ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP024

SPONTANEOUS COHERENT RADIATION OF STABILIZED DENSE ELECTRON BUNCHES*

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Abstract

Modern electron sources allow formation of dense bunches with energies of 3–6 MeV, ps pulse durations, and charges of up to 1 nC. Such bunches can be used for the realization of relatively simple terahertz sources based on spontaneous coherent radiation. This regime is realized when the effective bunch phase size doesn't exceed 2π. Power and duration of the process of such type of emission are limited due to an increase in the bunch length under the Coulomb repulsion. This complicates the effective implementation of the regime of spontaneous coherent radiation for dense bunches. Therefore, special methods for stabilization of the length of the bunch should be used. We describe several methods of the stabilization used in different systems (cyclotron radiation, emission in the traditional undulator system, and emission in the "negative-mass" undulator system).

CYCLOTRON RADIATION

We consider particles motion in a waveguide immersed in a uniform longitudinal magnetic field (Fig. 1a).There are two characteristic regimes of radiation for electrons moving in a waveguide depending on the value of the magnetic field (Fig. 1b): group synchronism, regime of the "grazing" of dispersion characteristics (G), at which the group velocity of the wave is close to the initial longitudinal velocity of particles, and intersection of the dispersion characteristics, at which high-frequency (H) and low-frequency (L) waves are simultaneously excited. In the case of grazing of dispersion characteristics, the total compensation of Coulomb repulsion takes place [1]. In the case of two waves excitation low-frequency spontaneous radiation provides the bunch forming respect to high-frequency wave [2-4].

The change in electron energy is the sum of the changes in energy due to the Coulomb interaction and the wave effect: $\Delta\gamma = \Delta\gamma_c + \Delta\gamma_w$. Evolution of the cyclotron electron phase is described as follows

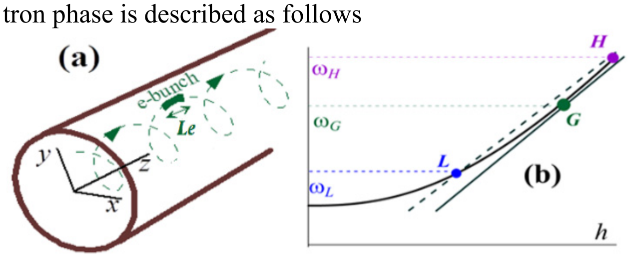

Figure 1. (a) Electron bunch moving along a helical undulator. (b) Dispersion diagram of the operating mode.

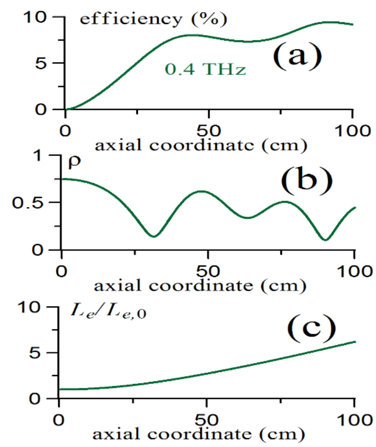

Figure 2: (a) Efficiency of the electron-wave interaction $\langle\gamma_0-\gamma\rangle/(\gamma_0-1)$. (b) Electron bunching efficiency $\rho =$ cy $\rho = \langle exp(-i\vartheta)\rangle$. (c) Effective normalized bunch length $L_e/L_{e,0}$(c) versus the axial coordinate.

$$\frac{d\vartheta}{d(\omega t)} = \frac{\Delta\gamma_c}{\gamma_0}(\beta_{z,0}-\beta_{gr})\left(\beta_{z,0}+\frac{1}{\gamma_{z,0}^2}\right)+\frac{\Delta\gamma_w}{\gamma_0}(1-\beta_{gr}{}^2). \quad (1)$$

here $\vartheta = \omega t - k_z z - \int \omega_c dt$ is the electron resonance phase change, ω is the frequency of the radiated wave, which described by the Doppler up-conversion of non-relativistic cyclotron frequency

$$\omega = \frac{\Omega_c}{\gamma(1-\beta_{gr}\beta_z)}, \quad (2)$$

$\gamma = \sqrt{1-\beta^2}$ is the relativistic gamma-factor, $\beta = V/c$ is the normalized electron velocity, β_z is the normalized longitudinal velocity, β_{gr} is the normalized wave group velocity; $\Delta = 1-\beta_{gr}\beta_{z,0} - b/\gamma_0$ is the mismatch of the electron-cyclotron resonance (here, $b = \Omega_c/\omega$).

Approximate equation (1) makes it obvious, that the Coulomb interaction of the particles does not change the phase of the electron relative to the wave in the regime of group synchronism, $\beta_{z,0} = \beta_{gr}$, despite change in bunch length. This is due to the electron bunch spreads along the helix of the constant phase [1].

We consider the spontaneous radiation of a cylindrical bunch with a diameter of 1 mm, a charge of 0.2 nC, a duration of 0.5 ps, a particle energy of 6 MeV, and initial transverse velocities $\beta_{\perp 0} = 1/\gamma_0$ in a waveguide with a diameter of 4 mm. The particles are in group synchronism with the TE_{11} mode at the field H_0 = 2.2 T. The frequency of radiation is 0.4 THz, and efficiency of about 8% (Fig. 2a). In the process of motion of the bunch along the operating waveguide, the bunch length increases (Fig. 2c). However, such an increase in the bunch length doesn't lead to a significant increase in the bunch phase size, described by the bunching efficiency $\rho = \langle exp(-i\vartheta)\rangle$, which remains at a level ρ~0.5 (Fig. 2b).

* Work supported by Russian Foundation for Fundamental Research, projects 18-32-00351 and 18-02-00765, as well as by the IAP RAS Project 0035-2019-0001.
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ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP024

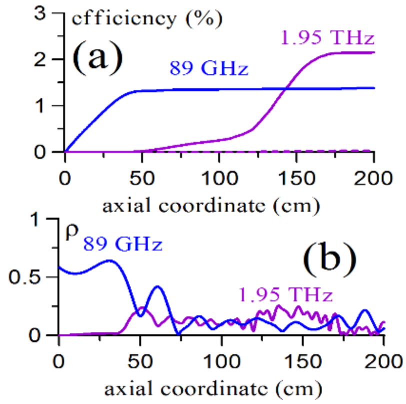

Figure 3: Numerical simulation for emission from the 1 nC / 3 ps bunch in the regime of the highly Doppler up conversion. Efficiency of the electron-wave interaction (a), electron bunching efficiency ρ (b).

In the regime of the highly Doppler up-conversion the group velocity of high-frequency wave is still close to the longitudinal electron velocity, and simultaneously is close to the speed of light (Fig 1b, H), so electron energy changes weak influence the electron phase change [5]. Therefore, an additional stabilization of the particle phase size is necessary, if an electron bunch initially is not phased respect to the high-frequency wave. Such stabilization can be provided by a low-frequency wave L (Fig. 1b) due to the simultaneous bunching by Coulomb [2,3] fields and by fields of the radiated wave fields [4]. At magnetic field of 5.5 T, the bunch emits in the same waveguide simultaneously at frequencies of about 89 GHz and 1.95 THz. The efficiency of high-frequency radiation is close to 2% (Fig. 3). This relatively low efficiency is caused by non-sufficient bunching with respect to the high-frequency wave.

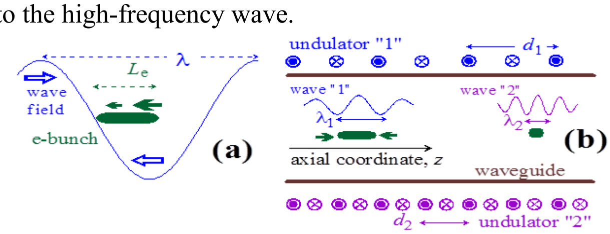

Figure 4: (a) Self-compression of the bunch in the radiated wave field. (b) Bicolor rf source: spontaneous radiation of the long-wavelength wave “1” leads to the compression of the bunch and spontaneous radiation of the short-wavelength wave “2”.

UNDULATOR RADIATION

A possible way to provide stabilization of the axial size of a dense electron bunch is super-radiative self-compression of the bunch [6] that occurs in the process of spontaneous undulator emission in the regime of “grazing” of the dispersion characteristics. In this regime, the bunch is shifted to $\pi/4$ relative to the maximum of the decelerating wave phase (Fig. 4a). If the bunch length is close to a quarter of the wavelength, then the front of the bunch is decelerated by the wave, whereas the tail is placed in the wave “zero” and, therefore, does not lose the energy. This results in compression of the bunch by its own radiated field.

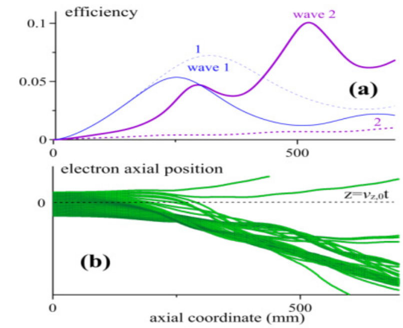

Figure 5: (a) Efficiencies of interaction of the electron bunch with waves “1” and “2” in the two-wave regime (solid curves) versus the axial coordinate, as well as efficiencies of excitation of each wave in the single-wave regime (dashed curves). (b) Axial positions of electrons with respect to the unperturbed coordinate of the bunch center in the two-wave regime.

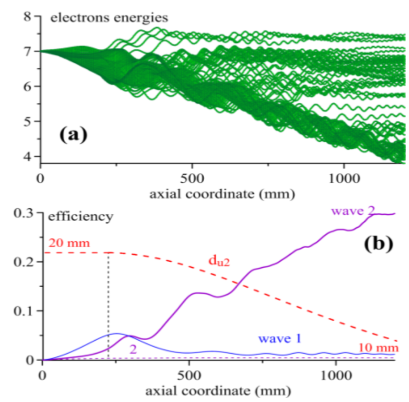

Figure 6: Two-wave radiation process in the sectioned profiled system. (a) Energies of electrons versus the axial coordinate of the bunch. (b) Efficiencies of interaction of the electron bunch with waves “1” and “2” versus the axial coordinate, as well as profiling of the period of the second undulator. The dashed curve corresponding wave “2” in Fig. 4b illustrates interaction of electrons with this wave in the single-wave process.

We propose to use this mechanism of self-compression in the field of relatively long-wavelength ($\lambda_1 > L_e$) wave to provide spontaneous emission of a wave with shorter wavelength ($\lambda_2 \sim L_e$). Figure 4 b illustrates a bicolor source based on the cascade two-wave super-radiative undulator radiation. Two undulators with different periods provide the “grazing” regimes of the electron-wave resonance (Fig. 1a) for two waveguide waves having the same transverse structures.

In simulations we consider an electron bunch with an electron energy of 3MeV, a total charge of 0.3 nC, the diameter 1 mm, and a pulse duration of 3 ps (L_e = 0.9 mm), $\lambda_1 = 2L_e = 1.8$ mm. For the both undulators, the undulator factors $K_{u1,2} = \gamma\beta_{u1,2}$ are assumed to be equal to 0.8. In this case, the grazing regime for wave “1” is provided when the waveguide diameter is 4.2 mm and the period of the first undulator is $d_1 = 31$ mm. The last step

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is to choose the frequency of wave "2" and the period of the second undulator. We consider a possibility to excite a 0.5 THz high-frequency wave ($\lambda_2 = 0.6$ mm). For this wave, the grazing regime is provided when $d_2 = 20$ mm. Figure 5a illustrates the result of simulations for the bunching: the compression by the radiated wave "1" makes the spontaneous radiation of wave "2" possible. The efficiency of this process is relatively high 10%. Thus, it is possible to obtain radiated pulses having a duration of ~0.1 ns and a power of ~3 MW. Note that the dashed curve in Fig. 5a describes the situation without stabilization by the wave "1".

The use of the trapping regime [7-10] ensures the enhancement of the saturated efficiency of excitation of the high-frequency wave (2) from ~10% up to 30% at a length of the electron-wave interaction ~1 m, due to decrease of the short-period undulator from $d_2 = 20mm$ to $d_1 = 10mm$ (see Fig. 6b).

NEGATIVE-MASS REGIME

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. 7 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 [11]. This effect is a result of an abnormal dependence of the velocity of undulator oscillations of electrons on the cyclotron frequency (Fig. 7 b).

Generation at high frequencies in two-waves regimes, such as described above (Fig. 1b) is more efficient in the negative-mass regime. The resonance phase $\vartheta = \omega t - (h + h_u)z$ (here $h_u = 2\pi/d$) change in the case of undulator radiation

$$\frac{d\vartheta}{d(\omega t)} \approx \frac{\Delta\gamma}{\gamma_0^3} - \delta, \qquad (3)$$

δ – the mismatch of resonance. In this case the parameter of bunching doesn't depend on the group velocity, moreover the coulomb interaction and the radiated wave effect have equally contributions [compare with (1)]. It is important to note, that the group synchronism mismatch is necessary condition to provide conditions for the bunching by the wave field (the superradiative self-compression opposite effect described above).

Let's consider the radiation of the bunch with pulse duration of 1 ps, with a diameter 1mm, with a charge 1. nC at frequencies of 0.12 THz and 1.35 THz (an undulator period of 3.5 cm, an undulator parameter 0.1, and guiding field of 4.4 T) in a waveguide wit diameter 4 mm. The efficiency of high-frequency radiation of 20% at the length ~1m, the low-frequency wave generation efficiency by half. Initially, the bunch compressed by Coulomb fields inside a bunch [12], thereafter by the high-frequency wave field [4] (Fig. 8). Centers of compression are slightly shifted relative to each other.

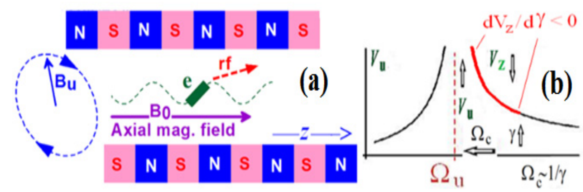

Figure 7: Electron motion in the combined helical undulator and uniform axial fields. Characteristic dependence of the transverse electron velocity on the cyclotron frequency.

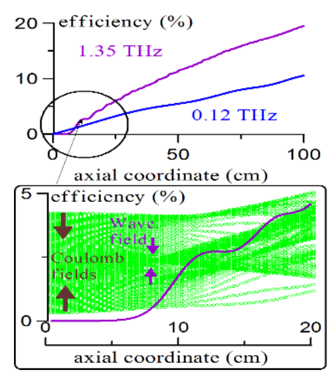

Figure 8: The efficiency of two-frequency generation in the negative-mass regime and the bunching process.

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