# Advances in AIMI "Second Generation" $MgB_2$ Wires, n-values, and Coils

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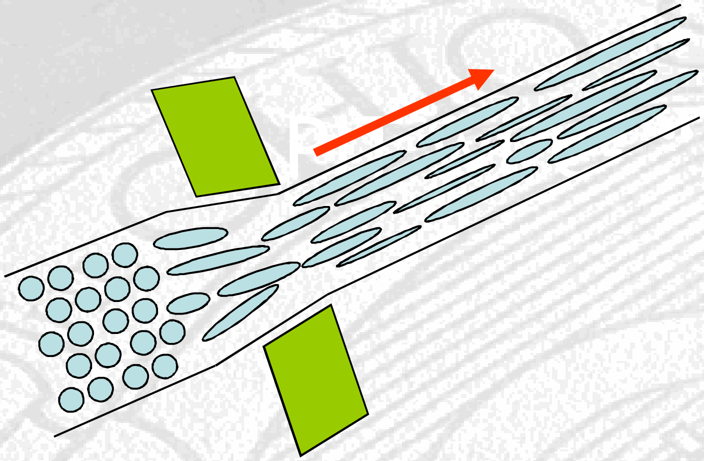
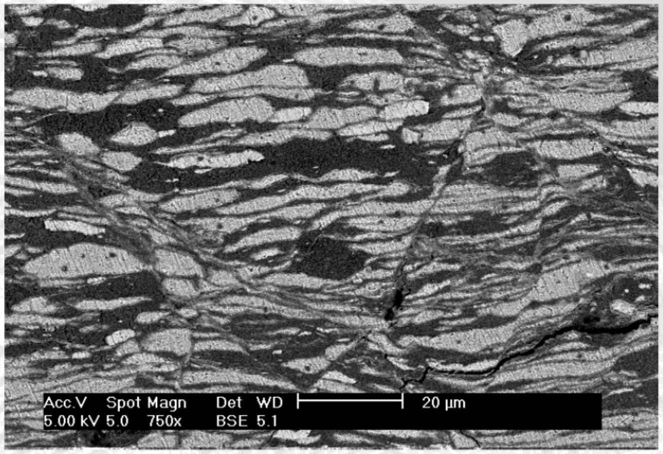
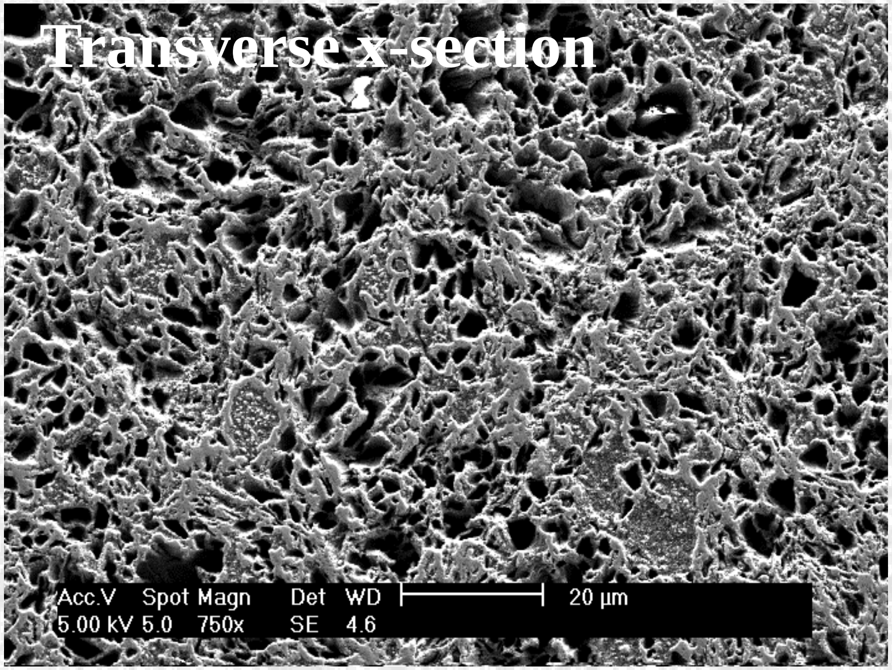
# Outline

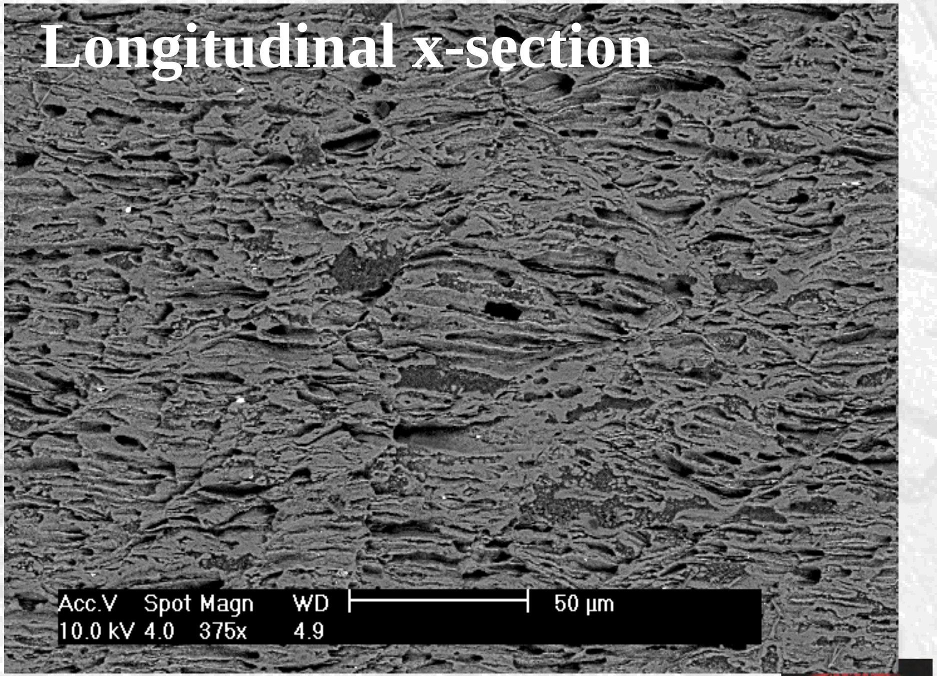
1. Transport Results for Multifilamentary Advanced Internal Magnesium Infiltration (AIMI) (2G) strands
2. Large increases in n-values for PIT strands at 4 K and as a function of B and T
3. Preliminary results for Wire-In-channel NZP and MRI-like Coil Winding

# PIT Conductors have porosity



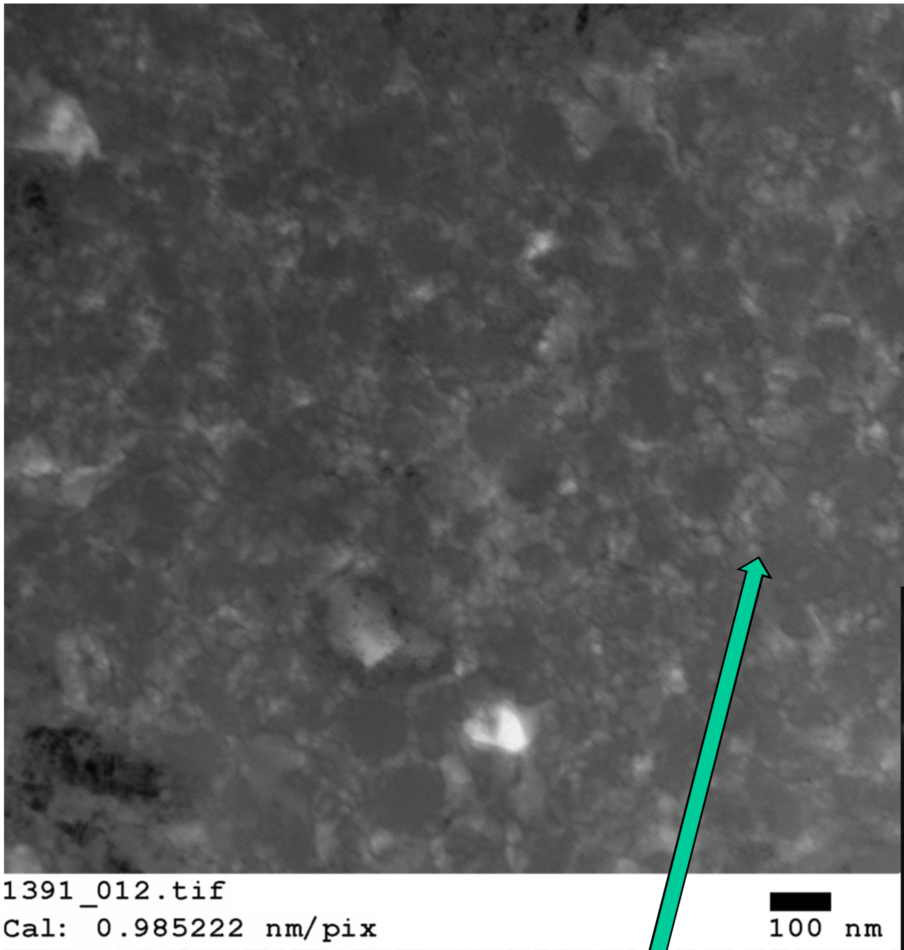


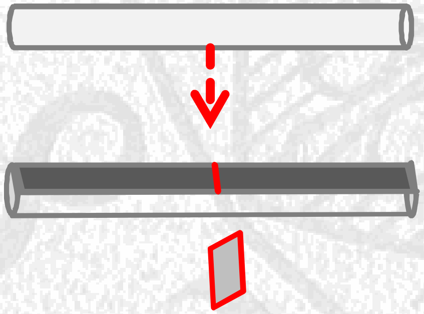

**Transverse x-section**


**Longitudinal x-section**

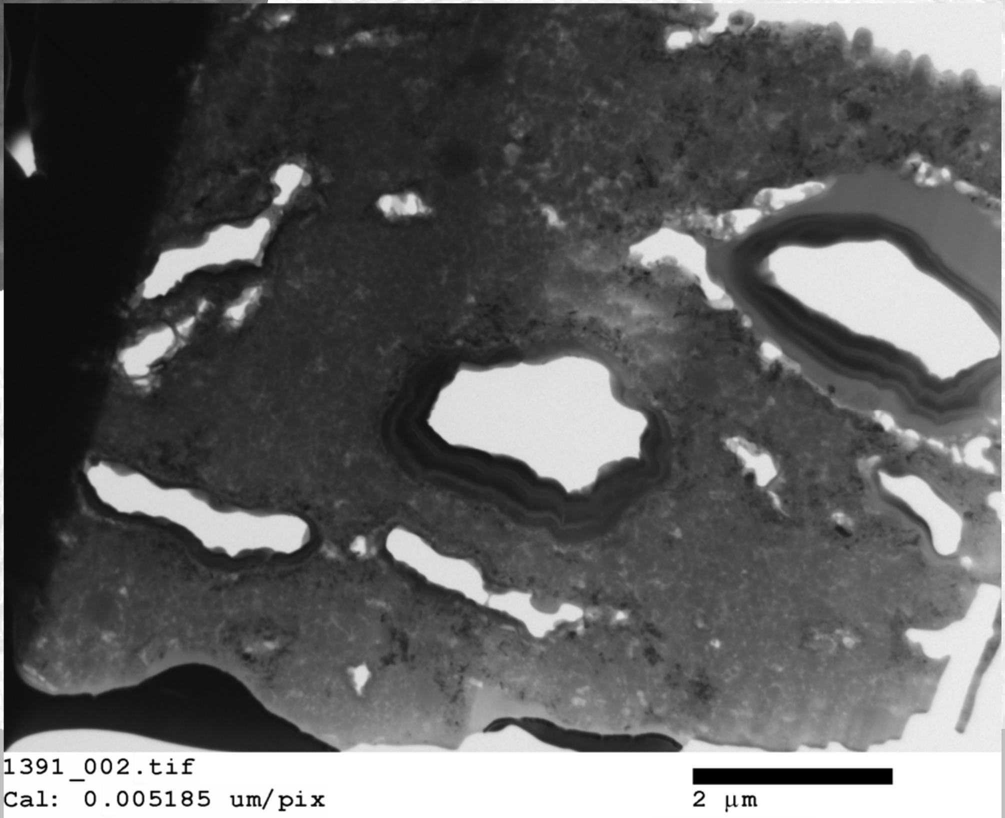
## But even in the "solid" regions, oxides limit current!

## BF TEM $MgB_2$ wire x-section

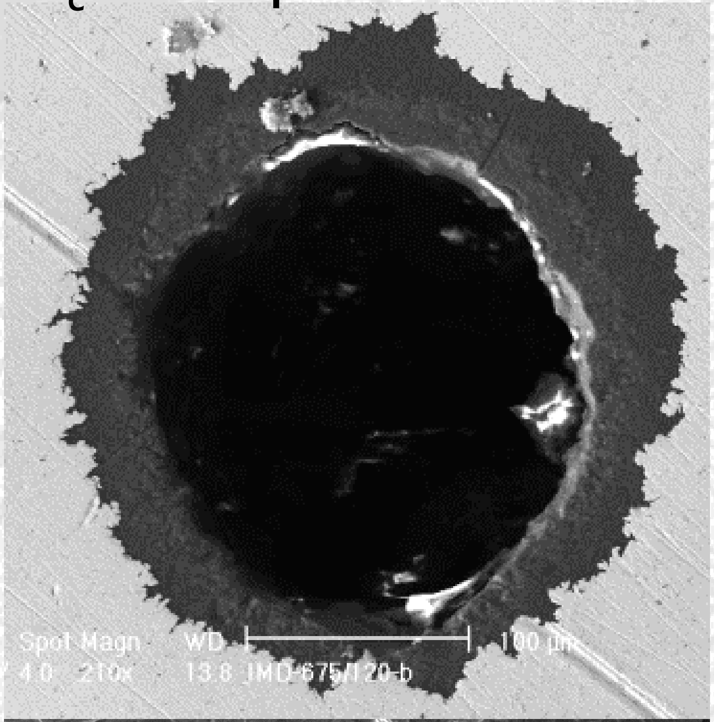


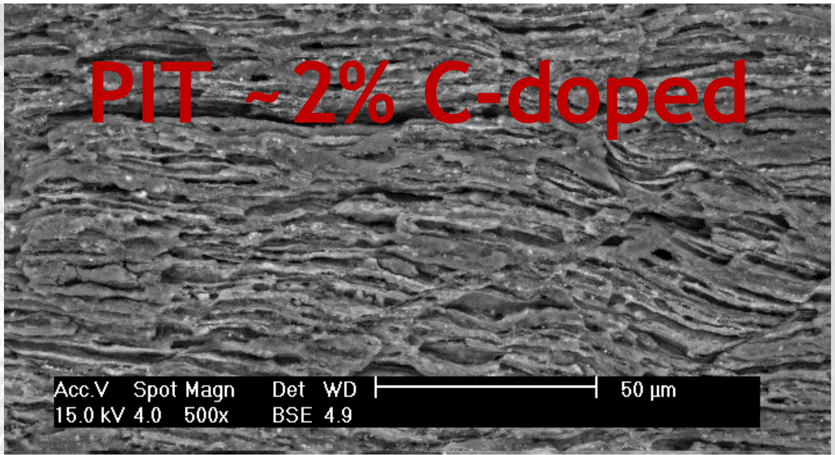


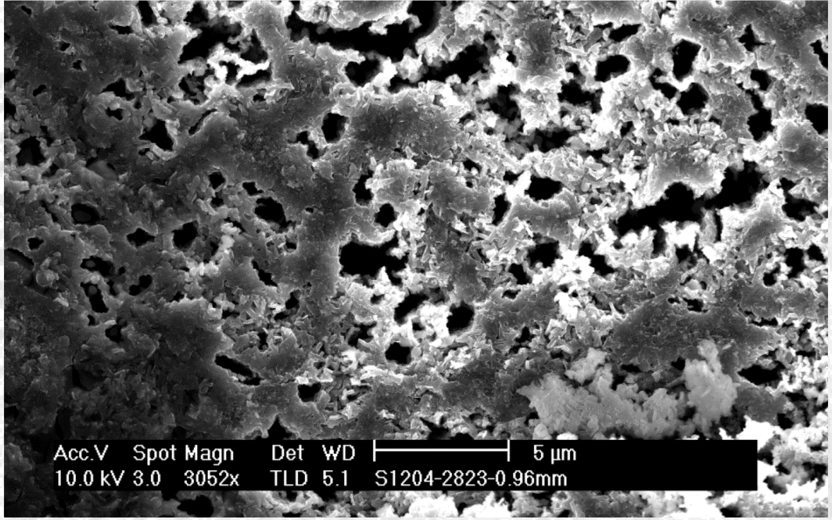
Notice marbled structure --- oxides at GB

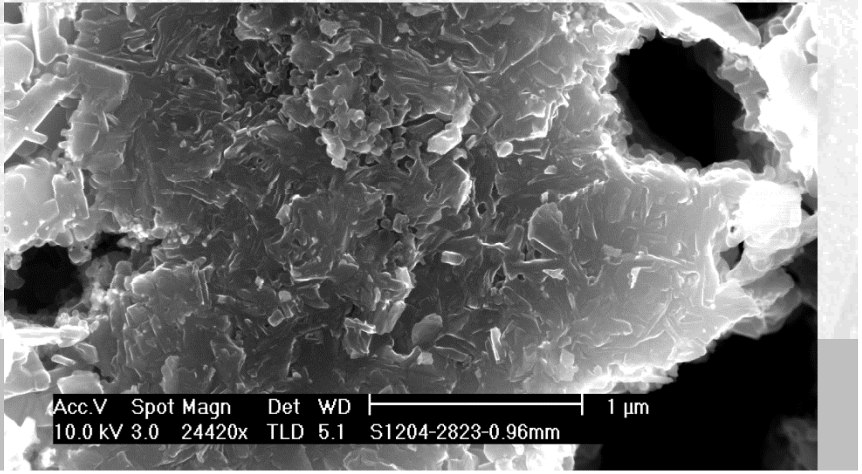


# But we could get much higher layer $J_c$ if we prevented this

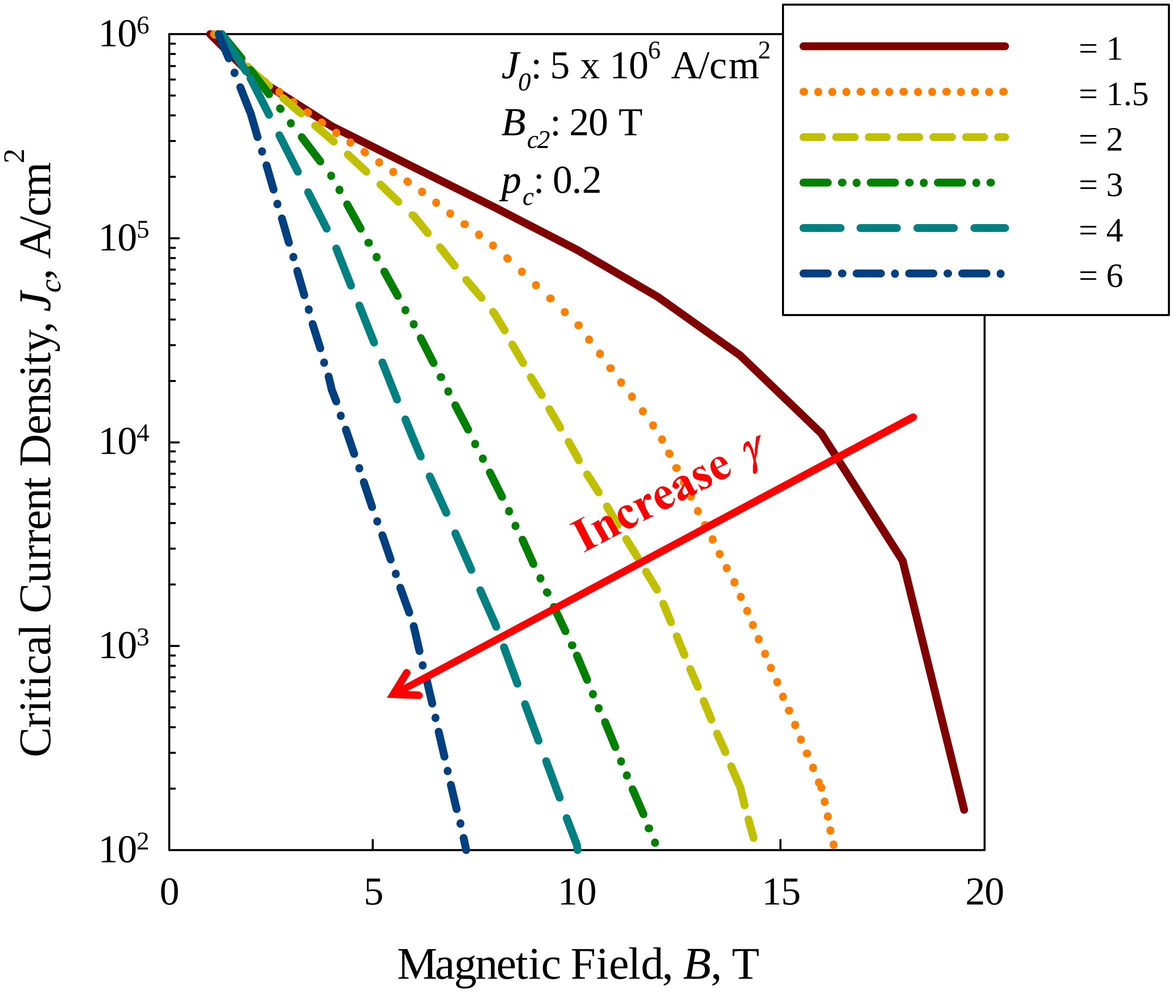








# What is the effect of Anisotropy?



Use a modified Eisterer model

-$J_0$: 5x$10^6$ A/cm$^2$

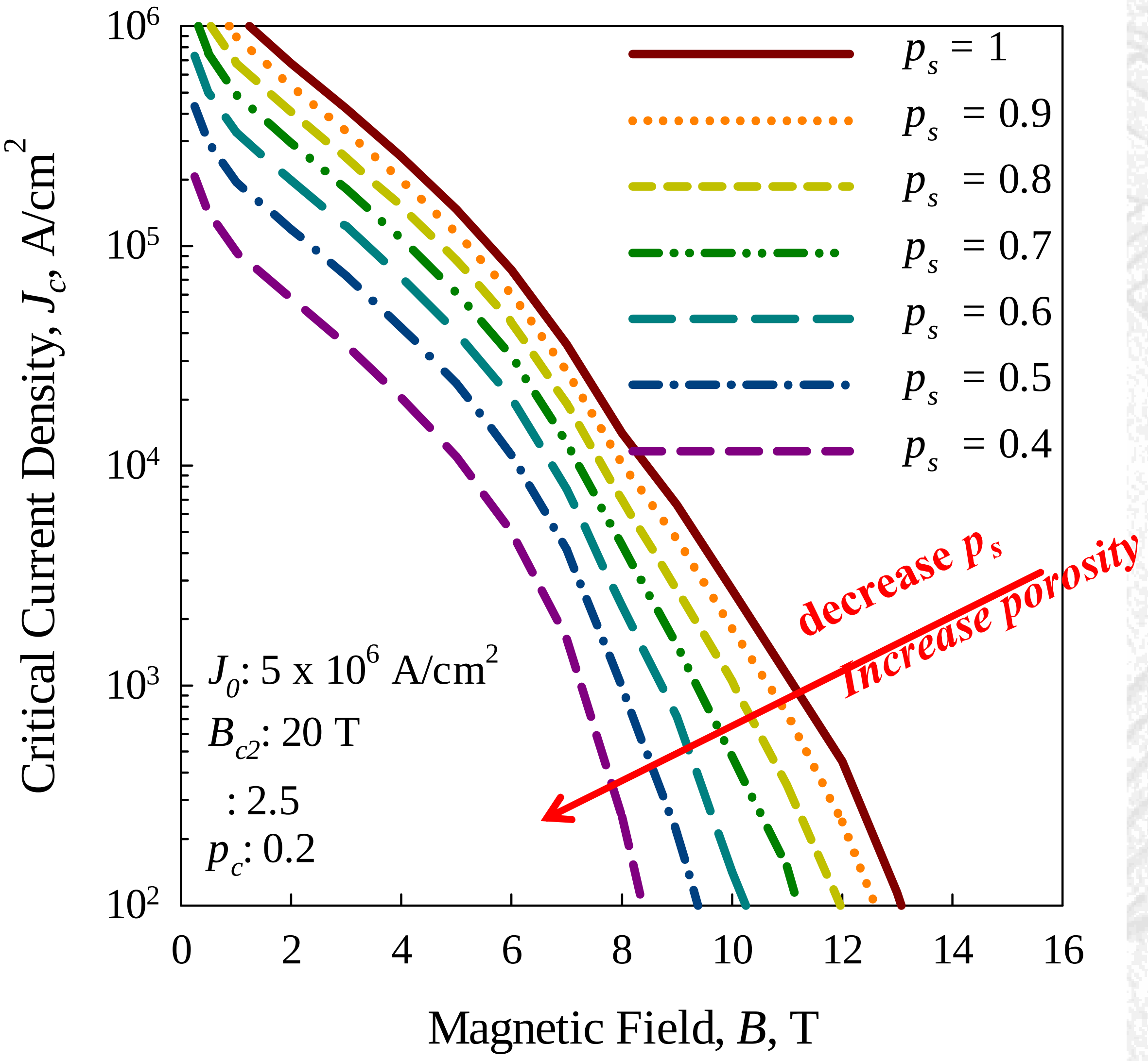
-$B_{c2}$: 20 T

-$p_c$: 0.2- densely packed system

Increasing γ causes a decrease in the amount of supercurrent percolation paths

As a result, $J_c$ at high $B$ decreases – effect intensifies with increase in γ

# How about the influence of Porosity?



Anisotropy (γ) fixed to 2.5

$p_c$: 0.2

$B_{c2}$: 20T

$J_0$: 5x$10^6$ A/cm$^2$

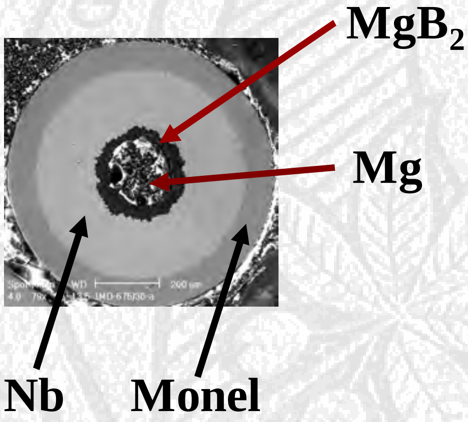
Porosity globally decreases $J_c(B)$

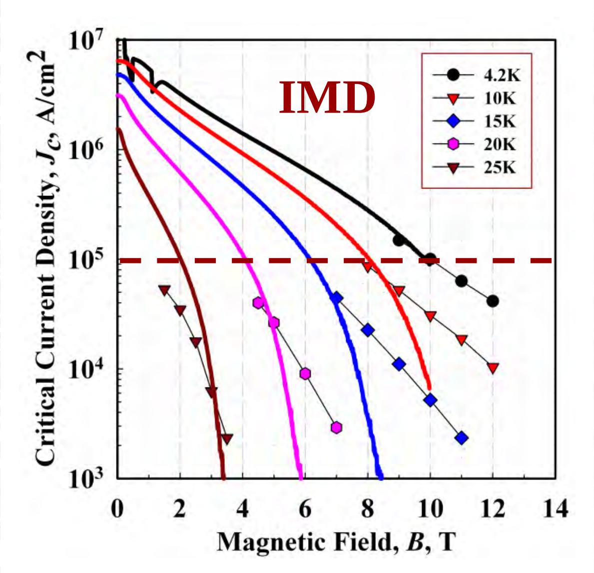
# So….

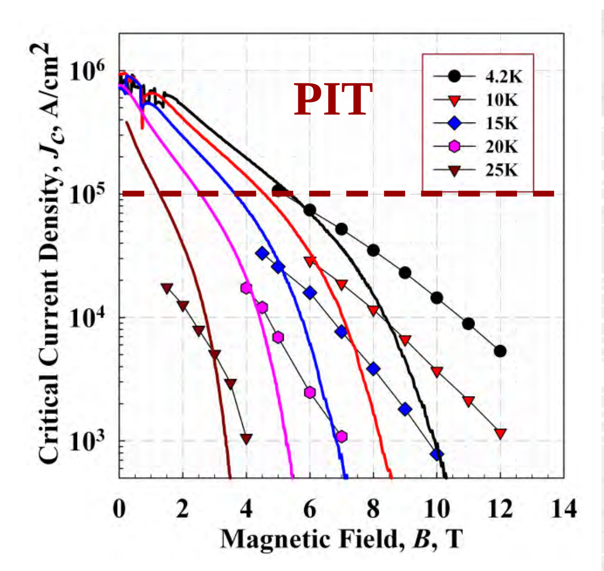
- PIT MgB2 is limited by the effects of nanoscale non-optimum connectivity, in addition to the larger scale porosity
- Thus, when MgB2 is densified, we get a factor of 10, rather than a factor of 2
- Higher field drop off is sometimes entirely attributed to anisotropy, but about half comes from nanoscale connectivity
- Application of percolation theory to $MgB_2$ wires of different designs isolated the effects of porosity and crystalline anisotropy.
- Porosity was seen to be just as important a factor as
  - In particular, at 10 T, 60% of supercurrent degradation comes from anisotropy, 40% from porosity
  - Can nearly eliminate the latter, reduce the former through doping

# *Motivation*

1. **Diffusion processed wire (Mg-RLI or IMD): initiated by Giunchi *et al.* (Edison SpA) – very dense, but low Jc because of powder type**
2. **Developed by Kumakura *et al. (NIMS) – their B, much higher Jcs***
3. ***Further developed at OSU-HTR – use of very fine B, and C-doping led to even higher Jcs***



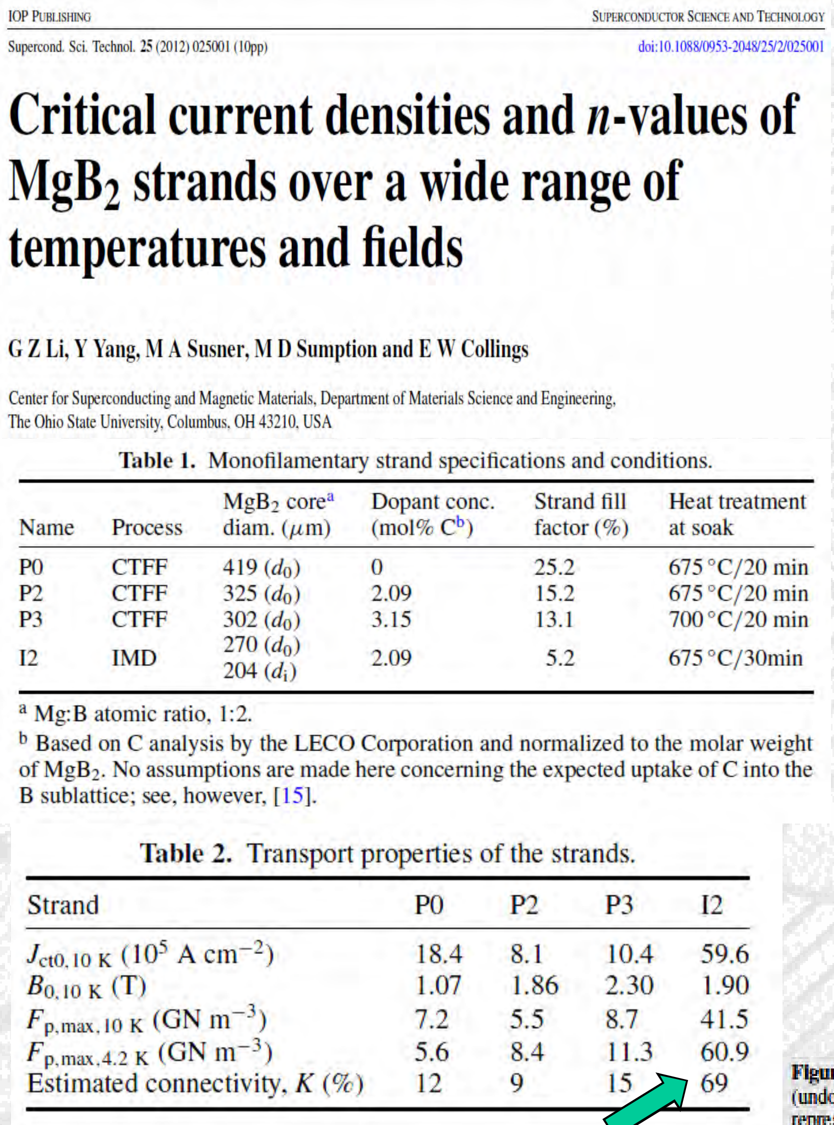




(G Z Li *et al*, SUST, 2012)

- high layer $J_c$. **1.0x10$^5$ A/cm$^2$ at 4.2 K, 10 T**

# Measurement of $J_c$ and $n$ for monofilaments



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doi:10.1088/0953-2048/25/2/025001

## Critical current densities and *n*-values of $MgB_2$ strands over a wide range of temperatures and fields

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**Table 1.** Monofilamentary strand specifications and conditions.

| Name | Process | $MgB_2$ core[a] diam. ($\mu$m) | Dopant conc. (mol% C[b]) | Strand fill factor (%) | Heat treatment at soak |
|---|---|---|---|---|---|
| P0 | CTFF | 419 ($d_0$) | 0 | 25.2 | 675 °C/20 min |
| P2 | CTFF | 325 ($d_0$) | 2.09 | 15.2 | 675 °C/20 min |
| P3 | CTFF | 302 ($d_0$) | 3.15 | 13.1 | 700 °C/20 min |
| I2 | IMD | 270 ($d_0$)<br>204 ($d_i$) | 2.09 | 5.2 | 675 °C/30min |

[a] Mg:B atomic ratio, 1:2.

[b] Based on C analysis by the LECO Corporation and normalized to the molar weight of $MgB_2$. No assumptions are made here concerning the expected uptake of C into the B sublattice; see, however, [15].

**Table 2.** Transport properties of the strands.

| Strand | P0 | P2 | P3 | I2 |
|---|---|---|---|---|
| $J_{ct0,10\,K}$ ($10^5$ A cm$^{-2}$) | 18.4 | 8.1 | 10.4 | 59.6 |
| $B_{0,10\,K}$ (T) | 1.07 | 1.86 | 2.30 | 1.90 |
| $F_{p,max,10\,K}$ (GN m$^{-3}$) | 7.2 | 5.5 | 8.7 | 41.5 |
| $F_{p,max,4.2\,K}$ (GN m$^{-3}$) | 5.6 | 8.4 | 11.3 | 60.9 |
| Estimated connectivity, *K* (%) | 12 | 9 | 15 | 69 |

$F_{p,max}$ reaches 60 GN/m$^3$– it's like $Nb_3Sn$

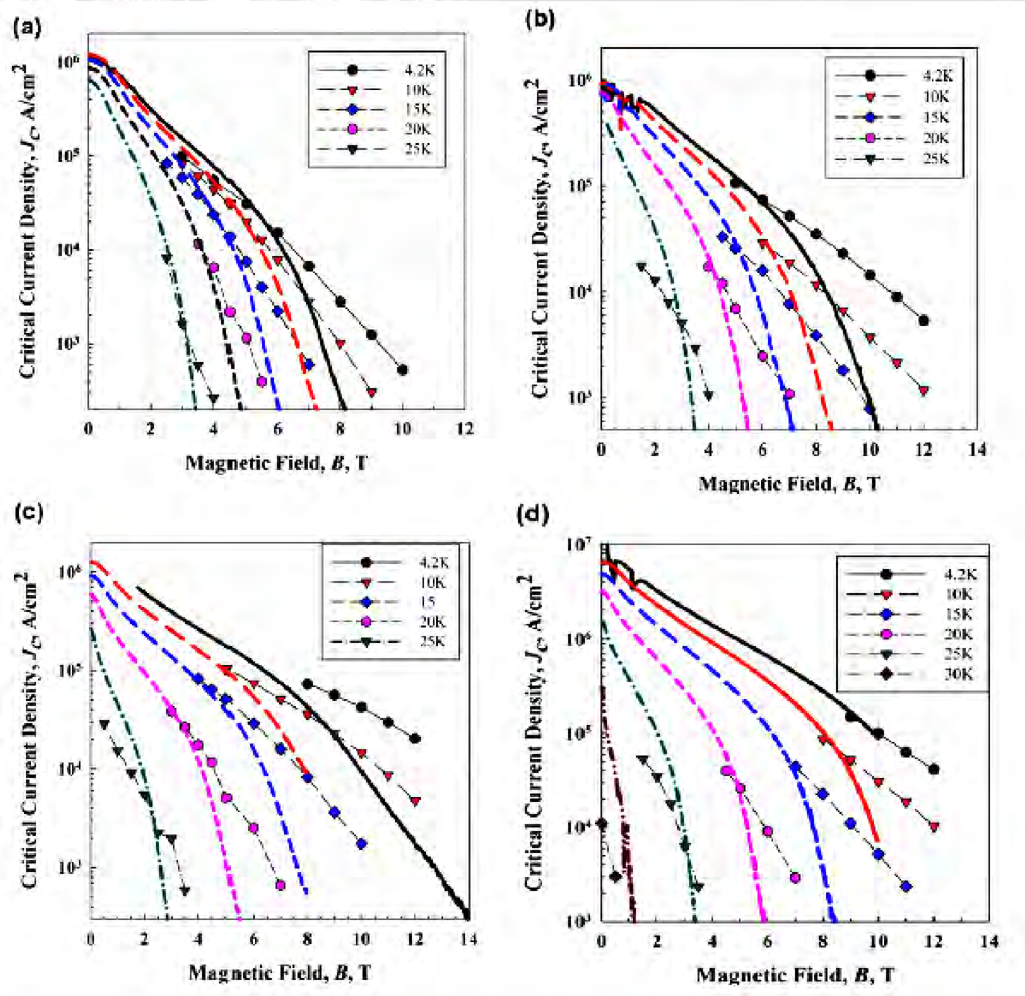


**Figure 2.** Transport $J_{ct}$ and magnetic $J_{cm}$ versus *B* in transverse applied fields at temperatures between 4.2 and 30 K for (a) strand P0 (undoped CTFF), (b) strand P2 (2% C-doped CTFF), (c) strand P3 (3% C-doped CTFF), and (d) strand I2 (2% C-doped IMD). The $J_{ct}$ are represented by lines through data points; the $J_{cm}$ are represented by the 'corresponding' full lines (arranged right-to-left in descending order of temperature).

Supercond. Sci. Technol. 25 (2012) 025001 G Z Li et al

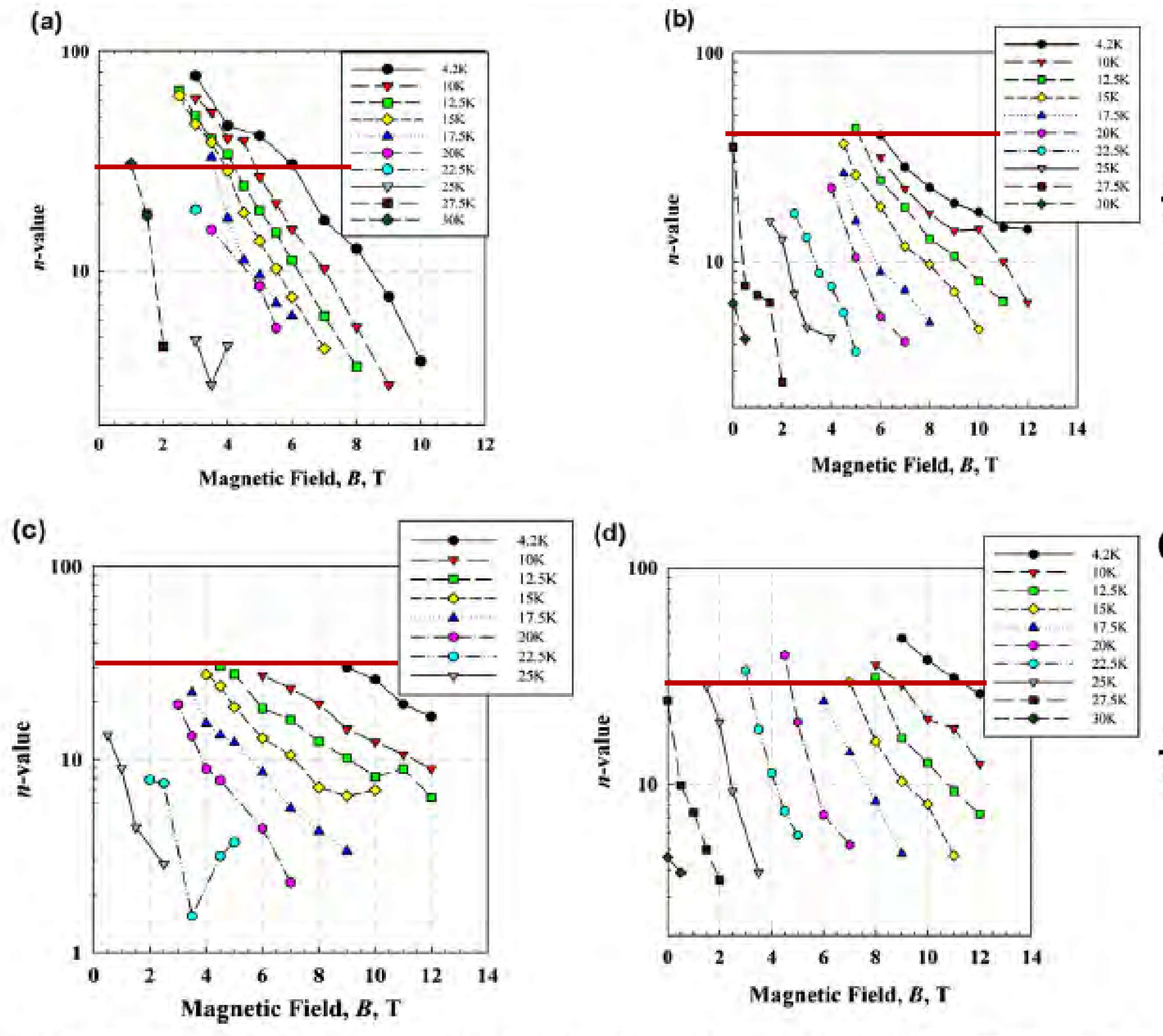
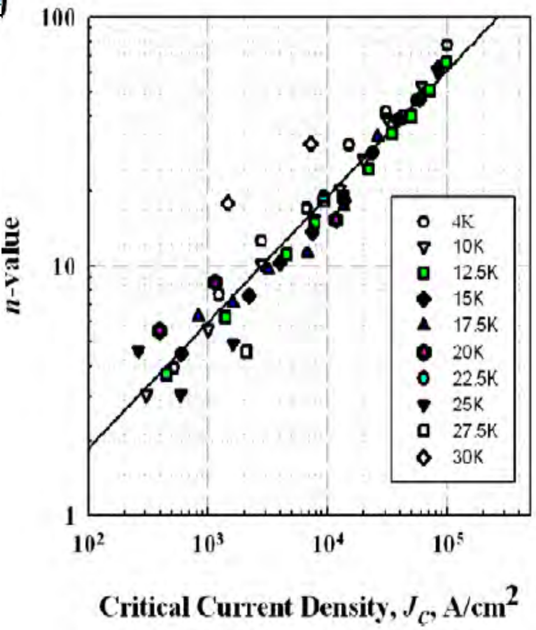
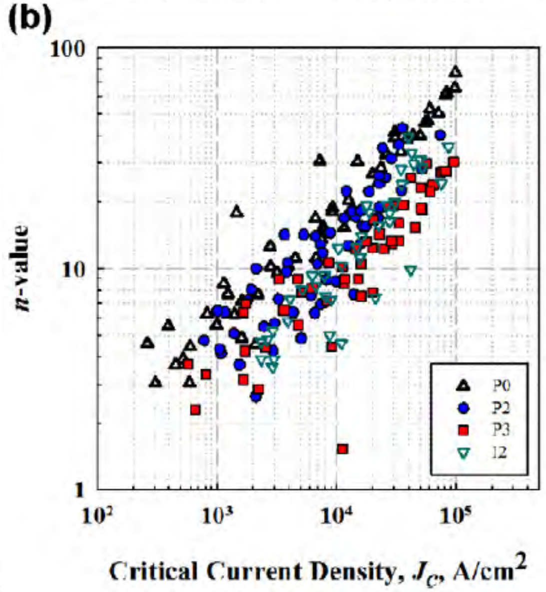


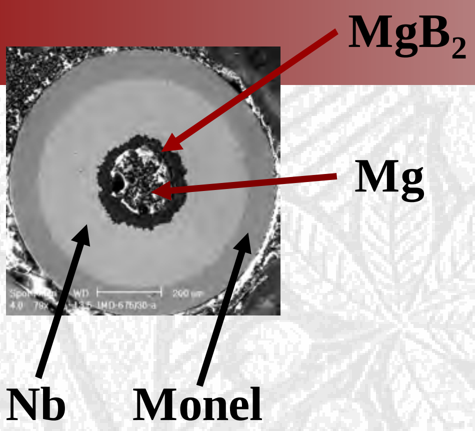
**Figure 6.** n-value versus B in perpendicular applied fields at temperatures between 4.2 and 40 K for: (a) undoped CTFF strand P0, (b) 2% carbon doped CTFF strand P2, (c) 3% carbon doped CTFF strand P3, and (d) 2% carbon doped IMD strand I2.



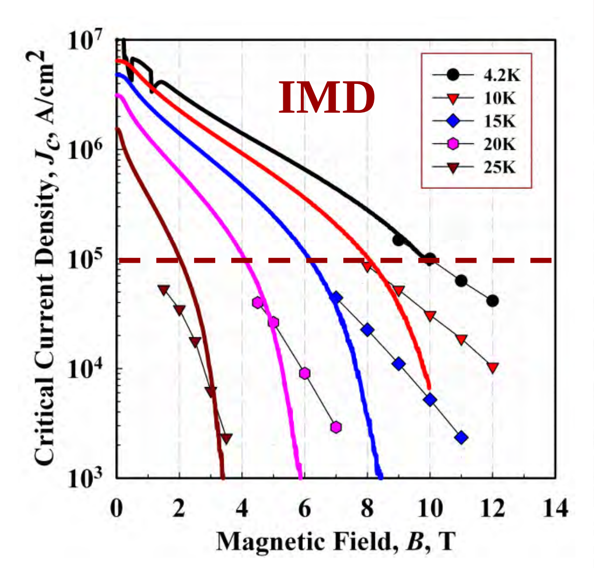


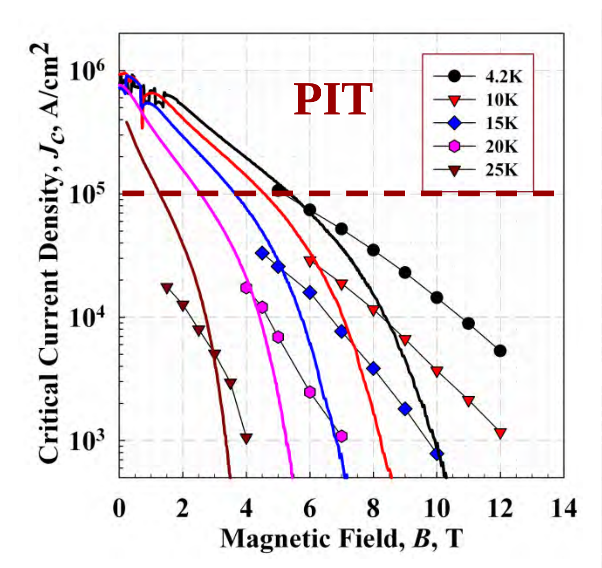
# *Motivation → Modification*

1. **Diffusion processed wire (Mg-RLI or IMD): initiated by Giunchi *et al.* (Edison SpA) – very dense, but low Jc because of powder type**
2. **Developed by Kumakura *et al. (NIMS) – their B, much higher Jcs***
3. ***Further developed at OSU-HTR – use of very fine B, and C-doping led to even higher Jcs***
4. ***But – area of MgB2 small – making this of more scientific than practical use. How to maximize conversion, and thus Ic?***



***low $MgB_2$ fill factor so low $J_e$!***



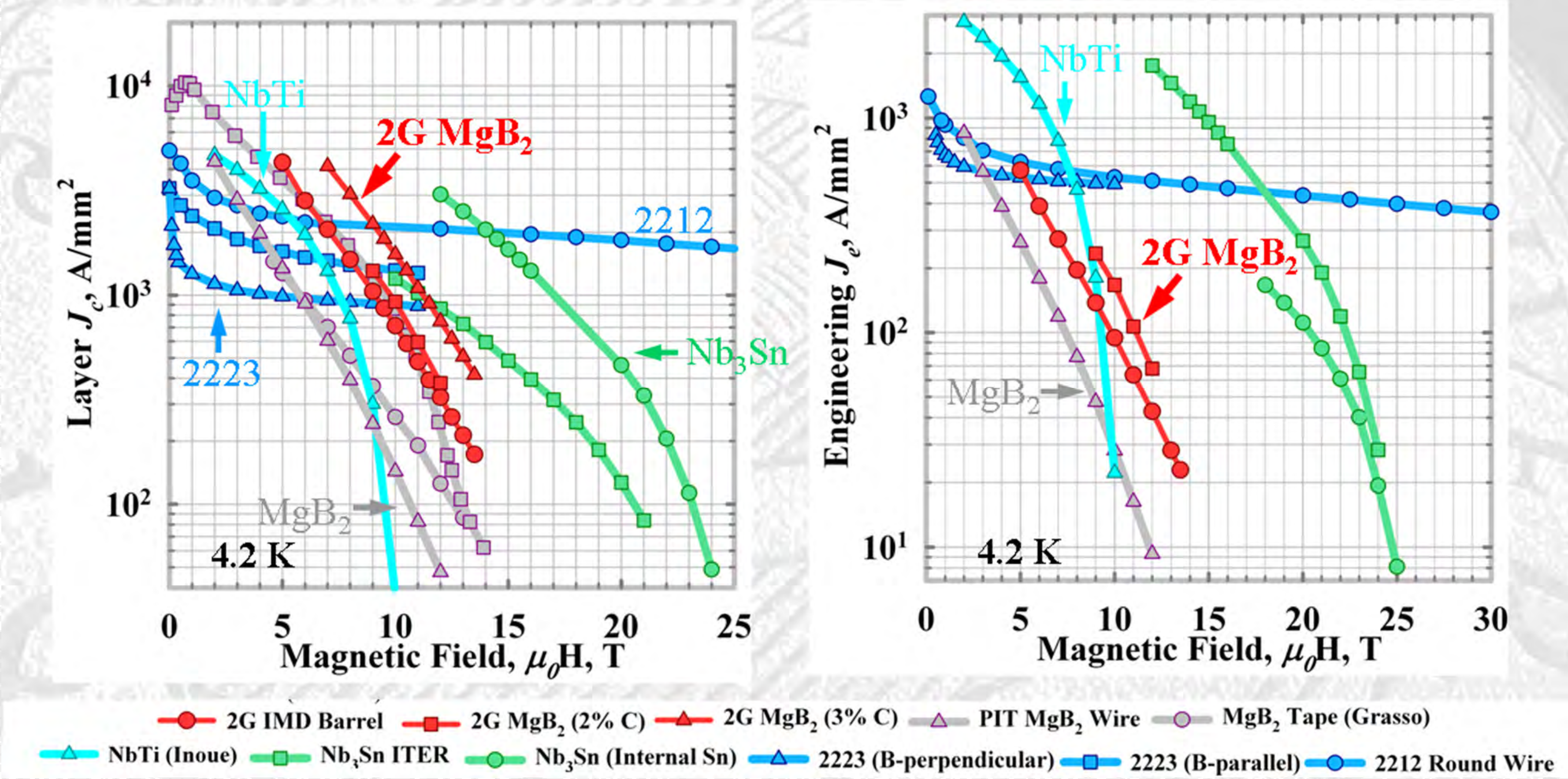


(G Z Li *et al*, SUST, 2012)

- high layer $J_c$. **1.0x$10^5$ A/cm$^2$ at 4.2 K, 10 T**

# *A comparison to best-of Results*

Second generation $MgB_2$ wires: both improved critical current density $J_c$ and engineering $J_e$.



# Samples

**Table 1 Monocore wire Diameter and HT Conditions**

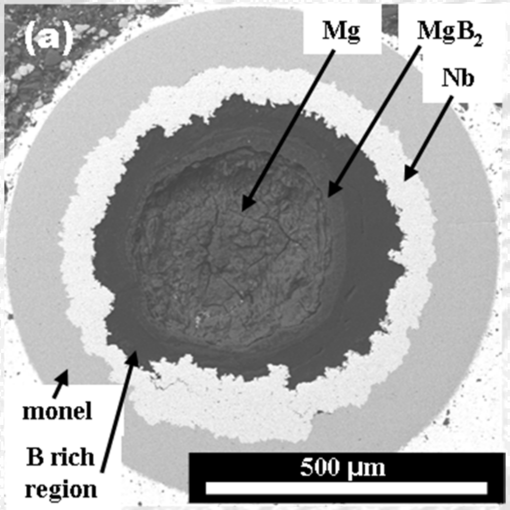
| Sample No. | Diameter, mm | HT time at 675 ˚C, h |
|---|---|---|
| A1 | 0.83 | 0.5 |
| A2 | 0.83 | 1 |
| A3 | 0.83 | 8 |
| B1 | 0.55 | 0.5 |
| B2 | 0.55 | 1 |
| B3 | 0.55 | 4 |

- 2% C doped plasma synthesized B (40 nm, Special Materials Inc.).
- Temperature: 675 ˚C, based on experience with PIT wires.
- Fabricated and heat treated at Hyper Tech Research, Inc.
- Transport $J_c$ measurement at 4.2 K, up to 12 T.

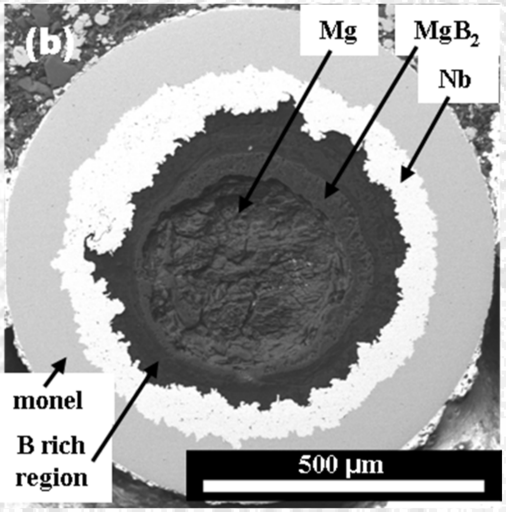
SEM & EDS: Quanta 200 with EDAX EDS system, FEI Sirion SEM.

# *A-series Infiltration-Processed Strands*

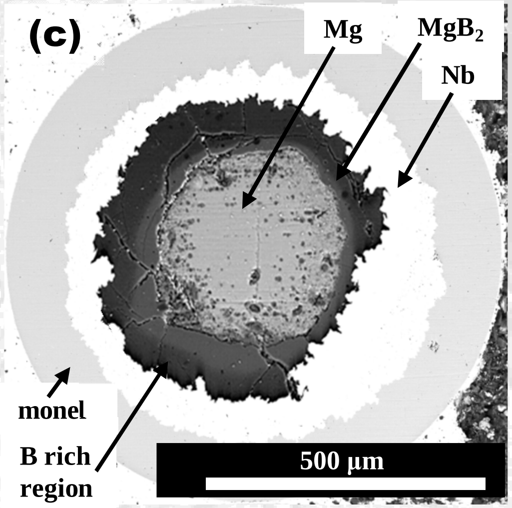
**A1: 0.5 h**



**A2: 1 h**

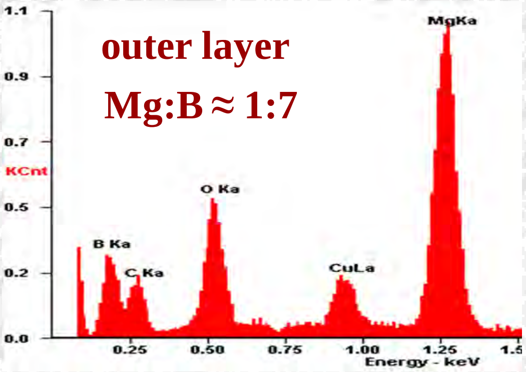


**A3: 8 h**

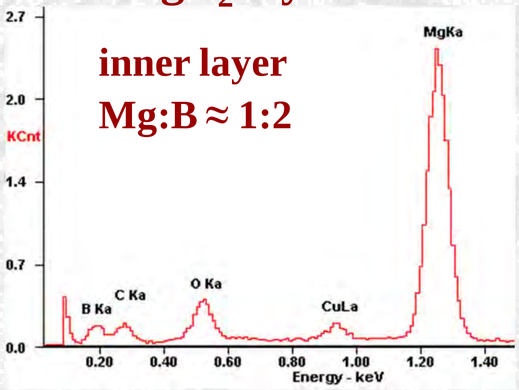


- $MgB_2$ circular layers are formed.
- $MgB_2$ composition and structure identified.
- B is not fully reacted even after 8 h at 675 ˚C.

**B-rich layer**



**$MgB_2$ layer**



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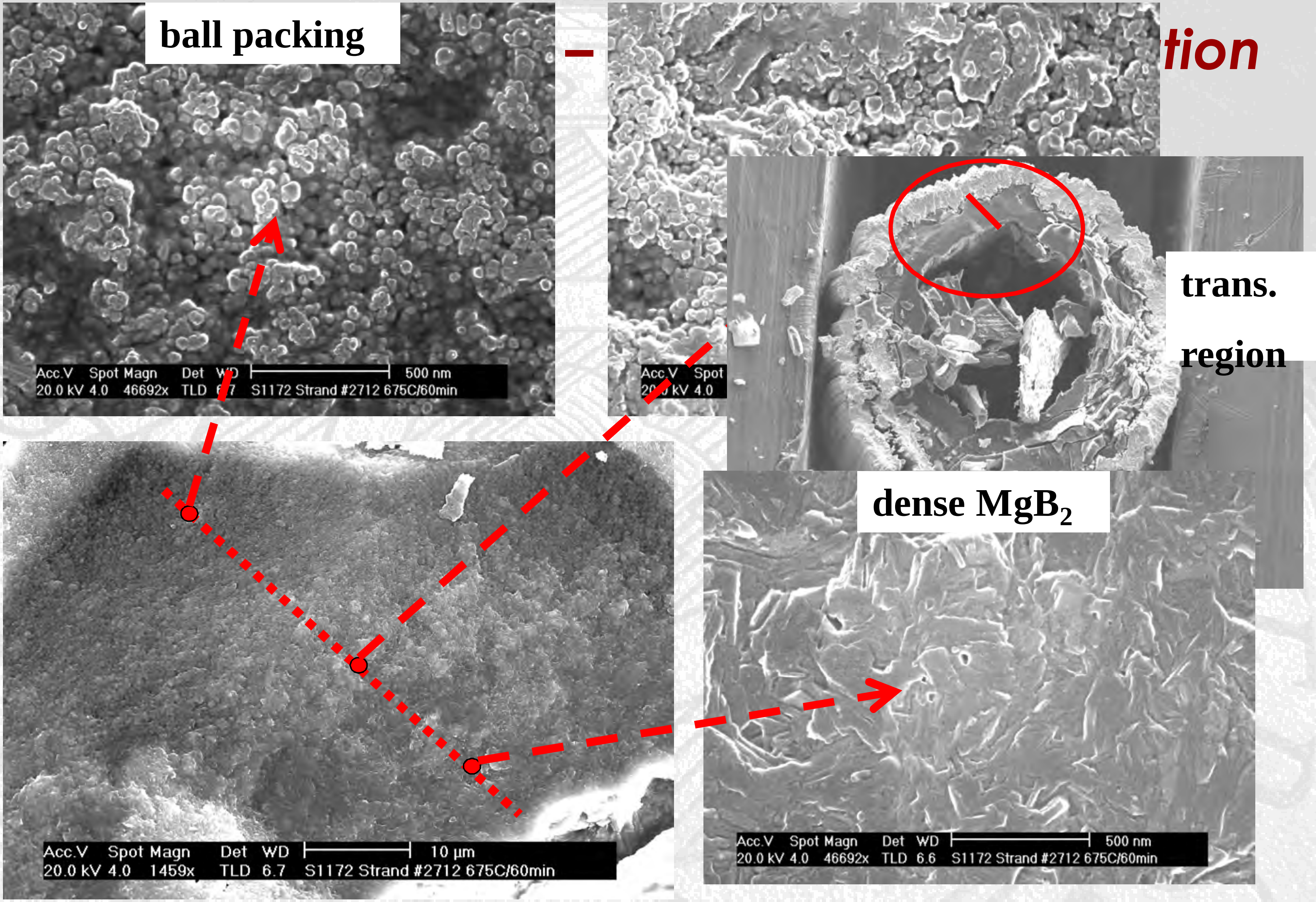
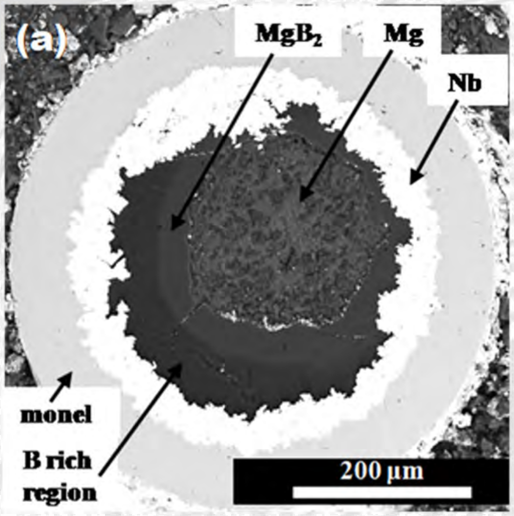
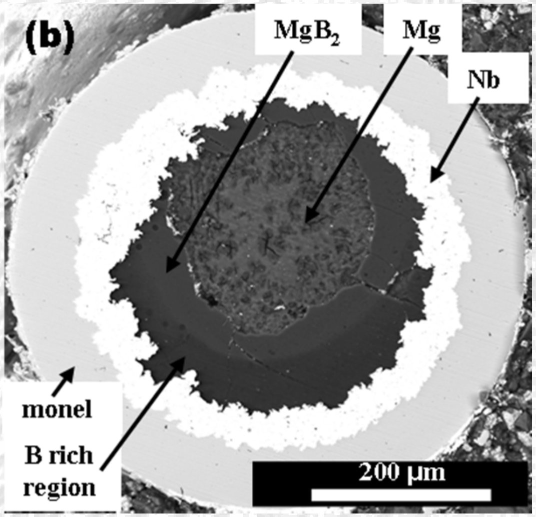

ball packing
Acc.V Spot Magn Det WD 500 nm
20.0 kV 4.0 46692x TLD 6.7 S1172 Strand #2712 675C/60min
Acc.V Spot
20.0 kV 4.0
trans.
region
dense MgB$_2$
Acc.V Spot Magn Det WD 10 µm
20.0 kV 4.0 1459x TLD 6.7 S1172 Strand #2712 675C/60min
Acc.V Spot Magn Det WD 500 nm
20.0 kV 4.0 46692x TLD 6.6 S1172 Strand #2712 675C/60min

# *B-series Infiltration-Processed Strands*

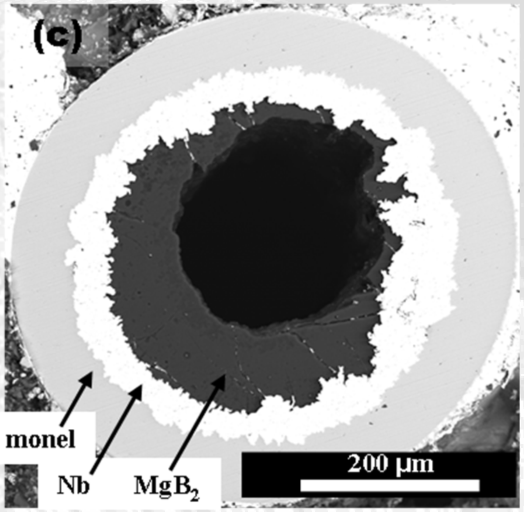
**B1: 0.5 h**



**B2: 1 h**



**B3: 4 h**



- $MgB_2$ circular layers are formed but the Mg rod is off-centered.
- B is fully reacted after 4 h heat treatment at 675 ˚C.

- $MgB_2$ area and layer thickness are listed in table 2.

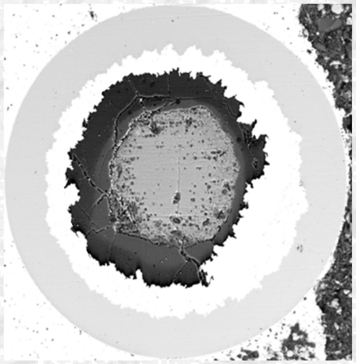
# Comparison of A- & B-series Strands

**Table 2: $MgB_2$ Layer Thickness, Areas and Corresponding Fill Factors**

| Sample No. | HT time at 675 °C, h | $MgB_2$ layer thickness, μm | $MgB_2$ area, $\mu m^2$ | $MgB_2$ fill factor, %* | $MgB_2$ + B fill Factor, %** |
|---|---|---|---|---|---|
| A1 | 0.5 | 0 ~ 30 | 26900 | 4.4 | 21.1 |
| A2 | 1 | 10 ~ 50 | 38200 | 6.3 | 19.7 |
| A3 | 8 | 15 ~ 60 | 44800 | 7.5 | 19.1 |
| B1 | 0.5 | 0 ~ 40 | 25100 | 10.1 | 19.6 |
| B2 | 1 | 0 ~ 49 | 28000 | 11.2 | 19.7 |
| B3 | 4 | 0 ~ 90 | 46700 | 18.8 | 18.8 |

* Area fraction of $MgB_2$ in the overall transverse cross section of the wire

** Area fraction of $MgB_2$ plus unreacted B powder after heat treatment



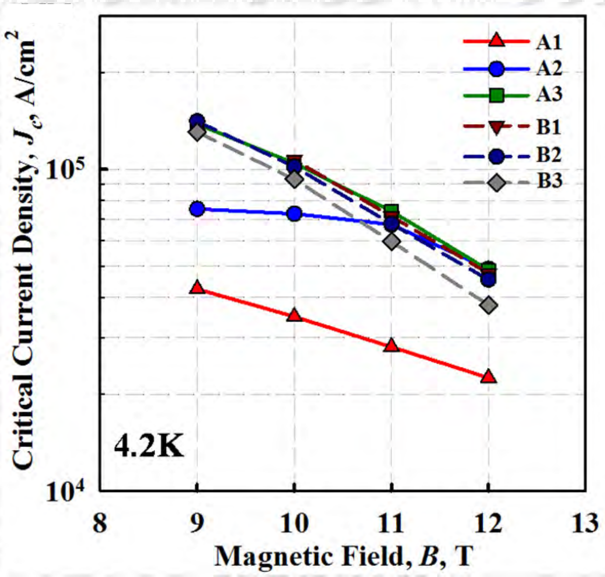
- $MgB_2$ layer thickness increases as HT time increases.
- $MgB_2$ fill factor increases as HT time increases.

# Layer $J_c$ & Engineering $J_e$

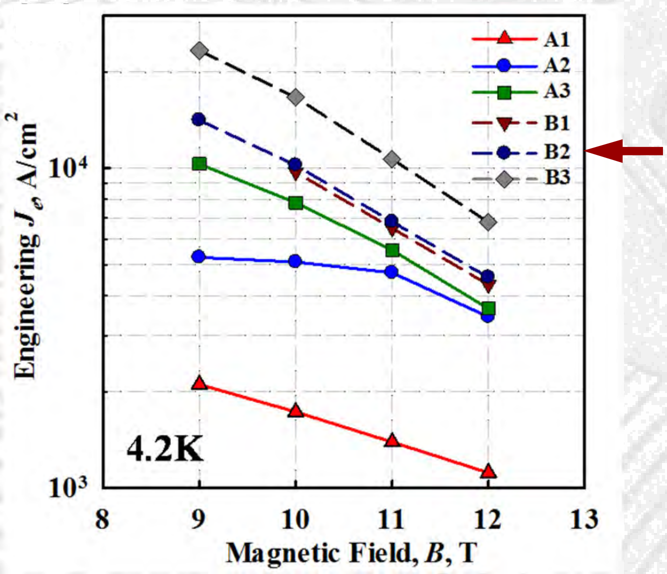
layer $J_c = I_c$ / $MgB_2$ area

$J_e = I_c$ / whole area

**layer $J_c$**



**Engineering $J_e$**

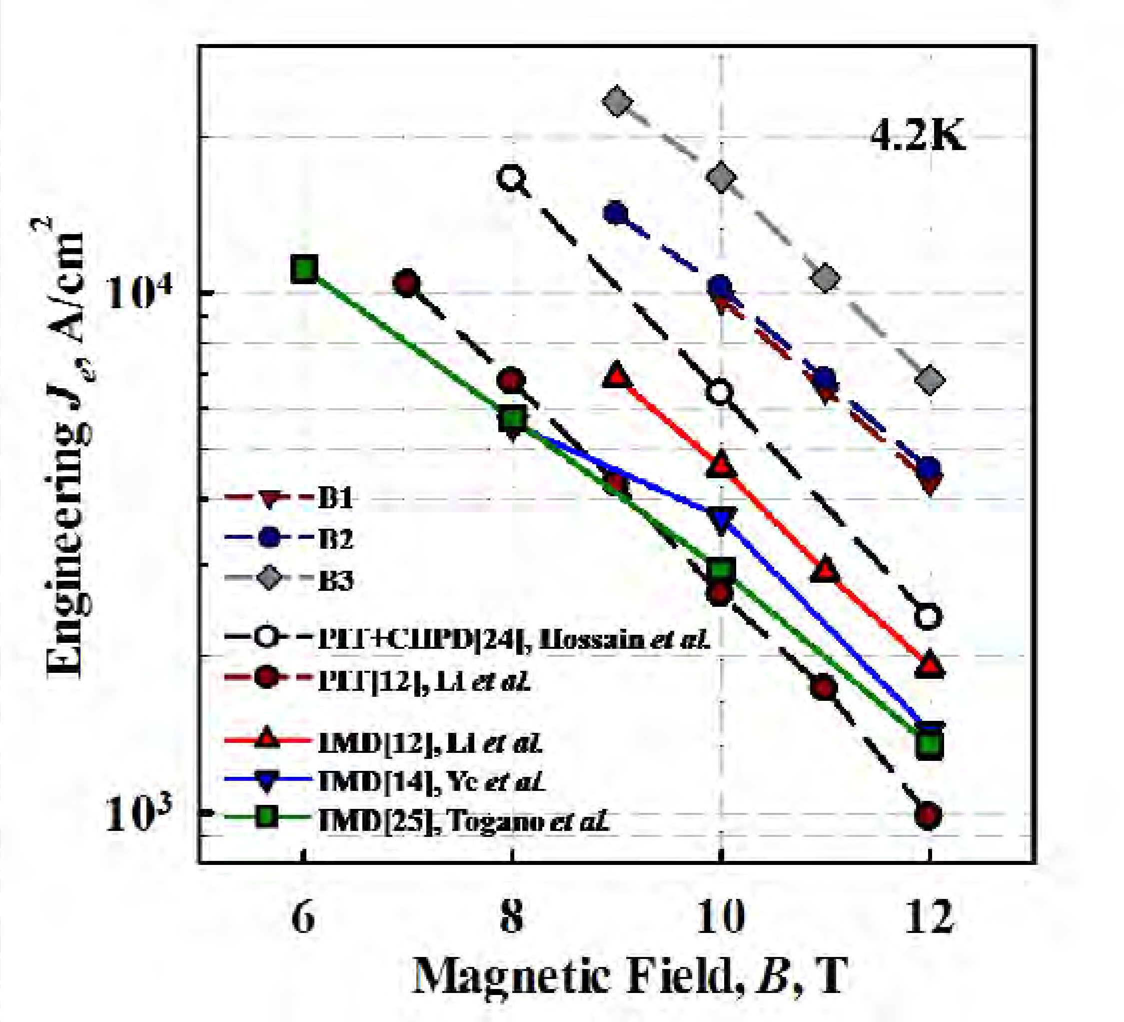


**B3: $1.67 \times 10^4$ A/cm$^2$ at 10 T**

**All wires quench when $B < 9$ T.**

- **layer $J_c$:**
  - ***A-series*** **HT time ↑, $J_c$ ↑; A3: $1.04 \times 10^5$ A/cm$^2$ at 10 T**
  - ***B-series*** **HT time ↑, $J_c$ ↓; B1: $1.07 \times 10^5$ A/cm$^2$ at 10 T**
- **Engineering $J_e$:**
  - ***B-series*** **is better than *A-series* because of its high $MgB_2$ fill factor.**

# So, layer $J_c$ is 10 x for 2G (and IMD), but How do the $J_e$ results compare to PIT?



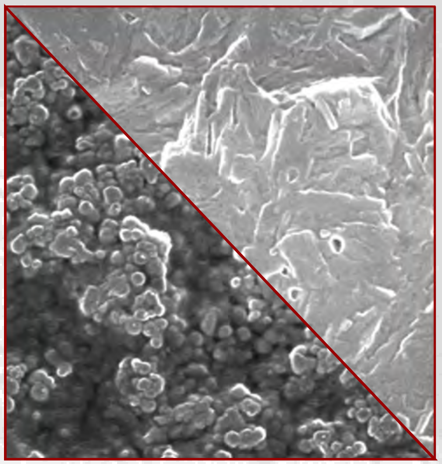
We have to correct for doping level and special processing

A head to head comparison is shown by the red filled circles and the gray diamonds – about a factor of 5 in $J_e$!

Pressure processing (sequential pressing, Flukiger/Hossain) on the same PIT wires is also shown (open circles)

We have found 3-4% C can given high $J_c$s in PIT wires, now implementing in IMD

# $MgB_2$ Layer Growth Mechanism



- **Step I: Melting of the Mg rod**
- **Step II: Liquid Mg infiltration and reaction with B**

$Mg + 2B \rightarrow MgB_2$

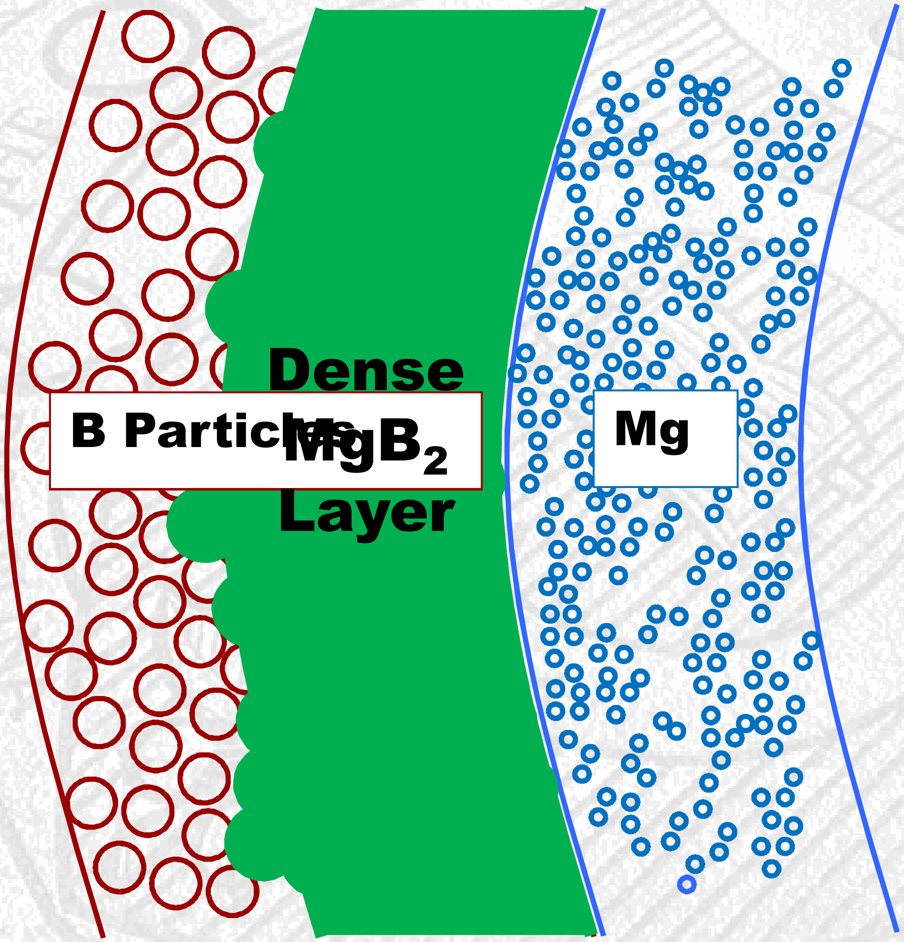
B particles volume expansion are **~ 90%** considering: (a) **$V_B$: 4.59 cm$^3$/mol** and (b) **$V_{MgB2}$: 17.46 cm$^3$/mol**

A dense $MgB_2$ circular layer is formed.

- **Step III: Mg atomic diffusion through the dense $MgB_2$ layer**

Atomic GB diffusion: Quite slower process than liquid Mg infiltration in step II.
Grain growth during long HT time, resulting in reduced layer $J_c$.

# *Demonstration: $MgB_2$ Layer Growth Mechanism*



**Melting of Mg**

⇩

**Liquid Mg Infiltration**

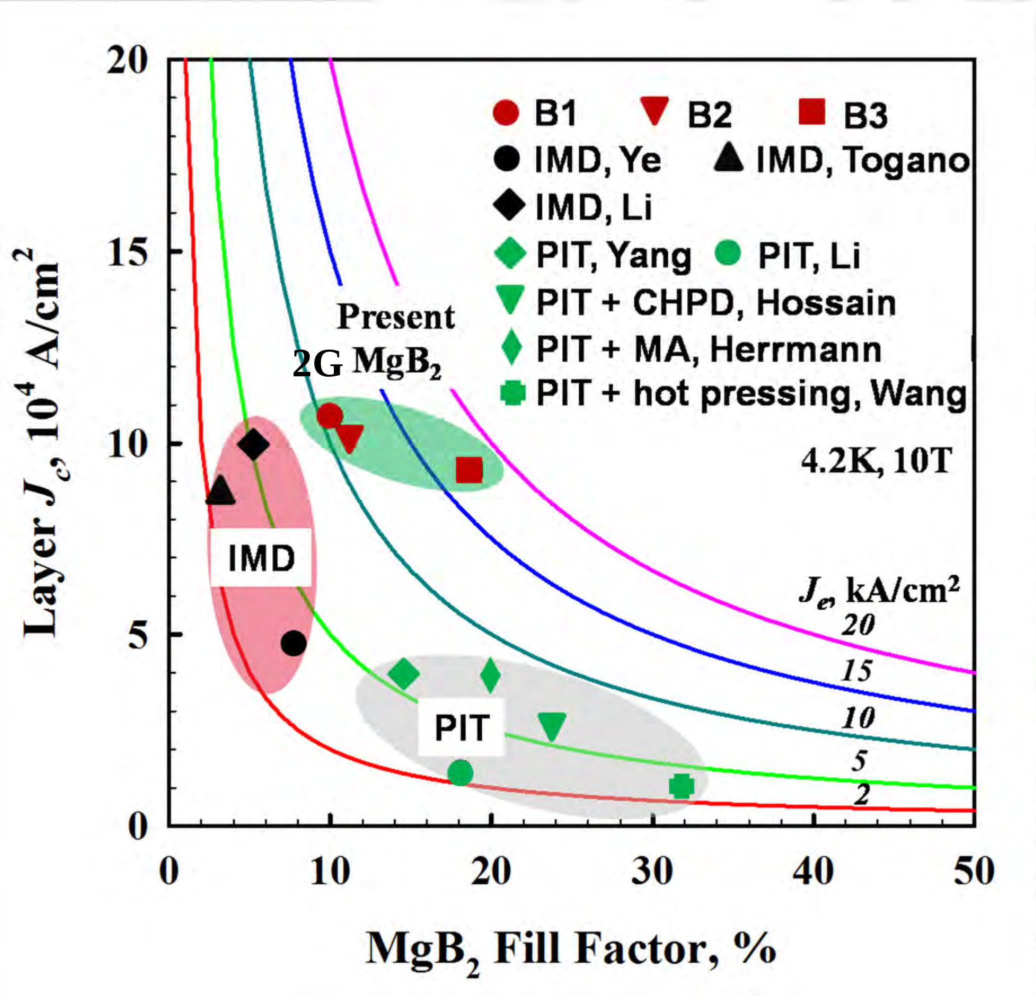
**& Reaction**

⇩

**Dense $MgB_2$ Formation**

**& Mg Atoms Diffusion**

# *Principle to Design a Well-Performed Wire*



*Directions to obtain a good conductor:*

**$J_c$ improvement.**

- doping
- pressing
- ball milling
- infiltration/diffusion method

**$MgB_2$ fill factor.**

- smaller diameter wire
- multifilamentary wire

$$\text{layer } J_c = \frac{J_e}{\text{MgB}_2 \text{ fill factor}}$$

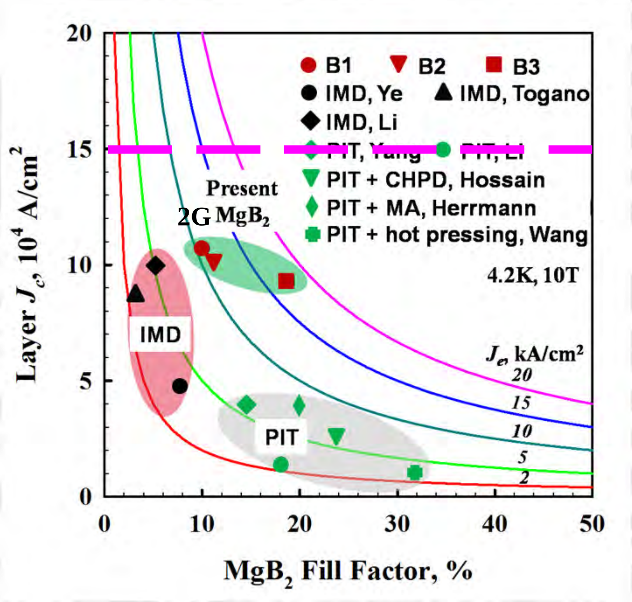
(S J Ye *et al*, Physica C, 2011; K Togano *et al*, SUST, 2009; G Z Li *et al*, SUST, 2012; Y Yang *et al*, IEEE Trans Appl Supercond, 2012; M Hossain *et al*, SUST, 2009; M Herrmann *et al*, APL, 2007; D L Wang *et al*, SUST, 2012)

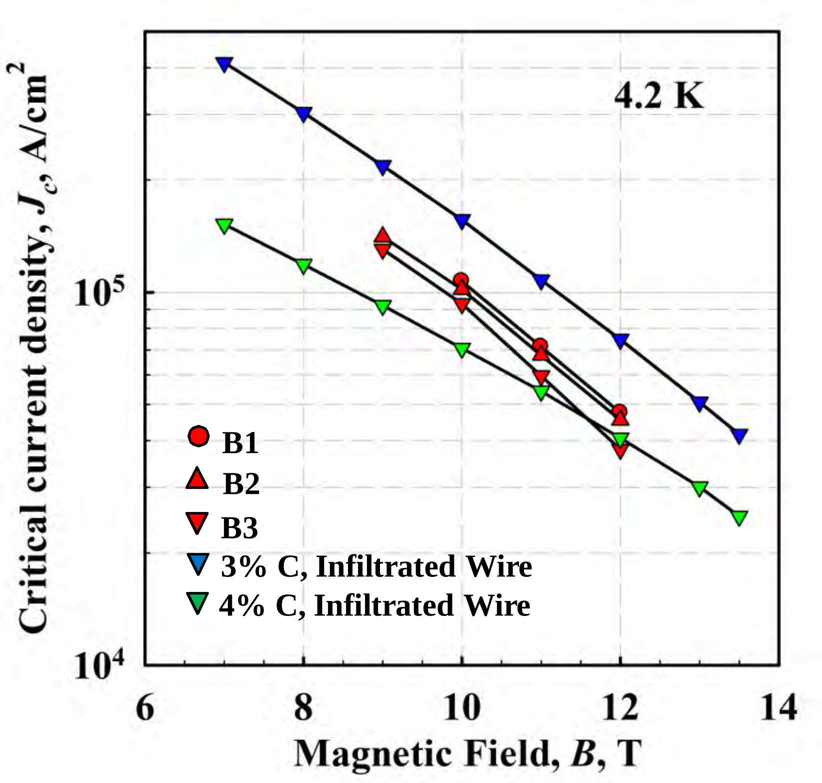
# Further Explorations I: layer $J_c$ enhancement

- **Carbon doping level**

3% and 4% C doped diffusion processed strands, heat treated at 675 C, 4H.

Best layer $J_c$ for 3% C doped diffusion processed strands: $1.57 \times 10^5$ A/cm$^2$ at 4.2 K, 10 T.

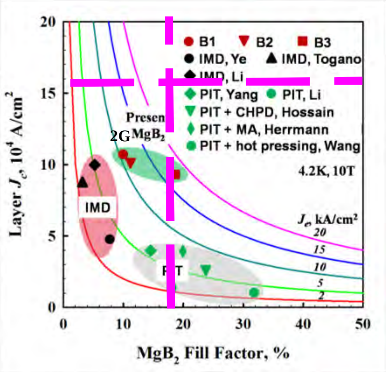


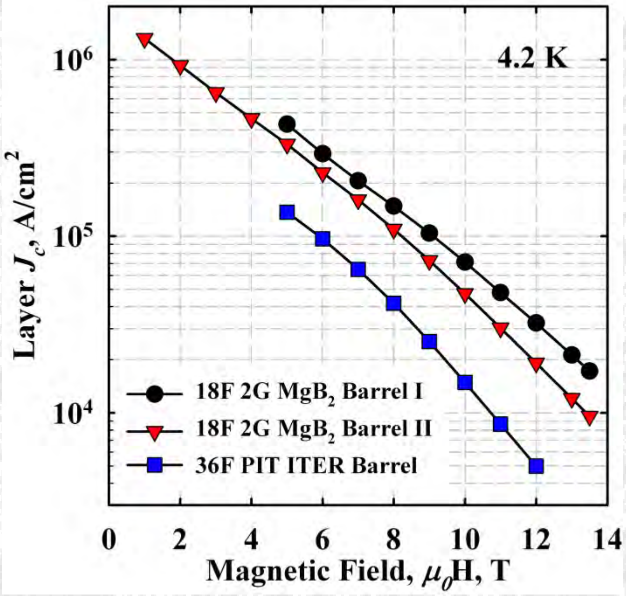


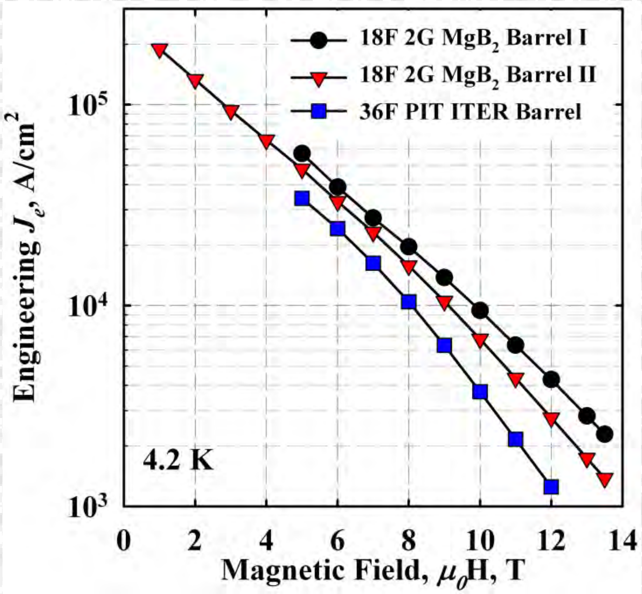
# *Further Explorations* *II: Multifilamentary 2G Wires*

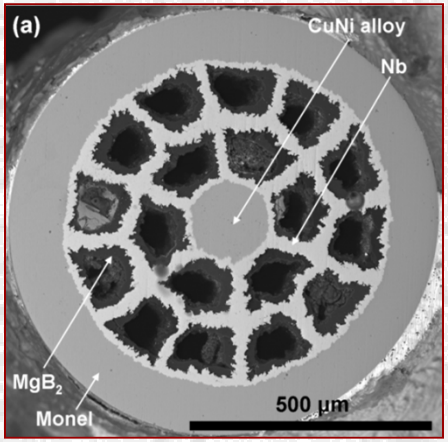
- **2G $MgB_2$ multifilamentary long strands (ITER barrel).**

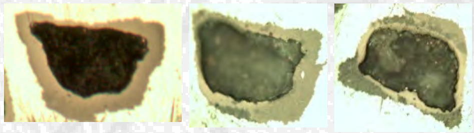
Layer $J_c$ and $J_e$ higher than typical multifilamentary PIT barrels, but lower than our best 2G monocore short wires.











# N-values in PIT $MgB_2$

- Improvements in 4 K values
- Improvements in n values as a function of *B* and *T*

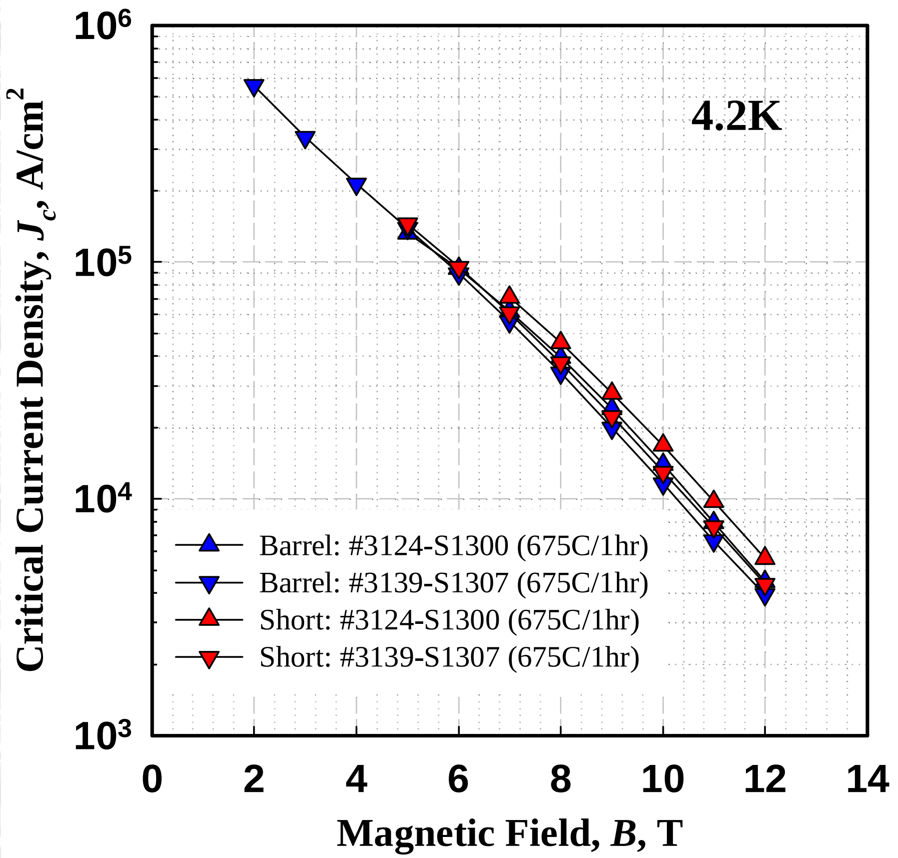
# Strand Types

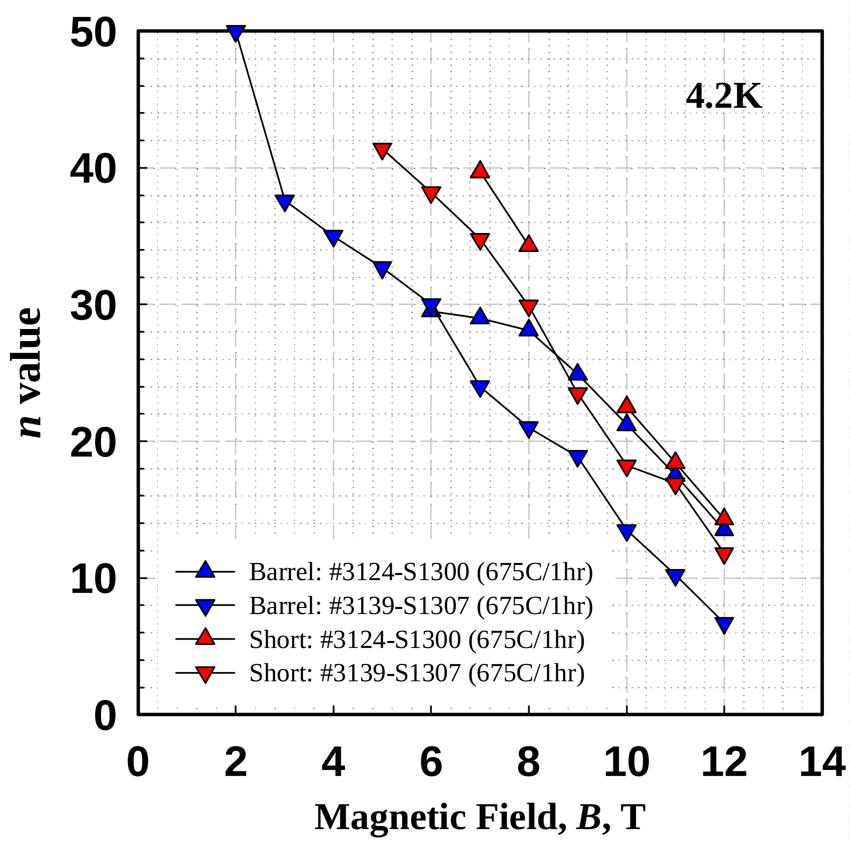
| Strand # | # Mono | Barrier | Mono sheath | Multi sheath | Central fil(s) | powder material | dia (mm) | % powder | HT (°C/min) |
|---|---|---|---|---|---|---|---|---|---|
| 3139 | 24 | Nb | - | Monel | Cu | MgB2_2%C‡ | 0.83 | 11.7 | 675 / 60 |
| 3139 | 24 | Nb | - | Monel | Cu | MgB2_2%C‡ | 0.83 | 11.7 | 700 / 60 |
| 3124 | 30 | Nb | - | Monel | Cu | MgB2_2%C | 0.83 | 23.3 | 675 / 60 |
| 3124 | 30 | Nb | - | Monel | Cu | MgB2_2%C | 0.83 | 23.3 | 700 / 60 |

*Early Barrel Study*

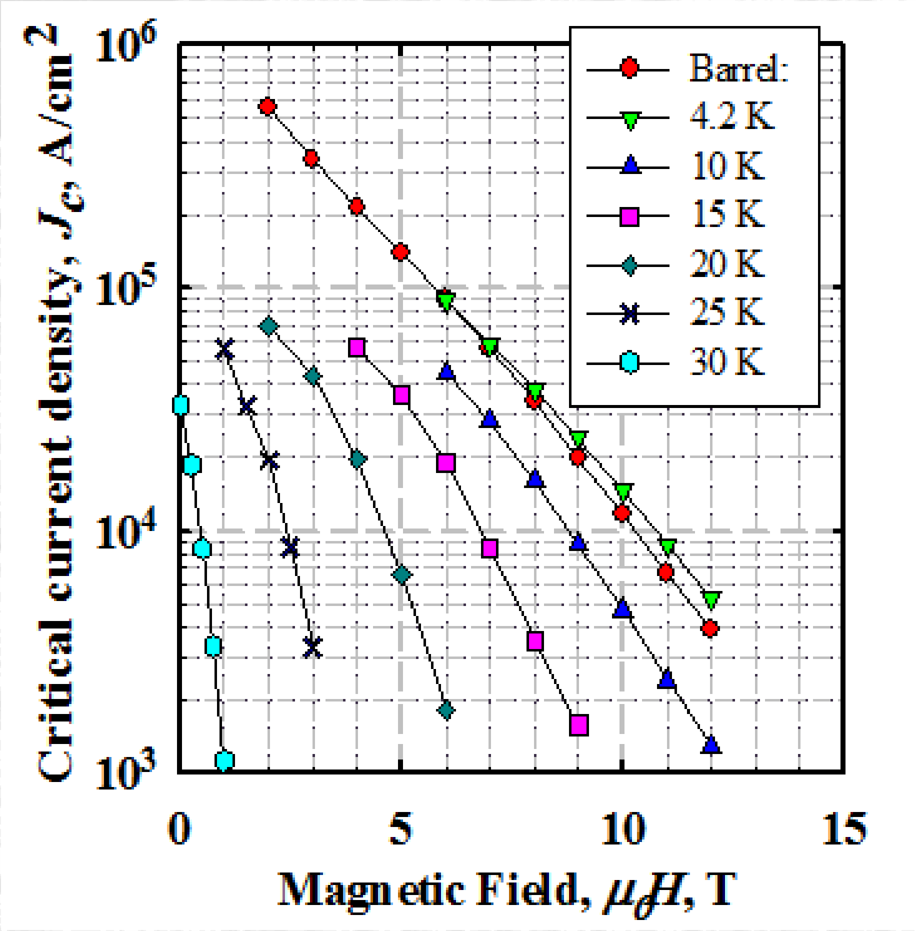
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 3139-S1307 | 24 | Nb | - | Monel | Cu | MgB2_2%C‡ | 0.83 | 11.7 | 675 / 60 |
| 3124-S1300 | 30 | Nb | - | Monel | Cu | MgB2_2%C | 0.92 | 23.3 | 675 / 60 |

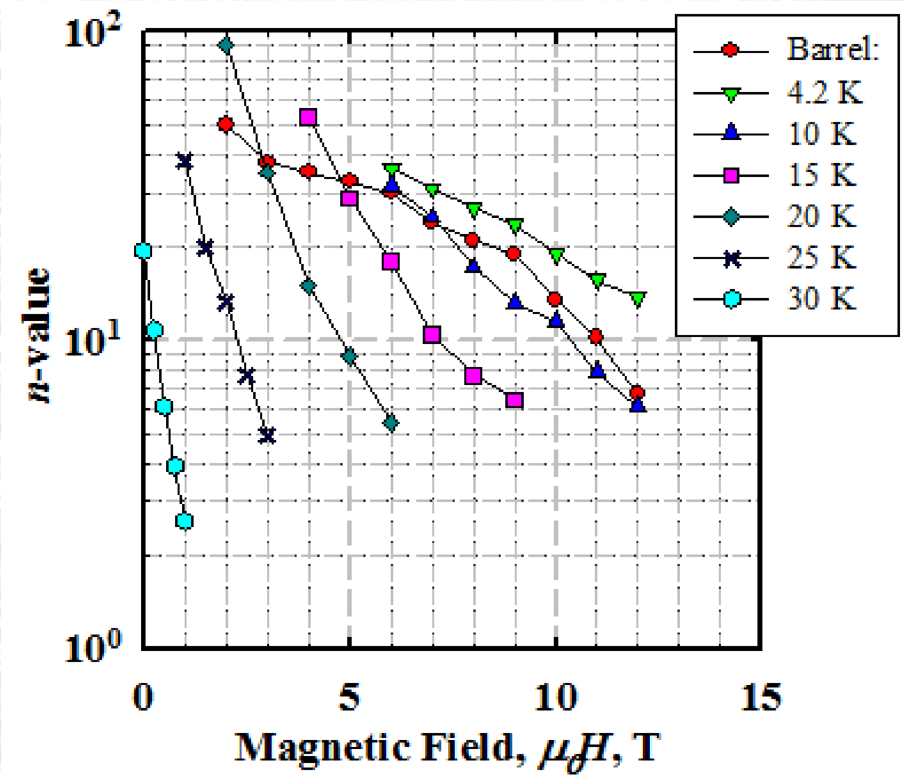
# $J_c$ and $n$ value at 4.2K



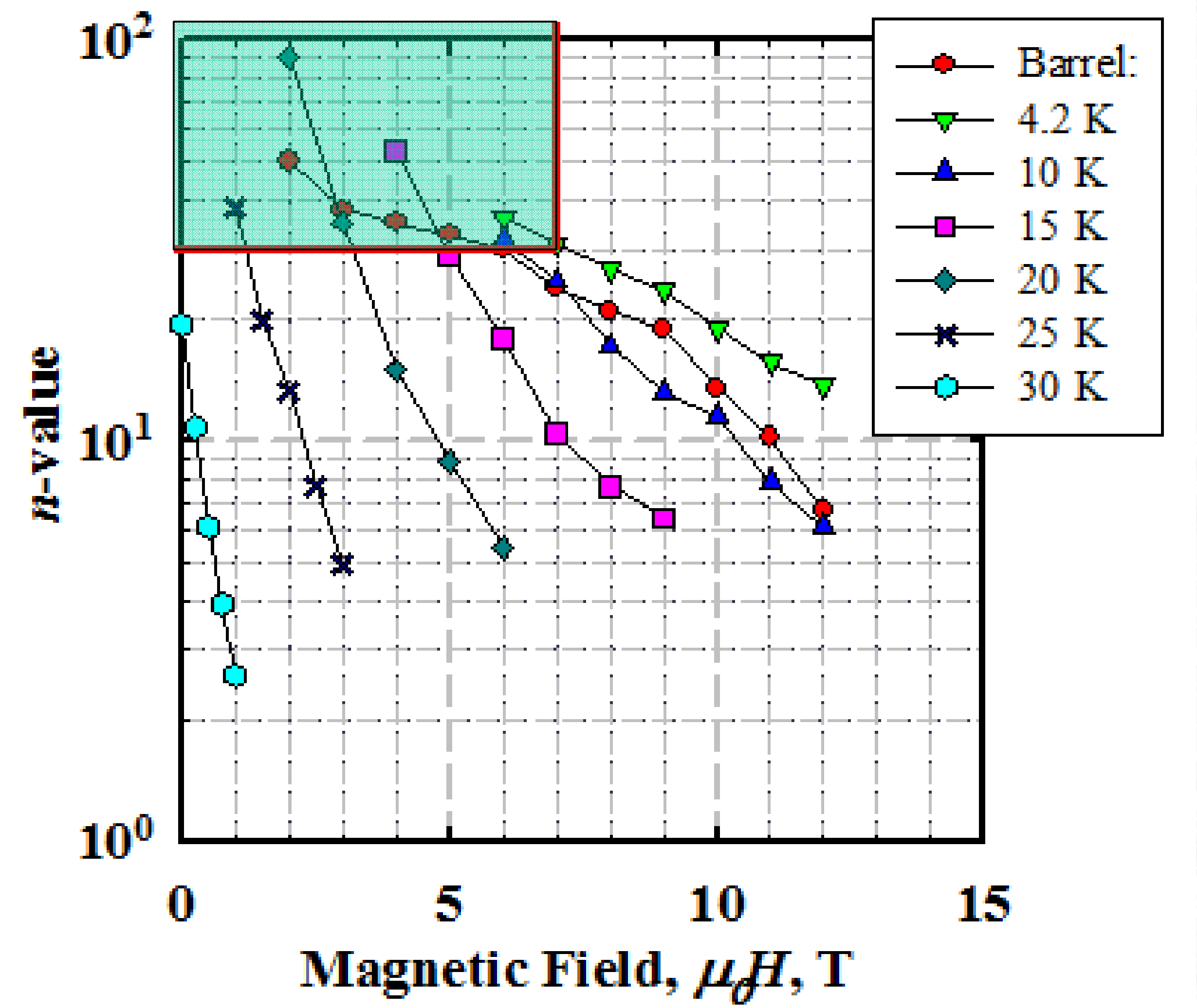


# 24 Filament (3139-S1307)





# Regimes of n-value

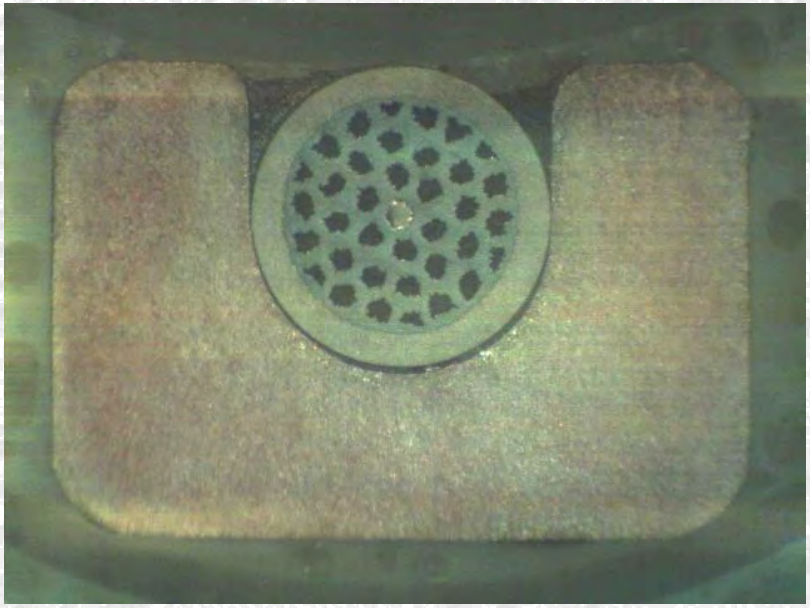


N > 30

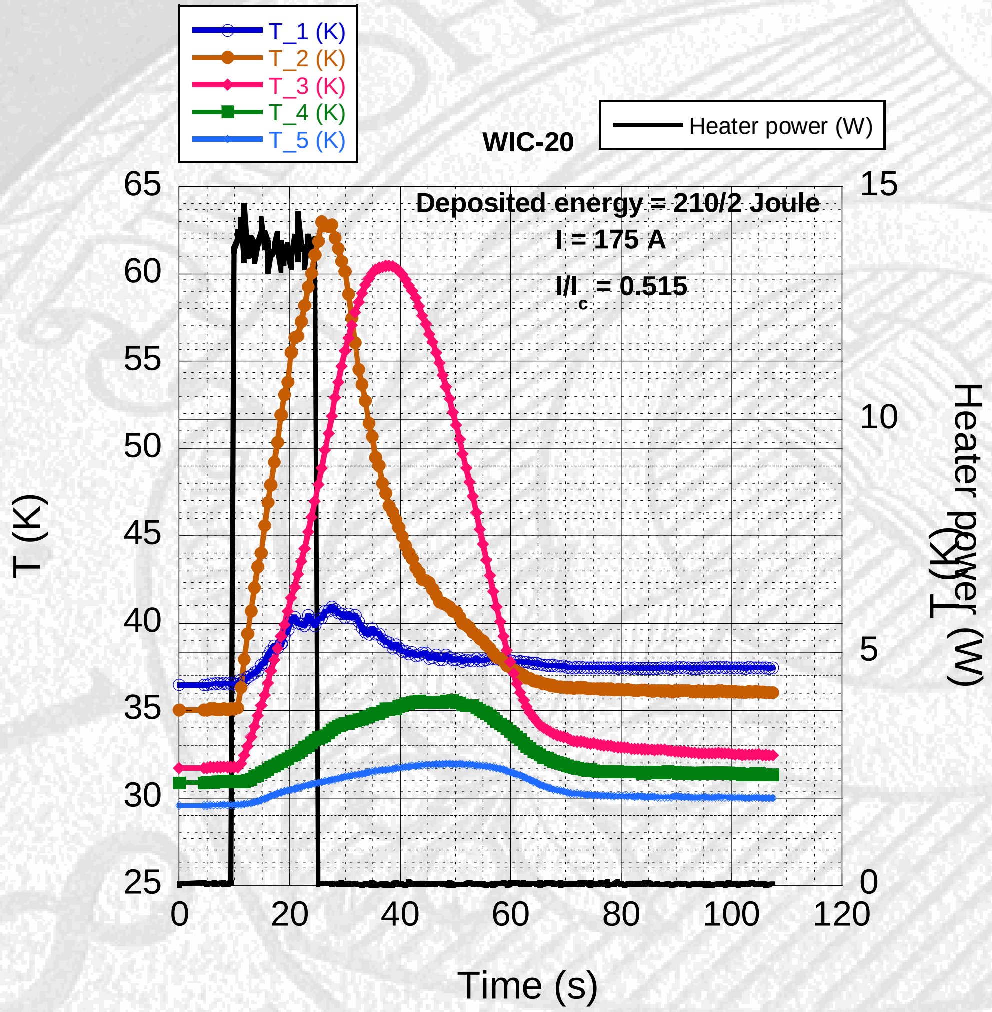
| | |
|---|---|
| 4K | 7 T |
| 10K | 6 T |
| 15K | 5 T |
| 20K | 3 T |
| 25K | 1 T |

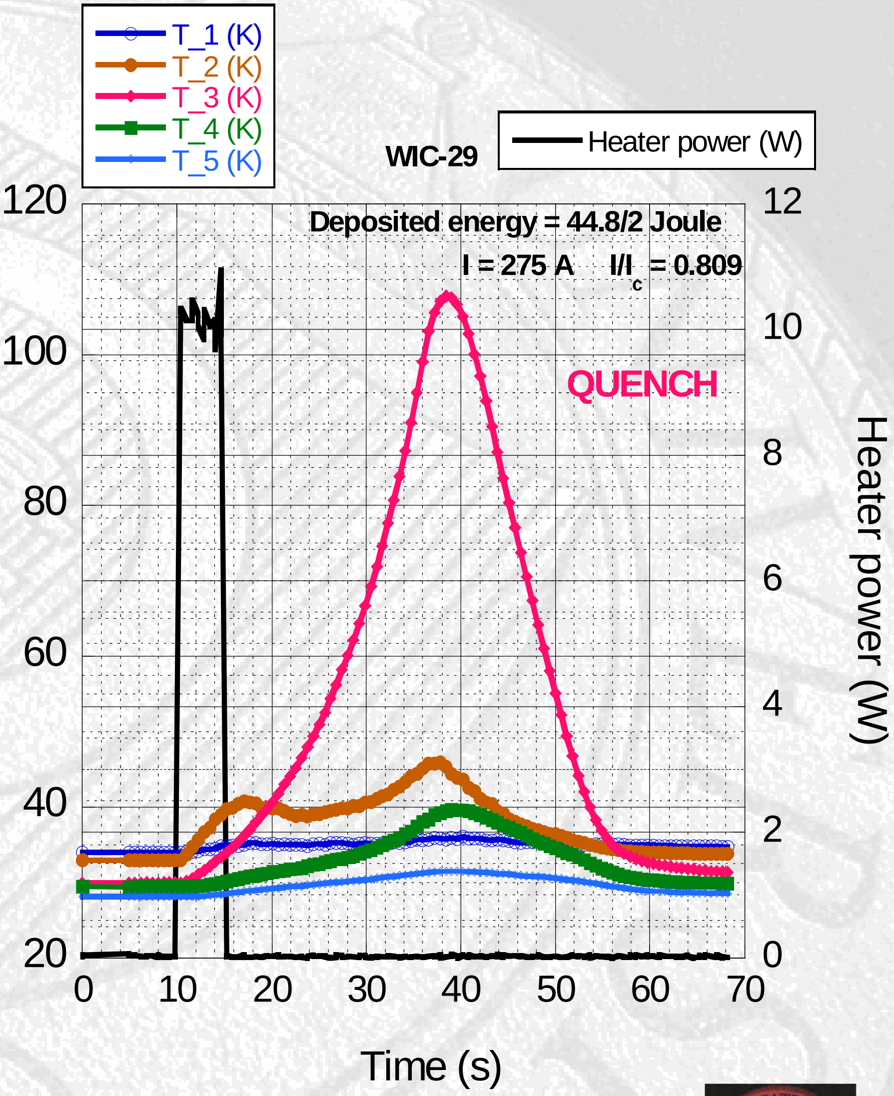
# WIC and Coil Test

- WIC Test
- Coil Manufacture and Test



# WIC NZP and Quench (gas cool)





**NZP: 0.5-1 cm/s**

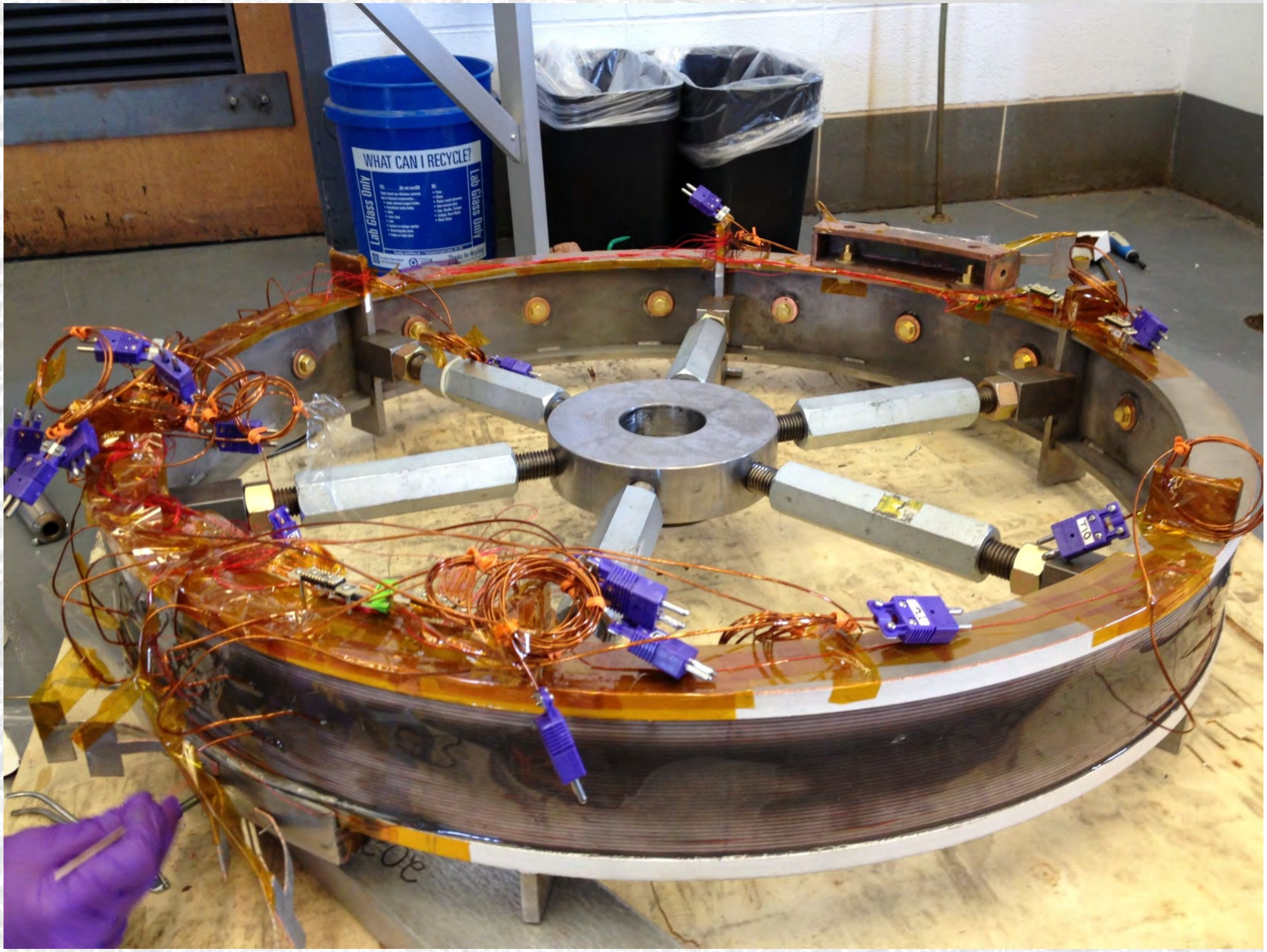
# MgB2 Coil, 100 m of WIC MgB2 Conductor

**HTR:** MgB2 strand, Wire-in-channel Conductor

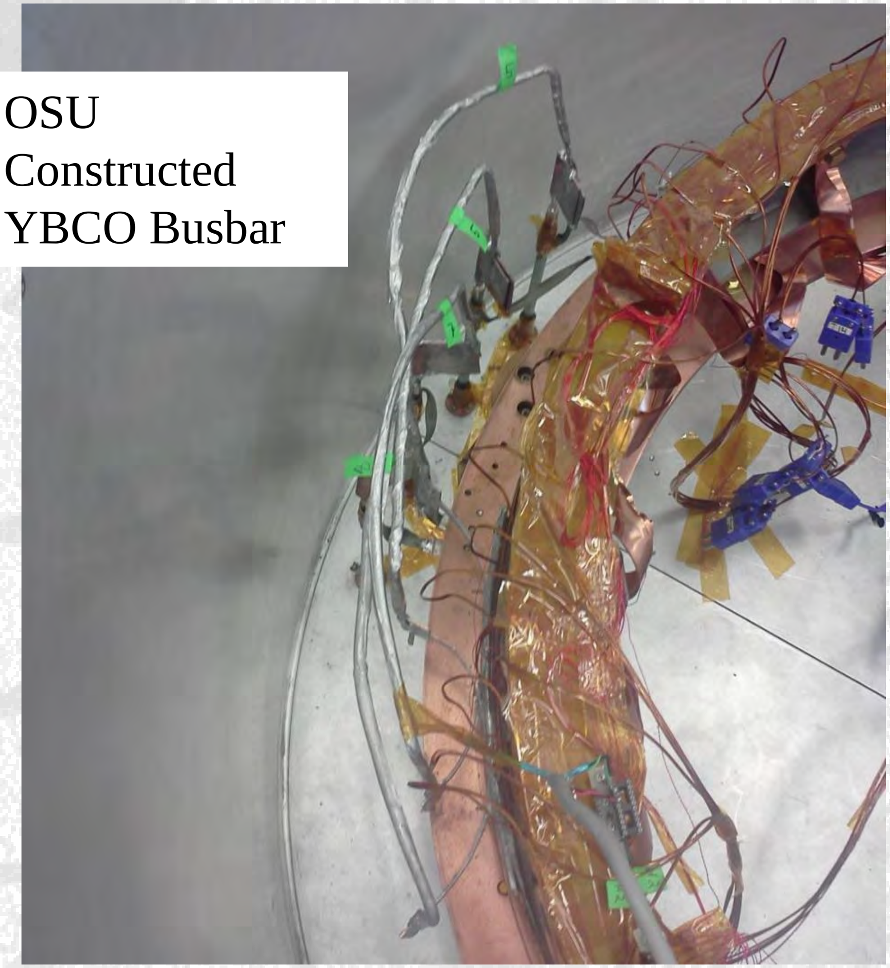
**HTR**: Coil wound, coil epoxy impregnated by HTR

**OSU:** Coil Instrumented with 30+ voltage taps, 18+ thermocouples, , other sensors

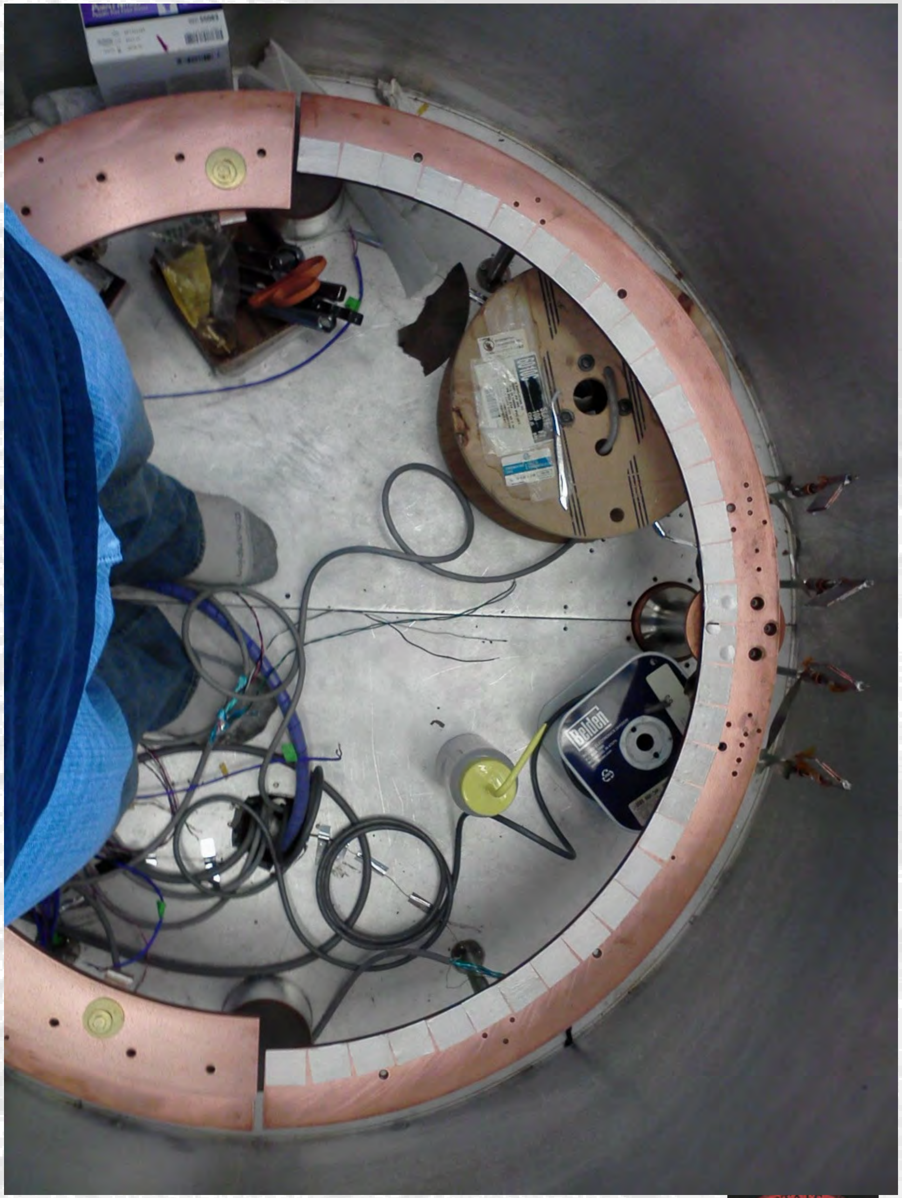
**OSU:** Cool down and Test



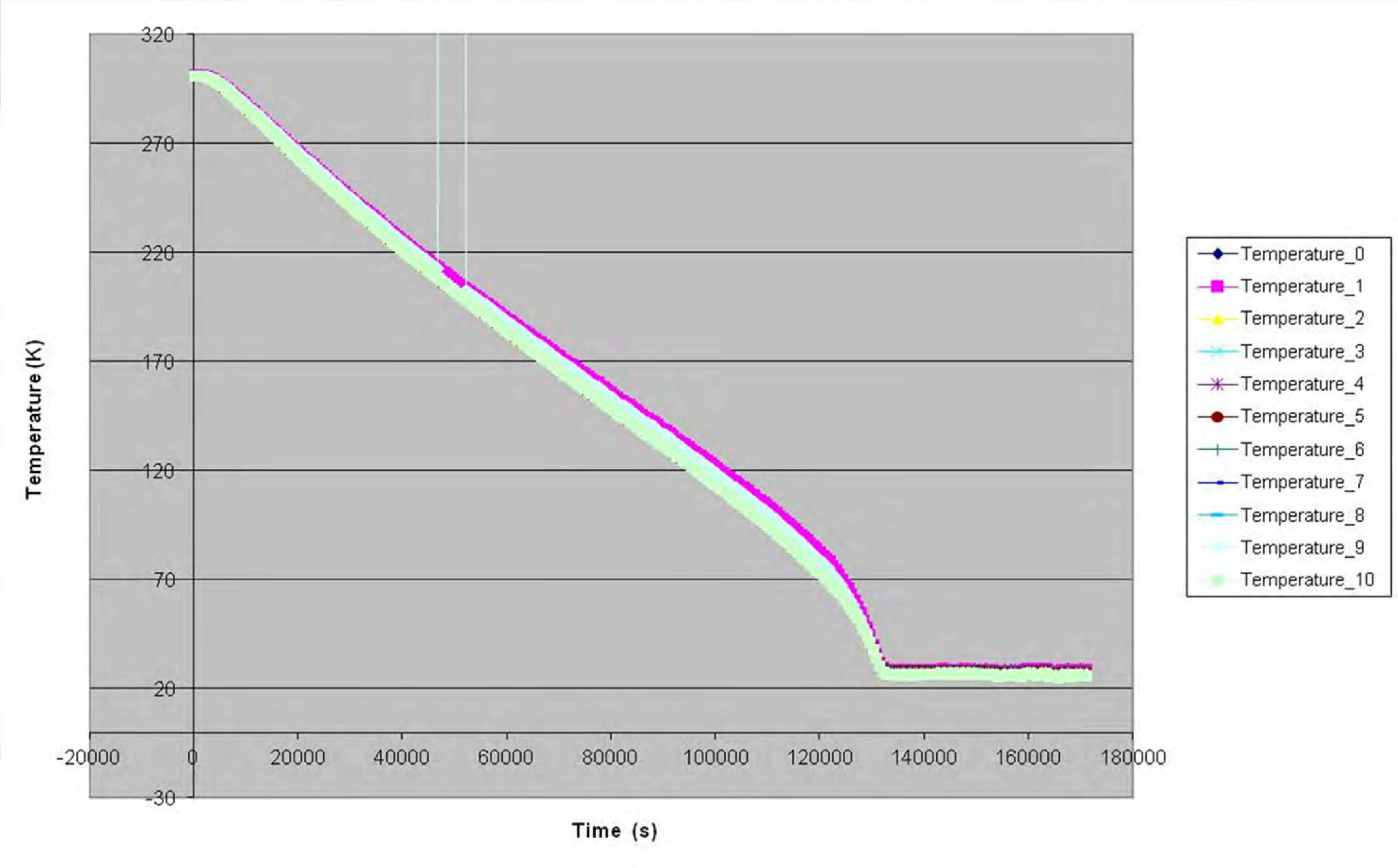
# Inside of OSU Dewar



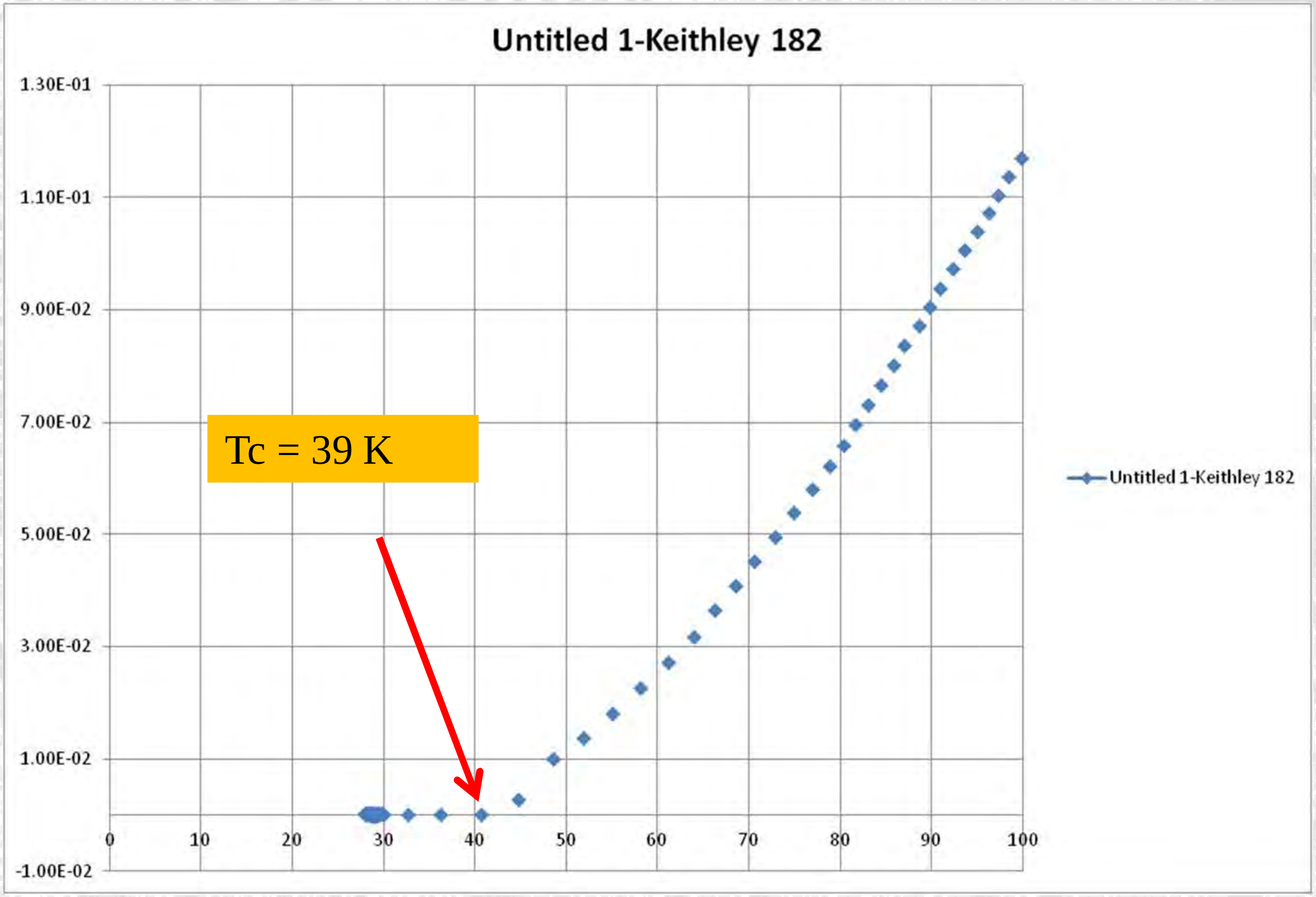
OSU
Constructed
YBCO Busbar



# Initial Coil Cool-down

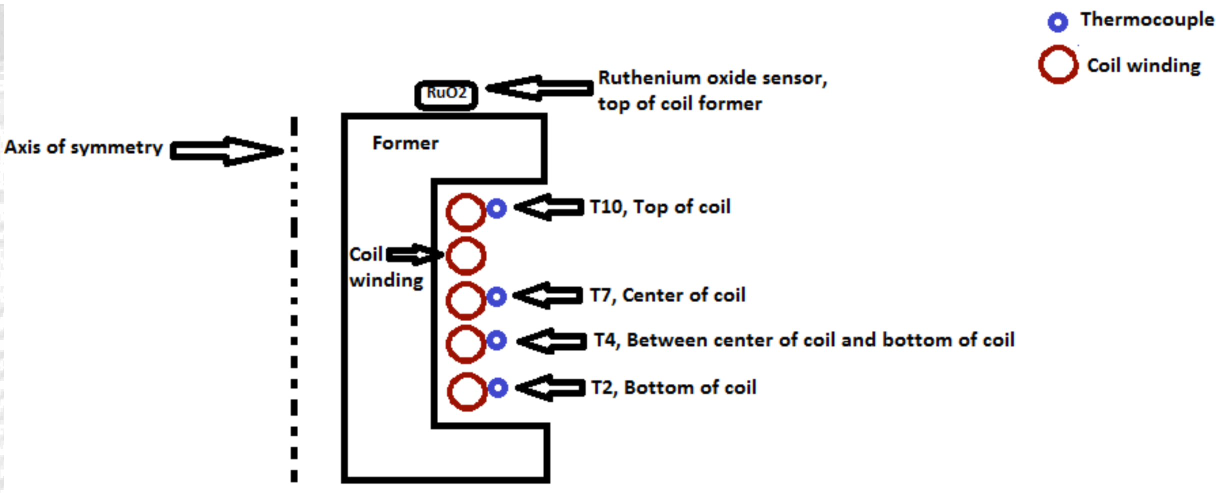


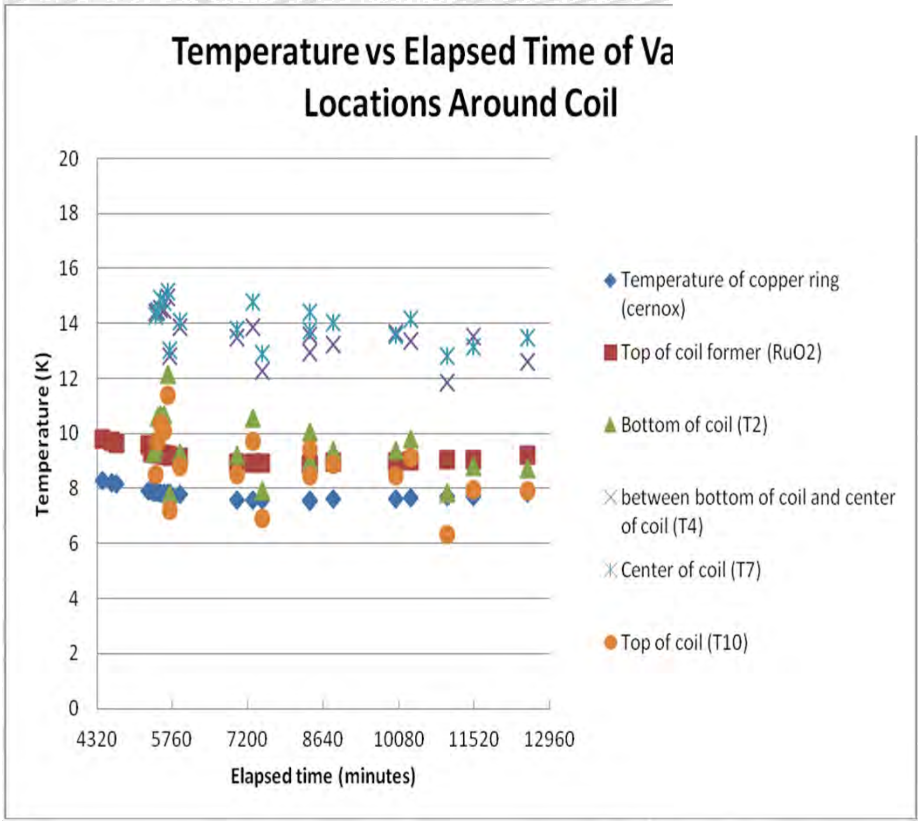
# Tc transition for coil

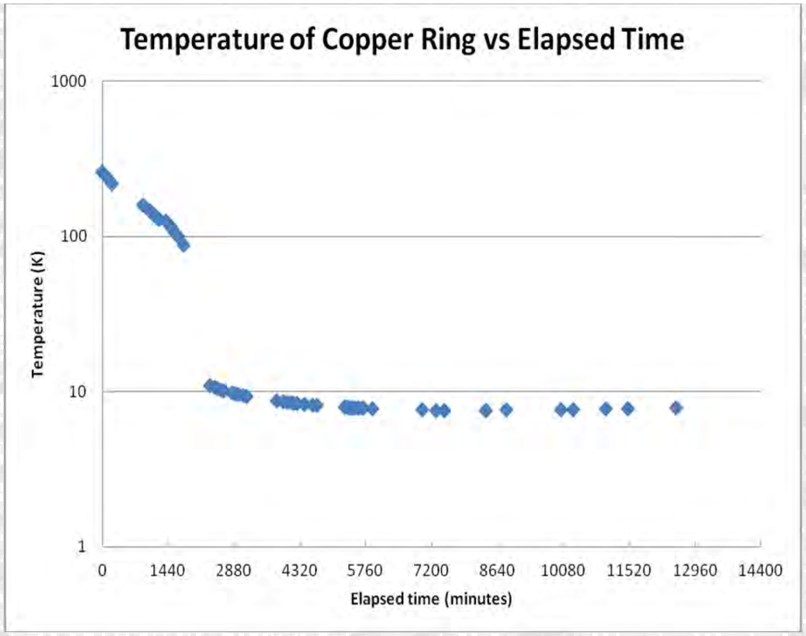


Tc = 39 K

# Coil T Instrumentation /Result







# *Summary*

- Percolation-based models were used to compare PIT and IMD $MgB_2$ wires, and it was found that previous treatments which attributed all high field $J_c$ loss to anisotropy were overly pessimistic, with about 40% (or a large reduction) due to porosity
- This led to an impetus to push IMD from "scientifically interesting" (high $J_c$ (10 X PIT), low $J_e$) to practical conductors
- These considerations led to advanced, "2G", $MgB_2$ wires were fabricated by incorporating (1) a Mg diffusion method, (2)fine B powder, (3) C-doping at the powder level, (4) Mg/B ratio, and (5) strand geometry modifications.
- 2G $MgB_2$ wires had dense $MgB_2$ layer structures, enabling best layer $J_c$ of $1.0 \times 10^5$ A/cm$^2$ at 4.2 K and 10 T (***an increase by a factor of 10!)***
- The best $J_e$ of sample B3 achieves 15.7 kA/cm$^2$, in increase of about 5 from the same chemistry PIT conductors, and ***a factor of 3 above the previous best ever*** (MA or higher C levels) PIT wires.
- 100 m length multis now being made, working to translate full improvements to these conductors
- An $MgB_2$ layer growth mechanism was proposed for diffusion processed wires.
- Further geometry optimization and anisotropy reduction should lead to even higher $J_c$s and $J_e$s

# Summary

- High Performance Internal Magnesium Infiltration Strands are achievable with Engineering Designs that have high reacted areas inside filaments and strand fill factors
- Je performance for some of these conductors is substantially higher than PIT, and mulitifilamentary versions are better than PIT
- The improvements are such that they can push MgB2 conductors into new operational regimes, to point to this we have called these more optimized Internal Magnesium Diffusion conductors, second generation
- N-values have been substantially increased, reaching above 30 for 4.2 K, 7 T, 10 K, 6 T, and 15 K-5 T.
- A wire in channel has been developed, and quench properties have been evaluated
- A coil has been wound with this WIC, and is being tested presently