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DEVELOPMENT OF THE STRONG ELECTROMAGNET WIGGLER

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Abstract

The Strong Electromagnet (SEM) wiggler is a permanent magnet-assisted electromagnet under development at the Lawrence Livermore National Laboratory (LLNL) as part of the Induction Linac Free-Electron-Laser (IFEL) program. This concept uses permanent magnets within the wiggler to provide a reverse bias flux in the iron and thus delay the onset of magnetic saturation. The electromagnet coils determine the wiggler field and operate at low current densities by virtue of their placement away from the midplane. We describe here the design approach used and test data from a 7-period wiggler prototype that includes curved pole tips to provide wiggler-plane focusing.

Introduction

The SEM wiggler is a further development of the permanent magnet-assisted electromagnet wiggler,¹ a type first introduced with the PALADIN wiggler.² It appears that the SEM is likely to meet the IFEL wiggler requirements of high fields, large gaps, moderate period length, small random field errors, and field tunability during operation.

The physics of the IFEL system drive these wiggler requirements. To reduce the growth of the transverse resistive wall instability, which affects high-current electron beams propagated long distances through small pipes with finite wall conductivity, we place the vacuum chamber wall as far as possible from the electron beam.³ This requires large pole gaps in the wiggler. Arbitrarily small period lengths prove detrimental to IFEL performance when effects such as finite emittance, beam offset, energy sweep, etc., are considered.⁴ Therefore, IFEL wigglers use a moderate period length of several centimeters. Random wiggler field errors cause electron-beam steering and are a particular concern with very long wigglers; thus, we seek designs that can reduce these errors while at the same time providing closed-loop beam steering systems. On-line field tunability is required to optimize the magnetic field taper to any set of potentially varying experimental conditions. Although modeling can predict optimum tapers for the wiggler with a fair degree of accuracy, we must still be able to tune the wiggler around this theoretical profile to allow for changes that might occur on a day-to-day basis throughout the remainder of the IFEL system.

It is the purpose of this paper to describe the single-period design procedure for the SEM wiggler now under development to meet the needs of the IFEL system. We will then discuss a prototype wiggler that demonstrates SEM wiggler performance.

Single-Period SEM Wiggler Design

The development of new wigglers at LLNL begins with the single-period magnetic design. Once this basic design is understood, we can then address ourselves to system design considerations, which are not included here.

A single-period schematic of the SEM wiggler is shown in Fig. 1. This device, which was first presented by Halbach,¹ is an iron core, DC electromagnet. Poles of identical magnetic scalar potential are attached to large iron plates. These "scalar potential busses" are bridged by iron plates around which the large primary coils are wound. A single set of primary coils can control the scalar potential of as many periods as desired. Smaller trim coils that provide the magnetic field taper are placed at the base of the poles. Both sets of coils can have large conductor cross sections and be operated at low current densities by virtue of their placement away from the midplane. Permanent magnet material, magnetized in a direction opposite that of the field created by the coils, is placed between the poles. The permanent magnets provide a "reverse bias flux" in the iron in the direction opposite that of the coils. Thus, the magnetic scalar potential of the poles can be elevated to the desired point while delaying the onset of magnetic saturation in the iron, a fundamental limit to the performance of conventional electromagnetic wigglers.

Fig. 1. Single-period schematic of the Strong Electromagnet wiggler.

While the wiggler is operating away from saturation, permanent magnet flux does not cross the midplane. The operating field, then, is controlled solely by the coils; thus, the SEM functions as an electromagnet.

We estimate that the ultimate on-axis field obtainable with the SEM is higher than that possible with a conventional permanent magnet hybrid wiggler of the same geometry and materials. The permanent magnet material next to the gap in the hybrid wiggler is driven to approximately $0.8 H_c$. Driving the permanent magnet closer to H_c to obtain higher fields requires a large increase in permanent magnet volume. In the SEM, the coils raise the pole scalar potential until the permanent magnets are driven fully to H_c . For the IFEL, the pole tips are curved greatly in the transverse plane to provide focusing. This reduces the peak field when compared with a flat-pole wiggler.

An interesting characteristic of any permanent magnet-assisted electromagnet is that as coil current is reduced, the large permanent magnet flux begins to saturate the iron, thereby placing a lower limit on the operation of such a device. In many cases, a significant field remains after the coils are turned off because the saturated iron causes permanent magnet flux to cross the midplane.

The design for the SEM is shown schematically in Fig. 2. The flux in the pole caused by the coils is balanced with an appropriate addition of permanent magnet material magnetized in the opposite direction.

For any given pole shape, the cross-sectional area of the pole limits the allowed net flux. Assuming infinite permeability in the iron, we calculate the distribution of flux caused solely by the coil when the pole is at the scalar potential required to produce the desired midplane field. The SEM design reduces the amount of iron in close proximity to surfaces of opposite potential so that "parasitic losses"—flux leaving the pole and not crossing the midplane—are also reduced. However, calculation of the flux profile caused by the coils is difficult because of the extremely three-dimensional nature of this configuration.

Permanent magnet material is then placed along the pole as dictated by the profile of the "electromagnet flux" and the pole cross section. The operating flux profile within the pole is the algebraic sum of permanent magnet and electromagnet flux. At any point along the pole, this resultant must be less than the amount of flux that causes significant saturation.

An important characteristic of the SEM wiggler is the ease with which the pole cross section can be changed. This allows a larger cross section near the base of the pole and can also re-

duce the total amount of permanent magnet material required. The design process becomes iterative as the desirable pole shape follows from the electromagnet flux profile, which in turn depends upon the shape of the pole.

As seen in Fig. 2, the strength and location of permanent magnet material affects both peak field and tuning range. At the top of the tuning range, the pole begins to saturate near its base, as in a conventional electromagnet. As the field is turned down, the unchanging permanent magnet flux causes saturation at the base of the permanent magnet material. These differing "planes of saturation" reduce the tuning range of the SEM when compared to that of a conventional electromagnet.

Our definition of tuning range limits wiggler operation between the points at which 1% of the coil ampere-turns (A-turns) are lost in the iron. This somewhat conservative approach allows the midplane field to be insensitive to inconsistencies in iron properties of a few percent. A-turn loss in the iron is integrated along the entire magnetic circuit, and the long iron paths in the SEM wiggler require us to limit the peak field in C1008 steel to less than 14 kG.

Differing pole and coil geometries are possible. The pole configuration (Fig. 3) is especially important. The angled poles introduce a small field in the transverse plane. Either a dipole or a quadrupole field is generated, and the two possible pole configurations are thus labeled. Note that as the field changes sign in the pole gaps immediately before and after a particular pole, so too does the direction in which the poles are attached to the scalar potential busses. Therefore, the sign of the error field does not change.

These small fields can have a significant impact on the operation of the IFEL. The effect of a dipole error field is obvious; a quadrupole error field detrap particles in the free-electron-laser interaction and significantly reduces laser performance. We are investigating the proper shape of the pole to avoid these error fields. Increasing the vertical extent of the pole tip seems to be effective in this regard.

A single primary coil may be used in place of the two shown in Fig. 1. The top coil plate can be removed, and large iron straps can be placed between the scalar potential busses of like polarity. Although this reduces the power consumption, side access to the pole gap is greatly reduced by the new iron.

Finally, note that the optimization of the SEM wiggler design requires the use of three-dimensional numerical modeling. We have used a series of two-dimensional calculations to arrive at the electromagnet and permanent magnet profiles for certain

Fig. 2. Schematic representation of the SEM design. The electromagnet flux is balanced by the correct location of permanent magnet material and the variation in pole cross-sectional area.

Fig. 3. Schematic showing how pole geometry introduces small error fields. Either quadrupole or dipole fields are produced in the transverse plane caused by the angled poles. Correct shaping of the poles reduces these unwanted fields.

specific cases. As will be shown, these calculations have yet to arrive at the optimum design. Computer simulation is essential because the operating range is the relatively small difference between two large flux components. At LLNL, J.J. Stewart is modifying the three-dimensional finite-element code TOSCA to run more efficiently on either of the LLNL Cray X/MP4 computers.⁵ Additionally, Stewart has developed a new preprocessor. We will use these codes in the final modification of our SEM wiggler prototype. They have also been used elsewhere.⁶

Prototype SEM Wiggler

We have designed, fabricated, and tested a prototype of the SEM wiggler. Our purpose was to demonstrate the peak field and tuning range possible with our current understanding of the device and in a geometry applicable to the IFEL.

Figure 4 shows the prototype hardware. The device has an 8-cm period and a 3-cm gap. The center period of the 7-period wiggler is studied to avoid end effects. All iron parts bolt together for easy modification; thus, the mechanical system is not optimized to reduce random errors. Sm_2Co_5 permanent magnets are used, along with C1008 steel plate, which was not annealed after machining. The primary coil is constructed from square, hollow copper conductor, cooled by low-conductivity water.

Figure 5 shows a plot of the midplane field measured on the wiggler centerline vs coil excitation. The peak field observed was 5.8 kG, although this point is well beyond the linear portion of the curve and thus does not follow our definition of peak field and tuning range discussed previously. Based on the slope of the linear region, peak field determined by a line with a 1% lower slope is 4.6 kG. The minimum field, determined in a

similar way, is 4.0 kG. Extrapolating the linear part of the curve to zero current results in an indicated field of 1 kG. We believe that this may indicate a contribution to the midplane field from the permanent magnets that is caused by saturation within the pole. Further work will address a modification to the present iron/permanent magnet design to achieve slightly higher fields and a larger tuning range.

Also shown in Fig. 5 is the midplane field measured on the wiggler centerline without permanent magnets installed. The peak field is approximately 1 kG, which is 22% of that achieved with permanent magnets.

Note that the curvature of Fig. 5 as the wiggler transitions from low fields ("permanent magnet saturation") into the linear range of operation is more pronounced than that seen in the transition to "electromagnet saturation." At higher fields, the base of the pole begins to saturate, while at lower fields saturation occurs just below the permanent magnets, where the pole cross section is smaller.

Also of interest is the fairly large amount of hysteresis exhibited. The long iron paths present in the solid iron core result in about 100 G between the upward- and downward-moving portions of the plot.

The correct pole-tip curvature has been discussed elsewhere,⁷ and its shape provides equal horizontal and vertical focusing in the wiggler. We provide the pole-tip curvature by adding iron to the pole as we move away from the wiggler centerline. This reduces the peak field when compared with a flat-tip pole.

Figure 6 is a plot of the normalized transverse field profile on the midplane resulting from the curved pole tips for a centerline wiggler field of 4.5 kG. The ideal pole shape would result in a hyperbolic field profile, as indicated. A curve fit to the measured data shows a very close match to the desired field shape. The exact shape of the pole tip deviates slightly from that determined by Scharlemann⁷ to account for the finite width of the pole and to provide for a less costly profiling of the pole.

Also note the slight nonsymmetry of the measured points with respect to the wiggler centerline. This is caused by the error fields associated with the pole geometry.

Fig. 4. Photograph of the 7-period SEM wiggler prototype.

Fig. 5. On-axis field vs coil excitation. The peak field is as determined by our definition of tuning range, 4.6 kG. The tuning range is 600 G. Hysteresis caused by the solid iron core is present. The dashed curve represents operation without permanent magnets.

Desired curve:

$$(B_y/B_0 - 1) = \cosh\left(\frac{k_w}{\sqrt{2}}x\right) - 1 - 0.154x^2$$

Curve fit to measured data:

$$(B_y/B_0 - 1) = 0.157x^2$$

Fig. 6. Transverse field profile on the midplane demonstrating the correct field shape for wiggle-plane focusing. Non-symmetric measured data result from error fields caused by the pole geometry.

Figure 7 shows an axial field profile on the midplane along the wiggler centerline, as well as an harmonic analysis of the measurement. The pole thickness along the electron-beam propagation direction is chosen to eliminate the third harmonic on axis. Our pole design was effective in achieving this. In general, the field shape exhibits reasonably low harmonic content.

Tests using this prototype device will continue. As it is very flexible, we will investigate new pole shapes to reduce the geometry-induced error fields and increase the peak field and tuning range. We will also use the prototype to begin the study of random-error propagation along an SEM wiggler.

Conclusions

We have described the Strong Electromagnet wiggler concept and its basic design procedure. This concept is under development to meet the requirements of the IFEL system. We have started testing a 7-period prototype (8-cm period, 3-cm gap) with curved pole tips. We predicted geometry-induced error fields, then observed them in the measurements. We found that the axial field harmonics were low. Development of the Strong Electromagnet wiggler will continue.

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Harmonic Content

	Amplitude (Gauss)	% Fundamental
First	4500	
Third	26.5	0.59%
Fifth	6.5	0.14%
Seventh	9.3	0.21%

Fig. 7. Axial field profile on the midplane demonstrating low harmonic content.

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