Status of Q4 Milestones & Progress Report at BNL Magnet Division

Ramesh Gupta and Piyush Joshi
(For Superconducting Magnet Division)

Status of Q4 Milestones

Task 2A: Small scale test coils fabricated and tested to determine mechanical properties of the conductor that can be used in the design. Demonstrate a cross-section design with deflection < 200 micron. Typical coils are built with about 2 m of wire, and a 2" ID

Completed in September 2011. Coil i.d. increased to 100 mm and made with 50 meter of wire.

Task 2B: Magnet design complete to produce coil with 2.5 MJ stored energy

Completed in August 2011.

Task 2C: Initial Magnet design

Completed in July 2011.

Task 10A: Define statistical sampling procedures for individual coil tests

Completed in September 2011.

GO/NO GO Decision/Review items: Successful test at 77 K, of a mini stack of coils demonstrating performance according to key design features

Completed construction and test at 77 K in September 2011 of a mini stack of two coils having an inner diameter of 100 mm and consuming a total of 100 meter of wire. In addition, we also performed several critical tests under more demanding circumstances at ~4 K with currents going up to 1140 A (design current ~660 A). These tests were introduced in the program to demonstrate the performance of key design and construction features before committing those techniques to a full scale production.

Please see more details of the above and other ongoing tasks under progress report section in following pages.

Progress Report

Magnetic Design and Analysis

The overall design of the SMES coil has been simplified by reducing from three radial subdivisions in the 3.4 MJ, 30 T presented in the original proposal to two radial subdivisions in the current 2.5 MJ, 24 T demo device. The magnetic design is shown in Fig. 1. By properly optimizing the spacers between the coil blocks the radial component of the field has been reduced to 6.2 T as compared to the ~10 T in the original proposal. The primary purpose purpose of the axial spacers, however, is to keep stress/strain on the narrow face of the tape within the acceptable limit. SMES coil will be made of ~32 pancakes, each using 300 meter of conductor.

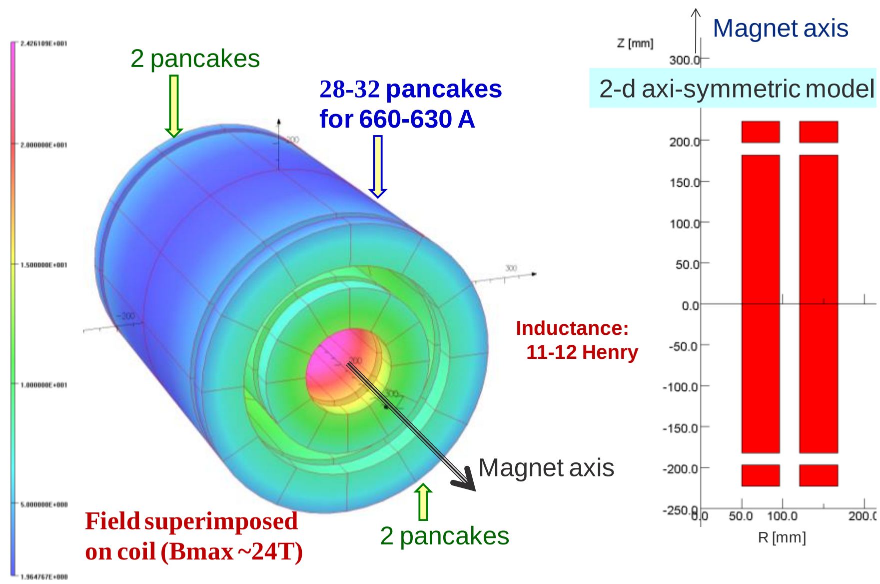

Fig. 1: 3-d (left) and axi-symmetric 2-d model (right) of the current design of the 2.5 MJ demo device.

A conceptual design of a 2 GJ GRID scale system, developed here, is shown in Fig. 2. This consists of double pancake coils of similar dimensions as used in the demo device. We were able to reduce the normal component of the field to ~0.4 T, which reduces the conductor requirements and energy loss by a factor of five or more.

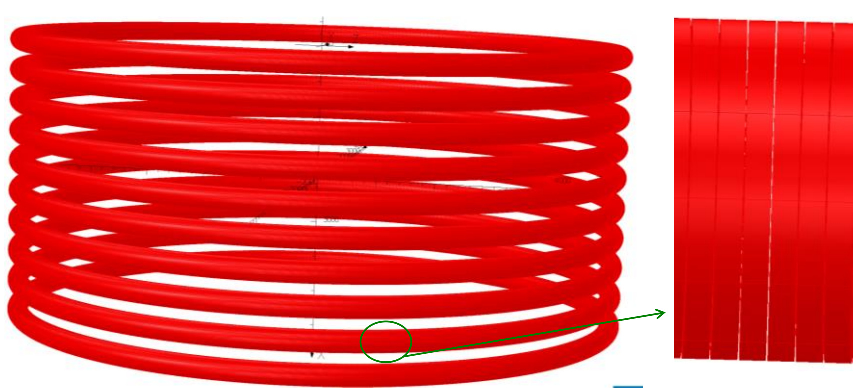

Fig. 2: A conceptual design of the GRID scale SMES device with a significantly reduced system cost.

Mechanical Analysis

Mechanical analysis is primarily carried out with a well established computer code ANSYS. Because of symmetry only the upper-half of the Fig 1 (right) model is required. A simplified mechanical model, where the coil blocks placed in solid stainless steel with no internal structure, is shown in Fig. 3 (left). The computed maximum deformation of ~171 microns occurs in HTS coils (with a radial component of ~144 microns and axial 148 micron); whereas, the maximum deformation in stainless steel is ~104 micron. The maximum computed equivalent stress in HTS coil is ~353 MPa (Fig. 3, left), which is in the HTS coils; whereas, the maximum computed stress in the stainless steel structure is ~225 MPa. The maximum computed strain in HTS coils is 0.27%. All of these are well within the maximum allowable limit. These numbers are, however, expected to increase when the actual structures with all engineering components are incorporated in a more complex model.

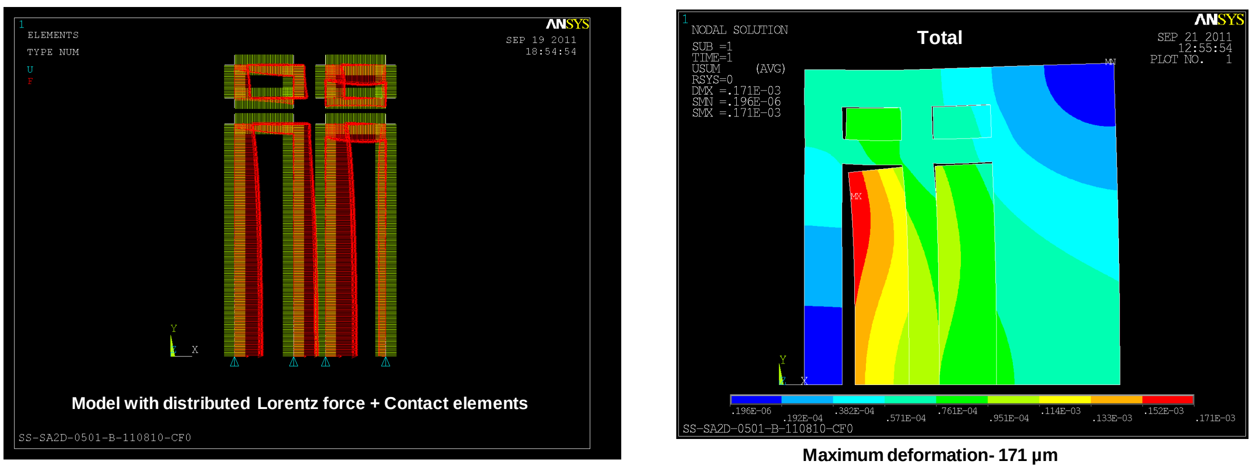

Fig. 3: Upper half of the axi-symmetric (right) and computed deformation in the structure.

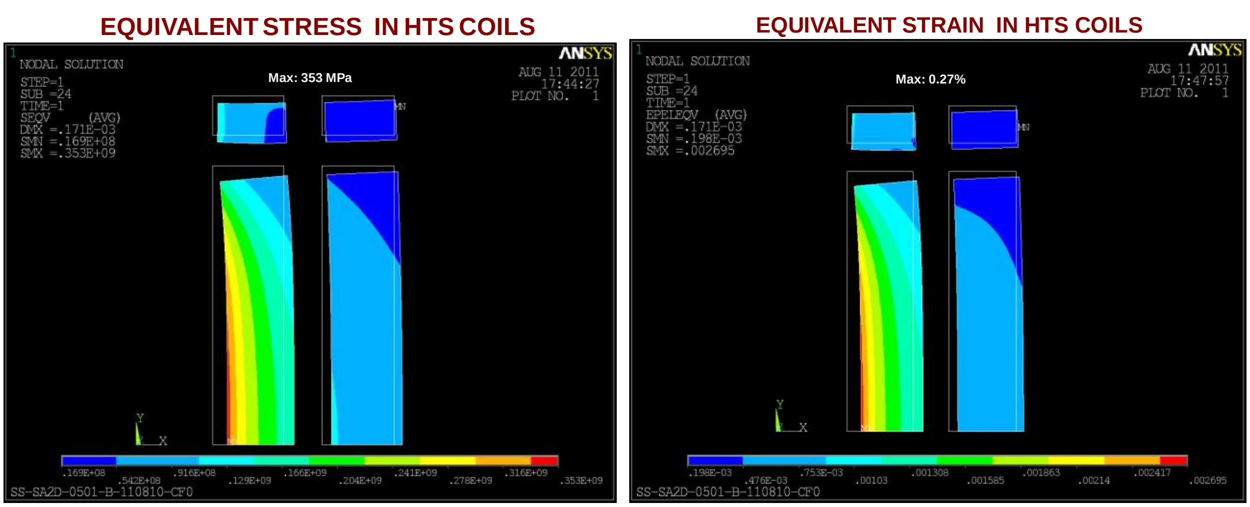

Fig. 4: Computed stress and strain in the HTS coils based on a simplified ANSYS model.

Construction

Three mini 100 mm inner diameter single pancake HTS test coils have been wound (Fig. 5). Each was wound with ~50 meter of 12 mm wide tape. Two of these coils were used to make a double pancake coil test setup, as shown in Fig. 6 (left). After the test, an internal splice will be made in each coil so that more turns could be added. Each pancake coil will have another 250 meter of conductor in addition to 50 meter already in the coil. Two of these single pancake coils will be spliced to make a double pancake coil module, as shown in the drawing in Fig. 6 (right). Fig 6 (right) also shows a possible design of the internal support structure on the top coil after 100 meter of conductor.

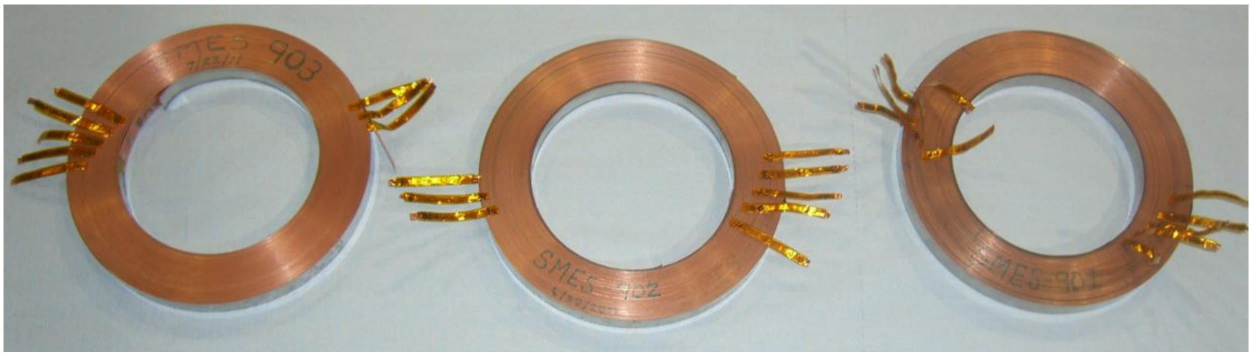

Fig. 5: Three test coils wound with ~12 mm 2G HTS received from SuperPower.

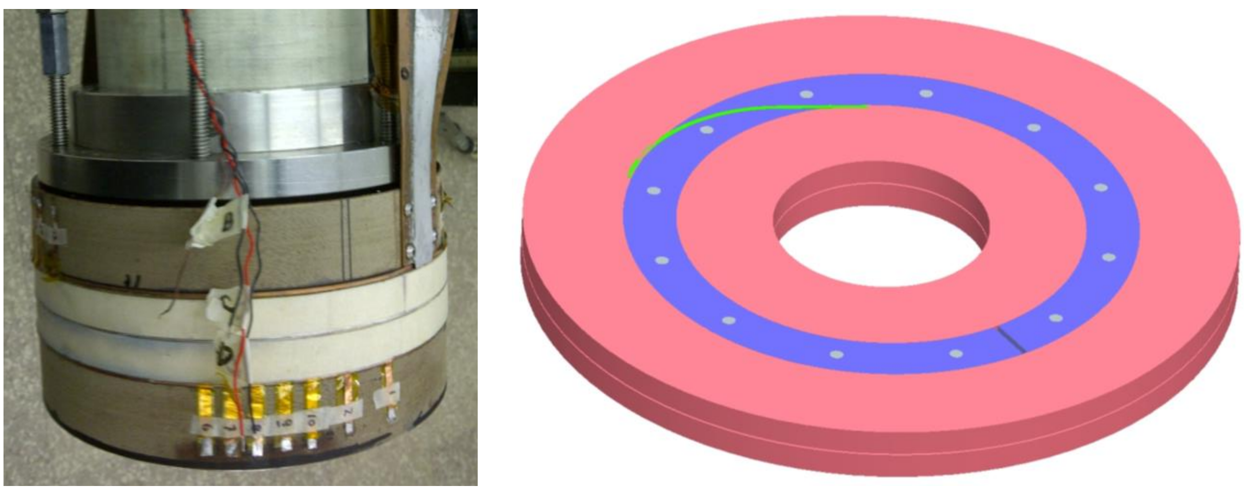

Fig. 6: Two of three test coils shown in Fig. 5 being prepared for a double pancake coil test (left). These coils will continue to be wound after the test with an internal support structure (right).

Splices are often one of the most critical parts of the magnet construction. Therefore, to reduce risk, an intermediate construction and 77 K test was carried out for each of two types of splices. The double pancake coil test setup shown in Fig. 6 (left) requires an internal splice between two single pancake coils. We have developed a new diagonal splice as shown in Fig. 7 (left). As shown in Fig. 7 (right), this coil-to-coil splice behaved well with a measured resistance of 6 nano-ohms per joint.

The internal joint within each coil (necessary since long length HTS wires are not yet available) is of different type. Here, we use the technique that is based on our previous experience with joints used in a large number of HTS coils built and successfully tested over a decade. A test fixture and 77 K measurements of this joint are shown in Fig 8. In this case, the joint resistance is found to be ~3 nano-ohms for 15 cm^2 area of joint (as compared to 6 cm^2 in joint shown in Fig. 7).

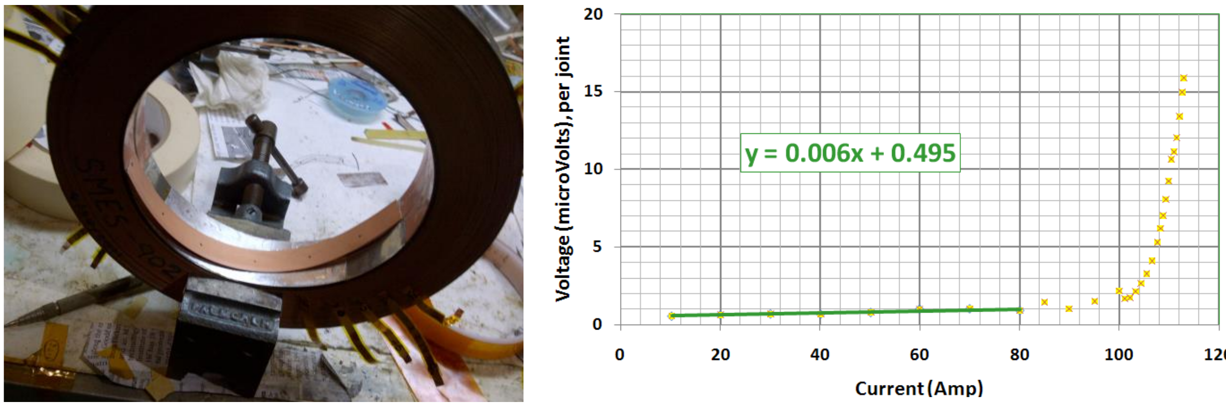

Fig. 7: Geometry of the new coil-to-coil diagonal joint on left and 77 K test results showing ~6 nano-ohms measured resistance per joint on right.

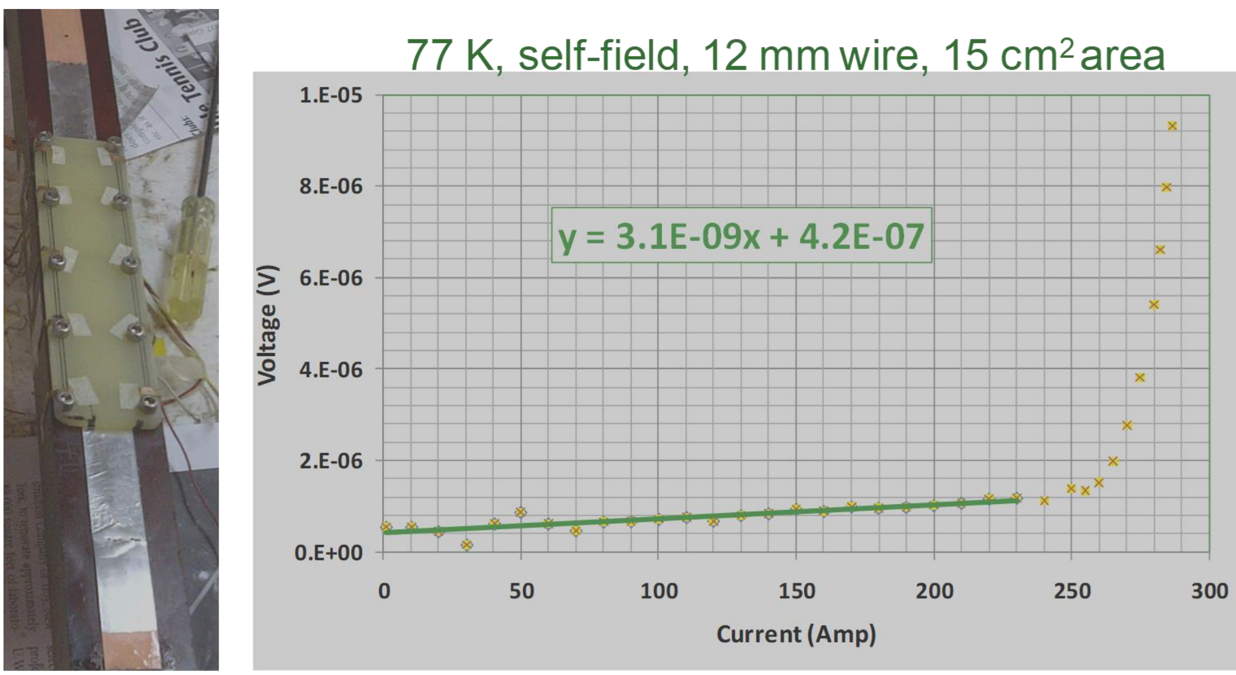

Fig. 8: Geometry of the internal splice joint based on techniques used in magnet division over a decade on left and 77 K test results showing ~3.1 nano-ohms measured resistance per joint on right.

With these two tests, we have demonstrated that we are ready to construct the coils with both internal and coil-to-coil joints. These joints should not limit the magnet performance. AEM/CMPMSD is developing an advanced joint. Once that becomes available, those techniques will be incorporated in the magnet program after having performed the similar tests at the coil level.

Fig. 9 (left) shows the magnet under construction. One can see a copper disc which is placed on either side of the coil. One can also see a large number voltage taps installed for initial diagnostic purpose. Future coils would not go through such rigorous tests and will not have so many diagnostics installed. Fig. 9(right) shows the coils spliced to top hat designed to test these coils to ~1000 Amp. Significant development work was required to upgrade the capability of this top-hat and associated set-up to increase the testing capacity from ~500 A to ~1000 A required for this and future SMES coil tests. More views of the fixture and power supply are shown in Fig. 10.

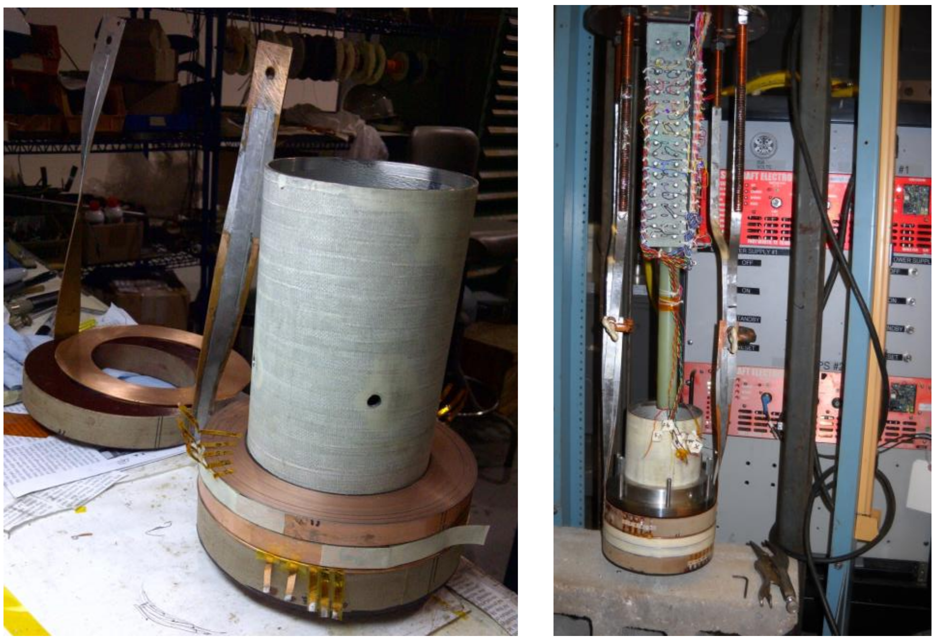

Fig. 9: Coils being prepared for test on left and installed on the top-hat to test them to ~1000 A on right.

Fig. 10: Views of recently upgraded top-hat and power supply, etc. to test coils to ~1000 A.

Test Results

The primary purpose of these tests was to demonstrate a number of design and technology features (including quench protection) in a reasonably sized coil before committing them to a full demo device. Fig. 11 shows the critical current performance of the first SMES test coils at 4 K and higher temperature. The two pancake coils, made with ~100 meters of 12 mm wide HTS wire from SuperPower (similar to what that would be used in rest of the project), reached ~1140 A and remained protected even when operated slightly above the critical current at ~4K . This value is well above ~660 A at which the coil will run in the SMES demo device. Higher current values were possible in these test coils because the field is lower than what it will be in the demo device.

Because of the relatively smaller size of the test coil as compare to the full demo coil, the field perpendicular component was ~3.6 T (design value ~6 T), and field magnitude was ~5.5 T (design value ~24 T). Nevertheless, several important technical points were proved. For example, these tests demonstrated that: (a) the new diagonal splice joint worked well, (b) winding techniques were acceptable, (c) ~100 micron copper on the conductor is acceptable (conductor and coil survived several quenches above the operating current) (d) the basic quench detection module worked well for 2 mV noise voltage during ramp and 0.7 mV during standby.

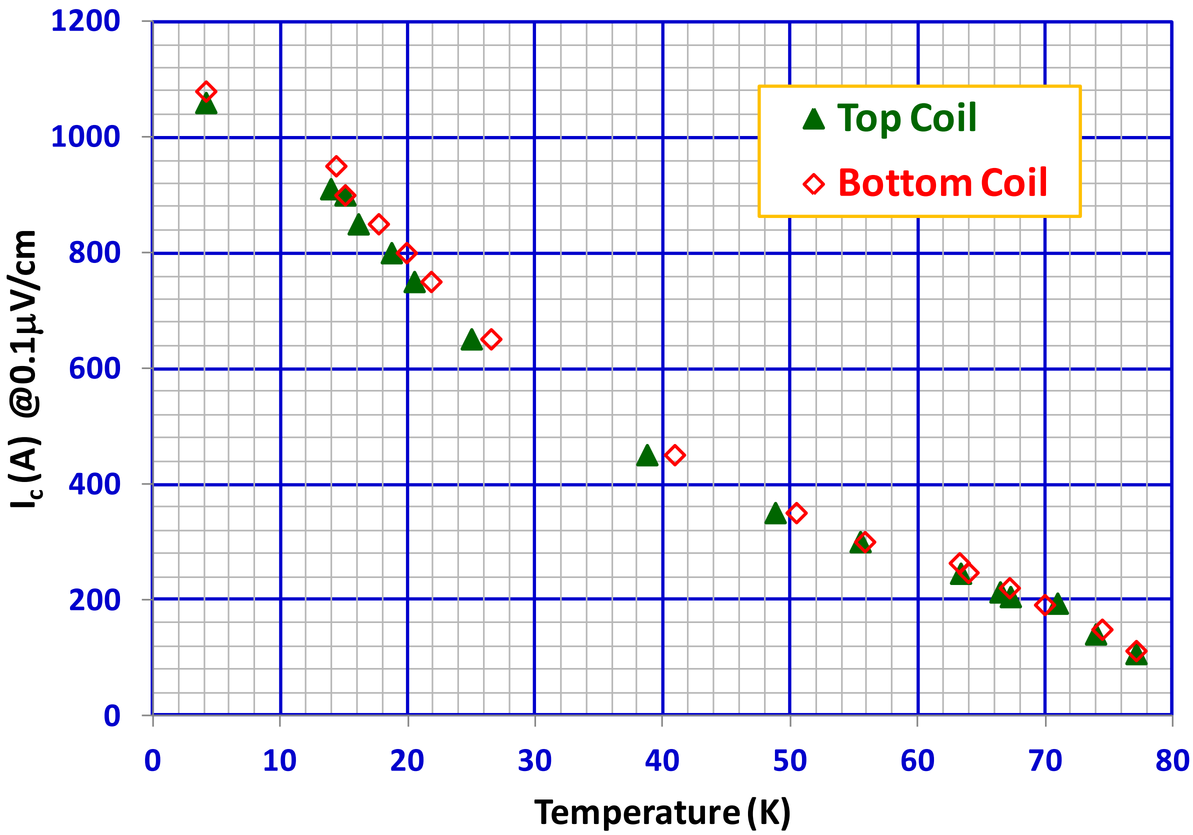

Fig. 11: A comprehensive summary of the test results. The coils were tested well above the design current of ~660 A. The tests below 60 K were carried out with helium and above 60 K with nitrogen.

A comprehensive summary of the test results is given in Fig. 11. The top and bottom coils made with the same batch of wire behaved similarly over a large range. The first test was carried out at 77 K in liquid nitrogen. After the first test, several other tests were performed in the temperature range of 60 K to 77 K, obtained by pumping on nitrogen. Finally tests below 60 K were performed by cooling provided by helium. The temperature was adjusted by controlling the gas flow of helium and by adjusting the currents in a heater mounted sufficiently away and insulated from the coil. This setup allowed us to carry out quench protection and other tests on the coil near the design current of ~700 A when it is operating near the critical surface. Since the critical current at ~4K is much higher because of lower fields, we decided to approach it by operating at a higher temperature. Please note that a more stringent criteria of 0.1 micro-volt/cm has been used here (which will also be used for protecting the SMES coil) than the typical industry standard of 1 micro-volt/cm used in defining the critical current.

Most of the tests were performed at ~20 K as it allowed us to approach the critical surface at ~700 A in the self-field of the coil. These tests included a large variation in ramp rate. We successfully ramped up the coil up to 10 A/sec which is ten times higher than the design value. We demonstrated that the coil remained protected throughout these high ramp rate tests. Successful operation at ramp rate much higher than the design value was very encouraging. However, one should remain cautious as these studies have been carried out in a small coil. We also performed several other similar tests at higher currents (lower temperatures) and higher temperatures (lower currents) to make sure that system and coil remain protected and robust over a wide range of operation.

The coil and system operated well during several charging (ramp-up) and discharging (ramp-down) cycles at ramp rates up to the design value of 1 A/sec. However, the system tripped repeatedly in ramping down (discharging) when the ramp rate was made higher than the design value. This observation became of particular interest as there was no such issue during several charging cycles to a current of 700 A and above with some of them at ramp rates 10 times higher. For this reason, most of the remaining test time was used in understanding this abnormality even though it is beyond the design value. The issue persisted even at lower currents (100 A to 200 A). There were no such problems when the current power supply and rest of the system is used with a smaller HTS coil (lower inductance) or when the power supply was shorted out. Similarly, there were no such problems when the same SMES test coil was tested with a different power supply and different system. Hence it was concluded that it is not a coil related issue but is more related to the particular power supply when used with this SMES coil. The power supply and the system issue will be addressed off-line and the coil has been set aside in case more cryogenic tests are warranted in future.

Overall, this was a very successful and productive test. Not only did it satisfy the first GO/NO GO review item, by testing at ~4 K in addition to ~77 K, we addressed and demonstrated several designs and technology issues which we could not have fully answered if we limited our tests to 77 K only. The successful outcome of these tests gives us more confidence in moving forward with the rest of this high risk and high reward program.

Quench Protection

Quench protection is one of the most critical issue in the SMES program and is appropriately identified as one of the highest risk components in the program. The main challenge is due to lower quench velocities in HTS coils. To partly overcome this inherent problem, we are developing a fast quench detection system that can detect small resistive voltage over noise.

The work performed during the last three quarters with the hardware used in other HTS projects demonstrated that the basic quench detection and quench protection module worked well with a pair of coils. The system successfully demonstrated that during the realistic operating conditions of high coil current at 4K, it can detect resistive voltages as low as 2 mV over noise voltage during ramp up (charging) and down (discharging) and 0.7 mV during standby (storage). There is still significant work left as now the complete system has to be built to protect all 32 coils and all modules should remain properly synchronized. Fig. 12 shows the quench detection and data logging system. Fig. 13 shows a snapshot of a Labview plot during quench detection.

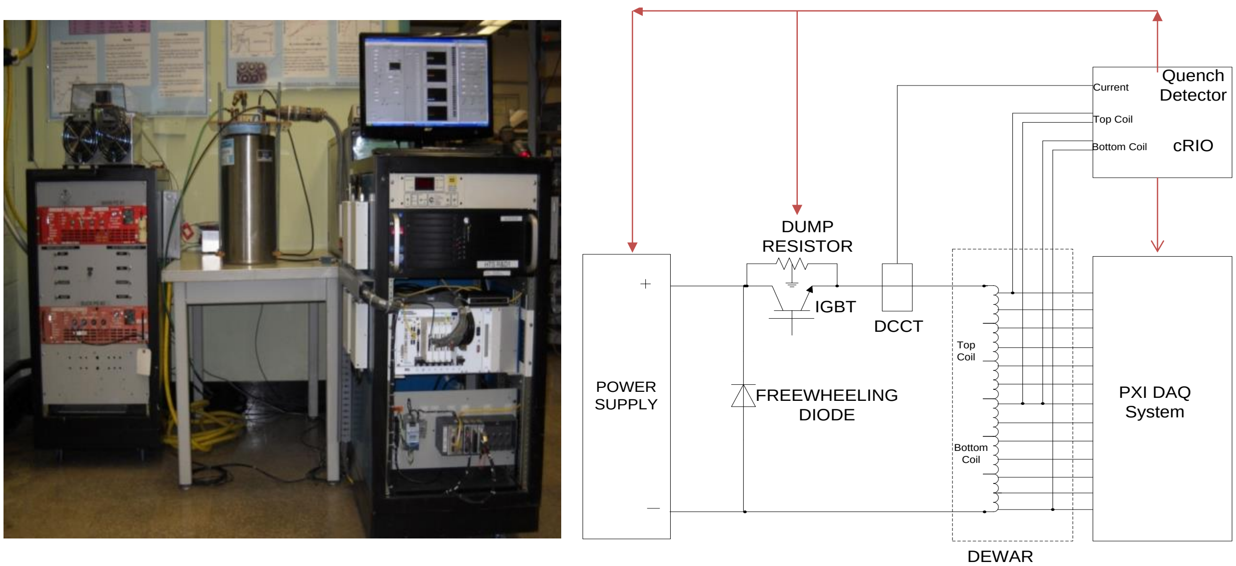

Fig. 12: Quench detection and data logging system.

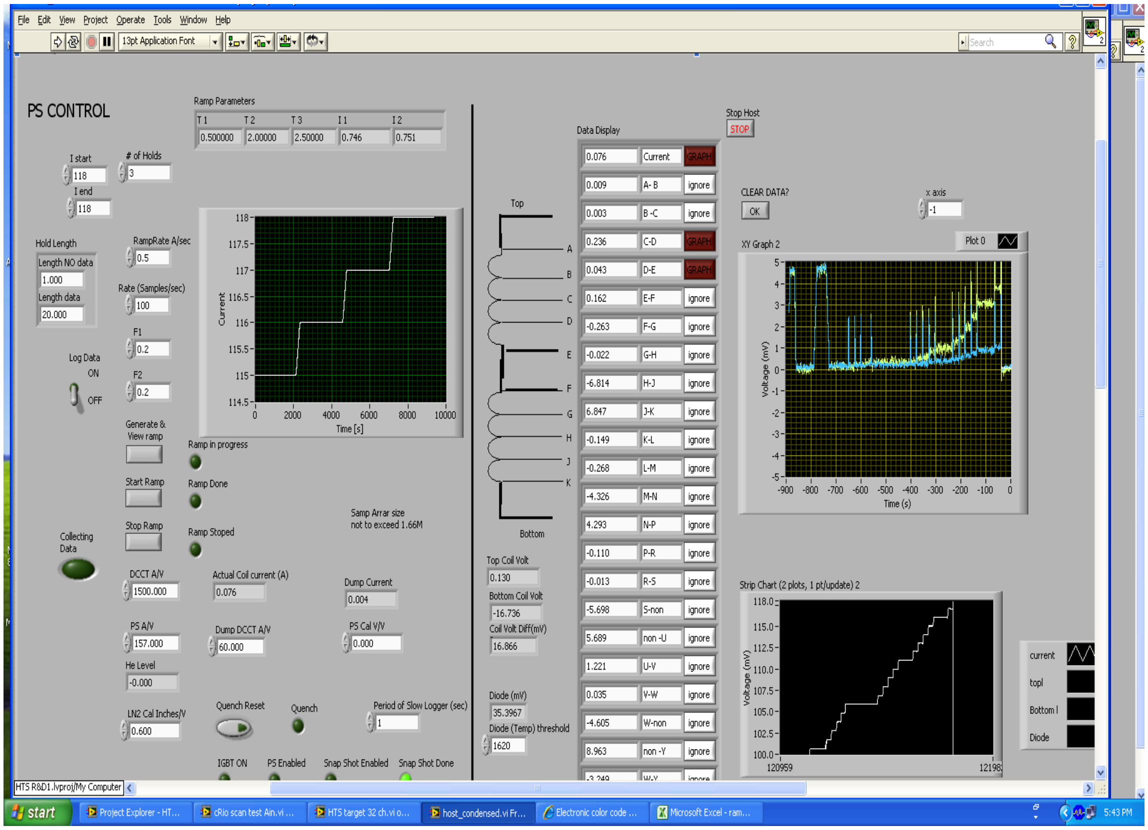

Fig. 13: A Labview plot showing quench detection.

Statistical sampling procedures for individual coil tests

As part of building the coil mini stack for the Q4 goal, we have tested two coils which gave "ok/not ok" information both at ~77 K and at ~4 K. We hope to continue the 77 K test of more coils and will take the fraction ok coils / all coils as the result of the sampling and assume that any conductor defects are random in order to project to the full coil set. This provides a reasonable sampling procedure that may be followed during rest of the program and minimize the need for more expensive ~4 K tests.