Conductor Properties and Coil Technology for a Bi2212 Dipole Insert for 20 Tesla Hybrid Accelerator Magnets

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

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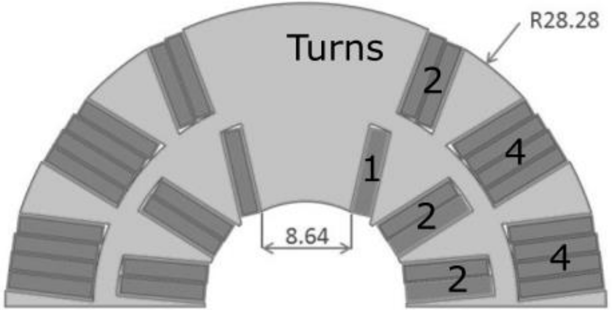
MDP meeting on design of a 20 T hybrid magnet and comparative analysis

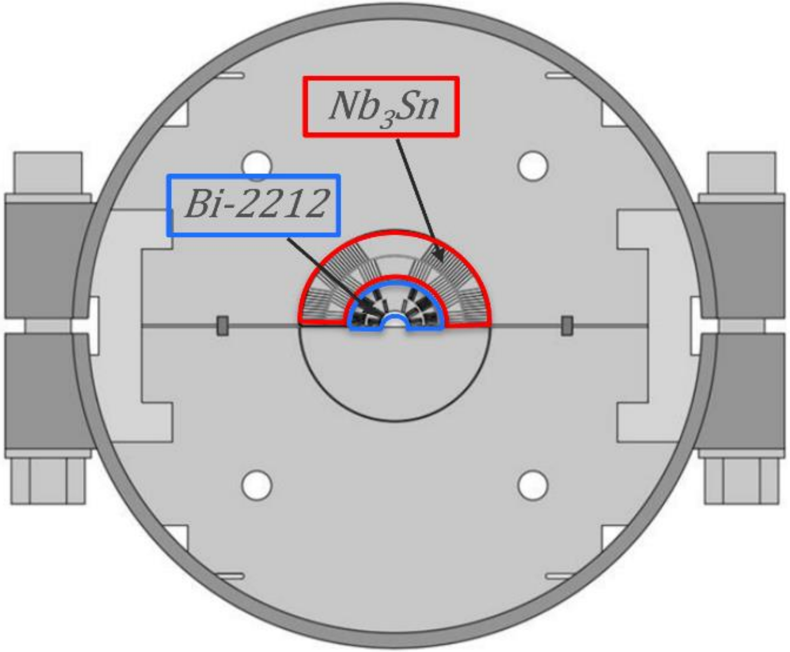
12/13/2022

Main Goal

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



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.



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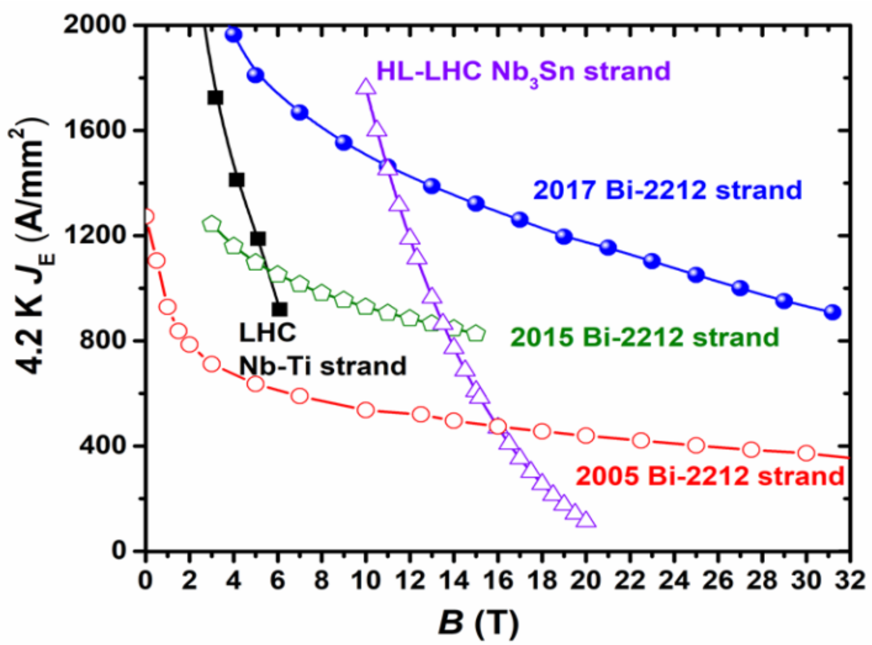
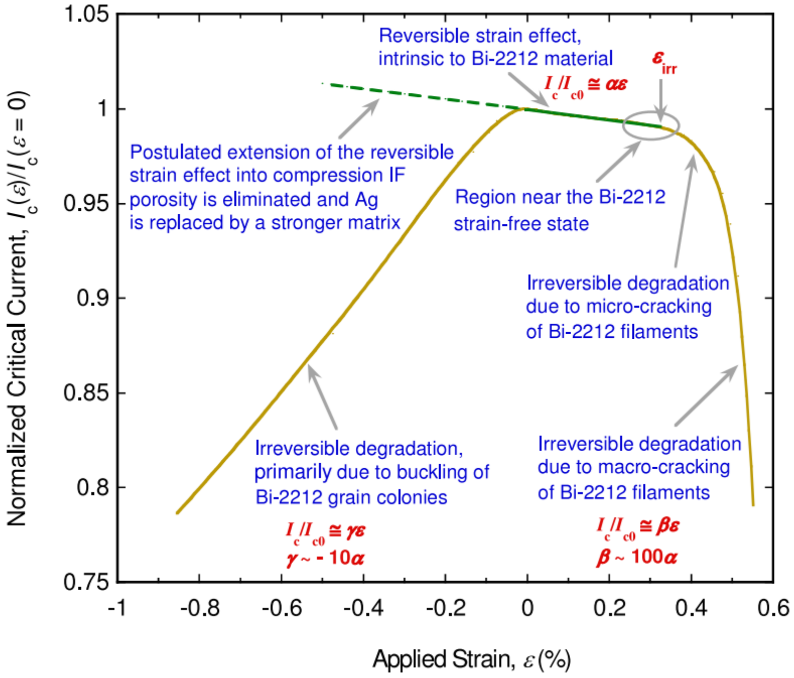
Why Bi-2212?

2017 curve is the one-time best performance obtained by Bruker-OST with the new Engi-Mat powders.



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*

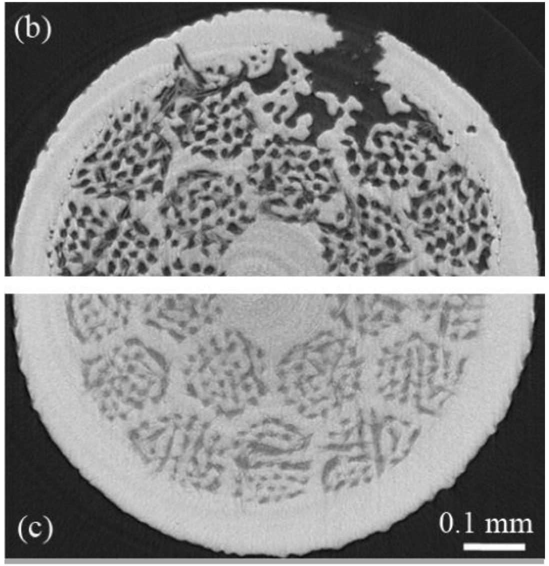
Recommendation 1

Heat treating Bi2212 at high gas pressure does not eliminate Bi2212 leaks from the conductor. Leaks are unacceptable in accelerator magnets due to the risk of shorts, for instances, and they are a major reason for the loss of critical current in coils.

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

- Increasing outer Ag barrier thickness
- Decreasing fill factor
- Reoptimizing subelement geometry

<u>This will 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.</u>



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

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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 Mullite sleeve and TiO_2-polymer slurry have not shown to completely eliminate leaks.

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

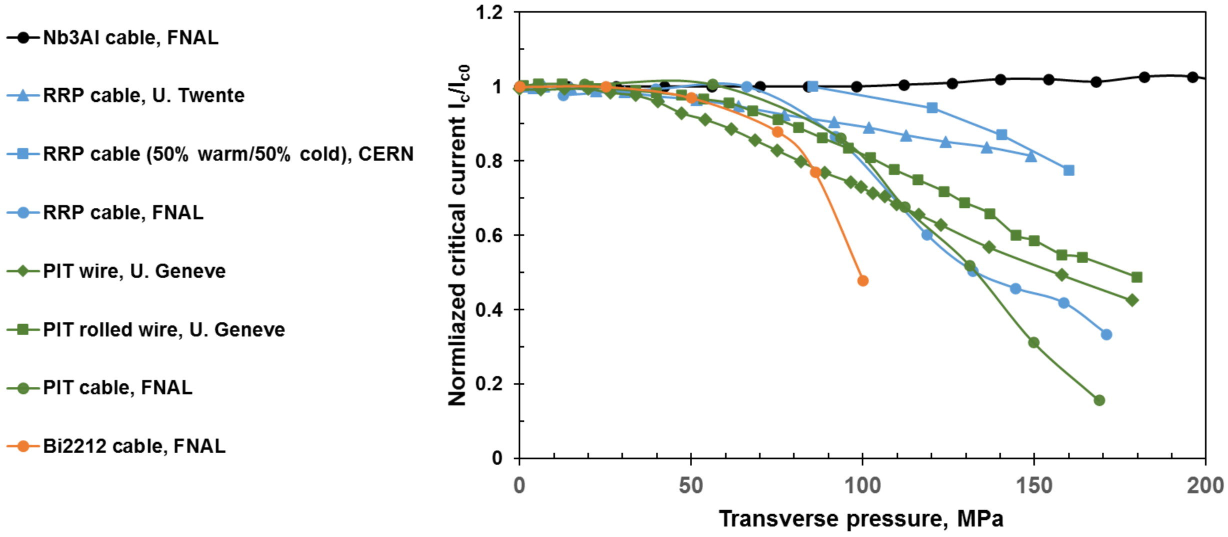
Recommendation 3

<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. Verify progress by accurate critical current measurements of Bi2212 cable samples under transverse pressure.



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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.

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

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

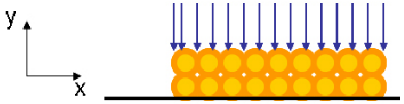
$$\varepsilon_{yy} = \frac{1}{E}\left(\sigma_{yy} - \upsilon\left(\sigma_{xx} + \sigma_{zz}\right)\right);$$

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

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

Case A

Uni-axial configuration

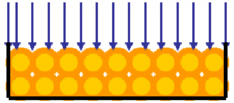


$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & -p & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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

Case B

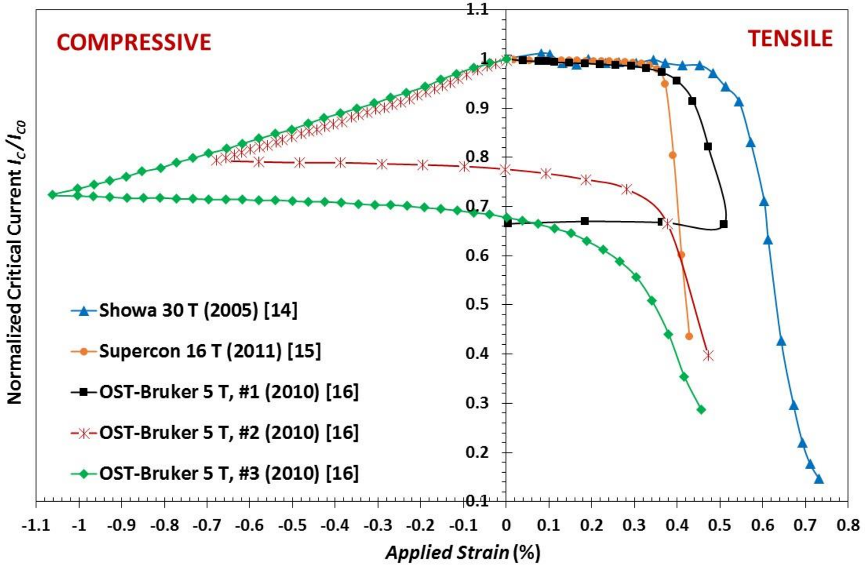
Multi-axial configuration



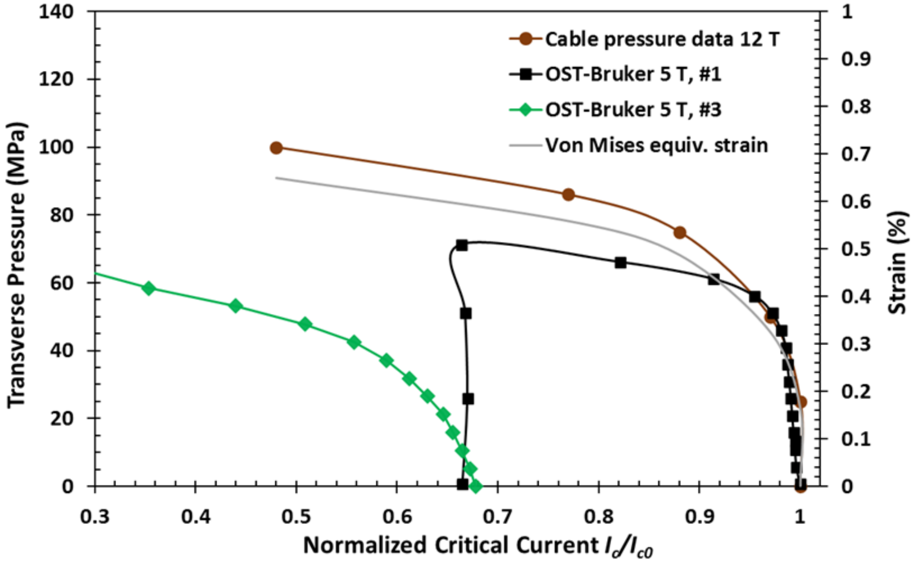
$$\begin{pmatrix} \nu\frac{p}{E} & 0 & 0 \\ 0 & -\frac{p}{E} & 0 \\ 0 & 0 & \nu\frac{p}{E} \end{pmatrix}$$

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

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.**

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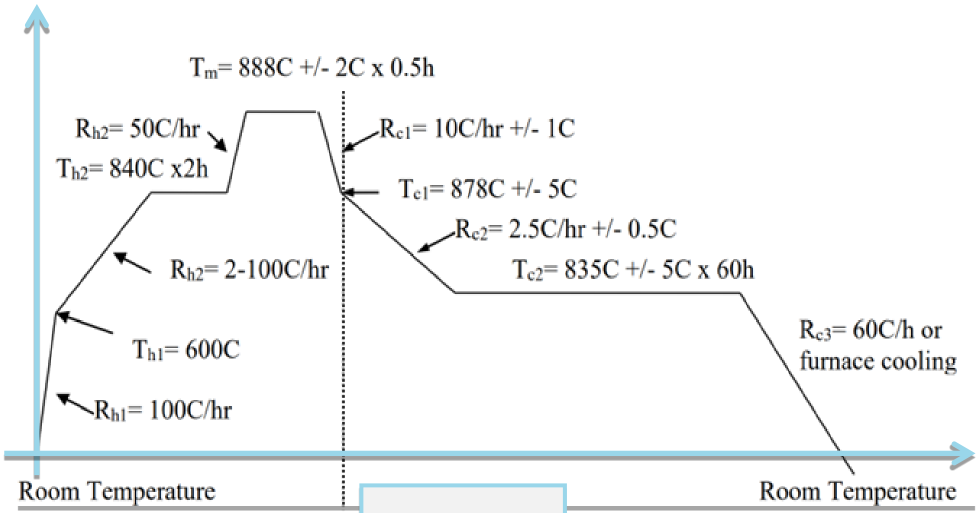
Recommendation 4

To lower costs and simplify the processing of Bi2212 inserts for hybrid accelerator magnets, it is worth reconsidering a Split Melt Process (SMP) in which the overpressure heat treatment of the Bi2212 is split into two separate heat treatments and the coil is wound between them. This would simplify temperature control for large magnets at the most sensitive temperature step, promote more homogenous Oxygen diffusion, and possibly prevent or reduce leaks. A hybrid approach where one or both cycles of the SMP are carried out at 50 bar was never explored experimentally and should be.



HT-SMP

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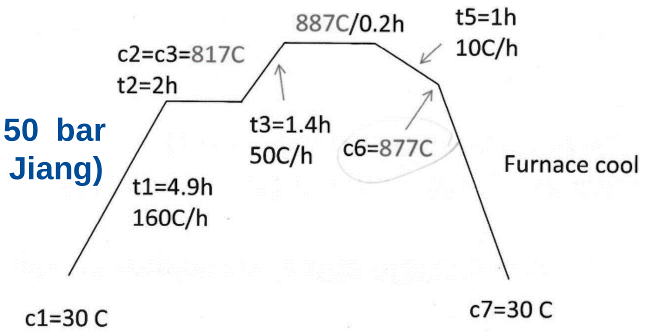
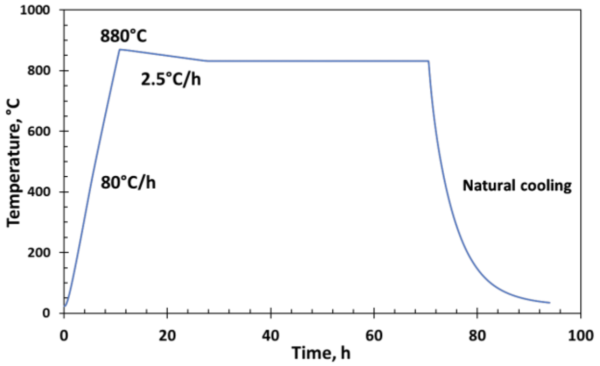
SMP Preliminary Results (FNAL)

First stage - 50 bar at FSU (Jianyi Jiang)



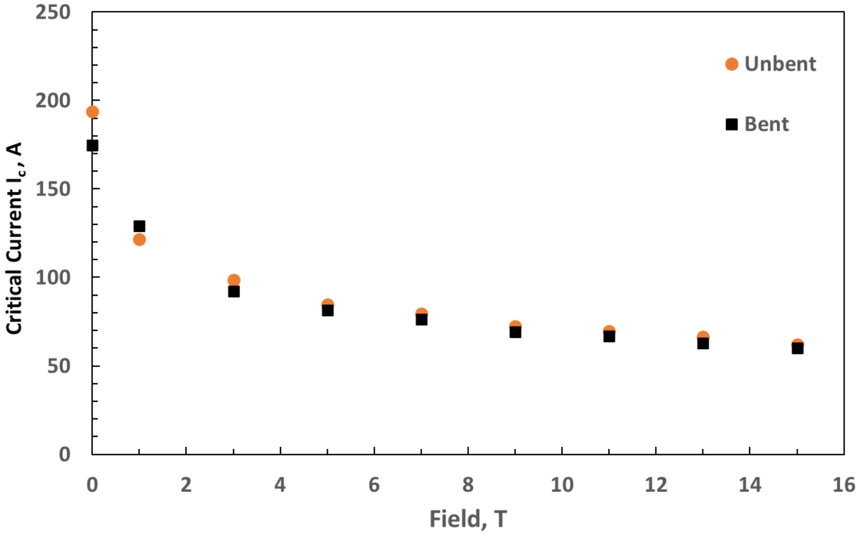
Second stage 1 bar at FNAL



B-OST wire PMM161111 (0.8 mm).

Straight samples were sealed at FSU.

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, called “Bent” in legend.



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. T
- However, to achieve the Bi2212 potential in accelerator magnets, however, a number of 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, which reduce transport current and increase the risk of shorts;
- Control and limit Bi2212 coils' stresses and strains;
- Reconsider the Split Melt Process (SMP) to lower costs and simplify the processing.