COMPARISON OF TWO FOCUSING METHODS IN LOW-ENERGY ION LINAC WITH ELECTRIC UNDULATOR FIELDS

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It is well known that nonsynchronous harmonics of RF field (RF undulator) are focusing the particles [1, 2]. In low-energy linear accelerators the periodic sequence of electrostatic lenses (electrostatic undulator) can be used for the ion beams focusing too. The conditions of the beam stability were found and analyzed for two undulator types.

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1. INTRODUCTION

The problem of the effective low-energy linac design is of interest to many fields of science, industry and medicine (e.g. nuclear physics, surface hardening, ion implantation, hadron therapy). The most significant problem for low-energy high-current beams of charged particles is the question of the transverse stability through Coulomb repelling forces influence. Low-energy heavy-ion beams transport is known to be realized by means of the periodic sequence of electrostatic lenses (electrostatic undulator) [3]. It offers to constructively join a periodic RF cavity and the electrostatic undulator (ESU) in the same device. To accelerate the low-energy ion beams one of the following RF focusing types can be used: alternating phase focusing (APF), radio frequency quadrupoles (RFQ), focusing by means of the nonsynchronous wave field as well as the undulator RF focusing. The main principles of APF were described in Refs. [4, 5]. The modification of APF was suggested in later studies [6]. A reached threshold beam current in RFQ [7] is about 100…150 mA and the further current rise leads to severe difficulties. A particle focusing with the use of the nonsynchronous wave in the two-wave approach was considered in Ref. [8]. The methods were used to describe RF focusing in reference mentioned above have a number of shortcomings. For example, there is no correct relationship between longitudinal and transverse beam motion, the averaging method which was used is not quite valid. Detailed analysis of the focusing by means of nonsynchronous waves of RF field shows that the focusing by the slow harmonic field in periodical ordinary Wideröe type and Alvarez type structures is not effective since the acceleration rate is very small. Increasing the fast harmonic amplitude leads to appearance of the longitudinal beam instability, which quickly disrupts the resonant conditions. The RF focusing by the nonsynchronous harmonics was studied in [2] particularly.

Alternatively, the acceleration and the focusing can be realized by means of the electromagnetic waves which are nonsynchronous with beam (the so-called undulator focusing) [9]. Systems without synchronous wave are effective only for the light ion beams. For the low-energy heavy-ion beams to be accelerated it is necessary to have the synchronous wave with the particles. In the case of RF focusing, in the bunch frame the slow wave affects the particles similar to the electrostatic undulator. The goal of this work is the analysis and the comparison of the RF focusing and the electrostatic one.

2. MOTION EQUATION

The analytical investigation of the beam dynamics in a polyharmonical field is a difficult problem. The rapid longitudinal and transverse oscillations as well as the strong dependence of the field components on the transverse coordinates does not allow us to use the linear approximation in the paraxial region for a field series. After all, the analytical beam dynamics investigation can be carried out by means of the averaging method over the rapid oscillations period (the so-called smooth approximation) in the oscillating fields, which was suggested by P.L. Kapitsa [10] for the first time. Let us express RF field in an axisymmetric periodic resonant structure and ESU field as an expansion by the standing wave spatial harmonics assuming that the structure period is a slowly varying function of the longitudinal coordinate z

$$\begin{aligned} E_z &= \sum_{n=0}^{\infty} E_n I_0(k_n r)\cos\left(\int k_n dz\right)\cos(\omega t); \\ E_r &= \sum_{n=0}^{\infty} E_n I_1(k_n r)\sin\left(\int k_n dz\right)\cos(\omega t); \\ E_z^u &= \sum_{n=0}^{\infty} E_n^u I_0(k_n^u r)\cos\left(\int k_n^u dz\right); \\ E_r^u &= \sum_{n=0}^{\infty} E_n^u I_1(k_n^u r)\sin\left(\int k_n^u dz\right), \end{aligned} \tag{1}$$

where E_n, E_n^u are the nth RF and ESU fields harmonic amplitude on the axis; $k_n = (\theta + 2\pi n)/D$ is the propagation wave number for the nth RF field spatial harmonic, $k_n^u = (\theta^u + 2\pi n)/D^u$ is the factor of the nth ESU field harmonic; D, D^u are the geometric periods of the resonant structure and ESU; θ, θ^u are the phase advances per period D, D^u respectively; ω is the angular frequency; I_0, I_1 are modified Bessel functions of the first kind.

We shall assume the beam velocity (the one-particle approximation) υ does not equal one of the spatial harmonic phase-velocities $\upsilon_n = \omega/k_n$ except the synchronous harmonic of RF field, the geometric period of RF structure being defined as $D = \beta_s\lambda(s + \theta/2\pi)$, where s is the synchronous harmonic number, β_s is the relative velocity of the synchronous particle, λ denotes RF wavelength. Thus, the solution of the motion equation (the particle path) in the rapidly oscillating field (1) we shall search as a sum of a slowly varying beam radius-vector component and a rapidly oscillating one. We assume that the amplitude of the rapid velocity oscillations is much smaller than the slowly varying velocity component for the smooth approximation to be employed. With the aid of the averaging over the rapid oscillations (as it was done in Ref. [1]) we obtain the motion equation, in the bunch frame, in the form

$$d^2R/dt^2 = -\mathrm{grad}U_{eff}, \qquad (2)$$

where $R = (\bar z - z_s, \bar r)$, U_{eff} is the effective potential function (EPF) which describes the tridimensional low-energy beam interaction with the polyharmonical field of the system and determines the beam-wave system Hamiltonian $H = 0.5(dR/dt)^2 + U_{eff}$. The EPF depends only on the slowly varying (in comparison with the rapid oscillation period) transverse coordinate $\bar r$ and the phase difference of the particle in the synchronous harmonic wave $\varphi = \int k_s d\bar z - \omega t$ and the quasi-equilibrium (synchronous) particle φ_s.

3. EPF FOR DIFFERENT STRUCTURES

3.1. WIDERÖE TYPE STRUCTURE

If we put $\theta^u = \theta = \pi$, $D^u = D$ and take point $\zeta = \rho = 0$ as the reference point of normalized EPF ($U_{eff} = U_{eff}/\beta_s^2$), then EPF for Wideröe type structure can be written as $U_{eff}^W = U_0^W + U_1^W + U_2^W$, where

$$U_0^W = -\frac{1}{2}e_s\left[I_0(\rho)\sin(\zeta+\varphi_s) - \zeta\cos(\varphi_s) - \sin(\varphi_s)\right];$$

$$U_1^W = \frac{1}{16}\sum_{n\neq s}\frac{e_n^2}{\nu_{n,s}^2}f_0^{n,s}(\rho) + \frac{1}{16}\sum_n\frac{e_n^2}{\mu_{n,s}^2}f_0^{n,s}(\rho) + \frac{1}{4}\sum_n\left(\frac{e_n^u}{k_n/k_s}\right)^2 f_0^{n,s}(\rho);$$

$$U_2^W = \frac{1}{16}\sum_{\substack{n\neq s\\ k_n+k_p=2k_s}}\frac{e_n e_p}{\nu_{n,s}^2}\left[f_1^{n,s,p}(\rho)\cos(2\zeta+2\varphi_s) + 2\zeta\sin(2\varphi_s) - \cos(2\varphi_s)\right] + \frac{1}{8}\sum_{\substack{n\neq s\\ k_n-k_p=2k_s}}\frac{e_n e_p}{\nu_{n,s}^2}\times \left[f_2^{n,s,p}(\rho)\cos(2\zeta+2\varphi_s) + 2\zeta\sin(2\varphi_s) - \cos(2\varphi_s)\right]. \qquad (3)$$

Here $e_n = eE_n\lambda/2\pi\beta_s mc^2$, $e_n^u = eE_n^u\lambda/2\pi\beta_s mc^2$, $\xi = 2\pi\bar z/\lambda\beta_s$, $\zeta = \xi - \xi_s$, $\rho = 2\pi\bar r/\lambda\beta_s$, $\tau = \omega t$ are the normalized values; $s, n, p = 0, 1, 2 \ldots$, $\nu_{n,s} = (k_n - k_s)/k_s$, $\mu_{n,s} = (k_n + k_s)/k_s$ and the functions of the dimensionless transverse coordinate are defined as

$$f_0^{n,s}(\rho) = I_0^2\left(\frac{k_n}{k_s}\rho\right) + I_1^2\left(\frac{k_n}{k_s}\rho\right) - 1;$$

$$f_1^{n,s,p}(\rho) = I_0\left(\frac{k_n}{k_s}\rho\right)I_0\left(\frac{k_p}{k_s}\rho\right) - I_1\left(\frac{k_n}{k_s}\rho\right)I_1\left(\frac{k_p}{k_s}\rho\right);$$

$$f_2^{n,s,p}(\rho) = I_0\left(\frac{k_n}{k_s}\rho\right)I_0\left(\frac{k_p}{k_s}\rho\right) + I_1\left(\frac{k_n}{k_s}\rho\right)I_1\left(\frac{k_p}{k_s}\rho\right).$$

From these expressions we can see that the term U_0^W of EPF is responsible for both the beam acceleration and its transverse defocusing. The term U_1^W influences only on the transverse motion, always focusing the beam in the transverse direction. The term U_2^W has an influence not only on the longitudinal motion but on the transverse one. The extreme point of U_2^W as well as U_0^W is a saddle point. Therefore, the necessary condition for simultaneous transverse and longitudinal focusing is the existence of the total minimum of EPF. If ESU is absent (i.e. $e_n^u = 0$) the term U_1^W is reduced. In this case the transverse stability is achieved only by using nonsynchronous harmonics of RF field. For the amplitudes of the nonsynchronous harmonics to be increased we should include additional electrodes. Thereby, the utilization of ESU allows us to achieve the transverse stability without the complication channel geometry if the equal in absolute value d-c potentials are supplied on the same electrodes which are used to excite RF field, i.e. we can constructively join the periodic RF system and ESU in the same device.

At first we analyze EPF in the paraxial region. The EPF U_{eff}^W is expanded in Maclaurin's series

$$U_{eff}^W = \omega_\zeta^2\zeta^2/2 + \omega_\rho^2\rho^2/2 + \varepsilon\zeta\rho^2/2 + \delta\zeta^3/6 + o(\alpha^4), \qquad (4)$$

where the expansion coefficients are given by

$$\omega_\zeta^2 = \frac{1}{2}e_s\sin(\varphi_s) - \frac{1}{4}\sum_{\substack{n\neq s\\ k_n+k_p=2k_s}}\frac{e_n e_p}{\nu_{n,s}^2}\cos(2\varphi_s) - \frac{1}{2}\sum_{\substack{n\neq s\\ k_n-k_p=2k_s}}\frac{e_n e_p}{\nu_{n,s}^2}\cos(2\varphi_s);$$

$$\omega_\rho^2 = -\frac{1}{4}e_s\sin(\varphi_s) + \frac{3}{32}\sum_{n\neq s}\frac{e_n^2}{\nu_{n,s}^2}\left(\frac{k_n}{k_s}\right)^2 + \frac{3}{32}\sum_n\frac{e_n^2}{\mu_{n,s}^2}\left(\frac{k_n}{k_s}\right)^2 + \frac{3}{8}\sum_n\left(e_n^u\right)^2 + \frac{1}{32}\sum_{\substack{n\neq s\\ k_n+k_p=2k_s}}\frac{e_n e_p}{\nu_{n,s}^2}\frac{k_n^2+k_p^2-k_nk_p}{k_s^2}\cos(2\varphi_s) + \frac{1}{16}\sum_{\substack{n\neq s\\ k_n-k_p=2k_s}}\frac{e_n e_p}{\nu_{n,s}^2}\frac{k_n^2+k_p^2+k_nk_p}{k_s^2}\cos(2\varphi_s); \qquad (5)$$

$$\varepsilon = \partial(\omega_\rho^2)/\partial\varphi_s;\ \delta = \partial(\omega_\zeta^2)/\partial\varphi_s.$$

It is necessary that the parameters of the channel will be chosen in terms of the conditions $\omega_{\zeta}^{2} > 0, \omega_{\rho}^{2} > 0$ (for the simultaneous transverse and longitudinal focusing). Furthermore, if we take into account the third-order terms in the anharmonic potential (4) it may lead to appearance of internal parametric resonances. It can destroy the stable beam dynamics due to beam-wave system energy transfer between two degrees of freedom. In this case the small oscillations frequencies satisfy the relation $\omega_\rho/\omega_\zeta = l/2$, where $l = 1, 2, 3 \ldots$. Another important restriction on the choice of the spatial harmonic amplitudes can be obtained from the condition of nonoverlapping for different waves resonances in the phase space $(\dot{\zeta}, \zeta)$. On the one hand, this restriction defines limits of the applicability of the averaging method. On the other hand, it is the necessary condition of the longitudinal (phase) stability.

The effective separatrix for the axial particles can be found analytically in terms of the system Hamiltonian. For the saddle point to be defined we are using the equation $x^4 + qx^3 + gx^2 + cx + d = 0$, where the coefficients are certain functions of the harmonic amplitudes and φ_s. Using Decartes – Euler or Ferrari's solution we have $\zeta_{left} = 2\mathrm{arctg}(x_i) - \varphi_s$, where x_i is a real root of the quartic equation, which is chosen so that $\zeta_{left} < 0$. Knowing the position of the effective separatrix saddle point the bucket boundary is determined by the equation

$$\dot{\zeta} = \pm\left(2U_{eff}^{W}(\zeta_{left}, 0) - 2U_{eff}^{W}(\zeta, 0)\right)^{1/2}. \quad (6)$$

The capture region of ESU in approach of the basic harmonic can be expressed as:

$$\beta^{u}/\beta_{s} = \left[2\left|e_0^u\right|\left(1 + \sin\left(\varphi^{u} + \psi\right)\right)\right]^{1/2}, \quad (7)$$

where $\psi = 0$, if $e_0^u > 0$ or $\psi = \pi$, if $e_0^u < 0$.

As it was said the condition which determines the bottom limit of the spatial harmonic amplitudes is the existence of the absolute minimum of EPF. When we are using the channel with a simple period (one electrode per period D) we can take into account only e_0, e_0^u in U_{eff}^{W} because the higher harmonics are smaller than written above. Therefore, the condition $\omega_{\rho}^{2} > 0$ may be represented as

$$\left(e_0^u/e_0\right)^2 > 2\sin(\varphi_s)/3e_0 - 1/16. \quad (8)$$

3.2. ALVAREZ TYPE STRUCTURE

The EPF for Alvarez type structure U_{eff}^{A} ($\theta = 0$, $\theta^u = \pi$; $D^u = D$) has a view similar to U_{eff}^{W}. The most important feature is the existence of an additional term in U_2^A, where superscript A denotes values of the structure at hand. Thus, the additional term in U_2^A and the term U_1^A become

$$\frac{1}{4}e_0 e_{2s}\left[I_0(2\rho)\cos(2\zeta + 2\varphi_s) + 2\zeta\sin(2\varphi_s) - \cos(2\varphi_s)\right];$$

$$U_1^A = \frac{1}{16}\sum_{n\neq s}\frac{e_n^2}{\nu_{n,s}^2}f_0^{n,s}(\rho) + \frac{1}{16}\sum_{n}\frac{e_n^2}{\mu_{n,s}^2}f_0^{n,s}(\rho) + \\ + \frac{1}{4}\sum_{m}\left(\frac{e_m^u}{k_m^u/k_s}\right)^2\cdot\left[I_0^2\left(\frac{k_m^u}{k_s}\rho\right) + I_1^2\left(\frac{k_m^u}{k_s}\rho\right) - 1\right], \quad (9)$$

where $s, n, p > 0$ and $m \geq 0$ unlike the system considered above. The harmonic amplitude of RF field e_n for Alvarez type structure is not equal to Wideröe type structure one. Moreover, in this case the basic harmonic is e_1, and e_0 is the dimensionless average field value. The existence of the additional term in U_2^A leads to the next serious result. The additional term may be comparable with U_0^A and essentially increases the acceleration rate since the average field value is large. One can assume that an Alvarez type structure, which is commonly used for acceleration of medium-beta particles, may be used for the low-energy beam acceleration. In this case the transverse stability can be achieved by using ESU in view of the period smallness. The resume made about the each term of U_{eff}^{W} in previous subsection is valid for U_{eff}^{A} in this subsection too.

4. NUMERICAL SIMULATION

The computer simulation of high-intensity proton beam dynamics in the discussed Wideröe type structure with the basic spatial harmonic (e_0) of the RF field was carried out by means of the specialized computer code BEAMDULAC – ARF3 [2]. In the case of RF focusing only the first nonsynchronous harmonic was taken into account. We examined only the basic spatial harmonic of ESU (i.e. e_0^u) studying the electrostatic focusing. Simulation parameters are the following: beam injection energy W_{in} is 80 keV; input current $I_{in} = 0.1$ A; beam radius $r_b = 2$ mm; $\psi = \pi$; longitudinal/transverse input beam emittance $\varepsilon_\varphi/\varepsilon_\rho = 3.2\pi$ keV·rad/20π mm·mrad; RF wave-length $\lambda = 1.5$ m; input (E_{in}) and output (E_{out}) values of the synchronous harmonic field strength are 1.7 kV/cm and 18.4 kV/cm respectively. The lengths of the accelerator (L), amplitude rise (L_e) and the equilibrium phase decay (L_{gr}) are 2.5 m, 2.325 m and 1.8 m; channel aperture $a = 4$ mm; relative energy spread is 2%; longitudinal/transverse input channel acceptance $A_\varphi/A_\rho = 33\pi$ keV·rad/40π mm·mrad. The amplitude ratio is $e_1/e_0 = e_0^u/e_0 \approx 10$, the law of the synchronous harmonic amplitude variation along L_e is given by

$$E_0 = E_{out}\left[0.093 + 1.676\sin^2\left(\frac{5\pi}{19}\frac{z}{L_e}\right)\right]. \quad (10)$$

The synchronous harmonic amplitude equals to E_{out} for $z \geq L_e$. The quasi-equilibrium particle phase is linearly reduced from value $\pi/2$ to $\pi/4$ at the length L_{gr} and equals to $\pi/4$ for $z \geq L_{gr}$.

The output longitudinal and transverse phase spaces are shown in Fig.1 (for the RF focusing) and Fig.2 (for the electrostatic focusing). As we can see in Fig.1,a the beam has uniform phase and velocity distributions inside the effective separatrix at the end of structure. In Fig.2,a it is shown that the beam has nonuniform phase and velocity distributions. Moreover, beam periodically traverses the synchronous harmonic separatrix boundary because the strong ESU field has an effect on the longitudinal particle motion. Particles remain inside of the separatrix in the case of the averaged motion. The output transmission, energy, longitudinal and transverse emittances are about 66%, 0.71 MeV, 100π keV·rad, 54π mm·mrad for two structure types respectively. The particle loss is observed in the longitudinal direction in both cases. It is the result of an interaction with the non-synchronous harmonic which leads to increase of the beam amplitude oscillations. Note that the law of the synchronous harmonic amplitude variation (10) is not optimal to obtain the maximal output energy under the high transmission. The numerical simulation results confirmed similarity between RF focusing and the electrostatic one. All results obtained in the smooth approximation coincide up to 10%.

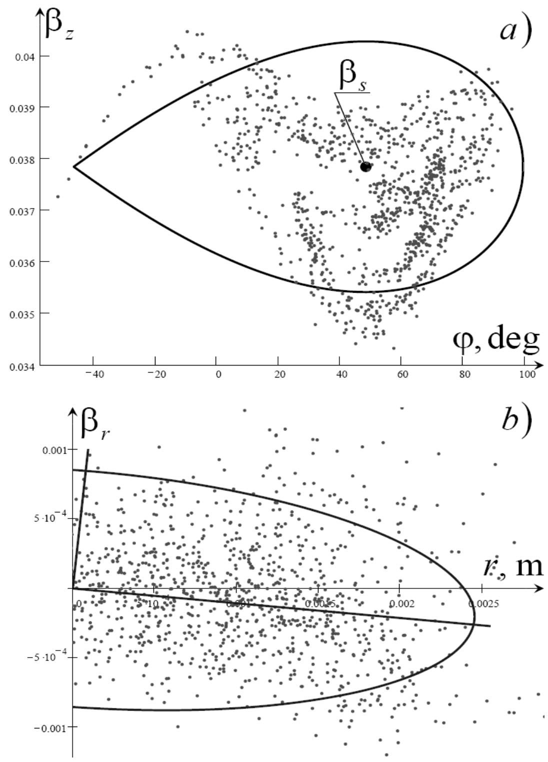

Fig.1. The output beam emittances for RF focusing: a – longitudinal; b – transverse

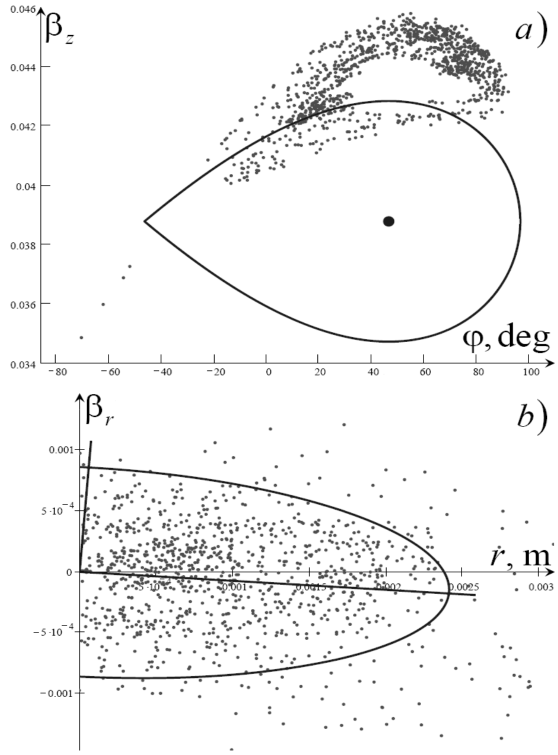

Fig.2. The output beam emittances for ESU focusing: a – longitudinal; b – transverse

5. CHANNEL GEOMETRY CHOICE

For Wideröe type structures with a simple period the spatial harmonic amplitudes are a rapidly decreasing function of its number which proportional to $E_{max} I_0^{-1}(k_n a)\sin(Y_n)Y_n^{-1}$, where E_{max} is the maximal field strength at the aperture a in the electrode-gap, $Y_n = \pi ng/D$, g – the inter-electrode gap width. For the amplitude e_1 to be increased up to $10e_0$ it is necessary to set three electrodes on the period D and either provide the adjacent electrodes (which have equal apertures) with different potentials or periodically vary the internal radius of the adjacent electrodes. Only the latter way can be practically realized in the RF cavity. In this case the additional electrodes with internal radius b must be shifted to the position $D/3 + \Delta$ and $2D/3 - \Delta$ respectively, where $\Delta = e_0 D \big/ 2\pi\sqrt{3}e_1$. By varying the length and corner radii of electrodes one can depress the higher harmonics and obtain only two waves in the structure. The ratio between internal radii b/a versus a/D for different values of e_1/e_0 is shown in Fig.3.

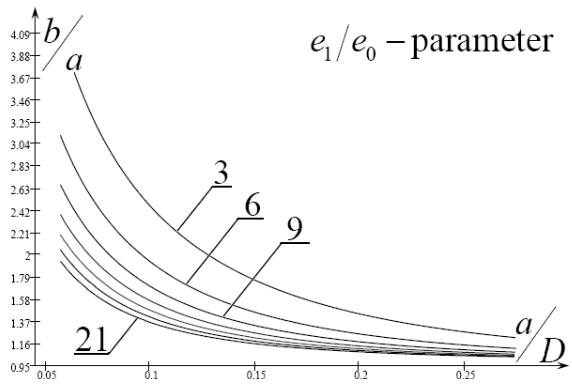

Fig.3. Values of b/a vs a/D for different ratio e_1/e_0

Note, if the beam injection energy is about 100 keV and λ = 1.5 m the electrodes lengths are about 3 mm. Thus, the significant amplitude e_1 may lead to RF discharge; also it is difficult to produce such small construction units.

As it was mentioned above, the additional d-c voltage generator can be used for the transverse focusing in the structure with the simple period. However, in this case we face difficulties which are that the desired value e_0^u must be held along the channel. The question of high-voltage input into RF cavity should be investigated too.

CONCLUSION

The comparison of two undulator types was done. The possibility of the electrostatic undulator application to focusing the low-energy high-intensity heavy ions was studied. The computer simulation of the high-intensity ion beam dynamics in Wideröe type structure with RF undulator as well as with ESU was carried out. It was shown that the electrostatic undulator can be a substitution for RF one. Using Alvarez type structure for low-energy beam acceleration was discussed. It is interesting to study a structure realization possibility with ESU operating at 0-mode for further increasing the acceleration rate. Thus, the discussed structures need the next deep research.

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СРАВНЕНИЕ ДВУХ СПОСОБОВ ФОКУСИРОВКИ ИОНОВ В ЛИНЕЙНОМ УСКОРИТЕЛЕ НА МАЛУЮ ЭНЕРГИЮ С ПОМОЩЬЮ ЭЛЕКТРИЧЕСКИХ ПОЛЕЙ ОНДУЛЯТОРОВ

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Известно, что несинхронные гармоники высокочастотного поля (ВЧ-ондулятор) фокусируют частицы. В линейных ускорителях на малую энергию периодическая последовательность электростатических линз (электростатический ондулятор) тоже может использоваться для фокусировки ионных пучков. Условия устойчивости пучка найдены и проанализированы для двух типов ондулятора.

ПОРІВНЯННЯ ДВОХ СПОСОБІВ ФОКУСУВАННЯ ІОНІВ У ЛІНІЙНОМУ ПРИСКОРЮВАЧІ НА МАЛУ ЕНЕРГІЮ ЗА ДОПОМОГОЮ ЕЛЕКТРИЧНИХ ПОЛІВ ОНДУЛЯТОРІВ

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Відомо, що несинхронні гармоніки високочастотного поля (ВЧ-ондулятор) фокусують частинки. У лінійних прискорювачах на малу енергію періодична послідовність електростатичних лінз (електростатичний ондулятор) теж може використатися для фокусування іонних пучків. Умови стійкості пучка знайдені і проаналізовані для двох типів ондулятора.