EFFICIENT ELECTRON SOURCES OF COHERENT SPONTANEOUS RADIATION WITH COMBINED HELICAL AND UNIFORM MAGNETIC FIELDS

N. Balal[1#], V. L. Bratman[1, 2], E. Magori[1]
[1]Ariel University, Ariel, Israel
[2]Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia

Abstract

Two methods to mitigate repulsion of electrons in dense bunches from photo-injectors with a relatively low particle energy and to enhance the power of terahertz radiation have been studied. First method is based on using very short bunches and small undulator periods that allows a significant shortening radiation sections. According to simulations bunches with duration (50-100) fs and energy 6 MeV that presumably could be formed in the constructing Israeli THz FEL [1] would fairly effectively radiate at frequencies up to (10-20) THz. The second method is based on an idea recently proposed by A.V. Savilov for longitudinal electron bunching [2, 3]. This is possible when a bunch moves in a combined magnetic field of a solenoid and of a undulator and the electron cyclotron frequency is sufficiently large in comparison with their undulator frequency. In such situation, an increase/decrease of particle energy in the repulsed Coulomb field of space charge leads to a decrease/increase in particle longitudinal momentum. Correspondingly, Coulomb repulsion can lead to an effective attraction of the particles (this effect is analogous to the known cyclotron negative-mass instability). A large value of the uniform field that is necessary in this method can be used to easily obtain a undulator field by inserting a simple steel helix inside a pulsed solenoid. Simulations confirm that the particle attraction can provide a powerful and narrowband radiation of the bunch with electron energy (5-6) MeV and duration 0.3 ps at the frequencies up to 3 THz.

SHORT BUNCHES IN MICROUNDULATORS

The first opportunity may be realized if bunches with duration of about of 100 fs or even shorter are formed at the entrance of a radiation section. In this case, one can use a mm-period undulator (microundulator) and produce the radiation with the frequency up to 10 THz and higher. A small undulator period provides a relatively narrow-band radiation at comparably short radiation length where the longitudinal particles expansion is not too large even at very high bunch charges if the corresponding energy chirp is also used. For such situation, we propose a helical undulator in the form of a set of a helically spaced magnet block interspaced with a preliminarily non-magnetized steel helix; such a set with helically periodic elements being inserted into a solenoid redistributes its field adding the required helical component in it (Fig. 1). The magnet block should be permanently magnetized toward the solenoid field. This method was successfully developed for a plane prototype in [4]. A strong solenoid field prevents also the transverse particles expansion. According to simulations on the basis Microwave Studio code the optimized undulator systems of such a kind with the ratio of longitudinal helix thickness to the separations 1:2 can provide a strong transverse helical field with the amplitude up to (0.7-1.0) T at an acceptable gap-period ratio 1:3 (Table 1). Such fields provide, in particular, a sufficiently large undulator parameter K=0.3-0.4 at the small period of (4-5) mm. Simulations of Coherent Spontaneous Undulator Radiation of an electron bunch in a combined magnetic field of the solenoid and steel and preliminarily magnetized helical insertions was carried out on the basis of a self-consistent one-dimensional model of the bunch in the form of a charged plane layer using simple formulas for the field of an arbitrary moving charged plane [5]. Such one-dimensional simulations were used for estimations of interaction and radiation from thin disc-like electron bunches with the following parameters: charge (50-200) pC, radius 0.4 mm, duration (50-100) fs, energy 5.5 MeV and a large energy chirp (0.3-1.0) MeV moving in a waveguide mounted into the undulator with the length (5-10) cm. According to calculations one may expect to obtain in such situation narrowband picosecond pulses with the radiation frequency up to (10-20) THz and energy up to (0.1-0.4) μJ.

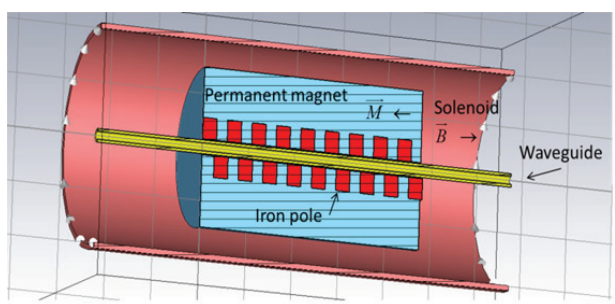

Figure 1: Microundulator for a source of Coherent Spontaneous Radiation of a dense electron bunch with the frequency up to (10-20) THz consisting of a solenoid and insertions in the form of a magnetized block and a non-magnetized steel helix.

#nezahb@ariel.ac.il

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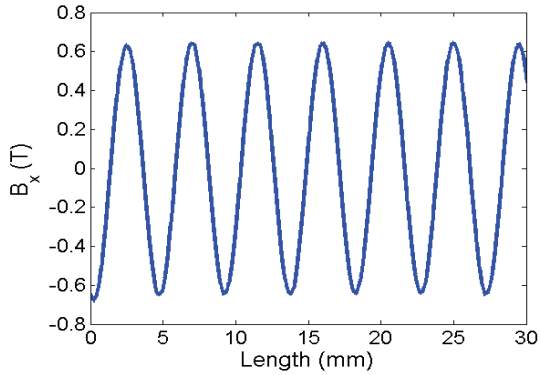

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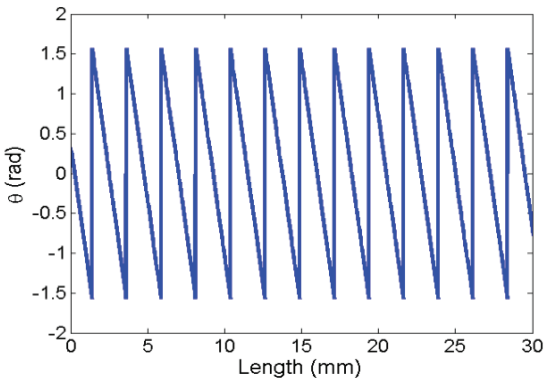

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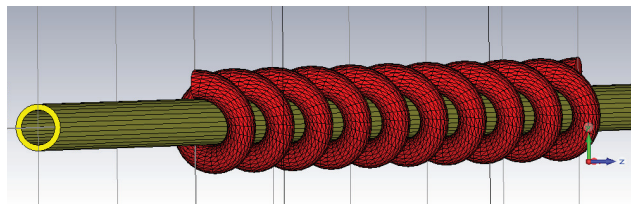
Figure 2: Results of simulations for transverse magnetic field at the axis of symmetry of microundulator on the basis of Microwave Studio code: a) x-component and b) phase.

Table 1: Parameters of Microundulator

Field of solenoid, T	0.8
Period, mm	4.5
Gap, mm	1.5
Height of steel poles, mm	6
Height of magnet block, mm	15
Helical undulator field, T	0.7

NEGATIVE-MASS BUNCH STABILIZATION

The second considered method is intended to realization of a promising idea [2,3] for an effective longitudinal electron bunching in a combined helical and very strong (over-resonance) uniform magnetic fields. Such effect can occur when the cyclotron electron frequency is significantly larger than its undulator bounce-frequency. It is known that in this region of parameters the longitudinal velocity of a particle can decrease/increase with an increase/decrease in its energy [6,7]. Correspondingly, like in the classic cyclotron negative-mass instability of non-isochronously oscillating and interacting charged particles [8,9], the change of the particle energy in the repulsing Coulomb field of a bunch leads to the longitudinal electron attraction and bunching of particles. In this paper, we propose to use a very large value of the uniform magnetic field that is required for such Negative-Mass Stabilization for easy obtaining the transverse undulator field by inserting a one steel helix inside a pulsed solenoid with a strong field that leads to a proper redistribution of this field. For example, a steel helix with the period 2.5 cm mounted in the axial magnetic field 8 T (Fig. 3) can easily provide the undulator parameter K=0.5-1.0 (despite the fact that the axial field significantly exceeds the saturation value for steel and other magnetic materials). In such fields the cyclotron frequency of the particles with energy 5.5 MeV



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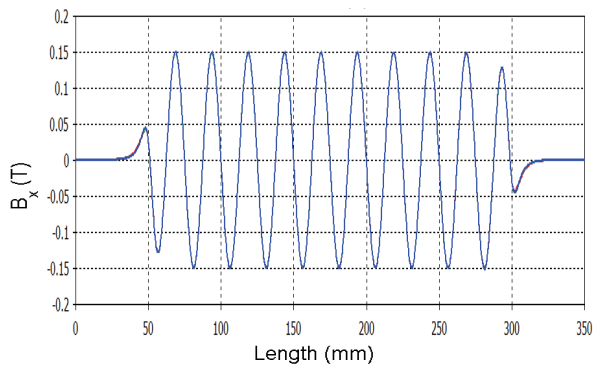

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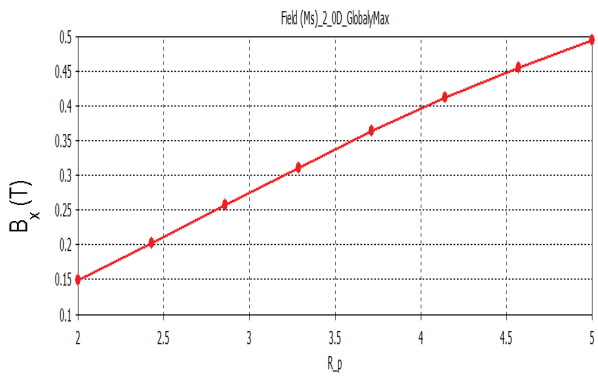

c)

Figure 3: Helical undulator for Negative-Mass Stabilization of the electron bunch: a) a steel helix wound on cylindrical waveguide with outside diameter 10 mm and inserted inside a solenoid with a strong field, b) axial distribution of transverse undulator field, c) dependence of amplitude of transverse field on helix radius r.

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is 60% larger than their undulator frequency. Simulations for the bunch with the charge 300 pC on the basis of General Particle Tracer code (Fig. 4) demonstrate a good coincidence with results of calculations for an ideal model studied in [2]. Due to the Negative-Mass effect the longitudinal size of the nucleus of the electron beam is nearly constant at a large undulator length. Correspondingly, the effective particle attraction in such conditions can provide a powerful and narrowband radiation at the frequencies (1-3) THz.

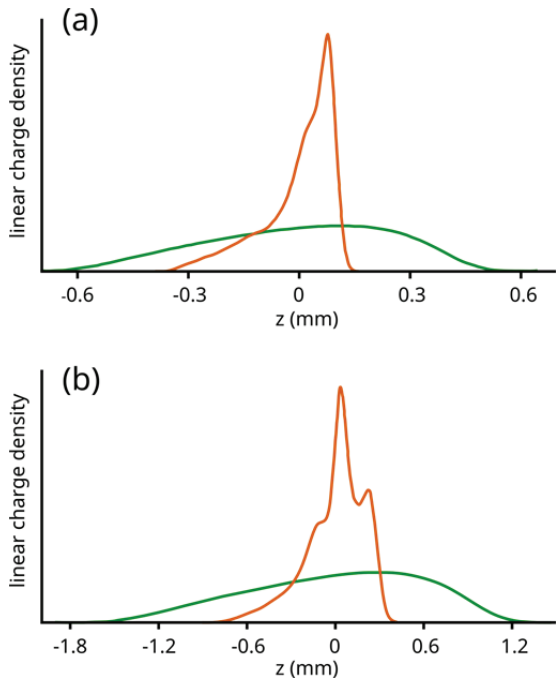

Figure 4: Density distribution for the electron bunch in the combined undulator and uniform magnetic fields in negative- and positive-mass regimes (solid and dashed curves correspond to the guiding field +8 T and -8 T, respectively) after the distance 45 cm (a) and 90 cm (b).

Table 2: Parameters of Electron Beam and Undulator for a THz Source with Negative-Mass Stabilization

Electron bunch		Undulator	
Energy, MeV	5.5	Period, mm	25
Charge, pC	300	Axial field, T	8
Duration, ps	330	Transverse field, T	0.15

CONCLUSION

Two methods have been proposed and theoretically studied for possible power and frequency enhancement in the constructing Israeli source of THz coherent spontaneous radiation of short ultrarelativistic electron bunches.

Use of very short electron bunches with duration of (50-100) ps and a large energy chirp together with a proposed helical modification of the microundulator based on redistribution of uniform magnetic field of a solenoid by a periodic set of preliminarily magnetized and non-magnetized materials (Fig. 1) could increase the maximum frequency of the source from (3-4) THz to (10-20) THz and significantly narrow its radiation spectrum.

The simple steel helical structure inserted into a strong field of solenoid (Fig. 3) can be also used for obtaining a helical undulator field and realization of Negative-Mass Stabilization regime that may lead to significantly higher efficiency and narrower bandwidth of radiation

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