Simulations of a FIR Oscillator with Large Slippage parameter at Jefferson Lab for FIR/UV pump-probe experiments

Simulations of a FIR Oscillator with Large Slippage parameter at Jefferson Lab for FIR/UV pump-probe experiments

S V Benson[2], L T Campbell[1,3], B W J McNeil[1], G R Neil[2], M D Shinn[2], and G P Williams[2]

[1]Dept. of Physics, University of Strathclyde, Glasgow G4 0NG, Scotland
[2]Thomas Jefferson National Accelerator Facility, Newport News, VA 23606 USA
[3]AsTeC, STFC Daresbury Laboratory and Cockcroft Institute, Warrington WA4 4AD, UK

felman@jlab.org

Abstract. We previously proposed a dual FEL configuration on the UV Demo FEL at Jefferson Lab that would allow simultaneous lasing at FIR and UV wavelengths [1]. The FIR source would be an FEL oscillator with a short wiggler providing diffraction-limited pulses with pulse energy exceeding 50 microJoules, using the exhaust beam from a UVFEL as the input electron beam. Since the UV FEL requires very short pulses, the input to the FIR FEL is extremely short compared to a slippage length and the usual Slowly Varying Envelope Approximation (SVEA) does not apply. We use a non-SVEA code [2] to simulate this system both with a small energy spread (UV laser off) and with large energy spread (UV laser on).

1. Introduction

Though subpicosecond lasers are routinely used in research, many experiments require the use of two synchronized lasers with very different wavelengths. We previously proposed using a far infrared (FIR) laser synchronized to an ultraviolet/vacuum ultraviolet (UV/VUV) oscillator in order to allow experiments to be carried out in which a sample is pumped in the UV or VUV wavelength range and then probed by FIR wave radiation after a known delay. In this way the photo-emitted electron wavefunction can be encoded and studied as was done, for example, in experiments on Kr at the FLASH FEL in Germany [3]. However, the longer wavelength is sufficiently powerful to be the pump as well, and thus one could envisage experiments similar to the pump-probe photoemission study of strongly correlated charge-density-wave materials [4,5], but with the additional flexibility of the wider wavelength range as well as the tuning offered by an FEL. In our earlier study, it was found that the standard FEL oscillator codes used to model the FIR FEL were not appropriate for this latter case due to the extreme violation of the Slowly Varying Envelope Approximation (SVEA). In addition, only one-dimensional simulations were done for the UVFEL so the input parameters for the FIR FEL were not well known. This work shows some of the simulations of both lasers with more appropriate codes and shows that the performance is still reasonable. In fact, the SVEA codes give surprisingly good predictions of the gain. The power output from the non-SVEA codes is smaller but still quite usable.

2. Description of the FEL facility

The UV Demo FEL facility is described in some detail in reference [6]. UV operation reported in that publication was for operation at low charge (60 pC) in order to provide a geometric emittance less than the laser wavelength divided by 4π. For operation with a FIR laser after the UVFEL it helps to have higher charge. Simulations done for this publication assumed 135 pC, which is the standard value for the IRFEL at Jefferson Lab.

Free-electron lasers naturally emit on-axis coherent radiation at the odd harmonics of the resonant wavelength. When the FEL is operated at 3 eV, for example, there is light emitted at 9 eV and 15 eV. At these photon energies there are very few transparent materials, so the best way to take advantage of these VUV harmonics is to lase with an output coupler in which a hole is drilled. The harmonic radiation is then transmitted through the hole and to a user station using reflective optics. The output coupling can be varied in this setup by changing the radius of curvature of the upstream mirror. Emission in the VUV has already been demonstrated on the UV Demo laser at 10 eV [7].

2.1. Far Infrared Laser Layout
Because of a specific user request we did our early studies of this system with the UV laser at 3.3 eV (372 nm wavelength) and the FIR laser at 40 meV (31 microns). To allow the introduction of a FIR FEL downstream of the UVFEL we intend to modify the downstream chicane magnets so that the electron beam travels along a zigzag path and the dispersion in the middle of the insertion is small (<3 cm). The basic layout is sketched in figure 1.

The angle of the wiggler with respect to the UV beam path is only 25 mrad. This offsets the mirrors of an 8 meter resonator by 10 cm, which is just sufficient for clearance of a 10 cm diameter resonator mirror. The vacuum chamber for the wiggler is approximately 3 meters long so the separation between the UV mode and the electron beam is 38 mm at either end of the vacuum chamber. This is then the maximum dispersion in the FIR FEL.
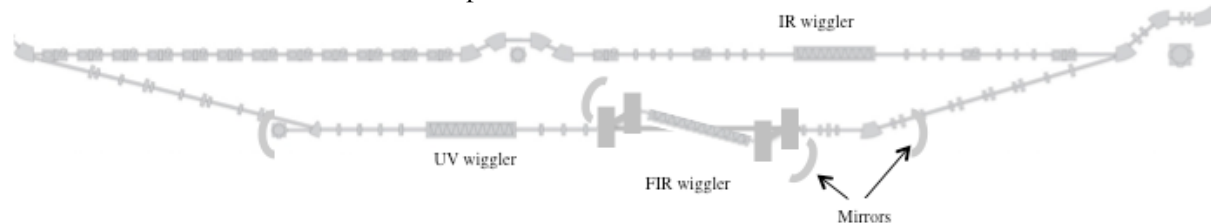

Figure 1. Proposed layout for the FIR FEL downstream of the UV wiggler. Note that the angles in the zigzag are greatly exaggerated and that the actual bend angle would be vertical.

3. Simulations

The parameters for the electron beam, optical resonator and wiggler for the FIR-FEL are given in table 1. The laser output was assumed to be out-coupled through a hole in the downstream mirror. The gain increases with decreasing wavelength so hole-coupling is better matched to the wavelength variation than edge coupling since reducing the wavelength increases both the gain and the output coupling. The resonator at 31 microns is an open resonator with very small diffractive losses. At longer wavelengths, one might have to go to a waveguide resonator to better confine the mode.

The FIR laser was simulated using a one-dimensional non-SVEA FEL code called Puffin [2] for two different energy spreads. The first was for when the UV laser is not lasing. This is useful for getting the FIR FEL to lase and optimizing the lasing. Once the FIR FEL is optimized, the UV FEL can be turned on and the rms energy spread should increase to ~0.9%.

The UVFEL was modeled using the 4 dimensional codes Medusa/OPC [8] as well as 3D Genesis/OPC [9]. When we operate near the peak of the gain curve using the parameters in Table 1 we find reasonably high gain (>60%) and extraction efficiency (0.5%) with the 135 pC bunch when corrected for slippage effects. The *rms* exhaust energy spread is approximately 0.9±0.1% in agreement with Table 1.

Table 1: FIR-FEL wiggler, resonator and simulation electron beam parameters.

Parameter	Value
Electron energy	135 MeV
Bunch charge	135 pC
Bunch length (*rms*)	0.18 psec
Peak current	300 A
Repetition rate	18.7125 MHz
Energy spread (UV FEL not lasing)	0.5%
Energy spread (UV FEL lasing)	0.9%
Emittance	8 mm-mrad
Wiggler wavelength	20 cm
Number of periods	12
Peak wiggler field	3.5 kG
Rayleigh range	108 cm
Losses	3%
Output coupling	1%
Laser wavelength	31 μm

3.1. Assumptions of the simulation

For the FIR FEL the wavelength is only one sixth of the *rms* electron bunch length. Thus, the SVEA simulations are not appropriate. The simulation also assumes that the pulse is Gaussian in time and this is almost never true for a linac-based accelerator. Initial simulations use a Gaussian distribution for the electrons with the *rms* parameters shown in Table 1, but we have also done UV simulations using the results of Start-to-End (S2E) simulations as well. We can then use the output from this program to find the conditions at the entrance to the FIR FEL. S2E simulations of the beam at 135 pC do show a lot of fine structure on the beam as shown in Figure 2.

This fine structure must be taken into account in any simulation. For the UVFEL, we simulated this case using 83 pC of the 135 pC bunch in a short parabolic current profile with 78 fsec full width, 0.6% energy spread, and 1600 A peak current. We used a 4D simulation code for this due to the very short bunch length. The exhaust distribution when just this spike is used in the FEL is shown in figure 3. The *rms* energy spread is still 0.9% but there will be much more coherent undulator radiation from this bunch. We have not yet run Puffin using the distribution in figure 2.

For the FIR FEL simulations using Puffin, we assumed simple Gaussian distributions. The gain and power are weakly dependent on the transverse emittance and the energy spread. We do expect the gain and efficiency to be higher when the S2E distribution is used instead of the Gaussian bunch.

Most users are interested in narrow spectral bandwidth and will want to operate on the shorter end of the cavity-length-detuning curve where the spectral brightness is higher. In figure 3 we show the energy distribution at the output of the UVFEL for operation near the peak of the gain curve. The spectral brightness is highest here and the operation is more stable with a hole out-coupler. The gain here is very high and the extraction efficiency is 0.28%. Approximately half of the extracted power exits the hole.

For the FIR FEL we looked at two different cases, one with the UVFEL on and one with it off. We did the simulations near the peak of the gain curve predicted from the 1D theory. This should produce the best spectral brightness. One critical aspect is the small signal gain. If this is much less than the 1D SVEA simulations, then the laser will not start up. In figure 4 we show the gain vs. pass number for the two cases. It can be seen that the gain, though about 15% lower than that predicted by the SVEA codes, is still sufficient to turn on assuming losses can be kept lower than about 3%. Note that

gain much larger than losses is not good in the laser because it produces too much energy spread, leading to losses in the downstream transport.
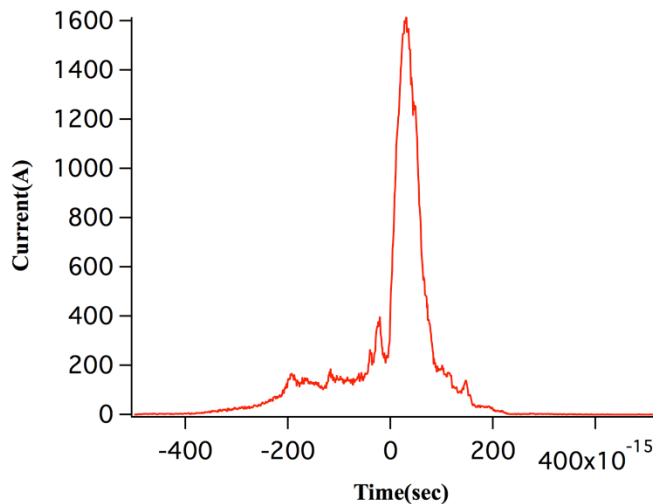

Figure 2. Current profile of a micropulse from an S2E simulation. The rms bunch length is 100 fsec but the FWHM is only 50 fsec.
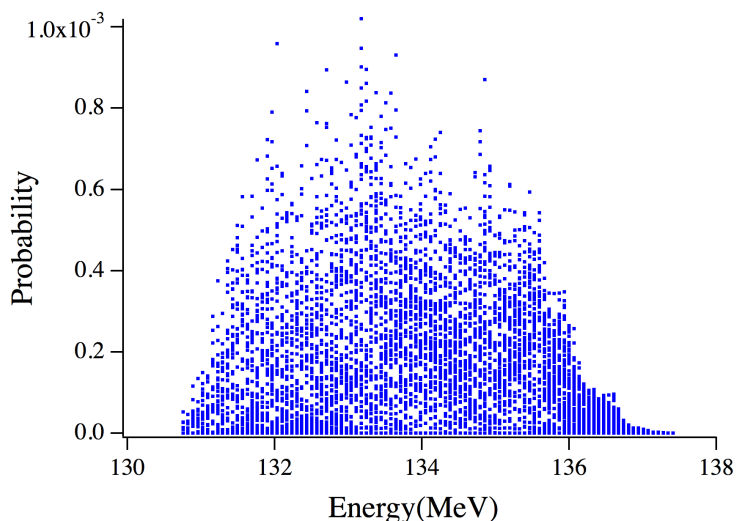

Figure 3. UVFEL exhaust energy distribution as calculated by 4D MEDUSA for the spike present in an S2E simulation (figure 2). The rms energy spread is 0.9% and the energy loss is 0.28%.

In figure 5 we show the saturated distribution with the UVFEL off. The saturated laser pulse is only about 10 optical periods FWHM, which is less than the number of wiggler periods. The spectral bandwidth, however, is only about 3% FWHM, which is very good for such a short bunch. The peak power in the microbunch is a respectable 40 MW. This corresponds to about 750 W of power at the repetition rate of 18.7 MHz. The exhaust energy spread is over 9% full width, which is close to the energy acceptance of the energy recovery arc.

In figure 6 the distributions with the UVFEL on are shown. The peak power drops by about 1/3 but the pulse length and spectral bandwidth are about the same as with the UVFEL on. The micropulse energy is approximately 25 μJ, which is more than enough to pump condensed matter systems.

The predicted gain from Puffin agrees reasonably well with the SVEA codes. The SVEA gain is about 15% more than that predicted by Puffin. The power predicted by Puffin is about half that predicted by the SVEA codes. Though not fatal, this result is interesting and will be explored in future work. As noted above, there is a need to calculate the gain and efficiency for the more realistic S2E phase space distribution.
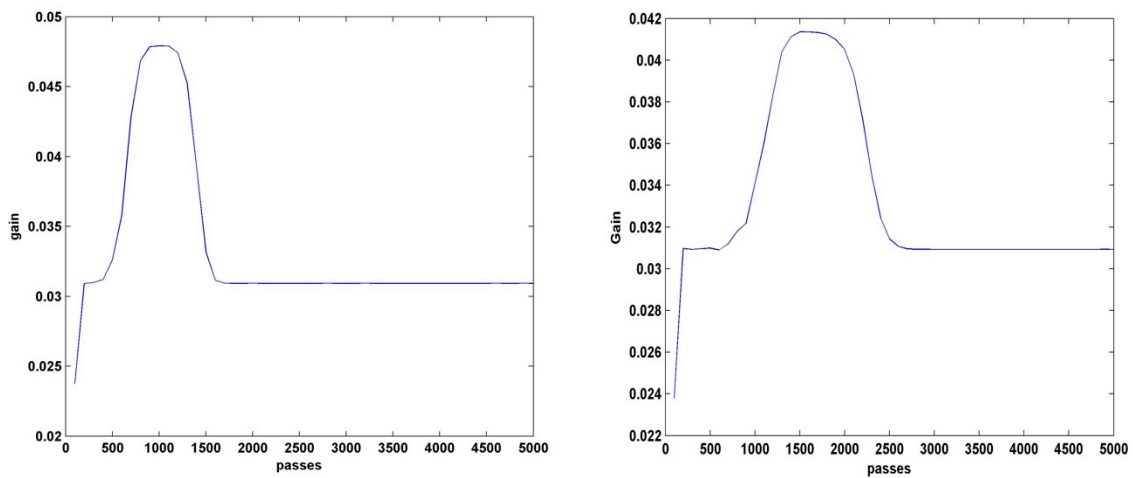
Figure 4. Gain vs. pass number at a cavity length detuning of 2 μm calculated using Puffin. The curve on the left is with the UVFEL off with 0.5% input energy spread. The one on the right is with the UVFEL on with 0.9% input energy spread.
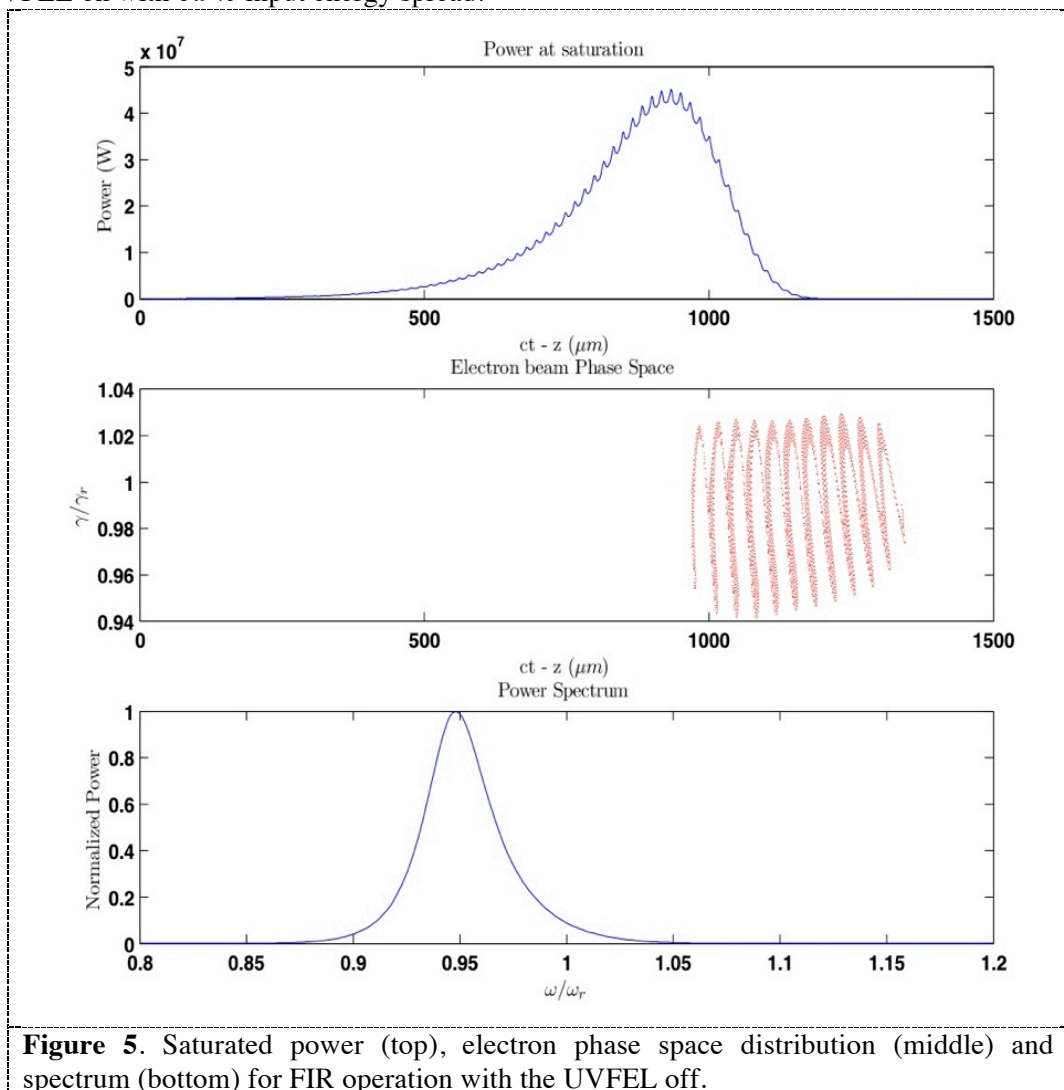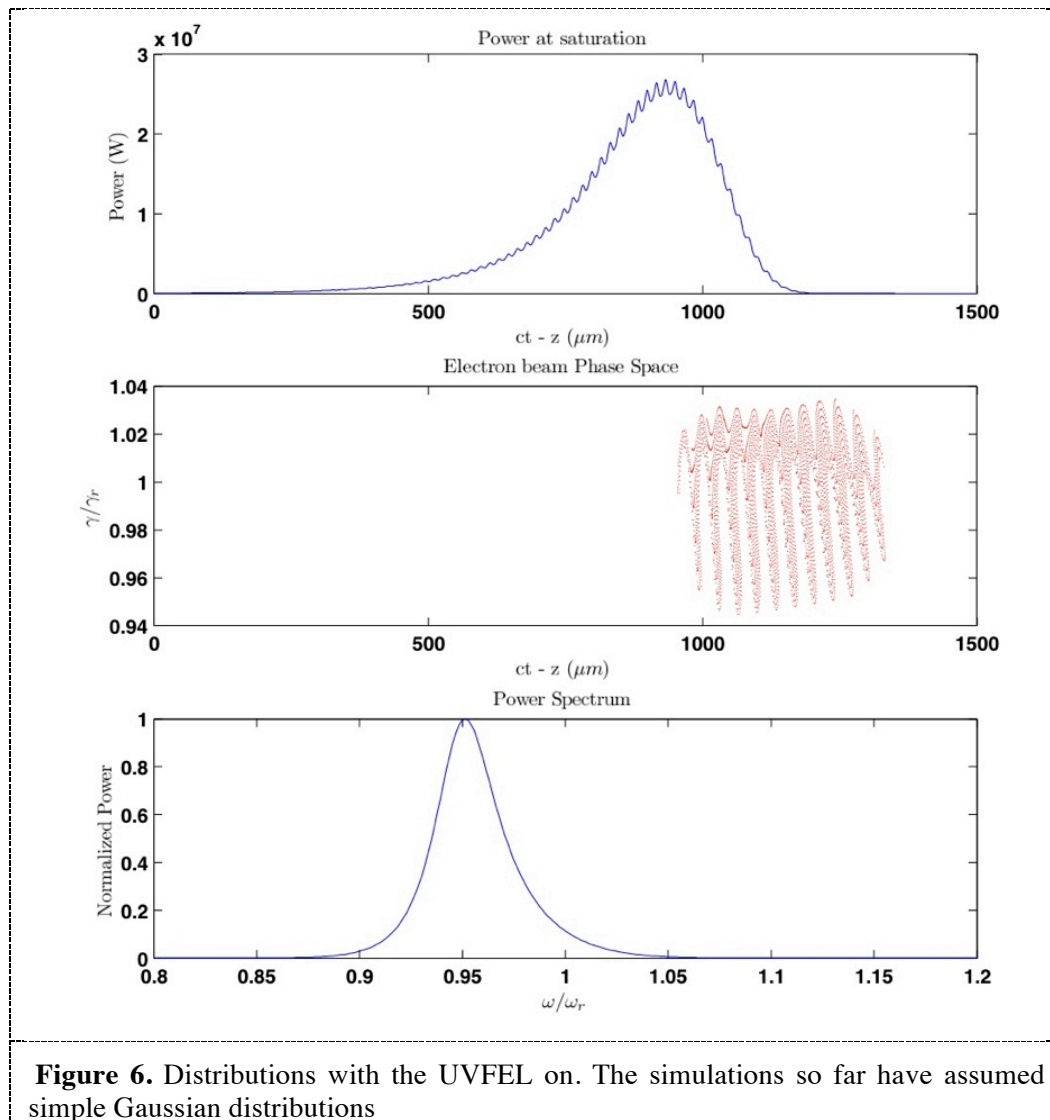

Figure 5. Saturated power (top), electron phase space distribution (middle) and spectrum (bottom) for FIR operation with the UVFEL off.

Figure 6. Distributions with the UVFEL on. The simulations so far have assumed simple Gaussian distributions

4. Conclusions

More realistic simulations of a combined VUV/FIR laser source show that the device should work well. Future work will look at the use of S2E simulations to better predict the performance of a physical system. The laser outputs expected for varying electron beam energies are summarized in table 2.

5. Acknowledgment

References

[1] Benson S V, Douglas D, Neil G, Shinn M D and Williams G P 2012 *Proceedings of IPAC'12, (New Orleans, LA: JACOW)* p. 1789
[2] Campbell L T and McNeil B W J 2012 *Physics of Plasmas* **19** 093119
[3] Fruhling U et al. 2009 *Nature Photonics* **3** 523

[4] Rohwer T et al. 2011 *Nature* **471**, 490

[5] Smallwood C L Jozwiak C Zhang W and Lanzara A 2012 *Rev. Sci. Instr.* **83** 123904

[6] Douglas D R et al. 2012 *Proceedings of IPAC'12 (New Orleans, LA: JACOW)* p. 2111

[7] Legg R A et al. 2011 *Proceedings of PAC'11 (New York NY: JACOW)* p. 2432

[8] Van der Slot P J M Freund H Miner W H Boller K-J Benson S Shinn M D 2009 *Phys. Rev. Lett.* **102** 244802

[9] Karssenberg J G Van der Slot P J M Volokhine I V Verschuur J W J and Boller K-J 2006 *JAP* **100** 093106

Table 2: Laser output parameters during simultaneous operation.

Parameter	Value
UV	
Photon energy	2–5 eV
Bunch length (FWHM)	0.2 psec
Bandwidth	0.3%
Pulse energy	>25 μJ
VUV(third harmonic)	
Photon energy	6–15 eV
Bunch length (FWHM)	0.2 psec
Bandwidth	0.2%
Pulse energy	>10 nJ
FIR	
Photon energy	0.03-0.1 eV
Bunch length	0.4–1.4 psec
Bandwidth	3%
Pulse energy	>25 μJ
All	
Repetition rate	18.7125 MHz