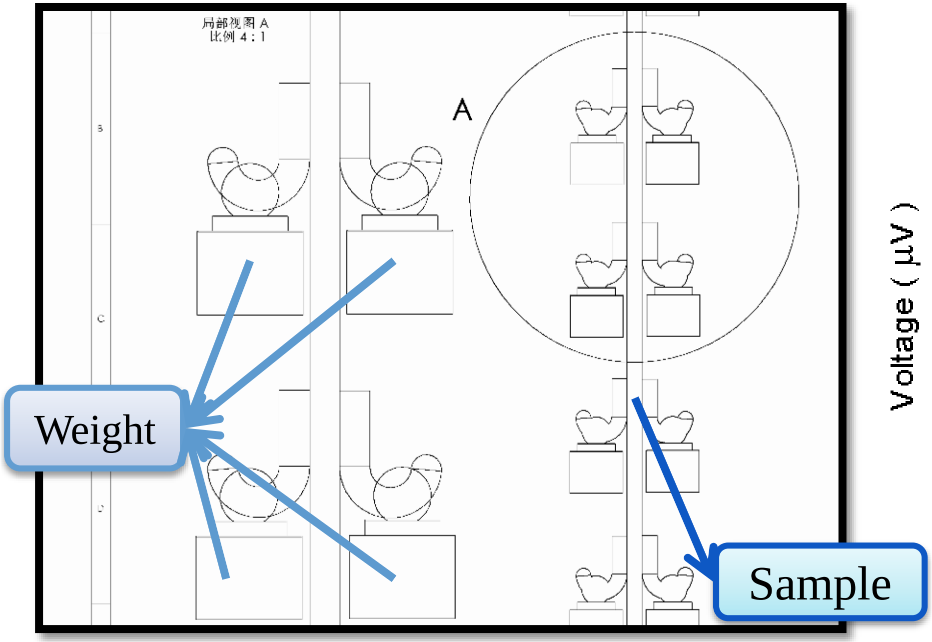
Superconducting Properties of km-grade wires

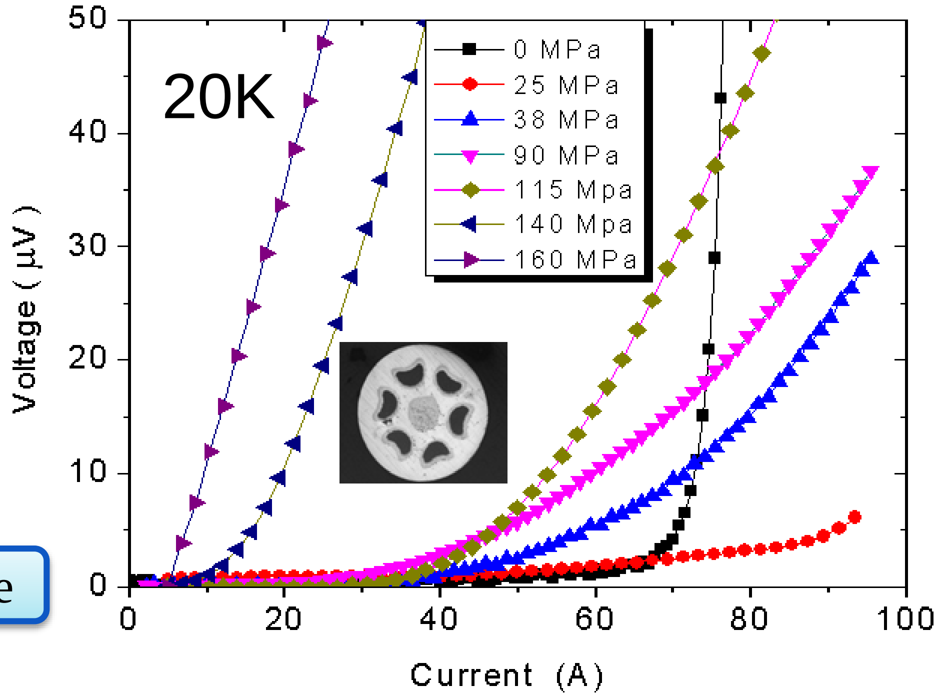


Now we can produce 1500 meter MgB_2 superconducting wires.
At 20 K、2 T, J_c= 43, 000 A/cm^2.

Fabrication of *km*-grade MgB_2 wires

Stress dependence of J_c---Tensile Stress

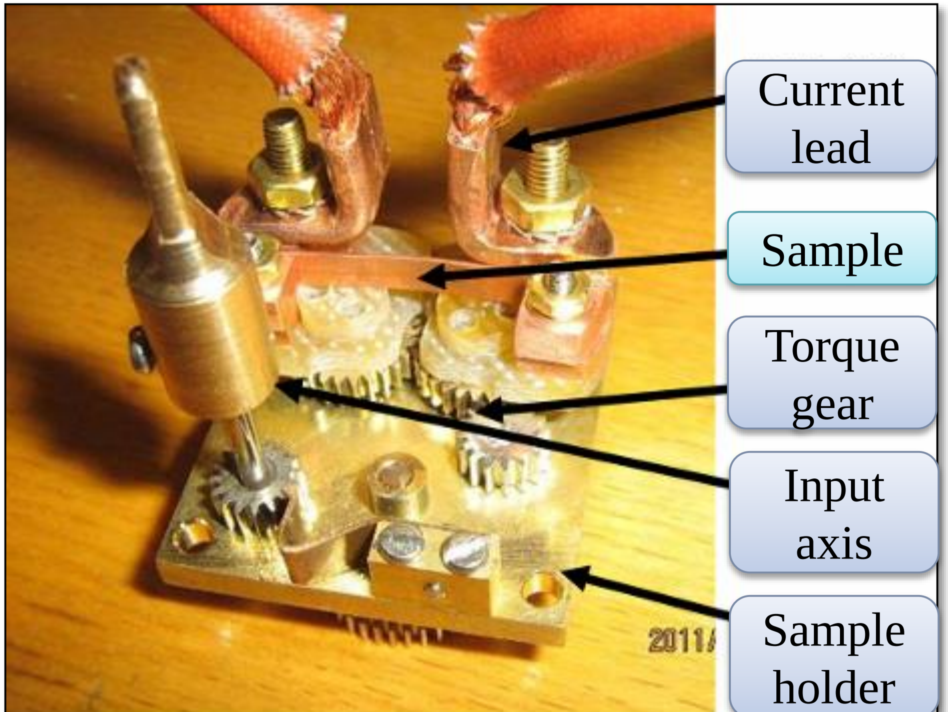


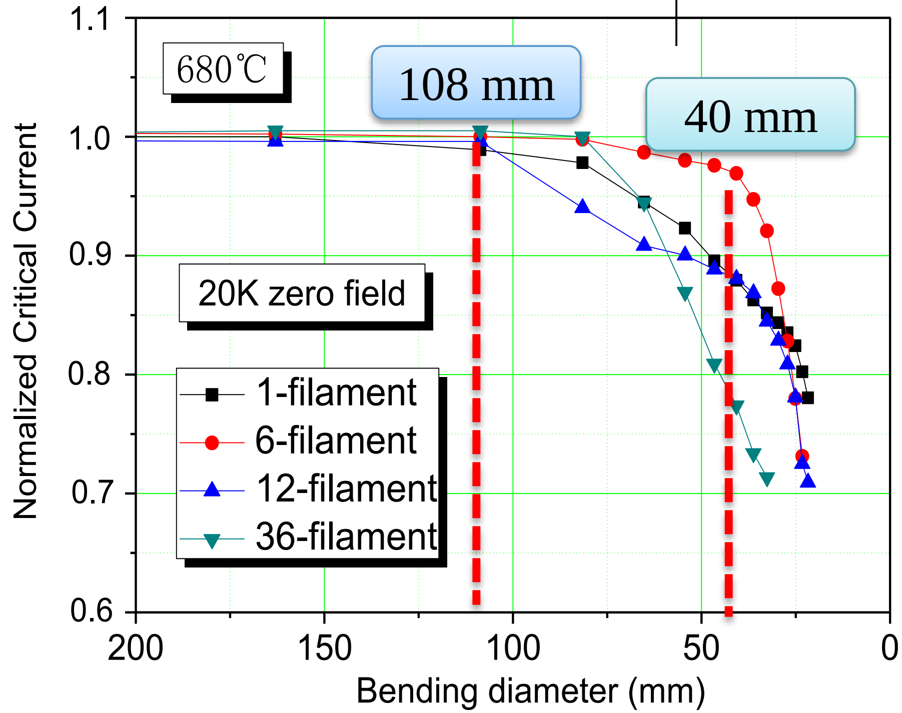


- ✓ In the elastic range, the effect of deformation on I_c is smaller, I_c decreased slowly; In the plastic range, I_c decreases sharply.
- ✓ When the strength of 167 MPa, the superconductivity losses completely.

Fabrication of *km*-grade MgB_2 wires

Stress dependence of J_c--Bending Stress





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- ✓ For all the wires, the critical current density has no loss when the radius is larger than 108 mm.
- ✓ Bending has smaller effect on the 6-filament wires when bending radius is larger than 40 mm.

Conclusions

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- Both the size and shape of Mg affects the density of MgB_2, as well as the superconducting properties.
- Nb reinforcement is good to improve the superconducting properties and strength of MgB_2 wires.
- 20 kilometers MgB_2 wires have been successfully produced by scale fabrication technique at NIN, which are with a J_c of 43000 A/cm^2 (±5%) at 20 K and 2 T.
- For all the wires, the J_c has no loss when the radius is larger than 108 mm; and 6-filament Nb-reinforcement wires have better bending properties, it has the smallest bending radius, up to 40 mm.

Thank you for your attention