1.1 Simulations of a Free-Electron Laser Oscillator at Jefferson Lab Lasing in the Vacuum Ultraviolet

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1.1.1 Abstract

The UVFEL at Jefferson Lab has provided a 10 eV photon beam for users by outcoupling the coherent third harmonic of the UVFEL operated at 372 nm. This can provide up to tens of milliwatts of power in the VUV. Operation of the FEL at the fundamental might enhance this power by up to a factor of 1000. With minor upgrades to the accelerator now underway and a new undulator proposed by Calabazas Creek Research, Inc. we show that we can lase in the fundamental at 124 nm. The predicted output is higher by four orders of magnitude on an average power basis and six orders of magnitude on a peak fluence basis than the Advanced Light Source at Lawrence Berkeley National Laboratory.

1.1.2 Introduction

Lasing in the vacuum ultraviolet is very difficult due to the lack of low loss optics in this wavelength range. One way to get around this limitation is to operate in the ultraviolet with a hole-coupled resonator and use the coherent third harmonic radiation naturally emitted by the FEL. This has been accomplished already at Jefferson Lab [1] but the power is rather low. If one can shorten the undulator wiggler wavelength, raise the electron beam energy, and enhance the electron beam brightness it is possible to produce gain sufficiently high for the relatively lossy mirrors in the vacuum ultraviolet.

1.1.3 FEL accelerator

1.1.3.1 *Present accelerator configuration*

The present accelerator for the Jefferson Lab FELs has already been described in detail in [2], so it will be described very briefly here. The accelerator source is a DC photogun operating at a nominal voltage of 350kV, which is then bunched and accelerated to ~ 10MeV with a modified CEBAF-style 2 cell booster. A merger injects this beam into a recirculating linac consisting of three cryomodules producing a total beam energy of 135 MeV.

1.1.3.2 *Proposed upgrades*

The injector for the Jefferson Lab FEL is presently undergoing an upgrade designed to allow higher voltage from the gun and a more optimal accelerating cavity design for the booster. Though this will not reduce the emittance and energy spread dramatically at the FEL, it should reduce it by approximately 20%. The linac will also be upgraded with the replacement of one cryomodule with a new high-performance version. With this module in place the accelerator should be capable of up to 160 MeV of electron beam energy. To obtain fundamental 10 eV with the present undulator it would be necessary to increase the energy to 235 MeV. This is far beyond the capability of the present accelerating voltage. To reach 124 nm we must change the undulator as well. Calabazas Creek Research, Inc. [3] has proposed building an undulator with iron poles embedded in a solenoidal field. Their design predicts an rms field of 5.1 kG in the helical undulator with a period of 15 mm. The rms value of K would then be 0.707. Similar undulators have been built in the past by several groups.

1.1.4 **FEL Oscillator**

1.1.4.1 ***FEL Modeling***

The availability of a pulse repetition rate of 4.678 MHz allows for the operation of the VUV-FEL as an oscillator, with a cavity length as long as ~32m. To overcome high mirror losses, the small signal gain should be high, yet the overall wiggler length is constrained to about 2 m in order for it to fit in the available space. The wiggler wavelength of 1.5 cm is short enough that an *in vacuo* device is required but the solenoid embedded design allows a helical undulator design, which permits a lower field for the same FEL gain. We are therefore assuming here a helical undulator with a period of 1.5 cm and an rms field of 5.1 kG. The bore of the wiggler would be 5 mm diameter, which would be a problem for very high average current but will not be a problem for a current of at most a few milliamperes. Such a design might have very good field quality and very low susceptibility to radiation damage. A more conventional superconducting electromagnetic undulator could achieve a similar field but with much more complexity and less flexibility in its design. A cryogenic permanent magnet wiggler could also achieve an equivalent rms field strength in a linearly polarized undulator, but would be more sensitive to radiation.

The performance of this FEL was predicted using two codes. One is a combination of the time-independent version of Genesis 1.3 to model the FEL interaction in 3-D, and the Optical Propagation Code (OPC) to model the oscillator [4,5]. OPC provides the flexibility to look at the effects of mirror figure distortions, add intra-cavity apertures, and analyze a number of other features, such as edge outcoupling, or the effect of mirror decentering and tilts. The wiggler can be placed anywhere in the cavity and the mirror ROCs can be unequal. It also allows one to evaluate the outcoupled mode and determine its profile and beam quality. The other FEL oscillator code is Wavevnm, developed by the Naval Postgraduate School. This code assumes the wiggler is located in the center of the resonator, and calculates the mirror's radii of curvatures (ROCs) based on an input Rayleigh range and waist position. Both codes treat the FEL interaction similarly in that a wiggle-averaged orbit approximation is used, i.e., the interaction is evaluated at each wiggler period and the average motion of the electrons over each period is used. In addition, the user defines a discrete mesh and the particle distribution and fields are evaluated on the mesh nodes.

For the chosen wiggler, optical cavity, and e beam parameters, simulations in Genesis 1.3 yield a single pass gain of ~3.6, insufficient for operation as a high-gain, low-*Q* oscillator [2], where a small amount of power from the output is fed back to the start to seed the next pulse. Instead, a near-concentric cavity is modeled, with the parameters given in Table 1. Power is outcoupled through a hole in the center of the mirror downstream of the wiggler. This provides an advantage in tunability, since for photon energies less than 12.4 eV, the mirrors are relatively broadband and the wavelength is controlled by the beam energy and the wiggler parameters. To add tunability, we plan to use the multiple mirror design employed on the other FELs at JLab [6] to change the coating parameters and outcoupler hole size.

The wiggler and optical cavity parameters for the Genesis/OPC simulations at 124 nm (10 eV) are shown in Table 1.

Table 1 Wiggler, electron beam, and optical cavity parameters for 124 nm operation

Parameter	Value
Wiggler period (cm)	1.5
Number of periods	120
K_{rms}	0.707
Energy (MeV)	155
Emittance (microns)	4
Energy spread (%)	0.17
Peak current (A)	180
Cavity length (m)	32.04196
Mirror radii (cm)	1.27
Mirror radius of curvature (m)	16.072
Hole radius (cm)	0.1
Mirror reflectivity (%)	80
Mirror microroughness (nm rms)	≤0.5
Slippage parameter	0.33
Nominal pulse bandwidth (FWHM)	0.2%

A few comments about the table are in order. The reflectivity at 124nm is typical, or slightly poorer (< 5%) than the value determined from curves published on manufactures websites, in order to provide a more realistic expectation of the losses encountered at this wavelength. The pulse bandwidth is an estimate based on the slippage parameter which itself is based on the electron pulse having an rms duration of 150fs. In comparing the results of the two codes, the Wavevnm simulations showed little tendency to avoid the hole, whereas the Genesis/OPC simulations showed a mode profile that was peaked slightly off center. The latter case matches our own experience. Both codes predicted a profile resembling a TEM_{01} mode, as shown in Fig. 1, with a peak roughly in the center. This is also true of the outcoupled profile. As shown in Fig. 2, the Genesis/OPC simulations indicate a peak lasing efficiency of 0.048%, an outcoupling efficiency of 27%, and an output energy per pulse of almost 5 μJ, or 23W average power at 4.678MHz.

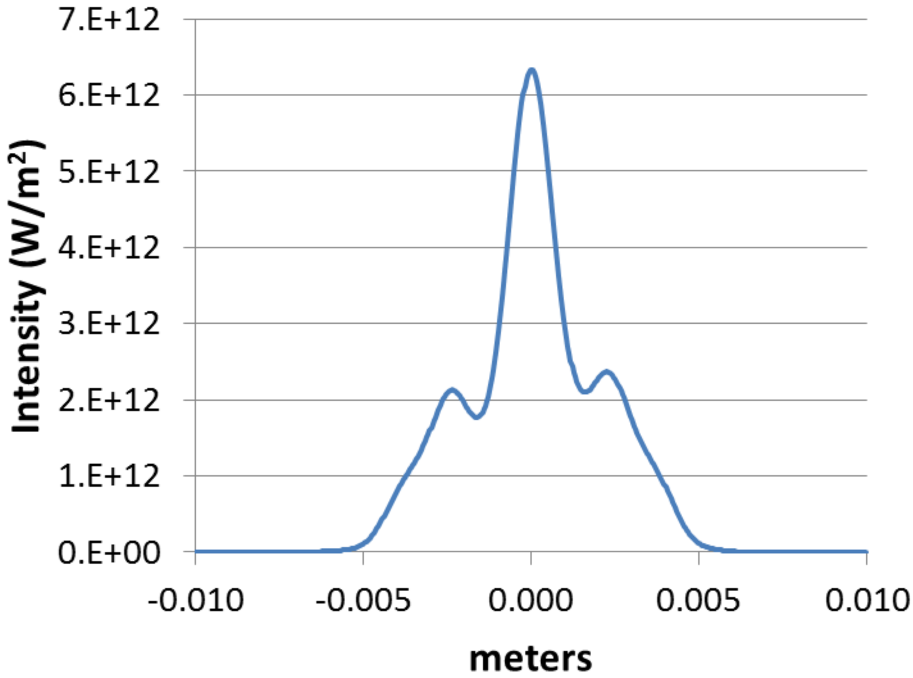

Figure 1: Transverse profile on OC mirror

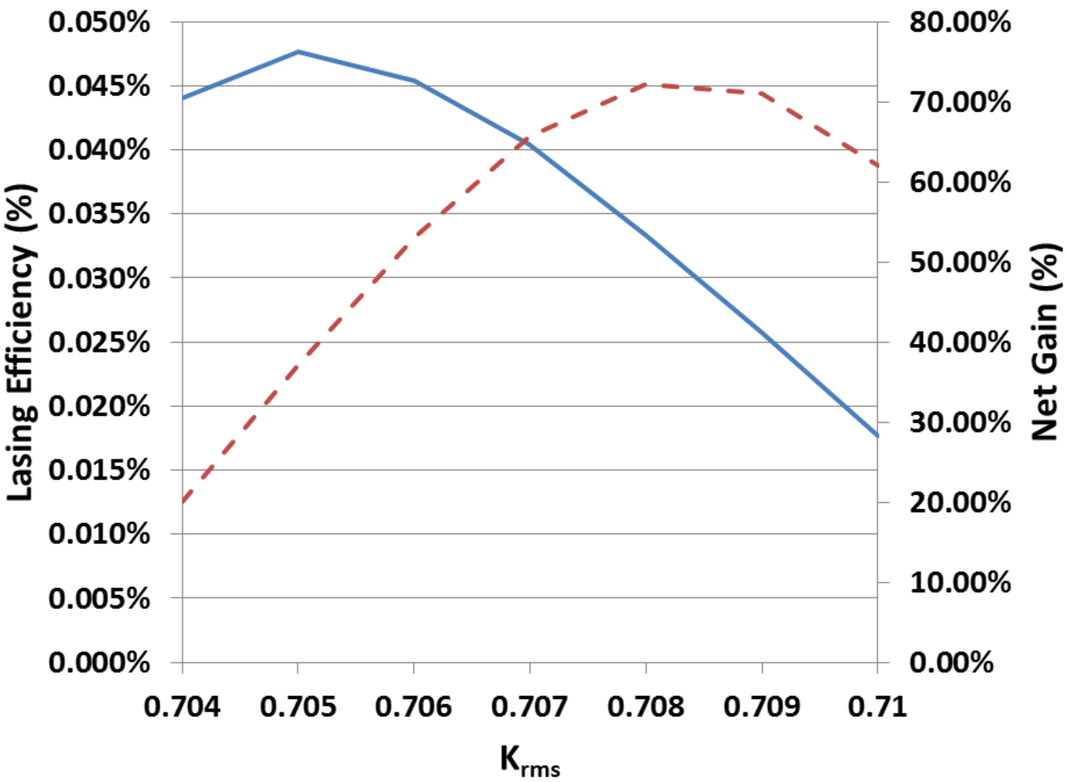

Figure 2: Lasing efficiency (solid line) and net gain (dashed line) as a function of K_{rms}

For comparison, the output at 10eV of the Advanced Light Source, operating at 500MHz with 70ps pulses, is about 3pJ/pulse with an average power of 1.6mW [2]. The measured 3rd harmonic output of the UV FEL was about 7 nJ [4]. Actual performance might be poorer when the effects of mirror thermal distortion and vibration, as well as electron beam slippage, are accounted for in the model.

1.1.5 **Optics Considerations**

Though the predicted output of the FEL makes it the highest average power laser in this wavelength range, this output is modest compared to lasers at longer wavelengths. Because the performance of the FEL is dependent on the Rayleigh range which is in turn determined by the mirror radii of curvatures, the mirror substrates will be cryo-cooled silicon, as this material is athermal, i.e., has a negligible coefficient of thermal expansion at ~120 K [7]. This material can also be superpolished to achieve a microroughness below 0.1nm, although the metal coating with protective overcoat may increase the roughness slightly. Besides the aforementioned thermal distortion of the mirrors, which can be partially compensated by deforming them [6], there are technical challenges associated with the maintenance of surface figure and finish along the periphery of the hole in the outcoupler mirror, which we believe can be met using ion milling and magnetorheological finishing.

The use of hole outcoupling in a near-concentric resonator architecture results in a low outcoupling efficiency, so the intracavity power falling on the mirrors is roughly 4 times higher than the output power. To determine whether damage to the cavity optics could be performance-limiting, consider that the mirror subjected to the highest irradiance is the high reflector (HR) mirror, since the peak intensity falling on the outcoupler mirror passes through the hole. The peak intensity on the HR is 3.46×10^8 W/m^2, on a fluence basis it is $0.1 mJ/cm^2$ for a 300fs pulse. This is well below the laser damage threshold of $56 mJ/cm^2$ estimated by using the measured damage threshold of $100 mJ/cm^2$ for 300fs pulses at 400nm [8] and an inverse square root wavelength dependence [9]. Thus, performance shouldn't be limited by damage to the cavity optics.

1.1.6 **Conclusions**

We have simulated the performance of an FEL oscillator operating in the VUV based on the existing Jefferson Lab linac and recirculator with an upgraded injector. The performance is based on 3D simulations, so 4D effects, such as slippage and bunch shape are ignored. The predicted performance is promising, with an outcoupled energy/pulse of 5μJ and an average power of 23W, making it much brighter than synchrotron light sources. With such high energy/pulse, even for the 3rd and 5th harmonics, along with a high repetition rate, this FEL offers unique opportunities to seed a soft x-ray FEL.

1.1.7 **Acknowledgements**

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1.1.8 **References**

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