MAKING DIPOLES TO SPECTROMETER QUALITY USING ADJUSTMENTS DURING MEASUREMENT*

G. Biallas#, D. Bullard, D. Douglas, A. Guerra, L. Harwood, T. Hiatt, J. Karn, T. Menefee, K. Sullivan, K. Tremblay, R. Wolfley, JLab, Newport News, VA and V. Christina, T. Schultheiss, F. Tepes, Advanced Energy Systems Inc., Medford, NY

Abstract

Twenty-seven window frame dipole magnets requiring spectrometer-like fields were made for the IR-FEL at the Thomas Jefferson National Accelerator Facility. These magnets incorporate Purcell gaps, mu metal pole faces and adjustable field clamps. After outlining their specifications, this paper describes the processes used in magnet manufacturing, the program of magnetic mapping used, as well as the adjustments made to meet tight optics-driven requirements. Described are the measurements made to quantify fringe fields, verify field homogeneity, map core and integrated field as a function of current, and characterize the horizontal and vertical focusing terms designed into the dipoles. Also described are the techniques that were successfully used to tune individual magnets to meet the tight tolerancing of all these parameters.

1 INTRODUCTION

Twenty-seven dipoles in six families were required for the injection, extraction and recirculation beam paths (Table 1) of the 1 kW IR Demonstration Free-Electron Laser at the Thomas Jefferson National Accelerator Facility (Jefferson Lab). The FEL [1] achieves higher efficiency by recycling the spent electron beam's energy. The injector for the accelerator produces a 10 MeV, 5 mA CW electron beam. The injected beam is accelerated to 42 MeV using a single CEBAF-style cryomodule. A wiggler and optical cavity produce light in the 3 to 6.6 μm range. A set of transport arcs recirculate the beam exiting the wiggler back through the cryomodule for energy recovery.

Table 1: Dipole Family Characteristics

Family and Use	Qty.	Effective Length	Core Field
		m	kG
DU - Injection/ Extraction	7	0.21	0.45 - 0.67
DV - Injection/ Extraction	2	0.43	0.45 - 0.67
DW - Optical Chicane	8	0.41	1.04 - 2.48
DX - Recirculation Jog	4	0.51	1.10 - 2.64
DQ- Recirculation Reverse Jog	4	0.51	1.10 - 2.64
DY- Recirculation Pi (180°) Bend	2	3.14	1.10 - 2.64

*Work supported by the U.S. DOE under Contract #DE-AC05-84ER40150

Email: biallas@jlab.org

All magnets met their tight specifications only after being extensively measured, adjusted and re-measured at the Magnet Measurement Facility at Jefferson Lab. The recirculation magnets were designed for use up to 79 MeV, and were characterized between their 37 and 79 MeV operating currents. Table 1 lists family characteristics.

2 SPECIFICATIONS

Specifications for the dipoles derived from a beam performance driven error budget [2]. This error budget evolved to ensure that stringent beam handling requirements would be met during commissioning and operation of the FEL, which demands both production of a properly configured phase space at the wiggler and the management and energy recovery of a very low energy (40 MeV), high current (5 mA CW) electron beam.

The transport system relies on the dipoles to both bend and focus the beam. Consequently, both field integral and absolute field magnitude must fall within specified tolerances. Stringent requirements on beam performance also demand that an accurate representation of all dipole focusing effects be included in the machine description. Dipole end field roll-off (K_1) profiles must therefore be known and included in machine modeling [3].

These constraints must be fulfilled to high precision at relatively low field (~1 kG), a limitation imposed by the low electron beam energy and a design philosophy that attempted to avoid excessively strong bending and focusing (with attendant sensitivities to chromatic effects and field inhomogeneities). The constraints must, in addition, hold over a relatively large working aperture to accommodate a high current beam that will, in some instances, exceed horizontal dimensions of 10 cm or more. The resulting specification suite is summarized in Table 2.

Table 2: Dipole Field Quality Specifications

Characteristic	Tolerance
Excitation - absolute core field error	$\Delta B/B < 10^{-3}$ (1 G at 1 kG)
Field quality - variation of core field and field integral over full working aperture	$\Delta B/B < 10^{-4}$ $\Delta BL/BL < 10^{-4}$ (0.1 G at 1 kG)
End-field roll-off integral K_1=0.27	±0.05 family to family, ±0.005 within family
Transverse aperture - focal length error tolerance	$\sigma_{\beta'\gamma} / \beta\rho < 6.25 \times 10^{-4}$/m

3 DESIGN

The lessons learned in the prototype effort [4] were included in the production designs. The Purcell gap [5] and mu metal pole tip were the greatest aid to transverse uniformity. Saddle coils and field clamps also contributed uniformity while reducing fringe fields and stabilizing the end field roll-off. Adjustability of field clamps along the beam axis provided first and second order adjustment of the field integral. The prototype effort also taught us to take extra care to evenly distribute conductors in the window frame gap to avoid nonuniformity.

Two prudent improvements were added. We widened the magnets to expand the expected zone of good field and we placed the coil terminations away from the yokes to avoid any unbalanced induction in the yokes [6].

Brass was chosen to form the Purcell (non-magnetic) gap because it is an acceptable match to the thermal expansion of iron and mu metal. Even with small differences in thermal expansion of bonded materials, a shear stress develops at the edges. We specified a 3 mm wide bullet shaped taper to all edges of the brass. Finite element analysis [7] showed this reduces peak shear stress in the bond at the edge from 7.5 MPa to 5.1 MPa with a 17 C temperature excursion.

We attached the Purcell gap and mu metal material to the pole tip with epoxy because this method attained simple and reliable placement of these materials against one another to the required accuracy. We selected an epoxy with average bond strength but low viscosity because it squeezed out of the bond area under 5 atmospheres of pressure to a predictable and reproducible minimum thickness of about 25 µm.

The most difficult specification to achieve was the field integral uniformity of $\Delta BL/BL < 10^{-4}$. This tolerance implies that the entire good field region of the 5 cm gap has a tolerance budget of 5 to 10 µm. In our designs many parts share this tolerance budget in series. The critical dimensions were (1) the height of the return leg pieces; (2) the flatness of the two pole faces and the thicknesses of (3) the two Purcell gap sheets, (4) the two mu metal sheets and (5) their four epoxy bonds.

4 MANUFACTURING

4.1 Material Considerations

To promote uniform high permeability, all dipole yoke parts were given a hydrogen anneal [8] before their final machining cut. We made the parts for the field clamps out of 1018, cold rolled steel because tests showed no performance difference. The cost advantage was that only sawing and drilling holes were necessary. The remaining surfaces were used as received.

4.2 Fabrication

These magnets required individual custom fabrication in order to achieve the tolerances required of the pole gaps. Uniformity of the height of the return legs at 1/10th the budget level was achieved by our contractors subcontracting the work to specialty grinding vendors while the pole slabs were machined flat within 1/2 the budget by the vendors themselves.

No supplier of brass or mu metal sheet would consider supplying those materials to the micron level tolerances we required. Instead, in cooperation with our vendors, we custom selected these parts from stock material. The brass sheet was uniform within 10 microns over the central 80% of a four foot wide sheet and consistent along its length. Jefferson Lab personnel inspected the mu metal at the vendor's supplier. The mu metal was found to be similarly uniform over 80% of its 3 foot wide sheet while it varied stepwise along its length. Consequently, we used material only out of these zones of high tolerance.

If all four sheets were randomly superposed, the thickness variation was beyond tolerance. Instead, we cut and oriented the pieces so that the deviations would cancel. For example, a piece of mu metal with a taper in thickness was paired opposite a piece with the reverse of the taper. For the magnet families that shared the same power supply, the gaps had to correlate at the 25 µm level. Since we knew the stackup of the actual thicknesses of the sheet materials, we revised the specification for the height of the return legs (which hadn't been final machined) so that the gaps of all the related magnets fell within their assigned tolerance.

4.3 Assembly

As one of the four successful bidders, (a single coil fabricator and three yoke manufacturers) Everson Electric received the fixed price contract to assemble the magnets on a "best effort" basis. Trial gluings of sheet materials to sample yoke slabs were funded as development items in the contract. These first trial gluings, using a press, gave Everson the confidence to proceed with most of the magnets. Additional trial gluings were necessary for the two Pi (180°) Bends because of their size and because the magnets had the complication of staggered seams in the sheet materials. In the Pi Bend's case, the 5 atmosphere pressure during gluing was achieved with its own bolts.

We specified taper pins as the mechanism to reestablish the relative position of the yoke pole pieces upon reassembly. However, if care was not taken during assembly, the weight of the slabs interfered with the taper pin's ability to jog the upper and lower pieces to their proper position. Instead, the soft annealed iron would "mushroom" under the high compressive pressure caused by the pin as it was being forced in. The mushroomed volume would distend into the joint with the return leg piece and consequently drive the height of the pole gap out of specification. We experienced this problem with magnets received from the assembly vendor and with magnets reassembled by in-house personnel. As a result, only trained personnel are allowed to reassemble these magnets. Hardened tooling pins and bushings installed in the yoke parts at the machining stage may be a cost effective solution for future designs.

5. MAGNET MEASUREMENT & ADJUSTMENT

5.1 Measurement Philosophy

Our philosophy was to measure, adjust and measure until the specifications were met. First we would run a suite of absolute magnetic measurements on the first article of each family. (The Pi Bends were treated somewhat differently [9].) Through a series of iterations, the field clamps were adjusted and magnetic measurements taken to set the effective length and verify uniformity of the integral gradient. With the positions of the clamps established for the first article, the field clamps of the family were adjusted to the identical positions and were given the suite of absolute measurements and the test for integral gradient uniformity. After passing these tests, each member of the family was measured against a member designated as the "standard" in very accurate, bucked probe coil configuration. This test gave relative field integral variation versus transverse position within the family.

5.2 Inspection

Magnets were inspected first, concentrating on the gap and the field clamp position and the centering of the coils in the yoke. (After many magnets were received and measurement started, we found that the saddle coils required better constraint and consistency along the Z axis.)

5.3 Absolute Measurements

All measurements started with 2 1/2 cycles to highest current and back to zero followed by bringing the current down from high current to the desired setting. This established the magnet at a reproducible point on its hysteresis loop. Using the Stepper Stand's (see below) Group 3 Hall Effect Probe and Metrolab NMR Tesla meter [4], we completely characterized the field in the aperture and fringe zones for the several levels of excitation of interest. This data revealed absolute core field plus absolute field integral to the 10^{-3} level (yielding effective length) as well as K_1 and core field transverse flatness.

Very adaptable for short runs, the Stepper Stand uses the probes mounted to an arm with a height adjustment for "y" on a cart that rolls on a granite surface plate. Readings are taken along lines as the cart is moved by hand to centimeter scale marks for "z" along a rail that is repositionable in "x". A PC-based data acquisition system records the probe values at each scale position.

5.2 Field Clamp Adjustments

The initially measured effective length was never the design value. Adjusting the Z position of the field clamps (to ±25 µm accuracy) corrected this error. At a later stage, by adjusting the yaw of the field clamps, we lowered the residual error in the gradient integral to the 10^{-4} level. (In retrospect, a micrometric adjustment for this feature would have been cost effective.) After acceptance, the field clamps were pinned in these adjusted positions. Note that K_1 was dependent on field clamp position but deviations were always in tolerance.

5.3 Integrating Coil Stand

The instrument that measures uniformity of the gradient integral and relative properties of the family members is the Integrating Coil Stand. It is an extension of the motion and resolver mechanisms of the device that measures CEBAF dipoles. It consists of two coil support sets, each with a stationary portion and a moving portion that is driven identically with the moving portion of the other set. Each support set is accurately mounted in the bore of one of the two magnets to be compared. The standard magnet uses the set with two 50 turn Litz wire coils. Unique to this set and mounted to its movable portion, a constant area coil measures integral gradient uniformity. A second coil changes area, with one coil segment mounted to the movable portion of the support while the remaining coil segment is mounted to the stationary portion. This coil is duplicated in the support set mounted in the second magnet. The signal from this pair of changing area coils is bucked as the moving portions of the supports trace out identical motions. The bucked signal resolves the field integral variation between the standard magnet and family members compared to it at the 10^{-5} level.

5.4 Additional Interventions

Three families required additional or further adjustment. The core field in the dipoles at the center of the injection/ extraction chicanes (DVs) was stronger than the core field in the matching wedge magnets (DUs). Soft iron shims added to the return legs of the DUs increased gap and lowered core field to provide the match. The DQ magnets didn't meet the transverse field integral gradient tolerance. A set of four pole tip windings, run at constant current, corrected the problem. A local field ripple in the second 180° dipole was caused by a combination of out-sized bullet nose tapers on the brass sheets at one joint and a coincident local thinning in the mu metal [9]

6 CONCLUSION

By a combination of exacting manufacturing, patient magnet measurement and adjustment by skilled technicians, twenty seven dipoles in six families met their spectrometer like field specifications. The quality journey by all involved is born out with the attainment of 3.8 mA recirculated beam achieving 710 W (5 mA & 1000 W goal) at an early stage of commissioning of the FEL [1].

7 REFERENCES

[1] Bohn, C. L. et al., "Performance of the Accelerator Driver of Jefferson Laboratory's Free-Electron Laser", Proc. 1999 IEEE Part. Acc. Conf., New York, (1999).
[2] D. Douglas, "Lattice Design for a High-Power Infrared FEL", Proc. 1997 IEEE Part. Acc. Conf., Vancouver, (1997).
[3] K. Brown "A 1st and 2nd Order Matrix Theory for the Design of Beam Transport Systems and Charged Particle Spectrometers", SLAC Report 75, (June 1982).
[4] J. Karn et al., "Magnetic Measurements of the Prototype Dipole for the IR-FEL at the TJNAF", Proc. 1997 IEEE Part. Acc. Conf., Vancouver, (1997).
[5] Suggested by L. Harwood.
[6] Our thanks to the management, engineers and designers of Advanced Energy Systems Group of Northrop Grumman Corp. for their help in designing these magnets.
[7] T. Schultheiss, Northrop Grumman Corp., private communication.
[8] 930 to 1000 C for 3.5 hrs. in H_2 or N2 w/5% H_2, cool at 27 C/hr. to 400 C.
[9] K. Tremblay et al., "Magnetic Measurement for the Pi Bend Dipole Magnets for the IR-FEL at TJNAF", Proc. 1999 IEEE Part. Acc. Conf., New York, (1999)