PLASMA PRODUCTION BY A SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES IN THE TRANSIT CHANNEL OF THE DIELECTRIC STRUCTURE

A.F. Linnik, I.N. Onishchenko, V.I. Pristupa, G.P. Berezina, O.L. Omelayenko, V.S. Us
National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail: aflinnik@kipt.kharkov.ua

In the concept of plasma-dielectric wakefield accelerator plasma presence in the transit channel of the dielectric structure plays at significant role in increasing the accelerating field and providing bunches focusing. The results of the study of plasma production directly by exciting relativistic electron bunches in the channel, filled with an inert gas of different pressure. Measured temporal evolution of the density of the produced plasma, that is in a good agreement with estimates of ionization due to binary collisions of bunch electrons with neutrals or to beam-plasma discharge in the corresponding ranges of the gas pressure.

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INTRODUCTION

Investigations of wakefield excitation by a relativistic electron bunch or a sequence of them in dielectric structures showed the perspective of this method for obtaining high-gradient accelerating fields [1 - 4].

Plasma filling the transit channel of the dielectric structure allows to change the topography of the excited wakefield so that the amplitude of its longitudinal component is increased simultaneously with providing accelerated bunches focusing [5, 6].

We study one of the possible ways to produce plasma in the channel of the dielectric structure, which consists in ionizing neutral gas of appropriate pressure in the channel directly by the sequence of electron bunches exciting wakefield. Earlier, we used such a method of plasma production at the study of plasma wakefield excitation [7]. The density of plasma produced in time during all bunches passing through the channel was measured for various pressures of neutral gas by HF-probe [8] or by an open barrel-shaped resonator (OBR) [9].

1. EXPERIMENT

1.1. EXPERIMENTAL SETUP

The scheme of the Installation is shown in Fig. 1. The sequence of relativistic electron bunches was produced by a linac "Almaz-2M" (1). Accelerated electron beam had the following parameters: energy 4.5 MeV, pulsed current 0.8 A, pulse duration 2 μs. Beam diameter at the accelerator exit was 1.0 cm. The beam consisted of a sequence of $6\cdot10^3$ electron bunches, each of duration 60 ps and charge 0.26 nC. Period of bunch repetition was 360 ps. Electron bunches were injected from the accelerator into the dielectric structure through a titanium foil (2) with a thickness of 30 μ, destined for separating the vacuum region of the accelerator from the region with the neutral gas. The sequence of bunches passed through the transit channel of diameter 2.1 cm in a cylindrical Teflon insert (4) ($\varepsilon = 2.1$, $\mathrm{tg}\delta = 1.5\cdot10^{-4}$) placed into a copper pipe of internal diameter 8.5 cm.

To provide the waveguide regime of wakefield excitation the reflections of wakefield excited in the dielectric structure were reduced by placing a matching cone (5) at the end of the Teflon insert and a ferrite absorber (7) at the structure exit.

The length of the insert was chosen to be equal to the wavelength of the excited dielectric wakefield λ=10.6 cm, that allows at the existing group velocity $v_g=v_0/2$ (v_0 is bunch velocity) to provide a single-bunch regime of the excitation [10], in which the removal of the wakefield of each bunch from the structure does not lead to overlap it with the wakefield of subsequent bunch. This will enable comparison of future experiments on the wakefield excitation in the plasma-dielectric structure with the existing theory of a single-bunch regime of the excitation.

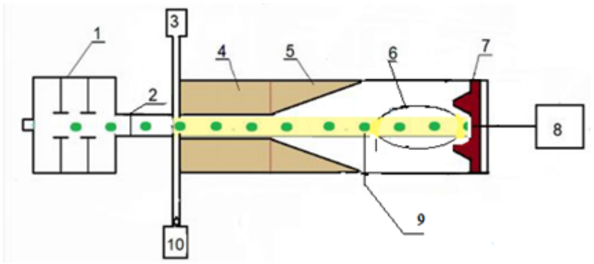

Fig. 1. Experimental setup: 1 – accelerator "Almaz-2M"; 2 – separating titanium foil; 3 – leak valve; 4 – dielectric structure; 5 – matching cone; 6 – open barrel resonator (OBR); 7 – ferrite microwave absorber; 8 – oscilloscope; 9 – HF-probe for plasma density measuring; 10 – forvacuum pump

Neutral gas pressure in the range of 10^{-3}…760 Torr was regulated by gas filling through the leak valve (3), followed by pumping with the forvacuum pump (10). The density of the produced plasma was measured by two methods.

In the first one, the HF probe (9) was placed at the end of the matching cone in the axial region. It determined plasma density by means of measuring the current between two plates, to which a given AC voltage was applied.

In the second one the resonator OBR (6), determining plasma density by means of measuring the shift of the OBR resonance frequency at plasma presence, was located outside of the dielectric structure in the empty part of the copper pipe so that the beam and the plasma formed around it being occurred in OBR was not in contact with OBR walls. Waveguides powering OBR were perpendicular to the axis and vacuum sealed with the waveguide chamber.

To monitor the influence of the plasma filling on the excitation efficiency the microwave probe was placed at the end of the chamber to register of the excited wakefield on an oscilloscope (8).

1.2. MEASUREMENT OF PLASMA DENSITY BY HF-PROBE

Experimentally, the density of plasma, produced by the electron bunches at different pressures of the neutral gas was measured using an HF-probe [8]. At high pressures, the conductivity of the produced plasma is given by the expression:

$$\sigma = e(n_e\mu_e + n_+\mu_+ + n_-\mu_-), \qquad (1)$$

where μ_e, μ_+ and μ_- respectively, the mobility of electrons, positive and negative ions, and e is the electron charge; n_e is density of electrons. In our case, the conductivity is determined mainly by the electron mobility. Knowing the mobility of electrons μ_e and measuring the plasma conductivity σ by the HF-probe, one can determine the density of plasma electrons n_e.

We used HF-probe of plane shape with the distance between the plates of sizes S=1×1 cm^2 was equal to d=1 cm. AC voltage of amplitude V=0.5 V was applied to the plates from HF-generator at a frequency of 250 kHz. The mobility of electrons in the plasma for parameters of the experiment was estimated $\mu_e=v_{dr}E$ by using drift velocity v_{dr} presented in [11]. So at P=100 Torr electron mobility was estimated as $\mu_e=10^4$ cm^2/V·s. By probe measurements of current I between the plates of HF-probe and calculating field value in the gap $E=V/d$ one can determine the plasma conductivity $\sigma=j/E=I\cdot d/V\cdot S=7.18\cdot10^{-5}$ $\Omega^{-1}\cdot$cm^{-1}. Then from (1) we found the plasma density $n_e=1.2\cdot10^{11}$ cm^{-3}.

1.3. MEASUREMENT OF PLASMA DENSITY BY RESONATOR OBR

For plasma density measuring we also used an open symmetrical barrel cavity (OBR) [9] operating in the 8 mm wavelength range, which was a nondestructive diagnostics, unlike HF-probe measurements. Measurements of plasma density were performed by using the modified method [12], developed for the case of a small shift in the resonance frequency of the OBR, at the eigen frequency of the resonator f = 37245 MHz, at which mode $TM_{8,5,1}$ was excited. The quality factor of the resonator at this mode was $Q=2\cdot10^4$.

Fig. 2 shows the dependence of the density of plasma, formed by the electron bunches, upon gas pressure in the transit channel of the dielectric structure.

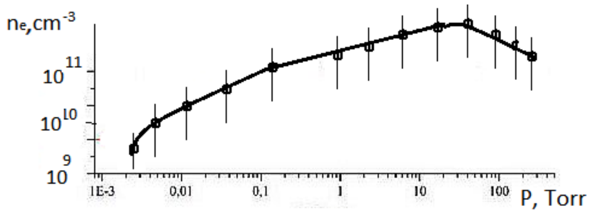

Fig. 2. Dependence of plasma density, produced by electron bunches, on gas pressure in the transit channel

It can be seen that the produced plasma reaches the resonance density $n_{res}=9\cdot10^{10}$ cm^{-3}, for which the plasma frequency is compared with the bunch repetition frequency $\omega_p=\omega_{rep}=2\cdot10^{10}$. This leads to an intensification of the wakefield excitation at resonant plasma density.

Fig. 3 shows the behavior of the plasma density during the pulse of passing bunches at gas pressure in the transit channel in dielectric structure 0.5 Torr (Fig. 3,a) and 10 Torr (Fig. 3,b).

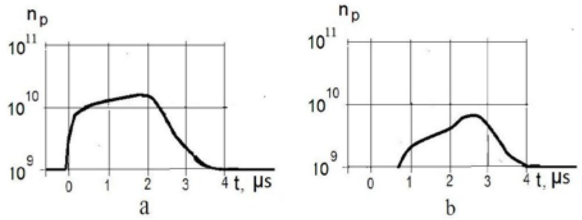

Fig. 3. Behavior of the plasma density during the pulse of passing bunches at gas pressure in the transit channel: 0.5 Torr (a) and 10 Torr (b)

Production of higher plasma density at the smaller gas pressure in the transit channel is caused by the fact that in this case to the collisional ionization of neutral gas by beam electros the ionization by plasma electrons gained energy from excited wakefield, which exceeded energy of ionization, is added (so-called beam-plasma discharge). This is confirmed by the increase of the amplitude of the wakefield excited at this gas pressure in the transit channel (Fig. 4).

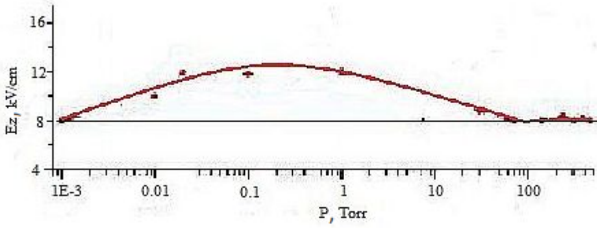

Fig. 4. Dependence of the excited wakefield amplitude on the gas pressure in the transit channel

Fig. 4 shows that the amplitude of the excited wakefield grows for the gas pressure in the range of P=0.2…1 Torr, where density of produced plasma is close to the resonance one (see Fig. 2) that leads to the resonant excitation of wakefield and the development of beam-plasma discharge.

At a gas pressure of more than 10 Torr in the plasma-dielectric structure the amplitude of the excited wakefield decreases, although the density of the produced plasma is resonant one. In this case, the decrease in the amplitude of the wakefield is explained by that the collision frequency of electrons and neutral particles accedes the plasma frequency $\nu_{en} > \omega_p$.

CONCLUSIONS

Plasma production is experimentally realized in the transit channel of the dielectric structure directly by relativistic electron bunches destined for wakefield excitation in the plasma-dielectric structure. For this the transit channel was filled with neutral gas (air) to a pressure in the range of 10^{-3}…760 Torr. Ionization of the gas is due to binary collisions of bunch electrons with neutrals at the high pressure and due to the development of beam-plasma discharge at the pressure of about 1 Torr.

The density of produced plasma measured by HF-probe and by an open barrel-shaped resonator OBR, is in the range of $5 \cdot 10^9 \ldots 5 \cdot 10^{11}$ cm^{-3} at gas pressure in the range of $10^{-3} \ldots 760$ Torr. The dependence of plasma density on time, i.e. on the number of bunches which passed through the gas, was measured. The phenomenon of plasma production is confirmed by the increase in the amplitude of the excited wakefield in the corresponding range of gas pressure.

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СОЗДАНИЕ ПЛАЗМЫ ПОСЛЕДОВАТЕЛЬНОСТЬЮ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОННЫХ СГУСТКОВ В ПРОЛЁТНОМ КАНАЛЕ ДИЭЛЕКТРИЧЕСКОЙ СТРУКТУРЫ

А.Ф. Линник, И.Н. Онищенко, В.И. Приступа, Г.П. Березина, О.Л. Омелаенко, В.С. Ус

В концепции плазменно-диэлектрического кильватерного ускорителя существенную роль в увеличении ускоряющего поля и обеспечении фокусировки сгустков играет наличие плазмы в пролетном канале диэлектрической структуры. Представлены результаты исследования процессов образования плазмы непосредственно возбуждающими релятивистскими электронными сгустками в канале, заполненном нейтральным газом различного давления. Измерена временная эволюция плотности возникающей плазмы, находящейся в удовлетворительном согласии с оценками ионизации за счет соударений электронов сгустков с нейтралами или развития пучково-плазменного разряда в соответствующих областях давления газа.

СТВОРЕННЯ ПЛАЗМИ ПОСЛІДОВНІСТЮ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОННИХ ЗГУСТКІВ У ПРОЛЬОТНОМУ КАНАЛІ ДІЕЛЕКТРИЧНОЇ СТРУКТУРИ

А.Ф. Лінник, І.М. Оніщенко, В.І. Приступа, Г.П. Березіна, О.Л. Омелаєнко, В.С. Ус

У концепції плазмово-діелектричного кільватерного прискорювача істотну роль у збільшенні прискорюючого поля та забезпеченні фокусування згустків відіграє наявність плазми в прольотному каналі діелектричної структури. Представлено результати дослідження процесів утворення плазми безпосередньо збуджуючими релятивістськими електронними згустками в каналі, заповненому нейтральним газом різного тиску. Виміряна часова еволюція щільності створюваної плазми, що знаходиться в задовільному узгодженні з оцінками іонізації за рахунок парних зіткнень електронів згустків з нейтралами або розвитку пучково-плазмового розряду у відповідних областях тиску газу.