On Use of Time-Dependent RF Field to Increase the FEL Oscillator Efficiency

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Abstract

Various schemes of a high efficiency FEL oscillator with time-dependent accelerating (or decelerating) microwave field in interaction region are proposed. All the schemes are based on standard accelerating structure and undulator technology. Realistic examples of FEL oscillators of infrared and visible wavelength ranges with efficiency about 20 % are presented.

1 INTRODUCTION

Nowadays, when free electron lasers have gone a long way from first experimental demonstration [1] to their wide applications in various regions of science and industry, the problem to increase an efficiency of FEL devices becomes a central one for free electron laser physics and technique.

A reliable method to increase the FEL amplifier efficiency was proposed more than ten years ago, consisting in sustaining the synchronism of the electrons with amplified electromagnetic wave by means of undulator tapering [2, 3]. The problem to increase a FEL oscillator efficiency has appeared to be a more complicated [4].

It is evident now that it is impossible to achieve a high efficiency in the FEL oscillator using conventional approach of undulator tapering. An approach to increase the FEL oscillator efficiency was proposed in ref. [5]. It is based on a natural feature of the FEL oscillator, namely the dependence on time of the radiation field stored in the resonator. It was proposed to introduce time-dependent accelerating fields into interaction region (which is equivalent in its action to the undulator tapering). As a result, it makes possible to trap electrons into the ponderomotive well and perform the conversion of microwave energy to the optical one. To increase a number of trapped electrons (which results in higher efficiency), the authors of ref. [5] proposed to use a prebuncher together with a homogeneous undulator. Numerical estimations, presented in refs. [5, 6] have shown that the efficiency about several tens of percent can be achieved in such modification of the FEL oscillator.

Present paper is devoted to the problem of the FEL oscillator efficiency increase by application of time-dependent microwave fields. On our opinion, giving a possibility to increase significantly the FEL oscillator efficiency, the approach presented in refs. [5, 6] is rather comprehensive and requires significant development of novel undulator an RF structure technology. In the present paper we propose several alternative technical solutions totally based on a well developed conventional RF structure and undulator technology.

A common feature of three proposed schemes is that their magnetic systems consist of a prebuncher and main undulator spaced by drift (or dispersion) section and time-dependent RF field fields are introduced inside the location of the main undulator. Here we describe briefly the proposed schemes and present numerical examples. Detailed study of the problem is presented in ref. [7].

2 ACCELERATING STRUCTURE INSIDE THE UNDULATOR

This scheme is similar to that proposed in refs. [5, 6]. The only difference is that we propose a more realistic way to realize this scheme which is totally based on standard undulator an RF structure technology. We propose to use standard undulator (for instance, a permanent magnet or hybrid one) with conventional iris-loaded waveguide installed in its gap (see Fig.1).

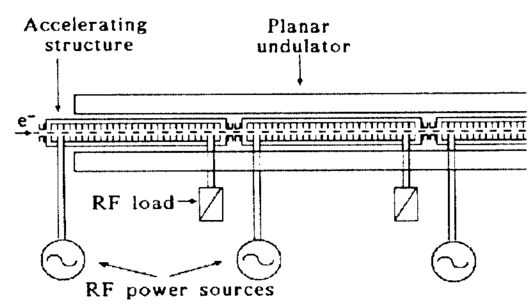

Figure 1:

This accelerating structure is fed by the RF power source operating at a harmonic frequency of the driving accelerator and is synchronized with the RF power system of the latter. Successful operation of this scheme takes place when the accelerating rate in the accelerating structure is proportional to the optical field amplitude in the resonator. It may be achieved, for instance, by introducing of the feedback from the optical field detector to the RF power supply.

Another important problem is that of the choice of optimal RF band. First, to minimize the size of the undulator gap, one should minimize the transverse dimensions of the waveguide by choosing as short RF wavelength as possible. On the other hand, there should exist high peak power RF

Table 1:

Electron beam	
Energy, $\mathcal{E}_o$	50 MeV
Peak current, I	110 A
Average macropulse current, I_a	20 mA
Micropulse duration	5 ps
Energy spread, $\sigma/\mathcal{E}_o$	0.5 %
Magnetic system	
Prebuncher	
Period, λ_p	9 cm
Magnetic field, B_p	0.49 kG
Number of periods, N_p	3
Length of drift space, D	39 cm
Main undulator	
Period, λ_w	6 cm
Gap, g	3.5 cm
Magnetic field, B_w	2 kG
Number of periods, N_w	30
Optical resonator	
Wavelength, λ	5 μm
Rayleigh length, z_R	90 cm
Total power losses	2 %
Reaccelerating system	
RF frequency	8 GHz
Number of sections	4
Section length, l_s	40 cm
Structure type	$\pi/2$
Iris / cell radius	4 / 13.3 mm
Reduced shunt impedance, R_s	94 MΩ/m
Attenuation constant, α	0.74 m^{-1}
RF power per section	1 MW
Maximal accelerating gradient	11.8 MV/m

amplifiers (with output power $W_{peak} \geq 1$ MW) with sufficiently long pulse duration (several microseconds or more) corresponding to that of the driving accelerator. Analysis of the present-day situation with RF sources shows that the most appropriate band for this purpose is the X-band. For instance, the Varian klystron X3030 operates in a CW mode at 8 GHz frequency with output power 1 MW. There is no problem to fabricate travelling wave X-band structure with transverse dimensions about of 3 cm. Table 1 presents parameters of the FEL oscillator with 26 % efficiency.

3 SECTIONAL UNDULATOR WITH SEPARATED ACCELERATING CAVITIES

The approach to increase the FEL oscillator efficiency by introducing accelerating RF fields into the interaction region, has limited possibilities due to severe technical limitations. The main problem is that of reducing the value of the undulator gap, so as peak field at the undulator axis depends exponentially on the gap value. As a result, it requires a necessity to develop novel types of undulator and RF structures [5, 6], or to use accelerating RF structures

Table 2:

Electron beam	
Energy, $\mathcal{E}_o$	35 MeV
Peak current, I	35 A
Energy spread, $\sigma/\mathcal{E}_o$	0.2 %
Magnetic system	
Prebuncher	
Period, λ_p	9.2 cm
Magnetic field, B_p	0.44 kG
Number of periods, N_p	3
Length of drift space, D	36 cm
Main undulator	
Period, λ_w	5 cm
Magnetic field, B_w	3 kG
Number of sections	5
Spacing between sections	10 cm
Number of periods, N_w	50
Optical resonator	
Wavelength, λ	10 μm
Rayleigh length, z_R	145 cm
Total power losses	2 %
Reaccelerating system	
Number of cavities	4
Maximal energy increment per cavity	1.9 MeV

operating at a small RF wavelength (see section 2).

In this section we consider another possibility to overcome this problem. We propose to use sectional main undulator and to install RF cavities between undulator sections (see Fig.2).

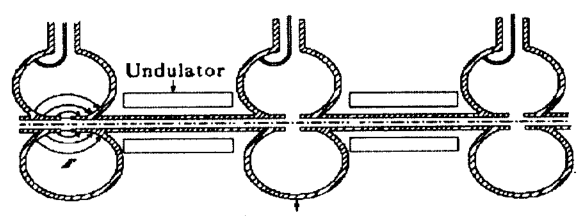

Figure 2:

So as there is no limitations on transverse dimensions of the accelerating cavities, they may operate at the same frequency as the driving accelerator (L- or S-band) and provide high accelerating gradient about several tens MV/m. Of course, such a separation in space of the electron beam acceleration in the RF field and deceleration in the optical field possesses some disadvantages with respect to the scheme with combined functions. First, due to the finite energy spread of electrons in the beam, additional phase debunching takes place in the space between undulator sections. Second, phase shift of electrons in the space between undulator sections with respect to optical field phase, and phase motion of electrons trapped into the ponderomotive well are changed while the RF field amplitude is changed. These effects lead to detrapping of electrons and result in efficiency decrease. Nevertheless, the results of numerical simulations have shown that these scheme may provide the efficiency about $10 \div 20\%$ which is much more than that of conventional FEL oscillator configuration. This scheme seems to be extremely attractive, so as it may be realized at the present level acceleration technique R&D.

Table 2 presents parameters of the FEL oscillator providing efficiency 16 %.

4 TAPERED UNDULATOR WITH TUNABLE DECELERATING RF STRUCTURE

In this section we study a novel scheme to increase the FEL oscillator efficiency exploiting time-dependent RF field technique. The proposed scheme consists of the prebuncher, the main undulator with tapered parameters and one or more tunable decelerating RF structures placed inside the gap of the main undulator (see Fig.3).

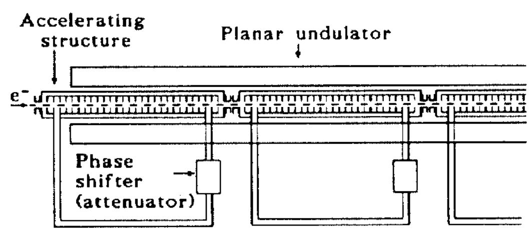

Figure 3:

The peculiar feature of the RF structure used is that it decelerates electron beam by self-induced RF field. Initially it is tuned in such a way to provide deceleration of electrons in accordance with the undulator tapering and exact resonance of electrons with optical field takes place along total undulator length. While optical field is increasing, the RF structure is detuned to decrease the induced RF field and to sustain resonance condition. Finally, when the optical field gain becomes equal to the resonator losses, the stationary regime with high efficiency is settled. The induced RF field is small in the stationary regime.

The advantage of the scheme with the tapered undulator and tunable decelerating RF structure is evident. It does not require RF power supply, so a more short RF band may be chosen (K_u-, K- or K_α-band) giving a possibility to place the RF structure in a smaller undulator gap. As a result, a more short undulator period may be used to generate the radiation with a more short wavelength.

We propose to use the travelling wave resonator technique to provide fast tuning of decelerating RF structure. Decelerating RF structure is conventional iris-loaded waveguide. Its exit and entrance are connected by means of the transmitting waveguide with the phase shifter or attenuator. Some possibilities of a fast change of the transmission coefficient have been considered in ref. [7]

Table 3 presents parameters of the FEL oscillator providing efficiency 18 %. RF deceleration system consists of 8 iris-loaded waveguides with parameters close to those accepted in the CLIC project [8].

Table 3:

Electron beam	
Energy, $\mathcal{E}_o$	120 MeV
Peak current, I	55 A
Average macropulse current, I_a	200 mA
Micropulse duration	1 ps
Energy spread, $\sigma/\mathcal{E}_o$	0.2 %
Magnetic system	
Prebuncher	
Period, λ_p	6.3 cm
Magnetic field, B_p	0.94 kG
Number of periods, N_p	4
Length of drift space, D	70 cm
Main undulator	
Period, λ_w	3.5 cm
Gap, g	1.4 cm
Magnetic field, B_w	4.5 kG
Number of periods, N_w	80
Tapering depth (parabolic), $\Delta B/B_o$	74 %
Optical resonator	
Wavelength, λ	0.65 μm
Rayleigh length, z_R	140 cm
Total power losses	2 %
Decelerating system	
RF frequency	30 GHz
Number of sections	8
Section length, l_s	25 cm
Structure type	$2\pi/3$
Iris / cell radius	2 / 4.35 mm
Reduced shunt impedance, R_s	110 MΩ/m
Attenuation constant, α	1 m^{-1}

5 CONCLUSION

It was shown in the presented paper that practical realization of the FEL oscillators with efficiency about of 20% is quite feasible at the present level of acceleration technique R&D using standard undulator and RF structure technology.

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