HIGH CURRENT FEL OSCILLATOR ON BASE OF MSU ELECTRON ACCELERATORS

V.K.Grishin, B.S.Ishkhanov, T.A.Novicova, Institute of Nuclear Physics of Moscow State University, Moscow 119899

Abstract

Peculiarity of high current FEL with a collective regime of electromagnetic wave excitation is considered. The start value of electron current in a FEL-Oscillator is estimated. Possibilities of such device creation on base MSU electron linear accelerator are discussed.

1 INTRODUCTION

In previous paper [1] it has been shown that a high current FEL (HCFEL) has a high coefficient of signal amplification, and this permits to extend the possibilities to create the coherent short-wave radiation sources. High signal amplification is a result of a collective interaction of an electron beam with an electromagnetic wave which is arisen due to the bunching of particles. The latter can be realised if the density of electron is sufficiency high. An intense beam acquires the properties of optical waveguide, and the electromagnetic radiation is concentrated in the beam volume. Therefore a high current regime can be realised in FEL having a moderate current but low emmitances of particles that is peculiar for an electron accelerators of new generation.

Present paper has two goals. It is of interest how are the properties of HCFEL revealed in a scheme of FEL oscillator? And can we have here any application of this scheme of the MSU electron accelerators?

2 START CONDITION IN HIGH CURRENT FEL OSCILLATOR

Consider a traditional scheme of a charged beam generator. A system constructed along the axis **z** consists of undulator with a period λ_0 and length L_{und} which is located between two mirrors. The mirrors separated by distance $\mathbf{L_m}$ ($\mathbf{L_m} > \mathbf{L_{und}}$) are forming an open resonator. Along the axis **z** in a point **z'** placed before the undulator a continuous beam of monoenergetic electrons is being injected into the system (by means of supplementary magnet system). The electron energy is $E = mc^2\gamma_L$ where γ_L is Lorenz's factor , the initial electron velocity is $v_0 = \beta_0 c$. Passing trough the undulator the electrons acquire a transversal velocity $v_\perp = \beta_\perp c$ that permits them to interact with an optical (i.e. transversal) wave. After passage the undulator the electron beam is being deflected from the system (by means of second supplementary magnets).

Analyse start condition of HCFEL oscillator. Let an initial signal of frequency ω be brought in the system. The signal passing through the undulator can be amplified by an electron beam and then being partly irradiated and reflected from the mirrors returns to the initial point. Usually a start condition of FEL oscillator is estimated from one if the amplification of circling signal begins surpass its total absorption. But the HCFEL has its important peculiarities.

An electron beam in the undulator is an electromagnetic medium in which some transversal waves of different modes can propagate in both directions. An initial signal is distributed among the co-travelling with beam waves some of which can interact with the electrons. Its interaction becomes resonant if the double conditions are carried out:

$$\omega = kc\,;\; k = k_0\beta_{0Z}/(1-\beta_{0Z}) \tag{1}$$

where k is a wave vector, $k_0 = 2\pi/\lambda_0$,

$$\beta_{0Z} = (\beta_0^2 - \beta_\perp^2)^{1/2}.$$

Practically one can consider only the mostly amplified wave among the co-travelling ones after passing the undulator and only one back travelling wave because an electron beam do not disturb the electromagnetic oscillations in last case.

Hence the final balance of amplification and absorption in system gives the nest condition of reliable generation start (see [2] too):

$$R_1R_2\exp\left(i\int_0^{L_m}(k^+ - k^-)dz\right) = 1 \tag{2}$$

where $R_{1,2}$ are the coefficients of wave amplitudes reflection from the first and second mirrors respectively (value of R_2 includes the loss of signal due to its irradiation), k^+ and k^- are the wave vectors of forward and back directions for given frequency and mode. Here we take into account that the waves coming in and out from an electron beam are almost not reflected. Outside electron beam

$$k^+ = k = \frac{\omega}{c}\,,\; k^- = -\frac{\omega}{c} \tag{3}$$

and inside one

$$k^+ = k + \delta k^+;\quad |\delta k| << k \tag{4}$$

Hence the equation (2) is reduced to

$$2kL_m + \delta k^+ L_{und} = 2\pi M + i\ln|R_1R_2| \tag{5}$$

where $M = S - \arg(R_1R_2)/2\pi$, S is an integer.

Separating the real and imaginary parts of (4) one can write

$$2kL_m+\mathrm{Re}(\delta k^+)L_{und}=2\pi M \qquad (6)$$
$$\mathrm{Im}(\delta k^+)L_{und}= -\ln|R_1R_2|$$

This equation is written for a given value of frequency. And the first equation in (6) determines conditions when the wave excitation of given mode is possible in beam system. But already after the first wave circulation, the excitation of electromagnetic oscillations in mirror resonator go to play the important role. Therefore it is necessary to add the condition of wave excitation in FEL resonator with the same value of frequency. Such condition produces a relation [3]

$$2kL_m=2\pi(N+(n+q+1)/2+\Delta) \qquad (7)$$

where N, n, q are the integers, Δ is a mode shift determined by resonator parameters.

The second equation in (6) determines the start condition for the electron beam current I_b. Really according with a solution of beam linear system the increment of wave excitation $\mathrm{Im}(\delta k^+)=-A\,I_b^{\alpha}$ (see below). Due to this the second condition in (6) drives to the direct dependence of start value of I_b on $R_{1,2}$, A, α ones:

$$I_{b_{st}} = \left(\frac{\ln\left|R_1R_2\right|^{-1}}{AL_{und}}\right)^{1/\alpha} \qquad (8)$$

The magnitude of $\alpha \approx 1/3 - 2/5$ for a wide and compressed beam respectively [1]. For the latter case

$$A = k_0\left(\frac{4}{ka_bI_A}\right)^{\alpha} \qquad (9)$$

where I_A= 17 kA, and $k = k_0\gamma^2_0$.

The value of $R_2 = (1 - \varepsilon)^{1/2}$ where factor $\varepsilon << 1$ including the fraction of electromagnetic flow irradiated through the second mirror.

To determine the value of R_1 it is necessary to take into analysis the fact of strong channelling of electromagnetic radiation in the beam volume. As a result the cross-section of electromagnetic flow becomes comparable with of beam one. The electromagnetic flow reflected from the second mirror returns to the first one and then to the undulator expanding due to a diffraction. As a result the fraction of electromagnetic flow returned in the beam volume is reduced to [4]

$$F = \left(\frac{a_ba_Ek}{2L_d}\right)^2 \qquad (10)$$

where $a_{b,E}$ are the radius of beam and electromagnetic flow canalized in it, $L_d = 2L_m - L_{und}$. Finally

$$R_1 = F^{1/2} / N^+ \qquad (11)$$

where N^+ is the number of forward travelling waves (usually N^+ = 2-3 [1,2]).

On the whole the collective regime indicates in FEL a relatively weak dependence of start current value on the resonator parameters.

3 FEL OSCILLATOR ON BASE OF MSU ELECTRON ACCELERATORS

In present time in Institute of Nuclear Physics of MSU there are two continuous wave electron accelerators with the particle energy of 1.2-2.3 and 6.6 MeV respectively. The first device is designed for different nuclear and applied studies and has the average current magnitude up to 10-30 mA. The electron beam has small emittances.

The values of γ_0 = 3.4 - 5.6 permit to use this accelerator for producing the electromagnetic radiation in a millimetre and submillimetre range what opens a very important applications in biology and so on. Estimate the start current value.

Let the system and beam parameters be the next: γ_0= 2 cm, L_m= $2L_{und}$, a_b = 0.1 cm, a_E = 2-3 a_b In this case the value of $I_{b\,st} \approx$ 30 mA is been reached only with $L_{und}\approx$200 cm and $\geq$ 250 cm for the electron energies 1.2 and 2.3 MeV respectively. Thus this accelerator can be used as FEL oscillator though for its reliable operation it is necessary to rise the current amplitude at several times.

The current in the second accelerator do not surpass 100 mkA. And in spite of excellent quality of electron beam this accelerator can be used only as FEL amplifier (in a special regime considered in [1]).

REFERENCES

[1] V.K.Grishin, B.S.Ishkhanov. T.A.Novicova, V.I.Shvedunov, FREE ELECTRON LASER - FEL -STUDY IN INSTITUTE OF NUCLEAR PHYSICS OF MSU, Proceeding of the Particle Accelerator Conference, Dallas, v.1, p.225.

[2] N.C.Erokhin, M.V.Kusilev, S.S.Moiseev e al., Neravnovesnye processy in plasmennoi radiophysike, Nauka Press, Moskva, 1982.

[3] O.Zvelto, Principles of Lasers, Plenum Press, New York.

[4] L.D.Landau, E.M.Lifshits, Theory of Field, § 61, Nauka Press, Moskva.