MAGNETIC MEASUREMENT OF THE 10 KW, IR FEL DIPOLE MAGNETS*

T. Hiatt†, K. Baggett, M. Beck, G. Biallas, D. Douglas, K. Sullivan and C. Tennant
Thomas Jefferson National Accelerator Facility, Newport News, Virginia

Abstract

Magnetic measurements have been performed on several families of dipoles for the 10 kW IR-FEL presently under construction at the Thomas Jefferson National Accelerator Facility. The requirements for these magnets include varying field strengths, large horizontal apertures and parts in 10,000 field homogeneity as well as setability of core and integrated field. Measurements were made to quantify the magnets according to these requirements and to determine the hysteresis protocol, ramp rate dependence, and field clamp settings that are used. This paper will describe the results of these measurements and the procedures used to accomplish them.

1 INTRODUCTION

A 10 kW infrared (IR) free electron laser (FEL) upgrade is under construction at the Thomas Jefferson National Accelerator Facility. The arc dipoles in this machine must handle beam momenta from 80 MeV/c to 210 MeV/c, while the injection and extraction dipoles must handle beam momenta from 8 MeV/c to 11 MeV/c. The dipoles were designed to meet several critical specifications to ensure maximum machine performance and setability. Some of the dipole design parameters are shown in Table 1. The nominal operating momentum for the GU and GV dipoles is 9.2 MeV/c and for the remaining dipoles the nominal is 145 MeV/c.

2 DESIGN REQUIREMENTS

The accelerator required a total of 22 bending dipoles comprising six different families, five of which are wedge shaped. This put constraints on the reproducibility of the magnets and on the accuracy of the core and integrated field. Each arc string, injection string or extraction string will be powered in series using a separate power supply. These strings link several families of dipoles. Both arc strings link the GY, GX and GQ dipoles. The first arc string also links the GW dipoles from the optical chicane region. The strings in the injection and extraction regions will power GV and GU dipoles. Out of tolerance core fields or field integrals could lead to undesirable steering and focusing effects. Excitation tolerances for the dipoles are listed in Table 2 [1].

Variable shunts across the GY, GW and GU magnets will be used to adjust core field strength to maximize magnet performance. The shunts will be able to operate up to a maximum current of 10 amps. The actual shunt values for each family by region are shown in Table 3.

Table 1. Dipole Design Parameters

Style	Momentum Range (MeV/c)	Core Field Range (kG)	Effective Length (cm)	Good Field Region (cm)
GU	8-11	0.445 - 0.612	43.43	7.62
GV	8-11	0.445-0.612	21.00	7.62
GX	80-210	2.22-5.84	91.75	10.16
GQ	80-210	2.22-5.84	89.48	25.4
GW	80-210	2.23-5.92	42.18	7.62
GY	80-210	2.67-7.11	314.16	20.32

Table 2. Dipole error tolerances (rms)

Parameter	Relative Error Tolerance
Core Field Accuracy#	0.1%
Transverse Field Integral and Core Field Flatness	0.01%
Field Integral Accuracy#	0.1%
Reproducibility	0.01%
#GY Relative Error Tolerance is 0.025%	

3 MAGNETIC MEASUREMENTS

The dipoles were required to qualify, by meeting the specifications in Table 2, at their nominal operating momentum. However additional effort was expended to qualify them over their entire range.

All FEL dipoles were measured using a Group 3, Hall effect probe on the magnet measurement Stepper Stand [2]. This stand was used to measure core and integrated field as well as transverse integral and core field flatness. A Stepper Stand measurement of the GX dipole is shown in Figure 1.

* This work supported by DOE Contract DE-AC05-84ER40150, the Office of Naval Research, Air Force Research Laboratory, the Commonwealth of Virginia and the Laser Processing Consortium
†hiatt@jlab.org

Table 3. Dipole Shunt Values

Region	Momentum (MeV/c)	Shunted Magnet	Shunt Value (%)
Injection	9.2	GU	6.95
Extraction	9.2	GU	7.84
1st Arc	145	GY	Not Available
Optical Chicane	145	GW	0.87
2nd Arc	145	GY	0.85

Figure 1. GX Dipole on Stepper Stand

The standard measurement procedure set the magnet's core field within 0.02% of the nominal design momentum after factoring out an estimated 0.20% vacuum chamber field contribution [3]. Transverse profiles were conducted to ensure that the core field was uniform across the required good field region of the magnet. Once field uniformity was confirmed, multiple straight through integral measurements were taken at different transverse locations across the magnet. These integral measurements were used to adjust the design field integral at the nominal centerline to match the design core field of the magnet by the use of adjustable field clamps [4]. The required field integral gradient was obtained by adjusting the field clamps angular position with respect to the pole ends. Once the magnets were satisfactorily qualified, the field clamps were pinned to the magnet core pieces to permanently secure their positions.

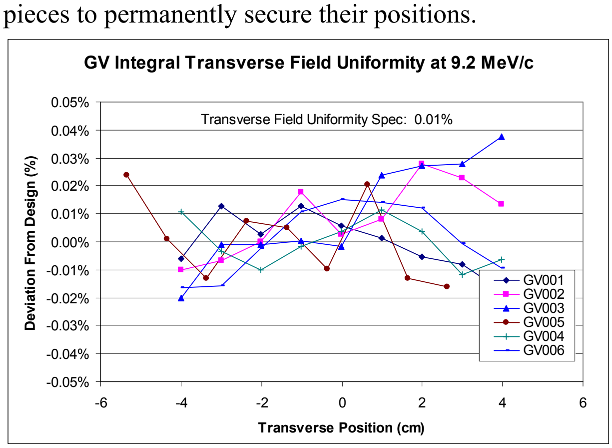

Figure 2. GV Integral Transverse Uniformity

3.1 Hysteresis and Ramp Rate Protocol

A current setting protocol was established to set the current for the main coils that started from a maximum current, specific to a given momentum and magnet family, standardizing the magnets residual field. A ramp rate of 5 amps/sec, +/- ~0.5 amp/sec was used to mimic the characteristic of the string power supplies. Magnets were run through one hysteresis loop using specific minimum and maximum current values for a given momentum, then set to the operating current from the maximum hysteresis current.

The exception to this procedure was the GV magnet, which used two power supplies for a given excitation. The trim coil for the GV dipoles was set to a ramp rate of ~1 amp/sec and operated on a bipolar 10 amp hysteresis loop.

3.2 The GV Injection/Extraction Dipole

The GV produced the least uniform field of the various families of dipoles. It has a wedge angle of 20º and is only 3.4 inches wide at its narrow end. In order to meet the dipole design specifications the magnet employed a trim coil that wrapped around the return legs of the magnet. When powered, the trim coil locally increased flux through the return legs to the point of saturation. This saturation effectively caused the field on one end of the dipole to excessively bulge resulting in a uniform transverse core field [5].

In order to meet the absolute field integral design requirements, these magnets were shifted transversely from the nominal centerline, taking advantage of the magnet's wedge shape to increase or decrease the field integral proportional to the transverse offset.

The GV proved to be the most labor intensive magnet to bring into specification due to the nature of its wedge shape and a combination of trim coil and field clamp adjustments. However, these adjustments allowed the magnet to be precisely tuned, and produced the nicest transverse integral uniformity, shown in Figure 2, of all the FEL upgrade dipoles.

3.3 The GU Injection/Extraction Dipole

Once the GU magnet was set to the appropriate core field, the integrated field was found to be 2% higher than the design. This difference was too large to correct using the adjustable field clamps, and the effect of the magnet's 2.9º wedge angle was not powerful enough to make shifting the magnet from the nominal center line plausible. To reduce the field integral the magnet pole face was shaved by 0.29 cm in order to reduce the integrated field so that it matched the core field. The integrated field was fine tuned by shifting the magnet from the nominal centerline, in the same manner as the GV dipoles.

3.4 The GW IR Chicane Dipole

The GW dipoles used in the IR optical chicane, were the least troublesome of the six families of dipoles, and was the only family that did not have a wedge shape.

Once the first magnet was qualified, the remaining magnets were identically set up and qualified with no exceptions, and were the first magnets installed in the accelerator.

These dipoles were measured on the translating coil stand as well as the Stepper Stand. Results between the two measurements have validated the ability of the Stepper Stand to confirm transverse field integral flatness. As a result only four GW magnets and one GQ magnet was measured on the translating coil stand.

3.5 The GX Bend Dipole

The 39.4º GX dipoles will be used to direct the electron beam to and from the ultra violet (UV) bypass. The switching will be engaged by physically changing the power lead configuration. UV operations will use half the coil package while IR operations will use the full coil package. Characterization in both configurations was made, but only the IR configuration will be discussed here.

Transverse core field measurements fell within specification, but a significant nonlinearity was found in the straight through integral measurements taken transversely across the magnet. An interesting characteristic about this magnet was that the electron beam is bent so extremely that straight through integral measurements sampled areas of field that the beam will not encounter. The good field region was specified normal to the beam orbit, not along a straight line about the nominal center line. For this reason straight line integrals could not be used to quantify the magnet's transverse field integral uniformity. Straight through integrals were used however, to quantify the field integral along the nominal centerline. To ensure the magnet met the design specification for all constraints, a grid of field readings was taken inside the magnet. These readings were compared to finite element models used to design the GX dipoles and were successfully qualified at 80 and 145 MeV/c [6].

3.6 The GQ Reverse Bend Dipole

Straight through field integrals for the 10.4º GQ reverse bend dipoles were significantly deficient across various excitations. To increase the integral of the GQ dipoles, a face shim system, 0.419 cm (0.165 in.) thick, was added to the magnet end faces to extend the poles adjacent to the magnet gap on the front and back of the top and bottom core plates. In order to meet the transverse field integral uniformity requirement, 0.478 cm (0.188 in.) thick shims were used to locally manipulate field in order to change the field integral to meet specification. These shims were bolted to the inside of each of the field clamps at the magnet centerline. The effect of these shim systems was only quantified at 80 and 145 MeV/c. The GQ was ultimately qualified using the same methods as the GX [7].

Further, this magnet is also used as a corrector dipole, designated GF. The GF was measured at 10 amps and found to produce a field integral of 1244 G-cm, which was consistent with the design field integral of 1000 G-cm.

4 CONCLUSIONS

To date all IR FEL arc dipoles have been measured except for the GY dipoles, though the first GY should be completed within days of this writing [8]. All dipoles have sufficiently passed their magnet measurement qualifications. Due to scheduling priorities the GV and GU magnets were qualified only at 9.2 MeV/c and the remaining arc dipoles were qualified only at 80 and 145 MeV/c. Integrated and core field measurements have suggested the necessary shunt settings to optimize each string's magnetic performance. If it is found that the magnets are not performing to a satisfactory level, or if extrapolation does not adequately predict magnet performance for arc dipole operations at 210 MeV/c, additional measurements will be performed.

5 REFERENCES

[1] D. Douglas and G. Biallas, "DC Field Quality Characterization of FEL Upgrade Dipoles", JLAB-TN-02-041, 24, September 2002. http://www.jlab.org/~douglas/FELupgrade/technote/JLABTN02041.pdf

[2] T. Hiatt, "Automated Stepper Stand Mechanical Calibration", Unpublished Report. 30, January 2001. http://www.jlab.org/MagTest/Documentation/Stepper Stand/Stepper Commisioning/Automated Stepper Stand Mechanical Calibration.doc

[3] T. Hiatt, et. al. "Vacuum Chamber Contributions to 10 kW FEL Dipole Field Maps", JLAB-TN-03-007, 17, March 2003.

[4] J. Karn, et. al. "Magnetic Measruements of the Prototype Dipole for the IR-FEL at the Thomas Jefferson National Accelerator Facility", Proc. PAC1997.

[5] G. Biallas, et. al. "Magnetic Modeling vs. Measurements of the Dipoles for the JLab 10 kW Free Electron Laser Upgrade", published in these proceedings.

[6] D. Douglas, et. al. "Performance Qualification of 3F Region GX/GQ Dipoles", JLAB-TN-03-015, 26, April 2003.

[7] Ibid.

[8] K. Baggett, et. al. "Magnetic Measurements of the 10kW, IR FEL 180 Degree Dipole", published in these proceedings.