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HIGH-FIELD PULSED MICROWIGGLERS*

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Abstract

Conventional wigglers made with periods of less than a few centimeters generate light of short wavelength, but usually have low gain because of their low fields. Iron-free electromagnets driven by high pulsed currents can generate the high fields needed. We will discuss the design and construction of such magnets.

1. Introduction

There has recently been considerable interest [1] in building microwigglers, i.e., wigglers with periods significantly shorter than one centimeter, because of their proposed use to generate light of short wavelength with electron beams of only moderate energy. Most wiggler designs being considered use ferromagnetic materials and so are limited to a maximum field at the magnets of 1 to 2 T and lower fields on the wiggler's axis. A parameter that is commonly used to characterize a wiggler is its K_{rms} value, given by $K_{rms} = e \cdot B_{rms} \cdot L_w / (2 \cdot \pi \cdot m \cdot c)$, where B_{rms} is the rms value of the wiggler's field on axis and L_w is the wiggler period. The wiggler's gain increases as K_{rms}^2 but saturates when $K_{rms} \approx 1$. If B_{rms} is limited to 1 T and L_w is continually reduced, K_{rms} drops below 1 at a period of 1 cm. The challenge for microwiggler designers is to shrink the period below 1 cm while maintaining K_{rms} as near 1 as possible. In this paper, we will identify a strategy to accomplish this. We will cover the following subjects: In Sections 2 and 3, choice of

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designs for microwigglers and estimates of the expected performance of the best design; in Section 4, the wigglers that we have built; in Section 5, the performance of these wigglers and the problems encountered; finally, in Section 6, conclusions.

2. Design choices

If K_{max} is maintained at 1 while L_w is reduced below 1 cm, B needs to exceed field values that can be produced by ferromagnetic materials. Thus, we must eliminate such materials from the wiggler. Superconductors look attractive as conductors but, at the present time, cannot support current densities in excess of 10^4 A/sq cm. Estimates show that densities in excess of 10^6 A/cm² are needed. In normal conductors, DC currents cannot exceed densities of about 10^3 A/cm² without excessive heating. Early experiments [2] show that current densities of the required magnitude can be generated by pulsed currents in copper coils. Pulsed currents in some configuration of copper-like conductors are, therefore, the basis of this work.

Various arrangements of conductors can be visualized. Simple, symmetrical structures are preferred for their ability to contain the magnetic forces, to avoid waste space in insulation, and to avoid arcing at crossovers. The simplest wiggler satisfying these conditions and providing a pure transverse field is the double (or bifilar) helix, shown in fig. 1a. This wiggler generates a helically polarized field, which is not always desired. The simplest wiggler producing a plane polarized field has two overlapping helices (fig. 1b). It has important advantages over the bifilar wiggler, particular at the end connections, but its fabrication techniques are more complex. A third candidate (fig. 1c) is a simple helix. Its field is a combination of a transverse, helically polarized field and a longitudinal field. Lasing with such an unusual field is probably possible but appears to present no advantages. Other more complex structures suggest themselves, but we have chosen, at this time, to work solely on the double helix built with a single conductor for each helix.

A double helix can be built by winding ordinary wire on a mandrel. Alternative techniques have also been investigated that provide certain advantages, for example, closer

tolerances, higher fields, or better cooling. A major problem with these techniques, however, is providing electrical contacts at the ends. A wound conductor automatically satisfies this need and, therefore, has been picked as our primary choice. Wound conductors can be round or have a rectangular or semicircular cross section that generates a higher field. A hollow conductor provides a passage for a coolant. We have, so far, chosen to work only with round, solid, or tubular copper conductors that are wound on an insulated, hollow metal tube, using a lathe and suitable wire feeders to maintain close tolerances on the period. We are certainly not the first investigators to work with a wound bifilar helix. What distinguishes our work is our emphasis on a K_{rms} value of 1 and our attempt to push technology to its limits to reach small values of period.

3. Estimates of performance

In estimating the performance of a double helix wiggler, we have chosen parameters to mimic the Los Alamos 1-m untapered wiggler. The ratio of period to gap, for example, is π . With this ratio, the conductors are wound at a 45° angle with respect to the axis. We have picked the conductors to be single strands of round copper wire with a diameter such that they cover two thirds of the wiggler surface. We have calculated the current necessary to generate a K_{rms} value of 1, we have used values of electrical conductivity and heat capacity as a function of temperature to evaluate the temperature rise in the conductors. We have determined the field at the conductors and evaluated the force on them. We have accumulated the results of these calculations for a series of different wigglers. Wiggler #W27 is an unscaled, double helix copy of the Los Alamos model with a period of 27 mm, while #W9, #W3, and #W1 represent models scaled down in all dimensions to periods of 9, 3, and 1 mm, respectively.

We find that the current required to achieve $K_{rms} = 1$ is always the same, ~ 5 kA, and the wire tension is always about 1 lb. The current density and tensile hoop stress, however, increase rapidly as the scale size is reduced. The wire's temperature at the end of a macropulse is an important limiting factor. It increases rapidly as the scale size is

reduced and the macropulse is lengthened. We have chosen to use a 100- μ s pulse because this is the planned pulse length of the FEL at Los Alamos. Pulse times as short as 1 to 10 μ s might be used, however, if the small-signal gain is large enough and the optical cavity short enough so that saturation is reached in this time. We have not scaled to sizes smaller than #W1 because the wire's temperature would exceed its melting point after 100 μ s.

Another limiting factor is the breaking stress of the conductor. For copper conductors used with a 100- μ s pulse, the temperature limit occurs first. For a shorter pulse, the breaking limit comes first. Both limits can be relaxed by various means, e.g., supporting the wire or cooling the conductor. Supporting the wire is an easy and successful fix. Immersing a conductor in a cool fluid is not usually effective in extracting heat from the conductor during the short heat pulse, but provides us with a lower starting temperature (allowing a longer macropulse) and provides better cooling between macropulses (allowing a higher pulse repetition rate). We have made estimates of the gains to be made in macropulse length by cooling to liquid nitrogen, hydrogen, or helium temperatures and find increases by factors of about 2, 4, and 8, respectively. These improvements may not be realized in practice because we have assumed ideal behavior of the conductors, i.e., perfect purity, no strain, no magnetoresistance, etc. Comparison has been made of the performance of various conductor materials including copper, aluminum, silver, and gold. Copper performs as well or better than the others and is inexpensive, easy to work with, and readily available in many shapes and forms. We have, therefore, concentrated our efforts on copper.

Our conclusions from these estimates is that wiggler #W9 should be easy to build, that #W3 might be built if a cryogen and a pulse shorter than 100 μ s were used, and that #W1 can probably not be built to satisfy $K_{rms} = 1$ using these techniques. In the following, we will discuss our work to validate that wiggler #W9 can be built.

4. Hardware

We have built an apparatus to test conductors with current pulses up to about 30 kA in a damped sine-wave format with a half period of 150 μ s. With this device, we tested the range of currents that different copper wires could tolerate before exploding. The results were in fair agreement with the calculated limit corresponding to the melting point of copper. This same apparatus was used in many tests with complete wigglers. The first wigglers that we built were wound of solid #16 copper wire (1 mm diam) covered with fiberglass-epoxy. The repetition rate for a 100- μ s pulse must be less than 1/min to avoid overheating. The next wigglers were wound of copper tubing covered with fiberglass-epoxy. The repetition rate could then be raised to about 1/s because of the internal cooling afforded. Designs have been advanced to further improve heat removal by providing many short, parallel paths for coolant flow between adjacent wires. No models have yet been built following these designs. If special care is not taken with the design of the ends of a wiggler, the fields generated there cause a net bend to the electron beam. This can be easily controlled by making the two windings of the double helix identical. One can show that the ends then generate no angular error and only a small offset to an electron beam in the body of the wiggler. To preserve this symmetry, the conductor leads at both ends of the wiggler must be connected to each other or to the power supply far away from the wiggler's axis. The details of these connections are being continually refined with the help of a special high-sensitivity field-measuring apparatus. A second power supply has been built to supply the flat current pulse needed during lasing. Its circuit incorporates 20 capacitors in an artificial delay line with a characteristic impedance of 0.1 Ω . Wigglers of #W9 size that we have built have a resistance of about 10 $\mu\Omega$ at room temperature and an inductance of about 0.25 μ H. At the end of a 100 μ s pulse, their resistance has increased because of heating by about 20%, adversely affecting the performance of the power supply. We have reduced this variation in resistance by adding a 90 $\mu\Omega$ dummy resistor in series with the wiggler. The deviations from constant current during a 100 μ s pulse, i.e., ripple

and slump, are then less than 2%. Modifications to the design of the power supply are being made to improve this performance by employing active feedback.

5. Performance of models of #W9 Built

Fig. 2 shows a wiggler made with copper tubing being wound by a lathe on an insulated stainless steel hypodermic mandrel of 2.8 mm o.d. and 2.2 mm i.d. This wiggler has 25 wiggles with a period of 8.5 mm; the copper tube has an o.d. of 2.1 mm and an i.d. of 0.8 mm; the insulating layer is 0.1 mm thick. When finished, the winding will be covered with fiberglass impregnated with epoxy. Fig. 3 shows a partially completed wiggler mounted between vacuum flanges and connected to a coaxial-cable current source and to coolant tubes. The outer aluminum shield has been removed for the picture. Models like this are checked for electrical integrity, field uniformity, and end effects with a pulsed-wire field-measuring setup. This measuring technique has been discussed in the literature [3,4]. When applied to pulsed wigglers, this technique works without new problems and presents several new advantages over alternative field measuring techniques: The "field probe" is a 1- to 2-mil tungsten wire threaded down the hypodermic tube. Clearly, very small wigglers can be measured with such a probe. Second, this technique uses a current pulse a few microseconds long passing through the tungsten wire. By changing the timing of the pulse, fields generated at different times in the macropulse can be investigated. Finally, the short current pulse generates a transverse deflection of the wire that propagates to the detector slowly, arriving several milliseconds after it is generated and, more importantly, several milliseconds after the electrical interference caused by the discharge of the main capacitor bank has subsided. Fig. 4 shows a trace from an oscilloscope illustrating the voltage waveform developed by the wiggler at the detector. The current pulse used was 15 μ s long and the trace in fig. 4 is directly proportional to the angle taken by a hypothetical electron passing through the wiggler. The magnetic field can be found by taking the derivative of this trace, the electron's displacement by taking the integral. Figs. 5 and 6 show such an integral taken for a wiggler with a serious end effect problem and one with

a problem that is small because of its symmetrical construction. Fig. 7 is a photo showing this field-measuring technique in use with a typical wiggler.

In addition to problems at the ends of a wiggler, one can detect nonsinusoidal displacements of the electron at other places in Figs. 5 and 6. These are caused by irregularities in the windings resulting from nonuniformities in the mandrel, the insulation, the tubing, or its positioning. The extraneous displacements are not significant as long as they remain small compared to the magnitude of the sinusoidal displacements. Such is the case for the examples shown. We expect to reduce these aberrations as we gain a better understanding of the winding technique.

6. Conclusions

Several models of a 9-mm-period pulsed wiggler have been built and tested. They easily produce a K_{rms} value of 1 and have acceptable field uniformity and end effects. Being built with a hollow conductor, they can be used with a pulse repetition rate of 1/s or so. The wigglers are housed in an assembly that provides convenient vacuum, electrical, and coolant connections, minimizes wakefields, and shields the wiggler and the ambient from each other. A power supply to provide the flat current pulse that is required has been completed and is undergoing tests.

Based on the experience gained with wigglers of this size, smaller models appear to be buildable, but modified designs such as the crossed-helix configuration and modified construction techniques including cryogenic coolants should be incorporated. We intend to pursue these approaches.

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Figure Captions

- Fig. 1a. A bifilar helix.
- Fig. 1b. A crossed double helix.
- Fig. 1c. A simple helix.
- Fig. 2. Bifilar helix being wound.
- Fig. 3. Completed wiggler assembly.
- Fig. 4. Signal from pulsed-wire system.
- Fig. 5. Integral showing deflection for bad wiggler.
- Fig. 6. Integral for good wiggler.
- Fig. 7. Field measuring setup, showing the fixtures used to test the effects of a nearby flange, bends in the wiggler, and different end connections.

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10-1
10-2

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Fig 3

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AREA = 1.894 E-5 VOLT-SECONDS

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Fig 1

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