SIMULATIONS OF THE NEWARK FIR FEL OPERATION

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Abstract

The operation of the Newark FIR FEL is simulated for the first time using a simulation code based on the coupled Maxwell-Lorentz equations of motion. The lasing behavior is explored for a wide range of parameters. Particularly, we studied the effects of the e-beam pulse phase stability on the operation of the microtron based FIR FEL. The study shows that for even very small systematic phase slews the lasing is suppressed. However, for a random phase slew up to 7 ps/pulse centered at the nominal micropulse frequency, the laser is still capable of turning on. We estimate the tolerance for different types of phase slew and discuss the possible proper operation condition of the device.

INTRODUCTION

The Newark FEL has been under re-commissioning recently. The device was initially developed in the 1980's at AT&T Bell Laboratory under the direction of Kumar Patel and Earl Shaw[1]. The system was integrated in the late 1980's, and in 1991 it achieved first lasing at AT&T. Soon after, the device was transferred to the campus of Rutgers University (Newark)[2]. During the last decade, considerable effort was devoted to commission the system. However, the slow progress of re-commissioning suggests that there could be design and component problems. The basic design specification includes:

Electron beam parameter:
16 μs macropulse
30 Hz macropulse repetition rate
19 Mev (γ=38) nominal energy
70 mA nominal macropulse electron current
30 ps micropulse width
3 GHz micropulse repetition rate
Undulator and cavity parameters:
Helical polarization
20 cm period
50 periods
10 meter length
10 cm bore
15 meter cavity length
Laser output parameters:
Optical wavelength tunable between 100-250 μm
Micropulse length ~50 periods
Micropulse peak power ~200 kW
Macropulse length 16μs
Macropulse average power ~10 kW

If operated at its nominal specifications, the Newark FEL would closely match the performance of the Felix-1[3]. However, the Newark system had never met the design expectations. We are hereby trying to find out the reason. Investigations of the fully integrated system show that all the required components are complete. The device has no obvious design problems, although engineering errors are often hard to exclude. If the system has any prospects for further development, we must have a clear understanding of the source of the problems encountered in the commissioning of the system. To this purpose, we have initiated a diagnosis of the system based on computer simulations. Many simulation codes aimed at entire FEL systems or particular subsystems were developed in the 1980's and 1990's, each code having been designed for a specific system. Although these systems are similar to the Newark FEL in certain aspects [4, 5, 6], the simulations reported in this paper are the first to be done specifically on the Newark FEL system. The simulation code used in the present study was originally developed at Stanford University to study pulse propagation effects and system performance in the Mark III FEL[7,8], and was modified here to incorporate the helical undulator and system parameters of the Newark FEL. The lasing behavior can be explored for a wide range of parameters using this modified simulation code.

POSSIBLE SOURCES OF PROBLEMS

There are two primary problems which could possibly affect the performance of the Newark FEL:

a) Study of the first lasering behavior[2] suggests that the resonator losses are anomalous, with an observed “ring-down time” for the optical resonator indicating 6% total losses versus 1% absorption losses per round trip. This number is also consistent with the net gain observed in the early experiments[2]. A possible source of these unanticipated losses may be the hole bored through the resonator mirror, which may outcouple more loss than anticipated.

b) Traditionally, the phase of the electron pulses has not been considered an experimental variable relevant to the operation of microtrons, and hence has not been treated as a source of problems. The mechanism that makes the energy stability intrinsic to microtrons also makes the phase of the electron pulses a function of accelerating cavity voltage. Interestingly, the cathode temperature change will lead to a significant change of the accelerated electron current[9], which in turn changes the accelerating voltage and hence the phase of the electron pulses. The change in phase of the electron pulses could suppress the lasing operation of the FEL

The simulation presented in this work employs the parameters used in the first lasing experiment on the Newark FEL with more efforts concentrating on the problems mentioned above.

ASSUMPTIONS OF THE SIMULATIONS AND ANALYSIS

The simulations are restricted to the performance of the resonant cavity, disregarding physical process used to prepare the electron pulses which are fed into the undulator; we study only what happens in the optical cavity if certain operating parameters are changed. The code assumes that the undulator is ideal without fluctuation of magnetic field, and incorporates only the lowest order Gaussian mode. The e-beam pulse is assumed to have a top-hat density profile whose amplitude and profile do not change during the macropulse. In other words, all of the e-beam pulses injected into the cavity during the macropulse are statistically identical in the simulation.

The electron pulse slew imposed on the micropulse, on the time scale of the μs macropulses, is modulated in four categories:

a) Linear phase slew (first order of Taylor expansion)

$$\phi(t) = \phi_0 + \frac{d\phi}{dt}\cdot t = \phi_0 + 2\pi f t$$

where $\frac{d\phi}{dt}$ is the angular frequency $2\pi f$ evaluated at t=0, and f is the RF frequency. In practical operation of the FEL, the gun repetition rate f can assume any value as an operational parameter. However, as long as it does not change during the macropulse and remains constant over many macropulses, we can simply tune the cavity length to synchronize the electron pulses with the optical pulses, thereby maintaining good overlap between them. In other words, a linear phase slew is not a problem for the operation of the FEL.

b) Higher order systematic phase slew (i.e. the micropulse repetition rate changes during lasering)

$$\phi(t) = \phi_0 + \frac{d\phi}{dt}\cdot t + \frac{1}{2}\frac{d^2\phi}{dt^2}\cdot t^2 + \frac{1}{6}\frac{d^3\phi}{dt^3}\cdot t^3 + \cdots$$

$$= \phi_0 + 2\pi f t + c_1 t^2 + c_2 t^3 + \cdots$$

where $c_1 = \frac{1}{2}\frac{d^2\phi}{dt^2}$, $c_2 = \frac{1}{6}\frac{d^3\phi}{dt^3}$, and the derivatives are evaluated at t=0. The effect of the electron pulse on the lasing due to the c_1 and c_2 terms in the above equation can not be eliminated by tuning the cavity length. One purpose of the simulations is to determine the extent to which these systematic higher order terms will suppress the lasing of the FEL.

c) First order random phase slew

$$\phi(t) = \phi_0 + 2\pi f t + Random\_noise$$

Both uniform (i.e. square) and Gaussian distributions of the random noise are considered. Here we assume that operation frequency f does not change, and the phase fluctuates evenly around the central value within a specified range. The simulation studies are designed to reveal the noise tolerance for this type of phase slew. Previous work on the phase stability issue has been published in the last two decades, and the estimated micropulse jitter tolerance is also discussed in the literature[10], but none of these studies provides systematic experimental or simulation data that can be applied to the Newark FEL.

d) Characteristic phase slew due to cathode heating by back bombardment of the electrons (assuming both a) and b) are presented).

SIMULATION RESULTS

Parameters employed (in addition to design parameters):

Cavity length detuning = 76μm
Energy spread $\frac{\Delta\gamma}{\gamma}$ = 0.25%
Emittance $\varepsilon_x = 8\pi$ mm mrad, $\varepsilon_y = 3\pi$ mm mrad
Micropulse length 20 ps
Normalized wiggler parameter K = 1
Rayleigh range R = 288 cm (instead of 433 cm in ref. [2])
Target operation wavelength 140 μm

In simulations of the effects of cavity loss, the 6% total loss (propagation and output coupling) of the Newark FEL was sufficient to suppress lasing. The output micropulse peak power versus total loss is shown in Figure 1.

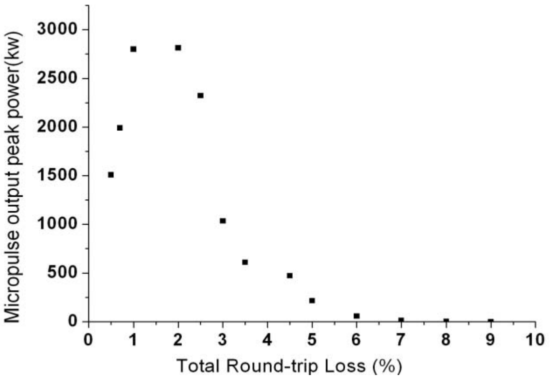

Figure 1: Loss performance

Simulations show that with an e-beam micropulse current of 2 A, lasing operation is optimized by reducing the total losses to 2%. However, if the micropulse peak current is increased from 2 A to 7 A, saturated lasing can be easily achieved even with losses up to 25%.

Simulations of higher order phase slew (i.e. systematic microwave "chirping", Figure 2) reveal that, even with a very small second order coefficient c_1 on the order of several rad/μs^2, e.g. 6 rad/μs^2, the laser could not give appreciable output, indicating that the FEL has almost zero tolerance to this kind of systematic phase slew. It is likely that third order or higher order terms give similar results.

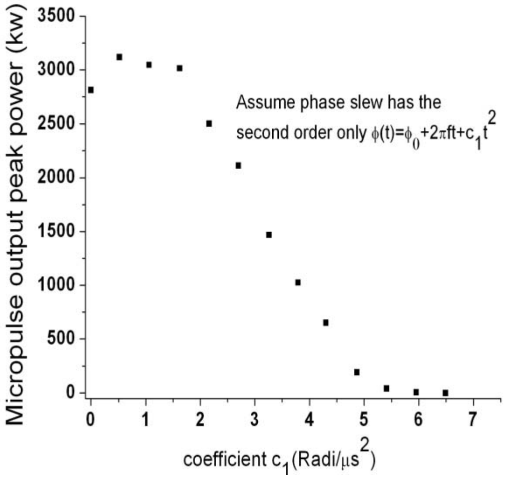

Figure 2: Effects of the second order phase slew

The real-time macropulse behavior of the FEL under this kind of phase slew (c_1>7 rad/μs^2) is shown in Figure 3. Evidently, at the early stages of oscillation, where the accumulated desynchronism between the pulses is still small, the lasing starts to build up, but it cannot continue as the phase desynchronism increases on subsequent passes in the cavity: eventually the lasing is suppressed. Simulations also show that, even with higher peak current, no lasing trend is observed, further indicating that this kind of phase slew is not permitted.

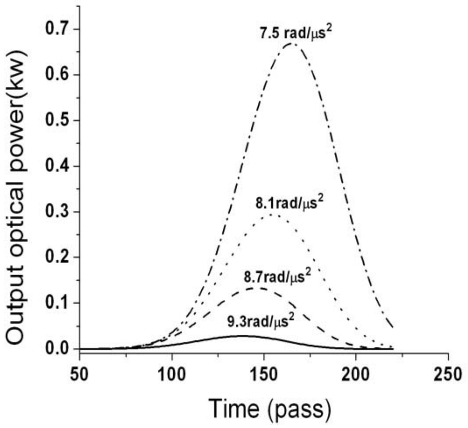

Figure 3: Lasing performances under the condition when c_1>7 rad/μs^2

This result is consistent with expectations, since the synchronization between the e-beam pulse and the optical pulse cannot be maintained for this situation and lasing is killed. To simulate the phase slew caused by random noise, two kinds of distribution are studied, uniform and Gaussian. The random noise sequence with uniform distribution is generated using the pseudo random process, which is good enough to mimic the natural random process.

The effect of the noise sequences with different standard deviations are simulated, and results show that the lasing could be achieved with relatively large electron pulse time jitters (standard deviation). Surprisingly, jitters of less than 2 ps/pulse show no effect on the laser performance, a result which is quite out of our expectations. Jitters of 7 ps/pulse are, however, sufficient to suppress the lasing. A summary of these simulations is shown in Figure 4. For the Gaussian distribution of jitter, the results appear to be indistinguishable from the results for the uniform distribution. Our simulations also demonstrate that the lasing behavior strongly depends on the noise sequence. When the averaged jitter is between 3 and 8 ps/pulse, the laser power could differ by as much as an order of magnitude depending on the specific noise sequence. The data in Figure 4 are indeed the average for different sequences with the same standard deviation.

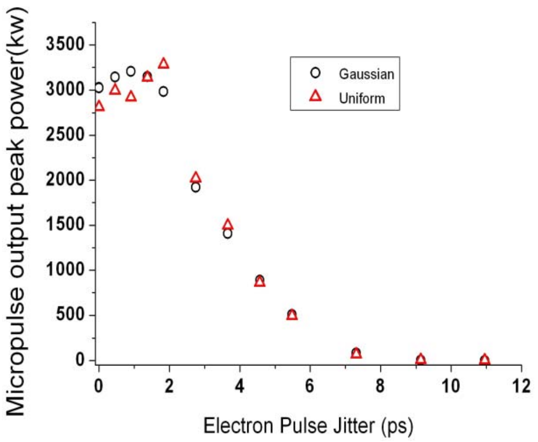

Figure 4: Effects of random electron pulse jitters on the operation of the Newark FEL

This simulation indicates that, if the e-beam pulse frequency is stable, jitters are not critical to lasing. This result can be understood in the following manner: the jitter changes the overlap between the electron and optical pulses at the beginning of the macropulse, but it does not destroy the synchronization between these pulses. Eventually, the jitter broadens the optical pulse, which in turn enhances the overlap between the electron and optical pulses. Thus, in actual operation, if the e-beam pulse is centered at one frequency, but with small fluctuations in arrival time as opposed to systematic frequency migrations, the FEL probably will produce laser output. This tolerance of 7 ps/pulse on the jitter differs substantially from the tolerance of 0.5 ps/pulse previously estimated in the literature[10].

DISCUSSION

Simulations show that a cavity loss of 6%, corresponding to the 6cm hole used for outcoupling in the Newark FIR FEL, is sufficient to suppress lasing. For a peak micropulse current of 2 A, the optimum total loss (cavity and coupling loss) is approximately 2% per round trip. The simulation results suggest that an analysis of the hole-coupling and re-fabrication of the resonator mirrors may be beneficial.

The actual phase slew of the e-beam pulses could be more complex than we have assumed in our simulations and analysis, due to nonlinear e-beam properties originating in the injector. These non-linearities arise in the microwave cavity and gun because the real and reactive components of their shunt impedance depend on the current drawn from the cathode, and this current depends in a non-linear and non-local way on the applied RF voltage due to Schottky non-linearities in the field emission process and the induced heating of the cathode by electron back bombardment. Consequently, the emitted current increases substantially during each macropulse and yields a non-linear and systematic variation with time in both the amplitude and phase of the accelerating voltage in the cavity during each macropulse.

In addition to the systematic variations in the RF amplitude and phase described above, the non-linear and stochastic nature of electron back-heating may also introduce a degree of pulse jitter, although the relative importance with respect to the systematic variations is unknown. Thus, a combination of the systematic and random types of phase slew may be appropriate to describe the microtron pulse generator. From the record of the first lasing experiment, the e-beam current did increase with time during the macropulse, suggesting that large phase variations could possibly have suppressed the lasing operation in later efforts to commission the facility. Possible solutions to the cathode heating issue include the installation of a phase-pick off electrode, replacing the dc gun with a microwave gun[9], and designing the feed-forward compensation or feedback control system to lock the phase to the RF system master oscillator. Furthermore, since the Newark FEL shows almost zero tolerance to the systematic frequency migration, an ultra-stable RF generator is also in high demand.

CONCLUSION

The first computer simulation of the Newark FIR FEL was performed. It was found that the anomalous loss per round trip could suppress the lasing of the FEL. It also showed that the FEL has a greater tolerance for random electron pulse jitter than conventionally estimated. However, the FEL has almost zero tolerance for systematic electron pulse frequency migration. As a result, we are examining techniques to suppress or compensate these systematic variations, including installation of a phase pick-off electrode, use of a microwave gun[9], and design of feed-forward or feedback compensation to control the RF phase.

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