Performance Characteristics, Optimization, and Error Tolerances of a 4nm FEL Based on the SLAC Linac

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Abstract

A 4nm free electron laser (FEL) operating in Self Amplified Spontaneous Emission (SASE), and using the SLAC linac as a driver has been extensively studied using the FRED3D[1] and TDA3D[2] codes. Using a 7 GeV beam with a normalized rms emittance of 3 mm-mrad and a peak current of 2500 A, obtained by longitudinal bunch compression, the FEL can provide about 20 GWatt of peak power, in a subpicosecond pulse. The FEL saturation length is about 60 m. Strong focusing in both planes is provided throughout the undulator by a FODO quadrupole system. We have studied the system gain, its optimization and FEL tolerance to beam parameter changes, wiggler errors and misalignments.

Introduction

The promise of producing bright, coherent, short wavelength XUV and X-ray radiation has yet to be fulfilled. Free electron lasers have long been touted as the right tool for this task. Yet, in the nearly twenty years since the first operation of the FEL, the short wavelength challenge has not been met because of the limitations on beam brightness. Now it seems possible to produce copious amounts of short wavelength radiation using technology developed in the last few years [3,4,5]. The primary distinguishing feature of this device is the electron beam. A high current, low emittance (high brightness) beam produced by an RF photocathode gun is accelerated to high energy (multi GeV) using a portion of the SLAC linac. This beam is what distinguishes this design from other potential x-ray FEL schemes [6].

A large parameter space was explored in order to optimize the FEL. The constraints where to maximize the output peak power while restricting beam and undulator parameters to state of the art. A three dimensional analytic model [7] was used to initially explore the parameter space while particle simulations where used to refine the choices. Table 1 lists a set of base parameters. Subsequent sections of this paper present FEL performance as functions of beam and undulator parameters. The main objective here is to establish the FEL tolerances with respect to changes in beam and undulator parameters and alignment errors.

Table 1: The base set of parameters for the SLAC based x-ray FEL.

γ	Energy (mc^2)	14000
ε_n	Emittance normalized (mm-mrad)	3×10^{-6}
	Peak Current (A)	2500
	Pulse Length (fs)	160
σ_E	Uncorrelated energy spread	4×10^{-4}
a_u	Undulator parameter	6
λ_u	Undulator period (cm)	8.3
λr	Optical wavelength (nm)	4
ρ	FEL parameter	1.7×10^{-3}

Beam Parameter Studies

The sensitivity of the FEL output to input beam parameters is paramount. The results presented below are given in terms of the power gain length, L_g,

$$P(z) = P_0 e^{z/L_g} \tag{1}$$

where P is the power as a function of the distance down the FEL, z, and P_0 is the input power. The effects of electron beam and undulator parameters on the FEL performance have been described by a 1-D model [3] and by a full 3-D analysis (reviewed in Ref. [5]).

Emittance

The usual constraint on the (unnormalized) beam emittance is that it be smaller than the wavelength of radiation divided by four pi ($\varepsilon<\lambda/4\pi$). Typically, the gain length of a device starts to increase dramatically when this limit is violated. Conversely, when the emittance is reduced, the gain length shortens. The total output power at saturation is not dependent on the emittance until the limit is strongly violated. This last statement is true for a fixed strength (beta function) focusing channel. It is possible to optimize the focusing strength for a given emittance .

For the 4nm case of interest here, a normalized beam emittance of 4.5×10^{-6} mm-mrad is required by the limit. As Figure 1 shows, the power gain length increases rapidly after the limit is exceeded.

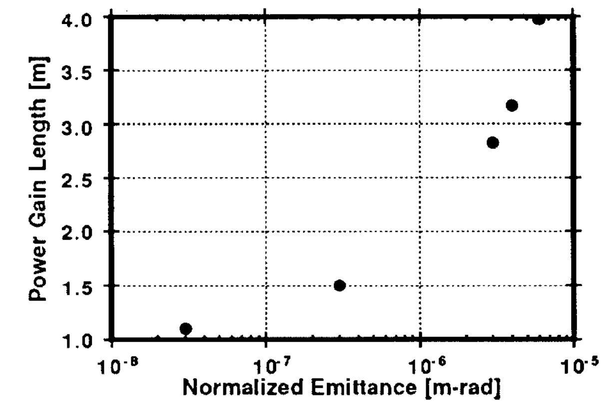

Figure 1: The power gain length for various emittances. Note that the emittance is a log scale.

Energy Spread

The energy spread is characterized in two ways: the correlated and the uncorrelated energy spread. FEL performance (gain length) is affected by the uncorrelated energy spread which is primarily determined by the electron source. The theoretical limit is that $\sigma_E<\rho$. The transport line and bunch compressors must preserve the minimum uncorrelated energy spread. The correlated energy spread is determined by the bunch compressor system and wakefields in the linac [8]. The correlated energy spread affects the radiation bandwidth but not the gain length. Users and experiments have varying requirements on the output radiation line width. Some of these requirements can best be met by using optical methods such as monochromators near the experiment. Effects of the uncorrelated energy spread have been investigated in the range where $\sigma_E<\rho$.

As Figure 2 shows, the saturation levels are nearly equal for a wide range of energy spreads. However, the gain length is adversely affected by an energy spread much larger than specified by the base parameters.

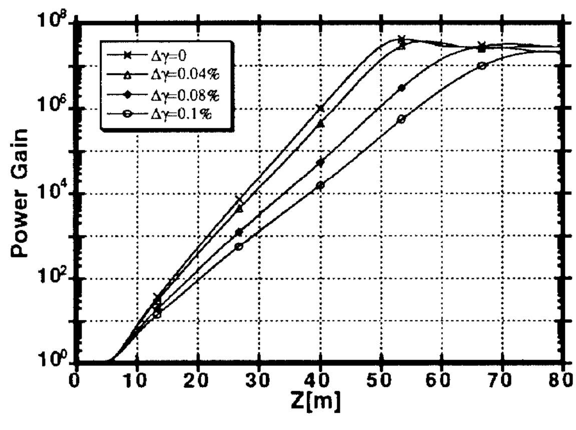

Figure 2: The power gain curves are shown as a function of the distance along the undulator for various uncorrelated energy spreads.

Beam Peak Current

Fluctuations in the electron beam peak current depend strongly on the pulse length and charge variations. Not only does the source have to be stable, but so does the compression scheme. Hence, it is important that the FEL not be strongly sensitive to variations about the design current. Simulations reveal that, again at saturation, the output level is nearly identical for a wide range of currents (see Figure 3). Of course, the gain length varies with the current, but not so much as to pose a problem.

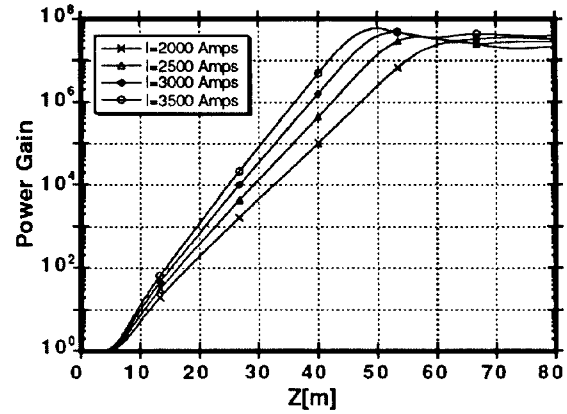

Figure 3: Power gain along the undulator for various peak beam currents.

Focusing

The SLAC X-ray FEL design calls for an undulator approximately 60 meters in length. The natural beta function of the undulator is 56 meters (and this is only in one plane) which gives a very large gain length. Additional focusing is required. Simulations show that there is substantial improvement for a beta function, β, ~10 meters and optimum performance for β~5 meters [9]. This is in agreement with the theoretical limit that $\beta>L_g$. External quadrupole FODO lattice can provide beta functions of ~10 meters with conventional magnets. Performance for various drift and focusing lengths have been done. A period of 60 cm drifts and 60 cm quads seems close to optimal in terms of gain length and number of quads required. Numerous ideas have been reviewed in the course of this study. Extensive simulations have been performed on the various concepts [8]. Alternative schemes which might offer much higher field gradients (~50-100 T/m) are being investigated [10]. Such gradients would allow for beta functions of ~5 meters, closer to the optimal.

Undulator Tolerances

Propagation of an electron beam through a long undulator has already been proven [11]. The beam alignment required is proportional to the beam radius. As beam energy goes up, radius decreases. At ~7 GeV and 4 nm the beam radius is ~50μm and the required mechanical tolerances are ~25μm, similar to those for the next linear collider [12]. The undulator must also satisfy tight magnetic tolerances.

Field Errors

Simulations have been performed using random walk models of undulator rms field errors. Errors in excess of 0.4% seriously degrade the output power (see Figure 4). The specified 0.2% tolerance is considered presently achievable. In fact, undulators meeting this requirement have already been constructed [13]. The question still remains whether rms errors are a figure of merit for free electron lasers. It is possible to construct undulators with large field errors and still achieve good lasing [14]. A more detailed study of field errors needs to be performed.

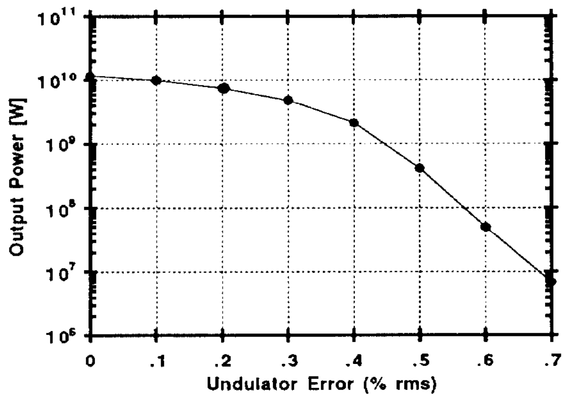

Figure 4: The output power as a function of the undulator field errors is plotted. A total (rms) steering accuracy of 30 μm is assumed.

Steering Errors

Whereas field errors are a dubious measure of the quality of the undulator, the second integral of the field is generally considered a good measure. Steering errors can be corrected by judicious undulator construction as well as a combination of beam position monitors and coils.

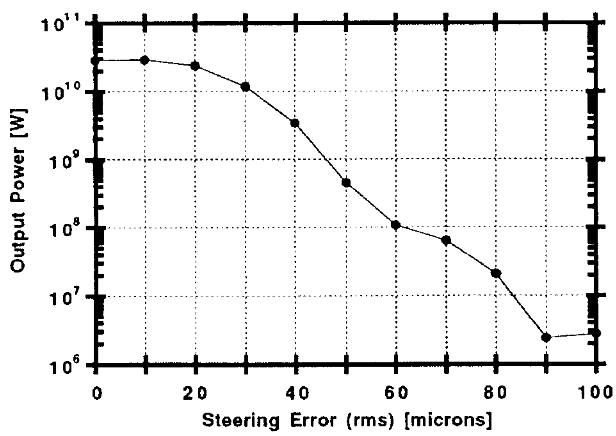

Figure 5: FEL output power as a function of the beam misalignment.

Simulations have shown that steering errors ~ 30 μm can be tolerated. Figure 5 shown the FEL output for various steering and alignment errors when correctors are placed every 2 meters and a perfect undulator (no errors) is assumed.

Conclusions

The numerous simulations performed for the proposed SLAC based X-ray FEL have shown that the parameters chosen are stable to fluctuations in beam parameters and achievable with present state of the art accelerator, mechanical and magnetic technology. Further theoretical work needs to be performed to extend the 1-D theory of the start up and saturation regimes (see Ref. [5] for a review). Simulations of these regimes will require codes which include pulse length (time) effects.

Acknowledgments

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