BNL-SMES-2014-1

Final Report

HTS-BASED SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

CRADA No. BNL-C-11-01 with ABB. Inc. for the US DOE, ARPA-E

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DISCLAIMER

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EXECUTIVE SUMMARY

The purpose of the project is to develop superconducting magnetic energy storage (SMES) for grid-level applications by developing a high energy-storage density, ultra-high field SMES coil using second generation (2G) high-temperature superconductor (HTS) wire. The key components of the system are: the ultra-high field superconducting storage magnet based on 2G superconducting wire, the superconducting switch (SS), new quench detection and energy extraction system, and an integrated control system (ICS).

The SMES magnet coil consists of inner and outer layers with each containing a number of pancake-shaped coils in them. The inner coil has 28 single pancakes and the outer has 16. Each pancake coil and the entire inner and outer coils have a significant amount of diagnostic instrumentation built into them, primarily voltage taps. The SS is used to switch between charge/discharge and storage modes. It features a rapid transition between superconducting and non-superconducting states. This transition is induced by a radio frequency field created by a compact flat coil, which is inductively coupled to the superconducting layer of the switch.

For protection of the SMES HTS magnet, we must detect the onset of any quench condition as early as possible (within few milliseconds), halt the energy being fed to the magnet, and quickly extract the stored energy. To protect the magnet during quench, we developed two systems: Quench Detection System (QD) and Energy Extraction System.

The ICS coordinates the operation of each component in the overall SMES so that charge, discharge and energy storage functions of the SMES system can be safely and efficiently performed.

Significant testing was completed throughout the fabrication of each of the major subcomponents: the 2G wire, the magnet pancake coils, the inner and outer coils, the full magnet, the SS, QD, and energy extraction. Some details of this testing and the test results are provided herein.

After individual testing, all components were assembled together for integrated testing. The ultimate design goal of the SMES is storage of 700 Amp at a temperature of 4 K, which generates a very high magnetic field of 25 Tesla. We had an intermediate test goal of reaching at least 350 Amp (50% of the design current) at an intermediate temperature. We successfully reached that and created a record magnetic field (12.5 T at ~27 K). After this test, the system experienced a false quench signal at 167 Amp and started the fast energy extraction. During this transient, the magnet incurred some damage. Our initial appraisal is that the inner coil has damage in at least two locations and the outer may also have some damage. Despite this mishap, we were subsequently able to test the full integrated SMES in all modes at low currents using the outer coil.

As the project concludes, BNL notes that the consortium of DOE/ARPA-E, ABB, BNL, SuperPower, and the University of Houston has worked very well together, and all have accomplished significant activities to advance the fields of superconducting materials, magnets, switches, and SMES devices. The magnet as-designed constitutes a record for an HTS

magnet at a value of 700 Amps, 25 Tesla, and 1.7 Mega Joules at 4 K. We do note that this has not yet been tested to these levels. The SS has an innovative design with a fast switch using RF-control, is 99% efficient, and has been tested to 600 A (at 77 K). We have also completed testing of the integrated SMES, including the BNL power supply / ABB power converter, ICS, QD and energy extraction system, magnet (outer coil), and SS. This testing included operation in all three modes: charge, storage and discharge.

ACRONYMS

2G	Second Generation
BNL	Brookhaven National Laboratory
CRADA	Cooperative Research and Development Agreement
FPGA	Field Programmable Gate Arrays
HTS	High-Temperature Superconductor
ICS	Integrated Control System
QD	Quench Detection
RF	Radio Frequency
SMES	Superconducting Magnetic Energy Storage
SS	Superconducting Switch

ACKNOWLEDGEMENTS

The work presented in this report includes work carried out during several years under the BNL SMES project. Many people helped in one way or another with this work, and we are grateful to them.

In particular, we thank Vyacheslav F. Solovyov and Qiang Li from the Advanced Energy Materials Group, Condensing Matter Physics and Material Sciences Division at Brookhaven National Laboratory (BNL) for their input to the Superconducting Switch sections of the report. We also thank Ramesh Gupta, S. Lakshmi Lalitha, Jesse Schmalzle and Peter Wanderer from the Superconducting Magnet Division at BNL for their input to the Magnet sections of the report. In addition, Piyush Joshi provided valuable input for the Quench Detection and Integrated Control System sections.

We express our appreciation to Jean Frejka for her excellent work on the assembly and editing of the report.

1. INTRODUCTION

1.1 Project Objective

The purpose of this project performed by BNL, under a CRADA with ABB Inc., is to enable superconducting magnetic energy storage (SMES) for grid-level applications by developing a cost-competitive, high energy-storage density, ultra-high field SMES coil using 2G HTS wire in combination with a flexible new modular power electronics interface capable of connection to medium voltage distribution networks. The CRADA work will be performed as a part of the ARPA-E Project with the title referenced above. The ARPA-E project team includes ABB Inc. (the project lead), SuperPower, Inc., and Brookhaven National Laboratory (BNL). The key component of the proposed system will be the superconducting storage coil developed at BNL. The designed coil will be capable of storing 1.7 MJ of energy for several hours and delivering 90% of the stored energy in a 1-hour discharge.

The BNL ARPA-E team pursued the following objectives:

1. Development of an ultra-high field storage magnet based on superconducting 2G wire from SuperPower
2. Development of components, including low resistive and persistent current joints, for a low-loss storage and drive system

2. DESIGN

2.1 Magnet Design

The SMES coil consists of inner and outer layers with each containing a number of pancake coils in them. The inner coil has 28 single pancakes and the outer has 16. The basic magnetic design is shown in Figure 2.1-1 with field contours superimposed over the coil at the design field.

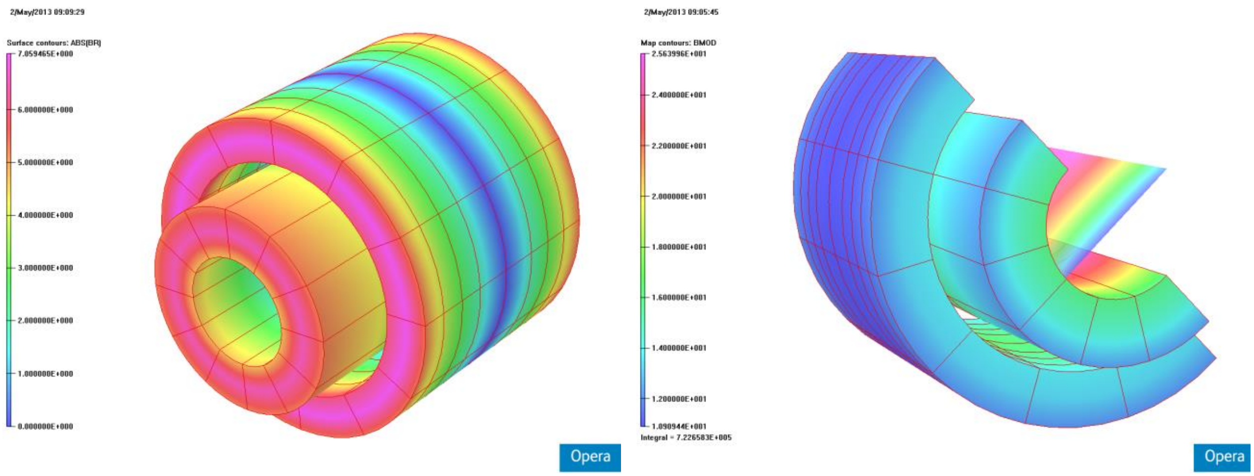


Figure 2.1-1 Magnetic field superimposed over the SMES coil consisting of inner and outer (left) and field on a patch inside the magnet (right, with only half coil shown for clarity).

An intermediate support structure between the inner and the outer layers is incorporated to keep stress and strain within the coil below limits so that the performance is not significantly degraded. The results of mechanical analysis with radial and axial strain shown are superimposed in Figure 2.1-2.

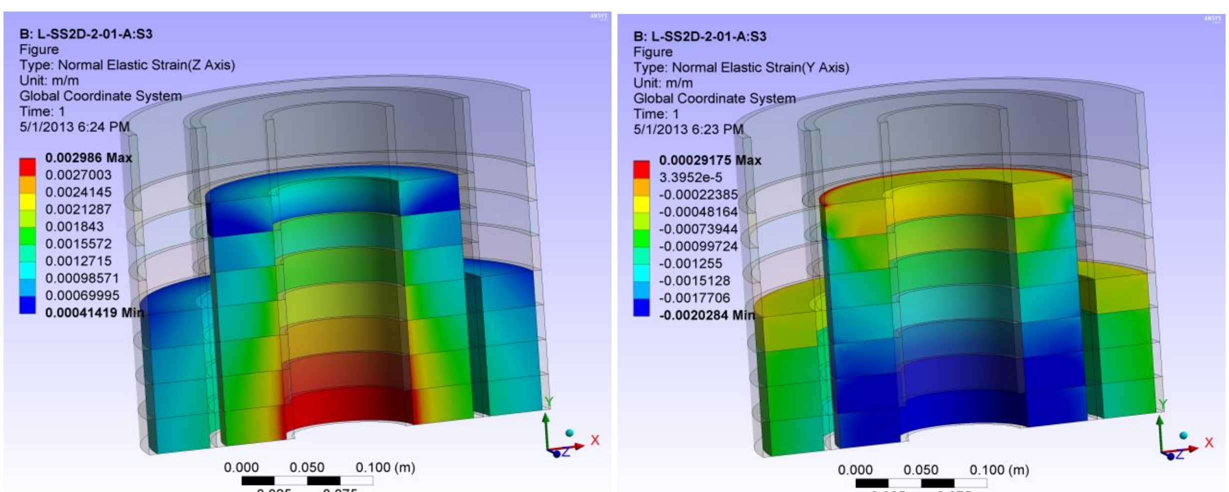


Figure 2.1-2 Mechanical analysis of SMES coil consisting of inner and outer coils with code ANSYS with radial (left) and axial (right) strain superimposed on the coil.

A grid scale device would be made of several such units making a toroid and, in addition, with several of them stacked vertically to store several gigajoules of energy (see Figure 2.1-3).

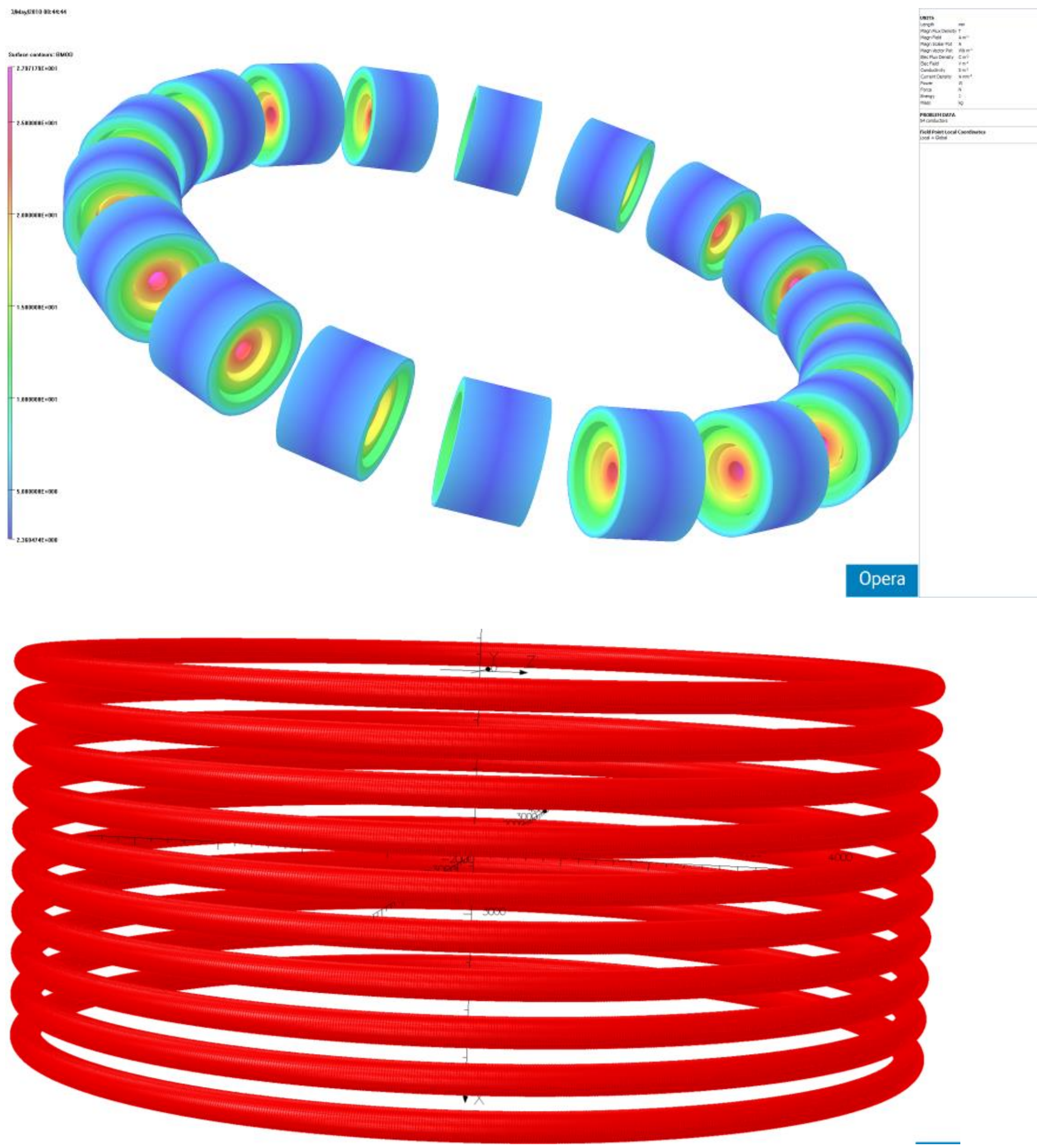


Figure 2.1-3 A toroid structure consisting of several solenoids (top) with a possibility of a number of toroids stacked vertically (bottom) to make a large device capable of storing several gigajoules of energy.

2.3 Quench Detection and Energy Extraction Systems

As with any superconducting magnet, the SMES magnet needs to protected from damage during quench conditions. This is particularly important for an HTS magnet. For the HTS magnet, we must detect the onset of a quench condition as early as possible (within few milliseconds), disrupt the energy being fed to the magnet and quickly extract stored energy. To protect the magnet during quench, we developed two systems called the Quench Detection System (QD) and Energy Extraction System. Together they are termed the Quench Protection System.

The Quench Detection System was developed using LabView programming language from National Instrument Inc. and associated hardware, consisting of Field Programmable Gate Arrays (FPGA) and fast "analog to digital" converter modules. The challenging part in the development of the QD System was to provide isolation between high voltage generated across the coil during energy extraction and low voltage sensor electronics. These isolators were specially developed by Verivolt Inc. for BNL (see Figure 2.3-1). Another unique feature of the QD System, which was successfully demonstrated, was the detection of small resistive voltage in the presence of significant noise and inductive voltages. Termination of current flow and energy extraction was also successfully demonstrated.

The operation of the QD System and energy extraction circuit is shown in Figure 2.3-2. There are four modes of operation coordinated with the persistent current switch and the power supply. During normal charge-discharge mode, the IGBT is on and Thyristor is off. During quench, to extract energy, the IGBT is turned off and the Thyristor is turned on. This allows stored energy to be extracted to the Dump resistor while voltage across the converter power supply is limited to -1.5V. A photo of the system is shown in Figure 2.3-3.

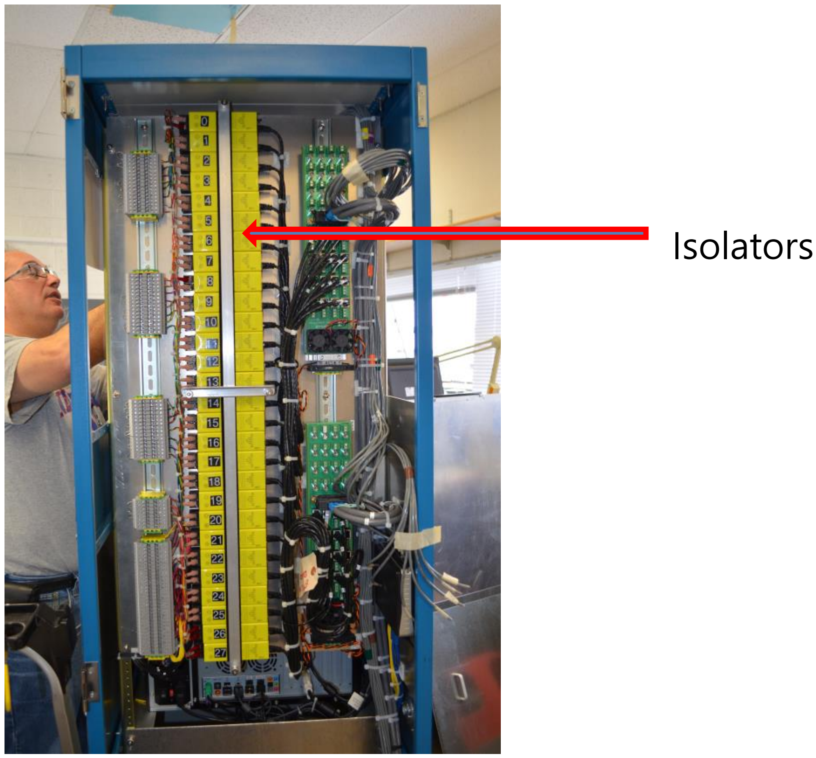
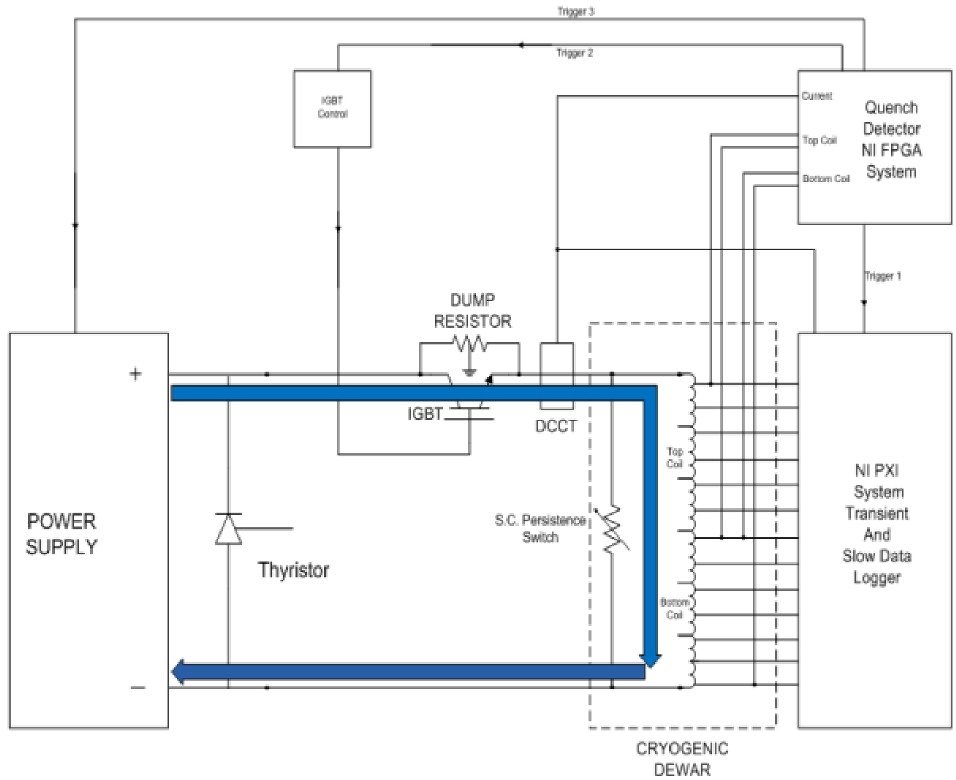
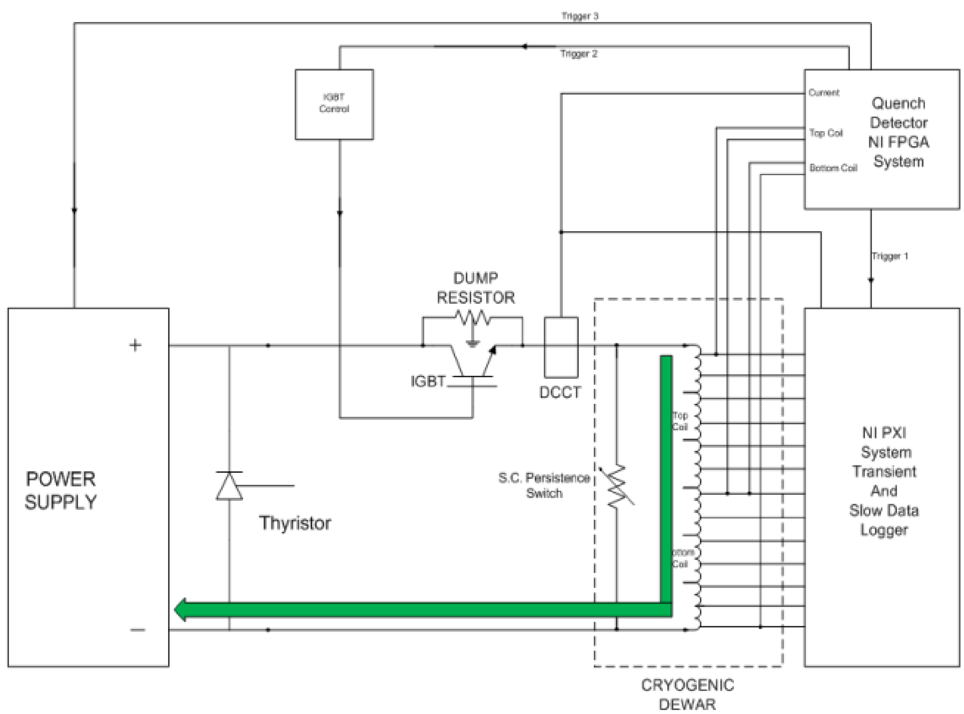


Figure 2.3-1 High voltage isolators.

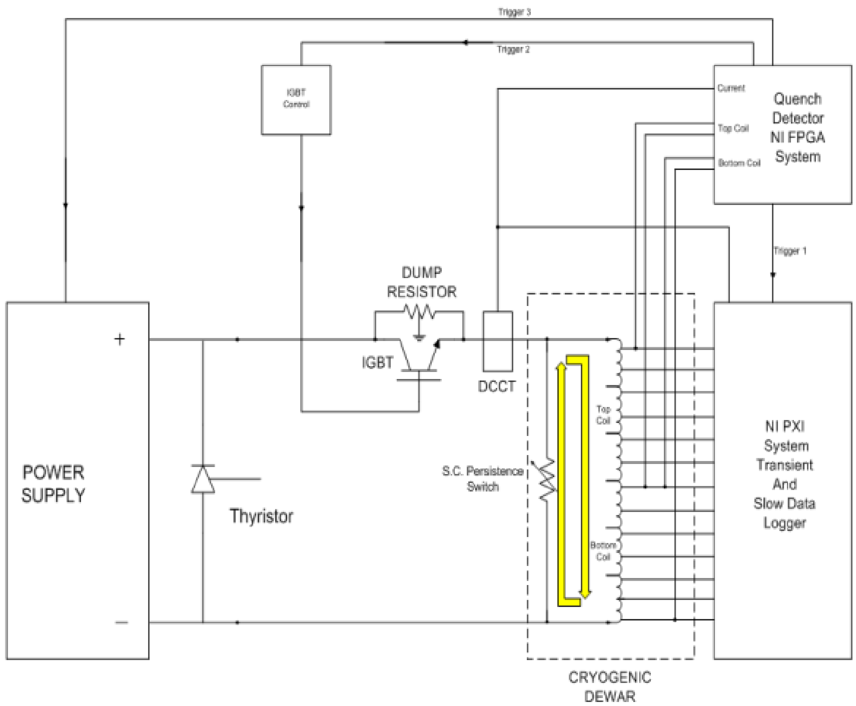


Discharge: Energy discharge to power supply, IGBT- ON

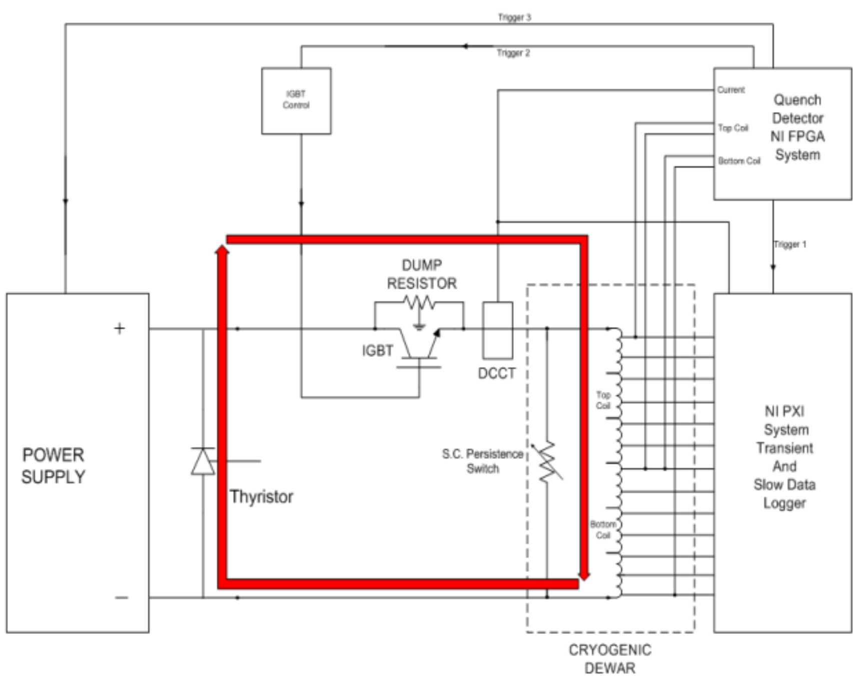


Charge: Energy flow to coil, IGBT- ON

Figure 2.3-2 Four modes of operation with persistent current switch and energy extraction circuit.



Storage: Current circulating thru persistence switch, IGBT- OFF



Quench: Energy extraction, Thyristor ON, IGBT- OFF

Figure 2.3-2 Four modes of operation with persistent current switch and energy extraction circuit (cont'd).

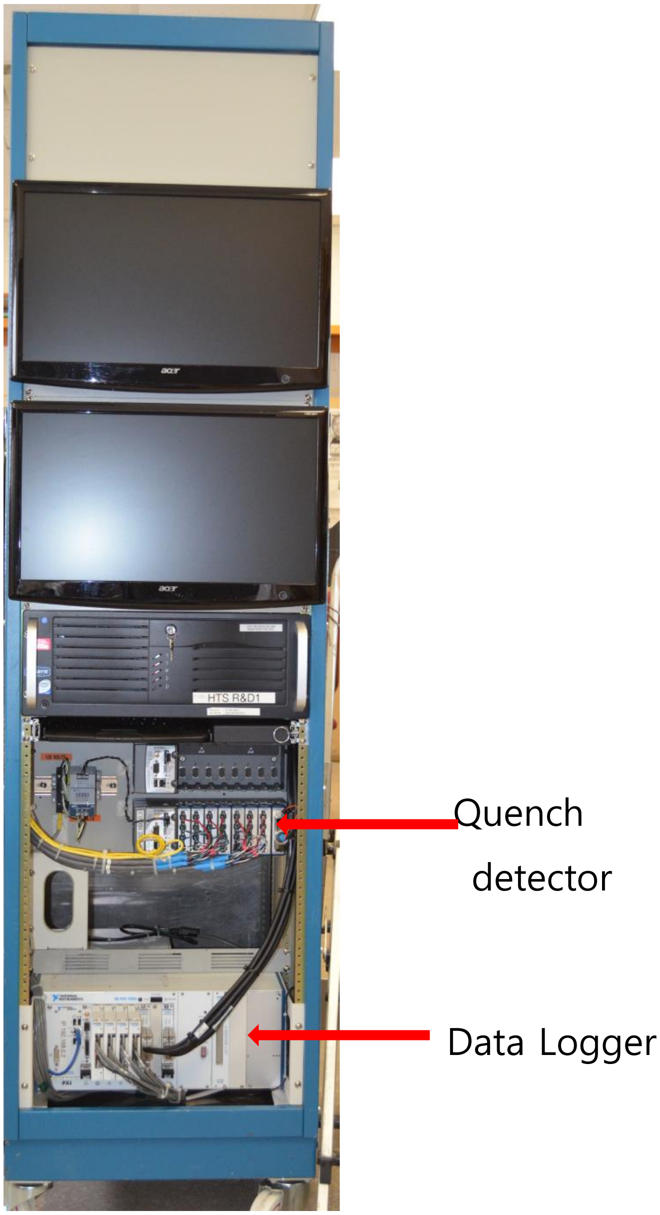


Figure 2.3-3 Electronic Rack Housing QD, Data Logger and Main Computer.

2.4 Integrated Control System (ICS)

The purpose of the ICS is to coordinate the operation of each component in the overall SMES so that charge, discharge and energy storage functions of the SMES system can be safely performed. The ICS uses LabView programming (Figure 2.4-1) and associated hardware modules for generating analog and digital signals. Figure 2.4-2 shows a block diagram of the integrated SMES system and Figure 2.4-3 shows an electrical schematic of integrated SMES system.

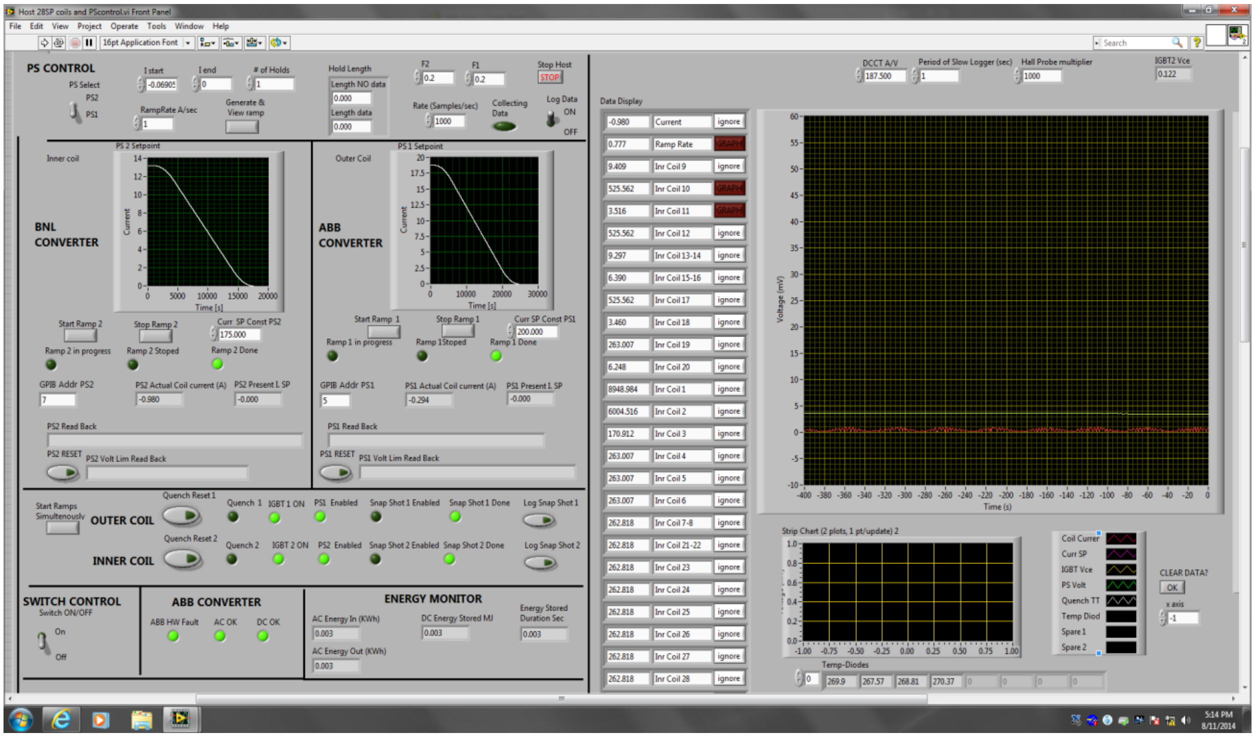


Figure 2.4-1 Screen shot of ICS LabView Program.

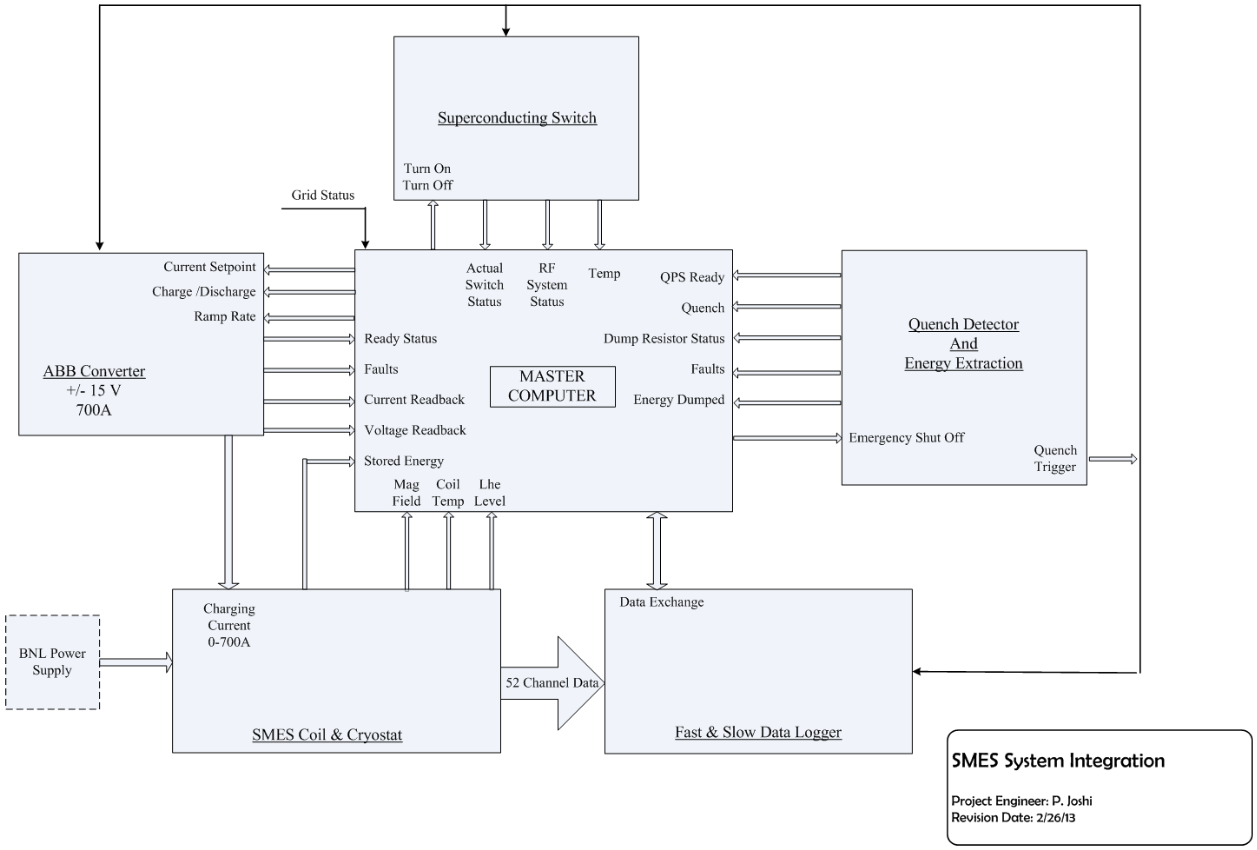


Figure 2.4-2 Integrated System Block Diagram.

Fully Integrated System

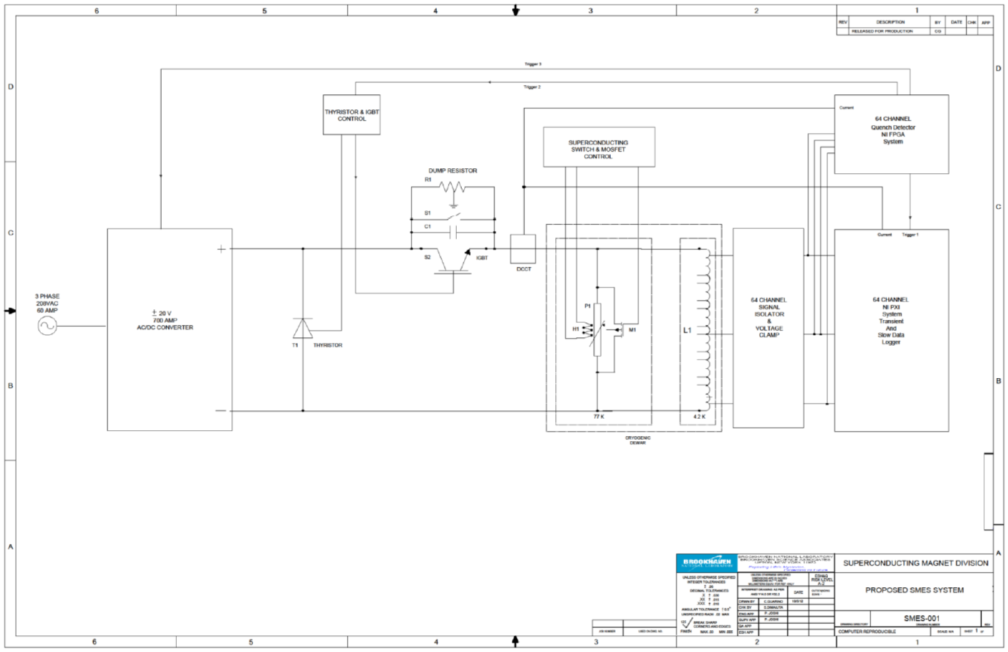


Figure 2.4-3 Schematic of Integrated System.

3. FABRICATION

3.1 Magnet

Full construction requires winding inner and outer pancakes, then assembling them into an inner and outer coil structure and then assembling the whole structure together with a large number of diagnostics and intermediate parts. One inner pancake coil, wound with the winding machine, is shown in Figure 3.1-1 (right). The bottom right part in Figure 3.1-1 shows the side of the coil with a number of voltage taps installed for diagnostics. The top part of Figure 3.1-1 shows the other side of the coil, as it will be in the final SMES coil package. Each inner pancake coil uses 100 meters of 12-mm wide HTS tape.

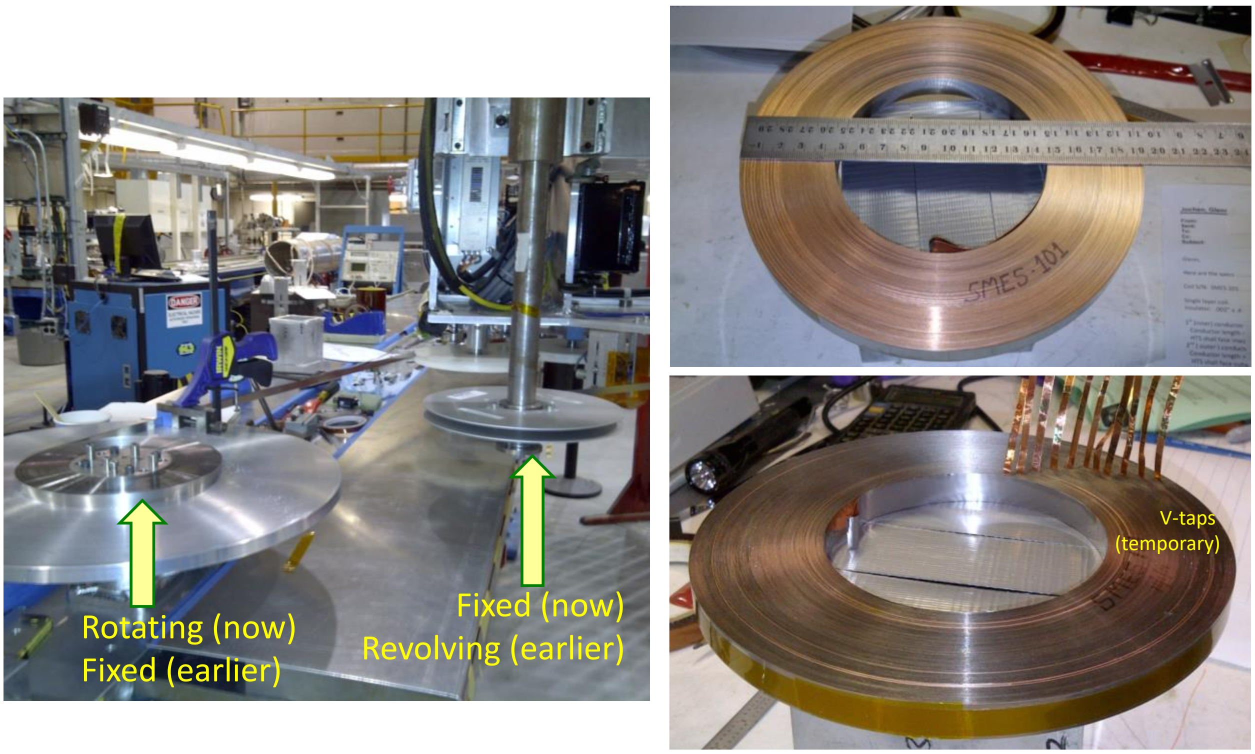


Figure 3.1-1 Updated coil wind machine (left) and two sides of a coil (right) wound with this machine. Bottom part of the picture on the right shows the side with the voltage taps.

Figure 3.1-2 below shows the inner and outer pancake coils during the construction process. Figure 3.1-3 shows the display of a number of SMES coil components laid out in the BNL fabrication and assembly facility of the Superconducting Magnet Division.

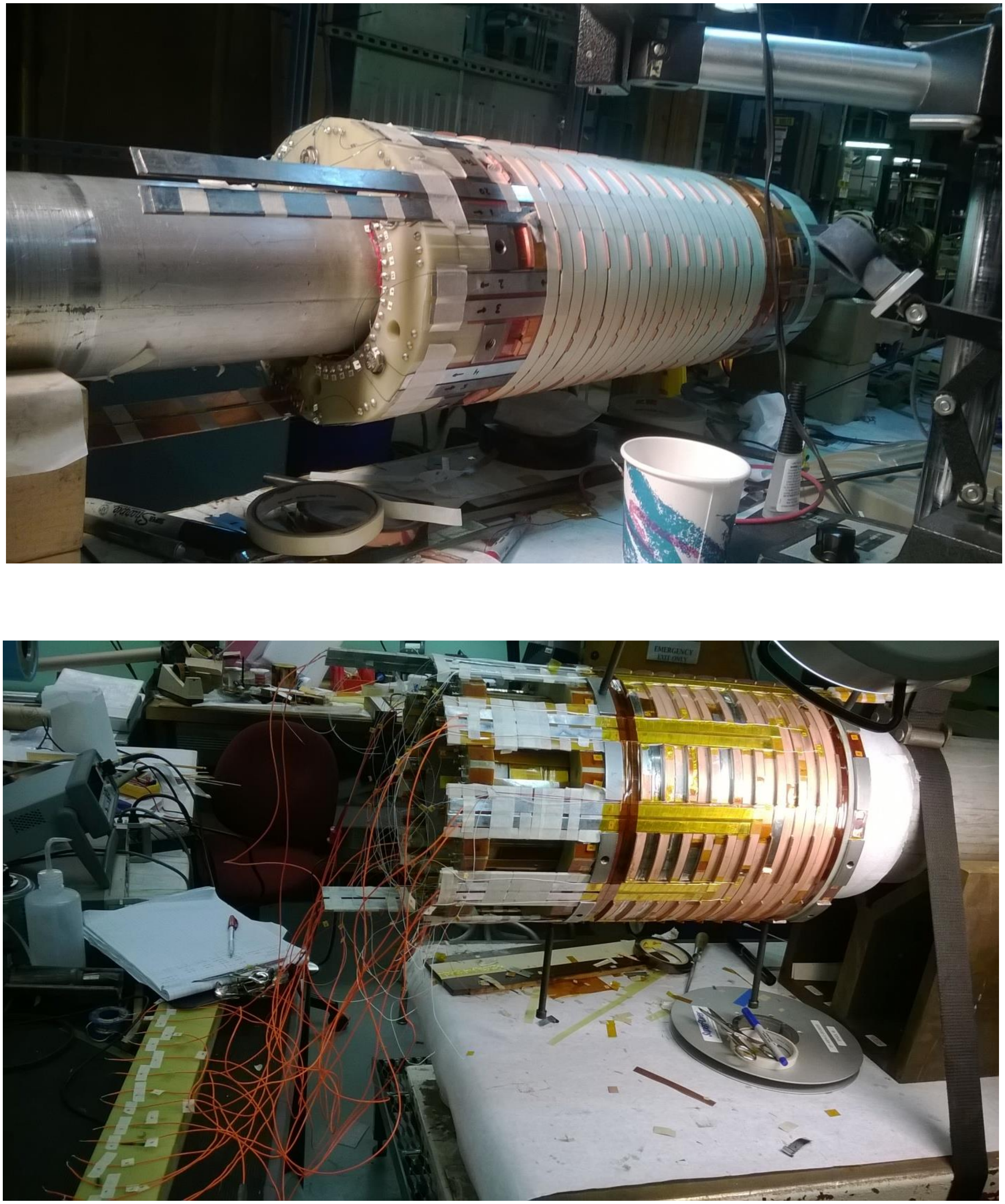


Figure 3.1-2 Inner (top) and outer (bottom) pancakes installed together to make full inner and outer coil assemblies.

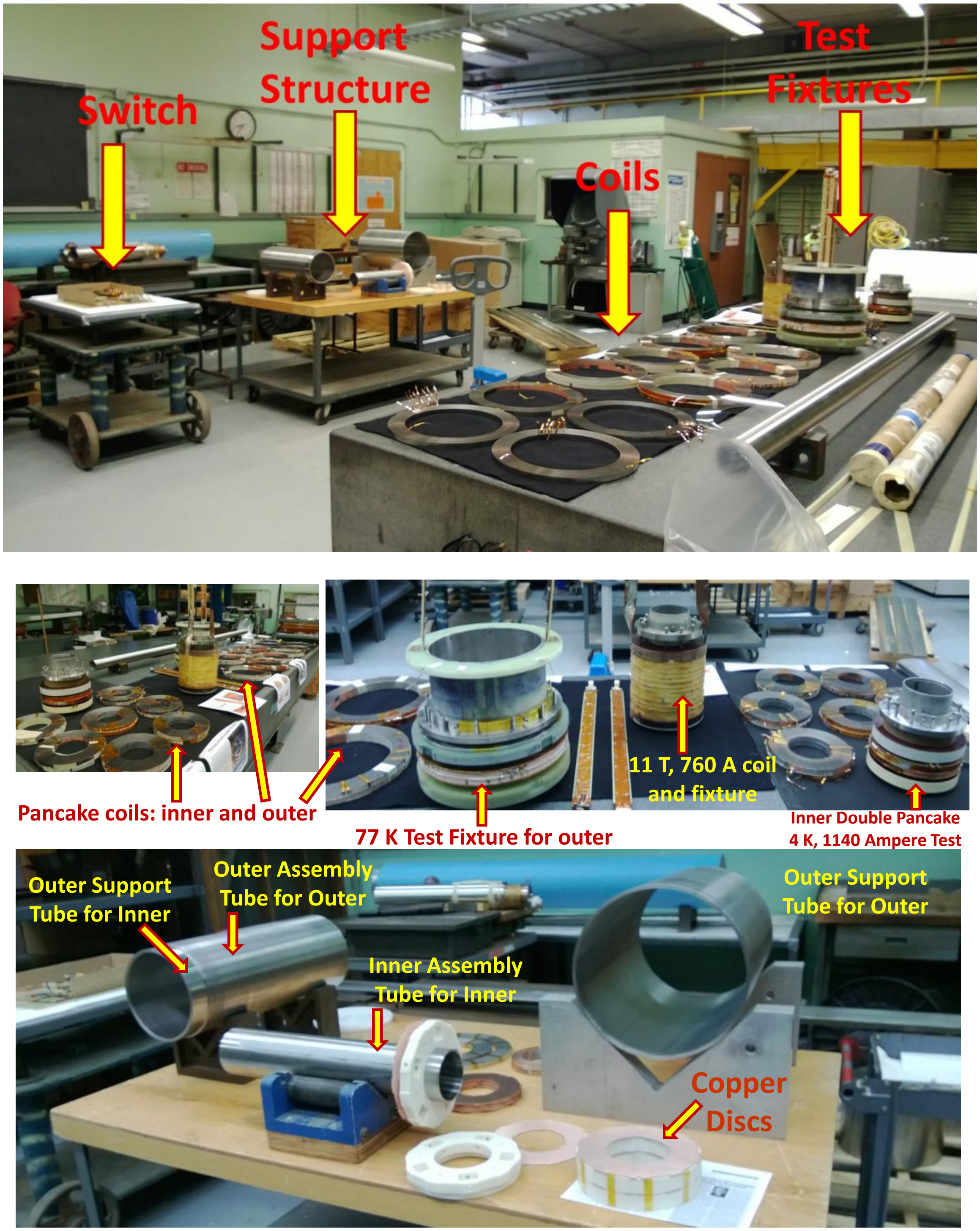


Figure 3.1-3 Components of high field SMES (coil and support structure).

4. TESTING

4.1 Magnet Testing

4.1.1 Splice Joint Test Results

SMES needs a number of splices both within the pancake (because wires of sufficient length to make a pancake without any splices are not available yet) and for joining a number of pancakes. Joints of several lengths were built and tested. Figure 4.1-1 (top) shows a typical joint in a test fixture. Measured joint resistance at 77 K as a function of overlap length is plotted on the left and as a function of 1/Area on right. The minimum value is about 1 nΩ. Based on these measurements, we determined a 15-cm length of joint should be acceptable for these joints. The splice resistance based on this construction technique remains well below the project goal of 5 n Ω. There is a further reduction in joint resistance in going from 77 K to 4 K (4.5 nΩ became 3.35 nΩ). Based on this work, it is clear that with sufficient overlap area of the joint, this technique can produce low-resistance joints with a value of less than 1 nΩ.

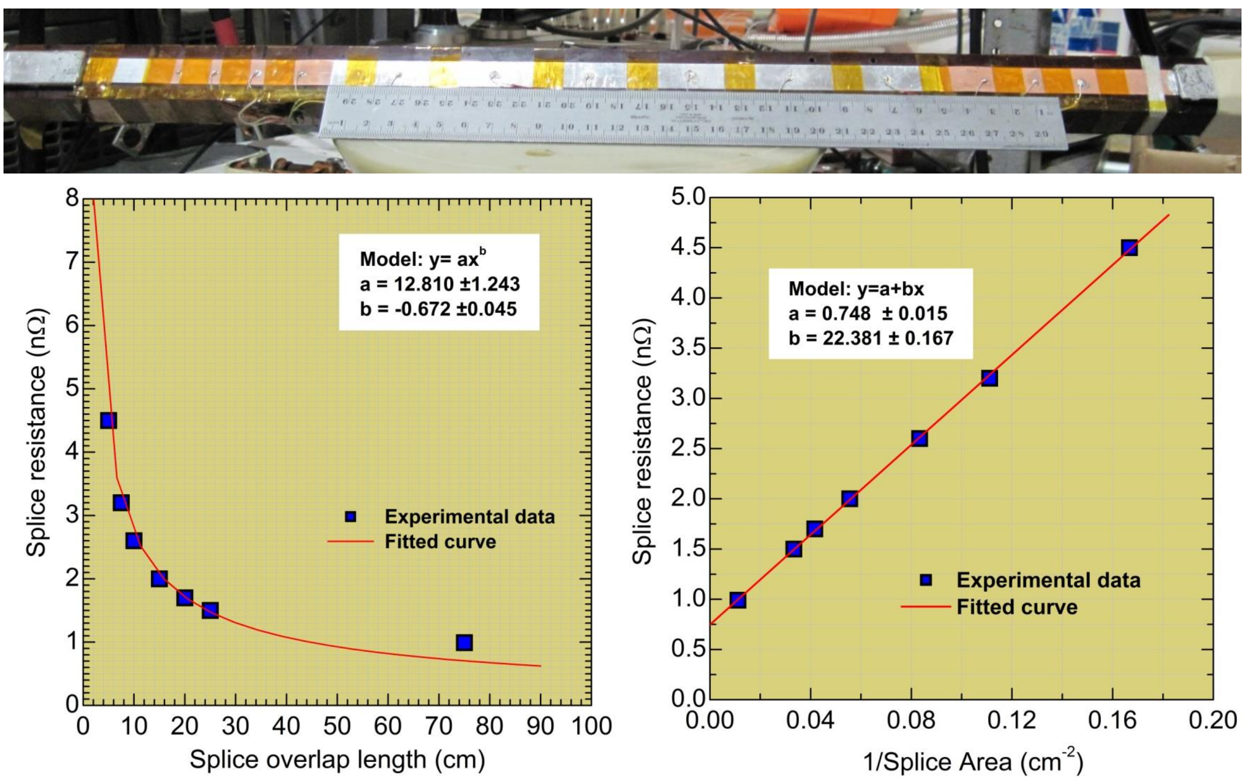


Figure 4.1-1 A comprehensive summary of the test results of several joints built and tested as a function of splice overlap length. A typical joint in a test set-up is shown on top. Measured joint resistance as a function of overlap length is shown on left and as a function of 1/area on right.

4.1.2 Pancake Coil Tests at 77 K

Each pancake was tested at 77 K with a large number of voltage taps to assure that all pancakes perform well individually before they are assembled in the large full-size SMES coil. Critical current based on 1 μV/cm criterion for inner pancakes is shown in Figure 4.1-2 and for outer pancakes in Figure 4.1-3. Figure 4.1-4 shows the value of joint resistance for diagonal splice between the two single pancakes to form a double pancake coil structure.

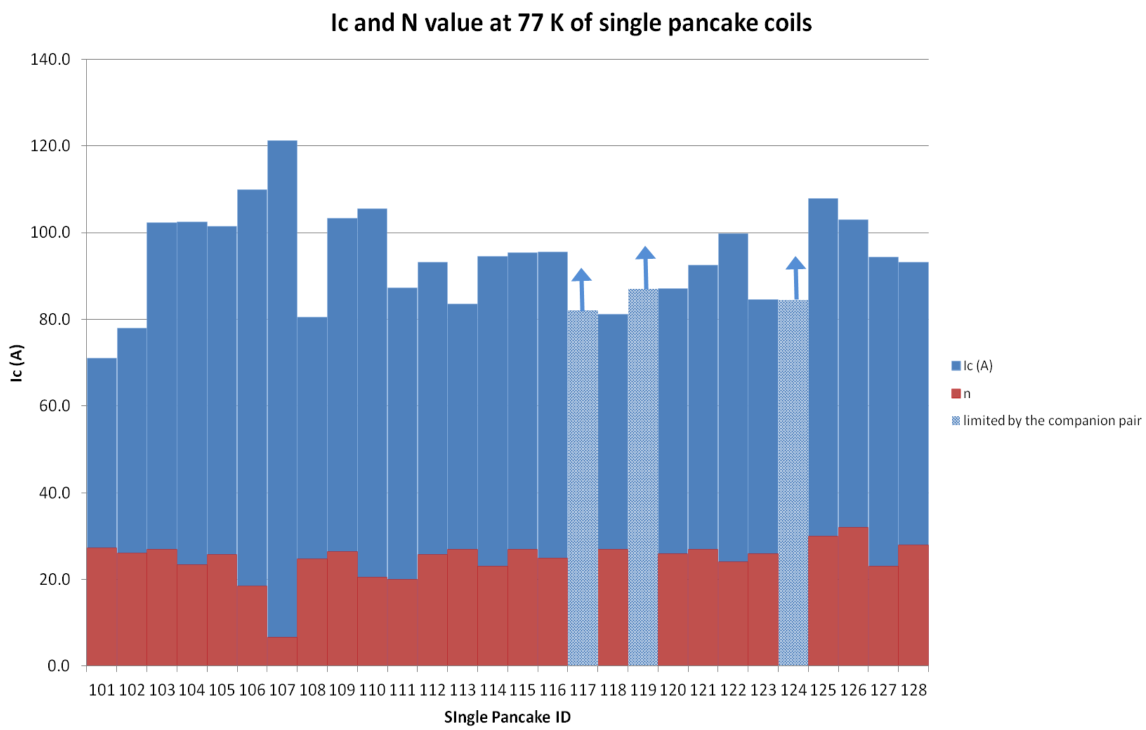


Figure 4.1-2 Histogram of critical current of 28 inner single pancakes unit at 77 K.

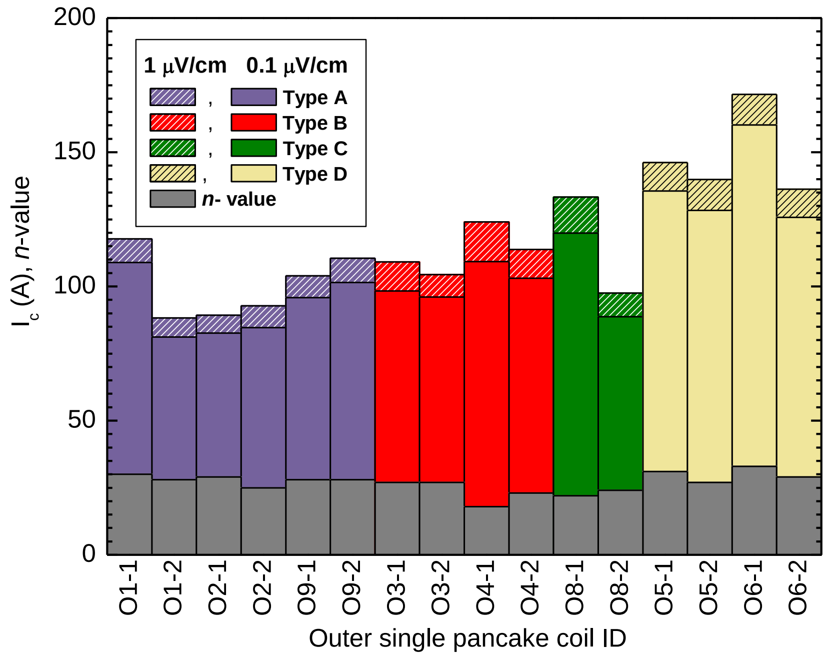


Figure 4.1-3 Histogram of critical current of 16 outer single pancakes at 77 K.

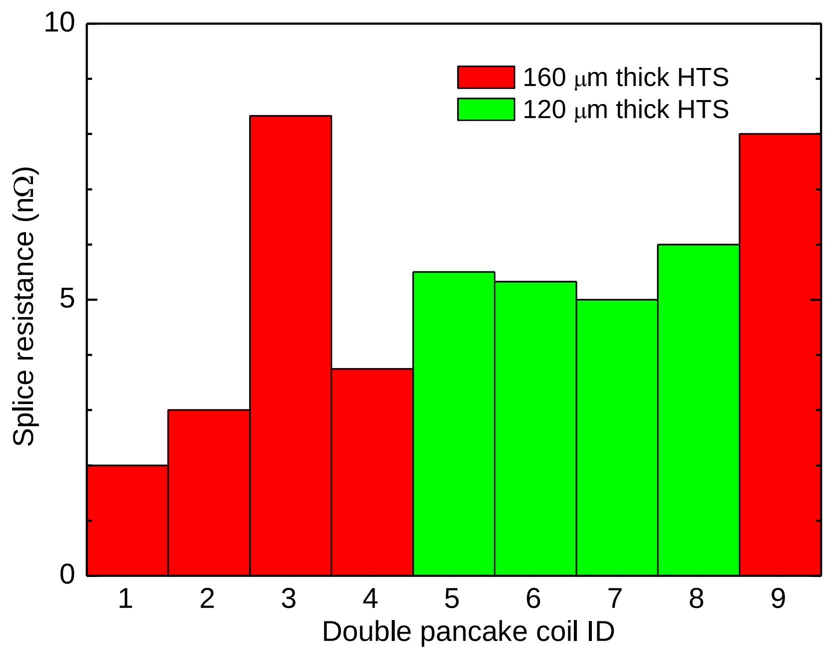


Figure 4.1-4 Histogram of resistance of diagonal splice between two outer single pancakes measured at 77 K. Since the measurement covers two splices, the average splice resistance per splice is half of this, which is significantly less than 5 nΩ.

In Figure 4.1-5, we show the case when a double pancake coil was not able to pass the QA tests. One can see an early onset of resistive voltage in the single pancake coil SMES 205, that is primarily responsible for the total voltage in the double pancake coil assembly DPC2003, which also contains SMES 206. In Figure 4.1-6, we show the case when both single pancake coils are powered individually with a number of voltage-taps monitoring voltage in small sections of the coil. Figure 4.1-6 (left) shows the measurement in a good coil and Figure 4.1-6 (right) shows the measurement in a defective coil. Incorporation of a large number of voltage taps allows us to identify the section of the conductor with poor performance and send the feedback to conductor manufacturer (SuperPower) to evaluate if there was something unusual during the fabrication. Only 2 single pancakes out of 46 that are needed for a 1.7 MJ device did not pass the QA test. Both were replaced by new coils for which SuperPower provided the extra conductor.

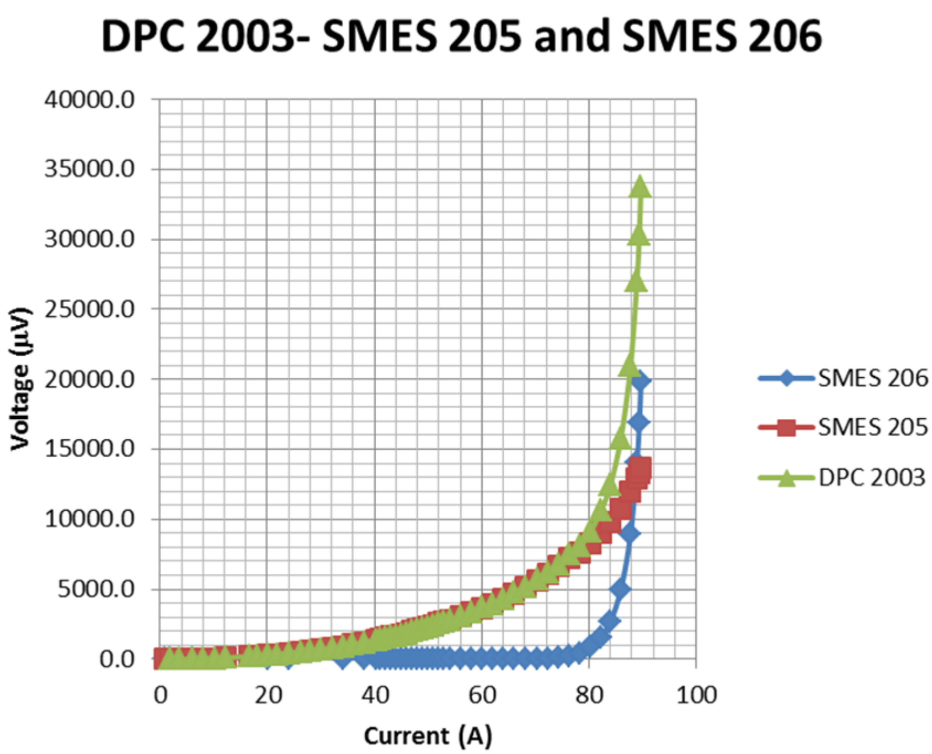


Figure 4.1-5 One single pancake coil (SMES 206) of the double pancake coil (OPC 2003) showed an early onset of resistive voltage during the QA test at 77K. This coil was not used in the entire 1.7 MJ SMES coil assembly. SMES 205 is acceptable.

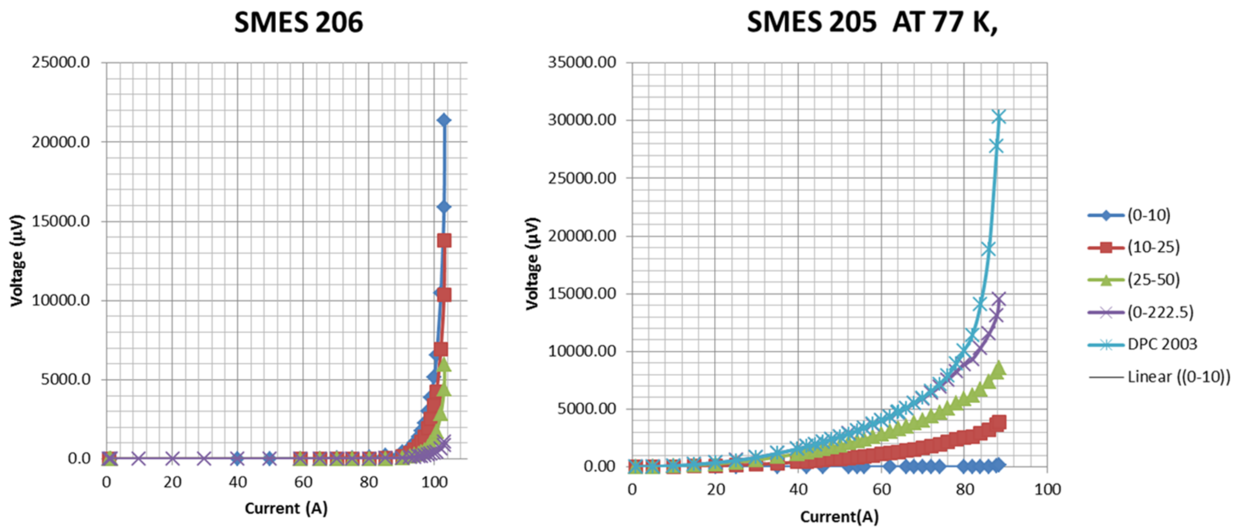


Figure 4.1-6 Performance during the test of individual coils (only one single pancake powered at a time). Good coil is shown on the left. Number of voltage taps help localize the bad region(s) in the coil (see early onset of resistive voltage on right).

4.1.3 Double Pancake Coil Test as a Function of Temperature

We built and tested the first double pancake coil at 77 K and then at 4 K to ensure that the entire process was reliable before starting the full-scale program. All systems (including quench protection and splice joint) worked well to over 1130 Amp (design current ~700 A). We also measured critical current of these coils as a function of temperature (see Figure 4.1-7).

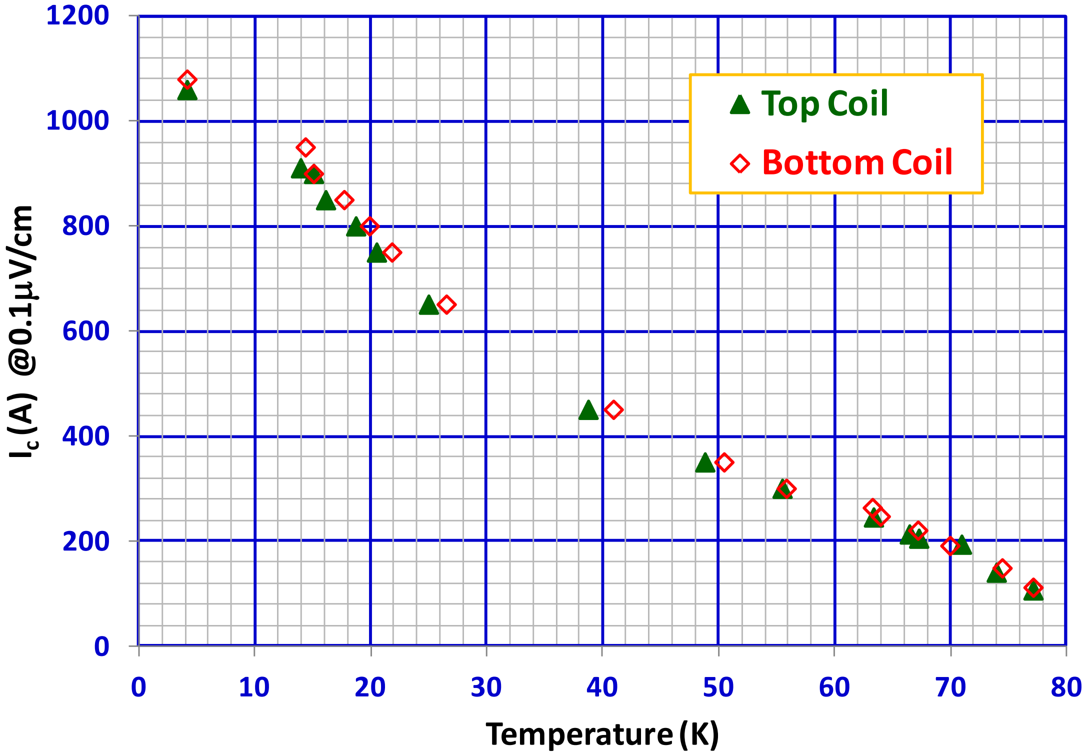


Figure 4.1-7 Critical current as a function of temperature for the first double pancake coil built for SMES project.

4.1.4 Test of High Magnetic Field SMES Coil

We constructed and tested a SMES coil for meeting the Go/NoGo milestone that requires a demonstration of the SMES coil producing over 10 Tesla. The milestone was met when we reached 11.4 T field on axis and 12.1 T in coil, exceeding original target of 10 T. The coil consists of 12 pancake coils having an inner diameter of 100 mm and an outer diameter of ~194mm. Figure 4.1-8 shows the coil being prepared for the high field test at 4 K. The test run in Figure 4.1-9 shows the coil energized to the 760 A at 4 K.

Figure 4.1-8 Photographs of the coil on top-hat with all instrumentation while being prepared for 4 K test.

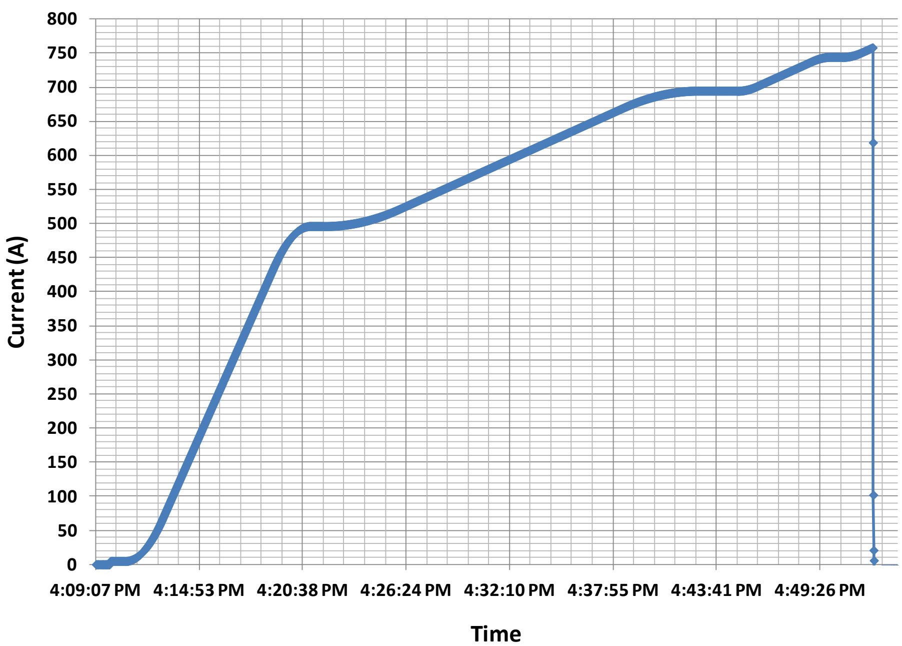


Figure 4.1-9 Charging sequence of SMES coil to a current of ~760 A. The run was terminated as the quench threshold was met and the energy was dumped to an external resistor.

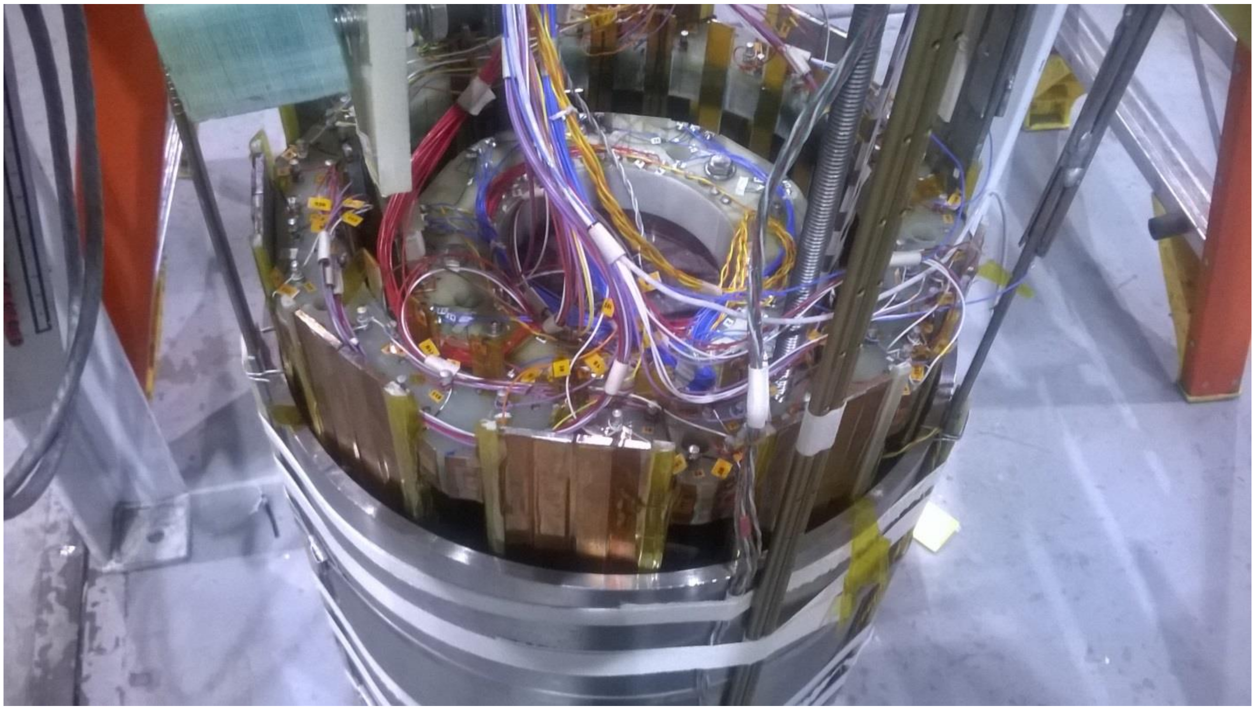


Figure 4.3-4 Fully instrumented SMES coil.

Figure 4.3-5 SMES coil installed on the top hat for testing.

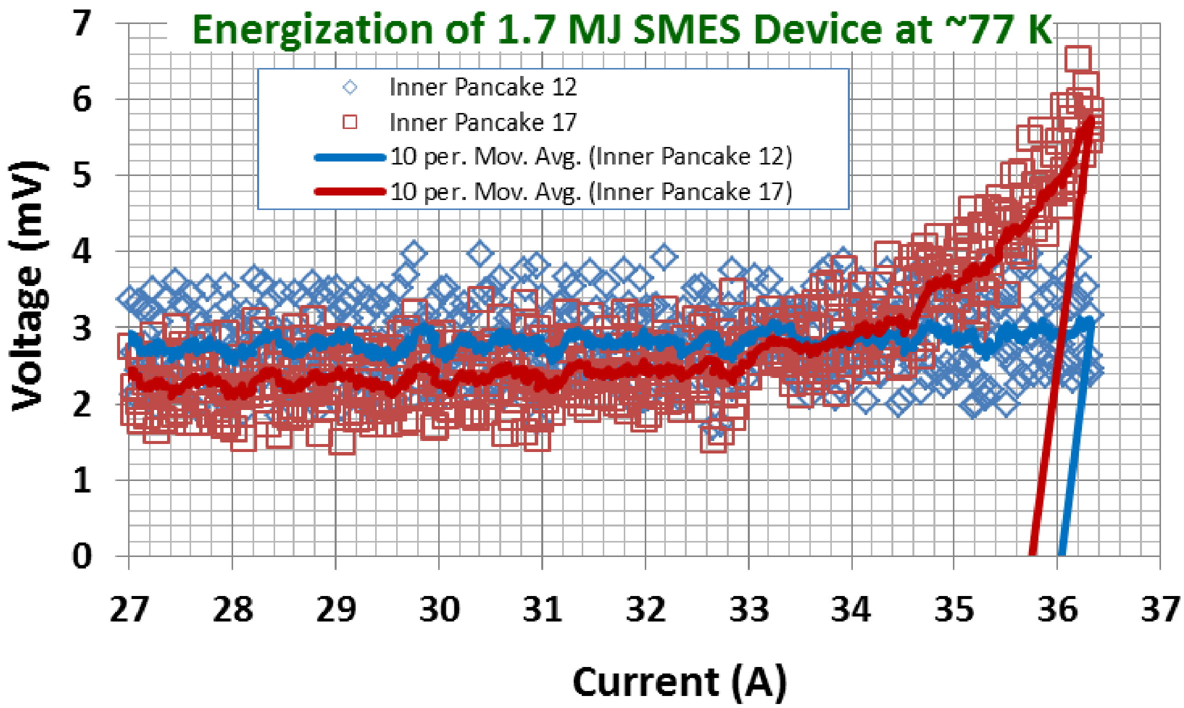


Figure 4.3-6 Coil reached a little over 36 A at ~77 K. The quench protection system turned off the power supply and extracted the energy when the voltage threshold for detecting quench was exceeded.

The ultimate design goal at ~4 K is 700 Amp (~25 T) is about 20 times more in current (over ~36 A) and about 400 times more in stored energy and forces. Therefore, we set an intermediate goal of reaching at least 350 Amp (50% of the design current) at an intermediate temperature. We successfully reached that and created a record magnetic field (12.5 T at ~27 K). We saw an early indication of the coil reaching its limit at that temperature but it was still below the threshold of tripping the quench detection system.

We let the temperature in coil rise drift (rise) slowly and began testing the system again at about 35 K. During this test, system issued a false quench signal at ~167 Amp and started the fast energy extraction. This was due to an operator error and not due to coil reaching its limit or showing any resistive signal. During this transient, the inner coil sustained some damage to the pancakes and/or the instrumentation on the inner coil. The outer coil appeared fully intact.

With little project funds or time left, BNL thus had to determine what additional testing would be accomplished. Since it had previously been established that a shut-off at 37 Amp doesn't cause any damage and since the outer coil didn't show any major sign of damage, the subsequent and final system integration test was limited to 37 Amp in the outer coil. Also, the operating temperature was lowered below 77 K to provide additional margin.

During the final testing at 35 to 37 Amps with the BNL power supply, the temperature was maintained in the range of 40-50 K and during the test with ABB convertor, the temperature was maintained in the range of 25-30 K.

Towards the end of this testing, the health of inner and outer coils was also examined. In the outer coil, the test was limited to 37 Amp and in inner to 2 Amp while the temperature was in the range of 25-50 K. During the current ramp and hold, the voltage signal in the outer coil appeared to be different from the original run. This might indicate some damage. However, it can't be definitively concluded that the pancakes in the outer coils have been degraded.

The inner coil has some definite damage in at least at two places. Figure 4.3-7 shows the onset of resistive voltage in two damaged regions right from the beginning. Despite the limited and compromised diagnostics or the inner coil, we are able to locate that damage to one single pancake and splice regions in one case, and one double pancake and splice regions at two places. Powering the inner coil and carrying out any significant tests with the compromised diagnostics could destroy the SMES coil. Hence, these coils need to be carefully examined and repaired before further testing.

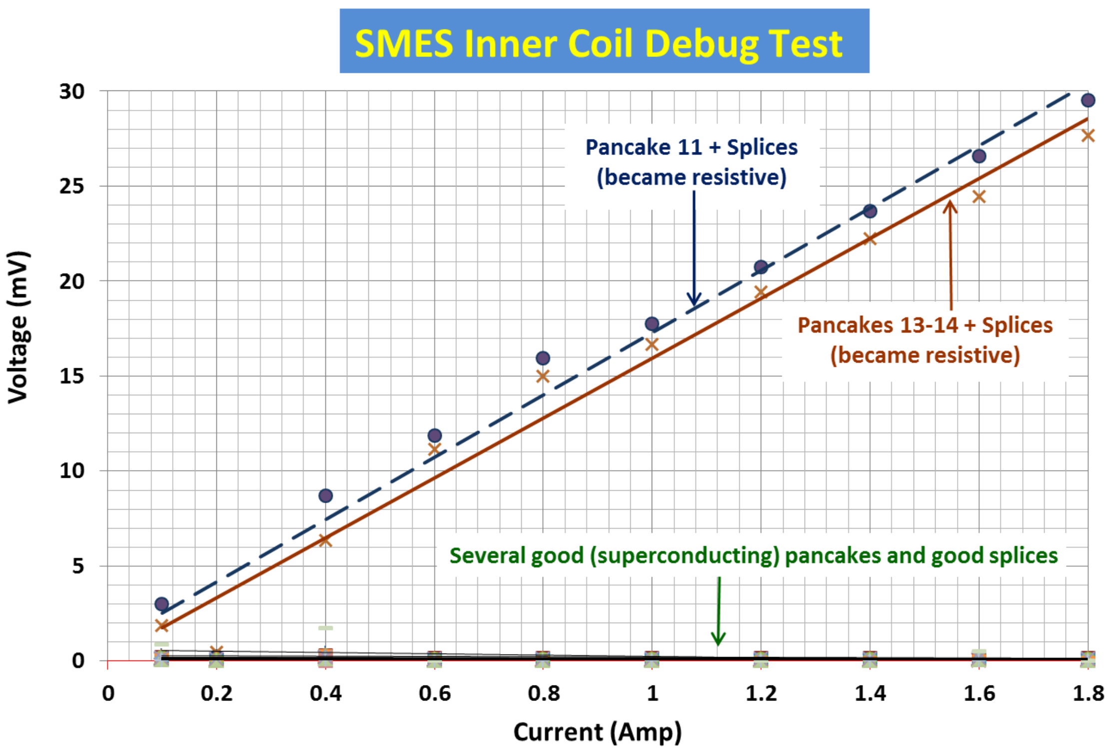


Figure 4.3-7 Inner coil test at low current. Early onset of resistive voltage shows the damaged area.

5. LESSONS LEARNED

The SMES coil was a very complex endeavor and required much more engineering than initially planned for and allocated. At 25 Tesla, the SMES coil was to be the highest field superconducting magnet ever to be built. The challenge included the use of new and brittle superconductor and in a large aperture, with high forces. The project was scheduled to be completed in short a time period for such R&D.

The project would have benefitted from a critical technical, budget, and management review by subject matter experts in the initial phases of the program.

One impact of the limited budget was the insufficient development of software and hardware to safely operate the coil. An accidental damage to the coil due to human error during the operation could possibly have been prevented with software interlocks or better, more detailed procedures.

The ReBCO conductor supplied by SuperPower is still an R&D conductor and several defects were detected. Since even a small defect may limit the performance of the entire SMES coil, continuous close monitoring and detailed testing of each pancake at 77 K became necessary. In fact, three pancake coils (two fully wound and tested) had to be replaced. Conductor has to be made significantly more reliable before SMES or any device can be seriously considered for reliable operation based on this conductor. Moreover, the conductor required splices (sometime several) within each coil. This could be avoided if conductor in longer lengths becomes available. In addition, the conductor performance should be monitored at the operating conditions. Whereas SuperPower measured the performance at 77 K with no applied field, the design operating conditions are at 4 K with significant field on the conductor. Measurements were performed at BNL in a few samples and showed a large variation in the critical current at 4 K (as much as a factor of two). Therefore, it is not known if the conductor used in the SMES coil meets the specifications or not at 4 K. Therefore, we cannot tell if the overall SMES coil performance would be limited by the conductor.

The convertor that came to BNL for integrated system testing was not finished soon enough for testing under inductive load as should have been done before testing with the SMES coil. Also, the as-built power convertor had a large amount of noise with the SMES coil load (over an order of magnitude), causing false trips. To allow the operation of SMES coil with the converter even at a reduced level (about an order of magnitude of critical current), the quench detection system had to be disconnected. Carrying out tests with the convertor with compromised diagnostics, at any significant current level, was potentially hazardous to the magnet coils.

As the project concludes BNL notes that the consortium of DOE/ARPA-E, ABB, BNL, SuperPower, and the University of Houston has worked very well and all have accomplished significant activities to advance the fields of superconducting materials, magnets, switches and SMES devices.

The Magnet as-designed constitutes a record for an HTS magnet at a value of 700 Amps, 25 Tesla, and 1.7 Mega Joules at 4 K. We do note that this has not yet been tested to these levels. Significant testing has been completed, summarized as follows:

- Magnet testing
  - Low resistance (<1 nano-ohms) HTS splice joint developed and tested at 4 K
  - Double pancake coils tested to 1140 Amps
  - 12 pancake inner coil assembly tested to 760 Amps
  - All 48 magnet pancake coils successfully tested at 77 K
  - Full completed magnet, with both inner and outer coils, tested to 50 % capacity, at 27 K to 350 Amps, 12.5T and ~ 0.4 MJ,
    - Record high values for HTS magnet even at 50% capacity

- Superconducting Switch (SS): innovative design; fast switch using RF-control; 99% efficient; tested to 600 A (77 K)

- Completed testing of integrated SMES: BNL power supply / ABB power converter, ICS, QD&QP system, magnet (outer coil), and SS; operation in charge, storage and discharge modes

As the project closes, BNL has determined that the following type of material generated during the project is categorized as “Protected CRADA Information”: details of design and construction of the SMES coil and quench protection system (where the quench protection system is equivalent to quench detection and energy extraction system).

6. RECOMMENDATIONS

In a relatively short period of time (three years) and with a modest funding, BNL has designed, built and tested this high field SMES coil. However, there was an unexpected event during the final integrated testing which terminated the test run and partially damaged the coil. As disappointing as it was, realistically one has to be prepared for such surprises during R&D that pushes the boundary of known science and engineering as is typical for ARPA-E projects. BNL has located the problem areas in the magnet, however, confirmation and repair requires at least partial disassembly of the magnet. Having designed, built and tested this magnet, BNL has the required in-depth knowledge of the construction and is in the best position to repair this.

It is important to note that one must be careful in operating such HTS coils made with entirely new technology. This is an R&D device, not production equipment, and must be protected with a sophisticated quench protection system. Energizing the coil without such protection would put the coil in immediate risk.

BNL Recommendations on the next steps for the SMES device:

1. Troubleshoot and repair damage to inner coli pancakes
2. Troubleshoot and repair damage to instrumentation (voltage detectors) system.
3. Troubleshoot outer coil to see if there is any damage there.   Repair as needed.
4. Retest SMES coils by themselves after all repairs are complete.
5. Develop design for operating the superconducting switch at 4 K to avoid transition between 4 K and 77 K in the SMES device.

APPENDIX A

Information Requested By ABB in Final Report

Final Scientific/Technical Report

<u>Content</u>. ABB specified that the final scientific/technical report must include the following information. The requirements here are in Italics with the necessary information following.

1. *Identify the ARPA-E award number; name of recipient; project title; name of project director/principal investigator; and consortium/teaming members.* –

   CRADA No. BNL-C-11-01:

   Project Title: Development of Ultra-High Field Superconducting Magnetic Energy Storage (SMES) for Use in the ARPA-E Project titled "Superconducting Magnet Energy Storage System with Direct Power Electronics Interface"

   PIs: Qiang Li and Ramesh Gupta; Project Manager: James Higgins

   Consortium team members: ABB, BNL, SuperPower, University of Houston

2. *Display prominently on the cover of the report any authorized distribution limitation notices, such as patentable material or protected data. Reports delivered without such notices may be deemed to have been furnished with unlimited rights, and the Government assumes no liability for the disclosure, use or reproduction of such reports*. – No restriction on material in this report.

3. *Provide an executive summary, which includes a discussion of (1) how the research adds to the understanding of the area investigated; (2) the technical effectiveness and economic feasibility of the methods or techniques investigated or demonstrated; or (3) how the project is otherwise of benefit to the public. The discussion should be a minimum of one paragraph and written in terms understandable by an educated layman*. – Done.

4. *Provide a comparison of the actual accomplishments with the goals and objectives of the project.* – See quarterly reports for details as completed. Summary provided herein.

5. *Summarize project activities for the entire period of funding, including original hypotheses, approaches used, problems encountered and departure from planned methodology, and an assessment of their impact on the project results. Include, if applicable, facts, figures, analyses, and assumptions used during the life of the project to support the conclusions*. – See text of this report.

6. *Identify products developed under the award and technology transfer activities, such as:*

a. *Journal Articles: Articles published in scientific and other journals. List author name, title, journal name, volume, issue, pages, and year of publication. You are required to send a copy of each journal article to the ARPA-E Program Director.*

1. V. F. Solovyov and Q. Li, "Fast high-temperature superconductor switch for high current applications." Applied Physics Letters, 2013. 103(3): p. 032603-3.

b. *Papers: Conference papers. List author name, title, conference name, location, and date of conference. You are required to send a copy of each paper to the ARPA-E Program Director.*

1. V. F. Solovyov and Q. Li, "*Fast high-temperature superconductor switch for high current applications."* Applied Physics Letters, 2013. **103**(3): p. 032603-3.

2. Abstract and paper submitted to Magnet Technology Conference MT-23 (Conference held at July 14-19, 2013 at Boston, MA), Test Results of High Performance HTS Pancake Coils at 77 K by L. S. Lakshmi, W. B. Sampson, and R. C. Gupta.

c. *Status Reports: Other progress reports and updates submitted to ARPA-E. List name of report and date of submission to ARPA-E*. – BNL Quarterly reports for Quarter 1 (Q1) through Q15.

d. *Media Reports: Any articles in newspapers, magazines, online media, etc. List author, title, publication and/or website, page number (if applicable), and date of publication.*

e. *Invention Disclosures: Subject inventions disclosed to ARPA-E and the U.S. Department of Energy under this Award. List title, date submitted, and name of inventor.*

f. *Patent Applications: Patent applications arising out of subject inventions disclosed to ARPA-E and the U.S. Department of Energy under this Award. List patent number, name of inventors, assignee, patent application number, date of filing, and title of patent application*.

1. BSA 12-18, Solovyov, V.F. and Q. Li, “Radio Frequency-Assisted Fast Superconducting Switch.” PCT Application No. US13/035723 published as WO 2014/011272, assignee: Brookhaven Science Associates, ROI submitted January 12, 2012.

2. BSA 12-29, Solovyov, V.F. and Q. Li, “Fast Superconducting Switch for Superconducting Power Devices,” PCT Application No. US13/63689, assignee: Brookhaven Science Associates, ROI submitted August 27, 2013.

3. BSA 12-13, Inventor: Piyush Joshi; “Quench Detection System for Superconducting Magnets,” Pub No: US2013/0293987 A1, Pub date: November 7, 2013.

4. Provisional Application S.N. 61/984,520 Filing date 4/25/2014. Title: Generation of a Splice Between Superconductor Materials.

g. *Licensed Technologies: Subject inventions licensed to third parties. List name of licensee, patent or patent application number, title, and expiration date of agreement.*

h. *Networks/Collaborations Fostered: Partnerships and other arrangements concluded with respect to the project or technology area. List name of network/collaboration (if any), name of entities involved, date of agreement (if any), brief description of network/collaboration, and technology area.*

i. *Websites Featuring Project Work or Results: Web site or other Internet sites that reflect the work or results of this project. List name of website, specific webpage(s) on which project work or results featured, and brief description of project work or results featured.*

j. *Other Products: Additional project output, such as data or databases, physical collections, audio or video, software or Netware, models, educational aid or curricula, instruments or equipment. List brief description of additional project output, date of release, and entity to which output was provided.*

k. *Awards, Prizes, and Recognition: Any awards, prizes, or other recognition for project work or results, subjection inventions, patents or patent applications, etc. List name of award/recognition/prize, name of sponsoring organization, date of receipt, and subject of award/prize/recognition*.

l. *Collaboration of the four parties to the SMES CRADA: ABB, BNL, SuperPower, and University of Houston*

You are encouraged not to submit patentable material or protected data in these reports, but if there is such material or data in the report, you must:

(1) clearly identify patentable or protected data on each page of the report;
(2) identify such material on the cover of the report; and
(3) mark the appropriate block in Section K of the DOE F 241.3.

Reports must not contain any limited rights data (proprietary data), classified information, information subject to export control classification, or other information not subject to release. Protected data is specific technical data, first produced in the performance of the award that is protected from public release for a period of time by the terms of the award agreement.

No patentable material or protected data is contained in this report.