Commissioning of Horizontal Bend Superconducting Magnet for Jefferson Lab's 11 GeV Super High Momentum Spectrometer

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Abstract—Commissioning characteristics of the Superconducting High Momentum Spectrometer (SHMS) Horizontal Bend (HB) magnet was presented. Pre-commissioning peer review of the magnet uncovered issues with eddy currents in the thermal shield, resulting in additional testing and modeling of the magnet. A three-stage test plan was discussed. A solution of using a small dump resistor and a warm thermal shield was presented. Analyses illustrated that it was safe to run the magnet to full test current. The HB magnet was successfully cooled to 4 K and reached its maximum test current of 4000 A.

Index Terms—Commissioning, Accelerator Magnets, Cool-down, Eddy Currents, and Finite Element Methods.

I. INTRODUCTION

Jefferson Lab is engaged in a major upgrade project to double the CEBAF Accelerator energy to 12 GeV/c and add major new experimental facilities [1]. JLAB Hall C is building an 11 GeV/c Superconducting High Momentum Spectrometer (SHMS) to enable nuclear physics experiments at the highest available beam energy [2], [3]. The SHMS is a focusing spectrometer with a magnetic arrangement of dQQQD. The first magnet, a small dipole named the Horizontal Bend (HB), permits the SHMS to reach 5.5 degree scattering angles. The three focusing quads are: a cold iron quad (Q1) [4], a pair of SC cosine(2 θ) quads (Q2, Q3), followed by a 60 cm warm bore cosine(0) dipole for momentum analysis. The HB is a warm iron, “C” type magnet with its warm bore tube tapered along the length of the magnet. It uses Superconducting Super Collider (SSC) NbTi cable. Its helium vessel was built in accordance with ASME 2007 Section VIII, Division 2, and its pressure piping per ASME 2008 B31.3.

The Facility for Rare Isotope Beams (FRIB) at Michigan State University was the subcontractor for the HB magnet. FRIB was responsible for the design, fabrication, testing, shipping, and documentation of the magnet. Jefferson Lab was in charge of supplying the Superconducting Super Collider

(SSC) Rutherford superconducting cable, the cryogenic control reservoir (CCR), the Power Supply Unit (PSU), the Programming Logic Control (PLC) system, and the current leads. Jefferson Lab was also responsible for installation and commissioning. The magnet was delivered to Jefferson Lab in March 2015. This paper will focus on installation and commissioning.

II. INSTALLATION, COOLDOWN, AND LOW POWER ENERGIZATION

A. Installation

After the magnet arrived at Jefferson Lab, it was moved to the floor of Hall C and unpacked. A series of tests were

Fig. 1. HB magnet installed on the SHMS platform

performed on the magnet, which included the leak-test, pressure-test and flow-test of the helium circuit and the nitrogen circuit; the leak-test of the vacuum space; check of the instrumentation; the high-pot test of DC circuit; and the calibration of valve actuators. The survey group fiducialized the magnet. After the magnet passed initial tests, it was lifted to the SHMS carriage platform (Fig. 1). JLAB's Hall C technicians and engineers then installed the helium and nitrogen pressure relief valves and rupture disks, connected

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Fig. 2. First Cooldown of HB magnet took 2.63 days or 63 hours.

the PLC control system, pumped and purged the magnet, connected the magnet to the cryogenic sources, and connected the DC power.

B. Cooldown

During cooldown, the PLC monitored the temperatures of the magnet at various locations and made sure that the maximum temperature difference among temperature sensors was not greater than 50 K by adjusting cooling speed. It took 2 days for the average temperature to reach about 100 K, and another 0.63 days to 4 K (Fig. 2). Suspension links, that are used to suspend the cold mass from the cryostat, were adjusted during cooling down of the magnet to maintain balance between the top and bottom links and to keep the horizontal compression links slightly under compression.

Due to very tight space constraints, the separation distance from warm to cold surfaces was only 6.5 mm in the area of the beam cutout; however, no thermal shorts and no condensation on the outer cryostat vacuum surfaces were observed. The coldest surface temperature of the vacuum vessel was 293 K in the area of the beam cutout while its average surface temperature was 297 K. MSU/FRIB did an excellent fabrication job.

C. Low Power Energization

The magnet was maintained at 4 K for three days before its first current energization. The low power test involved ramping the magnet to its set point, allowing it to soak at current and then to ramp down back to zero. This process was repeated in the opposite polarity. Low power test set points were in increments of 100 A, up to 400 A. This was followed by tests of ramping to set points and performing a fast discharge of the magnet through its dump resistor. The whole energizing process was smooth, and the magnet, PSU, quench detector, PLC controls, and cryogenics behaved as expected.

III. EDDY CURRENT

A. Eddy Current

The thermal shield of the HB magnet was made of $\frac{1}{4}$ hard ETP UNS C11000 copper (Fig. 3) and designed to cool to LN2 temperature by means of attached tubing. It was

Fig. 3. Thermal shield of HB Magnet was made of copper. T6 was a temperature sensor located at iron-side of the thermal shield.

manufactured from numerous pieces, being joined together either by soldered rivets or G10-insulated rivets. The G10-insulated rivets, which were effective in reducing the eddy currents, were located in the bore tube of the thermal shield. However, large pieces of the thermal shield, which would experience large magnetic field changes during fast discharges, were not slotted to minimize generation of eddy currents (Fig. 3). There were concerns that large eddy currents during fast discharges would produce significant Lorentz forces which might induce permanent deformation of the thermal shield; that the permanent deformation might lead to thermal shorts to the helium vessel and/or room temperature vacuum vessel; and that such a thermal short might make it difficult to maintain the magnet at 4 K.

The thermal shield was simulated using OPERA/ELECTRA. It was particularly difficult to model the thermal shield because its thickness was only 1.65 mm. Due to model size, complexity and spatial constraints, a single layer of quadratic elements could be used to model the thermal shield. A test FEA model with thicker shields was created to verify that it was adequate to use one layer of elements. Three layers of elements were generated along the thickness in the thick model. To make the test thick model equivalent to the actual thin model, the conductivity of the thick model had to be reduced by 6 times. Analysis results illustrated that the Lorentz force on the thermal shield was the same for both the thin model and the thick model. It was therefore concluded that the thin shield model could be treated as a representation of the reality. The Lorentz force density of the thermal shield was exported as a data file from OPERA/ELECTRA. Fig. 4 shows the eddy current density on the thermal shield generated from a fast dump at 2000 A.

ANSYS was used to perform the stress analysis of the thermal shield. Solid shell elements were used, as the thermal shield was particularly thin, which greatly reduced the total number of elements and therefore computation time. The Lorentz force density from OPERA/ELECTRA was mapped to the centroid of each solid shell element. The helium vessel and vacuum vessel of the magnet were simulated in ANSYS as contact constraints. Using midplane symmetry allowed for only half of the thermal shield needing to be modeled. ANSYS modeling results indicated that the existing configuration of

the magnet, using a 0.06 ohm dump resistor and an 80 K thermal shield, would lead to excessive stress and deformation due to eddy current from a fast discharge at high currents.

B. Material Properties and Allowable Stress of Thermal Shield

The nominal cold work of $\frac{1}{4}$ hard copper was 11% [5]. Table I lists the material properties for the copper used in the analysis. Cryogenic properties of a weaker C10700 were used as the authors did not have cryogenic properties for C11000. The ultimate tensile stress of $\frac{1}{4}$ hard C11000 was 265 MPa at room temperature while the calculated ultimate tensile stress of 11% cold-worked C10700 was only 241 MPa at room temperature [5], [7].

The allowable stress of the thermal shield at corner was defined as the minimum of $\frac{2}{3}\sigma_y$ or $\frac{1}{3}\sigma_u$ because the angle change at the corner may amplify the displacement in other area if the copper at the corner yields. The allowable stress of the thermal shield at the flat regions was defined as the minimum of σ_y or $\frac{1}{2}\sigma_u$ because the flat regions were less critical. These definitions were consistent with the allowable stresses for different stress categories in ASME Pressure

Fig. 4. Dark gray demonstrates large eddy current density of the thermal shield. It was noted that the T6 temperature gauge was installed right on a location with high eddy current density (Fig. 3). Light gray indicated small eddy current density.

Vessel Code.

C. Helium Heat Load

The consequence of shutting off liquid nitrogen supply to the thermal shield resulted in a higher helium heat load. Measured HB magnet helium heat load was 44 W with the shield at 218 K without active cooling while it was 32 W with shield at 80 K. The higher helium heat load imposed no difficulty to any operation of the Hall.

D. Test Plans and Test Results

A three-stage peer-reviewed test plan was used such that each stage of testing was confirmed as a safe range by previous analysis and confirmed by actual data. The first stage was the low current test plan, the second the medium current test plan, and the third the high current test plan.

The first stage was confined to 393 A. The safety of the first stage was confirmed by analysis only and backed by some measurements of shield properties. The analysis demonstrated that operation up to 2000 A with a cold thermal shield was within the stress and deformation allowable limits, providing

confidence that operation up to 393 A would be completely safe.

The low current test plan was to perform a series of fast current discharges by varying the magnitude of the dump resistor and changing the temperature of the thermal shield. The goal was to access the impact of these two parameters to generation of eddy current on the thermal shield. Liquid nitrogen supply was shut off to achieve higher temperature of thermal shield, which stabilized at about 218 K.

The low current test results illustrated that these two parameters had a significant impact to eddy current. Smaller dump resistance and higher temperature of the thermal shield led to significantly less eddy currents on the shield. The current decayed much slower after the dump resistor was changed from 0.06 ohm to 0.015 ohm. In addition, the resistivity of copper at 218 K was about five times of that of copper at 80 K, which substantially reduced eddy currents. So the safe path to higher current was to use a 0.015 ohm dump resistor and a warm shield. The data at 393 A were used to re-evaluated the eddy current effects at 2000 A and 4000 A with a warm thermal shield and a reduced dump resistor of 0.015 ohm. The analysis, based on the 393 A current decay scaled up to 4000 A, showed that the stresses (109 MPa [flat region] and 62 MPa [corner] with fast discharge) of thermal shield were within the allowable stress and deformation limits, during fast discharges, with a significant margin of safety.

TABLE I
MATERIAL PROPERTIES OF COPPER AT 218 K USED IN ANALYSIS

Parameter	Unit	Value
Young's modulus (E)	GPa	131
Yield stress (σ_y)	MPa	206
Ultimate tensile stress (σ_u)	MPa	296
Allowable stress at corners	MPa	99
Allowable stress at flat regions	MPa	148

The medium current test plan, with a 0.015 ohm dump resistor and a 218 K warm shield, was the second stage of the plan. The plan was to conduct a series of fast dumps from 400 A to 2000 A in a 400-A step with a small dump resistor and a warm shield. The rationale was to check the validity of assumptions used to scale up Lorentz forces of medium and high currents from low current, and to obtain measurement data with better accuracy due to an improved signal-noise ratio. The HB magnet was successful tested up to 2000 A without any incidents and any thermal shorts. The calculated average temperature rises from OPERA/ELECTRA models were consistently higher than the corresponding measured averaged rises, which indicated that the computer models were conservative. The slightly warmed thermal shield due to successive fast discharges went back to the equilibrium of 218 K, which indicated no permanent thermal short was produced due to fast discharges from 2000 A. There was a discrepancy between the computed and measured dissipated energy with the medium current tests (0.015 ohm dump resistor and 218 K warm shield). The discrepancy was due to measurement and calculation error.

Fig. 5 Stress distribution of thermal shield. An additional design factor of 1.5 was multiplied to the body force density. The maximum von Mises stress was 155 MPa in the flat region, which was slightly larger than 148 MPa. However, the area with stress larger than 148 MPa was particularly small.

Fig. 6. Calculated average temperature rise (dashed line) versus measured average temperature rise (solid line) at T6 (Fig. 3).

An additional conservative design factor of 1.5 (ratio of measured and computed dissipated energy at 2000 A) was multiplied to the body force density to compensate the discrepancy. The ANSYS modeling result of the fast discharge from 4000 A, with the additional design factor of 1.5, showed that the stresses at the corners and in the flat regions were acceptable (Fig. 5). The current decay of 4000 A was projected with the decay data of 2000 A and a 0.024 ohm dump resistor. The reason to increase the dump resistor from 0.015 ohm to 0.024 ohm was to reduce the hot spot temperature of the magnet during quench. The stresses of the thermal shield from quench simulation of 4000 A were also acceptable. It was therefore concluded that it was acceptable to run the magnet at full operating current if a small dump resistor of 0.024 ohm and a warm thermal shield were used.

The high current test plan, with a 0.024 ohm dump resistor and a 218 K warm shield, was the third stage of the plan. A number of ramping and fast discharge tests, from 500 A to 4000 A, in an increment of 500 A, had been performed. A series of trainings, starting from 2640 A, occurred; the trainings were mild because the magnet recovered within half of hour. The magnet eventually reached 4000 A and held for four hours. More tests are planned to establish a stable operating current.

Fig. 6 and Fig. 7 illustrate the test results of fast discharges with a 0.024 ohm dump resistor. Fig. 6 and Fig. 7 also show that the measured and calculated temperature and the

Fig. 7. Computed dissipated energy (dashed line) versus measured dissipated energy (solid line). The computed dissipated energy was the total energy consumed by the iron, thermal shield, helium vessel, vacuum vessel plus AC loss. The measured dissipated energy was equal to the stored energy minus the quench energy and the energy integrated from the voltage and current of the magnet circuit. The error bars of the measured dissipated energy were the sum, added in quadrature, of 1.5% (from TOSCA RMS) of stored energy, 6.7% (from error analysis) of measured consumed energy of the dump resistor and the bank, and 6.7% of the quench energy. The error bars of the computed one were 10% (from error analysis) of the calculated values.

measured and calculated dissipated energy matched reasonably well. The measured temperature and energy were always smaller than the calculated ones, which indicated that the calculation was conservative. Data analysis manifested that the AC loss caused meek quench when the magnet was fast discharged from 3500 A and 4000 A.

IV. CONCLUSION

The concerns of eddy currents were addressed and resolved by peer-reviewed testing and modeling. Analyses showed that it was safe to run the magnet to the maximum test current by using a small dump resistor and a warm thermal shield. The HB magnet was successfully cooled to 4 K and reached its maximum test current of 4000 A.

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