THZ PHOTO-INJECTOR FEM BASED ON SPONTANEOUS COHERENT EMISSION FROM A BUNCH OF NEGATIVE-MASS ELECTRONS*

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Abstract

It is proposed to utilize the effect of negative mass for stabilization of the effective axial size of very dense and short electron bunches produced by photo-injector guns by using combined undulator and strong uniform magnetic fields. It has been shown that in the "abnormal" regime, in which an increase in the electron energy leads to a decrease in the axial velocity of the electron, due to the negative-mass effect the Coulomb repulsion of electrons leads to their attraction and formation of a fairly stable and compact bunch "nucleus". The use of the negative-mass regime may provide realization of a source of the terahertz radiation, which is based on a long-pulse coherent spontaneous undulator emission from a short dense moderately-relativistic (5.5 MeV) photo-injector electron bunch with a high (up to 20%) efficiency and a narrow frequency spectrum.

INTRODUCTION

Laser-driven photo-injectors allow formation of fairly compact and accessible sources of dense electron bunches with a moderate energy of 3-6 MeV, sub-picosecond and picosecond pulse durations, and charges of up to 1 nC and greater. These bunches can be further accelerated up to the GeV energy level for the use in short-wavelength FELs or directly exploited for radiation in the THz frequency range. In the latter case, they can be used, in particular, for realization of comparatively simple and compact sources operating in the regime of spontaneous coherent undulator radiation of electrons [1-4]. This type of radiation is realized, when the effective axial length of bunches in the radiation section is shorter than the operating wavelengths. In this situation, the wave packets emitted by each of the electrons add up basically in phase; this provides high level of radiation power.

Evidently, the length of the operating region is strictly limited by the Coulomb particle repulsion leading to an increase in bunch sizes and, first of all, in the axial size of the bunch. In this letter, we propose a method of weakening the axial repulsion significantly and, simultaneously, of confining particles in the transverse direction by means of using the radiation of electrons in combined undulator and strong uniform guiding magnetic fields. The corresponding effect is similar to the Negative Mass Instability which is well-known in cyclic accelerators [5,6] and Cyclotron Resonance Masers [7-9]. In the combined field, the negative-mass effect can occur when the electron cyclotron frequency corresponding to the guiding magnetic field exceeds the bounce frequency of electron oscillations in the periodic undulator field. In such "abnormal" regime, an increase in the energy of the particle leads to a decrease in its axial velocity [10-13] and axial Coulomb repulsion of the electrons leads to their effective mutual attraction which slows down bunch degradation. The use of this regime can result in a substantial increase in the effective length of the coherent spontaneous emission, and, therefore, an increase in the power and narrowing of the spectrum of the output radiation pulse.

In this letter, we study a possibility to realize a powerful and very efficient source of long-pulse coherent radiation of the terahertz frequency range on the basis of the Israeli THz Source [3] as an example of the proposed approach. This THz source is based on the using coherent spontaneous undulator emission from a short dense photo-injector electron bunch with moderate energy (5.5 MeV). The stabilization of the axial size of the bunch (which is required to provide the coherent character of the radiation) is due to the negative-mass regime of the motion of the bunch through a long operating undulator. An undulator with a strong uniform magnetic field providing the negative-mass effect is proposed and designed for this experiment [14].

NEGATIVE-MASS EFFECT

For demonstration of the negative-mass effect, let us first recall the known properties of the electron motion in a helical undulator with period $\boldsymbol{d_u}$ and a homogeneous axial magnetic field $\boldsymbol{B_0}$ (Fig. 1a) within the approximation of negligible transverse inhomogeneity of the undulator field as well as the perturbations caused by the Coulomb and radiated fields [10-12]. The normalized oscillatory (transverse) electron momentum obeys the equation:

$$p_\perp = K / \Delta ,$$

where K is the undulator parameter in the absence of the guiding field, $B_0 = 0$, and $\Delta = 1 - \Omega_c/\Omega_u$ is the mismatch between the relativistic electron cyclotron frequency $\Omega_c = eB_0/mc\gamma$ and the undulator (bounce) frequency $\Omega_u = h_u V_z$. The dependence of the transverse electron velocity on the cyclotron frequency has a resonance character (Fig. 1b); $V_\perp(\Omega_c)$ is an increasing function at low axial magnetic fields ($\Omega_c < \Omega_u$) and a decreasing function at high magnetic fields ($\Omega_c > \Omega_u$).

The Coulomb interaction leads to an increase in the energies of the particles placed in the bunch front and to decrease in the energies of the electrons being in the tail. The type (positive/negative mass) of the Coulomb interaction is determined by the dependence of the axial

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*Work partially supported by the Russian Scientific Foundation (Project 14-19-01723).

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ISBN 978-3-95450-134-2

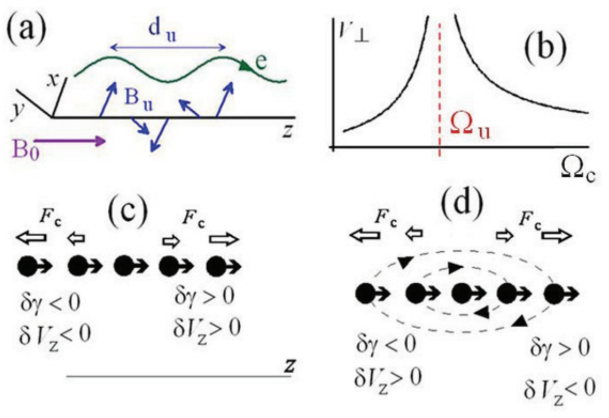

Figure 1: (a) Electron motion in the combined helical undulator and uniform axial fields. (b) Characteristic dependence of the transverse electron velocity on the cyclotron frequency. (c) Coulomb repulsion in the “positive-mass” regime. (d) Coulomb attraction and oscillations of electrons in the “negative-mass” regime.

velocity on the energy (relativistic mass-factor, γ):

$$\mu = \frac{dV_z}{d\gamma} = \frac{c}{\gamma^3}\left(1 + \frac{K^2}{\Delta^3}\right).$$

In the normal, “positive-mass” regime, $\mu>0$. In this case, the Coulomb interaction results in repulsion of the particles (Fig. 1c) and, therefore, in degradation of the bunch. However, it is possible to provide the “negative-mass” regime, when the axial electron velocity decreases with an increase in the energy, $\mu<0$. Actually, if the cyclotron frequency exceeds the undulator frequency, and the mismatch Δ is small enough,

$$\Delta < 0 \text{ and } |\Delta|^3 < K^2,$$

then an increase in the energy of a particle shifts this particle closer to the cyclotron-undulator resonance $\Omega_c = \Omega_u$. This results in an increase in the particle transverse momentum. Moreover, in the vicinity of the resonance, the transverse momentum may increase so fast, that it can lead to a decrease in the axial velocity, so that the negative-mass condition is fulfilled. In the “negative-mass” regime the Coulomb interaction leads to oscillations of particles around the "nucleus" of the bunch (Fig. 1d). This effect can be utilized in a straightforward way for stabilization of the dense electron bunch moving through a relatively long undulator.

NUMERICAL SIMULATIONS

The proposed regime has been studied on the basis of the original 3D numerical code using the exact relativistic formulas for Liénard–Wiechert potentials. We have studied the motion of the electron bunch with the parameters close to those discussed for the Israeli THz Source [3]: an initial charge of 0.3 nC, a length of 0.1 mm, diameter 1 mm, and the Lorentz-factor γ =12 in the helical undulator with a period of 2.5 cm and the undulator parameter K=0.45. In this case, the resonance magnitude of the guiding magnetic field is close to 5 T. When the axial magnetic field is high enough ($B_0 = 7 - 9\,T$), the dependencies of the transverse momentum and axial velocity of a particle on its Lorentz-factor (Fig. 2) indicate the possibility of the negative-mass regime. To ensure accurate pumping of the electron undulator oscillations, a smooth entrance into the undulator with gradually increasing amplitude of the transverse field was provided at the first 5 periods. The typical number of large particles in simulations was of the order of 10^3.

From the simulation results it can be clearly seen that the speed of bunch degradation decreases substantially, when the guiding field exceeds the resonant value (Fig. 3). Moreover, despite the rms length of the bunch increases in all regimes, in the negative-mass regime ($\mu < 0$) the main part of the bunch stays concentrated within a fairly small nucleus comparable with the initial volume.

Existence of a nucleus in the bunch allows efficient coherent spontaneous undulator radiation as soon as the length of this nucleus is less than the radiation wavelength. Figure 4 illustrates intensity and spectra of the forward radiation of the bunch in the far-field zone. In the positive-mass regimes ($B_0 < 5\,T$) the coherent spontaneous emission is provided during the bunch motion through several undulator periods; then, it is stopped due to the Coulomb repulsion. In contrast, in regimes of the negative-mass stabilization ($B_0 > 5\,T$), the coherent spontaneous emission is provided at the undulator length of about 1 m (40 undulator periods).

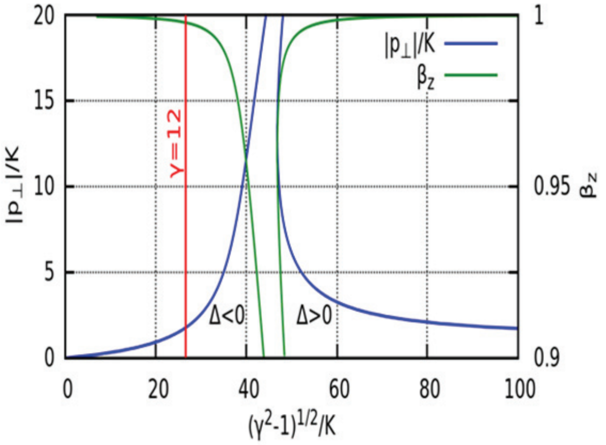

Figure 2: Dependency of the transverse momentum and axial electron velocity on the Lorentz-factor, γ. Vertical line marks the point corresponding to $\gamma = 12$.

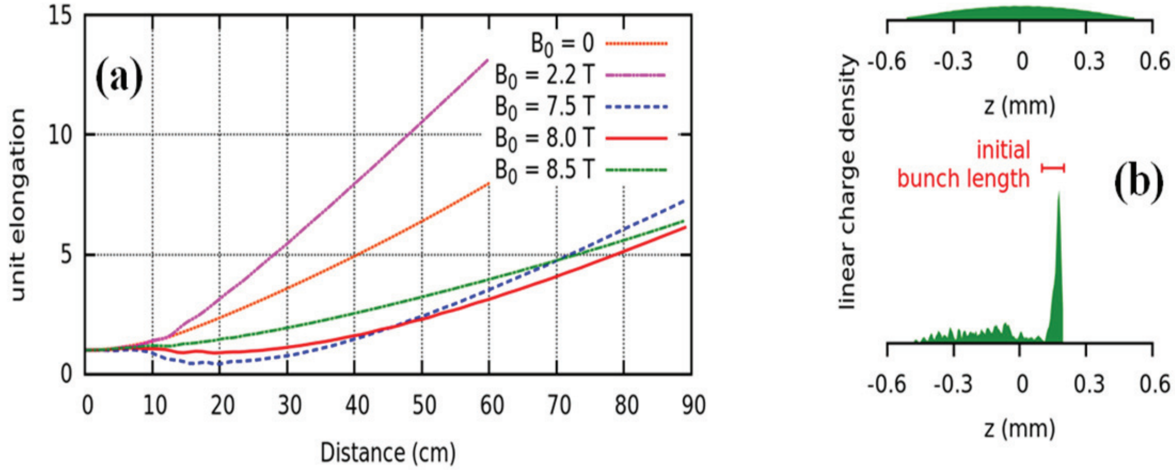

Figure 3: (a): Dependency of the rms unit elongation of the bunch l/l_0 on the trip distance in various regimes. (b): Comparison of the initial bunch with one after a 60 cm trip at $B_0 = 0$, and with the bunch after a 90 cm trip in the regime of negative-mass stabilization.

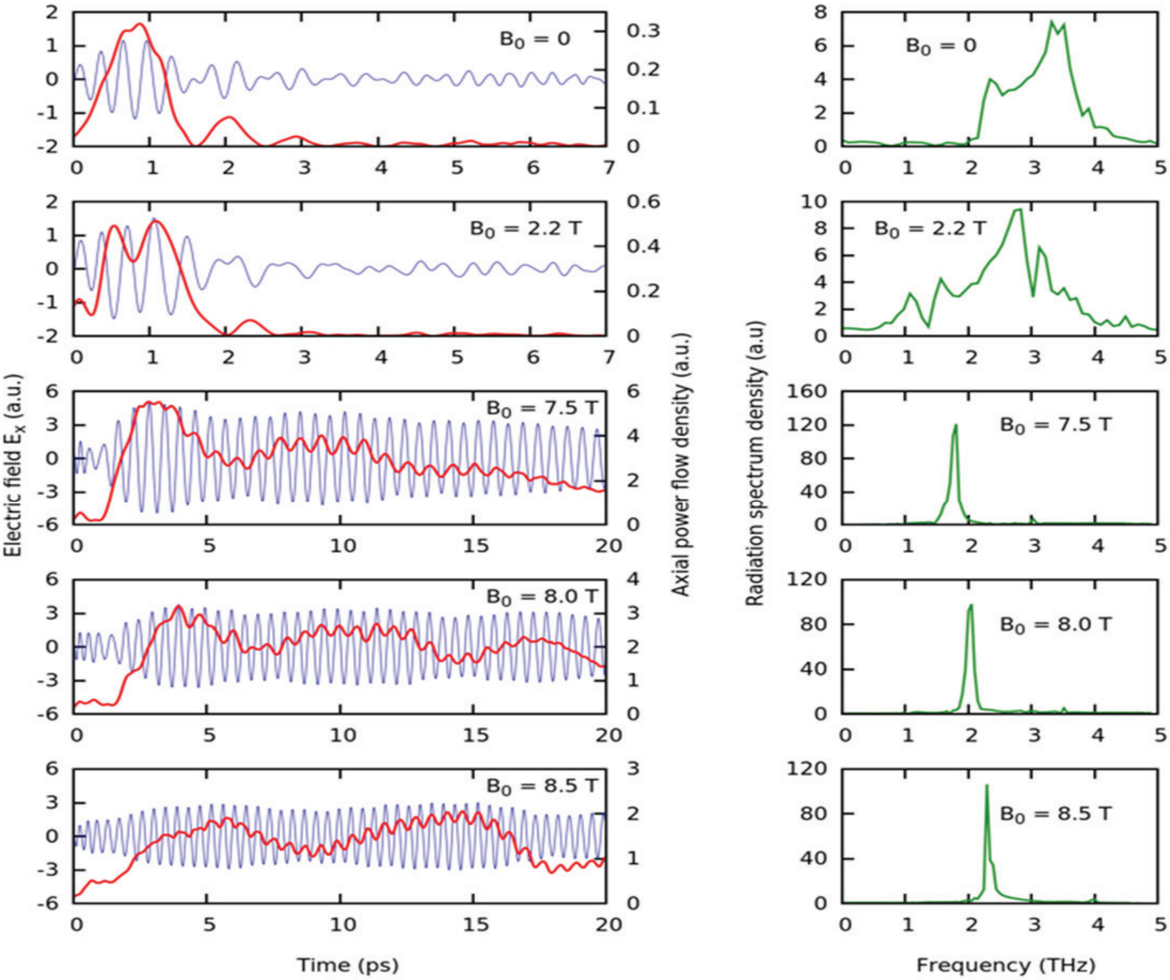

Figure 4: Forward radiation of the bunch in the far-field zone: x-component of electric field (thin blue curves) and axial power flow density (thick red curves) on the left, as well as the field spectrum density on the right.

ISBN 978-3-95450-134-2

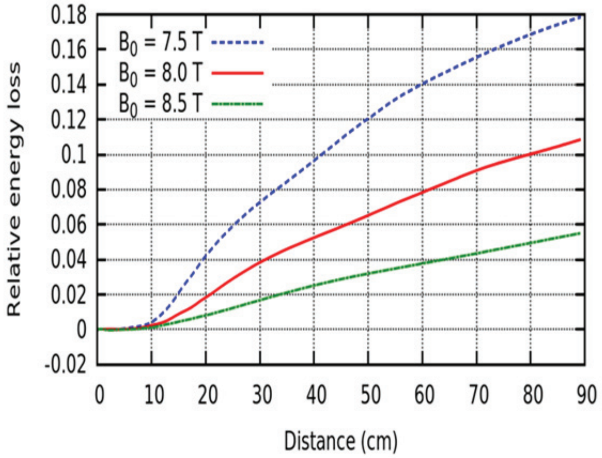

Figure 5: Energy losses of the electron bunch versus the axial position of the bunch in the negative-mass regimes.

The negative-mass effect leads to a significant enhancement in both the power and the duration of the radiated pulse, whereas the radiation frequency is lower than in the regime with the zero guiding field. The latter is due to a smaller Doppler upshift caused by the greater transverse and smaller axial electron velocities. According to simulations, the total bunch energy loss after of approximately 1 meter trip in the negative-mass regime can amount to 18% (Fig. 5). This corresponds to an average power of the order of 10 MW in the 20 ps forward-radiated THz pulse.

A large value of the uniform magnetic field that is required for realization of the negative-mass regime can be used to easily obtaining the required helical undulator field. It can be done, for example, by means of insertion of periodic conducting or magnetic structures into the solenoid creating the guiding magnetic field. In these cases, the undulator field is obtained due to excitation of eddy currents inside the conductors and due to magnetization of magnetics and redistribution of a uniform magnetic field, respectively. In particular, simple copper or iron helices can be placed inside a pulsed solenoid for obtaining a helical undulator field. For example, an iron helix with a period of 2.5 cm and an inner diameter of 10 mm wound of a wire with a radius of 3 mm and mounted into the solenoid with a uniform field of 8 T, provides the undulator parameter K=0.45 [14].

CONCLUSION

The simulations presented in this work confirm that realization of effective negative-mass stabilization of a short electron bunch is possible. They predict stability of the electron bunch during a 1 meter trip along the undulator (in contrast to ~10 cm in the positive-mass regime realized at low axial magnetic fields).

Using such a regime can provide significant power enhancement, a very high electron efficiency (up to 20%), and a significant spectrum narrowing for a radiation source, which operates at the frequencies ranging from 1 to 3 THz and is based on the spontaneous coherent undulator radiation from a short (0.1 mm) dense (0.3 nC) electron bunch with moderate energy (5.5 MeV).

Evidently, the proposed method could be also useful to provide the bunch stabilization in free-electron lasers, which are based on the stimulated undulator radiation.

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