# Coherent spontaneous THz undulator radiation from dense electron bunches formed in laser-driven photo-injectors

V.L. Bratman[1,2], N. Balal[1], I.V. Bandurkin[2], A. Friedman[1], Yu. Lurie[1], and A.V. Savilov[2]

[1]Ariel University, Ariel, Israel, v_bratman@yahoo.com
[2]Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia

## Introduction

Short dense bunches formed in advanced photo-injectors can be effectively used for generation of powerful coherent spontaneous Doppler-frequency-up-shifted radiation. Several methods have been proposed to weaken longitudinal Coulomb repulsion of electrons in bunches to significantly increase the radiation energy and frequency of such sources. In this presentation, we discuss methods which can be used in the THz source [1] that is now under construction in Ariel University, Israel, and in other relatively compact sources using particle energy of the order of 3–6 MeV. These are pre-modulation and energy chirping of bunches as well as using space charge of the bunch for stabilization of its longitudinal size due to development of Negative Mass Instability (NMI).

## Evolution of Modulated Bunches

One method of providing a modulation of bunches is the use of a temporal modulation of laser power at a photo-cathode. Due to fixation of the period of modulation, the electron density can be decreased by enlarging longitudinal or radial sizes of the bunch while maintaining the coherent nature of the process and the magnitude of the radiated energy.

If the bunch shape is close to a thread and its radius is much smaller than the period of modulation in the own reference frame, the Coulomb force decreases many times at the one period; different periods are almost independent and the value of the period stays nearly constant. This may lead to excitation of nonlinear plasma waves with disappearance and reappearance of modulation with narrow spikes at quarter and half of plasma wave period, respectively, (Fig. 1) [2]. The opposite case of quasi-planar disks as well as intermediate case, which are important for powerful generation, will be discussed in this presentation.

In contrast with threads, particle bunching and overtaking are impossible in modulated electron discs and 1D planar layers with a static initial density distribution; in such systems, longitudinal displace-ments of the particles do not generate sufficient restoring forces and plasma oscillations, but only lead to longitudinal expansion with an increasing period of modulation. For example, for the cosine initial distribution in a 1D planar layer (Fig. 2), the density evolves as

$$\rho(x) = \rho_0(x_0)/(1+q_0+\varepsilon q_0 \cos hx_0), \ \rho_0(x_0) =$$
$$= \rho_0(1+\varepsilon \cos hx_0)$$

where the function $x = x(x_0,t)$ describes motion of an electron with a constant invariant acceleration whose absolute value increases with an initial coordinate $x_0$,

$q_0 = (\omega_b t)^2/2$, and $\omega_b = (4\pi e\rho_0/m\gamma^3)^{1/2}$ is the electron plasma frequency. A developed 1D theory of evolution of moving layers and disks is confirmed with simulations based on General Particle Tracer (GPT) [3] as well as on original 3D space-frequency WB3D code [4]. The excitation of plasma waves in the treads occurs at constant modulation period and allows excitation of high-frequency radiation harmonics. However, at the same plasma frequency, the amplitude of modulation changes in this case faster than for disks where the period increases. Choosing one or the other bunch shape is mainly determined by the possibilities of specific accele-rators. In both cases, guiding magnetic field is needed for transverse confinement of the electron bunches.
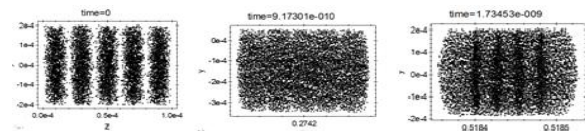


**Fig. 1**. Excitation of a plasma wave in a thread with 100% cosine density distribution (GPT-simulations; disappearance and reappearance of modulation in accordance with [2])
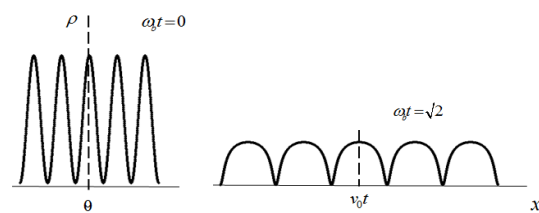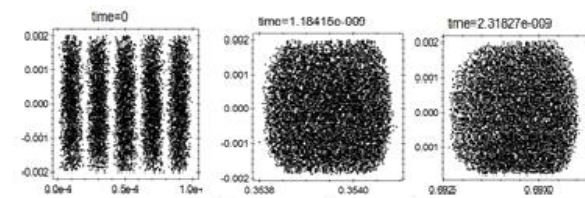


**Fig. 2.** Expansion of a disk (GPT simulations) and a 1D planar layer with 100% cosine density modulation (analytical result). No plasma wave excitation

## Negative Mass Instability in Bunches

Unlike the above situation, the space charge can even maintain the long-living electron "core" in the bunch [5, 6] if conditions for NMI in undulators [7, 8] are fulfilled. It can be achieved in a combined undulator and over-resonance uniform longitudinal magnetic field. In such conditions, increase/decrease in energy of an electron under action of space charge can lead to decrease/increase in its longitudinal velocity. In this case, development of NMI can lead to formation of a dense "core" with a sufficiently small longitudinal size (Fig. 3)

that can coherently radiate high energy at THz frequencies into a narrow vacuum wave-beam or into several dominant modes of a waveguide (Fig. 4).
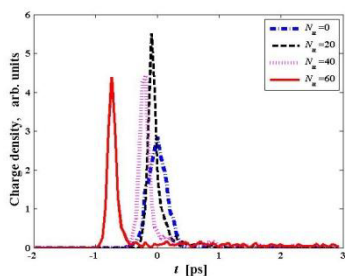


**Fig. 3.** Bunch density after each 20 undulator periods for charge 0.5 nC. Bunch tail shifts peak of distribution out of center of mass (time is given relative to center)
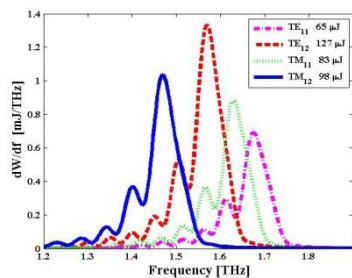


**Fig. 4.** Spectral density of the radiation at dominant waveguide modes for charge 0.5 nC after 40 undulator periods

It has been demonstrated in detail, both for the bunch moving in a transversely uniform undulator field and radiating in free space based on Lienard-Wichert approach, as well as for a more realistic 3D geometry of undulator field and THz waveguide with WB3D code [7, 8]. Injection of a dense bunch on a stationary helical trajectory with small amplitude of parasitic cyclotron oscillations can be provided if the bunch with a definite chirp of transverse velocities enters first a solenoid with an operating value of the guiding field and after that moves in a section with adiabatically increasing undulator and uniform field.

A strong magnetic field that is necessary in NMI regime can be used for creation of required undulator field. It can be done, for example, using a redistribution of the uniform field of the solenoid by a ferromagnetic (steel) helix (Fig. 5) [5]. For example, a helix with a period of 2.5 cm and an inner diameter of 10 mm wound of a steel wire with a radius 3 mm and mounted into solenoid with a field 75 kOe provides sufficient amplitude of transverse helical field 2 kOe (these parameters are used in Figs. 3, 4, 6, 7).

Simulations demonstrate a possibility for significant efficiency enhancement and narrowing of spectrum for THz undulator radiation from short and very dense electron bunches thanks to both pre-modulation and NMI-stabilization of dense electron bunches. Combination of these two methods allows formation of nearly periodic and long-living sets of dense narrow bunches (Fig. 6) which can be used for more selective excitation of waveguide modes (Fig. 7) and for obtaining radiation at higher undulator harmonics. All these methods open the way for implementation of efficient sources of narrow-band THz pulses with milli-Joule energy, picosecond duration and easy wide-band frequency tuning. Such pulses can be prospective for pump-probe experiments.
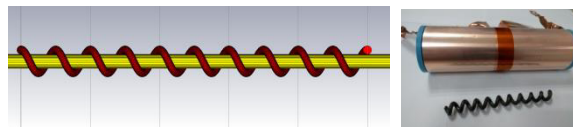


**Fig. 5.** Helical undulator in the form of steel helix wound on cylindrical copper waveguide and placed inside solenoid with strong guiding field
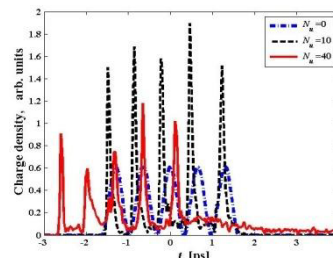


**Fig. 6.** Electron density after 10 and 40 undulator periods for a thread with 100% cosine initial density modulation and charge 2.5 nC (WB3D-simulations)
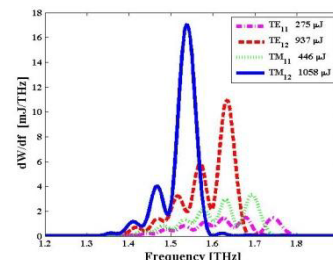


**Fig. 7.** Spectral density of the radiation at dominant waveguide modes for a thread with 100% cosine initial density modulation, charge 2.5 nC and 40 undulator periods

## References

1. *A. Friedman, N. Balal, E. Dyunin, Yu. Lurie, E. Magori, V.L. Bratman, J. Rosenzweig, H. Lay To, A. Gover.* Configuration and status of the Israeli THz free electron laser.// *Proc. 36th Intern. FEL Conf.*, Basel, 2014, 553.

2. *P. Musumeci, R. K. Li, and A. Marinelli.* Nonlinear Longitudinal Space Charge Oscillations in Relativistic Electron Beams // Phys. Rev. Lett., 106, 184801, 2011.

3. http://www.pulsar.nl/gpt.

4. *Y. Pinhasi, Yu. Lurie, A. Yahalom.* Space-frequency model of ultrawide-band interactions in free-electron lasers// Phys. Rev. E, 71, 036503, 2005.

5. *N. Balal, I. V. Bandurkin, V. L. Bratman, E. Magory, and A. V. Savilov.* Negative-mass mitigation of Coulomb repulsion for terahertz undulator radiation of electron bunches. // *Appl. Phys. Lett.*, 107, 163505, 2015.

6. *Yu. Lurie, V.L. Bratman, and A.V. Savilov.* Energy Enhancement and Spectrum Narrowing in Terahertz Electron Sources due to Negative Mass Instability. // Phys. Rev. AB 19, 050704, 2016.

7. *H.P. Freund and P. Sprangle,* Unstable electrostatic beam modes in free-electron-laser systems. //Phys. Rev. A 28, 1835, 1983.

8. *N.S. Ginzburg and N.Yu. Peskov,* Nonlinear theory of relativistic ubitrons with electron beams formed in adiabatically increasing undulator and uniform longitudinal magnetic fields. //Tech. Phys. 58, 859, 1988.