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THz radiation of stabilized dense electron bunches

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Laser-driven photo-injectors are capable to form very compact and dense electron bunches with a particles energy of 3-6 MeV, picosecond and subpicosecond duration, and charge of the order of 1 nC. When moving in the periodic field of the undulator with a period of a few centimeters, such bunches can generate coherent radiation in the near-terahertz range. The power and duration of such a generation is limited due to an increase in the axial length of the electron bunch under the action of the Coulomb repulsion, which under normal conditions does not allow for the effective implementation of such a scheme for dense nC bunches [1]. Therefore, a special methods of stabilization of the axial length of the operating bunch during its motion over a long enough electron-wave interaction region should be used. The report describes two such methods, namely, the so-called "negative-mass" stabilization and the radiative compression of electron bunches.

Negative-mass stabilization and compression

The negative-mass regime of the electron motion is realized in a combination of periodic undulator field and relatively strong homogeneous axial magnetic field (Fig. 1 a). The cyclotron frequency corresponding to the axial field should be slightly higher than the undulator bounce-frequency of the particle. In this case, the Coulomb field inside the bunch leads not to repulsion of electrons but to their mutual attraction [1]. This effect is a result of an abnormal dependence of the velocity of undulator oscillations of electrons on the cyclotron frequency (Fig. 1 b). Let us consider a particle moving in the front of the bunch (Fig. 1 c). The Coulomb field accelerates this electron, and its relativistic cyclotron frequency decreases. The electron approaches the undulator-cyclotron resonance, which is accompanied by a resonant increase in its transverse velocity; this leads to decrease in the axial electron velocity.

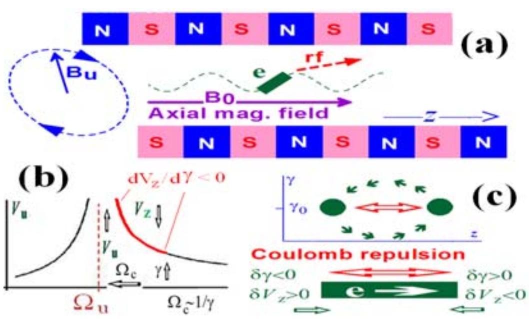

Fig. 1. (a): Electron motion in the combined helical undulator and uniformaxial fields. (b) Characteristic dependence of the transverse electron velocity on the cyclotron frequency. (c) Coulomb attraction and oscillations of electrons in the "negative-mass" regime.

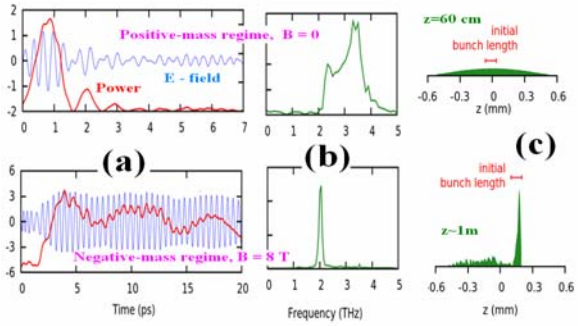

Fig. 2. (a): Radiated wave field and power (red) in the "positive-mass" and "negative-mass" regimes. (b): Spectra of the radiated rf signal. (c): Axial distributions of the charge in the bunch after the 60 cm trip in the positive-mass regime and after the 1m trip in the negative-mass regime.

Thus, increasing the energy of the particle causes it to slow down in the longitudinal direction. The opposite situation takes place for the particle moving in the tail of the bunch; this particle is decelerated by the coulomb filed, and this leads to an increase in the axial velocity. Overall, the Coulomb interaction of particles leads to compression of the bunch in the longitudinal direction. Such a behavior of electrons can be regarded as a consequence of its effective mass being negative [2,3], and this is very similar to the negative-mass effect in cyclotron masers [4-7].

Numerical simulations show [1,8] that in a certain range of parameters, significant improve of the radiation characteristics is possible when using the described scheme. Figure 2 illustrates an example, where an electron bunch with the particles energy of 5.5 MeV scatters the undulator field having a period of 2.5 cm into the wave with a frequency of about 2 THz. In this case, the resonant cyclotron frequency corresponds to the axial field of about 5 T, and effective negative mass regime is realized at magnetic fields near 8 T and the undulator field amplitude of about 0.2 T (Fig. 2). Simulations predict generation of a 20 ps rf pulse with a power of ~ 10 MW. According to simulations [8], the negative-mass regime can provide axial stabilization of extremely dense (with charges up to several nC) picosecond bunches. A prototype of the negative-mass undulator with a 8 T axial magnetic field is designed and tested in the experiment [9]. There is also an interesting option to use this regime for the axial compression of dense bunches by their own Coulomb fields, when the undulator is used not for the radiation but for providing the negative-mass electron motion only [10]. Since in this situation there is no goal to achieve THz radiation, undulators with longer periods can be used, and a lower magnitudes of the axial magnetic field are required to provide the negative-mass electron motion.

Radiative compression

An alternative compression method can be the undulator super-radiative radiation of a long-wavelength wave in an auxiliary long-period undulator [11]. A relatively long electron bunch propagates in a simple (with no axial magnetic field) helical undulator inside a waveguide (Fig. 3 a) and radiates a short wave packet propagating with a group velocity equal to the electron axial velocity (Fig. 3 b). Since the wavelength of the radiated wave is longer than the bunch length, the emission has the spontaneous coherent character. Such emission results in axial compression of the bunch (Fig. 3 c). This is due to the fact that in the situation described above the phase of the radiated wave is correlated in a certain way with the electron bunch phase, namely, there is a $\pi/4$ shift between the bunch center and maximum of the decelerating wave phase (Fig. 3 d). In the case of a bunch being four times shorter than the wavelength, the bunch is compressed in the radiated field, because the front of the bunch is placed in the maximum of the decelerating wave phase whereas the tail is placed close to the "zero" wave field.

This effect can be used for creation of a "bicolor" THz source based on the spontaneous emission from a short bunch, so that the super-radiation of the auxiliary long-wavelength wave is used to compress the bunch down to a size shorter than the wavelength of the short-wavelength wave. Figure 4 illustrates an example, where a 0.1 nC 3 MeV 0.6 mm bunch moves in two undulators ($\lambda_{u,1} = 2.3$ cm and $\lambda_{u,2} = 1.1$ cm). At the first stage, electron oscillations in the first undulator lead to the spontaneous coherent radiation of the long-wavelength ($\lambda_1 = 1.2$ mm) compressing wave. During this process, the bunch is compressed several times. This makes possible the spontaneous coherent radiation of the short-wavelength ($\lambda_2 = 0.3$ mm) wave in the second undulator with a relatively high (~10%) electron efficiency.

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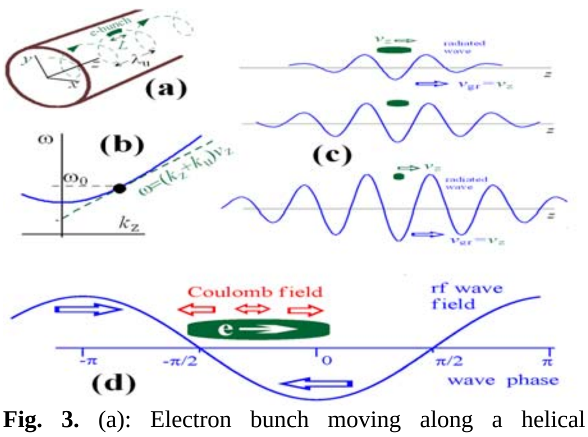

Fig. 3. (a): Electron bunch moving along a helical undulator. (b): Dispersion diagram of the operating waveguide mode. (c) Super-radiative radiation and the bunch compression. (d): Bunch phase with respect to the wave.

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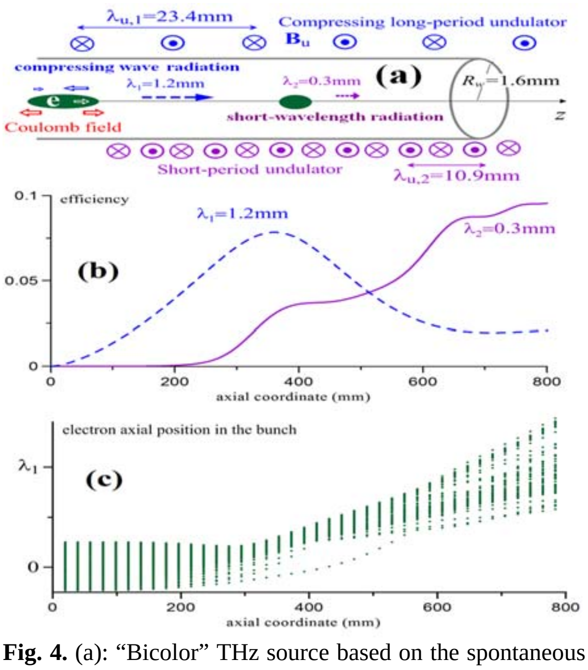

Fig. 4. (a): "Bicolor" THz source based on the spontaneous emission of two waves. (b): Efficiency of radiation of the two waves versus the axial coordinate of the bunch. (c): Evolution of axial distribution of electrons inside the bunch.