DEMONSTRATION OF 3D EFFECTS WITH HIGH GAIN AND EFFICIENCY IN A UV FEL OSCILLATOR*

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Abstract

We report on the performance of a high gain UV FEL oscillator operating on an energy recovery linac at Jefferson Lab. The high brightness of the electron beam leads to both gain and efficiency that cannot be reconciled with a one-dimensional model. Three-dimensional simulations do predict the performance with reasonable precision. Gain in excess of 100% per pass and an efficiency close to $1/2N_W$, where N_W is the number of wiggler periods, is seen. The laser mirror tuning curves currently permit operation in the wavelength range of 438 to 362 nm. Another mirror set allows operation at longer wavelengths in the red with even higher gain and efficiency.

INTRODUCTION

Since the initiation of the FEL program at Jefferson Lab (JLab) in 1995, three FELs have been designed and operating; the IR Demo [1], the IR Upgrade [2], and most recently the UV Demo, whose design [3] and operation [4] are reported in this Conference. In the past, these FEL's gain and power vs wavelength was predicted using the 1D formulas by Dattoli [5,6], as well as a pulse propagation code based on Colson's formulas [7]. The former is incorporated into a spreadsheet with Visual Basic macros, it runs quickly and is useful for studying the dependence of the gain and power on electron beam parameters in order to optimize the design. The latter program adds information such as an estimate of the detuning length, the turn-on time, and the pulse length. With these codes we found that for the IR FELs' (each with an electronic gain of order 100%) the gain was predicted fairly accurately. However, for the UV Demo FEL, the predicted gain appeared to be higher still, and the assumptions of the model were clearly violated. We have since measured gain, loss, and average power and in this report, present a comparison of the data to the results predicted by 1D and 3D models.

EXPERIMENT

The UV Demo FEL uses the same photo-injector and linac as the IR Upgrade FEL [2]. The design of the UV bypass is discussed and shown schematically in [3]. The optical cavity parameters are listed in Table 1. While the resonator architecture is near-concentric, the wiggler is displaced from the geometrical center towards the high reflector. The mirror substrates are single crystal sapphire from Crystal Systems (Salem, MA), fabricated by RMI (Lafayette, CO), and coated with ion-beam sputtered coatings by Advanced Thin Films (Boulder, CO). The reflectivity listed is obtained from data supplied by the vendor. The mirrors can be cryo-cooled, but for these experiments they were water-cooled. Four mirrors can be accommodated in each cavity vacuum vessel, to allow for more wavelength flexibility. Currently there are mirrors for lasing in bands centered at 372nm, 400nm, and 700nm. The shortest wavelength uses a hole outcoupler, while the other two are transmissive outcouplers. This report analyzes some of the data obtained when lasing with the 400nm mirror set.

To characterize the FEL output, an insertable mirror ~3m downstream of the outcoupler directed the beam through a UV grade fused silica (UV FS) viewport and routed it with two dielectrically-coated mirrors onto two 3° UV FS wedges, which are used as attenuators. One of the beams after two front surface reflections was focused onto a Si photodiode (Thorlabs DET-36) while the other beam was incident on a ceramic plate. The diffuse scatter from this surface was collected by a 32m optical fiber and analyzed with a spectrograph (Ocean Optics HR4000). The beam transmitted through the wedges was terminated by a Coherent PM300 power probe and readout on a Molectron PM5200 power meter interfaced to our EPICS control system.

OPTICAL MODELING

Three different 3D FEL oscillator codes were used in an effort to benchmark them against the actual performance. One is the Wavevnm code developed at the U.S. Naval Postgraduate School (NPS) [8]. 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. The next code is Genesis/OPC, which has been used to model two operating FELs [9,10]. Genesis 1.3 is used to simulate the FEL interaction, and the resulting optical field is passed to the optical propagation code (OPC)[9], which evaluates the effect of these fields by the optical cavity using the actual wiggler location. Aberrations of the mirror figure, whether due to fabrication, mounting, or thermal effects, are fully treated. The third code is Medusa/OPC, which in the past was used to model the IR Upgrade FEL [11].

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Medusa is used to simulate the FEL interaction and OPC the optical cavity. The Wavevnm and Genesis codes treat the FEL interaction similarly. 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. Medusa is different in that electron trajectories are integrated using the three-dimensional Lorentz force equations in the combined magnetostatic and optical fields. No wiggler-averaged orbit analysis is used. The optical field is represented as a superposition of Gaussian modes, so no meshing is used until the propagation reaches the end of the wiggler, at which time it is mapped onto the mesh that OPC uses.

For each code, the data from Tables 1 & 2 was used for input (subject to the limitations already discussed for the Wavevnm code) and the number of passes adjusted until the power saturated. For the three-dimensional simulations, the value of K_{rms} was then scanned to map out the net gain, which is what we measure, and the power at the wiggler exit, which we can use to compare to experimental measurements. The results are plotted in Fig. 1. We also plot the net gain determined from the two 1D methods and the experimental value. It can be seen that there are a wide range of values. The 1D calculated gain agrees well with the values calculated by Genesis and Wavevnm when the latter are multiplied by the expected slippage gain reduction of 0.82.

Table 1: UV Demo FEL Optical Cavity Parameters

Cavity length (m)	32.04196
Mirror radii (cm)	2.54
High reflector radius of curvature (m)	14.43±0.02
Output coupler radius of curvature (m)	17.72±0.02

Table 2: Wiggler and e-Beam Parameters

Wiggler period (cm)	3.3
Number of periods	60
K_{rms}	0.815
Emittance (microns)	5
alphax, alphay	1.25, 0.77
Beam radii (σx,σy)	196, 175
Energy spread (%)	0.3
Peak current (A)	200

The lasing efficiency η (laser power out/beam power) ranged from 0.62% to 0.72% in the 3D codes and the spreadsheet code, and was ~0.5% for the pulse propagation code. This compares relatively well with $\eta = 0.83\% = 1/2N_w$ [12]. The lasing efficiency as a function of output power is shown in Fig. 2. The decreasing efficiency with increasing power is due to mirror absorption, which increases the Rayleigh range and lowers the gain.

RESULTS

Gain and loss measurements were taken with the accelerator set up to produce 50 μs pulses at 60Hz to ensure that mirrors heating would not affect the results. The output of the photodiode was recorded by an oscilloscope (Tektronix TDS3034B) that is interfaced to a computer running a LabView program to interpret the data. A screen capture of an analysis done by this program is shown in Fig. 3.

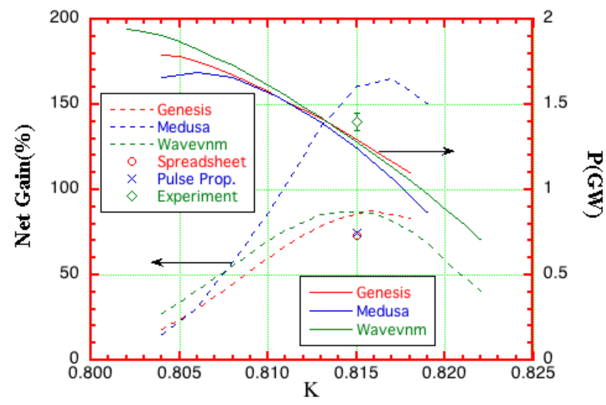

Figure 1: Modeled gain & power (lines), 1D calculated gain (points), and measured gain (point).

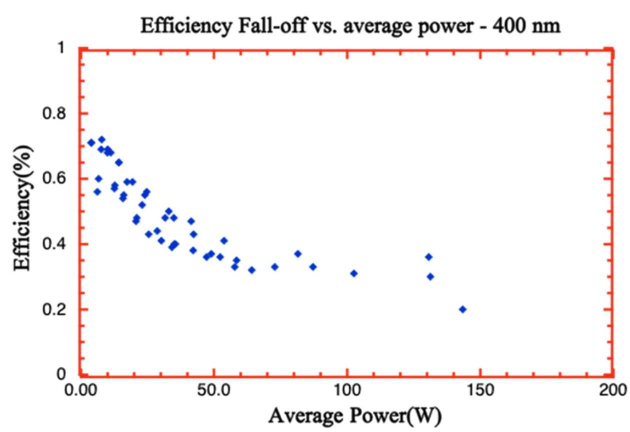

Figure 2: Lasing efficiency as a function of output power

We found that the error in determining the gain was about ± 5%, however, there were many cases logged where some systematic noise in the baseline prevented good fits by the software. The value plotted in Fig. 3 is thus the average over some +20 scans with a larger error. In contrast, the loss was fairly easy to measure and matched the coating vendor's data.

At low duty factors, *e.g.*, 1%, where mirror heating was still minimal, the lasing efficiency was 0.73±0.05%, and decreased roughly linearly as the duty factor was increased.

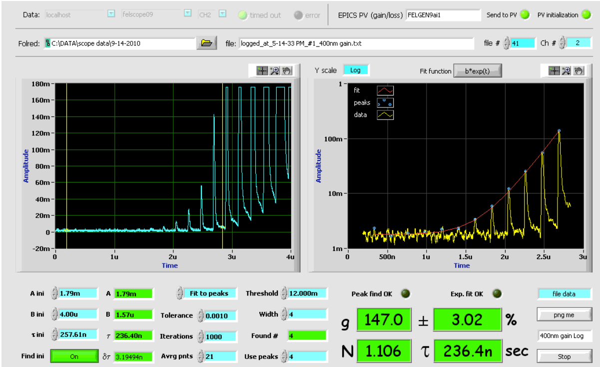

Figure 3: Data analysis software for determining the FEL net gain. The curve on the left uses a linear scale while the one on the right is logarithmic.

DISCUSSION

Fig. 1 clearly shows that the 1D models grossly underestimate the gain, as do the 3D models that use wiggler-orbit averaging. Medusa/OPC appears to agree better with the gain data, particularly when one considers that when the effect of slippage is accounted for the gain will decrease. Slippage effects are best treated with 4D modeling, which is on-going using Medusa/OPC at this time. Given the spread in the modeling results and the disagreement of most of the simulations with the experiment, one is compelled to examine the data for inconsistencies that might suggest a systematic error in the measurement technique or the analysis. Two other observations about the laser behavior are consistent with a high gain. One is the turn on time, which at 5 μs, is consistent with a net gain of ~145%. The other is the detuning curve, which is greater than 7 μm, and implies a net gain of ~180%. The experimental evidence is therefore strong that the gain is well above 100%. Having established this, it appears that the 3D Medusa/OPC simulation more accurately predicts the experimental results. However, a cursory comparison of 3D Medusa/OPC with the data obtained at 700nm suggests that code predicts a net gain far higher than the measured gain, so at this time we can't state that one 3D code is necessarily better than the other. Finally it should be noted that all the codes underestimate the efficiency, and hence the actual intracavity power, which is ~ 2GW. The highest simulated efficiency is close to the experimental value but will be lower when 4D simulations are carried out.

CONCLUSIONS

In this brief report we have benchmarked the UV Demo FEL gain and lasing efficiency data with two 1D codes and three 3D codes. Though the 1D and two of the 3D code agree well with each other they do not agree with the experiment. Amongst the 3D codes, the two using wiggler-orbit averaging evaluated on a mesh are in poorer agreement than Medusa, which does not. The latter's better agreement could merely be fortuitous. Another explanation is that the electron beam parameters are better than measurements indicate. The electron beam parameters in Table II, particularly the emittances and energy spread, are projected, not slice values, and are averaged over the 250 μs macropulse. We measure the gain near the beginning of the macropulse, where these parameters could be different. We intend on extending this study to encompass analysis of the 700nm lasing results, as well as compare them with the 4D version of Medusa/OPC.

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