Performance simulation and parameter optimization for high gain short wavelength FEL amplifiers

G. Travish *

UCLA Department of Physics, Los Angeles, CA 90024, USA

Abstract

The designers of short wavelength FELs must rely on theoretical and numerical predictions since no experimental data are available for this region. The numerical codes which have been developed, and are being used to design systems at SLAC, BNL, Duke, LBL, CEBAF, LANL and UCLA among others, contain our best theoretical understanding of these systems. This paper analyses the present simulation capabilities for short wavelength designs. We discuss how codes are used to design these new systems, which aspects of our models are well implemented and which are not, methods of verifying the models, comparison with experiment, and finally comments on extrapolating to short wavelengths.

1. Overview

Recently, a number of FEL proposals have been put forth in an attempt to provide users with high brilliance radiation at short wavelength (UV and beyond) [1-3]. These new systems propose to operate in wavelength and gain regimes far away from past or present FELs (see Fig. 1). While these new designs offer great promise by using state of the art beam and undulator quality, the performance claims must be carefully examined. Computer simulation being the most powerful tool used to predict the performance of new FELs leads one to investigate our present simulation capabilities.

We discuss in this paper the present computation capabilities for high gain, short wavelength FEL amplifiers. High gain implies many exponential gain lengths of growth of spontaneous emission or an injected signal, while short wavelength is used to indicate "wavelengths shorter than presently achieved" - deep UV and beyond. FEL performance can be modeled with various scaled parameters [4-6]; however, to determine the predictability of simulations we use wavelength as a fundamental parameter.

2. How FEL codes are presently used

The complexity and cost (in CPU time) associated with running three dimensional FEL codes along with the large parameter space available to explore, requires the use of simpler and quicker means for initial design work. Often one begins with one dimensional analytic formulas in order to chose an operating regime. More elaborate models which include diffraction, energy spread, etc. and are easily implemented in spread sheets or mathematics solvers can then be used to perform an initial exploration of a design’s sensitivity to parameters (an example is given in Fig. 2) [7]. A promising design can then be studied using three dimensional or multifrequency numerical codes.

An interesting question is whether the above process would be necessary if sufficient computing power were available. An incomplete answer is yes, since changes to the model (code) would still be more easily implemented in the analytic or spread sheet calculations. At present, it is time and CPU intensive to perform an exhaustive set of fully three dimensional, multifrequency simulations of a given design. As an example, for a given version of the SLAC LCLS, hours of NERSC Cray C-90 CPU time are required to perform three dimensional sensitivity studies.

A more relevant question is whether it is the numerical models or the measurement accuracy of beam and undulator parameters that limit present FEL performance predictability. With virtually no experimental data in the high gain short wavelength regime, this question will go unanswered here, save for a few comments in subsequent sections.

3. Strengths and weaknesses of the models

The question of what features of an FEL are modeled well by simulations would perhaps be answered differently by experimentalists and theorists: one experimentalist’s
answer will be given here. The statements below hold in general for available codes; some comments may not apply to a particular code or set of parameters.

Let us begin with the good news. Simulations can include virtually any theoretically predicted or experimentally measured effect. New phenomena such as optical guiding was first "observed" through the use of numerical codes [8]. Parameters which are experimentally robust or accurately measurable have reliable numerical models. Simulations of high gain amplifiers can include startup from noise, optical guiding, slippage, harmonic generation, multi-undulator systems, and undulator and alignment errors. However, in order to reduce the complexity and run time of the programs, different codes have been written to incorporate some, but not all of these effects (see Table 1).

Beam current and energy spread are considered well measured experimentally, and hence are well modeled numerically. Some codes can implement current distributions directly from field solvers or experimental data [9]. Another parameter which is in hand is beam steering errors due to mismatch and undulator field errors that are well modeled in three dimensional codes. Furthermore, straightforward BPM and steering magnet corrector schemes are implemented and understood both experimentally and within codes. The saturation regime also is well modeled in numerical codes, while useful analytic theories are still lacking [10]. A significant issue for short wavelength FELs which has received little experimental attention, but appears to be well modeled, is external focusing through quadrupoles, sextupoles, plasma or other means [11]. Complex simulations including multiple undulators and dispersion sections are also implemented in some codes [12].

The "less good" news is that there are a number of effects which may not be well modeled, but without experimental verification it is difficult to emphatically state if our models are accurate. Emittance is both difficult to measure and model, as mathematical models for, e.g., rms emittance do not contain information about distribution function correlations. As a result, few analytic models make claims about slice emittance versus cooperation length emittance or beam core emittance versus the emittance within an optical mode. The lack of theoretical guidance makes a study of emittance effects incomplete.

**Fig. 1.** Gain versus wavelength for a number of past FELs is plotted on a log-log scale. The shaded area represents the regime of the various recently proposed high gain, short wavelength FELs.

**Fig. 2.** An example of a multivariable optimization using a three dimensional semi-analytic model [26]. The parameters used here are similar to recent LCLS studies. The saturation length is plotted as a surface of the focusing beta function of the undulator period (assuming a fixed wavelength).
Table 1
A sample of FEL codes and some of their features [19–24]. Some codes have features not listed, others have limited capability in unmarked categories. For example, most codes have external focusing implements, but only ones with discrete focusing channels (not smooth approximations) were indicated.

<table>
<thead>
<tr>
<th>Code name</th>
<th>1D/2D/3D</th>
<th>Time dependent</th>
<th>Multiundulator</th>
<th>Dispersion section</th>
<th>Startup model</th>
<th>Steering errors</th>
<th>Undulator errors</th>
<th>Focusing</th>
<th>Harmonics</th>
<th>Optical modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>FELEX</td>
<td>3</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>FRED3D</td>
<td>3</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>GINGER</td>
<td>2</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>NUTMEG</td>
<td>2</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>SARAH</td>
<td>1</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>TDA3D</td>
<td>3</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

and time consuming. Multifrequency codes can model various emittance distributions, but only with azimuthal symmetry or with extensive run times. Issues such as fluctuations, startup from noise and superradiance are also nor well tested nor sufficiently sophisticated [13]. As an example, startup from noise is often simulated by assuming an input signal equal to the spontaneous emission within one power gain length. Multifrequency codes also generate particle distributions with the correct Poisson statistics to emulate spontaneous emission levels which agree with analytic models. However, neither of these models may be sufficient to account for experimental conditions where a beam distribution may not be completely uncorrelated. As is discussed in Section 5, startup levels have yet to be well modeled.

The disparity between the ~10\(^4\) particles used in simulations and the ~10\(^10\) particles in a beam may present a formidable problem. At issue is the number of particles, \(N_h\), within a cubic (resonant) wavelength. For particle distributions with \(N_h > 1\) higher spontaneous emission levels are expected due to coherent emission. Codes can model such distributions by simulating only a slice of the beam, and hence reduce the effective beam volume. Whether such approximations underestimate the actual startup level, or even contain the appropriate effects, is unclear without experimental measurements of SASE.

4. Model verification

Assuring the validity of a simulation requires both programming skills and physical insight. Codes often differ in the numerical methods used to solve a model and in the assumptions made in the model [14]. Agreement between two codes often lends credence to both programs; discrepancies often lead to improvements. Simulation results can also be checked against simplified models. Using parameter sets within one dimensional limits (no energy spread, smooth focusing, no diffraction or other assumptions) allows rapid comparison with analytic results. Additionally, numerical diagnostics (phase space plots, energy conservation checks, bunching parameters, etc.) can be generated within a program allowing for further verification of model performance. Nevertheless, numerical comparisons and verifications do not substitute for experimental authentication.

5. Comparison with experiment

A pessimist’s version of this section would be very short: there are no short wavelength, high gain experi-
ments. Still, a number of other FEL experiments can be used to evaluate the predictive powers of our codes.

Oscillator experiments have operated from microwave to UV wavelengths with a variety of beam energies and currents. Good agreement has been reported between experiments and simulations [15]. ‘After the fact’ simulations have the best agreement since deviations from design are included. The previous statement is not trite; the errors and practical problems involved in an experiment often dominate over the errors caused by simplifications made in a model. This fact implies that simulations must include all known sources of error such as undulator field errors, beam parameter variations, misalignments and steering errors.

High gain experiments have been performed at microwave frequencies and in the IR at the LLNL ATA Paladin [16]. The microwave results lend credence to the simulations ability to predict growth rates, saturation, performance variation with current and undulator specifications. Little consistent agreement is available for self-amplified spontaneous emission (SASE) (see Table 2). The Livermore IR FEL also showed good agreement with simulations on growth, optical guiding and saturation, but no SASE results were measured. While few measurements have been made, those that have indicate that theoretical predictions underestimate the startup power level. Relevant experimental work is clearly lacking especially in two major areas: SASE and short wavelengths (beyond visible).

6. Conclusions on extrapolating to short wavelengths

Extrapolating results is at best a questionable practice. Extrapolating FEL results is particularly difficult due to the limited knowledge of electron beam characteristics in even the most carefully controlled experiments. The added complexity of simulating the various tolerance and errors further reduces the reliability of projections. And there is always the possibility of new physics unaccounted for in present simulations.

The need for staged experiments to address the issues relevant to short wavelength, high gain systems has been stressed throughout this paper. In response to this need, initial experiments are being prepared at BNL [17] and UCLA [18]. Both Brookhaven and UCLA are developing and improving the codes needed to simulate their respective systems. The results from these experiments, and hopefully others to follow, should allow for the verification and improvement of our codes to a level sufficient to design the next generation of FELs.

At present, simulations are not sufficiently well tested to rely on their predictive power for the short wavelength, high gain regime.

Acknowledgements

This work was supported by the Department of Energy Grants DE-FG03-90ER40796 and DE-FG03-92ER40693 and by the UCLA Department of Physics. The author gratefully thanks Kwang-Je Kim and the other members of the FEL ’94 organizing committee. Bill Fawley, John Goldstein, Mark Hogan, Heinz-Deiter Nuhn, Claudio Pellegrini, James Rosenzweig, Ted Scharlemann and Ming Xie provided many useful comments and discussions.

References

M. Xie, to be published.
[12] See studies in Ref. [2].
[25] This table was provided by W.M. Fawley.
[26] The data for this graph was produced by M. Xie.