Final Report for STTR Project DE-SC0011267

Design and fabrication of a 30 T superconducting solenoid using overpressure processed Bi2212 round wire

Final Report for Project start date: Feb 18, 2014, end date: November 17, 2014

Principal Investigator: Dr. Gene Flanagan

Muons, Inc., 552 N. Batavia Ave., Batavia, IL 60510

Research Partner: Fermi National Accelerator Laboratory

FNAL Subgrant PI: Dr. Tengming Shen, Under CRADA FRA-2014-0009

Approved for public release; further dissemination unlimited. (Unclassified Unlimited)

PREPARED FOR THE UNITED STATES DEPARTMENT OF ENERGY

Work Performed Under SBIR grant DE-SC0011267

Design and Fabrication of a 30 T Superconducting Solenoid Using Overpressure Processed Bi2212 Round Wire

Abstract

High field superconducting magnets are used in particle colliders, fusion energy devices, and spectrometers for medical imaging and advanced materials research. Magnets capable of generating fields of 20-30 T are needed by future accelerator facilities. A 20-30 T magnet will require the use of high-temperature superconductors (HTS) and therefore the challenges of high field HTS magnet development need to be addressed.

Superconducting $Bi_2Sr_2CaCu_2O_x$ (Bi2212) conductors fabricated by the oxide-powder-in-tube (OPIT) technique have demonstrated the capability to carry large critical current density of 10^5 A/cm^2 at 4.2 K and in magnetic fields up to 45 T. Available in round wire multi-filamentary form, Bi2212 may allow fabrication of 20-50 T superconducting magnets. Until recently the performance of Bi2212 has been limited by challenges in realizing high current densities (J_c) in long lengths. This problem now is solved by the National High Magnetic Field Lab using an overpressure (OP) processing technique, which uses external pressure to process the conductor [1]. OP processing also helps remove the ceramic leakage that results when Bi-2212 liquid leaks out from the sheath material and reacts with insulation, coil forms, and flanges. Significant advances have also been achieved in developing novel insulation materials (TiO_2 coating) and Ag-Al sheath materials that have higher mechanical strengths than Ag-0.2wt.% Mg, developing heat treatment approaches to broadening the maximum process temperature window [2], and developing high-strength, mechanical reinforced Bi-2212 cables [3]. In the Phase I work, we leveraged these new opportunities to prototype overpressure processed solenoids and test them in background fields of up to 14 T. Additionally a design of a fully superconducting 30 T solenoid was produced. This work in conjunction with the future path outlined in the Phase II proposal would provide a major step toward qualifying Bi2212 technology for use in high-field accelerator magnets. Additionally, the performance parameters match key requirements of a final muon beam cooling solenoid. This technology will also be of interest to high-field NMR manufacturers.

Table of Contents

Design and Fabrication of a 30 T Superconducting Solenoid Using Overpressure Processed Bi2212 Round Wire

Demonstration of Technical Feasibility

The work performed in Phase I has set the stage for a strong coil program over the next two years. Important engineering measurements were made and a lot of experience was gained in all aspects of fabrication of coils. Details are discussed below.

The performance goals and schedule of the Phase I project were:
Two months after start of funding:

- Purchase conductor from industry.
- Review Phase I coil design (including strain measurement and quench plan).
- Design/fabricate any hardware required for overpressure processing and testing.
- Acquire and calibrate strain gauges/quench hardware and set up DAQ system.
- Begin making wire stacks for strain gauge calibration and thermal measurements.
- Begin winding coil and processing if conductor is available etc.
- Begin testing wire stacks

Four months after start of funding:

- Complete wire stack testing of mechanical properties.
- Complete coil fabrication including processing and instrumentation.
- Begin testing coil with SS outer shell (supported configuration).
- If previous tests complete, begin testing coil in unsupported configuration.
- Begin Phase II coil design (30+ T)

Six months after start of funding:

- Continue unsupported coil testing as function of background field (up to 14 T) - test until failure.
- Refine Phase II coil design including stress management and quench protection considerations
- Draft Phase II proposal

Nine months after start of funding

1) Submit phase II proposal

All elements of this schedule were accomplished during the Phase I project. Furthermore, due to schedule delays prior to the Phase I beginning the overpressure processing facility was commissioned and optimized during the phase 1.

Challenges of High Field Superconducting Magnets Based on High Temperature Superconductors

Two of the key challenges facing high field HTS magnets are stress management (conductor protection) and quench protection. The conductors within high field magnets are subjected to enormous pressures when the magnet is operating; at 20 T, the magnetic pressure is 320 MPa enough pressure to cause inelastic deformation in copper. After reaction, many superconductors, including Nb_3Sn and Bi-2212 are brittle. Under axial stress, I_c is virtually insensitive to tensile strain up to a sample dependent strain limit. When this limit is exceeded, I_c decreases steeply and irreversibly. Applying compressive strain to Bi2212 conductor causes a gradual and irreversible decrease of I_c. Magnetic fields have no noticeable effect on this typical $I_c(\varepsilon)$ dependence. For commercial Ag-0.2 wt% Mg/Ag/Bi-2212 (area ratio AgMg:Ag:Bi-2212 = 0.25:0.5:0.25) round wire, the working maximum is around 120 MPa at 4.2 K whereas the irreversible tensile strain is between 0.3% and 0.45% [4]. It is therefore important to understand the strain status in the superconductor and develop a support structure capable of minimizing the stresses in the coils from magnet assembly to final excitation.

During a quenching event, it is necessary to detect the quench quickly. A simple measurement of end-to-end coil voltage can provide quick quench detection for LTS magnets (<0.1s). However, this may be difficult to do in HTS coils because the normal zone propagation velocity is on the order of cm/s (two orders of magnitude slower than the velocity in LTS coils), as a result the voltage growth across the normal zone develops slowly, making quench detection difficult; this is the crux of the HTS quench protection challenge. Muons, Inc. and NCSU (DOE STTR Grant DE-SC0006251 – "Quench Detection Via Optimized Rayleigh Scattering in High-field YBCO Accelerator Magnets") have been developing a novel fiber optic quench protection system for HTS magnets [5]. This quench protection work is complementary to the core work being proposed here. Much expertise and infrastructure has been developed from DE-SC000625, this will exploited in this project.

Status of High Field Magnets based on Bi2212

Bi2212 was the first HTS material in round wire form that could develop high J_c. The first PIT Bi2212 round wire made by Heine et al. in 1989 exhibited a J_c of 150 A/mm^2 at 4.2 K, 26 T [6]. At present, commercial Bi2212 round wires are available from Oxford Superconducting Technology (OST) in New Jersey, Supercon in Massachusetts with J_c over 10^3 A/mm^2 at 4.2 K in fields up to 45 T. The high J_c in this Bi2212 round wire, together with the Bi2212 irreversibility field, which is > 100 T, showed that there is significantly more potential compared to Nb_3Sn to fabricate very-high-field magnets.

Since Bi2212 becomes brittle after reaction, the fabrication of a magnet from Bi2212 round wire uses wind-and-react fabrication. Wires, insulated with an alumino-silicate braided sleeve, are wound on a coil former (Inconel 600) and the coil package goes through melt processing in flowing O_2. Using this approach, many small scale coils have been successfully made and then tested. A UK group, led by Oxford Instrument Nanoscience, built a 22.5 T all superconducting magnet with a cold bore size of 25.5 mm, using a Bi2212 insert coil nested inside a 20 T LTS outsert with a 78 mm cold bore. The NHMFL group demonstrated a 1 T insert in a 31 T background, reaching 32 T. Godeke *et al*. at Lawrence Berkeley National Lab (LBNL) successfully wound and reacted small racetrack coils from Rutherford cables [7]. Despite many barriers still existing, these works demonstrated that wind and react fabrication of Bi2212 magnet is feasible.

But the demonstration coils revealed some obstacles. First, the reacted coils occasionally had ceramic leakages, where Bi2212 liquid flowed through the Ag matrix and reacted with external structures such as insulation. Second, the wire J_E at 4.2 K and 20 T in recent coils is ~200 A/mm^2, which is 60% of the short-sample limits of materials receiving corresponding heat treatments and far below the record J_E.

Recently, it was discovered that the major mechanism limiting critical current was the large gas bubbles that form during the melt processing due to the residual porosity in as-drawn wires. Removing porosity in short-length wires using cold isostatic pressing and swaging quickly improved the J_c (4.2 K, 5 T) of many of industrial wires to 3500 A/mm^2. The J_c degradation in long-length conductors was found to be caused by wire expansion due to silver creep, driven by internal gas pressure. The source of the leakage was identified as the creep rupture of the Ag alloy sheath. This deleterious effect of internal gases can be controlled by an overpressure (OP) processing, which was used by the NHMFL to develop J_E > 700 A/mm^2 at 4.2 K, 20 T. A recent solenoid insert made by NHMFL generated 2.6 T in a 31.2 T background field. This coil was processed in 10 bar external pressure and achieved a maximum quench current of 388 A (J_E = 252 A/mm^2 at 33.8 T). This coil showed no sign of leakage.

With overpressure processing moving the obstacle of eliminating leakage and achieving high J_c in long length conductor, Bi2212 coils are still facing other critical magnet engineering issues such as stress management. Insert coils envisioned for 30-50 T muon cooling solenoids would experience a complicated stress state, having tensile radial stress with hoop stress exceeding 200 MPa. Stress states of superconducting windings need to be determined experimentally, and a mechanical structure needs to be designed to confine this stress. Only a full 3D thermal-mechanical analysis, validated with high-field measurements, can provide a clear description of the best magnet fabrication strategy.

Phase I Approach

The ultimate objective of the proposed work is to design and construct a demonstration solenoid insert, capable of generating a central field B = 30 T in a useful bore of 30 mm, with adequate mechanical support and quench protection. The magnet we propose to test will match key requirements of the muon cooling solenoid for a proposed muon collider. Furthermore, it should also result in the significant advancement of high-field Bi2212 technology for cable based accelerator magnets in general.

In the phase I project, we leveraged the recent advances in overpressure processing and conductor engineering to address critical design, fabrication, and engineering issues of Bi2212 coils. A systematic study to understand the mechanical properties of wire stacks [8] was conducted. Additionally, Bi2212 coils were fabricated and tested in background fields up to 14 T. The results and experienced gained from the Phase I program is fed back into the coil modeling effort and preparation for the Phase II program. For details of results please see later sections (Section: An All Superconducting 30 T Solenoid Model Using Over Pressure Processed Bi2212 Wire).

Accomplishments and Highlights of the Phase I

The work performed in Phase I has set the stage for a strong coil program over the next two years. Important engineering measurements were made and a lot of experience was gained in all aspects of fabrication of coils. Details are discussed below.

Thermal-mechanical Properties of Epoxy-impregnated Bi-2212/Ag Composite

To obtain the thermal-mechanical properties of epoxy/superconductor/insulation composite important for designing, fabricating, and operating epoxy impregnated high field superconducting magnets near their ultimate potentials, we measured the modulus of elasticity, Poisson's ratio, and the coefficient of thermal contraction of epoxy-impregnated composite made from the state-of-the-art powder-in-tube multifilamentary Ag/Bi-2212 round wire at room temperature and cryogenic temperatures. Stress-strain curves of samples made from single-strand and Rutherford cables were tested under both monotonic and cyclic compressive loads, with single strands insulated using a thin TiO_2 insulation coating and the Rutherford cable insulated with a braided mullite sleeve. The description of sample, the measurement method, and the data were presented at the 2014 Applied Superconductivity Conference and accepted for publication by IEEE Transactions on Applied Superconductivity [8]. These data were used in a 30 T all superconducting solenoid design model that is capable of computing displacements, stress, and strain of all the components during assembling, cooling-down, and excitation for magnets. The paper, presented at ASC2014 by Pei Lei, is attached as appendix 2.

Commissioning and Optimization of Overpressure Processing Furnace and Establishment of Overpressure Processing Procedure

We installed and commissioned an overpressure-processing furnace at the technical division of Fermilab. Figure 1 shows the furnace and the temperature and pressure recording of a run at 50 bar. The furnace is a three-zone MTI tube furnace that is capable of heat-treating samples using a standard melt processing (with T_{max} reaching 895 °C) in a pressure of up to 100 bar using premixed gases (Argon + oxygen). The pressure vessel of the tube furnace has an inner diameter of 50 mm and an outer diameter of 85 mm.

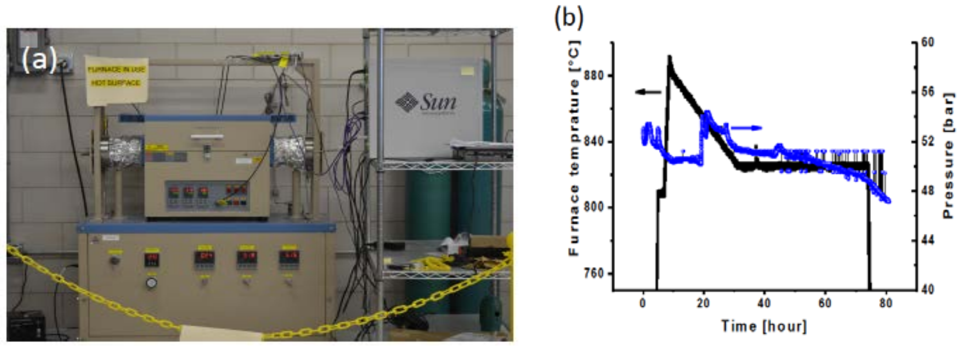


Figure 1: (a) An overpressure processing furnace facility installed and commissioned at the technical division of Fermilab. The furnace is a three-zone MTI furnace that is capable of heat-treating samples in a pressure of up to 100 bar. (b) A overpressure melt processing of Bi-2212 at 50 bar. This heat treatment uses a premixed gas comprised of 98% Argon and 2% oxygen, and therefore the oxygen partial pressure during melt processing is maintained at 1 bar.

Optimization of the furnace for high-pressure heat treatments is difficult because the thermal conductivity of the gases, an argon/oxygen mixture, increases significantly with gas pressure and also because temperature measurement inside the processing tube along its axis at high pressure becomes time-consuming. Nevertheless, the furnace has been gradually optimized for heat treating Bi-2212 samples, with the best samples (0.8 mm wire, 37x18 architecture) heat treated at 50 bar carrying a I_c(4.2 K and self field) of 650 A and those heat treated at 100 bar carrying a I_c(4.2 K and self field) of 870 A, more than twice of the I_c carried by the same 8 cm wires heat treated using the most optimized standard 1 bar processing. The best short sample was measured to carry an I_c of 400 A at 4.2 K and 5 T and a J_E of 900 A/mm^2 (an extrapolation shows that its J_E at 20 T is 600 A/mm^2. Overpressure processing of Bi-2212 wires requires sealing the ends of the wires. During the furnace optimization period, a reliable end-sealing procedure was developed to seal the ends of the samples using an acetylene torch.

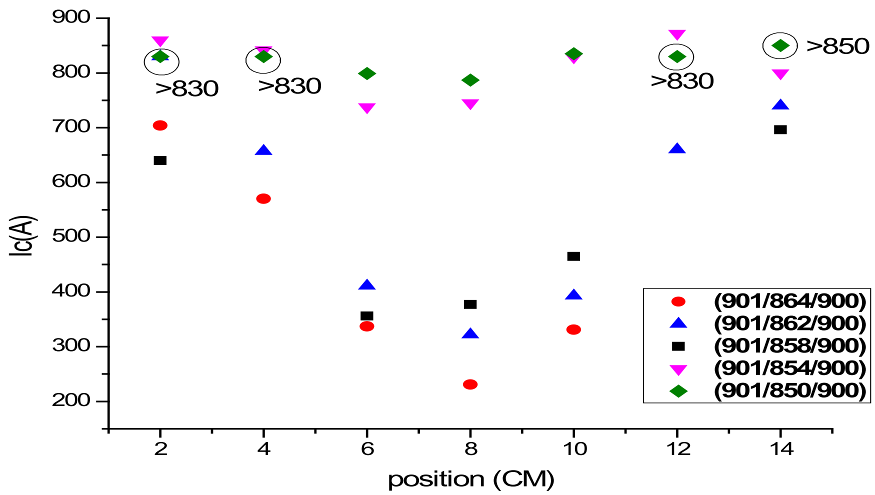


Figure 2: I_c of short samples (16 cm in length) as a function of position in the furnace. The heat treatments were performed at 100 bar.

Prototype coils and their overpressure processing procedures

To verify the high I_c attained in short-lengths of conductor by overpressure processing could be extended to coils, we fabricated and tested a number of prototype coils using the overpressure processing facility described above. Table 1 lists the specifications of these coils and Figure 3 shows one of the coils after heat treatment. The coil former design, also shown on the test probe in Figure 3, provides appropriate support to the current leads, whose largest bending diameter is 12 mm. The coil formers were made from Inconel 600. Before winding, the formers were thoroughly oxidized to help prevent shorts from conductor to coil former. Additionally, the body of the coil former was insulted with SiO_2 cloth tape.

Table 1: Specification of prototype overpressure processing coils

Material	AgMg/Ag-sheathed Bi-2212 round wire Oxford Superconducting Technology	
Wire	Diameter	0.8 mm
	Length	11 m
	Architecture	37x18
	Insulation	nGimat TiO_2 coating
Coil	Inner diameter	25.4 mm
	Outer diameter	28.8 mm
	Height	57.8 mm
	Turns/layer	64

	No. of layers	2
	Coil inductance	~20 mH
	Processing	Overpressure processing using TD-IB3a furnace @ 100 bar
	Self-inductance	20 mH

Coils were wound from a 0.8 mm Bi-2212 fabricated by Oxford Superconducting Technology. Before winding, the conductor was coated by nGimat LLC with an insulation coating that contains a green TiO_2 basecoat layer (~20 µm in thickness) and a polymer-only topcoat layer (~2 µm in thickness). The as-wound coils went through a decomposition heat treatment, which drives off the polymer at atmospheric pressure at 300°C for 12 hours (in another furnace), before being overpressure processed. The current lead sections (white wire sections on right hand side of Figure 3a) had an additional insulating mullite sleeve to reduce the risk of shorts in the transition regions.

Figure 3: (a) The Inconel 600 coil former assembly designed and fabricated, with the 2-layer prototype coil after polymer burn off heat treatment and a 100 bar overpressure melt processing, and (b) a machine shop design drawing of the coil being mounted onto a high current coil test probe. The probe is capable of testing the coil with a current capability of 2 kA. The current leads were supported through Inconel 600 pieces that will latter on be replaced with Inconel 600

Performance of Prototype Overpressure Processed Coils

Three prototype coils were wound, overpressure processed, and tested. Coils were tested at 4.2 K and in either self-field or in a 14 T Oxford Teslatron magnet, using a 2 kA probe and a LabVIEW based test program developed at Fermilab. The test program is capable of monitoring voltage taps up to 16 channels with a data acquisition rate of up to 1 kHz and determining whether the coil quenches by checking if the terminal voltage exceeds a predetermined threshold, now set to be 10 mV for these coils for a predetermined time period, for example, 10 ms.

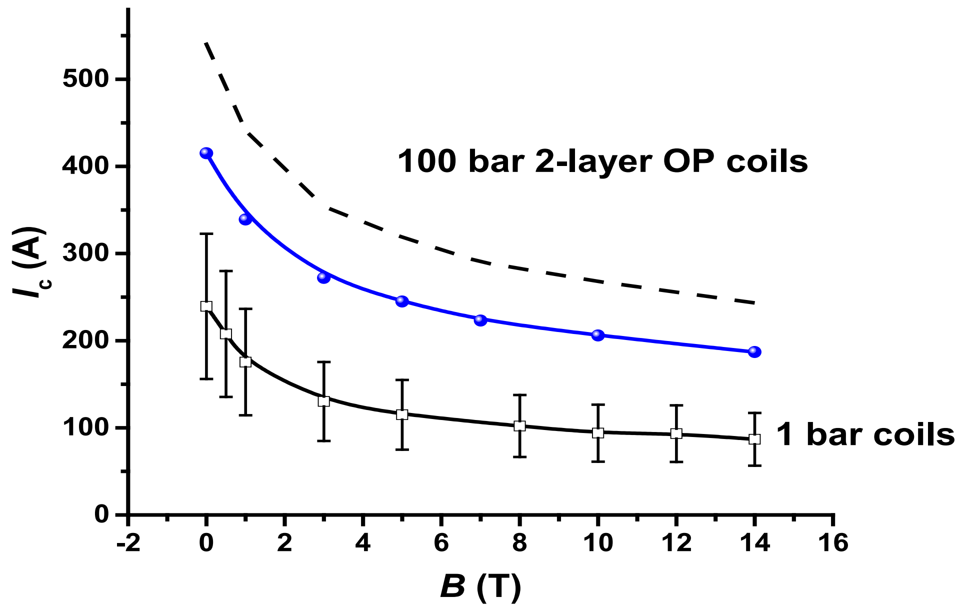


Figure 4: Field dependence of critical current of the prototype overpressure processed coils made, in comparison to typical I_c of those processing using 1 bar standard processing. The blue circles are the infield data collected on a Phase 1 OP processed coil, the dashed black line is the extrapolation of a second Phase 1 OP processed coil that was only tested in self-field. The black squares show what is expected from 1 bar processing.

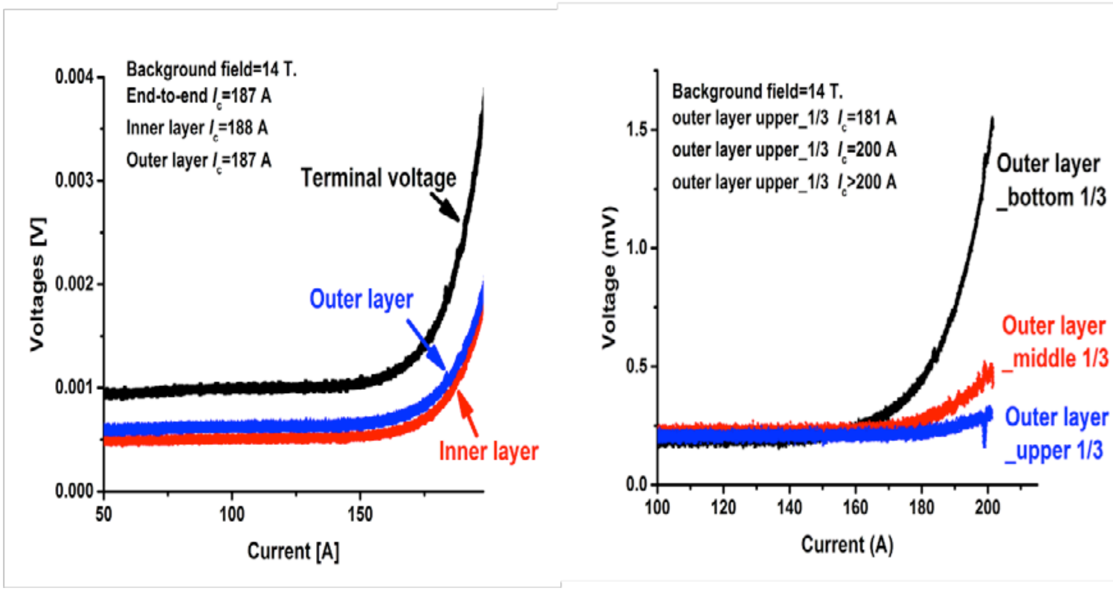


Figure 5: Voltage – current characteristics of one of Bi-2212 prototype overpressure processed coils at 4.2 K and 14 T. Its hoop stress reached 97 MPa@14 T. Using an electrical field criterion of 1 μV/cm, the inner layer and the outer layer carried a I_c of 188 A and a I_c of 187 A, respectively.

Figure 4 and 5 show the performance attained by these coils. The coils carried an I_c of 250-320 A at 4.2 K / 5 T, and carried an I_c of ~200-300 A at 4.2 K / 14 T, two times higher than what is expected for one-bar processed coils. One coil was used to do more extensive infield testing (Figure 4 (blue circles), Figure 5), including quench studies. The coil tested infield showed no degradation with the maximum hoop stress of 97 MPa. After I_c testing was completed the coil underwent a series of quench tests. The coil survived 110 quenches, initiated by an external heater, at 7 T, 9 T, and 12 T without degradation. The maximum temperature the coil experienced is 250 K. This work was presented at WAMHTS 2014 Kyoto by Tengming Shen, his talk is attached as appendix 1.

An All Superconducting 30 T Solenoid Model Using Over Pressure Processed Bi2212 Wire

Figure 6 presents a design of a Bi-2212 solenoid insert that produces 30 T in a cold bore size of 25.4 mm. Such a magnet can be used as a final cooling solenoid for a muon collider. The winding current density is 240 A/mm^2. *Assuming a filling factor of 0.84 (with a nGimat insulation) and a working margin of 20%, this will requires wires carrying a J_E at 20-30 T of 357 A/mm^2, which is less than those achieved in the prototype coils (an extrapolation shows that the wire in those coils carries more than 450 A/mm^2 at 20-30 T*). *Therefore, the coil critical current density used is well within reach of the capability of overpressure processing*. The main feature of the design are: (1) the magnet system consists of a LTS outsert, providing 19 T in a cold bore of 200 mm, and a high field Bi-2212 insert providing an additional 10 T; (2) both outsert and insert coils are divided into multiple thin sections to keep the radial stress within the coil pack negative or close to zero to prevent the cracking of epoxy. Such design considerations are important for Bi-2212 coils because (1) dividing a large coil into thin section allows Bi-2212 coils to be more easily heat treated; (2) such a design will makes stress management and quench protection easier.

2212 insert coils	Units	#1	#2	#3
Inner radius	mm	12.7	36.7	65.7
Outer radius	mm	24.7	49.7	78.7
Length	mm	160	200	240
Coil J_{ave}	A/mm^2	240	240	240
Reinforcement thickness	mm	10	14	15
Maximum magnetic field	T	30.3	26.8	23.3
Field increment	T	3.6	3.7	3.7

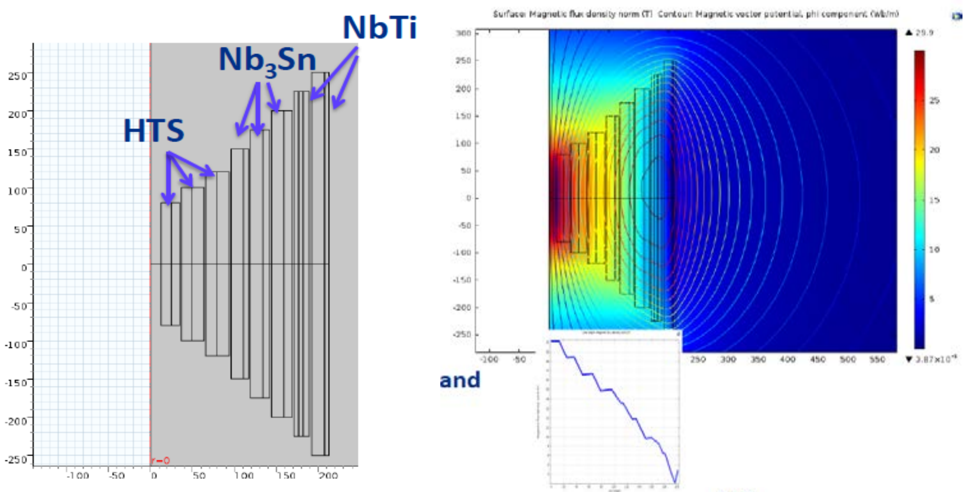


Figure 6: Cross section and design parameters of a 30 T hybrid solenoid comprised of a Bi-2212 insert generating 10 T in a 20 T outsert magnet.

The mechanical behavior of the Bi-2212 insert in Figure 6 was analyzed with a 2D finite element model implemented in COMSOL. The result is presented in Figure 7. The peak stress in superconducting coil winding is controlled to be <135 MPa by using a shell of stainless steel winding that intercepts the Lorentz force. The peak stress in the stainless steel shell is 250 MPa. The reinforcement shell is expected to be applied after Bi-2212 reaction, and then be epoxy impregnated with the superconducting windings.

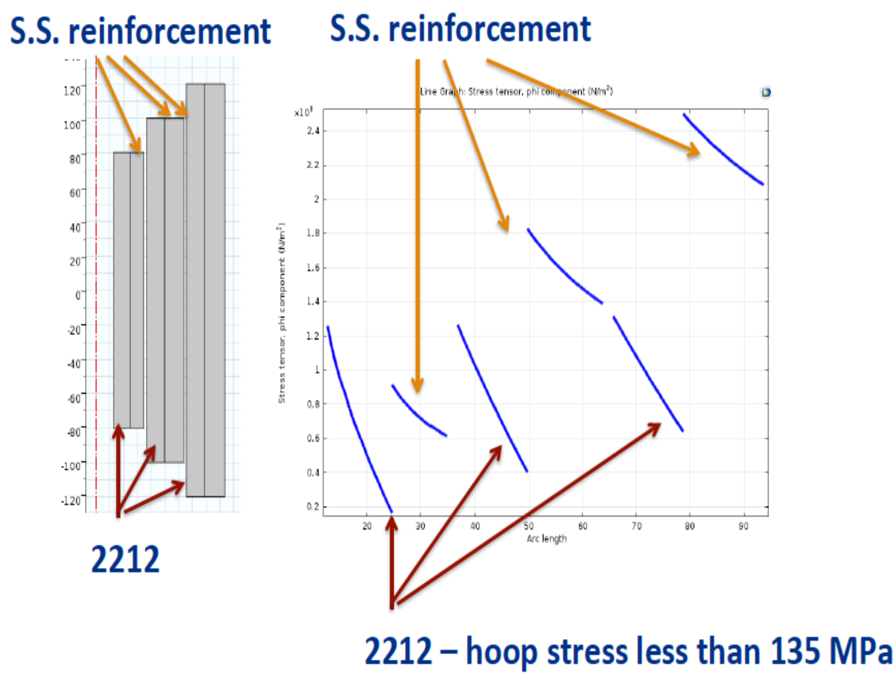


Figure 7: Hoop stresses in the 30 T Bi-2212 insert coils when fully energized (1/2 of the entire magnet cross-section is shown). All three coils are reinforced with an external stainless steel shell to reduce the mechanical load on coil. The maximum stress on the Bi-2212 coils is limited to 135 MPa with this strategy.

Summary

During Phase I an overpressure processing facility was commissioned and optimized. Three solenoids were fabricated using the overpressure processing facility. The coils were tested in fields of up to 14 T and showed I_c in the range of 200-300 A at 4.2 K /14 T- about a factor of two higher than that expected for 1 bar processed coils. A model of an all-superconducting 30 T hybrid HTS/LTS solenoid was developed. From the model it was seen that the Bi2212 section of solenoid requires a J_E ~360 A/mm^2 at 20-30 T, which is lower that what we expect to achieve based on extrapolating our test coil results. Extrapolating from the test coil performance we expect to be able to reach a J_E of 450 A/mm^2 at 20-30 T. This is a very important as it suggests that a 30 T all-superconducting solenoid is feasible.

References

[1] D. Larbalestier, J. Jiang, U. Trociewitz, F. Kametani, C. Scheuerlein, M. Dalban-Canassy*, et al.*, "Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T," *Nature Materials,* vol. 13, p. 375, (2014).

[2] T. Shen, J. Jiang, F. Kametani, U. P. Trociewitz, D. C. Larbalestier, and E. E. Hellstrom, "Heat treatment control of Ag-$Bi_2Sr_2CaCu_2O_x$ multifilamentary round wire: investigation of time in the melt," *Superconductor Science Technology,,* vol. 24, p. 115009, (2011).

[3] T. Shen, P. Li[1], J. Jiang[2], L. Cooley, L. Ye, D. McRae, and R. Walsh, "High strength kiloampere $Bi_2Sr_2CaCu_2O_x$ cables for high-field magnet applications", submitted to *Superconductor Science and Technology* for publication (available through https://www.dropbox.com/s/caqpou4gpr5nndd/high%20strength%20kA%202212%20cable%20arXiv.docx?dl=0)

[4] Cheggour, N., Lu, X., Holesinger, T., Stauffer, T., Jiang, J., and Goodrich, L. Reversible effect of strain on transport critical current in $Bi_2Sr_2CaCu_2O_{8+x}$ superconducting wires: a modified descriptive strain model. *Superconductor Science and Technology* **25**, 015001 (2012)

[5] G. Flanagan et al., "Evaluation and Implementation of High Performance Real-time signal Processing for Rayleigh Scattering Based Quench Detection for High Field Superconducting Magnets", Proc. IPAC 12

[6] Heine, K., Tenbrink, J., and Thoner, M. High-field critical current densities in $Bi_2Sr_2CaCu_2O_{8+x}$/Ag wires. *Applied Physics Letters* **55**, 2441-2443 (1989)

[7] A. Godeke*, et al.*, "Development of Wind-and-React Bi-2212 Accelerator Magnet Technology," *IEEE Transactions on Applied Superconductivity,* vol. 18, pp. 516-519, 2008.

[8] Li. P. Thermo-mechanical Properties of Epoxy Impregnated Bi2212/Ag Composite", accepted for publication at *IEEE Transactions on Applied Superconductivity* (2014) (available online at (10.1109/TASC.2014.2376178)

Fermilab

Operated by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Bi-2212 high-field magnet technology at Fermilab: Prototype overpressure processing coil fabrication and quench protection studies

Tengming Shen, Fermilab, November 14, 2014

With inputs from Pei Li (Fermilab), Liyang Ye (Fermilab & NCSU), Gene Flanagan (Muons Inc.), Lance Cooley (Fermilab), members of BSCCo, and collaborations with Justin Schwartz (NCSU).

Work supported by U.S. DOE-OHEP through early career program, SBIR-STTR program and GARD program

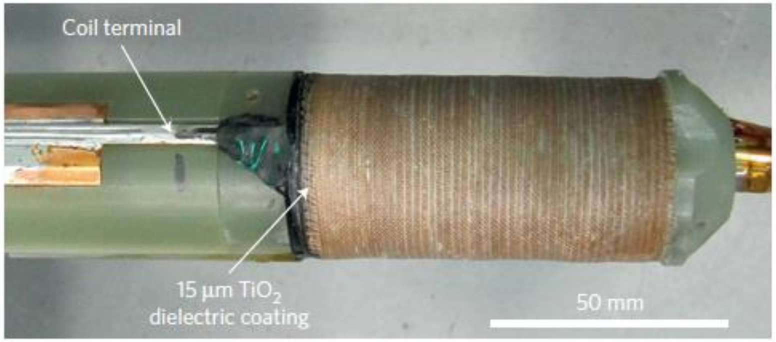
2014 Kyoto WAMHTS-2

Big 2212 steps in 2004-2014

- **VHFSMC (ARRA, $4 million, 2009-2011), and BSCCo**
  - **Industry supplied over 7 km of strand**
  - **Good Rutherford cables were made**
  - **Cable-wound racetracks achieving 75% of short sample**
  - **Small solenoids operating at stresses of >100 MPa in fields up to 32 T were made.**
- **Melt processing/wire design/J_c relationships better understood**
  - **Removing gas bubbles leads to high J_c.**
  - **Leakage caused by creep rupture of silver driven by internal gases**
- **Better insulation technology available**
- **Breakthrough in J_c – 20 T (4.2 K) J_E exceeds 700 A/mm^2**
  - **New paradigm: overpressure processing – heat treat conductor in a high pressure external gas**
  - **used to be 300 A/mm^2 in short commercial wire**
  - **used to be 200 A/mm^2 in coils**

Deploying OP 2212 for applications and some driving questions

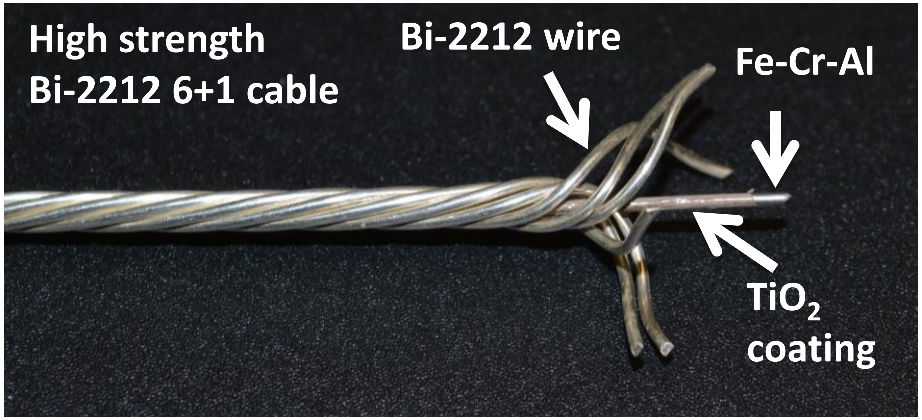
- **Coil fabrication common issues**
  - **What insulation and structural materials to use?**
  - **How to heat treat a coil with +/-2Ccontrol?**
- **Overpressure melt processing coil engineering**
  - **Can the success of overpressure processing be replicated in coils?**
  - **Will OP work well with cables?**
  - **How easy is overpressure melt processing @100 bar with +/-2C control?**



10 bar OP; J_E=252 A/mm^2 at 33.8 T (coil quenched). Add 2.6 T to 31.2 T background.

Larbalestier et al.,
(Nature Materials, 2014)

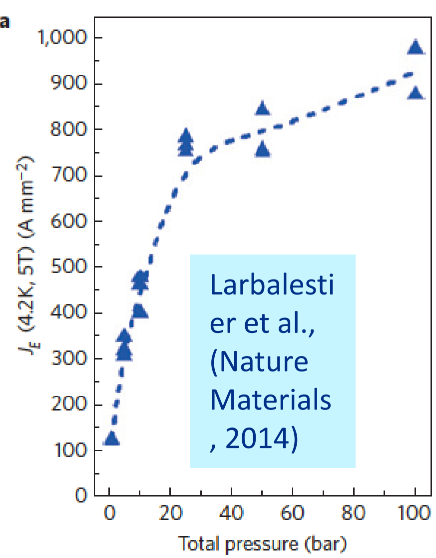
How does OP work out on cables? – Still effective

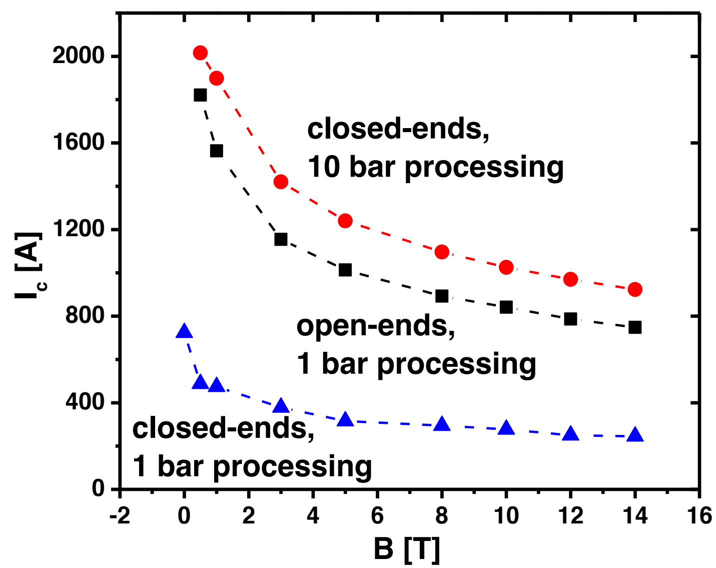


OP by J. Jiang (FSU)

Shen, Jiang et al., to be submitted to SuST and to appear in ArXiV

Single-strand data



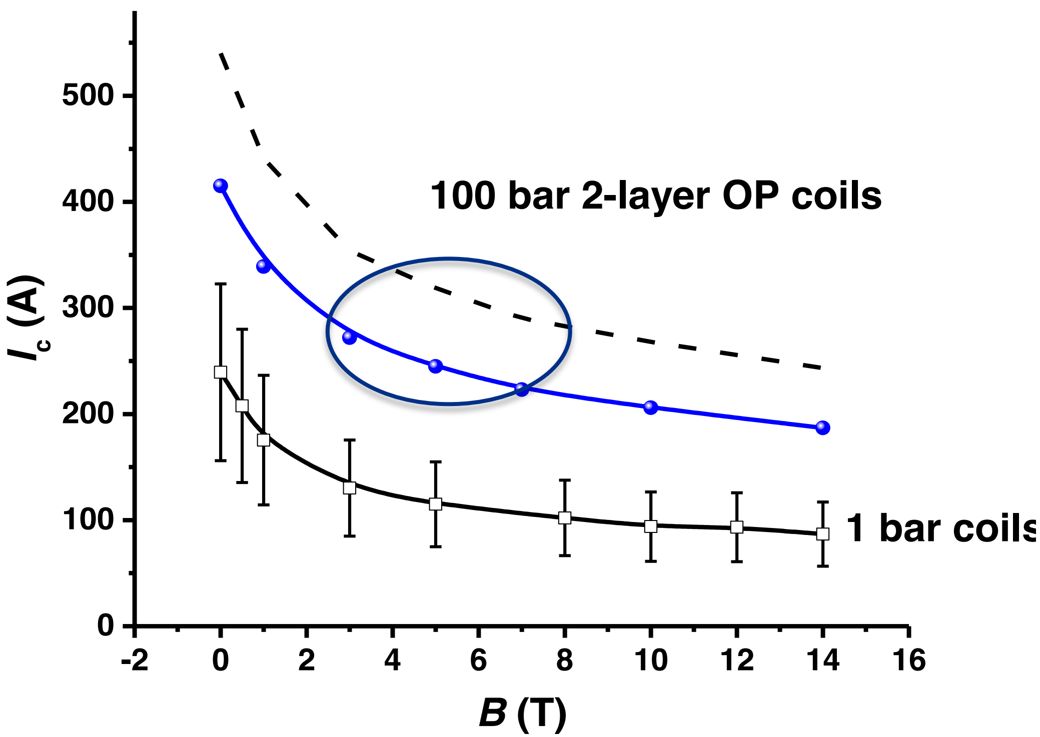


Average J_e(strand in 10 bar OP cable)= 415 A/mm²

Though two 100 bar OP attempts produced J_e=500 A/mm²

Prototype OP solenoids yielded I_c that is 2-2.6 times that of 1 bar solenoids

- **Muons Inc – Fermilab, U.S. DOE-OHEP STTR project**
- **OP coil I_c(5 T)=250-320 A vs. typical 120±40 A in 1 bar coils (0.8 mm strand)**
  - **400 A for the best witness sample (J_E=900 A/mm^2)**

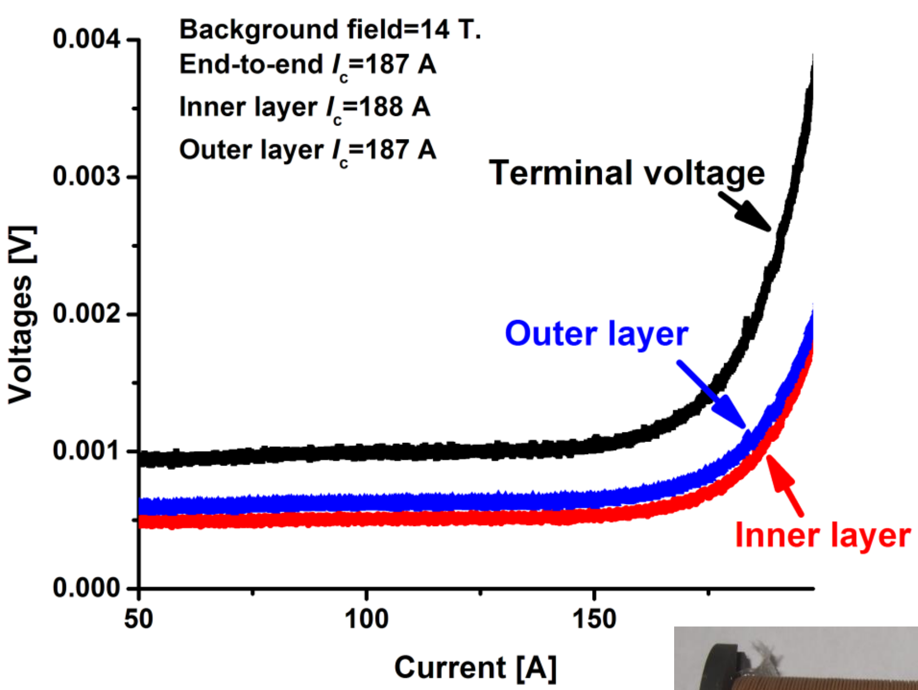


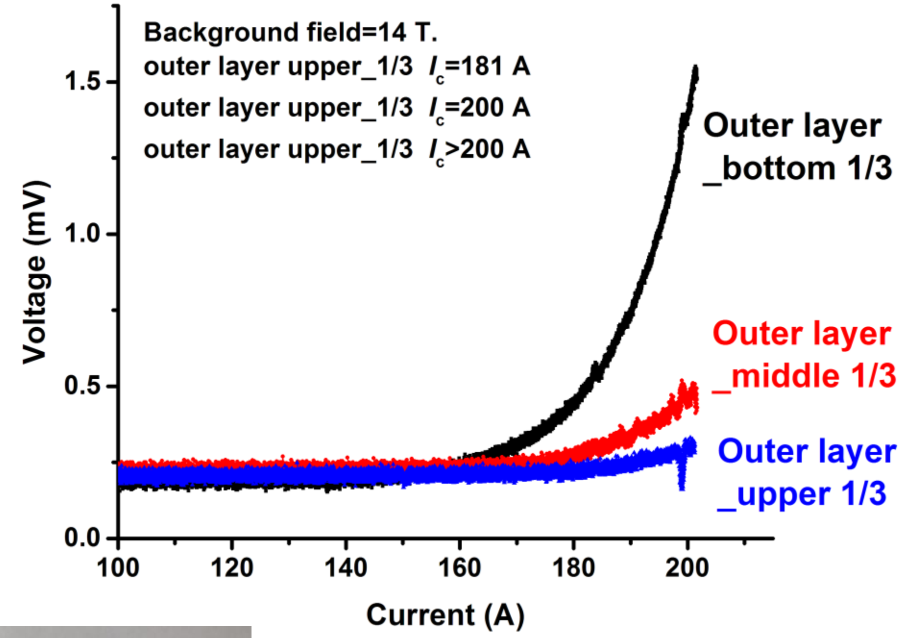
FNAL 100 bar OP system
Hot zone – 16 cm x 50 mm diameter

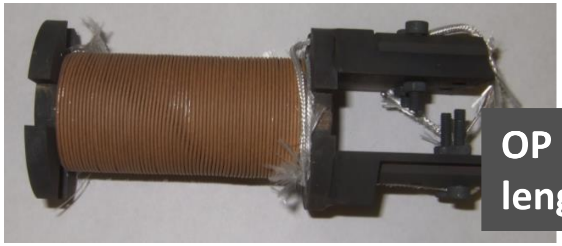
OP 2-layer coil; conductor length=11 m; nGimat insulation

Good superconducting transition seen, despite that coils were reacted in a temperature gradient; insulation is good as well

- Inner layer $I_c \approx$ Outer layer I_c
- No electrical shorts – nGimat TiO_2 insulation works well.
- Non-uniform Coil I_c – coil reacted in a temperature gradient





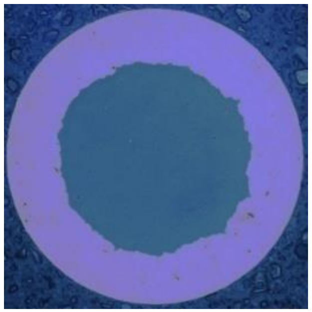


OP 2-layer coil; conductor length=11 m;

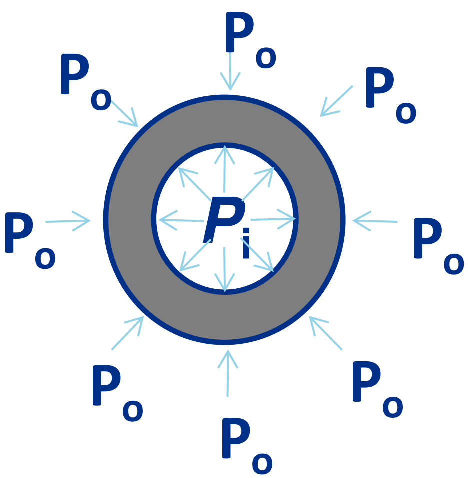
Coil survived >110 quenches and a hoop stress of 97 Mpa, and comments about OP

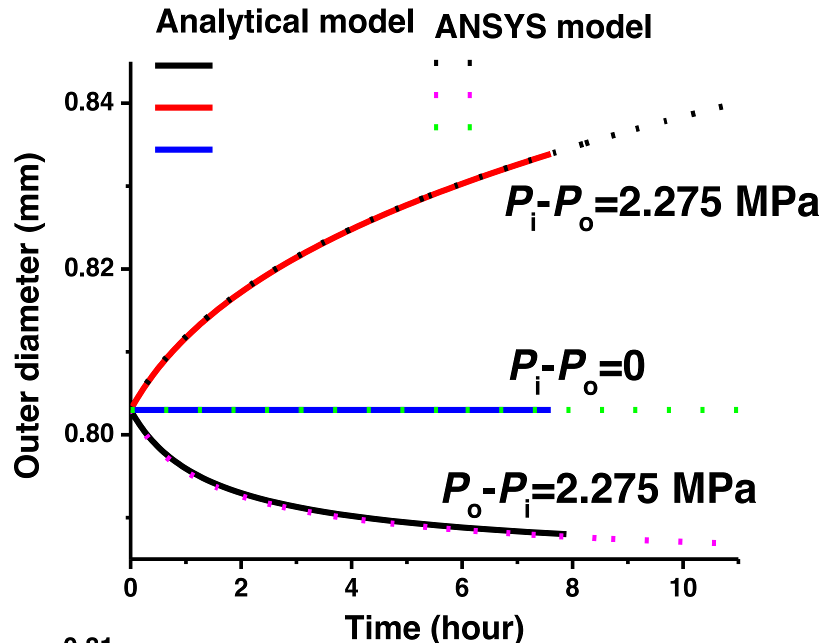
- **No degradation**
  - **after 110 quenches (initiated by a heater) at 7 T, 9 T, and 12 T**
    - **Maximum temperature reached = 250 K.**
  - **Hoop stress reached 97 Mpa at 14 T**
- **OP@100 bar with temperature control in +/- 2C is not easy**
  - **High thermal conductivity of pressured gas messed up temperature homogeneity.**
  - **Not-so-easy temperature calibration**
- **Sumitomo Bi-2223 300 bar OP furnace: +/- 1C in a sample space of 1 m diameter x 1.2 m height**
- **Can we reduce the OP pressure to 30-50 bar?**

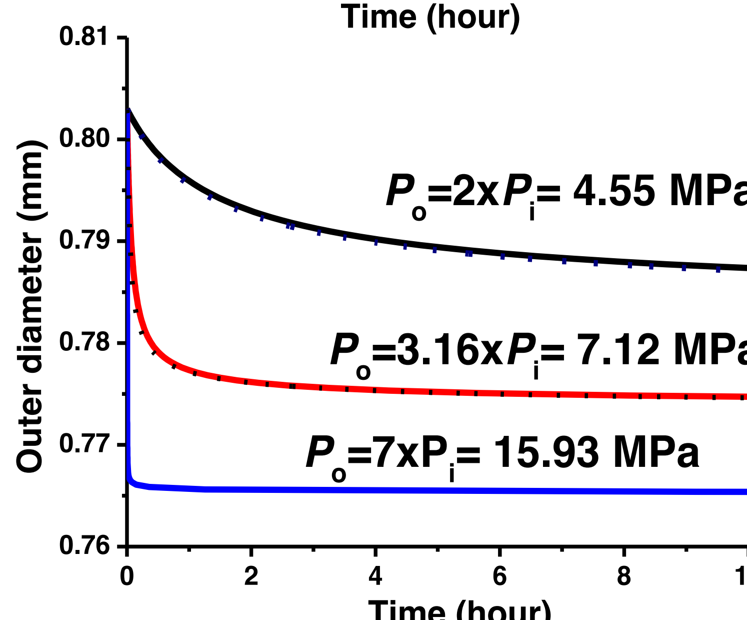
Model of OP: Under external pressure, Ag creeps inward, producing denser Bi-2212 core and raising J_c



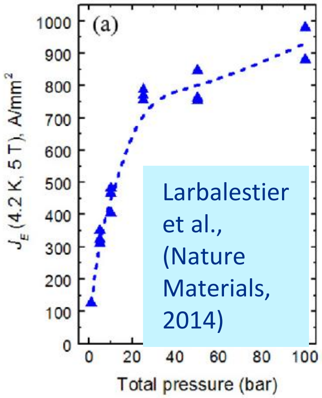
(courtesy of OST)





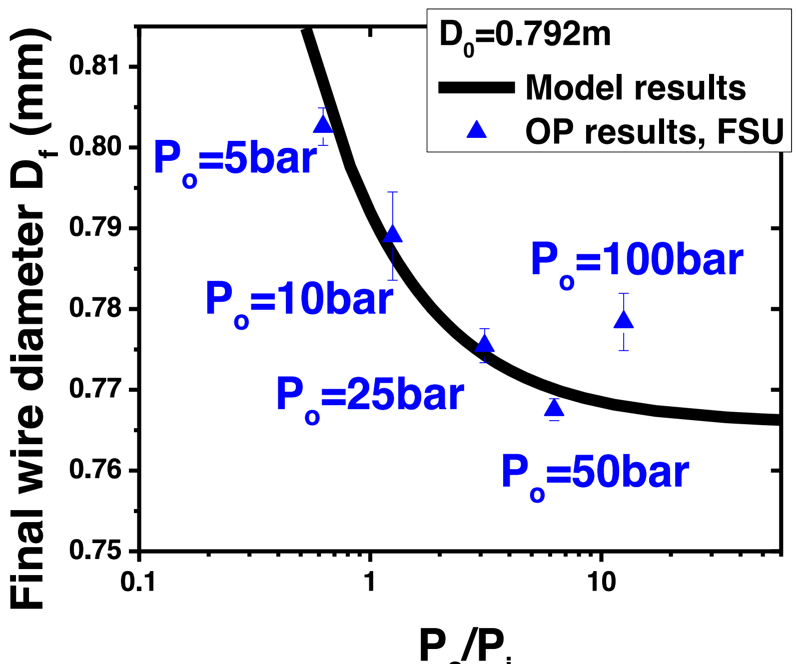


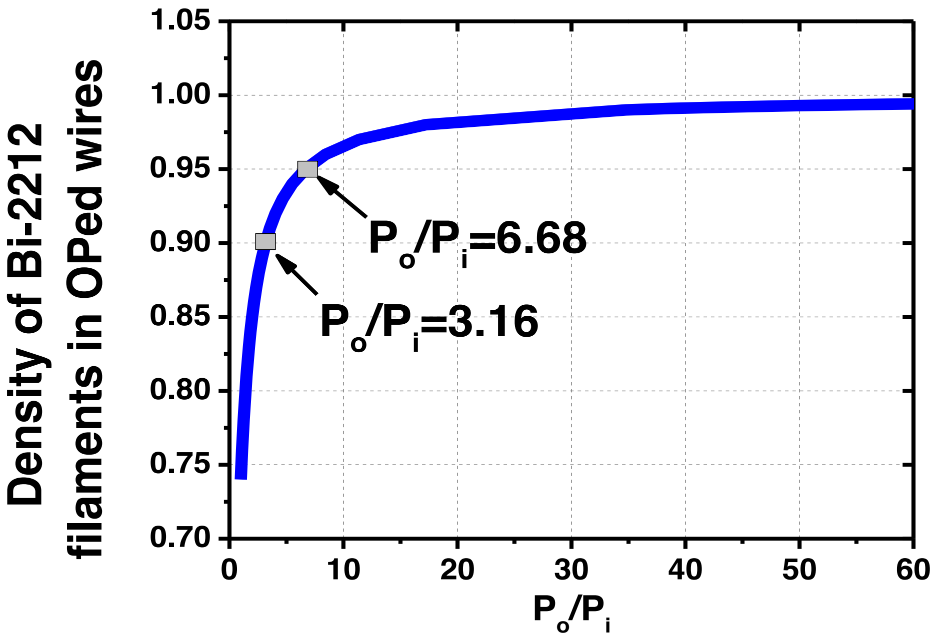
Model predicts that OP requirement decreases linearly with decreasing internal gas pressure



P_i=8 bar now

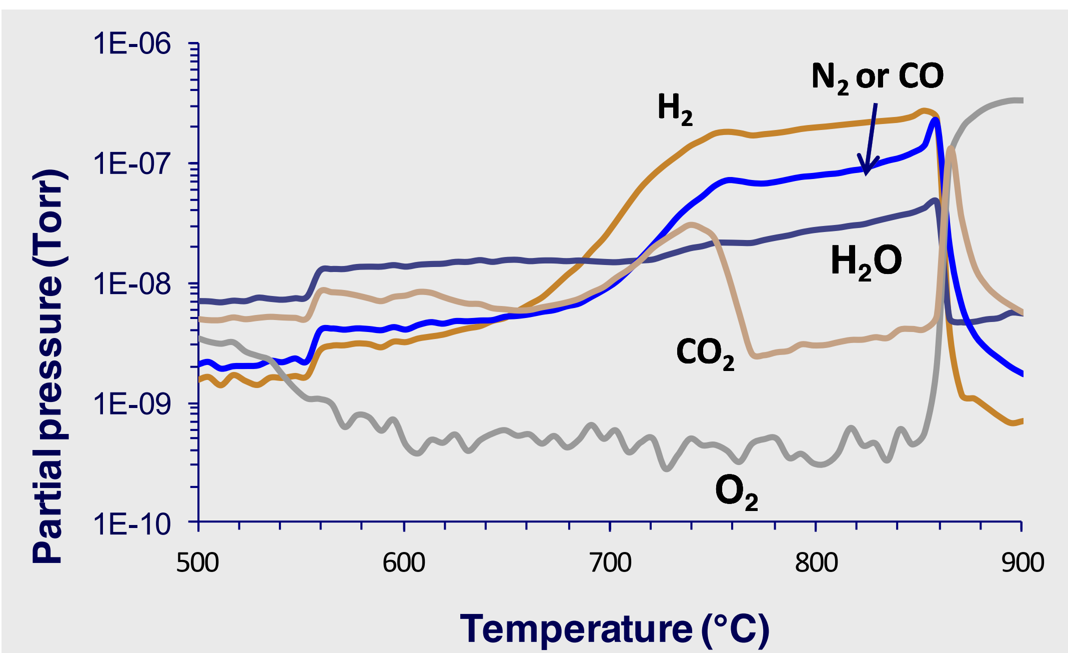
J_c goes up with the filament density.





Challenges to take on: decreasing the OP requirement from 100 bar to 30-50 bar

- **The model predicts that it is feasible.**
- **Mass spectroscopy indicates that wire releases plenty of gases while being heated up**
- **Need collaboration between powder manufacturer, wire manufacturer, and materials scientists.**



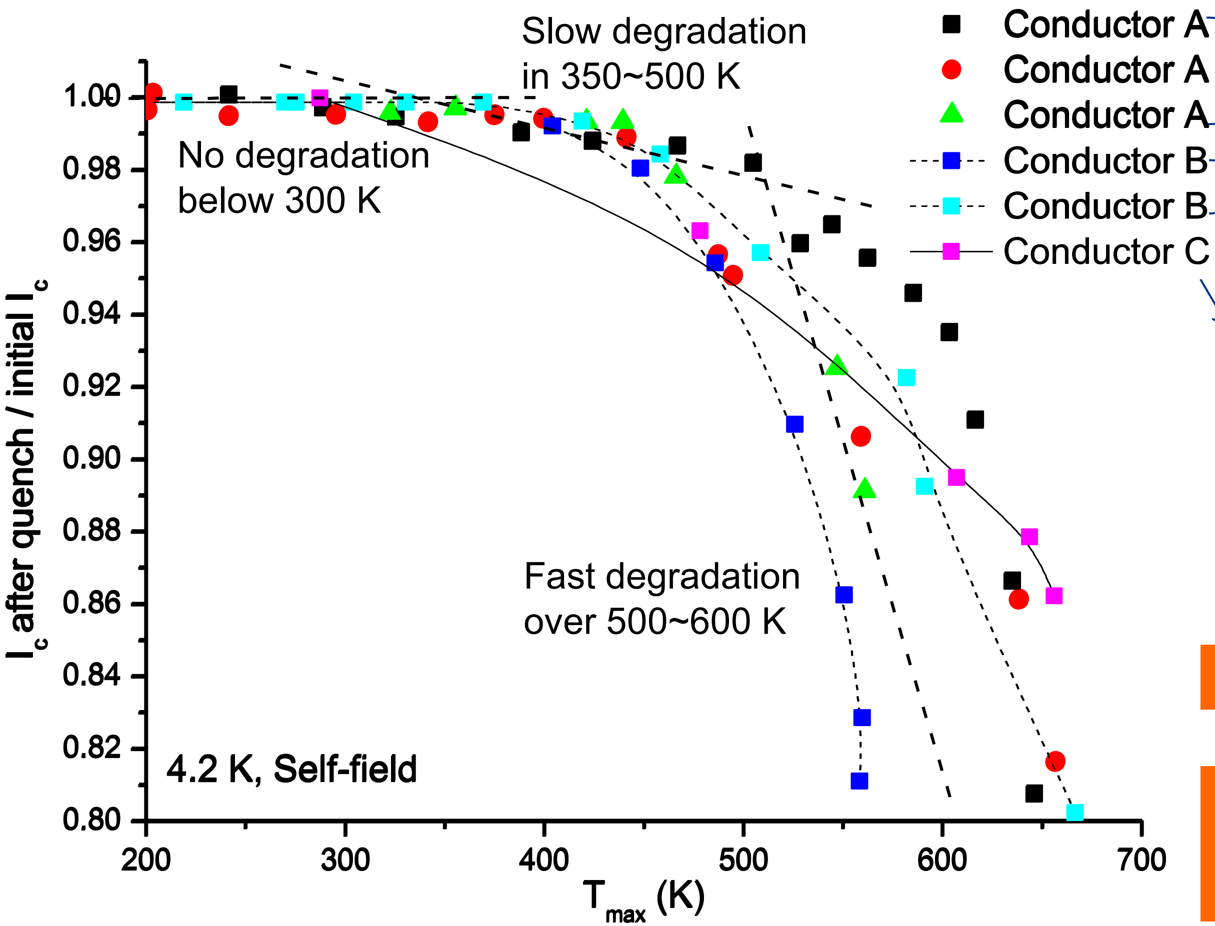
Gas species detected by a residual gas analyzer while heating Bi-2212 wires at 180 ° C/h in vacuum.

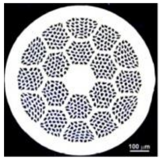
Shen et al., J. Appl. Phys., **113**, 213901 (2013)

Driving questions for the next section

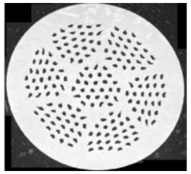
- **Quench detection and protection of Bi-2212 magnets**
  - **What are quench degradation limits and mechanisms?**
  - **How high the hot spot temperature needs to be for the resistive voltage of a normal zone to be detectable?**
  - **At what speed a normal zone propagates and how does this speed depend on operating conditions and conductor processing?**
  - **How can we achieve a quench protection with a time constant <500 ms.**

A large pool of wires, including OP wires, shows a consistent I_c/I_{co}-T_{max} behavior

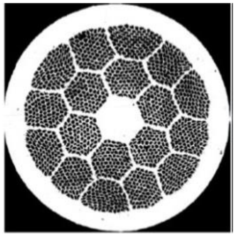




OST 0.8 mm, 37x18
I_c(s.f)=450A
Bench marker



OST 1.0 mm, 27x7
I_c(s.f)=150A
No Bridging



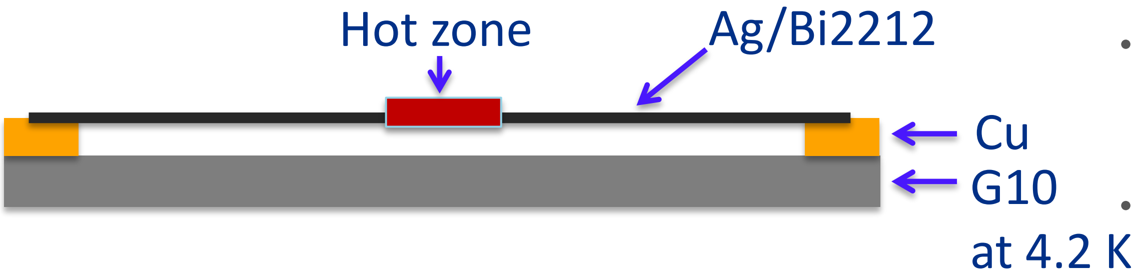
OST 1.2 mm, 85x18
I_c(s.f)=950A

See Schwartz talk

Liyang Ye, PhD thesis work
Justin Schwartz, Tengming Shen

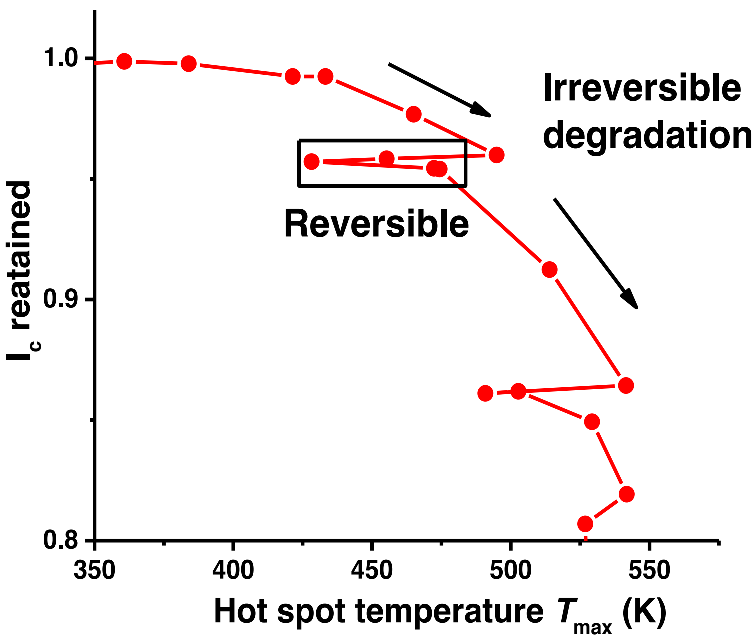
Fermilab
nc state ENGINEERING

The observed quench degradation is strain driven - first evidence: irreversible and reversible degradation behavior

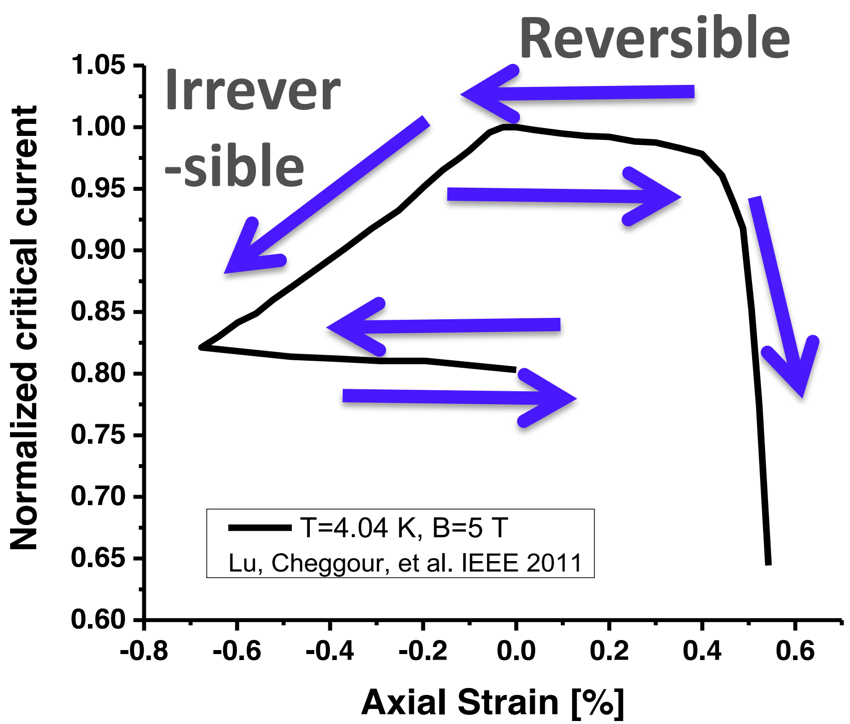


- Wires want to expand but couldn't.
  - Silver buckles under compressive stress.
- Silver and 2212 expand differently.

Irreversible and reversible degradation behaviors

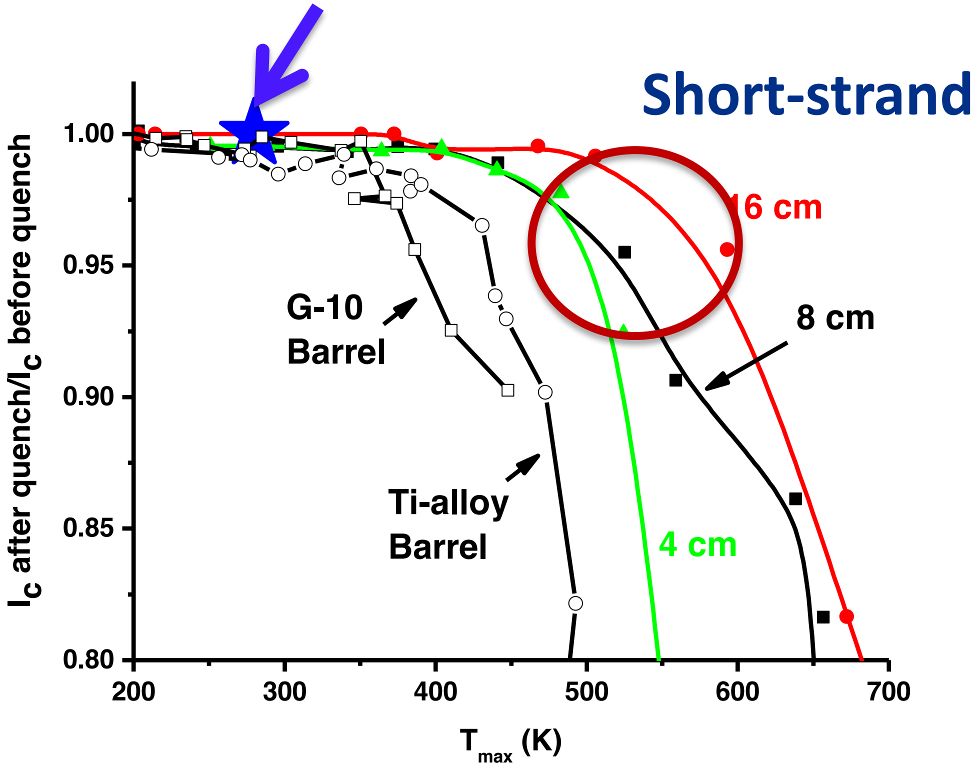


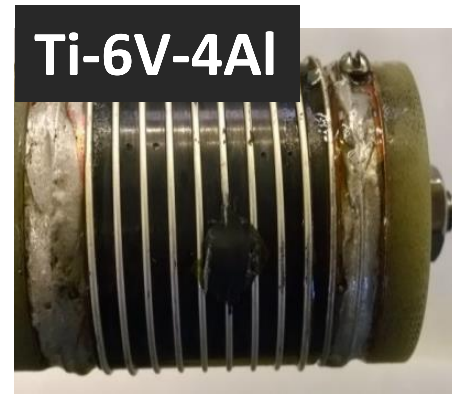
J_c-Strain for Ag/2212 wire

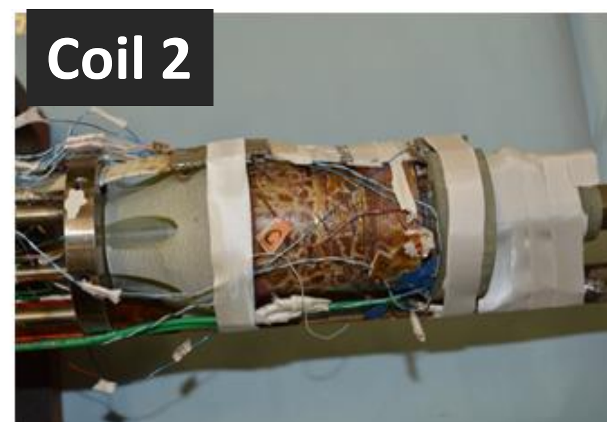


300 K seems safe – even for coils under good electromagnetic stresses

Coil 2 at 7 T, stress=60 MPa





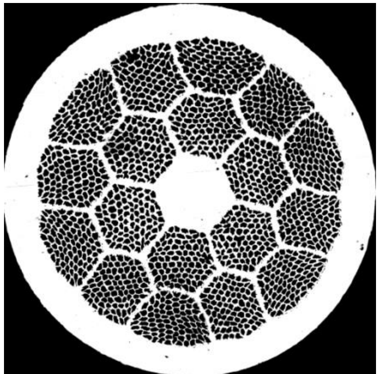


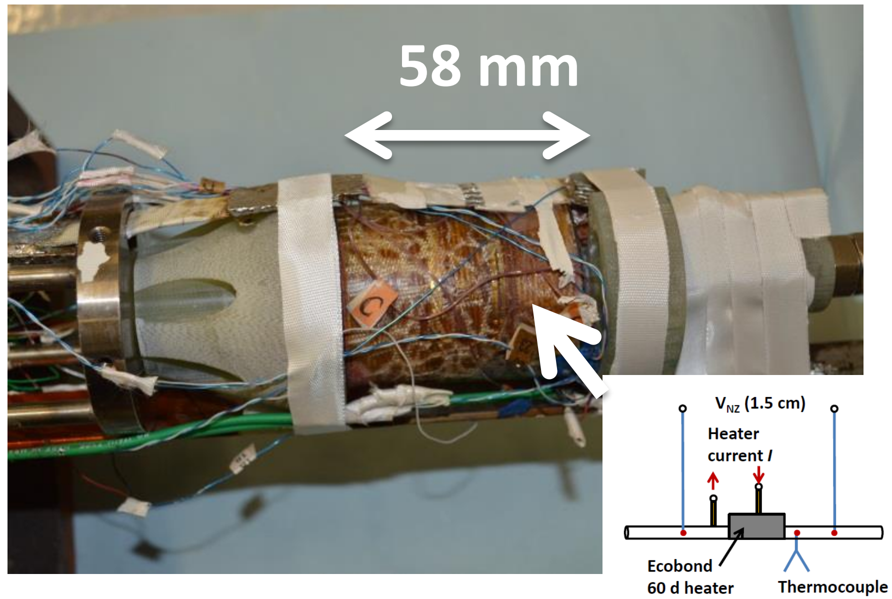
Liyang Ye, PhD thesis work
Justin Schwartz, Tengming Shen

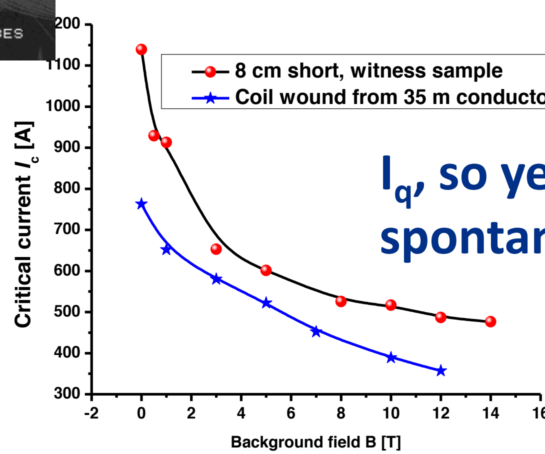
Fermilab nc state ENGINEERING

A 1 bar processed coil and heater-induced quench experiments

6-layer, 245 turns, epoxy impregnated Bi-2212 solenoid

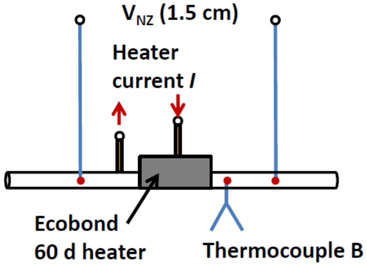


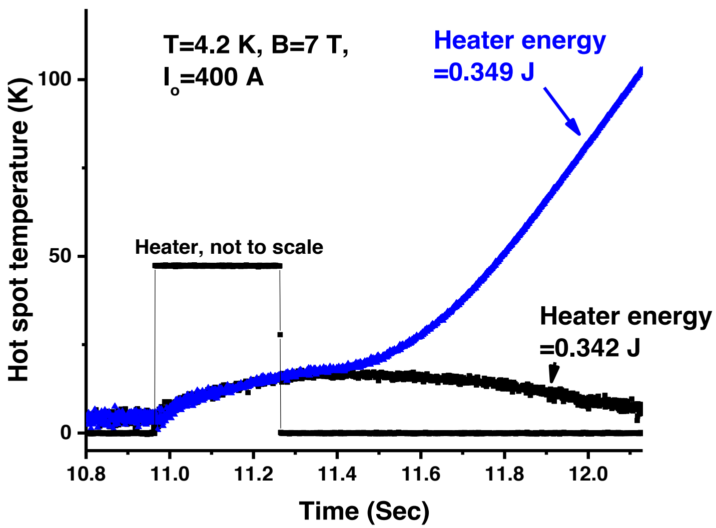


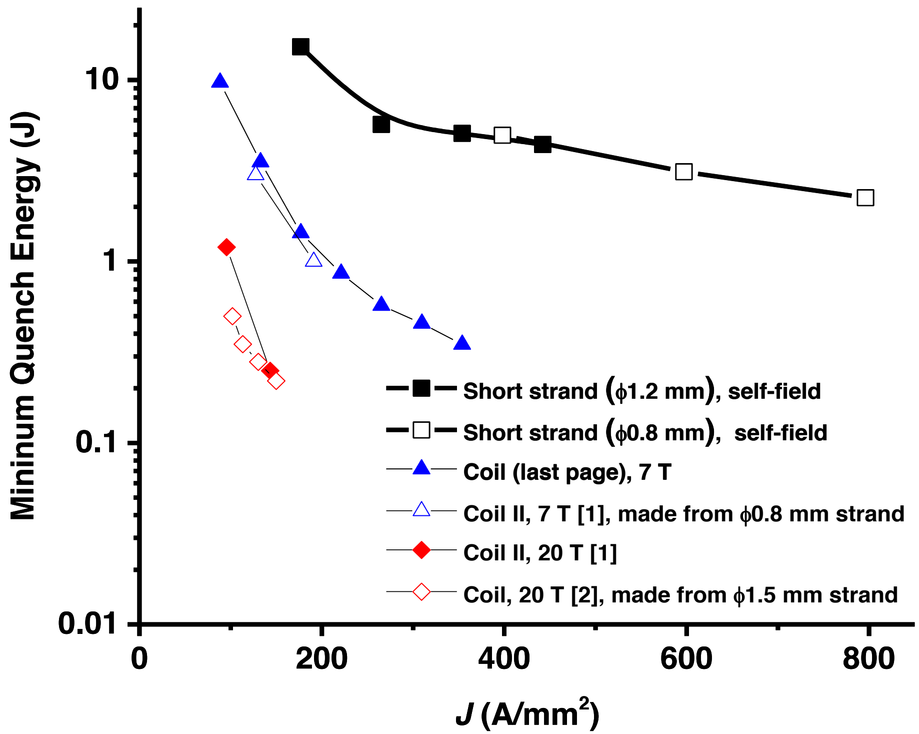


I_q, so yes, 2212 coil can quench spontaneously

MQE determined from heater-induced quench experiments: a master plot



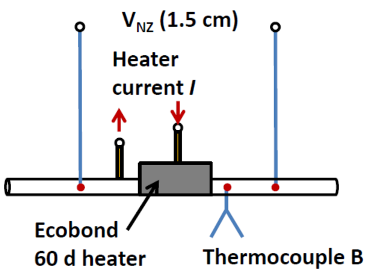


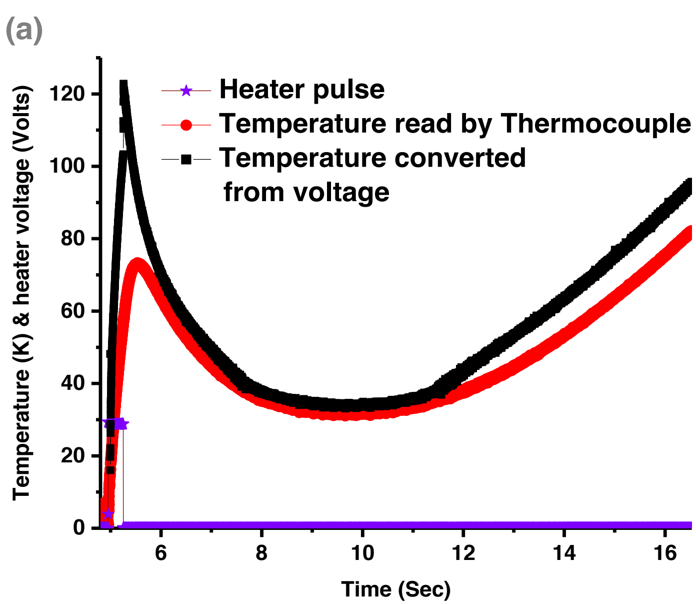


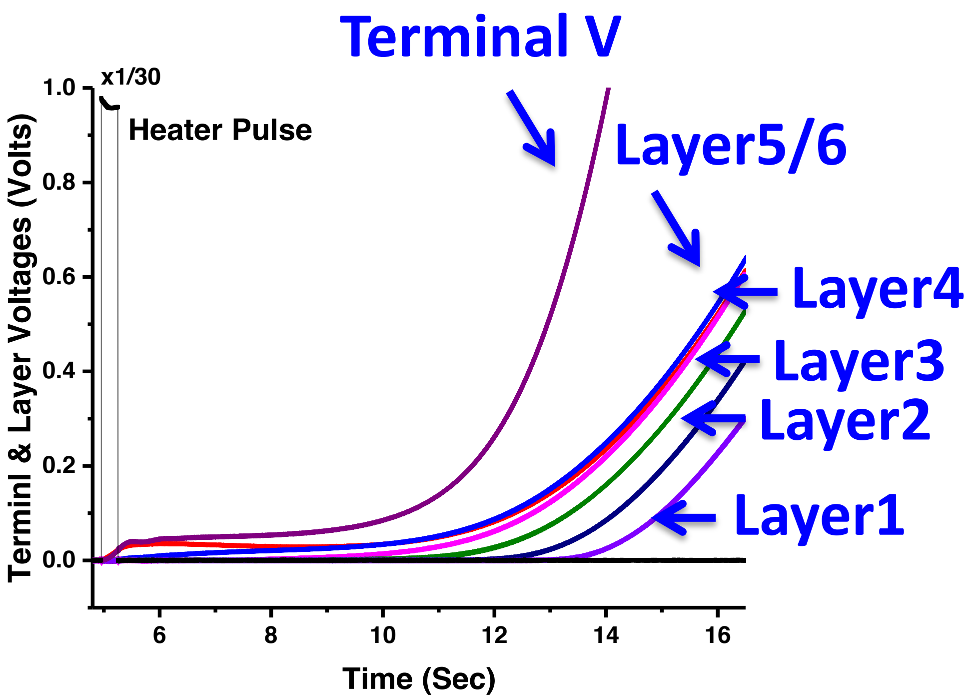
Shen, Ye et al., to be submitted and to appear in ArXiV

[1] Ye et al., SuST, 2013
[2] Yang et al., IEEE, 2012

T=4.2 K, B=7 T, I_o=100 A – Quench propagation and temperature rise at *J*=88 A/mm²

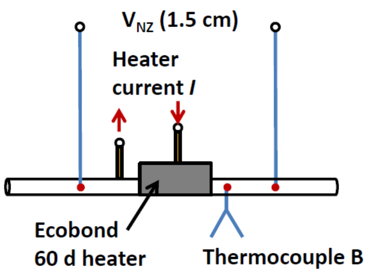


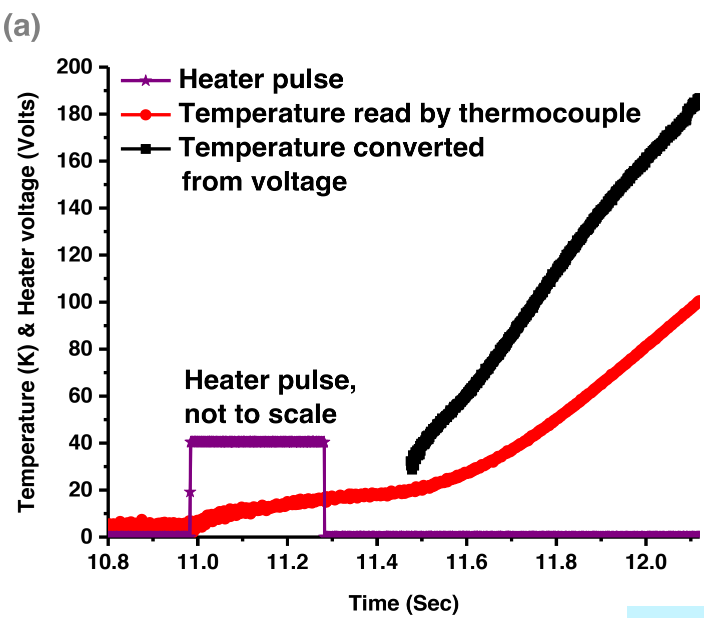


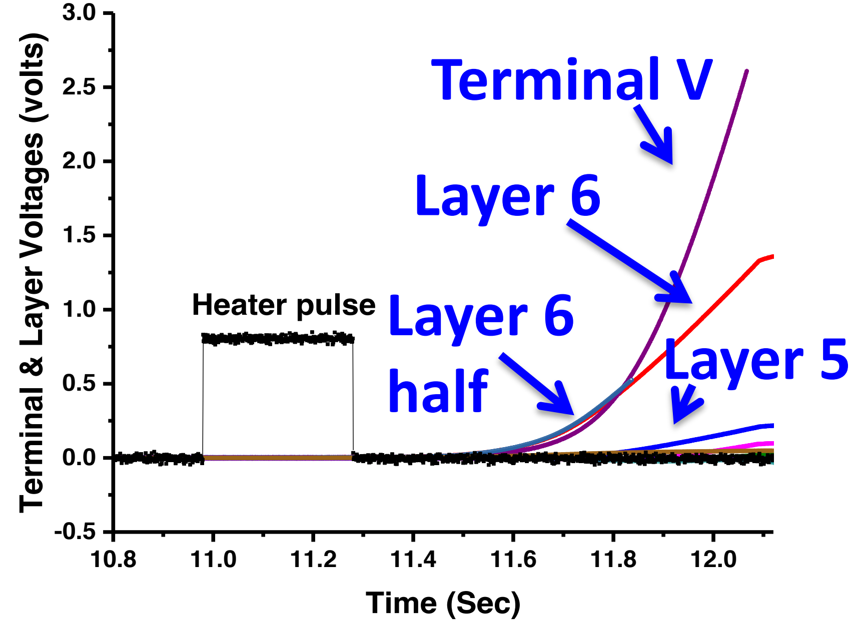


Shen, Ye et al., to be submitted and to appear in ArXiV

T=4.2 K, B=7 T, I_o=400 A – Quench propagation and temperature rise at J=354 A/mm^2

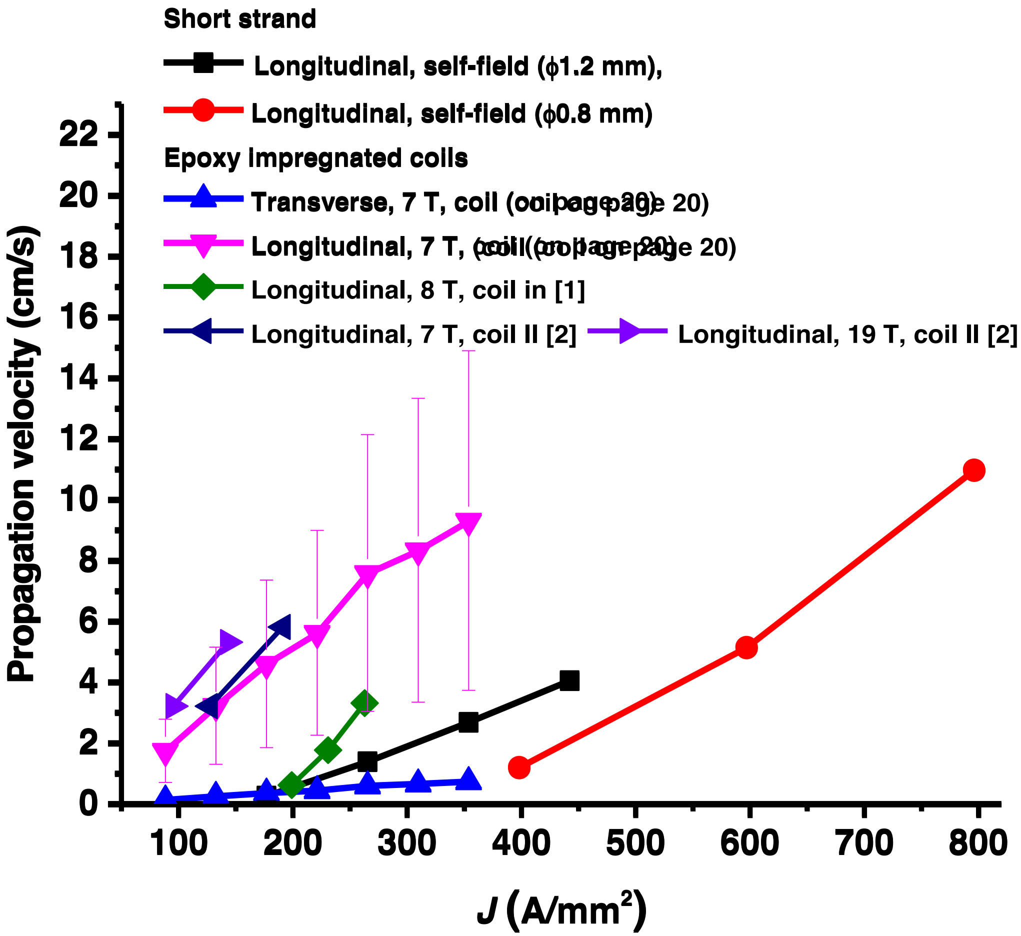






Shen, Ye et al., to be submitted and to appear in ArXiV

NZPV determined from heater-induced quench experiments: a master plot



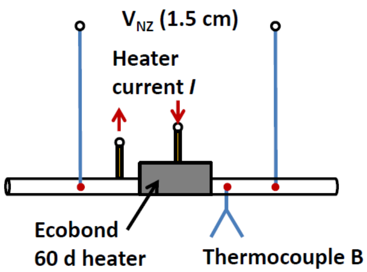
[1] Trociewitz, SuST, 2008
[2] Ye et al., SuST, 2013

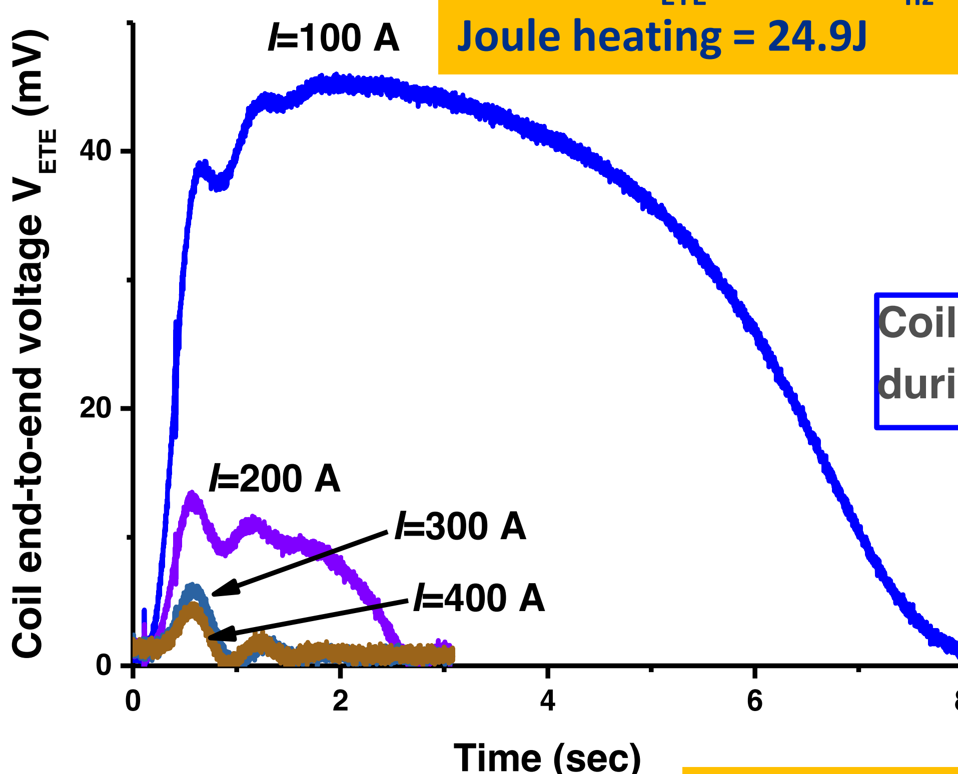
Shen, Ye et al., to be submitted and to appear in ArXiV

Quench detection – Terminal voltage that coil sustains without a quench varies with transport current

Should a dynamic quench detection threshold used?

I=100 A, V_{ETE}=45 mV. R_{nz}=0.45 m-ohm
Joule heating = 24.9J





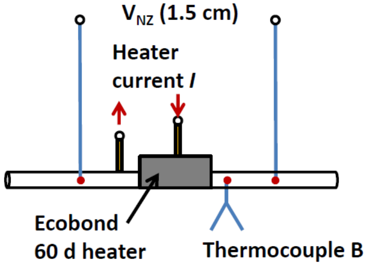
Coil terminal voltage during recovery cases

Shen, Ye et al., to be submitted and to appear in ArXiV

4.2 K, 7 T, coil experiment

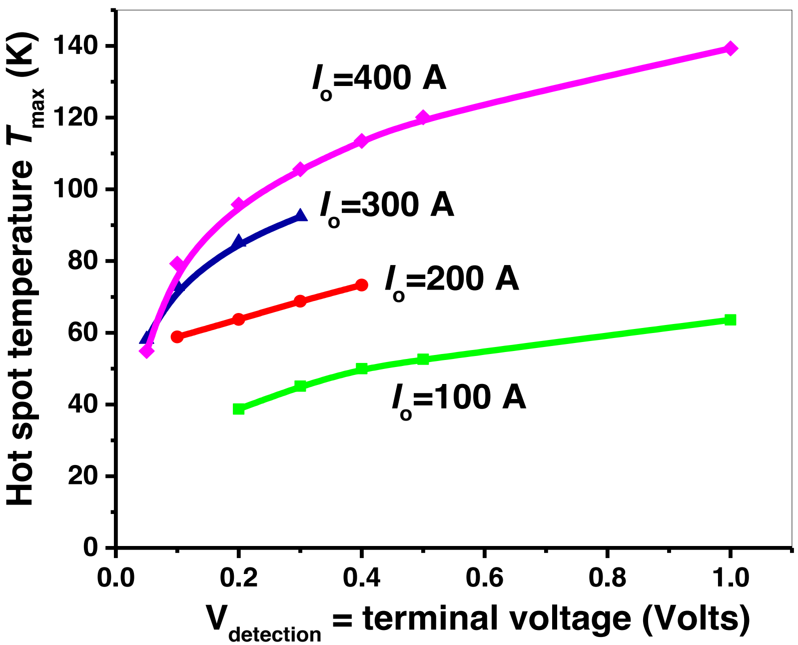
I=400 A, V_{ETE}= 4.26 mV. R_{nz}=10.6 μ-ohm
Joule heating = 1.18J

Hot spot temperature v.s. resistivity voltage across normal zone: quench detection is demanding; V_d=50-200 mV is preferred



Note: Temperature from voltage measurement, not from TCs. TCs tend to underestimate T_{max} when dT/dt>10 K/s.

Temperatures derived from voltages across the 1.5 cm hot zone:

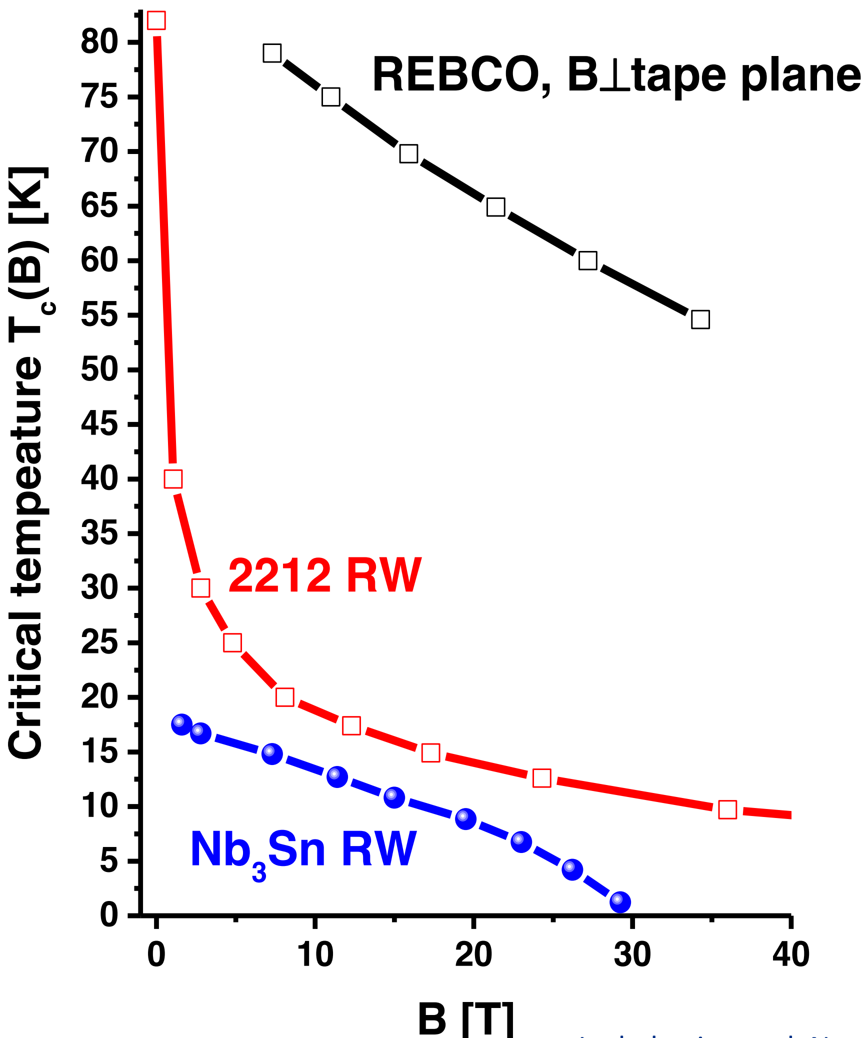


- **100 A-> 400 A, quench detection becomes more difficult.**
- **Beyond 400 A, quench detection should becomes easier (prediction)**
- **Not wise to increase $V_{detection}$ beyond 1 V**

Shen, Ye et al., to be submitted and to appear in ArXiV

4.2 K, 7 T, coil experiment

When B> 5 T, NZPV of 2212 is still in cm/s – but it should be in tens of cm/s or even m/s considering its small temperature margin



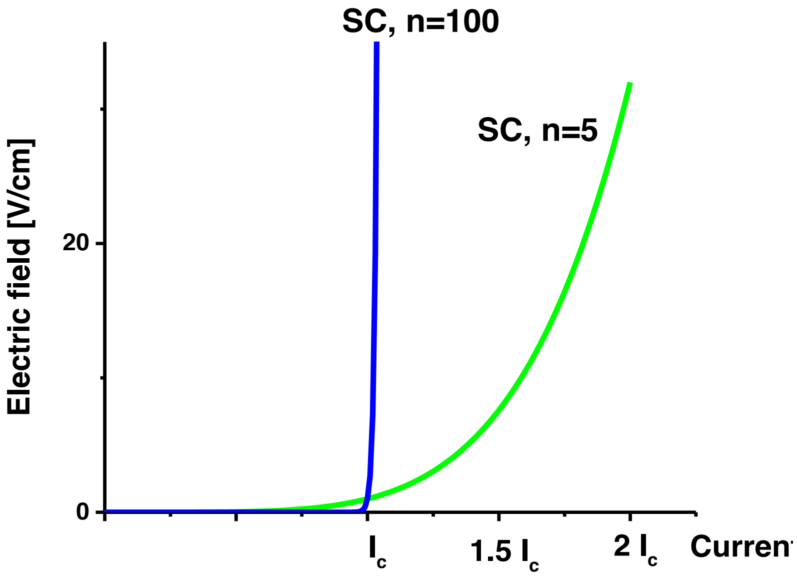
Larbalestier et al, Nature Materials, 2014

- T_c (2212) drops to 25 K when B>5 T
  - B=0: typical HTS, NZPV in cm/s
  - B>5 T: somewhat LTS, NZPV should be in m/s but actually in cm/s
- A big reason is low n-value in Bi-2212
  - Typical n-value for 1 bar coils: 5-12
  - Typical n-value for OP coils: 12-20

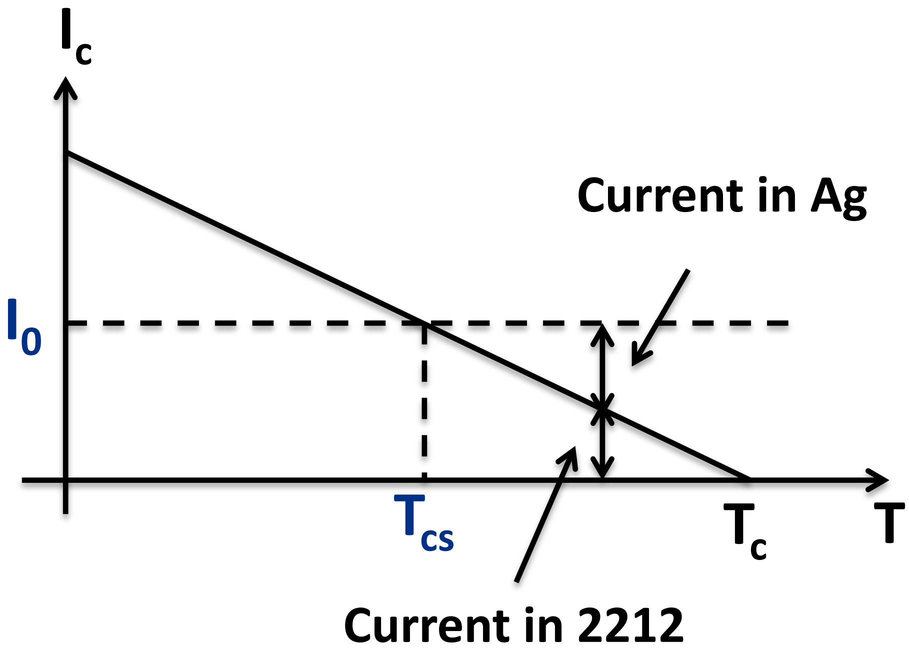
Summary

- Overpressure processing, though not easy, is fundamentally sound
  - Good OP cables and coils made and tested
- Found a consistent quench degradation behavior in a large spool of wires
- Deeper understanding of quenches
  - Measure MQE vs. J and B, and NZPV vs. J and B
  - First careful measurement of T_{max} v.s. V_d
  - Strong effects of n-values on quench propagation and detection revealed
- **Project pull:**
  - **28-30 T all SC solenoid – NHMFL NMR and DOE SIBR/STTR**
  - **The world's first cosine-theta Bi-2212 dipole**
  - **The world's first canted-cosine-theta Bi-2212 dipole**

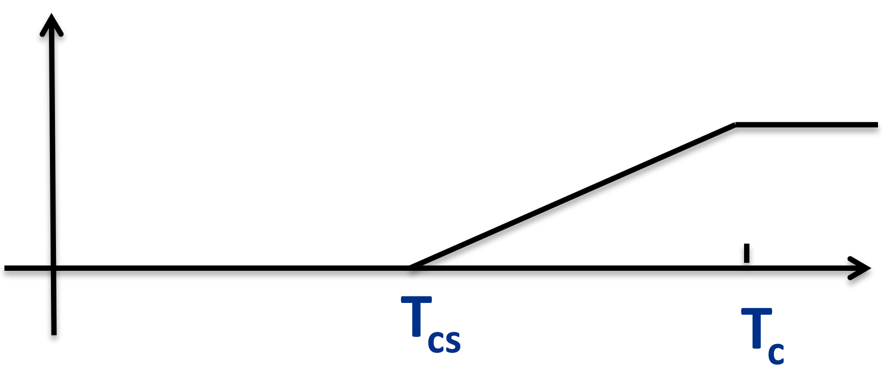
Slow propagation of normal zones in Bi-2212 magnets: Effects of conductor E-J characteristics

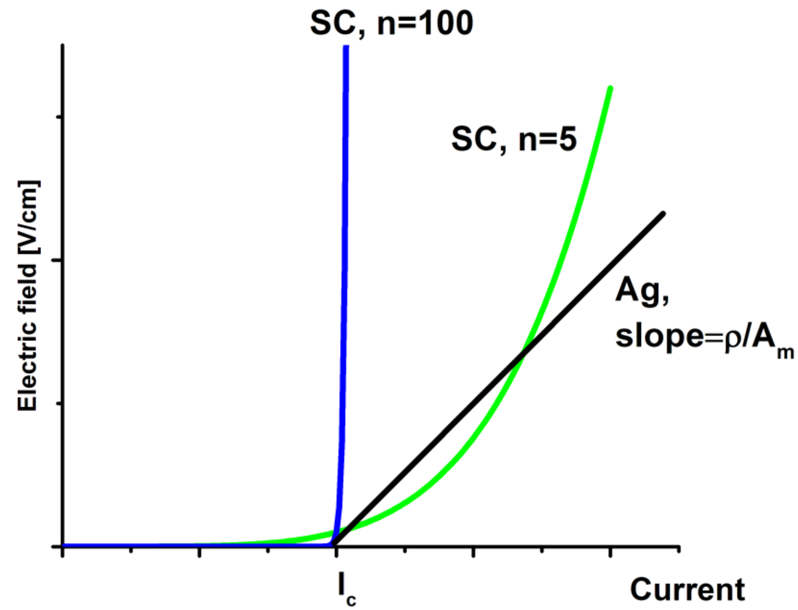


The joule power model that describes Nb-Ti and Nb_3Sn well is not suitable for 2212 because 2212 has a small n-value (5-15 in fields)



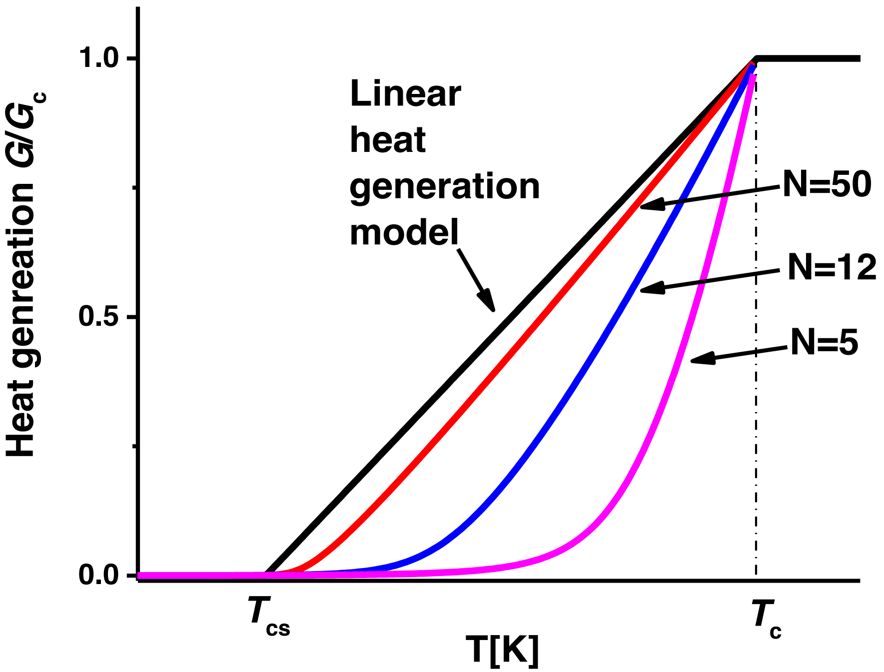
Joule heating

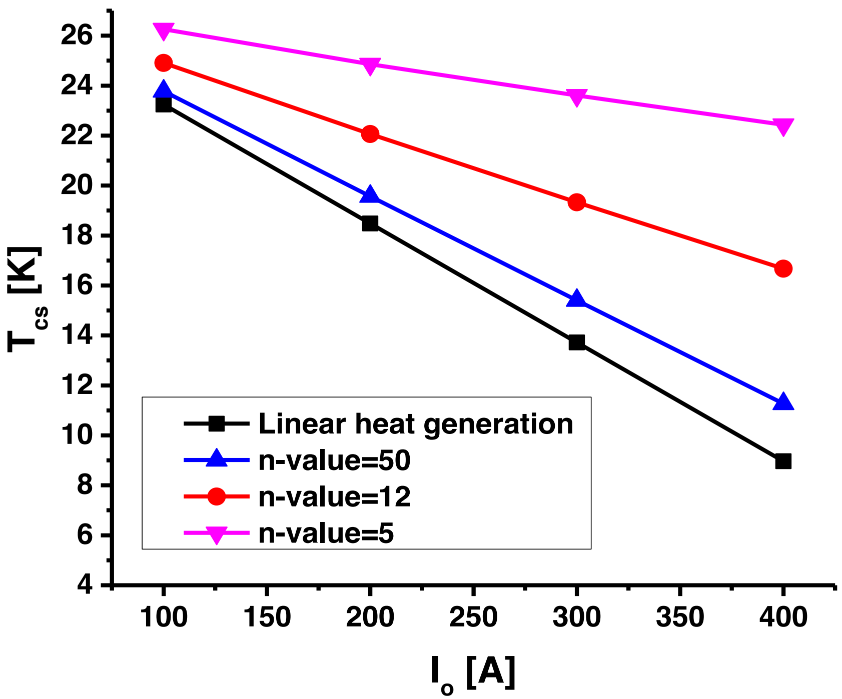




New nonlinear current-transfer model: Smaller N-value -> more difficult to drive formation of normal zones

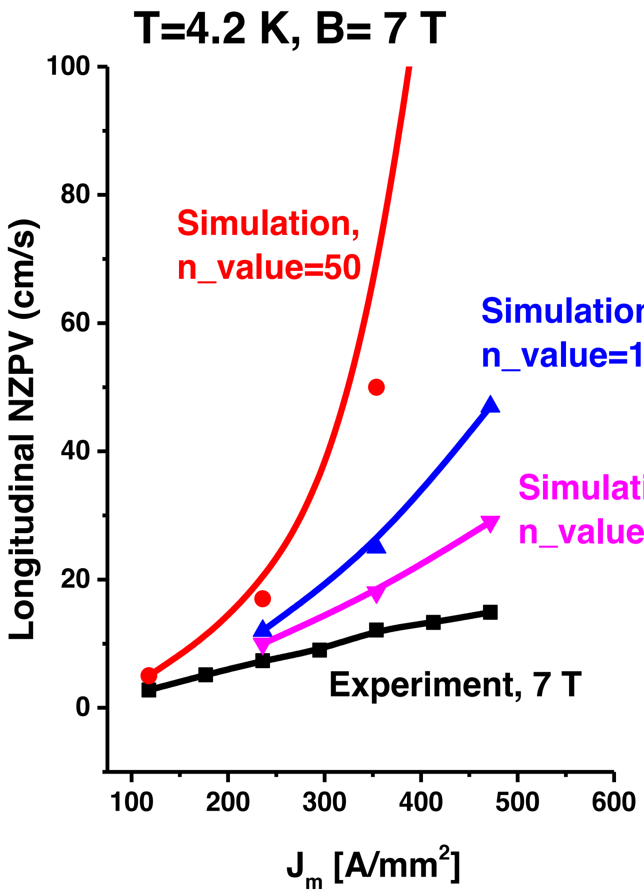
- Low N-values, in combination with small RRR, increase T_{cs}.
  - More pronounced at high I_o/I_c and at high magnetic fields.

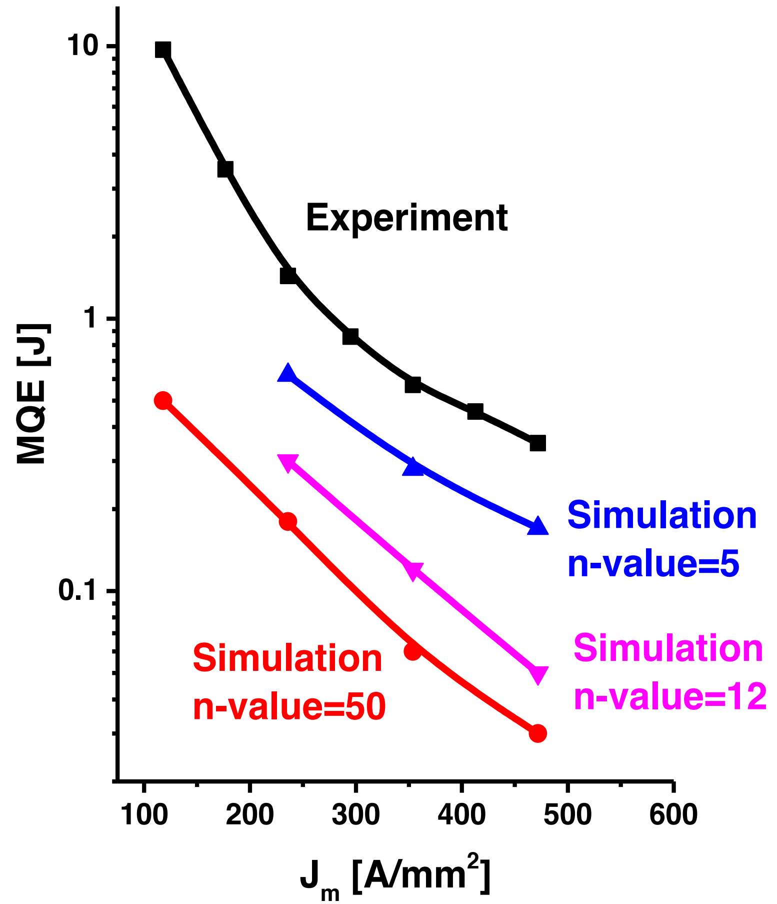




N-values ↓: conductor stability ↑, normal zone propagation speed ↓

- Low NZPV in 2212 at B > 5 T is largely caused by low n-values.
- Increase the N-value -> In-field NZPV in m/s (though sacrificing some stability)





Thermal-mechanical Properties of Epoxy-impregnated Bi-2212/Ag Composite

Pei Li, Yang Wang, Arno Godeke, Liyang Ye, Gene Flanagan, and Tengming Shen *Member, IEEE*

***Abstract*—Knowledge of thermal-mechanical properties of epoxy/superconductor/insulation composite is important for designing, fabricating, and operating epoxy impregnated high field superconducting magnets near their ultimate potentials. We report measurements of the modulus of elasticity, Poisson's ratio, and the coefficient of thermal contraction of epoxy-impregnated composite made from the state-of-the-art powder-in-tube multifilamentary $Ag/Bi_2Sr_2CaCu_2O_x$ round wire at room temperature and cryogenic temperatures. Stress-strain curves of samples made from single-strand and Rutherford cables were tested under both monotonic and cyclic compressive loads, with single strands insulated using a thin TiO_2 insulation coating and the Rutherford cable insulated with a braided ceramic sleeve.**

***Index Terms*—Bi-2212/Ag, mechanical property, strain, thermal contraction, composite material modeling.**

I. Introduction

With critical current densities (J_c) exceeding 2500 A/mm^2 in 20-30 T at 4.2 K [1, 2], Bi-2212/Ag round wire has long been considered as a candidate for constructing solenoids capable of generating fields that exceed the ~22 T limit of Nb_3Sn and constructing 16-20 T dipoles for particle accelerators. A critical issue is, however, how to manage the high electromagnetic stresses in such high field magnets. The conductors in high field magnets are subject to enormous pressures during operation; at 20 T, the magnetic pressure is 320 MPa, high enough to cause plastic deformation of copper. Stress management will be a crucial design consideration for high-field magnets based on Bi-2212 conductors since Bi-2212 is brittle after reaction and its current-carrying capability depends on strain. I_c of Ag-sheathed Bi-2212 wires is virtually insensitive to tensile strain up to a sample dependent strain limit, beyond which the I_c decreases quickly and irreversibly. Applying compressive strain to Ag-sheathed BSCCO conductor causes a gradual and irreversible decrease of I_c [3]. For commercial Ag-0.2 wt% Mg/Ag/Bi-2212 (area ratio AgMg:Ag:Bi-2212 = 0.25:0.5:0.25) round wire, the working stress maximum is around 120 MPa at 4.2 K whereas the irreversible tensile strain is between 0.3% and 0.45%. In addition to the electromagnetic stresses during normal operations, both solenoids and dipoles are subject to complex mechanical motions and significant non-uniform temperature changes during quenching, both result in changes in conductor strain states that can't be ignored when magnets work near their mechanical limits. Moreover, construction of cosine-theta dipoles requires the coils to be pre-stressed to reduce the potential conductor motion and thus minimize the probability of motion-initiated quenches.

To understand and predict the strain state in the superconductor and devise a support structure capable of minimizing the stresses in the coils from magnet assembly to excitation, Fermilab initiated a program to measure and compute displacements, stress, and strain of all the components during assembling, cooling-down, and excitation for magnets. Here we report measurements of the mechanical properties and thermal contraction for epoxy-impregnated Bi-2212-based composite materials fabricated using the same method as for full size magnet coils.

II. Sample Description

The wire stack samples were prepared as follows: commercial powder-in-tube Bi-2212/Ag wires from Oxford Superconducting Technology (0.8 mm diameter, 37x18 filament architecture with filament diameter of ~20 μm) were insulated with a *n*Gimat TiO_2 coating [4] that consisted of a TiO_2 basecoat ~20 μm thick and a polymer top-coat ~3 μm thick. The wires were hexagonally wound around a small Inconel 600 racetrack mandrel, heat-treated in 1 bar flowing oxygen using a standard heat-treatment procedure [5] of Bi-2212/Ag wires, and then impregnated with epoxy (CTD-101K). After reaction, no visible signs of leakage were found but we believe that the coil contains leakage spots because of silver creep driven by internal gases common in the 1 bar melt processing of long-length Bi-2212 wires [6]. The

Manuscript received August 12, 2014. This work was supported in part by an FY12 early career award from the Office of High Energy Physics (OHEP), U.S. Department of Energy and amplified by a SBIR phase I award from DOE-OHEP (DE-SC0011267).
Pei Li is with the Magnet Systems Department, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA (e-mail: peili@fnal.gov).
Yang Wang is a graduate student with the Illinois Institute of Technology, Chicago, IL, 60616, USA and he is also with the Fermi National Accelerator Laboratory (e-mail: ywang@fnal.gov).
Arno Godeke was with the Lawrence Berkeley National Laboratory, Berkeley, CA 94720. He is now with the National High Magnetic Field Laboratory, Tallahassee, FL 32310 USA (agodeke@lbl.gov)
Liyang Ye is a graduate student with North Carolina State University, Raleigh, NC, 27695 USA and he is also with the Fermi National Accelerator Laboratory. (e-mail: ye1024@fnal.gov).
Gene Flanagan is with the Muons Inc., Batavia, IL, 60510, USA (e-mail: flanagan@muonsinc.com).
Tengming Shen is with the Magnet Systems Department, Fermi National Accelerator Laboratory, Batavia, IL 60510 USA (e-mail: tshen@fnal.gov).

outer sheath of the wire was Ag-0.2wt%Mg, with area ratio of AgMg:Ag:Bi-2212 = 0.25:0.5:0.25. The density of filament was approximately 75% of theoretical value. The coil was expected to carry ~65-80% of short sample I_c (short samples carried ~440 A in self-field and 190 A in 5 T at 4.2K). The straight sections of the wire stack were cut (with Inconel removed) and polished. A typical sample size was about 12 mm x 12 mm x 18 mm (axial direction). A typical sample contained about 13-15 by 13-15 strands. Fig. 1a shows a typical sample stack. The mechanical properties of these samples are useful for designing solenoids wound from Bi-2212 strands.

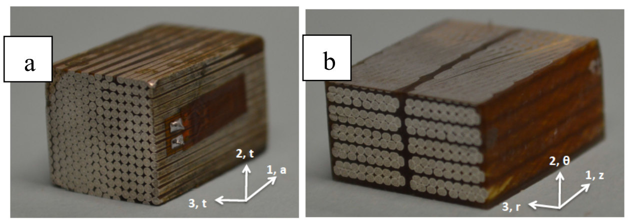


Figure 1. Samples with definition of loading directions: (a) strand sample (a=axial, t=transverse); (b) cable sample (z=axial, r=radial, θ=azimuthal).

Table 1: Specifications of the strand composite sample

Strand sample	
Conductor	Ag/Bi-2212
External sheath	Ag-0.2wt%Mg
AgMg:Ag:Bi2212	0.25:0.50:0.25
Strand diameter	0.8 mm
Insulation	nGimat TiO_2 coating
Insulation thickness	23 μm
Winding	Hexagonal
Sample size [mm^3]	12 x 12 x 18

Table 2: Specifications of the cable composite sample

Cable sample	
Conductor	Same as strand sample
Cable width [mm]	1.46
Cable thickness[mm]	7.80
Cable pitch length	39 mm
No. of strands in a cable	17
Cable insulation	Al_2O_3-SiO_2 sleeve
Insulation thickness	150 μm
Sample size [mm^3]	8.5 x 15.4 x 20.6

The Rutherford cable samples (Fig 1b) were cut from a racetrack coil (HTS-SC04) fabricated at Lawrence Berkeley National Laboratory (LBNL) [7]. The Rutherford cables were made from a 17-strand Bi-2212 wire (the specification of single strand is similar to that described above) with a nominal cross-section of 1.46 x 7.80 mm^2. The pitch length of the cable was 39 mm. Wires were not twisted before cabling. The cable was insulated with a braided Mullite fiber sleeve with a thickness ~150 μm (the sizing of the insulation was removed by baking the sleeve at 600 °C for 1 hour in a constant flow of O_2). The racetrack coil contained two layers of Rutherford cables impregnated with CTD-101K epoxy. The coil was tested at LBNL and carried 1526 A at 4.2 K. A typical mechanical sample size was 8.5 mm (azimuthal direction) by 15.4 mm (radial direction) by 20.56 mm (axial direction). Fig. 1b shows a section of a typical cable composite sample. The mechanical properties of these samples are useful for designing and fabricating accelerator dipoles and quadruples made from Bi-2212 Rutherford cable.

III. THERMAL CONTRACTION MEASUREMENT

A. Measurement Method

Thermal contraction of Bi-2212 samples was determined using a thin film gage technique. Strain gages (Micro-Measurements, WK-09 series) were mounted on the samples along principle orthogonal directions (defined in Fig. 1) using M-bond epoxy. Samples were then cooled down from room temperature to 77 K and 4.2 K. Before and after cooling down, resistance of strain gauge was determined by the standard four-point method. The resistance change ΔR consists of: (i) resistance change of gage material with temperature; (ii) resistance change proportional to the thermal contraction difference between the gage grid alloy and the tested material. The thermal output, defined by $\varepsilon_s = \Delta R / (R_0 \cdot F_G)$ (R_0 and F_G are the resistance of the strain gauge at room temperature and the gage factor), can be expressed as:

$$\varepsilon_s = \frac{\Delta R}{R_0 \cdot F_G} = [\frac{\beta_G}{F_G} + (\alpha_s - a_G)] \cdot \Delta T \quad (1)$$

where β_G is the thermal coefficient of resistivity of gage grid material, (α_s - α_G) is the thermal expansion coefficient difference between specimen and grid respectively, ΔT is the temperature change.

To obtain α_s, the same type of strain gage was mounted on a reference sample with known contraction coefficient α_R. The thermal output measured from the reference sample is:

$$\varepsilon_R = \frac{\Delta R}{(R_0 \cdot F_G)} = [\frac{\beta_G}{F_G} + (\alpha_s - \alpha_R)] \cdot \Delta T \quad (2)$$

Subtracting (2) from (1), and rearranging,

$$\alpha_s - \alpha_R = \frac{(\varepsilon_s - \varepsilon_R)}{\Delta T} \quad (3)$$

It should be pointed out that thermal contraction coefficient is usually not a constant over a large ΔT and the α appearing in the above equations should be understood as $\varepsilon/\Delta T$. The reference samples used in this study were high purity quartz, of which thermal contraction was taken to be zero, and

Al-6061. Several thermal cycles were performed to determine the repeatability and data scatter.

B. Measurement Results and Comparison to Analytical Thermal Contraction

The thermal contraction results are listed in table 3. For simplicity, α_{quartz} is taken to be zero. Data were averaged from three thermal cycles.

Table 3: Mean thermal contraction data for Bi2212 composite samples (specifications listed in table 1 and 2) from 293 K to 77 K, and from 293 K to 4.2 K

Temperature	ΔL/L (293K→77 K)	ΔL/L (293K→4.2K)
Strand – axial direction	-0.316%	-0.351%
Strand – transverse direction	-0.436%	-0.493%
Cable – axial direction	-0.424%	-0.478%
Cable – radial direction	-0.364%	-0.406%
Cable – azimuthal direction	-0.322%	-0.357%
Al-6061 (measured)	-0.387%	-0.423%
Al-6061 (theoretical)	-0.389%	-0.414%

IV. Room Temperature and 77 K Mechanical Property Measurement

A. Measurement Method

Stress-strain curves for samples were tested under compression for principal orthogonal directions using a loader and a stainless steel sample fixture, as shown in Fig. 2. The sample fixture features guiding pins to minimize non-uniform loading, which is further minimized by carefully polishing samples to ensure the distance variation between each pair of parallel planes to be less than ±0.8%. For 77 K measurements, samples were placed in a cryostat immersed in liquid N_2. The modulus of elasticity is calculated using Hooke's law.

To certify the validity and reproducibility of the measurement method, a reference Al-6061 sample was tested. The aluminum sample measured 12.7 mm x 12.7 mm x 25.4 mm. The measured value of the Young's modulus is 72.2 GPa (typically reported value is 69 GPa) whereas the measured Poisson's ratio at 293 K is 0.389 (comparing the typical reported value of about 0.35). The standard deviations of these measurements were lower than 6%.

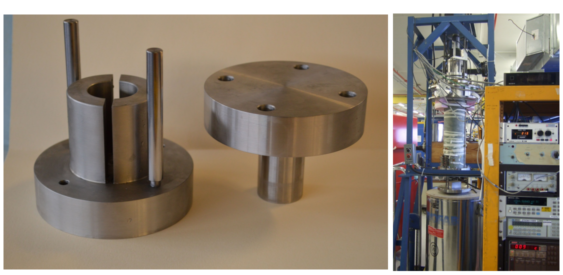


Fig. 2. Experimental setup used for the compression test. Left: The stainless steel compression test fixture that includes a bottom anvil (left) and a top piece (right). Right: the hydraulic loader with electronics and Dewar.

B. Modulus measurement of strand samples

Table 4 lists the measured Young's modulus of the strand composite sample along both axial and transverse directions at 293 K and 77 K. Table 4 also lists the room temperature, 77 K and 4 K elastic modulus for the strand composite sample calculated using a lamina modeling of fiber-embedded composite materials [8] by treating strands as fibers and epoxy as matrix. In this calculation, a Bi-2212 filling factor of 25% was used. A strand-packing factor of 0.785 was used for the strand sample and the epoxy was assumed to completely fill the gaps between strands. The calculation results agreed reasonably well with the experimental results.

Table 4: Elastic Modulus for Bi-2212 composite (strand sample)

Temperature	Axial (GPa)	Transverse (GPa)
293 K measured)	48.6	25.8
77 K (measured)	54.19	27.21
293 K (calculated)	51.64	24.01
77 K (calculated)	56.46	28.62
4.2 K (calculated)	57.93	31.38

The Young's modulus values listed in table 4 were measured with applied stresses no greater than 20 MPa, which ensures the stress-strain curves remain linear. Stress-strain curves of Bi-2212 strands were reported to become nonlinear for stress greater than ~40 MPa in the axial direction. Figure 3 shows the stress–strain curve of the strand sample loaded axially (cyclic loading, 77 K) up to 105 MPa. Both nonlinear strain-stress behavior and strain hardening effects were observed.

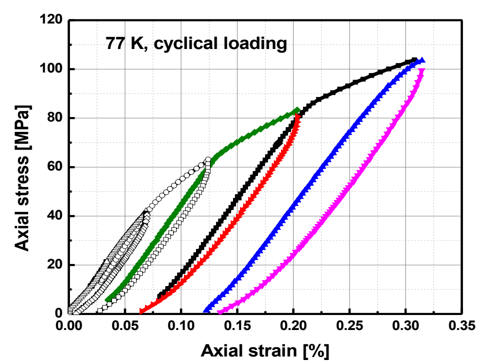


Fig. 3. Stress strain curves of the strand sample along the axial direction under cyclic loading with stress up to 105 MPa at 77 K

C. Poisson's ratio measurement results of strand samples

The Poisson's ratio measurement results are shown in Fig. 4 for which the loading direction was axial and the test occurred at 293 K. Table 5 summarizes the Poisson's ratios at 293 K and 77 K. For the strand samples, the Young's modulus and Poisson's ratio satisfies $E_1/\nu_{12}=E_2/\nu_{21}$, a typical behavior of orthotropic materials.

Table 5: Poisson's ratios for Bi-2212 composite (strand sample)

Temperature	ν_{12}	ν_{21}
293 K (measured)	0.35	0.16
77 K (measured)	0.36	0.14

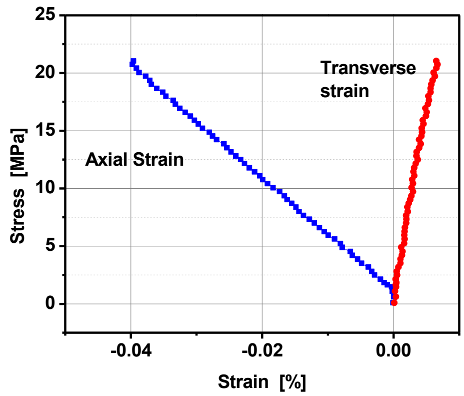


Fig. 4. Stress - strain measurement of the strand composite sample at room temperature. The loading was in axial direction and the strain was measured along axial and transverse directions.

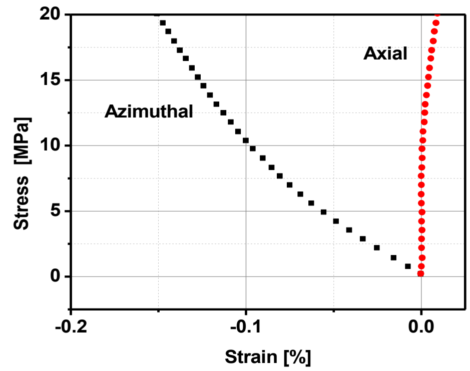


Fig. 5. Stress - strain measurement of the cable composite sample at room temperature. The loading was in azimuthal direction and the strains were measured along azimuthal and axial directions.

D. Modulus measurement of cable samples

Table 6 lists the Young's modulus values of the cable composite sample along three orthogonal directions. The Young's modulus values listed in table 6 were measured with applied stresses up to 20 MPa.

Table 6: Elastic modulus for the Bi-2212 cable composite sample

Temperature	Axial (GPa)	Azimuthal (GPa)	Radial (GPa)
293 K (measured)	38.58	18.2	12.68
77 K (measured)	40.21	20.5	14.0

E. Poisson's ratio measurement results of cable samples

The Poisson's ratio measurements are shown in Fig. 4 for which the loading direction is axial and the test occurred at 293 K. Table 5 summarized the Poisson's ratios at 293 K and 77 K.

Table 7: Poisson's ratios for Bi-2212 composite (strand sample)

Temperature	ν_{31}	ν_{13}	ν_{12}	ν_{21}
293 K (measured)	0.31	0.11	0.13	0.40
77 K (measured)	0.31	0.12	0.12	0.37

Note that the cable results reported above were measured with gages mounted on a layer of epoxy. If the cable samples were further polished so that the gages were mounted on the exposed strands, complicated strain-stress curves and Poisson's ratio results were observed. Poisson's ratio exceeded 0.5 or even 1 in such situation. This is probably because of the structure of cables; the strands are twisted and transposed so the loading directions were not strictly along principal orthogonal directions. Loading off axis may result in rather complicated local stress on the strand. Similar behavior has been reported in study of fiber-reinforced materials loaded along off-axis directions [9]. On the other hand, results measured by gages mounted on epoxy may be considered as an average behavior.

V. CONCLUSION

The stress-strain curves and the thermal contraction coefficients of epoxy/Ag-Bi2212 composites were experimentally established. The measurements are compared to values estimated using a rule of mixture calculation. The calculation is reasonably consistent with the experimental data. This data may be used for designing and operating high field magnets based on Bi-2212/Ag wires.

VI. ACKNOWLEDGEMENT

We thank Steve Krave and Tomas Wokas for their assistance during experiments.

REFERENCES

[1] D. Larbalestier, J. Jiang, U. Trociewitz, F. Kametani, C. Scheuerlein, M. Dalban-Canassy, *et al.*, "Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T," *Nature materials,* vol. 13, p. 375, 2014.

[2] H. Miao, K. R. Marken, M. Meinesz, B. Czabaj, and S. Hong, "Development of round multifilament Bi-2212/Ag wires for high field magnet applications," *IEEE Transactions on Applied Superconductivity,* vol. 15, pp. 2554-2557, 2005.

[3] N. Cheggour, X. Lu, T. Holesinger, T. Stauffer, J. Jiang, and L. Goodrich, "Reversible effect of strain on transport critical current in $Bi_2Sr_2CaCu_2O_{8+x}$ superconducting wires: a modified descriptive strain model," *Superconductor Science and Technology,* vol. 25, p. 015001, 2012.

[4] P. Chen, U. P. Trociewitz, M. Dalban-Canassy, J. Jiang, E. E. Hellstrom, and D. C. Larbalestier, "Performance of titanium oxide?polymer insulation in superconducting coils made of Bi-2212/Ag-alloy round wire," *Superconductor Science and Technology,* vol. 26, p. 075009, 2013.

[5] T. Shen, J. Jiang, F. Kametani, U. P. Trociewitz, D. C. Larbalestier, and E. E. Hellstrom, "Heat treatment control of Ag-$Bi_2Sr_2CaCu_2O_x$ multifilamentary round wire: investigation of time in the melt," *Superconductor Science and Technology,* vol. 24, p. 115009, 2011.

[6] T. Shen, A. Ghosh, L. Cooley, and J. Jiang, "Role of internal gases and creep of Ag in controlling the critical current density of Ag-sheathed $Bi_2Sr_2CaCu_2O_x$ wires," *Journal of Applied Physics,* vol. 113, p. 213901, 2013.

[7] A. Godeke, P. Acosta, D. Cheng, D. R. Dietderich, M. G. T. Mentink, S. O. Prestemon, *et al.*, "Wind-and-react Bi-2212 coil development for accelerator magnets," *Superconductor Science and Technology,* vol. 23, p. 034022, 2010.

[8] R. F. Gibson, *Principles of composite material mechanics*: CRC Press, 2011.

[9] L. Peel, "Exploration of high and negative Poisson's ratio elastomer - matrix laminates," *physica status solidi (b),* vol. 244, pp. 988-1003, 2007.