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MAGNETIC FIELD DIAGNOSTICS FOR AN FEL WIGGLER\*

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#### ABSTRACT

Magnetic field measurements have been performed on a 5-m wiggler magnet array that forms part of a freeelectron laser experiment currently in operation at LLNL. The pre-installation tests used a Hall probe to map the transverse field on and near the beam axis, and integrating coils to determine the cancellation errors that tend to steer the beam. For on-line diagnostics, we use a bank of 31 rotating-coil gaussmeters that are mounted off-axis but from which the on-axis field is inferred. The gaussmeters form part of a closed-loop control system through which the operator can set and automatically maintain a desired field profile to within 0.1 %. The paper discusses pre-installation measurement and calibration techniques and results, and operational experience with the closed-loop control system.

# Introduction

A free-electron laser experiment currently in operation at LLNL is designed to utilize a 3-kA, 50-MeV electron beam, derived from the ATA linear induction accelerator, to generate  $10-\mu m$  laser radiation. The wiggler consists of five, 5-m-long sections; it combines permanent and electromagnets in a manner that permits continuous, on-line control of the magnetic field profile while avoiding saturation in any part of the magnetic circuit [1,2]. The control and diagnostic systems maintain a magnetic field profile to within 0.1% RMS. In this paper we outline the basic design of the wiggler magnet and of the control system; we describe the pre-installation test setup and results; and finally, we give some on-line performance data for the control system during closed-loop operation.

#### Wiggler Construction

The design specifications for the wiggler magnet are summarized in Table I.

Table I.	Wiggler	Specif	ications
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Nominal wiggler field	2.5 kG
Period	8.0 cm
Gap width	3.0 cm
Total length	25 m
RMS field errors	< 0.1 %
Space harmonic content	< 1.0 %
Field tunability	0.5 to 2.5 kG

A single-period prototype of the wiggler magnet was built and tested earlier in order to verify some of the design parameters listed (Fig.1). Fig. 2 shows an input-end view of a fully assembled, 5-m wiggler section. The iron pole assemblies, top and bottom, are continuous, comb-like, iron structures, with rectangular cross-section poles on 4-cm centers. Each pole carries an array of two separate coils that produce a nominally steering-free field independent of the separate power supply settings. We use 32 power supplies per 5-m section, for a total of 64 wiggler periods, with excitations overlapping to produce the desired steering-free result. Steering coils nonetheless have been added to compensate, if necessary, for less than perfect operation of this excitation scheme.



Fig.1. Basic construction of the wiggler, showing one period of the magnetic circuit. The permanent magnets do not contribute to the nominal field across the gap; their role is to prevent critical regions in the iron from going into saturation.



Fig.2. Detail of a completed 5-m section of the wiggler, as seen from the input end.

## Pre-installation Tests

Our pre-installation test program was intended primarily to detect anomalies in the wiggler field due to errors in construction or assembly. As only a single period prototype had been tested prior to the construction of the first 5-m section, the first measurements performed on the long section also provided fully-assembled design verification, and allowed us to modify the design as required. Only

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Hall probe and search coil tests will be discussed here; further verification of the wiggler performance was obtained from ion beam transport measurements.

Using a Hall probe mounted on a computer-driven, three-axis translator, we mapped the midplane fields over one complete period. From such data we were able to verify the purity of the sinusoidal, axial variation (third and fifth harmonics were 0.145% and 0.472% of the fundamental amplitude, respectively), as well as the hyperbolic cosine variation in the transverse direction, which is essential for focusing the electron beam in the wiggle plane. During subsequent Hall probe measurements we mapped only the field on axis. Here we used a probe mounted in a lucite shuttle that was pulled through the wiggler beamtube. The shuttle is visible at the left in Fig. 2. Above and below the shuttle is a "clothesline" type of drive mechanism that moves the probe under computer control.

For the search coil tests we employed a horizontal, rectangular coil, mounted in a lucite shuttle and pulled through the wiggler beampipe similar to the Hall probe arrangement. This coil is 8 cm (one wiggler period) long, 1.34 cm wide, and 1.5 cm high, and carries 180 turns of #36 gauge magnet wire. The shuttle includes an error coil wound in quadrature with the search coil, to flag rotation of the shuttle away from the nominal, horizontal orientation. As this is a null measurement, it is much less sensitive to rotation about or to translation perpendicular to the wiggler axis, than the Hall probe measurement.

The search coil output is integrated and the resulting signal therefore is proportional to the net flux linking the coil at any instant. Any deviation of the search coil length from exactly one wiggler period leads to a sinusoidal signal variation as the coil travels axially through the wiggler. (We since have developed a method to suppress this error signal through using a matched pair of search coils and combining their signals.) A typical single-period loop signal is shown in Fig. 3. After subtracting out the integrator drift, the variation in the peak amplitude corresponds directly to the net steering flux associated with each of the poles. We found this error to be due in part to imperfectly sorted and matched permanent magnets, and we were able to reduce it somewhat after disassembling the wiggler and refitting it with carefully sorted magnet sets.



Fig.3. Integrated, single-period signal vs z, first 5-m section of the FEL wiggler. The dominant, periodic signal is due to the length tolerance on the search coil. The peak amplitude variations represent actual steering error, i.e., incomplete cancellation of flux over a one-period length.

The small bar in Fig. 3 corresponds to the signal magnitude that would be observed for a uniform field of 5 G linking the search coil; note that the data were obtained in the presence of a +/-2500-G wiggler field.

### <u>Control and Data Acquisition System (DAS)</u> for the Pre-installation Tests

A block diagram of the control and DAS for the Hall probe and search coil tests is shown in Fig. 4. The system is based on an LSI-11/73 computer that communicates with the measurement instrumentation via CAMAC modules. The operator keys in the type of test desired and the test parameters such as size of axial steps and shuttle speed. The computer then takes control of the shuttle, acquiring and recording data according to the protocol laid out. All raw data are stored on a hard disk; in addition, the data can be printed out as hard copy or can be plotted either on a CRT monitor or on an x-y plotter.



Fig.4. Control and DAS electronics for the 5-m wiggler pre-installation tests.

Control of the axial shuttle movement is achieved through CAMAC-controlled stepper motors. An absolute, 13-bit, pin-contact encoder gives a total of 8192 values in 32 shaft revolutions, which translates to a resolution of 0.8 mm/count. The encoder output is converted to binary in the computer. Data can be taken either "on the fly" or at periodic stop points.

# On-line Monitoring and Control System

The on-line monitoring and control system allows the operator to set, reset, and maintain a desired field profile in the wiggler to within 0.1% RMS. There will be a total of 160 power supplies in the full 25 m length of the finished wiggler. The power supplies are voltage programmable, and the control system supplies a reference voltage to each supply that corresponds to the desired target current. Because of hysteresis effects in the magnet iron, the required accuracy in field value cannot reliably be achieved with simple current control of the magnet power supplies, especially when a field profile is being set empirically, requiring many successive, arbitrary changes in the field values. We therefore decided to go to a closed-loop control system, in which the magnetic field and not the excitation current value becomes the reference for system regulation.

The basic diagnostic here is an array of 32 rotating-coil (RC) gaussmeters in each 5-m section (31 in the first section tested), one corresponding to each power supply. The RC probes are commercial units (Rawson-Lush Type 780). They were chosen over Hall probes because of the high-radiation environment in the accelerator tunnel, and because of their inherent linearity. The RC probes are mounted off axis, and hence they are calibrated, prior to beam tube evacuation, against a Hall probe on axis to obtain the transfer function that permits one later to infer the on-axis field from the RC reading. This transfer function is stored as a second-order polynomial in the control computer. The control system converts field measurements to the equivalent on-axis field before they are displayed to the operator.

A block diagram for the on-line, closed-loop control system is given in Fig. 5. The feedback controller is an analog system that includes circuitry to convert the 29-Hz, RC probe signal into a d.c. voltage proportional to the measured field. This is then compared to a reference voltage corresponding to the desired field value. A loop filter integrates the error and drives the power supply until the error goes to zero. A slew rate limiter restricts the rate of change of the current to less than 5 A/s in order to minimize eddy current effects in the wiggler iron.



Fig.5. Block diagram for the closed-loop control system.

Fig. 6 illustrates the operation of the on-line closed-loop control system. The data represent the normalized excitation current reached on one power supply, in A/kG, plotted vs a series of target fields set by the operator. After initially cycling the system to regain a known reference point on the magnetization curve, the target field value was increased monotonically from 500 to 2500 G, and was



Fig.6. Closed-loop system performance on the wiggler magnet.

then decreased back down to 500 G. The current values are different, depending on whether the iron was magnetized on the ascending or on the descending branch of the B-H curve. In the operating field range the difference in excitation is on the order of 0.3 %, well in excess of the allowable 0.1% RMS. This demonstrates both the necessity for and the functioning of the closed-loop control system.

As a further illustration of the operation of the control system, Fig. 7 shows the difference between measured field and target field under closed-loop operation, for one point along the wiggler. This demonstrates our ability to set and reset a wiggler field profile precisely within better than 2.5 G. The absolute accuracy of the field, as seen by the electron beam, depends on the accuracy of the transfer calibration from off-axis to on-axis fields.



Fig.7. Field error (measured field minus target field at rotating coil gaussmeter station No. 12) under closed-loop regulation. The 1.5-G average error is due to an offset in one channel. The DAS resolution is 0.1 G below 1 kG and 1 G above the 1-kG level. The error is well below the 0.1% allowable maximum.

# Conclusion

Pre-installation diagnostics on the first 5-m section of our FEL wiggler magnet have included single-period field mapping in the midplane, axial scans with a Hall probe to spot assembly errors, and axial scans with a search coil to test for steering error. All probe movement and data acquisition occur under computer control. These tests have demonstrated a need to sort and match the permanent magnets that form part of the system, even though these magnets do not nominally contribute to flux across the gap. The on-line magnet diagnostics for the complete wiggler consist of a bank of 160 rotating-coil gaussmeters that form part of a closed-loop During tests on the first 5-m control system. wiggler section, we have demonstrated the ability to return to and maintain predetermined setpoints in the wiggler field to within 0.1% RMS, in the presence of noticeable hysteresis in the iron.

#### References

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