A New Approach to Improving the Efficiency of FEL Oscillator Simulations

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Introduction

- When simulating FEL oscillators, a complete 4D model with a start-to-end (S2E) simulation electron bunch distribution is considered the most accurate.
  - One gets the lasing efficiency (or power out), detuning curve, gain, spectrum.
    - Power out – within User's requirements?
    - Detuning curve – short detuning makes it harder to maintain performance
    - Gain – helps determine outcoupling for efficient extraction of power
- However-
  - S2E simulations take weeks to complete
  - 4D simulations can easily take a week to complete for one set of parameters
  - Must be done on multi-cpu (12 or more cores) machines, preferably using parallelized supercomputing facilities.
- We looked at the efficacy of using 1D, 2D, and 3D simulations with parabolic electron distributions to substitute for a full 4D simulation.
- The advantage is that these can be done rather quickly (~ 1 day) on laptops or desktop computers with 4 cores or less.
- And, we asked, how well do the 4D codes, with a parabolic bunch distribution, predict the performance of oscillator FELs?

The JLab FELs were used for this study

- All 3 JLab FELs have a near-concentric architecture and transmissive outcoupling

	UV Demo	IR Demo	IR Upgrade
Cavity length (m)	32.04196	8.0104865	32.04196
Lasing wavelength (microns)	0.4	4.8	1.6
Mirror radii (cm)	2.54	2.54	3.81
Rayleigh range (m)	0.925	0.4	0.75
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
Slippage parameter	0.8	1.9	1.3
Gain/Loss ratio	17.2	9.6	6.1

1D Laser Modeling

- For 1D calculations we use
- A spreadsheet model based on Dattoli & Colson's semi-analytical formulas and a 1D pulse propagation code.
  - The spreadsheet model is very fast and can look at many cases at once. Modifications of the model are easy.
- The pulse propagation model gives much more detail with very few approximations, but it must be run many times to get the power and gain for one setup (hour or two per detuning curve)
  - We can, in principle upgrade the 1D code to 2D and add slice energy spread and emittance from S2E simulations.

1D Model Results

- Consider the agreement "good" if percent difference is ≤ 20%.

1D model results descending gain/loss ratio

	Net Gain (% diff)	Δ Detuning Length (μm)	Lasing Eff (% Diff)
UV Demo - spreadsheet	-48	~1	-8
UV Demo – pulse prop.	-52	~3	-14
IR Demo - spreadsheet	-17	28	3
IR Demo – pulse prop.	6	10	17
IR Upgrade - spreadsheet	-34	7.5	-26
IR Upgrade – pulse prop.	-16	3.5	-28

1D model results descending slippage parameter

	Net Gain (% diff)	Δ Detuning Length (μm)	Lasing Eff (% Diff)
IR Demo - spreadsheet	-17	28	3
IR Demo – pulse prop.	6	10	17
IR Upgrade - spreadsheet	-34	7.5	-26
IR Upgrade – pulse prop.	-16	3.5	-28
UV Demo - spreadsheet	-48	~1	-8
UV Demo – pulse prop.	-52	~3	-14

Agreement with experiment is poorer as slippage decreases

2D Laser Modeling

- These codes explicitly model effects from energy spread but the description of the oscillator is quite limited.
- Two codes were used:
  - Pulsevnm (Naval Postgraduate School - NPS)
  - Medusa1D (developed while coauthor was at SAIC)
- The NPS code employs wiggler averaging, Medusa does not.
- The overlap between the optical mode and electron beam is approximately calculated (Pulsevnm), or adjusted by the user (Medusa) .

2D Modeling Results

- Medusa runs with filling factor =1

2D model results in descending gain/loss ratio

	g_{net} (% diff)	$\Delta\ \delta l_c(\mu m)$	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

All Δg_{net} values are positive

2D model results in descending slippage parameter

	g_{net} (% diff)	$\Delta\ \delta l_c(\mu m)$	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

Medusa net gain agrees better with experiment as slippage parameter decreases. Pulsevnm does a better job predicting net gain – probably because it estimates the filling factor better.

3D and 4D Laser Modeling

- Two wiggler averaging codes were used for 3D modeling:
  - Wavevnm (NPS) written in C++.
  - Genesis/OPC Genesis is written in Fortran77, OPC in Fortran90.
- One non-wiggler averaging code:
  - Medusa/OPC Both written in Fortran90
    - Medusa propagates fields; no grid.
- 3D codes more fully treat the spatial aspects of the FEL interaction, *e.g.*, the filling factor. The current is constant, so slippage effects are not treated.
- 4D versions of Genesis and Medusa were also used with OPC.
  - Models “non-round” e beams, can accept S2E distributions.
  - OPC very flexible physical optics code.

3D Modeling Results

- Medusa/OPC lasing efficiency in excellent agreement with experiment.

3D model results descending gain/loss ratio

	Net Gain (% diff)	Δ Detuning Length (μm)	Lasing Eff (% Diff)
UV Demo – Medusa/OPC	16	-	-14
UV Demo – Genesis/OPC	-39	-	-8
IR Demo – Medusa/OPC	122	-	3
IR Demo – Genesis/OPC	36	-	5.5
IR Upgrade – Medusa/OPC	85	-	1
IR Upgrade – Genesis/OPC	-36	-	39

Increasing Δη with decreasing gain/loss ratio

3D model results descending slippage parameter

	Net Gain (% diff)	Δ Detuning Length (μm)	Lasing Eff (% Diff)
IR Demo – Medusa/OPC	122	-	3
IR Demo – Genesis/OPC	36	-	5.5
IR Upgrade – Medusa/OPC	85	-	1
IR Upgrade – Genesis/OPC	-36	-	39
UV Demo – Medusa/OPC	16	-	-14
UV Demo – Genesis/OPC	-39	-	-8

Decreasing trend in net gain agreement with slippage parameter

4D Modeling Results

- Currently do not have a 4D Genesis/OPC simulation for the UV Demo.
- So far, Genesis/OPC more accurately predicts the lasing efficiency.

4D model results descending gain/loss ratio

	Net Gain (% diff)	Δ Detuning Length (μm)	Lasing Eff (% Diff)
UV Demo – Medusa/OPC	-18	0	-44
UV Demo – Genesis/OPC	-	-	-
IR Demo – Medusa/OPC	-27.5	7	-43
IR Demo – Genesis/OPC	-12	+2	14
IR Upgrade – Medusa/OPC	-25	3.5	-29
IR Upgrade – Genesis/OPC	-51	0	6.5

4D model results descending slippage parameter

	Net Gain (% diff)	Δ Detuning Length (μm)	Lasing Eff (% Diff)
IR Demo – Medusa/OPC	-27.5	7	-43
IR Demo – Genesis/OPC	-12	+2	14
IR Upgrade – Medusa/OPC	-25	3.5	-29
IR Upgrade – Genesis/OPC	-51	0	6.5
UV Demo – Medusa/OPC	-18	0	-44
UV Demo – Genesis/OPC	-	-	-

Lower net gain than measured

2D result for net gain was too high

This gives us a clue to a solution

Recipe for getting 4D gain from 2D+3D

- Use Colson overlap integral to get reduction in gain factor g_0 from filament beam calculation (can also include Gouy phase shift.)
- Use Dattoli's formulas for gain vs. g_0 to get estimate of the CW gain.
- Compare this CW gain estimate to the 3D gain. Calculate a 3D gain effect factor (G_{3D}/G_{CW}) and multiply this by the gain factor g_0 again. (note that the 3D gain effect factor can be greater than or less than unity).
- Use the corrected value in 2D simulation to estimate the 4D gain and detuning curve length.
- Can double check this by extrapolating the gain vs. slippage to zero slippage and compare to the CW gain.
- This recipe does not seem to work for efficiency.

Demonstration of the 2D+3D → 4D procedure

- **IR Demo FEL**
- 2D gain – initial prediction is 104%
- Correcting for filling factor lowers it to 67%
- Calculate 3D effect = 0.022
- Final 2D gain = 67%*1.022 = 68% 4D prediction = 70%

- **IR Upgrade FEL**
- 2D gain – initial prediction is 92%
- Correcting for filling factor lowers it to 54%
- Calculate 3D effect = -25.2%
- Final 2D gain = 54%*0.748 = 40% 4D prediction = 39%

- Excellent agreement with the 4D simulation!
- It doesn’t imply the 4D simulation is correct. But, it’s much faster to reach almost the same result.

Conclusions

- We employed a variety of models to simulate the performance of the three JLab FELs.
  - Models ranged from analytical expressions to 4D computer simulations.
- All models tended to predict lasing efficiency better than they did gain.
- Non-wiggler averaged code Medusa/OPC did a good job calculating the lasing efficiency when used in 3D mode.
- Wiggler averaged code Genesis/OPC did a good job for the same parameter when used in 4D mode.
  - Still need to model the UV Demo FEL with Genesis/OPC to see if the trend continues.
- So far, agreement for lasing efficiency is remarkable given that we are using a parabolic distribution for the electron bunch.
- We have a procedure to use the wiggler averaged 2D & 3D codes to reproduce the 4D gain prediction to within 5%.
- We plan to attempt to extend this to estimate the lasing efficiency.

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