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DISCLAIMER

PRELIMINARY STUDY FOR THE OFFELO*

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Abstract

X-ray Optics-Free FEL Oscillator (OFFELO) has potential of becoming a choice for next generation light sources. Using electron beam for the feedback allows OFFELO to be completely tunable and to combine the peak power of high-gain SASE FELs with extremely narrow bandwidth of the oscillator. While the high-gain X-ray FELs has been studied in depth and has been successfully demonstrated, two other concepts (the transport and the feed-back) involved in OFFELO still need detail studies. In this short paper we focus on the simulation of the feedback process and the evolution of FEL spectrum in X-ray OFFELO.

INTRODUCTION

A fully coherent, high brightness X-ray beams are in great interest for next generation of light-source based research [1]. SASE FELs, such as LCLS [2], already demonstrated the capability of providing very high gain, short pulses of radiation and operation down to 0.1 nm wavelength [3]. However, the origin of SASE FEL lies with the shot noise in the electron beam. Thus, its radiation does not have full temporal coherence and have a rather wide spectrum in order of 0.1%. Many schemes, ranging from self-seeding to cascade high-harmonic FELs are under considerations for reducing the line-width of FEL radiation. Naturally, a tunable FEL CW oscillator would be an ideal source of this kind with capability of reducing lasing line-width, A few ppms line-width in FEL oscillators has been demonstrated by in a number of experiments [4–6].

A lack of good mirrors (or even their absence) extending through the range of interest for FEL user (i.e. from sub-Å to XUV) is the main driver for the schemes of OFFELO. In 1995 Vinokurov discussed first scheme of an OFFELO in a form of a ring FEL [7], as an expansion of his idea of electron out-coupling [8]. This scheme was later studied in detail [9,10] with conclusion that it has a fundamental limitation at short wavelengths (see discussion below). One of important development was the analytical study of saturation in such FEL [11] predicting extremely narrow lasing spectral lines for such systems.

An alternative scheme of OFFELO, one of which is shown in Fig. 1, was suggested in 2002 [12]. It uses a low-energy, low-current feed-back electron beam to close the FEL-oscillator loop. Analytical studies of this concept [13, 14] showed that main limiting factor for OFFELO in Å-range of wavelength is the quantum (random) nature of synchrotron radiation in the bends (which was later confirmed in [10]). These random effects can destroy the correlations between electrons at the scale of the FEL wavelength. Our studies showed that correlation on an angstrom scale can be preserved if the feed-back beam has relatively low energy < 1 GeV. We discuss details of this process elsewhere [15], while concentrating here on the modeling the feed-back and amplifier system using 3D FEL code Genesis 2.0 [16] and additional home-made software package. At present time we use superficially short wiggler periods for the modulator and the radiator. In practice we plan use high harmonics of these wigglers both for the modulation and radiation. This will be included into our future software package.

Even though we are discussing here the optics-free FEL oscillator, we want to mention for completeness that recently a mirror-based X-ray FEL oscillator has been also proposed [17].

SIMPLE CONSIDERATIONS

The following model illustrates some of important saturation effects in OFFELO (see [11] for more complete model). The OFFELO as any FEL oscillator starts from amplification spontaneous radiation and grows pass by pass as:

$$P_{n+1} = G_o\left(P_{n+1}\right) \cdot \left[P_{SR} + C_{fb}\left(P_n\right) \cdot P_n\right] \qquad (1)$$

where G_o is the HGFEL gain, $C_{fb} = P_{input}/P$ is the feed-back coefficient and P_{SR} is the power of spontaneous radiation into the amplified mode. The OFFELO will lase if the low signal gain per pass is larger than one:

$$G_o\left(0\right) C_{fb}\left(0\right) > 1 \qquad (2)$$

As any oscillator, OFFELO will saturate at:

$$P_{sat} = \frac{G_o\left(P_{sat}\right)}{1 - G_o\left(P_{sat}\right) C_{fb}\left(P_{sat}\right)} P_{SR} \qquad (3)$$

The OFFELO can be saturated by two mechanisms: a) by over-bunching of the feed-back beam; b) by gain saturation in the HGFEL. The later will provide better spectral quality of the FEL radiation, and therefore is preferable. Qualitatively it can be seen from following considerations: In the absence of spontaneous radiation the FEL oscillator would have infinitely narrow (or Fourier limited) lasing line-width. Thus the ratio of the feed-back power to that of the spontaneous ration is the measure of the spectral purity of the system, i.e. for a a narrow line-width oscillator we need $C_{fb} P_{sat} \gg P_{SR}$.

Saturation of the feedback can be described in a simple term by the bunching mechanism in an optical

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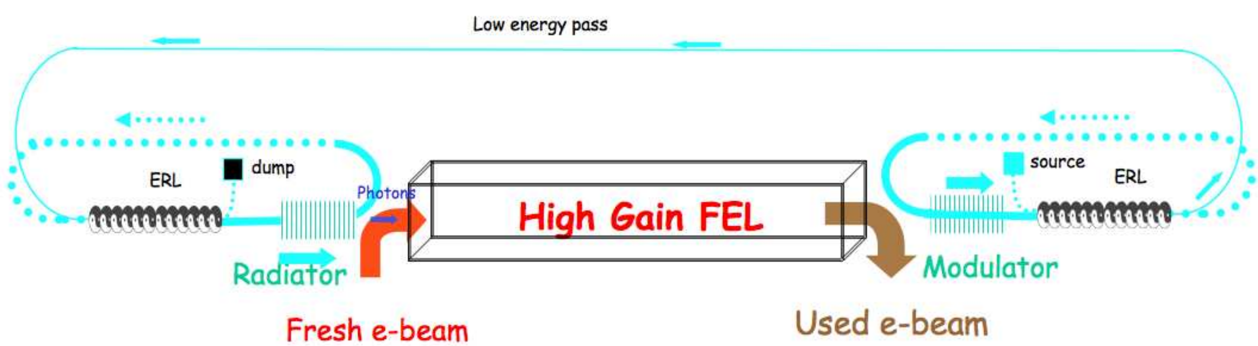

Figure 1: One of possible schemes for X-ray OFFELO. The central cube represents a high-gain X-ray FEL (HGFEL) fed by a high-energy (~10 GeV) CW ERL. A low-energy electron beam interacts with X-ray radiation exiting the HGFEL in the modulator, and carries the imprinted energy modulation to the entrance of the HGFEL. There the energy modulation is transferred into the density modulation and the beam radiates coherently in the radiator. This radiation is further amplified in the HGFEL, which completes the close loop of the oscillator.

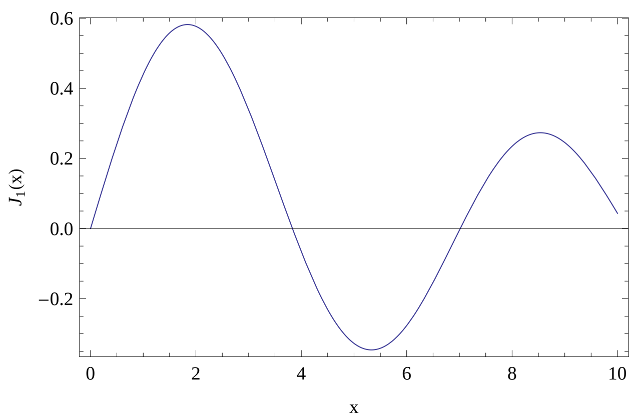

Figure 2: Saturation of the feedback ~ $J_1^2(x)/x^2$

klystron [17]. The bunching of the electron beam at the entrance of the radiator is given by:

$$b = J_1(X)\, e^{-Y^2/2} \tag{4}$$

where $X = 2kR_{56}\delta\gamma/\gamma$, $Y = 2kR_{56}\sigma_\gamma/\gamma$ and $\delta\gamma = ea_w[JJ]L_w\sqrt{8\pi P/cA}$. Here, $k = 2\pi/\lambda_{FEL}$ is the radiation wave number, $\gamma = E/mc^2$ is the relativistic factor of the feed-back electron beam, R_{56} is the longitudinal dispersion of the transport system, P is the power at the exist of HGFEL, a_w and L_m are the undulator vector potential and length of the modulator repectively, and A is the area of the X-ray beam in the modulator. As seen from the Fig 2, X should be held well below 2 to avoid saturation in the feed-back system.

Saturation of the HGFEL gain is well studied in FEL literature and we will not discuss it here.

Table 1: The Beam Parameter of the High Energy Electron Beam and the Main Oscillator

Parameters	Values
Energy (GeV)	13.6
Energy spread ($\delta\gamma/\gamma$)	1×10^{-4}
Peak current (A)	3000
Normalized emittance (mm mrad)	1.5
Undulator Period (m)	0.03
Undulator Length (m)	60
Undulator Parameter K	2.616
Radiation Wavelength (nm)	0.166
Average beta function (m)	18

RESULTS OF PRELIMINARY SIMULATIONS

We use Genesis 2.0 [16] to simulate the processes in the OFFELO. As a demonstration example we assume a the HGFEL typical design parameters for LCLS with13.6 GeV electron beam and 1.66 Å wavelength. Table 1 lists the rest of the parameters. Power saturation can be studied in both time-resolved and single frequency simulation mode. The single-frequency simulations are much faster and we used them to adjust the feedback beam parameters and two wigglers to maximize the output power of the FEL.

Many parameters of the system are in the process of optimization. Table 2 list the parameters used for the feedback system. Figure 3 shows typical growth of the FEL power from the initial HGFEL amplification of the spontaneous radiation to the saturated FEL oscillator. One can see that the ratio of the purity $C_{fb}P_{sat}/P_{SR}$ ratio is at least 500 for this pre-defined synchrotron radiation power. Hence, one expects this system having about 500 time narrower linewidth than SASE-FEL in this case.

As seen in Fig. 3, the OFFELO reaches saturation at about 1 GW of the peak power in about five cycles. The es-

Table 2: The beam parameter of the feedback electron beam, the modulator and the radiator. *The micro-wigglers are temporary tool, which will be replaced by interaction with high harmonics of a high-K wiggler.

Parameters	Values
Energy (GeV)	1
Energy spread ($\delta\gamma/\gamma$)	1×10^{-5}
Peak current (A)	15
Normalized emittance (mm mrad)	0.015
Undulator period (m)	$6.36 \times 10^{-4*}$
Number of undulator period Modulator/Radiator	120/3000
Undulator parameter K	0.1
Radiation wavelength (nm)	0.166

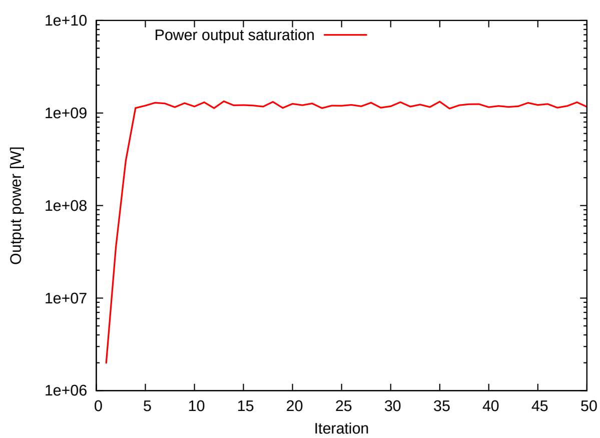

Figure 3: The evolution of the output power in the OFFELO. One iteration corresponds to one feed-back cycle of the system.

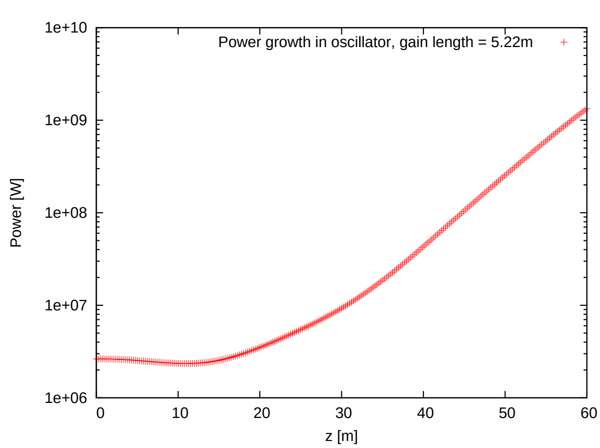

Figure 4: Power in main oscillator at 40th iteration.

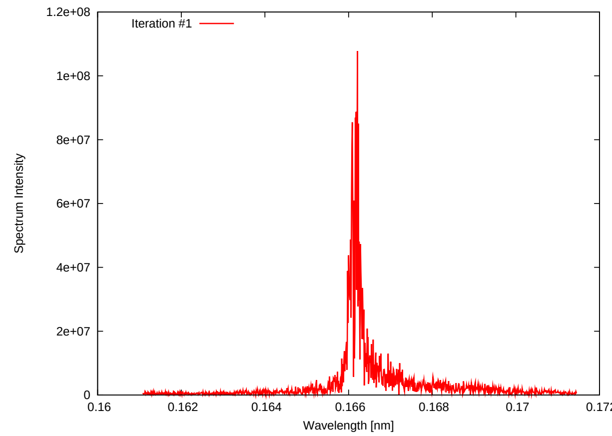

Figure 5: Spectrum of the radiation at the pass #1.

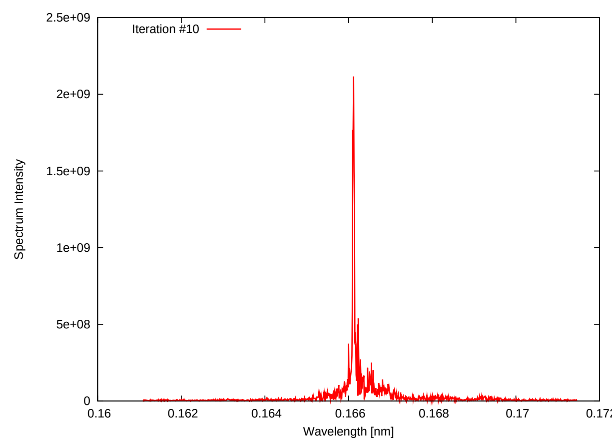

Figure 6: Spectrum of the radiation at the pass #10.

tablished level of saturated power in the HGFEL is shown in Fig. 4.

The time-resolved simulations are much slower and we used them to study evolution of the OFFELO lasing spectra. Initial spectrum from OFFELO is identical to that from SASE FEL. Laser, because of the wavelength gain dependence, the spectrum becomes narrower and narrower. This process of line-width narrowing is rather slow (i.e. proportional to the square root of the natural logarithm of the accumulated gain [19]) and the computations time is rather long. Here we show preliminary results indicating that OFFELO exhibits typical behavior of an oscillator. Fig.5 shows OFFELO spectrum at the pass one, i.e. the typical single pass SASE FEL spectrum. Figure 6 shows the spectrum of the FEL radiation at the pass one with typical 0.2% FWHM line-width.

Theory predicts that the OFFELO lasing line-width will continue reducing and will eventually reach level of few ppms. We plan to demonstrate this feature using more advanced computer facilities. Meanwhile, we can state that the line width reduced by about factor of ten, while the spectral density grew by a factor of twenty (see Fig. 7). This is consistent with the expectation that in the oscillator

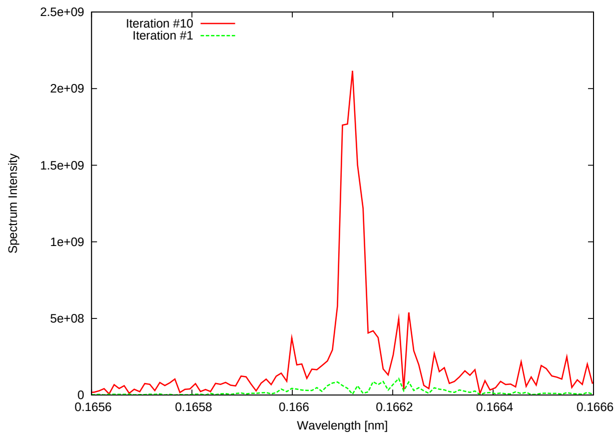

Figure 7: Evolution of the OFFELO spectrum during first ten iterations.

the reduction of the lasing line-width will boost the spectral power density (and therefore the spectral brightness) inverse proportionally to its line-width.

DISCUSSION

In our initial studies of OFFELO studied the saturation of the system and also its evolution using Genesis 2.0 code with a homemade wrapping code. While we could carry out single-frequency simulation for many turns, the time-resolved simulation are very time consuming and we had studies so far only the initial evolution of the system.

In the future, we extend the time-resolved simulation to study to steady-state lasing spectrum. We also plan adding the tracking of the feed-back beam through a realistic lattice as the part of the complete simulation package. In spite of the limited extent of our studies, we found that evolution of radiation in the OFFELO follows up very closely the prediction for a typical oscillator with smooth saturation of the gain. In other words, the OFFELO has potential of becoming a stable X-ray FEL oscillator with Fourier limited pulses of radiation.

As we had mentioned before, we also will replace in the model both the modulator and radiator micro-wigglers with high-K wigglers providing identical interaction with eh TEM waves. While been a trivial theoretically – i.e. equalizing the intensity of the radiation at FEL wavelength - this modification will require a minor software development to comply with the i/o imposed by the Genesis 2.0.

CONCLUSIONS

In our initial studies of OFFELO studied the saturation of the system and also its evolution using Genesis 2.0 code with a homemade wrapping code. While and lattice design from the modulator to the radiator, in order to minimize the feedback information loss in transporting the beam.

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