# Progress Report and Status of Q7 Milestones

Ramesh Gupta, Piyush Joshi, S. Lakshmi Lalitha and P. Wanderer
(For Superconducting Magnet Division)
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## Summary

### Major Activities:

#### SMES coil design update

Design options have been examined to reduce the cost of the construction and testing of original design. Moreover, 2.5 MJ design is being adjusted to 1.7 MJ to meet budget and funding limits. The mechanical structure will be such that it can accommodate either 1.7 MJ or 2.5 MJ devices with minimal changes.

#### Fabrication of pancake coils for inner layer

All 20 single pancakes for inner layer of the 1.7 MJ SMES device have been fabricated.

#### Fabrication and test of the SMES coil demonstrating field strength > 10 T

This task was completed during the current quarter as we reached afield strength of 11.4 T on axis and 12.1 T in coil, exceeding the original target of 10 T. This is a major achievement of the SMES program and is discussed in some detail in this report.

### Status of Q7 Milestone(s):

#### Task 9B: Quench protection and energy extraction systems completed

This task was completed and reported in Quarter 4. It required energizing a coil module to the design current and demonstrating that the coil remained protected (not damaged) during the ramp-up and ramp-down cycles. A double pancake coil was fabricated and tested at 4K. The coil was energized and remained protected to 1140 A, which is 60% above the design current of ~700 A. During that test, the coil was successfully ramped up and down to design current at design ramp rate and the energy from the coil was removed and dumped to an external circuit, meeting all requirements of the task. Further progress was made during this quarter (Q7) as the quench protection and energy extraction system was demonstrated in the larger coil which was fabricated to meet Q6 Go/No Go milestone. The larger coil module was energized to 760 A (design current ~700 A) at 4K, with an order of magnitude more energy than that tested in Q4. The energy was removed and dumped to an external resistor while the coil remained protected (not damaged).

# Q7 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. The 2.5 MJ design consists of 28 pancakes in inner layer and 28 in outer layer. An intermediate support structure between the inner and the outer layers is incorporated to keep stress and strain within the coil below a limit so that the performance is not significantly degraded.

A number of design options have been explored to reduce the cost of construction and test. The outer radius of the outer coil is reduced so that tests can be carried out in a smaller and simpler cryostat test facility. This choice reduces the cost of the test and the need to develop necessary infrastructure.

A smaller length SMES coil was designed with a reduced 1.7 MJ stored energy (original design 2.5 MJ). 1.7 MJ SMES device requires 20 pancakes in the inner layer and 20 in the outer. In order ensure that the reduced stored energy does not reduce the technical challenge, we decided that the maximum field is still to be maintained at 24 T. A similar field means that a successful test will still demonstrate meeting the same technical challenges. Achieving the same field in smaller length solenoid requires increasing the current density in coil. This is accomplished by reducing the amount of copper from 100 micron to 65 micron in the HTS tape for the coils yet to be built.

A 2-d mechanical analysis is being carried out with the code ANSYS for both the 1.7 MJ device and 2.5 MJ device. A preliminary analysis indicates that the 1.7 MJ structure may require some additional reinforcement when coils are added to achieve 2.5 MJ, as the field level increases to about 27 T from the original design of 24 T.

Here we report the results of mechanical analysis with ANSYS when the numbers of pancakes in the inner and outer layers are 28 each. Since the current density is kept the same as in 1.7 MJ design, the field on the coil becomes 27.5 T and stored energy 2.6 MJ (see magnetic model in Fig. 1). As the peak field is above 24 T design, stress, strain and deflections in the actual coil will be smaller than those obtained by this analysis. Fig. 2 shows the hoop stress in the HTS coil remain below the desired 500 MPa. Fig. 3 shows the hoop strain in the HTS coil will remain below the desired 0.005. Fig. 4 shows the radial deformation in the HTS coil. The maximum deformation when the support structure chosen for 1.7 MJ is expanded to 2.6 MJ is 265 micron which is somewhat higher than 200 micron desired. This indicates that either the support structure may need some additional reinforcement, or the coil should be operated at lower field. Pending a more detailed calculation, it is estimated that the maximum deflections will be below 200 micron when the maximum field in the coil is limited to 24 T.

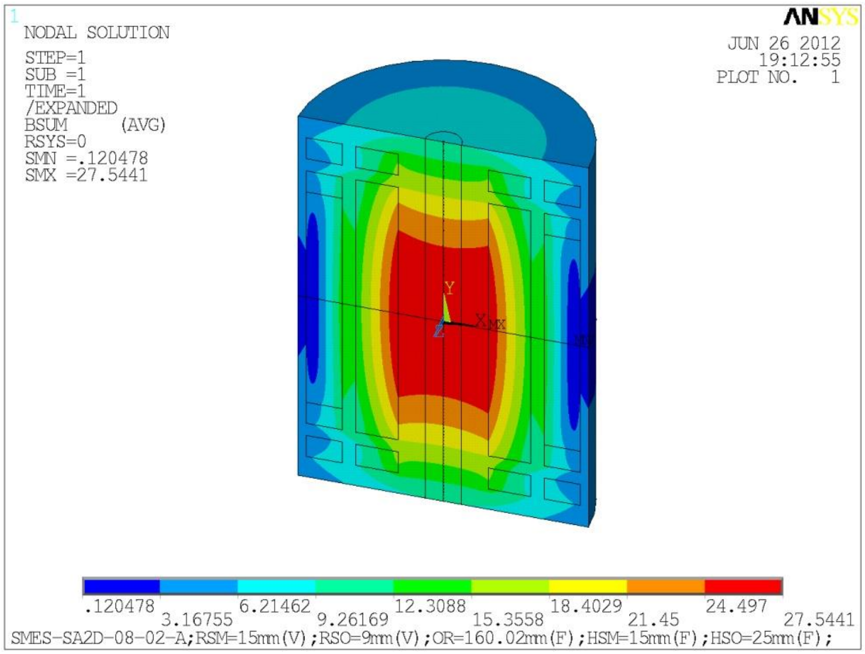



*Fig. 1: Magnetic field in the coil when 20 pancake coil model for 1.7 MJ coil model is expanded to 28 pancake coil model for 2.6 MJ. Since the peak field in the coil becomes 27.54 T, above 24 T design, the actual stress, strain and deflections in the coil would be smaller than those obtained by this analysis.*

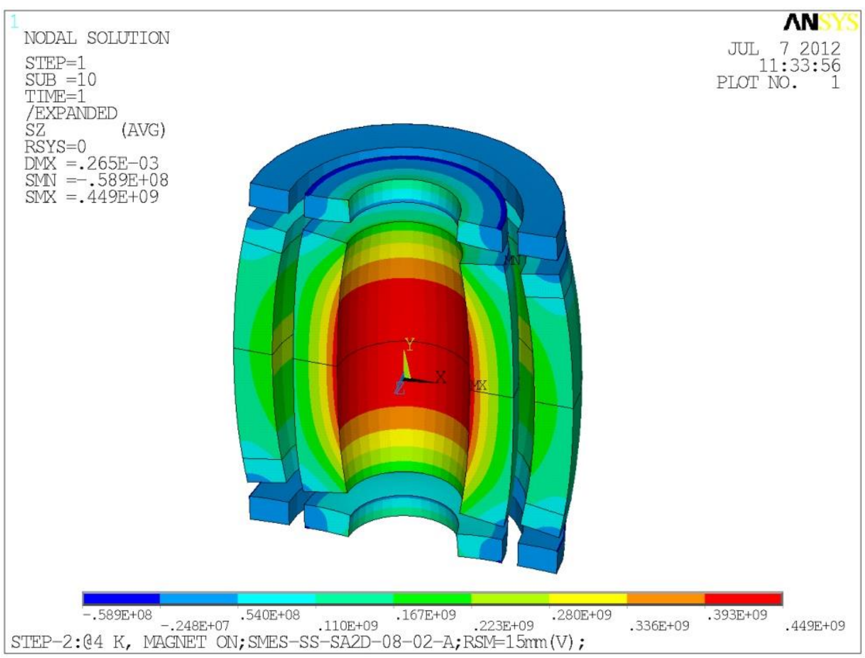



*Fig. 2: Hoop stress in the 28 pancake coil model with 2.6 MJ stored energy.*

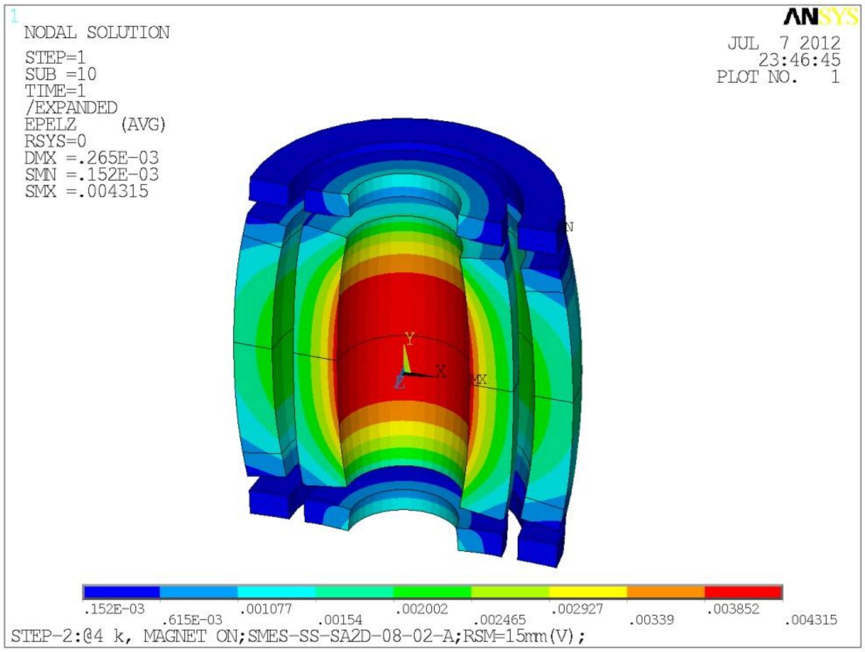



*Fig. 3: Hoop strain in the 28 pancake coil model with 2.6 MJ stored energy.*

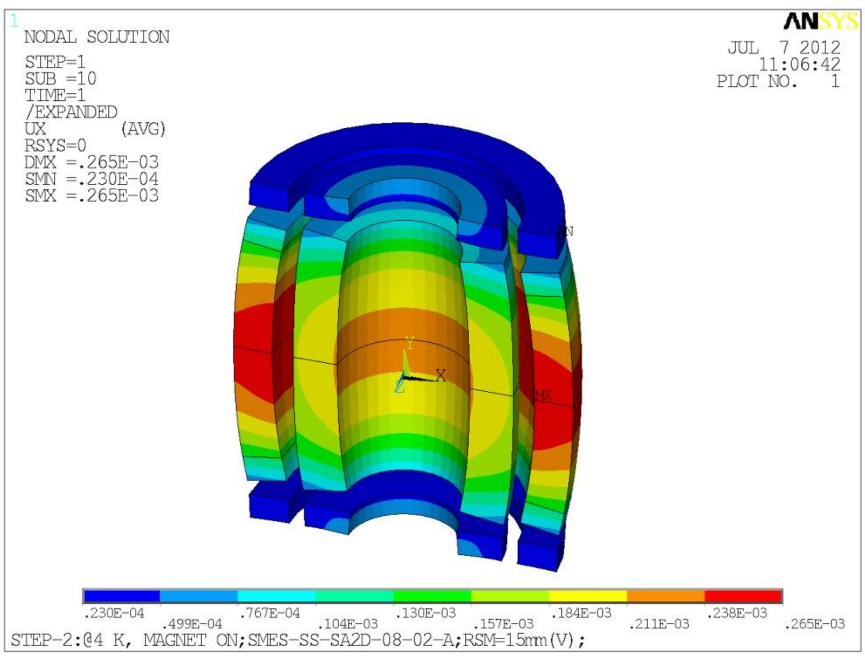



*Fig. 4: Radial deformation in the 28 pancake coil model with 2.6 MJ stored energy.*

## Fabrication of Pancake Coils for Inner Layer

The 1.7 MJ design consists of 20 single pancakes (10 double pacakes) in inner layer and 28 single pancakes (10 double pancakes) in outer layer. We have completed fabricating 22 single pancake coils for 10 double pancake required for the design plus one spare. Pancake coils having an inner diameter of 100 mm and outer diameter of ~194 mm are shown in Fig. 5.

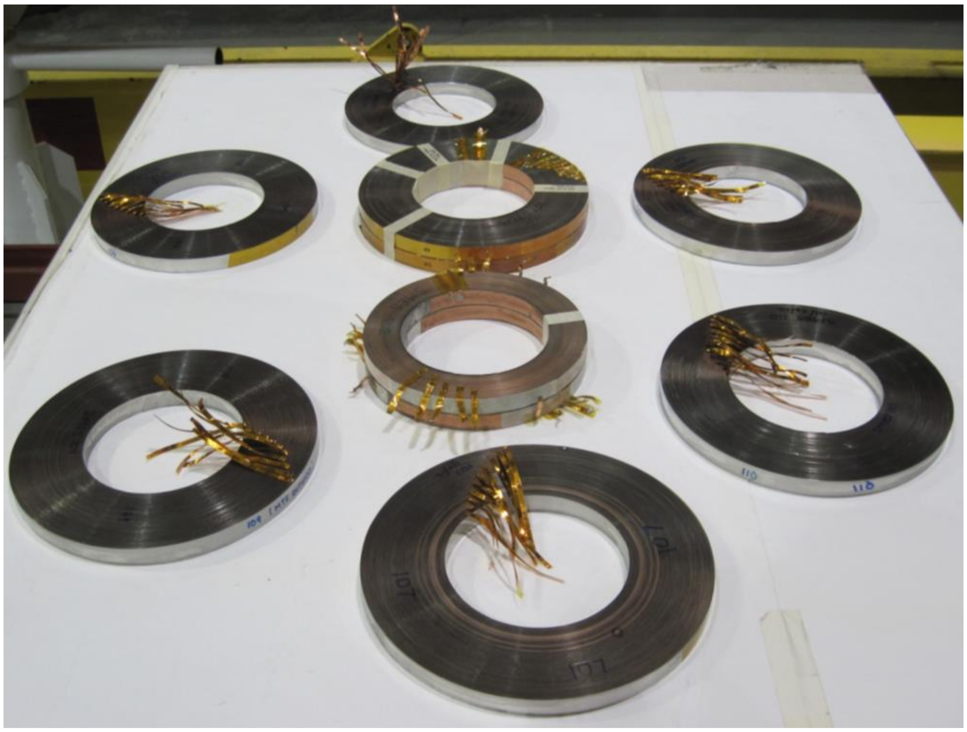


*Fig. 5: Pancake coils for inner layer.*

First 16 of these single pancake have been used in building 8 double pancake. The test results for the first sixteen single pancakes at 77 K in liquid nitrogen are shown in Fig 6 . 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. Coil #107, however, has a lower n-value. A detailed analysis, with the number of voltage taps installed, showed that this was in the middle section of the coil which does not limit the performance. Fig. 7 shows the measured performance of eight double pancakes (each assembled with two single pancakes) at 77 K. Fig. 8 shows the correlation of self field wire performance and coil performance (both at 77 K). Except for a few cases, there is a reasonable correlation between the minimum Ic in the wire and that in the coil at 77 K. We place higher performing pancakes towards the ends as the SMES coil performance is expected to be limited by the coils near the ends.

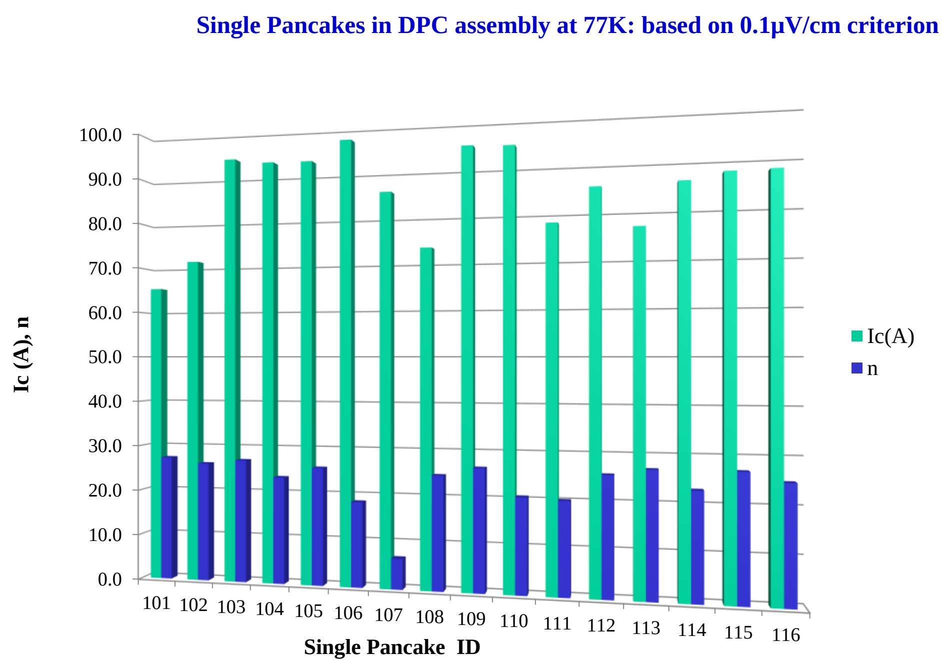



*Fig. 6: Measured performance of first sixteen single pancake coils at 77 K.*

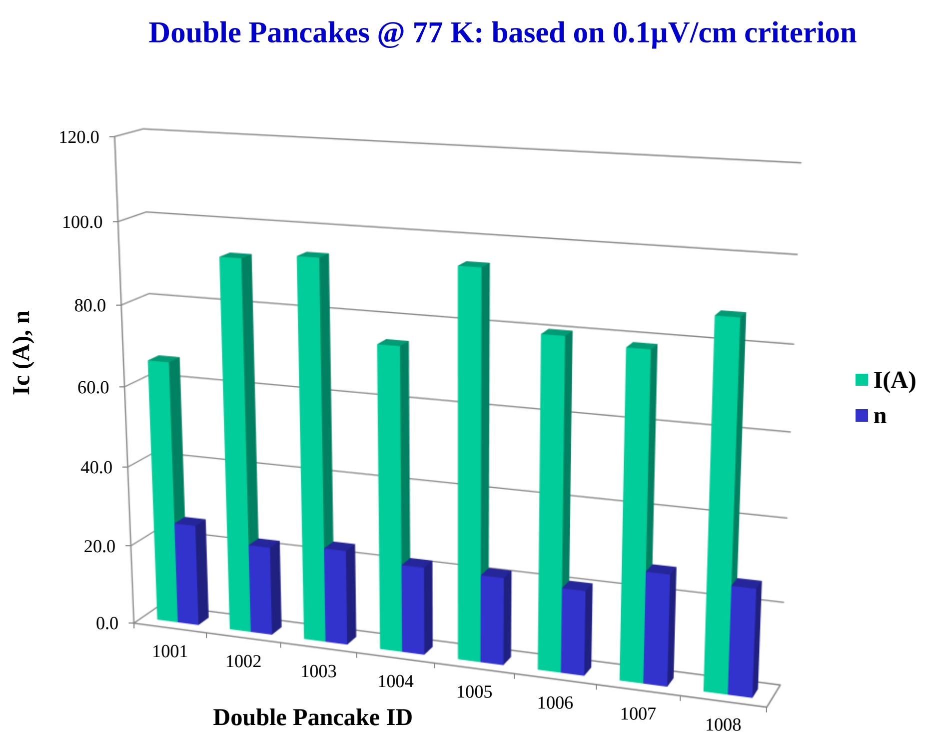



*Fig. 7: Measured performance of first eight double pancake coils at 77 K.*

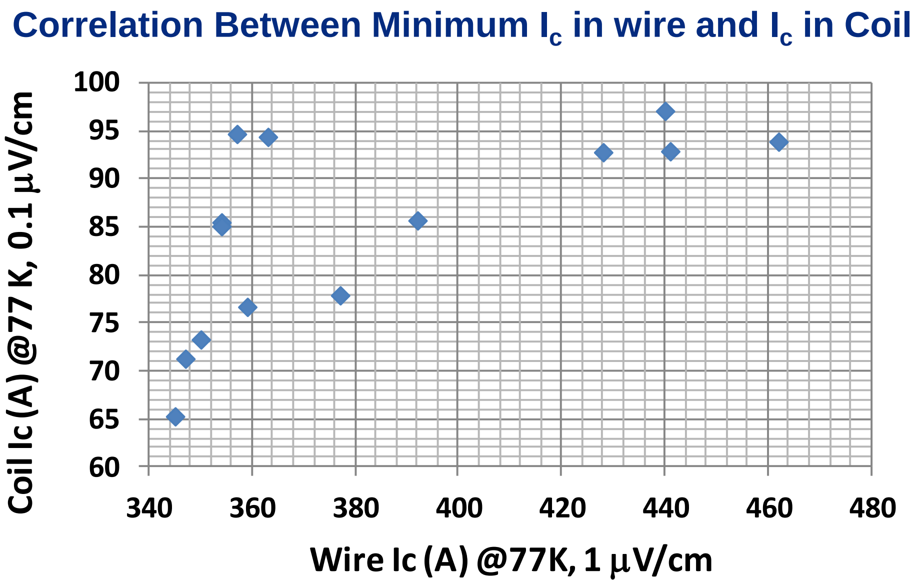



*Fig. 8: Correlation between the wire performance and coil performance.*

## Construction and Test of >10 T SMES Coil (Go/NoGo Milestone)

We successfully constructed and tested a SMES coil for meeting the Go/NoGo milestone that requires a demonstration of the SMES coil producing over 10 T. The milestone was met we reached 11.4 T field on axis and 12.1 T in coil, exceeding original target of 10 T. This is a major achievement of the SMES program. The coil consists of 12 pancake coils having an inner diameter of 100 mm and outer diameter~194mm. Various steps of fabrication process are shown in Fig. 9. Fig. 10 shows the coil being prepared for high field test test at 4 K. The test results are shown in Fig. 11 where the coil was energized to the 760 A at 4 K. Appearance of voltage gradient across a pancake indicates the onset of resistive voltage, a pre-cursor to quench. The operation of SMES coil will be limited to 0.1 $\mu$V/cm (1 mV for 100 m). This criterion was met when the voltage between coil #2 and coil #11 was compared. Fig. 12 shows the complete sequence of this run where the charging current is plotted as a function of time. The run was terminated by the quench detection and protection system after the quench detection threshold of 2 mV between two pancakes was met. The energy was then extracted to the external dump resistor at room temperature.

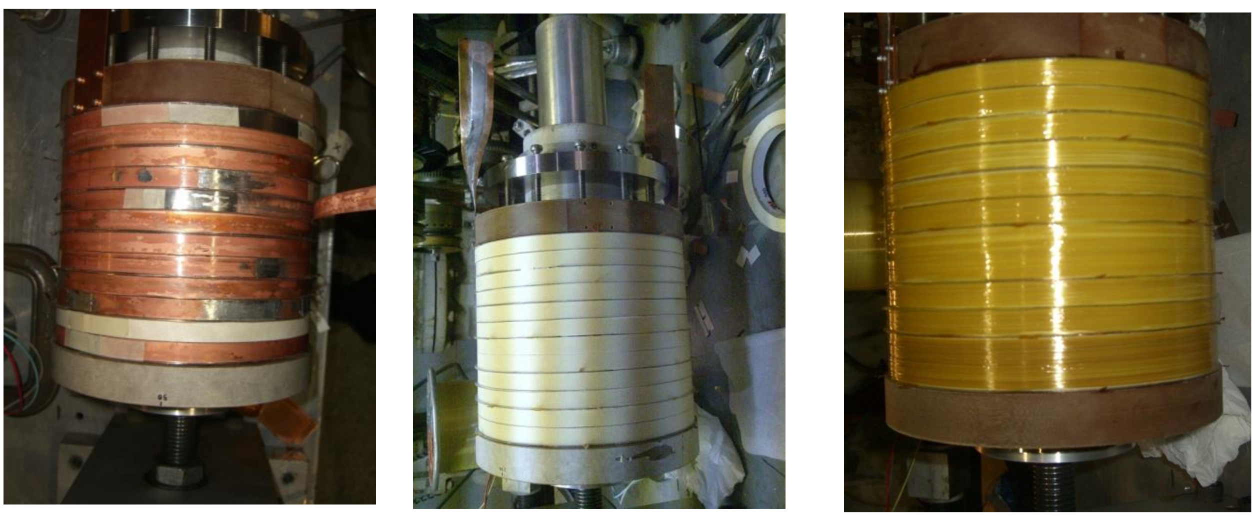


*Fig. 9: Various steps of fabrication process of the SMES coil made to meet Go/NoGo milestone. Initial stack-up of 12 pancake coil is shown on the left, after all splicing and Nomex wrap in the middle and after wet-wrap of Kevlar and epoxy on the right.*

*Fig. 10: Photographs of the coil on top-hat with all instrumentation while being prepared for 4 K test.*

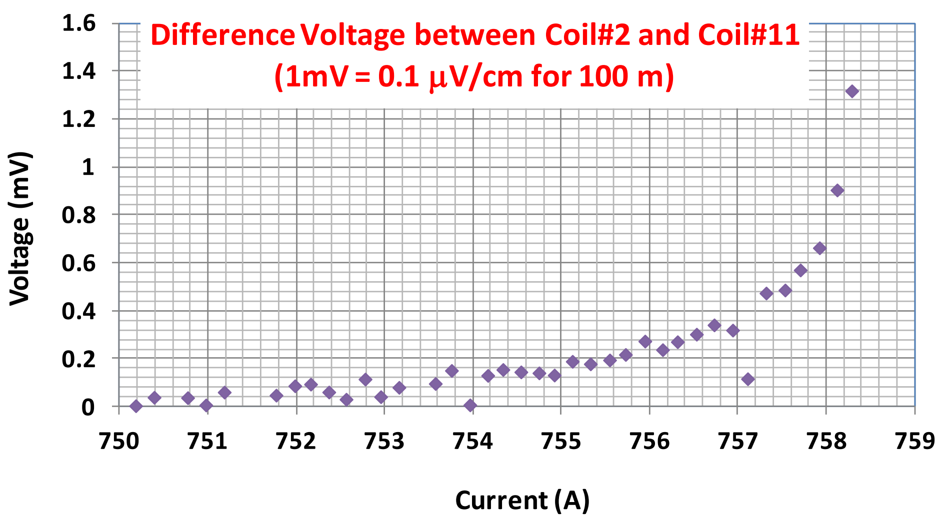



*Fig. 11: SMES coil energized to highest field before the quench. Onset of resistive voltage indicate the criterion of onset of quench (>2 mV) is being met before the run is terminated at a current of ~760 A.*

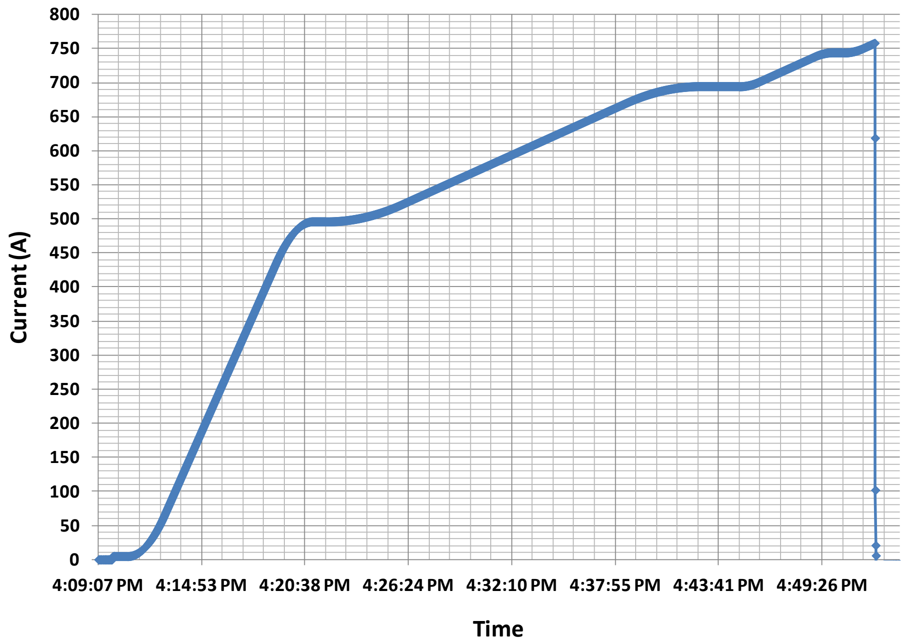



*Fig. 12: Charging sequence of SMES coil to a current of ~760 A. The run was terminated as the quench threshold was met and the energy was dumped to external resistor.*

### Quench protection and energy extraction systems (Q7 milestone)

This milestone required energizing a coil module to its design current and demonstrating that it remained protected (not damaged) during the ramp-up and ramp-down cycle. The milestone was completed in 4th quarter and reported in Q4 quarterly report. A double pancake coil was fabricated and tested at 4K. Fig. 13 show the coil ramped up to 700 A at 4K and down to 0 K at a ramp rate of 1 A/sec (Fig. 14).

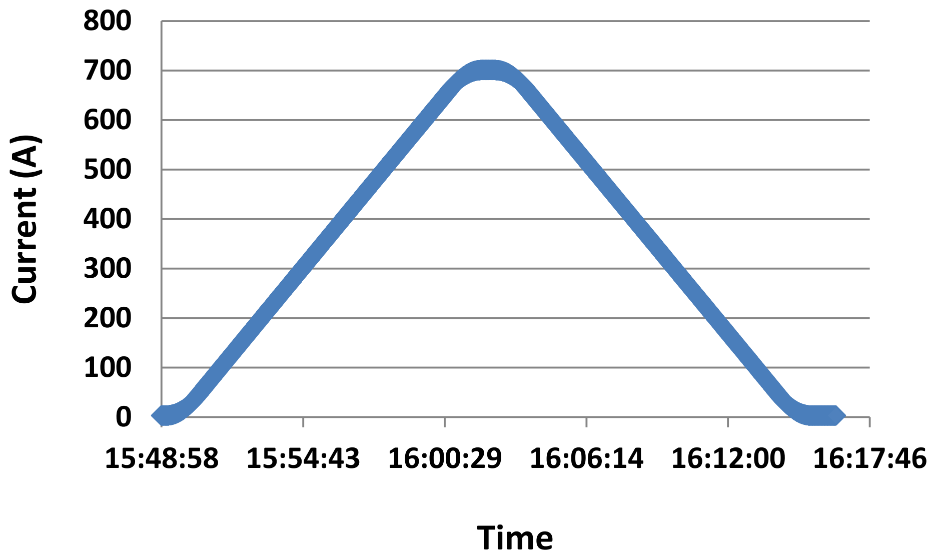



*Fig. 13: Successful demonstration of ramp up and ramp down of a double pancake coil to a current of 700 at 4K.*

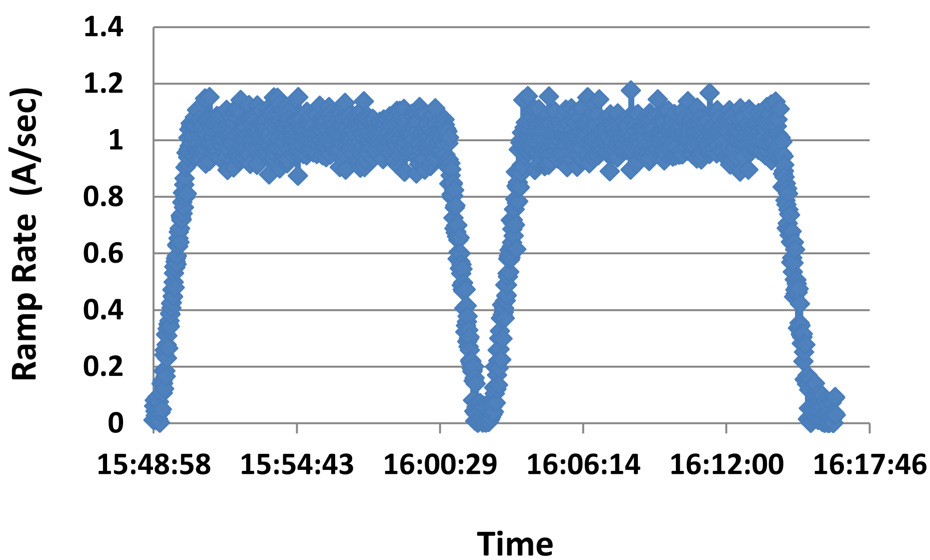
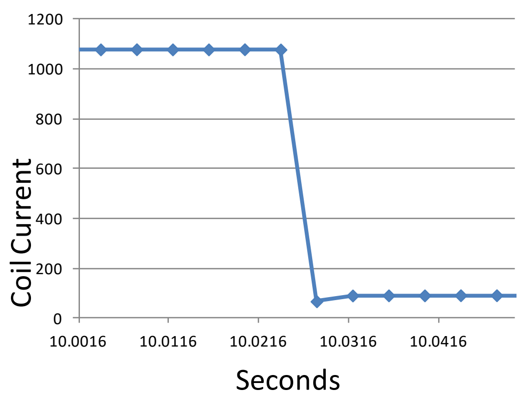



*Fig. 14: Ramp rate during the up and down ramp of the run shown in Fig. 12.*

Several charge (ramp-up) and discharge (ramp-down) cycles to a current of 700 A (and above), at a ramp rates of 1 A/sec, were accomplished with the power supply system in use for most of these tests. Moreover, several charging cycles were also accomplished (with some at ramp rates as high as 10 A/sec) with the same system. The same power supply system tripped repeatedly and when being used for down ramp at rates much higher than 1 A/sec. We were able to ramp coil up and down at a significantly higher ramp rate (~10 A/sec) with a different system.

The coil was energized and remained protected to 1140 A, which is over 60% of the design current of ~700 A.  During that test, the coil was successfully ramped up and down to design current at design ramp rate and the energy from the coil was removed and dumped in to an external circuit, meeting all requirements of the task.  Fig. 15 shows the coil current during storage and quench as well as the current in the external resistor after quench. The energy was safely extracted to external dump resistor within a few tenths of a second after the quench.



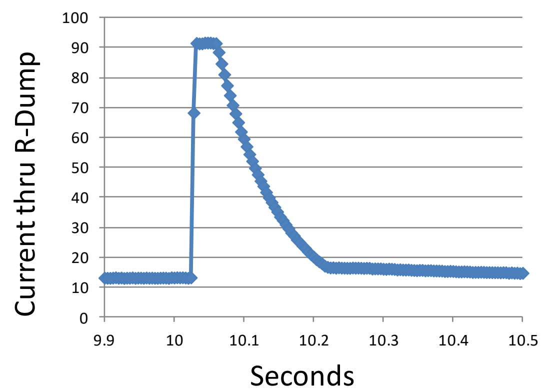




*Fig. 15: Current in the coil (left) and in dump resistor before and after quench. One can see a sharp drop in current flowing through the coil just after the quench.*

Further progress was made during this quarter (Q7) as the quench protection and energy extraction was demonstrated in the large coil which was fabricated to meet Q6 Go/NoGo milestone. The larger coil module was energized to 760 A (design current ~700 A) at 4K, with an order of magnitude more energy (~130 kJ) than that tested in Q4. The energy was removed and dumped in to an external resistor (~0.9 ohms) while the coil remained protected (not damaged). The current in the coil as a function of time is plotted in Fig. 16.

The follow-up test at 77 K show no degradation in the performance of coil after the above quench.

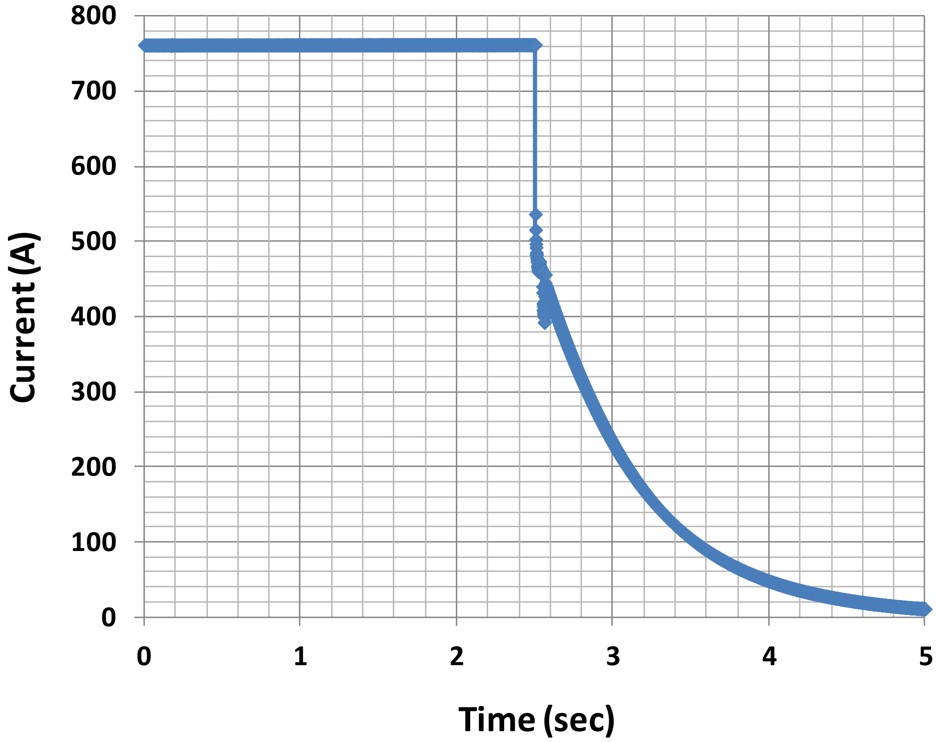



*Fig. 16: Current in the coil as a function of current during charge and after the quench. The run was terminated at t=2.5 seconds when the system detected a quench.*