POSSIBILITY OF SUPER-RADIANCE IN THE FREQUENCY RANGE OF 3-5 THz FROM SHORT ELECTRON BUNCHES MOVING IN MICRO-UNDULATORS

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ABSTRACT

The Israeli THz source based on the use of dense picosecond and sub-picosecond electron bunches with energy 3-6.5 MeV obtained in a hybrid photo-injector gun will be able to emit at the first stage a powerful coherent spontaneous undulator radiation or super-radiance at the frequencies of 0.5-3 THz when undulator period is 2-2.5 cm. An available frequency range of radiation can be significantly enhanced if one uses a micro-undulator with a smaller period and a sufficient transverse field. The necessary undulator with a convenient helical symmetry and a high transverse field can be easily realized by means of redistribution of a strong uniform magnetic field by a ferromagnetic insertion in the form of helix or by excitation of eddy current in a copper helix placed in a pulsed uniform field. 3D numerical simulations demonstrate that using such undulators with period of 8-10 mm enable efficient coherent spontaneous radiation from short bunches with duration of (0.08-0.15) ps and super-radiance from extended bunches with duration of about 2 ps in frequency range of 3-5 THz.

1. Introduction

Advanced laser-driven photo-injectors make possible formation of very dense picosecond and sub-picosecond electron bunches with charge of the order of 1 nC and larger at moderate relativistic energy [1–4]. Such bunches can be attractive for simple production of power THz electromagnetic pulses [5-16] using various mechanisms of the so-called coherent spontaneous radiation and super-radiance. In particular, the first stage of experiments at the Israeli THz source [13] is planned to conduct using a spontaneous coherent Doppler-upshifted undulator radiation of bunches whose longitudinal size or period of preliminary density modulation is smaller than the wavelength of radiation. The modulation can also arise self-consistently in extended bunches during their interaction with the radiated electromagnetic pulses in process of super-radiance (see, e.g., [10-12] and literature cited therein).

At the fixed electron energy, the radiation frequency of the Israeli source could be enhanced if the undulator period is decreased. Simple and efficient ways for creation of helical undulators with small periods and strong amplitudes of a transverse magnetic field are proposed in [17, 18, 15] (see also [19-22]). They present modifications of old ideas and based on redistribution of a uniform magnetic field by ferromagnetic or conducting bodies placed inside a solenoid [23-25]. Such undulators will be described in Section 2.

In a helical undulator, electrons can move along stationary helical trajectories with ultrarelativistic longitudinal and fairly large transverse velocities. This provides their efficient Doppler-shifted radiation with the frequency that is many times larger than the frequency of particle oscillations in the undulator field. The radiation of particles is coherent if the bunch axial size is smaller than the radiation wavelength and spread in particle parameters is sufficiently small (coherent spontaneous radiation). When using a small-period undulator it is necessary to provide a very short initial bunch duration. Because of very strong mutual Coulomb repulsion of the particles in the dense bunch these conditions can be only fulfilled at a limited length of bunch propagation. Other opportunities are opened when one uses radiation of pre-modulated bunches or super-radiance of extended bunches; in the latter case a self-modulation of density in the field of the radiated wave occurs [10-12]. THz sources based on these mechanisms are studied in Section 3.

2. Helical micro-undulators based on redistribution of uniform magnetic field

The undulator field with a small period and a large transverse amplitude can be created by redistributing the strong uniform field on a periodic ferromagnetic insertion [17-22, 15]. This method was successfully demonstrated many years ago in planar systems with periodic planar ferromagnetic insertions [23-25]. We have proposed [17, 18, 15] to use a steel helical insertion for creation of a helical undulator field (see also [20-22]).

It is obvious that magnetization of a ferromagnetic helix placed in the guiding field (Fig. 1) provides a helical component of the magnetic field. In the case of a very strong field $\vec{B}_0 = B_0\vec{z}_0$ the magnetization of the helix is saturated, $M = M_\infty$, its direction practically coincides with direction of the uniform field and value does not depend on B_0 [18]. Consider an infinite ferromagnetic helix with period (step) d, inner and outer radii R_1 and R_2, respectively, a thickness b, and axial size $a = R_2 - R_1$. According to [18], a thin helix, for which $R_1 \approx R_2 = R,\ b << R$, provides at its axis a helical field:

$$\vec{B}_u(r=0) = \mathrm{Re}\left[\left(\vec{x}_0 + i\vec{y}_0\right) B_u e^{i(hz-\pi/2)}\right], \tag{1}$$

where,

$$B_u = \frac{1}{\pi} h^2 Rb \sin\left(ha/2\right) K_1\left(hR\right) \mu_0 M_\infty, \tag{2}$$

$h = 2\pi/d$, K_1 is McDonald function, μ_0 is the magnetic permeability of vacuum. Maximum of the transverse field is achieved when the longitudinal size of the helix is equal to half of its period, $a = d/2$. Integration of expression (4) by radius gives solution for the helix of finite thickness.

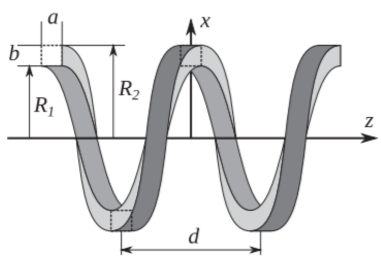
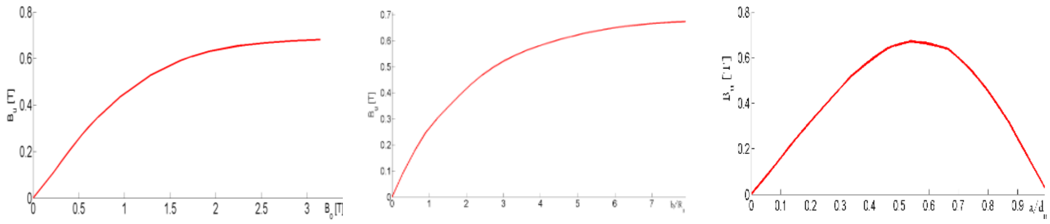


Fig. 1. Ferromagnetic helical insertion into solenoid.

The applicability of the solution (1) - (2) was verified in [18] and in the present work by direct solving of magnetostatic equations using *CST Studio*. This code allows one to consider a finite thickness, arbitrary profiles of the helix as well as nonlinear dependence of magnetic permeability of a ferromagnetic on applied field. Simulations demonstrate a high accuracy of the solution (1) - (2) for thin and long enough helices [18] and allow obtaining saturation curves for the undulator field with increasing the uniform field (Fig. 2a) and helix thickness (Fig. 2b) The simulated dependence of undulator field B_u on the axial helix size *a* (Fig. 2c) is close to that described by the (2).

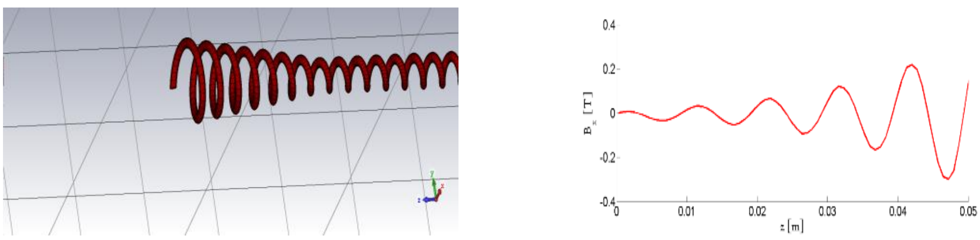


a) b) c)

Fig. 2. Saturation curves for steel helix with quadratic cross-section, period *d*=10 mm, and inner radius $R_1 = 1mm$. Dependences of undulator field B_u on: (a) axial field B_0 (*a*=5 mm, $R_2 = 4.5mm$), (b) helix thickness *b* (*a*=5 mm, B_0 =4 T), and (c) helix axial size *a* ($R_2 = 4.5mm$, B_0 =4 T).

Experiments with helical insertions including ones with small periods (Fig. 3) demonstrated a satisfactory coincidence with calculations [18]. The field redistribution allows easy implementation of adiabatic entrance of the electron bunch into or its exit from the undulator field decreasing an amplitude of parasitic cyclotron oscillations of particles by means of a smooth decreasing or increasing the inner helix radius (Fig. 4).

Fig. 3. Pulsed foil solenoid with strong magnetic field and helical insertion of 12-mm period used in measurements.

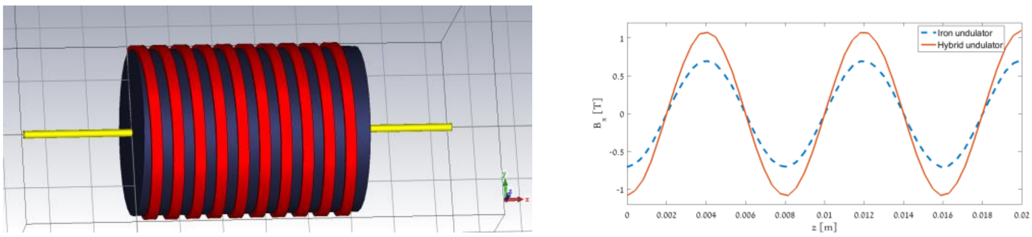


a) b)

Fig. 4. Helical steel insertion with changing radius for adiabatic entrance of particles (a) and corresponding distribution of *x*-component of undulator field (b).

A steel helical insertion in a strong uniform field of 4 T can provide a helical undulator field with the amplitude of 0.6 T (Fig. 2). The larger amplitude can be obtained using a hybrid system [17] consisting of a steel helix ("bolt") placed inside a permanently magnetized helical block ("nut") with magnetization that is opposite to direction of the uniform field of solenoid (Fig. 5a). To avoid changing the direction and value of the magnetic field of the permanent magnet we performed the calculations for a relatively low value of the solenoid magnetic field of 1.2 T (Fig. 5b); the rest parameters are as
follows: $a = 4mm$, $R_1 = 0.75mm$, $R_2 = 4.5mm$, and $d = 8mm$. This system can provide the helical undulator field with the amplitude of 1.1 T.

Another simple and efficient way to obtain a strong helical undulator field with a small period is to use an eddy current induced in a copper helix placed into a strong uniform field of a pulsed solenoid [17]. For example, in the uniform field of 3 T changing with the frequency of 300 Hz the copper helix with parameters a=5 mm, R_1 =5 mm, R_2=4.5 mm, and d=10 mm the amplitude of the helical undulator field at the axis is as high as 0.9 T. This value obviously increases at larger field or frequency. Thus, helical insertions in a uniform magnetic field can provide the amplitude of undulator field of about or even higher than 1 T at the undulator periods 10 mm and smaller.



a) b)

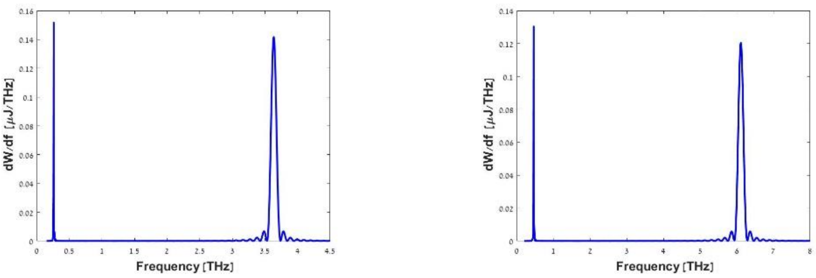
Fig. 5. A hybrid insertion consisting of a steel helix ("bolt", red) placed inside a permanently magnetized helical block ("nut", blue) with magnetization that is opposite to direction of the uniform field of a solenoid (a) and distributions of undulator field without and with a permanent block (b).

3. Radiation of short and extended bunches

Let us consider now possibilities of using micro-undulators for production of radiation in the frequency range of (3-5) THz from dense electron bunches with a certain energy 6 MeV, which are obtained in the photo-injector and then brought to required axial and transverse dimensions in a special forming section. Taking into account a symmetry of magnetic system and electron bunches it is convenient to use a circular metal waveguide placed inside the helix as a electrodynamic system of such a THz source. If a waveguide diameter is small enough, a selective single mode generation can be obtained in such a system with predominant high-frequency and following low-frequency radiations. First method for this is based on using very short bunches with duration of the order of (0.08-0.15) ps that are approximately equal to halves corresponding radiation wavelengths and provide an efficient coherent spontaneous undulator radiation of particles at the length, which is essentially limited by a longitudinal expansion caused by their mutual Coulomb repulsion [5, 6, 8,9, 13-17]. Second method supposes using long extended bunches with smoothed edges and durations of a few picoseconds that are sufficient in the considered wavelength range for development of a density bunch self-modulation due to its interaction with the radiated wave, which is typical for regimes of super-radiance (see, e.g., [10]).

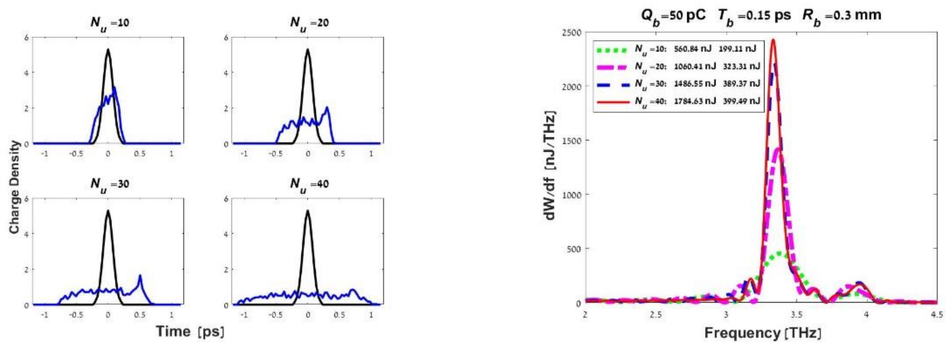
Numerical simulations of the bunch and THz radiation evolution during their propagation in the waveguide is based on the space-frequency approach [26] and corresponding numerical WB3D code, which have been successfully applied for the simulation of various FELs. In this method, the total RF field in the operating waveguide is considered in the positive-frequency Fourier domain by expansion of the monochromatic field components in terms of waveguide eigenmodes. The electron bunch is represented by an ensemble of macro-particles interacting with the RF field and each other through a free-space Lorenz-transformed Coulomb field of the rest of the macro-particles. A self-consistent system of equations describes the particle motion and evolution of the radiation along the interaction region. The WB3D code enables a self-consistent consideration of multi-mode radiation of particles occurring simultaneously at various undulator harmonics and in a very broad frequency band.

We consider here the undulators with periods of 10 mm and 8 mm, for which amplitude of transverse field can be as high as 1 T (see Section 2), and very small waveguide diameters D_w =1.5 mm and D_w =1 mm, respectively. According to simulations for a point-like small charge moving in these undulators, the high-frequency and low-frequency TE_{11} modes are basically excited at the fundamental (s = 1) undulator harmonic in the chosen over-sized waveguides (Fig.6). At chosen periods and the same value of undulator field, B_u = 1 T, the undulator parameters are K=0.93 and K=0.75. The radiation frequencies being in synchronism with 6 MeV beam are 3.7 THz and 6.2 THz, respectively.



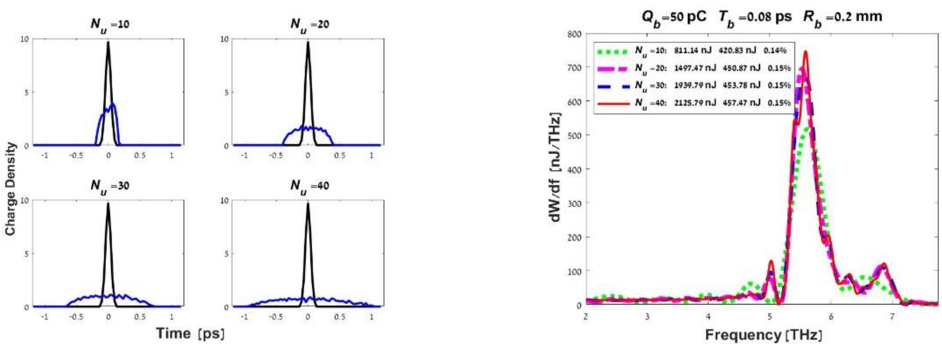
a) b)

Fig. 6. Spectrum of radiation for a single point-like particle with charge 1 pC and energy 6 MeV passing 40 undulator periods in waveguide: a) d=10 mm, D_w =1.5 mm and b) d=8 mm, D_w =1 mm.



a) b)

Fig. 7. Evolution of bunch density (a) and high-frequency parts of radiation spectra (b) for a bunch with charge 50 pC, radius 0.3 mm, duration 0.15 ps, and energy 6 MeV passing the distance of (10-40) cm in undulator with period of 10 mm and waveguide with diameter of 1.5 mm.



a) b)

Fig. 8. Evolution of bunch density (a) and high-frequency parts of radiation spectra (b) for a bunch with charge 50 pC, radius 0.2 mm, duration 0.08 ps, and energy 6 MeV passing the distance of (10-40) cm in undulator with period of 8 mm and waveguide with diameter of 1 mm.

When using short and very dense bunches with durations and radii 0.15 ps, 0.3 mm for the first undulator and 0.08 ps, 0.2 mm for the second one the radiation frequency is lower than for a point-like particle even at low charge 50 pC (Figs. 7 and 8). In this case, the electron bunches significantly expand already after N_u=20 undulator periods when the radiated energy is 0.32 μJ and 0.45 μJ.

It is important that the initial length of the electron bunches can be much larger than the radiated wavelength. In this case of extended bunches, whose edges can be even very smooth, at sufficiently large density and charge simulations demonstrate development of a particle self-modulation and super-radiance (Figs. 9 and 10). The effect of super-radiance of the extended bunches was first discovered for longer waves and various radiation mechanisms (see, e.g., [10-12]). It is successfully used for generation of very powerful electromagnetic pulses at millimeter waves. Possibility of undulator super-radiance at THz waves was studied in [10].

According to our simulations, the undulator super-radiance can be efficient at fairly high frequencies. For example, using of 1-nC bunches with radii 0.2 mm and initial length 10 wavelengths moving in the considered waveguides and undulators can provide single-mode generation with energy of 0.15 mJ and 0.24 mJ at the frequencies higher than 3 THz and 5 THz with efficiency (2.5-4)%, respectively (Figs. 9 and 10). The efficiency of radiation is many times higher than for short bunches of the same initial density.

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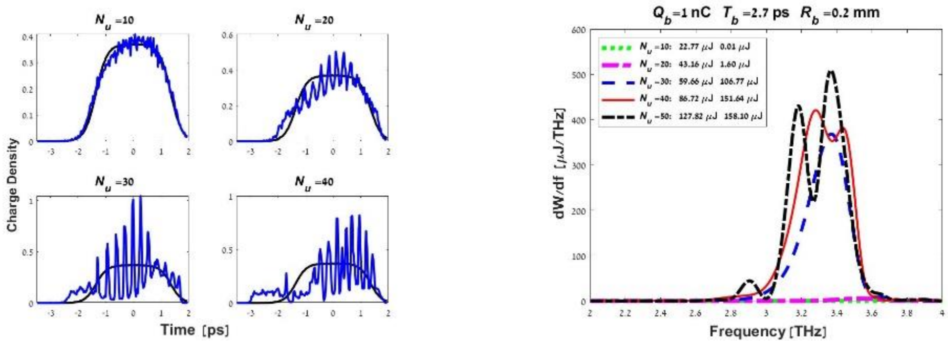

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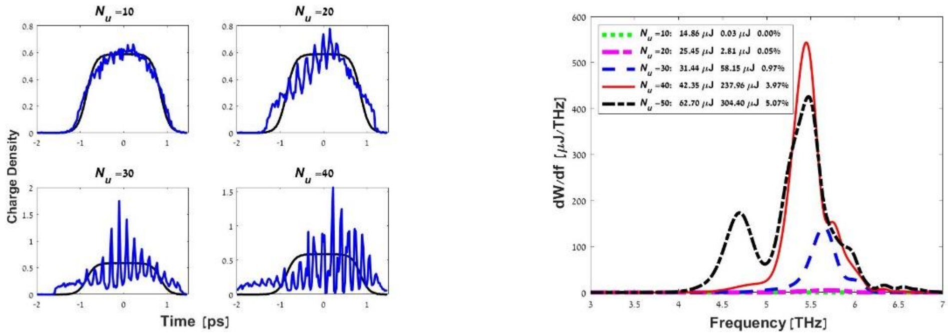
Fig. 9. Evolution of bunch density (a) and high-frequency parts of radiation spectra (b) for an extended bunch with charge 1 nC, radius 0.2 mm, duration 2.7 ps, and energy 6 MeV passing the distance of (10-40) cm in undulator with period of 10 mm and waveguide with diameter of 1.5 mm.



a) b)

Fig. 10. Evolution of bunch density (a) and high-frequency parts of radiation spectra (b) for a bunch with charge 1 nC, radius 0.2 mm, duration 1.7 ps, and energy 6 MeV passing the distance of (16-64) cm in undulator with period of 8 mm and waveguide with diameter of 1 mm.

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