Bi-2212 Challenges as a Magnet-ready Conductor

Snowmass White Paper https://arxiv.org/abs/2204.01072

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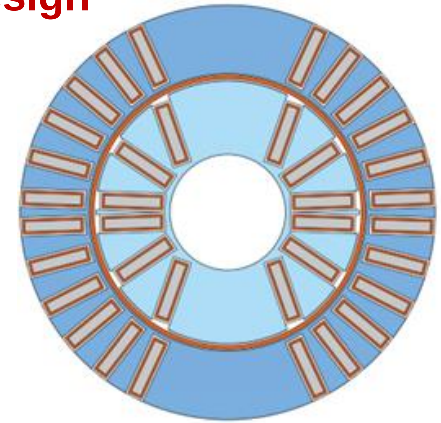
Main Goal

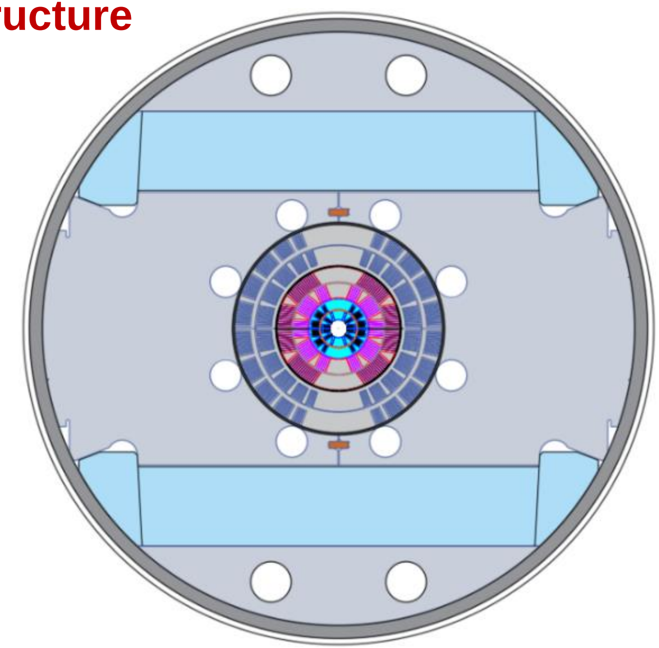
Develop **adequate Bi-2212 coil technology** and an **approach to manage azimuthal and radial strains** of high temperature superconductor inserts when integrated within Nb_3Sn outserts as a 20T hybrid magnet system.

FNAL most recent Bi2212 dipole insert design



➔

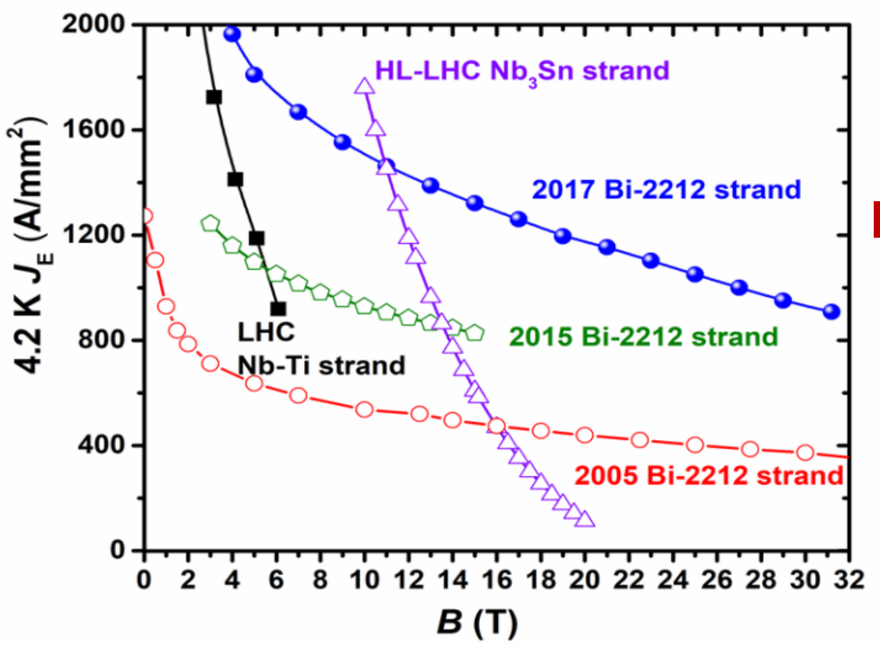
Bi2212 dipole insert in FNAL 17 T dipole structure



HTS dipole inserts have to produce > 5T within 15 T Nb_3Sn outserts to generate 20 T or higher fields for future high energy colliders.

Why Bi-2212?

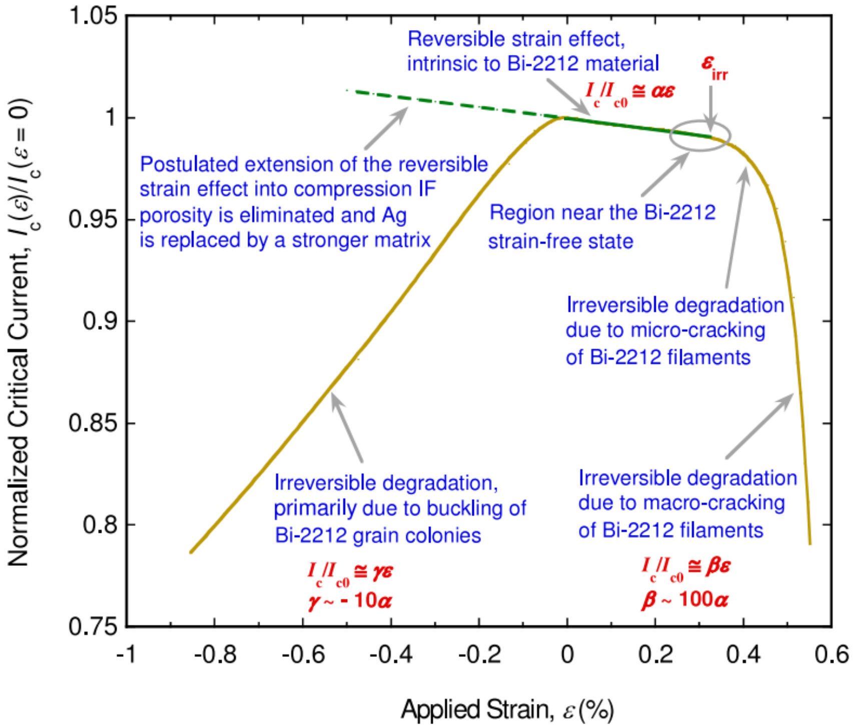
2017 curve is the peak performance obtained by Bruker-OST with the new Engi-Mat powders with billet PMM170123 .



Courtesy Tengming Shen

BUT

I_c Sensitivity to Tensile/Compressive Strain



'Reversible effect of strain on transport critical current in $Bi_2Sr_2CaCu_2O_{8+x}$ superconducting wires: a modified descriptive strain model' *N Cheggour, X F Lu, T G Holesinger, T C Stauffer, J Jiang and L F Goodrich. Article in Superconductor Science and Technology · December 2011*

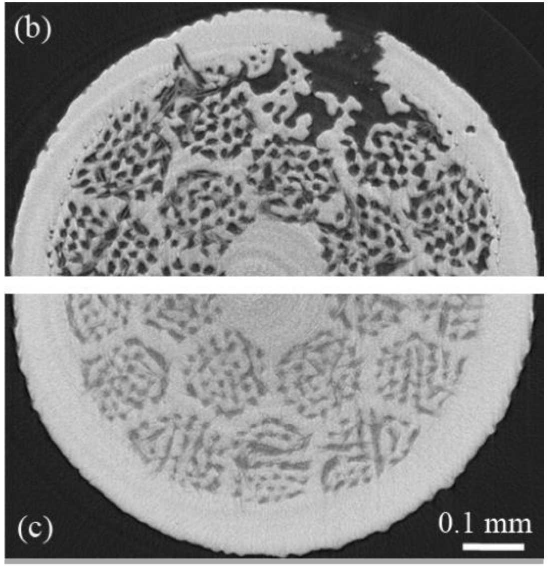
Recommendation 1

Heat treating Bi2212 at high gas pressure does not eliminate leaks from Rutherford cables. Any cable defects are unacceptable in accelerator magnets. Superconducting leaks are a major reason for the loss of critical current in coils.

⇒ **Collaborate with OST-Bruker and other capable industry to design billets that are adequate for Rutherford cabling.** This includes:

- Increasing outer AgMg sheath thickness
- Decreasing fill factor
- Reoptimizing subelement geometry

This may sacrifice superconductor real estate, hence the I_c of the round wire, but this decrease will be compensated with much smaller degradation of the critical current in the magnet itself.



EXAMPLE OF Bi2212 LEAK THROUGH BROKEN ROUND WIRE HEAT TREATED AT 1 BAR

Images from: D.C. Larbalestier, J. Jiang, U.P. Trociewitz, F. Kametani, C. Scheuerlein, M. Dalban-Canassy, M. Matras, P. Chen, N.C. Craig, P.J. Lee, E.E. Hellstrom, "Isotropic round wire multifilament cuprate superconductor for generation of magnetic fields above 30 T", Nature Materials, Vol. 13 (2014), 10.1038/nmat3887

Recommendation 2

To realize an effective accelerator magnet an insulation material chemically compatible with Bi2212 and its high temperature processing in oxygen is necessary and still has to be found. Existing methods using alumino-silicate braid and mullite sleeve and TiO_2-polymer slurry have not shown to completely eliminate leaks. There are indications that it is the Silica that is not compatible with the Ag.

⇒ **Further investment in research and development of compatible insulation is needed.**

EXAMPLE OF Bi2212 LEAKS THROUGH INSULATED RUTHERFORD CABLE, WHICH HAPPENS AT BOTH 1 BAR & 50 BAR

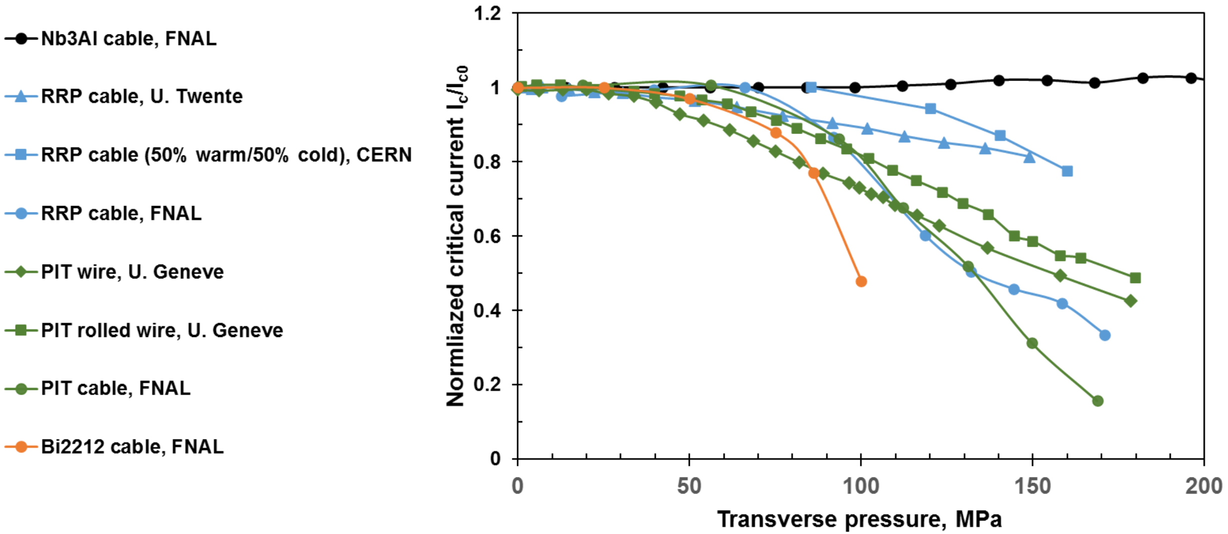
Recommendation 3

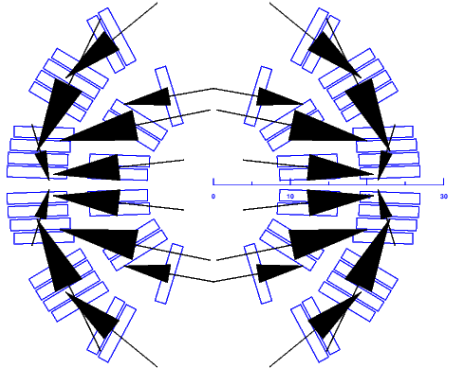
<u>In order to use Bi2212 coils as inserts in very high field magnets, it is critical to control and limit their stresses and strains as Bi2212 is more sensitive to stress than Nb_3Sn.</u> This can be done by acting on the following fronts:

1. Invest in research and development of methods to mechanically reinforce the wire (i.e. Recommendation 1) and/or the Rutherford cable itself.

2. Use coil stress management elements to reduce stress in the insert coils while also being chemically compatible with the Bi2212 processing.

3. Monitor progress by accurate critical current measurements of Bi2212 cable samples under transverse pressure.





Equivalent Strain of Transverse Pressure Configurations

Because of the greater availability and accuracy of axial strain data, it would be profitable to establish a strain equivalent model for transverse pressure configurations. The Von Mises equivalent strain, defined by the following formulae, is a good candidate for a strain that might be representative of a cable specimen under transverse pressure.

$$\varepsilon_{eq}{}^2 = \frac{1}{2}\left[\left(\sigma_{xx}-\sigma_{yy}\right)^2 + \left(\sigma_{yy}-\sigma_{zz}\right)^2 + \left(\sigma_{zz}-\sigma_{xx}\right)^2 + 6\left(\sigma_{yz}^2+\sigma_{zx}^2+\sigma_{xy}^2\right)\right];$$

$$\varepsilon_{xx} = \frac{1}{E}\left(\sigma_{xx} - \upsilon\left(\sigma_{yy}+\sigma_{zz}\right)\right);$$

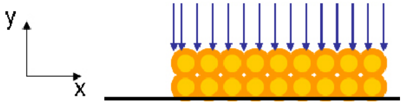
$$\varepsilon_{yy} = \frac{1}{E}\left(\sigma_{yy} - \upsilon\left(\sigma_{xx}+\sigma_{zz}\right)\right);$$

$$\varepsilon_{zz} = \frac{1}{E}\left(\sigma_{zz} - \upsilon\left(\sigma_{xx}+\sigma_{yy}\right)\right);$$

$$\varepsilon_{xy} = \frac{1}{2G}\sigma_{xy}\ ;\ \varepsilon_{xz} = \frac{1}{2G}\sigma_{xz}\ ;\ \varepsilon_{yz} = \frac{1}{2G}\sigma_{yz}\ .$$

Case A

Uni-axial configuration

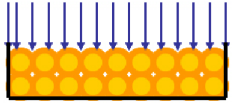


$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & -p & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\varepsilon_{eqA} = \frac{p}{E}(\nu + 1)$$

Case B

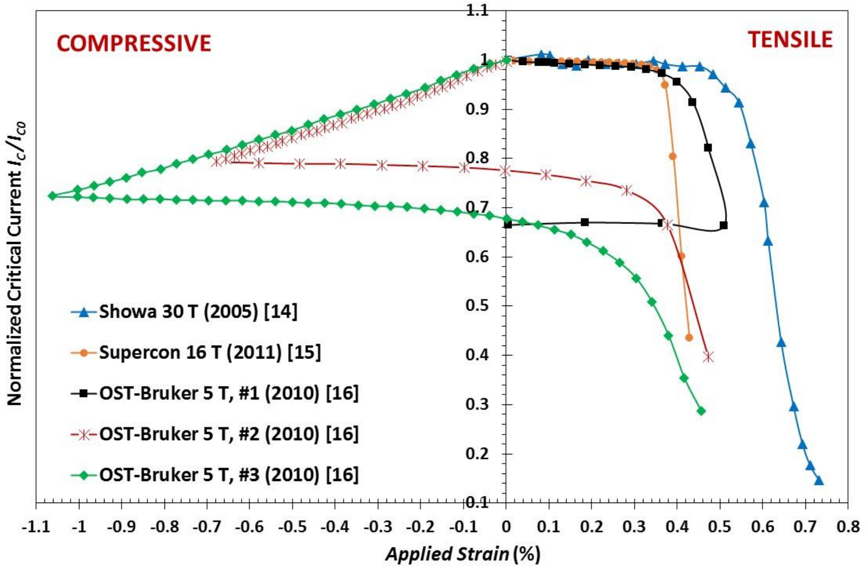
Multi-axial configuration



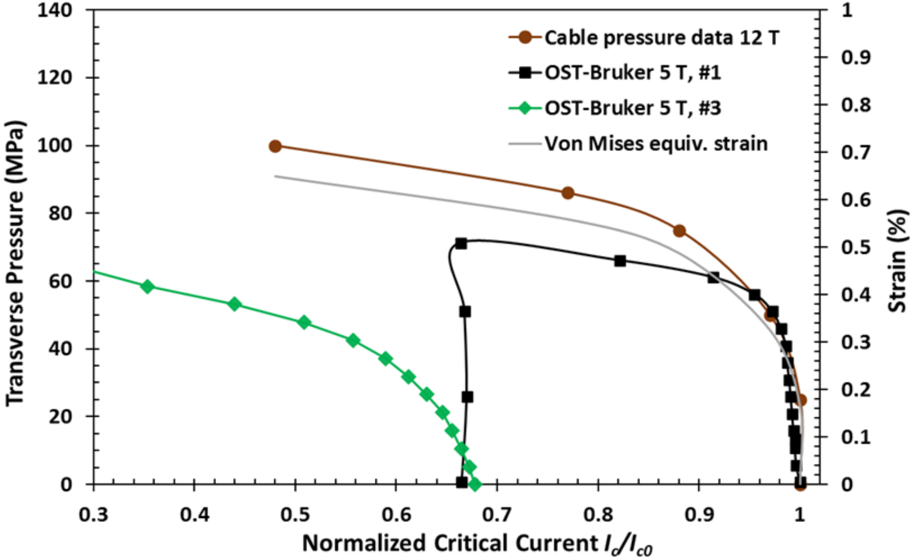
$$\begin{pmatrix} \nu\frac{p}{E} & 0 & 0 \\ 0 & -\frac{p}{E} & 0 \\ 0 & 0 & \nu\frac{p}{E} \end{pmatrix}$$

$$\varepsilon_{eqB} = \frac{p}{E}\sqrt{(\nu^3+1)(\nu+1)}$$

Example of Applying Equivalent Strain Concept



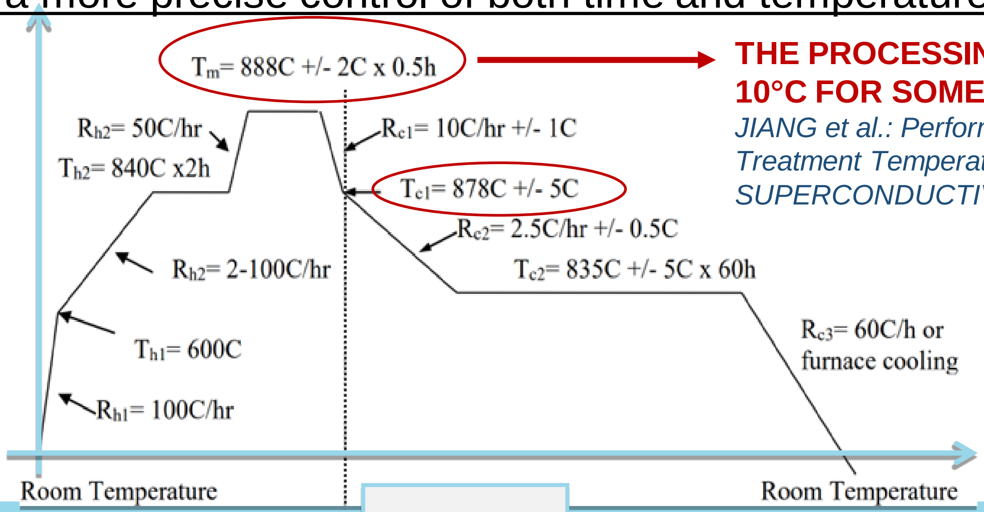
Poisson ratio $\nu=0.3$
Young modulus E = 20 GPa



From these very limited data, it appears that the Von Mises equivalent strain of the cable sample under compression reasonably represents the tensile strain behavior of the wire up to the I_c drop. After the drop, it is likely that it is the compressive strain behavior of the wire that will control the Von Mises strain. **Investing in more transverse pressure experimental data is vital, both for magnet design and to improve equivalent strain models.**

Recommendation 4

To lower costs and simplify the processing of Bi2212 inserts for hybrid accelerator magnets, the Split Melt Process (SMP) needs reconsidering. SMP is the heat treatment of the Bi2212 when split into two separate heat treatments and the coil is wound between them. This would simplify temperature control for large magnets a most sensitive temperature step T_{max}. A hybrid approach where one or both cycles of the SMP are carried out at 50 bar was never explored experimentally and should be. Either loosely wound wire or even just Rutherford-type cable wound on a spool would have a more compact volume than a large coil, with a more precise control of both time and temperature.



HT-SMP

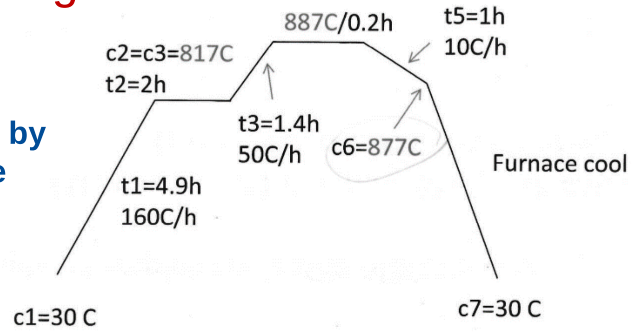
THE PROCESSING WINDOW FOR T_{max} WAS EXTENDED TO 10°C FOR SOME BILLETS

JIANG et al.: Performance and Microstructure Variation with Maximum Heat Treatment Temperature, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 33, NO. 5, AUGUST 2023, 6400105

SMP Preliminary Results

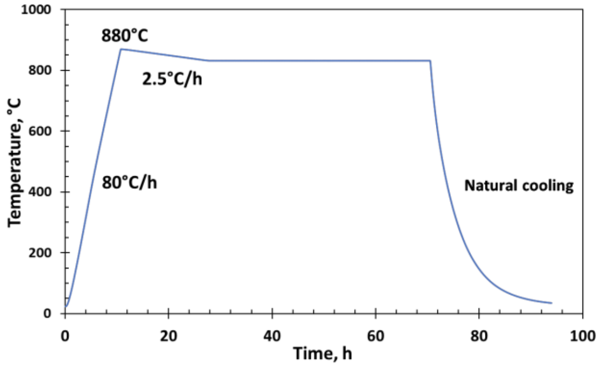
First stage

First part of SMP heat treatment performed at FSU by at 50 bar pressure (courtesy of Dr. Jiang)

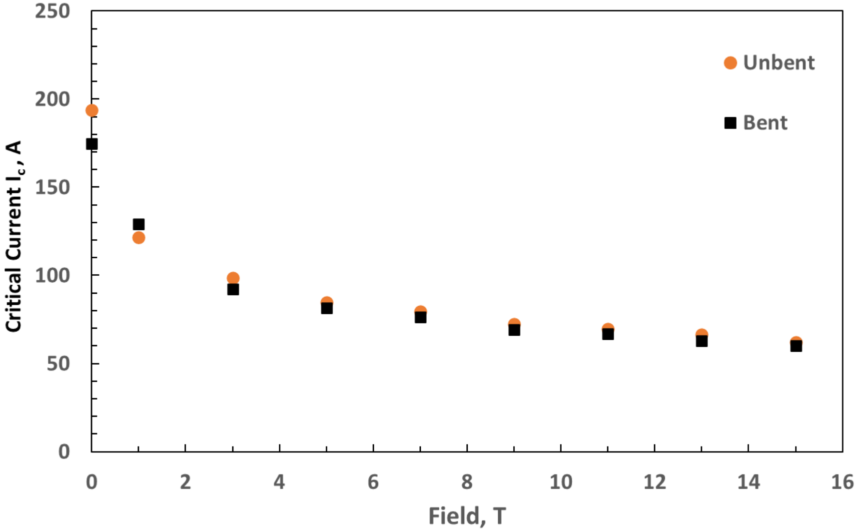


Second stage

Second part at 1 bar at FNAL



- B-OST wire PMM161111 (0.8 mm).
- Straight samples were sealed at FSU under the lead of Dr. Jiang.
- **After first stage, some samples were wound around a metal cylinder of 13.13 mm in diameter before unwinding them and bringing them back to their original straight form ("Bent" in legend).**



SMP Preliminary Results (2)

- **Wire PMM161111 leaked in the second part of the heat treatment, and only sections of samples without leaks were used for testing their critical current I_c as function of field.**

- **A concern on the effectiveness of the SMP is based on the concept that the bi-axial grain alignment that occurs during the cooling from T_m and that is required for a good J_c would break during bending. However, the results show that for this specific billet, the Bi2212 material phases that formed after the cooling down to room temperature from the T_m step were not strain sensitive. How can this be reconciled in light of the existing theories?**

- **The experiment needs to be repeated with a better-quality billet.**

Conclusions

- The Bi2212 dipole insert program started at Fermilab a couple of years ago is to test and develop the technology of HTS inserts based on Bi2212 Rutherford cable and cos-theta coil configuration.
- On paper, the potential reach for the maximum magnetic field in existing or planned Nb_3Sn outserts is close to 20 T, thanks to the progress realized in wires' critical current density.
- However, to achieve the Bi2212 potential in accelerator magnets, a few technological challenges still have to be faced. These for instance include:

- The need to design billets that are adequate for Rutherford cabling;
- Developing insulation processes and materials that prevent leaks;
- Control and limit Bi2212 coils' stresses and strains;
- Reconsider the Split Melt Process (SMP) to possibly lower costs and simplify processing for coils and coils' scale-up.

Fermilab