THE NET CURRENT INCREASE AT MOVES SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES IN PLASMA WITH DECREASING DENSITY

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The results of experimental studies of increasing the net current (sum of the beam current and the plasma current) during propagation of the sequence of 6000 relativistic electron bunches with a charge 0.32 nQ and duration 60 ps for each in a plasma with decreasing density are presented. A plasma with decreasing density in the initially neutral gas (air) is formed by the electron bunches due to the angular divergence of electrons in bunches. The maximum increase of the net current is observed in the pressure range of 10…100 Torr. It was found that during propagation of electron bunches in the open atmosphere also is observed increase of the net current which depends on the distance from the exit of the accelerator.

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INTRODUCTION

Earlier studies propagation of intense electron beams in gases [1, 2] showed that under certain conditions, a full net current (also referred as total or effective current) $I_n = I_b + I_p$ (I_b - beam current, I_p - plasma current) may be greater than the beam current, i.e., beam and plasma currents have the same direction and the sum of these currents is greater than the injected beam current.

The increase of the net current (also referred as multiplication or enhancement of the current) was observed in a variety of conditions, in the propagation electron beam with a current from a few to tens kA in various gases in the pressure range near atmospheric [3, 4] to the sub-Tor [5, 6]. It has been shown that an increase in the net current may be due to the development of various types of instabilities, including large-scale (e.g. hose instability), due to field-induced trailing edge of the current pulse and the plasma electrons drift in crossed magnetic and electric fields not compensated the spatial charge of the beam's head part.

The net current increase during injection of the sequence relativistic electron bunches into the air experimental studies the paper presents. The current value of each bunch is a few amperes.

It is shown that the injection of a long regular sequence of relativistic electron bunches into the air is formed plasma with decreasing density along the propagation axis. During propagation electron bunches in such plasma, the net current increase with the highest value of the current at pressures from 10 to 100 Torr was observed.

Measurement current by Rogowski coil showed an increase of the net current four times during propagation bunches into the open air at atmospheric pressure at a distance of 40 cm from the exit of accelerator.

1. PLASMA FORMATION

Experiments were conducted with a sequence of electron bunches produced on a linear accelerator with a traveling wave. Sequence of electron bunches is shown schematically in Fig. 1.

From the accelerator is injected impulse, which consists of 6000 electron bunches with the period following T≈360 ps. Charge each bunch q=0.32 nQ (average current of the bunch 6 A) the duration of the bunch τ_b≈60 ps.

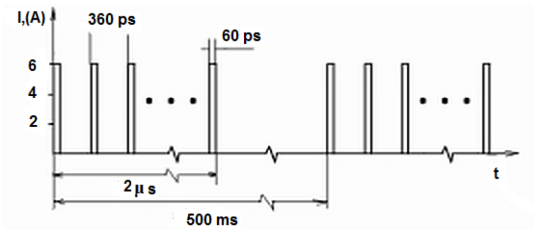

Fig. 1. Schematic representation of the sequence of electron bunches at the exit of the accelerator

Bunches followed with a period of 360 ps. Nominal energy bunches W=2 MeV, the average current in the macropulse with duration τ_{im} = 2 μs was I_{ev} = 1 A. The diameter of bunches at the exit of the accelerator $2r_b$≈ 1 cm. The angular divergence, in the presence of titanium foil thickness of 30 μm at the output of the accelerator is θ ≈ 12º.

Let us consider creation of plasma during injection of sequence relativistic electron bunches into the atmosphere.

Divergent electron beam when propagating in a neutral gas without external magnetic field produces a plasma density which is determined balance of ionization and recombination processes [7]:

$$\frac{\partial n_e(z)}{\partial t} = \frac{I_b}{eA_p(z)E_{ei}}\left(\frac{dE}{dZ}\right) - \alpha n_e n_i - k_{st} n_{e_0}^2, \qquad (1)$$

where I_b – beam current; A_p – area of plasma channel created by the beam; dE/dZ – beam ionization losses per unit path length; E_{ei} – the energy of formation of ion-electron pair for air at a beam energy $E \approx (1…5)\cdot 10^6$ eV and $dE/dZ \approx 10^{-16} n_o$, and E_{ei} respectively 34 eV [8]. Thus, the first term on the right hand side of (1) gives the number of electrons produced by the beam. The second and third terms determine the loss of plasma electrons, which are determined by dissipative recombination with the constant α and attachment to oxygen with a constant k_{st}; n_i is the density of the ions, which in our case is equal to the electron density n_e. Taking α and k_{st} for electron energy 1 eV [9] and substituting our data in (1) we get the plasma density at a distance of 10 cm from the separating foil $n_e \approx 7.4\times10^{10}$ см$^{-3}$. The density of the beam in this cross section $n_b \approx 1{,}5\times10^{8}$ см$^{-3}$.

Since the both values dE/dZ and α proportional to the gas pressure, this result is valid for a wide pressure range (from 10 to 760 Torr).

The time of establishment constant plasma density in the pressure range from 1 to 760 Torr – τ_{est} = 20…40 ns [10].

The characteristic time energy loss of the plasma electron's $\tau_{los} \sim 10^{-11}…10^{-10}$ s. Neutralization by dissociative or triple recombination (depending on n_e) or by sticking with the subsequent pair recombination $\tau \sim 10^{-9}…10^{-8}$ s [11]. Table 1 shows the values of the average density of electrons in a bunch – N_b, steady-state plasma density- n_e, and value of the plasma frequency $\omega_{pe} = (4\pi ne^2/m)^{1/2}$ and the radial field E_r bunches at different distances L from the exit of the accelerator.

L (cm)	R (cm)	N_b (bunch)	n_e (st)	ω_{pe} c^{-1}	E_r (V/cm)
0	0.4	4.4×10^{9}	4×10^{11}	3.6×10^{10}	1600
10	2.16	1.5×10^{8}	7.4×10^{10}	1.5×10^{10}	260
20	3.92	4.5×10^{7}	4×10^{10}	1.1×10^{10}	160
30	5.68	$2{,}2\times10^{7}$	2.8×10^{10}	9.4×10^{9}	115
40	7.44	1.3×10^{7}	2.1×10^{10}	8.2×10^{9}	85.7
50	9.2	8.1×10^{6}	1.7×10^{10}	7.4×10^{9}	67.5
60	11	5.8×10^{6}	1.4×10^{10}	6.7×10^{9}	57.4

Fig. 2 shows the calculated and measured values of the average density of the plasma formed at different distances from the separating foil.

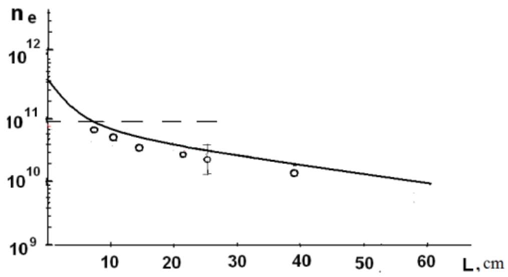

Fig. 2. The calculated plasma density along the beam axis; the points experimentally measured plasma density

Fig. 3 shows the calculated value of the instantaneous change in the density of the plasma formed by the sequence electron bunches in the atmosphere along the length.

Plasma, which is formed, is not uniform in space and time.

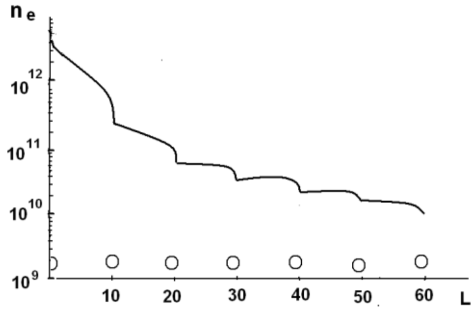

Fig. 3. The instantaneous values of the plasma density, circles denote position of bunches

2. DEPENDENCE OF THE NET CURRENT FROM PRESSURE

The dependence of the total current from air pressure during the propagation the sequence bunches in a glass cylindrical chamber with a diameter of 12 cm was investigated. The total current measured by the Faraday cup 5 cm in diameter, which was located in the first case at a distance of 27 cm, and the second – 74 cm from the foil off the accelerator. The highest value of the total current at a distance of 27 cm was observed in the pressure range from 7 to 100 Torr, Fig. 4,a. When Faraday cup was located at a distance 74 cm from the foil off the maximum total current was observed at a pressure of about 10 Torr, Fig. 4,b.

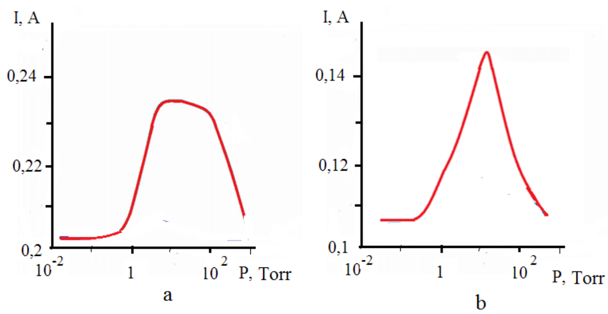

Fig. 4. The net current dependence from pressure

The value of the measuring resistor connected to the Faraday cup was equal to 50 Ohm.

3. THE NET CURRENT INCREASE AT MOVES BUNCHES IN THE ATMOSPHERE

Fig. 5 shows the total current registered by a Rogowski loop the diameter of 30 cm. When it is moved along the axis of the beam propagating in open air at atmospheric pressure. At a distance of 43 cm from the exit of the accelerator total current 4 times higher than vacuum current accelerator.

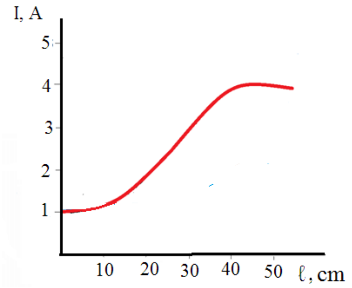

Fig. 5. Current measured by a Rogowski loop along the axis of the beam propagation

With the aluminum foil having a thickness of 0.5 mm, and is transparent to a beam of electrons, but detecting the plasma current were measured plasma current along the beam axis. The diameter of the foil sensor was equal to the diameter of the Rogowski coil – 30 cm, and the value of the measuring resistor connected to the foil sensor was equal of 1 or 20 Ohms, Fig. 6.

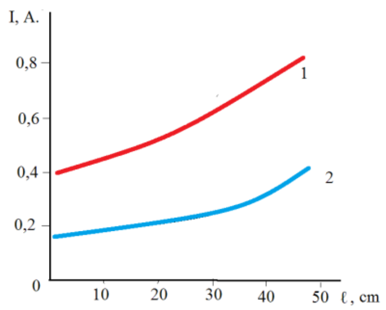

Fig. 6. Dependence of the plasma current on the aluminum foil from distans: 1. with 1 ohm resistance; 2 with 20 Ohms resistance

With increasing value of the measuring resistor, which determines the negative potential at the foil, from 1 to 20 Ohms, the plasma current, the detected sensor plasma current decreases twice. This indicates low energy plasma electrons leading to an increase in the total current.

4. DISCUSSION OF RESULTS

To explain the results of experimental studies to increase the net current during the injection sequence of electron bunches in a neutral gas to determine the frequency of collisions of the plasma electrons. In the pressure range 1…760 Torr coefficient of gas ionization $n_e/N_0<10^{-5}$, so that you can take into account only the collision of electrons with neutral gas molecules it gives to air under normal conditions $\nu_{e0}=4.7\cdot10^{12}\,c^{-1}$, which is much higher than the frequency of the plasma oscillations (Table) and makes difficult the development of plasma instabilities, at least at air pressures above 10 Torr.

Time of charge neutralization the electron bunches (this is also the time of decompensating of the charge in the plasma) can be calculated from [12]:

$$\tau_s=1/(4\pi\sigma)=\nu_{e0}/\omega_{pe}^2,\ \text{for}\ \omega_{pe}<<\nu_{e0}/2 \qquad (2)$$

$$\tau_s=1/(4\pi\sigma)=1/\omega_{pe},\ \text{for}\ \omega_{pe}>>\nu_{e0}/2.$$

In our case $\omega_{pe}<<\nu_{e0}/2$ and corresponds to the minimum time charge neutralization at the exit accelerator $\tau_s\approx4\cdot10^{-9}$ s it is much longer than the duration of the bunch $\tau_b\approx6\cdot10^{-11}$ s. Magnetic neutralization is also determined by the expression (2) [12].

The absence of charge and current neutralization bunches makes it possible to assume the reason an increasing in the net current due to the drift plasma electrons in the crossed electric and magnetic fields not compensated on charge and current electron bunches. Due to the high collision frequency motion of the plasma electrons will occur only in the initial sections of the cycloid after each collision.

Previously, such a mechanism was observed to increase the current of the electron beam with a current of 7.5 kA [2, 13]. The increase in net current can also be caused by the resulting average electric field arising in the expansion of clusters [14].

Increase of the net current with increasing distance from the foil in the atmosphere (Figs. 5, 6) needs further investigation, but it may be associated with increased space charge time decompensating with decreasing plasma density. At a distance of 40 cm from the exit of the accelerator time decompensating of the space charge is equal to 10^{-8} s, which is much greater than the repetition period of bunches $T_b=3.6\cdot10^{-10}$ s.

SUMMARY

Experimentally discovered the effect of increasing the net current $I_n = I_b + I_p$ during the propagation sequence of 6000 relativistic electron bunches with currents 6 A of each in the air. The increase of the total current is observed in a wide range of pressures up to atmospheric pressure. The total current is maximum in the pressure range of 7…100 Torr.

A possible mechanism for the increase of the net current can be the motion of electrons of the plasma in not compensated electric and magnetic fields of electron bunches, and the electric field occurs during the expansion of electron bunches.

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REFERENCES

1. R.J. Briggs, J.C. Clarc, T.J. Fessenden. Transport of selffocused relativistic electron beams // *Proc of the 2nd International Topical Conf. on High Power Electron and Ion Beam* (Cornell University, Ithaca NY, 35 oct. 1977). J.A. Nation and R.N. Sudan eds., p. 319-330.
2. J.M. Wachtel, S.Safran. Current Amplificatioin in a Relativistic Electron Beam // *Phys. Rev. Lett.* 1974, v. 32, № 3, p. 95-98.
3. N.A. Kondratyev, G.I. Kotlyarevskiy, V.I. Smets. Change in the total current in the development of instability REP // *JTF*. 1998, v. 58, № 10, p. 1915-1923.

4. Y.F. Cooper, A.A. Manko, V.I. Klimov, G.P. Mkheidze, A.A. Savin, A.P. Yanovsky. Dynamics of plasma currents induced electron beam in a dense gas // *Plasma Physics.* 1991, v. 17, № 8, p. 911-917.
5. G.P. Gupta, V.K. Rohatgi. Current multiplication during relativistic electron beam propagation in a subTorr pressure gas // *J. Appl. Phys*. 1988, v. 64, p. 6626-6630.
6. P.V. Vedenin. Current gain when transporting modulated electron beam through a weakly ionized plasma // *JTF.* 1992, v. 62, № 7, p. 79-89.
7. V.P. Grigoriev, A.I. Koriakin, A.G. Potashev Numerical simulation of the plasma channel and the dynamics of the electron beam // *Plasma Physics.* 1984, v. 10, № 4, p. 783-787.
8. S.P. Slinker, A.W. Ali, R.D. Taylor. Hight Energi Electron Beam Depositson in Partly Ionized N_2 // *J. Appl. Phys*. 1990, v. 67, № 2, p. 679-690.
9. I. Mc Daniel. *Processes collisions in ionized gazah*. M.: "Mir", 1967, p. 696.
10. L. Olson Chage. Neutralization Processes for Intense Relativistic Electron Beams // *Phys. Rev.* 1974, v. 9A, p. 2631-2635.
11. V.L. Bykov, A.V. Eletskii, V.A. Uschapovsky. Nonequilibrium supercooled beam plasma // *Plasma Physics*. 1981, v. 14, № 12, p. 1493-1503.
12. R.B. Miller. *An Introduction to the Physics of Intense Charged Particle Beams* (Plenum, New York, 1982).
13. G.P. Mkheidze, A.A. Savin. Formation and application of pulsed high-current electron beams // *Applied physics*. 2008, № 5, p. 51-65.
14. V.A. Kiselev, A.F. Linnik, V.I. Maslov, I.N. Onishchenko, V.V. Uskov. Mechanism of Modulated REB current increase during its propagation through plasma // *PAST.* 2002, № 5, p. 98-100.

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УВЕЛИЧЕНИЕ ПОЛНОГО ТОКА ПРИ РАСПРОСТРАНЕНИИ ПОСЛЕДОВАТЕЛЬНОСТИ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОННЫХ СГУСТКОВ В ПЛАЗМЕ СО СПАДАЮЩЕЙ ПЛОТНОСТЬЮ

В.А. Киселев, А.Ф. Линник, И.Н. Онищенко, В.И. Приступа, Г.П. Березина

Представлены результаты экспериментальных исследований увеличения полного тока (сумма тока пучка и плазменного тока) при распространении последовательности из 6000 релятивистских электронных сгустков с зарядом 0,32 нК и длительностью 60 пс каждого в плазме со спадающей плотностью. Спадающая плотность плазмы в первоначально нейтральном газе (воздухе) формируется самими электронными сгустками за счет углового расхождения электронов в сгустках. Максимальное увеличение полного тока наблюдается в диапазоне давлений 10…100 Торр. Обнаружено, что при распространении последовательности электронных сгустков в атмосфере также наблюдается увеличение полного тока пучка, зависящее от расстояния до выхода из ускорителя.

ЗБІЛЬШЕННЯ ПОВНОГО СТРУМУ ПРИ РОЗПОВСЮДЖЕННІ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОННИХ ЗГУСТКІВ У ПЛАЗМІ ЗІ СПАДАЮЧОЮ ГУСТИНОЮ

В.О. Кисельов, А.Ф. Лінник, І.М. Оніщенко, В.І. Приступа, Г.П. Березіна

Представлені результати експериментальних досліджень збільшення повного струму (сума струму пучка і плазмового струму) при поширенні послідовності з 6000 релятивістських електронних згустків із зарядом кожного 0,32 нК і тривалістю 60 пс кожного в плазмі зі спадаючою щільністю. Спадаюча щільність плазми в початково нейтральному газі (повітрі) формується самими електронними згустками за рахунок кутової розбіжності електронів у згустках. Максимальне збільшення повного струму спостерігається в діапазоні тиску 10…100 Торр. Виявлено, що при поширенні послідовності електронних згустків в атмосфері також спостерігається збільшення повного струму пучка, величина якого залежить від відстані до виходу з прискорювача.