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DISCLAIMER

A LONG ELECTROMAGNETIC WIGGLER FOR THE PALADIN FREE-ELECTRON LASER EXPERIMENTS

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We have designed, built, and tested a 25.6-m-long wiggler for a free-electron-laser (FEL) experiment. It is a DC iron-core electromagnetic wiggler that incorporates a number of important and unique features. Permanent magnets are used to suppress saturation in the iron and extend the linear operating range. Steering-free excitation allows real-time adjustment of the field taper without causing beam steering. Wiggle-plane focusing is produced by curved pole tips. The magnitude of random pole-to-pole field errors is minimized by a mechanical design concept that reduces tolerance stackup in critical locations. To date, we have tested 15 m of this wiggler, and our measurements have shown exceptionally low levels of random errors.

Introduction

Our FEL experiment,[1] which is currently in operation at the Lawrence Livermore National Laboratory (LLNL), is intended to examine the physics of high-efficiency induction-linac free-electron lasers (IFELs) operating near the visible regime. This experiment employs the Advanced Test Accelerator (ATA) to provide a 50-MeV, 3-kA, 50-ns electron beam, which is used to amplify an input 0.25- to 50-J CO_2 laser pulse within the wiggler. The wiggler that we have designed, built, tested, and partially installed for this experiment has a number of unique features. Table 1 summarizes some of the most important overall specifications and features that are discussed in more detail below.

TABLE 1. The LLNL electromagnetic wiggler specifications and features.

Laser wavelength	**10.6 μm**
Electron beam energy	**50 MeV**
Nominal wiggle field	**2.5 kG**
Wiggle period	**8.0 cm**
Gap	**3.0 cm**
Section length	**5.12 m**
Total length	**25.6 m**
Field tuning range	**0-100%**
Random field error	**<0.2% rms**
Allowed losses in iron	**<1.0%**
Steering independent of field tuning	
Near-axis field profile:	

$$B_y = B_0 \cosh(K_x x) \cosh(K_0 y) \cos(K_w z)$$

Magnetic Design

The "Permanent-Magnet Assist" Concept

One of the primary design requirements for our wiggler was the ability to change rapidly the axial profile of the transverse field magnitude, or magnetic "taper."[1] This led us to consider the concept of a DC, iron-core, electromagnetic (EM) wiggler because of its inherent real-time tunability and the simplicity of the hardware required (as compared with an equivalent pulsed air-core system, for example). Unfortunately, the on-axis field attainable in such devices is inherently limited because of the saturation of the iron poles.[2] This effect is illustrated in Fig. 1, which shows flux lines in the top half of one period of a typical iron-core EM wiggler. Figure 1 shows clearly that the maximum flux density in the iron pole is at the base; this is therefore the location at which the pole will saturate first. For our application, saturation would occur before a meaningful field is attained on axis. Direct solutions to this problem, such as decreasing the pole height or increasing the cross-sectional area of the pole, all have the net effect of increasing the current density in the coil, which results in an untenable coil design. Our solution to this problem is to employ a permanent-magnet (PM) "assist,"[2] in which PMs are used to suppress saturation in the iron, *without* contributing appreciably to the field in the wiggler gap. This is accomplished in our wiggler as illustrated in Fig. 2. PMs

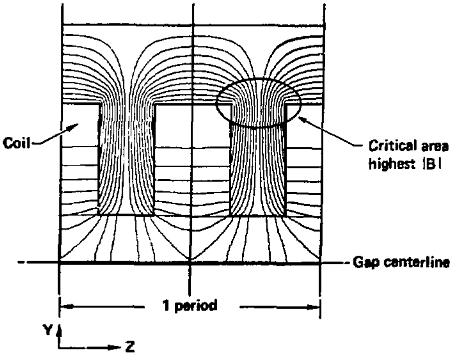

Figure 1. Magnetic flux lines in upper half of one period of a conventional EM wiggler.

are attached to the sides of the poles (in front of and behind the plane of the paper in Fig. 2) in such a way as to produce flux in the iron that is in the opposite direction of the flux produced by the EMs; this provides a continuous "reverse-bias" flux in the iron. The effect can be seen in the magnetization curve for the device, shown in Fig. 3. A similar curve for a conventional EM would be symmetrical about the origin, because it could be energized equally in either direction. The curve for our wiggler, however, is shifted into the first quadrant, indicating that the wiggler can be energized in only one direction, but to approximately twice the field for a given level of saturation. This same effect is being exploited to an even greater extent in more recent wiggler designs.[2,3,4] The net effect has been to allow on-axis fields in the range 0 to 3.2 kG to be attained, with 99% linearity between field and coil current. Figure 4 shows a schematic of our design, with the PM blocks affixed to the sides of the poles and surrounded by the EM coils; the direction of magnetization of the PM blocks is into/out of the poles, parallel to the horizontal midplane.

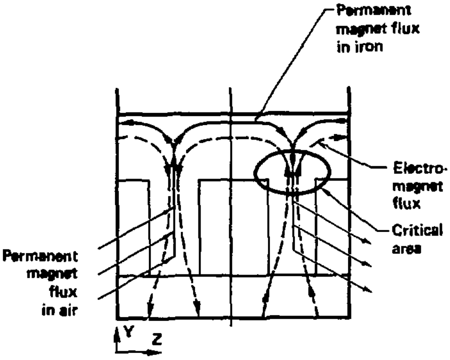

Figure 2. Magnetic fluxes for PM assist.

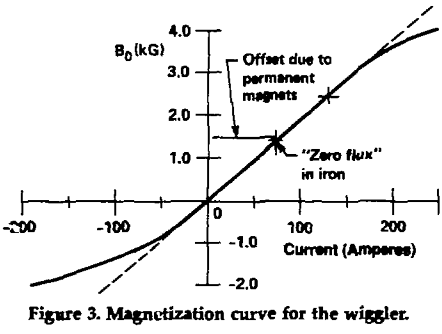

Figure 3. Magnetization curve for the wiggler.

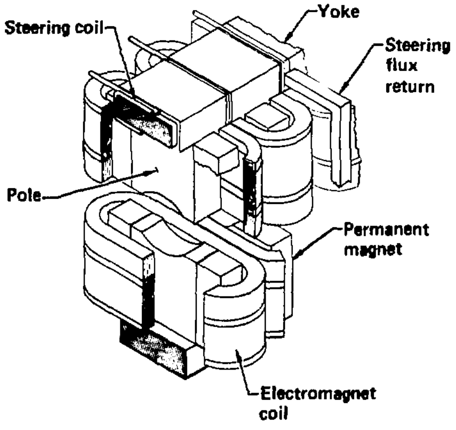

Figure 4. Schematic of the wiggler.

Steering-Free Excitation

As discussed in Ref. 1, one of the requirements for ILFEL wigglers is the ability to produce various tapers of the transverse field magnitude. In our wiggler, this is done by energizing every two periods (16 cm) of the wiggler with a separate power supply. This allows any desired taper to be approximated in 16-cm flat steps, over the entire 25.6 m of wiggler. This, however, implies an extremely important additional constraint on the magnetic design: each individually tunable two-period unit must not steer the electron beam. Otherwise, every adjustment of the taper would require retuning of the horizontal matching and steering, which would be quite tedious, and would probably result in radiation damage to the wiggler because of frequent beam spills during tuning. Simply energizing the wiggler in two-period units leads, in general, to a net electron-beam offset. This can be shown by simply integrating twice the sinusoidal field produced by such excitation down the axis: the first integral, which is equivalent to electron-beam angle, shows no net value at the end of one period; however, the second integral, corresponding to electron-beam position, does show a net offset for each and every period. This clearly motivates us to work toward a more sophisticated pattern of pole excitation. A number of such patterns have been identified;[5] for our wiggler, we adopted the simplest of these. The field produced on axis by a single power supply is shown schematically in Fig. 5; adjacent power-supply units overlap on one pole, so that every fourth pole is actually energized by two separate power supplies. This is accomplished by using bifilar coils on the shared poles, with the two independent circuits connected to adjacent power-supply units. Details of the coil design are discussed in a later section and in Ref. 6.

Figure 5. Axial profile of magnetic field produced by one power supply.

Wiggle-Plane Focusing

Focusing is required in a long wiggler to compensate for nonzero electron beam emittance, which would otherwise cause the beam cross section to gradually grow. Focusing of the beam in the vertical direction normal to the wiggle plane arises naturally in any wiggler from the interaction of the transverse wiggle motion of the electrons and the axial component of the magnetic field (between poles). Focusing in the horizontal transverse direction, in the wiggle plane, requires special design features. In other linear wigglers, this has been accomplished by employing external quadrupole coils, or "canted" pole tips, which also produce quadrupole focusing. For our wiggler, we wanted the focusing to be continuous and of equal strength in both transverse directions.[7] This was accomplished by making the pole tips curved (Fig. 4). This results in a three-dimensional field profile as specified in Table 1; Fig. 6 shows a measured two-dimensional field profile on the midplane; the hyperbolic-cosine curvature near the axis is apparent. We selected the specific tip curvature to compensate also for finite-width poles; thus, in addition to the curvature required for focusing, the edges are shimmed to attain the desired field uniformity near the axis.

Random Magnetic-Field Errors

In any wiggler, it is important to minimize pole-to-pole differences in the magnitude of the transverse magnetic field. An error in the field under any pole represents an angular kick to the electron beam; hence, a series of random errors throughout a wiggler will cause the beam to undergo a random walk. The performance of the FEL is quickly degraded as the electron beam becomes physically removed from the laser. This leads to two additional design requirements. First, for a wiggler of any given length, there is a maximum allowed magnitude of random magnetic field errors; for our device, it was required that the random scatter of the field integral over each half-period be less than 0.1% rms of the mean value of that integral for all poles. This represented the most stressing design requirement. Many independent tolerances interact to lead to random field errors, but the most important source of errors is from random variations in the wiggler gap dimension; the design goal for this dimension was to maintain it within ± 0.0004 in. (± 10 μ) over the 25.6-m length of the wiggler (640 poles). Another contribution to random field errors is saturation effects in the poles. Clearly, if all poles could be expected to saturate exactly the same at the same field levels, there would be no concern. However, we were concerned that there might be variations in the composition, heat treatment, or mechanical stress state of the pole material that could lead to differences in the relative permeability at high flux densities. We therefore required that magnetic losses in the poles should always total less than 1% of the total pole excitation for any operating point; then, variations of the permeability on the order of 10% would not be significant. This effectively limited the flux density allowed in the pole and, combined with the field, period, and gap specifications, motivated the use of the PM-assisted EM wiggler concept. The second design requirement arising directly from the need to minimize random error effects was the requirement for a horizontal steering capability. The steering coils and steering flux returns, shown in Fig. 4, were included for this purpose. The coils can excite individual poles or groups of poles and thereby apply the required small vertical dipole field at the midplane via the poles themselves.

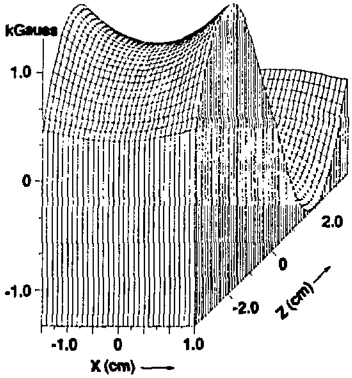

Figure 6. On-axis transverse field profile for one period.

Mechanical Design

As discussed above, the most stressing design requirement is the gap tolerance, which drives the choice of mechanical design concept. Clearly, when working to such tight tolerances, the major focus of the design must be on minimizing the stackup of tolerances on individual parts, particularly the number of such tolerances that are additive. The design concept we employed starts with a very stiff lower support structure, on which the lower pole assemblies are mounted. The cast-steel pole modules are 64 cm long; they are individually machined and then mounted on the 5.12-m-long lower support structure. With all pole modules in place, the entire assembly is mounted in a surface grinder, and the pole tips are ground to shape. This ensures that random variations in the pole heights are minimized. The upper half of the wiggler is machined in a similar manner, but its supporting structure is designed to be rather flexible, so auxiliary support is required during grinding. In operation, the top half is forced down onto lapped aluminum blocks, which gage between the flat areas on the upper and lower pole tips. The closing force is provided by the weight of the upper assembly and by compression springs located above each gage block, which are placed every four poles. The upper wiggler half, being somewhat flexible, is forced to conform to the surface defined by the lower pole tips. In this manner, there are only three tolerances that interact to specify the random gap variation: tolerances on the tip profile (for both upper and lower halves), and the tolerance on the gage block thicknesses themselves. Because all three of these areas are finish-machined by grinding or lapping, repeatability can be excellent.

The EM coils constitute the other major assembly within the wiggler. The coils are tape-wound from copper strip and are edge-cooled. They are mechanically pressed against 2.5-mm-thick water-cooled heat sinks, with a layer of thermal joint compound in between to eliminate air from the interface (Fig. 4). The two individual coils on a pole are electrically in series and operate at the same current density. Their heights are different in order to balance the heat flux at each coil/heat sink interface. The coils operate at a net current density (averaged over the entire coil assembly) of approximately 1000 A-turns/cm^2 at the peak field of 3.2 kG. At a nominal operating point of 2.5 kG, the power required is 700 W per period, or 8.9 kW per meter. More details on the coil assemblies can be found in Ref. 6.

Performance

Each of the 5-m-long sections is individually tested prior to final installation.[8] Figure 7 shows the currently installed 15-m wiggler system, which is now being used for FEL experiments; a Hall probe scan of this device is shown in Fig. 8. The characteristic signature of a power supply that is off the desired current setpoint is easily visible in two locations. The measured random error level for the first 5-m wiggler section was 0.14% rms, more than the design requirement of 0.1% rms. However, detailed analysis of the error distribution has shown that the errors are not truly random, and the net effect on steering is much less than would be expected from random errors of the same magnitude. Analysis is still in progress to identify the cause of this beneficial effect.

Conclusions

Our wiggler is the first PM-assisted DC iron-core EM wiggler that has been constructed and operated. This wiggler, one of the longest yet constructed, has demonstrated not only the concept of the PM assist, but also the use of curved pole tips for equal-strength transverse focusing, and of steering-free excitation as well. Most importantly, we have achieved random field error levels that are among the smallest ever attained. We are now looking forward to the imminent demonstration of the FEL physics goals for which the system was designed.

Figure 7. Photograph of installed 15-m wiggler system.

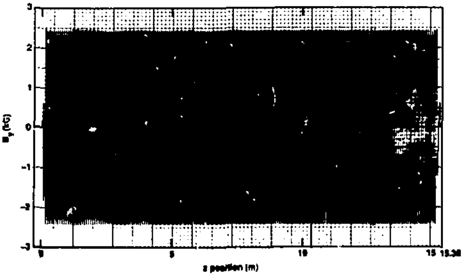

Figure 8. Axial profile of magnetic field in 15-m wiggler system.

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