Superconducting Magnet Performance for the LCLS-II Project

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Abstract—The new LCLS-II Superconducting Linear Accelerator Cryomodules are under construction at Fermilab. Installed inside each Super Conducting Radio Frequency (SCRF) Cryomodule is a superconducting magnet package to focus and steer an electron beam. The iron-dominated magnet package has conductively cooled racetrack-type coils with both quadrupole and dipole windings. For ease of installation, the magnet is splittable in the vertical plane. To confirm magnet specifications, we performed a quality acceptance in a liquid helium bath for quench testing, and we performed high-precision magnetic field measurements. The magnetic and mechanical center alignment was investigated using the vibrating wire technique. Several prototypes and all production units have been tested. This paper summarizes the magnetic measurements and quench test results of all tested units, including comparison of performance and repeatability between different units.

Index Terms—Accelerator magnets, electromagnetic measurements, linear accelerators, superconducting magnets.

I. INTRODUCTION

THE SLAC Linac Coherent Light Source (LSLS-II) [1] is under construction, using Super Conducting Radio Frequency (SCRF) cryomodules for the Main Linear Accelerator. Cryomodule production takes place at both JLAB and FNAL. A cryomodule has eight SCRF cavities, and one superconducting magnet package: combined quadrupole (QUAD) with two dipole correctors, one in the horizontal, one in the vertical plane (HCOR, VCOR). The magnet design, fabrication, and prototype tests are described in [2]–[9]; test results of magnet package performance inside some Cryomodules are described in [10]. All magnet packages underwent rigorous tests, summarizes in this paper.

II. MAGNET PACKAGE

Fig. 1 shows the superconducting magnet package installed inside the Cryomodule. Each magnet is iron dominated, whereas the magnetic field is formed by four iron poles. Splittable in the vertical plane, the magnet can be clamped around the beamline, thus being decoupled from SCRF cavity assembly in a clean room. Clamped to the 2 K liquid helium supply line, pure aluminum heat sinks conductively cool the magnet. Each magnet half has three current leads for the QUAD, HCOR and VCOR; the current leads are conductively cooled with three thermal intercepts clamped to the 2 K, 5 K and 50 K helium supply lines. Before installation in a Cryomodule, all magnet packages underwent rigorous tests, performed to verify quality, quench performance, and magnetic field strength and field homogeneity in liquid helium. The field quality was measured with rotating coil method and coupling between the quadrupole and dipoles was also studied. The magnet and current leads conduction cooling and magnetic performance was verified during pre-production prototype tests [8], [9]. Prototypes 03 and 04 as well as magnets 101–136 produced by vendor Milhouse [11] were certified for use in the cryomodules. Table I summarizes the magnet package parameters. The magnet package is instrumented with thermal sensors and voltage taps. Thermal sensors monitor the magnet and current leads temperatures during cool down and operation. The magnet package is powered by three bipolar KEPCO power supplies (max. ±20 A, ±5 V). A SLAC developed quench protection system monitors the voltage taps. It triggers at a rise above 0.5 V, disconnecting the corresponding power supply and discharging the magnet through an external dump resistor. Four coil heaters are provided but unused, they could be used to heat coils above a critical temperature to clear the superconductor persistent currents.
TABLE I
LCLS-II MAGNET PACKAGE PARAMETER

| Parameter                              | Units | Value |
|----------------------------------------|-------|-------|
| Integrated peak gradient at 10 GeV    | T     | 2.0   |
| Integrated peak gradient at 0.4 GeV   | T     | 0.05  |
| Clear bore aperture                   | mm    | ≥78   |
| Ferromagnetic pole tip bore diameter  | mm    | 90    |
| Effective length                      | mm    | 230   |
| Peak quadrupole gradient              | T/m   | 8.67  |
| Quadrupole field harmonics at 10 mm radius | % | ≤1.0 |
| Quadrupole magnet inductance (DC)     | H     | 0.66  |
| Number of superconducting coil packages|       | 4     |
| Number of superconducting sections in the coil package | | 3 |
| Number of turns in the quadrupole section | | 426 |
| Number of turns in vertical/horizontal dipole sections | | 39 |
| Peak superconductor current           | A     | ≤20   |
| NbTi superconductor diameter          | mm    | 0.5   |
| Superconductor filament size          | μm    | 3.7   |
| Dipole corrector integrated strength  | T-m   | 0.005 |
| Max magnetic center offset in cryomodule| mm | ≤0.5 |
| Magnet physical length                | mm    | 340   |
| Magnet width/height                   | mm    | 322/220|
| Quantity required                     |       | 35    |

Fig. 2. Overview (left) of SPQA03 attached to the header and close-up (right) of the SPQA105 magnet package for installation in the stand 3 Dewar for cold testing in 4.5 K liquid helium bath.

III. MAGNET ACCEPTANCE TESTS

Two pre-production magnet packages and 36 vendor-produced packages will be used for the LCLS-II cryomodules. All magnet packages were cold tested at FNAL Test Stand 3 in a helium bath at 4.5 K. The test campaign went from July 2016 to September 2018. Fig. 2 shows an overview of the installed magnet package and top plate assembly, ready to be installed in the helium Dewar. Two available top plate assemblies allowed to test one package, while test preparation for the next package was underway. A 30 mm warm bore tube is mounted through and centered in the magnet aperture for magnetic measurements. The right of Fig. 2 shows a close-up of SPQA105. Warm electrical checks (e.g., resistance, inductance, polarity, hipot) of the magnet package, the assembly and instrumentation were performed prior to cool down, repeated when cold and before shipment of the package for installation into a cryomodule. The quench performance was tested individually for the quadrupole, vertical dipole and then the horizontal dipole. Each magnet was ramped at 0.5 A/s to 20 A, with no quenches (prototypes test went up to ~100 A quench current for ILC model magnets in LHe bath). All three circuits were then powered simultaneously at 20 A for several minutes with no quench, before ramping down to zero current. High current magnetic measurements were then completed, again with no quenches for all fabricated magnets.

A. Magnetic Center

The magnet package gets mounted into the cryomodule via four precision machined brackets, adjustment is possible to center the magnet axis with the axis of the beam pipe. The vibrating wire technique [12] was used to compare the electric and geometric center. The used motion stage hardware is based on the Magnet Test Facilities stretch wire system described in [13], with upgraded components. The magnet and baseplate were leveled using the Taylor Hobson M112-4515 Talyvel 6 Single electronic level. The original Newport linear stages (arranged in XZ pairs with <50 μrad orthogonality are powered by VEXTA PK260-02B - Stepper Motors with D6CL-6.3F Clean Dampers to reduce vibrations and HEIDENHAIN LIP 57 incremental linear encoders) are used for feedback via a 5-axis Aerotech Ensemble Epaq stand-alone controller. The magnet is powered via a KEPCO power supply (max. ±1 A, ±200 V), driven with a 0.1 Hz square wave generated by a frequency generator (HP33120A), the current is crosschecked via a shunt monitored with an Agilent Digital Multimeter 34401 A. The magnet polarity thus switching between positive and negative currents allows rejection of any stray fields in the center determination. A custom National Instruments (NI) LabVIEW interface allows automated movement of the stages. The wire is excited using a PXI-5402 14-Bit, 20 MHz waveform generator driving a KEPCO power supply (max. ±12 A, ±40 V). The vibrating wire frequency is measured by a 2D micrometer, composed of two Keyence LS-9006 1D optical Micrometer mounted at an angle of 90° degrees, read out via the Keyence LS-9501 optical micrometer controller. The analog output of the LS-9501 is sent to a NI PXI-4472B 102.4 kS/s, 0.5 Hz AC/DC-Coupled, 8-Input PXI Sound and Vibration Module. The NI PXI-5402 and NI PXI 4472B are housed in a NI PXI-1033 chassis, controlled via the same LabVIEW interface mentioned before. An FFT analysis of the signal allows to identify the peak amplitude of the wire vibrating at fixed resonant frequency; an offset from the magnet quadrupole axis is visible by a square pattern (because of the reversing magnet current) of the maximum peak, which gets minimized to find the center. The mechanical and magnetic axis were measured for each magnet. Studies with the prototypes established a torque specification of 67.79 Nm to combine the halves consistently. For the production run, both centers were found to be within agreement of 0.254 mm, fulfilling specification. Indicated in Fig. 3 are three planes along which the measured mechanical offset versus the beam line fit. Adjustable mounting brackets allow optimize the positioning of the magnet axis to the beam line.
B. Magnetic Measurements

The magnet package magnetic measurements were performed via rotational coil method. The rotational coil system utilizes a printed circuit board (PCB) design [14] and provides a measurement accuracy of $\sim 1$ unit ($10^{-4}$). The probe rotates in a warm bore tube (anti-cryostat) placed within the magnet aperture as the assembly is suspended in the helium Dewar. The probe radius is limited by the $\sim 30$ mm inner diameter of the warm bore. The PCB is 1 m long and extends out on both ends of the magnet. Due to the magnet package mounting, the probe is not centered in the magnet; it only extends out the far end by about 100 mm ($\sim 200$ mm short of capturing the full end field). The board is a spare from a previous project [15]. All harmonics are reported here at a reference radius of 10 mm. After some initial tuning of the setup with the prototypes, the same test setup and procedure was used for the remainder of the measurement campaign. During the campaign, the probe and drive system required repairs including replacement of the probe bearings, and stepper motor encoder and gear box replacement. These changes did not affect the measurement performance. The field quality is one of the most critical magnet specifications; quadrupole, and dipole corrector field reproducibility must be in the range of $\pm 1\%$. Most of uncertainty in the magnet strength is caused by the iron core hysteresis effects which substantially increase at low field levels. To reduce these effects, degaussing and standardization procedures were used. For degaussing the following current drive formula was used: $I = k e^{-t/t} \sin(t^2/m)$ (1). For $I_{\text{max}} = 20$ A at peak degaussing current we used the following parameters: peak current $k = 44$ A, current amplitude decay $\tau = 30$ s, cycle period $m = 380$ s. The bipolar degaussing current levels were approximated for more robust power supply regulation by the control system scripts, and so they have intervals of cosine and linear functions with predetermined dI/dt (see [9]).

C. Integral Strength Transfer Function

The integral strength Transfer Function (TF) was measured, using various current ramps as shown in Fig 5 and Fig. 6. Fig. 7 shows the summary for the TF for all full hysteresis cycles, the reproducibility among magnets is better than 0.5%, and exceeds the 1% specification. The integrated magnetic field quality was also investigated. Fig. 8 shows the quadrupole field harmonics at different currents in the range of 0.2 A – 20 A, averaged over the all SPQA magnets. Except for the b6, most field harmonics are less than 1 unit (1 unit = $10^{-4}$) at 10 mm reference radius. For an individual measurement, the harmonics were usually well within 5 units or less than 1% at 10 mm, fulfilling the design specification (Table I).

D. Quad and Dipole Measurements

For different combinations of the horizontal and vertical dipole corrector currents we investigated the quadrupole
Fig. 7. (a) Transfer Function of the SPQA magnet series. (b) Zoom of the Transfer Function of the SPQA magnet series, the mean of all measurements is added and the 1% allowed from specification is highlighted via error bars for the rising leg of the hysteresis cycle.

Fig. 8. Quadrupole normal integrated field harmonics for the SPQA series.

Fig. 9. Quadrupole and dipole current variations.

We show the results for SPQA136 only, as all magnets are very similar. The plots show the change in the TF for the ramp of QUAD and HCOR in Fig 10(a). Fig. 10(b) and (c) show the relevant displacement of the center in dy and dx, respectively, having their slope removed after a linear fit, the fit parameter is given in the legend. The linear slopes for the magnet series agreed within 3%. To explain the shape of the TF during the ramp, we simulated the 2D and 3D magnetic fields for the quadrupole and dipole with both currents. The analysis at 1 A current and reference radius \( R = 10 \text{ mm} \) gave the main field absolute harmonics at 1 A current as 

\[ B_1 = -1.171 \times 10^{-3} \text{T} \quad (\text{Dipole}), \]
\[ B_2 = -3.505 \times 10^{-3} \text{T/m} \quad (\text{Quadrupole}), \]
\[ B_3 = -5.644 \times 10^{-3} \text{T/m}^2 \quad (\text{Sextupole}). \]

Solving the equation 

\[ F(x) = B_1 \cdot \frac{I_d}{I} + B_2 \cdot \frac{x}{R} + B_3 \cdot \frac{x}{R}^2 = 0 \]

(2), with \( I_d \) as dipole and \( I_q \) as quadrupole current, gives the magnetic center shifts \( X_o \) for different currents. One can see that the quadrupole field gradient coupling with the magnetic center shift of Fig. 10(a) is caused by the sextupole feed-down. This parabolic TF dependence has an approximate ideal fitting by the function:

\[ Y(x) = -0.471 \cdot \left( \frac{x}{R} \right)^2 \% \]

(3) consistent with Fig. 10(a). Magnetic measurements showed that vertical and horizontal dipole fields are fully decoupled. It should be noted, because the fitting coefficient was received from magnetic field simulations, and provides independently the good fitting of measurement data, this formula could be distributed for all production magnets.

E. Accelerator Operation Cycles and Repeatability

Accelerator operation cycles and repeatability of magnet strength in various current setting scenarios were investigated in further measurements. One driving question was the effect of persistent currents in the superconductor due to degaussing on the field quality. Various studies with magnet warmup above the critical temperature of the superconductor and various degaussing scenarios (QUAD only, all magnets, HCOR or VOR only) for SPQA113 were done to evaluate the optimal degaussing scenario in operation with ramps of all three magnets. After these, however, independent of the magnet history, the spread of the TF stays within a 1% variance around the center value. No changes
Fig. 10. (a) TF for the ramp of QUAD and HCOR. (b) Displacement of the center in the Y-axis for the QUAD and HCOR ramp. (c) Displacement of the center in the X-axis for the QUAD and VCOR ramp. Note that in the plots (b) and (c) the linear component of center offset generated by the dipoles has been removed to show the non-linear portion: the slope value is included in the legend.

on the dipole displacement $dx$ and $dy$ could be observed during these tests – an important result for operation of the cryomodule. A set of dedicated QUAD current variations was performed to study the spread of the transfer function during accelerator operation. As example, Fig. 11(a) shows the current profile of the 15% variation around a set current of 6 A, in one case the current went from point to point, in the other case it was set to zero in between steps. In Fig. 11(b) and (c) the comparison with the regular hysteresis cycle and the two profiles is seen: the point-to-point being labeled CA measurement 2 and the runs reset to zero by CA measurement 3. If the current is varied over the course of the measurement, a spread of about 0.5% can be observed. By resetting the current between the steps, the spread reduces to 0.2%. Many other measurements, including simultaneous ramp of HCOR and VCOR, were made to estimate performance and are available in the LCLS-II document database.

IV. CONCLUSION

The splittable conduction cooled magnet packages of the SPQA series were thoroughly tested and showed good performance. The magnet package combines a quadrupole with orthogonal dipole correctors. During cold tests the field quality and reproducibility were within acceptance criteria, the field geometric harmonics were low and meet the specification and each magnet was successfully excited to 20 A without quench...
Both pre-production prototypes and the 36 vendor-produced SPQA magnets had comparable measurements and consistent results. During the measurement campaign, the new designed LCLS-II quench protection worked in conjunction with the one of Test Stand 3, leading to improvements to the LCLS-II quench protection as well as to the powering system. The test campaign identified two magnets with small need of rework, one had mismatched labels for the power leads, the other a loose cooling shield for the coils. The test results were used to formulate the magnet operation procedures in the accelerator to obtain reproducible magnet strength vs. current variations for quadrupole and dipole magnets. This successfully completed test campaign validated the magnet design and fabrication of the SPQA magnet series.

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