MATERIALS, STRANDS, AND CABLES
FOR SUPERCONDUCTING ACCELERATOR MAGNETS
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CY begin 2010-end 2012
Final Report

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by

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INTRODUCTION (until 2010)

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. This report details activities during the three year period 2010-2013.

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 CY2010-12 other members of the group were:

Students 2010

Mike Susner
Scot Bohnenstiel
Yuan Yang
Guangze Li
Chris Kovacs
Xingchen Xu
Cory Myers
Hyun Sun Kim
Ashwini Chandra
Yi Ding* (visiting scholar, 2 year, Southeast China U)
Shobhit Bhartia M.S. 2010 Winter

PROGRAM 2010--2012

Our program consisted of the three components: Materials Research, Strand Research, and Cable Research.

One of the main focuses of the **"Materials"** research in 2010-2012 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. Attention was paid to the "intermediate-temperature superconductor", magnesium diboride emphasis being placed on (i) irreversibility field enhancement, (ii) critical current density and flux pinning, and (iii) connectivity. In 2011 we established HT facilities for Bi-2212, and since then have reported on measurements of magnetization and heat capacity for these conductors. The second area of the program has been in the area of **"Strands"** in which, aside from the materials aspect of the conductor, its physical properties and their influence on performance was studied. Much of this work was in the area of magnetization estimation and flux jump calculation and control. One of the areas of investigation was strand instabilities in high-performance Nb_3Sn conductors due to combined fields and currents. Additionally, we investigated quench and thermal propagation in YBCO coated conductors at low temperatures and high fields. The last section, **"Cables"**, studied interstrand contact resistance, ICR, it origins, control, and implications. Following on from earlier work in NbTi, the present work in Nb_3Sn was aimed to make ICR intermediate between the two extremes of too little contact (no current sharing) and too much (large and unacceptable magnetization and associated beam de-focussing). The program was (and has always been) run in collaboration with both LBNL and FNAL. We also collaborated with other HEP oriented groups (CERN, and various university groups), and HEP related industrial partners. Here too, we investigated the use of YBCO coated conductors in HEP applications.

Interstrand contact and current sharing measurements were made on YBCO-based Roebel cables using transport current methods. Finally, quench was investigated for YBCO cables and the magnets wound from them, presently with a focus on 50 T solenoids for muon collider applications.

Program Results

Introduction: *Nb_3Sn cables will be required for the Phase-II IR-region LHC 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. Overall, we proposed to investigate not only Nb_3Sn, but also, for various HEP applications, (i) MgB_2 strands (low field, wide temperature margin) (ii) Bi:2212/Ag strands and YBCO tapes (very high field insert applications). Thus we had proposed research on all of these superconductors as (1) "materials", (2) "strands" and (3) "cables". The 2010-2012 work statement, along with the final program results, are described in short below.*

1. RESEARCH TASKS IN MATERIALS

1.1. Property Enhancement of Nb_3Sn: We proposed to further investigate the basic properties of high performance Nb_3Sn conductors, both rod-in-tube (RIT) distributed barrier and tube-type. We wished to see if better methods for stoichiometry control could be adopted for tube conductors, allowing them to reach the same performance levels as RIT. We also planned to complete our studies of the Ti-Ta additions in RIT based strands for increased performance-stability.

Results 2010-2012* on this task is detailed in the below articles. A number of important advances and discoveries were made. First, we discovered the fact that while the non-Cu J_c is higher for the RIT conductors as compared to the Tube conductors, the layer J_c is the same [1-3]. This allows researchers and conductor manufacturers to focus on maximizing conductor area utilization. Secondly, HT time and temperature optimization studies were pursued for Tube conductors, allowing stoichiometry, microchemistry, and grain size to be optimized in these conductors, which occupy a different part of the ternary diagram than the distributed barrier Rod-in-Tube conductors [1-3]. We have also looked in detail at optimizations in RIT conductors, and have collaborated with a commercial manufacturer to reach a record J_c of 3450 A/mm^2 at 12 T and 4.2 K [3]. We also studied the relative influence of Ti doping vs higher temperature heat treatments to flatten the conductor J_c vs B performance curve and thus increase stability [4]. We also collaborated with LBNL on a study of strain and stoichiometry in Nb_3Sn bulks by using heat capacity to probe the stoichiometry [5]. We studied phase evolution in Tube conductors, and tied this to the ternary phase diagram, a useful effort for maximizing performance in these conductors[6].

1. M.D. Sumption, M. Susner, C. Kovacs, M. Border, D. Putnam, and E.W. Collings, "Transport, Magnetic, and Microstructure Studies for Rod-In-Tube and Tube Type Nb_3Sn Strands Optimized for Different Operational Regimes", Applied Superconductivity Conference, Washington DC, Aug 2010.
2. M.D. Sumption, D. Putnam, M. Susner, C. Kovacs, M. Border, and E.W. Collings, "Stoichiometry and Morphology Studies of the Microstructures of Tube Type Nb_3Sn Strands", Applied Superconductivity

Conference, Washington DC, Aug 2010.
3. S. Bhartiya, M.D. Sumption, X. Peng, E. Gregory, M.J. Tomsic, D. Doll, and E. W. Collings, "Comparison of A15 Stoichiometry and Grain Morphology in Internal Sn and Tube Type Strands; Influence of Strand Design, HTs and Alloying", Adv. Cryog. Eng. **56** (2010) 175.
4. X. Xu, C. J. Kovacs, M. D. Sumption, X. Peng, M. J. Tomsic, E. W. Collings, "Studies of Rod-in-Tube Distributed Barrier Nb_3Sn Strands Optimized for Different Operational Regimes", Presented at the ICMC-CEC 2011 Spokane, WA.
5. C.J. Kovacs, M.D. Sumption, X Peng, E.W. Collings, "Phase Evolution and Morphology Studies for Tube-Type Nb_3Sn Strands", Presented at the ICMC-CEC 2011 Spokane, WA.
6. M. G. T. Mentink, A. Anders, M. M. J. Dhalle, D. R. Dietderich, A. Godeke, W. Goldacker, F. Hellman, H. H. J. ten Kate, D. Putnam, J. L. Slack, M. D. Sumption, and M. A. Susner, "Analysis of Bulk and Thin Film Model Samples Intended for Investigating the Strain Sensitivity of Niobium-Tin", IEEE Trans. Appl. Supercond. **21** (2011) 2550.
7. M.D. Sumption, S. Bhartiya, C. Kovacks, X. Peng, E. Gregory, M.J. Tomsic, E.W. Collings, "Critical Current Density and Stability of Tube Type Nb_3Sn Conductors", Cryogenics 52 (2012) 91–99.
8. M.G.T. Mentink, M.M.J. Dhalle, D.R. Dietderich, A. Godeke, W. Goldacker, F. Hellman, H.H.J. ten Kate, M.D. Sumption, M.A. Susner, "The effect of Ta and Ti additions on the strain sensitivity of bulk Niobium-Tin", Physics Procedia 36 (2012) 491 – 496.

1.2. Bi:2212 Strand-Materials Studies: We proposed to study Bi:2212 materials from a strand and cable perspective, with three main areas (1) oxygen diffusion, (2) cable damage, and (3) reaction with core and insulation.

<u>Results 2010-2012</u> on this task is detailed in the below articles. The work this area focused on the installation and setting up of a proper Bi-2212 heat treatment facility at OSU, as well as strand level characterization (transport and SEM). Below we list papers focused on characterization of a new kind of Bi-2212 strand, notable for its wider HT window as compared to conventional Bi-2212 conductors, and possibility for a less coupled strand architecture, and therefore lower magnetization-related beam defocusing [1-2].

2. C. S. Myers, M. A. Susner, L. Motowidlo, J. Distin, M. D. Sumption, and E. W. Collings, "Transport, Magnetic, and SEM Characterization of a Novel Design Bi-2212 Strand", IEEE Trans. Appl. Supercond. **21** (2011) 2804.
3. C.S. Myers, L.R. Motowidlo, J.Distin, T. Holesinger, M. A. Susner, M.D. Sumption, and E. W. Collings, "Transport, and Magnetic, and SEM Characterization of a Novel, Two-Dimensional, Random-Oriented Single Stack Design (2D-ROSS) Bi-2212 Strand", Presented at the ICMC-CEC 2011 Spokane, WA.

1.3.MgB_2 for HEP: MgB_2 materials, especially thin films with their very high B_{c2}, had early interest for HEP applications. However, their use is in practice limited to lower fields due to: (i) their much lower irreversibility field, (ii) porosity, (iii) lack of connectivity, (iv) crystalline anisotropy, and (v) the lack of good dopant diffusion. We focused our efforts during 2010-2012 on two areas.

*1. **Determine if very dense materials with very uniform dispersions of dopants can be produced, and measure the resulting properties.*** This was a relatively high risk-high reward activity, but if fruitful would provide a basis for actual magnet conductor development.

2. ***Evaluate application niches for present MgB_2 strands***, ones: (a) that recognize its still rather low usable field regime, and (b) that exploit its relatively high T_c (40 K). There will be some HEP applications in which MgB_2 will be preferred over NbTi and Nb_3Sn. Examples are feeder cables and possibly superferric magnets.

Results 2010-2012 ***on this task is detailed in the below articles. Progress in Area 1 above, is given in papers 1-5, while progress in area 2 is given by papers 6-11. In Paper [1], we investigated the transport and magnetic J_c divergence present in many strands, which had led to some level of confusion in the literature, making transport and magnetic J_c comparisons unreliable, and irreversibility measurements inconsistent. Paper [1] clarified these effects and showed that they were due to an anisotropic connectivity in the strands. Paper [2] clarified the maximum level of C-dopant dispersion possible in present day PIT strands, when C doping was added in the starting powders, this is relevant for maximizing the upper critical field. Paper [3] sought to de-convolute the contributions of density, connectivity, and texture in MgB_2 by comparing textured and untextured films with standard PIT and 100% dense PIT MgB_2. The heart of Task 1, however, was taken on in paper [4], and the completed PhD thesis of Scot Bohnenstiehl. For this work an RF induction furnace with a capability of 1500 psi was constructed, because it was estimated that this would allow us to take MgB_2 into the peritectic melt without Mg loss. We were quite successful with this, allowing us to properly determine the peritectic temperature for the first time, but more relevantly for HEP, allowing us to both allow extended high temperature diffusion of dopants, and to attempt to dope from the melt. The ingots thus made turn out to be the most dense and uniform finger ingots of MgB_2 ever made. We have succeeded in determining the maximum limit for C-doping, verified by EPMA, which is useful for knowing the ultimate limits of B_{c2} enhancing C doping, both in terms of its absolute amount, and homogeneity. For Task 2, papers [6] and [7] clarify the properties of best available PIT MgB_2 strand, and the papers [8 -10] document the development of an improved property strand with layer J_cs (but not yet conductor J_es) 10 times higher than present day strand, possibly interesting for HEP applications if the strand design can be optimized. Paper [11] described the present HEP niche for MgB_2.***

1. Z.X. Shi, M.A. Susner, M. Majoros, M.D. Sumption, X. Peng, M. Rindfleisch, M.J. Tomsic and E.W. Collings, "Anisotropic Connectivity and its Influence on Critical Current Densities, Irreversibility Fields, and Flux Creep in in-situ Processed MgB_2 Strands, "Supercond. Sci. Tech. **23** (2010)-045018.
2. M A Susner, Y Yang, M D Sumption, E W Collings, M A Rindfleisch, M J Tomsic and J V Marzik, "Enhanced Critical Fields and Superconducting Properties of Pre-doped B Powder-Type MgB_2 Strands", Supercond. Sci. Technol. 24 (2011) 012001.
3. M.A. Susner, Y. Yang, M.D. Sumption, M.A. Rindfleisch, M.J. Tomsic, and E.W. Collings, "Pinning in MgB_2 Superconducting Strands and Thin Films", Presented at the ICMC-CEC 2011 Spokane, WA.
4. S. D. Bohnenstiehl, Mike Sumption, E. W. Collings, "Limits of Dopant Solubility in MgB_2 for B_{c2} Enchancement", Presented at the ICMC-CEC 2011 Spokane, WA.
5. S.D. Bohnenstiehl, Thesis in preparation for graduation fall of 2011.
6. Z X Shi, M A Susner, M D Sumption, E W Collings, X Peng, M Rindfleisch and M J Tomsic, "Doping Effect and Flux Pinning Mechanism of Nano-SiC Additions in MgB_2 Strands", Supercond. Sci. Technol. 24 (2011).
7. S.D. Bohnenstiehl, M.A. Susner , Y. Yang, E.W. Collings, M.D. Sumption, M.A. Rindfleisch, R. Boone, "Carbon Doping of MgB_2 by Toluene and Malic-Acid-in-Toluene", Physica C **471** (2011) 108–111.
8. G. Li, Y. Yang, M A Susner, M D Sumption, M A Rindfleisch, M J Tomsic, and E W Collings, "Transport Property Measurements of MgB_2 Wires over a Wide Range of Temperatures and Fields", Presented at the ICMC-CEC 2011 Spokane, WA.
9. Y. Yang, G. Li, M.A. Susner, M.D. Sumption, M. Rindfleisch, M.Tomsic, and E. W. Collings, "The Influence of Densification on the Critical Current Density of MgB_2 Strands", Presented at the ICMC-CEC 2011 Spokane, WA.
10. Y. Yang, M. A. Susner, M. D. Sumption, M. Rindfleisch, M. Tomsic, E. W. Collings, "Critical Current and n-Values of MgB_2 Strands in a Range of *B-T*", Presented at the ICMC-CEC 2011 Spokane, WA.
11. M.D. Sumption, MgB_2 for Accelerator Applications, LTSW 2010

12. Y. Yang, M.A. Susner, M.D. Sumption, M. Rindfleisch, M. Tomsic, and E.W. Collings, "Influence of Strand Design, Boron Type, and Carbon Doping Method on the Transport Properties of Powder-in-Tube MgB2−XCX Strands", IEEE Trans. Appl. Supercond. 22 (2012) 6200110.
13. G Z Li, Y Yang, M A Susner, M D Sumption and E W Collings, "Critical Current Densities and n-values of MgB2 Strands over a Wide Range of Temperatures and Fields", Supercond. Sci. Technol. 25 (2012) 025001 (10pp).
14. M.A Susner, T.W. Daniels, M.D. Sumption, M.A. Rindfleisch, C.J. Thong and E.W. Collings, Drawing Induced Texture and the Evolution of Superconductive Properties with Heat Treatment Time in Powder-in-tube in-situ Processed MgB_2 Strands", Supercond. Sci. Technol. 25 (2012) 065002 (13pp).
15. G. Z. Li, K. M. Reddy, J. B. Zwayer, M. A. Kuldell, M. A. Susner, Y. Yang, M. D. Sumption, J. J. Yue, M. A. Rindfleisch, M. J. Tomsic, C. J. Thong, and E. W. Collings, "Critical Current Density and Current Transfer Length of Multifilamentary MgB_2 Strands of Various Design", IEEE Trans. Appl. Supercond, 23, (2012) 6200204.
16. G Z Li, M D Sumption, M A Susner, Y Yang, K M Reddy, M A Rindfleisch, M J Tomsic, C J Thong, and E W Collings, "The Critical Current Density of Advanced Internal-Mg-Diffusion-Processed MgB_2 Wires", Supercond. Sci. Technol. 25 (2012) 115023.

2. RESEARCH TASKS IN STRANDS

2.1. Stability in Nb_3Sn Strands: Nb_3Sn, as the material at hand for the development of high performance magnets in the near term (up to 15 years?) is an important material to optimized at the strand as well as material level. Stability has been a key issue for Nb_3Sn strand, and OSU has been a key group investigating the stability limitation. A number of key issues related to stability remain, especially for the construction of a predictive model. A effort was propped for 2010-2012 which included analytic, numeric, and FEM approaches, to answer a number of related issues, including *(1) Determining the Rules for Mixing of Self-Field and Magnetization Current Effects at Given Field Ramp Values and Field-Current Sweep Protocols, (2) Determining the Role of Self-Field Effects in Cables and Magnets, (3) Investigating the Sensitivity of Instability to d_{eff} in Self-Field Measurement Protocols.*

<u>Results 2010-2012:</u> The following paper [1] presented our present understanding of the key questions. Both magnetization and current related instabilities are present and possible in these conductors, but it is crucial to distinguish between what an isolated conductor may see, and what a magnet may experience.

1. M. D. Sumption, "Stability in Nb_3Sn Conductors; Magnetic and Self-Field Instability Considerations at 4 K And 2 K", Adv. Cryog. Eng. **56** (2010) 199.

In order to make realistic and predictive models, experimental verification is crucially important. Thus the following tasks were laid out. *(4) Refine Recommended Goals for Filament Diameters, Strand Diameters, and RRR, (5) Further Develop Models at both 2 K and 4.2 K for Magnetization and Self-Field Stability, and (6) Estimate Heat Transfer in Cryogen as Well as Potted Magnets at 2 K and its Influence on Magnet Stability. These tasks were* measurement tasks, aimed at model verification and development.

<u>Results 2010-2012:</u> The first paper [1] describes stability measurements on Tube strands. The second [2] is looking at the effect of HT choices on magnetization and RRR on stability, seeking to separate out any influence of reduced HTs on reducing J_c from RRR differences with respect to their influence on stability.

1. M.D.Sumption, S.Bhartiya, C. Kovacks, X. Peng, E.Gregory, M.J.Tomsic, and E. W. Collings, "Critical Current Density and Stability of Tube Type Nb_3Sn Conductors", Submitted to Cryogenics, June 2011.
2. X. Xu, C. J. Kovacs, M. D. Sumption, X. Peng, M. J. Tomsic, E. W. Collings, "Studies of Rod-in-Tube Distributed Barrier Nb_3Sn Strands Optimized for Different Operational Regimes", Presented at the ICMC-CEC 2011 Spokane, WA.
3. X. Peng, E. Gregory, M. Tomsic, M. D. Sumption, A. Ghosh, X. F. Lu, N. Cheggour, T. C. Stauffer, L. F. Goodrich, and J. D. Splett, "Strain and Magnetization Properties of High Subelement Count Tube-Type Nb_3Sn Strands", IEEE Trans. Appl. Supercond. **21** (2011) 2559.
4. X. Peng, E. Gregory, M. Tomsic, Mike Sumption, "Progress on Application and Manufacture of Tube Type Nb_3Sn Superconductor", Presented at the ICMC-CEC 2011 Spokane, WA.

2.2. Quench Propagation Measurement and Modelling/Analysis of Various Strands

At 4.2 K: As we move into a new era of HEP machine development, new magnets and new materials are becoming relevant. However, most HEP applications are expected to operate at 4.2 K, so the properties at that temperature must be measured and made available. One of the crucial items to be investigated is conductor stability and quench, both for Bi:2212 and YBCO. In addition, an organized accounting of the basic thermal, electrical, and magnetic properties is needed for proper modeling of these conductors and their expected performance. Below we break down this task into various subcategories.

(1) Quench Measurements of Various Conductors and Coils at 4.2 K: We worked to extend previous measurement of quench propagation and thermal conductivity in YBCO at 40 K-77 K down to lower temperatures, initially, followed by higher fields.

Results 2010-2012: ***Here we decided that it would be important to couple FEM calculations of quench in YBCO conductors with measurements. The first paper [1] below describes our FEM modeling for the conductor (an activity distinct from, and at a different length scale than, the magnet level modeling below – but one which we will ultimately integrate with the magnet model).***

1. M. Majoros, M. D. Sumption, E. W. Collings, "Stability and Quench Propagation in YBCO Coated Conductor Coils at 4.2 K and Subjected to High Applied Magnetic Fields -Measurements and FEM Modeling", Presented at the ICMC-CEC 2011 Spokane, WA.
2. M.D.Sumption, "Quench Aspects of YBCO at 4 K" Post LTSW 2010 Program"

(2) Thermal Property Measurements of Various Conductors at HEP Operating Conditions Heat Capacity and thermal conductivity measurements from 2 K to T_c and above was made for YBCO, Bi:2212, and MgB_2 strands.

Results 2010-2012: ***AC Loss and Magnetization Studies as well as J_c and n-values have been measured for MgB_2. 4 K data on loss and magnetization has been taken for YBCO, to complement the 77 K data, which looked at the magnetization of stacks of conductor as might be seen in a magnet, and may be expected to give a different magnetization than that measured for a single tape at lower fields where beam injection should occur. Heat capacity measurements have been made on Bi-2212 strands, YBCO and MgB_2.***

1. M. Majoros, M. D. Sumption, M. A. Susner, E. W. Collings, J. Souc, F. Gomory, M. Vojenciak, L. M. Fisher, A. V. Kalinov, and I. F. Voloshin, "AC Magnetization Loss of a YBCO Coated Conductor Measured Using Three Different Techniques", IEEE Trans. Appl. Supercond. **21** (2011) 3293.

2. **Invited:** M.D. Sumption, "M. D. Sumption, M. Majoros, and E.W. Collings, "YBCO Conductors for HEP applications", MS&T, Oct 17-21, Houston TX.

(4) Estimation and Measurement of Thermal Properties of Insulations for HTS Materials
(5) Quench Modelling for Strands and Coils: Analytic and FEM modeling of strand stability and quench is needed for HTS materials under HEP-relevant conditions. In order to do this we extended our modeling of stability in Nb_3Sn based conductors to HTS conductors. We will focus the simulations at 4.2 K and high fields. Relevant thermal environments were taken into account, as well as the shape and materials anisotropies of the various conductors.

<u>Results 2010-2013:</u> Here we have focused on YBCO based conductors and cables, and have put them in the context of magnets, specifically a high field, 50 T magnet, for muon colliders. In presentations [1-2] we first used a simple tape conductor and un-segmented magnet, but using a model for YBCO coated conductor which includes full J_c, n-value, heat capacity and thermal conductivity data (mostly from literature data). In all cases we also looked at the J_c anisotropy and its effect on magnet performance, as well as the mechanical response of the system to make sure relevant strains were within proper limits. In presentation [3], also with a submitted paper to IEEE, we considered a more detailed system, with a segmented shell magnet, with stated thermal boundary conditions, and a YBCO cable. In the last study, we found that segmentation size optimization could lead to conductor minimization. However, the key issue found in all three studies was the character of the normal zone propagation in these liquid helium temperature, very high field magnets made of coated conductor cable. We found the creation of relatively static normal zones under some conditions, and also verified the strongly 3-D character of the normal zone propagation seen in our earlier 77 K studies.

1. M. Majoros, M. D. Sumption, E. W. Collings, "Normal Zone Propagation in a 50T YBCO CC Solenoid – FEM Modeling", Presented at the ICMC-CEC 2011 Spokane, WA.
2. M. Majoros, Presentation on Quench in YBCO high field magnets, LTSW 2010.
3. M. Majoros "Stability and Normal Zone Propagation in a 50 Tesla Solenoid Wound of YBCO Coated Conductor Tape FEM Modeling", Magnet Technology Conference (MT22), Marseille, France, Sept 12-16, 2011.

2.3. Strand Suitability and Cable Design Studies for Various HEP Related Applications: As a group intimately familiar with various conductor materials, including NbTi, Nb_3Sn, MgB_2, Bi:2212/Ag, Bi:2223/Ag, and YBCO, we planned to continue to evaluate MgB_2 and the HTS materials for various HEP applications, including "newly" emerging ones such as the muon collider and Project X. This was to include not only high field magnets, but also specialty applications such as the CERN current links.

<u>Results 2010-2012:</u> Our focus here was in exploring the relevance of YBCO and MgB_2 for various HEP applications. We viewed the CERN uplinks as a place to consider MgB_2 and YBCO conductors and cables, and to compare them to other possible candidates. In the first work [1], we assessed the suitability of MgB_2 for various HEP applications. In the second [2], we gave critical properties over a whole range of B and T to help in this assessment In [3], we discussed the suitability for YBCO in high field applications.

1. M.D. Sumption, "MgB_2 for Accelerator Applications", LTSW 2010
2. G. Li, Y. Yang, M A Susner, M D Sumption, M A Rindfleisch, M J Tomsic, and E W Collings, "Transport

Property Measurements of MgB_2 Wires over a Wide Range of Temperatures and Fields", submitted to IEEE Trans. on Applied Supercond. 2011.
3. **Invited:** M.D. Sumption, M. Majoros, and E.W. Collings, "YBCO Conductors for HEP applications", MS&T, Oct 17-21, Houston TX.
4. C. Kovacs, M.D. Sumption, "Temperature Distribution and Current sharing in Helium Gas Cooled YBCO Cables", manuscript in preparation.

3. RESEARCH TASKS IN CABLES

3.1 Nb_3Sn Rutherford Cables: Coupling Loss : 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 through the introduction of new core materials and cores of optimal width. This study of ***Coupling Loss of Nb_3Sn Rutherford Cables with New Core Materials and Cores of Various Widths*** was performed under very close collaboration with both LBNL and FNAL.

Results 2010-2012:

3.1.1 The FNAL Collaboration on Cables: *It is important to determine how wide metal cores should be to reduce loss but not completely suppress current sharing. Cables made at FNAL were measured by OSU in paper [1], in this case finding that the core was not sufficient to control the ICR. In the second paper, LBNL samples were HT at FNAL, and we could investigate any differences due to this. However, the difference was seen to be in the core placement [2], and in this case very high ICR were found, in fact higher than the target, this was followed up below with an LBNL collaboration action item.*

1. E.W. Collings, M.D. Sumption, M.A. Susner, D.R. Dietderich, E. Barzi, A.V. Zlobin, and A. Nijhuis, "Coupling-Current and Persistent-Current Magnetizations in Nb_3Sn Rutherford Cables And Strands", Adv. Cryog. Eng. **56** (2010) 191.
2. E.W. Collings, M.D. Sumption, M.A. Susner, E. Barzi, D. Turrioni, R. Yamada, A.V. Zlobin, and A. Nijhuis, "Coupling- and Persistent-Current Magnetizations of Nb_3Sn Rutherford Cables", IEEE Trans. Appl. Supercond. **20,** (2010) 1387.

3.1.2 The LBNL Collaboration on Cables: *Here LBNL proposed the use of MgO and S-glass cores for good mechanical properties and thermal contraction compatibility. The ICR values are in the right range, but need further control (at present too much or too little). Nevertheless, the results are quite promising, and may lead to the best choice for future Nb_3Sn cables.*

1. E. W. Collings, M. D. Sumption, M. A. Susner, D. R. Dietderich, and A. Nijhuis, "Coupling Loss, Interstrand Contact Resistance, and Magnetization of Nb_3Sn Rutherford Cables With Cores of MgO Tape and S-Glass Ribbon, IEEE Trans. Appl. Supercond. **21** (2011) 2367.
2. E.W. Collings, M.D. Sumption, M.A. Susner, D.R. Dietderich, and A. Nijhuis, "Magnetic Measurement of Interstrand Contact Resistance And Persistent-Current Magnetization of Nb_3Sn Rutherford Cables with Cores of MgO Tape and Woven S-Glass Ribbon", Presented at the ICMC-CEC 2011 Spokane, WA.
3. E.W. Collings, "Interstrand Contact Resistance of Nb_3Sn Rutherford Cables With Cores of MgO Tape and s-Glass Ribbon", Industrial Research Ltd, Lower Hutt, New Zealand, March 10, 2011

4. E.W. Collings, "Control of Interstrand Contact Resistances of Nb_3Sn Rutherford Cables With Cores of Woven s-glass and e-glass Ribbon and 304 and 316 Stainless Steel Tapes", Magnet Technology Conference (MT22), Marseille, France, Sept 12-16, 2011
5. E. W. Collings, M.D. Sumption, M. A. Susner, D. R. Dietderich, E. Krooshoop and A. Nijhuis, "Interstrand Contact Resistance and Magnetization of Nb3Sn Rutherford Cables with Cores of Different Materials and Widths", IEEE Trans. Appl. Supercond. 22 (2012) 6000904.

3.2 Nb_3Sn Rutherford Cables: Stability (Current Sharing) in Cored and Uncored Cables: Bare uncored Nb_3Sn cables with R_c values around 0.2 μΩ although very stable possess high coupling loss under field ramping. It has been suggested that with the introduction of a core coupling loss would be reduced to the detriment of stability, all the crossover contacts having been eliminated. During our studies of cored cables we suspected that a cable with a full width core ($R_c \cong 200$ μΩ) would be highly unstable, and that reducing the core width, leaving uncovered crossovers near both cable edges, would yield a low-loss cable with acceptable stability.

We have designed and constructed a single strand experiment to be performed at OSU. In this case a single strand of a Nb_3Sn cable is energized, the cable itself prepared on a U-shaped holder and exposed to 12-15 T. A short heater pulse will be used to observe current-sharing-related transfer to neighboring strands (or the lack thereof). This set-up will have the advantage of relatively simple and inexpensive operation, and is expected to allow us to investigate various cable types and preparation conditions.

3.3-3.4 Bi:2212 and YBCO Cables -- AC Loss and Magnetization*:* Rutherford cables wound with Bi:2212/Ag round wire and or YBCO coated conductor may be useful as insert windings of accelerator magnets with fields beyond 15 T.

Results 2010-2012: ***In the first round of measurements, we attempted to use low temperature diffusion bonding of the Cu-surface. However, comparisons to control samples showed that no loss difference was present; in addition, the process seemed impractical for YBCO, unlike NbTi conductors. In the second round, small Cu links were soldered across nearest neighbor strands. While AC loss was not modified, direct ICR measurements showed three orders of magnitude reduction in ICR, into the target value range of hundreds of nano-ohms [2]. Progress in relating measurements to models was made also in paper [2]. Further work is described below.***

1. L.S. Lakshmi, M.P. Staines, R.A. Badcock, N.J. Long, M. Majoros, E.W. Collings and M.D. Sumption, "Frequency Dependence of Magnetic AC Loss in a Roebel Cable Made of YBCO on a Ni–W substrate", Supercond. Sci. and Tech. 23 (2010) 085009.
2. M.D. Sumption, "Current Sharing and AC losses in Coated Conductor Roebel Cables", European Conference on Applied Superconductivity (EUCAS 2011), The Hague, ND, Sept 19-23, 2011
3. 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—FEM Modeling", IEEE Trans. Appl. Supercond. 22, (2012) 4705104.

Research Highlights 2010-2012

1. **Materials**
    1.1. **Property Enhancement of Nb_3Sn**
    1.2. **Bi:2212 Strand-Materials Studies**
    1.3. **MgB_2 for HEP**

2. **Strands**
    2.1. **Stability in Nb_3Sn Strands**
    2.2. **Quench Propagation Measurement and Modelling/Analysis of Various Strands At 4.2 K**
    2.3. **Strand Suitability and Cable Design Studies for Various HEP Related Applications**

3. **Cables**
    3.1. **Nb_3Sn Rutherford Cables: Coupling Loss**
    3.2. **Nb3Sn Rutherford Cables: Stability (Current Sharing) in Cored and Uncored Cables**
    3.3. **Bi:2212 and YBCO Cables -- AC Loss and Magnetization**

Research Highlights

1. Materials

1.1. Property Enhancement of Nb_3Sn

Strand Investigations: Phase evolution and Morphology of Tube-type Nb_3Sn

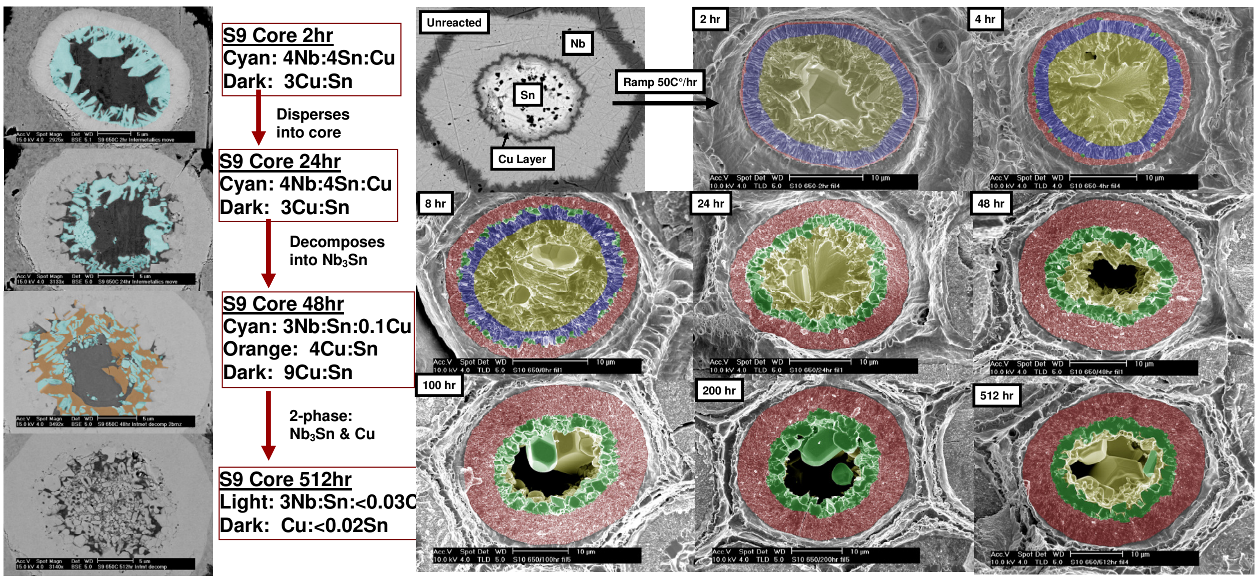


Figure 1.1.1. Phase formation in Nb_3Sn "Tube" approach strands.

A Nb_3Sn Tube-type formation was model examined for strands with various amounts of Cu-Sn. The systematics of phase formation were examined, as shown in Figures 1.1.1 and 1.1.2. The results have led to a number of papers, with transport J_c and stable strands based on a "tube" approach.

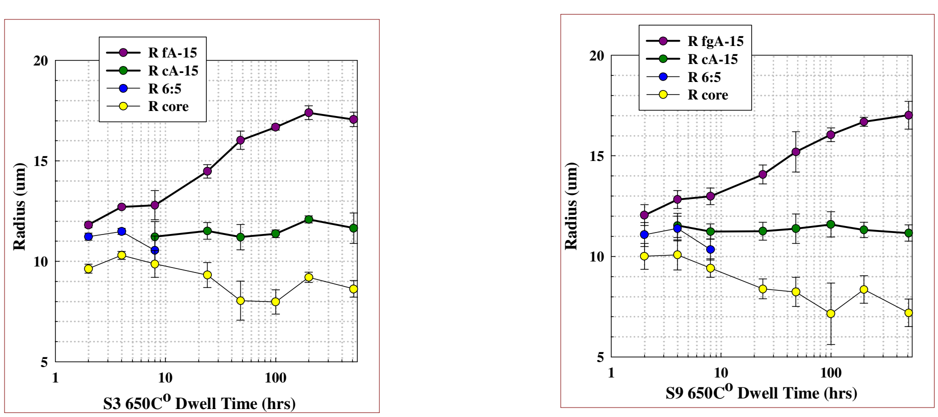


Figure 1.1.2. $NbSn_2$, Nb_6Sn_5, and Nb_3Sn growth in "Tube" conductors.

1.2. Bi:2212 Strand-Materials Studies

An oxygen annealing furnace assembly was installed for the heat treatment of Ag-sheathed $Bi_2Sr_2Ca_1Cu_2O_{8+x}$ (Bi2212) wire composites. One of the purposes of the study was to analyze the effect different heat treatment procedures, filament and strand geometries, and sheath material had on the properties of the strands. A second was heat capacity studies for use in magnet design. Pulsed calorimetry was performed on Bi2212 samples using the heat capacity option of the PPMS in order to measure the specific heats of the Bi2212 composite. The specific heats of a 2D-ROSS (Supramagnetics) and a conventional 18 x 85 filament (OST) configuration were measured and fit to a sigmoidal function using Sigmaplot. The results are shown in Figure 1.2.1 (a). In addition, magnetization was performed on Bi:2212 strands, results are given in Figure 1.2.1 (b), and are published as described below.

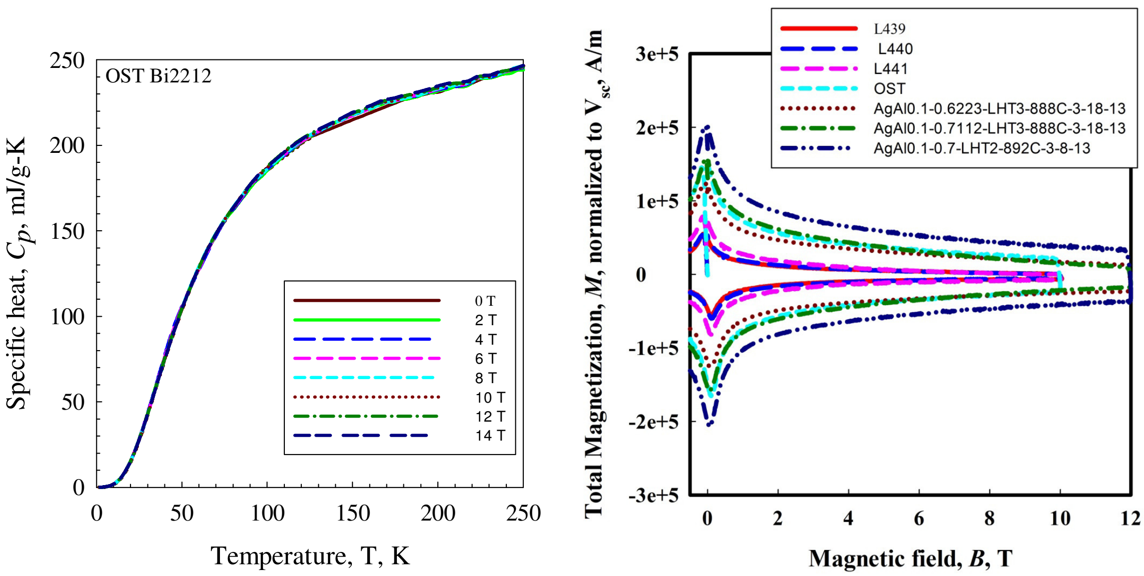


Figure 1.2.1 (a). Specific heat of 1.2 mm 18 x 85 filament OST Bi2212 strand, (b) 12 T *M-B* of samples heat treated at OSU and at OST.

1.3. MgB_2 for HEP

In this area we worked to increase the performance of MgB_2 conductors for possible use as CERN connectors. We were able to substantially increase the layer J_c and conductor J_e, as shown in Figure 1.3.1 (a) and (b). We also investigated the SEM and TEM of these super dense Advanced Internal Magnesium infiltration conductors, as shown in Figure 1.3.2.

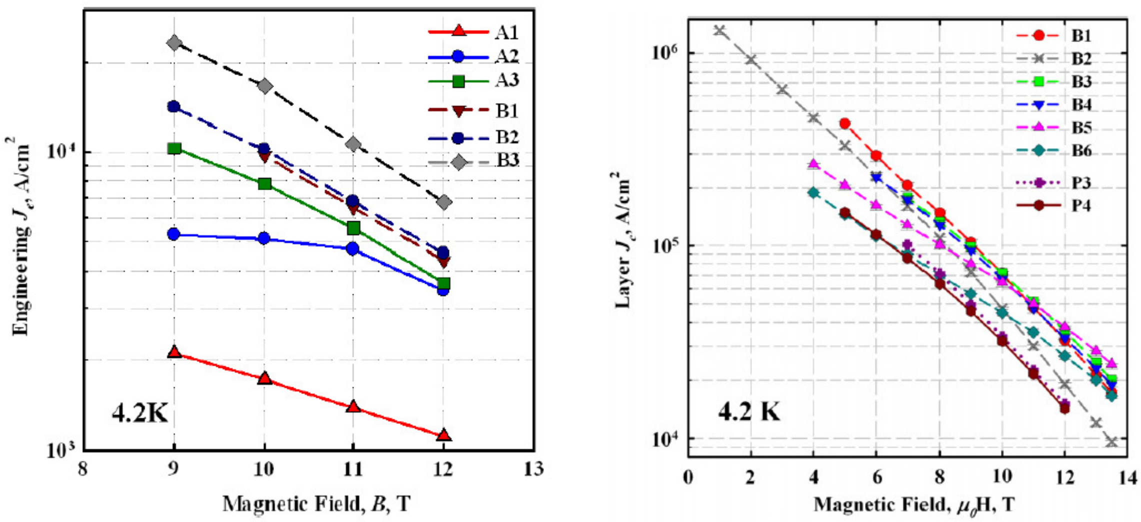


Figure 1.3.1 (a) Engineering J_c for Monofilamentary MgB_2 strands, (b) layer J_c for multifilamentary MgB_2 strands.

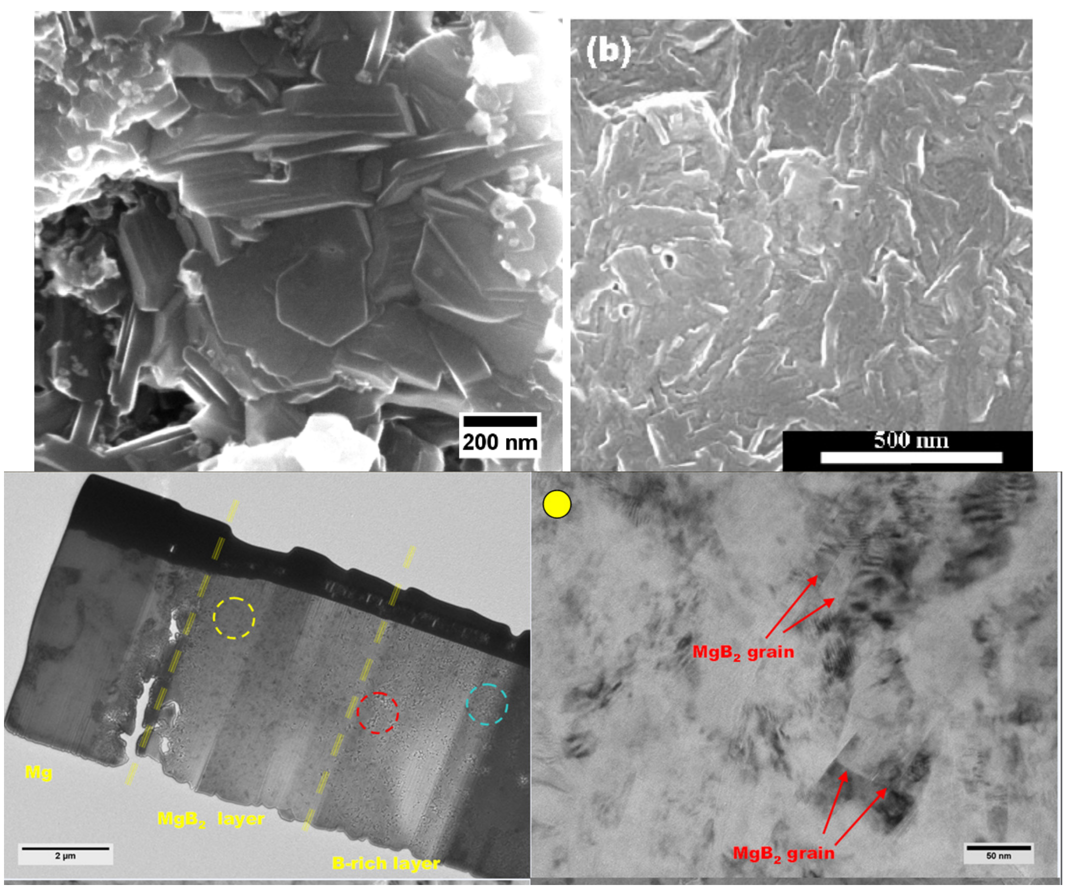


Figure 1.3.2. SEM and TEM of fully dense IMD –AIMI strand.

2. Strands

2.1. Stability in Nb_3Sn Strands

Strand Investigations: ***Nb_3Sn Strand Stability:*** J_c Transport, $J_{stability}$, *M-H*, and Heat-capacity measurement comparison with Analytical Model.

Nb_3Sn strands of variable strand parameters (diameter, filament diameter, RRR and J_c) were measured on ITER barrels. J_c Transport and $J_{Stability}$ measurements were performed by field (range: 0-2T) or current ramping (but not both consecutively). Some representative results shown in Figure 2.1.1, and results are published (as described below).

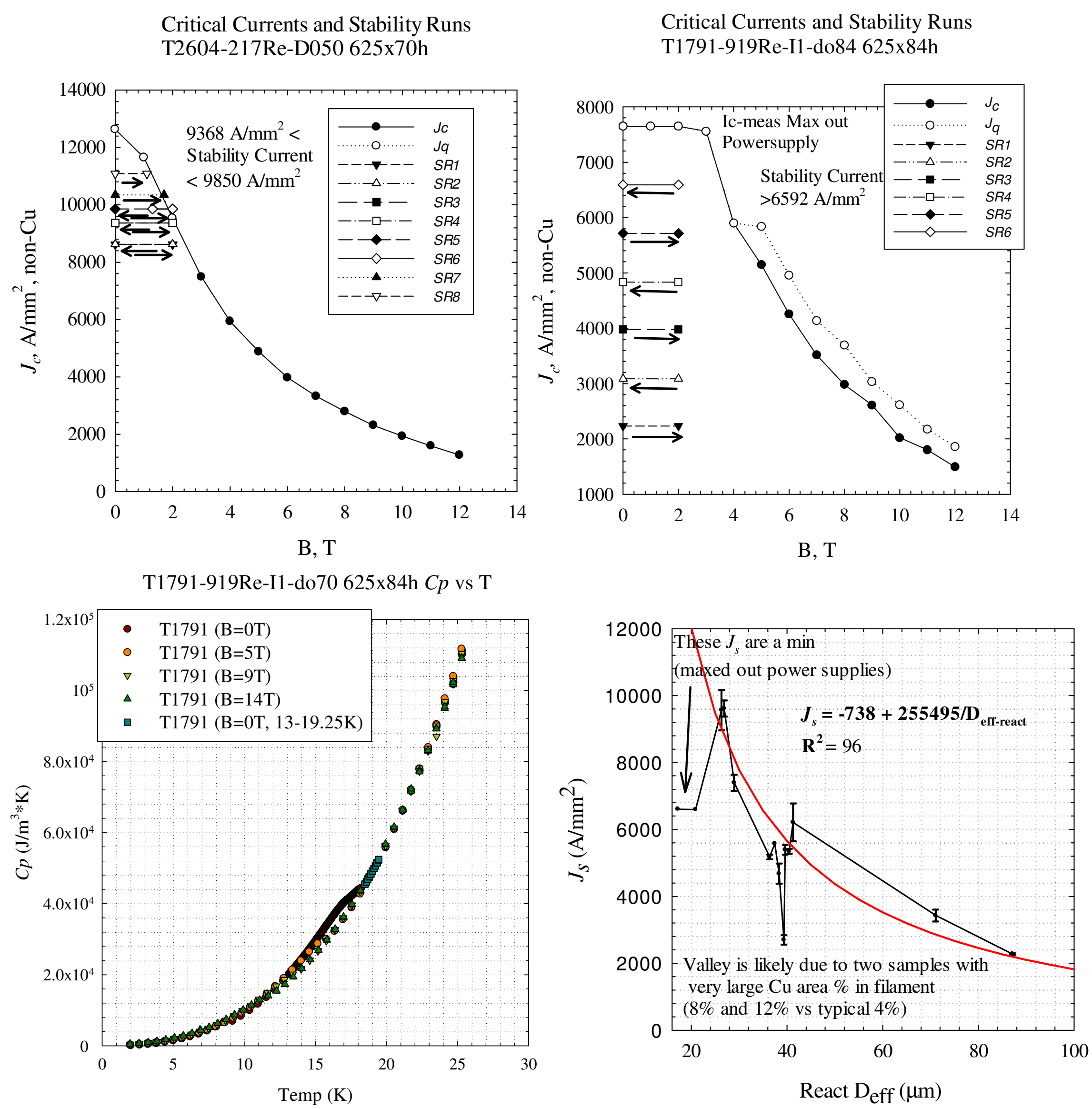


Figure 2.1.1. Nb_3Sn strand stability representative measurements.

2.2. Quench Propagation Measurement and Modelling/Analysis of Various Strands At 4.2 K

YBCO pancake coils: winding, testing, autopsy, protection:

In the present work we have modeled (using FEM) the thermal conductivity and heat propagation in a YBCO pancake coil at 4.2 K in liquid helium bath and in applied magnetic fields up to 15 Tesla at different transport currents. A pancake coil with 27 mm ID and 37 mm OD was modeled. It represents a real experimental design of a coil to be wound using YBCO tape and instrumented for voltage and temperature measurements at several places around the winding, such that both radial and azimuthal quench propagation could be measured. A heater was included in the modeling for both quench initiation and thermal gradient calculations. Our newly developed anisotropic continuum model was employed in the modeling. Obtained numerical results can be used as a guide when designing the real experimental coil.

Based on the modeling we found out that a heater power of 2.5 W/cm^2 is sufficient to warm the coil above its T_c locally. Applied magnetic field of 15 T, parallel to the pancake coil axis, affects magneto-resistivity of the stabilizing copper but has a little effect on J_c. For the heater power of 2.5 W/cm^2 and at current of $0.095I_c$ maximum temperature of 90.25 K was found in zero applied field and 90.85 K at applied field of 15 T. These results have been published in:

[1] M. Majoros, M. D. Sumption and E. W. Collings, YBCO pancake coils – stability and normal zone propagation, presented at 23rd International Conference on Magnet Technology, Boston, Massachusetts, USA, July 14 – 19, 2013.

2.3. Strand Suitability and Cable Design Studies for Various HEP Related Applications

Cable current sharing in YBCO cables:

a) **Roebel cable:** A dc transport current was applied to the strands of a Roebel cable at 77 K in liquid nitrogen bath. The inter-strand contact resistance was measured. It was modified either by applying a pressure on the cable at 77 K in liquid nitrogen bath or using different soldering patterns between the strands of the cable. Magnetization ac losses were measured in frequency range 50 – 200 Hz in applied magnetic field 4 – 100 mT perpendicular to the broader face of the cable to test the inter-strand contact resistance effect. High stability and very low level of coupling losses was observed in the cables even with the lowest inter-strand resistances.

   In an effort of aiming current sharing between the strands in Roebel cables we studied experimentally an effect of different kinds of inter-strand connections on inter-strand resistances. Just applying a pressure of 8 kPa gives a maximum inter-strand resistance of 105 mΩ. Using a tin foil placed on top of the Roebel cable gives the maximum inter-strand resistance of 31.5 mΩ under a pressure of 8 kPa. The lowest maximum inter-strand resistance of 0.1 mΩ was achieved by soldering copper shunts (strips 5 mm wide and 0.1

mm thick). Even such a low inter-strand resistance value does not cause any significant coupling losses up to 200 Hz. However, on the other hand it will allow a significant current sharing between the strands of the Roebel cable.

b) **CORC cable:** A very large strain window, especially in compression, in which YBCO coated conductors can be operated, form a basis of the CORC (**C**onductor **O**n **R**ound **C**ore) cabling method. In this method YBCO coated conductor tapes are helically wound around a former with the supeconducting YBSO film on the inside, under axial compression (Fig. 1). It was shown that the conductor performance in this configuration is not degraded irreversibly, even when a relatively small former of 3.2 mm in diameter is used. Multi-kA cables have been demonstrated. Quench properties of CORC cables have been studied at 77 K in liquid nitrogen bath. An existence of a narrow region of stagnant NZs was observed (Fig. 2.3.1) in a limited range of normalized currents $i=I/I_c$.

Fig. 1: YBCO CORC cable.

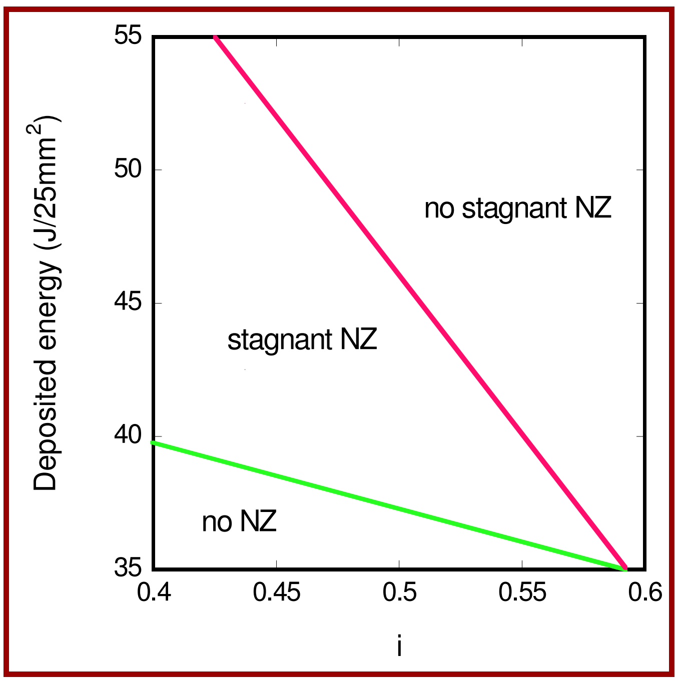


Fig. 2.3.1. "Phase" diagram of NZ in CORC cable (i = I/I_c).

In a case of propagating NZs quench occurs but it is not detrimental to the coil winding even in a case of its duration of more than 6 minutes.

These results have been published in:

[1] M. Majoros, M. D. Sumption, E. W. Collings and N. J. Long, "Stability, inter-strand contact resistance and ac losses in YBCO Roebel cables", presented at 23rd International Conference on Magnet Technology, Boston, Massachusetts, USA, July 14 – 19, 2013.
[2] M. Majoros, M. D. Sumption, E. W. Collings and N. J. Long, "Stability, inter-strand contact resistance and ac losses in YBCO Roebel cables", IEEE Trans. Appl. Supercond., vol. 24 (2014) p. 6600505.
[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", presented at 2013 Low Temperature High Field Superconductor workshop, the Hilton St. Petersburg Bayfront, FL, USA, November 4 -6, 2013.

Strand/Cable Investigations: YBCO splice measurements

This work was focused on examining the possibility of YBCO coated conductor cable for current leads that are in a thermal gradient (CERN current leads). This was done by creating a splice from a two-tape region and reducing it a one-tape region. This required monitoring of the He-gas flow-rate, current tap resistance balancing/measurement, splice resistance balancing/measurement, and examination of the splice region. This measurement led to the creation of the Mk.I and Mk.II He-gas probe. Current sharing was seen in the samples and the ability of YBCO cables to current share under flowing He-gas. Probe and typical results are shown in Figure 2.3.2.

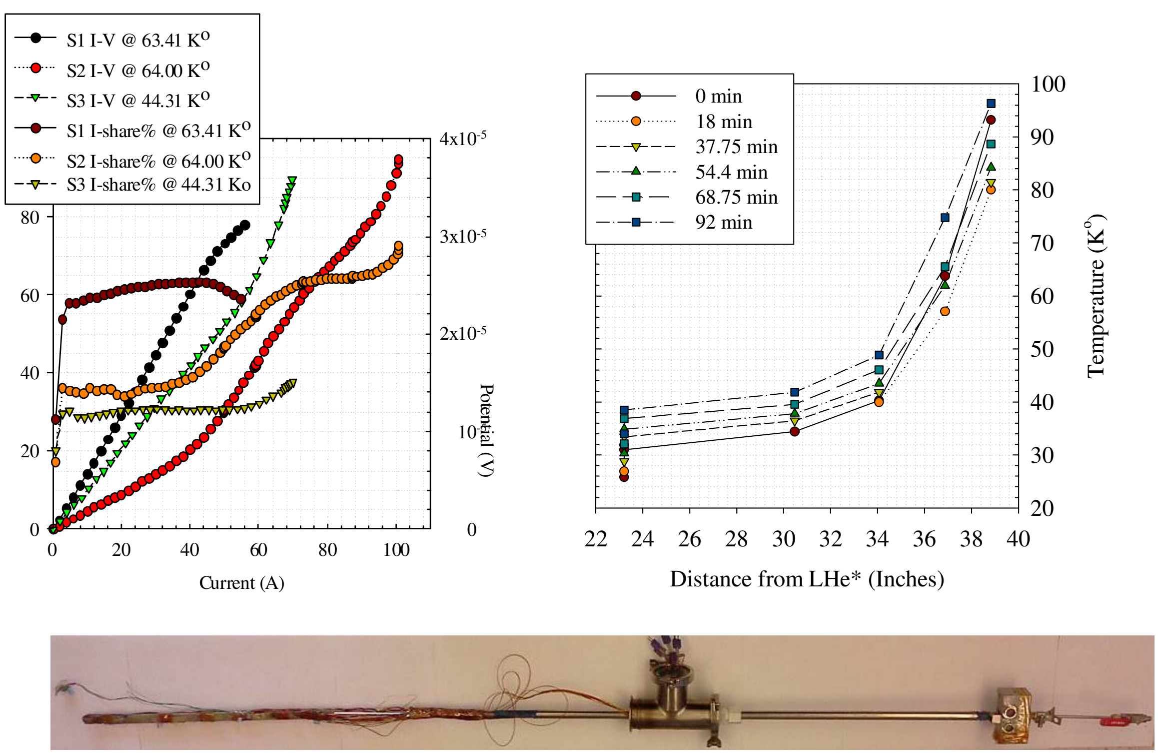
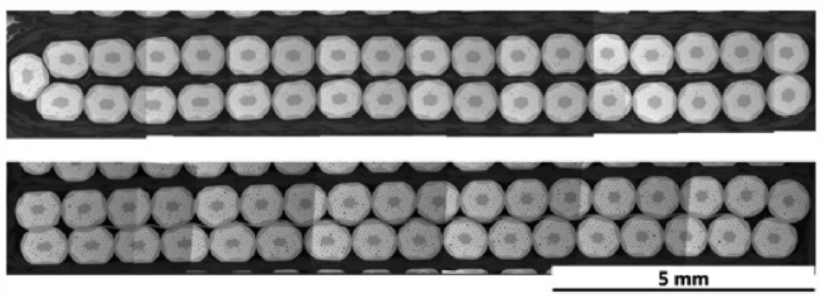


Figure 2.3.2. He gas flow probe for YBCO cables.

3. Cables

3.1. Nb_3Sn Rutherford Cables: Coupling Loss

Rutherford cables with cores of E-glass and S-glass woven tape and types AISI-316 and AISI-304 stainless steel (SS) ribbon were subjected to calorimetric AC loss measurement in transverse magnetic fields of amplitude 400 mT and frequencies of up to 90 mHz applied in the face-on (FO) and edge-on (EO) orientations. The results yielded the effective interstrand contact resistances (ICR), (to be defined), and corresponding estimates of the FO coupling magnetizations generated by fields ramping at the LHC-specified 6.5 mT/s. Detailed analysis of the results indicated: 1) a cable with a full-width 316-SS core and a satisfactory value would be suitable for magnet winding; 2) a cable with an off-center partial-width core had a very low and an excessively large coupling magnetization; 3) The cables with glass-tape cores although characterized by large and very small coupling magnetizations turned out to have mostly uncoupled strands with intermittent points of low resistance contact. In order to achieve the target ICR values, the level of glass insulation insert should be reduced and cable compaction adjusted. Figure 3.1.1 shows SEM micrographs of the cables with E-glass and S-glass.



3.1.1. SEM micrographs of Cable EG1 (upper) and Cable SS1 (lower).

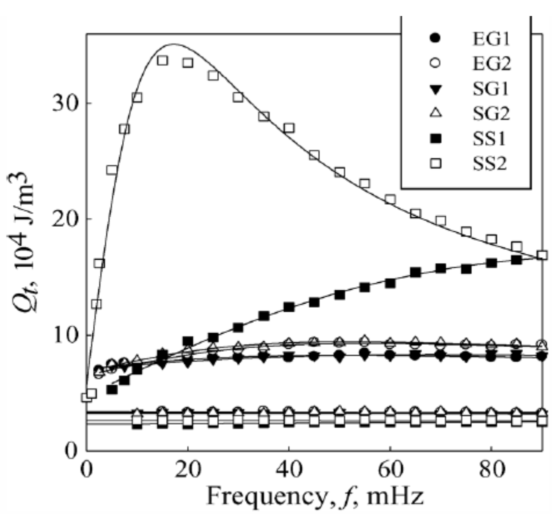


Table 3.1.1.

SUMMARY OF CALORIMETRICALLY MEASURED R_{eff} S

Cable Name	Core width mm	$R_\perp$ init.[(a)] μΩ	$R_\perp$ init. fit[(b)] μΩ	f_c mHz	$R_\perp$ from f_c [(c)] μΩ
EG1	12.7	--	68	50	1.8
EG2	12.7	--	33	55	2.0
SG1	12.7	--	88	69	2.4
SG2	12.7	--	33	52	1.9
SS1	12.7	14.5	16	116	4.3
SS2	8	0.8	1.0	17	0.6

Fig. 3.1.2. Total calorimetrically measured AC losses in FO applied fields (upper set of curves) and EO applied fields (lower set of horizontal lines).

Figure 3.1.2 shows the loss as a function of frequency for the different cables, and the summary of the Reff values are given in Table 3.11.

3.2. Nb_3Sn Rutherford Cables: Stability (Current Sharing) in Cored and Uncored Cables -- The development of a Nb_3Sn Single-Strand Excitation ICR/Current-Sharing Probe:

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 is done by mounting 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 3.2.1. The Nb3Sn Single-Strand Excitation ICR/Current-Sharing Probe.

3.3. Bi:2212 and YBCO

FEM modeling of very high field YBCO solenoids

YBCO coated conductor tapes are of interest in a number of possible high-energy physics applications, including high field solenoids for muon colliders operating in liquid helium bath. The final stage of phase space cooling for a muon collider uses a solenoid magnet with a field approaching 50 Tesla. Stability, the heat and quench propagation, and conductor protection are highly important in these applications. In the present contribution we performed a numerical Finite Element Method (FEM) modeling of stability, heating and quench propagation in a 50 Tesla solenoid immersed in liquid helium bath. It was supposed to be wound of a cable made of YBCO coated conductor tapes with a stainless steel interlayer insulation. A macroscopic anisotropic model for thermal propagation, with input data taken from experiments was developed and adopted in FEM simulations. Magnetic field and temperature dependent parameters, such as electrical and thermal conductivities, heat capacities etc., also taken from experiments, were considered. Obtained results are compared with our previous work in which a kapton tape was used as an interlayer insulation. We obtained the following main results (Fig. 3.3.1-3):

- mechanical stresses do not cause I_c degradation
- magnetic field component B||c axis of YBCO film is a limiting factor of I_c of the 50 T solenoid
- a less anisotropic YBCO film with a higher $I_c(B||c)$ might be useful
- YBCO CC tape is stable even if its $I \approx 0.5I_c$
- Compared with kapton interlayer insulation (in which case stagnant NZs exist) the same hot spots in the solenoid with stainless steel inter layer insulation cause only a moderate temperature increases (see Fig. 3 – 5) well below T_c of YBCO. This means that replacing kapton interlayer insulation by stainless steel substantially improves stability of the magnet (both thermally and mechanically). This is achieved by the fact that thermal conductivity of the stainless steel is significantly higher than that of kapton.
- Operating the solenoid at $I > 0.5I_c$ either a higher magnetic field can be achieved, or for getting just 50 T the solenoid size can be smaller
- Increasing the operating current I above $0.5I_c$ decreases the stability margin of the solenoid

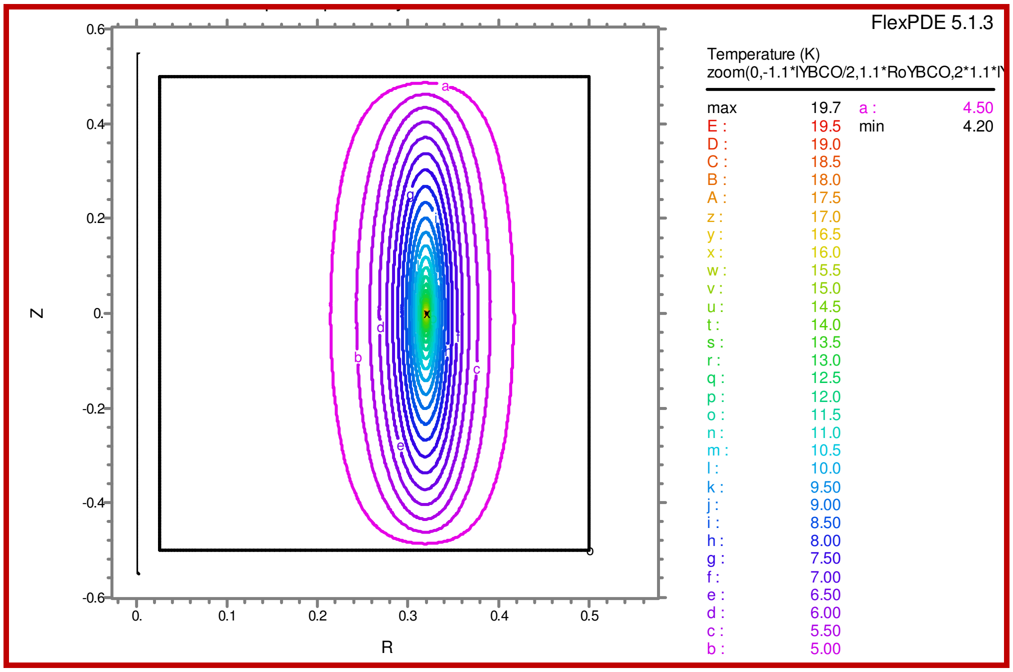


Fig. 3.3.1. 50 T solenoid with stainless steel interlayer insulation. Hot spot size= 100 μm x 1.2 mm, Hot spot resistivity=0.4 μΩm, J_e = 9.583 x 10^7 A/m^2 , Max. temperature = 19.7 K. The same hot spot in 50 T solenoid with kapton interlayer insulation led to max. temperature of 105 K !

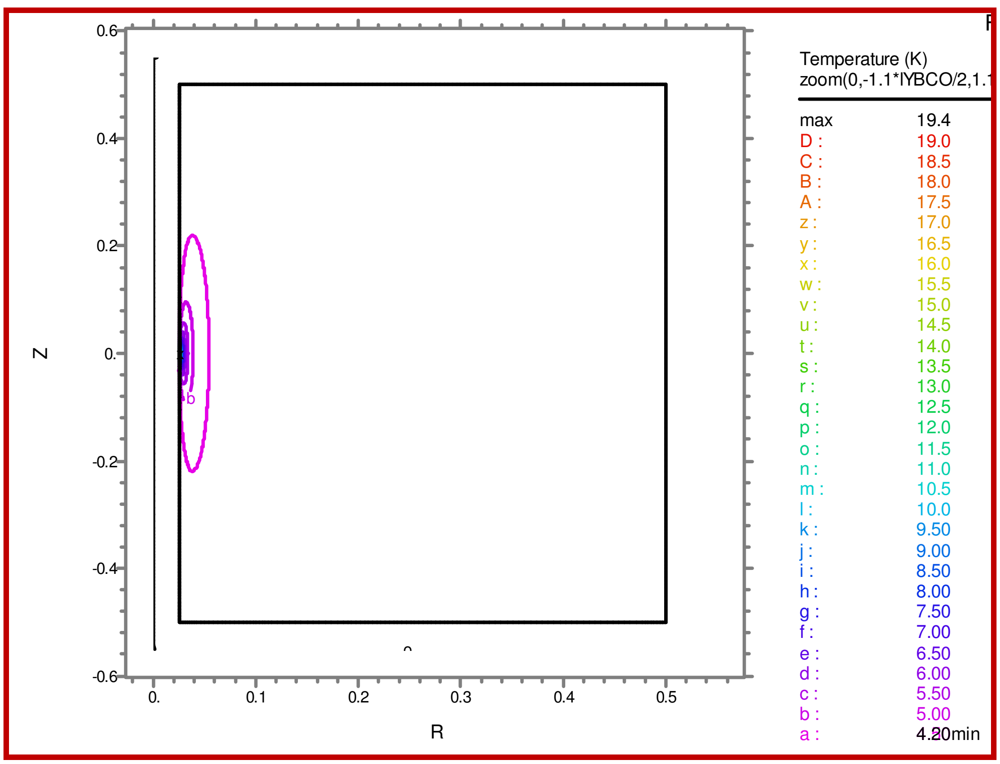


Fig. 3.3.2. 50 T solenoid with stainless steel interlayer insulation. Hot spot size = 100 μm x 1.2 mm, Hot spot resistivity = 0.85 μΩm, J_e = 9.583 x 10^7 A/m^2 , Max. temperature = 19.4 K. The same hot spot in 50 T solenoid with kapton interlayer insulation led to max. temperature of 93.3 K !

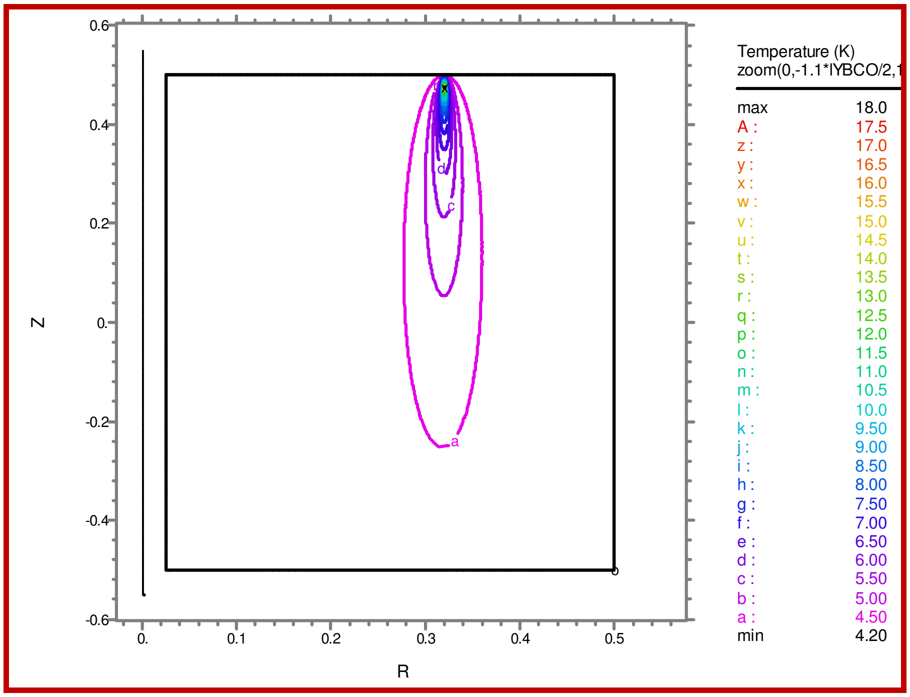


Fig. 3.3.3. 50 T solenoid with stainless steel interlayer insulation. Hot spot size= 100 μm x 1.2 mm, Hot spot resistivity=0.5 μΩm, J_e = 9.583 x 10^7 A/m^2 , Max. temperature = 18 K. The same hot spot in 50 T solenoid with kapton interlayer insulation led to max. temperature of 92.8 K !

These results have been published in: *[1] M. Majoros, M. D. Sumption and E. W. Collings, "Stability and normal zone propagation in a 50 T solenoid wound of YBCO coated conductor tape with a stainless steel interlayer insulation – FEM modeling", Presented at Cryogenic Engineering Conference & International Cryogenic Materials Conference, Anchorage, Alaska, USA, June 17 – 21, 2013.*

List of Papers Published, Presentations made, and Theses defended based on this Program (2010-2013)

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

I. A list of papers published from beginning 2010 through end of 2012

II. A list of Presentations made from 2010-2012

III. A list of Theses defended on this program from 2010-2012

I. PAPERS PUBLISHED IN 2010

9. S. Bhartiya, M.D. Sumption, X. Peng, E. Gregory, M.J. Tomsic, D. Doll, and E. W. Collings, "Comparison of A15 Stoichiometry and Grain Morphology in Internal Sn and Tube Type Strands; Influence of Strand Design, HTs and Alloying", Adv. Cryog. Eng. **56** (2010) 175.
10. E.W. Collings, M.D. Sumption, M.A. Susner, D.R. Dietderich, E. Barzi, A.V. Zlobin, and A. Nijhuis, "Coupling-Current and Persistent-Current Magnetizations in Nb_3Sn Rutherford Cables And Strands", Adv. Cryog. Eng. **56** (2010) 191.
11. M. D. Sumption, "Stability in Nb_3Sn Conductors; Magnetic and Self-Field Instability Considerations at 4 K And 2 K", Adv. Cryog. Eng. **56** (2010) 199.
12. J. V. Marzik, R. C. Lewis, M. R. Nickles, D. K. Finnemore, J. Yue, M. Tomsic, M. Rindfleisch, M. D. Sumption, "Plasma Synthesized Boron Nano-Sized Powder For MgB_2 Wires", Adv. Cryog. Eng. **56** (2010) 295.
13. M. Majoros, M. D. Sumption, M. A. Susner, S. Bhartiya, M. Mahmud, E. W. Collings, M. Tomsic, M. Rindfleisch, J. Phillips, D. Lyons, and J. Yue, "A Nb_3Sn-Based, Model Superconducting Helical Undulator Fabricated Using a Wind and React Process", IEEE Trans. Appl. Supercond. **20**, (2010) 270.
14. E.W. Collings, M.D. Sumption, M.A. Susner, E. Barzi, D. Turrioni, R. Yamada, A.V. Zlobin, and A. Nijhuis, "Coupling- and Persistent-Current Magnetizations of Nb_3Sn Rutherford Cables", IEEE Trans. Appl. Supercond. **20,** (2010) 1387.
15. Z.X. Shi, M.A. Susner, M. Majoros, M.D. Sumption, X. Peng, M. Rindfleisch, M.J. Tomsic and E.W. Collings, "Anisotropic Connectivity and its Influence on Critical Current Densities, Irreversibility Fields, and Flux Creep in in-situ Processed MgB_2 Strands, "Supercond. Sci. Tech. **23** (2010)-045018.
16. M.D. Sumption, M. Majoros, M. Susner, D. Lyons, X .Peng, C.F. Clark, W.N. Lawless and E.W. Collings, "Thermal Diffusion and Quench Propagation in YBCO Pancake Coils Wound with ZnO and Mylar Insulations", Supercond. Sci. and Tech. **23** (2010) 075004.
17. L.S. Lakshmi, M.P. Staines, R.A. Badcock, N.J. Long, M. Majoros, E.W. Collings and M.D. Sumption, "Frequency Dependence of Magnetic AC Loss in a Roebel Cable Made of YBCO on a Ni–W substrate", Supercond. Sci. and Tech**. 23** (2010) 085009.

PAPERS PUBLISHED IN 2011

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II PRESENTATIONS

Presentations 2010

1. M. D. Sumption, M. Kanuchova, M. Majoros, M. Susner, C. Myers, E.W. Collings, "Properties of $SmFeAsO_{1-x} F_x$ Type Oxypnictide Bulks and Wires Made via Several Routes", APS March meeting, Portland, Oregon, 2010.
2. M.D. Sumption, "Stability in Nb_3Sn Conductors; Magnetic and Self Field Instability Considerations at 4 K And 2 K", Applied Superconductivity Conference, Washington DC, Aug 2010.
3. M.D. Sumption, M. Susner, C. Kovacs, M. Border, D. Putnam, and E.W. Collings, "Transport, Magnetic, and Microstructure Studies for Rod-In-Tube and Tube Type Nb_3Sn Strands Optimized for Different Operational Regimes", Applied Superconductivity Conference, Washington DC, Aug 2010.
4. M.D. Sumption, D. Putnam, M. Susner, C. Kovacs, M. Border, and E.W. Collings, "Stoichiometry and Morphology studies of the microstructures of Tube Type Nb_3Sn Strands", Applied Superconductivity Conference, Washington DC, Aug 2010..
5. M.D. Sumption, M. Susner, S. D. Bohnenstiehl, Y. Yang, S. Dregia, "Phase Formation in MgB_2, and the Influence of Density and Connectivity on a Transport--Magnetic Measurement Bifurcation", CIMTEC 2010, Montecatini Terme, Italy, July 2010.
6. **Invited**: M.D. Sumption, "Superconducting Materials for Application", The University of Houston and the TcSUH center, July 2010.
7. M.D. Sumption, "Anisotropic Connectivity and its Influence on Critical Current Densities, Irreversibility Fields, and Flux Creep in in-situ Processed MgB_2 Strands", The Materials Research Society Meeting, San Francisco, April 2010
8. **Invited:** M.D. Sumption, "M. D. Sumption, M. Majoros, and E.W. Collings"YBCO Conductors for HEP applications", MS&T, Oct 17-21, Houston TX.
9. **M.**D. Sumption, MgB2 for Accelerator Applications, LTSW 2010
10. **M.**D.Sumption, Quench Aspects of YBCO at 4 K" Post LTSW 2010 Program"

11. “Formation, Flux Pinning, Connectivity, and the Evolution of Structural and Superconducting Properties with Heat Treatment Time in *in-situ*-C-Doped MgB_2” E.W. Collings, M.D. Sumption, M.A. Susner, S.D. Bohnenstiehl, Z.X. Shi, and T.W. Daniels
12. “Evolution of Superconductive Properties and Texture with Heat Treatment Time in Carbon-Doped *in-situ*-Processed MgB_2 Strands”, E.W. Collings, M.D. Sumption, M.A. Susner, Z.X. Shi, and T.W. Daniels
13. “Phase Formation in MgB_2, and the Influence of Density and Connectivity on a Transport--Magnetic Measurement Bifurcation”, M.D. Sumption, M. Susner, S. D. Bohnenstiehl, Y. Yang, S. Dregia
14. M. Majoros, M. D. Sumption, D. Turrioni, E. Barzi, A. Zlobin, A. Nijhuis, E. W. Collings, “AC Losses and Transport Current in Roebel Cable Made of YBCO Coated Conductor Tapes”.
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18. S. Bohnenstiehl, M. D. Sumption, E. Collings, “Exploring the Limits of B_{c2} and Dopant Solubility in MgB_2 Using High Temperature and High Pressure Processing”.
19. M. Majoros, M. D. Sumption, M. A. Susner, V. Lombardo, D. Turrioni, E. Barzi, E. W. Collings, “Heat and Quench Propagation in YBCO Coated Conductor Coils at 4.2 K and Subjected to Applied Fields - Modeling and Measurement”.
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22. M.A. Susner, M.D. Sumption, E.W. Collings, “Pinning and Connectivity MgB_2 Thin Films and PIT Strands”.
23. X. Peng, J. Phillips, M. Rindfleisch, M. Tomsic, E. Gregory, M.D. Sumption, E.W. Collings, “Progress of Nb_3Sn Conductor Fabrication at Hyper Tech Research”.
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Presentations 2011

1. E.W. Collings, Part-I, "Critical current density optimization of ideal grain-boundary pinned MgB_2 in various field ranges: influence of irreversibility field and connectivity": Part-II "Normal and superconducting radiofrequency cavities for high energy accelerators" ISEM, University of Wollongong, Wollongong, NSW, Australia, Feb. 8, 2011
2. E.W. Collings, "Interstrand contact resistance of Nb_3Sn Rutherford cables with cores of MgO tape and s-glass ribbon", Industrial Research Ltd, Lower Hutt, New Zealand, March 10, 2011
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21. Y. Ding, Y. Sun, X. D. Wang, J. C. Zhuang, L. J. Cui, Z. X. Shi, M. A. Susner, C. S. Myers, M. Majoros, M. D. Sumption, and E. W. Collings, “Effects of the sintering atmosphere on the superconductivity of $SmFeAsO_{1-x} F_x$ compounds”, Presented at the ICMC-CEC 2011 Spokane, WA.
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1. M.D. Sumption, M. Majoros, and E.W. Collings, "Contact Resistance, Current Sharing, Coupling Currents, and Magnetization for Coated Conductor Roebel Cables and CORC cables for HEP Applications", 2012 Applied Superconductivity Conference, Portland, Oregon
2. M.D. Sumption, X. Xu, and E.W. Collings, "Studies of Sn limits in Nb3Sn Conductors of Several Types", Low Temperature Superconductor Workshop, Napa Valley, CA, Nov 5-7, 2012
3. M.D. Sumption, M. Majoros, E.W. Collings, "Contact Resistance, Current Sharing, Coupling Currents, and Magnetization for Coated Conductor Roebel Cables and CORC cables for HEP Applications", Low Temperature Superconductor Workshop, Napa Valley, CA, Nov 5-7, 2012
4. M.D. Sumption, Cables for HEP Applications, MAP Meeting, Fermilab, May 2012.
5. M.D. Sumption, M.Susner, S. Bohnenstiehl, and E.W. Collings, "Multilayer Structures in MgB_2 Superconducting thin Films; Doping Pinning, Connectivity", The 2012 APS March Meeting, Boston MA.
6. **G Li**, M Susner, Y Yang, M Sumption, M Rindfleisch, M J Tomsic, J Yue, C Thong, E W Collings Transport and connectivity properties of internal magnesium diffusion MgB_2 wires, 2012 ASC Portland, Oregon.
7. M Susner, M Sumption, **G Li**, Y Yang, M Rindfleisch, E W Collings, Connectivity in MgB_2 thin films and wires, 2012 ASC Portland, Oregon,
8. Y Yang, **G Li**, M Susner, M Sumption, M Rindfleisch, M J Tomsic, E W Collings2012 Strong enhancement of critical current density and upper critical field in rare earth oxide nano-particle doped MgB_2, ASC Portland, Oregon,
9. C. Kovacs, "Stability measurements in Nb_3Sn strands with various wire and sub-element diameters and thermal environments", ASC Portland, Oregon,
10. C. Kovacs, "Single-strand excitation measurements for probing current sharing in Nb_3Sn Rutherford Cable at 4.2 K up to 15T", ASC Portland, Oregon.
11. X. Xu, "Correlation of A15 microstructure and transport in Nb_3Sn tube type and Rod-in-Tube (RIT) strands: the influence of heat treatments, Cu/Sn ratio, and filament size", ASC Portland, Oregon.
12. M. Majoros, "FEM Quench Modeling of a 50 Tesla Solenoid Wound of YBCO Coated Conductor Tape", ASC Portland, Oregon.
13. E.W. Collings, "Magnetic Measurements of AC Loss and Interstrand Contact Resistance in Nb3Sn Rutherford Cables with Cores of Different Materials and Widths", ASC Portland, Oregon.
14. C. Myers, "Specific Heats and Thermal Conductivities of Bi2212, Nb_3Sn, MgB_2, and YBCO Conductors", ASC Portland, Oregon.
15. Y. Yang, "Strong enhancement of critical current density and upper critical field in rare earth oxide nano-particle doped MgB_2", ASC Portland, Oregon.

16. X. Xu, "Studies of stoichiometry, upper critical field (B_{c2}) and transport for tube type and Rod-in-Tube (RIT) Nb3Sn strands heat-treated at various temperatures", ASC Portland, Oregon.
17. C. Myers, "Transport, Magnetic, and SEM Characterization of Novel and Conventional Bi-2212 Strands and Rutherford Cables", ASC Portland, Oregon.
18. M. Majoros, "YBCO pancake coils - stability and normal zone propagation", ASC Portland, Oregon.

Theses

1. Scot David Bohnenstiehl, *Thermal Analysis, Phase Equilibria, and Superconducting Properties in MgB_2 And Carbon Doped MgB_2.*

2. Michael Adam Susner, *Influences of Crystalline Anisotropy, Doping, Porosity, and Connectivity on the Critical Current Densities of Superconducting Magnesium Diboride Bulks, Wires, and Thin Films,* PhD Thesis, 2012.

3. Shobhit Bharitya, *A15 Stoichiometry and Grain Morphology in Rod-In-Tube and Tube Type Nb_3Sn Strands; Influence of Strand Design, Heat Treatments and Ternary Additions*, M.S. Thesis, 2010.