Upgrade of the NHMFL Cryogenic System and the Index Heating Test Results on the 45-T Hybrid

Hongyu Bai, John G. Kynoch, and Scott T. Hannahs

***Abstract*—The 45-T Hybrid at the National High Magnetic Field Laboratory (NHMFL) has been the only facility in the world capable of providing a dc field of above 40 T. The 45-T hybrid magnet, consisting of a superconducting outsert and resistive insert, was commissioned in 2000 reaching a field of 45 tesla. The cryogenic system for the NHMFL has been in service since 1994 and has provided cryogenic service for the 45-T hybrid superconducting outsert since testing in 1998. It was recently upgraded, replacing a majority of the original system. The 45-T Hybrid was cooled down successfully with the new cryogenic system in February 2014. The new cryogenic system has been proved more efficient and reliable in the past years, providing increased availability to the users. After the upgrade of the cryogenic system, a standard index heating test was performed on the outsert of the hybrid. This test is mainly for evaluating the performance of the outsert, particularly the degradation of the innermost Nb_3Sn coil of the outsert that suffered an unprotected quench in 2000 and degradation since then. The results of index heating tests in the past are compared and presented.**

***Index Terms*—Cryogenic system, high-field magnet, index heating, superconducting magnet, 45-T hybrid magnet.**

I. Introduction

THE 45 T magnet at the National High Magnetic Field Laboratory (NHMFL) has been the only magnet in the world capable of providing a DC field of above 40 T. It has served as a user facility since it was commissioned and reached the full field of 45 T in 2000. The 45-T hybrid magnet is currently operated with a combination of a 33.5-T resistive insert and 11.5 T superconducting outsert operated in a superfluid helium (He-II) bath. It runs at full field with the insert and the outsert about 30 weeks for the users each year. The cryogenic system runs more than 10 months every year to maintain the outsert cold. The 45-T hybrid mainly supports condensed matter physics experiments. Recently experiments include users working on graphene, 2-D electron gas in semiconductors, topological insulators, multiferroics, semi-metals, and high temperature superconductors. The cryogenic system for the NHMFL has been in service since 1994 and has been servicing the 45-T hybrid since testing began in 1998. For the development of the new Series-Connected Hybrid (SCH), a new cryogenic system of 1 kW@4.5 K has been built and installed [1], [2]. The new cryogenic system consists of a helium refrigerator, a central distribution box, an 80 K coldbox for the cooldown of magnets, an 18 g/s purification system, enlarged helium storage tanks, and many cryogenic transfer lines. The new helium refrigerator was commissioned in 2011 and the distribution system was delivered one year later and commissioned in 2013. The 45 T cryogenic system then underwent a major upgrade by removing the two old piston liquefiers, the transfer lines and the valve box and replacing them with the new system. New cryogenic transfer lines were installed to connect the 45-T hybrid and the new central distribution box. Part of the cryogenic controls, such as the controls for cooldown, 4.5 K bath level and 20 K thermal shield temperature, were also upgraded. The 45-T hybrid was cooled down successfully with the new system in February 2014, and then reached its full field. The SCH magnet is currently in the final integration stage and it will also be connected to the new cryogenic system when the integration is completed late 2015. The new cryogenic system has proven to be more efficient and reliable in the past years, providing increased availability to the users. After upgrade of the cryogenic system, an index heating test was performed on the outsert of the 45-T hybrid. This is a standard procedure for the 45 T to evaluate the performance of the outsert since 2000 [3], [4]. The results of index heating tests in the past are compared and presented here.

II. New Cryogenic System for 45-T Hybrid

The 45 T cryogenic system for the 45-T hybrid was upgraded to the new system in late 2013. First, the superconducting outsert was warmed up to room temperature for the upgrade. It was followed by the disconnection of the two old piston-expander based PSI-1630 helium liquefiers, the original cryogenic transfer lines, a valve box, and relevant instruments. A new cryogenic helium transfer line connecting the hybrid cryostat to the central distribution box and a liquid nitrogen supply line for the thermal shields cooling were installed. The automatic controlled cooldown, the level control of the 4.5 K upper reservoir and the temperature control of the 20 K thermal shield were also upgraded. No changes were made on the pumping system for 1.8 K cooling. The superconducting outsert was cooled down from room temperature to 4.5 K in February 2014, which took three weeks, followed by a one day cooldown to 1.8 K. The 45-T hybrid was then energized to full field.

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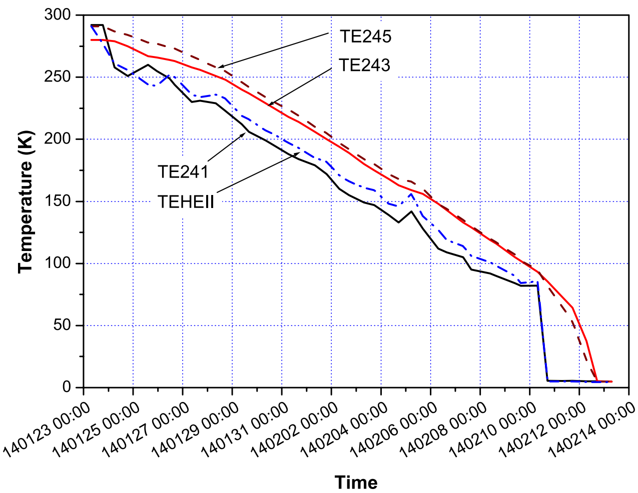

Fig. 1. First cooldown after upgrade of the cryogenic system for the 45-T hybrid. TE241 is the supply helium temperature, and TE245 is the return helium temperature during cooldown. TEHeII is the temperature in He-II bath. TE243 is the temperature of the magnet vessel. After cooldown, all the four sensors are immersed in liquid helium. The format of time shown in the x-axis is in a sequence of Year (2014), Month (01 is January and 02 is February), Day, Hour, and Minute.

Fig. 1 shows the first cooldown with the new cryogenic system. Three weeks cooldown is almost two weeks less that the required cooldown time in the past. There were temperature data communication problems in the beginning of cooldown and this is why the temperature is not stable during this period. Since the magnet was cooled down, the outsert has been maintained at 1.8 K up to now with a few weeks exception for the cryostat cold test for the SCH.

Many benefits were achieved after upgrade: 1) Large reduction of maintenance work on the helium system since the old piston liquefiers have been in service for more than 20 years with increased maintenance load as the system has aged along with the increasing difficulty in obtaining spare parts. 2) Increased user availability of the hybrid due to the new turbine helium system requiring less regular maintenance while providing more capacity. The new system showed a very good reliability in the past two years since the cooldown. 3) Higher efficiency (COP=1/350) of the new system reducing the electrical power consumption. 4) Lower operating temperature of the outsert now increasing the stability of the magnet, explained later. 5) Reduced heat load on the cryogenic system due to the removal of the original valve box.

III. Index Heating Tests on the 45-T Hybrid Outsert

As J. Miller pointed out [3], [4], there may be index heating in the superconducting coils at high current due to damages caused by the unprotected quench of the outsert in 2000. The index heating shows up when the operating current I of the superconductor approaches the local critical current I_0 which is determined by the local magnetic field and temperature.

$$Q_{\text{index}} = IE_0 \iint \left(\frac{I}{I_0}\right)^n dldt. \quad (1)$$

TABLE I
Index Heating Test Procedure

Step	Operation
1	Ramp to 8 kA at 2 A/s (4,000s).
2	Ramp to 0 amps at 4 A/s (2,000s).
3	Wait. Monitor recovery 30,000 s.
4	Ramp to 7.0 kA at 2 A/s (3,500s).
5	Hold for 1000 s.
6	Ramp to 8 kA at 0.4 A/s (2,500s).
7	Hold for 5000 s.
8	Ramp to 0 amps at 4 A/s (2,000s).
9	Monitor recovery for 30,000 s.

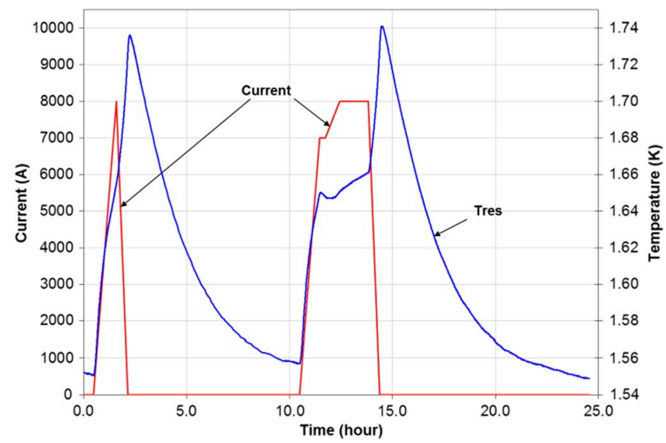

Fig. 2. Current of the outsert and the temperature reponse in the He-II reservoir (Tres) during ramping of the 45-T hybrid outsert. The maximum operating current is 8 kA to achieve 11.5 T.

Q is the heat generated, n is the index value which reflects the resistive transition, E_0 is the electrical field criterion for establishing the critical current I_0 and the integral is over the length l of conductor and the period of time t.

Routine tests on the superconducting coils to evaluate the index heating in the outsert are performed once in a while or after re-cooldown if there is a warm up above 80 K. A standard procedure is used for the index heating tests, shown in Table I. It was usually done in the morning after the temperature in the 1.8 K bath is stabilized overnight. This procedure is different from the procedures shown in [3], but the same method was used for the data analysis.

Fig. 2 shows the current and temperature response in the coils during the index heating test in March 2014. It happened when the cooldown to 1.8 K was completed after the upgade of the cryogenic system. During the ramping up and down of the outsert, there is an obvious rise of temperature in the He-II bath due to AC losses generated in the coils. Once the outsert was ramped down to zero current, the temperature began to drop because the J-T refrigerator was kept running to remove the generated heat. The heat losses during the tests were calculated based on this calorimetric method. The temperature profile obtained in the test was used for calculating the total heat deposit in the whole process.

During ramping of the outsert, the heat generated in the outsert Q_{dep} is transferred to the He-II in the magnet vessel. It includes the joule heating of joints Q_j, AC losses in the coil (hysteresis loss $Q_{\rm hys}$ and coupling loss $Q_{\rm coupling}$), and the index heat if present at high currents.

$$Q_{\rm dep} = Q_j + Q_{\rm hys} + Q_{\rm coupling} + Q_{\rm index}. \tag{2}$$

The joule heating and calculated AC loss is based on the data shown in [3].

$$Q_{\rm calculated} = Q_{\rm hys} + Q_{\rm coupling}. \tag{3}$$

The heat deposit in the He-II is partially $(Q_{\rm rec})$ removed away by the J–T refrigerators operating at about 1.6 K during the tests. The remaining heat $(Q_{\rm res})$ results the rise of the He-II bath temperature (helium in the reservoir), the magnet vessel and the magnet itself.

$$Q_{\rm dep} = Q_{\rm rec} + Q_{\rm res}. \tag{4}$$

The heat removal rate is assumed proportional to the temperature difference between the bath temperature and the base temperature $(T - T_{\rm base})$, which can be obtained from the temperature recovery line after the outsert is ramped down to zero current.

$$T_{\rm res} = (T_{\rm ini} - T_{\rm base})e^{(-t/\tau)} + T_{\rm base}. \tag{5}$$

T is the temperature, $T_{\rm ini}$ is the initial temperature in the bath, t is the time, and τ is the time constant for the temperature recovery.

The heat absorbed by the magnet vessel and the magnet itself can be neglected compared with the heat absorbed by the He-II. The heat deposit in He-II can be calculated by

$$\Delta Q_{\rm res} = V\rho_{He}c_p\Delta T. \tag{6}$$

V is the volume of He-II which is 1.718 m^3. ρ_{He} and c_p are the density and heat capacity of He-II, respectively.

The measured loss less joule heating is

$$Q_{\rm corrected} = Q_{\rm dep} - Q_j = Q_{\rm rec} + Q_{\rm res} - Q_j. \tag{7}$$

By comparing $Q_{\rm calculated}$ and $Q_{\rm corrected}$, we can know how much index heating was generated during the tests.

IV. Results of Index Heating Tests

The temperature response of the first ramp is shown in Fig. 3. The data of index heating tests performed in 2010–2013 are also shown in the same figure. After the upgrade of the cryogenic system, the operating temperature is obviously lower than that of before upgrading. This is because the "20 K" thermal shield and thermal intercept are operating at a lower temperature of about 10 K instead of 20 K, the heat load to 1.8 K level is then reduced. With the same J-T refrigerators and pumping system, the lower temperature in the He-II bath can be achieved.

Fig. 4 shows the calculated AC losses $Q_{\rm calculated}$ and the actual losses $Q_{\rm corrected}$ based on the calorimeter tests in the past 4 years. $Q_{\rm corrected}$ of all the four tests are within 10% of the calculated losses for the first ramp. No substantial changes were observed for the four tests.

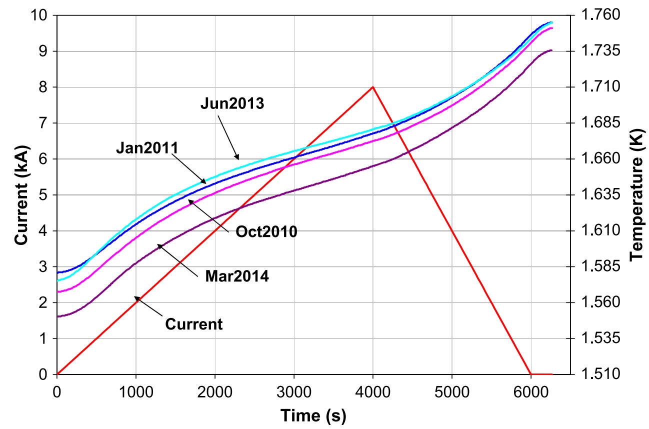

Fig. 3. Temperature response of the first ramp of the index heating tested in March 2014, compared with that in October 2010, January 2011, and June 2013. The current operation temperature of outsert (2014) is lower than that in the past after the LR280 was connected to the hybrid.

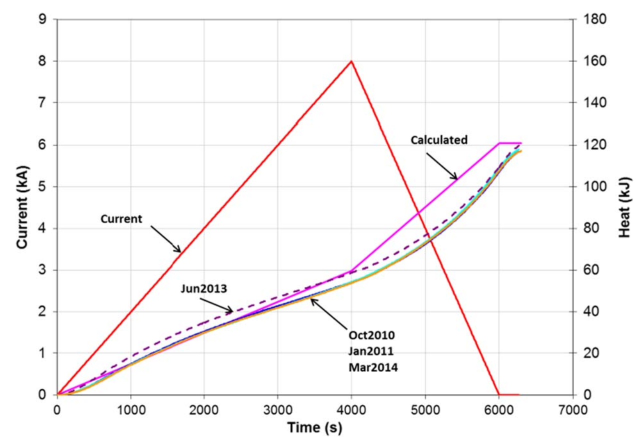

Fig. 4. Corrected heat deposition of the first ramps in October 2010, January 2011, June 2013, and March 2014. The four curves are almost laid over each other, and no substantial changes were observed for the four tests.

The temperature responses of the second ramp up and down are shown in Fig. 5 for the same four tests. The operating temperature is also obviously lower after upgrading than that of before upgrading. When the current was held constant at 7 kA, the temperature in the He-II dropped. But when the temperature was held constant at 8 kA for 5000 seconds, the temperature in the He-II rose slightly, which means there is additional heating in the superconducting coils. Usually the outsert is operated at 8 kA and the temperature of He-II bath rises all the time if the current is kept at 8 kA. Once the temperature rises to a threshold, for example 1.8 K, the outsert has to be ramped down for the recovery of temperature to a lower value, which usually takes place at night. Since the operating temperature is lower after upgrading, the magnet can stay at 8 kA longer if we try to limit the maximum temperature not more than a set limit.

Fig. 6 shows the calculated AC losses $Q_{\rm calculated}$ and the actual losses $Q_{\rm corrected}$for the second ramps in the past 4 years. The tested losses $Q_{\rm corrected}$ are greater than $Q_{\rm calculated}$ and the difference is contributed to the index heating.

The additional heating during the 5000 s when the current is held constant at 8 kA is shown in Table II. The index heating test result from July 2010 is also included. When normalized

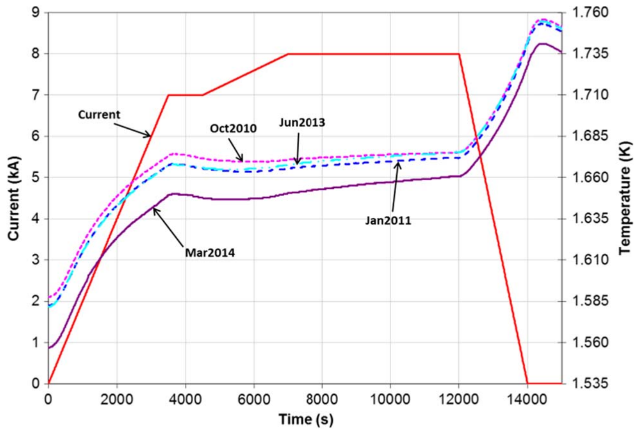

Fig. 5. Temperature response of the second ramps in October 2010, January 2011, June 2013, and March 2014. The temperature curves between 2010 and 2013 are almost the same. The temperature in the test of 2014 was lower than that in the past.

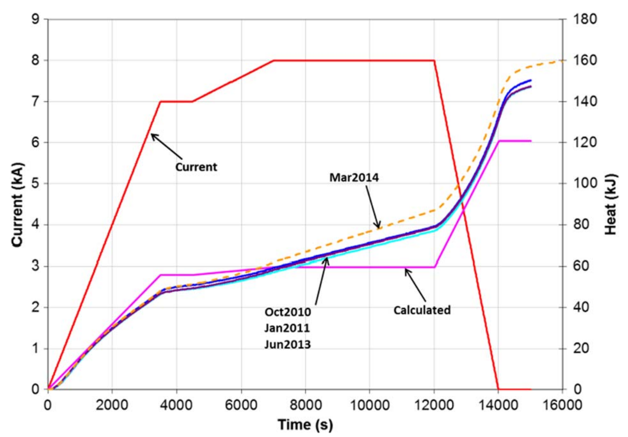

Fig. 6. Corrected heat deposition of the second ramps in October 2010, January 2011, June 2013, and March 2014. The test in March 2014 showed a bigger heat loss, and this may be caused by the new base temperature since it was lower than that in the past after the new cryogenic system was connected to the 45-T hybrid.

by measured heat deposited during the ramp up to 8 kA, this additional heat is very similar for each test. Within the accuracy and precision of the available data and data-reduction techniques, there seems to have been no substantial change in performance of the 45-T Hybrid Outsert between 2010 and 2013, which can be explained due to (1) AC losses are essentially unchanged; (2) Degradation (due to index heating) is essentially unchanged. The tests in 2014 showed an increase of the additional heating. The reason is not clear, but it is likely

TABLE II
ADDITIONAL HEAT DURING 5000-S HOLD AT 8 kA

Step	Additional heat	Percentage
Jul. 2010	~ 20-25 kJ	36.6%
Oct. 2010	~ 20-25 kJ	33.4%
Jan. 2011	~ 20-25 kJ	34.5%
Jun. 2013	~ 20.3 kJ (4.1 W)	34.8%
Mar. 2014	~ 25 kJ (5 W)	40.5%

because the new base temperature causes the systematic error in the analysis. It should be compared with the data in the future under the same base temperature. The data were not sufficient to confirm that further degradation happens in the outsert.

V. CONCLUSION

The 45-T hybrid cryogenic system was upgraded successfully and it has been in operation since March 2014. The new cryogenic system has proven to be more efficient and reliable in the past two years, providing increased availability to the users. Index heating tests were performed on the 45-T hybrid before the upgrade and after the upgrade of the cryogenic system, no obvious changes were observed. We will continue performing the index heating tests for the outsert in the future to estimate the further degradation and evaluate whether it is necessary to replace the degraded Nb_3Sn coil A in the outsert.

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