EXCITATION OF THE REPETITION FREQUENCY HARMONICS OF ELECTRON BUNCHES AT THEIR INJECTION TO ATMOSPHERE

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The origin of microwave radiation when injecting a regular train of relativistic electron bunches into atmospheric pressure air is studied experimentally. Measurements of the wavelength of microwave oscillations were made when they form a standing wave. The microwave oscillations have the largest amplitude, when their frequency is close to the tripled repetition frequency of the electron bunches. The radiation mechanism is a direct conversion of excited plasma oscillations to periodic small-scale in homogeneities of the plasma. When the sequence of bunches is injected into the atmosphere, the radiation with the greatest amplitude is observed from the plasma region with a plasma frequency close to the tripled bunch repetition frequency. This is because the frequencies of the first and second harmonics are much lower than the frequency of collisions of plasma electrons with neutral molecules at an air pressure close to atmospheric. The frequency of the third harmonic is only half the collision frequency; this allows plasma oscillations to develop at this frequency. The wavelength of the third harmonic is twice as long as the length of the electron bunches, which also leads to an increase in its amplitude relative to the first and second harmonics.

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INTRODUCTION

The issue of the generation of electromagnetic radiation near the plasma frequency has been actively studied for tens of years. This problem is still of interest for investigations of various astrophysical phenomena [1] and also in the interpretation of the results of laboratory beam-plasma experiments [2]. In this case, modulated electron beams or a train of electron bunches can be used to excite intense plasma oscillations, with possible further conversion into microwave radiation. Due to the pre-modulation of the beam, regular narrow-band signals with deterministic phases can be excited in the plasma. Only such waves can be used to implement plasma methods for accelerating charged particles. Moreover, preliminary modulation makes it possible to reduce the region of linear increase in the amplitude of the excited waves and to increase the efficiency of converting the beam power into the power of the excited waves in the plasma. In this case, the excitation efficiency of plasma waves increases [3]. Also, the problem of acceleration with wake field excited in plasma remains actual. Therefore, further investigation plasma oscillations and microwave radiation excited by electron bunches in a plasma is necessary. The paper presents experimental results of investigations of microwave radiation and wake fields during the injection of a regular train of relativistic electron bunches into a plasma created by the bunches themselves in air at atmospheric pressure.

The electromagnetic wave excited by the bunches has a maximum of the field amplitude at a distance of 8…10 cm from the output foil, in this region the plasma density is close to $8{\cdot}10^{11}$ cm^{-3}, that corresponds to the plasma resonance density for a plasma frequency equal to the frequency of the third harmonic of bunch repetition frequency. In this case, the transverse dimensions of plasma and the transverse dimensions of the beam are comparable with the wavelength of the excited oscillations.

1. PLASMA CREATION

The experiments were carried out by injecting electron bunches from the traveling-wave linear accelerator "Almaz-2M" into the air. The electrons have the energy of 4.5 MeV, the pulse current is 0.5 A, and the pulse duration is 2 μs. Each pulse consists of a sequence of $6{\cdot}10^3$ electron bunches, the repetition frequency of bunches is 2805 MHz with a duration of each $\tau_b \approx 60$ ps, (bunch length $\ell \approx 17$ mm), and a time interval of about 300 ps. The charge of each bunches is 0.16 nC. The beam diameter at the exit from the accelerator is ~ 10 mm. Electron bunches from the accelerator were injected through a titanium foil 50 μm thick, with an increase in the angular divergence of the beam <θ>. If there is no foil <θ> = 0.15°, then after passing through the titanium foil, the divergence increases to ≈ 12°.

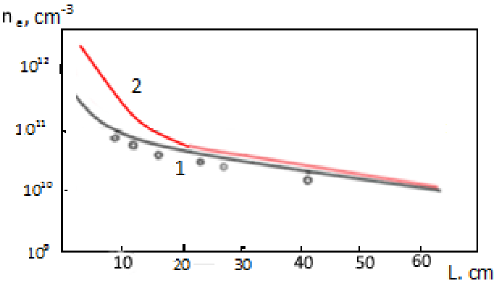

Fig. 1. The value of the plasma density along the beam axis as a function of the distance to the accelerator: 1 is average density value per pulse, 2 is the maximum value of the plasma density. The circles are the average measured value of the plasma density

When the electron bunches are injected into the air at atmospheric pressure, an inhomogeneous no stationary plasma is formed with a density that decreases along the propagate axis [4]. In Fig. 1, curve 1 corresponds to the calculated average steady-state plasma density [4]. The circles show the experimentally measured average density value. At the same time, the plasma density, which is maximal during the bunch repletion period, can be an order of magnitude higher (see Fig. 1, curve 2).

2. EXPERIMENTAL RESULTS

Measurements of the wavelength of microwave oscillations excited when injecting the regular sequence of relativistic electron bunches into the plasma created by the bunches themselves at atmospheric pressure air were made when electromagnetic waves formed standing waves. A standing wave was formed when the beam was injected into a glass tube (interaction chamber) of 6 cm in diameter and 60 cm in length. The tube was filled with air, the pressure of which could be varied within 50…760 Torr. At the other end of the pipe was a copper collector, from which the microwave radiation could be reflected (Fig. 2).

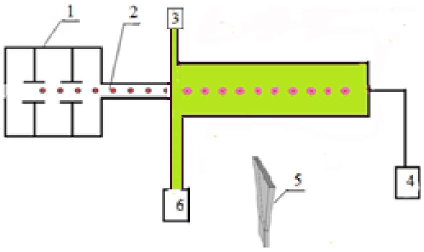

Fig. 2. Installation for standing wave formation in a glass interaction chamber: 1 is electron accelerator; 2 – electron bunches; 3 – vacuum meter; 4 – oscilloscope; 5 – H-sector horn antenna; 6 – gas valve

Along the tube, at a distance of 2…5 cm a horn antenna of 3 cm wavelength range can be moved, the wide side of the horn was located perpendicular to the axis of the beam. Then the signal was detected and fed to an oscilloscope. To increase the spatial resolution, the width of the narrow side of the horn was reduced to 1 cm (H-sector horn antenna). The measurement result is shown in Fig. 3.

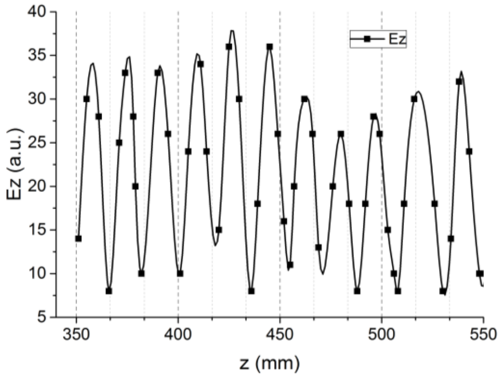

Fig. 3. Standing wave formed in a glass tube

The distance between the minima of the standing wave is about 1.7 cm, which corresponds to the excitation of microwave oscillations with a wavelength of 3.4 cm (frequency of 8.8 GHz).

When the air pressure in the interaction chamber varied within 50…760 Torr, the frequency of the excited microwave oscillations did not change.

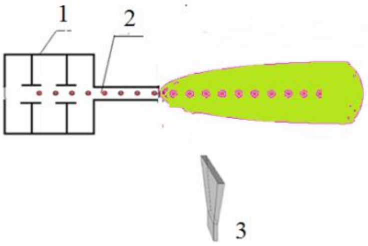

Fig. 4. Injection of electron bunches into the air: 1 – electron accelerator; 2 – electron bunches; 3 – H-sector horn antenna

Also, studies were made of the excited microwave oscillationsduring the injection of a sequence of electron bunches into the atmosphere after they left the linear accelerator (Fig. 4). The horn antenna was moved at a distance of the axis of the beam of 12 cm.

The amplitude of the microwave radiation on the distance from the output foil of the accelerator changes as shown in Fig. 5. The maximum amplitude of the field is observed at a distance of 8…10 cm from the output foil, in this region the maximum plasma density is close to $8\cdot10^{11}$cm^{-3} that corresponds to the resonance density of the plasma for the third harmonic of the bunch repetition frequency.

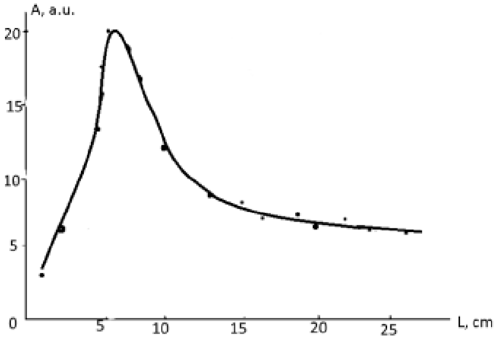

Fig. 5. Dependence of the amplitude of 3 cm radiation from the distance to the exit from the accelerator

Soft X-ray radiation is also observed from this plasma region. At a distance more than 10 cm from the output foil, a significant change in the energy spectrum of the electron bunches is observed.

These phenomena clearly indicate the development of a beam-plasma discharge in this region at the frequency of the third harmonic. It should be noted that the maximum amplitude of X-ray and microwave radiation is observed at a width of the energy spectrum of electrons in bunches $\delta E<15\%$. We carried out possibility of an electromagnetic oscillations excitation which have frequencies equal to the (the first harmonic) and at the double bunch repetition frequency (the second harmonic). As in previous case a wavelength was measured by finding the distance between nodes of standing wave. To record the radiation, we used a 90×45 mm waveguide section with a coaxial-waveguide transition [5] and a detector head with a diode. This section of the waveguide, as in the case of the third harmonic, moved along the interaction chamber parallel to its axis at a distance of about 10…15 cm from the wall. Microwave radiation having a wavelength close to 5 cm with a small amplitude (slightly exceeding the noise level) was recorded. No reliable evidence of excitation of microwave oscillations at the frequency of following clots at atmospheric pressure was observed experimentally.

3. THE DISCUSSION OF THE RESULTS

At the present, there are many theoretical approaches to the problem of electromagnetic emission from a beam-plasma system. Most of these approaches describe a wide enough plasma, whose characteristic dimensions are much larger than the wavelength of the generated radiation. In narrow plasma, several other mechanisms of electromagnetic emission operate. For example, in a system whose transverse dimensions are comparable with the wavelength of the radiation, electromagnetic waves can be emitted directly into the vacuum. The mechanism of radiation of such a system can be compared with the radiation of an ordinary antenna [6]. Its essence is as follows. Because of the development of a two-stream instability that arises during the injection of a beam into plasma, a quasi-stationary longitudinal wave forms in it. In order for it to interact resonantly with vacuum electromagnetic waves, its phase velocity must exceed the speed of light. Since the wave is at the Cherenkov resonance with the beam, this condition can’t be satisfied in homogeneous plasma. If, however, the plasma density is modulated along the beam propagation axis in a harmonic manner, scattering by density in homogeneities will generate superluminal field perturbations that can effectively interact with vacuum electromagnetic waves. Thus, a necessary condition for the appearance of radiation in such system is the presence of longitudinal perturbations of plasma density.

A theoretical model describing such a mechanism of electromagnetic emission from a thin beam-plasma system near the harmonic of the plasma frequency is presented in [7, 8]. In our case the diameter of the plasma at a distance of 8 cm from the exit foil is about 4 cm and it is close to the wavelength of the third harmonic λ_3=3.4 cm. The spatial period of the plasma density gradients is 10 cm. This suggests that a direct conversion of plasma oscillations to microwave oscillations occurs at the frequency of plasma oscillations. A beam-plasma antenna is formed. However, the frequency of the microwave radiation in this case should be close to the frequency of the plasma wave excited by bunches. Plasma oscillations, like microwave oscillations, should oscillate at the tripled bunch repetition frequency. To explain the experimental results it is necessary to determine the collision frequency of plasma electrons.

The characteristic time of energy loss by plasma electrons is ~ $10^{-11}\ldots10^{-10}$ s [9]. After this time, the electron temperature in the molecular gases is apart of 1 eV. Thus, in plasma formed by an electron beam in air at atmospheric pressure, the energy of plasma electrons is close to 0.03 eV (v_e= 10^7 cm/s) [10]. The cross section of electron collisions with nitrogen molecule sat this electron energy $\sigma_{ea}\approx 4\cdot10^{-16}$ cm^{-2} [11]. Thus, the collision frequency of plasma electrons with gas molecules is $\nu_{ea}=N_a v_e \sigma_{ea}= 2.7\cdot10^{19}\cdot10^{7}\cdot4\cdot10^{-16}=1.08\cdot10^{11}s^{-1}$. This value of the collision frequency agrees well with the data of [12], where plasma is produced by an RF discharge in the atmosphere. At that conditions electron energy was 1 eV and the measured collision frequency $\nu_{ea} = 2\cdot10^{11}s^{-1}$.

According to [13], the criterion for the possibility of the development of plasma oscillations is the expression

$$2\omega_p>\nu_{ea}.$$

When this criterion is satisfied, the plasma is weakly collisional and plasma oscillations can develop in it. This is obviously due to the fact that when the plasma electrons are scattered, the latter must experience several collisions before the direction of its momentum changes [14]. The reason for the absence of plasma oscillations at the frequency of bunch repetition ($\omega_1 = 1.76\cdot10^{10}$ rad/s) and their insignificant amplitude at the doubled frequency ($\omega_2 = 3.51\cdot10^{10}$ rad/s) is that the frequency of collisions of plasma electrons with neutral air molecules at atmospheric pressure significantly exceeds frequency of the first and second harmonics. At the same time, the frequency of the third harmonic ($\omega_3 = 5.27\cdot10^{10}$ rad/s) is only half the collision frequency, with $2\omega_3\approx\nu_{ea}$ and this makes possible the development of plasma oscillations at this frequency.

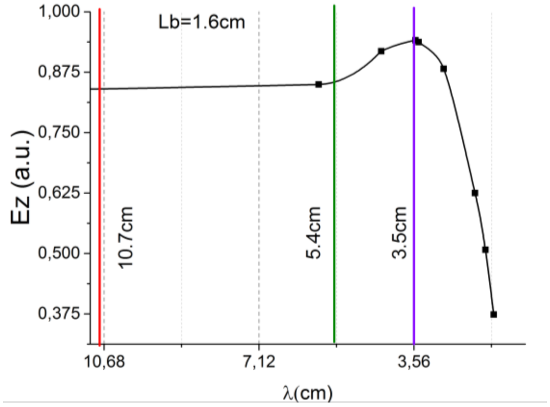

Fig. 6. Wakefield amplitude versus a wavelength. Vertical lines show the wavelength of excited harmonics: the first (10.7 cm), the second (5.4 cm) and the third (3.5 cm) ones. The bunch length is 1.6 cm

The theoretically calculated dependence of the amplitude of plasma oscillations (the intensity of the excited wakefield) on its wavelength for our bunch length is shown in Fig. 6 [15]. Theoretical model applied for these simulations used collisionless plasma. That is for the parameters of the experiment the third harmonic has maximal amplitude even in case of absence collisions in plasma. This result gives additional advantage of an excitation of the third harmonic.

The wakefield with the frequency of the third harmonic is also optimal for wakefield acceleration using electronic bunches obtained at the accelerator “Almaz-2M”. In the wake accelerator, the ratio of the maximum energy gain of the accelerated bunch to the maximum energy loss of the electrons of the driver's bunch is the transformer ratio. The coefficient of transformation has a maximum value for the case when the length of the driver bunch is 0.25…0.5 of the wavelength of the field being excited [16]. In our case, with a bunch length of 1.6 cm, the wakefield with a wavelength equal to the third harmonic of the bunch repetition period (λ_3 = 3.4 cm) satisfies the conditions for obtaining the maximum transformation coefficient.

SUMMARY

When a regular sequence of relativistic electron bunches is injected into an air of atmospheric pressure, plasma that decreases in density is formed. Since the frequency of collisions of plasma electrons is much higher than the bunch repetition frequency, plasma oscillations do not develop either at the bunch repetition frequency or at the double bunch repetition frequency. However, the appearance of microwave oscillations at a tripled frequency of bunch repetition has been experimentally detected. The microwave radiation has a maximum in a localized plasma region in which the plasma frequency is equal to the frequency of the third harmonic of the bunch repetition frequency. Microwave radiation is formed due to direct conversion of plasma oscillations on periodic in homogeneities in the plasma density (a beam-plasma antenna is formed). Plasma oscillations develop when a collision frequency of plasma electrons twice that of the third harmonic ($2\omega_p\approx\nu_{ea}$).

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ВОЗБУЖДЕНИЕ ГАРМОНИК ЧАСТОТЫ СЛЕДОВАНИЯ ЭЛЕКТРОННЫХ СГУСТКОВ ПРИ ИХ ИНЖЕКЦИИ В АТМОСФЕРУ

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Экспериментально исследовано возникновение СВЧ-излучения при инжекции регулярной последовательности релятивистских электронных сгустков в воздух при атмосферном давлении. Измерения длины волны СВЧ-колебаний производились при образовании ими стоячей волны. Наибольшую амплитуду имеют СВЧ-колебания, частота которых близка к утроенной частоте следования электронных сгустков. Механизмом излучения является прямая конверсия возбуждаемых плазменных колебаний на периодических мелкомасштабных неоднородностях плотности плазмы, которая создается электронными сгустками в воздухе. При инжекции последовательности сгустков в атмосферу максимальная амплитуда излучения наблюдается из области плазмы, плазменная частота которой близка к утроенной частоте следования сгустков. Это объясняется тем, что частоты первой и второй гармоник значительно меньше частоты столкновений плазменных электронов с нейтральными молекулами при давлении воздуха, близком к атмосферному. Частота третьей гармоники только в два раза меньше частоты столкновений, что позволяет плазменным колебаниям развиваться на этой частоте. Длина волны третьей гармоники в два раза превышает длину электронных сгустков, что также приводит к увеличению ее амплитуды относительно первой и второй гармоник частоты следования сгустков.

ЗБУДЖЕННЯ ГАРМОНІК ЧАСТОТИ СЛІДУВАННЯ ЕЛЕКТРОННИХ ЗГУСТКІВ ПРИ ІНЖЕКЦІЇ ЇХ В АТМОСФЕРУ

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Експериментально досліджено виникнення НВЧ-випромінювання при інжекції регулярної послідовності релятивістських електронних згустків у повітря атмосферного тиску. Вимірювання довжини хвилі НВЧ-коливань проводилися при утворенні ними стоячої хвилі. Найбільшу амплітуду мають НВЧ-коливання, частота яких близька до потроєної частоти проходження електронних згустків. Механізмом випромінювання є пряма конверсія збуджуваних плазмових коливань на періодичних дрібномасштабних неоднорідностях щільності плазми, яка створюється електронними згустками в повітрі. При інжекції послідовності згустків в атмосферу максимальна амплітуда випромінювання спостерігається з області плазми, плазмова частота в якій є близькою до потроєної частоти проходження згустків. Це пояснюється тим, що частоти першої і другої гармонік значно менші частоти зіткнень плазмових електронів з нейтральними молекулами при тиску повітря, близькому до атмосферного. Частота третьої гармоніки тільки в два рази менше частоти зіткнень, що дозволяє плазмовим коливанням розвиватися на цій частоті. Довжина хвилі третьої гармоніки в два рази перевищує довжину електронних згустків, що також призводить до збільшення її амплітуди щодо першої і другої гармонік частоти проходження згустків.