Parametric Study of an X-ray FEL

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An FEL utilizing a high energy, high current and low emittance beam to produce radiation shorter than 2 Å is investigated in this paper. This device is an extension of the previously proposed 40 Å Linac Coherent Light Source based on the Stanford linear accelerator. Here we investigate the performance characteristics and parameter sensitivities of this single pass, high gain FEL amplifier operating by self amplified spontaneous emission (SASE). We begin by comparing various approaches to this short wavelength source and justify our choice of a helical undulator operating on the fundamental frequency. Numerical simulations as well as extensions of previous studies are used to show performance as a function of undulator parameters, startup noise, emittance, focusing, current and energy spread. Further studies and parameter modifications are proposed where needed.

1. Introduction

The Linac Coherent Light Source (LCLS) was conceived as a high gain, single pass, SASE FEL amplifier operating in the "water window" near 40 Å [1]. It was proposed to combine the emerging RF photocathode gun technology with the high energy Stanford linear accelerator and a long undulator to obtain a new, powerful short wavelength light source. After two application workshops were held, it became clear that the demand for a < 2 Å device was far greater than for the water window source [2,3]. Spurred by these demands a study began on how to lower the wavelength by more than an order of magnitude.

Our study began with a general survey of the parameter space. Various constraints exist on the beam parameters (emittance, current, energy spread, etc.) as well as the undulator (period, gap, field strength, etc.). These constraints serve to define an operating regime. Using a semi-analytic 3D model to rapidly explore this regime allows us to find a base parameter set which is nearly optimal [4]. The optimization can minimize undulator (saturation) length or maximize output power. Generally, these devices provide several orders of magnitude more brilliance, average and peak power than existing devices so that power is not a concern. Rather, minimizing the undulator length is a higher priority. All cases require the FEL to saturate in order to minimize output fluctuations. The results of this model are a useful starting point for numerical simulations which can more carefully account for 3D effects (diffraction, optical guiding, startup, etc.). Additionally, a comparison of helical, planar, harmonic and multiundulator generation schemes was done. The helical case offers shorter saturation lengths compared to a planar undulator, desirable circularly polarized light to users, and simplicity over multiundulator schemes. Nevertheless, these other concepts need further investigation before a final comparison can be made. Here we only consider the helical case.

Table 1: The approximate base parameters for the 1.4 Å LCLS FEL.

Electron Beam	
Energy	15 GeV
Energy spread (rms, uncorrelated)	0.02%
Peak current	5 kA
Bunch charge	1 nC (6 x 10^9 e^-)
Normalized emittance (rms)	1 mm-mrad
Bunch length (rms)	15 µm (~60 fs)
Repetition rate	120 Hz
Helical Undulator	
Period	2.7 cm
Undulator parameter (K)	2.9
Magnetic field	1.6 T
External focusing betafunction	6 m
FEL	
Wavelength	1.4 Å
Output power	>10 GW
FEL parameter (ρ)	1 x 10^{-3}

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The base set of parameters chosen for the helical case using the semi-analytic model is presented in Table 1. The following sections of this paper discuss the FEL performance as functions of various parameters.

2. Undulator Requirements

The undulator for a one angstrom LCLS presents a technical challenge due to its length, high field, short period and high field quality. The need to incorporate strong focusing quadrupoles, steering magnets and beam diagnostics adds to the engineering challenge. Various technologies are under consideration including permanent magnet [5], electromagnet [6] and superconducting structures. At present, the superconducting bifilar (double helix) solenoid geometry [7] seems promising. Regardless of the geometry chosen, certain constraints such as the field strength (or undulator parameter), period, gap size and field quality must be satisfied.

The length of the undulator (~ 40 m) requires that the beam steering be corrected along the device. Combinations of BPMs and steering coils can accomplish this and could be integrated into the chosen undulator design. Both past simulations of a 40 Å device and 1D theory indicate that correcting the beam steering on the scale of the beam radius within each gain length is sufficient to maintain FEL performance within a factor of two of the perfect steering case [8]. This would suggest BPMs and steering magnets every 2.5 m with an accuracy of ~10 µm. Poorer correction is expected to degrade performance; however, BPMs with sufficient accuracy are being designed for Next Linear Collider (NLC) applications [9].

Undulator errors have traditionally been stated in terms of rms field error. Simplistic arguments (using effective energy spread) show that a ~0.1% rms field error can be tolerated (again with the nominal factor of 2 reduction in output power). Undulators and wigglers meeting this field quality have been built as third generation insertion devices.

3. Startup Level and Fluctuations

The LCLS has been proposed to operate in SASE mode because of the lack of a short wavelength source to act as a “seed” and the lack of high reflectance mirrors to form a cavity at these wavelengths and powers. This introduces the need to understand the startup regime in this high gain FEL. Various analytic models have been proposed, but none have been tested due to the lack of operating experiments [10]. Upcoming experiments at UCLA [11], BNL [12] and other institutions will address the startup regime at longer wavelengths. Presently, however, we must rely on models and simulations.

The effective startup power is the spontaneous emission within the first gain length of the FEL which acts as an input to the remaining undulator amplifier. Three methods have been used to estimate the effective startup power of the LCLS: a simplistic 1D model, integration of the spontaneous emission of a single electron over the appropriate (FEL) solid angle, and numerical simulations using the code GINGER [13]. Perhaps the most realistic model was the simulation which yielded ~10 kW. Regardless, the results of the three methods agreed with a factor of two. This is in agreement with past comparisons of the startup level from numerical simulations and 1D theory.

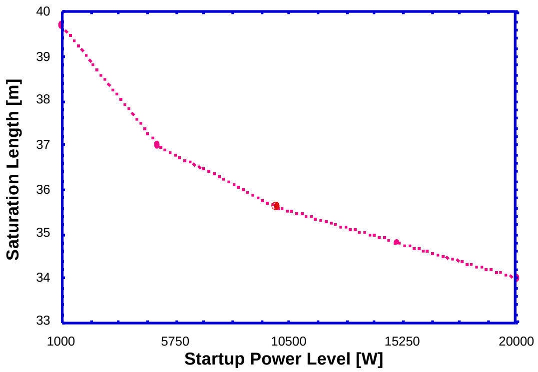

Figure 1: Saturation length as a function of effective input (startup) power is plotted. All other parameters are as given in Table 1. The line connecting the simulation data serves only to aid in viewing.

Unfortunately, we still do not know if any of the above models are correct. Certainly, precise numbers for the startup level cannot be predicted with confidence. Thus, it is important to study the sensitivity of the LCLS to effective input power. The code TDA3D [14] was used for this and subsequent simulation results. The results are presented in Figure 1. The saturation power is similar from 1 kW to 20 kW, however the saturation length becomes longer for lower input powers; the saturation length scales logarithmically with input power.

Fluctuations in the saturation power due to statistical variations in the effective startup power have been studied for the 40Å LCLS [15]. The conclusion was that these fluctuation would be on the ~10% level. For the 1Å LCLS these fluctuations may be reduced to the ~1% level since the number of cooperation lengths in a bunch is >1000.

4. Emittance and Focusing Requirements

Failure of past FELs has often been blamed on poor beam quality with high emittance being the primary problem. The pioneering work of Los Alamos on RF photocathode guns has produced beams of unprecedented brightness. Normalized rms emittances of ~2 mm-mrad have been reported at 1 nC of charge [16,17]. Extrapolating these achieved performances to the near future leads us to assume a 1 mm-mrad emittance is achievable. Preserving the beam emittance through transport, compression and acceleration would also be required. An important point which has been emphasized by some authors is that an FEL is sensitive to the "slice" emittance rather than the overall ("bulk") emittance [18]. It is possible that present RF photocathode guns already produce slice emittances of 1 mm-mrad at 1 nC of charge. Careful simulations of the FEL performance as a function of different emittance profiles are yet to be done.

With the above statements in mind, it is possible to simulate the FEL performance as a function of overall (uniform) beam emittance. Figure 2 shows the results of these simulations. The performance of the FEL is seriously degraded by higher emittances; the saturation length increases while the saturated power is relatively unaffected. This is somewhat expected since the 1D constraint on the emittance and wavelength is not satisfied. Thus, it is critical that emittance dilution effects in the transport lines, compressors and linac be minimized.

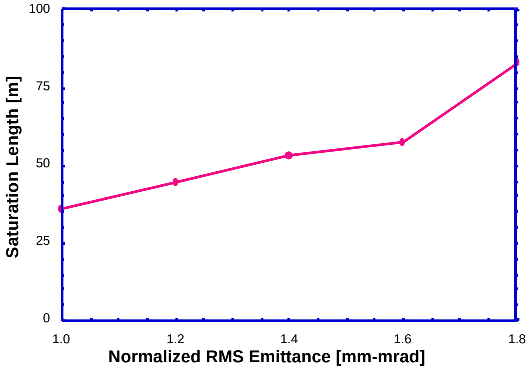

Figure 2: The saturation length as a function of emittance is plotted from results of numerical simulations. Other parameters are fixed as in Table 1.

Two options may alleviate severe emittance sensitivity. First, the slice emittance may not be effected as much as the bulk emittance. Second, higher beam energy could be used to lower the (normalized) emittance requirement. A further issue is that of optimizing the focusing for a given emittance.

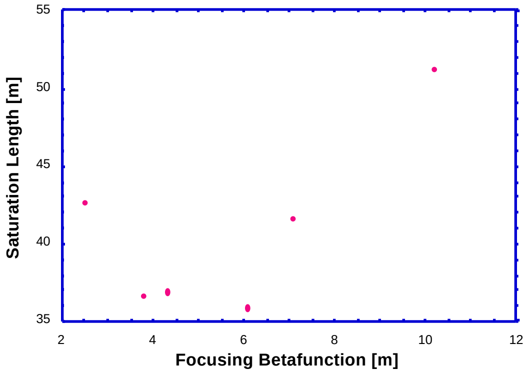

Figure 3: Variation of the external focusing betafunction and its effect on the saturation length is plotted. The strong alternating focusing is simulated with a realistic lattice (no smooth approximation) and the deviation of the data points from a smooth curve is due to the different phase advances of each case. The remaining parameters are given in Table 1.

The previously presented results assume a fixed quadrupole focusing channel. A strong focusing channel is required to propagate the beam over distances of tens of meters while maintaining high beam densities necessary for peak FEL performance. In reality, the focusing channel would be tuned to the achievable emittance. The 1D theory states that the focusing betafunction (β) should be equal to or larger than the field gain length (L_g) for optimal performance. For a fixed emittance of 1 mm-mrad, we plot the saturation length versus the betafunction in Figure 3. The optimal focus is near 6 meters. Sensitivity to beam mismatch does not seem to be an issue for the precision achievable at the Stanford linear accelerator.

5. Current and Energy Spread

A typical RF photocathode gun produces a beam of one to a few nC with a pulse length of a few picoseconds [19]. Thus, peak currents of a few hundred amps are produced with higher currents excluded (at low emittance) by space charge problems. The LCLS requires much higher currents to operate. Bunch compression has been extensively developed at SLAC to meet the needs of lepton linear colliders, and can be applied to FEL beams to produce short pulses with high peak currents ~ kA [20]. The LCLS may employ two stage compression to achieve peak currents ~ 5 kA with uncorrelated rms energy spreads ~ 0.02%. The compressors are susceptible to fluctuations in the beam current from the gun and timing jitter from the RF and gun drive laser. Hence, the sensitivity of the FEL to current variation is relevant (see Figure 4).

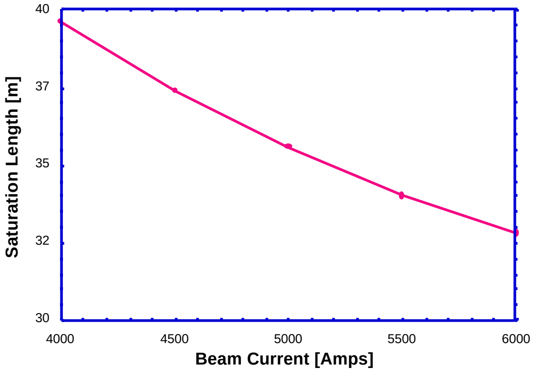

Figure 4: Simulations of the effect of current variation on the saturation length of the LCLS with the effective startup level varied in proportion to the current. Parameters other than current are given in Table 1.

Simulations reveal that beam current fluctuations as large as 10% cause less than a 5% difference in the saturation length and about 9% variations in the saturated power. The undulator should be designed long enough to still saturate with a reduced beam current.

The uncorrelated energy spread is related to the beam current through the compressor. Larger beam currents generally imply larger energy spreads. However, the 1D theory predicts that energy spreads as large as ~ 0.1% would not be detrimental. Simulations and experience at SLAC show that energy spreads of 0.02% at 5 kA should be obtainable [21]. Hence, achievable uncorrelated energy spreads should not be detrimental to the FEL.

The correlated energy spread contributes to the line width of the FEL and this may be a factor for some users. However, due to the high photon fluxes the use of a monochrometer could be possible. Other coherence and line width issues have been studied for previous parameter sets and indicate general agreement with 1D theory with the exception of a "spiky" time structure to the radiation pulse (see Figure 5). Again users will have to contend with this issue, but with a time scale of femtoseconds this may be a non-issue [22].

6. Acknowledgments

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