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**V.N. Litvinenko, Y. Hao, D. Kayran, D. Trbojevic**

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# OPTICS-FREE X-RAY FEL OSCILLATOR\*

Vladimir N. Litvinenko<sup>#,1,2</sup>, Yue Hao<sup>1,2</sup>, Dmitry Kayran<sup>1</sup>, Dejan Trbojevic<sup>1</sup>

<sup>1</sup> Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973

<sup>2</sup> Center for Accelerator Science and Education, Stony Brook University, NY 11794

## Abstract

There is a need for an Optics-Free FEL Oscillators (OFFELO) to further the advantages of free-electron lasers and turning them in fully coherent light sources. While SASE (Self-Amplified Spontaneous Emission) FELs demonstrated the capability of providing very high gain and short pulses of radiation and scalability to the X-ray range, the spectra of SASE FELs remains rather wide (~0.5%-1%) compared with typical short wavelengths FEL-oscillators (0.01% - 0.0003% in OK-4 FEL). Absence of good optics in VUV and X-ray ranges makes traditional oscillator schemes with very high average and peak spectral brightness either very complex or, strictly speaking, impossible.

In this paper, we discuss lattice of the X-ray optics-free FEL oscillator and present results of initial computer simulations of the feedback process and the evolution of FEL spectrum in X-ray OFFELO. We also discuss main limiting factors and feasibility of X-ray OFFELO.

## INTRODUCTION

A fully coherent, high brightness x-ray sources are of 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]. With current advances in the FEL gain at the level of  $10^5$ - $10^7$  per pass in X-ray region of spectrum are attainable. It is apparent that such an FEL can become an oscillator providing a rather weak feed feedback at a few p.p.m. level.

As self-evident from their name, Self-Amplified Spontaneous Emission, the light in a SASE FEL

originates from the shot noise in the electron beam density.

Its radiation does not have full temporal coherence and, as the result, has a rather wide spectrum. Many schemes, ranging from self-seeding to cascaded high-harmonic FELs are under considerations for reducing the line-width of FEL radiation. At present time only concept of self-seeding FEL using narrow-band monochromator has a potential of operating in X-ray range.

A single-pass amplifier, which narrows the radiated spectrum line-width to about

$$\delta\lambda_{FEL} \propto \delta\lambda_{BW} / \sqrt{\ln G_{FEL}}$$

where  $G_{FEL}$  is the FEL gain and  $\delta\lambda_{BW}$  is the FEL amplification bandwidth. In contrast with a single-pass amplifier in an oscillator the radiation spectrum narrows at each and every pass and its final bandwidth can be extremely small. Naturally, a tunable FEL CW oscillator would be an ideal source of this kind with capability of reducing lasing line-width to few ppms as was demonstrated by in a number of FEL experiments [4,5,6]. Lack of good mirrors (or even absence of those) 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 the first scheme in a form of a ring FEL [7] as an expansion of his idea of electron out-coupling in FELs [8]. It was later studied in detail [9,10] with conclusion that this scheme has fundamental limitation at short wavelengths.

One of important development was analytical studies of power saturation in such FEL and the evolution of the radiation line-width [11]. This study predicted extremely narrow lasing spectral lines for such OFFELO.

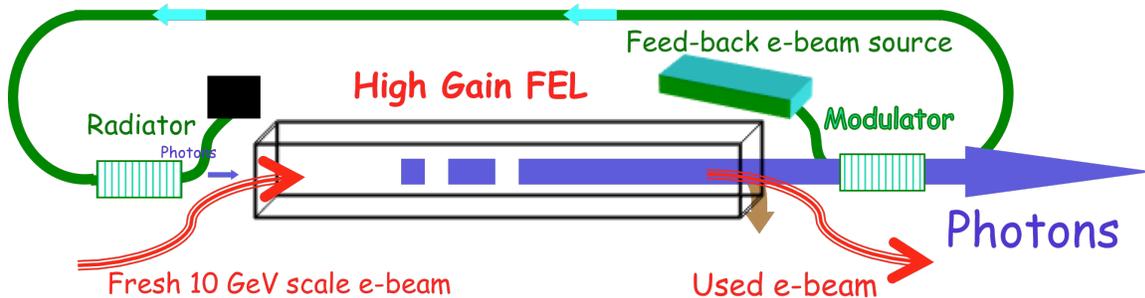


Figure 1. One of possible schemes for X-ray OFFELO. The central cube represents a high-gain X-ray FEL fed by a high-energy, 10 GeV scale, CW ERL. A low-energy electron beam energy-modulated by X-ray radiation exiting the FEL carries the imprinted modulation to its entrance. There the energy modulation 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.

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<sup>#</sup>vl@bnl.gov

Alternative schemes of OFFELO, one of which is shown in Fig.1, were suggested in 2002 [12]. These

schemes are using a dedicated low-energy, low-current electron beam to the feedback to close the FEL-oscillator loop. Analytical studies of this concept [13-14] showed that main limiting factor for OFFELO to access Å-range of wavelength is the randomness of quantum synchrotron radiation of bent beam (which was confirmed in [10]). This requirement can be satisfied if the feed-back beam has relatively low energy ( $\leq 1$  GeV). We discuss details of this process elsewhere [15]. Here we concentrate 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].

## FUNDAMENTALS OF THE CONCEPT

The OFFELO relies on two most basic ideas. First is that the information in the form of the energy modulation imprinted into the feed-back beam is preserved after the pass from the OFFELO exit to its entrance. It means that the electrons stay correlated at the scale of FEL wavelength:

$$\delta S_{turn} = c(\tau_{exit} - \tau_{input}) < \tilde{\lambda}_{FEL}.$$

Preserving such correlation requires used of periodic asynchronous lattice [19] with total integer tune advances in both planes and zero chromaticity [20]. Such lattice is natural second order achromat [21] and will completely eliminate time of flight dependence on the transverse emittance. One possible lattice for such lattice is shown in Fig.2.

Second idea is that the spectral density of the power generated by the feedback e-beam is significantly larger than that of the spontaneous radiation from the amplifier-beam. This means that the coherent input from the feedback will saturate the gain of the main FEL and suppress SASE noise.

Hence we are studying the regime in which the feedback works in linear mode:  $P_{fb} = c_{fb} \cdot P_{out}$  (where  $P_{out}$  the OFFELO output optical power). The OFFELO will lase if the low signal gain per pass is larger than one:

$$G_{HG}(0) \cdot c_{fb} > 1. \quad (2)$$

where  $G_{HG}$  is the gain of high-gain FEL section. The OFFELO saturation happens because of saturation of the high gain FEL section:

$$P_{out} = G_{HG}(P_{out}) \cdot (c_{fb} \cdot P_{out} + P_{sr}).$$

When  $c_{fb} \cdot P_{out} \gg P_{sr}$ , the OFELO radiation will have orders of magnitude better spectral purity compared with that of SASE FEL.

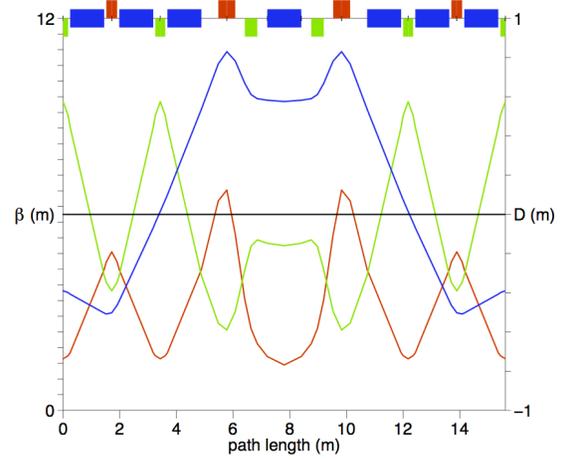


Figure 2: An isochronous cell with tune advance 0.95 and 0.525 in horizontal and vertical planes correspondingly.

## RESULTS OF PRELIMINARY SIMULATIONS

We use Genesis 2.0 [16] in combination with additional homegrown program to simulate the processes in the OFFELO. Genesis 2.0 was used for high-gain FEL, modulation and radiation processes, while the other program used to connect these processes. This temporary combination operates only for fundamental harmonic of the wigglers and is the reason behind the need for use of micro-undulator\* concept, instead of the high harmonic of more conventional undulator. The later will be used in the next generation of our simulations.

Table 1. Parameters of the FEL amplifier

Electron energy (GeV)	13.6
Energy deviation $\sigma_E/E$	1e-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

Table 2. Parameters of the feed-back

Electron energy (GeV)	1
Energy deviation $\sigma_E/E$	1e-5
Peak current (A)	15
Normalized emittance (mm-mrad)	0.015
Undulator period [mm]	0.636
Number of undulator periods	
(Modulator/Radiator)	120/800
Undulator parameter K	0.1
Radiation wavelength [nm]	0.166

\* The micro-wigglers are used as temporary tool, which will be replaced by interaction with high harmonics of a high-K wiggler with next stage of simulation.

As a demonstration example we assume a HGFEL typical design parameters for LCLS with 13.6 GeV electron beam and 1.66 Å wavelength. We performed self-consistent simulation of the OFELLO feed-back system for beam parameters using beam and wiggler parameters listed in Table 1 and Table 2.

Figures 3 and 4 show the process of the OFELLO saturation and the self-consistent power profile in the high-gain FEL section.

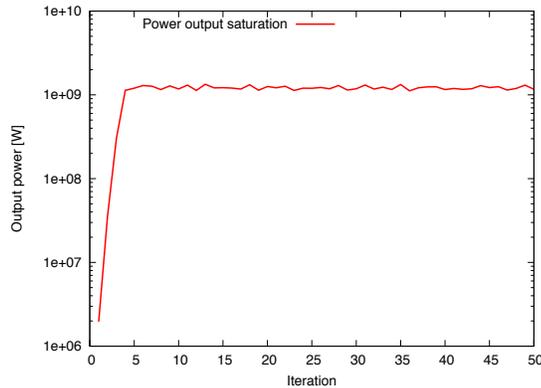


Figure 3: Saturation of the OFFELO output power.

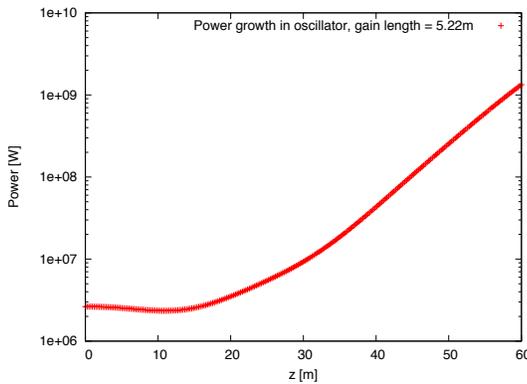


Figure 4: Power evolution inside the high gain FEL at the OFFELO saturation.

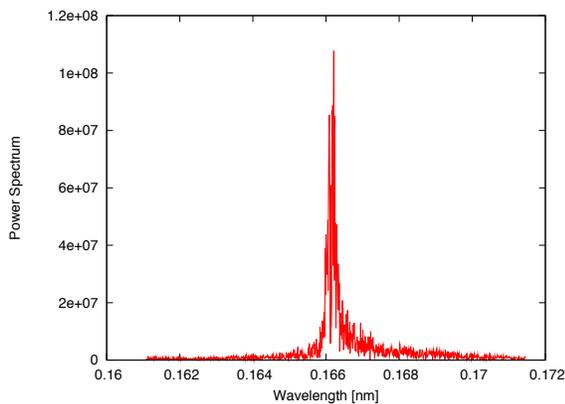


Figure 5: Radiation spectrum at pass #1 .

Figs. 5 and 6 show preliminary results of the evolution of the OFFELO radiation from the SASE (on the pass #1) with broad-band spectrum to a more typical oscillator like (on the path #10). In ten passes the spectral purity of radiation (i.e. spectral brightness) grew 20-fold.

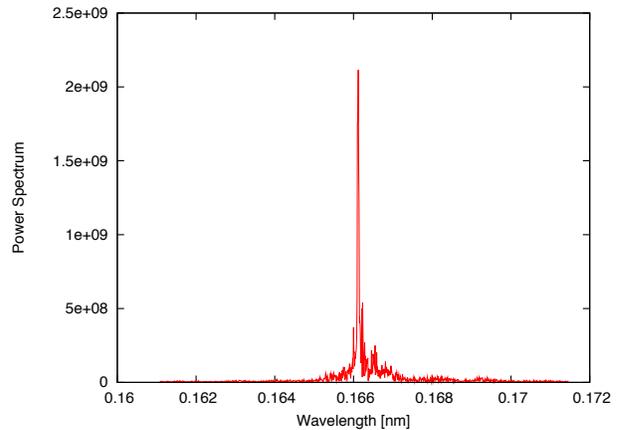


Figure 6: Radiation spectrum at pass #10 .

## CONCLUSIONS

We tested some of the key assumptions of OFFELO concept in direct 3D-FEL simulations and observed the behavior consistent with our theoretical models. The concept is very promising and we plan to continue more detailed and more realistic simulation of such system.

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