Final Report for CRADA #C-12-08

With Particle Beam Lasers, Inc. on

Magnet Coil Designs Using YBCO High Temperature Superconductor

By

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(Text of the report originally prepared by Erich H Willen)

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Executive summary

Magnet coils built with the superconducting “cos θ” technology have proven extraordinarily popular, cost effective and reliable in modern particle accelerators. The term “cos θ” describes a coil design in which current conductors are placed on the surface of a cylindrical tube with more turns near the mid-plane and less near the pole proportional to the cosine of the angle measured from the mid-plane. Once this challenging technology is mastered, the design offers many options regarding cost, field intensity and quality, size of aperture, and multipole fields that are important to accelerator designers and builders for bending and controlling beam particles. The workhorse conductor used to date has been NbTi, with some magnets built with the more challenging but higher field-producing Nb_3Sn, both operating at the very low temperature of liquid helium. However, the current carrying capacity of Low Temperature Superconductor (LTS) drops rapidly with increasing field. This makes it unattractive for magnets above 15 T. Now, High Temperature Superconductor (HTS), which is able to carry significant current above 15 T, has reached a level of development where it is commercially available for some applications. Its use as a replacement for LTS material for particle accelerators would probably be limited for now because of its cost. However it could prove very useful in places where limited numbers of high field, elevated temperature and/or good radiation resistant magnets are needed---for instance in focusing of beams near collision points, or in places where space is limited but strong bends are still required. Such applications are to be found for instance in upgrade goals for the LHC at CERN. This project addresses primarily the issues involved in using the YBCO HTS superconductor to build cos θ dipole magnets for accelerators.

The focus of this project is to investigate coils made with YBCO. Other alternate choices of HTS are Bi2212 in the form of wires, which allows Rutherford cable, and Bi2223 tape. An advantage of YBCO is that it is the most widely available HTS superconductor. Moreover, coils made with YBCO tape from SuperPower, Inc. can operate at high stress levels as the tape can tolerate stresses over 500 MPa and strains over 0.5%. These limits are not possible with other HTS materials. A challenge for magnets made with tape are possibly large field errors generated by higher magnetization than would be the case with smaller wires. Confronting this and other challenges is a major purpose of this work.

Upon approval of our Phase I proposal in February 2012, we proceeded with a more detailed design of a cos θ partial coil including the dimensions of such a winding and the tooling that would be required to fabricate a prototype. Our immediate goal was to learn whether the somewhat fragile YBCO tape would be amenable to the mechanical stresses, the handling, and the environment found in a cos θ coil of the desired small dimensions. Upon completion of the tooling and receipt of the conductor, we fabricated a 300 mm long winding of 20 turns on a 50 mm mandrel using a 12 mm YBCO tape. The conductor was wrapped with Kapton CI for protection and fabrication purposes, a new and promising Brookhaven design approach for such conductor. The winding operated successfully in liquid nitrogen without quench up to the expected 200 A before reaching the 5 mV voltage limit across the winding that we had established to protect the conductor. Moreover, several voltage taps that had been placed in various sections of the coil indicated that there was no degradation in local conductor performance despite the complex shape of end region that must be negotiated by HTS tape. These were most encouraging results and give confidence that a full cos θ coil could be possible in the future with this approach.

The continued development of High Temperature Superconductor is beneficial to most areas of science and technology that require the use of strong magnetic fields---pure research, medical applications, defense, and homeland security items. Their ability to remain superconducting at elevated temperature up to that of liquid nitrogen enhances performance, reduces cost and eases construction requirements. They are clearly the foundation stone for significant future technologies. This project aids in the development of an industry that can furnish these existing and even newer such materials now and into the future.

Scientific and Technical Achievements

Actual accomplishments compared with goals and objectives

T*he following goals are listed in the Phase I Work Plan:*

- Design flat coil and cos θ coil with dimensions to be established in initial design effort
    - Flat coil: expected dimensions in range: 15 cm wide, 25 cm long
    - Cos θ coil: expected dimensions in range: dipole half coil, 40 mm ø, 25 cm long
- Order conductor
- Ongoing design and engineering work to parameterize end configuration in cos θ coils
- Design necessary coil containment structures
- Build prototype coils, containment structure: mostly technician labor, some shop work
- Test at LN2 temperature

The major performance milestone accomplishments listed in the Phase I Performance Schedule are:

Three months after the start of funding:

1. Place order for YBCO superconductor for test coil.
2. Develop conceptual design of the cos θ and racetrack coil magnet.

Six months after the start of funding:

1. Finalize design parameters of Phase II magnet and outline coil construction techniques.
2. Wind coil block(s) in cos θ configuration with stainless steel tape having the same size as YBCO tape ordered for the test coil.

Nine months after the start of funding:

1. Wind coil block(s) in cos θ configuration with YBCO tape.
2. Perform 77 K testing of YBCO coil at nitrogen temperature.
3. Finish analysis studies and prepare conceptual design report.
4. Prepare and submit Phase II proposal.

Taking the list of goals in sequence and adding items from the Performance Schedule as appropriate, our accomplishments are as follows:

1) ***Design flat coil and cos ϑ coil***: The flat coil would have width and length dimensions similar to the cos θ coil and would serve as a performance comparison marker for that coil. No special tooling beyond pieces available in the Lab was needed to make this coil. We elected to make the cos θ coil diameter 50 mm, the same as used for the SSC dipole magnet design in 1993. This could provide a useful reference in the future while also representing an aperture size that is of general interest. Thus we designed and built tooling for a 300 mm long winding of 20 turns on a 50 mm mandrel using a 4 mm YBCO tape, the width that early discussions indicated could be provided by Superpower, Inc. One winding would be a pole winding reaching 70° where stresses in the ends would be at their maximum. Another winding on the same mandrel would be at the mid-plane and would provide a useful performance comparison. While limited in size, these windings would serve as useful prototypes for a complete coil (two coils needed in a complete magnet), and would begin to answer questions about winding requirements and about possible conductor degradation in this geometry.
2) ***Order conductor***: The offer from Superpower to make available some 50 m of 4 mm tape conductor without charge, as a collaborative effort and as part of their ongoing R&D work, was accepted with gratitude in view of the limited funds available in our Phase I grant. This tape would be sufficient for some 20 turns in a winding of length 300 mm for each of three windings. They also kindly offered to wrap the conductor with Kapton CI, provided by BNL. They expected to deliver the material in July. However, when the conductor arrived at Brookhaven in September, it was beautifully wrapped with Kapton CI as promised but was 12 mm in width and 15 m in length. Its performance parameters as measured at SuperPower were stellar. We determined that we should use this conductor, but it required that we modify our tooling at the lab bench to accommodate 12 mm width and that, with only 15 m length, we abandon two of the three windings that we had planned to

build. An advantage of 12 mm tape is that it is closer to the width that would probably be desired in future magnets, though it would certainly be more challenging to use in this early prototyping work.

3) ***Ongoing design and engineering work***: Figure 2 shows a CAD drawing of the mandrel and some required fixtures from the design effort. The winding to be made on this tooling was first a 20 turn pole winding where the mechanical stresses on the tape in the ends would be greatest. The pole angle was designed for 70 degrees, which is about the maximum required in a cos θ type winding. Second would be a 20 turn mid-plane winding which would be for comparison to the pole winding. We found that the CAD software in use was not able to detail the tape geometry as it traversed the ends in the detail needed for an analysis of strain in the material. We undertook a separate effort to calculate and understand this behavior, and succeeded in parameterizing some aspects of the path, but further work with a different software package is needed. This further work is underway but is not yet producing results that can be reported [1].
4) ***Design necessary coil containment structures:*** The coil containment was designed to use the fabrication tooling (the winding mandrel) for interior support and to add a wrap of Kevlar applied with low force for exterior support. Additionally, metal bars were designed and fabricated for side support of the winding. Since the winding would not experience large forces in the planned test, this containment would suffice to hold the coil together. For future testing of a full coil at high current in liquid helium, or in an exterior magnetic field where forces would be larger, more robust support would be necessary.
5) ***Build prototype coils, containment structure:*** The winding equipment and the tooling were commissioned with stainless steel tape as a stand-in for the valuable and scarce HTS material. Then a 20 turn winding using the 12 mm wide HTS YBCO tape wrapped with Kapton CI tape was made. This would serve as a prototype for a future complete cos θ coil of this design. Voltage taps and current leads were added to prepare the winding for testing. Containment pieces as needed were fabricated and other items such as Kevlar tape were secured to allow the containment of the winding. While forces would not be large, there are still considerable forces from the several hundred ampere currents expected in the conductor, and we wanted no chance of any loose conductor in the test.
6) ***Test at LN2 temperature:*** The winding was positioned in the test containment and power leads attached. The voltage leads were connected to the control/monitor electronics. This control system is designed to protect against damage to the conductor if voltages develop. After cooling to liquid nitrogen temperature, the current was increased in steps until a threshold voltage of 5 mV developed in the coil. This was reached with some 200 A in the winding, the expected level for this configuration. This success points the way to a promising new method of building a high field magnet.
7) ***Conceptual design report, Phase II proposal:*** Work on these items is underway and we expect to submit the appropriate documents for a continuation of this work on the required schedule.

Products developed under the award and technology transfer activities

a. ***Publications:*** none

b. ***Web site for results of this project:*** www.bnl.gov/magnets/staff/gupta/

c. ***Networks or collaborations fostered:*** This work is collaboration between Particle Beam Lasers, Inc. and Brookhaven National Laboratory. Previously, this collaboration has produced several world record solenoid magnets, including one which achieved more than 15 T in a 50 mm bore. The conductor used and the wrapping of the conductor was provided by Superpower Corp. and furthered their interest in the development and use of YBCO tape. The support of CERN for this work as a possible path to planned upgrades for the LHC was expressed in a letter from Luccio Rossi contained in the Phase I proposal.

d. ***Technologies/techniques:*** Several new technologies were explored in this project, e.g. a cos θ dipole magnet made with YBCO tape, the use of YBCO tape wrapped with Kapton CI in a HTS magnet, the approach of using an adhesive material to bind the turns of a HTS coil during construction and later operation to make a cos θ coil possible, and further use of a high sensitivity quench protection system on a different style of magnet.

e. ***Inventions/patent applications:*** None filed at this time.

f. ***Other products:*** None.

Detailed description of the Phase I activities

Design & Tooling:

Superconducting "cos θ" coils have generally common features---conductor turns are placed around a cylinder with more current turns near the mid-plane and less at the top and bottom poles. The distribution of current density ideally follows a cos θ distribution. Distributing the current density in this way results in a dipole field for two poles, a quadrupole field for four poles, etc. Figure 1 is a conceptual drawing of a cross section from a magnet of this type.

Discussions with the SuperPower Corporation suggested that they would make available some 50 m of 4 mm wide YBCO tape as part of their R&D effort. They would also wrap the conductor with Kapton CI insulating tape furnished by Brookhaven. This is a unique and important design feature of our approach to building this type of magnet.

Kapton CI is available in small quantities as excess inventory from the RHIC construction program. There it was widely used in building cos θ coils for the accelerator magnets. It is a product developed jointly by Brookhaven and DuPont Corporation as a replacement for the many problems caused by fiberglass/epoxy in earlier cos θ coils. In this program, it would protect the fragile YBCO tape from damage in coil fabrication and from delamination of the conducting layer on the tape when coated with filler epoxy in the ends. Mechanically securing the ends is a requirement for success in construction of cos θ coils. The "CI' in the designation signifies a polyimide adhesive layer on the one mil thick Kapton tape. Upon heating to 225 deg. C, this adhesive activates, resulting in a winding in which all the turns are stuck together and form a package that can be handled and kept intact. In contrast to epoxy, the polyimide adhesive is quite radiation-resistant and thus can be used in high radiation environments without fear of degradation. There are other polyimide-like products on the market that allow lower activation temperatures for the adhesive, but that is achieved by chemical alteration of the polyimide molecules in the adhesive that renders the product less radiation resistant.

Our cos θ tooling was designed and built to accommodate the indicated 4 mm wide tape from Superpower though with options for adjusting dimensions. Figure 2 shows one piece of the tooling and Figure 3 shows the mandrel with windings. The CAD work that produced this drawing was done by a knowledgeable college engineering student summer intern [2]. (This project presented a good opportunity to expose several young college students to the complex problems of doing R&D in a new field.) Since the existing CAD package alone was not able to optimize the path of the end turns as they traversed the path from side to side, this problem is still being investigated with ongoing studies offline [1]. In fact, the full optimization of the exact path of the conductor in the winding is beyond the scope of Phase I and would be carried out in Phase II by using other programs such as ROXIE and/or BEND. For Phase I, the details of end geometry were developed by iterating actual winding patterns using stainless steel tape for mock-up coils. The flat coil envisioned for this project did not require any such specialized tooling. Thus, we planned to build a flat coil of approximately the same dimensions using existing lab hardware.

We elected to make the cos θ coil diameter 50 mm, the same as used for the SSC design in 1993. This would provide a useful reference for performance milestones should we get so far as to build a complete magnet in the future. Thus we designed and built tooling for a 300 mm long winding of 20 turns on a 50 mm mandrel using 4 mm YBCO tape. One winding would be a pole winding reaching 70° where stresses in the ends would be at their maximum. Another winding on the same mandrel would be at the mid-plane and would provide a useful performance comparison. While limited in size, these windings would serve as useful prototypes for a complete coil, or for two coils in a complete magnet, and would begin to answer questions about winding requirements and about possible conductor degradation in this geometry. The 100 m of tape from Superpower would be sufficient for some 20 turns of length 300 mm for each of three windings.

Fabrication: When the tooling was ready, we set up the winding station and made practice windings with 4 mm wide stainless tape. Figure 4 shows one such winding at the station. The effort invested in this practice winding proved helpful in later making YBCO coils with a minimum of difficulty and stress.

The YBCO tape delivered from Superpower was high quality tape wrapped well with the Kapton CI and with very good and uniform measured current capacity. However, in a major surprise, the tape we received was 12 mm, not 4 mm, wide, and only 15 m long. The 12 mm width is actually more useful for testing the cos θ concept since it will more readily reveal fabrication problems in the ends, and is closer to a width that would be desirable in a full coil. However, to use this width, we had to adjust the width of the mandrel pole piece as well as other parts; the reduced length meant we had to give up the mid-plane cos θ coil and the flat coil we were planning as part of the effort. With the necessary tooling revisions, we successfully wound the 20 turn winding, shown in Figures 5 and 6. The winding was then placed in the oven for activating the polyimide adhesive at 225 °C. After curing, the winding could be removed from its mandrel and handled for the addition of voltage taps and current leads. Gaps between turns in the ends would be eliminated at this stage by filling with a loaded epoxy, but we found that this was unnecessary with this small winding. Upon completion of this work, the winding was reinstalled on its mandrel, the restraining bars attached, and the entire structure wrapped with Kevlar cord under light tension. This step emulates the restraint that would be required in a true cos θ magnet and ensures that nothing will be loose in the test of the winding in liquid nitrogen. Figure 7 is a picture of the winding ready for cryogenic test.

<u>Testing & Results</u>: The test in liquid nitrogen went well and produced good results [3]. When the overall voltage across the winding reached 5 mV at somewhat over 200 A, the power was turned off and the test concluded. A summary plot of the results is shown in Figure 8. Some 14 voltage taps scattered through the 20 turns all showed low and nominal voltages.

The current reached corresponds to a critical current of 204 A based on a 1 V/cm criterion (industry standard, used by conductor manufacturer) and 187.8 A based on a 0.1 V/cm criterion (a more stringent limit used by magnet builders.) Based on previous experience with other programs using similar conductor, we had established that a conductor without any significant defect can be safely operated to such levels at 77 K.

SuperPower had measured the current capacity of this tape during manufacture. The capacity averaged around 480 A at 77 K with only self-field. This capacity is for a straight length of conductor; as a function of field, it initially falls rapidly and then more slowly at higher fields. A computer model of the coil winding was made to obtain the expected field at 200 A. Since the conductor critical current is highly anisotropic in HTS, the coil performance is generally limited by the perpendicular field (or more strictly by a field component at an angle closer to the perpendicular field). However, we find that the measured coil critical current is higher than those estimates and closer to that expected from the parallel field (see Figure 9 for data from the manufacturer.) The calculation gives a critical current of about 200 A. This lower-than-measured value may be due to the fact that the perpendicular effect only occurs in a smaller section along the width of the tape. Moreover, it may also be mentioned that a significant variation between the measured conductor critical current (77 K, self-field) and the coil critical current has been observed in a number of coils measured at BNL [5]. The measured critical current of ~200 A, even though slightly higher than our initial expectations, can be understood based on these considerations. In any case, the measured performance clearly demonstrates that the coil fabricated is a good coil and meets our optimistic expectations.

Finally, a close examination of voltage gradients on the ~14 voltage taps installed in the winding indicated no local degradation in the complex end sections (please see Figure 10.) The large "n-values" measured along the coil including the ends further confirms that the winding and curing techniques did not cause significant if any degradation.

<u>Conclusions</u>: The results indicate that there was little or no degradation of the conductor in making this winding. This is a significant result as it gives promise that making a full cos θ coil of 50 mm diameter with 12 mm wide YBCO tape is feasible using the techniques employed here. We learned the following: the tape can be wrapped with Kapton for protection of the conductor without degradation; the tape can be wound into a coil without damaging the conductor in the process, especially in the ends; the wound coil can be heated to the required 225 °C and thereby form a structure that can be handled for further fabrication steps; leads and voltage taps can be attached; the assembled structure can be compressed into a compacted dimension as required in an actual magnet; after all these steps the resulting assembly can perform at an impressively high level. We plan to propose in Phase II to build and test a full cos θ coil with 12 mm tape to confirm and extend this work.

We were not able to accomplish our secondary goals of a mid-plane winding or a flat winding in this Phase I because of an insufficient length of the expensive YBCO conductor. But since the winding we built worked well, the loss of these additional results was disappointing but less significant. The central and most important goal, learning how a cos θ magnet might be made with HTS conductor, was accomplished with good success.

<u>Magnetization:</u> Calculations indicate that the effect of magnetization on field quality may be tolerable. Please see the reference [4] for a short discussion of the work on this issue.

References

[1] Xiaoping Ding, private communication.

[2] C. Kolz et al., Structural Design of a High Temperature Superconductor Cosine Theta Coil, Report submitted at conclusion of the Summer Intern Program, Brookhaven, 2012, unpublished.

[3] The testing and results for the Phase I winding have been comprehensively reported by: L. S. Lakshmi, et al., Construction and Test Results of Kapton Insulated 2G HTS cos θ Coil, Presentation at the 2012 IEEE Low Temperature High Field Superconductivity Workshop (LTHFSW), Napa, CA, November 6, 2012.

[4] R. Weggel, private communication. In an email dated June 19, 2012, Weggel reports that for a plausible magnetization that is proportional to the distance from the magnet mid-plane in a cos θ dipole operating at 20 T, the field-homogeneity contour shrinks negligibly at the 10^{-4} level, and shrinks only ~40%, from ~32 mm to ~20 mm at the 10-ppm level, compared to the case with no magnetization.

[5] Y. Shiroyanagi, W. Sampson, A. Ghosh, R. Gupta, The Construction and Testing of HTS coils for 10T Solenoid, presented at the 2010 Applied Superconductivity Conference, Washington, DC, August 2010.

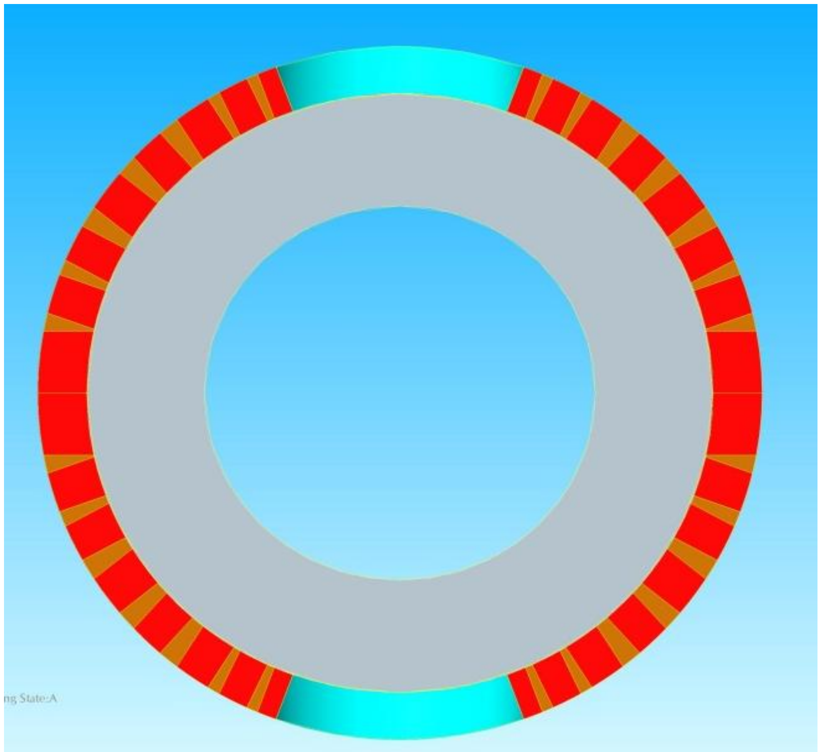

Figure 1: Concept drawing of a dipole “cos θ” coil cross section. The red rectangles are each made of many conductor turns. These current blocks are spaced around a circular perimeter with a cos θ dependence of the current density. This conductor arrangement when powered gives a dipole field in the aperture.

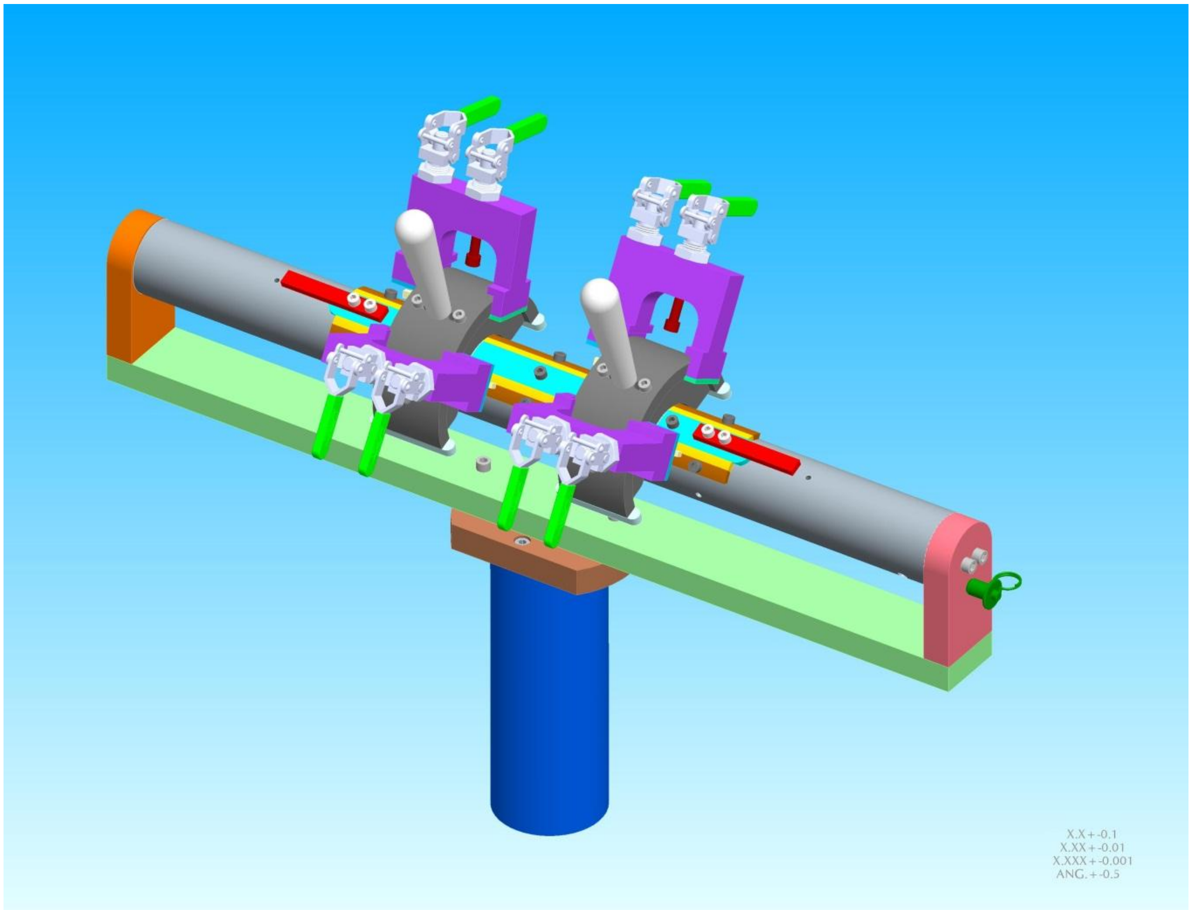

Figure 2: A CAD drawing of the tooling prepared for winding cos θ coils. Mounted on the cylinder that represents the coil mandrel are various clamping fixtures designed to hold conductor turns in place as they are wound onto the mandrel. The long yellow rectangle in this drawing represents a block of conductor turns in place at the pole. The long blue tube at the bottom will be mounted into a lathe to allow rotation during the winding operation, and the mandrel is mounted to its end supports on bearings to allow rotation there too.

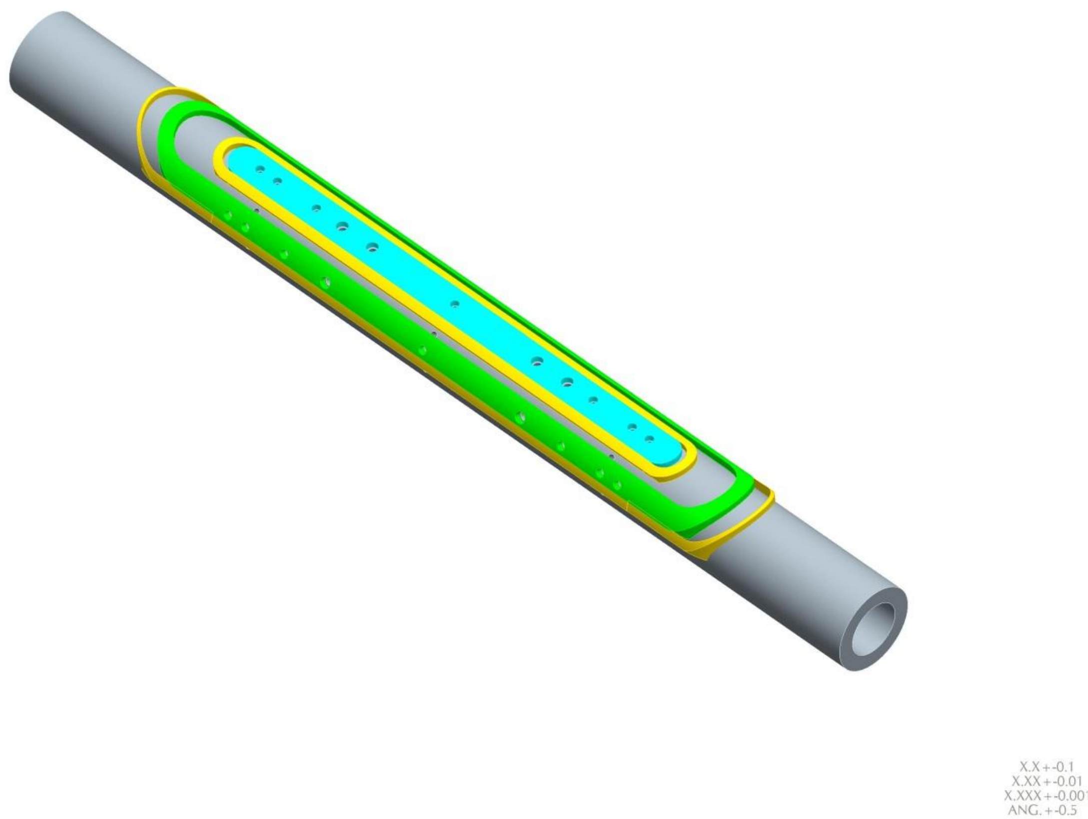

Figure 3: A CAD drawing of the mandrel with two windings (in yellow), the pole (in blue) and the retainer piece for the mid-plane winding (in green). Only the pole winding was made and tested because of insufficient HTS conductor to also make the mid-plane winding.

Figure 4: A photo showing the winding of a practice coil using stainless steel tape. This allowed us to commission the newly built tooling and the winding apparatus before risking the valuable HTS tape needed for making a working coil.

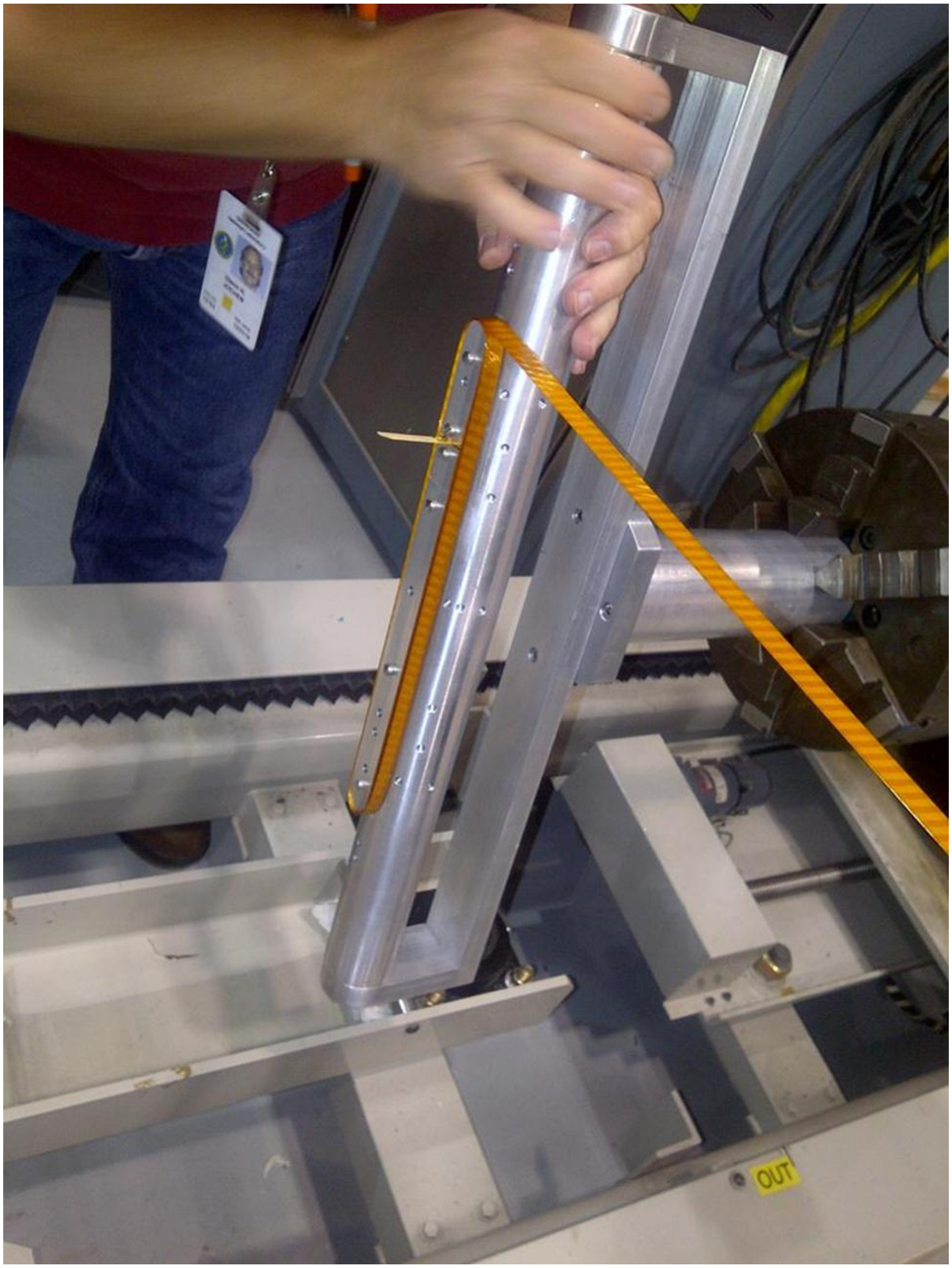

Figure 5: A photo of the HTS coil being wound on the winding apparatus. Much of the tooling used in this Phase I work will be useful in Phase II work as well.

Figure 6: A photo of the 20 turn pole winding after fabrication on the winding machine. The 12 mm wide HTS tape conductor with its Kapton CI wrap is visible on the left. The next step in the construction process was to heat the winding in a controlled oven to 225 °C in order to activate the polyimide adhesive of the Kapton CI. Before testing in liquid nitrogen, current leads and voltage taps were attached to this winding, then it was mounted back on its mandrel and secured with various restraints.

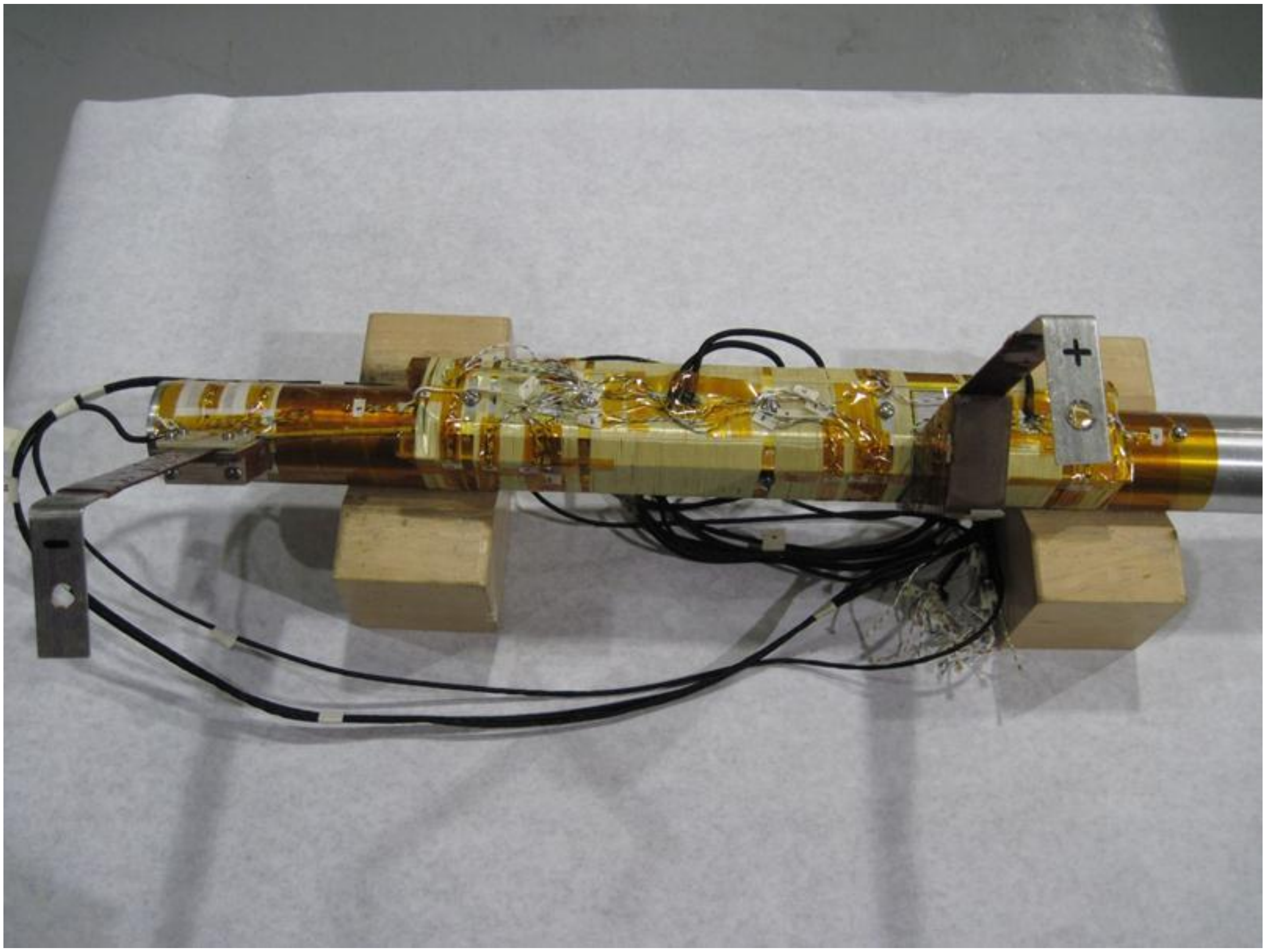

Figure 7: The 20 turn winding ready for testing in liquid nitrogen. The winding has been firmly secured to its mandrel, and current leads and voltage taps are in place for the test.

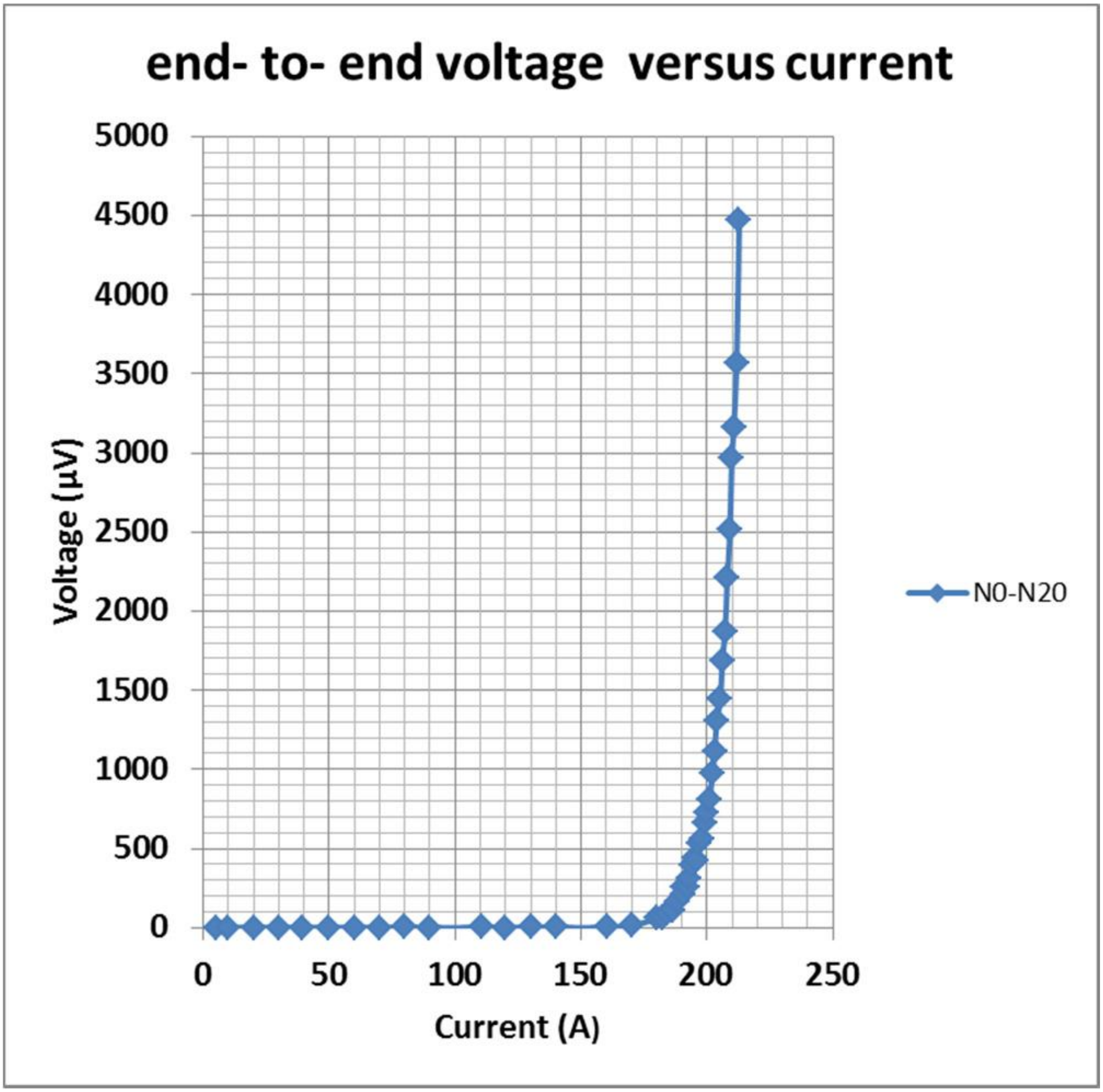

Figure 8: Measured voltage across the 20 turn winding at 77 K. At the turn-off threshold of 5 mV, the current exceeded 210 A. Stated differently, the coil carried 205 A at 1 µV/cm. The manufacturer's specification for the conductor was 483 A at 1 µV/cm. The reduction here is due to field in the coil. This measurement demonstrates that a cos θ winding using YBCO tape is possible without significant damage to the conductor. Please see reference 3 for a more detailed presentation of the test results.

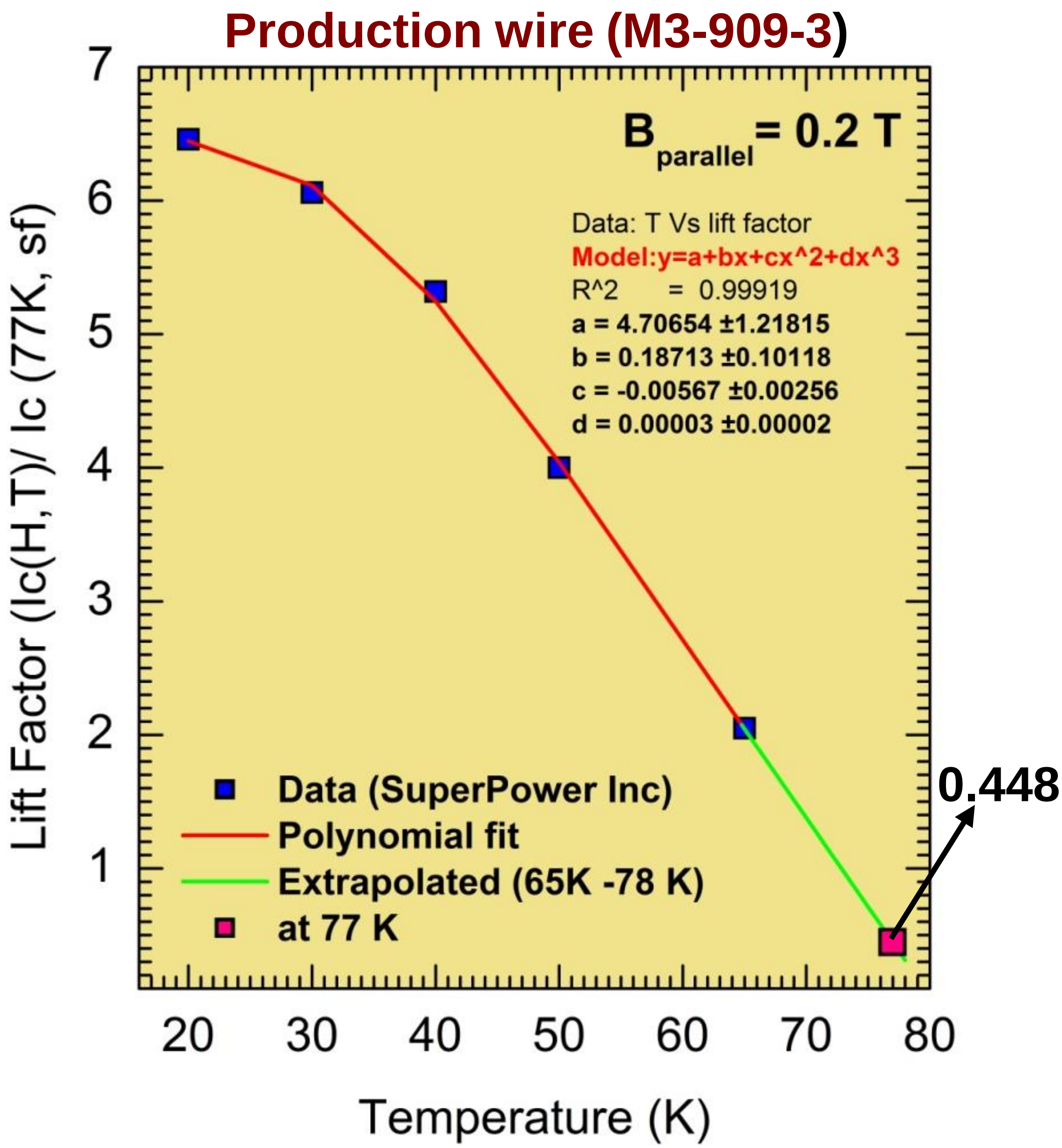

Figure 9: Lift factor (or scaling factor) provided by SuperPower in a direction of field parallel to the wide face of conductor at 0.2 T. Since the average self-field current of the conductor is 483 A, a scaling factor of 0.448 gives a current of 217 A. A lower value is expected in the coil since the maximum field is higher (0.23 T). Moreover, the scaling factor is lower in field perpendicular direction. Therefore, a measured critical current of over 200 A means meeting an optimistic expectation.

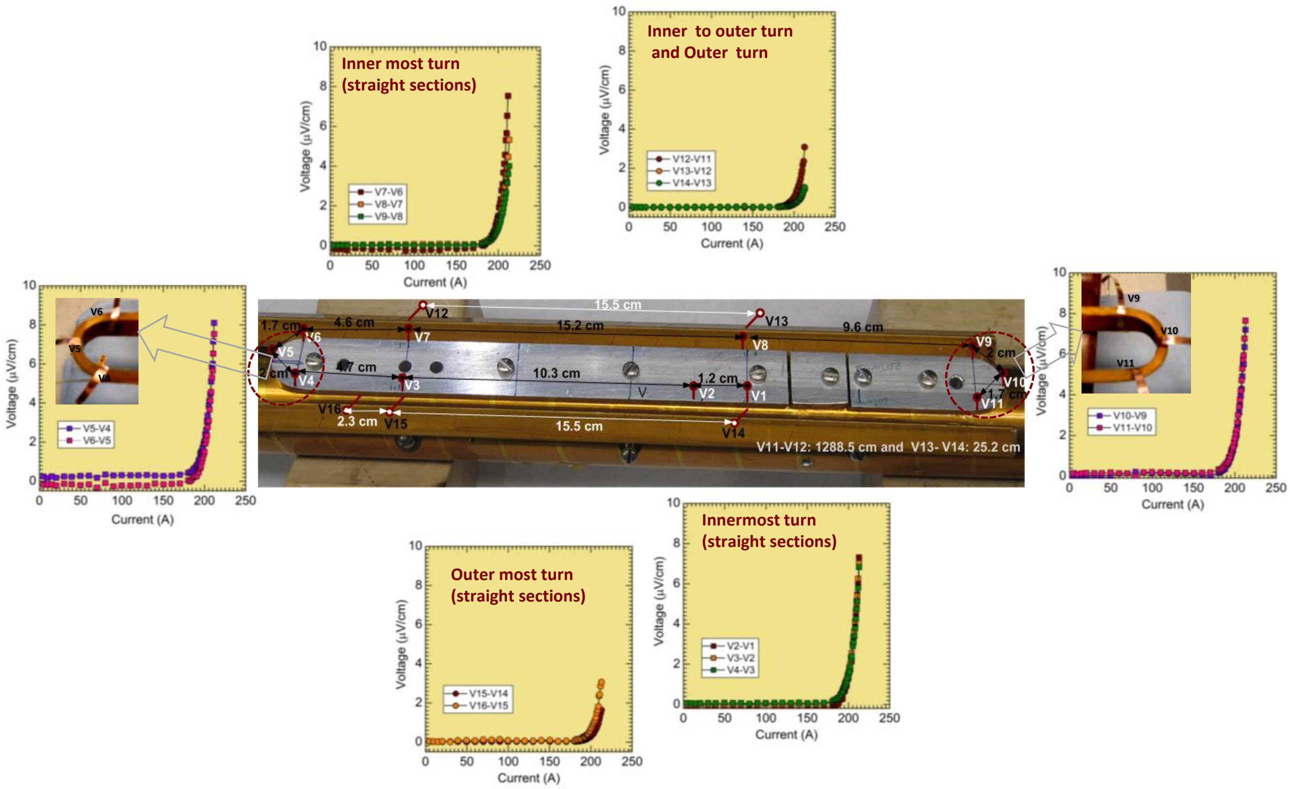

Figure 10: Measured V-I curves along innermost turn (where the field is maximum) in several sections of the coil. No significant degradation was observed at any location (including in the pole region where coil shape is complex and the field is highest.)