FINAL REPORT

DOE Grant Award Number **DE-SC0004062**
Recipient: **Tufts University**
Project Title: **Superconducting technology for magnet systems in fusion machines**
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Date of report: **7/15/2015**
Period Covered by Report: **4/15/2010-4/14/2015**

INDEX: *Page*

1. Executive Summary

The focus of the research supported by this grant is superconductivity and in particular the electromechanical behavior of superconducting materials and wires used in powerful magnets (for magnetic fields between 8 and 20 T). Superconducting materials are metal alloys or ceramic compounds whose electrical resistance disappears within controlled conditions. This property allows superconducting materials to carry much higher currents than conventional materials. The applications for these materials ranges from healthcare and sustainable energy production and transmission, to the development of high-energy systems required in nuclear fusion energy technology and fundamental research on the origin of matter (high-energy physics).

In the area of ***healthcare***, superconducting magnets are used in Magnetic Resonance Imaging (MRI) devices. These superconducting magnets can operate indefinitely without dissipation of power, allowing considerable savings. Additionally, the high magnetic fields achieved by superconducting magnets provide improved resolution of the images and thus improve detection of abnormalities. In ***energy production***, superconducting wires are being used to create high-efficiency generators and transformers. In *energy transmission*, superconducting cables are proposed as a means to efficiently transmit energy over long distances, such as from distant wind turbine farms to populated areas.

The research in the PI's group is strongly motivated by ***high-energy physics*** and ***fusion energy*** research that requires superconducting wires and magnets. The Large Hadron Collider (LHC) is a *particle accelerator* at CERN in Switzerland that uses superconducting magnets to confine and accelerate charged particles to very high energies [1]. The collisions between the charged particles allows for a fundamental understanding of the structure of matter at the subatomic level. The International Thermonuclear Energy Reactor (ITER), currently under construction in Cadarache, France, is an experimental *fusion energy machine* whose aim is to demonstrate the feasibility of producing energy through nuclear fusion [2]. In this case the magnets are used to confine a plasma (very hot charged particles) inside a vessel for enough time such that nuclear fusion can occur and excess energy can be extracted to run conventional steam power production cycles. Nuclear fusion has several advantages compared to the more conventional nuclear fission, namely that it creates almost no radioactive waste and no danger of meltdown or accidents causing radioactive pollution.

With the support of the DOE-OFES Early Career Award and the Tufts startup support the PI has developed experimental and analytical expertise on the electromechanical characterization of Low Temperature Superconductor (LTS) and High Temperature Superconductor (HTS) for high magnetic field applications. These superconducting wires and cables are used in fusion and high-energy physics magnet applications. In a short period of time, the PI has built a laboratory and research group with unique capabilities that include both experimental and numerical modeling effort to improve the design and performance of superconducting cables and magnets. All the projects in the PI's laboratory explore the fundamental electromechanical behavior of superconductors but the types of materials, geometries and operating conditions are chosen to be directly relevant to real machines, in particular fusion machines like ITER. ***This work has generated scientific and engineering knowledge published in 19 articles and presented in 6 conferences.*** The work also generated new collaborations with top scientist in the field of superconductivity at national laboratories around the world like CERN in Switzerland and the National High Magnetic Field Laboratory (NHMFL) in Florida. All the activities have been carried out by mechanical engineering students at Tufts University (three Ph.D., seven M.S. students and thirteen undergraduates) and the PI herself.

The PI would like to stress the importance of the support from DOE-OFES for the research findings described in this document. This grant allowed the PI's team to ***deepen the understanding of the electromechanical behavior of superconducting strands in cables*** (as shown by the several scientific publications) ***to design more efficient magnets for the fusion program*** given that superconducting magnets are currently one of the largest investments of a fusion machine.

More importantly, ***this work allowed the PI to establish herself as educator and researcher in the area***. Superconductivity is a multidisciplinary subject that enhances the knowledge of students on multiple levels: physics, material science and mechanical and electrical engineering. ***This grant allowed the PI to engage and prepare future engineers in the strategic area of magnet technology***. The students involved in this project would have to learn the physics principles of a fusion machine and its engineering challenges. They developed an in-depth knowledge of superconductivity and the techniques of precise measurements at cryogenic temperatures. The work presented in this report ***allowed the establishment of a unique educational program*** which is currently present in only very few US universities and expanded the number of universities offering an education related to fusion science.

The PI's hope is ***to maintain the excellent program that was established during the last few years and to continue the effort of educating the next generation of engineers in the field of superconducting magnets for fusion machine through any support that DOE-OFES can provide in the future***.

2. Technical Relevance

For a material to be superconductive, it has to operate within certain limits of current density (A/mm^2), magnetic field (T) and temperature (K). These limits become more restrictive when the superconductor experiences mechanical strain. The superconducting wires used in the magnets for high-energy physics and fusion energy applications, experience large and/or cyclic stresses that inevitably cause the superconducting material to experience mechanical strain. Therefore, it is necessary to ***design experiments to quantify*** how superconducting materials and wire respond to strain and to **measure** the impact of mechanical strain on the operating limits. This allows ***developing numerical and analytical models*** with predictive capability. By integrating experimental design, measurement and modeling, the PI's research group addresses three aspects of superconductivity research that are critical for successful implementation of superconducting materials and wire in highly complex and expensive applications.

3. Research Focus

Superconductors are loosely classified according to their operational temperature: Low Temperature Superconductors (LTS) operating typically at 1.9 K or 4.2 K; and High Temperature Superconductors (HTS) typically operating at 77 K. The PI's group studies Nb_3Sn and YBCO, the top of the line LTS and HTS respectively. For both materials the PI and her research group perform complementary experimental and modeling activities.

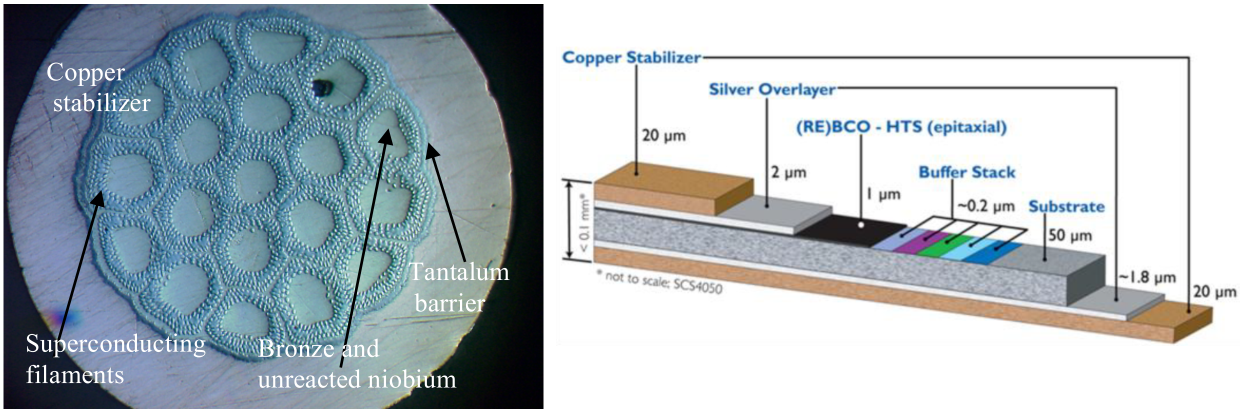

Fig. 1 Left: Cross section of Nb_3Sn superconducting strand (internal tin type, diameter ~0.8 mm) and its material components [3]. Right: Schematic view of the various layers of materials forming a HTS-YBCO conductor [4].

In Fig. 1 (left) the cross section of a typical LTS superconductor (Nb_3Sn) is shown. The PI's research group studies Nb_3Sn, which is composed by copper, niobium and tin; because it is the conductor of choice for future high-energy physics and fusion energy applications requiring high magnetic fields. The cross section shows the superconducting filaments (roughly 5 μm in diameter) contained by a tantalum barrier and surrounded by copper. When formed the Nb_3Sn filaments are very brittle and can easily deform and break under mechanical strain.

Another material of interest for the PI's research is HTS Rare-Earth-Barium-Copper-Oxide (REBCO) material (for example YBCO, yttrium-barium-copper-oxide). In this case the material is manufactured through a vapor deposition process in which various buffer layers are deposited over a metal substrate. Those layers allow to properly depositing a 1 μm thick superconducting layer (Fig. 1 - right). The HTS conductor of interest for the PI's research is a tape instead of a round wire and can achieve even higher magnetic fields than Nb_3Sn. Also in this case the superconducting layer is very brittle and sensitive to mechanical strain.

Despite the performance limitation caused by strain for both Nb_3Sn and YBCO, those materials are the most advanced and most promising and the prime candidates for applications requiring high magnetic fields.

3.a Experimental Effort

The focus of the PI's experimental research is to better understand the electromechanical behavior of superconducting materials (Nb_3Sn strands and small cables composed of up to 45 strands, YBCO tapes and small cables composed of up to 50 tapes) under loading conditions that are similar to the ones experienced during operations. A typical superconducting cable is composed of several strands twisted together and the description of the interaction among all those strands is a very complex problem. The interaction of current and field of those strands during operation creates large forces on the materials. Such forces include: (i) axial forces, caused by operation and the cool-down process and thermal contraction of the different components in a magnet, (ii) bending forces, caused by the twisting of the strands in a cable; and (iii) transverse load, due to induced electromagnetic load during operation (electromagnetic force or Lorentz force is the product of current and magnetic field). Depending on the application, the design of a cable and the magnet will be tailored to obtain the most desired conditions [5-6].

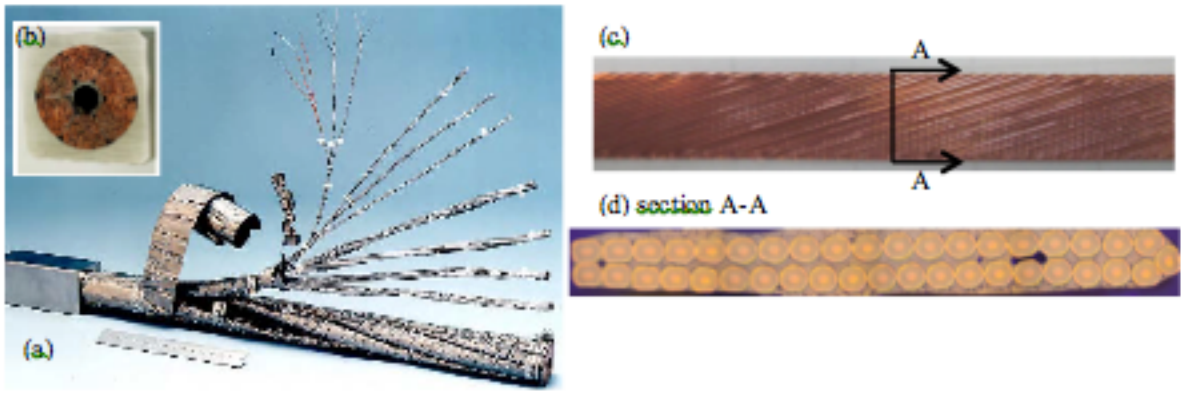

Fig. 2 (a) Typical configuration for a Cable In Conduit Conductor (CICC) used for fusion energy applications (~1000 strands). Those cables have an outside jacket for mechanical support (a square with side of ~ 40 mm, see cross section(b)) and to contain the cryogenic fluid that is forced through the winding. Current and field of interest are ~40-60 kA, 10-20 T respectively [3]. (c) Typical configuration for a Rutherford cable used in High-Energy Physics applications (top view). The strands (typically 40 strands, see cross section (d)) are wound to form a flat compact cable (~15 mm wide and 2 mm thick). Current and field of interest are 15 kA and 11 T [7].

In high energy physics applications, the magnets need to be very stable and the magnetic field extremely precise, therefore the coils are designed to be compact and very well supported mechanically to avoid any conductor movement (Fig. 2(c-d)). In fusion energy applications, high currents are required and thermal stability of the conductor is a key factor (Fig. 2(a-b)).

Unfortunately, tests on full size cables would be extremely expensive (more than $ 500,000 for each test) and impractical at the laboratory level since they require large bore magnets with high magnetic fields (up to 12-15 T) and high test current (up to 20 kA for high-energy physics applications and up to 40-60 kA for fusion applications). Therefore, experiments are typically done on single strand or small sub-sized cables with an external mechanical force simulating the electromagnetic force experienced during operations. The experimental findings are then extrapolated to the full size cable with numerical modeling analysis. The extrapolation process is a key topic of interest for the PI’s research group and the PI’s scientific community at large.

The PI’s research group designs and builds custom equipment and develops procedures to apply mechanical strain to the conductors of choice (e.g., pure bending and transverse forces) and make the necessary measurements of their mechanical and electromagnetic response. We perform experiments on HTS conductors at Tufts University, as only a temperature of 77 K is required and often self-field conditions are sufficient to characterize the conductor. We perform experiments on LTS conductors (or large HTS cables carrying high currents), which require very low temperature and high magnetic field (12-20 T), at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, FL.

3.b Modeling Effort

Along with experiments, we develop finite element analysis (FEA) codes to extrapolate the experimental results obtained at the small scale to the full size applications. The experiments on strands and small cables are used to validate the FEA. The FEA is then used to predict the behavior of larger cables that would be too costly and difficult to test for a university research laboratory (power supplies in the range of 20-50 kA and a facility to produce/recover helium would be necessary).

The FEA program used in the PI's group is ANSYS®, which is commercially available and well suited for the type of simulations we perform. The program is used to determine the mechanical response of a superconductor (strand or cable) to mechanical or electromagnetic loading conditions. We are typically interested in the strain distribution inside the material to be able to predict its electrical performance. The multi-scale nature of simulating superconducting materials (μm scale) and their integration into strands (mm scale), cables (~ 50-100 mm scale) and magnets (m scale), is one of the main challenges to the modeling effort.

4. Comparison of actual accomplishments with goals and objectives of the project

Table I summarizes the activities that were originally proposed and what as been accomplished. As reported in Table I, most of the activities have been accomplished. The few activities not completed were modified with more economical choices and studies more relevant to the scientific community. In particular, a new device to test 3-strand Nb_3Sn samples was preferred to the more expensive option originally proposed due to the shortage and increase in price of liquid helium. Additionally, the PI decided to spend more time in the modeling and experimental characterization of HTS-REBCO materials and cables. This choice was made for several reasons: both the High Energy Physics and Fusion communities are interested in HTS materials for future high field magnets, REBCO does not require any additional treatment and can be tested as received by the manufacturer and given its properties it can be tested at 77 K in self-field allowing the PI and her group to perform the experimental activities locally at Tufts.

Some of the funding fro the grant was spent to acquire a cryocooler system. Additional funding from the PI's startup was used to make the system operational (water chiller, electrical work). The cryocooler will be used to continue the research activities on REBCO materials.

Table I actual accomplishments with goals and objectives of the project.

Year	Activities	Status	Comments
1	Pure bending experiment on 12 single strand Nb_3Sn samples (@NHMFL)	✓	
	Design and construction of the material characterization probe and calibration of known materials	✓	
	2D finite element analysis of single strand and 3-strand cable. Perform simple tests to verify the results.	✓	
	Participation to one conference: ASC-2010, Washington D.C.	✓	Two poster contributions.
2	Transverse load experiment of 6 different cable samples. Among the samples we will consider 6-round-1 cable configuration. (@NHMFL)	✓✗	We decided to build a new device that would allow us to test 3-strand sub-cables while saving on helium cost.
	Pure bending experiment on 12 single strand Nb_3Sn samples (@NHMFL)	✓	
	Acquisition and installation of cryocooler for material test characterization	✓	Recently acquired (August 2014). Extra funding from PI's startup was used to make the system operational were necessary (water chiller, extensive electrical work).
	Use of the material characterization probe to test single strands to study stress-strain curve characteristics	✓	
	Extension of finite element analysis of single strand and 3-strand cable to 3D.	✓	
	Participation to one conference: CEC-ICMC 2011, Spokane (WA)	✓	Two poster contributions.
3	Pure bending experiment on 12 single strand Nb_3Sn samples (@NHMFL)	✓	
	Stress-strain curves and Young's modulus measurements of 20 single strand samples (LTS)	✓	
	Design and build stress-strain characterization test setup for sub-cables samples. Stress-strain curves and Young's modulus experiments of 5 sub-sized cables (LTS)	✗	A shift towards HTS conductor was made to save helium and perform tests at Tufts instead that going to NHMFL. More work has been done on HTS single tapes cable options.
	Finite element analysis of 6-in-1 cable and higher stage cables (LTS). Start analysis on HTS single strand or tape	✓✗	A shift towards HTS conductor was made to save helium and perform tests at Tufts instead that going to NHMFL. More work has been done on HTS single tapes cable options.
	Participation to one conference: ASC-2012, Portland (OR)	✓	Five poster contributions. One oral contribution.
4	Test of samples using the material characterization probe: Stress-strain curves and Young's modulus measurements of 10	✓✗	Many single strand LTS samples were tested. Cables were not tested as the focus

	single strand samples and 5 sub-sized cables (LTS, HTS).		was shifted to HTS conductors. In the future HTS cables could be tested with the probe.
	Finite element analysis of HTS cable designs	✓	
	Participation to one conference: MT-23, Boston (MA)	✓	One poster contribution. One oral contribution.
5	Test of samples using the material characterization probe: Stress-strain curves and Young’s modulus measurements of 10 single strand samples and 5 sub-sized cables (LTS, HTS).	✓✗	Many single strand LTS and single tape HTS samples were tested. Cables were not tested as the focus was shifted to HTS conductors. In the future HTS cables could be tested with the probe.
	Finite element analysis of HTS cable designs	✓	Work is done on TSTC cable option and the ENEAN cable option (in collaboration with ENEA laboratory in Italy). See later for more details.
	Conglomeration of the 5-year project results	✓	
	Participation to one conference: ASC-2014, Charlotte (NC)	✓	Two poster contributions. One plenary talk contribution.

5. Key Results

In this section the key results obtained by the PI's research group's experimental and modeling efforts are summarized. All experiments are designed to isolate a single loading condition that a conductor (Nb_3Sn or YBCO) would experience in a magnet to understand the overall behavior of a superconductor inside complex magnets where multiple types of loads are present simultaneously.

5.a Electromechanical characterization of Nb_3Sn wires and cables

We routinely perform tests to study the behavior of single Nb_3Sn strands under pure bending conditions and transverse loads. Two devices (pure bending and transverse load devices) were developed and tested at the National High Magnetic Field Laboratory (NHMFL) since high magnetic field (10-20 T) and low temperatures (4-10 K) are required.

5.a-I Pure bending device

Fig. 3 shows the variable bending-strain device that was designed and built to characterize the critical current of Nb_3Sn strands for up to 1.25% bending strain (critical current being the maximum current a superconductor can carry at given field and temperature without losing its superconducting state).

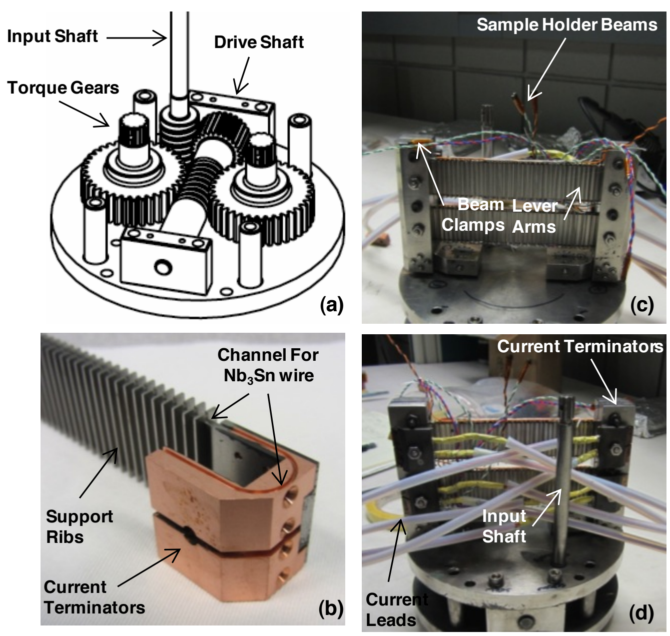

Fig. 3 Pure bending test device. (a) Gear train consisting of two continuous worm drives [8]. (b) Sample holder beam highlighting vertical support ribs, wire channel and current terminator [9]. (c) Front view of bending device showing two sample holders, lever arms and beam clamps [10]. (d) Back view of bending device indicating current leads, current terminators and input shaft [10].

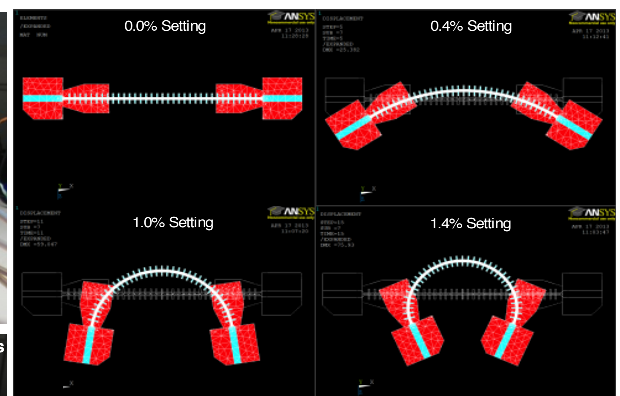

Fig. 4 Deformed shape of the pure bending device for four strain values covering the entire bending range, as determined by numerical simulation [10].

Fig. 3 shows a schematic view of the device, with strands mounted in channels at the upper and bottom edges of the ribbed support. Fig. 4 shows a finite element simulation of the ribbed support and a strand when bending strain up to 1.4% are applied. Fig. 5 shows typical experimental data for the critical current as a function of strain collected during an experiment.

The change in critical current as a function of the strain is significant: one type of strand (Hitachi Bronze Route) recovers completely when the strain is removed, whereas the other one (Oxford, Internal Tin) shows significant permanent degradation when the strain is removed. Internal Tin and Bronze Route refer to the different manufacturing processes of the two types of strands that produce different filament architectures in the cross section. This type of data is valuable for scientists to generate a database of electrical properties of superconductors used in fusion magnet applications. Additionally, these measurements allow verifying our numerical simulations and creating predictive capability.

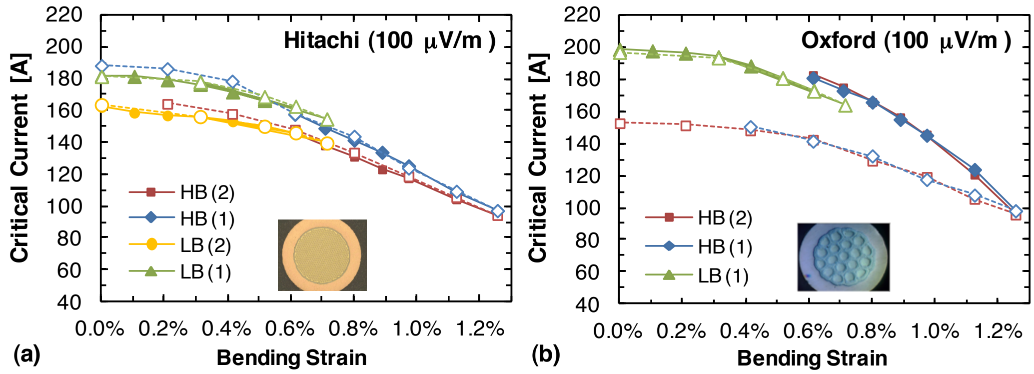

Fig. 5 Critical current results for low bending (LB) and high bending (HB) sample holders. Two samples from each wire type were tested on each sample holder. (a) Results for Hitachi samples (bronze route wire). (b) Results for Oxford samples (internal tin wire, see Fig. 1). White symbols with dashed lines indicate recovery data after reaching maximum bending (LB(2) data is missing due to premature transitions of the sample, preventing the measurements of critical current values). Internal Tin and Bronze Route refer to the different manufacturing process of the two types of strands that produces different filament architecture in the cross section. Both types of strands are used in the ITER machine.

5.a-II Transverse load device

Another device designed by the PI's research group, was built to apply transverse load onto Nb_3Sn strands and small cables. Its main components are shown in Fig. 6. Similar critical current measurements as those shown in Fig. 5 are performed this time as a function of transverse load.

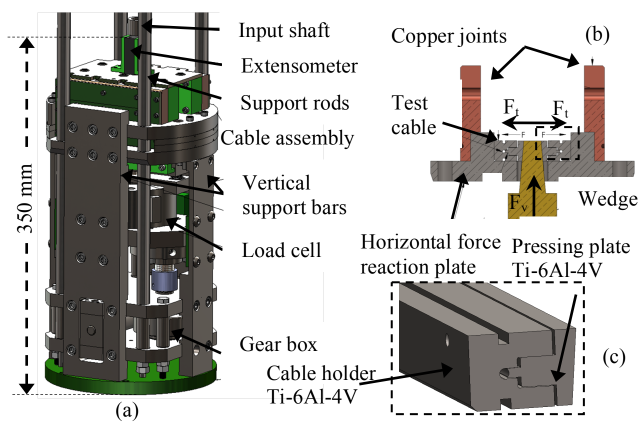

Fig. 6 Probe head and its major components. (b) Cross section of the cable assembly. The sample holder and the pressing pieces are constrained vertically by two reaction plates (only the bottom one is shown in the cross section). (c) Detail of the cable holder section and the matching pressing piece applying the load. F_t = transverse force, F_v = vertical force.

5.b Electromechanical characterization of YBCO tapes and cables

High temperature superconductors, especially YBCO coated tapes, have excellent high current capabilities at high magnetic fields (much higher than LTS conductors). For this reason it is desirable to develop a large multi-strand cabling method for flat HTS tapes to be used in future superconducting magnets. A cabling method of a Twisted Stacked-Tape Conductor (TSTC) for YBCO tapes has been developed recently at MIT [11]. This cable consists of a stack of HTS tapes twisted together along the stack's axis (Fig. 7). Given the expertise established by the PI's group on characterization of LTS conductors, we started a collaboration with MIT and the PI's group was asked to developed test devices and numerical analysis using FEA to electromechanically characterize twisted single tapes and stacked-tape cables.

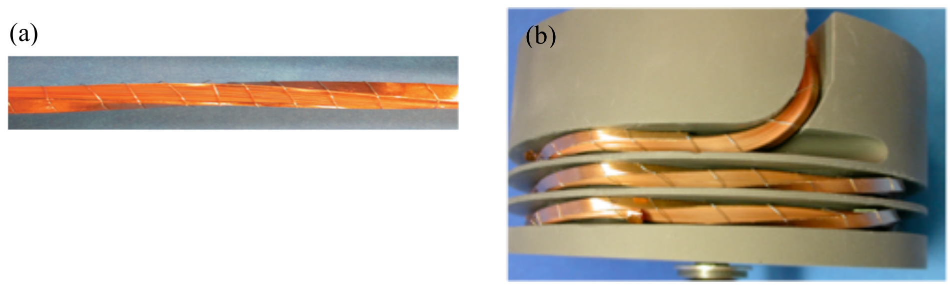

Fig. 7 TSTC conductor composed of (a) 32 tapes stacked and twisted, (b) 50 tapes stacked twisted and wound on a aluminum former.

As in the case of Nb_3Sn, during operation the tapes will experience different types of loads: axial load (due to the cool down), torsion load (due to the design of the cable and the tapes being twisted) and transverse load (caused by the electromagnetic force product of the current and magnetic field, for example 200 kN/m for a cable carrying 10 kA at 20 T).

The PI's group performed a series of experiments to determine the electromechanical behavior of twisted stacked-tape cabling behaviors [12]. We developed a probe to simultaneously measure the torsion torque and the critical current as a function of twist pitch for single tapes. Additionally, we performed a series of experiments to measure the critical current as function of transverse load [13]. Since the tapes are twisting along the cable's axis, it is important to know the effect of transverse load not only on the wide face of the tape but also on its thin edge. The transverse load was first applied on the wide face of the tapes for a direct comparison with already available studies by other researchers [4]. The load was then applied on the thin edge of the tapes (see Table I below). This second experiment is a novel test and to our knowledge no data on the behavior of tapes under this load have been reported before.

The type of information collected with these experiments is very unique as no one else has the setups as the ones developed in the PI's lab capable of measuring simultaneously electrical and mechanical behavior of superconducting tapes and cables. This type of information is crucial to future design and manufacturing choices.

4.b-I Simultaneous measurements of critical current and torque for twisted single tape

The device used for critical current measurements as a function of twist pitch (shorter pitch means a tighter twist) is shown in Fig. 8. The torque meter shown in the figure is used to evaluate the mechanical response of the material to torsion (elasto-plastic behavior and mechanical hysteresis). Simultaneously, critical current data as function of twist pitch can be collected and a set of typical measurements is shown in Fig. 9. As seen in Fig. 9 the critical current is constant up to a twist pitch of ~ 120 mm. Decreasing the twist pitch further degrades the reversible critical current by few percentages (second cycle, 70 mm twist pitch). Further reduction of the twist pitch irreversibly degrades the sample and rapidly reduces the critical current values to 73% of the initial values for SuperPower (company producing the tape), for a twist pitch of 50 mm. This information is crucial to the understanding of the twisting limitations of the tapes while assembling a cable. The behavior of the conductor under these loading conditions will drive the design and manufacturing choices of researchers making large-scale magnets.

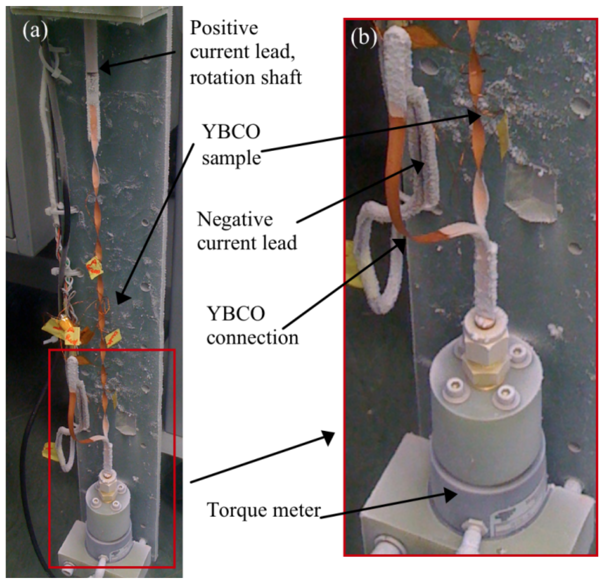

Fig. 8 (a) Overall picture of the torsion device. The sample is soldered to two copper plates. The top plate acts as both a positive current lead and a rotation shaft to twist. The bottom plate is fixed on the torque meter. (b) Detail of the torque meter and the copper termination on a G10 adapter where the sample is soldered to the negative current lead through an extra YBCO tape.

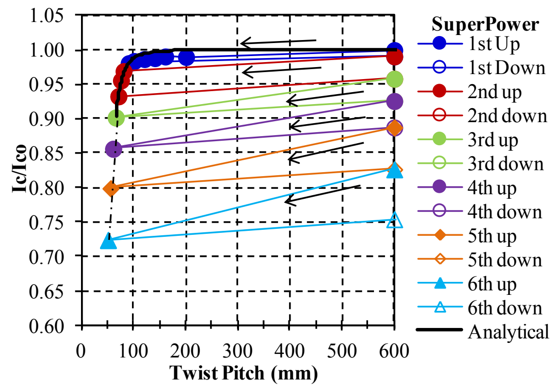

Fig. 9 Normalized critical currents as a function of the twist pitch for SuperPower tape. The voltage tap length is 100 mm, critical current criterion of 100 μV/m. Measurements at 77 K and self-field conditions (no external field applied).

5.b-II Transverse load test device

As mentioned earlier, besides torsion effects, it is important to understand the effects of the electromagnetic load on the tapes during operation. Since the tapes are twisted along the cable's axis, they could experience transverse load perpendicular to their wide face or load on their thin edge. To access this data, the PI's group designed and built a device, shown in Fig. 10, to characterize single YBCO tapes under transverse load conditions.

The load is applied through a commercially available bolt-grip push-puller (10 tons capacity). The forcing screw is rotated to push rod downward, applying a force to the sample area. The load can be applied either on the wide face of the tape or on its thin edge (Fig. 11). The tape is more sensitive to the load applied on the thin edge when visible delamination of the different layers composing the tape occurs (i.e., the layers separate). The same device is used to characterize multiple tapes (stacked tapes without twisting them) and TSTC cables. These measurements will provide useful information to manufacturers and users of this material so that the material can be improved and/or its limitations taken into account during the fabrication of cables and magnets for expensive applications.

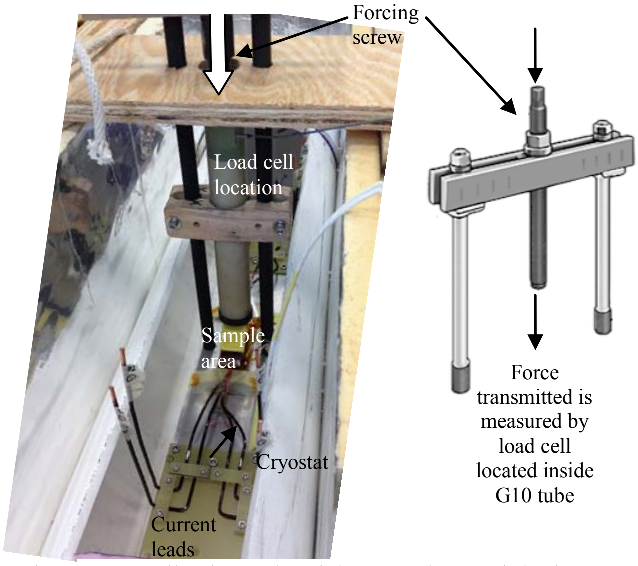

Fig. 10 Overall schematic of the experimental device. The load is applied through a forcing screw onto the sample area where different pressing pieces were interfaced depending on the sample tested. A load cell measures the vertical load applied to the sample.

Table I

EXPERIMENTS PERFORMED ON CABLES AND SINGLE TAPES

Sample type	Experiment performed	$L_{pressed}$ in mm (VT length in mm)
I. Single tape (AMSC) Single tape (SP)	Wide face transverse load	25 (50)
II. 2 parallel tapes (AMSC) 4 parallel tapes (SP)	Thin edge transverse load	170 (175)

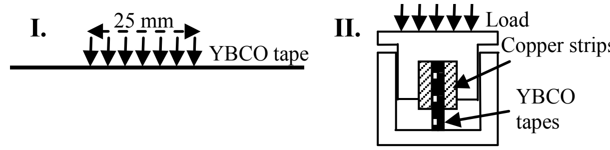

Fig. 11 Schematic view of the experiments performed: I wide face transverse load, II. Thin edge transverse load.

5.c Measurements of mechanical properties of superconducting materials

We use a test setup (designed and built in our lab) to measure stress-strain curves of different superconducting samples. This research activity allows a better determination of the mechanical properties of the materials that can be used in the Finite Element Analysis (next section). In addition, the test setup can be used to generate fundamental material property data for users of such materials and can be adapted for quality-control qualification testing by users, manufacturers, or government agencies and regulators. The mechanical stress is applied by a mechanical screw jack actuator powered by a speed-controlled DC motor and measured by a load cell (Fig. 12). Strain applied to the sample is measured by a high-resolution ultra-light double extensometer system designed to operate at low temperatures and to minimize strain imparted to the sample [14] (Fig. 13).

An example of the experimental results (at 77 K) for YBCO tapes from two different manufacturers (SuperPower and SuNAM) compared to the numerical analysis is shown in Fig. 14. A very good agreement is obtained between experiemnts and simulations. From those type of measurements the overall mechanical properties of the conductor can be determined (Young's modulus, Yield strength, Tangent modulus).

This device can also be easily modified to study the effect of axial strain on YBCO tapes and cables (work recently presented at CEC-ICMC 2015).

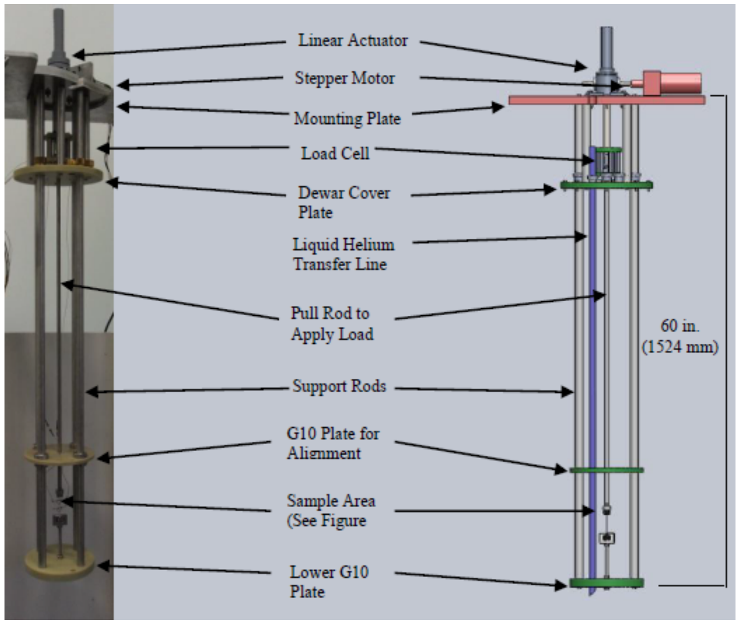

Fig. 12 Overview of apparatus assembly [14].

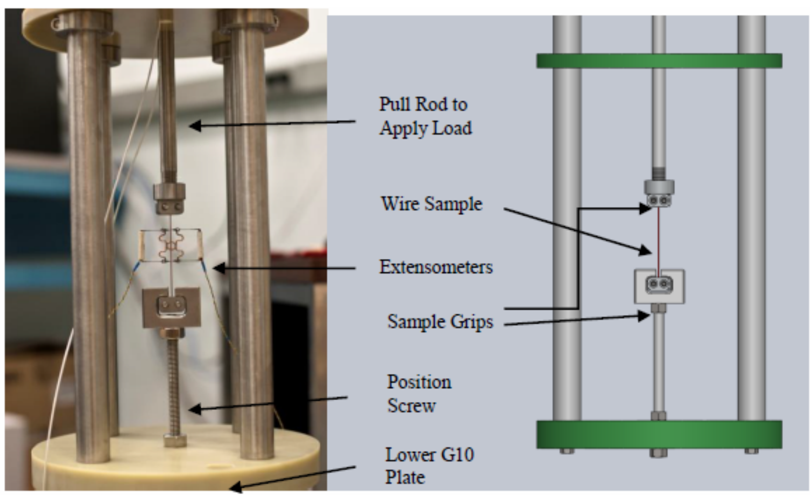

Fig. 13 Overview of sample area.

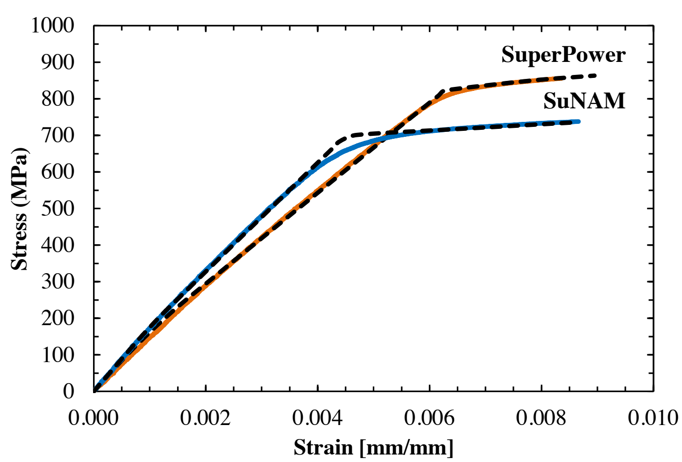

Fig. 14 Experimental and numerical stress-strain curves for SuperPower and SuNAM tapes at 77 K (solid lines are experimental data, dashed lines are for the numerical simulations performed with ANSYS®).

5.d Finite Element Analysis (FEA) modeling of strands and cables

As mentioned earlier, the PI's group develops finite element analysis codes to extrapolate the experimental results at the small scale to the full size applications. To validate our modeling and predict the performance of full size cable, we recently developed a novel method to derive the critical current degradation under transverse loading based on a strain scaling law (existing empirical equations used to find the critical current of a conductor given its strain state) and FEA. Using this method we estimated the critical current of Nb_3Sn under transverse load for which data are available. This new methodology succeeds in predicting the overall behavior of the critical current but more accurate material properties (key parameters for the finite element modeling) and more experiment data are necessary to fully validate it [16].

A similar approach is being followed for YBCO tapes and cables and some promising results have been obtained. Capturing the behavior of the different layers of materials in each single tape (see Fig. 2) is crucial to determine the overall behavior of the samples. Simulations of the twisting process were successfully performed and good agreement between the predicted and measured strain was found. Simulating multiple tapes is more challenging as we need to consider the interaction between each tape and boundary conditions are also very important.

Fig. 15 shows representative results obtained through the finite element model. The left figure shows the strain map of the superconducting filaments of a Nb_3Sn wire. Given the strain value it is possible to evaluate the critical current as a function of transverse pressure. The FE model currently does not capture the electrical interaction between filaments but it can be seen that the methodology appropriately estimates the critical current as function of load and it is in reasonable agreement with the experimental results (UG_17T) (normalized critical current is the ratio of the current to the initial current value). "Twisted strand" and "Untwisted strand" are two types of simulations designed to capture details of the current behavior of the filaments of a strand. The experimental results should (and they do) fall in between the two curves but more work is needed to properly simulate the current sharing between the filaments.

Fig. 16 shows the simulation of a REBCO tape at different twist pitches and the strain distribution observed in the material. More work in this direction is also needed and is planned as part of our future work.

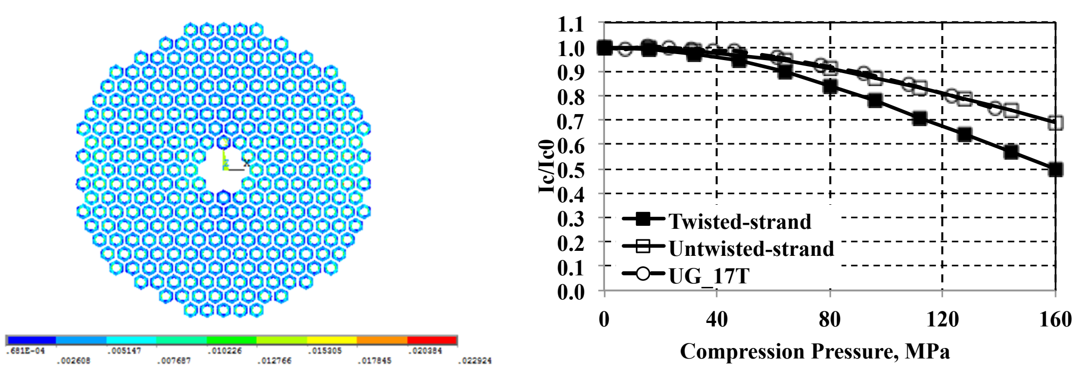

Fig. 15 Left: strain map of the superconducting filaments of a Nb_3Sn strand with a load of 160 MPa. Right: estimated normalized critical current using the FEA model (twisted and untwisted strand)compared directly with experimental results (UG_17T).

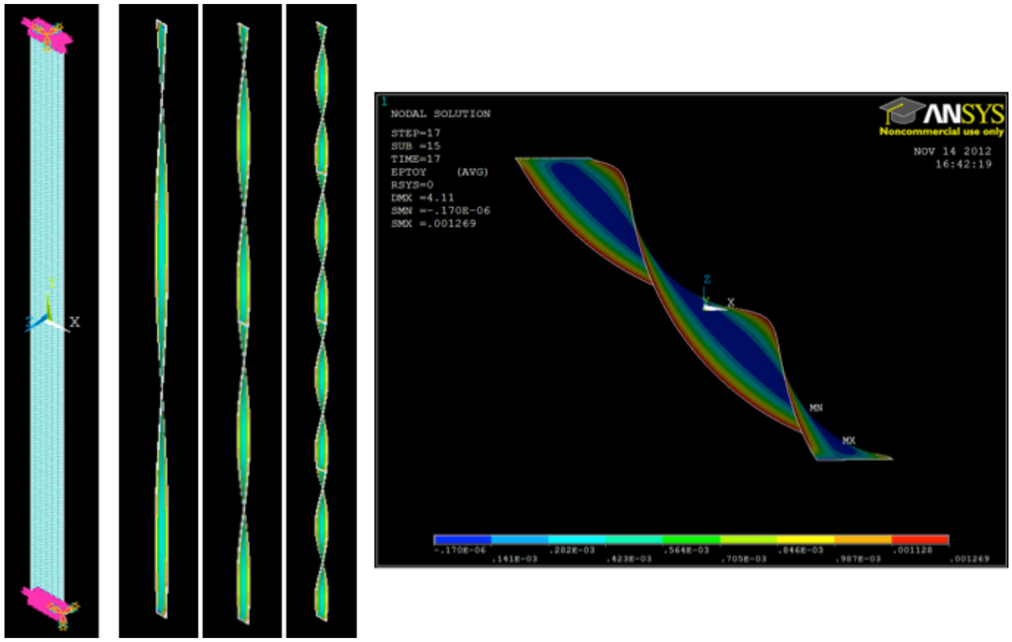

Fig. 16 Left: Modeling of a YBCO tape during the twisting process. Right: strain distribution caused by the twisting process.

6. Collaborative Research and Broader Impact

The PI's research activity is versatile and has been carried out in a framework of national and/or international collaborations. For tackling complex problems (e.g., achieving energy sustainability) and developing complex machines (e.g., fusion energy sources), the ability and willingness to share expertise and resources at this level, such as accessing unique and world-class facilities around the world, is essential. In addition, interacting with fellow researchers through meetings, committees, conference presentations and collaborative research efforts ensures the work performed is relevant and visible and provides excellent training and career opportunities for the PI's students.

The PI's work is original and places itself between fundamental material science/conductor research and design/production of large magnets for practical applications. The research performed provides useful information that can be fed both ways towards the improvement of properties of the conductor and/or its implementation in large magnets.

The PI currently has active collaborations with the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, FL where some of the PI's experiments are performed. The visits of the PI and her students have been highlighted in their annual report and "Look who's at the lab" website which features some of the scientists using their facilities on a regular basis [17]. The facility is run by Florida State University and supported by NSF and Florida State, and it is the national user facility for researchers needing high magnetic fields to perform their research (spanning from material science to medical applications). When requesting magnet time the experiment proposal is reviewed and time granted based on intellectual merit and impact of the research. Being able to access this facility indicates the importance of the research performed by the PI's group. The experiments performed at the NHMFL are very challenging (high field and cryogenic temperatures) so a single person alone never performs them. Dr. Takayasu from MIT-PSFC is a key collaborator for these experiments. The collaboration is very fruitful and truly collaborative, as each group has unique capability. For example, the PI's group has developed unique experimental devices and has unique capability for performing numerical simulations (all simulations presented in the papers below were developed by the PI's group). Dr.

Takayasu's group provides other experimental expertise and historical knowledge. Additionally, to optimize helium consumption (major expense for the PI's group), both Tufts and MIT independent experiments are arranged so that the same magnet system at NHMFL can be utilized in the same week.

Another major collaboration is with the Magnets, Superconductors and Cryostats (MSC) group at CERN (Switzerland) in the Superconductor and Devices section (SCD). CERN has an extensive research program on superconducting materials and magnets. The collaboration started after they expressed interest in the PI's research during a conference for a collaborative project in which the PI's group's expertise was needed. The collaboration included a graduate student from the PI's group spending roughly a year at CERN.

During conferences and workshops the PI's group interacts with scientists from different national laboratories where the PI previously worked (Berkeley National Lab, Fermilab), to receive input on the PI's work and to explore possible funding and collaborative opportunities. A new collaboration has started with the Superconductivity group at ENEA (Italy) on activities related to HTS cables. In addition to national laboratories, the PI constantly pursue opportunities of collaboration with private companies (Philips-Healthcare, GE, Tai-Yang Research and Supercon) for projects funded through NSF and DOE SBIR-STTR programs or through sponsorship of a Tufts graduate student in the PI's group.

In the past few years the PI has been heavily involved with IEEE and the Council on Superconductivity. The PI has been an editor for the IEEE Transaction on Applied Superconductivity Journal since 2010. Additionally, she has also been elected an Advisory Committee IEEE Council on Superconductivity (CSC) in 2010, and a board committee member for the Cryogenic Engineering Conference (CEC) in 2013.

Finally, the PI has been a committee member of the major conferences in her field (Applied Superconductivity Conference (ASC) and Magnet Technology Conference (MT)). The PI gave a plenary talk at ASC-2014 and she will be the Chief Editor for the upcoming MT conference (MT-24). The involvement with IEEE provides the PI access to key players in the PI's field and many opportunities to explore new scholarship areas, applications and funding opportunities.

7. Future Plans

7.a Immediate Plan 1-3 years

In the next few years, the PI's research will extend the experience acquired on Low Temperature Superconductors to High Temperature Superconductors. The PI's research will focus on HTS-YBCO for different high-field applications as this conductor will probably be one of the conductor of choice for next generation high-field magnet. The PI's group will continue performing both experiments and modeling to understand the limitations of the conductor and its appropriate utilization in the next generation cables and magnets. Additional measurements to further the understanding of the behavior of this conductor due to torsion and several mechanical loadings (transvers, axial) will be necessary. More time and effort will be spent in understanding the fundamental causes of degradation of those materials through post-mortem micro-graphical analysis through an ad hoc optical microscope system setup in our laboratory and/or utilizing SEM capabilities at Tufts. The measurements performed on HTS-YBCO are currently performed at 77 K and self-field conditions but it will be necessary to broaden the spectrum of our measurement capability to provide even more relevant results, for example including measurements at various temperature between 4.2 K and 77 K and with external background magnetic field. In order to perform HTS-YBCO experiments at various temperatures the PI's group will utilize the recently acquired cryocooler.

7.b Medium Term Plan 4-6 years

Considerable effort will be given to enhancing the PI's superconductivity laboratory and bringing the capabilities of the laboratory to a higher level. To perform more experiments at various low temperatures (4-77 K range) and with high magnetic fields the PI plans to actively look for funding for a cryocooler magnet which is operated at 5 K without liquid helium (to avoid the issue with the national liquid helium shortage). Additionally, the PI will pursue funding for the acquisition of an additional cryocooler and the necessary components to outfit an existing magnet to this cryocooler (the cryocooler system in (a) is different from the systems described here in (b)). This laboratory upgrade will provide higher visibility for the research effort at Tufts in the larger superconductivity community. The ultimate goal of the PI's research at this stage will be to provide the necessary information to the community so that new magnets can be designed taking in consideration the inherent limitation of the conductor. Possible sources of funding are within the Department of Energy (the Office of Fusion Energy Science and the office of High Energy Physics). At this stage, while expanding the PI's research capabilities, the PI's collaborative work with national laboratories and MIT-PSFC will also increase opportunities for securing additional funding.

7.c Long Term Plan 6-10+ years

In the long term, the PI is planning to be responsible for a large project involving high field magnets for fusion and/or high-energy physics. Ultimately, the PI wants the program at Tufts University to be recognized as a place where high quality research and important progress on superconductivity technology and its applications are made.

An equally important goal, of utmost importance to the PI, is to continue providing the necessary education and training to the future generation of high field superconducting magnets engineers. As stressed earlier, very few academic institutions offer this type of training and during the last five years the PI clearly showed her effort in educating undergraduate and graduate students in this research field.

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8. Publications

Listed below are the PI's publications under review (1) and accepted for publications or published (2). Publications published before joining Tufts are also reported as relevant to the work performed at Tufts (3) and part of previous work done in National Laboratories (Fermilab and Lawrence Berkeley National Laboratory) (4). Underlined names are former or current Tufts students who are a lead author or coauthor in the publication.

Given the type of research is applied science and engineering few journals are available for us to publish in. Among them the most important are IEEE Transaction on Applied Superconductivity, Cryogenics and Superconductor Science and Technology.

It is important to point out that most of the PI's publications are with multiple authors. The PI really values the participation of students in the publication process, as she believes writing scientific papers is an essential skill to master by the end of their graduate studies.

8.a Publications currently under review

[53] N. C. Allen, L. Chiesa and M. Takayasu "Numerical and Experimental Investigation of the Electromechanical Behavior of REBCO Tapes", submitted for review and presented at the CEC-ICMC conference in Tucson, AZ, June 2015.

[52] M. Takayasu, L. Chiesa, "Analytical Investigation in Bending Characteristic of Twisted Staked-Tape Cable Conductor", submitted for review and presented at the CEC-ICMC conference in Tucson, AZ, June 2015.

8.b Publications published since joining Tufts University (January 2009, mainly supported by Early Career Grant Award)

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9. <u>Invited participation in professional conferences and other similar activities</u>

[21] “Superconducting materials used in high magnetic field superconducting magnets for high energy physics and fusion energy applications”, Speaker at Masdar Institute, Electrical Engineering and Computer Science Department, Abu Dhabi, UAE (March 2015).
[20] “Niobium for superconducting materials used in high magnetic field superconducting magnets for high energy physics and fusion energy applications”, Speaker at Companhia Brasileira de Metalurgia e Mineração (CBMM), Brazil (January 2015).
[19] “Electromechanical Characteristics of REBCO Tapes for their use in the High-Current Twisted Stacked-Tapes Cable (TSTC) Conductor for Magnet Applications.” Speaker at KIT, Karlsruhe Institute of Technology, Germany (December 2014).
[18] “Electromechanical Characteristics of REBCO Tapes for their use in the High-Current Twisted Stacked-Tapes Cable (TSTC) Conductor for Magnet Applications.” Speaker at CERN, Switzerland (December 2014, CERN-TE Magnet Seminar).
[17] “Electromechanical characteristics (or lack thereof) of High-current HTS cables for magnet applications.” Speaker at Fermilab National Accelerator Laboratory (November 2014).
[16] Plenary talk at Applied Superconductivity Conference, "High-current HTS Cables for Magnet Applications" was given at the last Applied Superconductivity Conference, ASC2014, held in Charlotte, NC (August 2014).
[15] “Nuclear Power.” Annual invitation as guest lecturer in ME-145: Power Generation Systems to cover the class on Nuclear Power (Tufts University).

[14] “Superconductivity: Case studies of heat transfer phenomena in the world of cryogenics.” Speaker at the Heat Transfer Tea seminar series in the Mechanical Engineering department at Tufts (September 2012).
[13] “Here Comes the Sun! Harnessing a sun in a magnetic bottle. Essentially unlimited source of clean, carbon-free electricity.” Speaker at Littleton High School in NH (May 2012).
[12] “Electro-Mechanical Characterization of Superconducting Nb_3Sn Strands and Cables for Fusion Energy Application.” Poster presentation at the NHMFL NSF Site Visit Review (December 2011).
[11] “Critical Current and Mechanical Behaviors of Superconducting Materials Used in Magnet Technology Applications Under Various Loading Conditions.” Speaker at the University of Rhode Islands, Mechanical, Industrial and Systems Engineering (November 2011).
[10] “Power Plants of the Future The role of Superconductivity in Energy Applications.” Speaker at The Osher Lifelong Learning Institute at Tufts (October 2011),
[9] “Electro-Mechanical Behavior of Superconducting Materials Used in Magnet Technology Applications: Research Activities.” Speaker at University of Geneva, Switzerland (May 2011),
[8] Guest lecturer for four classes of the class on Superconducting Magnets offered at MIT (class 22.68J / 2.64J) in the Spring of 2011.
[7] “Critical Current and Mechanical Behaviors of Superconducting Materials Used in Magnet Technology Applications Under Various Loading Conditions.” Speaker at CERN, Switzerland (June 2010).
[6] “Critical Current and Mechanical Behaviors of Superconducting Materials Used in Magnet Technology Applications Under Various Loading Conditions.” Speaker at the ME seminar series, Tufts University (January 2010).
[5] “Superconducting Magnets for Fusion Application.” Speaker at the seminar series in the Physics and Astronomy Department at Tufts University (October 2009).
[4] “Superconducting Magnets for Fusion Application.” Speaker at Fermilab National Laboratory, FNAL (October 2009).
[3] “Mechanical Engineering: Where it all started and why I am where I am. Subtitle: Superconducting Materials for Energy Applications” Speaker at the Computational Science, Engineering, and Mathematics (CSEM) meeting at Tufts University (April 2009).
[2] “Mechanical and Electromagnetic Transverse Load Effects on Superconducting Niobium-Tin Performance.” Speaker at the National High Magnetic Field Laboratory, NHMFL (March 2009).
[1] “Mechanical and Electromagnetic Transverse Load Effects on Superconducting Niobium-Tin Performance.” Speaker at the Lawrence Berkeley National Laboratory, LBNL (February 2009).

Several contributed orals and posters have been presented at the main conferences in the PI’s field of research (CEC-ICMC 2009 (1 oral), ASC2010 (2 posters), CEC-ICMC 2011 (2 posters), ASC2012 (2 orals, 4 posters), MT23 (1 oral, 1 poster), CHATS-AS (2 orals)).

10. **Fellowships, awards, grants, or other prizes**

Fellowships:

- February-August 2014: Visiting Scientist at CERN, Switzerland.

Awards:

- January 2010: Recipient of the Early Career Grant Award from the Department of Energy Office of Fusion Energy and Science (DOE-OFES): $750,000 over five years. (2010-2015). The title of the grant is “Superconducting technology for magnet systems in fusion machines”. This grant allowed the accomplishment of the vast majority of the research activities performed in the last 5 years.
- April 2014: ASME Award of Excellence, Tufts University.
- August 2014: Ph.D. student Nate Allen received the IEEE-CSC graduate student award fellowship.
- April 2015: Ph.D. student Nate Allen received the School of Engineering Outstanding Graduate Researcher at Tufts University.
- May 2015: Ph.D. student Nate Allen received the Mechanical Engineering Outstanding Research Assistant award at Tufts University.

11. Master and Ph.D. students supported through the Early Career Award period

PhD dissertations

3. Federica Pierro, start date was September 2014. Expected graduation Spring of 2019.

2. Nathaniel Allen, start date was September 2013. Expected graduation Spring of 2016.

1. Tiening Wang, *Transverse mechanical load effects on superconducting Nb_3Sn current-carrying performance*, Completed at Tufts University Degree List of February 2014.

Tiening Wang, Nathaniel Allen and Federica Pierro all received the Dean’s fellowship in 2010, 2013 and 2014 respectively. This fellowship is given by the dean to deserving Ph.D. students and provides additional funding to their salary. Tiening Wang is currently working for Chrysler where he is leading the simulation efforts for a more efficient engine design.

Master of Science Theses

7. Daniel Catanzano, *Critical Current Behavior of PIT Nb_3Sn Strands Under Transverse Load Using Finite Element Analysis*, Completed in Summer 2014.

6. Nathaniel Allen, *Pure Bending Characterization of Nb_3Sn Superconducting Strands Using Experimentation and FEA Modeling*, Completed in Spring 2013.

5. David Bader, *Design, Fabrication, and Testing of an Apparatus for Mechanical Properties Characterization of Nb_3Sn Superconducting Wires*, Completed in Spring 2012.

4. Joseph King, *Effects of Wide Range Bending Strain on Critical Current of Bronze Route Nb_3Sn Superconducting Strands*, Completed in Spring 2012.

3. Konstantin Derman, *Design and fabrication of a device to characterize the electromechanical behavior of Superconducting Nb_3Sn 3-strand cables under transverse load*, Completed in Spring 2012.

2. Phil Mallon, *Characterization of Nb_3Sn Superconducting Strands under Wide Range Pure-Bending Strain*, Completed in Spring 2011.

1. Tiening Wang, *Stress analysis of transverse load on superconducting Nb_3Sn strand(s)*, Completed in Spring 2010.

12. Undergraduates involved in the research activities supported by the Early Career Award

Nixon, Laura; Gomes, Jay; Goldenberg, Matt; Porter, Oliver; Ching, Madeline; Anwar, Zahra; Derras-Chouk, Amel; Hill, Nick; Shum, Andrew.

13. Memberships, offices in professional or scholarly societies and other relevant professional activities

In the past few years the PI has been heavily involved in activities with the IEEE Council on Superconductivity (CSC). Those are relatively time consuming activities involving conference related activities and peer review processes for the main journal in our field (IEEE Transaction on Applied Superconductivity). The PI believes those activities are extremely important for the PI's professional growth as they allow networking with people in the PI's field and foster collaborations and funding opportunities.

- Fall 2013-present IEEE Senior member (only ~10% of all IEEE members have this title).
- 2010-present: Member of the Advisory Committee IEEE Council on Superconductivity (CSC).
- June 2013-present: Board committee member for Cryogenic Engineering Conference (CEC) (Academia representative).
- April 2010-present: IEEE Transaction on Applied Superconductivity editor.
- June 2010-Present: Part of the committee for the section of Student fellowships for the IEEE-Council on Superconductivity.
- Board committee member for the Applied Superconductivity Conference (ASC) and the Magnet Technology conference (MT). ASC-2012, ASC-2014, MT-23 (Magnet Technology conference) committee member for the organization of those conferences, technical editor and reviewer.
- Reviewer for papers presented at conferences I participated in the past 2 years (Cryogenic Engineering Conference-International Cryogenic Materials Conference CEC- ICMC, Applied Superconductivity Conference ASC).
- Reviewer of journals in the PI's field of research: IEEE Transactions on Applied Superconductivity and Superconductor Science and Technology (SUST IOP science journal).
- Reviewer of SBIR/STTR Phase I and Phase II programs and selected national labs programs.
- The PI will be the Chief Editor for the next MT-24 conference to be held in Seoul, Korea in 2015.
- Organized CHATS on Superconductivity workshop (October 2013) and I have been a special guest editor to follow the review process of the papers presented at the workshop and published on Cryogenics, "The scope of the workshop is to encompass all aspects of superconducting system modeling, with special emphasis on bringing together modelers and experimentalists in support of magnet system design from many different applied superconductivity communities: HEP, fusion, power applications, etc.".
- Gave a plenary talk at ASC2014 (Charlotte, NC August 2014).

- Lecturer for four classes of the class on Superconducting Magnets offered at MIT (class 22.68J / 2.64J) in the Spring of 2011.
- Presentations:

a. Speaker at Masdar Institute, Electrical Engineering and Computer Science Department, Abu Dhabi, UAE (March 2015).
b. Speaker at Companhia Brasileira de Metalurgia e Mineração (CBMM), Brazil (January 2015).
c. Speaker at KIT, Karlsruhe Institute of Technology, Germany (December 2014).
d. Speaker at CERN, Switzerland (December 2014, CERN-TE Magnet Seminar).
e. Speaker at Fermilab National Accelerator Laboratory (November 2014).
f. Speaker at the Heat Transfer Tea seminar series in the Mechanical Engineering department at Tufts (September 2012),
g. Speaker at Littleton High school in NH (May 2012),
h. Poster presentation at the NHMFL NSF Site Visit Review (December 2011),
i. Speaker at the University of Rhode Islands Mechanical, Industrial and Systems Engineering (November 2011),
j. Speaker at The Osher Lifelong Learning Institute at Tufts (October 2011),
k. Speaker at University of Geneva, Switzerland (May 2011),
l. Speaker at CERN, Switzerland (June 2010),
m. Speaker at Physics and Astronomy Department at Tufts University (October 2009),
n. Speaker at Fermilab National Laboratory, FNAL (October 2009),
o. Speaker at the Computational Science, Engineering, and Mathematics (CSEM) meeting at Tufts University (April 2009),
p. Speaker at the National High Magnetic Field Laboratory, NHMFL (Match 2009),
q. Speaker at the Lawrence Berkeley National Laboratory, LBNL (February 2009).