BEAM LINE COMMISSIONING OF A UV/VUV FEL AT JEFFERSON LAB*

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Abstract

Many novel applications in photon sciences require very high brightness and/or short pulses in the vacuum ultra-violet (VUV). Jefferson Lab has commissioned a UV oscillator with high gain and has transported the third harmonic of the UV to a user lab. The experimental performance of the UV FEL is much better than simulated performance in both gain and efficiency. This success is important for efforts to push towards higher gain FELs at short wavelengths where mirrors absorb strongly. We will report on efforts to characterize the UV laser and the VUV coherent harmonics as well as designs to push towards lasing directly in the VUV wavelength range.

INTRODUCTION

At the 32nd International FEL Conference in Malmo, Sweden we announced the results of operation at 700nm of the UV Demo FEL [1]. Since then, we have published [2-5] reports on different aspects on this high average power FEL, including the motivation, design, and commissioning and operation. The last report [5] concerned itself with the interleaving of commissioning with the installation of the UV Demo's optical components, as well as characterization and operation of the driver ERL. This report will emphasize the optical performance in the visible and ultraviolet, with particular attention devoted to how modelling of the performance agrees with measurement. It will briefly note our first results at delivering 10eV (124nm) light to a user lab, as a more detailed report is in preparation [6], and touch upon our design for an oscillator-based FEL that would lase directly in the VUV [7].

FEL, OPTICAL TRANSPORT AND DIAGNOSTICS IMPLEMENTATION

The UV Demo FEL uses the same photo-injector and linac as the IR Upgrade FEL [8]. The design of the UV bypass is discussed and shown schematically in [2]. 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).

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

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 with a 5.5mm diameter hole, while the other two use transmissive outcouplers (R = 90±0.5%).

To transport the UV output upstairs to the user labs, the output is first collimated using a slightly (~ 4°) off-axis Newtonian reflector architecture, where the radius of curvature (ROC) of the primary mirror is adjusted appropriately for the spectral range of interest. As the laser output undergoes ten reflections before entering the user lab, it is important to use transport mirrors with a high (> 99%) reflectivity for both S and P polarizations. An enhanced aluminum coating with reflectivity maxima at 400 and 700nm was designed and e-beam deposited on silicon substrates by RMI. These mirrors are installed on water-cooled, remotely actuated holders. For the VUV output, where mirror reflectivities can be lower, particularly if p-polarized [9], the two turning flats in the collimator vacuum vessel are moved out of the beam path so the hole-outcoupled radiation undergoes a drift of ~ 15m before reflecting first vertically to the first user lab, and then again after an additional ~ 7m to direct the beam horizontally. In this way it undergoes two s-polarized reflections, with a net reflectance at ~ 124nm of ~ 80%. The coatings were aluminum protected with MgF_2 by Princeton Instruments on RMI-polished silicon substrates.

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To characterize the UV FEL output, an insertable mirror ~ 3m downstream of the outcoupler directed the beam through a UV grade fused silica (UV FS) viewport. It was then routed 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 EPM-2000 power meter interfaced to our EPICS control system. To characterize the VUV output, the beam is incident on the entrance slits of a McPherson 218 0.3m vacuum monochromator with a grating blazed at 150nm and detected with an IRD AXUV-100 silicon photodiode. If a determination of the absolute flux in the VUV is desired, the monochromator can be replaced with a windowless far ultraviolet aluminum photodiode from NIST.

RESULTS

The laser efficiency η=laser power out/beam power vs. output power was measured by keeping the charge/bunch fixed and varying the duty factor (macropulse frequency ·macropulse length) for both 700 & 400nm. The data is shown in Figs 1 & 2.

Note that in both cases, the initial lasing efficiency was of order 0.8% (though slightly lower than that for 400nm lasing) This compares relatively well with η = 0.83% = $1/2N_w$ [10] Also note that one can see a linear decrease in efficiency with increasing laser power that is due to thermal aberrations caused by absorption in the coatings. In this regime the transverse mode is smooth and approximately Gaussian, and decreasing in diameter as the Rayleigh range increases. At higher powers, where the distortion levels are higher, the transverse profile shifts to a higher order pattern due to hopping between several modes in rapid succession. Nonetheless, we were able to extend the power output at an almost constant lasing efficiency to ~ 150W at 400nm and 250W at 700nm. We have lased at both wavelengths for several hundred hours and to date, have not seen any degradation in mirror performance. We believe this is primarily due to the fact that, unlike storage ring FELs, we do not have the high levels of incoherent spontaneous radiation in the VUV to crack residual hydrocarbon and deposit carbon on the cavity mirrors. Cavity length detuning curves were about 12.5µm long at 700nm and ~7µm long at 400nm. So long as we weren't close to the synchronous point, spectral profiles were smooth and without sidebands with bandwidths of about 0.3-1%.

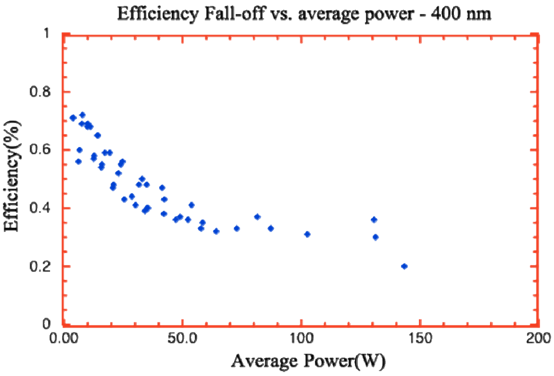

Figure 1: 400 nm lasing efficiency as a function of output power.

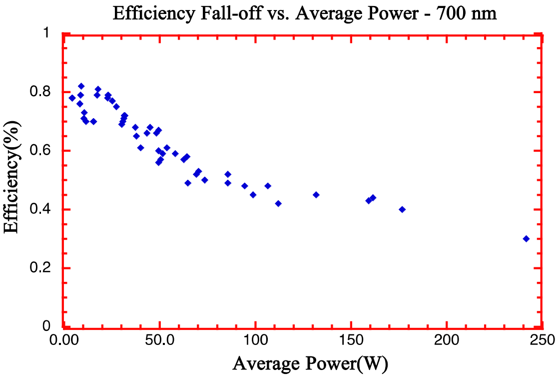

Figure 2: 700 nm lasing efficiency as a function of output power.

Gain and loss measurements were taken with the accelerator set up to produce 50 µs pulses at 60Hz to ensure that mirror 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.

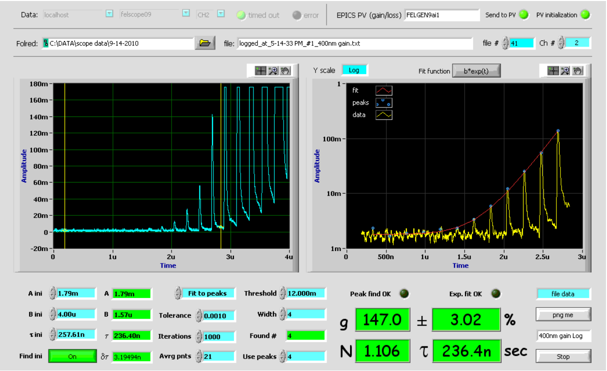
Data: localhost felscope09 CH2
EPICS PV (gain/loss) FELGEN9ai1
Folred: C:\DATA\scope data\9-14-2010
file: logged_at_5-14-33 PM_#1_400nm gain.txt
file # 41
Ch # 2
Y scale Log
Fit function b*exp(t)
A ini 1.79m
A 1.79m
Fit to peaks
Threshold 12.000m
B ini 4.00u
B 1.57u
Tolerance 0.0010
Width 4
τ ini 257.61n
τ 236.40n
Iterations 1000
Found # 4
Find ini On
δτ 3.19494n
Avrg pnts 21
Use peaks 4
g 147.0 ± 3.02 %
N 1.106 τ 236.4n sec
400nm gain Log

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.

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In this case the laser was operating at 400nm and the cavity length was set to maximize the gain. 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. In contrast, the loss was fairly easy to measure and matched the coating vendor's data. This sets the gain per pass (or electronic gain) at ~175% with the same error bars.

Attempts to transport 700nm beam to the user lab configured to receive it were stymied by the failure of the mirror deformer in the collimator. With this mirror's ROC longer than optimum, the output mode was underfocused and thus too large to be useful for experiments.

For the VUV characterization, we initially transmitted the beam straight into a vacuum vessel with viewers and the aluminum photodiode. As these components were uncooled, the duty factor was a relatively low 1.4%. The data confirmed that the modelling of the propagation was correct, and a relatively high number, 4.8 x 10^{12} photons (± 3%) during the macropulse were produced [6]. The ratio of the 3rd harmonic to the fundamental was 1.2 x 10^{-3} ± 5%. When we attempted to transport the beam upstairs to measure the bandwidth of the 1st and 3rd harmonics, we found that we could only measure the former, as evidenced by the lack of change in the spectrum when we passed the output through a closed vacuum valve with a fused silica window. We swapped the monochromator for the aluminum photodiode and measured a lower ratio of 1.2 x 10^{-4}. Subsequent to these experiments, we removed the turning mirror vessels and discovered that the first turning mirror was damaged uniformly where it had been illuminated. In retrospect, we realized this was due to the application of VacSeal® to close a leak diametrically opposite the mirror. Apparently it vaporized and coated the mirror, and subsequently underwent photodecomposition when illuminated. This resulted in a loss of reflectivity and high scattering. The transport ratio should therefore be regarded as a lower limit.

FEL MODELING

During the UV Demo design phase some 8 years ago, the FEL performance was predicted using 1D formulas by Dattoli [11,12], as well as a pulse propagation code based on Colson's formulas [13]. For our IR FELs we found that the codes did a reasonably good job, within 20%, of predicting the gain and power. As these FELs had electronic gains of order 100%, these codes, even with modifications to account for the higher gain, were nearing their limits of applicability. For the UV Demo FEL, the predicted gain appeared to be higher still, and the assumptions of the model were clearly violated. Hence, we used the UV Demo performance at 400nm to benchmark 3D and 4D models. We are particularly interested in their predictive ability as we used the 3D codes in designing an FEL oscillator that would operate in the 124-12.4nm range [7]. Three different 3D FEL oscillator codes were used and the differences between them described in [3]. The three codes were the Wavevnm code developed at the U.S. Naval Postgraduate School (NPS) [14], Genesis/OPC [15,16], and Medusa/OPC [17]. Medusa/OPC was also run in 4D to determine the detuning curve, gain, and laser efficiency.

For each code, the data from Tables 1 & 2 was used for input 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 in Fig. 4 and summarized in Table 3. 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 0.86 [18]. As shown in Table 3, the lasing efficiency ranged from 0.63% 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 $\eta = 0.83\% = 1/2N_w$ [10].

Table 2: Wiggler and e-beam parameters

Wiggler period (cm)	3.3
Number of periods	60
K_{rms}	0.816
Emittance (microns)	5
α_x,α_y	1.25, 0.77
Beam radii (σ_x,σ_y) (microns)	196, 175
Energy spread (%)	0.3
Peak current (A)	200
Full pulsewidth (fs)	450

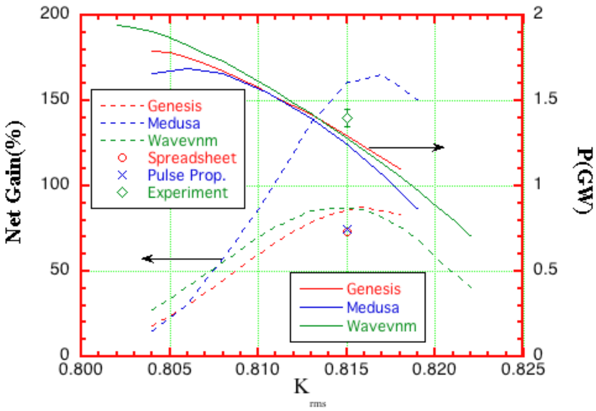

Figure 4: 3D Modelled gain & power (lines), 1D calculated gain (points), and measured gain (point).

Table 3: Comparison of FEL models with experiment

	Net gain (%)	Lasing eff. (%)
Jlab spreadsheet	75	0.7
Jlab pulse prop.	75	0.5
Genesis/OPC (3D)	88	0.67
Wavevnm (3D)	88	0.72
Medusa/OPC (3D)	168	0.63
Medusa/OPC (4D)	119	0.41
Expt.	145±7	0.73±0.05

The 4D net gain result is in better agreement with the experiment than the 1D pulse propagation simulation, yet lower than the experiment, and no better than the 3D version, once it is scaled for slippage. Note too that the lasing efficiency is the lowest of the group. As shown in Figure 5, the shape of the efficiency curve (dotted line) has a slightly decreasing plateau after the maximum efficiency. This is not like the experimental result, which is triangular in shape. One can see that if instead of the plateau, the efficiency were to increase until about 7.5µm, then the experimental result would have been better reproduced. However, the length of the detuning curve reproduces the experimental result, unlike the 1D model, which predict a detuning length of 4.5µm. As this is a preliminary result, we are investigating varying other parameters *e.g.*, the number of macroparticles, to see if the experimental curve can be better reproduced.

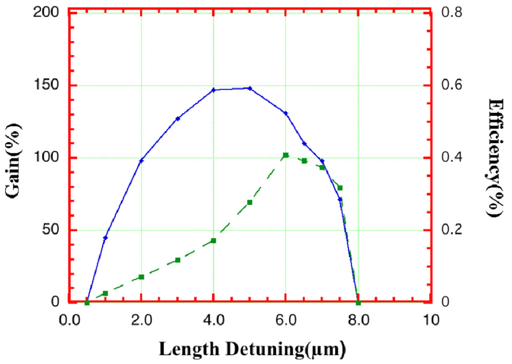

Figure 5: 4D Modelled gain (solid line) and efficiency (dotted line) as a function of cavity detuning.

DISCUSSION

The importance of benchmarking a number of FEL oscillator codes against the performance of a high gain FEL is important when designing new FELs with similar (or higher) gain. As mentioned in the previous section, we recently went through that design exercise for a VUV oscillator.[14] To build this machine, we propose to replace our linac with a higher gradient version and recirculate beam through the linac to raise the beam energy to 600MeV. These changes to the accelerator produce peak currents at the wiggler of over 1 kA. The wiggler will be longer as well, 6m, in order to achieve the high gains necessary to offset the high losses from the mirrors and, with high optical guiding, prevent the mode from wandering on the hole outcoupler. The 1D codes predicted a saturated gain of about 100%, while 3D Genesis/OPC predicted a saturated gain of 500%. Clearly, the 1D codes severely underpredict the performance. Relative to the 1D codes, the 3 & 4D codes, particularly those using OPC, also add far more versatility in their ability to optimize the design of the optical cavity.

Table 3 shows that two of the three codes do not agree with the gain data. Why is the measured performance so good? At this time, we speculate that this could be due to the fact that our measured energy spread and emittances are projected values and the slice values are lower. Another possibility is that the model results are with analytic functions, *e.g.*, a parabolic variation of the electron bunch distribution with time. Another possibility is that we measure the gain near the beginning of the macropulse, where the electron beam parameters could be different. The electron beam parameters are values averaged during a 250 µs macropulse. To help resolve these open questions we intend to systematically vary the idealized parameters and determine the impact on the performance. We also have the capability of importing a start-to-end (S2E) distribution into Medusa/OPC, as well as into the 4D version of Genesis/OPC. To summarize the results of our modelling efforts to date, while there is a temptation to declare that the different treatment of the FEL interaction by Medusa, relative to Wavevnm and Genesis, is more correct; we feel this is premature until we have benchmarked more FEL experiments

CONCLUSIONS

In this brief report we have presented the latest benchmarking results for the UV Demo FEL operating at 400nm. Amongst the 3D codes, the two using wiggler orbit averaging evaluated on a mesh are in poorer agreement than Medusa, which does not. Preliminary 4D Medusa/OPC results are in reasonable agreement for the gain, but almost 2X too low in efficiency. This will be explored in more detail. Commissioning of the UV and VUV beam lines has been schedule-constrained and work remains to be done. Beam was delivered through both beam lines and initial characterization started. If the VUV efficiency measured at low (1.4%) duty factor remains roughly constant when we operate cw, then the VUV average power will be of order 100mW, making this a unique, ultrashort coherent source in that spectral region.

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REFERENCES

[1] S.V. Benson, "First Lasing of the Jefferson Lab UV Demo Laser",Abstract MOOAI8, Proc. FEL10 Malmö, Sweden (2010)

[2] D. Douglas et al., “Design of the SRF driver ERL for the Jefferson Lab UV FEL”, Paper THP173, Proc. PAC11 New York, NY (2011).

[3] [3] S. Benson, et al. “Demonstration of 3D Effects with High Gain and Efficiency in a UV FEL Oscillator”, Paper THP171, Proc. PAC11, New York, NY (2011).

[4] S.V. Benson, et al.”The VUV/IR/THz free electron laser program at Jefferson Lab”, Nucl. Inst. And Meth. **A649** 9 (2011).

[5] R.A. Legg, et al., “Operation and Commissioning of the Jefferson Lab UV FEL using an SRF Driver ERL”, Paper THP172, Proc. PAC11 New York, NY (2011)

[6] M.D.Shinn, et al., “Initial Characterization of the VUV Harmonic Output of a High Average Power Free-Electron Laser”, in preparation.

[7] S.V. Benson, et. al.,”A Proposed VUV Oscillator-based FEL Upgrade at Jefferson Lab”, J. Mod. Opt. (2011) DOI:10.1080/09500340.2011.606375.

[8] G.R. Neil, et al., “The JLab High Power ERL Light Source”, Nucl. Instr. & Methods **A557** 9 (2006).

[9] W. R. Hunter, “Reflectance Spectra of Single Materials”, in Vacuum Ultraviolet Spectroscopy 1, Vol. 31, Experimental Methods in the Physical Sciences, J.A. Sampson and D. L. Ederer, Eds. Academic Press, London (1998).

[10] C. Pellegrini, “Synchrotron radiation problems in storage ring version of FEL”, DOE-BNL Pub 26737 (1979).

[11] G. Dattoli, L. Giannessi, and S. Cabrini, “Intensity Saturation Mechanism in Free-Electron Lasers”, IEEE J. Quantum Electron **28**, 770 (1992).

[12] G. Dattoli, et al., “Parametrizing the Gain Dependencies in a Single Passage FEL Operation with Moderate Current e-Beams”, Nucl. Inst. and Meth. **A285** 108, (1989).

[13] W. B. Colson, “One-body electron dynamics in a free electron laser”, Phys. Lett. **64A** 190 (1977).

[14] P.P. Crooker, et al., “Short Rayleigh length free electron laser: Experiments and simulations”, Phys. Rev. ST Accel. Beams **11**, 090701 (2008).

[15] J. G. Karssenberg, P. J. M. van der Slot, I. V. Volokhine, J. W. J. Verschuur, and K.-J. Boller, “Modeling paraxial wave propagation in free-electron laser oscillators”, JAP **100**, 093106 (2006).

[16] M.D. Shinn, S. Benson, G. Neil, and A. Watson “Modeling and Operation of an Edge-Outcoupled Free- Electron Laser”, talk TUOC3 FEL2010 (2010).

[17] P.J.M. van der Slot, Henry Freund, W.H. Miner, K.-J. Boller, Stephen Benson, Michelle Shinn, “Time-dependent, three-dimensional simulation of free-electron-laser oscillators,” Phys. Rev. Letts. **102**, 244802 (2009).

[18] D.A. Jaroszynski, D. Oepts. J.M. Ortega, C.R. Pigeon, and P.W. van Amersfoort, “Enhancement of FEL efficiency by using short electron pulses”, NIM **A318**, 582 (1992).