WAMS 2004

March 22-24, 2004, Archamps, France

Status and Perspectives for Technical Use of MgB_2 Conductors

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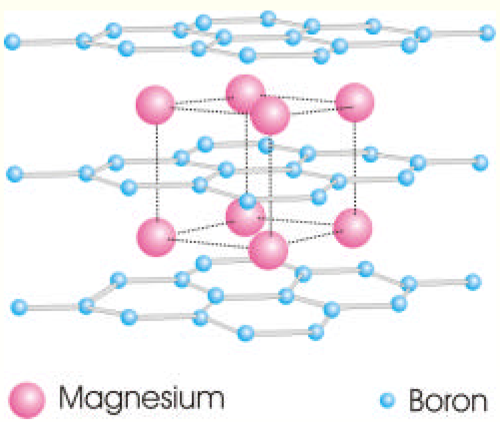
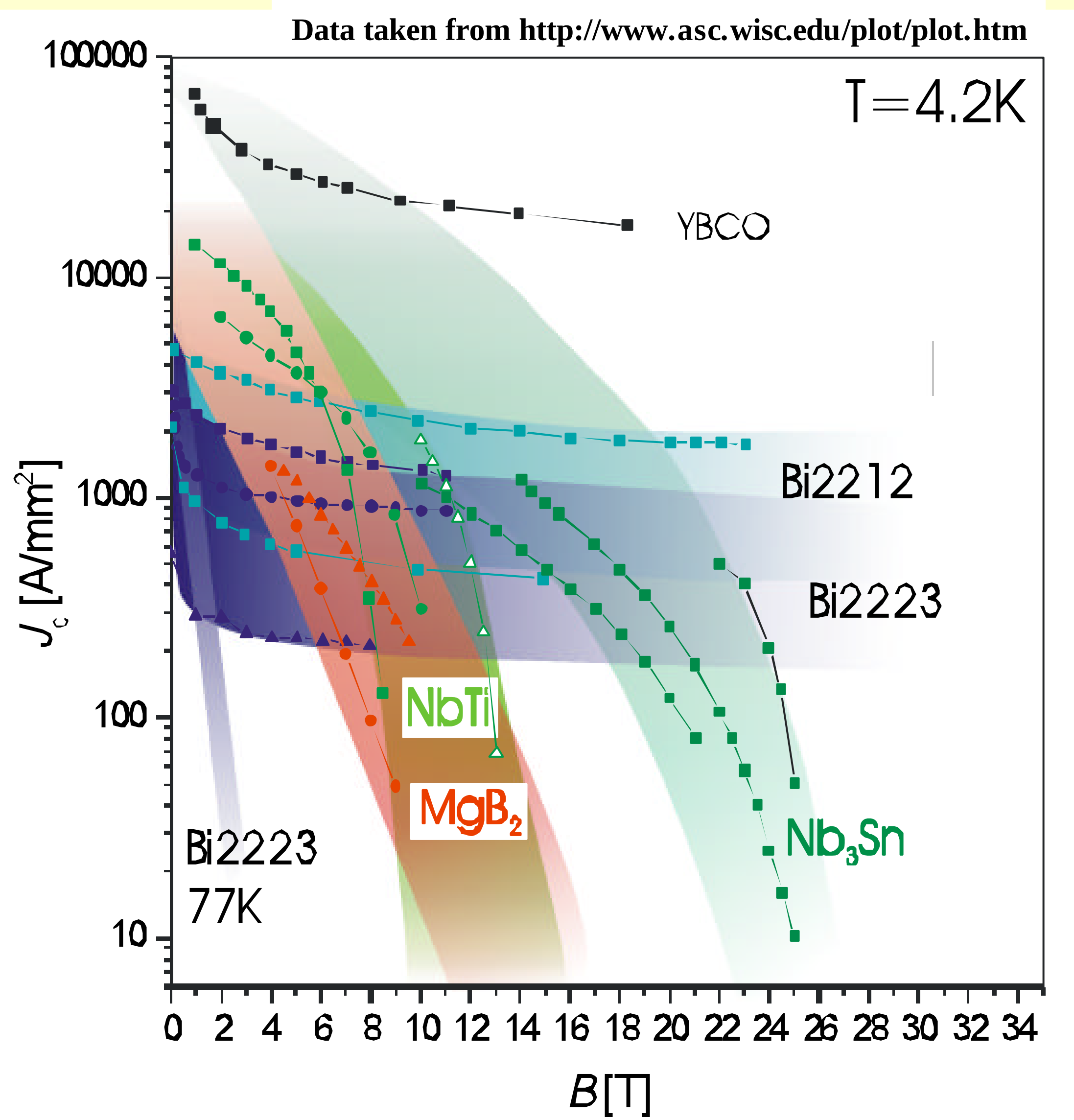
Heinrich Orschulko, Hans Reiner, and Silke Zimmer

MgB$_2$: „Genie in a bottle“ (R.J. Cava, 2001)

- $T_c = 39$ K
- no weak-link behavior
- cheap



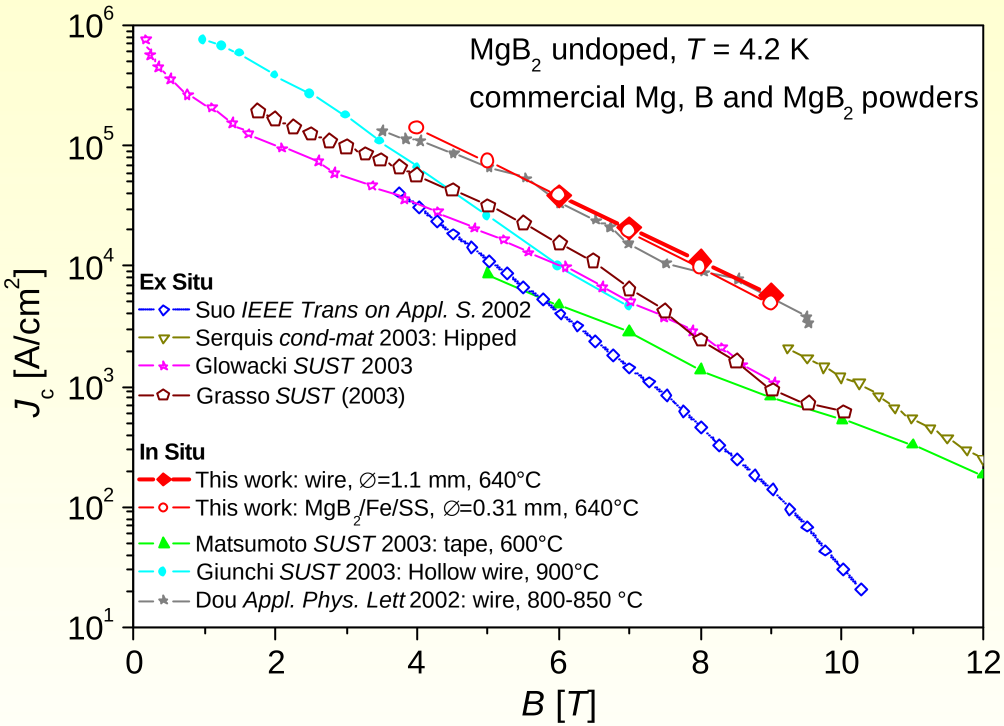


State of the Art for Powder-In-Tube (PIT) Conductors

- Two Routes:
  - *Ex situ*:
    - Prereacted MgB_2-powder
    - Phase formation heat treatment not necessary, however: improvement of J_c when heat treated (grain connectivity)
  - *In situ*:
    - Mixtures of Mg- and B-powders
    - Phase formation heat-treatment necessary

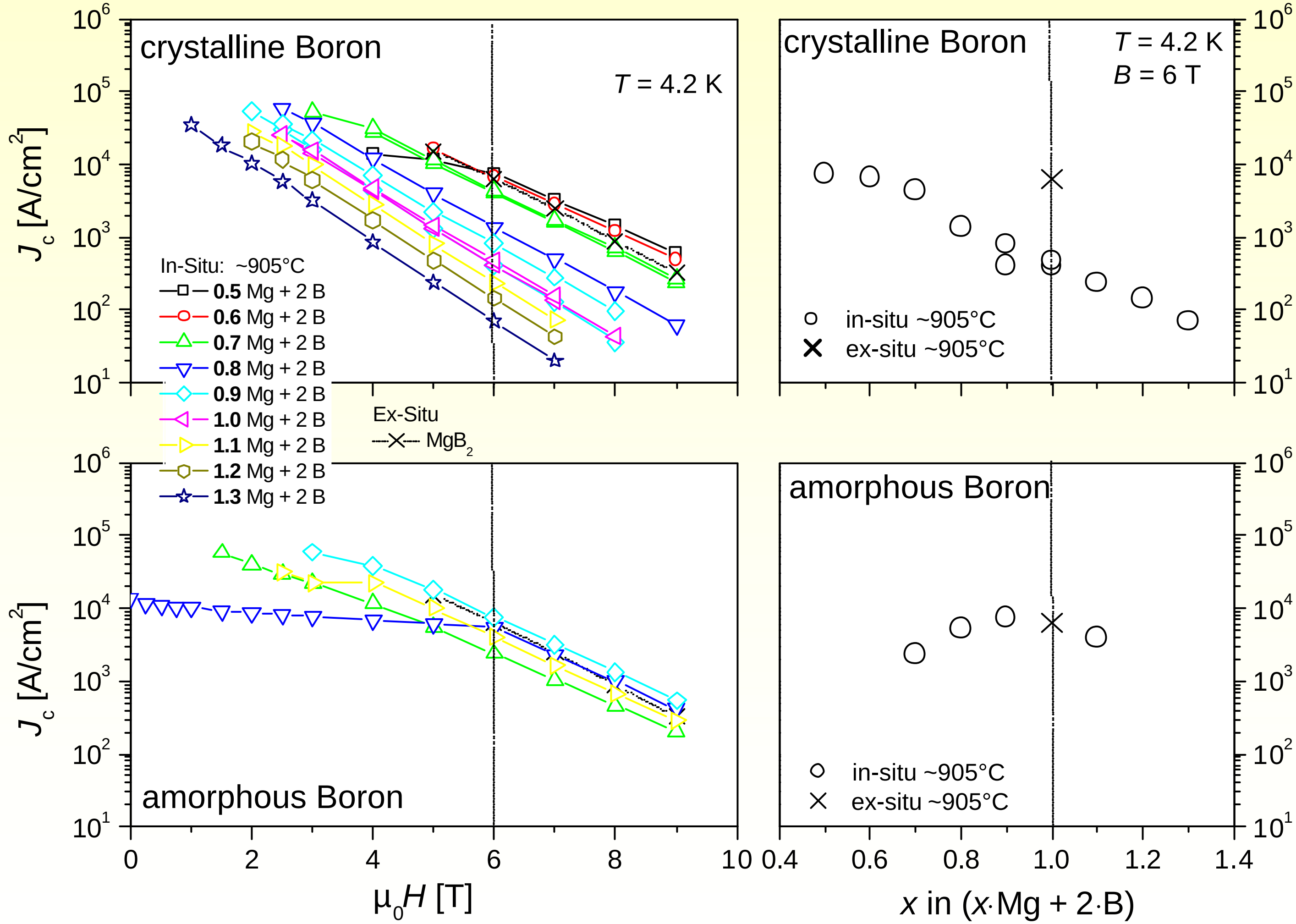
- Sheath Materials:
  - Fe, Cu, Monel, Ni, Nb, Ta, stainless steel and composites of these materials

Challenges for technical MgB_2 PIT conductors:

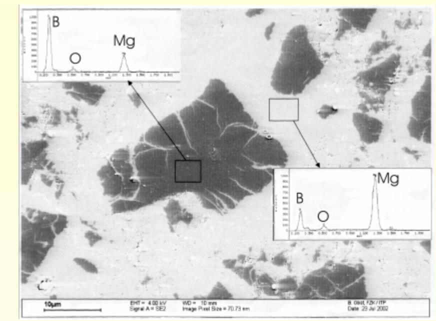


- Increase of $J_c(B,T)$
  - Ideal powder mixture $x \cdot Mg + 2 \cdot B$
  - Homogeneous microstructure
  - Good grain connectivity
  - Small grains
  - Improvement of $B_{irr}(T)$ Pinning centers / doping
  - Improvement of B_{c2} 'Clean' → 'dirty' limit
- Improvement of thermal stability
  - Filament homogenization
  - Multifilament structures
  - Conductive sheath Material
- Improvement of mechanical stabilization

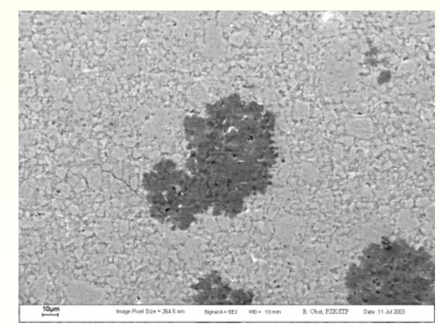
Improvement of $J_c(B,T)$: Precursor: crystalline and amorphous boron powder



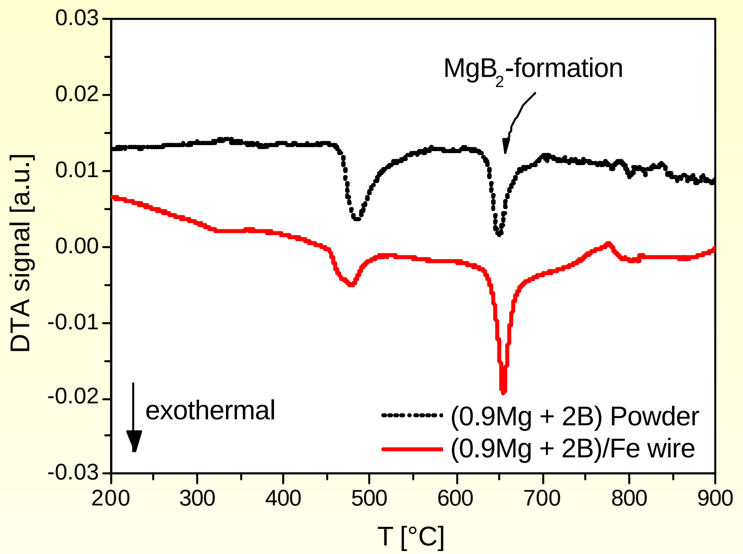
crystalline

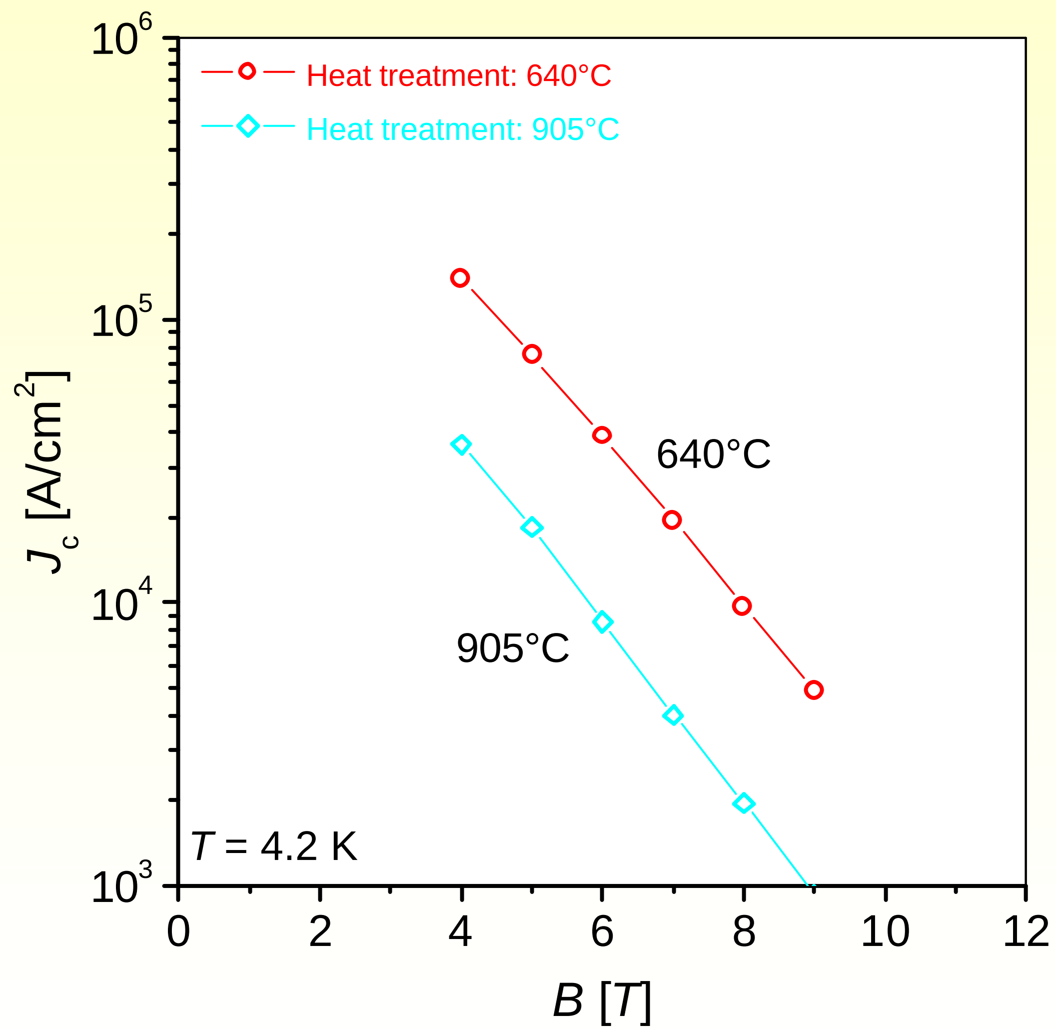


amorphous



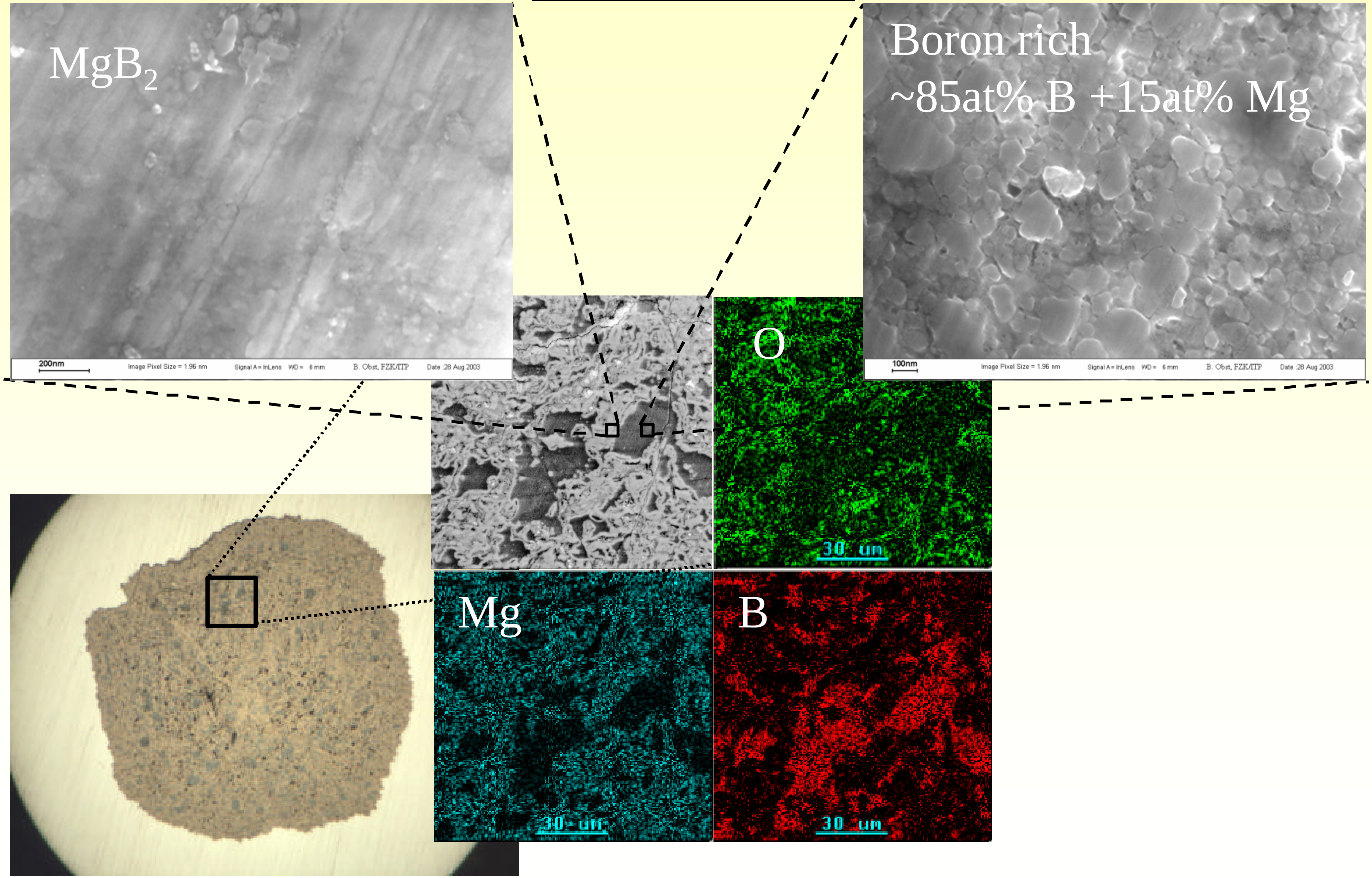
Improved Heat Treatment



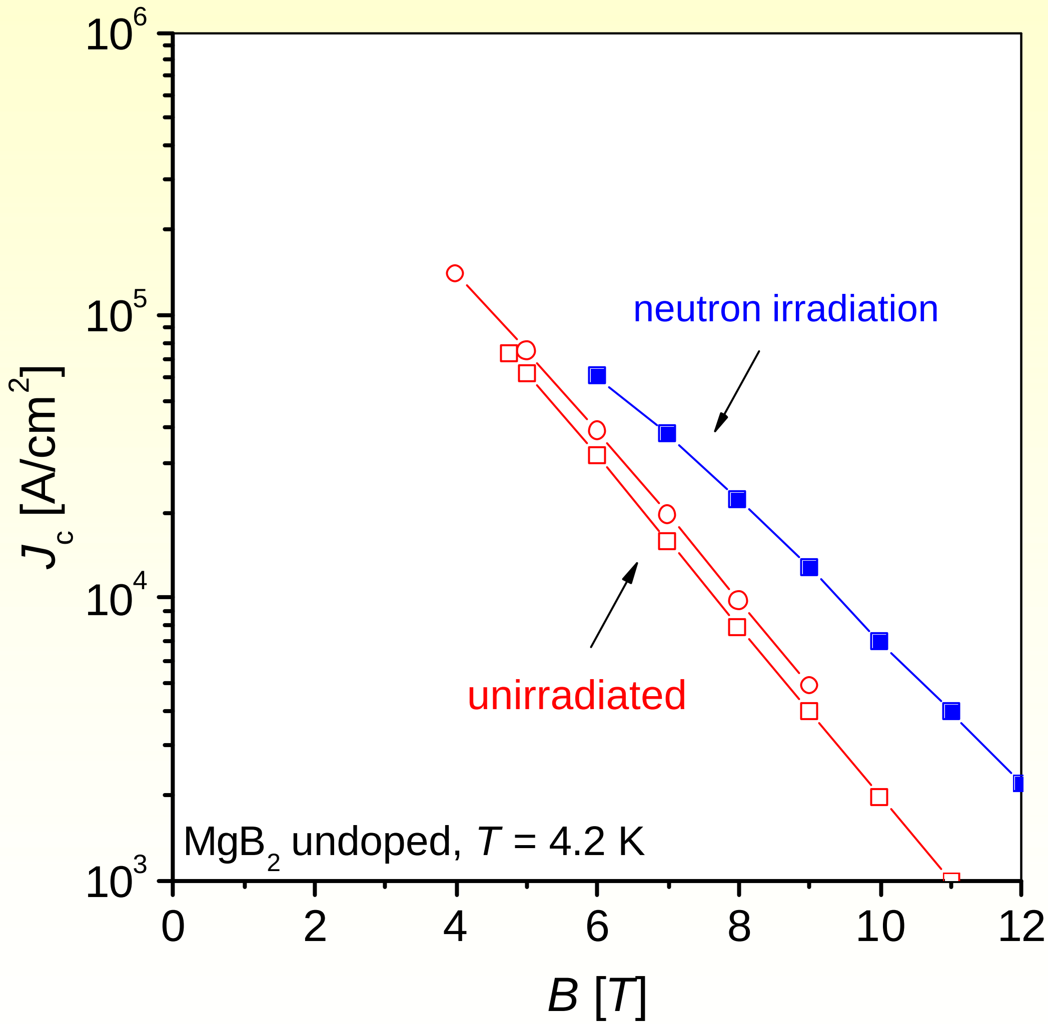


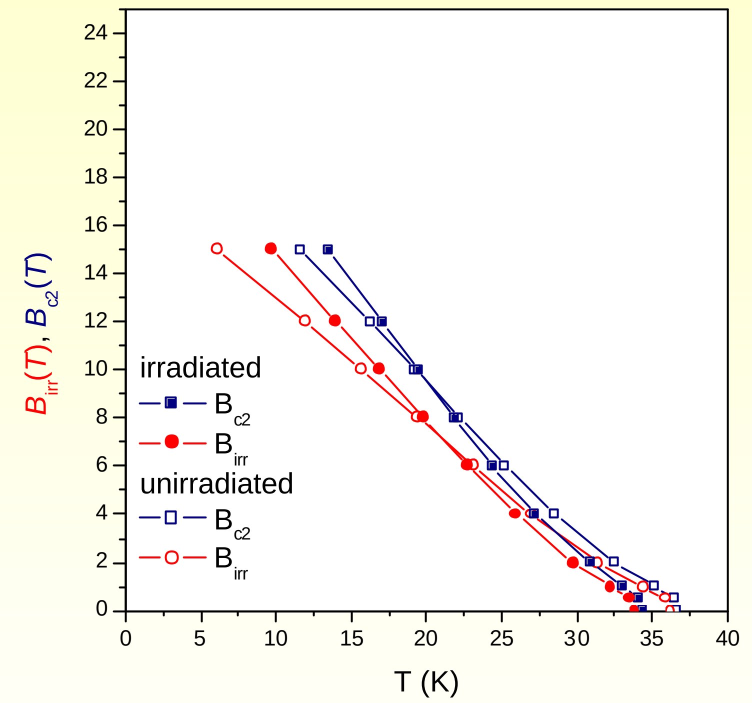
Phase formation temperature around 650°C

Microstructure



Additional Defects by Neutron Irradiation



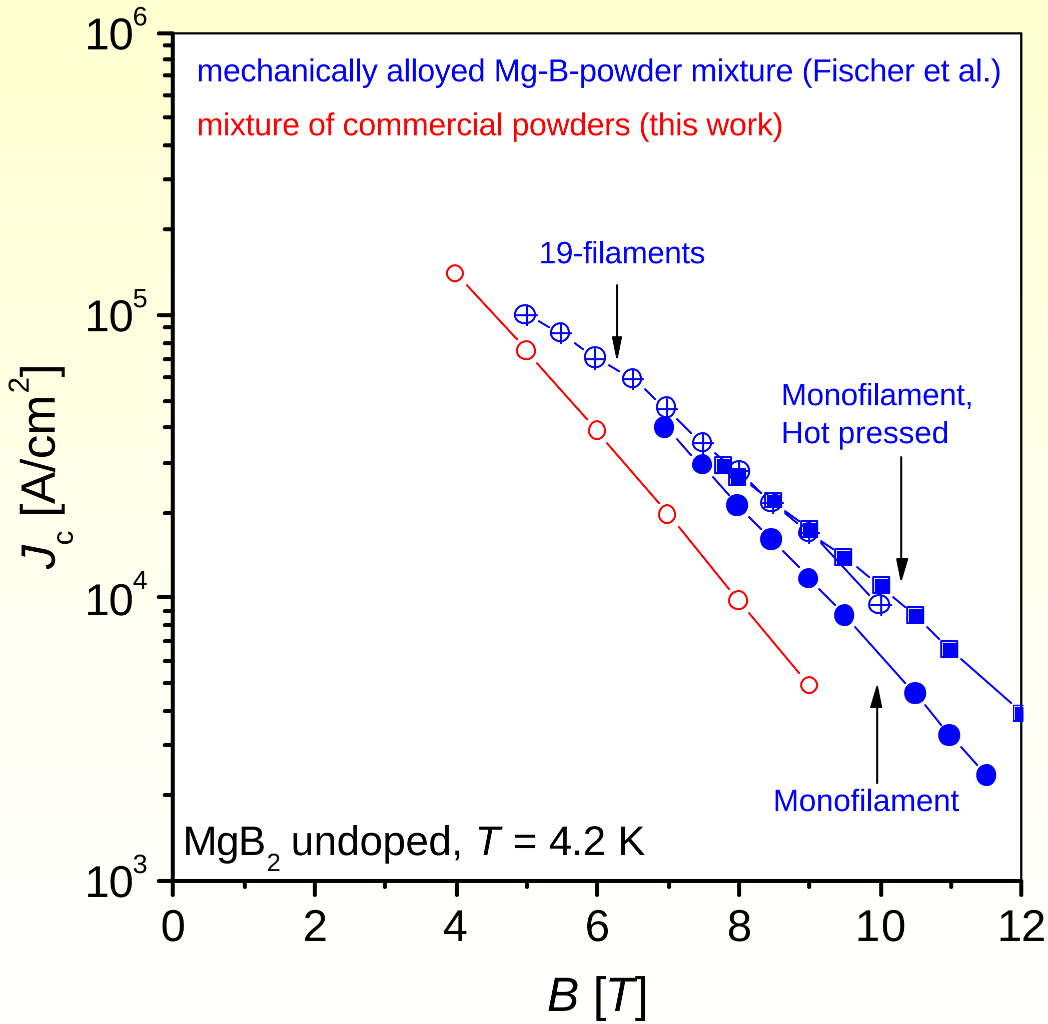


Neutron irradiation:

M. Eisterer and H.W. Weber,
Atomic Institute of the Austrian Universities, Vienna, Austria

Improvement of J_c by mechanical alloying

(Fischer *et al*., Preprint, IFW Dresden)

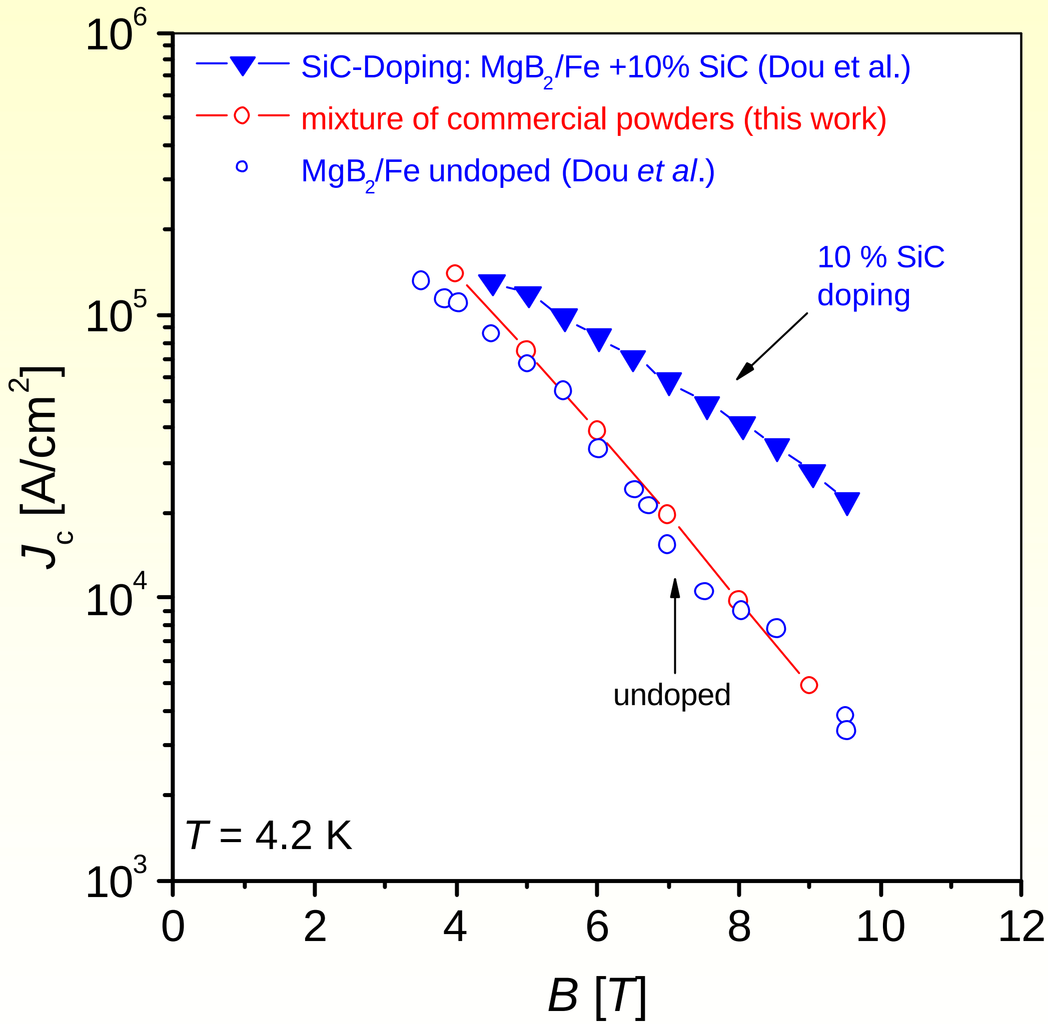


Mechanical alloying:

- Decrease of phase-formation temperature
- Small grains
- Problem: Low T_c

Improvement of $J_c(B)$ by nano SiC doping

(Dou *et al*., Appl. Phys. Lett. 81 (2992) 3419, Wollongong)



Nano SiC-Doping:

- High density of dislocations
- ~10 nm inclusions of SiC and Mg_2Si inside the grains

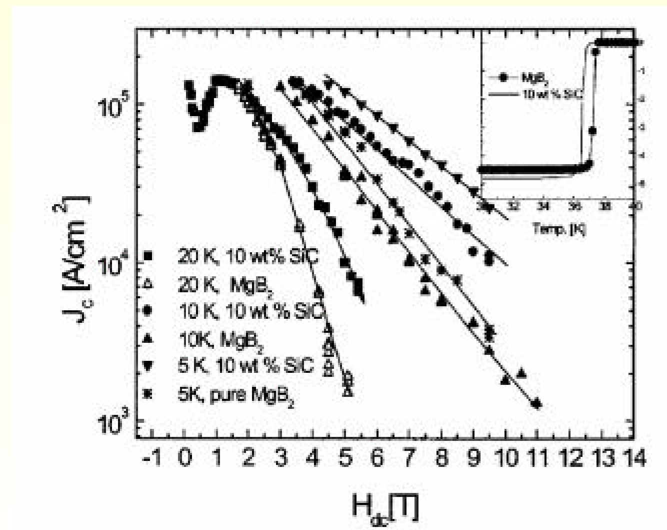
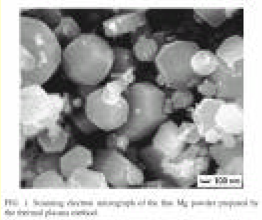
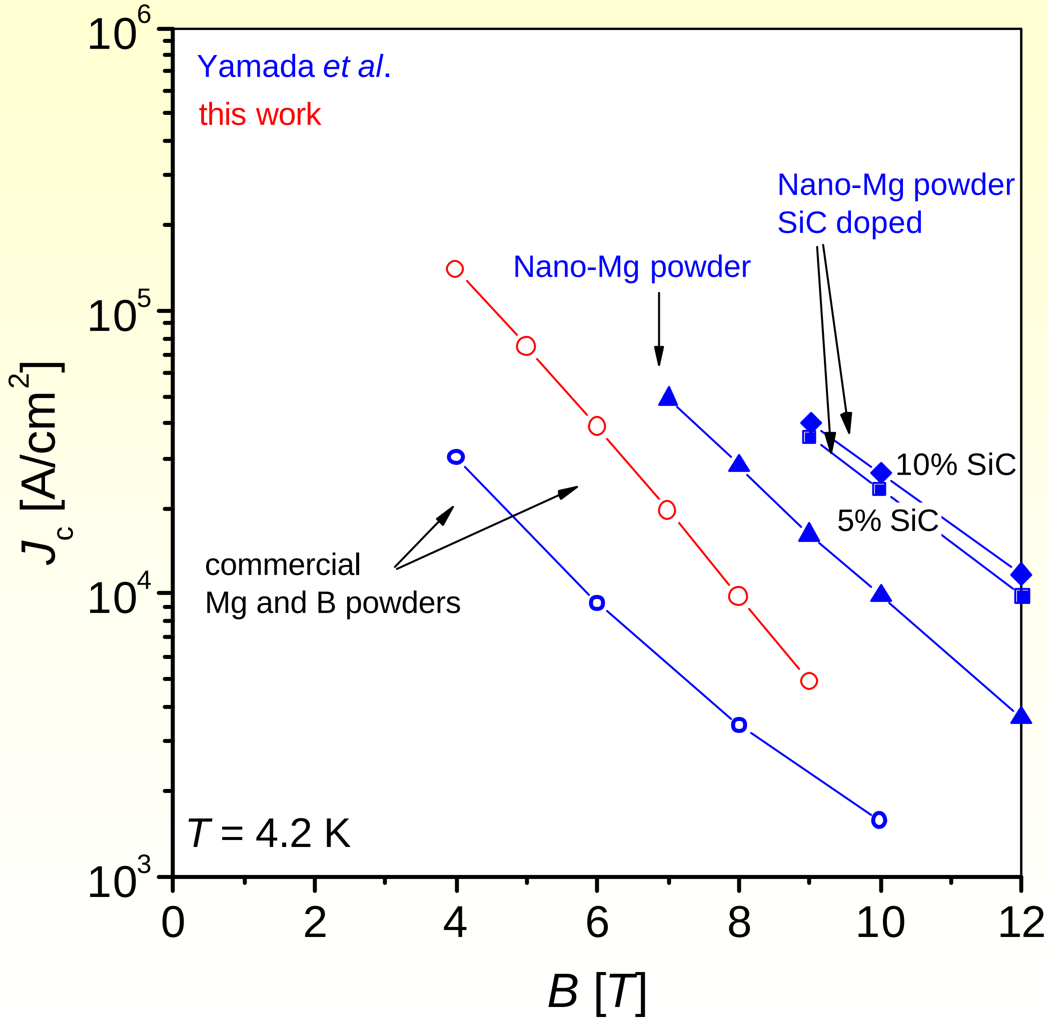


FIG. 4. Transport J_c for SiC doped (sample 5) and undoped MgB_2 (sample 6) wires (the lines only serve for guiding the eyes). Inset shows T_c for these samples.



Improvement of $J_c(B)$ with nano Mg powder

(Yamada *et al.* Appl. Phys. Lett. 84 (2004) 1728)



- Homogeneous phase formation (small Mg grains)
- Less oxygen ingot
- Small MgB_2 grains

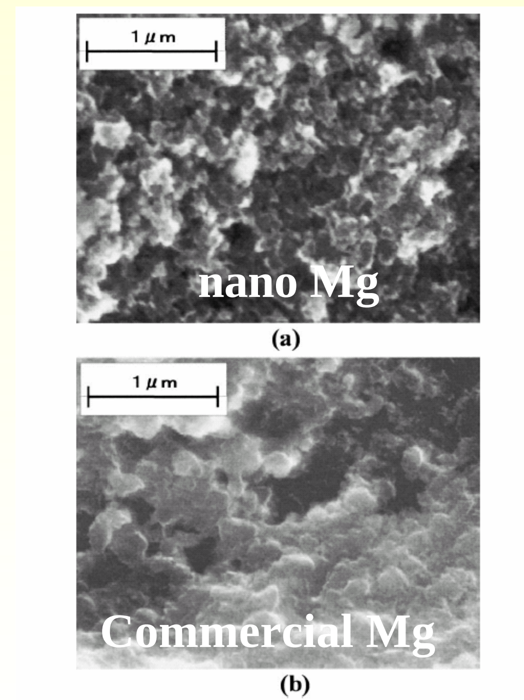
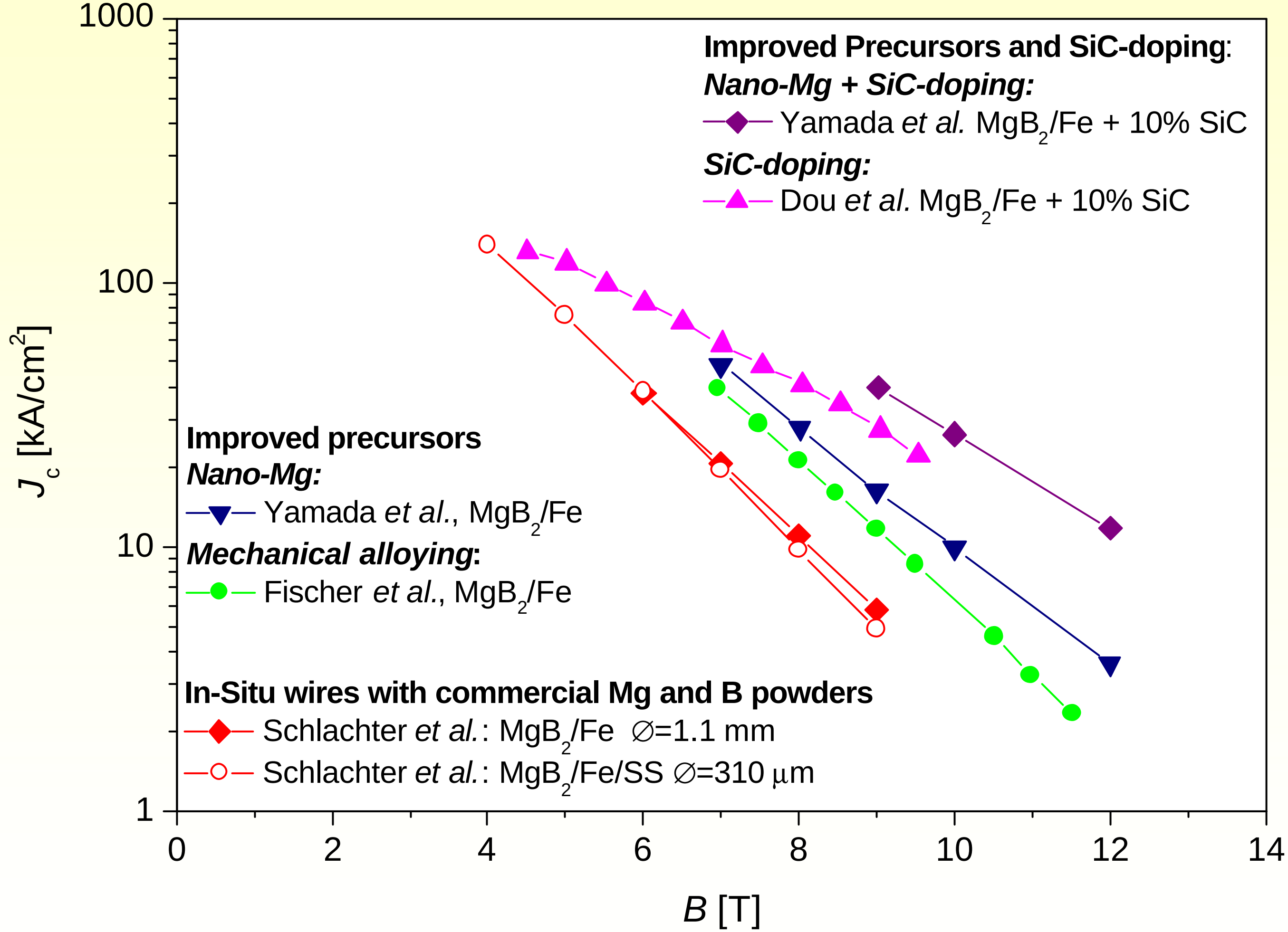
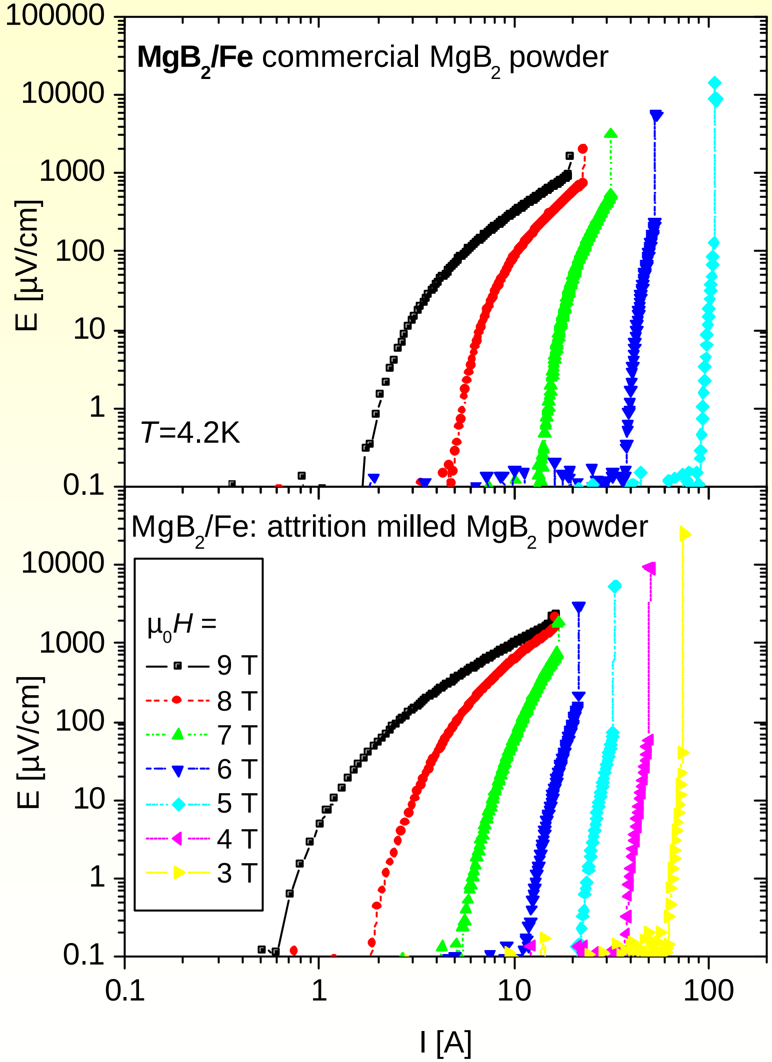


FIG. 4. Scanning electron micrographs of the surfaces of the MgB_2 core removed from tapes heat treated at 600 °C for 1 h. (a) nanometer-size Mg + commercial B; (b) commercial Mg + commercial B.

Comparison of the best $J_c(B)$ data of monofilament MgB_2/Fe wires and tapes



Improvement of thermal stability

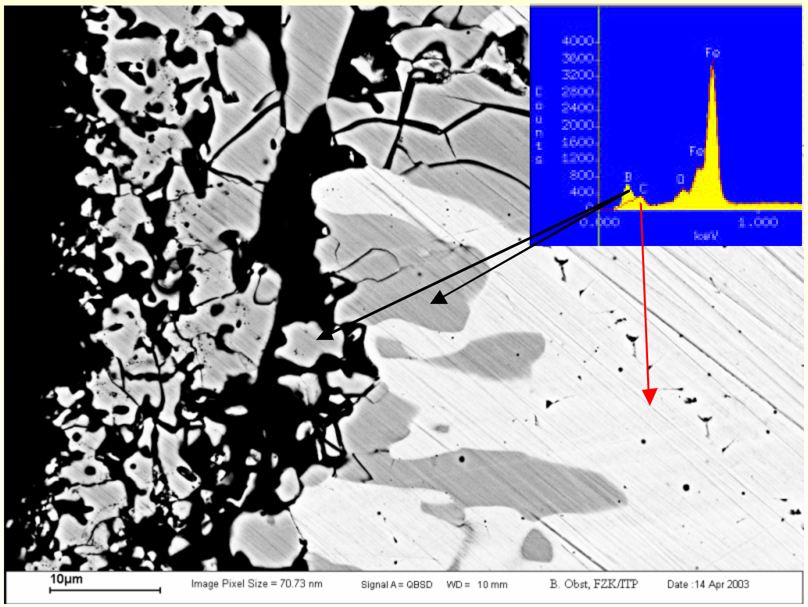


- Improvement of thermal stability:
  - High conductive sheath materials
  - Multifilament structure

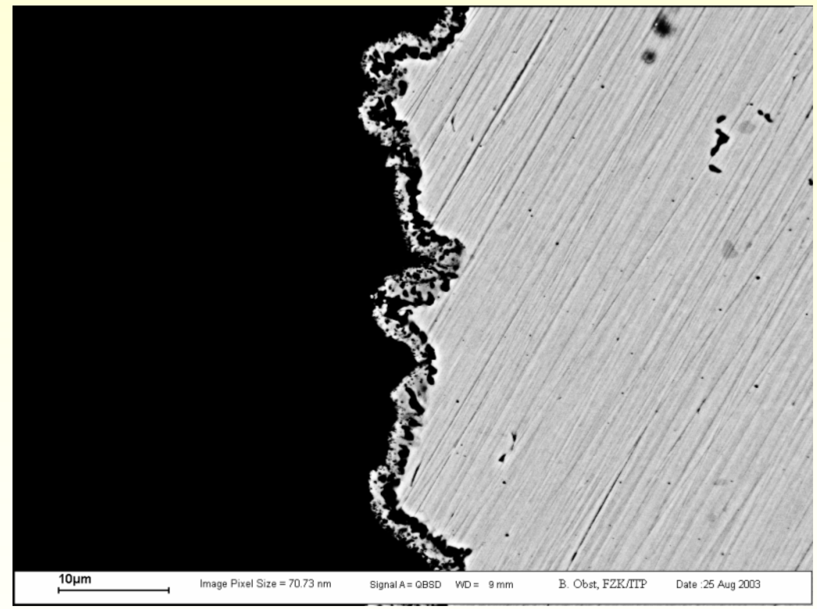
- Challenges
  - ⇒ Small reaction layer at filament sheath interface
    - ⇒ Reduction of phase formation temperature
      - ⇒ Mechanical alloying
      - ⇒ Doping
  - ⇒ MgB_2 phase with small grains for small filaments

Interface Filament - Sheath

Heat treatment: **905°C**
→Thick reaction layer

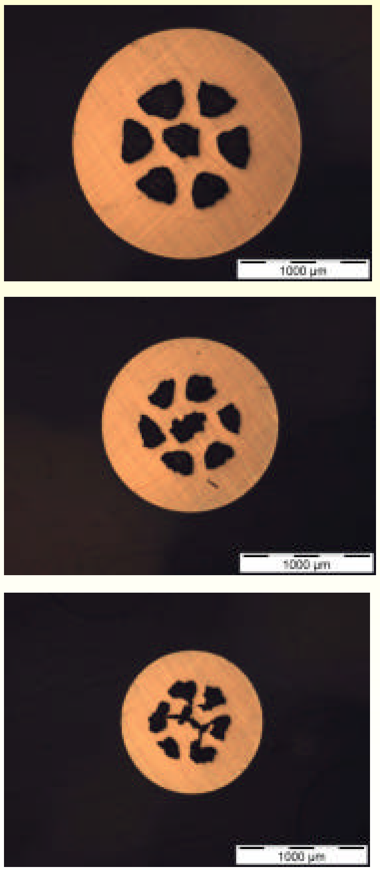


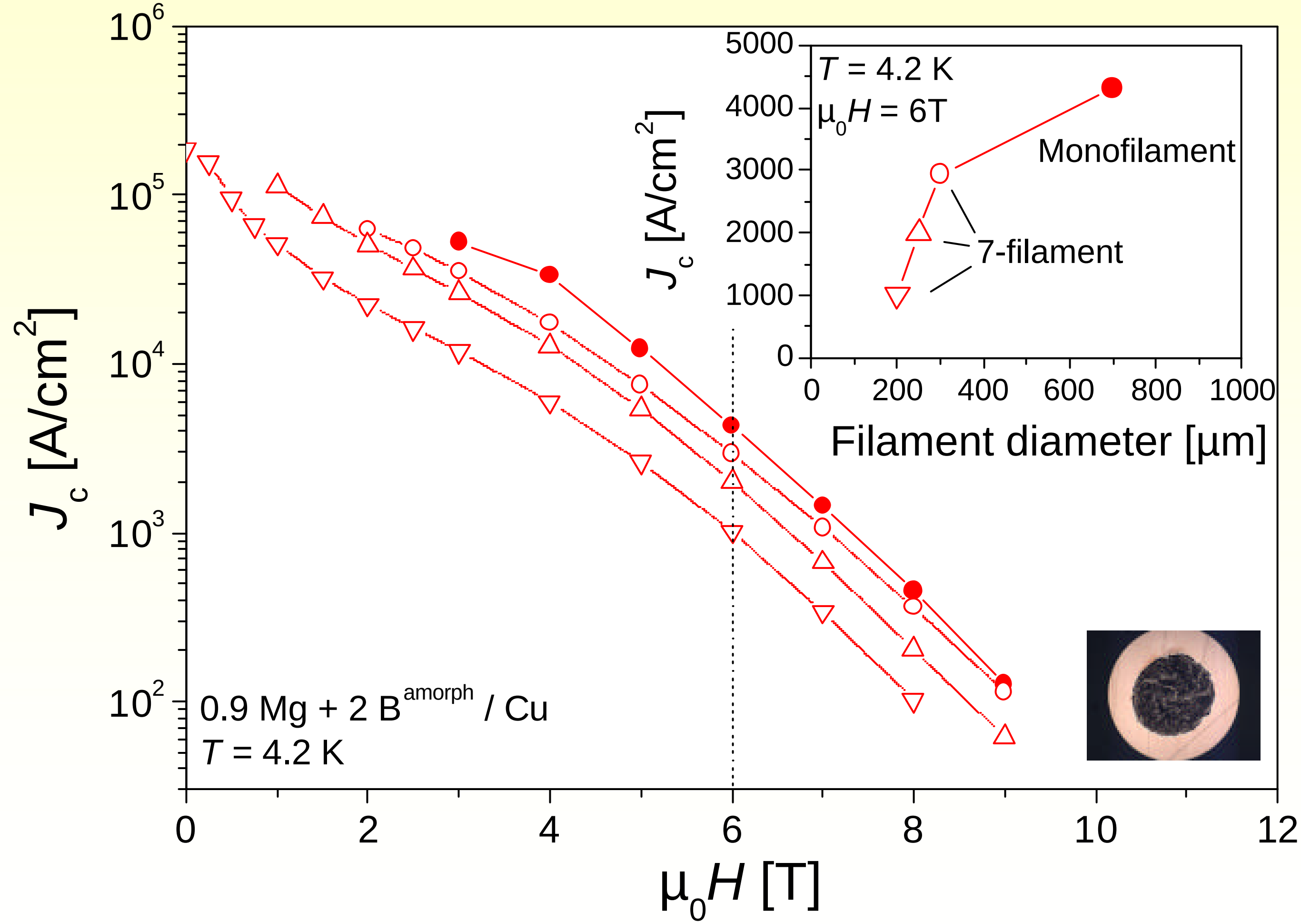
Heat treatment: **640°C**
→ Thin reaction layer



➡ Lower temperature favorable for thin filaments / thin wires

Wires with conductive sheath





Decrease of phase formation Temperature

Mechanical alloying

(Fischer *et al*., Preprint, IFW Dresden)

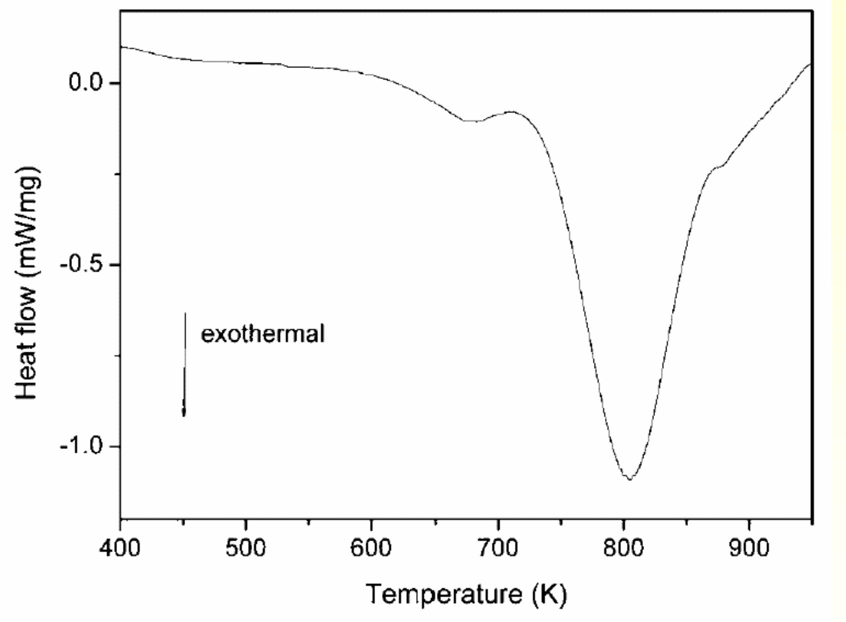


Figure 2. Differential scanning calorimetry (DSC) scan of the as-milled powder recorded at a heating rate of 20 K min^{-1} revealing the transformation of the precursor powder into MgB_2 at rather low temperatures.

SiB_6 doping

Cooley et al. cond-mat/0403130

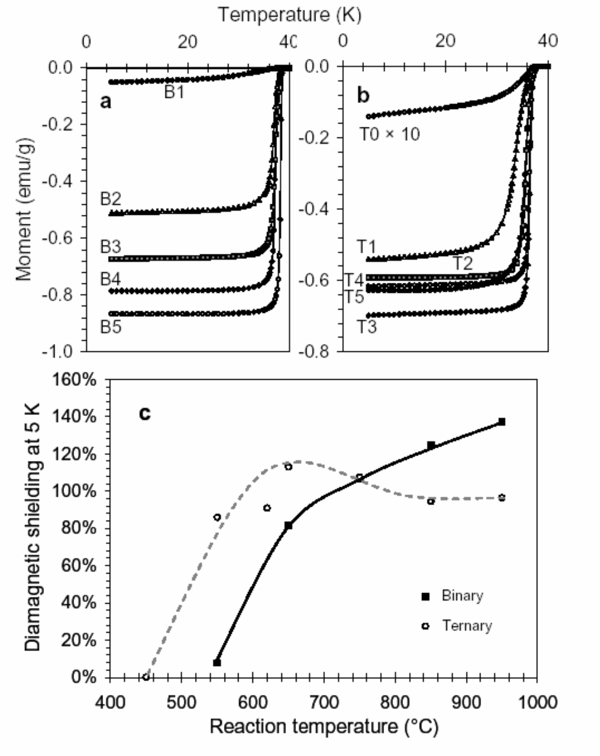


Fig. 1. Inductive superconducting transitions at 1 mT after cooling in zero field for samples made by the binary reaction (plot a) and the ternary reaction (plot b). The data for sample T0 in plot b has been multiplied by 10 to resolve it from the temperature axis. Plot c compares saturation magnetization as a fraction of diamagnetism for both sets of samples as a function of reaction temperature corresponding to the parameters in Table I.

On the way from the "Genie in a bottle" to first conductors for applications:

Test of current limiting behavior

A small magnets

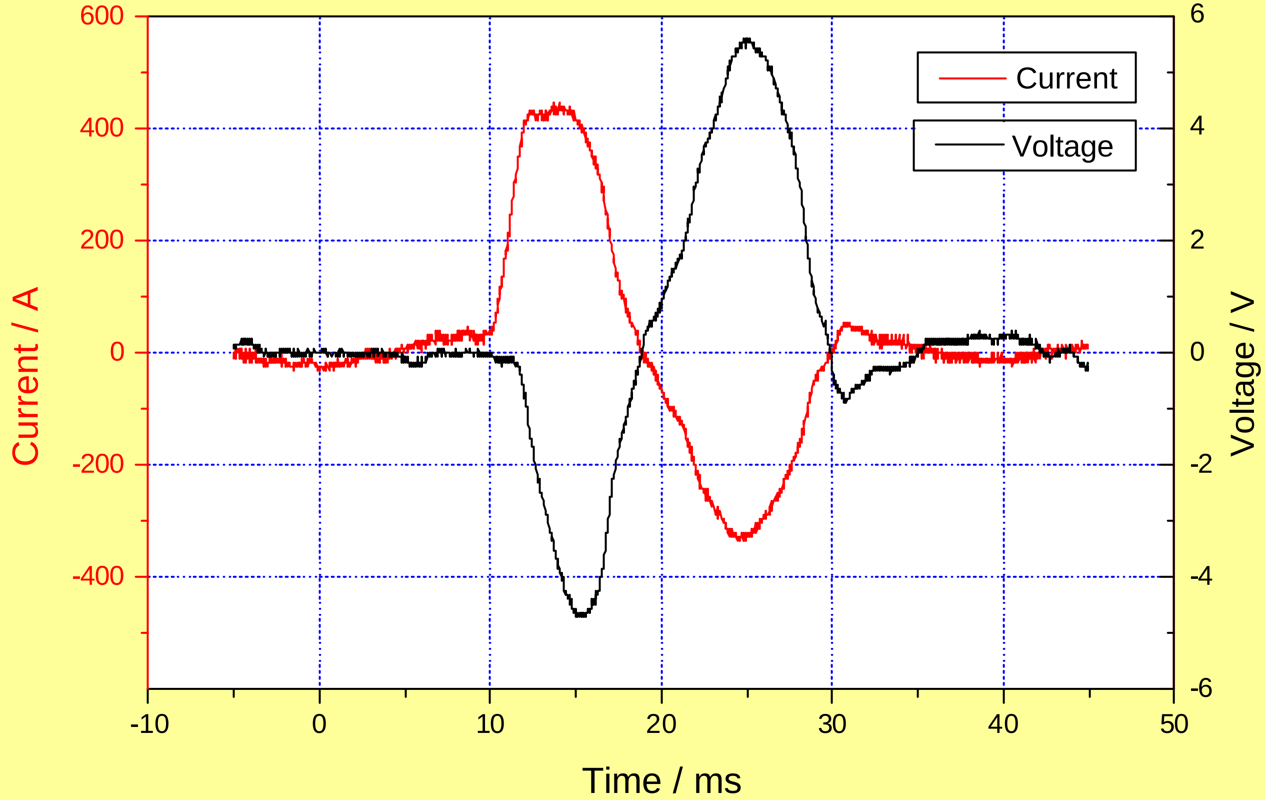
Current leads for "XRS" on "Astro-E2"

Test of current limiting behavior of MgB_2/Fe wire

Application of one 50 Hz AC current period

Sample shows limitation of current at 400 A (4.2 K self field)

Sample burns through for DC current ramp (1-5 Amps/sec) at half current value !



Unpublished: Jensen, Noe, Goldacker, Schlachter et al.

Cu/Cu monocore insulated solenoid, 1 T, 4.2 K

M.D. Sumption, **M. Tomsic**, M. Bhatia, Y. Hascieck, S.X. Dou, E. W. Collings

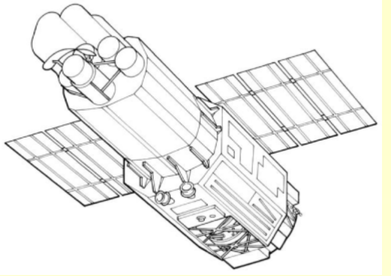
Presented at the ICMC Topical Conference Feb. 10-13 2004, Wollongong, Australia

Coil OD	29.2 mm
Coil ID	22 mm
Coil Height	45 mm
Conductor length	20 m of CTFF Cu/ MgB_2 wire
Conductor diameter	1 mm
Number of turns	170
Insulation type	Sol-gel ceramic
Coil technology	W&R, Layer wound
Coil constant	0.00367 Tesla/A
Inductance	0.186 mH
Coil I_c in self field	278A at 4.2K, 90 A at 20 K
I_c of the sister sample	475A at 4.2K, 110 A at 20 K
Coil J_c in self field	66190 A/cm^2 at 4.2K, 21428 A/cm^2 at 20 K
J_c of the sister sample	113095 A/cm^2 at 4.2K, 26190 A/cm^2 at 20 K
Axial field	1.02 Tesla at 4.2K and 0.33 Tesla at 20K
Maximum field at the turns	1.05 Tesla at 4.2K and 0.3407 Tesla at 20 K

NHMFL

Hyper Tech Research

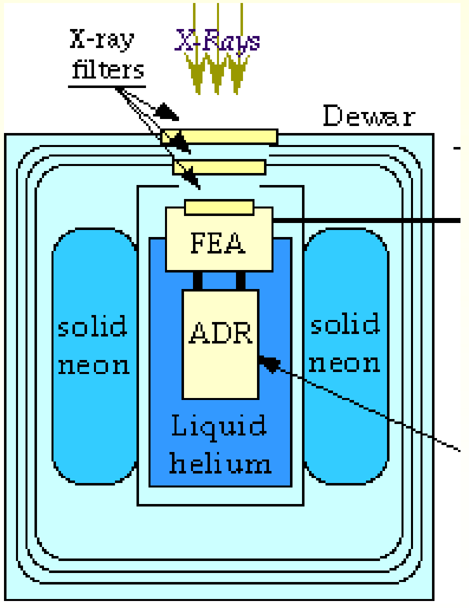
Development of thin steel reinforced wires as current leads for XRS on Astro-E2



- Current leads to connect magnets and valves (T = 1.3 K) to the power supply (T = 17 K)

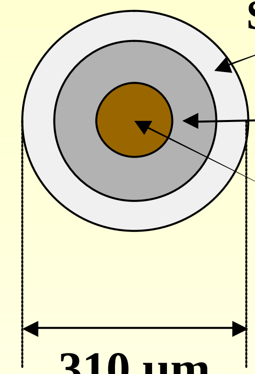
Pictures: NASA

- Demands:
  - High mechanical stability
  - Low thermal conductance
  - Current carrying capability 1- 2 A @ 17 K
  - Length of the wires: ~ 0.3 m

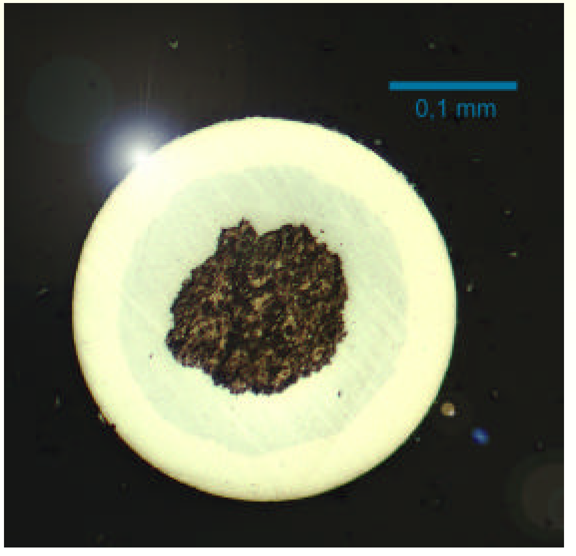


- Challenges:
  - Stainless steel reinforcement
  - Thin wires → small filament size → homogeneous microstructure

Development of thin steel reinforced wires as current leads for a NASA satellite



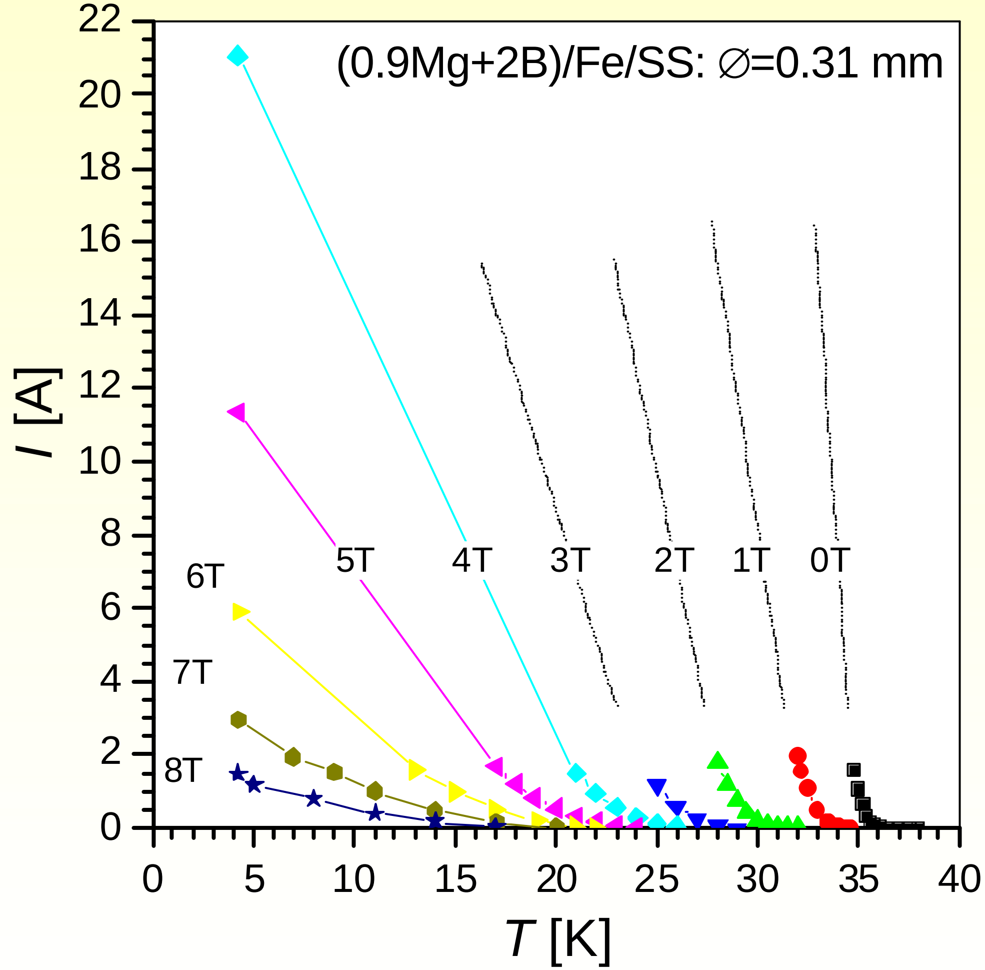
- Design of the wires
  - Precursor: 0.9 Mg + $2B^{\text{amorphous}}$
  - Fe-tube: 10 x 1.5 mm
  - Stainless Steel tube: 2.5 x 0.3 mm
  - 3 softening heat treat-ments at diff. diam.: 600-620°C
  - Final Heat treatment: 640°C (old batch: 905°C)
  - Wire diameter: 310 µm (old batch: 400 µm)



- Critical-current test for **all** wires:
  - wire length: ~ 35 cm (old batch: 45 cm)
  - Voltage contact dist.: ~ 30 cm (old batch: 40 cm)
  - Temperature: 4.2 K
  - Magnetic Field: self field
  - Maximum test current: $\boldsymbol{I_{max}}$ **= 12 A** (old batch: 15 A)

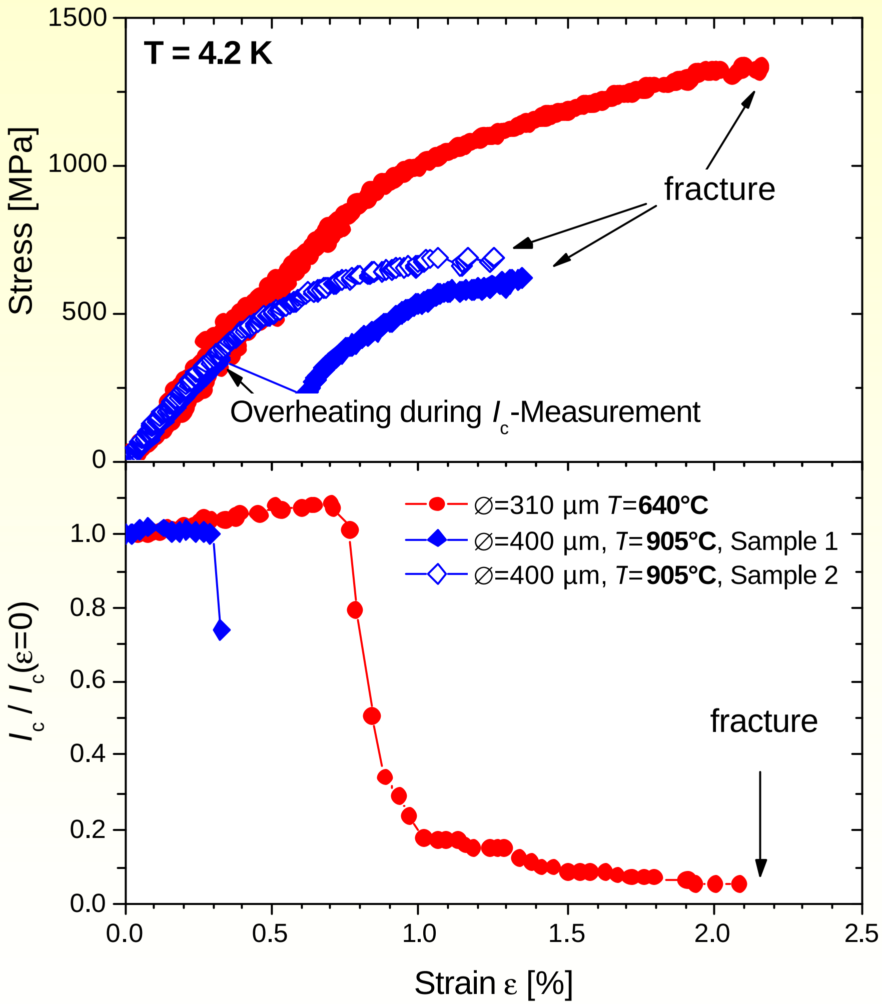
⇒ **Less than 10 % of the wires failed the test**

$I_c(B,T)$ of MgB_2/Fe/SS current lead wires Ø = 310 µm



The current of 2 A required for the satellite application can be transferred through the current leads up to T ~ 34 K in self field.

Mechanical properties of steel reinforced MgB_2/Fe/SS current lead wires

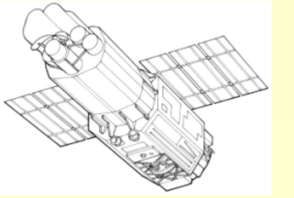


Tolerable stress and strain (I_c / I_c (ε = 0) ≥1):

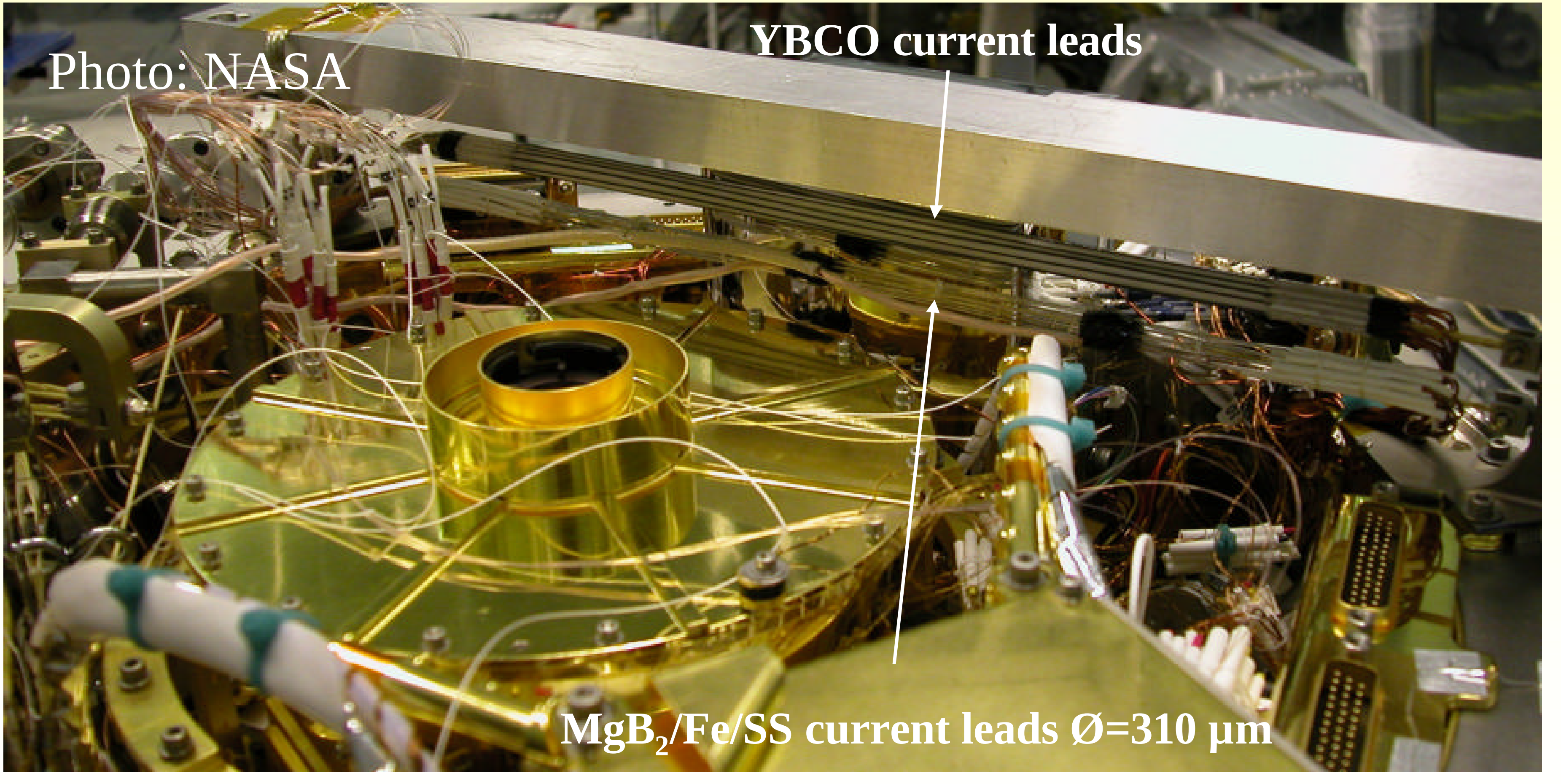
- MgB_2/Fe/SS (Ø = 400 µm, T = **905°C**):
  - Tolerable strain: ~ 0.3 %
  - Tolerable stress: ~ 320 MPa
- MgB_2/Fe/SS (Ø = 310 µm , T = **640°C**) :
  - Tolerable strain: ~ 0.8 %
  - Tolerable stress: ~ 800 MPa

⇒ Improved mechanical performance for wires with low-temperature heat treatment, because stainless steel sheath is not softened.

Current Leads for XRS on ASTRO-E2



Picture: NASA

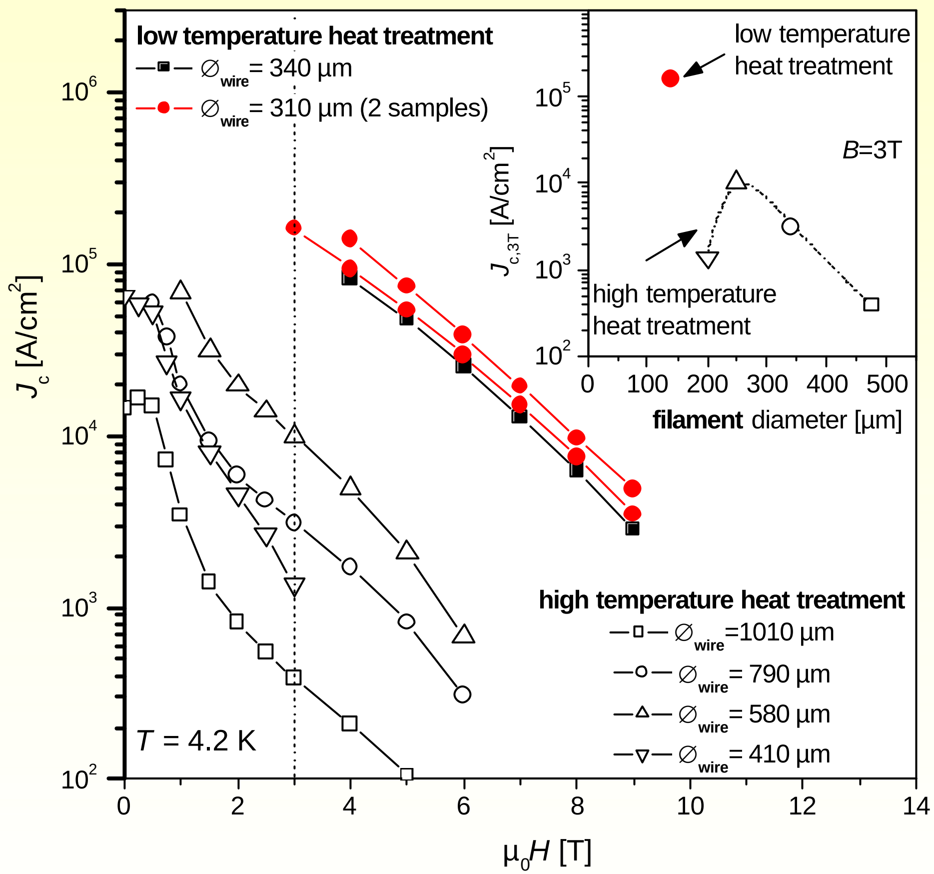


Outlook

- MgB_2
  - Cheap material
  - High T_c (compared to LTS)
  - No weak-link behavior
  - Critical currents and critical fields can compete with NbTi at 4.2 K
  - High potential for higher temperatures

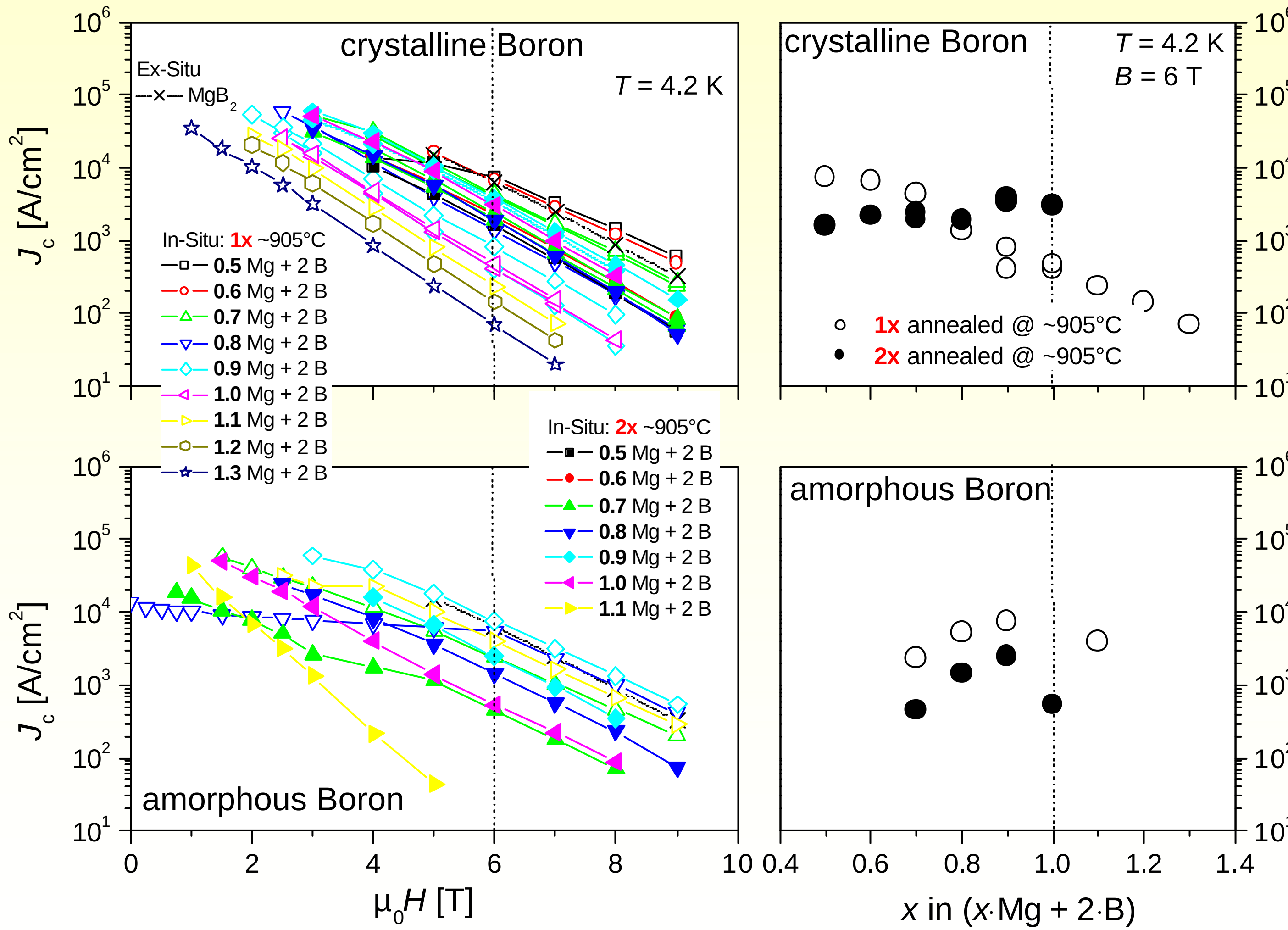
- Bottlenecks and Challenges
  - Thermal stability → small filaments have to be realized
  - Mechanical stability
  - Superconducting joints
  - Long lengths fabrication process

Influence of filament diameter

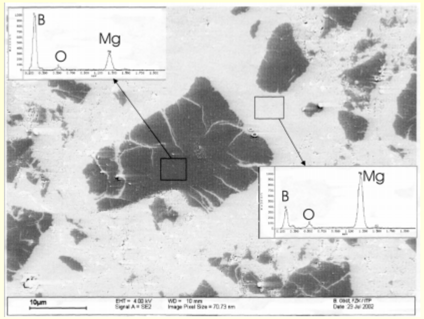


- Heat treatment **905°C**:
  - With decreasing wire diameter (above 250 µm) J_c increases
    - Influence of filament precompression ?
  - Below 250 µm filament diameter filament homogeneity becomes more and more important
- Heat treatment **640°C**:
  - J_c is much higher than for wires heat treated at 905°C, even at smaller filament diameters.

Improvement of $J_c(B,T)$:
Precursor: crystalline and amorphous boron powder



crystalline



amorphous