COMPARATIVE ANALYSIS OF ACCELERATION OF TEST ELECTRON BUNCH BY TRAIN OF BUNCHES IN THE DIELECTRICAL WAVEGUIDE AND RESONATOR FILLED WITH PLASMA

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Results of numerical simulation of acceleration of test bunch by sequence of relativistic electron bunches in the dielectrical cylindric slowing-down structure filled with plasma for the cases opened and closed by the conductive grid of output end face of structure are provided. The entrance end face has been closed by the conductive grid. The initial sizes and energy of all bunches were identical. The distance between bunches of sequence is equal to the wavelength of electromagnetic field in the structure. The test bunch followed the last bunch of the sequence. Acceleration of test bunch at changing of number of drive bunches in a sequence was investigated. We have found out that at certain number of bunches in the resonator it is possible to obtain significantly greater acceleration, than in waveguide.

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INTRODUCTION

For obtaining high rates of acceleration of charged particles by wakefield it is necessary to use single drive bunch with great charge [1].

Another way of increasing of amplitude of the accelerating wakefield is using of periodic sequence of drive bunches with smaller charge [2 - 4].

Earlier for stabilization of the transverse motion of the drive and accelerated bunches and, thus, for obtaining the accelerated bunches of particles with small emittance it was proposed to fill the drift channel of dielectric structure with plasma [5]. Such structure was called the plasma-dielectric wakefield accelerator (PDWA). At that for creation of the accelerating wakefield only a single drive bunch was used [5 - 7].

Research of test electron bunch acceleration in PDWA where the wakefield is created by sequence of drive bunches is of interest. We will carry out comparative analysis of acceleration in two kinds of accelerating structures: opened from the output end face – the waveguide and closed – the resonator.

STATEMENT OF THE PROBLEM

The dielectric tube with an inner radius a and dielectric constant ε is inserted into a cylindrical metal wave guide of radius b. Length of a metal waveguide L coincides with length of a dielectric tube. The entrance end face of a waveguide is closed by the metal grid transparent for electron bunches. In case of the resonator the output end face of structure is closed by the metal grid also. The internal area of a dielectric tube is filled by uniform plasma of density n_p. Into the slowing-down structure the sequence of electron bunches is injected. After the certain delay time t_{del} the test electron bunch is injected in the system. The studied system is schematically shown in Fig. 1.

We investigated change of energy of test bunch electrons at the system output end face at the motion in the electromagnetic fields created by drive sequence depending on number of bunches in the sequence. In Table the parameters used in calculation are given.

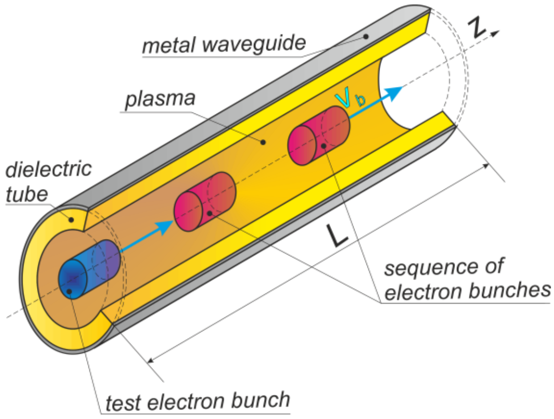

Fig. 1. General view of the dielectric structure, excited by sequence of electron bunches. Into a metal cylindrical waveguide of length L the dielectric plug is inserted (yellow color). The internal area of dielectric tube is filled by plasma. Drive electron bunches (pink color) propagate along a cylinder axis from left to right. Blue cylinder shows test electron bunch

Parameters used in calculation

Inner radius of dielectric tube a	0.5 mm
Outer radius of dielectric tube b	0.6 mm
Operating frequency f	357.2 GHz
Waveguide length L	4.196 mm (5λ)
Relative dielectric constant ε	3.75 (quartz)
Bunch energy E_0	5 GeV
Total drive bunch charge	3 nC
Total witness bunch charge	0.3 nC
Bunch diameter $2r_b$	0.9 mm
Bunch axial RMS dimension 2σ (Gaussian charge distribution)	0.1 mm
Full bunch length used in PIC simulation	0.2 mm
Number of bunches in drive sequence	1…50
Test bunch length (homogeneous charge distribution)	0.4 mm
Delay injection time of test bunch releative to the last drive bunch t_{del}	1.151 ps
Plasma density n_{p0}	$4.41\cdot10^{14}$cm^{-3}
Ratio m_i/m_e of model plasma	1836 (hydrogen)

INJECTION OF BUNCHES AND TREATMENT OF NUMERICAL SIMULATION RESULTS

The analysis of acceleration of test electron bunch by sequence of drive bunches was carried out by us by means of 2.5-dimensional numerical code in the following way:

1. The given number of drive bunches was injected into the investigated structure.

2. Later the delay time t_{del} after the beginning of the last drive bunch injection the test bunch was injected and moved after drive bunches in the electromagnetic field created by them up to the system output end.

3. From the calculated values of electrons energies of the test bunch, which was near output end face of structure, the maximum energy was calculated. This energy was taken as test bunch acceleration.

4. Having done the actions described above in items 1…3 for different number of drive bunches, the dependence of test bunch electrons energy on number of drive bunches obtained. At that two cases of longitudinal boundary conditions were investigated: the resonator (tangential components of electric field are equal to zero) and waveguide (impedance matching of dielectric waveguide and free space).

RESULTS OF 2.5D-PIC CODE SIMULATION

As examples of numerical simulation results of acceleration process in PDWA are shown in Fig. 2: the longitudinal $F_z(z)$ and transverse $F_r(z)$ forces affecting on test electron and the phase plane energy – the longitudinal coordinate of the last drive and test bunches when injecting one, two, three and four drive bunches in the resonator and the waveguide. Figures correspond to time when the last drive bunch of a sequence approaches output end face of the slowing-down structure. As appears from Fig. 2, the increase in number of drive bunches leads to growth of longitudinal force $F_z(z)$ and, as a result, to growth of the maximum energy of the accelerated electrons of test bunch.

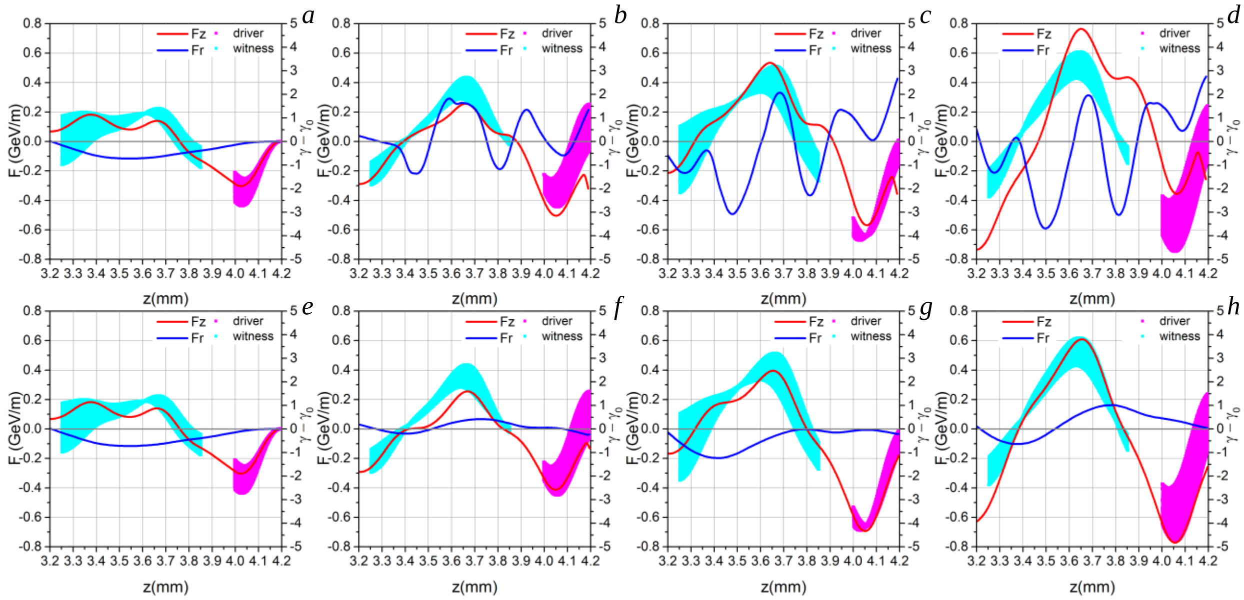

Fig. 2. Longitudinal $F_z(z)$ and transverse $F_r(z)$ forces affecting on test electron (r = 0.2 mm), phase plane energy – the longitudinal coordinate of the last drive (magenta dots) and test (cyan dots) bunches when injecting one (a, e), two (b, f), three (c, g) and four (d, h) drive bunches for resonator (a, b, c, d) and waveguide (e, f, g, h)

In Fig. 3 the dependence of electron energy gain of test bunch on number of the injected drive bunches for the resonator and waveguide is shown.

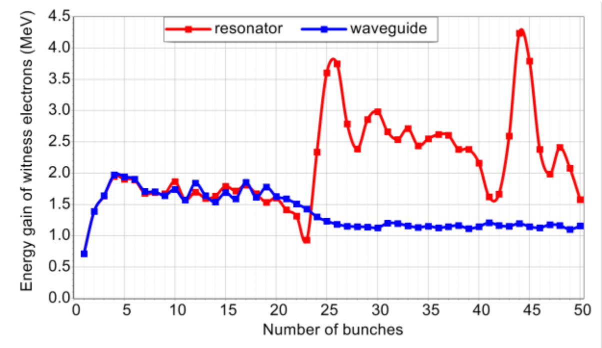

Fig. 3. Dependence of electron energy gain of test bunch on number of the injected drive bunches for the resonator (red curve) and waveguide (blue curve)

Symbols in Fig. 3 have shown the exact values of energy gain of test bunch electrons obtained at numerical experiment, and curves represent average dependence.

To understand behaviour of the dependences given on Fig. 3, we analyzed structure of the longitudinal forces $F_z(z)$ affecting on electrons, depending on number of the injected drive bunches for the resonator and waveguide.

Colour maps for longitudinal force $F_z(z)$ at $r = 0.2$ mm depending on number of the injected bunches in case of resonator accelerating structure (Fig. 4,a) and in case of the waveguide accelerating structure (Fig. 4,b) are given in Fig. 4. Time for which configuration of forces are given in Fig. 4, correspond to the moment of approach of the last drive bunches of sequence to output end face of structure.

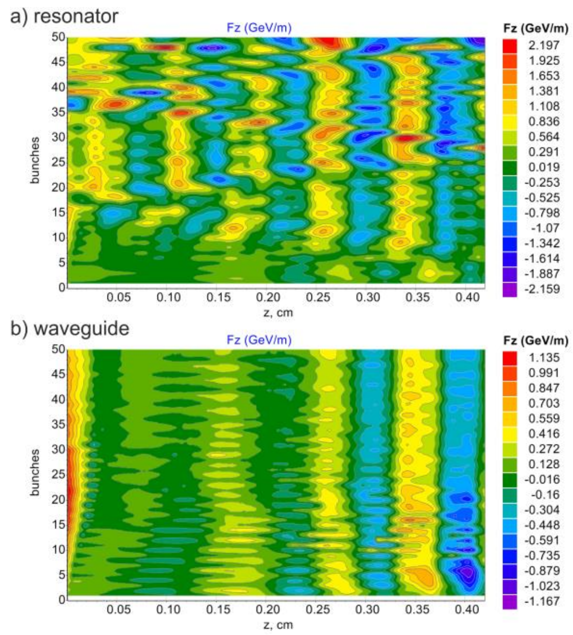

Fig. 4. Configuration of the longitudinal forces $F_z(z)$ acting on test electron, depending on number of the injected drive bunches for the resonator (a) and waveguide (b) at $r = 0.2$ mm in the form of colour map

As one can see in Fig. 4,a, when changing a number of drive bunches from 1 to 20 wakefield wave, reflected from output end face of the resonator (backward wave), moves to its input end face, but does not reach it. At injection of the 21st drive bunch the backward wave reaches input end face of the resonator. From here when increasing a number of drive bunches injected in the system the wave reflected from input end face of the resonator (direct wave) forms. This wave influences electrons of test bunch together with wakefield wave and accelerates them. Let's note that at injection of 23 drive bunches the small decay of strength of the longitudinal accelerating field resulting in local minimum on dependence of energy increase of test bunch electrons on number of the injected drive bunches is observed (see Fig. 3). When injecting 24…26 drive bunches there is rapid growth of strength of the longitudinal accelerating field that leads to sharp increase in energy of test electrons. When further increasing number of drive bunches the strength of longitudinal electric field in area where the test bunch is located, falls down a little that leads to weaker acceleration of bunch, than in maximum. When injecting 41…42 drive bunches in the resonator are observed the decay of the longitudinal accelerating field strength leading to local minimum on curve in Fig. 3 again. Injection of the next 44th bunch leads to sharp increase in energy of the accelerated bunch at the resonator output end face.

The configuration of longitudinal forces $F_z(z)$ for waveguide shown in Fig. 4,b has more regular character, than for the resonator, described above (see Fig. 4,a). It is caused by absence of reflection of electromagnetic fields from output end face of waveguide. Therefore at the time when the last drive bunch approaches to output end face of structure the identical amount of the periods of electromagnetic wakefield forms in the drift space independently of number of drive bunches of sequence. Only field amplitude changes. In the analyzed structure at the same time there can be no more than five bunches which fields summed up: either 5 drive, or 1 test and 4 drive. Therefore in Fig. 4,b the maximum of force F_z is reached for 4 drive bunches. When increasing in a number of drive bunches little changes of amplitude F_z in comparison with the maximum value are observed.

It is possible to mark out some stages of acceleration of test bunch connected with number of bunches of drive sequence in Fig. 3.

At the first stage while the group front of wakefield wave from the first drive bunch does not go beyond output end face of system, the linear growth of energy of the accelerated test bunch with increase in number of bunches of drive sequence is observed. In our research this stage is observed at injection from 1 to 4 drive bunches. Distinctions in behavior of the resonator and waveguide at the first stage it is not observed (see Fig. 3).

At the second stage the additional growth of energy of the accelerated test bunch when increasing in a number of bunches of drive sequence is not observed. For waveguide it is connected with that the electromagnetic field leaves system through output end face and does not give contribution to acceleration of electrons of test bunch. It is limit stage of test bunch acceleration for waveguide case. For resonator case reflection of electromagnetic wave from output end face is observed. This reflected wave moves towards to test bunch and therefore does not provide cophased energy increase of its electrons. At the end of the second stage the reflected wave reaches the input end face of the resonator. In our research the second stage of acceleration is observed at injection from 5 to 22 drive bunches. Let's note almost identical the curve of acceleration at the second stage for the resonator with waveguide curve.

The next stages of acceleration of test bunch are observed only for the resonator.

The third stage is similar to the first one as for an energy growth of test electrons and it is connected with additional acceleration of electrons in the field of the wave reflected both from output and from input resonator end faces. This stage finishes when the wave reaches output end faces of the resonator for the second time. In our case the third stage of acceleration is observed at injection from 23 to 26 drive bunches.

Then the fourth stage similar to the second one as for relative constancy of test electron energy is observed. This is connected with the motion of the wave three times reflected from resonator end faces towards to test bunch that does not increase its energy (from 27 to 41 drive bunches).

The fourth stage is changed to fifth one when an energy growth of test electrons is observed again (from 42 to 44 drive bunches).

And, finally, at the sixth stage the falling-down area of energy change of test electrons is observed (from 45 to 50 drive bunches). We believe that it is connected with breakdown of cophased addition of fields of the backward and direct waves in the resonator.

Let's note that in work [8] authors already observed alternation of stages of linear growth and constant value of longitudinal electric field strength as functions of time at injection of sequence of bunches in the rectangular dielectric resonator.

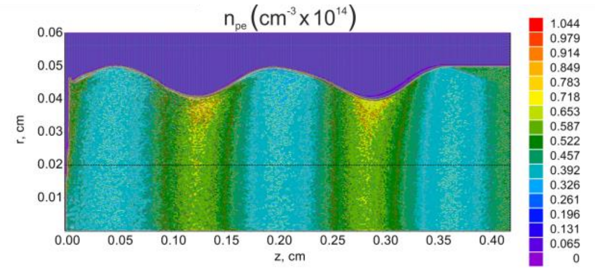

Fig. 5. Dependence of density of plasma electrons n_{pe} after injection of single drive bunch for the resonator in the form of colour map

To find out the reason of impairment of cophased addition of fields of the backward and direct waves in the resonator when a number of drive bunches is more than 39 we analyze behavior of plasma in the drift channel. In Fig. 5 dependence of density of plasma electrons n_{pe} after injection of single drive bunch for the resonator in the form of color map is shown. In the picture it is possible to see that after injection of one drive bunch it appears a density n_{pe} modulated with the period of transverse force $F_r(z)$ change (i.e. with plasma wavelength).

When increasing number of the injected drive bunches a change of plasma density become more essential. In Fig. 6 dependence n_{pe} and n_{pi} after injection of different number of drive bunches for the resonator (see Fig. 6, a,b) and waveguide (see Fig. 6,c,d) is shown, $r = 0.2$ mm. The horizontal dashed line shows the initial plasma density n_{p0} in system. As follows from Fig. 6,a and c, after injection of 30 drive bunches in the resonator the electron density n_{pe} falls more, than twice, and after injection of 50 bunches plasma electrons in the resonator are nearly absent. Plasma ion density as function of drive bunches number decreases significantly more weakly than plasma electron density (see Fig. 6,b,d), however, already at injection of 50 bunches in the resonator $n_{pi} \approx 0.5\, n_{p0}$.

Carrying out of plasma from system when injecting a large number of drive bunches leads to change of its frequency characteristics. In result the resonant excitation of the electromagnetic waves excited by drive bunches which are periodically injected in the resonator is violated.

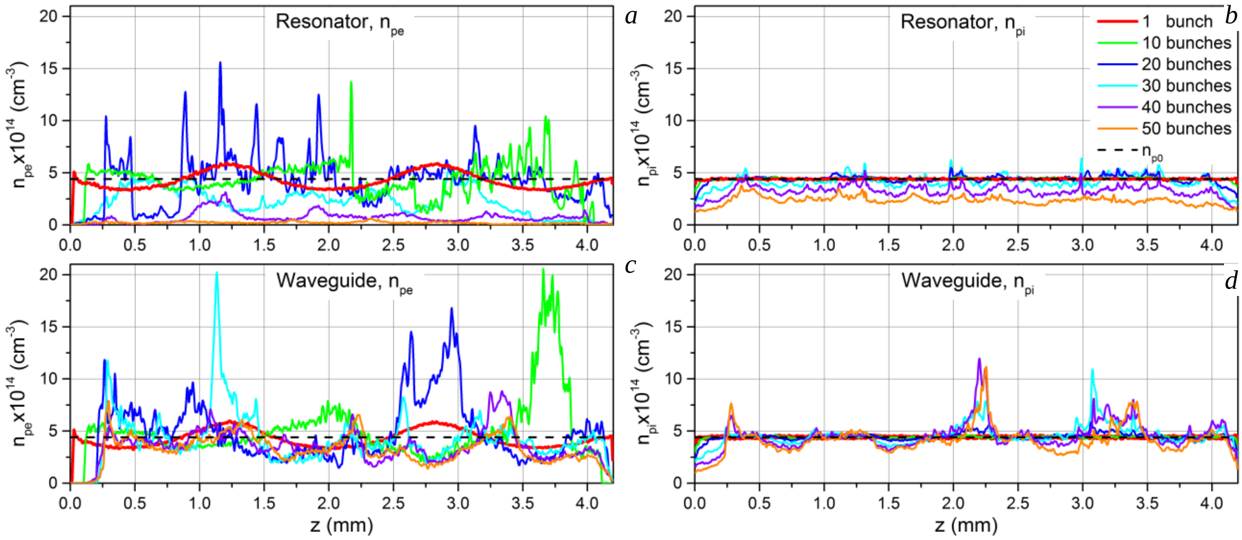

Fig. 6. Dependence of plasma density of electrons n_{pe} and ions n_{pi} after injection of different number of drive bunches for the resonator (a, b) and waveguide (c, d), $r = 0.2$ mm

CONCLUSIONS

At numerical simulation of acceleration of test bunch by the field of sequence of drive bunches in case of plasma filling of the drift channel we have found some stages of acceleration of test bunch connected with a number of drive sequence bunches.

For waveguide two stages are observed: 1) linear growth of energy of the accelerated electrons of test bunch with increase in number of drive bunches of a sequence which follows, 2) practically, invariable value of energy of the accelerated test bunch when changing a number of drive bunches. For parameters of numerical experiment, the energy gain of test bunch increases at stage of linear growth by 2.76 time for 4 drive bunches in comparison with single drive bunch.

For the resonator the stages of linear growth of energy and constant value of energy of the accelerated test bunch when increasing in a number of bunches of drive sequence have repeated in pairs three times when using for wakefield excitation up to fifty drive bunches. At that the step growth of electron energy of test bunch is observed. Thus the maximum of energy gain of test bunch electrons increases by 5.29 times for 44 drive bunches in comparison with single drive bunch.

When injecting drive bunches into wakefield accelerating system plasma electrons and ions are lost from system so much more strongly, than more bunches are injected in system that leads to change of its frequency characteristics and violation of resonance in system. Therefore to increase energy gain of test bunch it is necessary: either to create in system of condition of additional generation of plasma during the injection process, or to carry out nonperiodic injection of bunches, changing interval between bunches with growth of their number.

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REFERENCES

1. I. Blumenfeld, C.E. Clayton, F.-J. Decker, et al. Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator // *Nature*. 2007, v. 445, p. 741.
2. A.K. Beresin, Ya.B. Fainberg, L.I. Bolotin, A.M. Egorov, V.A. Kiselev. Experimental investigation of interaction of the modulated relativistic bunches with plasma // *Pis'ma v ZhJeTF*. 1971, v. 13, p. 498-503 (in Russian).
3. A.K. Beresin, Ya.B. Fainberg, V.A. Kiselev, A.F. Linnik, V.V. Uskov, V.A. Balakirev, I.N. Onishchenko, G.L. Sidel'nikov, G.V. Sotnikov. Wake-field excitation in a plasma by pulse of relativistic electrons containing of controlled number of short bunches // *Plasma Physics*. 1994, v. 20, № 7, 8, p. 663-670.
4. K. Nakajima. Plasma wake-field accelerator driven by a train of multiple bunches // *Particle Accelerators*. 1990, v. 32, p. 209-218.
5. G.V. Sotnikov, R.R. Kniaziev, O.V. Manuilenko, et al. Analytical and numerical studies of underdense and overdense regimes in plasma-dielectric wakefield accelerators // *NIM*. 2014, v. A 740, p. 124-129.
6. R.R. Kniaziev, O.V. Manuilenko, P.I. Markov, et al. Focusing of electron and positron bunches in plasma-dielectric wakefield accelerators // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration"*. 2013, № 4, p. 84-89.
7. P.I. Markov, R.R. Kniaziev, I.N. Onishchenko, G.V. Sotnikov. Focusing of electron bunches in the plasma-dielectric rectangular slowing-down structure // *Problems of Atomic Science and Technology.* 2016, № 3(103), p. 57-61.
8. G.V. Sotnikov, I.N. Onishchenko, T.C. Marshall. 3D Analysis of Wakefield Excitation in a Dielectric Loaded Rectangular Resonator, in Advanced Accelerator Concepts / M. Conde and C. Eyberger eds. // *AIP Conference Proceedings.* 2006, p. 888-894.

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ УСКОРЕНИЯ ТЕСТОВОГО ЭЛЕКТРОННОГО СГУСТКА ПОСЛЕДОВАТЕЛЬНОСТЬЮ СГУСТКОВ В ДИЭЛЕКТРИЧЕСКОМ ВОЛНОВОДЕ И РЕЗОНАТОРЕ, ЗАПОЛНЕННОМ ПЛАЗМОЙ

П.И. Марков, И.Н. Онищенко, Г.В. Сотников

Представлены результаты численного моделирования ускорения тестового сгустка последовательностью релятивистских электронных сгустков в плазменно-диэлектрической цилиндрической замедляющей структуре для случаев открытого и закрытого проводящей сеткой выходного торца структуры. Входной торец был закрыт проводящей сеткой. Начальные размеры и энергия всех сгустков были одинаковыми. Расстояние между сгустками последовательности равнялось длине волны электромагнитного поля в структуре. Тестовый сгусток следовал за последним сгустком последовательности. Исследовалось ускорение тестового сгустка при изменении количества сгустков последовательности. Мы обнаружили, что для волновода наблюдаются две стадии: 1) линейный рост энергии ускоренного тестового сгустка с увеличением количества сгустков драйверной последовательности, за которым следует 2) практически, неизменное значение энергии сгустка при изменении количества драйверных сгустков. Для резонатора отмеченные две стадии линейного роста энергии и постоянного значения энергии тестового сгустка с увеличением количества сгустков драйверной последовательности повторяются попарно несколько раз. При определённом количестве сгустков в резонаторе можно получить существенно большее ускорение, чем в волноводе.

ПОРІВНЯЛЬНИЙ АНАЛІЗ ПРИСКОРЕННЯ ТЕСТОВОГО ЕЛЕКТРОННОГО ЗГУСТКА ПОСЛІДОВНІСТЮ ЗГУСТКІВ У ДІЕЛЕКТРИЧНОМУ ХВИЛЕВОДІ ТА РЕЗОНАТОРІ, ЗАПОВНЕНОМУ ПЛАЗМОЮ

П.І. Марков, І.М. Оніщенко, Г.В. Сотніков

Представлені результати чисельного моделювання прискорення тестового згустка послідовністю релятивістських електронних згустків у плазмово-діелектричній циліндричній сповільнюючій структурі для випадків відкритого й закритого провідною сіткою вихідного торця структури. Вхідний торець був закритий провідною сіткою. Початкові розміри й енергія всіх згустків були однаковими. Відстань між згустками послідовності дорівнювала довжині хвилі електромагнітного поля в структурі. Тестовий згусток йшов за останнім згустком послідовності. Досліджувалося прискорення тестового згустку при зміні кількості згустків послідовності. Ми виявили, що для хвилеводу спостерігаються дві стадії: 1) лінійне зростання енергії прискореного тестового згустка зі збільшенням кількості згустків драйверної послідовності, за яким іде 2) практично незмінне значення енергії згустка при зміні кількості драйверних згустків. Для резонатора відзначені дві стадії лінійного зростання енергії й незмінного значення енергії тестового згустка зі збільшенням кількості згустків драйверної послідовності повторюються попарно кілька разів. При певній кількості згустків у резонаторі можна одержати суттєво більше прискорення, ніж у хвилеводі.