Comparison of Measured and Simulated Quench Behaviors of Superconducting Magnets for Jefferson Lab's 11 GeV Super High Momentum Spectrometer

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Abstract— Super High Momentum Spectrometer (SHMS) of Hall C, part of 12 GeV Upgrade at Jefferson Lab, was successfully commissioned. Early quench analysis indicated that the quench would be violent and that the coil temperature would be high. Actual training quenches were mild; coil temperature was low; the magnets were able to recover within a short period of time—about three hours. A series of fast dump tests were performed using oscilloscopes, and it was found that fast dump tests from high current triggered quench due to eddy current heating in the copper stabilizer of the coil. The threshold was 1500 A for Q2 and Q3 magnets and 2250 A for Dipole magnet. The behaviors of training quenches and fast dumps were eminently similar because rapid magnetic field change induced eddy current and therefore triggered quench in the coil. Energy balance calculation was performed to figure out the energy deposited into the coil, iron, force collar, helium vessel, vacuum vessel, and liquid helium during fast dump. The differences between the measured and simulated behaviors were discussed.

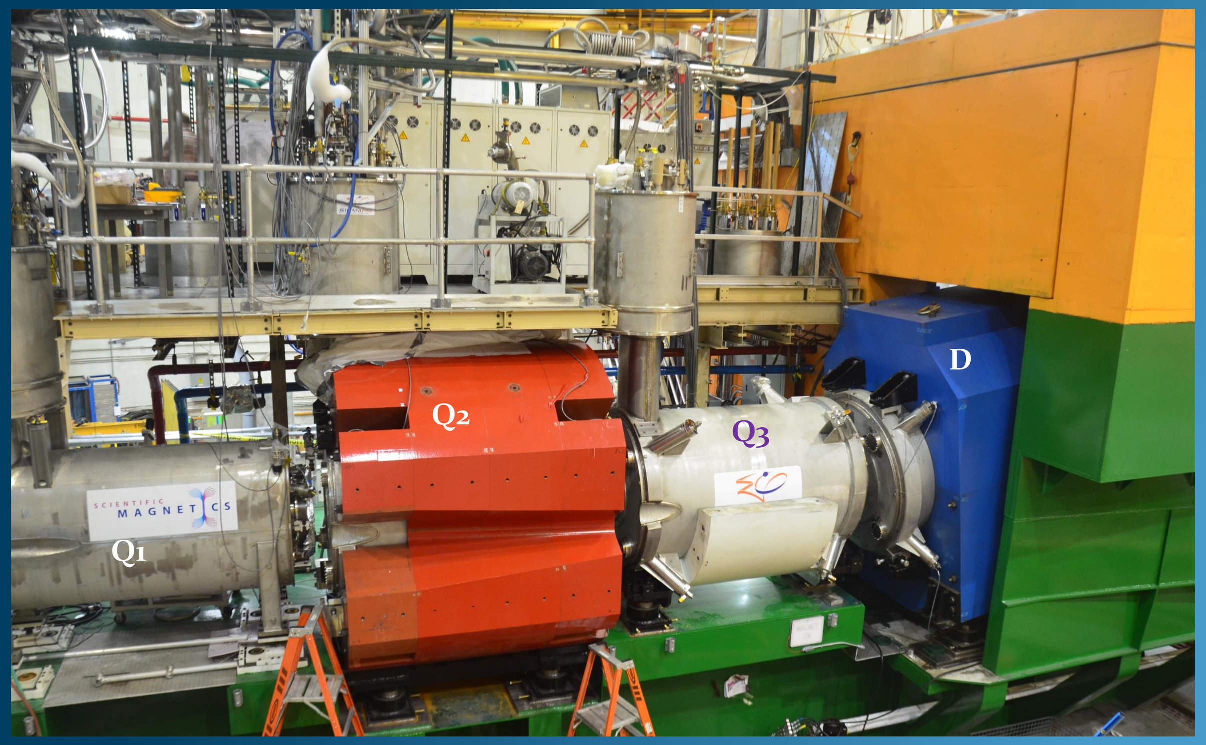

Fig. 1 Q1, Q2, Q3, and Dipole magnets installed on the SHMS platform. Jefferson Lab's 11 GeV Super High Momentum Spectrometer (SHMS) has been successfully commissioned. All five superconducting magnets—Horizontal Bend (HB), Q1, Q2, Q3, and Dipole—met the 11 GeV specifications. Q1 was commissioned in April 2015; HB in January 2016; Q2 in December 2016; and Q3 and Dipole in February 2017. HB experienced a series of trainings, starting from 2640 A, and it eventually reached 4000 A—its 11 GeV current is 3900 A. Its trainings were mild as the magnet was able to recover within half hour. No quench was ever observed during Q1 commissioning. Q2, Q3, and Dipole also experienced a series of training quenches before they reached test currents. These training quenches were eminently mild too. These were surprises because early quench analysis indicated that quench behavior would be much more violent.

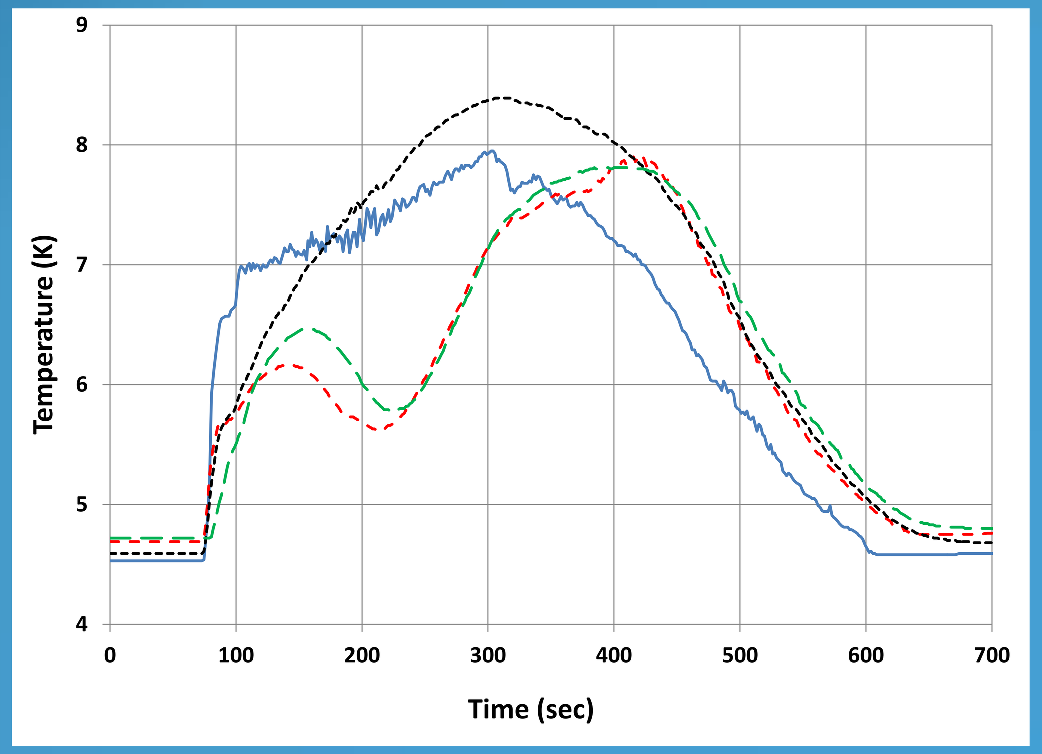

Fig. 2 Temperature changes of four temperature sensors mounted on SHMS Q2 coil. This is the first training event (3316 A) for this magnet. Four temperature sensors were used to measure the temperature of the coil at various locations. The peak temperatures of these four sensors are 7.95 K, 7.92 K, 8.39 K, 7.81 K; the peak average temperature of the four sensors, 7.80 K. Although their mounted locations are far away, their peak temperatures are not far away. Since the pressure rose during quenching, the warm return valve reacted to relieve the helium into the warm return line. This effectively stopped further rise of the pressure. When Q2 quenched at 3316 A, its helium rose from 1.34 atm to 3.02 atm.

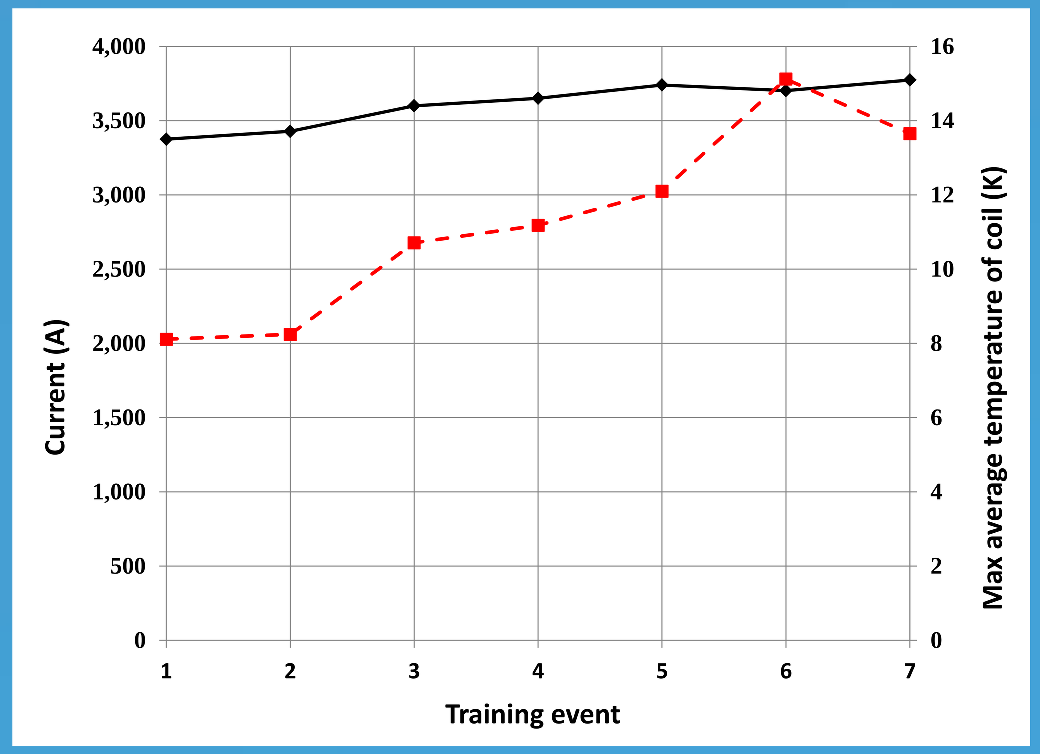

Fig. 3 Training curve of SHMS Q3. The solid line is the training curve. The dashed line is the corresponding maximum average temperature of the coil. The magnet started to train at 3375 A, and its maximum average temperature was 8.11 K after the quench. The seventh training event pushed the current to 3774 A—well above the required 11 GeV current (2480 A). SHMS Q2 and Dipole have similar training curves. Q2, Q3, and Dipole all behaved similarly. Q2 and Q3 are identical except their yoke steel, so they should have similar behaviors. Since the same superconducting cable and copper stabilizer were used in Dipole as in Q2 and Q3, they were expected to behave similarly.

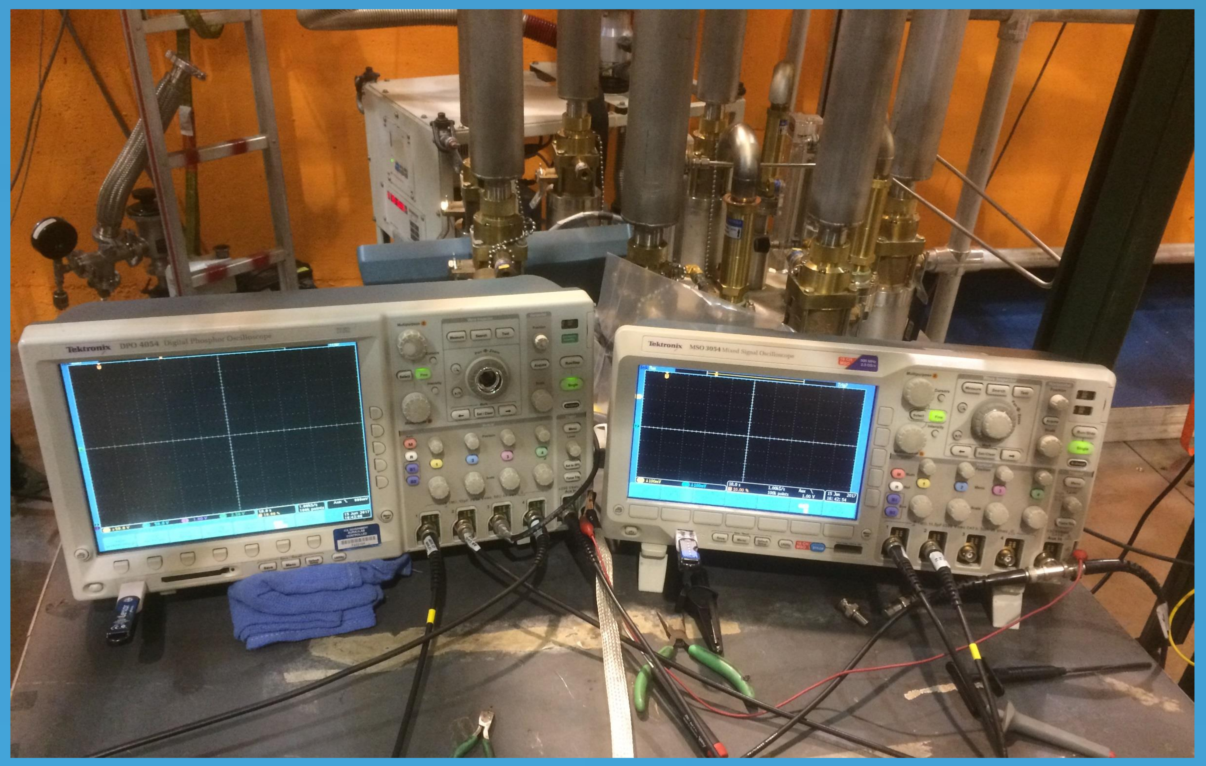

Fig. 4 DPO 4054 and DPO 3054 used in tests of fast dumps. The oscilloscopes were synched by using the same trigger voltage of the current signal. The probes (Tektronix P5200 or P5200a) employed in the tests to pick up the signals are differential. Calibration was conducted for each channel at the same test settings. The measured raw data was processed according to corresponding calibrated curves. Four channels were employed to measure the voltages of Q3's four pancakes, one for the current and one for the voltage of the whole coil. Similarly, three channels were used for the voltages of three pancakes of Dipole coil.

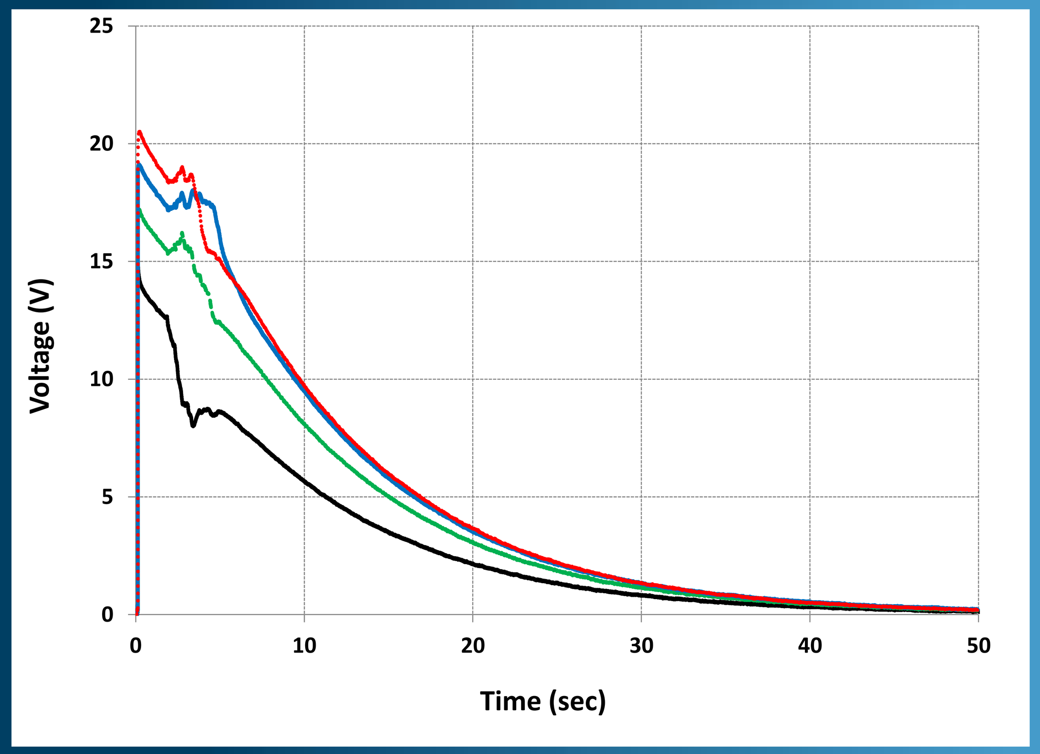

Fig. 5 Voltage decay curves of four pancakes of Q3 with the dump current of 3500 A. Q3 coil has four pancakes; each curve represents the voltage change of one pancake. The bottom solid curve is the voltage of the most inner pancake. The top curve (its voltage larger than 20 V when the time is zero) is the voltage of the most outer pancake. The disturbance started to show up at 1.8 seconds and disappeared at 5.0 seconds. This disturbance did not show itself when the current was below 1500 A for Q2 and Q3, and 2250 A for Dipole. The magnitude of disturbance was much smaller at lower current. All liquid helium was gone when the magnet was fast dumped from 3500 A. The recovery time was about three hours.

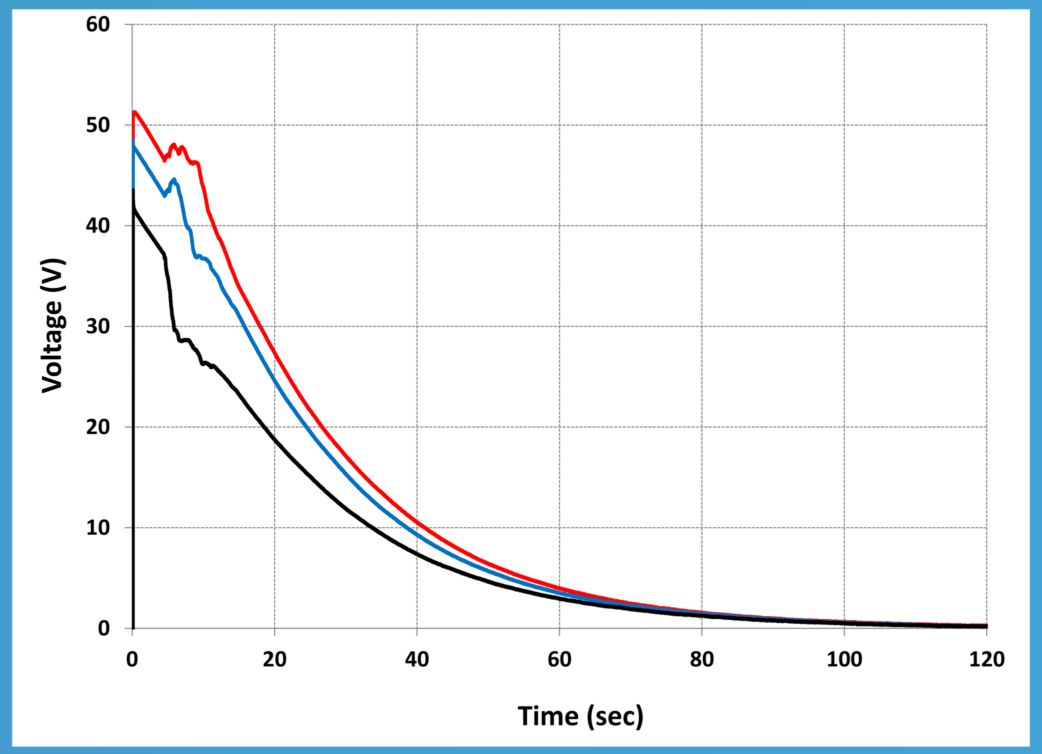

Fig. 6 Voltage decay curves of four pancakes of Dipole with the dump current of 3308 A. Dipole has three pancakes. The bottom solid curve is the voltage of the most inner pancake. The top curve (its voltage larger than 50 V when the time is zero) is the voltage of the most outer pancake. The disturbance started to show up at 4.5 seconds and vanished at 11.3 seconds. The disturbance was caused by eddy current in the copper stabilizer of the coil. The natural logarithm curve of the current does have two slopes—a flat slope (-0.019) between 0 to 4.5 seconds and a steeper slope (-0.049) after 11.3 seconds. The slope change is consistent with the voltage disturbance.

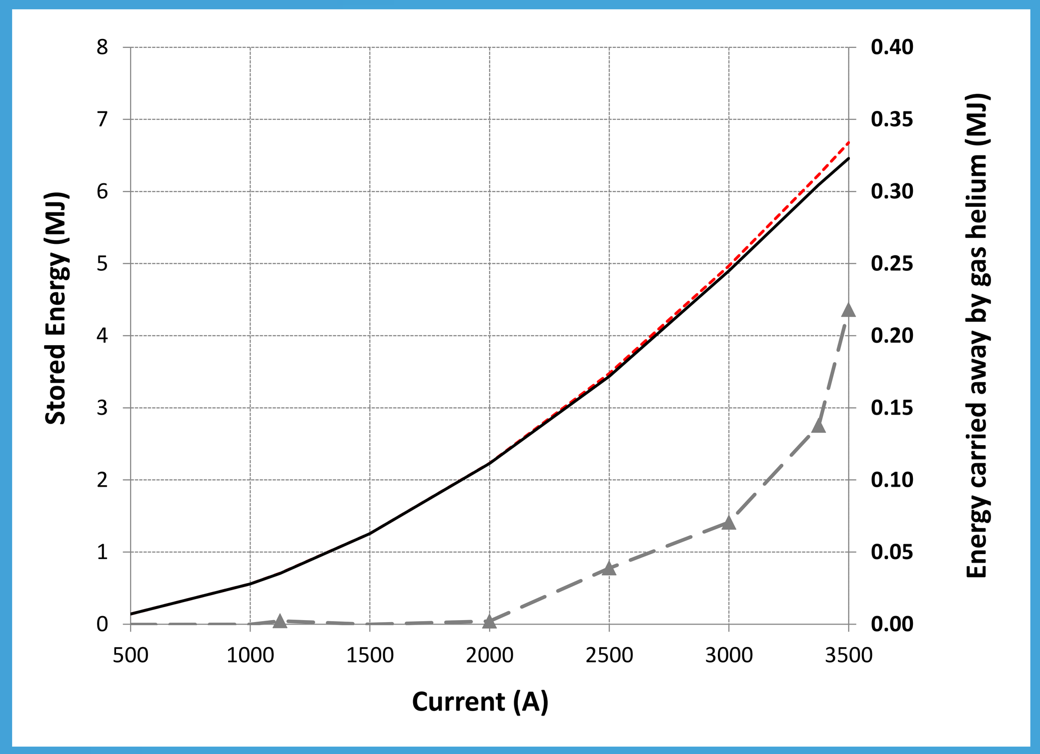

Fig. 7 Energy balance calculation of Q3. The short dashed line represents the stored energy of the magnet; the solid line, the measured energy; the long dashed line, the energy carried away by gas helium. Q2 is the same as Q3 except the yoke steel, and its energy balance is almost the same. Dipole also exhibits similar energy balance behaviors. The measured energy includes the energy consumed by the dump resistor and leads; the energy consumed by eddy current in the iron, force collar, helium vessel, and vacuum vessel; the latent energy of depleted liquid helium in the magnet; the energy required to raise the coil temperature; the latent energy of liquid helium supply during the period of coil temperature measurement (from the start of dump to the peak temperature)

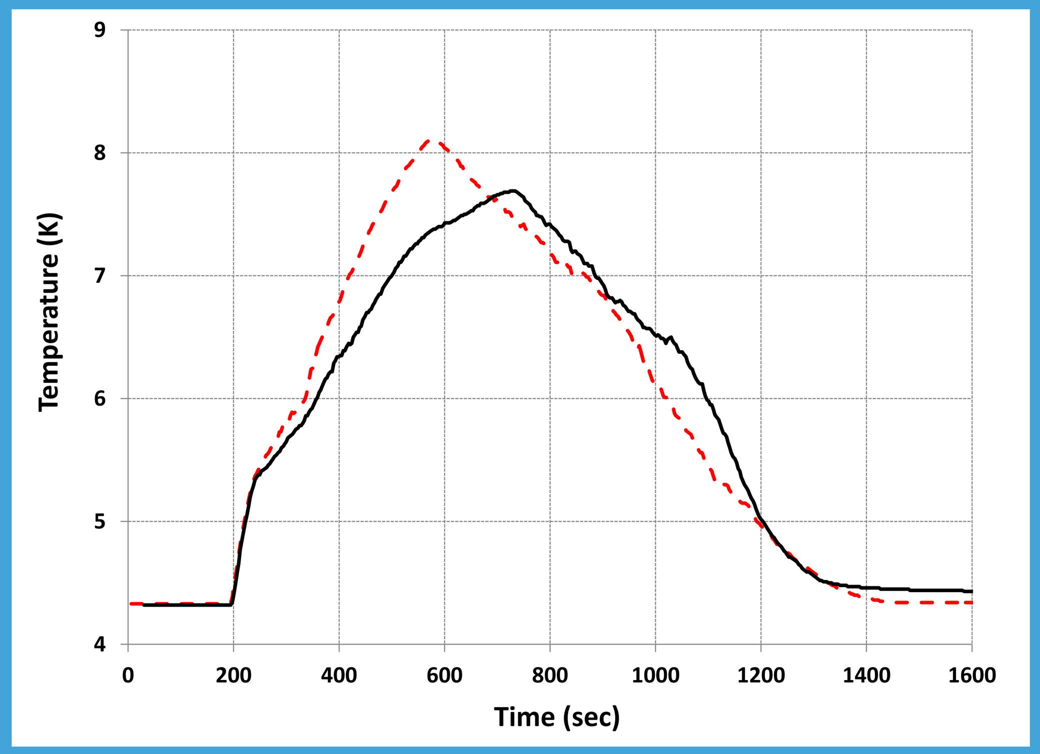

Fig. 8 Temperature versus time after the training quench (3375 A) and the fast dump (3375 A) for Q3. The solid line represents the temperature change after fast dump test from 3375 A; the dashed line, the temperature change after the first quench of Q3 at 3375 A. Q3's time-based pressure curves were also similar for quench and fast dump. When Q3 initially quenched at 3375 A, it immediately turned on the dump resistor. The dump resistor forced the current to decay fast; the eddy current due to rapid magnetic field change in the copper stabilizer then triggered a large portion of coil to quench. The protected quench and fast dump behaved similarly.

Conclusion - The early quench simulations of SHMS magnets were extremely conservative because of three major assumptions: no liquid helium, one-spot-initiated quench, and low dump resistance. The actual training quenches were surprisingly mild as a result. The fast dump tests show that rapid current decay triggered quench due to eddy current heating in the copper stabilizer. Future work is to reduce the dump resistors so that the minimum quench-triggered current could be increased to an optimized level.