GENERATION OF NON-RELATIVISTIC ELECTRON BUNCHES AND MEASUREMENT OF THEIR BASIC PARAMETERS

V.N. Bolotov, S.I Kononenko, V.I. Muratov, V.D. Fedorchenko
Karazin National University, Kharkov, 61007, Ukraine
E-mail: bolotov@vl.kharkov.ua

This research aims to explore a possibility of generation of short electron bunches by Bernstein-Green-Kruskal (BGK) – waves and measurement of their parameters. The experiments showed that the BGK-waves can be used to form short electron bunches with time durations ranging between 50 and 100 ps.

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1. INTRODUCTION

For a number of certain applications, the problem of forming short electron bunches, which could be stable against the Coulomb repulsion, and taking measurements of their parameters looks very challenging, indeed. As shown in reference [1], this problem can be resolved in part by utilizing the ponderomotive force which is accounted for by the radiation fields. This indicates that particles in the bunch must be imparted such transverse oscillatory velocity that would result in appearance of the radiation fields which are employable to focus the electron bunch in the longitudinal direction. The oscillatory motion may well be either particle gyration in a homogeneous longitudinal magnetic field, or it can be attributed to particle oscillations in an external electromagnetic field. The ponderomotive force with which two phase-locked oscillating particles interact is the one of attraction, if the distance between the particles is smaller than half of the radiation wavelength [2].

The measurement of lengths of single relativistic electron bunches have been the subject of many research works to date [3, 4, 5]. In this way [3], the longitudinal shape of an electron bunch was coded electro-optically in the spectrum of a chirped laser pulse. The length of the bunch was determined by analyzing the spectrum of a single laser pulse as produced in the presence and absence of the electron bunch. Since the pulse width of the chirped laser can be easily modified, the electron bunch can be visualized in different timeframes. This technique has a lot of promise for non-destructive testing diagnostics in the real timeframe.

At one and the same time, the issues of formation of the indestructible, short non-relativistic electron bunches and measurement-takings of their parameters have hardly been studied well enough. The non-relativistic electron bunches can be formed either by solitons or by the Bernstein-Green-Kruskal waves (BGK-waves). The BGK-waves are non-linear quasi-stationary waves that have a great number of captured particles [6, 7] and propagate without changing their profile and amplitude. The experiment [8] demonstrated that the quasi-stationary wave was brought about by an electron beam passing through plasma which was viewed as a periodic sequence of steady-density bunches.

2. EXPERIMENTAL RESULTS

The objective of this research was to make a feasibility study on production of short electron bunches, using the BGK-waves, and measurement of their parameters.

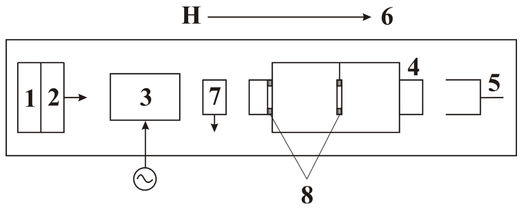

Fig.1. Experimental setup: 1, 2 – electron guns; 3 – modulator; 4 – cavity resonator; 5 – collector; 6 – coil of magnetic field; 7 - capacity probe; 8 – aperture

The setup of the experimental facility is given in Fig.1. Two inter-penetrative electron beams (1, 2, Fig.1) were passed through a metallic pipe placed in a homogeneous magnetic field of the strength 400 Oe. (6, Fig.1). The velocities of both beams exceeded the critical one and were $3\cdot10^9$ cm/s and $3.6\cdot10^9$ cm/s, the total current being 40…50 mA.

The effective pressure in the chamber was $2\cdot10^{-6}$ Torr. The initial perturbation was made when the oscillator fed high-frequency voltage to the modulator (3, Fig.1). The modulating voltage at the frequencies 500…1200 MHz came from 1W-oscillator. Downstream from the collector (5, Fig.1) was an electrostatic analyzer used to measure the energy characteristics of the beams.

The measurements were made of the wave amplitude distribution along the system's length and wave phase velocities with a movable high-frequency probe which was an antenna terminated by a resistance that was equal to the characteristic impedance of the cable. The phase velocity of oscillations for different modulation frequencies was measured by using a technique of comparing the reference signal phase and probe signal. To measure the harmonic content of the oscillations of the bunch potential we used a capacity probe (7, Fig.1) terminated to the characteristic impedance of the cable. In further experiments, downstream from the modulator was a circular movable cavity resonator (4, Fig.1), signals from which were detected using a coupling loop and fed to either an oscillograph, or a spectral analyzer operating in the range up to 40 GHz. At the input and in the center of the cavity resonator were apertures (8, Fig.1) used to generate transition radiation when the electron bunches passed through them [11].

In the absence of the modulating signal the two-beam electron system was stable, because the beams were under beyond-the-critical conditions. The feeding of the finite amplitude signal brought the system into unstable state, the wave amplitude growing exponentially with an increasing modulator-probe distance. The phase velocity, as taken at different beam velocities and modulation frequencies, was $(3\ldots4)\cdot10^9$ cm/s. Upon reaching certain amplitude, the wave captured electrons of the beams and a non-linear BGK wave was thus formed after which the phase velocity variations became impossible.

The evaluation of the capture amplitude was made according to the capture formula:

$$\varphi_0 = \frac{m}{2e}\left(v_b - v_{ph}\right)^2,$$

where v_b – beam velocity, v_{ph} – wave phase velocity. The capture amplitude was as high as 10…15 V at different beam energies and modulation frequencies.

Table 1. *Amplitudes of harmonics*

Harmonics	Modulation frequencies		
	648 MHz	925 MHz	1850 MHz
1	12.5	2	2
2	4.5	2	2
3	3.5	3	3
4	1	1.35	1.35
5	2.5	1.4	1.4
6	1.5	0.33	0.33
7	–	0.66	0.66
8	–	0.75	0.75

At a certain beam velocity-to-current ratio the capacity probe registered a broadband signal. The harmonic content of this signal was obtained experimentally for modulation frequencies 648 and 925 MHz. The spectral analyzer was used to measure relative amplitudes of the broadband signal harmonics, the high-frequency path calibration done with the aid of the reference oscillators. Table 1 gives relative amplitudes of the harmonics for different modulation frequencies.

We assumed that the process of electron bunch formation should occur with the scales for the high frequencies of modulation remaining unchanged, and, bearing this in mind, in the event of the modulation frequency 1850 MHz we left in the same relationship between harmonic amplitudes as was the case for the frequency f_0=925 MHz.

By solving the inverse Fourier problem for different modulation frequencies, one can determine accordingly the bunch potential shape vs. time. This shape is seen as a narrow pulse the half-width of which is 192 ps for the modulation frequency 648 MHz, 96 ps for the modulation frequency 925 MHz and 48 ps for the modulation frequency 1850 MHz (Fig.2).

Knowing the bunch velocity and its potential half-width, one could now evaluate its longitudinal dimension. Thus, for example, for the modulation frequency f_0=925 MHz the bunch longitudinal dimension was on the order of 3 cm, the bunch transverse dimension determined by sizes of the cathode and being 0.6 cm.

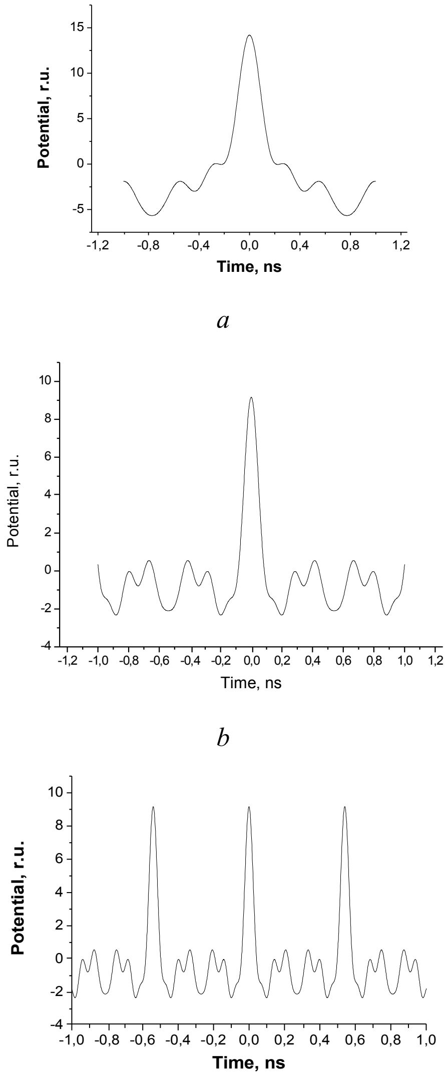

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Fig.2. Relationship of electron bunch potential vs. time for different modulation frequencies:
a) f_0=648 MHz; b) f_0=925 MHz;
c) f_0=1850 MHz

The particle density in the bunch was 10^8 cm^{-3}, the total number of electrons being $N = 4\cdot10^7$.

To check on the bunch equilibrium we developed the following technique. For the measurement-takings we employed a cavity resonator which could be moved along the length of the system. The cavity resonator pipe had a wire mesh placed over it. This cavity resonator was employed to diagnose the transition electromagnetic radiation generated by the electron bunch on the mesh, with the cavity oscillator being excited at its proper frequencies which were the modulation frequency harmonics. At the modulation frequency 1220 MHz the fifth harmonic amplitude was measured relative to the modulator-cavity resonator distance (4, Fig.1).

From Fig.3 it is obvious that at a distance l<12.5 cm the cavity resonator is not excited. With increasing distance the harmonic amplitude increases, as well, and remains constant. This implies that after the bunch is formed, it remains in equilibrium over a considerable transit distance.

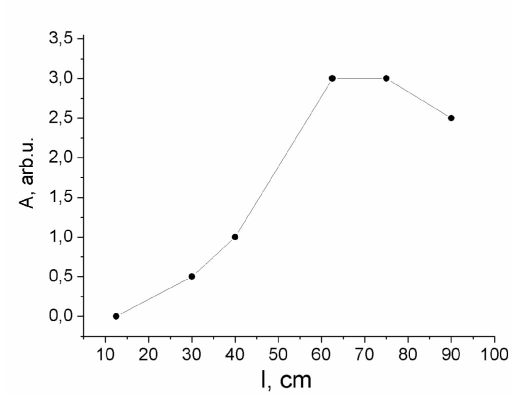

Fig.3. Dependence of 5[th] harmonic f_{mod}=1220 MHz on modulator-cavity resonator distance

The measurements of the beam energy spectrum indicated that the smaller portion of electrons was wave-accelerated. The energy analyzer was used to measure electron velocities in the presence of the wave of the finite amplitude and in its absence. The difference obtained between velocities of the fastest electrons and wave phase velocity, as substituted in the capture formula, came out with the value of the high-frequency wave potential which was equal to 15 V.

CONCLUSIONS

In a two-electron beam system a quasi-stationary non-linear wave was produced in constant magnetic field with a large number of particles captured, if its amplitude exceeded the capture amplitude. Our research tends to show that by using this wave one can form non-relativistic electron bunches the potential of which over time is a narrow pulse (100 ps). This is achievable by bringing up to the optimum the beam current-to-power ratios. Parameters of the bunches were measured, the feasibility demonstrated of their remaining in equilibrium over certain lengths.

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ГЕНЕРАЦИЯ НЕРЕЛЯТИВИСТСКИХ ЭЛЕКТРОННЫХ СГУСТКОВ И ИЗМЕРЕНИЕ ИХ ОСНОВНЫХ ПАРАМЕТРОВ

В.Н. Болотов, С.И. Кононенко, В.И. Муратов, В.Д. Федорченко

Работа посвящена исследованию возможности генерации коротких электронных сгустков волнами Бернштейна-Грина-Крускала (БГК) и измерению их параметров. Эксперименты продемонстрировали, что БГК-волны могут быть использованы для формирования коротких электронных сгустков продолжительностью от 50 до 100 пс.

ГЕНЕРАЦІЯ НЕРЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОННИХ ЗГУСТКІВ ТА ВИМІРЮВАННЯ ЇХ ОСНОВНИХ ПАРАМЕТРІВ

В.М. Болотов, С.І. Кононенко, В.І. Муратов, В.Д. Федорченко

Робота присвячена дослідженню можливості генерації коротких електронних згустків хвилями Бернштейна-Гріна-Крускала (БГК) і вимірюванню їх параметрів. Експерименти продемонстрували, що БГК-хвилі можуть бути використані для формування коротких електронних згустків тривалістю від 50 до 100 пс.