MEASUREMENT OF PLASMA DENSITY FORMED AT PASSING OF A SEQUEENCE OF RELATIVISTIC ELECTRON BUNCHES THROUGH THE NEUTRAL GAS

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Using an open barrel-shaped resonator (OBR) plasma density, produced by a sequence of duration 2 μs of relativistic electron bunches, each of energy 4.5 MeV and charge 0.16 nC, in air at pressure of 10…60 Torr was measured. The plasma density was determined from the shift of the OBR resonant frequency estimated after measuring the reduction of oscillations amplitude in plasma loaded OBR at the initial frequency of OBR. It was shown that the maximum density of the produced plasma reaches $3\cdot10^{10}$ cm^{-3} at wakefield excitation in a semi-infinite plasma waveguide and 10^{11} – in plasma resonator

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INTRODUCTION

Among the known methods of noncontact high-frequency diagnostics for measuring the density of a weakly ionized plasma, in which the frequency of the plasma electrons collisions with the neutrals is comparable with plasma frequency, the method of open barrel-shaped resonator (OBR) is the most reasonable [1]. OBR has rarer spectrum of eigen frequencies compared to closed cylindrical resonator. The use of distributed coupling provides additional rarefaction of the spectrum [2]. As a result, it is managed to achieve the absence of other resonances in the frequency range equaled to the resonance mode frequency shift, caused by the plasma.

Existing methods for measuring plasma density by the shift of resonator frequency are applicable for plasma densities at which the frequency shift is greater of the half-width of the working resonance mode of the resonator. In the case of low-density plasma that leads to the smaller frequency shift for measuring plasma density it is necessary to modify the known method [1].

In this paper, plasma density was determined by the estimated shift of OBR resonance frequency, using the measuring the changing of oscillations amplitude in the plasma loaded OBR on the initial resonant frequency. This modified method we used in the experiments on plasma production and wakefields excitation in plasma by a sequence of relativistic electron bunches, injected into the waveguide filled with a gas.

1. MODIFIED METHOD

Shift of the resonance frequency of the resonator at its filling with plasma of averaged density $\overline{n}_p$ is given by [5]:

$$\frac{\Delta\omega}{\omega} = \frac{1}{2} C_V \frac{\overline{n}_p}{n_c} \frac{\omega^2}{\omega^2+\nu^2} \frac{V_p}{V_{RF}} , \qquad (1)$$

where $\omega=2\pi f_0$, C_V is value of the form-factor, V_{RF} is the volume of the resonator, filled with a microwave field, V_p is the volume of plasma in the microwave field of the resonator (in our case, $V_p/V_{RF}=9.7\cdot10^{-2}$), ν is effective frequency of collisions of plasma electrons with neutrals, which in the investigated pressure range is $\nu=7\cdot10^{10}…2\cdot10^{11}$ s^{-1} [4], n_c - is critical electron density, which is equal to $n_c=m\omega^2/4\pi e^2=1.714\cdot10^{13}$ cm^{-3} (*m* and *e* are mass and charge of electron).

Form-factor C_V in the case of plasma is equal to the form-factor in the case of inserting into the same place (the same displacing from the resonator axis) the foamed plastic core with ε=1.09 (at frequency 10^{10} Hz) of the same dimensions (length and diameter).

It is known that the shift of the resonance frequency of the resonator at inserting a dielectric rod is given by [2]:

$$\frac{\Delta\omega}{\omega} = \frac{1}{2} C_V (\varepsilon-1) \frac{V_d}{V_{RF}} , \qquad (2)$$

where V_d is the volume of dielectric rod. By measuring the shift of the resonance frequency, we find from (2) form-factor C_V = 0.67.

Substituting into (1) found above values of all variables we obtain an expression for determining the density of the plasma through the resonant frequency shift $\Delta\omega$:

$$\overline{n}_p = 10^{15} (\Delta\omega/\omega). \qquad (3)$$

In our case of low plasma density our experimental equipment does not allow to measure directly the resonance frequency shift $\Delta\omega$. Therefore, the frequency shift caused by plasma load was determined by means of measuring the change in the microwave signal amplitude on the initial resonance frequency. Fig. 1a shows that the shift of the resonator frequency at plasma load from f_0 to f_1, leads to the amplitude decrease of the signal at the initial (without plasma) resonant frequency from I_0 to I_1.

By measuring the amplitude of the microwave signal in the receiving waveguide without plasma I_0 and in the presence of plasma I_1, the frequency shift can be determined from the relation [5]:

$$\Delta\omega = \frac{\omega (I_0^2 - I_1^2)^{1/2}}{2 Q_n I_1} , \qquad (4)$$

where Q_n is loaded *Q*-quality on a given mode, which is determined from $1/Q_n=1/Q_o+\Delta(1/Q_0)$, where Q_o is *Q*-quality of resonator without plasma, $+\Delta(1/Q_0)$ is the term corresponding to change of resonator *Q*-quality at plasma load that is determined by the expression [3]:

$$\Delta\left(\frac{1}{Q_0}\right) = C_V \frac{\overline{n}_p}{n_c} \frac{\omega\nu}{\omega^2+\nu^2} \frac{V_p}{V_{RF}} . \qquad (5)$$

With increasing plasma density from 10^9 to 10^{11} cm^{-3} loaded Q_n decreases from $1.94\cdot10^4$ to $1.0\cdot10^4$.

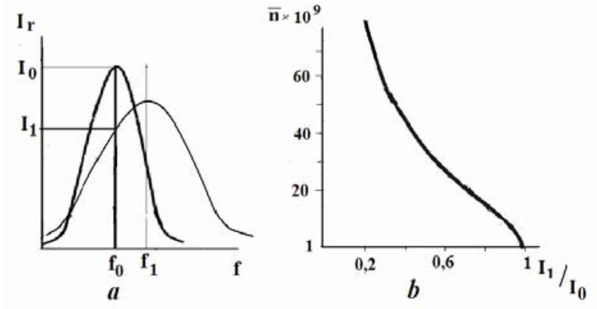

Fig. 1. a – relationship between decrease of signal amplitude I_1 with plasma at frequency f_0 and frequency shift $f_0 \to f_1$; b – plasma density dependence upon decreased signal amplitude

Substituting the value of $\Delta\omega/\omega$ found from (4) into (3) we obtain the expression for determining plasma density by the change of the signal amplitude on the initial frequency f_0 when resonator is loaded with plasma:

$$\overline{n}_p = 5 \cdot 10^{14} \frac{(I_0^2 - I_r^2)^{1/2}}{Q_n I_r} . \qquad (6)$$

Fig. 1,b shows the calculated from (6) dependence of plasma density in the resonator upon the normalized signal with the presence of plasma.

At operation in the pulsed mode, an important parameter is the transition time of oscillations in the resonator, which in our case is equal to $\tau \approx Q/\omega$=8,53·10^{-8} s that allows to measure the change in the density of plasma produced by a sequence of electron bunches of duration τ_b=2·10^6 s.

2. EXPERIMENTAL SETUP

At the experimental stand plasma was produced by a sequence of 6000 bunches of relativistic electrons of energy 4.5 MeV, each bunch of charge 0.16 nC and duration 60 ps, sequence duration 2 μs. From the accelerator bunches were injected through separating by vacuum Ti-foil into a circular waveguide, filled with gas at various pressure. which is part of the OBR with distributed coupling was a part of the waveguide.

We used OBR (Fig. 2) destined to work in 8 mm wavelength range and experimentally investigated in [3]. The resonator is made of copper, on its inner surface after polishing of copper coated silver cover-ment was deposited to increase the quality-factor. The resonator length L= 70 mm, radius a_0 = 34 mm, the curvature of the barrel r_0 = 204 mm. Distributed coupling is realized by means of the coupling holes in the common wall of the resonator and the feed and receiver waveguides. These waveguides of cross-section 3.4×7.2 mm have 7 rectangular coupling holes of size of 2×0.5 mm each.

Fig. 2. Open barrel-shaped resonator

Measurements of plasma density were made using OBR mode $TM_{8,5,1}$ with resonant frequency f_0=37245 MHz, which is excited with considerable amplitude. Q-quality of OBR on this mode Q_0=2·10^4.

Radius of the inner caustic surface on mode $TM_{8,5,1}$ is equal to 11 mm, radius of the electron bunches at the exit of OBR is 20 mm, so in order the beam to propagate in the area, occupied with a microwave field, the axis of the beam should be removed from the resonator axis by 21 mm. Note that for gas pressure P> 10 Torr plasma radius is close to the beam radius. Scheme for measuring plasma density is shown in Fig. 3.

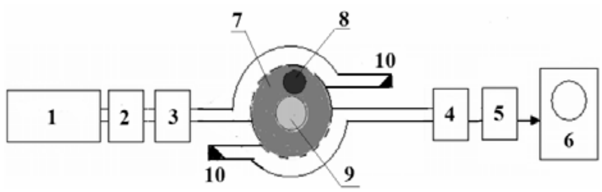

Fig. 3. The scheme of the plasma density measurement: 1 – microwave oscillator; 2 – ferrite valve; 3 – wavemeter; 4 – microwave detector; 5 – amplifier; 6 – oscilloscope; 7 – microwave field region; 8 – electron beam; 9 – region inside inner caustic; 10 – matched loads

3. EXPERIMENTAL RESULTS

Measurements of plasma density were performed for low microwave signal at resonator exit (amplitude of the signal in the receiver waveguide is two orders smaller than amplitude at resonator entrance), and high levels of electromagnetic stray. Therefore, the signal amplitude was found by subtracting the signal without plasma (stray) from the signal in the presence of plasma.

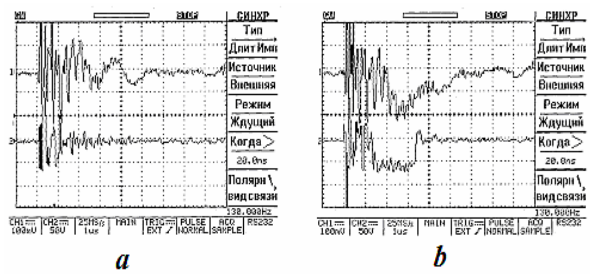

Fig. 4. Oscillograms of signal from OBR (upper) and beam current (bottom): a – without plasma; b – with plasma (X-axis – 1 μs/div)

Fig. 4 shows the oscillograms of the beam current (bottom traces) and of the signals (upper) from the detector of the receiving waveguide in the absence of the beam and produced plasma in a resonator (a) and in the presence of the beam and plasma in the resonator (b). Subtracting the signal of Fig. 4,a from the signal of Fig. 4,b, we obtain the dependence of the change of amplitude of the microwave signal upon the plasma density in the OBR.

In Fig. 5,a the change of plasma density upon time at injection of bunches in the semi-infinite waveguide filled with air at a pressure of Torr is presented. The dependence of the plasma density upon time is obtained taking into the count the change of the plasma loaded resonator Q-factor. In this case, the plasma was produced of density up to $3 \cdot 10^{10}$ cm^{-3}.

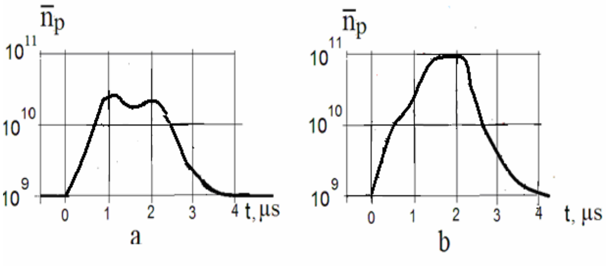

Fig. 5. Plasma density vs time; a – semi-infinite waveguide; b – resonator

If the interaction chamber is resonator for wakefields excited by a sequence of electron bunches and bunch repetition frequency coincides with the eigenl frequency of the resonator, plasma density increases considerably. The dependence of plasma density on time for this case is shown in Fig. 5,b. Plasma density in this case reaches value 10^{11} cm^{-3}. The increase in the plasma density can be explained by additional ionization of neutrals by plasma electrons, collisionally gained energy in the excited wakefield. Indeed, the probe measurements of the Ez component of wakefield confirmed this, showing in this case its increase by 7 times.

CONCLUSIONS

From the change in the microwave signal amplitude at a fixed frequency of the open barrel-shaped resonator the plasma density produced by relativistic electron bunches at their injection into air at pressure 10…60 Torr has been measured. Plasma density was in the range of around 10^{10} cm^{-3} for semi-infinite waveguide and 10^{11} cm^{-3} for resonator cases.

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ИЗМЕРЕНИЕ ПЛОТНОСТИ ПЛАЗМЫ, ОБРАЗОВАННОЙ ПРИ ПРОХОЖДЕНИИ ПОСЛЕДОВАТЕЛЬНОСТИ СГУСТКОВ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОНОВ ЧЕРЕЗ ВОЗДУХ

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С помощью открытого бочкообразного резонатора (ОБР) измерена плотность плазмы, образуемая последовательностью релятивистских электронных сгустков длительностью 2 мкс, с энергией 4.5 МэВ, зарядом 0.16 нК каждого в воздухе с давлением 10...60 Торр. Плотность плазмы определялась по сдвигу резонансной частоты ОБР, оцененного по измерению уменьшения амплитуды колебаний в нагруженном плазмой ОБР на исходной резонансной частоте ОБР. Показано, что максимальная плотность образуемой плазмы достигает $3 \cdot 10^{10}$ см$^{-3}$ для возбуждения кильватерного поля в полуоткрытом волноводе и 10^{11} см$^{-3}$ – в плазменном резонаторе.

ВИМІРЮВАННЯ ГУСТИНИ ПЛАЗМИ, ЯКА УТВОРЮЄТЬСЯ ПРИ ПРОХОДЖЕННІ ПОСЛІДОВНОСТІ ЗГУСТКІВ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОНІВ КРІЗЬ ПОВІТРЯ

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За допомогою відкритого бочкоподібного резонатора (ВБР) виміряна густина плазми, яка утворюється послідовністю релятивістських електронних згустків тривалістю 2 мкс, з енергією 4.5 МеВ, зарядом 0.16 нК кожного в повітрі з тиском 10...60 Торр. Густина плазми визначалася по зсуву резонансної частоти ВБР, яка оцінювалася по вимірюванню зменшення амплітуди коливань у навантаженому плазмою ВБР на вихідній резонансній частоті ВБР. Показано, що максимальна густина утворюваної плазми досягає $3 \cdot 10^{10}$ см$^{-3}$ при збудженні кільватерного поля в напіввідкритому хвилеводі і 10^{11} см$^{-3}$ – у плазмовому резонаторі.