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HIGH-EFFICIENT XFELO BASED ON OPTICAL RESONATOR WITH SELF-MODULATED Q-FACTOR*

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Abstract

We suggest an efficient XFELO having a new non-stationary out-coupling scheme. It consisted of two undulator sections located in sequence with a free space gap in-between. The first section is a conventional uniform undulator, the second one is a tapered undulator. At start time point X-ray radiation is basically produced by the uniform section. Mirrors of XFELO's optical resonator are calculated so that diffraction Q-factor reaches the highest value, i.e. losses are near to zero. As X-ray power increases the tapered undulator begins to bring more contribution in radiation power. Finally, at a new steady state regime all power is being produced by the tapered section. Because mirrors were optimized for Gaussian wave-beam to be produced in the first section, in the final steady state regime a portion of X-ray power will be out-coupled missing partly the mirrors.

INTRODUCTION

The Free Electro Laser Oscillator concept, included two undulators and a bending magnet, was suggested for THz FEL [1]. The sketch of this conceptual FEL is shown in Fig. 1. The first undulator produces microbunching of e-beam, the second undulator operates in a so-called SASE regime generating X-rays. The idea aimed avoiding high field exposure of mirrors in XFELO resonator.

This idea could also be applicable for a future XFELO [2-3]. In viewpoint of the XFELO the proposed scheme allows easily to start up. However, essential concerns are that 1) bending magnet spoils e-beam; 2) X-rays accumulated in the resonator are lost; 3) high efficiency might be problematic.

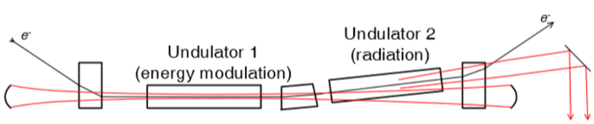

Figure 1: Electron out-coupling scheme with two undulators and bending section between them.

We suggest improving the described concept to be acceptable for a high-efficient XFELO. For that purpose we suggest, first, to insert both undulators inside the optical resonator, in order to avoid side extraction of the modulated e-beam. The first undulator is implied to be uniform, it is necessary to start up XFELO. The second undulator should be responsible for a high efficiency, therefore, it has to be tapered one as high-efficiency regimes were shown obtainable for that types of undulators [4-5]. The field structure of X-ray radiation in XFELO resonator is assumed to be different at start condition when X-ray beam waist is located near centre of the uniform undulator and in steady state condition when the waist is shifted near to the centre of the tapered section. In the steady state regime the resonator is out-coupled and looks like an unstable optical cavity [6-7].

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SELF-MODULATED RESONATOR

The sketches of the suggested XFELO are shown in Figs. 3 and 4. In accordance with our concept XFELO consists of two undulators. The first undulator is classical uniform, the second is tapered one. At start condition Q-factor of XFELO resonator obtains maximum possible value due to proper optics (Fig. 2). The waist of the X-ray beam in resonator is located at the center of the uniform undulator. The uniform undulator leads the XFELO. The tapered undulator is almost "silent". This principle helps to ignite oscillations.

At steady-state condition the tapered undulator mainly produces X-rays and provides high efficiency (Fig. 3). The Q-factor in this case reduced due to necessary out-coupling. Out-coupling is caused by the change of X-ray beam waist position. A new waist position corresponds to the center of the tapered undulator. CRL optics, optimized for the described regime when beam waist is inside the uniform undulator allow some part of X-rays to pass by one of Bragg mirrors. In this regime the uniform undulator does not bring an essential contribution in X-ray production.

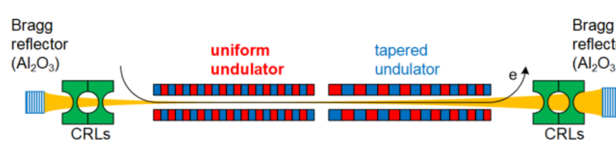

Figure 2: Sketch of XFELO with self modulated Q-factor resonator in regime of starting up.

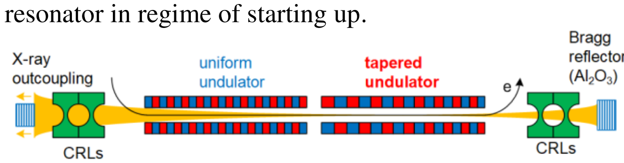

Figure 3: Sketch of XFELO with self modulated Q-factor resonator in steady state regime.

The tapered undulator can be based either static DC-magnets or RF wave as it was shown in [8].

The two-undulator concept works well only if the amplification in the tapered undulator is much greater than power loss due to outcoupling (in this case X-ray field structure can be considered as fully controlled by the

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tapered undulator). This condition means that Pierce parameter must be as large as to satisfy:

$$\exp\left(L_{tu}/L_{gain}\right) \gg P_{out}, \tag{1}$$

where P_{out} – normalized power loss per single wave passage in the resonator, L_{tu} – length of the tapered undulator, $L_{gain}=\lambda_u/4\pi\rho$ - gain length, ρ - Pierce parameter:

$$\rho \sim (K_u I/\gamma_0^3)^{1/3} \tag{2}$$

The above equations show that high-current bunches of small cross-section sizes are preferable. Such bunches can be produced by laser-plasma accelerators. Large energy spread can be mitigated by trapping regime in the tapered undulator.

DIAMOND XFELO COMPONENTS

The output X-ray beam of the suggested XFELO is not Gaussian as one can see at Fig. 3. That is why, it is necessary to elaborate mode converter to transform ring-like beam shape into Gaussian one or flat one. This problem could be solved using a so-called phase plate. The Fig. 4 shows calculation results of phase plate surface synthesis using principles published in [9].

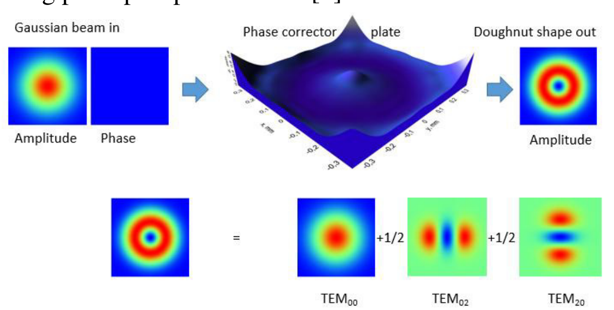

Figure 4: Gaussian beam is converted into a mix of three free space eigenmodes that combine to form the doughnut shape.

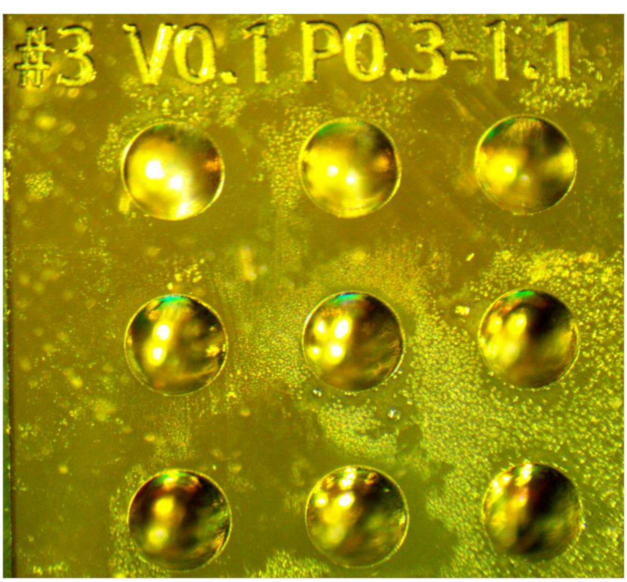

Figure 5: Diamond refractive lens.

The phase plate is assumed to be made of single crystal diamond, because high heat peak and average loads are assumed. In Fig. 5 one can see the diamond lens produced by Euclid Techlabs. Production technology is based on fs laser ablation and polishing. In Euclid Techlabs this system was installed to produce refractive x-ray diamond lenses (Fig. 6). We implemented computer controlled ultra-fast laser beam rastering across a large area. Femtosecond laser ablation typically produces surfaces with roughness on the order of a few hundred nanometers to 1 micron. We developed polishing procedures for cylindrical features like conical and parabolic holes. The typical dimension we worked with was a ~ 500 μm diameter entrance hole, ~250 μm deep. We used a conformal geometry needle to spin a diamond slurry for several hours inside of the hole. Currently, we are able to polish full surfaces to less than ~1 nm rms roughness (Fig. 7).

The CRL produced by Euclid Techlabs was successfully tested at APS facility [10].

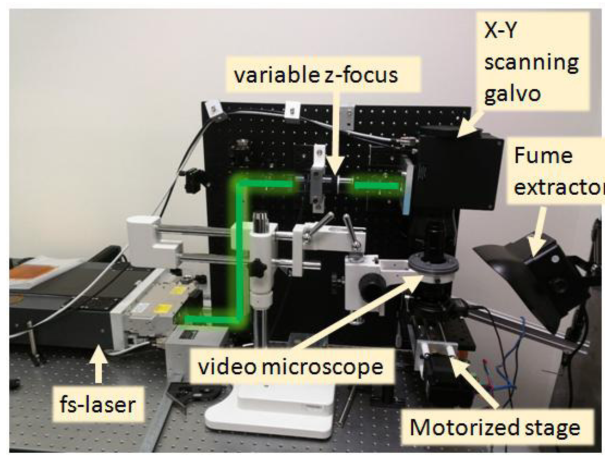

Figure 6: Femtosecond lens cutter tool.

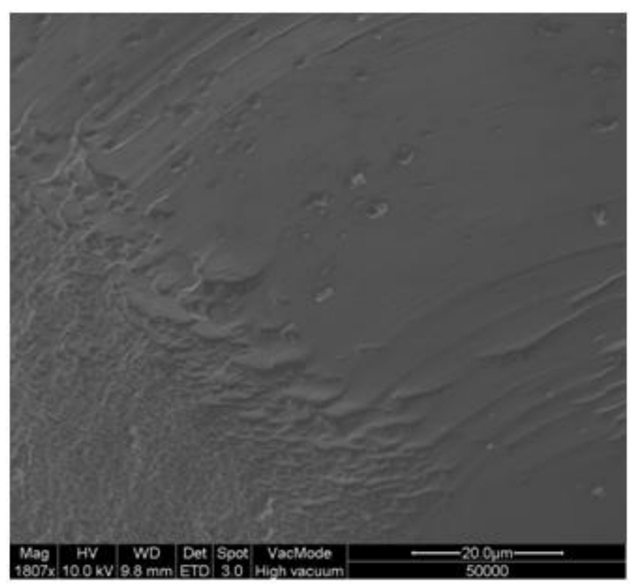

Figure 7: Inspected diamond surface after cutting and post-polishing.

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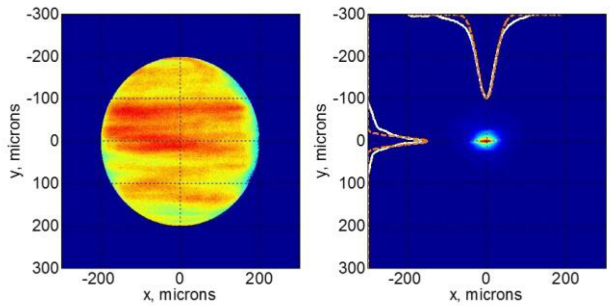

Figure 8: Test of source refocusing by CRL at BIOCAT II - APS.

CONCLUSION

A concept of the XFELO with self-modulated Q-factor allows XFELO easy to start up and to provide high efficiency at steady state condition due to trapping regime.

Smart diamond CRLs and phase plate converters are under investigation at Euclid.

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