A NEW APPROACH TO IMPROVING THE EFFICIENCY OF FEL OSCILLATOR SIMULATIONS*

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Abstract
During the last year we have been benchmarking FEL oscillator simulation codes against the measured performance of the three Jefferson Lab oscillator FELs. While one might think that a full 4D simulation is *de facto* the best predictor of performance, the simulations are computationally intensive, even when analytical approximations to the electron bunch longitudinal distribution are used. In this presentation we compare the predictions of the 4D FEL interaction codes Genesis and Medusa, in combination with the optical code OPC, with those using a combination of the 2D & 3D versions of these codes, which can be run quickly on a single CPU core desktop computer.

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 [3,4]. All three FELs were designed using 1D models as discussed in Ref [5]. Clearly, use of these programs requires acceptance of a number of simplifications, such as the use of analytical (parabolic or Gaussian) electron beam distributions that interact with a low order TEM optical mode, or some superposition of modes that doesn't vary as the oscillator power saturates. Nevertheless, we found that these two FEL simulation tools reasonably (better than 30% difference) predicted the lasing efficiency of all 3 FELs the IR FELs. The gain predictions were also in reasonable agreement for the IR FELs, but low by about 50% for the UV Demo. This discrepancy has been studied using 3D and 4D FEL simulation codes [6].

While we believe that the use of a 4D code with a start-to-end (S2E) simulation of the electron bunch characteristics will yield the most accurate prediction, in our experience the creation of such a distribution takes weeks, and then a 4D FEL simulation takes about a week when performed on a parallelized cluster of computers comprising +40 cpus. This does not allow one to look at the performance of the FEL parametrically on a reasonable time scale. So we investigated whether we could use somewhat more sophisticated time dependent 2D FEL oscillator codes, with time independent 3D codes, that fully treat the spatial interaction of the electron and optical fields, as a good approximation to the full 4D codes. These lower dimensional codes can be run on dual core personal computers quickly, *i.e.*, in seconds to a couple of hours, To keep the computational times reasonable for the 4D simulations, all codes used parabolic longitudinal distributions. In this paper, we present preliminary results of our investigations to predict the measured performance of the 3 JLab FELs

THE FEL MODELS

Several performance parameters for the JLab FELs were used for benchmarking the codes. These parameters are 1) the lasing efficiency η, 2) the detuning length δl_c, and 3) the net gain g_{net}. Determining the lasing efficiency, equal to the average output power/electron beam power allows one to design an FEL to have considerable margin in this parameter, to ensure the end user's requirements are met. Knowing in advance the length of the detuning curve tells the FEL designer how insensitive the FEL parameters are to small cavity drifts. And the net gain tells the designer whether they are outcoupling the FEL efficiently. The measured values are given in Table I. Inputs for each of the FELs are given in Table 2. The 1D pulse propagation codes were discussed in the Introduction; we also used two 2D codes and 4D codes, and three 3D codes. In brief, the 2D codes are known as Pulsevnm, developed by the Naval Postgraduate School [7], and Medusa1D, developed by one of the co-authors [8]. The former code has been in use for some time, while the latter code has heretofore not been used for oscillator modelling. While both codes model the FEL interaction between an optical field and an electron bunch matched to the wiggler, there are differences. Pulsevnm averages the Lorentz force equations that describe the electron dynamics over a wiggler period. Medusa1D does

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not, so the integration step size must now be small enough to resolve the electron motion, typically 30 steps/wiggler period are used. This increases the time to do the calculations, however this facilitates the treatment of harmonic generation and complex orbit dynamics due to different wiggler configurations and, if they exist, beam transport magnets between wiggler sections. Both codes treat the oscillator rather simply; Pulsevnm models a Gaussian mode defined by the Rayleigh range, whose waist is at the center of the oscillator with a known length and outcoupling. Medusa also requires the cavity length and outcoupling, but more simply models a mode that encompasses the electron beam. The filling factor can be input by the user, or, in high gain situations, with the phenomenological equations developed by Xie et al.[9].

Table 1: JLab FEL Measured Performance Parameters The minimum repetition rate υ_{min} = 4.678125MHz.

	UV Demo	IR Demo	IR Upgrade
Laser wavelength (μm)	0.4	4.8	1.6
Repetition rate (MHz)	υ_{min}	$4\upsilon_{min}$	$16\upsilon_{min}$
η (%)	0.73	1.27	1.55
g_{net} (%)	145±10	80±10	80±10
δl_c (μm)	7	28	5.5

The 3D codes used are discussed in [5] and are Wavevnm, Genesis/OPC, and Medusa/OPC. Finally, we used 4D versions of Genesis/OPC and Medusa/OPC. Here the time dependent phenomena are restored to the 3D versions discussed above.

Table 2: FEL Input Parameters Used in All Simulations Cavity lengths are scaled by the minimum length L_{min} = 2.00262163m.

	UV Demo	IR Demo	IR Upgrade
Cavity length (m)	$16L_{min}$	$4L_{min}$	$16L_{min}$
Mirror radii (cm)	2.54	2.54	3.81
Rayleigh range (m)	0.925	0.4	0.75
Outcoupler radius of curv. (m)	17.72	4.0452	16.0
High reflector radius of curv. (m)	14.43	4.0452	16.115
Wiggler period (cm)	3.3	2.7	5.5
Number of periods	60	40	30
K_{rms}	0.816	0.99	1.36
Emittance (microns)	5	8	8
Matched beta	0.86	0.34	0.877
Beam energy (MeV)	135	38.45	115
Energy spread (%)	0.3	0.25	0.4
Peak current (A)	200	60	300
rms bunchlength (μm)	30	101	36.9
Slippage parameter	0.8	1.9	1.3
Gain/Loss ratio	17.2	9.6	6.1

RESULTS

To quickly judge the agreement between the prediction and experiment, the percent difference for each parameter (save the detuning length) was calculated and listed in the following tables. Because the detuning lengths for two of the FELs are not long (*c.f.* Table 1), it is better to simply take the difference between the calculated and the measured values for that parameter. In an effort to discern some dependence of the agreement on other FEL parameters, results are tabulated with respect to two parameters listed at the end of Table 2, the first is the slippage, or coupling parameter equal to the slippage = $N_w\lambda$ divided by the rms electron bunch length. The second is the gain to loss ratio.

We then consider each set of simulations in order of complexity. The 1D results are shown in order of descending gain/loss ratio in Table 3, and in order of descending slippage parameter in Table 4. In these tables, SS is the spreadsheet model and PP is the pulse propagation code.

Table 3: 1D Model Results in Descending Gain/Loss Ratio

	g_{net} (% diff)	Δ δl_c(μm)	η (% diff)
UV Demo - SS	-48	~1	-8
UVDemo – PP	-52	~3	-14
IR Demo - SS	-17	28	3
IR Demo – PP	6	10	17
IR Upgrade - SS	-34	7.5	-26
IRUpgrade – PP	-16	3.5	-28

Table 4: 1D Model Results in Descending Slippage Parameter

	g_{net} (% diff)	Δ δl_c(μm)	η (% diff)
IR Demo - SS	-17	28	3
IR Demo – PP	6	10	17
IR Upgrade - SS	-34	7.5	-26
IRUpgrade – PP	-16	3.5	-28
UV Demo - SS	-48	~1	-8
UVDemo – PP	-52	~3	-14

Inspection of these two tables results in two conclusions, 1) that these relatively simple codes do a better job predicting lasing efficiency than net gain, and 2) that as the slippage parameter decreases, the net gain's agreement with experiment becomes poorer.

2D results are displayed in the same way in Tables 5 and 6 respectively. In the Medusa1D code, while a provision exists to input a manual filling factor, in practice, it is not clear what that should be. We tried several interpretations, such as the ratio of the waist area for the electron beam to the optical mode, etc., but nothing immediately made sense. So for now we simply

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report the results for a unity filling factor, admitting it is not physical.

Table 5: 2D Model Results in Descending Gain/Loss Ratio

	g_{net} (% diff)	Δ $\delta l_c(\mu m)$	η (% diff)
UV Demo - Medusa	16	-1	-14
UVDemo – Pulsevnm	26	-1.5	160
IR Demo - Medusa	354	2	-66
IR Demo – Pulsevnm	30	13	50
IR Upgrade - Medusa	56	9.5	-34
IRUpgrade - Pulsevnm	15	4.5	-12

Table 6: 2D Model Results in Descending Slippage Parameter

	g_{net} (% diff)	Δ $\delta l_c(\mu m)$	η (% diff)
IR Demo - Medusa	354	2	-66
IR Demo – Pulsevnm	30	13	50
IR Upgrade - Medusa	56	9.5	-34
IRUpgrade – Pulsevnm	15	4.5	-12
UV Demo - Medusa	16	-1	--14
UVDemo – Pulsevnm	26	-1.5	160

One notes that in contrast to the 1D results, the overall agreement of the net gains predicted from these 2 codes to experiment improves as the slippage parameter decreases. There is also a trend for Pulsevnm, but not Medusa1D's lasing efficiency to be in better agreement with experiment as the gain/loss ratio decrease.

In presenting the 3D results we should point out that while OPC was used with both Genesis and Medusa, in the interest of table formatting it isn't explicitly listed.

Table 7: 3D Model Results in Descending Gain/Loss Ratio

	g_{net} (% diff)	Δ $\delta l_c(\mu m)$	η (% diff)
UV Demo – Medusa	16	-	-14
UV Demo – Genesis	-39	-	-8
UV Demo-Wavevnm	-39	-	-1
IR Demo – Medusa	122	-	3
IR Demo – Genesis	36	-	5.5
IR Demo - Wavevnm	15	-	9
IR Upgrade – Medusa	85	-	1
IRUpgrade – Genesis	-36	-	39
IR Upgrade-Wavevnm	-35	-	40

Table 8: 3D Model Results Descending Slippage Parameter

	g_{net} (% diff)	Δ $\delta l_c(\mu m)$	η (% diff)
IR Demo – Medusa	122	-	3
IR Demo – Genesis	36	-	5.5
IR Demo-Wavevnm	15	-	9
IR Upgrade – Medusa	85	-	1
IRUpgrade – Genesis	-36	-	39
IR Upgrade - Wavevnm	-35	-	40
UV Demo – Medusa	16	-	-14
UV Demo – Genesis	-39	-	-8
UV Demo-Wavevnm	-39	-	-1

We note that, as Genesis/OPC and Wavevnm use wiggler averaging and evaluation on a mesh, both give very similar results. When considered on the basis of gain/loss ratio, the lasing efficiency agreement trended in the positive direction. And, for all three FELs, Medusa/OPC, did a very good job predicting the lasing efficiency.

For the 4D cases, we note that only the IR FELs have been modelled with Genesis/OPC.

Table 9: 4D Model Results in Descending Gain/Loss Ratio

	g_{net} (% diff)	Δ $\delta l_c(\mu m)$	η (% diff)
UV Demo – Medusa	-18	0	-44
IR Demo – Medusa	-27.5	7	-43
IR Demo – Genesis	-12	-0.5	14
IR Upgrade – Medusa	-25	3.5	-29
IRUpgrade – Genesis	-51	0	6.5

Table 10: 4D Model Results in Descending Slippage Parameter

	g_{net} (% diff)	Δ $\delta l_c(\mu m)$	η (% diff)
IR Demo – Medusa	-27.5	7	-43
IR Demo – Genesis	-12	-0.5	14
IR Upgrade – Medusa	-25	3.5	-29
IR Upgrade – Genesis	-51	0	6.5
UV Demo – Medusa	-18	0	-44

The trends noted here are, like with Medusa1D, the laser efficiency is too low. And, for the two FELs studied, Genesis/OPC does a very good job predicting the lasing efficiency and detuning length.

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INTERPRETATION

Recall that the purpose of this exercise was to see if one could take the 2D and 3D results and predict the 4D result. To answer this question, one must first make two adjustments to the 2D results. One is to account for gain adjustments the 2D models don't fully account for, the filling factor, and 3D effects As Pulsevnm calculates the small signal gain as a function of the Colson parameter $jF=2\pi g_0$, we can reduce the gain by multiplying it by the filling factor calculated in the spreadsheet model. This corrected jF is then run back through Pulsevnm to calculate a corrected pulsed gain. By comparing the calculated CW gain from the corrected jF to the 3D gain predicted by Wavevnm or Genesis/OPC, (*cf* Table 7), we can then generate a 3D correction to the 2D gain. This is then used to correct the pulsed gain to get a final estimate of the 4D gain. This 2D gain agrees with the 4D gains predicted by Genesis/OPC to better than a 7% difference. We can't do this yet with Medusa, as we don't have a recipe for determining the filling factor it needs. We will report on this in future work. We have not yet come up with a procedure to obtain the 4D efficiency from the combination of the 2D and 3D efficiency.

CONCLUSIONS

In this brief report we have presented a preliminary benchmarking of the JLab FEL oscillators using simulation codes of increasing sophistication. By using the wiggler orbit averaging 2D and 3D codes we created a procedure that allowed us to estimate the 4D net gain value to a high degree of accuracy. Note that this isn't the same as saying we predicted the experimental gain, as Table 9 shows. We hope to develop a similar procedure to see if it works for the 2D version of Medusa.

The tables show that in general, calculated lasing efficiencies and detuning lengths are usually in better agreement with experiment than net gain. With 3D Medusa/OPC or 4D Genesis/OPC the agreement is better than 15%, rather amazing when one considers that we are using an analytic approximation for the actual electron bunch distribution, and that other experimentally-determined parameters like the emittance have similar experimental uncertainties. Of course, simply using the well-known expression[10] that $\eta=1/2N_w$ results in the same level of agreement. However, that simple expression does not provide any information on the efficiency in the presence of real-world phenomena such as thermal deformation or vibration of the cavity mirrors.

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