DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Title:

MEASUREMENT AND CORRECTION OF MAGNETIC
FIELDS IN PULSED SLOTTED-TUBE MICROWIGGLERS

Author(s):

C. M. Fortgang and R. W. Warren

Submitted to:

15TH International Free Electron Laser Conference
The Netherlands
August 23-27, 1993

RECEIVED

SEP 07 1993

OSTI

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Se

Form No. 836 R5
ST 2629 10/91

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MEASUREMENT AND CORRECTION OF MAGNETIC FIELDS IN PULSED SLOTTED-TUBE MICROWIGGLERS *

C.M. Fortgang and R.W. Warren
Mail Stop H825
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

Pulsed electromagnetic microwigglers are capable of creating stronger fields with shorter periods than conventional wigglers. Wiggler field parameters of 1 Tesla and 5-mm period are achieved by passing ~25 kA down a slotted 3 mm outer diameter copper tube. The taut-wire technique is used to measure the wiggler magnetic field in a small aperture (~1.7 mm) with the required spatial (0.1 mm) and temporal (~5 μ s) resolution. The absence of midplane symmetry, in contrast to permanent magnet wigglers, causes unique problems in our microwigglers. We have measured strong dipole (bending) and quadrupole (defocusing) field errors with both dc and time-dependent parts. The effects on the magnetic field of current redistribution caused by heating in the copper tube has been measured. We have identified causes for the various field errors and their sensitivities to fabrication tolerances. Improvements we have made towards meeting the required tolerances and our field-correction technique will be discussed.

1. Introduction

Pulsed electromagnetic microwigglers can develop higher magnetic fields with shorter periods than conventional wigglers. We are interested in microwigglers because of the special advantage of the high field and short period in generating short wavelength light (UV-XUV) using electron beams of modest energy (<100 MeV). Also, because the magnetic field of a microwiggler is easily variable it provides a method for rapid tuning of the wavelength of the FEL light. Figure 1 illustrates the wiggler system composed of the inner slotted wiggler tube, the outer tube that returns the current, the electrical short connecting the two tubes, and the cooling tubes that also serve as field trim coils. Because of the slots, the current flowing on the inner tube is forced to alternate from one side to the other side of the tube, thus generating a wiggler field. A field strength of 1 Tesla and period of 5-mm are achieved by passing ~25 kA down the slotted inner tube (3-mm OD). In previous work we have reported on the mechanical design, the pulsed current supply, the transformer which impedance matches the current supply to the microwiggler, the trim coils, and the cooling and vacuum systems [1,2]. In this paper we discuss in detail the magnetic field errors found in these microwigglers, the causes of the errors, and techniques we have developed to minimize them. We use the pulsed-wire technique to measure directly the first integral of the magnetic field [3,4]. It has the temporal resolution (2-5 μ s) to measure the magnetic field during the current pulse (15-120 μ s) and the spatial resolution (~0.1 mm) to measure field multipoles (we have measured field errors out to third order (octupole)), in the small wiggler aperture (1.5-2.0 mm).

Work supported by the US Department of Energy, Office of Defense.

2. Field errors and their causes

The four most important errors found in our microwigglers are: first, a z-independent (uniform down the wiggler) dipole (steering) field; second, a z-independent quadrupole (defocusing) field; third, a wiggler entrance (and exit) dipole field; fourth, an entrance (and exit) quadrupole field. These four errors cause the beam to bend off-axis quadratically with z, to defocus exponentially with z in one plane, to move off-axis linearly with z, and to defocus linearly with z in one plane, respectively. These errors have both average and time-dependent parts because of wiggler heating and magnetic diffusion, both of which cause a redistribution of current and thus a change in field.

Three of these errors (the z-independent dipole and quadrupole errors and the end quadrupole error) are caused by a lower symmetry than is present in conventional wigglers. Permanent magnet wigglers have north poles opposite south poles; helical wigglers have positive currents opposite negative currents. Because a slotted tube microwiggler has current of just one sign, (switching back and forth between alternate sides of the tube) it lacks a similar odd midplane symmetry, causing unique systematic errors. If a permanent magnet wiggler were built with alternate magnets removed from the top and bottom (eg. all south pole magnets missing) it would have the same lower symmetry as our microwiggler. We now discuss the details of the microwiggler field errors in the order introduced above.

We have identified two causes of a z-independent dipole error. First, if the wall thickness of the wiggler tube is not uniform (an asymmetry) then on average more current will flow on the thick side of the tube, creating a uniform dipole field in addition to the sinusoidal wiggler field. For this error to be negligible the wall thickness has to be uniform to about 0.1 %. Commercial tubing is uniform to just a few percent and therefore is not suitable for our purposes. Second, if the slotted tube is not concentric (an asymmetry) with the outer tube a dipole field is created inside the wiggler tube. Both of these errors are time-dependent due to magnetic diffusion with a time constant of about 50 μ s (given the wall thickness (~ 0.7 mm) of the tubes). Wall non-uniformity has no effect at early times, because the current flows only on the skin of the conductors. As the field and current diffuse into the tube walls non-uniformity becomes more important and the dipole field error reaches a steady state value if the pulse is long enough. When the tubes are non-concentric, currents that flow on the tube surfaces are not symmetric but are greater on the side with the smallest gap, again creating a non-sinusoidal dipole field error. As the current diffuses into the tubes it tends to approach a uniform distribution that decreases the magnitude of the error field. Thus these two effects are time-dependent in the opposite sense; the wall thickness error increasing with time and the non-concentricity error decreasing with time.

The sign of the local wiggler dipole field depends on which side of the tube the slot is cut. Because the current flows only on one side of the tube at any z-position (an asymmetry) there is, in addition to the dipole field, a quadrupole field. The sign of the quadrupole field caused by a slot depends only on its depth and not on which side of the tube the slot is cut. If the depth is varied, a depth can be found that generates no quadrupole field. Therefore, a quadrupole field with a non-zero (line average) value is caused by slots of identical depth not having precisely the correct depth. Again the tolerance is tight, the slot depth has to be correct to about 0.1% (~ 20 μ m) for the quadrupole field to have only a small effect on the beam size. Unfortunately, wiggler heating causes a time-changing quadrupole field. The copper heats up mostly at the tips of the slots where the current density is highest. The local resistance rises, pushing

the current away from the slot and effectively increasing the slot depth. We use a 2-D analytic model [5] (which neglects heating) as a guide to finding the best slot depth.

As with conventional wigglers the ends need special treatment. To keep the electron beam parallel with the wiggler axis the end slots are made approximately half as deep as the other slots. Because end effects are not treated in the 2-D model, we find the proper depth solely by trial and measurement. Because the end slots are not as deep as the other slots they create a large, but localized, quadrupole field. The end slots act as thin lenses (in addition to their dipole field) and cause the beam to diverge in one plane.

3. Field error measurements and techniques to correct them

To minimize the problem of wall non-uniformity we make our own tubes by a plating process; they are 50 to 100 times more uniform than commercial tubes [2]. However, even these tubes usually have a non-negligible variation in wall thickness. To solve the problem of non-concentricity we center the inner tube by using nylon screws inserted through tapped holes in the outer tube (spaced every 2.5 cm). The screws are adjusted while pulsing the wiggler at low current (so effects due to heating are negligible) until the wiggler field is time-independent. Figure 2 shows the first integral of the wiggler field as a function of time before and after centering of the inner tube. If the steady-state dipole field is non-negligible (due to wall thickness non-uniformity) it is subsequently corrected by another technique (hole drilling), described below.

To find the slot depth that gives zero quadrupole field we make trial wigglers with slots that are arranged into 3 to 5 sections, each section with a different depth covering a range around our best estimate of the correct depth. Measurements (first integral) of the quadrupole field are made and plotted and by interpolation the correct slot depth is determined. Figure 3 shows results from such a trial wiggler. First, we measure the wiggler field on axis (center trace). Measurements are then made off-axis ($\pm$, top and bottom traces) and subtracted from the on-axis data. The resulting difference signals are proportional to the quadrupole field; where a slope of zero is indicative of zero quadrupole field. In Fig. 3 the 5 different sections and their respective quadrupole fields are clearly seen. Data is taken at various currents and times to measure the effect of heating upon the quadrupole field. We find that the effective change in slot depth due to heating changes the quadrupole field by an unacceptable amount during a 50 μ s, 25 kA pulse. A compromise slot depth is chosen so that the quadrupole field in conjunction with the natural betatron focusing of the microwiggler provides two plane focusing during a limited time of the current pulse. The time during which two plane focusing exists is inversely proportional to the microwiggler current squared. For present wigglers this time is ~ 6 μ s but will be much longer for the new wigglers now under construction because of their larger diameter and thicker walls. This time changing quadrupole field caused by heating (and not melting of the copper tube) is a fundamental limit on the current, pulse length, and period for our pulsed microwigglers.

The trial wigglers are made with end slots of two different depths. The data from these two choices are used to determine the depth necessary to keep the beam on axis when transversing the ends of the wiggler. The jump at the beginning of the center trace in figure 3 clearly shows that the first slot is too deep, whereas the smaller jump at the last slot shows it is closer to being correct. The jumps in the off-axis data at the ends

of the wiggler are caused by the quadrupole field generated by the end slots. To cancel this field two small holes are drilled in the wiggler tube (at 90 degrees with respect to the center of the slot) about one period upstream and downstream of the wiggler ends. Holes of the correct diameter create a quadrupole field of equal strength and opposite sign to that of the end slots making the line integral of the quadrupole field through the ends of the wiggler nearly zero.

After the four major errors are corrected as described above, residual systematic errors (ie. z-independent caused by asymmetry) and localized errors (caused by fabrication tolerances) still remain. We characterize these remaining errors by their orientation (normal or skewed) and their order (dipole, quadrupole, sextupole, or octupole). We correct them by both enlarging the existing tapped holes and drilling new ones in the outer tube. (The nylon screws are removed after the two tubes are centered and potted with an inorganic cement.) Holes of the appropriate symmetry modify the current distribution to generate a new field that cancels the error field. This procedure is performed while the wiggler is repeatedly pulsed and measured (~ 0.3 Hz) with the taut-wire. The wiggler is on a x-y translation stage that provides a convenient method for measuring the field integrals at different transverse positions which is necessary to measure field multipoles. Figure 4 shows data from a completed wiggler. The first integral data of the wiggler field and the orthogonal field (ideally zero) are shown at four transverse positions (taken at 0.1 mm intervals). The four traces, in each of the two planes, have zero average slope and are nearly identical indicating the absence of dipole and multipole field errors. The ends of the wiggler have the correct entrance and exit kicks on axis and the kicks vary little with transverse position.

In spite of all our labor, these results are still a factor of 5 to 10 worse, in terms of particle trajectories, than we obtain with permanent magnet wigglers. We show this by integrating the data once numerically, obtaining the second integral of the field, which is proportional to particle trajectory. We find that the on-axis errors are negligible; that is a particle that starts on axis wanders off-axis by a negligible amount as it transverses the wiggler length. However, trajectories of beam particles that enter the wiggler off axis, while having no net displacement, do have a rms deviation from the wiggler axis about equal to their initial displacement. These observations indicate that the dipole field error along the microwiggler is negligible but that the z-averaged rms amplitude of the higher order multipoles is still important. The net effect of these errors is an undesirable changing of both size and divergence of the beam as it travels down the microwiggler. We estimate that these changes to the beam phase space increase the effective (z-averaged) beam emittance by a factor of 2 to 4. In contrast, field errors in our permanent magnet wigglers have a negligible effect on beam emittance; they have second integrals that keep all the beam particles within one peak wiggle amplitude of their initial position [6,7].

4. Conclusions

We have identified causes of the most serious field errors for pulsed slotted-tube microwigglers. We have developed techniques to correct these errors and are continuing to improve upon our techniques. For microwigglers we have made in the past and for situations where gain is sensitive to beam emittance, our microwiggler field-errors are serious. However, we continue to make improvements to the fabrication process (such as more uniform tubes) and to our field correction techniques (hole drilling). We are also investigating incorporating strong (alternate gradient quadrupole)

focusing in these microwigglers. This is easily achievable by alternating the depth of the slots, every few periods, about the depth that gives zero quadrupole field. A microwiggler with a strong focusing lattice is affected less by field errors than one without strong focusing. The time-changing quadrupole field, caused by heating at the tips of the slots, is the most fundamental effect that limits the design parameters (a_w , period, and pulse length) of these microwigglers.

References

- [1] R.W. Warren, Nucl. Instr. and Meth. A318 (1992) 789.
- [2] R.W. Warren and C.M. Fortgang, in the proceedings of the 14th International FEL Conference (1992) Kobe, Japan.
- [3] R.W. Warren, Nucl. Instr. and Meth. A272 (1988) 257.
- [4] D.W. Preston and R.W. Warren, Nucl. Instr. and Meth. A318 (1992) 794.
- [5] R.L. Gluckstern, Phys. Rev. A15 (1991) 3889.
- [6] C.M. Fortgang, 1992 Linear Accel. Conf. Proceedings, Ottawa, Canada, 169.
- [7] R.W. Warren and C.M. Fortgang, in these proceedings.

Figure Captions

- 1. Simplified drawing of the wiggler tubes.
- 2. On-axis data at 30 μ s intervals (a) before and (b) after centering of the slotted tube.
- 3. Data from a trial wiggler showing sensitivity of quadrupole field to slot depth.
- 4. From a completed microwiggler, first integral data in both transverse planes at four different transverse positions (0.1 mm apart).

c)

d)

e)

END

**DATE
FILMED**

10 / 22 / 93