BNL Quarterly Report on Superconducting Magnetic Energy Storage Prepared for ARPA-E Through CRADA No. BNL-C-11-01 with ABB Inc.

Q8 Progress Report and Status of Milestones

Superconducting Magnet Division
Ramesh Gupta, Piyush Joshi, S. Lakshmi Lalitha and P. Wanderer

BNL Project Manager, James Higgins

October 15, 2012

Q8 Progress Report and Status of Milestones

Superconducting Magnet Division
Ramesh Gupta, Piyush Joshi, S. Lakshmi Lalitha and P. Wanderer
October 15, 2012

Summary

Task 10A: Laboratory Testing

Progress towards Q8 milestones	Actual performance
10.A. Q8-2 - A statistical sampling of individual coils and blocks tested 4.2K to verify performance and that lessons from Tasks 5 and 9 have been implemented.	100% complete. Physical inspection of the conductors at BNL and careful review of conductor data provided by SuperPower coupled with extensive 77 K testing of pancake coils with a number of diagnostic voltage taps has been very effective. Based on the detailed examination of 77 K test results, we have been able to use all pancake coils by properly choosing the location of individual pancake within complete SMES coil. Two test pancake coils, each made with ~50 meters of conductor and twelve inner pancake coils, each made with 100 meters of conductor, that passed 77 K QA test at BNL, also performed satisfactorily in a 4 K test at BNL. Thus, based on the experience so far (as described above), we should be able to use all pancake coils that pass 77 K QA test.

Major Activities:

SMES coil design update

The 1.7 MJ SMES coil design presented earlier has the same number of pancakes in the inner layer and the outer layer; and the inner and outer coil lengths were the same. We have determined that, for the same stored energy, the magnetic and mechanical designs becomes more robust if the inner coil is longer and the outer shorter. In this new configuration, the inner coil will now have 28 single pancakes and the outer 16. The mechanical structure will be such that it can accommodate either 1.7 MJ or 2.5 MJ devices with a minimal change.

Fabrication of pancake coils for inner layer

27 single pancakes for inner layer of the 1.7 MJ SMES device have been fabricated and tested at 77 K. In addition 2 single pancakes for the outer layer have been fabricated.

Electrical circuit for various modes of operation for SMES coil

An electrical circuit has been laid out for four modes of operation (charge, discharge, storage and energy extraction). The SMES coil will be divided into three sections to keep the voltage across the external resistor, coil and other components low when the energy is extracted in the event of a quench.

Q8 Progress Report

SMES Coil Design Update

The SMES coil consists of inner and outer layers with each containing a number of pancake coils in them. 1.7 MJ SMES coil design presented earlier has same number of pancakes (twenty) in the inner layer as in the outer layer. Moreover, the inner and outer coil lengths are same. It has been found that the magnetic and mechanical designs become more robust if the inner coil becomes longer and the outer shorter for the same stored energy. In the current configuration, the inner coil will now have 28 single pancakes (instead of 20) and outer 16 (instead of 20). The mechanical structure will be such that it can accommodate either 1.7 MJ or 2.5 MJ devices with minimal changes – only the number of outer coils and the length of the outer coils will increase. The two designs are shown in Fig. 1.

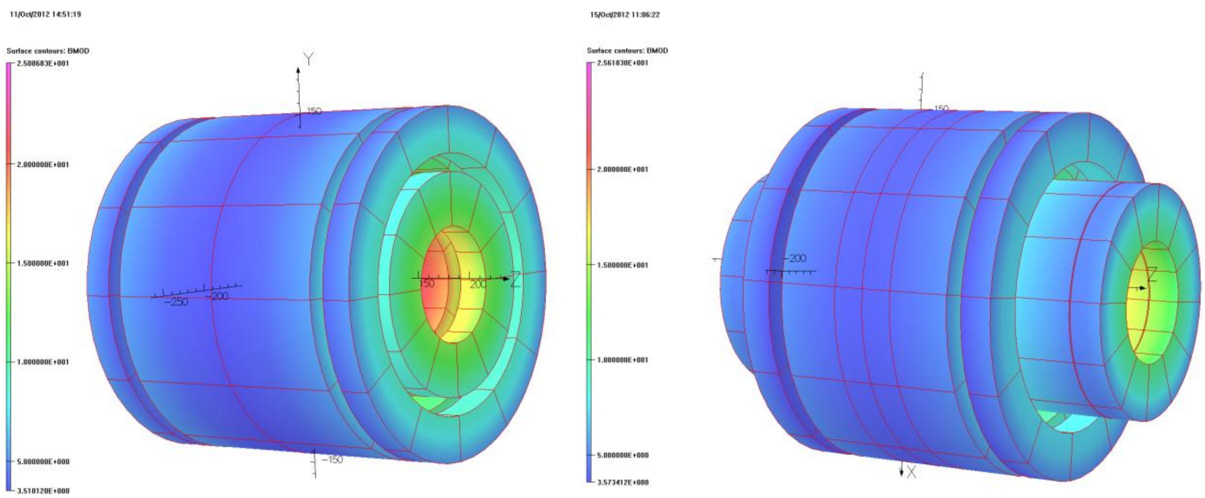


Fig. 1: Previous 1.7 MJ SMES coil design was based on 20 inner pancake coils and 20 outer pancakes coil (see left). The current design is based on 28 inner pancake coils and 16 outer pancake coils (see right).

The nominal cross section (with radial dimensions listed) is shown in Fig. 2. The nominal design parameters are listed in Table 1.

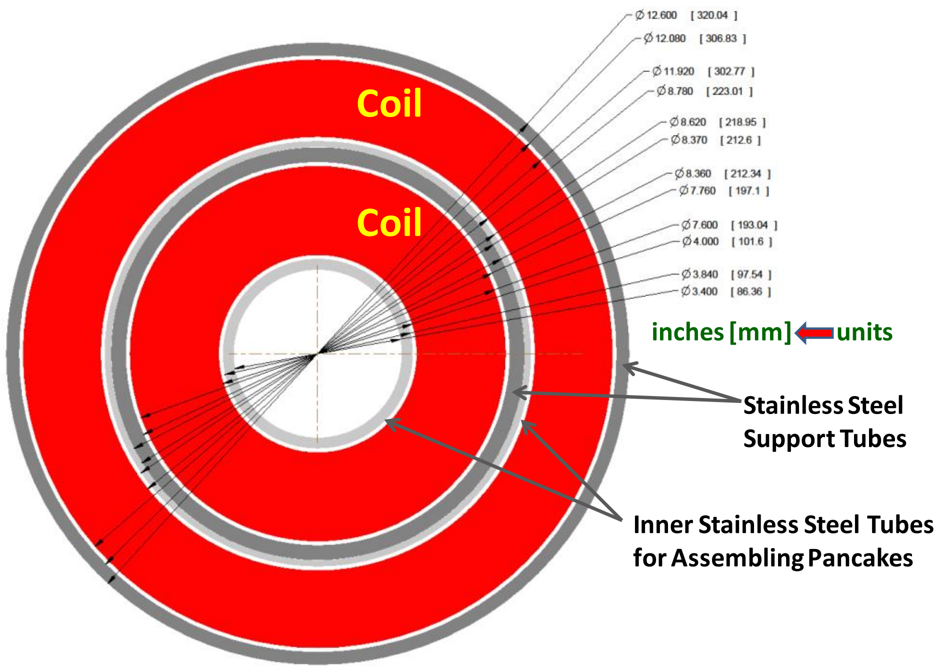


Fig. 2: Cross section and nominal radial dimensions of 1.7 MJ SMES coil design. Inner and outer pancakes are shown in red, inner tube in light gray and outer support tube in dark gray.

Table 1: Nominal design parameters of 1.7 MJ SMES coil.

Nominal Parameters		
Stored Energy	1.7	MJ
Currrent	720	Amperes
Inductance	7	Henry
Maximum Field	25	Tesla
Operating Temperature	4.2	Kelvin
Overall Ramp Rate	1.2	Amp/sec
Number of Inner Pancakes	28	
Number of Outer Pancakes	16	
Total Number of Pancakes	44	
Inner dia of Inner Pancake	101	mm
Outer dia of Inner Pancake	193	mm
Inner dia of Outer Pancake	223	mm
Outer dia of Outer Pancake	303	mm
Intermediate Support	15	mm

Fabrication and Testing of Pancake Coils for Inner and Outer Layers

The current 1.7 MJ design consists of 28 single pancakes (14 double pacakes) in the inner layer and 16 single pancakes (8 double pancakes) in the outer layer. We have completed fabrication of 27 single pancake coils for the inner and 2 single pancake coils for the outer coil. We have also completed testing 13 double pancake coils (26 single pancake) for the inner at 77 K. All coils pass the Quality Assurace (QA) test. The details of these test results (critical current and distribution of voltage between various voltage taps installed in the coil) will help determine the exact location of these coils in the 1.7 MJ coil. 4 of the 28 inner pancakes are made with conductor having 65 micron copper and the rest with 100 micron. The tooling for testing the outer pancake at 77 K is being fabricated.

The test results for the first 26 single inner pancakes at 77 K in liquid nitrogen are shown in Fig. 3 and Fig. 4 using 1 μV/cm (industry standard) and 0.1 μV/cm (more stringent requirement used by us) criterion for critical current (I_c). Three coils (indicated by arrows) have higher critical current than the one indicated by the shadow as the measurement was limited by the other coil in the double pancake (companion pair). In a double pancake coil structure structure, the two single pancake coils are in series and therefore if two single pancake coils have significantly different critical current, the measurement can't be carried out without risking the weaker coil. In addition to the critical current (Ic), we also plot the n-value. A lower n-value generally indicates a weak spot in the conductor. These 77 K measurements play an important QA role before these pancakes are assembled in the full coil. All coils have accetable performance. We will place higher performing pancakes towards the ends as the SMES coil performance is expected to be limited by the coils near the ends.

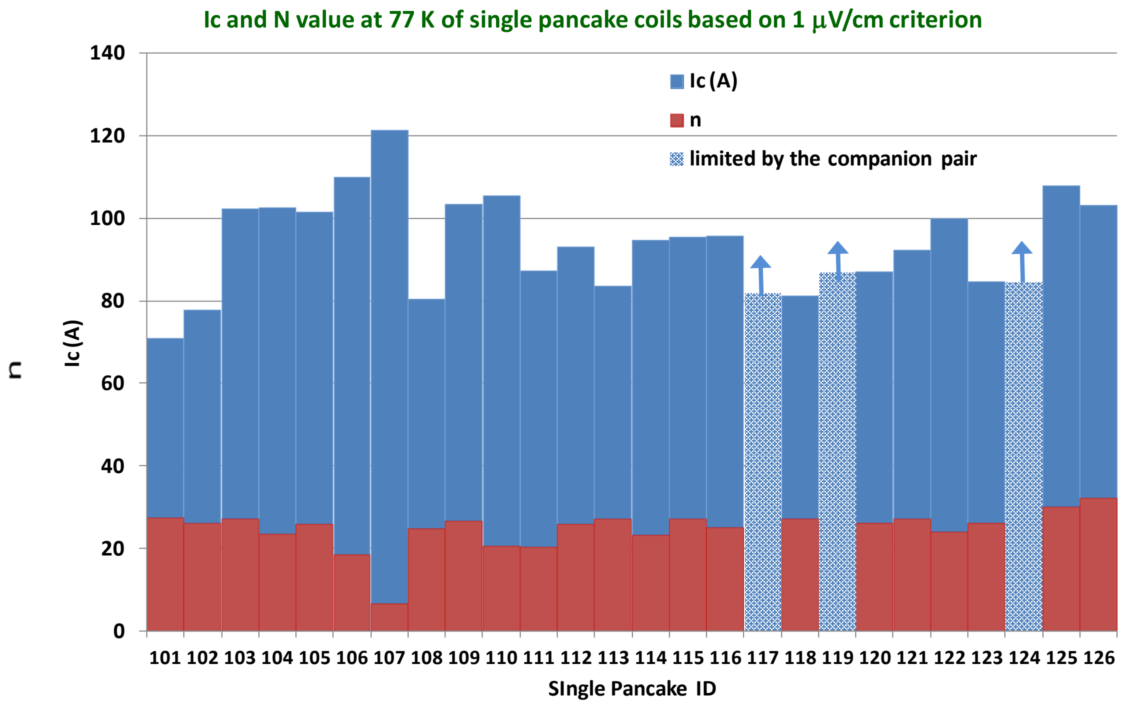


Fig. 3: Measured performance of 26 pancake coils at 77 K at 1 μV/cm definition. The actual performance of the three coils with arrow on top is higher as the test was limited by the companion coil in a double pancake coil test.

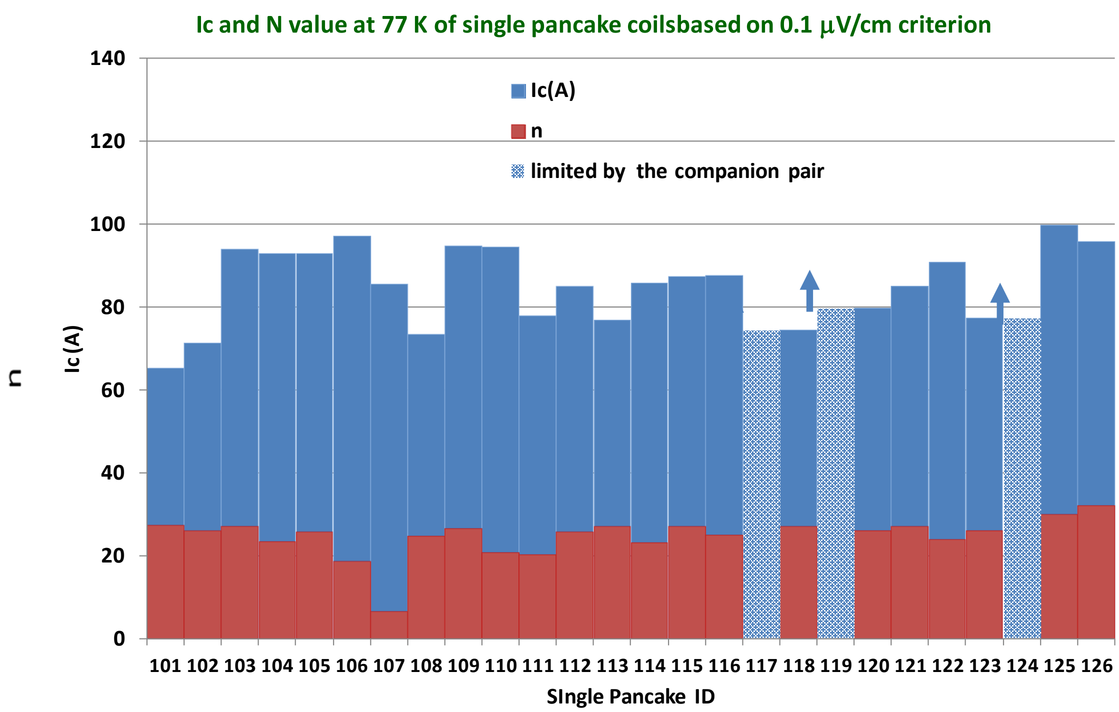


Fig. 4: Measured performance of 26 pancake coils at 77 K at 0.1 μV/cm definition. The actual performance of the three coils with arrow on top is higher as the test was limited by the companion coil in a double pancake coil test.

Quench protection and energy extraction systems

Quench protection consists of three operations (a) quench detection, (b) disruption of current flow in the coil and (c) energy extraction. Advanced quench detection system has been discussed in reports in earlier quarters where we have demonstrated that a small resistive voltage can be detected in presence of large noise and inductive voltages. Disruption of current flow and energy extraction in the test set-up is discussed below. In the real storage test, the persistent current switch will also be in the circuit which will be in the "on state" during energy storage phase and in the "off-state" during the energy extraction phase.

The basic energy extraction circuit at the Magnet Division for testing the SMES coil with a power supply is shown in Fig. 5. This circuit does not include the switch and convertor at this early testing phase. 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 dumped in the Dump resistor while voltage across the power supply is limited to -1.5V. Putting Thyristor instead of a diode in the freewheeling path allows power supply (converter) voltage to go negative. This will allow energy discharge into the grid at higher ramp rate.

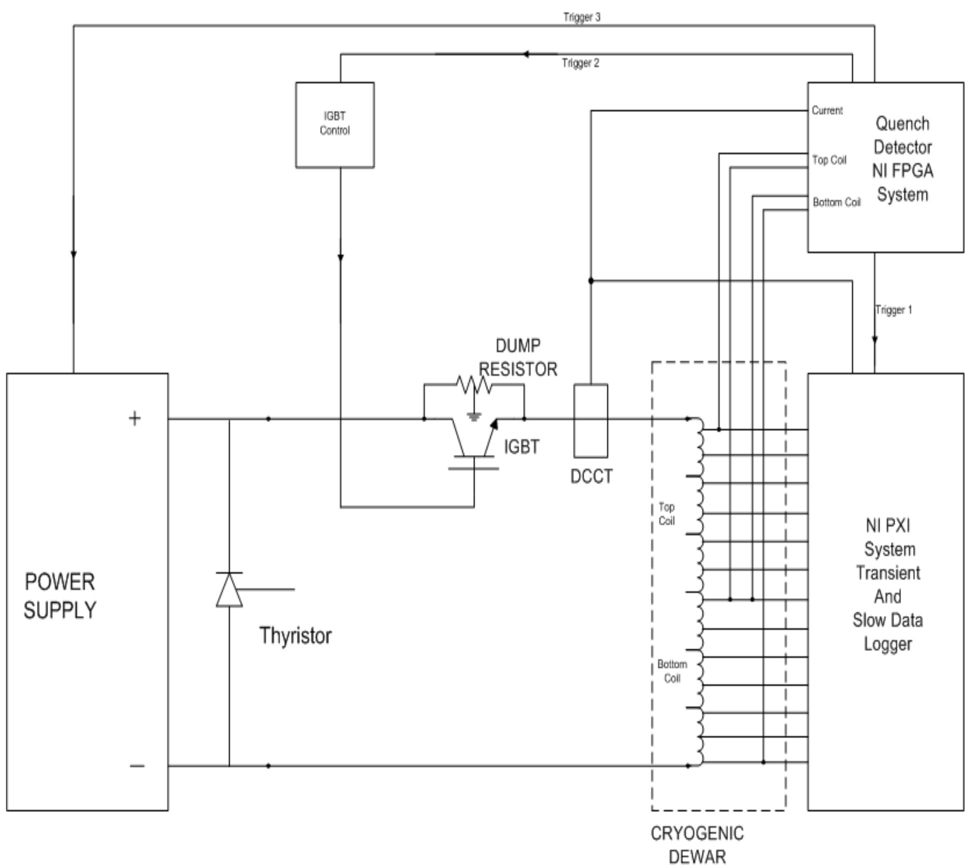
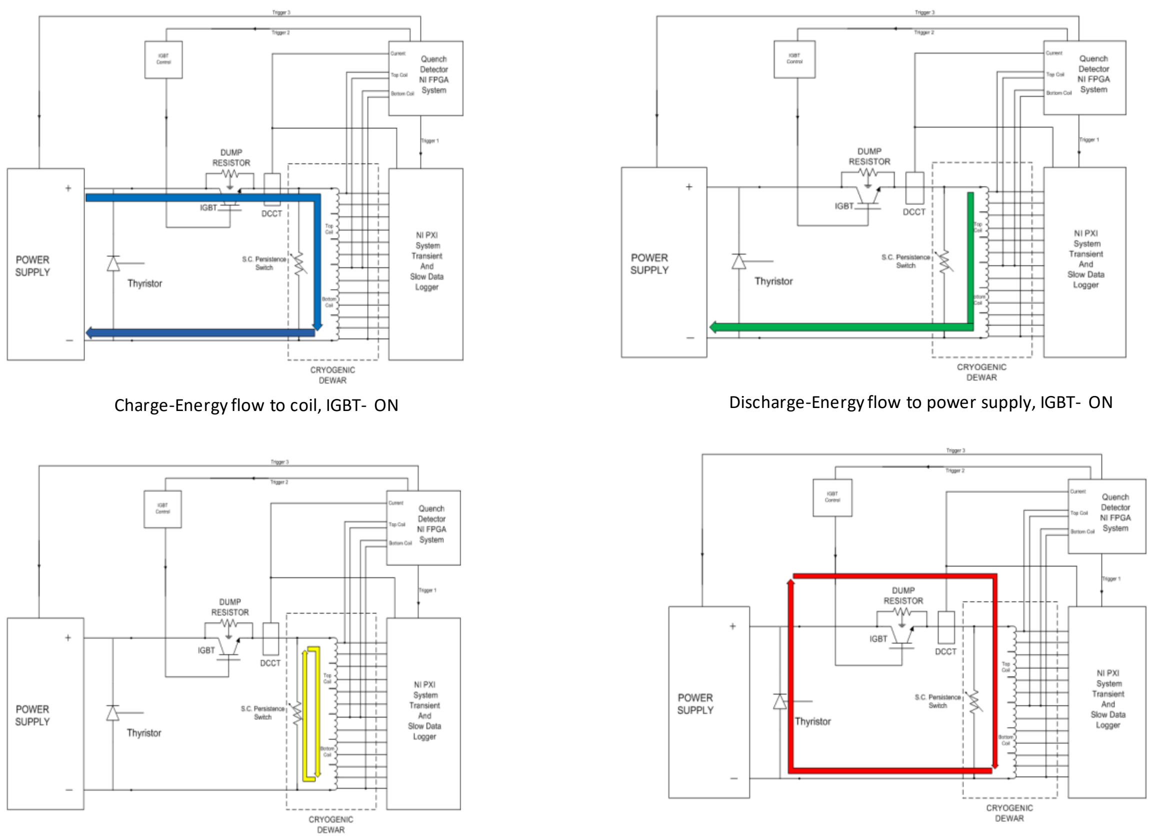


Fig. 5: Energy extraction circuit at magnet division for testing SMES coil with power supply. This circuit does not include switch or convertor.

There are four modes of operation with the persistent current switch and the energy extraction circuit for testing SMES coil with power supply. This circuit shows the powers supply instead of convertor. In the final test, the power supply will be replaced by convertor.

Four modes of Operation- Power Supply does not see high voltage



Storage- Current circulating thru persistence switch, IGBT- OFF

Quench- Energy dump thru thyristor switch, IGBT- OFF

Fig. 6: Four modes of operation with persistent current switch and energy extraction circuit for testing SMES coil with power supply. The power supply will be replaced by the convertor for the final test.

As the value of inductances (L) increases for larger stored energy devices, the value of external dump resistor (R) must also increase to maintain the same time (L/R) for energy extraction. This, however, also increases the voltage (V) created during the energy extraction (I*R). To reduce the maximum voltage generated by the energy extraction during the testing at BNL, we propose to sectionalize the coil in three sections as shown in Fig. 7 for the current design of 1.7 MJ system. This circuit will be used for testing at BNL to detemine the value quench current. The system with converter and persisitent switch will be operated safely below this value of current determined by the test.

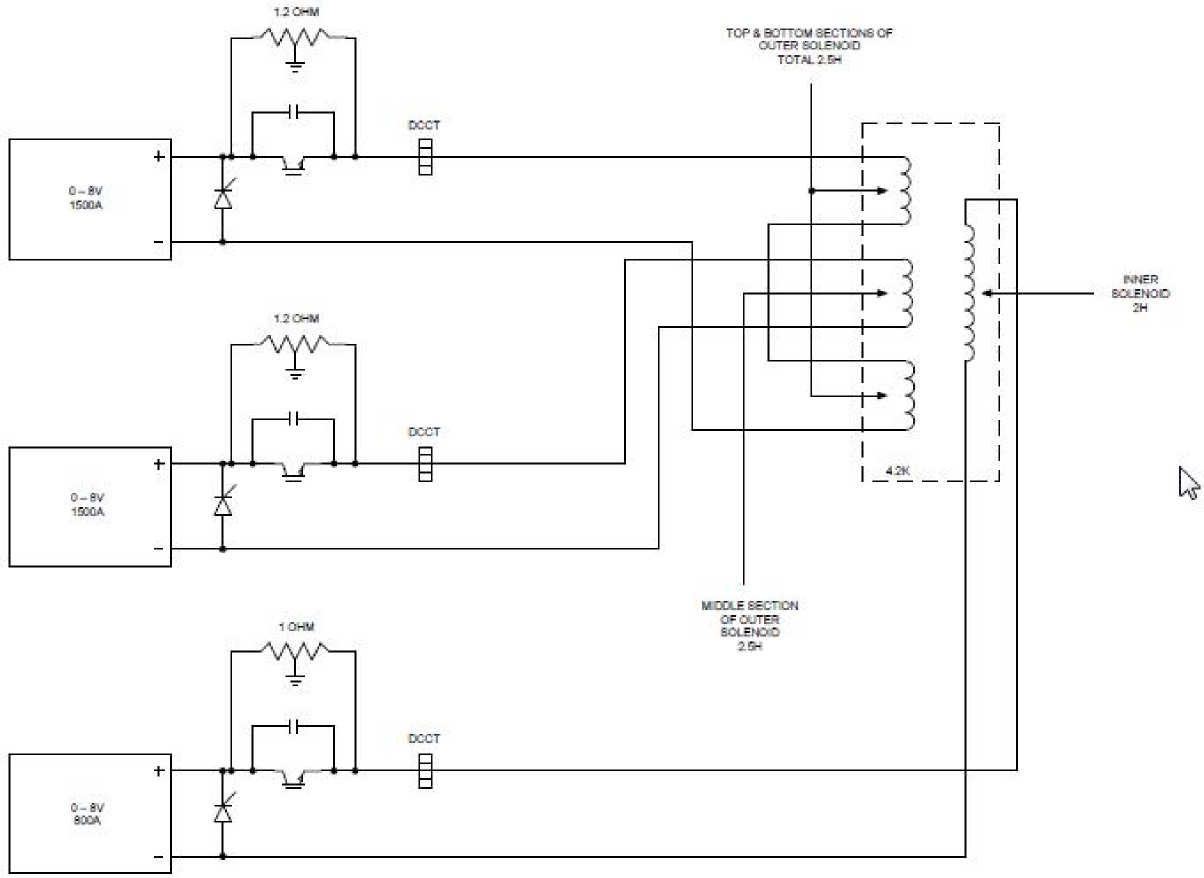


Fig. 7: 1.7 MJ coil divided in three sections to reduce the maximum voltage during testing of the energy extraction phase after quench.

Laboratory Testing – Statistical Sampling (Task 10 A)

We carefully inspect the conductor data provided electronically by SuperPower. We also carefully inspect the conductor physically. SuperPower has replaced the conductor which was of concern and provided more detailed feedback. In addition, we put a large number of diagnostic voltage taps in the single pancake coils to find any irregularity in the coils during the extensive 77 K testing of each pancake coil. These methods have been very effective as Quality Assurance (QA) method. Based on above and a detailed examination of 77 K test results, we will choose the location of individual pancakes within the complete SMES coil to optimize the performance.

The real test of this QA came during the two high current, high field tests at 4 K. The first test was carried out with two pancake coil each made with about 50 meters of HTS tape where the coils were successfully tested to 1140 A (well above the required ~700 A). The second test was carried out during the 6th quarter when twelve pancake coils, each made with 100 meters of tape, were energized to 740 A, creating a field above 11 T (well above the original target of 10 T). Based on these results, it was concluded that all coils which pass the 77 K test can be used in the 4K test of the SMES (i.e., that the performance of the SMES will not be limited by the early onset of resistivity in a short section of conductor).

Thus, based on the experience so far and with the laboratory testing methods developed, we are confident that we can use all pancake coils that pass the 77 K QA test.