FABRICATION AND MEASUREMENT OF 12 GeV PROTOTYPE QUADRUPOLES AT THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY*

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Abstract

Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) currently has maximum beam energy of 6 GeV. The 12 GeV Upgrade Project will double the existing energy and is currently scheduled for completion in 2014. This doubling of energy requires modifications to the beam transport system which includes the addition of several new magnet designs and modifications to many existing designs. Prototyping efforts have been concluded for two different designs of quadrupole magnets required for the upgrade. The design, fabrication and measurement will be discussed.

INTRODUCTION

Two new quadrupole designs were required for the Jefferson Lab 12 GeV upgrade. The new designs were based on existing CEBAF quadrupole designs that are currently in operation. The designs allowed both magnets to fit within space constraints of beam line components and mount onto existing girders, thus eliminating the need to modify or design new girder parts and assemblies. The pole tip designs on these magnets were scaled from the existing CEBAF QA quadrupole design. Pole root saturation and harmonic effects were studied and optimized using Vector Fields OPERA-2d simulation software. Table 1, shows a list of some salient parameters for the two magnets [1].

QUADRUPOLE FABRICATION

Core Fabrication

Quadrupole cores were fabricated from 1/16 inch, 1008 steel laminations. The laminations were stacked in a stacking fixture, and welded to two steel strong backs along the top of the laminations. To prevent 'fanning' at the pole tip, the laminations were held together at the pole using 3/8 inch all-thread and nuts.

Preliminary vendor estimates for a quantity of 50 QR quadrupoles, showed laminated QR magnets to be 7% more cost effective, on a per magnet basis, than the same magnet as a solid core. This quote confirmed a general rule of thumb used when building magnets, that solid core magnets are only cheaper when building less than about 4 magnets [2]. In general, when building more than 4 magnets, the added expense of stamping tooling to produce laminations, on a per magnet basis, is cheaper than the operating cost for precision machine operations required to produce an equivalent solid core magnet.

Table 1: 12 GeV Quadrupole Parameters

Parameter	QP	QR
Design Current (amps)	19	19
Design Voltage (V)	38	62
Resistance (ohms)	2	3.3
Turn Count / AWG	208 / 9	243 / 10
B'L Requirement (kG)	81.7	191.4
Measured B'L (kG)	84.3	193
Length (in/cm)	12/30.5	14/35.6
Width (in/cm)	12/30.5	12/30.5
Bore (in/cm)	1.5/3.81	1.13/2.85
Current Density (amps/mm^2)	2.07	2.5
Coil Surface dT (C)	45	49

Laminations were manufactured using a compound die and included a pre-blank stamping to more accurately control dimensions. The stamped laminations adequately met JLab requirements and were stacked into magnet cores by the JLab Machine Shop. Enough laminations were ordered to build six quadrants for each magnet design.

An existing horizontal stacking fixture left over from the original CEBAF quadrupole build was refurbished and used to stack the 12 inch QP magnet. A new stacking fixture was manufactured to stack the longer, 14 inch QR magnet. Both fixtures performed well in creating precision core stacks suitable for use in the magnet assembly.

Coil Fabrication

The QP quadrupole was designed to use the same coils as the CEBAF QC quadrupole. The QP prototype used spare QC coils that were already available in the inventory, therefore it required no new coils to be manufactured for the assembly. The coil design for the QR quadrupole however, was an entirely new design, utilizing inner and outer cooling plates, which required manufacturing. Initial attempts to attach the cooling plates to the coil body lead to ground shorts on several of the coils. The coils were repaired and the assembly

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tooling was improved to more effectively fit the cooling plates to the coil, eliminating the shorting problems. Six QR coils were manufactured by the JLab Machine Shop. Of those six coils, one coil had an incorrect turn count and was scrapped. The remaining coils were hipot tested to 1500V, turn count verified and used on the magnet with one coil as a spare.

QUADRUPOLE MEASUREMENT

Mechanical Measurement

First article laminations, and several production laminations, were dimensionally inspected on the CMM machine. The pole profile and several points on the mating surfaces were measured and output into a 'dxf' file. The file was imported into a CAD system (IDEAS), and compared to the model of the actual part. After assessing the deviation of the inspection points relative to the modeled part, it was determined that the laminations were sufficiently acceptable for use in building the prototype quadrants.

Once the quadrants were assembled into magnets, CMM measurements were conducted on the QP and QR prototypes to measure the deviation in pitch, roll and length of the four quadrants. Improper alignment of the poles/quadrants introduces random multipole errors, also referred to as assembly errors, which can lead to unacceptable magnet performance. A CEBAF QA magnet (QA238) was also measured in the same way to get a relative perspective on the difference in assembly errors between the two epochs of magnets. The gaps between the poles were also measured using precision gauge pins. The four gap dimensions (A thru D), shown in Figure 1, are listed in Table 2, along with a summary of the CMM measurements. Harmonic measurement results, discussed later, confirmed that the assembly errors were not sufficient to adversely affect the harmonic performance of either of the 12 GeV quadrupole prototypes.

Thermal Measurements

Thermal measurements were conducted on each of the 12 GeV prototype quadrupoles to determine the maximum operating temperature of the coils and other thermal parameters. Resistance Temperature Detectors (RTDs) were attached to the prototypes on the Low Conductivity Water (LCW) supply line, LCW return line, core steel and several coils. All magnets were run at a variety of currents up to 20 amps, dwelling at the set current for several hours to reach thermal equilibrium. The LCW flow through the magnets was controlled using a sight glass flow meter and data was taken at flow rates of 0.3 gpm, the expected operational flow rate, and 0.15 gpm, a worst case operating condition. The results of the 0.3 gpm measurements are shown in Tables 3 and 4, for the QP and QR prototypes respectively. The data for the 0.15 gpm measurements is not discussed here, as there were no significant differences in temperatures on the coil or steel core, between 0.3 and 0.15 gpm flow rates.

The location of the maximum temperature, for both magnets, was found on the coils. Coil temperatures reached 80 C for the QR and 77 C for the QP at a flow rate of 0.3 gpm. The insulation and epoxy temperature rating used in manufacturing the prototype coils was 200 C, well above the temperatures experienced for flow rates as low as 0.15 gpm. Similar insulation and epoxy temperature specifications will apply to the 12 GeV production quadrupole coils as well.

Table 2: Gauge Pin and CMM Result Summary

	QR Prototype	QP Prototype	CEBAF QA Quadrupole
Quadrant Pitch (degrees)	0.009	0.018	0.032
Quadrant Roll (degrees)	0.021	0.007	0.041
Pole Length Difference (in/cm)	0.012 / 0.005	0.015 / 0.006	0.004 / 0.002
Gap A (in/cm)	0.391 / 0.154	0.523 / 0.206	0.388 / 0.153
Gap B (in/cm)	0.389 / 0.153	0.518 / 0.204	0.389 / 0.153
Gap C (in/cm)	0.391 / 0.154	0.523 / 0.206	0.388 / 0.153
Gap D (in/cm)	0.389 / 0.153	0.519 / 0.204	0.389 / 0.153

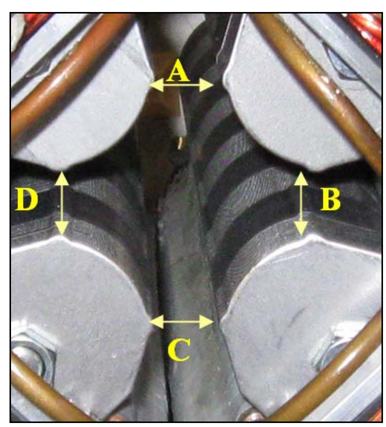

Figure 1: Gap legend.

Table 3: QP Temperature Data at Equilibrium – 0.3 gpm

Current (amps)	Voltage (V)	Avg. Coil Temp. (C)	Max. Coil Temp. (C)	Avg. Coil dT (C)	Steel Temp. (C)	Steel dT (C)	LCW dT (C)
0	0	29	29	0	28	0	-1
17	33	61	63	32	46	17	4
18	36	65	67	36	48	19	4
19	38	69	72	40	49	21	5
20	41	74	77	45	52	23	5

Based on the results of the thermal testing, a simulation was conducted to estimate the maximum temperatures inside the coil pack where measurements could not be made. Simulation and hand calculation showed an approximate 5 C gradient from inside coil pack to the outside surface of the coil pack, still leaving temperatures well below the 200 C rating of the epoxy.

Table 4: QR Temperature Data at Equilibrium – 0.3 gpm

Current (amps)	Voltage (V)	Avg. Coil Temp. (C)	Max. Coil Temp. (C)	Avg. Coil dT (C)	Steel Temp. (C)	Steel dT (C)	LCW dT (C)
0	0	31	31	0	30	0	-1
17	57	64	65	34	42	12	9
18	58	69	70	39	44	14	10
19	63	74	75	43	45	16	11
20	67	79	80	49	48	18	13

Cool down data was taken on the QR prototype to determine the time required for the hot surfaces of the magnet to cool below 50 C once power was removed from the magnet. Considering a 0.15 gpm, worst case scenario, flow rate, it took the coils ~25 minutes to drop in temperature from 88 C to 50 C from a 20 amp equilibrium condition. The steel core took ~35 minutes to drop in temperature from 55 C to 50 C. This information can be used in the evaluation, development and implementation of administrative and engineering safety controls that will be implemented to protect personnel from hot surfaces when working around the magnets immediately following accelerator shutdowns.

Magnetic Measurements

Initial measurements of the harmonic spectrums on both of the 12 GeV prototypes appeared promising even prior to chamfering. A series of three, 1/16 inch, 45 degree chamfers were machined on each of the quadrupoles beginning with the QR to investigate how the chamfering would reduce the dodecapole content (n = 6) in the harmonic spectrum. Figures 2 and 3, show the harmonic spectrum for the QR and QP prototypes over the entire chamfering range. As the chamfers were increased on each prototype, the dodecapole content systematically decreased and contributed to an improvement in the harmonic performance of each magnet, though some error terms, such as the octupole (n = 4) term for the QR and sextupole (n = 3) term for the QP, systematically increased with each chamfer. This is likely due to some systematic misalignment during the machining process. Ultimately, a final production chamfer of 3/16 inches for the QP and 1/8 inches for the QR has been implemented based on the chamfering results shown in Figure 2 and 3.

Strength measurements, shown in Table 5, confirm that the prototype quadrupoles meet the engineering design requirements for the QP and QR of 81.7 kG and 191.4 kG respectively at 19 amps. From the strength measurements, the saturation effects for both prototypes was characterized and also shown in Table 5. At 19 amps the prototypes experience 4.5% and 8.5% saturation for the QP and QR respectively.

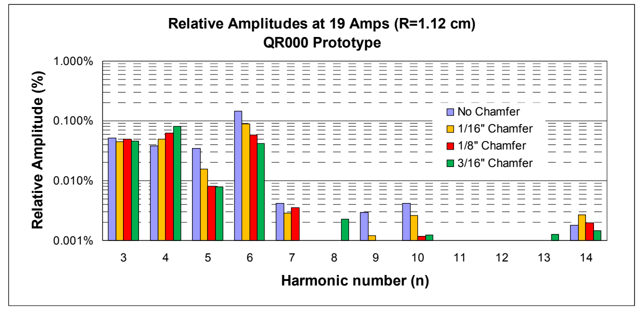

Figure 2: QR chamfer harmonic spectrum at 19 amps.

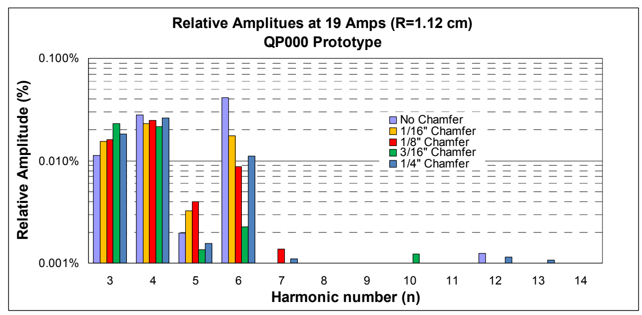

Figure 3: QP chamfer harmonic spectrum at 19 amps.

Table 5: Gradient and Saturation Effects on the 12 GeV Prototypes

Current	QP Gradient / Saturation	QR Gradient / Saturation
(amps)	(G) / (%)	(G) / (%)
18.94	84,293 / 4.5%	193,071 / 8.6%
14.94	68,853 / 1.3%	163,500 / 2.2%
9.95	46,583 / 0.4%	111,380 / 0.62%
4.98	23,872 / 0.0%	57,104 / 0.0%
0.01	960 / 0.0%	2,190 / 0.0%

CONCLUSIONS

The 12 GeV quadrupole prototyping effort has confirmed that the QR and QP prototype quadrupoles meet the design requirements of the project. Both magnets have been thoroughly tested mechanically and magnetically and the results of the measurements used to make final design modifications that will be incorporated in the production quadrupole procurement.

REFERENCES

[1] M. Wiseman *et al.*, "12 GeV Accelerator Upgrade, 2007 Quadrupole Magnet Design Summary", JLab TN 07-025.

[2] J. Tenabe, Iron Dominated Electromagnets Design, Fabrication, Assembly and Measurements, January 26, 2005.