THz Photo-Injector FEM with the Negative-Mass Bunch Stabilization

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***Abstract*—The characteristics of spontaneous coherent undulator radiation of a short electron bunch can be essentially improved in the presence of guiding magnetic field. In proper regime, the axial Coulomb repulsion of the electrons leads to their mutual attraction, which slows down bunch degradation and increases the radiated energy.**

I. Introduction

LASER-driven photo-injectors allow formation of fairly compact and accessible sources of dense electron bunches with moderate energy of 3–6 MeV, sub-picosecond and picosecond pulse duration and charge of up to 1 nC and larger. These bunches can be further accelerated up to GeV energy level for the use in short-wavelength FELs or directly exploited for radiation in THz frequency range [1], [2]. In the latter case they can be in particular used for realization of a comparatively simple and compact sources operating in the regime of spontaneous coherent radiation of electrons. Evidently, in this regime the length of the operating region is strictly limited by the Coulomb particle repulsion leading to an increase in bunch size. We propose the method of significant weakening of the electron axial repulsion in the combined undulator and strong uniform guiding magnetic fields. The corresponding effect is similar to the Negative Mass Instability (NMI) which is well-known for cyclic accelerators [3], [4] and Cyclotron Resonance Masers [5], [6]. 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 this "abnormal" regime [7]–[9], an increase in the particle energy leads to a decrease in its axial velocity, 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, in an increase in the power and narrowing of the spectrum of the output radiation pulse.

II. Mechanism of electrons attraction

Let us consider the electron moving in the infinite magnetostatic field of a helical undulator with period d and an axial guiding magnetic field B_0 along the stationary trajectory. It is easy to show that the normalized by mc transverse momentum of the electron in this case is proportional to the inverse resonance mismatch, $p_\perp = K/\Delta$ with $\Delta = 1 - \Omega_c/\Omega_u$, where K equals to the undulator parameter in the absence of the guiding field, $\Omega_c = eB_0/mc\gamma$ is the relativistic electron cyclotron frequency, $\Omega_u = hv_\parallel$ is the undulator (bounce) frequency, $h = 2\pi/d$, d is the undulator period, $v_\parallel = c\beta_\parallel$ and γ are the electron axial velocity and its gamma-factor. From this dependency follows that in the case of $\Omega_c > \Omega_u$ and $\Delta < 0$, increase of the electron energy shifts the particle closer to the cyclotron-undulator resonance and increases its transverse momentum. It is also easy to show that the rate of this increase can be such that the axial electron velocity decreases with the energy increase. Indeed,

$$\frac{d\beta_\parallel}{d\gamma} = \mu = \frac{1}{\gamma^3}\left(1 + \frac{K^2}{\Delta^3}\right), \tag{1}$$

and $\mu < 0$ when $\Delta < 0$ and $|\Delta|^3 < K^2$. Thus, choosing the right magnitude of the guiding field, one can control the sign and the intensity of the axial Coulomb interaction. In the proposed system it is possible that the particles moving in the head of the bunch decelerate gaining the energy from the particles in the tail of the bunch, and vice versa.

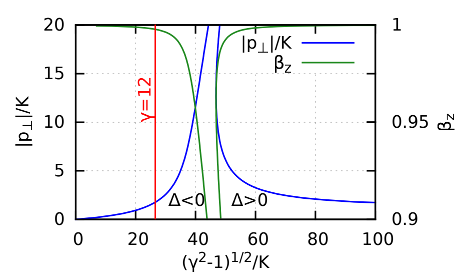

Fig. 1. Dependency of the transverse momentum and axial velocity of the electron moving along the stationary trajectory on the mass-factor. Vertical line marks the point corresponding to the Lorentz-factor of $\gamma = 12$.

III. Results of simulations

The proposed regime has been numerically simulated on the basis of the original 3D numerical code using the exact relativistic formulas for Liénard-Wiechert potentials and allowing taking into account the electron-electron interactions and also calculating the undulator radiation. We have studied the motion of the electron bunch with the parameters close to ones discussed for the Israeli THz Source [1]: the bunch charge of 0.3 nC, initial length of 0.1 mm, initial diameter of 1 mm, Lorentz-factor of $\gamma = 12$, period of the helical

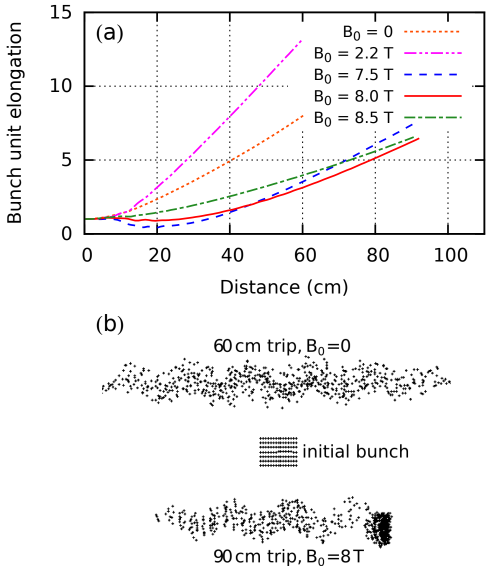

Fig. 2. Simulations on the basis of the original 3D LinardWiechert-potential numerical code. Dependency of the rms unit elongation of the bunch on the trip distance in various regimes (a) and comparison of the initial bunch with one after a 60 cm trip in the absence of guiding field and after a 90 cm trip in the regime of negative-mass stabilization (b).

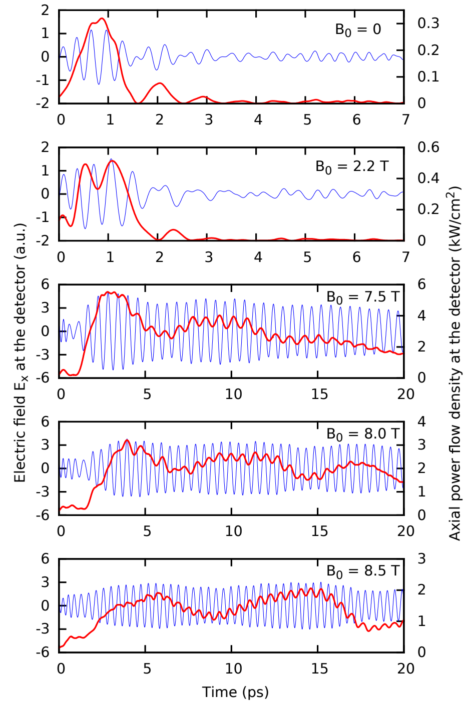

Fig. 3. Forward radiation of the bunch as seen at a distance of 6 m after entrance in the wiggler: x-component of electric field (blue thin lines) and axial power flow density (red thick lines).

undulator of 2.5 cm and undulator parameter of $K = 0.45$. In this case, the resonance magnitude of the guiding magnetic field is close to 5 T. When the axial magnetic field is high enough, for example $B_0 = 8$ T, the dependencies of the transverse momentum and axial velocity of a particle on its Lorentz-factor (Fig. 1) 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 simulations results (Fig. 2) it can be seen that choosing the guiding field higher than the resonant one substantially decreases the speed of bunch degradation. 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. Indeed, both the power and the duration of the radiated pulse in the regime of negative-mass stabilization are much greater than in other regimes (Fig. 3). According to simulations, the total bunch energy loss after of about of 1 m trip in the negative-mass regime can amount to 18% (Fig. 4).

IV. Conclusion

The simulations demonstrate a good coincidence with the results of the theoretical analysis and confirm that realization of effective particle negative-mass attraction is possible. Using such regime can provide significant power enhancement and spectrum narrowing for radiation source at the frequencies of 1–3 THz.

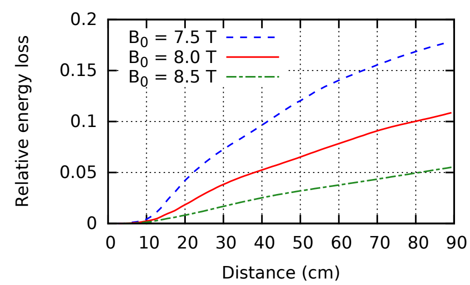

Fig. 4. Energy losses of the electron bunch in the negative-mass regimes.

Acknowledgment

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