A SCALLOPED ELECTRON BEAM FREE-ELECTRON LASER *

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Abstract

Typical high-gain FEL amplifiers employ an electron beam that is "matched" to the wiggler so that the envelope remains constant throughout the wiggler. This paper describes a novel approach in which the electron envelope undergoes scalloping motion along the wiggler because the beams are deliberately mismatched at the wiggler entrance. We present an analysis of the electron scalloping motion and the FEL interaction with a scalloped electron beam. Using MEDUSA simulations, we show the advantages of the scalloped-beam FEL and the properties of the radiation beam it produces.

INTRODUCTION

In high-gain FEL amplifiers, the electron beam radius plays a crucial role in determining the FEL interaction strength. Most FEL amplifiers use a tightly focused electron beam to enhance the FEL interaction, i.e. both the FEL gain and saturated power increase with smaller electron beam radius. A typical FEL employs electron beams that are "matched" to the wiggler so that the envelope remains constant throughout the wiggler. Since the matched beam radius is proportional to $\sqrt{\varepsilon_n}$, a small beam radius requires a small normalized rms emittance.

The use of external magnets to focus the electron beam to a radius smaller than allowed by the normalized rms emittance in order to pinch the optical beam was first suggested by Sprangle *et al*. [1]. In this paper, we suggest the use of natural betatron motion in a weak focusing wiggler, to refocus the electron beam periodically in the wiggler, resulting in pinching near the wiggler exit (Fig. 1). It is possible to select a combination of input laser power and wiggler length such that the FEL saturates near the second waist. Optical guiding causes the radiation beam to follow the electron beam's motion, resulting in pinching of the radiation beam near the exit [2].

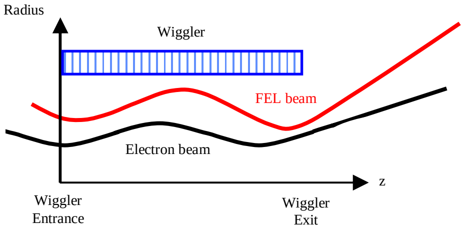

Figure 1: Illustration of a scalloped electron beam FEL with a uniform wiggler.

THEORY

The evolution of the rms radius σ of a relativistic, axi-symmetric beam with equal transverse emittance and equal two-plane focusing can be written as follow

$$\frac{d^2\sigma}{dz^2} = -k_\beta^2\sigma + \frac{2I}{\gamma^3 I_A \sigma} + \frac{\varepsilon_n^2}{\gamma^2\sigma^3}, \tag{1}$$

where k_β is the betatron wavenumber, I the peak current, I_A the Alfven current, γ the relativistic factor, and ε_n the normalized rms emittance. Under steady-state condition, the emittance-dominated rms matched beam radius is

$$\sigma_0 = \sqrt{\frac{\sqrt{2}\varepsilon_n}{k_w a_w}}. \tag{2}$$

Using a first order perturbation analysis of Eq. (1) we can show that

$$\sigma = \sigma_0 - \delta_0 \sin(k_\Sigma z) \tag{3}$$

where $\delta_0 = (\sigma_0 - \sigma_{min})$ is the initial deviation from the matched radius, and k_Σ, the scalloping wavenumber, as given by

$$k_\Sigma = 2k_\beta\sqrt{1 - \frac{I}{I_A}\frac{1}{\gamma^2 k_\beta \varepsilon_n}} \tag{4}$$

The power gain length in a high-gain FEL amplifier scales with the electron beam radius as follow [3]

$$L_G = \frac{\gamma}{\sqrt{3}}\left(\frac{I_A}{a_w^2 f_B^2 k_w I}\right)^{1/3}\sigma^{2/3}\left(1+\Lambda_{3D}\right) \tag{5}$$

where f_B is the difference in Bessel functions, and Λ_{3D} is the three-dimensional effect. Since the electron beam radius varies slowly with distance, the FEL power gain length also varies along the wiggler. The saturated power scales inversely with electron beam radius.

$$P_s = \frac{1}{\gamma}\left(\frac{a_w f_B}{2\sqrt{2}k_w\sigma}\right)^{2/3}\left(\frac{I}{I_A}\right)^{1/3}\frac{P_{beam}}{\left(1+\Lambda_{3D}\right)^2} \tag{6}$$

where P_{beam} is the electron beam power. The scalloped beam FEL performance depends on how the electron beam is focused in the wiggler and the scalloping period. We look at two cases: 1) the electron beam waist is focused near the entrance, and 2) the waist is the centre of the wiggler. In the first case, the electron comes to second waist near the wiggler exit and the FEL output power, which scales inversely with radius, is at a maximum. In the second case, the beam radius is largest near the wiggler exit and the output power is at a minimum [4].

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SIMULATION

Table I summarizes the FEL and beam parameters used in the MEDUSA simulations. These parameters are chosen for a 1.06-micron wavelength where high-power seed lasers exist. The wiggler is a conventional permanent-magnet design with parabolic pole faces to provide equal two-plane, sextupole focusing. Alternatively, the magnets can be notched to approximate sextupole focusing [5]. We chose an input power of 10^6 W (1 μJ pulse energy and 1 ps FWHM, for instance) to achieve saturation in about 2 m of wiggler length with a matched electron beam. For the scalloped beam FEL, the saturation length is 2.6 m. The scalloping period is about 2 m so the second waist of the electron beam envelope is near the exit of the wiggler in both cases. The effects of using matched- and scalloped-beams in the two-stage wiggler are illustrated in Figs. 2 and 3. The power reaches a maximum of 0.84 GW in the matched case, and 1.03 GW in the scalloped case. The extraction efficiency increases correspondingly from the usual 1% to 1.27%. The only drawback is a 30% increase in the wiggler length required to reach saturation.

Table 1: MEDUSA simulation parameters and results.

Parameters	**Values**
Beam Energy	80.8 MeV
Peak Current	1000 A
Emittance	10 mm-mrad
Energy Spread	0.25%
Wiggler Period	2.18 cm
Wiggler Peak Magnetic Field	8.247 kG
rms Wiggler Parameter	1.187
Wiggler Length	2.6 m
Matched Beam Radius	0.27 mm
Scalloped Beam Minimum Radius	0.16 mm
Scalloping Period	2.05 m
Wavelength	1.058 µ
Peak Injected Power	1 MW
Injected Radiation Waist	0.305 mm
Matched Beam Peak Power	0.84 GW
Matched Beam Efficiency	1.0%
Matched Beam Saturation Length	1.96 m
Scalloped Beam Peak Power	1.03 GW
Scalloped Beam Efficiency	1.27%
Scalloped Beam Saturation Length	2.6 m

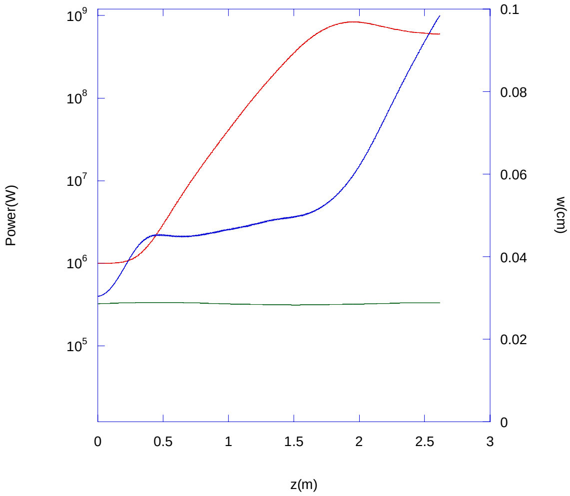

Figure 2: FEL power (red), optical beam radius (blue), and electron beam radius (green) for the matched case.

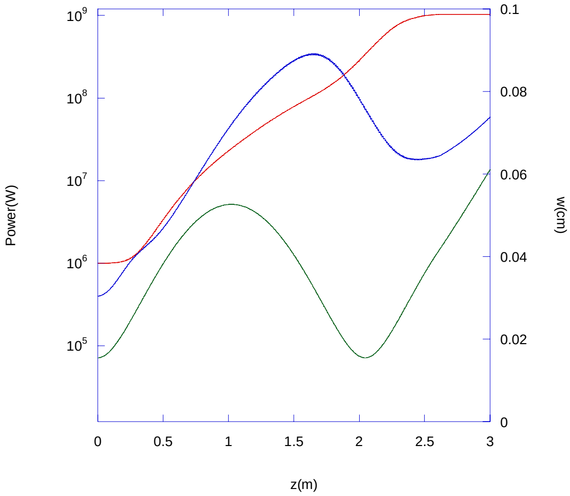

Figure 3: FEL power (red), optical beam radius (blue), and electron beam radius (green) for the scalloped case.

It is noteworthy that the lethargy region is reduced in the scalloped beam FEL as a result of high gain (short gain length) at the wiggler entrance. In the middle of the wiggler, exponential gain is reduced and the reduction in optical guiding causes the radiation beam to expand rapidly. At saturation, the scalloped beam optical waist is larger than the matched beam case. Thus, scalloping the electron beam in a uniform wiggler does not pinch the optical beam to a smaller radius. To significantly pinch the optical beam, we need additional optical guiding, for instance with the addition of a step-taper wiggler.

For seeded FEL amplifiers, it is advantageous to tune the input wavelength while keeping the electron beam energy constant in order to find where the power is maximized. In the matched beam case, the FEL output power increases toward larger detuning, namely longer wavelength at a fixed electron beam energy (or higher electron beam energy at a fixed wavelength) and then drops sharply. In the scalloped beam case, the FEL output power decreases rapidly on both side and the detuning bandwidth is narrower. This is a result of lower FEL gain due to the scalloped electron beam, but the FEL saturated power is higher than the matched beam case.

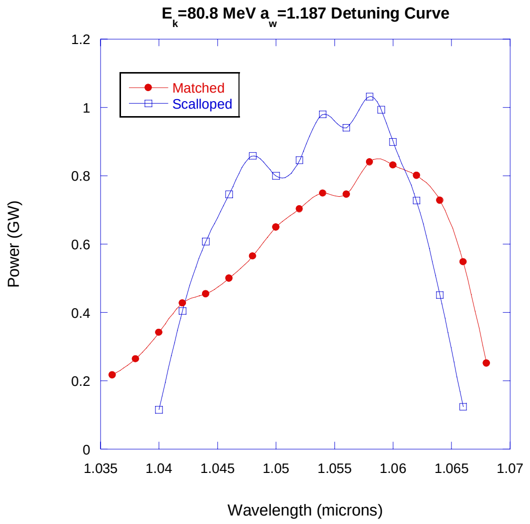

Figure 4: Detuning curves for the matched (red) and scalloped (blue) electron beam FEL.

We also study scalloped beam FEL with a step-taper wiggler to increase the extraction efficiency (Fig. 5). The step-taper starts at z = 1.92 m and the magnetic field is reduced to 8.032 kG while the period remains the same. The FEL peak power grows to 1.45 GW, corresponding to 1.8% efficiency (Fig. 6). The optical beam is pinched to a 0.3 mm radius in the second wiggler segment, compared to a 0.6 mm radius of the uniform wiggler. The optical divergence angle is increased from 0.8 to 1.6 mrad.

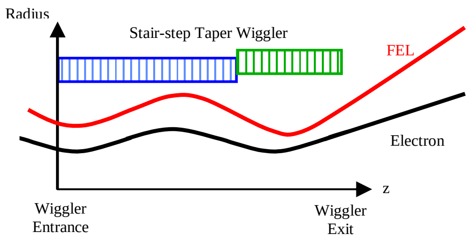

Figure 5: Illustration of a scalloped beam FEL with a step-tapered wiggler.

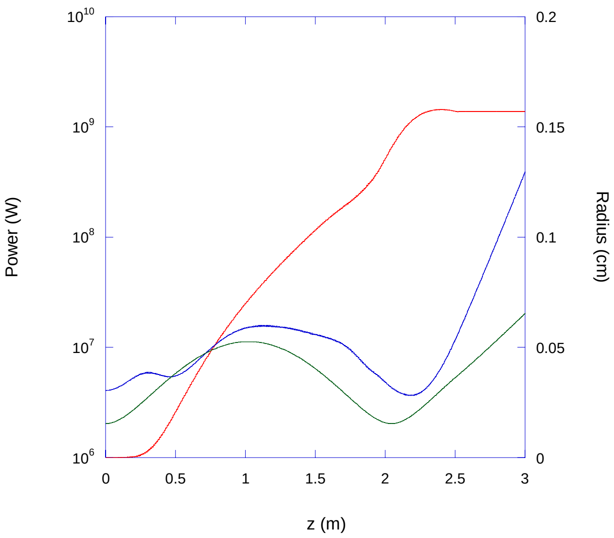

Figure 6: FEL power (red), optical beam radius (blue), and electron beam radius (green) for scalloped beam FEL with a step-tapered wiggler.

SUMMARY AND DISCUSSION

We have studied a new kind of FEL interaction in which the electron beam's envelope undergoes scalloping motion and the exponential gain varies along the wiggler length. For maximum power, the optimum approach is to focus the electron beam near the wiggler entrance and chose a wiggler length that is slightly longer than the scalloping period so that the second waist occurs near saturation. The smaller electron beam radius at saturation increases the saturated power of a uniform wiggler. The scalloped beam FEL detuning spectrum is narrower than the matched beam case. This is indicative of a lower net gain for the scalloped beam FEL.

As a result of this study, we conclude that the use of a scalloped-beam is advantageous even at the expense of a longer wiggler length to reach saturation. In addition, the combination of scalloped electron beams and a step-tapered wiggler can double the output power, and thus the FEL efficiency. The radiation beam is also pinched near the exit and expands rapidly afterward, thereby reducing the risk of damaging optics intercepting the FEL beam.

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