Final Assembly and Factory Testing of the Jefferson Lab SHMS Spectrometer Quadrupole and Dipole Superconducting Magnets.

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***Abstract*—Jefferson Lab is constructing the Super High Momentum Spectrometer (SHMS) an 11 Gev/c spectrometer as part of the 12 GeV JLAB upgrade for experimental Hall C. Three of the five superconducting SHMS magnets are under construction at SigmaPhi France. The three magnets Q2, Q3 and the dipole are complete or near complete and have many design features in common. All three magnets share a common superconductor, collaring system, cryostat design, cold to warm support, cryogenic interface, burnout proof current leads, DC power supply, quench protection, instrumentation and controls. The three magnets are collared, installed in cryostats and welded up and in various stages of final testing. The Q2 quadrupole is due to ship from France to America in September and has passed all final hipot, leak and pressure tests. The dipole is in leak testing as of September 2016 while the Q3 quadrupole requires some outer vacuum vessel assembly. Delivery of the Q3 and Dipole magnets will follow the Q2 at about 1 month intervals. Factory tests have included hipot, electrical,low field magnetic, coil centering, leak tests and ASME Code pressure tests. Upon installation in Hall C at JLAB cold testing will commence.**

***Index Terms*—Detector magnets, spectrometer magnets, dipole magnets, quadrupole magnets, cosine theta magnets.**

I. Introduction

Jefferson Lab is in the final steps of completing the 12 GeV Upgrade to the CEBAF site. The CEBAF accelerator has met all Key Performance Parameters and has operated for Physics at 12 GeV supplying beam to the recently completed Experimental Hall D, Hall A and for an experiment to measure the proton radius in Hall B. Construction continues in Hall B and Hall C while we await delivery of the last of the new superconducting magnets. The Hall B CLAS12 SC Torus is complete and being cooled down as of this writing. The CLAS12 Solenoid is nearing completion at Everson Tesla in Pennsylvania. The Hall C SHMS Spectrometer is near to completion and has received and tested two of the five new SC magnets the Horizontal Bend (HB) Dipole and the Q1 quadrupole. Both have been tested and accepted with Q1 reaching 3000 Amps (110%) in June 2015 and the HB reaching 4000 Amps (102 %) in February 2016. This paper is concerned with the final assembly and factory testing of the SHMS Q2 and Q3 identical twin quadrupoles and the SHMS Dipole.

TABLE I
Properties of the SHMS Q2,Q3 and Dipole magnets

Magnet	Q2Q3 quads	Dipole
Type	Cosine 2Θ	Cosine Θ
Optimization	2 sector	2 sector
Wind Layers	6	8
Warm bore	60 cm	60 cm
Length	2.8 meters	4 meters
Field/Gradient	11.8 Tesla/m	3.9 Tesla
EFL	1.64 meters	2.85 meters
Stored energy	7.6 Mega Joules	13.7 Mega Joules
Current @ 11GeV/c	3350 Amps	3625 Amps
Turns/pole	608	400
Coil Weight	18 tons	25 tons
Yoke weight	72 tons	126 tons
Conductor	SSC outer cable in copper channel	3.05 by 19 mm

The Q2, Q3 and Dipole are all under construction with SigmaPhi located in Vannes, Brittany in the western Celtic part of France as the result of a pair of design build contracts issued late in 2010. These three magnets share many common systems provided by JLAB including stabilized superconductor, cryogenic interface reservoirs (CCR), DC power supply (DCPS), quench protection system and they share a common PLC based control system. All magnets have a warm iron yokes to minimize stray fields and add a nearly 20% boost to the central field. SigmaPhi maintained this principal of using common components and designed common cryostats, cold to warm support system, coil winding system, conductor insulation system, vacuum impregnation system and an Aluminum shrink fit collar system for all three magnets. Much

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of this has been reported earlier [5] and this paper will concentrate on the cryostat assembly, final magnet assembly, coil alignment, warm low current field testing, vacuum and leak testing and shipping preparations.

II. Q2-Q3-Dipole Cold Mass Construction

The coil winding for the SHMS Q2-Q3 and Dipole magnets began in early 2014. These three magnets use a common superconductor furnished by JLAB to the magnet manufacturer SigmaPhi. The conductor is a soldered composite of an SSC outer cable in a copper extruded channel. The channel was made for JLAB under contract by FreeportMacMoran and Phelps Dodge in Elizabeth New Jersey and the soldering was performed by Advanced Engineering Systems of Allentown Pa. AES is a small startup that was engaged by JLAB to develop the technology for wave soldering due to the global absence of the traditional suppliers. This DIY approach was not without frustration but eventually yielded a sufficient quantity of acceptable conductor for this project. JLAB strived to make a soft, easy to wind conductor and this proved problematic. The stress levels, especially in the dipole, required a harder conductor. SigmaPhi came up with an innovative process using a pair of presses operating sequentially and fully automated that were able to squeeze the conductor in one direction only and thus simultaneously harden but not damage the solder. This device known as “The Consolidator” was efficient and cost effective and produced usable conductor with acceptable mechanical properties. A side effect was the extremely uniform thickness in the thin or wind build direction while allowing some variation in the radial direction. This made the Q2, Q3 and Dipole coil winding much more predictable and allowed some extra turns to be included due to the lack of coil build up uncertainty. A three shift operation was required with two winding lines and two complete sets of tooling in order to complete the coil winding in a timely manner.

The coil winding for these three magnets was completed in early 2015. After winding, the coils were vacuum impregnated in molds using CTD 101K epoxy and simple homemade ovens. The potted coils were assembled by epoxy gluing the four Quad coils and two Dipole coils together. The quads used a set of quadrant forms that could be pinned together and to the pole former to maintain alignment. A significant effort was expended to hand polish the interface planes in order to arrive at a final size close to design. Subsequent to coil assembly, the completed coils were machined to a uniform diameter to prepare for the collaring. Splicing the many coil layers together was accomplished with automated splice heaters and clamps and a lot of qualifying with pre and post splice trials since testing of the actual splices would have been difficult.

The coils were collared with Aluminum rings by shrink fitting. The coil sizes were carefully machined and the resulting size used to determine the final collar dimension with the appropriate interference. Numerous test collaring operations with a four part collar was used to rehearse the operation and to measure in situ the actual coil modulus. The day of dipole collaring was fraught with apprehension but in the end it proved to be an efficient and routine operation with no snags. The collars were preheated to about 180 C first en masse in a large oven and then in a final post heat using small individual ovens to provide faster access and also to reach the final temperature. The collaring operation went off without a hitch and finished in about 7 hours. The days of rehearsal and practice paid off.

III. First magnet tests

The dipole and Q2, Q3 quads were magnetically tested to validate the splices. Special fixtures were made to hold hall probes in careful relation to the pole spacers and at 25 Amps, measurements of the mid plane field and gradient were performed. These measured fields were compared to TOSCA simulations and were within expectations. More importantly they confirmed that all splices were made correctly and that all coils had the correct polarity.

The coils were Hipot tested frequently at 1500 volts to validate the isolation from the pole spacers and between coil double layers. The resistance measured was 50 – 100 giga-ohms and leakage currents were a few micro amps for all three magnets. After splicing, the isolation tests between double layer sub coils was no longer possible but tests of isolation to the pole and mid spacers continued. After the coils were enclosed in their respective Helium vessels isolation to ground or the helium vessel was the only test possible. The numerous voltage taps which permit measurement of each sub coil and each splice came at a price. The multipin feedthrus used could only Hipot to 500 Volts. Thus further isolation tests are limited to 500 volts, which is twice the highest fast dump voltage.

The Instrument wiring was tested for continuity, isolation and functionality at regular intervals and at each major stage of assembly. This allows tracking of any degradation. None has been detected so far. Besides the numerous voltage taps, each coil has eight helium temperature measurement locations plus redundancy and each N2 shield main panel also has four temperature measurement locations plus redundancy. The eight cold to warm support rods each have a two axis strain gauge and a backup strain gauge since the coils will have to be dynamically centered in the warm yokes during testing at JLAB.

Fig. 1. Q2 Superconducting quadruple ready to ship.

Fig. 2. Q3 Superconducting quad final assembly.

IV. Cryostat Construction and Final Assembly

The Q2, Q3 and Dipole cryostats were built under a contract between SigmaPhi and SDMS, located in the eastern part of France. SDMS had the work scope to fabricate all cryostat components, LN2 shield panels, install the Q2, Q3 and Dipole coils in the helium vessels and test those vessels according to the ASMS boiler and pressure vessel code. This included dye testing all welds, leak testing and pressure testing to 7 Bar in air. The three coils were shipped to SDMS during the summer of 2015 and by January 2016 the first of these, the dipole, was returned to SigmaPhi for final assembly. The Q2 and Q3 returned at about one month intervals. All final assembly welding at SigmaPhi was performed by ASME qualified welders from SDMS, leak tests were witnessed by certified inspectors and all welds were dye tested by ASME Code certified weld examiners. This preserved the ASME code compliance of the Q2, Q3 and Dipole final assembly.

The final assembly steps included adding the LN2 outer shield panels and inner MLI to the coil helium vessel and installation of that sub assembly into the vacuum vessel. The coil/shield was then hung from eight support rods. A complete dry run assembly of just the coil and vacuum vessel was performed so that the support rod mounting flanges could be tack welded into position and any required adjustments made. This extra step proved essential to wring out the accumulated tolerances of the previous component fabrications. After the successful assembly of the Helium vessel with coil, outer shield, vacuum vessel and support rods, the Helium and Nitrogen piping could commence. The Helium piping was installed first and tested and this was followed by the LN2 piping because the LN2 piping laid on top of and partially obstructs access to the Helium piping.

The Q2, Q3 magnets then had the Cryogenic Control Reservoir (CCR), supplied by JLAB integrated with the Q2, Q3 coils. After an initial alignment and mounting in an assembly and shipping frame the SC bus was spliced to the burnout proof current leads, insulated and tested. The insulated SC bus was carefully insulated against welding heat by aluminized thermal cloth and the three helium tubes and smaller He cool down tube were welded closed. Hipot testing and helium mass spec. leak testing followed and a successful pass was required before the LN2 piping between the CCR and Q2, Q3 coils was completed. The LN2 circuit was leak tested and this permitted the final chimney closure between the CCR and Q2, Q3 coil cryostat and insertion of the vacuum bore and end flanges. A double pass seal weld was put in place and a final in vacuum leak test performed. After passing the final leak test the vacuum vessels were fully welded out by a sequence of first TIG welding and finally several MIG welding passes to fill up the weld grooves. The vacuum vessel welds are not pressure welds and thus were not dye tested or pressure tested.

The dipole final assembly sequence is somewhat different because the dipole when finished would be too tall to ship or to be delivered into JLAB's Hall C. The chimney extensions on both the dipole CCR and the dipole coil cryostat and the size of the field joint were optimized so that both parts were "normal" shipping sizes as far as height. Both the dipole and CCR had chimney extensions added at SigmaPhi. A special "test cap" was designed by SigmaPhi to permit leak testing the dipole coil and cryostat. This proved successful after some time lost trying to use soft seals for the entire dipole cryostat. Once the decision was reached to use a double pass TIG weld seal the leak test was accomplished quickly. This lesson learned was passed on to the Q2, Q3 final assembly. The Dipole CCR had its chimney extension added and this assembly was shipped to JLAB in May 2016. After arrival the dipole CCDR was leak and pressure tested successfully. It is stored in hall C awaiting the final assembly on the SHMS support structure.

The shipping for the three magnets uses the same basic system. Following comprehensive analysis of expected shipping loads the three magnets are enclosed in a rigid frame and support by shock isolation springs. The entire assembly is then carted in wood with an internal plastic shrink wrap to protect against water intrusion. The Q2 quadrupole is on board ship in Antwerp as this is being written with the expected docking at Norfolk Virginia on Sept 25th. The Dipole and Q3 will ship at one month intervals on October 1st and November 1st respectively thus ending this long 6 year fabrication.

V. SHMS Dipole Warm Field Mapping

Room temperature field mapping of the SHMS dipole coils occurred at Sigma Phi from April 21 to 26, 2016, before the magnet's cryostat was sealed and without the iron yoke. The magnet and mapping table were first fiducialized using a laser tracker system. A three axis Hall probe was employed to measure the field at currents of 50A and 25A. The range of measurements consisted of radial field maps of 32 points on a circular radius of 250mm, taken at the center of the magnet, field homogeneity maps along the longitudinal axis from +/-700mm in 50mm increments, both taken at 50A and a series of integral field measurement from +/-2000mm at 25A. The integral field maps were done at 25A to minimize heating of the coils due to the large number of data points and time required to complete the mapping.

A three axis hall probe, Bell BH703:SDH3, with a range of +/-0 0.1T was used to measure the field. Each axis probe was cross calibrated to an NMR probe and a fitted curved obtained. The stability of the probes and the power supply unit (PSU) were measured over 1000 measurements at 50A and 25A. The PSU's stability was of the order of 10ppm and the hall probe, for the field component Bx, was 0.2% at 4.7mT.

The reproducibility of the system was checked at 50A over the longitudinal range of +/-700mm. The time between mapping passes was 15min. Excellent reproducibility was obtained with variance less than 0.06% between the set of measurements.

A. SHMS DIPOLE TOSCA COIL MODEL

The measured data was compared to a Tosca model of just the coils with no iron yoke. The Tosca coil model consisted of 37 individual constant parameter coils excited to 50A or 25A. The 37 coils was an attempt to represent the division of the actual wound coils where keys and spacers were employed. No meshing was employed and the fields were obtained by using Biot-Savart integration in the post processor. The coil geometry was closely matched to the as-built coil. Using Tosca's constant perimeter coil generator at large diameters and thickness does not allow for a good match of the coil azimuthal surfaces. The coils, as modeled, did not lay flat against the keys and mid plane but had a slight tilt to them.

B. WARM FIELD MEASUREMENTS

Field homogeneity along a segment of the length of the magnet as compared to the central field was better than 1% for the vertical points (midplane between the two coils) and less than 1.5% for the horizontal points (poles of the magnet). This length was chosen as not too include the field fall off due to the ends of the coil. The central field component, Bx, as a function of angle and compared to the Tosca model is shown in Fig 6. The measured average Bx component was 47.52mT and the agreement with the modeled coil geometry is better than 0.9%. The average of the measured By and Bz components were 0.32 and -0.98 mT respectively. The integral field strength was obtained by measuring along the center of the magnet from +/-2000mm at 25A. The Effective Field Length (EFL) was calculated by dividing the integral field strength by the central field. The measured EFL was 2817.4mm and the model predicted an EFL of 2824.2mm, an agreement of 0.5%. The warm field measurements are evidence to a quality constructed magnet that will meet the magnet field quality specification for JLAB.

Fig. 3. Warm coil field mapping of the SHMS Dipole at Sigma Phi.

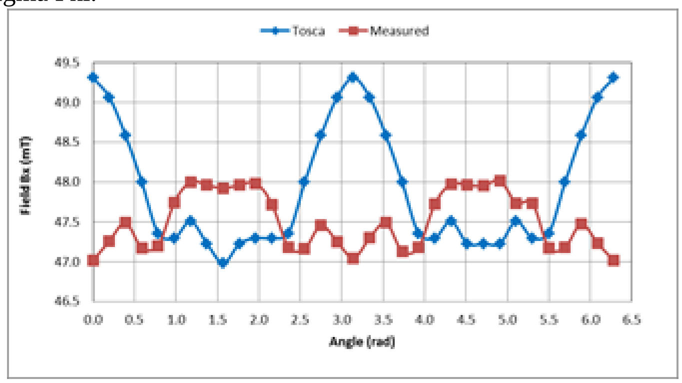

Fig. 4. Field Bx as a function of angle, measured at the center of the magnetic I=50A.

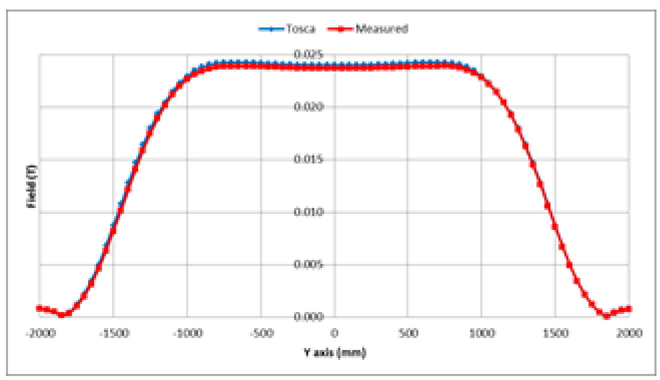

Fig. 5. Field Bx as function of longitudinal axis location, I=25A..

VI. CONCLUSION

The long design and fabrication of the SHMS Q2, Q3 and Dipole magnets is drawing to a close after 6 long years and the authors are looking forward to the installation, cold testing and commissioning of these unique superconducting magnets.

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