ION BEAM SPACE CHARGE NEUTRALIZATION USING FOR BEAM INTENSITY INCREASE IN LINACS

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As it is well known, the space charge is the main factor limiting the beam intensity in ion bunchers and low energy linacs. It can be declared that the limit low energy beam current is achieved or close now. But it must be enlarged up to 300…1000 mA for the same purposes as neutron generators, accelerating driven systems and other. It is provide to discussion about new acceleration and focusing methods which can to be used for this facilities. There are two ways to increase ion beam intensity: to enlarge the beam's cross section and to use the space charge neutralization. The second way of the limit beam current enlargement is more discussable. It is known three (or more?) ideas for beam space charge neutralization: (i) neutralization using plasmas, ionized residual gas or electron cloud; (ii) so-called "funneling" method; (iii) simultaneous acceleration of positive and negative ions in the same bunch. Some results in beam space charge neutralization will discussed for RFQ, DTL, UNDULAC.

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1. INTRODUCTION

Production of high intensity ion beams in a linac is a challenging task of contemporary accelerator physics and technology. Such accelerators can be employed in nuclear energetic, neutron sources, thermonuclear synthesis as well as in other applications. The RFQ structures are usually used as the buncher of linac. The current in the RFQ can be limited by the losses due to influence of the space charge fields. Therefore, the maximum proton beam current achieved in the RFQ is 120…150 mA [1]. As it is well known, the space charge is the main factor limiting the beam intensity in ion bunchers and low energy accelerators. We can say that the limit low energy beam current is achieved or close now. But it must be enlarged up to 300…1000 mA for same uses. It is provide to discussion about new acceleration and focusing methods which can to be used for this facilities. There are two ways to increase ion beam intensity: to enlarge beam's cross section and to use space charge neutralization. The aperture of accelerator and the necessary RF potential on electrodes should be enlarged in first case. The ribbon or hollow ion beam acceleration can be used as an alternative method of beam current enlarging.

The second way to limit beam current enlargement is more discussable. It is known three (or more?) ideas for beam space charge neutralization: (i) neutralization using plasmas, ionized residual gas or electron cloud; (ii) so-called "funneling" method; (iii) simultaneous acceleration of positive and negative ions in the same bunch. The idea of beam space charge neutralization by means of electron cloud was proposed and analytically studied in [2, 3]. It was shown that electron cloud can really provide to the proton or heavy ion partially neutralization. The neutralization of Coulomb field influence by means of plasma lenses is widely used in beam transport lines [4]. More interest results were analytically shown and experimentally verified by number of research groups [5-9] for bunched and continuous proton and ion beams. The ionized residual gas influence was studied in all noted experiments. It was shown that influence of ionized gas can provide to beam emittance decreasing.

2. FUNNELING TECHNOLOGY

The term "funneling" we can find in 30-years old reports [10, 11]. The LAMPF DTL linac long time works in LANL uses the funneling (but not use this term) [12, 13]. The previously accelerated to 200 MeV H^+ and H^- beams were injecting in last section of LAMPF linac and simultaneously accelerated to 800 MeV. The acceleration was provided in different (opposite) reference phases and bunches of H^+ and H^- ions were spatially separated. The systems for beam bunching and low energy acceleration with funneling were proposed later in LANL [14] and Frankfurt University [15-17] using RFQ or magnetic quadrupole lenses. In these linacs funneling is used to increase the total beam current. The four stage funneling scheme was presented in [18]. Frequency multiplying is necessary in funneling method if only positive or negative ion beam are accelerates. The linac with very high current can be used for designing fusion technologies facilities or spallation neutron sources [19]. Other bunching and acceleration mechanism can be realized in case when the positive and negative ions were accelerated simultaneously.

3. SIMULTANEOUS ACCELERATION OF POSITIVE AND NEGATIVE IONS IN RFQ

As it is well known, RFQ linacs are more useful for low energy proton and ion beams bunching and acceleration. This linac was proposed by V.A. Teplyakov and I.M. Kapchinskiy [20] and the beam dynamics in RFQ was studied by many authors [21-24]. Popular codes as simplest LANL PARMTEQ or more accurately DYNAMION [21] and LIDOS [25] uses for numerical beam dynamics simulation in RFQ linacs.

It was shown by numerical simulation that the total beam flux is lower and beam transverse emittance decreases in case of simultaneously acceleration of H^+ and H^- ions [26]. The decreasing of output beam flux seems very strange result and can be caused by specific model used for simulation. The space-charge forces in these models are calculated by assuming that the charge distribution is periodic and treating by following a separate group of particles for each beam. In case when the two beams have equal input parameters the problem is simplified by following only the positive ions.

The results of simulation and experiential study of simultaneously acceleration of O^+ and O^- ions were represented in [27]. It was shown that the total beam flux can be sufficiently (approximately 1.8 times) increased using funneling method. Analysis of beam dynamics shows that in RFQ or DTL the intensity of the ion beam can be made twice as higher by simultaneous acceleration of ions with opposite charge signs. The accelerating force in these linacs is proportional to the charge of the ion. Oppositely charged ions are bunched and accelerated in the different phases of the accelerating wave. Two bunches (one with a positive and another one with a negative charge) become separated and weakly interact with each other after the initial part of the buncher. In this case the phase separation of the bunch is large and the space charge neutralization can't be achieved. The intensity of the ion beam can be made twice as higher therefore. These results were confirmed in general by numerical simulation [27-28].

Thus the simulation shows that the total beam flux can be only twice enlarged in RFQ using simultaneous negative and positive ions acceleration. Note that the simulation results [26-29] were observed using modified PARMTEQ code. The distribution of ions and Coulomb fields was calculated separately for positive and negative ions on 2D grid. The full field is calculates by superposition that is not all correct for two beam acceleration because the beams of oppositely charged particles are overlapping in buncher.

Different results were done by A.P. Durkin using LIDOS code. It was shown [30] that the current transmission coefficient can be "significantly (up to 10%) diminishes". These differences provide us to necessary of more detail investigation of simultaneous negative and positive ions acceleration in RFQ.

4. USING BEAMDULAC CODE FOR DUAL BEAM DYNAMICS SIMULATION IN RFQ

The BEAMDULAC code is developing in MEPhI for self-consistent beam dynamics investigation in RF linacs and transport channels [31-32]. The 2D and 3D ion beam dynamics can be studied by means of this code. The motion equation for each particle is solved in the external fields and the inter-particle Coulomb field simultaneously. The BEAMDULAC code utilizes the cloud-in-cell (CIC) method for accurate treatment of the space charge effects. The charge density is deposited on the grid points using the CIC technique. To determine the potential of the Coulomb field, the Poisson equation is solved on the grid with periodic boundary conditions at both ends of the domain in the longitudinal direction. The aperture of the channel is represented as an ideally conducting surface of rectangular or circular cross-section. Therefore the Dirichlet boundary conditions are applied at transverse boundaries of the simulation domain. In such an approach, the interaction of the bunch space charge with the accelerating channel boundaries is taken into account. This allows consideration of the shielding effect, which is sufficiently important for transverse focusing in the narrow channel. The fast Fourier transform (FFT) algorithm is used to solve the Poisson equation on a 3D grid. The Fourier series for the space charge potential obtained can be analytically differentiated, and thus each component of the Coulomb electrical field can be found as a series with known coefficients. Accordingly in our code, the space charge field can be calculated with the same precision as the Coulomb potential.

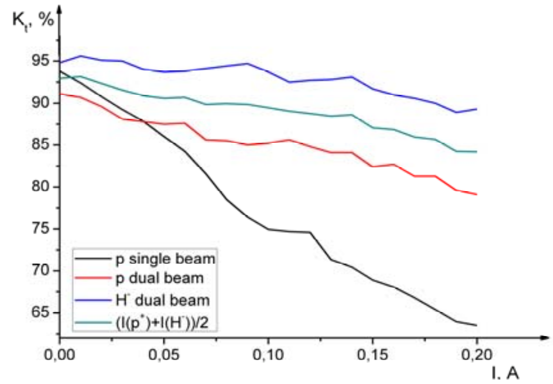

Fig.1. Current transmission coefficient versus initial beam current for proton and dual beam. The simulation was done using BEAMDULAC code for RFQ linac with parameters [29]

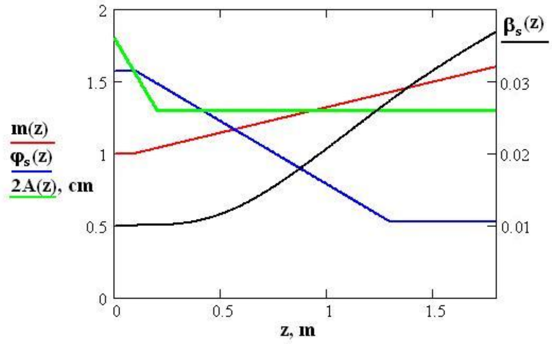

Fig.2. Main parameters of RFQ channel

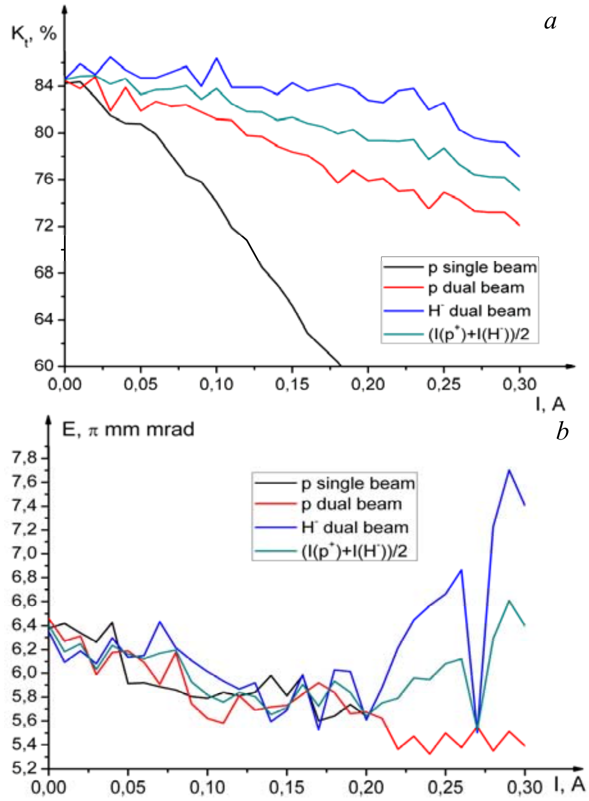

Fig.3. Current transmission coefficient (a) and output transverse emittance (b) versus initial beam current for proton and dual beam

The code modification was provided for the investigation of multi ion beam dynamics [33]. The Coulomb field calculation was updated mainly. The modification of space charge distribution calculation and algebraic equation for Fourier coefficients was provided for multi ion beam self-consistent dynamics simulation in especial BEAMDULAC-2B code version.

At first the results obtained by Y. Ogury in [29] were verified: it was shown that the current transmission coefficient is lower that he predicates. The limit beam current for such linac is equal to 80 mA approximately (Fig.1). Next the dual beam dynamics in this linac was simulated using BEAMDULAC-2B code. It was shown that the total beam flux can achieve 200 mA (Fig.1). This value not confirms the simulation results which were done by Y. Ogury using modified PARMTEQ code. Note that the very low value of initial transverse emittance was used in [29].

It can be expected that the differences between the results are caused by non correct Coulomb field influence treatment in PARMTEQ code. The main differences should be observer in bunching part of linac in which the H^+ and H^- bunches will overlap. The abstract RFQ linac with long buncher and conventional dynamic matching part at front end of linac was proposed to study of dual beam bunching process. The main parameters of this linac are shown in Fig.2. The limit proton beam current for this linac is also equal to 80 mA and up to 400 mA for dual beam (Fig.3). It is also clear from Fig.3,b that the limit beam flux is defined by non linear effects in the beam: the transverse emittance grows nonlinearly if the beam flux is higher than any limit value. The process of dual beam bunching in RFQ linac with described above parameters is shown in Fig.4 for different beam fluxes. It is clear that positive and negative ions are interacting appreciably in bunching part of linac and interaction is stronger for largest current. This interaction partially compensates the Coulomb field influence and the limit beam flux can be 4-5 lager than limit current for proton or H^- beam. But this interaction provides to more intensive halo formation if the flux is lager than any limit value.

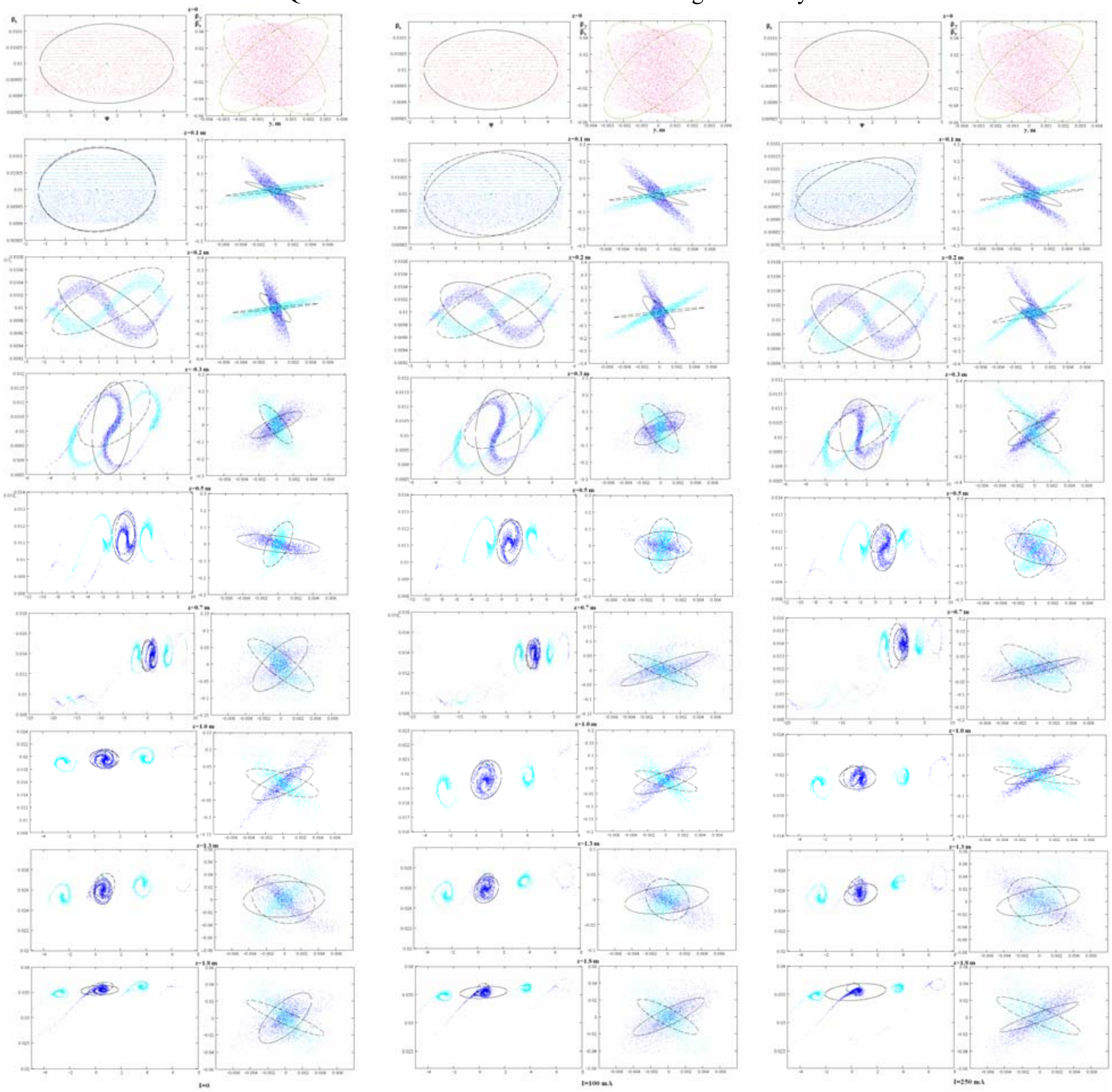

Fig.4. Dual beam bunching process: longitudinal and transverse beam spaces in different channel cross-sections. Current of each particles type: I=0 (left), I=100 mA (middle), I=250 mA (right)

It is also interest to study the beam dynamics in case when the initial beam currents are not equally for protons and H^-. This case is illustrated in Fig.5 and 6.

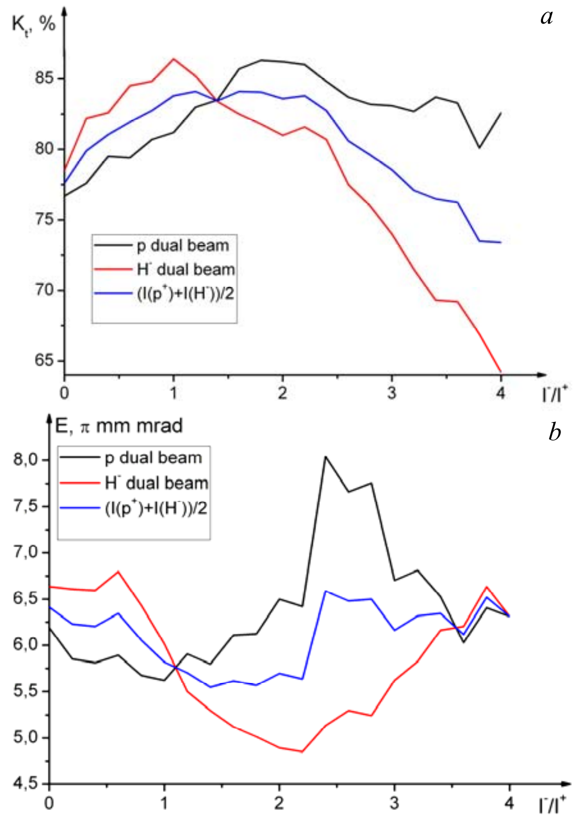

Fig.5. Current transmission coefficient (a) and output transverse emittance (b) versus of the ratio of initial beam fluxes of H^- and protons, I^+=100 mA

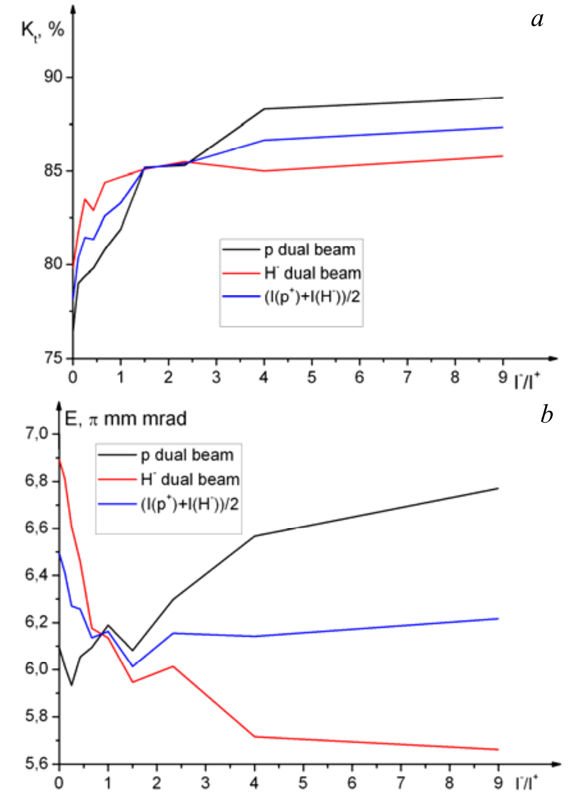

Fig.6. Current transmission coefficient (a) and output transverse emittance (b) versus of the ratio of initial beam fluxes of H^- and protons, I^++|I^-|=150 mA

The current transmission coefficient K_t (a) and output transverse emittance E (b) versus of the ratio of initial beam fluxes of H^- and protons I^-/I^+ are shown in Fig.5 in case when proton beam current is fixed and equals to I^+=100 mA. The same dependences are shown in Fig.6 in case when initial beam flux is fixed and $I^+ + |I^-|$= 150 mA. The transmission coefficient of H^- ions, $K_t^{(-)}$, in the dual beam is approximately equal to the transmission coefficient for the single H^- beam with current $I=|I^{(-)}|-|I^{(+)}|$. The $K_t^{(+)}$ for H^+ ions increases and $K_t^{(-)}$ for H^- decreases when the ratio of $|I^{(-)}|/|I^{(+)}|$ enlarges. The beam with smaller current has the smaller output emittance. The simulation shows that in “quasi-neutral” beam current transmission coefficients for H^+ and H^- are closely, even in case when I^- and I^+ differs significantly.

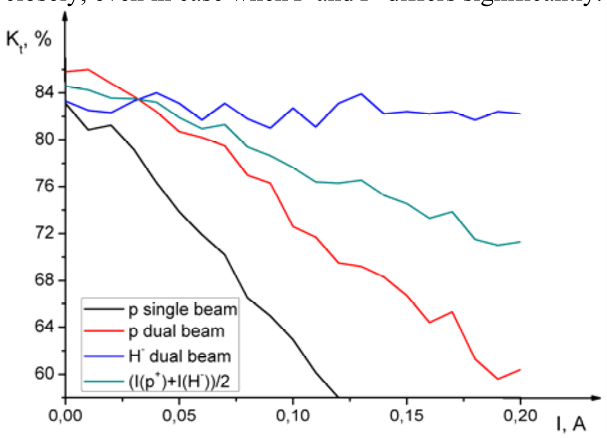

Fig.7. Current transmission coefficient versus initial beam current in RFQ for bunched dual beam

Finally it is interest to study the bunched dual beam dynamics in RFQ. It was shown that bunches of H^+ and H^- are interact but the interaction is weakly comparatively not bunched beam. The current transmission versus initial beam flux is shown in Fig.7 for bunched beam. It was shown that the longitudinal interaction is observing and the bunch phase size will smaller for largest currents. This effect explains the limit flux value enlargement.

5. DUAL BEAM DYNAMICS SIMULATION IN DTL

The DTL (Alvarez type) linac is the classical system for ion beam acceleration in energy range 0.5…100 MeV. One of DTL linacs was the first accelerator in which protons and H^- ions were successfully accelerated simultaneously (LAMPF, LANL). The parameters of LAMPF DTL linac are unavailable but it is known that the operation current is 100 mA for protons and I^+=100 mA, I^-≈80 mA in dual mode. It is interest to verify this result for other DTL linac. The first tank of LINAC4 for CERN SPL linac was R&D in MEPhI, ITEP and VNIIEF (Sarov). The parameters of this DTL linac can be founded in [31], the input/output energy is equal to 3/10 MeV and operation current 40 mA.

The simulation was done using especially designed version of BEAMDULAC_DTL-2B code. It was shown that bunches of H^+ and H^- interact weakly and space charge influence not compensates but transverse emittance and beam envelope will some smaller for dual beam.

6. ACCELERATION OF POSITIVE AND NEGATIVE IONS IN THE SAME BUNCH

In a conventional RF linac the beam is accelerated by a synchronous wave of the RF field. An alternative method of ion acceleration can be realized if the oppositely charged ions will bunched and accelerated in the same bunch. The structure where such acceleration mechanism can be realized was proposed by E.S. Masunov and called linear undulator accelerator (UNDULAC) [34, 35]. The acceleration mechanism in UNDULAC is similar to the acceleration mechanism in an inverse free electron laser (IFEL), where the electron beam is accelerated by a ponderomotive force. In UNDULAC the beam bunching, acceleration and focusing are realized in the accelerating force which is driven by a combination of two non-synchronous waves (two undulators). As it has been shown, one of the undulators must be of the RF type, the second one being, optionally, of magnetic (UNDULAC-M), electrostatic (UNDULAC-E) or RF (UNDULAC-RF) types. The accelerating structure of UNDULAC can be realized as an interdigital H-type (IH) periodic resonator with drift tubes. As it is well known the ponderomotive force is proportional to charge of ion squared. It is possible to bunch and to accelerate the positive and negative ions simultaneously in the same bunch by means this property. As two examples, the equation of ion motion is $\mathrm{d}\beta/\mathrm{d}\tau = (e\lambda/2\pi mc^2)^2(E_0E_1/\beta)\sin 2\varphi$,

$\mathrm{d}\beta/\mathrm{d}\tau = (e\lambda/2\pi mc^2)^2(E_0E_0^o/2\beta)\cos\varphi$ for UNDULAC-E.

Here β is the ion velocity, $\tau=\omega t$ is the dimensionless time, λ – the length of wave, e and m – the ion charge and mass, φ – the phase of particle in accelerating combined wave, E_0 and E_1 are the amplitudes of base and first RF field spatial harmonics in periodical resonator, E_0^o is the amplitude of electrostatic undulator field. The analysis of numerical simulation results shows that the limit dual beam flux value is very high: about 4 A for UNDULAC-RF and 20 A for UNDULAC-E [36]. Note that this flux value is unachievable for contemporary accelerator technology because the limit beam current of modern ribbon ion sources is achieves 1 A approximately. The beam power could be equal to 10 MW when the total beam flux is equal to 10 A and the output beam energy is 1 MeV. This is impossible for modern RF generators.

CONCLUSIONS

The efficiency of space charge neutralization for ion limit beam current enlargement was discussed. It was shown that this mechanism can be very effective for ion bunchers as RFQ. The high accuracy codes are need for dual beam dynamics simulation and correct physical interpretation should be done for all results.

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ИСПОЛЬЗОВАНИЕ НЕЙТРАЛИЗАЦИИ ВЛИЯНИЯ ОБЪЕМНОГО ЗАРЯДА ПУЧКА ДЛЯ ПОВЫШЕНИЯ ИНТЕНСИВНОСТИ ПУЧКОВ В ЛИНЕЙНЫХ УСКОРИТЕЛЯХ

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Как принято считать, влияние объемного заряда пучка является основным фактором, ограничивающим интенсивность ионных пучков в линейных ускорителях на небольшие энергии. Можно утверждать, что в настоящее время в ускорителях на небольшие энергии достигнут (или вскоре будет достигнут) предел по току пучка. Для увеличения тока ионного пучка до 300…1000 мА, что требуется для некоторых приложений, таких как нейтронные генераторы или ядерные установки, управляемые ускорителем, существуют два основных пути: увеличение поперечного сечения пучка и использование нейтрализации влияния объемного заряда. В настоящее время второй путь обсуждается все более активно. Известно три (или более) способа нейтрализации влияния объемного заряда: использование плазмы, ионизованного остаточного газа или электронного облака; метод «сложения» пучков; ускорение ионов с разным знаком в одном сгустке. Некоторые результаты исследования динамики «нейтрализованного» ионного пучка в линейных ускорителях с ПОКФ, ускорителях Альвареца, линейных ондуляторных ускорителях представлены в данной работе.

ВИКОРИСТАННЯ НЕЙТРАЛІЗАЦІЇ ВПЛИВУ ОБ'ЄМНОГО ЗАРЯДУ ПУЧКА ДЛЯ ПІДВИЩЕННЯ ІНТЕНСИВНОСТІ ПУЧКІВ У ЛІНІЙНОМУ ПРИСКОРЮВАЧІ

С.М. Полозов

Як прийнято вважати, вплив об'ємного заряду пучка є основним чинником, що обмежує інтенсивність іонних пучків у лінійних прискорювачах на невеликі енергії. Можна стверджувати, що в даний час у прискорювачах на невеликі енергії досягнута (або незабаром буде досягнута) межа по струму пучка. Для збільшення струму іонного пучка до 300...1000 мА, що потрібно для деяких додатків, таких як нейтронні генератори або ядерні установки, керовані прискорювачем, існують два основних шляхи: збільшення поперечного перерізу пучка і використання нейтралізації впливу об'ємного заряду. В даний час другий шлях обговорюється все більш активно. Відомо три (або більше) способи нейтралізації впливу об'ємного заряду: використання плазми, іонізованого залишкового газу або електронної хмари; метод «складання» пучків; прискорення іонів з різним знаком в одному згустку. Деякі результати дослідження динаміки «нейтралізованого» іонного пучка в лінійних прискорювачах з ПОКФ, прискорювачах Альвареця, лінійних ондуляторних прискорювачах представлені в даній роботі.