MAGNETIC PERFORMANCE OF A VARIABLE PERIOD, FAST EXCITATION, WIGGLER*

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Abstract - With the objective of carrying out an Inverse Free Electron Laser (IFEL) electron accelerator experiment, an iron dominated (Vanadium Permendur) fast excitation, laminated (variable period length) planar wiggler, making use of copper field reflectors, has been constructed and has been measured in several period length tapering configurations. This report presents an analysis and experimental results of this wiggler, typically of which the parameters are $\lambda(w) = 3.7$ cm, $B(max) = 1.8$ T.

I. INTRODUCTION

The study of the INVERSE FREE ELECTRON LASER (IFEL), as a potential mode of electron acceleration has been pursued at Brookhaven National Laboratory for a number of years. More recent studies focussed on the development of a low energy (few GeV), high gradient, multistage linear accelerator[1]. Specifically also, the design of a short accelerator module has been pursued which will make use of the 50 MeV Linac beam and high power ($2 \cdot 10^{11}$ Watts) CO_2 laser beam of the Accelerator Test Facility (ATF), Center for Accelerator Physics (CAP) of Brookhaven National Laboratory; and a fast excitation pulsed electromagnetic wiggler. In the IFEL accelerator mode the electron beam is accelerated through its interaction with the high power laser radiation in the medium of the periodic wiggler field. For acceleration it is necessary to maintain synchronism for the propagating electron beam and radiation wave, hence for a laser field with constant λ (laser) it is necessary to "taper" the wiggler. This taper can be accomplished while holding the wiggler parameter $K_w (=93.4 B\lambda_w [Tm])$, the period length λ_w , or the maximum wiggler field B_w constant. The choice is restricted by the maximum practical wiggler field and the minimum wiggler period length. It has been shown[2] that the maximum rate of acceleration, averaged over the full accelerator length, is obtained for a constant B_w accelerator. Hence, for the IFEL accelerator the use of a period length tapered wiggler, maintaining B_w constant has been adopted. Although such a wiggler structure could be constructed using permanent magnets, the requirement of a specific period length taper would be costly and also difficult to subsequently change, if need be. Instead, the design and construction of a laminated, fast excitation electromagnetic wiggler has been pursued[3],[4] which permits ready variation of the wiggler period length taper. This wiggler consists of stackable, geometrically alternating substacks of identical ferromagnetic (Vanadium

Permendur [VaP]) laminations, assembled, in $(\lambda_w/4)$ thickness substacks, separated by nonmagnetic laminations (Fig. 1,2). Four straight conductive rods, parallel to the axis and interconnected only at the ends of the assembly, constitute the single current loop that drives the wiggler. The stacks are easily assembled, are compressed by simple tie rods, and allow ready variation of wiggler period taper. A dramatic improvement in maximum achievable wiggler field, B_w , results from using conductive material for the nonmagnetic laminations, so that the induced fields from the eddy currents uncouple the wiggler "up" field from the "down" field. These, effectively "field reflectors", enhance significantly the maximum achievable field on axis as shown in Fig. 3, where B_w vs $I(excit.)$ is given (wiggler gap = 4 mm). Field saturation is evident in these results for higher excitation current values. The onset of field saturation is clearly discernable with the onset of distortion of the magnetic measurement probe voltage versus time display. The field value corresponding to the onset of saturation for a sequence of model measurements with different period length values, was obtained both for the case of wiggler models without field reflection and with field reflection.

Fig.1
Fast Excitation, Variable Period, Wiggler
[IFEL Accelerator, Wiggler Prototype]
Stackable, Interleaved VaP laminations
and Cu eddy current "field reflectors"

*Work performed under the auspices of the U.S. Department of Energy
under contract DE-AC02-76CH00016.

This is shown in Fig. 4 clearly indicating the effectiveness of the field reflectors for this type of fast excitation (pulse length 200 μ sec) pulsed wiggler magnet.

Further characterization of this wiggler is provided in Section II where the basic analytical field expressions are derived, and in Section III where detailed field plots and related parameters for a constant period wiggler and a tapered period wiggler are presented.

Fig.2

"Exploded View" Fast Excitation Variable Period Wiggler
[Stackable Laminated Structure]

Fig.4
Fast Excitation Wiggler, B_{sat} vs λ_0
Gap = 4.0 mm

II. WIGGLER FIELD

For the IFEL interaction to take place it is required that electron beam and radiation wave effectively overlap, hence the precise trajectory of the electron beam in the body of the wiggler need to be deduced from actual wiggler fields. Hence, it is necessary to obtain a complete reconstruction of the field in the wiggler gap from the measured field values. From general principles[5] the magnetic scalar potential is expressed as:

$$\phi(x,y,z) = X(x)Y(y)Z(z)$$

with $\bar{B}(x,y,z) = -\nabla\phi(x,y,z)$.

If symmetry is assumed in the horizontal plane and periodicity in the longitudinal direction then $X(x) = X(-x)$ and $Z(z) = \cos nkz$ where $k = 2\pi/\lambda$ with λ the period, the most general expression for the scalar potential can be written as:

$$\phi(x,y,z) = \sum_{n=1}^{\infty} \cosh(nk_1 x) [A_n \exp(nk_2 y) + B_n \exp(-nk_2 y)] \cos(nk_3 z)$$

with the constraint $k_3^2 = k_1^2 + k_2^2 \equiv k_2^2(1+r^2)$.

Notice that there is no median plane symmetry and the deviation can be represented with a single parameter η such that,

$$B_y(x, -g, z) = \eta B_y(x, g, z)$$

where g is the gap magnitude. This relation can be understood making use of the Gauss theorem in the transverse plane (see Fig. 1).

Fig.3

Fast Excitation Wiggler, B vs I

Simple algebraic manipulations lead to the expression of the field in the gap, as follows:

$$B_x(x,y,z) = \sum_{n=1}^{\infty} nk_1 \sinh(nk_1 x) [A_n \exp(nk_2 y) + B_n \exp(-nk_2 y)] \cos(nk_3 z)$$

$$B_y(x,y,z) = \sum_{n=1}^{\infty} nk_2 \cosh(nk_1 x) [A_n \exp(nk_2 y) + B_n \exp(-nk_2 y)] \cos(nk_3 z)$$

$$B_z(x,y,z) = - \sum_{n=1}^{\infty} nk_3 \cosh(nk_1 x) [A_n \exp(nk_2 y) + B_n \exp(-nk_2 y)] \sin(nk_3 z)$$

The coefficients A_n and B_n are determined by the boundary conditions at the poles and the peak vertical magnetic field on axis B_{on} ; it follows:

$$A_n = \frac{B_{on}}{2nk_2(1+\eta) \sinh(nk_2 d) [\exp(nk_2 d) - \eta \exp(-nk_2 d)]}$$

$$B_n = \frac{B_{on}}{2nk_2(1+\eta) \sinh(nk_2 d) [\exp(-nk_2 d) - \eta \exp(nk_2 d)]}$$

With the fields so determined the electron trajectory in the wiggler field can be calculated.

III. PERFORMANCE OF THE FAST EXCITATION WIGGLER

Measured field values $B_0(z)$ vs z , on axis, for an excitation current of 6 kA, are given in Fig. 5. The rms fluctuation of the peak field $\sigma_B = \sqrt{\langle \delta B^2 \rangle / B^2}$ about the average is under 0.2% and the maximum scatter is 1.0%. A complete measured field representation $B_y(x,y,z)$ for a single pole region ($g = 4$ mm, $0.5 \lambda = 18.8$ mm, $I = 6$ kA) is given in Fig. 6 for $-1.2 \leq y \leq 1.2$ mm and $-6.0 \leq x \leq 6.0$ mm. A Fourier transform analysis of the entire field map on axis has been performed. The power spectrum is shown in Fig. 7. From the power spectrum plot, the odd harmonics up to order 7th are clearly in evidence, a natural consequence of the periodicity of the field. The magnitude of the noise level is about 10^{-6} and up to that level there is no indication of even harmonics. The 3rd. harmonic is about 3% of the fundamental. The normalized horizontal velocity $x' = v_x / v_z$ is given essentially by the first integral of the vertical component of the magnetic field $B_y(0,0,z) = B_0(z)$, i.e.,

$$x' = \frac{K 2\pi}{\gamma \lambda_w} \int_{-\infty}^z dz' \frac{B_0(z')}{B_{max}}$$

Similarly so, the position x is given by the second integral of the field as,

where $K = eB_{max}\lambda_w / mc^2\beta_z 2\pi = 0.934 B_{max}[T] \lambda_w[cm]$,

$$x = \frac{K 2\pi}{\gamma \lambda_w} \int_{-\infty}^z dz' (z-z') \frac{B_0(z')}{B_{max}},$$

with $B_{max} \sim 1.4$ T and $\lambda_w \sim 3.754$ cm. The magnitudes of x vs z and x' vs z are shown in Figs. 8 and 9, respectively. As evident, the maximum x oscillation amplitude is ≈ 0.4 mm. The displacement and steering of the beam at the exit of the wiggler are approximately 0.001 mm and 3.4 mrad, respectively.

For completeness sake a plot of the field $B_0(z)$ vs z for a tapered period wiggler with 2.98 cm $< \lambda_w < 5.04$ cm is shown in Fig. 10.

CONCLUSION

It has been shown that the fast excitation driven, laminated Vanadium Permendur wiggler with periodic interleaving of conductive copper field reflectors is capable of satisfying both the FEL and IFEL requirements. As indicated, a specific tapered period slope can readily be achieved. The wiggler structure, as presently executed is robust and simple to assemble and lends itself for easy modifications of period length, field magnitude and taper. These are very important features in actual FEL and IFEL experiments.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contribution of M. Woodle and J. Armendariz to the experimental work. They are also grateful to L. Gianessi for making the code SIN-LUCE available. This work was supported by the Advanced Technology R&D Branch, Division of High Energy Physics, U.S. Dept. of Energy.

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Fig. 5
Constant Period Wiggler, B_y vs z
 $\lambda = 3.76$ cm, $g = 4.0$ mm

Fig. 6
Wiggler Field Distribution
 $\lambda = 3.76$ cm, $g = 4$ mm, $I_{ex} = 6$ kA

Fig. 7
Power Spectrum, Constant Period Wiggler
 $\lambda = 3.76$ cm, $g = 4.0$ mm, $I_{exc} = 6$ kA

Fig. 8, Second Field Integral: $x = (K/r)(2\pi B_y \lambda_z) \int_0^z dz \int_0^z B_y(0, z') dz'$

Fig. 9, First Field Integral: $x'(z) = (K/r)(2\pi B_y \lambda_z) \int_0^z B_y(0, z') dz'$

Constant Period, Fast Excitation, Wiggler
 $\lambda = 3.76$ cm, $g = 0.40$ cm

Fig. 10
Variable Period, Fast Excitation, Wiggler
(IFEL Accelerator, Wiggler Prototype)
 $\lambda = 2.98 - 5.04$ cm, $d\lambda/dz \approx 4\%$, $g = 4.0$ mm

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