TRANSPORT OF BUNCHES IN A DIELECTRIC WAKEFIELD ACCELERATOR USING AN ARRAY OF PLASMA CELLS

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An array of short sections of plasma dielectric wakefield accelerator modules spaced by vacuum zones (without plasma) is proposed to avoid the "underdense" operating regime. A calculation of the dynamics of the accelerated particles in such an array of accelerating-drift sections is given. The parameters of bunches which are available in SLAC are used for this calculation. A dielectric structure using fused silica provides an operating frequency ~ 350 GHz. Lengths of plasma and vacuum sections providing stable transportation of the accelerated bunch are found. The bunch size in the focal plane is determined.

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INTRODUCTION

Recent interest in dielectric wakefield accelerator physics directed toward an advanced high-gradient accelerator [1] has been rekindled by the finding that certain dielectrics can withstand very high fields (>1 GV/m) for the short times involved in the passage of charged bunches along a dielectric-lined channel [2]. A cylindrical, single-channel dielectric-lined structure has been shown to be an attractive and simple symmetric structure for high gradient acceleration of electron or positron bunches [3]. However, two problems have stood in the way of the implementation of this concept: first, the bunch motion is afflicted with instabilities (see [4] and references therein), and second, the transformer ratio is only ~ 2 [5]. Stabilizing the instabilities using external focusing is challenging in a small structure as required for high gradient acceleration. Also, while a ramped-charge drive bunch or train of bunches has been shown to increase the transformer ratio [6], such a bunch train may suffer unstable motion. One cure that has been suggested for these difficulties is the coaxial DWA, where the introduction of an inner coaxial dielectric tube has been shown [7] to offer better stability and elevated transformer ratio. Nevertheless, the complication of centering and suspending the inner tubing of the coax in a lengthy accelerator structure can be challenging.

Recently we have proposed to revisit the single channel configuration through which both the collinear drive and witness bunches move, but now fill this single channel with plasma [8] – plasma-dielectric wakefield accelerator (PDWA). We have found that the plasma can provide an important radial focusing force on the witness bunch; this might secure the advantage of higher transformer ratio using drive bunch ramping without the penalty of unstable bunch motion, in an axially-symmetric, smooth-bore, one-channel structure.

Plasma filling the transport channel of DWA operates similar to a plasma lens. In a lengthy unit this focusing could lead eventually to over-compression of the bunch, in which case the bunch density will exceed the plasma density and the undesirable "blowout" regime obtains. Besides, it is very hard to create plasma and sustain this homogeneity on a long distance. Thus a PDWA will inevitably consist of plasma cells with gaps between them. Therefore, for a bunch transport, we propose the use of a series of relatively short focusing PDWA units that are spaced by vacuum zones so that the "focal point" (minimum bunch radius) would lie in a vacuum space. Our requirement is only that these vacuum spaces not be filled with plasma – they could still be accelerator units, e.g. vacuum dielectric wakefield accelerator sections, that maintain the acceleration gradient but do not supply a strong radial force. The results of a study of the dynamics of the accelerated particles in such an array of accelerating-drift sections are presented in this paper.

STATEMENT OF THE PROBLEM

The principal scheme of the proposed accelerator based on plasma-dielectric modules is given in Fig. 1 which presents two PDWA cells separated by a vacuum space. Each PDWA cell is a section of cylindrical dielectric waveguide filled with plasma [8]; the gap between them (drift space) is the vacuum section of the same waveguide. The length of the first cell is L_{p1}, the length of the second cell is L_{p2}, the gap length is L_s.

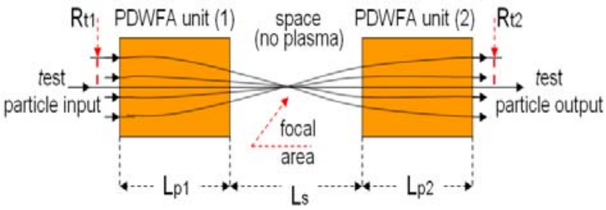


Fig. 1. Schematic of a pair of PDWA units used as focusing elements to transport a bunch of test particles that are located at the witness bunch

A drive bunch travelling through the accelerating system excites in each PDWA cell a wakefield [8] which accelerates the particles of a witness bunch. In the vacuum gap any forces acting on the witness bunch particles are absent.

A dynamics of witness bunch particles are described by relativistic motion equations:

$$\frac{du_z}{dz} = \frac{q\gamma}{mu_z}\left[E_z(r,\psi) + \frac{u_r}{c\gamma}H_\phi(r,\psi)\right],$$

$$\frac{du_r}{dz} = \frac{q\gamma}{mu_z}\left[E_r(r,\psi) - \frac{u_z}{c\gamma}H_\phi(r,\psi)\right],$$

$$\frac{dr}{dz} = \frac{u_r}{u_z}, \quad \frac{d\psi}{dz} = \frac{v_d\gamma}{u_z} - 1, \quad \gamma = \left(1 + u_r^2 + u_z^2\right)^{1/2}, \quad (1)$$

where $\psi = v_d t(z) - z$, q and m are the electron charge and mass, v_d is the longitudinal velocity of the drive bunch. If a certain witness bunch electron ("test" particle) is inside the drift space $L_{p1} < z < L_{p2}$ then electromagnetic field components acting on it is equal 0:

$$E_z = E_r = H_\phi = 0, \quad (2)$$

or else they can be presented in a sum of two items:

$$E_z = E_z^L + E_z^d, \; E_r = E_r^L + E_r^d, \; H_\varphi = H_\varphi^d. \quad (3)$$

In eq. (3) E_z^L, E_r^L are components of electric field of Langmuir wave, and E_z^d, E_r^d, H_φ^d are components of the electric and magnetic fields of the dielectric wave. Explicit form of all components of the wakefield is given in ref. [8].

DYNAMICS OF TEST PARTICLES

For numerical calculation of the components of the wakefield (2), (3) which accelerates the witness bunch electrons we used parameters of electron bunches accessible at SLAC: the energy of drive bunch electrons was 3 GeV, the bunch charge was 3 nC, its length was L_b = 0.2 mm, the drive bunch radius was $r_b = 0.45$ mm. The PDWA cell is a section of a cylindrical dielectric waveguide with an outer radius of the quartz tube ($\varepsilon = 3.75$) of 0.6 mm, inner radius 0.5 mm. Isotropic plasma filled the drift channel entirely and its density was $n_{p0} = 4.41 \cdot 10^{14}$ cm^{-3}. For analysis of trajectories (1), we supposed that the initial energy of witness bunch electrons is equal to the energy of drive bunch electrons.

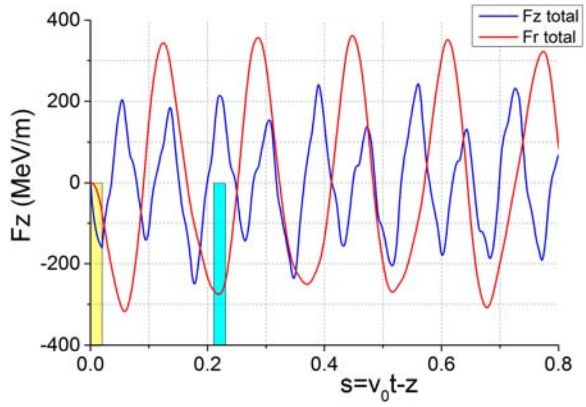


Fig. 2. Axial profile of the longitudinal force (blue solid line) and axial profile of the transverse force (red line) at the distance 0.45 mm from the waveguide axis. Drive bunch (the yellow rectangle) moves from right to left. The cyan rectangle shows the location of the electron witness bunch

In Fig. 2 are shown the axial profiles of longitudinal and transverse forces that can act upon witness bunch electrons. For the computation of the trajectories, the initial location of the test electrons will be taken around the third maximum of accelerating field $z = 2.21$ mm (see cyan rectangle in Fig. 2). One can see that this location of test particles provides both acceleration and focusing simultaneously.

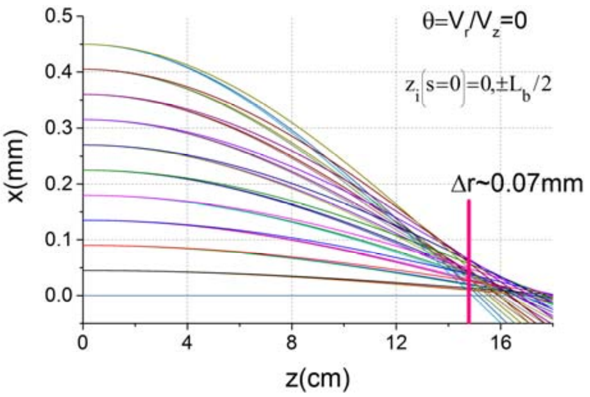
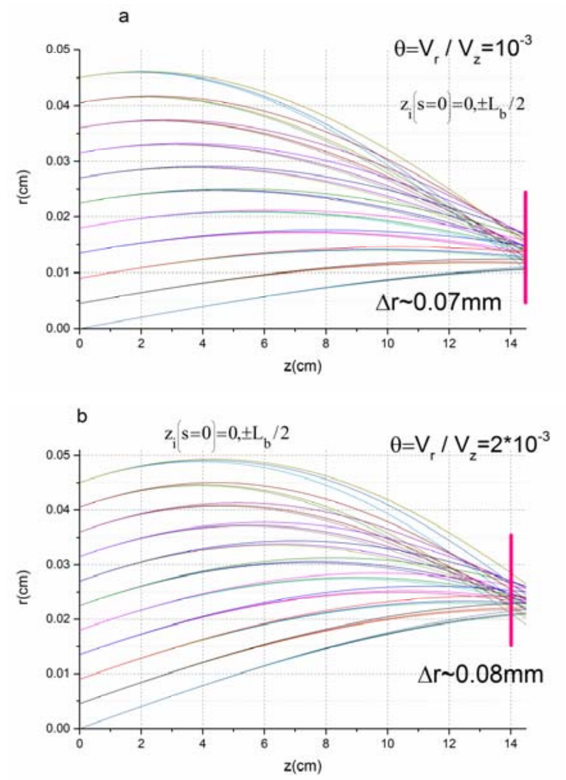


Fig. 3. Location of test witness bunch electrons in the plane (x, z) accelerated by the wakefield of a drive bunch. Initially the center of witness bunch is located at a distance 2.21 mm behind the center of the drive bunch. At the same radius are located 3 witness electrons (at the head z=2.21-L$_b$/2, at the center z=2.21 an at the tail z=2.21+L$_b$/2. Zero initial transverse velocity of test electron was used in this computation

In Fig. 3 is presented the trajectories of test electrons in the plane (y=0). At a travel distance of 8 cm a transverse focusing deflection ~ 0.15 mm of the 0.45 mm radius witness bunch is found. If we use a longer unit, the minimal radius of the witness bunch can be reached at z~14.8 cm where it is 0.07 mm. The aberration visible in the "focal plane" z~14.8 cm is due to the deflection of the focusing force from its linear dependence.

In Fig. 3, the trajectories of witness bunch electrons are computed when the initial transverse velocity is zero. Similar trajectories of test particles for different transverse initial velocities are shown in Fig. 4.



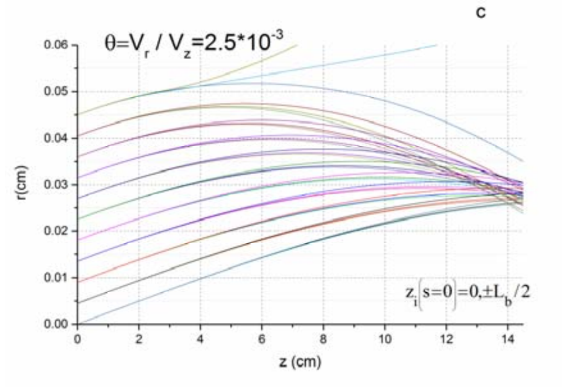


Fig. 4. The same as Fig. 3 except for different ratios of initial radial to axial velocities: $\theta = \mathrm{v_r} / \mathrm{v_z} = u_r / u_z$ *: a)* $\theta = 0.001$ *; b)* $\theta = 0.002$ *; c)* $\theta = 0.0025$

We find that the initial transverse velocity does not cause a considerable shift of "focal plane". The width of the witness bunch changes modestly there too. Furthermore, if the initial transverse velocity is greater than a certain value (for our parameters this is 0.0025), some of the test particle will deposit on the dielectric surface (see Fig. 4,c).

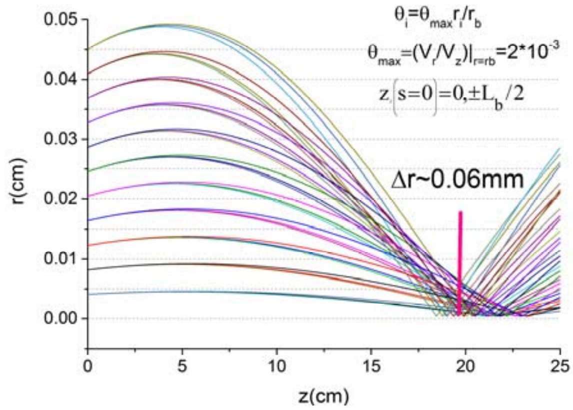


Fig. 5. Radius of test electrons accelerated in the wakefield of drive bunch. Initial velocities of test electrons are $\theta = u_r / u_z = \theta_{\max} \cdot r / r_b$ *,* $\theta_{\max} = 2 \cdot 10^{-3}$ *. The remaining parameters are the same as in Fig. 3*

A more realistic situation of the transport of a witness bunch having initial energy spread when the initial velocity of a test particle depends on its distance from the axis is shown in Fig. 5. Minimal width of the witness bunch at the "focal plane" is ~0.06 mm, i.e. it is about the same for all previously considered cases.

From this, one can see that the focusing of the witness bunch by the transverse field is strong and we can't avoid the over-compression of the accelerated bunch. The only way remaining is to shorten the length of the PDWA section so that the "focal plane" is located in a vacuum portion of the waveguide.

One possibility to choose the lengths of the PDWA cells and vacuum gap is: let the first PDWA cell be 7.5 cm, the length of the second PDWA cell be 6.5 cm, and the vacuum gap length be 11 cm. For this case, Fig. 6 shows the characteristics of the test particles during the transport through the PDWA. In this example the test electrons entering into the first PDWA cell do not have a radial velocity.

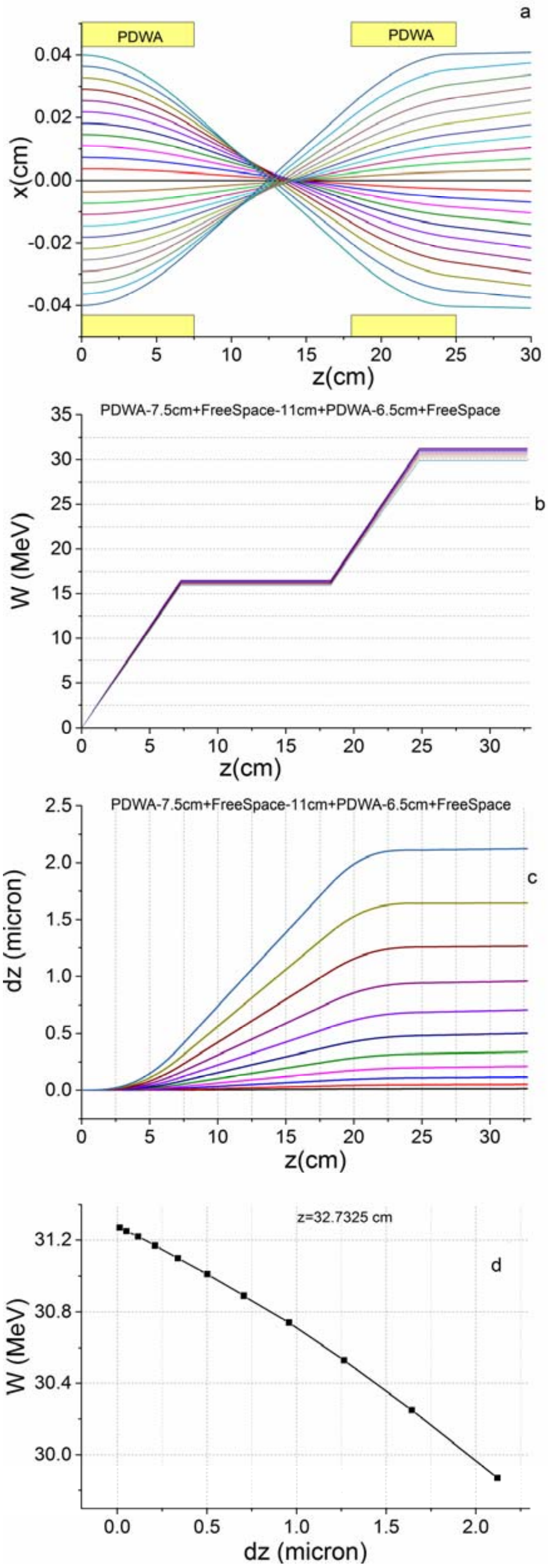


Fig. 6. Transverse coordinate (a), energy gain (b), shift from initial axial position (c) of test witness bunch electrons accelerated by the wakefield of a drive bunch travelling through two PDWA cells separated by a vacuum space. Initially the test electrons are located at a distance 2.21 mm behind the center of the drive bunch. Composite plot (d) shows energy gain of test electrons in the plane z-32.7 cm versus their axial shift from initial location. Yellow rectangles mark the axial location of the PDWA cells

One can see that after passing the second PDWA cell the motion of the test witness bunch particles is nearly laminar. Their energy spread at the output of the second PDWA cell is ±0.7 MeV (~2%) and the maximal displacement of test particles from the resonance wave phase is 2 microns. We note that the least displacement and the largest energy gain has occurred for the on-axis particles.

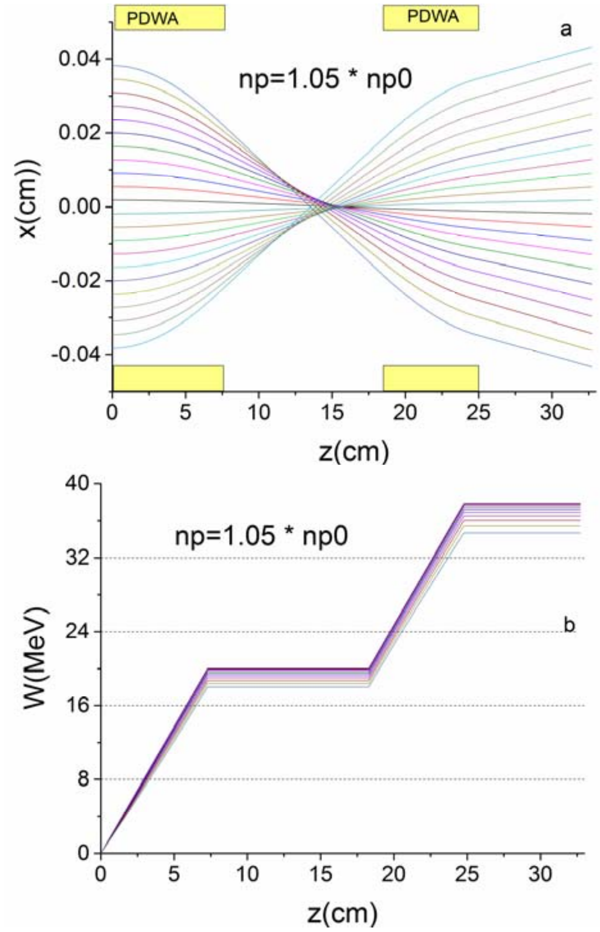


Fig. 7. The same in Figs. 6,a,b for the plasma density increased by 5%, $n_p = 1.05 n_{p0}$

In Figs. 7 and 8 is demonstrated a change of characteristics of the witness bunch upon varying the plasma density from that used in the previous figures. One can see that a 5% variation of the plasma density is not harmful for the stable transport of the witness bunch through the accelerator unit. When increasing the plasma density there is a small divergence of the witness bunch at the output of the second PDWA cell. Very likely, it is connected with the change of the wavelength of the total wakefield so that the test particles are displaced from the optimal location (maximum of accelerated and focusing field). More accurate placing of the witness bunch could decrease the observed divergence.

CONCLUSIONS

One can avoid over-compression of the bunch radius of an accelerated bunch inside the plasma cell by using an array of plasma cells separated by vacuum spaces.

At the output of the second cell it is possible to obtain laminar straight-line flow of the witness bunch.

A small variation of plasma density (tolerance) is not significant for the proposed scheme of transporting the accelerated bunch.

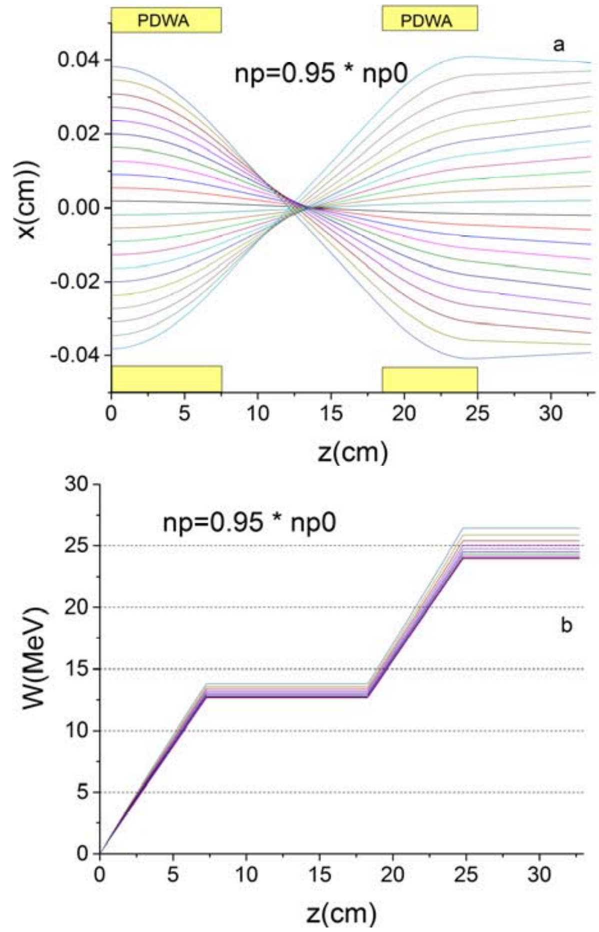


Fig. 8. The same in Figs. 6,a,b for the plasma density reduced by 5%, $n_p = 0.95 n_{p0}$

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ТРАНСПОРТИРОВКА СГУСТКОВ В ДИЭЛЕКТРИЧЕСКОМ КИЛЬВАТЕРНОМ УСКОРИТЕЛЕ С ПОМОЩЬЮ МАССИВА ПЛАЗМЕННЫХ ЯЧЕЕК

Р.Р. Князев, Т.К. Маршал, Г.В. Сотников

Предлагается использовать массив относительно коротких секций плазменно-диэлектрических кильватерных ускорительных (ПДКУ) модулей, разделенных вакуумными промежутками (без плазмы, хотя они могут содержать диэлектрическую структуру), с цель избежать нежелательной перефокусировки ускоряемого сгустка. Проведен расчет динамики ускоряемых частиц в такой решетке ускорительно-дрейфовых секций ПДКУ. Для расчета использованы параметры сгустков, имеющиеся в SLAC. Диэлектрическая структура на основе плавленого кварца обеспечивает рабочую частоту ~ 350 ГГц. Найдены длины плазменной и вакуумной секций, обеспечивающих устойчивую транспортировку ускоряемого сгустка. Определены размеры сгустка в фокальной плоскости.

ТРАНСПОРТУВАННЯ ЗГУСТКІВ У ДІЕЛЕКТРИЧНОМУ КІЛЬВАТЕРНОМУ ПРИСКОРЮВАЧІ ЗА ДОПОМОГОЮ МАСИВУ ПЛАЗМОВИХ СЕКЦІЙ

Р.Р. Князєв, Т.К. Маршал, Г.В. Сотніков

Пропонується використовувати масив відносно коротких секцій плазмово-діелектричних кільватерних прискорювальних (ПДКП) модулів, розділених вакуумними проміжками (без плазми, хоча вони можуть містити діелектричну структуру), з метою уникнути небажаного перефокусування згустку, що прискорюється. Проведено розрахунок динаміки частинок, що прискорюються, у такій решітці прискорювально-дрейфових секцій ПДКП. Для розрахунків використані параметри згустків, наявні в SLAC. Діелектрична структура на основі плавленого кварцу забезпечує робочу частоту ~ 350 ГГц. Знайдено довжини плазмової й вакуумної секцій, які забезпечують стійке транспортування згустку, що прискорюється. Визначені розміри згустку у фокальній площині.