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CAPABILITIES OF TERAHERTZ SUPER-RADIANCE FROM ELECTRON BUNCHES MOVING IN MICRO-UNDULATORS

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Abstract

An available frequency range of powerful coherent radiation from sub-picosecond and picosecond bunches with high charge and comparatively moderate particle energy of 3 - 6 MeV that are formed in laser-driven linacs significantly extends if one uses a micro-undulator. Such an undulator with a helical symmetry and a high transverse field can be implemented by redistributing a strong uniform magnetic field by a helical ferromagnetic or copper insertion. According to simulations and experiments with prototypes, a steel helix with a period of (8-10) mm and an inner diameter of (2-2.5) mm inserted in the 3T-field of a solenoid can provide a helical undulator field with the same periodicity and an amplitude of about of 0.6 T. Using a more complex hybrid system with a permanently magnetized helical structure can increase this value up to 1.1 T. The necessary helices can be manufactured on the machine, assembled from steel wires, formed from powder placed into a hollow helical shell or 3D - printed. Simulations based on the WB3D code demonstrate that using such undulators with the length of (30-40) cm enable single-mode super-radiance from bunches with charge of 1 nC and duration of 2 ps moving in an over-sized waveguide in frequency range of 3-5 THz. The calculated efficiency of such process many times exceeds efficiency that can be obtained with short bunches of the same initial density.

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 powerful THz electromagnetic pulses using various mechanisms of the so-called coherent spontaneous radiation and super-radiance [5-16]. In particular, it is planned to use a coherent spontaneous Doppler-upshifted undulator radiation of bunches whose longitudinal size or period of preliminary density modulation is smaller than the wavelength of radiation in first experiments at the Israeli THz source [13]. 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 can be obviously increased by decreasing of the undulator period. Simple and efficient ways for creation of helical undulators with small periods and strong amplitudes of a transverse magnetic field were independently proposed in [15-18] and [19-22]. They present modifications of old ideas and based on redistribution of a uniform magnetic field by ferromagnetic [23-25] or conducting bodies placed inside a solenoid.

When using a small-period undulator for implementation of coherent spontaneous radiation 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 this can be only fulfilled at a very 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 and particle bunching in the field of the radiated wave occur [10-12].

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 [15-18, 20-22]. This method was successfully demonstrated many years ago in planar systems with periodic planar ferromagnetic insertions [23-25]. In papers [20-22] and [15-18], it has been proposed to use a helical insertion for creation of a helical undulator field. Experiments with helixes including ones with small periods (Fig. 1a) have demonstrated a satisfactory coincidence with calculations [17]. A steel helixes with the period of 8-10 mm and inner diameter of 2-2.5 mm placed into a strong uniform field of 3 T can provide a helical undulator field with the amplitude of 0.6 T (Fig. 1). The larger amplitude can be obtained using a hybrid system (Fig. 2). [15] consisting of a steel helix ("bolt") placed inside a permanently magnetized helical block. To avoid changing the direction and value of the magnetic field of the permanent magnet we performed the calculations for the latter system with a low solenoid field of 1.2 T; the rest parameters (Fig. 1a) are as follows: a=4 mm, R_1=0.75 mm, R_2=4 mm, and d=8 mm. According to simulations this system can provide the helical undulator field with the amplitude of 1.1 T at the axis.

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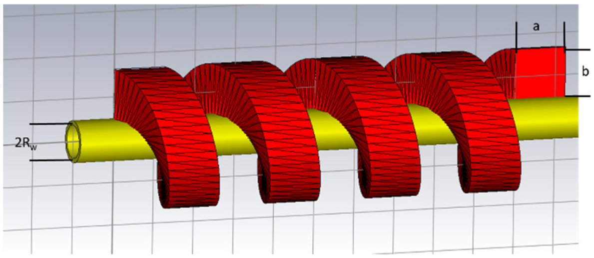

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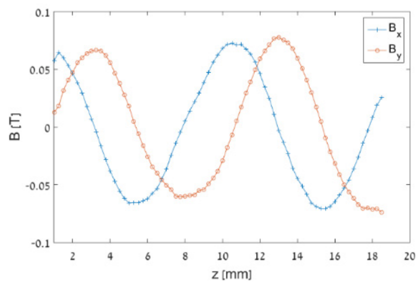

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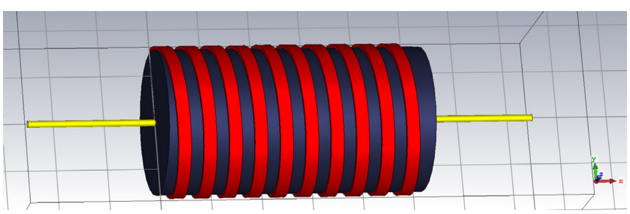
Figure 1: Measured distribution of transverse magnetic field at the axis of the steel helical insertion (a) with the period of 10 mm at a low uniform guiding field of 2 T (b).



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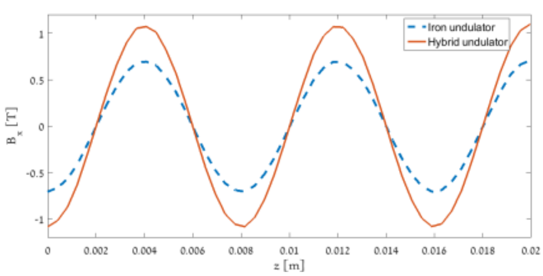

b)

Figure 2: A hybrid insertion (a) consisting of a steel helix (“bolt”, red) placed inside a helical block (“nut”, blue) with permanent magnetization opposite to the direction of the uniform field of a 1.2-T solenoid and CST simulations of distributions for transverse undulator field without and with a permanent magnetized block (b).

RADIATION OF SHORT AND EXTENDED BUNCHES

Let us consider now possibilities of using micro-undula-tors for production of a high-frequency radiation from dense electron bunches with a certain energy 6 MeV, which are obtained in the photo-injector and then brought to re-quired axial and transverse dimensions in a special forming section. Considering a symmetry of magnetic system and electron bunches it is convenient to use a circular metal waveguide placed inside the helix as an electrodynamic system of such a THz source. At a relatively small wave-guide diameter a selective nearly single-mode generation can be obtained in such the 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 radiation periods and provide a 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 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]).

Consider here the undulators with periods of 10 and 8 mm, for which amplitude of transverse field can be as high as 1 T (see Section 2), and very small (but over-sized) 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} waveguide modes are basically excited at the fundamental undulator harmonic. At the chosen periods and the same value of undulator field, Bu = 1 T, the undulator parameters are K=0.93 and K=0.75. The radiation frequencies being in synchronism with a 6-MeV particle are 3.7 THz and 6.2 THz, respectively.

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 a low charge of 50 pC. 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, respectively.

It is important that the initial length of the electron bunches can be much larger than the radiated wavelength. In this case of dense extended bunches, whose edges can be even very smooth, simulations demonstrate development of a particle self-modulation and super-radiance (Fig. 3a). 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 millimetre waves. Possibility of undulator super-radiance at THz waves was also studied in [10].

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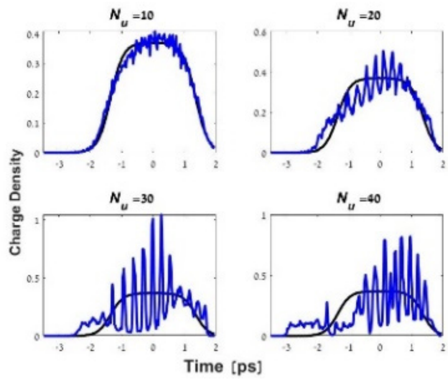

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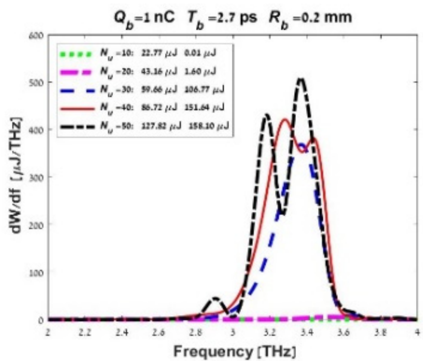

b)

Figure 3: Evolution of bunch density (a) and high-frequency parts of radiation spectra (b) for an extended bunch with charge of 1 nC, radius of 0.3 mm, duration of 2.7 ps, and energy of 6 MeV passing the distance of (10-40) cm in un-dulator with period of 10 mm and waveguide with diameter of 1.5 mm.

According to our simulations, the undulator super-radiance can be efficient at fairly high frequencies. For example, using of 1-nC bunches with radii (0.2-0.3) mm and initial length of 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 (Fig. 3). The energy efficiency of such super-radiance from extended bunches is many times higher than the efficiency of coherent spontaneous radiation from short bunches of the same initial density.

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