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An optical cavity design for a compact wave-undulator based-FEL

A. Curcio [a,b,*], G. Dattoli [c], M. Ferrario [a], D. Giulietti [d], F. Nguyen [c]

[a] INFN-LNF, via Enrico Fermi 40, 00044 Frascati (Rome), Italy
[b] Department of Physics, "Sapienza" University of Rome, Piazzale A. Moro 2, I-00185 Rome, Italy
[c] ENEA, via Enrico Fermi 40, 00044 Frascati (Rome), Italy
[d] Physics Department of the University and INFN, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy

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ABSTRACT

We have considered a novel scheme of wave undulator FEL. The system employs a recirculated radiation pulse serving as undulator provided by a high power laser. Non conventional electron acceleration schemes promise nowadays high gradient acceleration yielding the GeV on the scale of few centimeters, however these solutions might solve the problem of the accelerator length, but not that associated with the saturation length and thus of the length of the undulator, which remains on the order of tens of meters. The option of wave-undulator based FEL might provide a valid solution in the future.

1. Introduction

Free Electron Laser (FEL) devices are reliable experimental tools, which have been successfully operated in different regions of the electromagnetic spectrum, under different conditions. An increasing attention is being devoted to the possibility of realizing FEL facilities in the VUV- X region without the use of large accelerators and long undulator sections. The use of non conventional electron schemes, like laser plasma based techniques [1,2] promises high gradient acceleration providing the GeV on the scale of few centimeters. Anyway this solution might solve the problem of the accelerator length, but not that associated with the saturation length and thus of the length of the undulator, which remains on the order of tens of meters. The option of wave-undulator based FEL might provide a tailor suited solution [3–12]. In this scheme the undulator is replaced by a laser wave (CO_2, Ti:Sa), therefore the associated period is extremely short and consequently the saturation length is also strongly reduced with respect to that of conventional undulator magnet FELs. Just to give some reference numbers, the length of the period of a static magnetic undulator λ_u is few centimeters, that of a CO_2 wave undulator λ_0 is almost 10^{-4} shorter, therefore we expect that the associated saturation length undergoes an analogous reduction. The further advantage is that the electron beam energy necessary to reach the short wavelength region scales as $\gamma_e \propto (\lambda_0/\lambda_u)^{1/2}$, so in this case the required beam energy can be reduced by a factor 100. This means that the accelerator size can be reduced too. In order to achieve sufficient gain in such scheme, a large wave undulator strength K is required and thus a significant amount of laser power should be handled. As it is well known [13] to reach $K \simeq 1$ values, lasers with intensities larger than 10^{18} W/cm^2 are required. In a previous paper [11] the conditions for a wave undulator FEL operation have been studied, in terms of beam current, beam qualities and laser power but not too much attention has been paid to the laser beam transport. In this paper we propose a compact VUV-X FEL device consisting of a low energy LINAC and a ring cavity to confine and recirculate the wave undulator, which is then exploited for multiple interactions with the e-beam. The device we propose is reported in Fig. 1, which displays a cavity whose length is adjusted on the distance separating two successive electron bunches. The FEL interaction is supposed to occur in the first section confined within two parabolic mirrors, the electron beam is then spent, while the laser is recirculated. The paper consists of four sections, in Section 2 we discuss the details of the cavity design. In Section 3 we define some operational parameters for our FEL scheme, clarifying the principles of working. In Section 4 we discuss the FEL interaction, the relevant performances and the feasibility of the entire system.

2. The optical cavity

The optical cavity [14] we consider here is a ring cavity composed by two plane mirrors, two parabolic mirrors and one focusing lens. The design is shown in Fig. 1.

This configuration is chosen in order to get two waists of the laser beam along the same straight line, which is also the line where

* Corresponding author at: INFN-LNF, via Enrico Fermi 40, 00044 Frascati (Rome), Italy.
E-mail address: alessandro.curcio@lnf.infn.it (A. Curcio).

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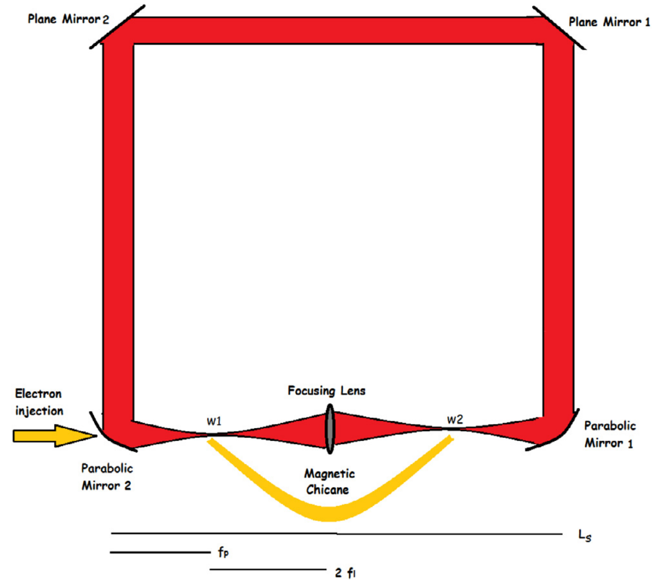

Fig. 1. The optical cavity design. The electron beam is injected from the left, while the laser is clockwise circulating inside the ring. The device is conceived as a buncher-radiator: the electrons first interact at the waist w_1, where they undergo microbunching, then they interact at the waist w_2 where they emit coherent radiation .

an electron beam is thought to be counter-propagating injected. The electron beam interacts at the first laser waist section, acting as a buncher, the region of the second waist provides the radiator, where the FEL emission occurs. The length of the cavity is L_c and it is a square of side $L_s = L_c/4$. The focusing lens is positioned in the middle between the two parabolic mirrors at a distance $L_c/8$ from each. Being f_p the focal length of both the parabolic mirrors and f_l the focal length of the focusing lens, the relative distance between one waist and the focusing lens is $d = 2f_l$ and the following equation must hold $L_s = 2f_p + 4f_l$, as shown in Fig. 1. The electron beam, passing through the magnetic chicane after the first interaction, travels for a time interval T_{mc} before reaching the second interaction point. This time has to be synchronized to the laser pulse in such a way that the two beams can "meet" at the waist w_2 (see Fig. 1), in formulas we get $cT_{mc} = 2f_p + 3L_s$, where c is the velocity of light in vacuum. Assuming a gaussian mode TEM_{00} circulating inside the optical cavity we can relate the beam waist w_0 to the focal length f_p. In fact when the radiation has traveled a distance f_p from the waist to the parabolic mirror, it assumes the same curvature radius $R_p = 2f_p$ of the latter, in formulas:

$$R_p = 2f_p = f_p\left(1 + \frac{\pi^2 w_0^4}{\lambda_0^2 f_p^2}\right) \tag{1}$$

from which the laser beam waist w_0 (in the case of negligible diffraction) is found:

$$w_0 = \sqrt{\frac{\lambda_0 f_p}{\pi}} \tag{2}$$

where λ_0 is the laser wavelength. The photon lifetime inside the cavity is given by:

$$\tau_c = \frac{2L_c}{c\Gamma} \tag{3}$$

where Γ is known as the logarithmic cavity loss, whose expression, relative to the design of Fig. 1, is [14]:

$$\Gamma = \log\left[\frac{1}{R_1 R_2 R_3 R_4 (1 - T_i)}\right] \tag{4}$$

where R_1, R_3 are the power reflectivities of the first and second plane mirror respectively, R_2, R_4 are the power reflectivities of the first and second parabolic mirror respectively and T_i is a factor which takes into account of all internal losses, which are mainly determined by diffraction, by the absorption of the focusing lens and by the interaction with the electrons at the waists. The quality factor of the cavity accounts for the ratio of the energy stored to the energy lost in one electromagnetic cycle, and it is given by:

$$Q = 2\pi \frac{c\tau_c}{\lambda_0}. \tag{5}$$

A high quality factor implies low losses in the cavity, which is important for a device to be operated for long time at relatively high repetition rate. The quantity $\Delta\nu_0 = 1/2\pi\tau_c$ is the laser line width inside the resonator, which is another important parameter to be carefully considered. The strength parameter for such an electromagnetic undulator is defined:

$$a_0 = \frac{\lambda_0 e E_p}{2\pi mc^2} \tag{6}$$

where E_p is the peak electric field of the laser, related to the laser intensity at the waist as:

$$E_p = \sqrt{2Z_0 I_p}. \tag{7}$$

Z_0 is the vacuum impedance and I_p is the laser peak intensity calculated as:

$$I_p = \frac{P_L}{\pi w_0^2} = \frac{P_L}{\lambda_0 f_p} \tag{8}$$

where P_L is the laser peak power inside the cavity. Therefore we can give an expression for the strength parameter related to the characteristics proper of the laser and the cavity:

$$a_0 = \frac{e}{mc^2}\sqrt{Z_0 \frac{\lambda_0 P_L}{2\pi^2 f_p}}. \tag{9}$$

The resonator matrix for a round trip will be the matrix product of the matrices describing the free propagation along one side L_s of the resonator, the focusing through the first parabolic mirror, the free space propagation along a distance $2f_l + f_p$, the focusing of the lens, the free space propagation again for a distance $2f_l + f_p$, the focusing of the second parabolic mirror and the free space propagation along a path $2L_s$ long. We highlight the fact that in such a symmetric scheme the resonator is so-called marginally stable because the stability condition [14]

$$-1 < \frac{A + D}{2} < 1 \tag{10}$$

where A and D are the diagonal elements of the resonator matrix, is not perfectly satisfied, in fact it can be shown that in our case $(A + D)/2 = 1$.

3. FEL scheme

The strength parameter,associated with a wave undulator of intensity I_p and wavelength λ_0, in practical units reads as

$$K = a_0 = 0.85 \times 10^{-5} \lambda_0[m]\sqrt{I_p(W/m^2)}. \tag{11}$$

A CO_2 laser ($\lambda_0 = 10.6$ μm), with an intensity $I_p = 4.2 \times 10^{18}$ W/m^2, corresponding to an energy per pulse of 40 J delivered in 300 ps ($P_L = 130$ GW) over an effective area $\Sigma = \pi w_0^2 \sim \pi \times 10^{-8}\ m^2$ would be enough to provide a wave undulator with sufficiently large K to support the FEL SASE operation [15–17]. The value of the radius w_0 we choose is around 100 μm, nevertheless by referring to Eq. (2), and considering a reasonable value for $f_p \sim 1$ m, it should be much greater, i.e. $w_0 \sim 1.8$ mm. The laser intensity corresponding to a $w_0 = 1.8$ mm would be not enough to ensure reasonable operational conditions for the wave undulator.

Therefore a little modification to the design of the cavity is needed in proximity of the interaction points (Fig. 2). Two symmetric couples of short focal length positive lenses satisfying the condition $f_i \ll f_p$ have to be put in correspondence of the two interaction points. In