Laser Powered Beam Conditioner for Free-Electron Lasers and Synchrotrons*

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Abstract

A new method of using an additional laser for electron beam conditioning in free-electron lasers (FELs) and synchrotrons is proposed. Theoretical analysis and calculations are presented, showing that the axial energy spread of electrons due to their betatron motion in undulators can be dramatically reduced by interacting with a quasi-TEM_{10} Gaussian mode optical beam. It is required that the electrons be pre-bunched over half an optical cycle in advance.

I. INTRODUCTION

As is well known, *emittance* of an electron beam is one of several major limitations to the performance of free-electron lasers (FELs) and synchrotrons. It causes an axial velocity spread owing to the electrons' betatron motion in undulators. This axial energy spread severely affects the interaction between electrons and optical waves in the form of phase spreading in FELs or degradation of the spectral purity of radiation in the form of non-homogeneous broadening in synchrotrons. Therefore, *beam conditioning* using rf standing waves or traveling waves has been proposed as an attempt to reduce this axial velocity spread for improving the performance of coherent radiation sources [1,2].

In this paper, we propose another new method of beam conditioning using a conventional laser as the conditioning power for the first time. It is of significance to explore the new features and possibilities that a laser powered beam conditioner can provide especially for ultraviolet and x-ray coherent radiation, since a difference of several orders of magnitude in frequency exists from microwave to optical waves. This tremendous difference may result in new features and alter scaling relationships.

Before describing and analyzing the laser powered beam conditioner, the idea is placed in context with previous research in three different areas: the research of Sessler, et al. [1] which uses a set of cavities operating in the TM_{210} mode before the undulator, of Sprangle, et al. [2] which uses a slow TM waveguide mode internal to the undulator, and a new scheme of emittance compensation for FELs using a conventional laser the authors are pursuing [3,4]. The possibility of conditioning an electron beam using the axial electrical component of a TEM_{10} mode Gaussian beam *in vacuum* occured when we noticed that such an axial electrical component has been considered for laser acceleration [5,6]. The basic argument is that if the axial component works for laser acceleration, it may work easily for beam conditioning, since in the latter case, much smaller energy exchange is needed.

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II. CONDITIONING MECHANISM

First, let us examine the axial velocity spread introduced when an electron moves through a common magnetostatic undulator. We assume that the undulator is linearly polarized in the y (vertical) direction and provides a natural focusing. In this case, in the absence of external focusing, the normalized mean axial velocity of an electron, averaged over one undulator period, is

$$\beta_z = 1 - \frac{1}{2\gamma^2}(1 + a_u^2) - \frac{1}{2}(k_\beta^2 y_0^2 + \theta_{x0}^2 + \theta_{y0}^2), \qquad (1)$$

where γ is the relativistic energy factor of the electron, $a_u = |e|B_0/\sqrt{2}mck_u$ is the rms undulator strength parameter in mks units, e is the charge of an electron, m is the rest mass of an electron, c is the speed of light, B_0 is the peak magnetic field of the undulator, $k_u = 2\pi/\lambda_u$, λ_u is the undulator period, $k_\beta = 2\pi/\lambda_\beta = a_u k_u/\gamma$ is the betatron wavenumber, and y_0, θ_{x0} and θ_{y0} are the initial conditions of the electron's position and divergence angles, respectively. The beam conditioning is made possible due to the fact that, as has been noted in Ref. [7], this axial velocity depends only on the initial conditions for each individual orbit and is constant along any given betatron orbit. Therefore, we conclude that the ideal case is to condition an electron beam at the beginning part of an undulator so that the benefit of conditioning can be fully utilized during the remaining greater part of the undulator.

Next, we discuss the axial electrical field component of a Gaussian mode laser beam *in vacuum*. It is clear that there is no longitudinal field components as far as an infinite plane electromagnetic wave is concerned. As has been proved theoretically and experimentally [8,9], however, axial field components do exist when there is a transverse gradient associated with the transverse field components. Based on such a fact, the axial electrical field component associated with a TEM_{10} mode Gaussian beam in vacuum was proposed for laser acceleration [5]. Here we turn this axial electrical field component for beam conditioning by using its transverse gradient.

Assuming that a Gaussian beam in a TEM_{10} mode, or quasi-TEM_{10} mode, as suggested in Ref. [5], is linearly polarized in the y direction, we can write its electrical and magnetic field components to first order in θ_d in mks units as follows

$$E_y = E_0(\frac{w_0}{w})(\frac{\sqrt{2}y}{w})e^{-\rho^2/w^2}\cos\psi, \quad (2.1)$$

$$B_x = -E_y/c, \quad (2.2)$$

$$E_z = \frac{E_0\theta_d}{\sqrt{2}}(\frac{w_0}{w})^2 e^{-\rho^2/w^2}[(1-\frac{2y^2}{w^2})^2 + s^2]^{1/2}\sin(\psi+\theta), \quad (2.3)$$

where E_0 is the electrical field amplitude, w_0 is the minimum optical beam spot size defined by $\pi w_0^2 = \lambda Z_R$, λ is the optical wavelength, Z_R is the Rayleigh range, $w(s) = w_0(1+s^2)^{1/2}$ is the beam radius at a longitudinal position z normalized to $s = z/Z_R$, $\rho = \sqrt{x^2+y^2}$, $\theta_d = w_0/Z_R$ is the diffraction angle, and ψ and θ are defined as follows

$$\psi = \omega t - kz + 2\arctan(s) - s(\frac{\rho^2}{w^2}), \quad (2.4)$$

$$\theta = \arctan(\frac{sw^2}{2y^2 - w^2}), \quad (2.5)$$

where ω is the angular optical frequency, and $k = 2\pi/\lambda$ is the optical wavenumber. The longitudinal magnetic field component, B_z, is neglected for its trivial effect on the transverse particle dynamics. The third term on the right-hand side of Eq. (2.4) represents the so-called Guoy phase shift associated with the TEM_{10} Gaussian mode [10]. The variable θ is an additional phase shift introduced into the axial electrical field component, resulting from the transverse variation of both amplitude and phase front of the transverse electrical field component.

As can be seen from Eqs. (2.3) and (2.5), there exists a turning point vertically around which the axial electrical field vector reverses its direction. This provides a mechanism for accelerating and decelerating electrons according to their betatron amplitude. By further examing the expression for the axial electrical field component, it can be found that the optimum conditioning is reached when the condition $y \simeq w$ is fulfilled. This indicates that the electron beam should possess about the same size as the conditioning laser beam does.

In general, an electron can never be steadily accelerated or decelerated along its propagation with the conditioning wave. Instead, it will experience an oscillatory process of being accelerated and decelerated, and there will be no net energy exchange between the electron and the conditioning wave. However, if we have the beam waist of the conditioning wave located around the entrance of an undulator longitudinally, there will be a net energy exchange between the electron and the conditioning wave owing to the natural divergence of a Gaussian beam.

III. NUMERICAL CALCULATIONS

The impact of the laser powered beam conditioner is demonstrated by computer simulation with two numerical examples. In the first example, a CO_2 laser is used. The energy and the 4σ normalized emittance of the beam are 101.7 MeV and 26 π mm mrad, respectively. The undulator period is arbitrarily chosen to be 2 cm, and the peak magnetic field strength is 7.57 kG, corresponding to a_u=1. The conditioning laser has the following parameters: wavelength λ=10.6 μm, Rayleigh range Z_R=6 cm, and field strength parameter a_c=0.01. The starting point where the interaction between the electrons and the conditioning laser begins is s_0=0, i.e., the laser beam waist is located exactly at the entrance to the undulator. The initial phase ψ_0=155°. With the above parameters, the fundamental undulator radiation wavelength is 0.5 μm. In the computer simulation 500 particles were used. As is shown in Fig. 1, the rms axial energy spread is reduced from 0.29% to 0.12% within a conditioning range of 12 cm or so, corresponding to a factor of 2.4 reduction of the axial energy spread.

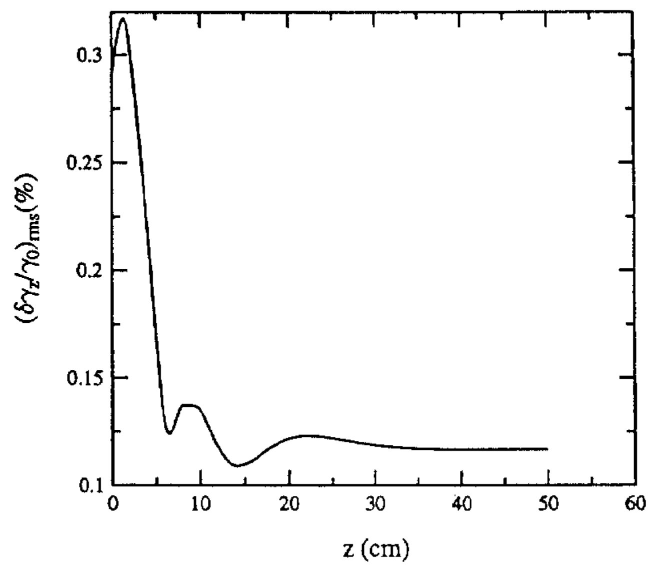

Fig.1 Variation of rms axial energy spread of an electron beam (101.7 MeV, ϵ_n=26 π mm mrad) along the beginning part of the undulator, conditioned with a CO_2 laser (λ=10.6 μm, Z_R=6 cm) for 0.5 μm radiation.

In the second example, a Neodymium glass laser is used as the conditioning source. The electron beam energy is raised to 320 MeV. The undulator period remains 2 cm. With a peak magnetic field strength of 6.6 kG, the fundamental undulator radiation wavelength is 0.045 μm. The parameters for the conditioning laser are: λ=1.06 μm, Z_R=20 cm, a_c=0.0035, and conditioning starting position s_0=0.1, i.e., the optical waist is 2 cm inside the undulator. The 4σ normalized beam emittance is 9 π mm mrad. The initial phase is ψ_0=150°. As is shown in Fig. 2, the beam is conditioned within a distance of about 42 cm inside the undulator, and the axial energy spread is reduced from 0.076% to 0.032%, a reduction by a factor of 2.4. Note that the conditioning length is about twice the Rayleigh range in both examples.

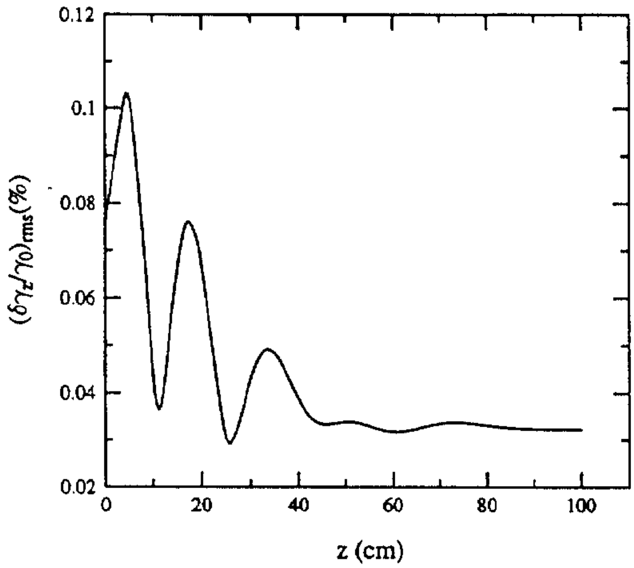

Fig.2 Variation of rms axial energy spread of an electron beam (320 MeV, ϵ_n=9 π mm mrad) along the beginning part of the undulator, conditioned with a Neodymium glass laser (λ=1.06 μm, Z_R=20 cm) for 0.045 μm radiation.

IV. DISCUSSIONS

One attractive feature of a laser powered beam conditioner is the relatively modest laser requirement. The optical power required for conditioning can be estimated according to the following formula [3]

$$P(\mathrm{GW}) = 3.4a_c^2 Z_R/\lambda. \tag{3}$$

For the CO_2 laser in the first example, the corresponding optical power is about 2 GW; for the Neodymium glass laser in the second example, the required optical power is about 8 GW. Both of them are readily achieved.

The laser powered beam conditioner may have some potential advantages. Among them are the elimination of rf structures, that may cause beam breakup instability as well as wakefields, and relatively less severe transverse kick effects due to the fact that the conditioning wave is diffraction limited.

Next, note that there are two kinds of sources of constraints on the beam emittance: one is the overlap requirement, the other is the synchronism requirement [11]. In general, the second constraint is more restrictive than the first one for long undulators, which is the case the "conditioning" is mainly for. In this case, it is advantageous to have the electrons well conditioned just within the very beginning part of an undulator so that the full benefit can be realized. Further, there is no possibility of beam degradation between the conditioner and undulator as would be the case for separate systems.

We found that the conditioning is dependent on the initial phase from one half optical cycle to the other. Therefore, it is required that the electrons be pre-bunched over half an optical cycle in advance. This pre-bunching can be realized at a lower electron beam energy using the identical laser wave [6] or using a segment of undulator as for an optical klystron [11]. The latter method has been experimentally verified. This may finally determine the easy implementation of the laser powered beam conditioner.

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