SMALL PERIOD ELECTROMAGNET WIGGLERS FOR FREE ELECTRON LASERS

W. W. Destler, V. L. Granatstein, I. D. Mayerogyz, and Z. Segalov

Electrical Engineering Department
University of Maryland
College Park, Maryland 20742

Introduction

Small period wiggler magnets for Free Electron Lasers (FEL´s) are currently a topic of considerable interest because a small wiggler period leads to a reduced electron energy requirement for a desired radiation wavelength. A great deal of effort has been expended on the design of permanent magnet wigglers in recent years,[1] and high quality wigglers of this type have been constructed with periods typically in the range 1-10 cm (although methods for constructing even shorter period wigglers are currently under development). Recently our group has reported[2] a technique for fabricating small period (1-10 mm) electromagnetic wigglers in which the magnetic field amplitude can be varied continuously by varying the current in the electromagnet "windings." In addition, the proposed design is bilateral, thus increasing the magnetic field amplitude and reducing the transverse gradient in the magnetic field in the central region between the two magnetic structures. As these wiggler electromagnets are inexpensive and easily constructed, they might prove useful for studying FEL physics and for the development of practical, lower voltage, FEL devices. In this paper we present the initial results from a program to investigate the performance characteristics of such wiggler electromagnets, and gain and efficiency calculations for an FEL employing a small period electromagnet wiggler of this type.

Magnet Design

The basic design of the simplest form of the wiggler electromagnet is shown in Fig. 1. A conducting sheet of copper runs through a stack of insulated ferromagnetic laminations in alternating directions, and the laminations and copper sheet are squeezed together forming a rigid structure. A current is passed through the copper sheet to produce a periodic magnetic field, and two such structures (or one with an appropriate beam channel) can be used to produce a bilateral wiggler magnetic field suitable for a pencil or sheet electron beam. If we consider a region within the electron beam channel which corresponds to one period of spatial variation of the magnetic field (see Fig. 2), and assume that the permeability of the laminations approaches infinity, then the field in the channel is given approximately by:

$$B_y(y, \ell_o/4) = \frac{4\mu_o I}{\pi h} \frac{\sin(\pi h/\ell_o)}{\sinh(\pi\delta/\ell_o)} \cosh(2\pi y/\ell_o) \ .$$

Under these assumptions, and assuming $\delta = \ell_o = 3$ mm and $h = 1$ mm, the field in the center of the gap is $B/I \simeq 10^{-4}$ Tesla/Amp. Thus, a wiggler field magnitude of 0.1 T would be generated by a current of 1 kA. For a central region of the gap with width 0.5 mm, the inhomogeneity of the field is about 7%. The current density in the copper sheet is about

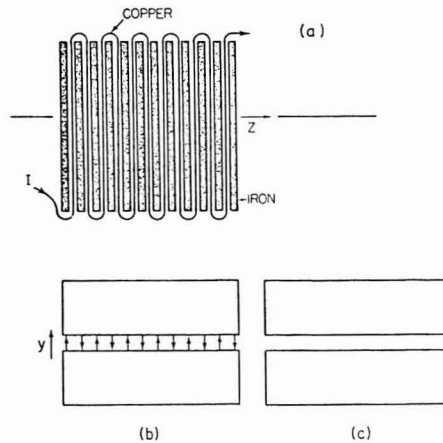1 kA/cm^2 assuming a sheet height of 10 cm.

FIG. 1. (a) top view, (b) simplified side view, and (c) front view of wiggler electromagnet.
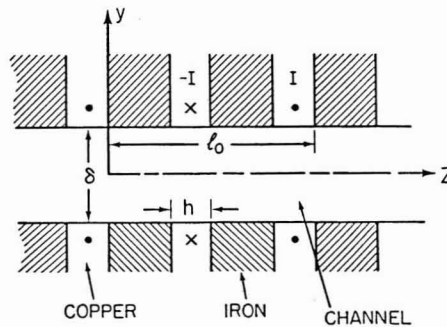

FIG. 2. Region within the electron beam channel which corresponds to one period of spatial variation of the magnetic field.

Experimental Measurements

In a previous paper,[2] we presented measurements verifying the periodic nature of the magnetic field and the field amplitude at relatively low current levels. Because at high current levels saturation in the ferromagnetic laminations can be an important effect, we have constructed several wiggler electromagnets to determine to what extent the achievable magnetic field strengths are limited by saturation effects. These magnets have been powered by both dc and pulsed current sources; dc operation has been maintained at current densities well in excess of 1 kA/cm^2 without any noticeable heating of the magnet, and pulsed currents several times higher have been obtained using a small capacitor

bank. Results of measurements of the magnetic field amplitude 1 mm above the surface of the magnet as a function of current are shown in Fig. 3. These field amplitudes would be multiplied by two for a bilateral magnet. The results are from a 3.9 mm period magnet using standard transformer laminations. Significant, although not devastating saturation is clearly evident in the steel core magnet. Interestingly, pulsed operation results in improved performance at high current levels, perhaps because the current is forced to flow near the edge of the copper sheet, thus enhancing the field strength in the beam channel and reducing the leakage flux saturation of the core. Preliminary results from a magnet with Supermendur laminations indicate that this material may substantially reduce saturation effects at high operating current.
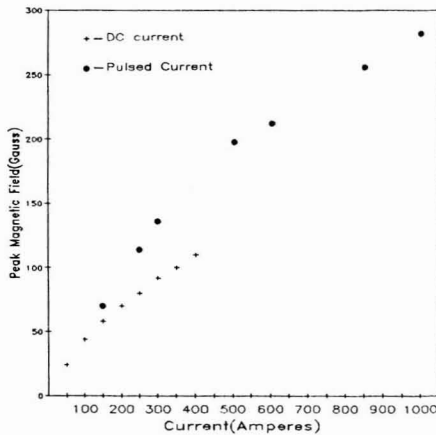

FIG. 3. Results of measurements of the magnetic field amplitude 1 mm above the surface of the magnet as a function of current.

Implications for Free Electron Laser (FEL) Design

The availability of planar wiggler magnets with sub-centimeter period would have important implications for FEL design. As an example, for a wavelength of λ = 1 mm (300 GHz) and electron energy of 400 keV (γ = 1.78, β = 0.83) we calculate the required wiggler period as ℓ_o = $\beta(1 + \beta)\gamma^2\lambda$ = 4.8 mm. Then with a gap spacing of δ = 2 mm, we estimate based on the wiggler magnet studies described above that a wiggler field of $B_y(0, \ell_o/4)$ = 0.05 T will readily be achievable. We also assume a modest beam electron density of n_b = 3 × 10^{10} cm^{-3}. The approximate expressions for FEL power gain, G, and intrinsic efficiency, η, are those for the "low gain" regime;[3] viz.,

$$G = \pi^3\xi^2\beta_{o\perp}^2N^3(1 + \beta)/2\beta \quad (1)$$

$$\eta = 1/2N \quad (2)$$

where $\beta_{o\perp}$ = $eB_o/m\gamma ck$, ξ^2 = $e^2n_b/\epsilon_o m\gamma c^2k^2$, k = $2\pi/\ell_o$, and N is the number of periods in the wiggler. Usually in the expression for G, the factor $(1 + \beta)/2\beta$ is set equal to unity as is appropriate for $\gamma \gg 1$, but we have generalized the gain expression so that it also applies in the $\gamma \gtrsim 1$ case. Also, in Eq. (1), we have assumed the filling factor is unity as would be

approximately the case, if the electron beam were inside a closely fitting waveguide.

For the parameters in the present design we calculate $\beta_{o\perp}$ = 1.26 × 10^{-2} and ξ = 1.02 × 10^{-2}. Then choosing the number of ripples as N = 50 to give a compromise between acceptable G and acceptable η, we calculate G = 7% and η = 1%. In a low loss 300 GHz cavity, a single pass power gain of 7% should be sufficient to ensure oscillator operation. Overall efficiency could be enhanced by using depressed collector techniques to recover part of the energy in the spent electron beam.[4,5] For example with efficiency of energy recovery η_R = 90%, overall efficiency η_T = $\eta/[1 - \eta_R(1 - \eta)]$ = 9%. Further efficiency enhancement might be possible by tapering wiggler parameters.[6] The oscillator output power depends on the cross-sectional area of the electron beam. If we take a sheet beam having a 6 cm width and a thickness, t = 0.5 mm, then, beam current I = 36 A. The corresponding 300 GHz output power, P_o = ηIV = 140 kW.

To develop a practical FEL amplifier one needs to use an "optical klystron" configuration.[7] Such an amplifier having two wigglers with N periods each, separated by a drift space of optimal length, will have gain, G_{ok}, given by G_{ok} = $G/[\pi N(\Delta\gamma_z/\gamma_z)]$, where $(\Delta\gamma_z/\gamma_z)$ is the spread in axial electron energy and G is given by Eq. (1). We evaluate the contribution to axial energy spread from the following factors: (1) variation in magnetic field strength over the beam cross-section $\Delta B_y/B_y$ = 0.07 corresponding to

$$(\Delta\gamma_z/\gamma_z)_1 = 2.5 \times 10^{-5} ;$$

and, (2) variation in electrostatic potential over the beam cross section $\Delta V = (e/8\epsilon_o)n_bt^2$ corresponding to

$$(\Delta\gamma_z/\gamma_z)_2 = 3.3 \times 10^{-5} .$$

Other contributing factors such as emittance depend on hardware design details, and are not included. From Factors (1) and (2), we calculate a combined axial energy spread

$$\Delta\gamma_z/\gamma_z = [(\Delta\gamma_z/\gamma_z)_1 + (\Delta\gamma_z/\gamma_z)_2]^{1/2} = 4.1 \times 10^{-5} .$$

The corresponding amplifier gain is G_{ok} = 155 G = 10.85. Thus, gain > 10 dB is predicted for this unoptimized example and practical 300 GHz amplifiers may be possible.

References

1. K. Halbach, J. Appl. Phys. 57, 3650 (1985).
2. V. L. Granatstein, et al., Appl. Phys. Lett. 47, 643 (1985).
3. P. Sprangle, et al., in Infrared and Millimeter Waves, ed. K. Button (Academic Press, New York, 1979), Vol. 1, pp. 279-329.
4. F. Dolezal, et al., IEEE J. Quantum Electronics QE-19, 309 (1983).
5. D. Arnush, et al., Int. J. Electronics 53, 605 (1982).
6. P. Sprangle, et al., Phys. Rev. Lett. 43, 1932 (1979).
7. B. Girard, et al., Phys. Rev. Lett. 53, 2405 (1984).