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FOCUSING-TAPERED WIGGLER FOR A HIGH AVERAGE  
POWER FEL

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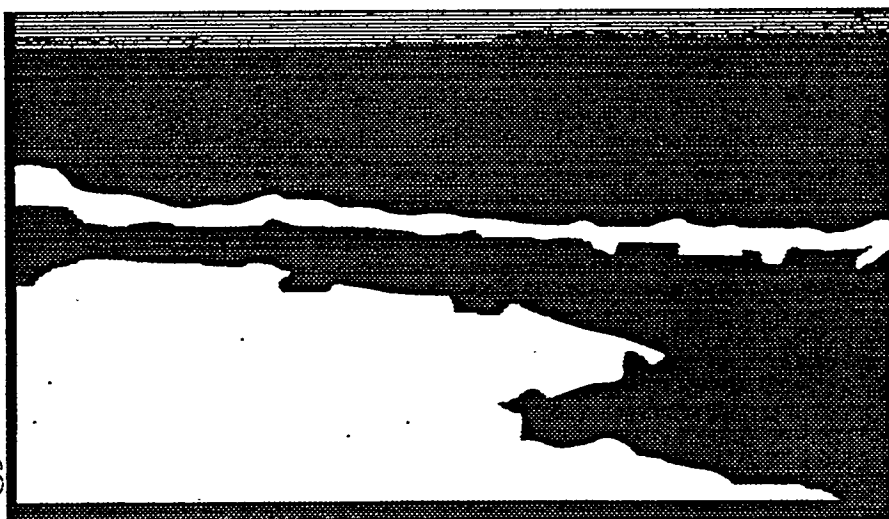
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# A PURE PERMANENT MAGNET-TWO PLANE FOCUSING-TAPERED WIGGLER FOR A HIGH AVERAGE POWER FEL

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# A PURE PERMANENT MAGNET-TWO PLANE FOCUSING-TAPERED WIGGLER FOR A HIGH AVERAGE POWER FEL\*

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## Abstract

A high-average power FEL is under construction at Los Alamos. The FEL will have aspects of both an oscillator and a SASE (self-amplified spontaneous emission) device. That is, a high-gain and high-extraction efficiency wiggler will be used with a very low-Q optical resonator. FEL simulations reveal that a tapered wiggler with two-plane focusing is required to obtain desired performance.

The wiggler is comprised of a 1 meter long untapered section followed by a 1 meter tapered section. The taper is achieved with the magnetic gap and not the wiggler period which is constant at 2 cm. The gap is tapered from 5.9 mm to 8.8 mm. The gap, rather than the period, is tapered to avoid vignetting of the 16  $\mu\text{m}$  optical beam. Two-plane focusing is necessary to maintain high current density and thus high gain through out the 2 meter long wiggler.

Several magnetic designs have been considered for the wiggler. The leading candidate approach is a pure permanent wiggler with pole faces that are cut to roughly approximate the classical parabolic pole face design. Focusing is provided by the sextupole component of the wiggler magnetic

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field and is often called 'natural' or 'betatron' focusing. Details of the design will be presented.

## 1. Introduction

A two-plane focusing, tapered wiggler, is presently under construction at Los Alamos. The wiggler is to be used in a high-average power ( $\sim 1\text{ kW}$ ) FEL. The electron beam energy is 17 MeV and the optical wavelength is 16  $\mu\text{m}$ . The FEL has aspects of both an oscillator and a SASE device. To achieve high-average power the optical resonator is designed with large output coupling ( $\sim 98\%$ ). Therefore, the wiggler must provide both high gain and high extraction efficiency. To achieve high-gain, and thus high electron current-density, simulations [1] indicate it is necessary to have two-plane focusing. The high extraction efficiency requirement leads us to a wiggler design that includes a taper. The taper is achieved using the magnetic gap rather than the magnetic period. The larger gap avoids vignetting of the optical beam which has non-negligible tails that are critically important to the optical resonator [1].

In addition to the physics requirements mentioned above other constraints are imposed on the wiggler design. Because we are modifying an existing facility (AFEL [2]) the wiggler length is limited to 2 meters or less. Also, funding and schedule require the design to be inexpensive and as simple as possible. More details regarding the overall plans for the high-average power experiment can be found in these proceedings [3].

## 2. Magnetic Design

All of the wigglers ( $\sim 10$ ) fabricated during the Los Alamos FEL program have been of the pure permanent-magnet design with single-plane focusing. Our lack of experience and tight schedule precluded us from considering hybrid wigglers even though they can be easily adapted to have two-plane focusing [4]. Designs for two-plane focusing pure permanent-magnet [5,6] and hybrid wigglers have been previously investigated [7-9]. The magnet geometry we decided upon is illustrated in Fig. 1. The configuration is a standard Halbach type with 4 blocks (SmCo) per period. The magnetic period is constant at 20 mm along the entire 2-meter long

wiggler. The magnetic gap is 5.9 mm for the first meter and tapered to 8.8 mm over the second meter. The wiggler is built in four 50 cm long segments. The second two segments are independently linearly-tapered in gap resulting in each having a field taper that is exponential. The desired linear-taper in field is well approximated by two exponential tapers because the taper is not large.

The magnets are machined to make a first order approximation to the curved pole face design. Focusing comes from the alternating gradient sextupole field and is often called natural or betatron focusing [4]. The design code RADIA [10] was used to optimize the magnet geometry. The depth and width of the step machined into the magnet was optimized to both provide equal plane focusing (approximately) and to keep the aperture as large as possible. All the magnets are machined identically. The distance to the corner of the step (dimension  $b$  in Fig. 1) is larger (3.11 mm) than the half-gap (2.95 mm) for the first meter of wiggler and is slightly smaller (4.0 mm) than the half-gap (4.4 mm) at the end of the wiggler.

### 3. Results and Discussion

To second order the vertical field of the wiggler is expressed as,

$$B_y(x, y, z) = B_{y0}(z) \sin(k_w z) \left( 1 + \frac{(k_x x)^2}{2} + \frac{(k_y y)^2}{2} \right) \quad (1)$$

where  $B_{y0}(z)$  is a slowly varying function that describes the taper. Figure 2 shows the variation of the calculated wiggler field off-axis at a  $z$ -location where the gap is 5.9 mm and the field is a maximum. The field off-axis increases quadratically (approximately) with approximately equal values for both  $k_x$  and  $k_y$ . Similar calculations are made at other gaps. At each gap, values for  $k_x$  and  $k_y$  are obtained and then used to calculate betatron wave-numbers using the formulas,  $k_{\beta x} = a_w k_x / (\gamma \sqrt{2})$  and  $k_{\beta y} = a_w k_y / (\gamma \sqrt{2})$ , where  $a_w$  is the peak value of the usual normalized vector potential. For equal plane focusing the ideal value for  $k_x$  and  $k_y$  is  $k_w / \sqrt{2}$ . The corresponding ideal betatron wave-numbers are given by  $k_{\beta x} = k_{\beta y} = a_w k_w / (2\gamma)$ . Because of the taper  $a_w$  varies from 1.31 to 0.91

over the second meter of the wiggler. Figure 3 shows the ideal and predicted localized betatron-wavenumbers at various gap values along the taper. The agreement is not perfect because the magnets are cut to give only a first-order approximation to a parabolic field profile. Also, to save time and money we chose not to vary the dimensions of the magnet cross-section along the taper which would have allowed optimization at all gaps.

Figure 4 shows betatron orbits in both the wiggle (x-z) and non-wiggle (y-z) planes for electrons that enter the wiggler with various initial conditions. The two-plane focusing is clearly evident.

#### 4. Summary

A pure permanent-magnet, two-plane focusing, tapered wiggler is designed and under construction. The wiggler design is simple and inexpensive. The magnets are machined to generate a parabolic transverse field profile. The focusing comes from an alternating-gradient sextupole field. The magnetic taper is done by increasing the gap rather than the period to avoid vignetting of the optical beam.

#### 5. References

- [1] J.C. Goldstein, 'Theoretical Study of the Design and Performance of a High Gain, High Extraction Efficiency FEL Oscillator', in these proceedings.
- [2] D.C. Nguyen et al., Nucl. Instr. and Meth. A 358 (1995) 27.
- [3] D.C. Nguyen et al., 'Synchronously Injected Amplifiers, A Novel Approach to High-Average-Power FEL', in these proceedings
- [4] E.T. Scharlemann, J. Appl. Phys. 58 (1985) 2154.
- [5] R.W. Warren and C.J. Elliot in : Undulator Magnets for Synchrotron Radiation and Free Electron Lasers, Symp. in the Adriatico Conf. Series, Trieste, Italy. 1987 (World Scientific, Teaneck, NJ 1988) p. 28.
- [6] Y. Tsunawaki et al., Nucl. Instr. and Meth. A 304 (1991) 753.



- [7] D. Quimby and J. Slater, Proc. Orcas Isl. FEL Conf., SPIE 453 (1984) 92.
- [8] A.A. Varfolomeev and A.H. Hairtdinov, Nucl. Instr. and Meth. A 341 (1994) 462.
- [9] Y.M. Nikitina and J. Pfluger, Nucl. Instr. and Meth. A 375 (1996) 325.
- [10] J. Chavanne and P. Elleaume, RADIA Version 2.0, internal report ESRF-SR/ID-90-46 (1990).

### Figure Captions

1. Magnet geometry;  $a$  varies from 5.9 mm to 8.8 mm,  $b$  varies from 3.11 mm to 4.0 mm,  $c=1.5$  mm,  $d=5.5$  mm,  $h=12.7$  mm,  $w=30$  mm, and  $\lambda_w = 20$  mm.
2. The off-axis variation of the wiggler field. The parabolic field profile creates two-plane sextupole focusing.
3. The local betatron wave numbers at various wiggler gaps and the ideal value for equal two-plane focusing.
4. Some examples of betatron orbits in the wiggle ( $x$ - $z$ ) and non-wiggle ( $y$ - $z$ ) planes.

