8

CONF-870901--5

[redacted]

Preprint

Electromagnetic Wiggler Technology Development at the Lawrence Livermore National Laboratory

G. A. Deis, M. J. Burns,
T. C. Christensen, F. E. Coffield,
B. Kulke, D. Prosnitz, and
E. T. Scharlemann
Lawrence Livermore National Laboratory

and K. Halbach
Lawrence Berkeley Laboratory

Prepared for the Tenth International
Conference on Magnet Technology
Boston, Massachusetts

September 23-26, 1987

Beam Research Program

Lawrence Livermore National Laboratory

MASTER

DISCLAIMER

ELECTROMAGNETIC WIGGLER TECHNOLOGY DEVELOPMENT AT THE LAWRENCE LIVERMORE NATIONAL LABORATORY

UCRL--96290

DE88 000974

G. A. Deis, M. J. Burns, T. C. Christensen, F. E. Coffield,
B. Kulke, D. Prosnitz, and E. T. Scharlemann
Lawrence Livermore National Laboratory
P.O. Box 808, Livermore CA 94550
and
K. Halbach
Lawrence Berkeley Laboratory
One Cyclotron Road, Berkeley, CA 94720

As a part of the program at the Lawrence Livermore National Laboratory (LLNL) in induction-linac free-electron laser (IFEL) research, we are conducting a variety of activities addressing the unique requirements imposed on IFEL wiggler systems. We are actively developing improved DC iron-core electromagnetic wiggler designs to attain higher peak fields, greater tunability, and lower random error levels. We are pursuing specialized control systems, such as magnetic-field and beam-position controllers, which can relax requirements on the wiggler itself. We are also pursuing basic studies to establish the effect of radiation on permanent magnets.

Introduction

The LLNL is actively pursuing the development of free-electron lasers (FELs) driven by induction linear accelerators. These devices show great promise as high-efficiency sources of intense coherent radiation over a wide range of wavelengths, from microwave through visible. The requirements placed on wigglers for this application are strict and somewhat unique, as discussed below, and they motivate new wiggler system concepts. We have been developing the technology necessary to address these requirements over the last several years at LLNL. The scope of our activities is outlined in the following paragraphs.

IFEL Wiggler Design Requirements

An FEL converts the kinetic energy of a relativistic electron beam directly into coherent electromagnetic radiation. The main components of an IFEL are shown in Fig. 1. The electron beam from the accelerator interacts with an input laser in the wiggler. The periodic magnetic field of the wiggler forces the electrons to oscillate in phase with the input electromagnetic wave, when the wiggler wavelength, magnetic field, and electron energy are in the proper relationship ("resonance"). When resonance is maintained, the electrons can give up energy directly to the electromagnetic field, and thus amplify the input radiation. The IFEL operates as a single-pass power amplifier, and thus must convert a large fraction of the electron energy into output radiation to attain high efficiency. However, as the electrons travel through the wiggler and give up energy, they fall out of resonance; the wiggler magnetic field amplitude must therefore be reduced down the length of the wiggler, or "tapered," to maintain resonance. Figure 2 shows a typical range of wiggler tapers and illustrates a number of other unique requirements for IFEL wigglers, including long length, tunability, and high field capability. To attain high efficiency, the electrons must transfer a large portion of their kinetic energy to the light wave, and this requires wigglers up to 100 m in length. In contrast, wigglers and undulators for other applications typically are less than 5 m long, with constant magnetic field amplitude. An additional requirement that applies to experimental IFEL wigglers (as opposed to future well-developed IFEL devices) is also indicated in Fig. 2: the exact taper that yields optimum performance in an IFEL system will depend on many system parameters, including the electron beam properties, the intensity of the input laser, etc. For an experimental device, additional flexibility in the capability to taper the wiggler is required to ensure that the proper taper can be attained for a variety of conditions resulting from off-nominal performance of other systems. Thus, for IFEL experiments, the wiggler must be "tunable" over some range of

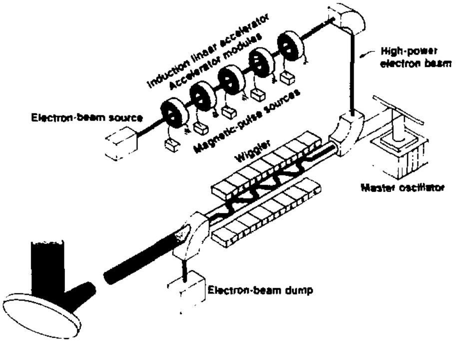

Figure 1. Schematic of an induction-linac free-electron laser (IFEL).

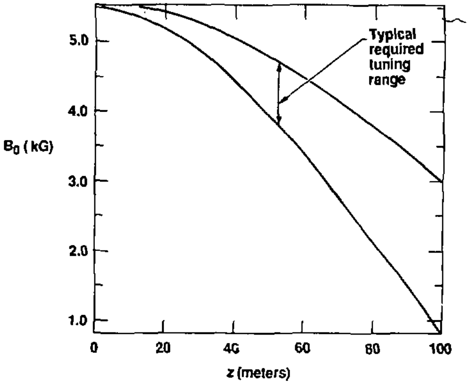

Figure 2. Typical operating range of magnetic field taper required for an experimental IFEL wiggler.

magnetic field amplitude, as shown in Fig. 2. We also share the requirement of most other wiggler and undulator designs, to maximize the wiggler magnetic field amplitude and shorten the period; this is a common requirement because higher field allows shorter-wavelength output radiation in all devices (including synchrotron light sources).

Recent wiggler and undulator designs for most applications have concentrated on minimizing the magnitude of pole-to-pole errors in the peak magnetic field. If each individual dipole in the wiggler is not identical in strength, then the electron beam will experience a sequence of random deflections, resulting in a "random walk" trajectory. As the wiggler length increases, the maximum displacement in the random walk becomes larger, and hence random errors are more important for long wigglers. Furthermore, IFEL performance is rapidly degraded as illustrated in Fig. 3, which shows the predicted output laser energy per pulse, normalized to the pulse energy attained for a perfect wiggler, as a function of the RMS value of the random variation of the peak magnetic field normalized to the average value of the peak field. Use of applied steering to correct the beam trajectory can relax the field error requirement somewhat, although recent system concepts still require errors less than 0.1% rms even with steering. This requirement is at or beyond the state of the art in wiggler design, and it represents a major design driver for all of our concepts.

There are several other requirements unique to IFEL wiggler systems. The magnetic field of the wiggler must provide equal-strength focusing in each of the transverse planes in order to compensate for nonzero electron beam emittance. Finally, since the use of high-current, high-energy electron beams usually results in a great deal of gamma and neutron radiation, all materials within the wiggler must be radiation-hard; we have concerns for permanent magnet materials in this regard.

Wiggler Concept Development

One of our primary activities at LLNL has been the development of new wiggler concepts that meet our unique requirements more fully than previous approaches. We have developed and deployed one large wiggler, which is now in use in IFEL experiments. We are also developing two new designs and have tested magnetic prototypes of each.

The PALADIN Wiggler

This wiggler (Fig. 4) was the first DC iron-core electromagnetic wiggler we developed to meet these unique requirements.[1] This wiggler was designed for a major IFEL experiment, producing laser light at 10.6 μ. It has an 8-cm period, 3-cm gap, and can operate up to 3.2 kG peak field on axis. It will eventually be 25.6 m long. To date, 15 m of wiggler have been tested and installed, and the remaining 10 m will be installed in late 1987.

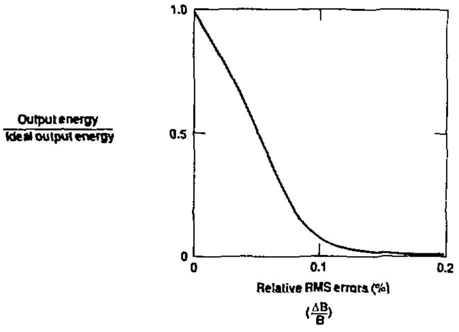

Figure 3. Effect of random pole-to-pole magnetic field errors on IFEL performance.

This wiggler is unique in that it was the first wiggler to demonstrate the concept of the permanent-magnet (PM) "assisted" electromagnet.[2] In this concept, high-energy permanent magnets are used to suppress saturation in the iron poles. The magnets are attached so that they do not contribute significantly to the field in the wiggler gap, but rather produce a large flux in the iron in the direction opposite to that of the flux produced by the coils alone. In this manner, the permanent magnets produce a negative bias flux in the iron, which can postpone saturation. This is clearly evident in the magnetization curve shown in Fig. 5. The permanent magnets are actually applied to the sides of the pole in this design, allowing the entire area between the poles to be filled with coils. This wiggler also demonstrated for the first time the use of curved pole tips to provide equal-strength focusing in both transverse directions. We used high-precision fabrication techniques in the construction of this wiggler, and the resulting field errors were measured at 0.14% rms for the first 5-m-long section. We have

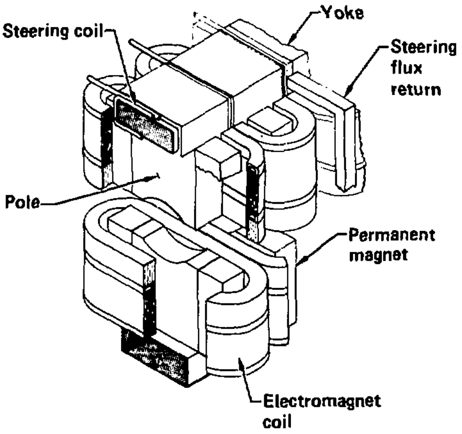

Figure 4. Schematic of the PALADIN wiggler concept.

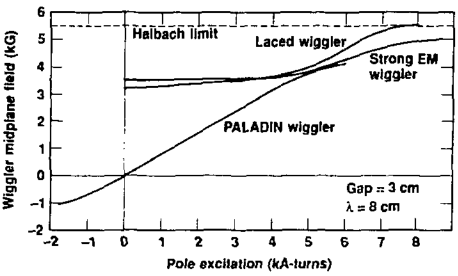

Figure 5. Magnetization curves for PM-assisted electromagnetic wigglers.

found, however, that these errors do not appear to be truly random, and their effect on the beam trajectory is predicted to be much less than expected.

The Strong Electromagnet Wiggler

For future IFEL systems, we saw the need for higher fields than those attained in PALADIN. To satisfy this goal, we have developed two more wiggler concepts that we are now exploring. Both of these concepts employ the PM-assist approach to a greater degree and may permit us to produce fields as high as those attainable with PM/steel hybrid wigglers. The first of these two approaches is the Strong electromagnet wiggler, shown in Fig. 6.[3] In this concept, all of the area between poles is occupied by PM, and the coil is located away from the gap. The large permanent magnets provide a high bias flux and thereby permit significantly higher fields to be attained; however, this negative bias flux saturates the poles when the coil current is reduced, giving this wiggler the interesting property that it cannot be fully turned off, as is evident from Fig. 5. One of the advantages of this wiggler is that the location of the coil away from the gap, allows more conductor area, resulting in lower power consumption. It is also attractive in that it minimizes the number of individual parts (coils, heat sinks, permanent magnets, etc.), with resulting cost advantages. A prototype of this concept, with period and gap as in PALADIN, has been built and tested, and we are now working on improving the pole design to allow higher fields to be attained.[3]

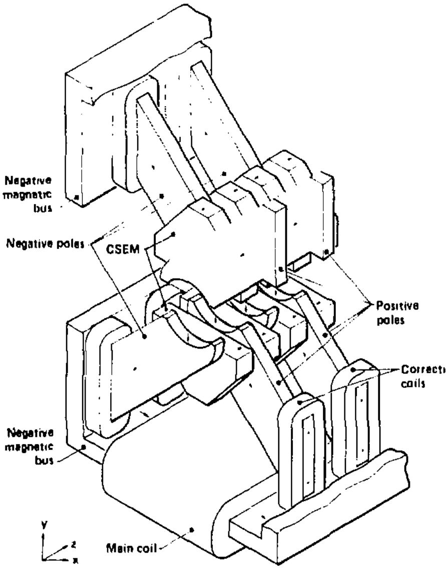

Figure 6. Schematic of the Strong electromagnet wiggler concept.

The Laced Wiggler

The second concept we are pursuing to attain higher magnetic field amplitude employs another extension of the PM-assist approach. The laced wiggler, shown in Fig. 7, mixes permanent magnets and coils in the area between poles and uses magnets on the sides of the poles, as in PALADIN.[4] This concept also should be capable of peak fields comparable to PM/steel hybrid wigglers. The predicted tuning range for this concept is similar to that for the Strong electromagnet wiggler, so it also cannot be fully turned off. The general similarity of this concept to the PALADIN wiggler is attractive, because it permits the use of analysis, design, and fabrication techniques that have already been demonstrated. The more complex pole concept seems to offer more design flexibility, in that trades between coil power, number of coils, permanent magnet volume, peak field, and tuning range are identified. In addition, it is likely that the favorable field-error correlation apparently found in PALADIN will also apply to the laced wiggler. We have recently completed the assembly of a one-period magnetic prototype of the laced wiggler, and some initial test results are reported in Ref. 4.

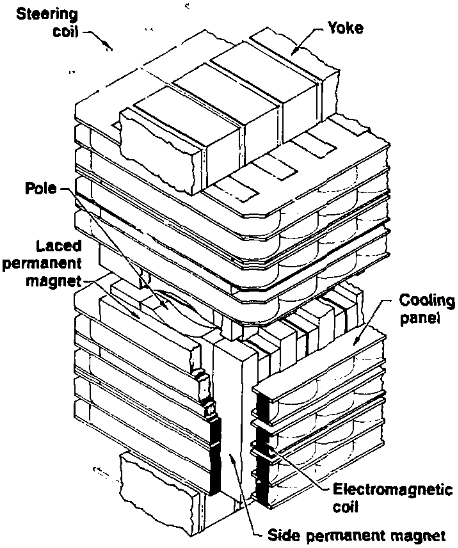

Figure 7. Schematic of the laced wiggler concept.

Supporting Activities

In addition to our ongoing efforts on the development and demonstration of wiggler concepts, we are conducting a number of supporting activities to address issues and capabilities that are critical to the eventual success of IFEL wiggler systems. One of these issues is the integration of control systems with the overall design; a second is the issue of radiation hardness of permanent magnet materials. We are also actively developing our capabilities for performing accurate magnetic measurements.

Wiggler Control Systems

In order to satisfy the IFEL design requirements, we feel that it is important to consider the wiggler and all of its controls and diagnostics as an integrated system. We have already identified two areas where the application of specialized control systems helps to satisfy a difficult design requirement, and we are now developing the system designs.

One difficulty with iron-core electromagnets is that there is a possibility for both nonlinearity (of field vs current) and hysteresis. For our wiggler designs, we require that the magnetization curve be 99% linear over the operating range, as a means of minimizing random errors arising from material differences in the poles; nonlinearity is therefore not an important controls issue for our devices. However, we have found that there is enough hysteresis in the magnetization curve (that is, difference in the field attained at a given coil current depending on whether the current has been increased or decreased to that point), that we cannot arbitrarily adjust the coil currents during FEL experiments. One solution to this problem is to require that all settings be made by, for instance, increasing the current; if a current decrease is required, then it must be decreased a large amount and then increased to the desired value. A better solution is the use of a field control system, which monitors the actual magnetic field and then adjusts the coil current as required to attain the desired field. This type of system has the additional advantages that it can compensate for changes in the magnetization curve (caused by changes in the permanent magnets, for instance), and that it can effectively deal with nonlinear magnetization curves, if desired. We are now experimenting with such a system on the PALADIN wiggler. It employs rotating-coil gaussmeters (which are relatively radiation-hard) to sense the actual magnetic field and a set of dedicated controllers that drive the power supplies to attain the desired field.[5]

A second area where control systems have relaxed difficult requirements on the wiggler itself is in the allowed random error level. Simulations have shown that the error tolerance can be relaxed somewhat if the electron trajectory in the wiggler can be corrected periodically to a straight line. We are now studying a beam-postion control system to accomplish this. Such a system will require a position sensor, a beam-steering capability, and a controller to actually apply the correction. Of these three elements, the most difficult is the position sensor, because it must be sufficiently accurate (better than 100 μ), and it must operate in the wiggler environment without perturbing it; this requires that it be nonmagnetic, radiation-hard, and physically compatible with the space available. We are now bench-testing a prototype of a device that measures beam position by using eight loops to sample the azimuthal field of the beam (Fig. 8), and the initial results appear promising. We plan to continue development of this sensor, and perhaps test a closed-loop position control system in the next year.

Permanent-Magnet Radiation Hardness

A small amount of data exists that indicates that permanent magnets are susceptible, to varying degrees, to demagnetization when subjected to radiation.[6] Because this is an extremely important issue for FEL wigglers, we have begun a program to evaluate available materials and develop new materials with advantages in this area. Initially, we are irradiating a variety of PM materials in a Co-60 source, as a rapid means of examining the effect of gamma radiation alone. We are also assembling an experiment that will expose materials to linac-produced radiation and measure the resulting demagnetization. Until these experiments are completed, we are basing our wiggler designs on those materials that seem to have the highest radiation resistance; unfortunately, these materials are not the strongest permanent magnet materials currently available.

Magnetic Measurements

A key element of our IFEL program has been the development of a general-purpose magnetic measurements laboratory, which has been used for most of the activities described here.[7] Such a facility is essential for performing the detailed and high-accuracy measurements required in many cases, as well as for allowing rapid and inexpensive tests to study new concepts or develop data required for design activities.

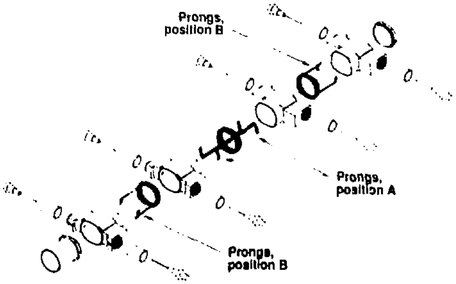

Figure 8. Schematic of precision beam position monitor (exploded view).

Conclusions

At LLNL, we are approaching the wiggler design as a system and developing not just the magnetic structure, but the control systems, materials data base, measurement capabilities, and support facilities as well. We are now operating the first PM-assisted EM wiggler, and we are developing two new concepts that will operate at almost twice the magnetic field. We are also conducting basic studies into PM radiation hardness. Although these activities are diverse, all are focused on satisfying the unique requirements of IFEL systems in the most cost-effective manner.

References

[1] G. A. Deis, *et al.*, "A Long Electromagnetic Wiggler for the PALADIN Free-Electron Laser Experiments," presented at the Tenth International Conference on Magnet Technology, Boston, MA, September 23-26, 1987.

[2] K. Halbach, "Some Concepts To Improve the Performance of DC Electromagnetic Wigglers," *Nucl. Inst. Meth.*, vol. A250, pp.115-119, 1986.

[3] M. J. Burns, *et al.*, "Development of the Strong Electromagnet Wiggler," presented at the Tenth International Conference on Magnet Technology, Boston, MA, September 23-26, 1987.

[4] T. C. Christensen, *et al.*, "Development of the Laced Electromagnetic Wiggler," presented at the Tenth International Conference on Magnet Technology, Boston, MA, September 23-26, 1987.

[5] B. Kulke, *et al.*, "Magnetic Field Diagnostics for an FEL Wiggler," presented at the 1987 Particle Accelerator Conference, Washington, D.C., March 16-19, 1987.

[6] E. W. Blackmore, "Radiation Effects of Protons on Samarium-Cobalt Permanent Magnets," Trans. IEEE *NS-32* (1985), p. 3669.

[7] M. J. Burns, *et al.*, "The Livermore Free-Electron Laser Program Magnet Test Lab," presented at the Tenth International Conference on Magnet Technology, Boston, MA, September 23-26, 1987.

Work performed jointly under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under W-7405-ENG-48 and for the Department of Defense under SDIO/USA-SDC MIPR No. W31RPD-7-D4041.