High performance iron-based superconducting wires: fabrication and properties

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1. Background on iron-based superconductors (IBS)

2. Development of high $J_c$ PIT 122 IBS wires

3. Application property of the IBS wires

4. Recent advances in long-length wires, joints, pancake & racetrack coils, cables

5. Conclusions and outlook
Iron-Based Superconductors (IBS)

Prof. Hideo Hosono 2008

Varieties of Iron-based superconductors (IBS)

High performance:
- High $T_c$~55 K
- High $H_{c2}$~100 T, $H_{irr}$ very close to $H_{c2}$
- Small anisotropy, $\gamma$<2
- High $J_c$~6 MA/cm$^2$ & $J_c$-depairing~160 MA/cm$^2$

High $T_c$~55 K

At 20 K, the $H_{c2}$ can be >70 T where IBS outperform both MgB$_2$ and Bi-2223.

<table>
<thead>
<tr>
<th>Bi-system</th>
<th>YBCO</th>
<th>IBS 122</th>
<th>MgB$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>50-90</td>
<td>5-7</td>
<td>1-2</td>
</tr>
<tr>
<td>$\xi_{ab}$</td>
<td>2.3</td>
<td>2.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Gi</td>
<td>$10^{-2}$</td>
<td>$10^{-4}$</td>
<td>$10^{-5}$</td>
</tr>
</tbody>
</table>
The cost of IBS wire can be four to five times lower than that of Nb$_3$Sn, making it more expensive than NbTi, but with much higher critical parameters than Nb$_3$Sn.

From a practical point of view, IBS are ideal candidates for applications.

High $J_c$ of IBS wires: Very weak field dependence in high field region

$I_c$ data of Sr-122 tape, measured in 2013 at HFLSM, Sendai

122 IBS wire: Large $J_c$, at $B > 20T$
IBS have potential for high-field applications

- Working Temp: 4.2 K – 30 K
- ITER: 10 m, 15 T (4.2 K)
- Accelerator (20 T)
- MRI (14 T)
- >1GHz NMR
- >23.5 T

Development of high-performance conductors is essential

J. Shimoyama, SuST 27 (2014) 044002
What makes a good superconducting wire?

**Characteristics:**

- **Intrinsic**
  - Low anisotropy
  - High $J_c$, $H_{c2}$
  - Chemically stable

- **Extrinsic**
  - Low AC loss (Multifilament)
  - Thermal stability (Thermal quench)
  - Good mechanical strength (Lorentz force)
  - Scalable production (powders & wires)
  - Small aspect ratio: round wire
  - Low cost—Conundrum for HTSC

**Commercial superconducting wires and tapes**

- NbTi
- Nb$_3$Sn
- MgB$_2$
- Bi$_2$2212
- Bi$_2$2223
- YBCO
Fabrication process for IBS wires and tapes

(Powder-in-tube method)

- Low cost, simple deformation process

122 PIT wires are expected to be much cheaper than BSCCO conductors:

1. Many types of sheaths of Ag, Cu, Fe, and Ag-based composites (Ag/Fe, Ag/Cu, Ag/stainless steel) can be employed.
2. For BSCCO, Ag is the only material that is inert to the BSCCO superconductor and permeable to oxygen at the annealing temperature.
Misorientation dependence of $J_c$:
GBs are less detrimental to current flow

- $\theta_{GB} \approx 3^\circ$ vs $122$ IBS $\theta_c \approx 9^\circ$ (The critical angle of GBs)
  - Misorientation angle of IBS grains < $9^\circ$ usually do not impede the $J_c$ flow
  - Highly textured templates are not necessary: *PIT and low-cost CCs are possible*

M. Putti presented at EUCAS-2015

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High $J_c$ values were achieved in hot pressed (HP) Ba122/Ag tapes

At 4.2 K, 10 T: $J_c \sim 1.5 \times 10^5$ A/cm$^2$, $I_c = 437$ A, $\gamma = 1.37$

18 T: $J_c \sim 10^5$ A/cm$^2$

27 T: $J_c \sim 5.5 \times 10^4$ A/cm$^2$

Latest: Record $J_c$ of HP Ba122 tape = $1.81 \times 10^5$ A/cm$^2$ at 4.2 K, 10 T

The grains are aligned along the c-axis, most of the misorientation angles are 5-20

No apparent in-plane texture was found
High-$J_c$ Ba-122 HIP wires improved by GR+HIP

Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ powder → Ag tube

packing

groove rolling

Ba$_{122}$/Ag+Cu
groove rolling

HIP sintering

700 °C, 150 MPa, 4 hours

by enhancing the texture

Ba-122 round wire

4.2K

improved by ~ 5 times

present work

Pyon et al.(2018)

Liu et al.(2017)

Weiss et al.(2012)

mono-core wires

$4.7 \times 10^4$ A/cm$^2$

(4.2 K, 10 T)

Cu/Ag sheath

Ba-122 7-filament wires

$3.3 \times 10^4$ A/cm$^2$

(latest result)

tape-in-tube method

JMCC 11 (2023) 1460

2 times higher

Ba$_{122}$/Ag+Cu

Cu/Ag sheathed Ba-122 tapes with practical level $J_c$

$J_c (4.2 \text{ K}, 10 \text{ T}) = 1.1 \times 10^5 \text{ A/cm}^2$

➢ $J_c$ exceeding $10^5 \text{ A/cm}^2$ for the first time for Cu/Ag sheathed tapes
➢ A scalable and cost-effective fabrication route!

Liu et al., *Sci. China Mater.* 64 (2021) 2503
Comparison of hysteresis loops for HP and HIP 122 tapes

**Hot Pressing**

- **HP Ba-122/Ag**
  - Critical Current ($I_c$) vs. Magnetic Field ($B$)
  - $J_c = 1.8 \times 10^5$ A/cm² (10 T)
  - Fraction with $\theta < 10^\circ$: ~42%

**Hot Isostatic Pressing**

- **HIP Ba-122/Ag/Cu**
  - Critical Current ($I_c$) vs. Magnetic Field ($B$)
  - $J_c = 1.1 \times 10^5$ A/cm² (10 T)
  - Fraction with $\theta < 10^\circ$: ~10%

**Properties**

- **HP Temperature (880°C)**
  - Grain size: ~3 μm
  - Lotgering orientation factor F: 0.87
  - Hv: ~140

- **HIP Temperature (740 °C)**
  - Grain size: ~0.5 μm
  - Lotgering orientation factor F: 0.46
  - Hv: >230

**Remarks**

- Much room for the $J_c$ improvement

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Courtesy: C. Senatore

Bonura et al., *SuST* 33 (2020) 095008

High $J_c$ values were achieved in Stainless Steel (SS)/Ag/Ba122 tapes, due to higher core density ($H_v \sim 230$), the $J_c$ is $8 \times 10^4$ A/cm$^2$ at 4.2 K and 10 T.

$J_c$ distribution of 1.08 m SS/Ag/Ba-122 tape

◆ 1.08 m long SS/Ag/Ba122 tape shows good $J_c$ uniformity, the lowest $J_c$ is over $7 \times 10^4$ A/cm$^2$.

High $n$ value:
@10 K, 10 T, $n \sim 47$

Dong et al., *IEEE TAS* 29 (2019) 7300504
Critical current density of SS/Ag composite tapes

**Stainless steel/Ag/Ba$_{1-x}$K$_x$Fe$_2$As$_2$ tapes** were made with a wide doping range (0.25 ≤ x ≤ 0.6)

- The highest $J_c^{\text{trans}} > 0.1 \text{ MA/cm}^2$ at $x = 0.458$ @ 4.2 K, 10 T
- Grain boundary transparency parameter $\varepsilon = J_c^{\text{inter}}/J_c^{\text{intra}}$ continuously increases with doping
- Grain boundaries are contaminated by FeAs, doping enhances proximity effect and inter-grain $J_c$.

The state-of-art high $J_c$ tapes still contain many contaminated GBs which disconnect the Ba122 grains. The $J_c$ can be largely improved if we can eliminate these secondary phases.
NEXT STEP for iron-based PIT wires?

**Dirty grain boundaries**

- $J_{c,\text{inter}} \approx 0.1 \text{ MA/cm}^2$
- $J_{c,\text{intra}} \approx 1 \text{ MA/cm}^2$

**Clean grain boundaries**

- $J_{c,\text{inter}} \approx 1 \text{ MA/cm}^2$
- $J_{c,\text{intra}} \approx 1 \text{ MA/cm}^2$

- Most GBs are contaminated by FeAs, largely limiting intergrain current transport

- **Slightly overdoping is a good way to enhance $J_{c}^{\text{trans}}$**

- Clean GBs without FeAs phase is always the best choice!

- $\varepsilon \sim 100\%$ may be achieved in the **GBs without FeAs** (misorientation angle $\theta < 9^\circ$)

**But how to remove FeAs?**
New record high $J_c$ in PIT SS/Ag Ba122 tapes

Special technique to remove FeAs wetting phase, details will be published soon.

- High $J_c$ @ 4.2 K:
  - $J_c \approx 2.2 \times 10^5$ A/cm$^2$ @ 10 T
  - $J_c > 10^5$ A/cm$^2$ even @ 30 T
- High mechanical strength
- Low material cost
- Easy fabrication process scalable to long length tapes

Very promising to be used in high field magnets!

No published data
Strategies to further improve $J_c$ in 122 PIT wires

◆ To further reduce secondary phases at GBs

◆ To improve the texture degree especially increase the fraction of misorientation angle $<9^\circ$.

◆ To further increase flux pinning force
  (1) decrease grain size to make more GBs,
  (2) increase point pinning sites, e.g. irradiation or the introduction of nano-particle inclusion.

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**Neutron Irradiation of Ba122 Single Crystals**

Courtesy: M. Eisterer

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**巴122 薄带**

Courtesy: M. Bonura & C. Senatore

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122 tapes – Strain properties

The \( I_c \) of 122 tapes exhibits less strain sensitivity than that of the \( \text{Nb}_3\text{Sn} \), which is important for ITER application.

Reversible critical currents under a large compressive strain of \( \varepsilon = -0.6\% \)

Almost no \( J_c \) degradation under a large compressive strain of 0.6%

Liu et al., SuST 30 (2017) 07LT01

Yao et al. 2017 SuST 30 075010
Bending test of 122 IBS tapes

---Heated samples

**122/Ag IBS tapes**

- Critical bending diameter is 4.4 cm for Sr-122/Ag tapes in thickness of 0.3 mm.
- For high strength Ba-122 tapes, the bending diameter is even smaller, only of 2~3 cm.

Cooperated with Prof. Huajun Liu in IPP-CAS

**SUS/(Ag-Sn)/Ba-122 tapes**

Coz op erated with Prof. Huajun Liu in IPP-CAS

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Bending diameter of 7-filament 122/Ag tapes

By courtesy of Prof. Q. Xu at IHEP-CAS

Ratio = $I_c$ (bending) / $I_c$ (pristine~135A)

- Good retention above Φ15 mm
- Rapid decrease of $I_c$ in the D10 sample

<table>
<thead>
<tr>
<th><a href="mailto:Ic@4.2K">Ic@4.2K</a>/10T</th>
<th>D10</th>
<th>D15</th>
<th>D20</th>
<th>D25</th>
<th>D30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>90</td>
<td>113</td>
<td>114</td>
<td>119</td>
<td>125</td>
</tr>
<tr>
<td>Group 2</td>
<td>70</td>
<td>110</td>
<td>118</td>
<td>120</td>
<td>124</td>
</tr>
<tr>
<td>Group 3</td>
<td>95</td>
<td>107</td>
<td>110</td>
<td>121</td>
<td>125</td>
</tr>
<tr>
<td>Average Ic (A)</td>
<td>85</td>
<td>110</td>
<td>114</td>
<td>120</td>
<td>125</td>
</tr>
<tr>
<td>Ratio (%)</td>
<td>63.0%</td>
<td>81.5%</td>
<td>84.4%</td>
<td>88.9%</td>
<td>92.6%</td>
</tr>
</tbody>
</table>

Li et al., IEEE TAS 32 (2022) 7300304
The AC loss for 7-core tapes reduced by ~50% at 20 K, due to the negligible eddy current losses by using more resistive AgSn alloy outer sheath.

Due to highly conductive Ag sheath, large eddy current losses (ecl) was observed for single-core tape.

\[ Q_{1\text{-Ba}122/\text{Ag} - \text{ecl}} = Q_{1\text{-Ba}122/\text{Ag}} - Q_{\text{ecl Ag-99\%}} \]

Kovac et al., *Cryogenics* 116 (2021) 103281

*The difference observed between the extracted \( Q_{\text{ecl}} \) (red lines) and those measured for etched Ag (green lines) could be attributed to different \( J_c \)s due to sample degradation.*
Thermal properties are dominated by the sheath materials

The thermal conductivity ranges from 1 to 1000 W/m K by adjusting the sheath materials

@4.2 K: Cu/Ag: 400 W/m K at 0 T; >100 W/m K at 9 T--magnets

SS/Ag: ~10 W/m K-- current leads

Atoms diffusion between different sheathes and superconducting cores

**$J_c$ anisotropy of 122/Ag tapes**

Awaji et al., *SuST* 30 (2017) 035018

Senatore et al., *SuST* 33 (2020) 095008

- The $I_c$ in applied magnetic fields is slightly higher in the perpendicular field ($I_c\perp$) than in the parallel field ($I_c\parallel$).
- The anisotropy ratio ($\Gamma = I_c\perp/I_c\parallel$) is quite low, less than 2, very good for applications.

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**Figure:**

- Graph showing $I_c$ vs. $B$ at 4.2 K for Sr122 (L1001) 2nd.
- $V_{tap} = 2.5 \text{mm} 4-13 \text{uV fit} 10 \mu\text{V criterion}$
- $I_c\parallel < I_c$ only at low temperature and fields

**Graph 2:**

- Graph showing $I_c\parallel/I_c$ vs. Temperature (K) with $B=10 \text{ T}$ and $B=19 \text{ T}$.
- $\sim 2$ for $B=10 \text{ T}$
- $\sim 1.5$ for $B=19 \text{ T}$

At 20 K, the \( n \) value was over 30

At 4.2 K, 10 T, the \( n \) value was over 20
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Powder-In-Tube 122 tapes: Long length

100 m long, 7-core Ba122 tapes are fabricated by rolling process, and the $J_c$ is continuously improving.

Recently, the $J_c$ of long wires has been increased above $6 \times 10^4$ A/cm$^2$ @ 4.2 K, 10 T by optimizing fabrication process.

Supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDB25000000)
High-performance joints were developed for IBS tapes, with a high critical current ratio (CCR) of 95%.

The IBS joint was tested in a closed-loop coil, showing a low resistance of $2.7 \times 10^{-13}$ Ohm.

Meet the application requirements in persistent mode MRI magnets.
Powder-In-Tube 122 tapes: Pancake coils

New IBS pancake coils have been made, measured up to very high fields reaching 62 A @ 4.2 K, 30 T

Qian et al., *Physica C* 580 (2021) 1353787
**IBS Racetrack coils made using the 100 m long tapes**

7-filaments IBS 100-m long tapes

\[ J_c(\text{coil}) = 87\% \ J_c(\text{short tape}) @ 10 \ T \]

Tapes’ Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of IBS tape</td>
<td>0.33</td>
</tr>
<tr>
<td>Width of IBS tape</td>
<td>4.5</td>
</tr>
<tr>
<td>Non-SC/SC ratio</td>
<td>5</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of coil winding</td>
<td>57.6</td>
</tr>
<tr>
<td>Width of coil</td>
<td>235.2</td>
</tr>
<tr>
<td>Width of coil winding</td>
<td>4.66</td>
</tr>
<tr>
<td>Length of straight part of coil</td>
<td>200</td>
</tr>
<tr>
<td>Thickness of SS tape</td>
<td>0.3</td>
</tr>
<tr>
<td>Turns</td>
<td>96</td>
</tr>
<tr>
<td>Bending radius</td>
<td>60</td>
</tr>
</tbody>
</table>

✓ Metal-as-insulation technique
✓ Wind & react > 800 °C
✓ \( I_c \approx 65 \, \text{A} \) @ 4.2 K, 10 T

87 % of the short sample at 10T

Very promising for next generation accelerator!

Zhang et al., *SuST* 34 (2021) 035021
First Tesla class IBS coil for high field application

✓ Six double pancake coils
✓ Self field 1.03 T @ 4.2 K, 20 T

The poorest IBS double pancake coil still had a critical current of about 84 A at the background field of 20 T
Outperformed all previously reported IBS coils

Ding et al., SuST, 36 (2023) 11LT01
A high $J_c$ of 71 kA/cm$^2$ ($J_c \sim$67 A) at 4.2 K, 10 T was measured in short segments picked up from the mono-core coil.

**Powder-In-Tube HIP 122 wires: Coils**

- 17~18 m mono- and 7-core Ba-122 wires
- Wires covered by glass sleeve are wound on SS bobbins
- HIP process is applied (Wind & React)
- Rapid increase in dissipation starts above 53 and 47 A for mono- and 7-core wires
- $I_c$ of the whole coil wires are 30 and 18 A in self-field, corresponding $H = 1.75$ and 1.0 kOe for mono- and 7-core wires

Pyon et al., SuST 26 (2023) 015009
FeSe$_{0.5}$Te$_{0.5}$ coated conductor tape and coil

FeSe$_{0.5}$Te$_{0.5}$ single pancake coil (SPC) was fabricated and tested under magnetic field

- One-meter FeSe$_{0.5}$Te$_{0.5}$ coated conductor tapes can be fabricated via PLD
- The transport critical current of the SPC was 108 A at self-field and 17 A at 10 T, which is as same as the tape.

Wei et al., *SuST* 36 (2023) 04LT01
High Field Model Dipole Magnet: HTS Cable R&D

Cable design

The advantages of the designed cable:
- High current-carrying compacity
- Low dynamic loss
- High mechanical stability

IBS transposed cable reached 1.3 kA

REBCO transposed cable reached 2 kA

J. Wang et al, Superconductivity 3 (2022) 100019

Courtesy of Prof. Qingjin Xu
• The **engineering current density** of the long-length IBS still needs a significant improvement, to reach the similar level as ReBCO or Bi-2212 conductors.

• The **materials of stabilizer** should be shifted to copper or any other low-cost metals to realize the low cost of IBS.

• **Structure and fabrication methods** of IBS and corresponding coils should be further optimized to minimize the $J_c$ degradation at high field and high stress.

• Many other issues like detailed magnetic and mechanical properties study of IBS, quench detection and protection of the IBS coils/magnets and etc.
Currently, a platform for the preparation of kilometer-scale long IBS wire is constructing in China.

Platform for kilometer-scale IBS wire

Equipment in place

Wire drawing machine

Tape rolling machine

HIP furnace

Plant layout, ~3000 square meters
Projects on IBS & Financial support

CAS funded “Science and Technology Frontier Research for the Next Generation Superconducting Magnet Applications” within the Strategic Priority Research Program of CAS

MoST funded “Next Generation High-field Magnet Technology Based on Iron-based Superconductor” within the National Key R&D Program of China

NSFC funded “High-performance Fe-based Superconducting Materials for High Magnetic Field Applications” within Major International (Regional) Joint Research Project
Conclusions

✓ Currently, iron-based wires and tapes are in the rapid development stage of research and development.

✓ Transport $J_c$ of 122-type IBS wires has been significantly improved, and has surpassed the practical level at 4.2 K & 10 T with a maximum of $2.2 \times 10^5$ A/cm$^2$.

✓ Transport $J_c$ of 100-m-class Ba-122 IBS tapes was further improved to $> 6 \times 10^4$ A/cm$^2$ at 10 T & 4.2 K.

✓ Highlights some remarkable advances of IBS relevant to practical applications, including superconducting joints, cable, the first IBS inserted coils and racetrack coils.

✓ We believe that Fe-based wires are very promising for applications in high magnetic fields, e.g. >20 T at 4.2 K or >10 T at 20-30 K.
Thank you for your attention!

From a movie: Avatar