

STATUS OF THE UCLA HIGH-GAIN INFRARED FREE ELECTRON LASER*

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A compact, infrared (10-20 μm), high-gain FEL is being commissioned at the Particle Beam Physics Laboratory (PBPL) at UCLA. A 60 cm long undulator with a period of 1.5 cm and an undulator parameter $K \approx 1$ has been built to be used in conjunction with the PBPL beam. Experiments will focus on FEL physics pertinent to proposed short wavelength devices. Of particular interest is exploration of startup from noise, self amplified spontaneous emission (SASE), beam parameter effects on gain, and output power fluctuations. Beam micro-bunching due to the FEL action will also be measured using coherent transition radiation. Here we present an overview of the relevant diagnostics, FEL simulation results and proposed experiments.

I. INTRODUCTION

The Free Electron Laser has shown potential as a light source in the infrared, UV and, as recent proposals indicate, in the XUV and X-ray regime. While oscillator experiments have provided a number of verifications and enhancements to theory and operational experience, few high-gain amplifier systems have operated in the optical regime. This paper describes the UCLA IR FEL – a system designed to study critical issues in high-gain systems and to improve the operational FEL and accelerator experience with the requisite high-brightness beams.

The UCLA experiment was designed to study issues important to future short wavelength devices at a minimum of cost and space. The short-period undulator, combined with our moderate-energy beam produces radiation in the infrared (IR), where a large number of diagnostics are available, without the added complexity of producing a higher-energy beam necessary for operation at shorter wavelengths. Further, working in the IR does not suffer from the beam noise problems associated with past microwave FELs. The lack of suitable sources at short wavelengths makes the feasibility of start up from noise (SASE) important [1]. Additionally, the difficulty of producing high reflectance mirrors makes an oscillator configuration impractical for short wavelengths, so successful operation in the high-gain regime is a necessary precursor to designing short-wavelength devices. For these reasons the FEL studies will begin from SASE in the high gain regime.

II. OVERVIEW

a. The Beamline

The beam is produced in an S-band RF copper photocathode gun driven by a frequency-quadrupled, pulse-compressed Nd:YAG laser (UV) [2]. Solenoids control the highly divergent beam and provide for emittance compensation [3] into the linac. A Plane Wave Transformer linac (PWT) accelerates the electrons from an injection energy ~ 4 MeV to a final energy of ~ 17 MeV [4].

Six of the quadrupoles are used to match the four phase-space parameters needed for injection into the undulator. The magnetic center of the beamline is passively aligned to $\sim 100\mu\text{m}$ using machined brackets, optical tables, and linear bearings (rails). This tolerance was chosen based on the performance simulations of our FEL. A second dipole after the undulator will bend the electron beam away from the optical pulse to facilitate the IR optics/diagnostics.

b. Diagnostics

An unsaturated high-gain FEL is highly (exponentially) sensitive to certain beam-parameter fluctuations. Thus, beam diagnostics on the UCLA system are designed for single-bunch (shot-to-shot) operation. Beam position, size, charge and emittance are measured using the following:

- Stripline beam position monitors (BPMs) for non-destructive measurements.
- Phosphor screens and video cameras.
- Integrating Current Transformer (ICT).
- Slits (1D pepper pots) to measure the effective transverse emittance of the space-charge dominated beam [5].
- A SLAC-like pulse-length monitor to make non-destructive shot-to-shot pulse-length measurements [6].

The first dipole magnet, in conjunction with the quadrupoles, is used as a spectrometer to measure the energy and the energy spread. The second dipole will also allow for a crude energy measurement after the beam exits the undulator. Other diagnostics include Faraday Cups for charge

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measurement and Cherenkov radiators, in conjunction with a streak camera, to measure the absolute pulse length.

c. Microbunching monitor

Coherent transition radiation (CTR) can be used to measure the extent of bunching in the FEL. We plan on installing a foil at the exit of the undulator to study the bunching. Calculations indicate that the expected 5% bunching factor should produce CTR in the FEL band comparable to the FEL output itself [7].

d. The Undulator

A planar undulator 60 cm long with a 1.5 cm period, 5 mm fixed gap spacing and a greater than 7 kG peak field awaits installation into the beamline. The undulator was designed to provide IR radiation from modest beam energies (< 20 MeV) while maintaining a strong coupling ($K \sim 1$). An rms field uniformity of better than 0.18%, measured using both a Hall probe and the pulsed wire technique [8], should assure good FEL performance. Additionally, the second integral of the undulator field satisfies the requirement that the rms electron beam deflection in the wiggle plane ($\sim 105 \mu\text{m}$) be less than the rms beam waist ($\sim 200 \mu\text{m}$). It should be noted that the construction of the FEL is not well suited to studying the effects of varying undulator parameters such as field strength and error.

Table 1: Electron Beam and FEL Parameters expected for the UCLA IRFEL.

Electron Beam Parameters [Expected]	
Energy	17 MeV
Energy Spread (uncorr.)	0.1%
Current (peak)	200 Amps
Pulse Length (rms)	~ 5 psec
Norm. Emittance (rms)	5 mm mrad
Undulator Parameters [Measured]	
Total length	60 cm
Undulator period	1.5 cm
Peak field on axis	7.3 kG
Pole face gap (fixed)	5 mm
Undulator parameter (K)	~ 1
FEL parameter (ρ) [9]	$\sim 1 \times 10^{-2}$
FEL Parameters [Simulations @10.6 μm]	
Radiation wavelength	10-20 μm
Power gain length	7.2 cm
SASE peak power	3 mW @ 7.2cm ~ 1 W @ 60cm

III. SIMULATION PREDICTIONS

The lack of experimental work on SASE optical FELs necessitates relying on numerical simulations to predict the performance of our experiment. Earlier work in the IR on the Paladin FEL at LLNL has helped test high gain codes, but has not provided information on startup from noise [10]. Fluctuations in FEL performance, especially from startup, and sensitivities to system parameters are a critical issue in future short-wavelength high-gain systems where output stability and saturation are significant to users. Simulations of the UCLA system have been performed to investigate such sensitivities in hopes of performing experimental comparisons. Most of the following work was performed with TDA3D [11] and includes 3D effects, diffraction, emittance and energy spread.

a. Current

The beam current is our easiest parameter to control and measure. Spontaneous emission can be differentiated from amplified (stimulated) radiation by observing the dependence on current: spontaneous emission is broadband and scales linearly with the current, while amplified radiation power, P , scales as $P \sim I \exp(\alpha I^{4/3})$ where α is a constant and I is the beam current.

Simulations of gain vs. current show that current variations $\sim 10\%$ vary the FEL output power $+40\%/-25\%$. Current variations of this order are within our ability to measure, and power (energy) fluctuations of a few percent are within our detector / electronics bandwidth. The challenge will lie in deconvolving a variation of beam current from parameters such as beam size, pulse length, energy spread and emittance.

b. Beam Size

Beam-size changes, such as those caused by space charge, affect the beam density as well as the matching into the undulator. The FEL is sensitive to the overall (six dimensional) beam density, however small changes in the transverse beam size should cause predictable changes in the FEL performance. Further, simulations predict FEL performance is insensitive to achievable beam matching. Regardless, matching is a technical issue that needs to be resolved with experience in beam handling. Phosphor screens and BPMs should provide sufficient operator feedback on beam size.

c. Pulse Length

Only a few "finite pulse" simulations have been performed on our system. Slippage is a factor in the performance of this system; however, over the short undulator

being initially used the output power is not degraded severely. Further work is needed to quantify (through simulations and experiment) this effect.

The pulse length is also a factor in much the same way that beam size is. The variation of the pulse length due to laser fluctuations and space charge are still an experimental uncertainty.

d. Energy Spread

Wakefields (primarily from the linac) are expected to produce a correlated energy spread $\sim 1\%$. This spread can be ameliorated by running the linac “off crest”. Any residual correlated energy spread will give rise to a broader radiation bandwidth. Our IR detectors are broadband and nearly linear over such linewidths, so that integrating over the wavelengths is inherent in the instrumentation. The expected uncorrelated energy spread (PARMELA [12] simulated and initially measured) of $<0.5\%$ does not substantially degrade FEL performance.

e. Emittance

The only single-shot emittance measurements available to us are destructive slits. Hence, we will not be able to measure emittance “on line” with the FEL operating, but by knowing all the other beam parameters it may be possible to calibrate the emittance. Simulations indicate that an emittance much poorer than the design value can still yield measurable gain.

IV. DETECTION OF SASE

The low-level SASE signal (see Table 1.), which can be calculated from numerical integration or simple 1-D theory [13], requires the use of cryogenic detectors to obtain the necessary sensitivity. A non-imaging optic (Winston Cone) will maximize collection efficiency during initial operation, but may degrade the signal-to-noise ratio (SNR) by collecting large amounts of background. Background (blackbody) radiation constitutes a DC offset/pedestal that may be compensated for up to the level of the shot noise. Commercially available IR detectors have relatively long time constants (\sim nsec) with respect to the pulse (\sim psec), so that the integrated background noise may be significant. An available copper-doped germanium detector should provide a SNR of $\sim 10^3$, neglecting signal loss in the optics, pre-amplifier noise, and reduction in detectivity due to operating far below the

response time of the detector. By removing the Winston Cone and aperturing the field of view of the detector to limit the collected background, the SNR can be increased by several additional orders of magnitude. Other detectors such as Mercury-Cadmium-Telluride photodiodes may offer the advantage of faster response times and/or higher quantum efficiencies, while only needing to be cooled to liquid Nitrogen temperature. Both the spontaneous emission and the amplified signal should be well within our sensitivity, and studies of SASE FEL radiation production should be feasible.

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VI. REFERENCES

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