Final Report: MATERIALS, STRANDS, AND CABLES FOR SUPERCONDUCTING ACCELERATOR MAGNETS [Grant Number DE-SC0010312]

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Final Report

to the
Advanced Technology Research and Development Branch
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by
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INTRODUCTION (Work under Prior DOE Contract - until 2013)

During the early years of this Grant the research conducted by the above authors while at Battelle Columbus Laboratories (through 1994) focused on some special properties of ternary alloyed NbTi as superconductor and binary alloyed Cu as stabilizer material. But during the last fifteen years, following a move to The Ohio State University (OSU) and the establishment of a research group there (the Center for Superconducting and Magnetic Materials, CSMM, and its associated Superconductor Technology Center), together with the expansion of opportunities to collaborate with small businesses, the authors have been able to make further innovative contributions to the design and characterization not only of superconducting *materials* as before but also to several classes of *multifilamentary (MF) strand*, and *Rutherford cables* wound from them.

Under close collaboration with the Superconducting Magnet Group at Lawrence Berkeley National Laboratory (LBNL), CSMM has played a key role in the design of advanced Rutherford cables wound from NbTi, Nb_3Sn, Bi:2212/Ag, and Nb_3Al superconducting strands, and has studied at various times the effects of strand coatings, the presence of cores, and supplemental Cu "stabilization" on AC coupling loss, the associated effective interstrand contact resistance, and magnetization. In collaboration with LBNL we investigated coupling loss and stability in special research cables as well as LARP-relevant Rutherford cables. For several years now, accelerator cable research has been an important element of CSMM's program. The research programs undertaken by our GRAs under this program have embraced the “materials” and “strand” segments of the overall program. As such they included, for example: (1) solid state diffusion, phase formation, and the ordering of A15 phases in Nb-Sn systems with particular reference to "internal-tin" and "tube-type" strands. (2) studies of solid-state diffusion, phase formation, and the influence of dopants on the superconducting properties of MgB_2 in bulk and wire forms. Research undertaken by senior members of CSMM included: studies of stability and AC loss in strands, tapes, and cables. The work in the most recent period represents a transition to the inclusion of HTS and electromagnetic aspects of conductors, and the report below details activities during 2013.

STAFFING

The senior program staff of CSMM are Dr Edward W. Collings, Dr Michael D. Sumption, and Dr Milan Majoros. During all or part of CY2013 other members of the group were:

Students 2013

Yuan Yang
Guangze Li
Chris Kovacs
Xingchen Xu
Cory Myers
Hyun Sun Kim
Post Doc: Mike Susner

PROGRAM 2013

Our program consisted of the two components: Strand Research and Cable Research. This was a continuation of the 2010-2012 program. During this period we were re-focussing work from Materials based efforts in MgB_2, Nb_3Sn, and Bi:2212 (as well as conductor and cable work) to a more focused effort on conductor and cable, in support of HEPs focus on CERN upgrades and possible muon collider programs.

One of the main focuses of the "Materials" research in previous 2010-2012 program was Nb_3Sn. Work included studies of basic reactions, diffusion, transformations, and phase assemblage. These materials science aspects were married to results, in the form of flux pinning, B_{c2}, B_{irr}, and transport J_c, with an emphasis on obtaining the needed J_c for HEP needs. Even while shifting in this 2013 program from this materials development work to more focused conductor work, we did show a method to refine the grains in Nb_3Sn by a factor of two, reaching 45 nm grain sizes, and layer J_cs of 6 kA/mm^2 at 12 T. Later work has shown this has increased to 10 kA/mm^2 at 12 T, 4.2 K. However, in this 2013 program, we also have been re-focusing on the very important area of conductor magnetization for field quality. This has been done both with Nb_3Sn conductor, as well as Bi:2212 strand. During this period also we developed winding machines and probes for performing quench studies of YBCO coils, these are ongoing in 2014. Cable loss studies in Nb_3Sn focused on connecting and comparing persistent magnetization and coupling magnetization for considering their relative impact on HEP machines. In the area of HTS cables, we have investigated both the quench in multistrand YBCO CORC cables, as well as the magnetization of these cables for use in high field magnets. In addition, we continued our work in the magnetic and thermal properties of large (50 T) solenoids.

Program Results

Introduction: *Nb_3Sn cables will be required for the LHC luminosity upgrade. For this and future quadrupole and possibly dipole applications, strands operating at 12 T and eventually at higher fields will be required. For example, the muon collider will need an extensive menu of magnets with field strengths ranging from 1 to 20 T. In addition, with the new push for high fields for future energy upgrades the LHC, as well as the final stages of cooling in a muon collider, Bi:2212/Ag strands and YBCO tapes are also of intense interest. Of course, not only the conductors, but magnet and cables fabricated from them of high interest. We proposed work studying Nb_3Sn, Bi:2212/Ag, and YBCO strands, as well as the cables and certain aspects of coils (mostly YBCO) made with them. The 2013 final program results are described in short below, organized in terms of the original Task outline.*

1.0 STRAND AND COILS: PROPERTIES, MAGNETIZATION, STABILITY, QUENCHING

1.1 Property Enhancement of Nb_3Sn: In this area, we continued to study the properties of the new Tube Sn conductors, in this time period producing definitive work which compared their properties to internal Sn distributed barrier conductors (e.g., RRP). Here we found that the layer J_cs of the two conductors were the same, driven by the similarity of grain size and stoichiometry, although the area fraction was lower for Tube conductors [1]. We also published a detailed model for the phase formation in Tube conductors, and compared the model to experiment [2]. We also published a detailed study on the dependence of the properties of these conductors on HT, including B_{irr} values [5,6]. Work was also started on a new conductor geometry intended to increase the stoichiometry of Nb_3Sn conductors generally, and thus improve their high field performance. The idea behind this was that the width of the A15 phase in the phase diagram made it difficult to control stoichiometry by diffusional boundaries; our approach was to use an array of Sn sources, and we were successful both in increasing the stoichiometry, and in developing a new high fill factor Tube conductor [3]. Finally, we worked on refining the grain sizes in Nb_3Sn in order to increase the J_c substantially. We did this by modifying the approach for internal oxidation of Nb-1Zr by providing a thermodynamically acceptable path for oxygen supply to the Nb alloy. This led to a factor of 2 reduction in grain size (45 nm). Layer J_cs of this conductor slightly exceeded the best Nb_3Sn at that time [4], work to be reported in 2014 shows that this technique can double the layer J_c.

1. X Xu, M D Sumption, S Bhartiya, X Peng, and E W Collings, "Critical current densities and microstructures in Rod-in-Tube and Tube Type Nb_3Sn strands – Present status and prospects for improvement", *Supercond. Sci. Technol.* 26 (2013) 075015
2. X Xu, M D Sumption and E W Collings", A Model for Phase Evolution and Volume Expansion in Tube Type Nb_3Sn Conductors", *Supercond. Sci. Technol*. 26 (2013) 125006
3. X. Xu, E. Collings, M. Sumption, C. Kovacs, and X. Peng", The Effects of Ti Addition and High Cu/Sn Ratio on Tube Type $(Nb, Ta)_3Sn$ Strands, and a New Type of Strand Designed to Reduce Unreacted Nb Ratio*", IEEE Trans. Appl. Supercond*. 24 (2014) 6000904.
4. X. Xu, M. Sumption, X. Peng, E. W. Collings, "Refinement of Nb_3Sn grain size by generating ZrO_2 precipitates in Nb_3Sn wires", Applied Physics Letters 104, 082602 (2014); doi: 10.1063/1.4866865.
5. M.D. Sumption, X. Xu, C. Kovacs, X. Peng, and E.W. Collings, Influences of heat treatment and Ti addition on high performance Rod-in-Tube $(Nb,Ta)_3Sn$ Strands", 2013 International Cryogenic Materials Conference, Anchorage, Alaska (presentation).

6. X Xu, M D Sumption, E W Collings, "Influence of Heat Treatment Temperature and Ti doping on Low Field Flux Jumping and Stability in $(Nb\text{-}Ta)_3Sn$ Strands", Submitted to Superconductor Science and Technology, 2014.

1.2. Magnetization and stability of strands; experiment and modeling: In this area we worked to measure the magnetization of conductor relevant to the LARP program and the luminosity upgrade [1]. We also measured the magnetization of a Bi:2212 conductor which was developed for a lower magnetization with high transport, and also measured the specific heat of Bi:2212 and Nb_3Sn strands, as this is a critical input to stability models [2]. We measured the magnetization and decay of OST Bi:2212 and Nb_3Sn strands, as well as the magnetization and decay of YBCO conductor, and then developed an approach to compare their magnetization contribution in accelerators, and also to estimate how important the creep would be in contributions at injection [3]. Finally, we investigated the use of Ti additions for the suppression of low field J_c (while retaining high field J_c) for improved stability in Nb_3Sn conductors, and compared this approach to simply increasing the reaction temperature. We found that both approaches had some merit [4,5].

1. E.W. Collings, M.A. Susner, M.D. Sumption, D.R. Dietderich, "Extracted Strand Magnetizations of an HQ Type Nb_3Sn Rutherford Cable and Estimation of Transport Corrections at Operating and Injection Fields IEEE Trans on Supercond. 24 4802605
2. C. S. Myers, M. A. Susner, L. Motowidlo, J. Distin, M. D. Sumption, and E. W. Collings, "Specific Heats of Composite Bi2212, Nb_3Sn, and MgB_2 Wire Conductors", IEEE Trans. Appl. Supercond. 23 (2013). 8800204
3. M.D. Sumption, "Magnetization and decay effects in Nb_3Sn, Bi:2212, and YBCO relevant to field errors", The Low Temperature Workshop, St. Petersburg, Florida, Nov 2013
4. M.D. Sumption, X. Xu, C. Kovacs, X. Peng, and E.W. Collings, Influences of heat treatment and Ti addition on high performance Rod-in-Tube $(Nb,Ta)_3Sn$ Strands", 2013 International Cryogenic Materials Conference, Anchorage, Alaska
5. X Xu, M D Sumption, E W Collings, "Influence of Heat Treatment Temperature and Ti doping on Low Field Flux Jumping and Stability in $(Nb\text{-}Ta)_3Sn$ Strands", Submitted to Superconductor Science and Technology, 2014.

5.2. YBCO pancake coils: winding, testing: Here our efforts were focussed on assembling the coil winding machine and coil formers for the coil winding and testing. They were designed to allow for tests at 4.2 K, in fields up to 12 T, and at currents up to 1800 A. The holders allow for thermal transport measurement, as well as quench propagation measurement. These devices, described in more detail below, are in use in our 2014 year program.

2. CABLES AND MAGNETS

2.1. **Cable AC loss (excess magnetization and ICR: Nb_3Sn):** During the heat treatment of compacted Nb_3Sn cables the strands tend to become diffusion bonded at the crossover points. The result is a very low crossover interstrand contact resistance, R_c, leading to cable magnetizations during field ramp that are two orders of magnitude higher than those desired for accelerator magnets. It is important to suppress these contacts, but not completely, so that current sharing is still allowed. For this reason we investigated methods of controlling ICR.

This work was performed in close collaboration with LBNL. For 2013, our efforts were first in the area of comparing cables with cores of stainless steel and glass-fiber tape [1]. Both were found to be effective, although the glass fiber tape was interesting because of its more moderate ICR, good for stability as well as loss suppression. We also did a comparison of the persistent current magnetization and coupling current for an HQ type Rutherford cable [2].

1. E. W. Collings, M. D. Sumption, M. A. Susner, D. R. Dietderich, E. Kroopshoop, and A. Nijhuis, "Coupling- and Persistent-Current Magnetizations of Nb_3Sn Rutherford Cables With Cores of Stainless Steel and Woven Glass-Fiber Tape Measured by Pick-Up Coil Magnetometry", IEEE Trans. Appl. Supercond, 23 (2013) 4702305.
2. E. W. Collings, "Extracted Strand Magnetizations of an HQ Type Nb_3Sn Rutherford Cable and Estimation of Transport Corrections at Operating and Injection Fields", Magnet Technology Conference 23, Boston MA, July 14-19, 2013

2.2. Cable current sharing, YBCO: In this area we worked with both Roebel and CORC cables. For Roebel cables we studied the contact resistance between various strands in the cable under various cable conditions, including pressure, pressure + solder, and finally direct strand-to-strand soldering [1,2]. We also measured the current distribution in CORC cables, as well as the current re-distribution under quench [3]. The cables were tested twice, and the results compared. A stability diagram was obtained. It was seen that the CORC cable is prone to thermal recovery and difficult to quench [3].

1. M. Majoros, M.D. Sumption, E.W. Collings, N.J. Long, "Stability, Inter-Strand Contact Resistance, and AC Losses in YBCO Roebel Cables*", IEEE Trans. Appl. Supercond* 24 (2014) 6600505
2. M. Majoros, "Stability, Inter-Strand Contact Resistance and AC Losses in YBCO Roebel Cables", Magnet Technology Conference 23, Boston MA, July 14-19, 2013
3. M. Majoros, M. D. Sumption, E. W. Collings and D. van der Laan, "Measurements of current sharing, contact resistance, and quench in YBCO cables", Low temperature high magnetic field superconductor workshop – St Petersburg Nov. 2013

2.3. **Cable current sharing/stability, Nb_3Sn:** This portion of the program was focused on the finalization of the probe and the method for cable heater and instrumentation attachment. The probe is now is use in 2014, and results have been presented; these will be reported in 2014.

2.4. FEM Modeling of very high field YBCO solenoids Magnetization of Cables: In this portion of the work, we studied the magnetization and loss of CORC cables [1,4]. We also studied (by FEM) the stability and normal zone propagation in a high field solenoid, in this case with a stainless steel interlayer insulation [2]. Finally we investigated the quench and normal zone propagation in YBCO coils at a more detailed level (again by FEM) [3].

1. M. Majoros, "AC losses in CORC cables measured at 77 K in liquid nitrogen bath", 2013 International Cryogenic Materials Conference, Anchorage, Alaska
2. M. Majoros, M.D. Sumption and E.W. Collings Stability and normal zone propagation in a 50 Tesla solenoid wound of YBCO coated conductor tape with a stainless steel interlayer insulation, International Cryogenic Materials Conference, Anchorage, Alaska
3. M. Majoros, M.D. Sumption, and E.W. Collings YBCO pancake coils – stability and normal zone propagation. Magnet Technology – Boston – July 2013 – presentations.
4. M Majoros, M D Sumption, E W Collings and D C van der Laan, "Magnetization losses in superconducting YBCO conductor-on-round-core (CORC) cables", to be published in Supercond. Sci. and Tech. 2014.

Research Highlights April 1 2013-March 31 2014

1. STRAND AND COILS: PROPERTIES, MAGNETIZATION, STABILITY, QUENCHING

1.1. Nb_3Sn Property Enhancement

In this portion of the work, a Nb_3Sn subelement was fabricated in which Nb-1Zr alloy was used, and oxygen was supplied via SnO_2 powder. The results showed that such a design could supply sufficient oxygen to internally oxidize the Zr in a Nb-1Zr alloy, and that the sample reacted at 650° C had grain sizes of about 45 nm, less than half the size of the grains in present Nb_3Sn conductors. Magnetic measurements showed that the peak of the pinning force vs. field (F_p-B) curve was shifted to $0.3B_{irr}$ (the irreversibility field).

Tube type Nb_3Sn samples were made, with Nb-1Zr allow Nb tubes, and an additional oxide powder included which acted as an oxygen source to oxidize the Zr and suppress A15 grain sizes. Figure 1.1 (a) shows the result with a NbO_2 powder (expected not to work, given the Ellingham diagram), and that at right, one with a SnO_2 powder source (expected to be effective). Indeed the grain sizes were reduced from the typical 100 nm seen at left, to 45 nm with an effective oxygen source to internally oxidize the Zr, and refine the A15 grains.

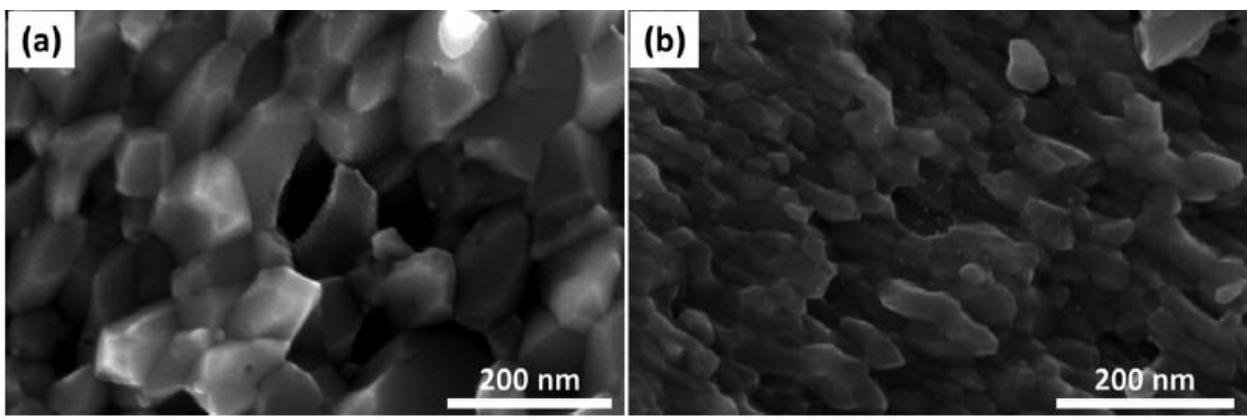


Figure 1.1. Fracture SEM images of (a) a Nb_3Sn sample with a NbO_2 powder oxygen source, and (b) a Nb_3Sn sample with a SnO_2 powder oxygen source, each reacted at 650°C for 150 h.

Figure 1.2 (left) shows a TEM image of the grains of the sample with SnO_2 additions, where we can see what appears to be ZrO_2 particles. Figure 1.2 (right) shows the grain size dependence on reaction temperature for samples HT with and without oxygen (with and without Zr internal oxidation based grain refinement). The effect is remarkable, and amounts to a large suppression in grain size. Figure 1.3 shows the *m-T*, F_p-B, and reduced F_p-B curves of samples with and without grain refinement 650 °C for 150 h.

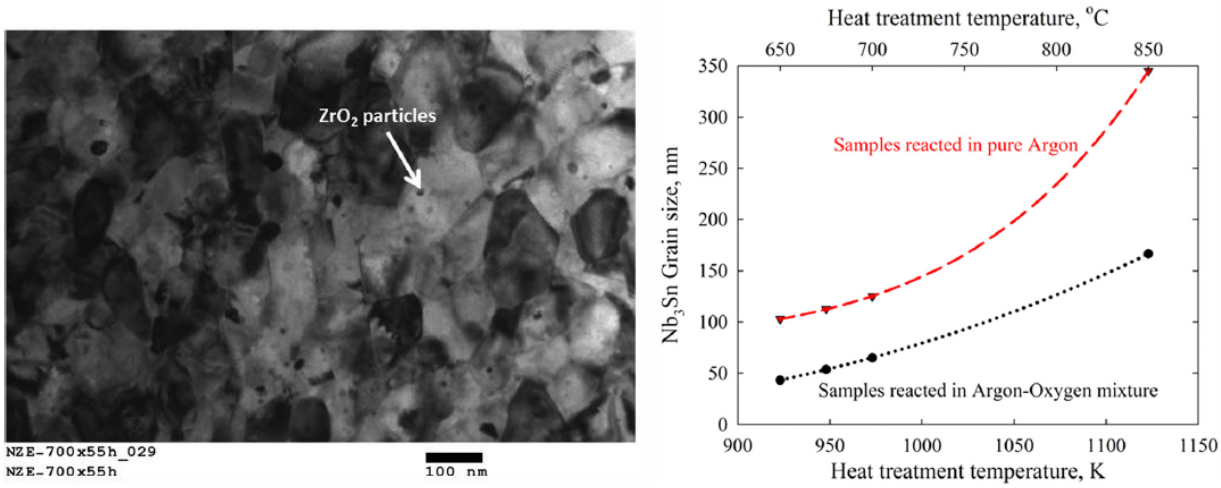


Figure 1.2. (a) TEM image of sample A reacted at 700°C for 55 h in an argon-oxygen atmosphere. An example of a ZrO_2 particle is marked, (b) Average Nb_3Sn grain size as a function of reaction temperature for type A samples reacted in pure argon and in argon-oxygen atmospheres. The dashed lines are exponential fits to the data.

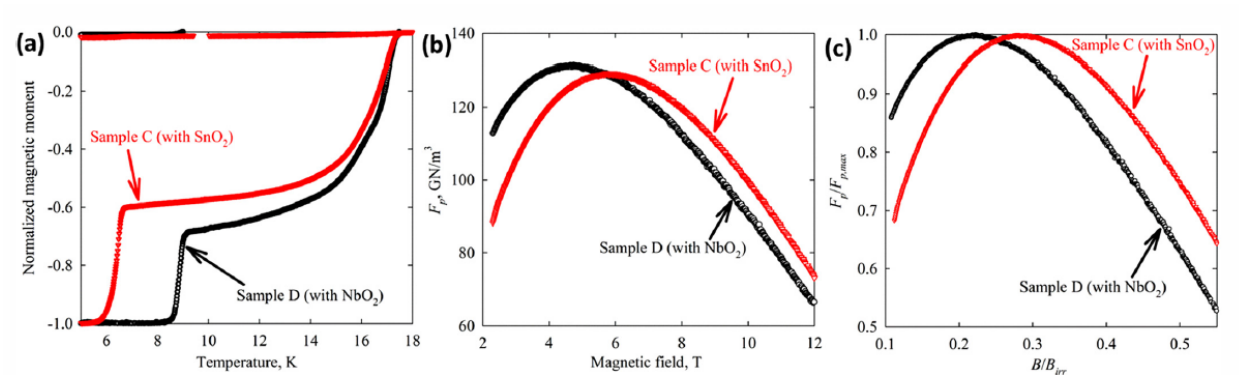


Figure 1.3. The (a) *m-T*, (b) F_p-*B*, and (c) reduced F_p-*B* curves of samples with NbO_2 (D-no refinement) and SnO_2 (C-refinement) reacted at 650 °C for 150 h.

The 12 T layer J_c of sample C is around 6.1 kA/mm^2, these results were reported in an article to the Journal of Applied Physics, listed below. More recent results, to be reported in FY 2014, show that layer J_c values of 10 kA/mm^2 can be reached even for a binary allow, caused by a significant shift in the position of the pinning peak. It is worth noting that a secondary benefit that the shift of the F_p-*B* curve to higher field brings is a lower J_c at low field, which benefits the low field stability. In summary, this work explores the way to apply the internal oxidation method to Nb_3Sn wires for grain size refinement. In light of the results obtained, we anticipate that this approach could lead to substantial improvement in the performance of Nb_3Sn conductors at both high and low fields.

1.2.Magnetization and Stability of Strands; Experiment and Modeling

Magnets made from Bi:2212 may generate higher error fields than NbTi or even Nb_3Sn-based magnets (dipole and quadrupole accelerator magnets). Even so, filament bridging is often considered essential to maximize transport J_c. However, it is of interest to see if it is possible to increase the critical current without the need for significant increases in bridging. In this work, we study Bi:2212 strands which are designed to minimize bridging and attempt to determine if the level of bridging and the transport current characteristics can be correlated with conductor design and sample heat treatment parameters. To this end, strands with diameters of 1.34 mm, 1.2 mm, 0.89 mm, 0.83 mm, 0.71 mm, 0.70 mm, and 0.62 mm were heat treated in 100% flowing oxygen and then samples from these strands were characterized using magnetic, transport, and electron optics techniques. One set of samples comprised a single stack of randomly oriented highly-aspected filaments, the so-called 2D-ROSS design. Another set of samples comprised highly-aspected filaments arranged in a 43 x 7 filament configuration. The final set of samples had a conventional 85 x 18 filament configuration. The transport J_c of the heat treated strands was measured and combined with magnetic measurements in an attempt to determine if interfilamentary bridging affects strand performance. The sample specifications are given in Table 1.2.1

Table 1.2.1. Bi:2212 Strand Design.

Sample	Diameter (mm)	Number of filaments	SC fraction	T_{max} (ºC)
OSU samples	1.34	257	~0.25	890
LANL samples	1.34	257	~0.25	887
L439	0.83	~301 (7 x 43)	~0.24	894
L440	0.83	~301 (7 x 43)	~0.24	894
L441	0.83	~301 (7 x 43)	~0.24	894
OST -1-1.2	1.2	-	0.255	888
AgAl0.1-0.7-LHT2-892C-3-8-13	0.83	~200	~0.4	892
AgAl0.1-0.7112-LHT3-888C-3-18-13	0.71	~200	~0.4	888
AgAl0.1-0.6223-LHT3-888C-3-18-13	0.62	~200	~0.4	888

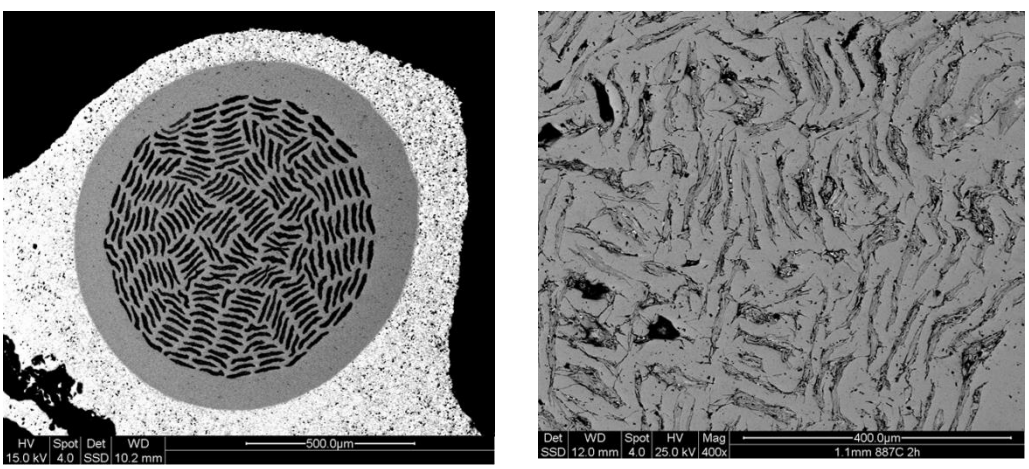
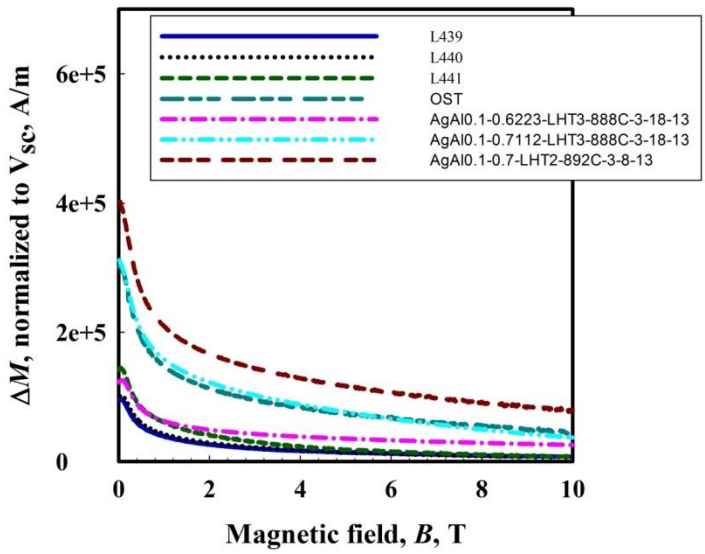


Figure 1.2.1. SEM of 2D Ross strand (left), and a higher mag showing local bridging (right).



The d_{eff} values were extracted using the volume magnetization (normalized to superconducting area) and J_c values at the corresponding applied magnetic fields using the standard formula given above. The analysis is made more difficult because the expression given above is strictly valid for cylindrical filaments, while the filaments in these samples are randomly oriented slabs. For a fully bridged sample, the d_{eff} should be on the order of the filamentary array diameter. The subelement diameter is about 2.5 times d_{eff} of L439 and about twice d_{eff} of L440. This indicates more coupling is occurring than that seen in previous 2D-ROSS strands. However, J_c is larger than in previous 2D-ROSS strands of same diameter. The results are given in Table 1.2.2.

Table 1.2.2. D_{eff} results for Bi:2212 Strands.

Sample	5 T D_{eff} (μm)	Subelement diam. (μm)
LANL-1-0.9	327	~600
LANL-1-1.1	317	~600
LANL1-1.3	214	~800
L439	73	~185
L440	89	~188
L441	131	~188
AgAl0.1-0.7-LHT2-892C-3-8-13	632	~571
AgAl0.1-0.7112-LHT2-888C-3-18-13	293	~563
AgAl0.1-0.6223-LHT3-888C-3-18-13	143	~505

1.3 **YBCO Pancake Coils: Winding, Testing**

During this period the coil winding machine (Figure 1.3.1) was fabricated. This coil winder is made for small YBCO coils, and can apply a constant tension during winding. There is a counter, and the design is such as to allow instrumentation during winding. This device is being used in the present 2014 year program. In conjunction, the coil probe was made, the end of which is shown in Figure 1.3.2. This holder is also made to allow instrumentation throughout the coil for thermal and voltage measurements during quench.

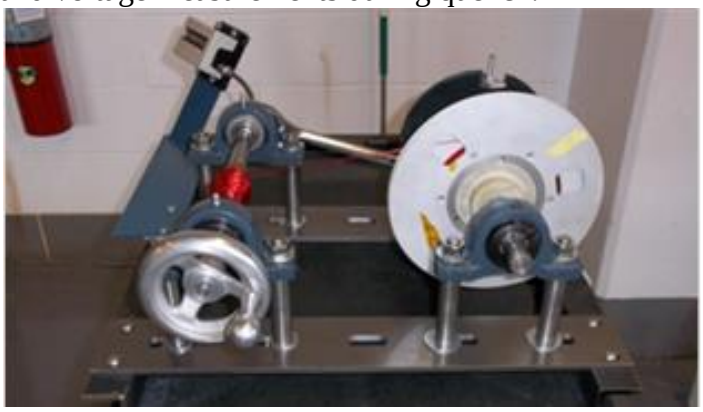


Figure 1.3.1. Dedicated winding machine for YBCO single-pancake coils. The machine is equipped with turn counter and adjustable fixed tension control.

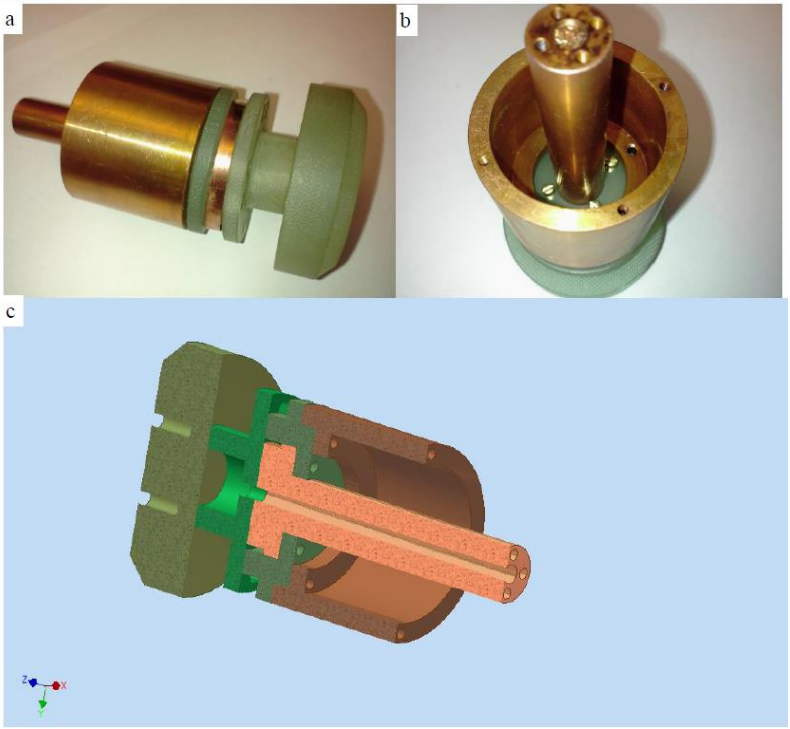


Figure 1.3.2. Small YBCO Coil Holder (a,b) pictures at different angles, (c) cut-away view. Current feed is coaxial, with one lead the central Cu post, and the second the outer Cu can. Tape starts on inner lead, feeds out to winding. Instrumentation comes in from the bottom, and lower G-10 section detaches for ease of instrumentation. Made to mate to bottom of existing 1800 A transport probe, and to be used in conjunction with 15 T transport station.

2.0 Cables and Magnets

2.1 Cable AC loss (excess magnetization and ICR: Nb_3Sn):

For accelerator magnets field quality at the bore is a critical requirement for which reason the parasitic magnetization of the windings must be reduced to manageable limits. In other words it is necessary to minimize (i) the static intrastrand persistent current magnetization of the cable and (ii) the cable's coupling magnetization caused by coupling currents passing through interstrand contact resistance during field ramping. This report focuses on persistent-current magnetization and then compares it to loss estimated from previous ICR measurements on a section of heat treated HQ cable. In that sense this work is at a boundary between the strand magnetization and that at the cable, it is placed here to emphasize the cable coupling loss comparisons.

Table 2.1.1 gives the cables and the strands taken from them, while Table 2.2.2 gives our assessment of the magnetization of these strands in the cable, as compared to the ICR derived magnetization on the shielding branch.

Table 2.1.1 Strand and Cable detail.

(a) Strand Details	DS dipole	HQ Quadrupole
OST-RRP Billet ID No.s	--	13091, 13658, 13659
No. of strands per billet, resp.	--	13, 15, 7 (= 35)
Strand type (element #)	108/127	108/127
Filament gggcount††	--	108
Strand diam., mm	0.7	0.778
Av. filament OD, d_o, μm	--	51.5*
Prior internal-Sn diam., d_i, μm	--	28.8*
Effective fil. diam., d_{eff}, μm	--	61.3**
Non-Cu content, %	47.6	44.9
Strand anneal	--	4h/185-190°C
* Measured at OSU by SEM after cable RHT		
** Calculated using $d_{eff} = d_0[(1-R^3)/(1-R^2)]$ with $R = d_i/d_0$ [22]		
(b) Cable Details		
Cable name	--	HQ1021ZB (LBNL)
Cable maker	**FNAL**	**LBNL**
OSU cable name	--	HQ2
Strand count	40	35
Pitch, $2Lp$, mm	--	95
Width, w, mm	14.70	14.77
Av. thick, t, mm	1.269	1.375
Keystone angle, deg	0.79	0.722
Average pack's factor, %	--	85.53
Core material	--	AISI 316L
Core width, mm	--	8
Heat treatment (RHT), **BNL**	--	72h/210°C + 48h/400°C + 48h/650°C

† supplied by LBNL (2012), †† Filament (Subelement) count, see Fig 2

Table 2.2.2. Shielding magnetization of Cable HQ1021ZB.

		1	12	14	15	16	16.5
$M_{sh,strand}$	kA/m	200	21.2	13.2	10.0	7.43	
$J_{c,non\text{-}Cu}$	kA/mm^2	48.5	3.55	2.13	1.62	1.26	1.04
$J_{non\text{-}Cu}$	kA/mm^2	0.06	0.76	0.89	0.95	1.01	1.04
$M_{sh,cable}$	kA/m	171	17.2	9.32	5.8	2.03	

* $M_{sh,strand}$ is directly measured below 14 T, KDH-extrapolated above that. $J_{c,non\text{-}Cu}$ is deduced from ΔM and KDH-extrapolated. $J_{non\text{-}Cu}$ is magnet current density along a load line that touches $J_{c,non\text{-}Cu}$ at 16.5 T.

Bench-mark data for the NbTi-wound LHC are $M_{sh,inj,LHC}$ = 10.3 kA/m and $M_{coup,LHC}$ = 2.64 kA/m. The present cable, HQ1021ZB, with an 8 mm stainless steel core wound at LBNL, is similar to a previously measured LBNL-wound HQ-KC3 cable. As such we would expect to find the same 8-mm-core-moderated ICR and coupling magnetization, 1.02 μΩ and 70.3 kA/m, respectively. Clearly such a narrow core width is inadequate to properly suppress M_{coup}. With regard to persistent-current magnetization at injection, Nb_3Sn's large J_{cdeff} product guarantees a large value, estimated here to be $M_{sh,cable,inj,1T}$ = 171 kA/m. On the other hand as the magnet is ramped up to operating field $M_{sh,cable}$ steadily decreases such that at 15 T in the windings it has dropped to 5.8 kA/m, clearly an acceptable value. Previous M_{coup} results indicated that a full width core would be needed to adequately suppress coupling magnetization, and the $M_{sh,cable}$ data of Table 2.2.2 indicates that although $M_{sh,cable}$ is not a problem close to operating field, strong compensation will be required near injection.

2.2 Cable current sharing and quench, YBCO

This work, begun in 2012 already, was expanded in 2013. Here the Quench properties of CORC cables have been studied at 77 K in liquid nitrogen bath (Figure 2.1.1). An existence of a narrow region of stagnant NZs was observed (Fig. 2.3.1) in a limited range of normalized currents $i=I/I_c$. Results of a particular quench measurement are shown in Figure 2.2.2, and a revised phase stability map in Figure 2.2.3.

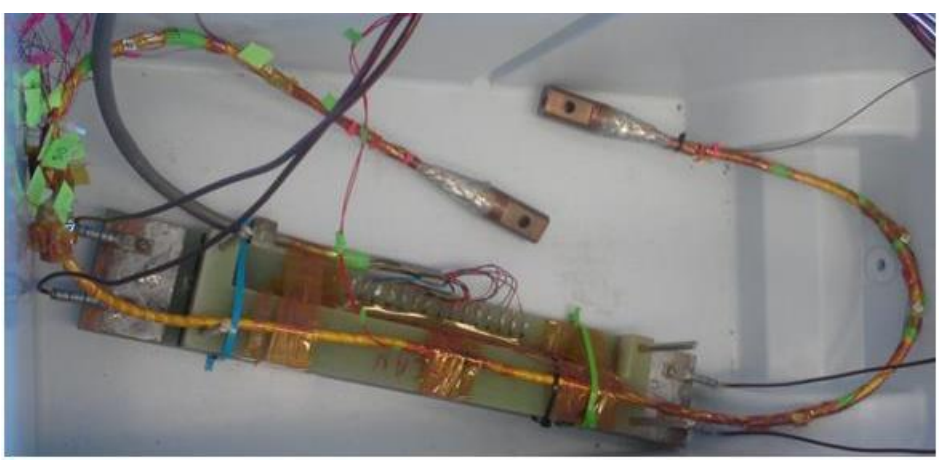


Figure 2.2.1. Set-up for the study of quench in CORC cables.

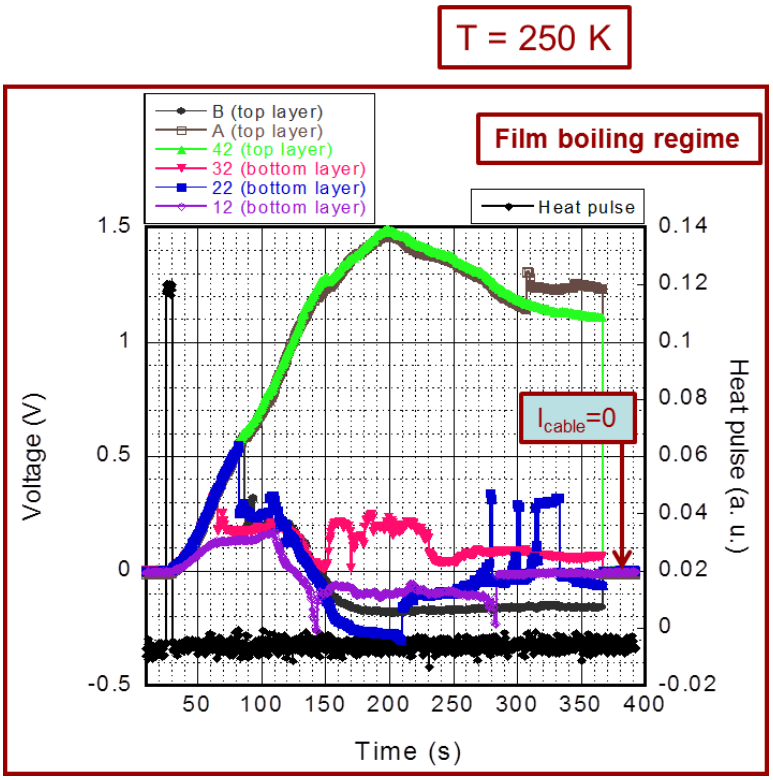


Figure 2.2.2. Quench for I_{cable} = 200 A, $I_{cable}/\langle I_c \rangle$ = 0.5831, I_{heater} = 0.415 A/5 s
Deposited energy = 36.16725 J/25mm^2

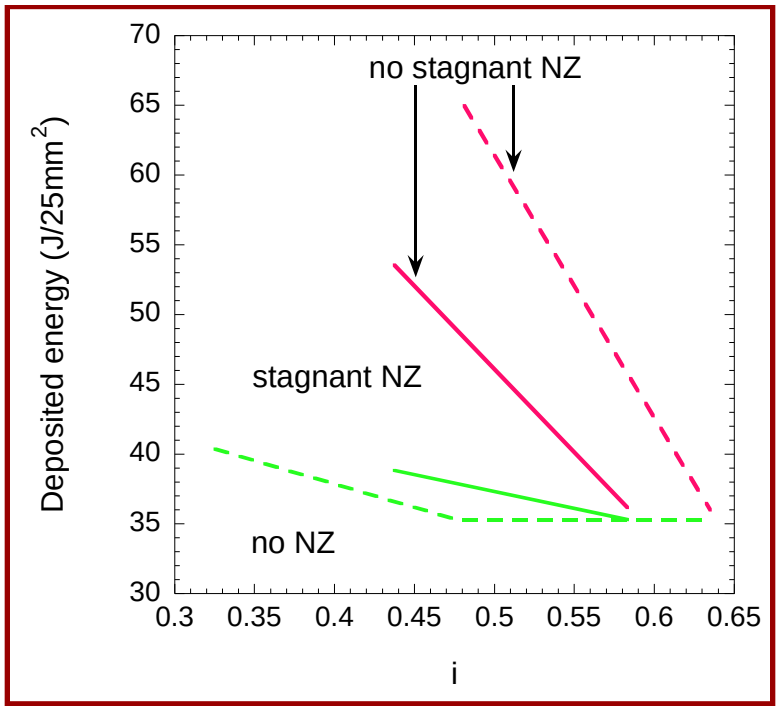


Figure 2.2.3. Revised Tentative NZ "phase" diagram: Solid lines 1st experiment
Dashed lines 2nd experiment after 4 months.

2.3 Cable current sharing/stability, Nb_3Sn

In this area of the program the goal was to make a probe with the ability to measure ICR and Current-Sharing in Nb_3Sn Rutherford Cable in a Laboratory-scale magnet with the sample under conditions seen inside of an accelerator magnet (Pressures, Self-field to 15 Tesla, Epoxy Impregnation Capability). This has been a multiyear effort, with probe design spanning 2012 and 2013. The approach is to mount the cable on a U-shaped holder and injecting current into one strand and then exciting this strand with an epoxy/graphite small-contact heater. Issues with cable splaying during sample mounting onto the U-shaped holder have been resolved. At the end of this program the probe was designed and fabricated. Figure 2.3.1 shows the probe. The effort in 2013 was in how to mount the heaters and sensors on the probe, although here we do not show the instrumentation details. Initial runs (now complete in 2014) will be reported in the 2014 report. They show an interesting two modes of operation, both instantaneous quench, and also static current sharing with over-excitation. Both are being employed in 2014.

Figure 2.3.1. The Nb_3Sn Single-Strand Excitation ICR/Current-Sharing Probe.

2.4 FEM Modeling of Very High Field YBCO Solenoids, Magnetization of Cables

Large-scale superconducting magnets require a large number of ampere-turns and call for a choice between low currents and large inductances or vice versa. The usual choice is the latter, hence the need for cables. High-temperature superconducting (HTS) cables available to the device manufacturer are 'twisted stacked-tape' (TSTC), Roebel, and CORC. Below we focus on the magnetization loss properties of CORC cables. Our continuing measurements of losses in Rutherford cables direct attention to the two components of loss (total magnetization): those due to persistent currents in the individual strands of the cable (we will refer to this as 'magnetization loss'), and those due to coupling currents that flow from strand-to-strand across points of inter-strand contact. Magnetization loss is ramp-rate independent but coupling loss depends on ramp-rate, or frequency. In this report we discuss the magnetization in an ac field of several CORC cables that are not terminated, and in which the tapes are not soldered together. But in practice the cable will experience the combined effects of ac field in the presence (to a first approximation) of dc transport current (which is known to suppress magnetization). We measured magnetization ac losses in CORC cables in ac magnetic fields, applied perpendicular to the cable axes, up to 80 mT in amplitude at 77 K in liquid nitrogen bath and at different frequencies (50, 75, 100, 150, 200 Hz). Several different cables were measured with number of tapes in them ranging from 1 up to 40, wound into as many as 13 layers. Apart from the effects such as magnetic field amplitude and frequency, also the cable parameters such as the width of the tape used, number of tapes per layer, twist pitch orientation in different layers and number of layers in the cable have been studied, the sample particulars are given in Table 2.4.1.

Table 2.4.1. Parameters of CORC Cables for Magnetization Measurement.

	CORC cable SS304 former						
CORC cable	ID (mm)	OD (mm)	Tape width (mm)	Number of tapes per layer	Number of layers in cable	Cable twist pitch (mm)	Comment
A	3.13	4.76	12	1	1	39	—
B	3.13	4.76	4	3	1	40	—
C	3.13	4.76	4	3	2	34	Alternating twist directions in layers
D	3.13	4.76	4	3	2	34	The same twist direction in layers
E	3.13	4.76	4	1	1	14	Single tape helix
F	3.13	4.76	4	1	1	14	The same as sample *E* but kapton tape insulation removed (figure 2)
G	—	—	12	—	—	—	Straight tape
H	3.13	4.76	4	3	1	34	—
I	3.13	4.76	4	6	2	34	Alternating twist directions in layers
J	3.13	4.76	4	9	3	34	Alternating twist directions in layers
K	3.13	4.76	4	12	4	34	Alternating twist directions in layers
L	3.13	4.76	4	40	13	34	Alternating twist directions in layers

Figure 2.4.1. shows representative sections of cable as measured for magnetization. The magnetization results are shown in Figure 2.4.2.

Figure 2.4.1. A photo illustrating the densely wound (left), and singly wound (right) CORC cables (with minimum gap between the tapes and with open ends) used in this study.

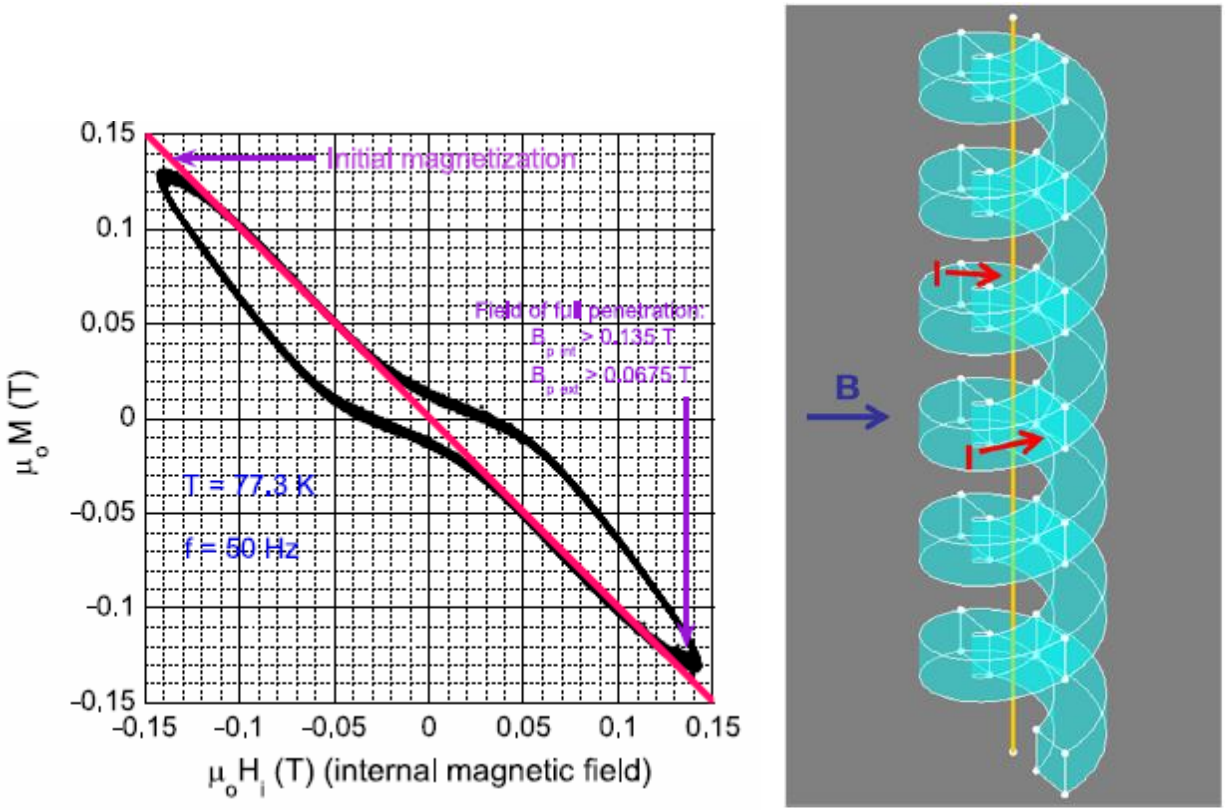


Figure 2.4.2. (left) The *M*(*H*) loop of Sample L, containing 40 tapes wound into 13 layers, measured at 50 Hz and at 77.3 K in magnetic field applied perpendicularly to the cable axis vs. internal magnetic field. The magnetization was determined using the volume of the cable. The internal magnetic field is the applied field corrected for the demagnetizing factor of a cylinder in perpendicular magnetic field. (right) field orientation and geometry.

Further details of this work are given in the article below

1. M Majoros, M D Sumption, E W Collings and D C van der Laan, "Magnetization losses in superconducting YBCO conductor-on-round-core (CORC) cables", to be published in Supercond. Sci. and Tech. 2014.

List of Papers Published, Presentations made, and Theses defended based on this Program (April 1, 2013-March 31, 2014)

Our research progress for the current period is well described by:

I. A list of papers published from April 1 2013-March 31 2014

II. A list of Presentations made from April 1 2013-March 31 2014

I. PAPERS PUBLISHED April 1 2013-March 31 2014

3. E. W. Collings, M. D. Sumption, M. A. Susner, D. R. Dietderich, E. Kroopshoop, and A. Nijhuis, "Coupling- and Persistent-Current Magnetizations of Nb_3Sn Rutherford Cables With Cores of Stainless Steel and Woven Glass-Fiber Tape Measured by Pick-Up Coil Magnetometry", IEEE Trans. Appl. Supercond, 23 (2013) 4702305.
4. C. S. Myers, M. A. Susner, L. Motowidlo, J. Distin, M. D. Sumption, and E. W. Collings, "Specific Heats of Composite Bi2212, Nb_3Sn, and MgB_2 Wire Conductors", *IEEE Trans. Appl. Supercond*. 23 (2013). 8800204
5. X Xu, M D Sumption, S Bhartiya, X Peng, and E W Collings, "Critical current densities and microstructures in Rod-in-Tube and Tube Type Nb_3Sn strands – Present status and prospects for improvement", *Supercond. Sci. Technol.* 26 (2013) 075015
6. X Xu, M D Sumption and E W Collings", A Model for Phase Evolution and Volume Expansion in Tube Type Nb_3Sn Conductors", *Supercond. Sci. Technol*. 26 (2013) 125006
7. X. Xu, E. Collings, M. Sumption, C. Kovacs, and X. Peng", The Effects of Ti Addition and High Cu/Sn Ratio on Tube Type $(Nb, Ta)_3Sn$ Strands, and a New Type of Strand Designed to Reduce Unreacted Nb Ratio*", IEEE Trans. Appl. Supercond*. 24 (2014) 6000904.
8. M. Majoros, M.D. Sumption, E.W. Collings, N.J. Long, "Stability, Inter-Strand Contact Resistance, and AC Losses in YBCO Roebel Cables*", IEEE Trans. Appl. Supercond* 24 (2014) 6600505.
9. E.W. Collings, M.A. Susner, M.D. Sumption, D.R. Dietderich, "Extracted Strand Magnetizations of an HQ Type Nb_3Sn Rutherford Cable and Estimation of Transport Corrections at Operating and Injection Fields *IEEE Trans on Supercond.* 24 4802605
10. X. Xu, M. Sumption, X. Peng, E. W. Collings, "Refinement of Nb_3Sn grain size by generating ZrO_2 precipitates in Nb_3Sn wires", Submitted to Applied Physics Letters, Jan 2014.

9. X Xu, M D Sumption, E W Collings, "Influence of Heat Treatment Temperature and Ti doping on Low Field Flux Jumping and Stability in $(Nb\text{-}Ta)_3Sn$ Strands", Submitted to Superconductor Science and Technology, 2014.

10. M Majoros, M D Sumption, E W Collings and D C van der Laan, "Magnetization losses in superconducting YBCO conductor-on-round-core (CORC) cables", to be published in Supercond. Sci. and Tech. 2014.

II PRESENTATIONS

Presentations April 1 2013-March 31 2014

5. M.D. Sumption, X. Xu, C. Kovacs, X. Peng, and E.W. Collings, Influences of heat treatment and Ti addition on high performance Rod-in-Tube $(Nb,Ta)_3Sn$ Strands", 2013 International Cryogenic Materials Conference, Anchorage, Alaska
6. M.D. Sumption, "Magnetization and decay effects in Nb_3Sn, Bi:2212, and YBCO relevant to field errors", The Low Temperature Workshop, St. Petersburg, Florida, Nov 2013
7. M. Majoros, "AC losses in CORC cables measured at 77 K in liquid nitrogen bath", 2013 International Cryogenic Materials Conference, Anchorage, Alaska
8. M. Majoros, "Stability, Inter-Strand Contact Resistance and AC Losses in YBCO Roebel Cables", Magnet Technology Conference 23, Boston MA, July 14-19, 2013
9. E. W. Collings, "Extracted Strand Magnetizations of an HQ Type Nb_3Sn Rutherford Cable and Estimation of Transport Corrections at Operating and Injection Fields", Magnet Technology Conference 23, Boston MA, July 14-19, 2013
10. X Xu, X Peng, M.D. Sumption, Chris. Kovacs, E.W. Collings, "The effects of Ti addition and high Cu/Sn ratio on tube type $(Nb,Ta)_3Sn$ strands, and a new type strand targeted for higher non-Cu J_c", Magnet Technology Conference 23, Boston MA, July 14-19, 2013.
11. C.S. Myers, M. A. Susner, L.R. Motowidlo, J.Distin, M.D. Sumption, and E. W. Collings, " Transport, Magnetic, and electron optics studies of Bi2212 strands", Magnet Technology Conference 23, Boston MA, July 14-19, 2013.
12. M. Majoros, M.D. Sumption and E.W. Collings Stability and normal zone propagation in a 50 Tesla solenoid wound of YBCO coated conductor tape with a stainless steel interlayer insulation, International Cryogenic Materials Conference, Anchorage, Alaska
13. M. Majoros, M. D. Sumption, E. W. Collings and D. van der Laan, "Measurements of current sharing, contact resistance, and quench in YBCO cables", Low temperature high magnetic field superconductor workshop – St Petersburg Nov. 2013
14. M. Majoros, M.D. Sumption and E.W. Collings YBCO pancake coils – stability and normal zone propagation. Magnet Technology – Boston – July 2013.