THE BEAM SPACE CHARGE NEUTRALIZATION IN UNDULAC-E

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One of main problems in accelerator physics is the increasing of ion beam intensity. The linear undulator accelerator with electrostatic undulator (UNDULAC-E) was proposed for ion beam acceleration. The accelerating force in UNDULAC is produced by an electric field which is a combination of two or more spatial harmonics, none of them being synchronous with the ion beam. In UNDULAC-E one of RF field space harmonic and field of electrostatic undulator are used. The value of this force is proportional to the particle charge squared. This effect allows neutralizing the beam space charge by accelerating ions with opposite charge sign within the same bunch. In this paper some results of analytical and numerical study beam space charge neutralization in UNDULAC-E using transverse electrostatic undulator are represented.

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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 used as neutron generators and can also be employed in nuclear energetic, thermonuclear synthesis as well as in other applications. In a conventional RF linac the beam is accelerated by a synchronous wave of the RF field. The RFQ structures are usually used in the buncher of linac. The current transmission coefficient in the RFQ can be limited by the losses due to small channel aperture and influence of the space charge fields. Therefore, the maximum proton beam current in the RFQ is 120…150 mA [1]. Another limitation of the RFQ structure is the low rate of the energy gain (usually not greater than 300…400 keV/m).

An alternative method of ion acceleration in electromagnetic fields without a synchronous wave was presented in [2]. Some analytical studies have already been published in [3]. The acceleration mechanism is similar to the acceleration mechanism in an inverse free electron laser (IFEL), where the electron beam is accelerated by a ponderomotive force. In IFEL the accelerated gradient equals the product of undulator field amplitude (*B* or *E*) and electromagnetic wave amplitude (E_v). In our case, the accelerating force is driven by a combination of two non-synchronous waves which are supplied by two undulators. This type of linac was called an undulator linear accelerator (UNDULAC).

There are three different types of undulators that can be used to design the required configuration of accelerating fields – magnetic (UNDULAC-M), electrostatic (UNDULAC-E, see Fig.1) and RF undulator (UNDULAC-RF). As it has been shown, one of the undulators must be of the RF type, the second one being, optionally, of magnetic, electrostatic or radio frequency types. The accelerating structure of UNDULAC can be realized as an interdigital H-type (IH) periodic resonator with drift tubes. It is simpler than RFQ and extends the limit of the beam current and the rate of energy gain as well as it increases the transmission coefficient [4].

As the main factor limiting beam intensity in ion accelerators is the space charge force influence, there exist two ways to increase ion beam intensity: (i) to enlarge beam cross section and (ii) to use space charge neutralization. We was study these methods for UNDULAC-RF and UNDULAC-E.

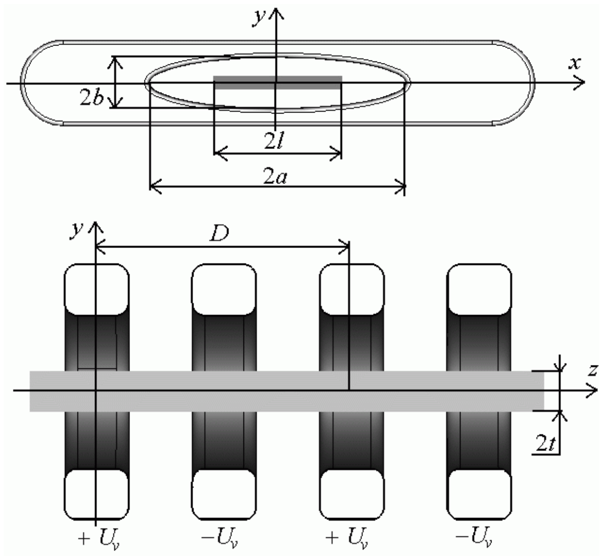

Fig.1. The scheme of UNDULAC-E

Acceleration of ribbon beams is possible in UNDULAC-E [3] and UNDULAC-RF [2]. The ribbon beam has the large transverse cross-section and limit beam current can be sufficiently enlarged this case. The results of ribbon beam dynamics study in UNDULAC-RF are discussed in [5, 6].

In a conventional RF linac (RFQ, DTL) the intensity of the ion beam can be made twice as high by simultaneous acceleration of ions with opposite charge signs (H^+,H^- or D^+,D^-) (see for example [7]). 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.

2. ION BEAM ACCELERATION IN UNDULAC

In UNDULAC the beam bunching, acceleration and focusing are realized in the accelerating force which is driven by a combination of two non-synchronous

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waves. This force in proportional to charge of ion squared. As two examples, the equation of motion in UNDULAC-RF is

$$\frac{d\beta}{d\tau}=\left(\frac{e\lambda}{2\pi mc^2}\right)^2\frac{E_0E_1}{\beta}\sin2\varphi\,, \qquad (1)$$

and for UNDULAC-E

$$\frac{d\beta}{d\tau}=\left(\frac{e\lambda}{2\pi mc^2}\right)^2\frac{E_0E_0^o}{2\beta}\cos\varphi\,. \qquad (2)$$

Here β is the ion velocity, τ=ωt is the dimensionless time, λ – the length of wave, e – the ion charge, φ – the phase of particle in accelerating wave, E_0 and E_1 are the amplitudes of base and first RF field harmonics in periodical resonator, E_0^o is the amplitude of electrostatic undulator field.

The study of dynamics for dual deuterium D^+ and D^- beam in UNDULAC-RF was done. The especially computed code BEAMDULAC-2B was used for study [8]. The results of the simulation of two beam dynamics are discussed detail in [5, 9]. Let us represent some of them briefly. It was shown by means of numerical simulation that D^+ and D^- ions are accelerating within the same bunch in UNDULAC as it was proposed. In the phase-space the trajectories for positive and negative ions are oscillating in the opposite directions. The output beam flux of neutral dual beams in UNDULAC-RF can be very large. Current transmission coefficients for two ion types D^+ and D^- are equal: $K_t^{(+)} \approx K_t^{(-)}$ if $|I^{(+)}| \approx |I^{(-)}|$. These coefficients do not reduce due to increasing of every beam current in case when intensities of ion beams D^+ and D^- equals: $|I^{(+)}| = |I^{(-)}|$. These results are observable if the current of every beam $|I^{(\pm)}| \le 4$A. The current transmission coefficient abruptly decreases and the beam emittance enlarges when every beam current is larger than 4 A, although the total Coulomb field compensation is taken place. The analysis of numerical simulation results shows nonlinear Coulomb effect is primary cause of this two beam instability. Note that the limit current for D^- ion beam in UNDULAC-RF is no higher than 350 mA.

3. D^-ION BEAM DYNAMICS IN UNDULAC-E

The results of numerical simulation of deuterium D^- ion beam dynamics were discussed in [4]. It was shown that the limit current for the UNDULAC-E are higher and the rate of energy gain is smaller than for the UNDULAC-RF. The accelerator consisted of two sub-sections: the first for beam bunching and the second for acceleration. The rate of energy gain in the accelerating sub-section of the UNDULAC-E is 500 keV/m. The optimal values of the undulator field amplitude and the RF field are E_0^o=120…180 kV/cm and E_0=150…200 kV/cm. In this case the output beam energy is W=1 MeV for accelerator length L=2.5 m. The bunching sub-section length is L_b=0.3L (L is the total length of accelerator). The current transmission coefficient is K_t=80% for zero current beam. The limit beam current for the UNDULAC-E can be very high. In a transverse undulator field, the limit current is I_{max}=1.0 A (initial beam size $l \times t$=6×0.2 cm). The current transmission coefficient is K_t=75% in this case. The current transmission coefficient versus the initial beam current is shown in Fig.2. The particle loses observed in the bunching sub-section are caused by no ideal choosing the reference phase and amplitudes of the field. The influence of the Coulomb field is the basic reason for ion losses in the accelerating part.

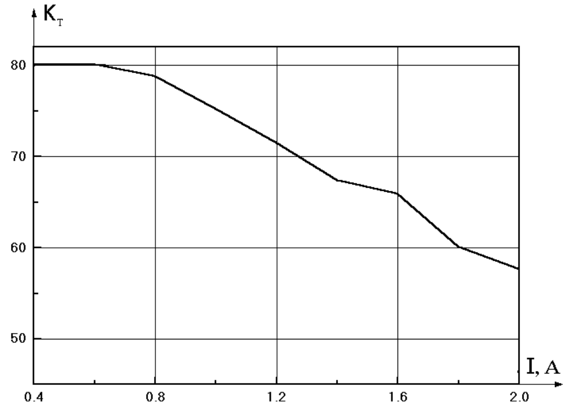

Fig.2. Current transmission coefficient K_T versus the initial beam current I in UNDULAC-E

4. SIMULATION OF DUAL BEAM DYNAMICS IN UNDULAC-E

The study of dynamics for dual deuterium D^+ and D^- beam was done using the new code BEAMDULAC-2B. The results of simulation are the similar in UNDULAC-E and UNDULAC-RF.

Let us represent some results of the simulation of two beam dynamics. The input and output dual beam parameters are shown in Fig.3. The input and output normalized transverse emittance in (y,β_y) plane are shown in Fig.3,a. The output parameters are shown by the symbol "x" and thick solid lines for D^+ ions and by "o" and dotted thick lines for D^-. The initial beam transverse emittance is shown by points and thin solid line. The oscillations of phases for mass centre are plotted in Fig.3,b for both particle types. The output phase spectra for D^+ and D^- ions are shown in Fig.3,c. Figs.3,b,c are plotted by solid line for D^- and by dotted lines for D^+. Fig.4 shows the longitudinal phase-spaces for different z coordinates and illustrates the beam bunching. It is clear from figures that D^+ and D^- ions are accelerating within the same bunch in UNDULAC as it was proposed. In the phase space the trajectories for positive and negative ions are oscillating in the opposite directions as UNDULAC-RF, but the D^+ and D^- ions are oscillate oppositely in transverse plane also.

The numerical simulation shows that the space charge neutralization is observing and output beam flux of neutral dual beams in UNDULAC-E can be very large (Fig.5,a). Current transmission coefficients $K_t^{(+)} \approx K_t^{(-)}$ if $|I^{(+)}| \approx |I^{(-)}|$. These coefficients do not reduce due to increasing of every beam current in the case when intensities of ion beams D^+ and D^- are equal but the beam transverse emittance is enlarging (Fig.5,b).

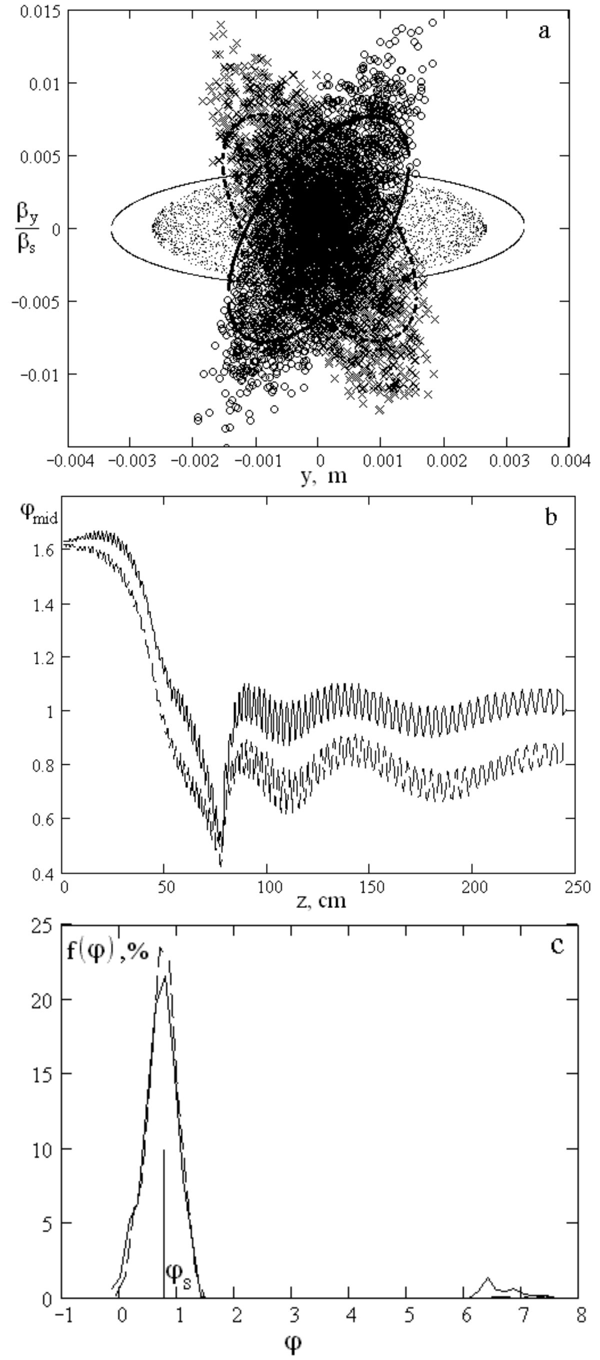

Fig.3. The input and output normalized transverse emittance in (y,β_y) plane (a), the oscillations of phases for mass centre (b) and output beam phase spectra (c) for D^+ and D^-

Note that this current value is unachievable for contemporary accelerator technology. For example the limit beam current of modern ribbon ion sources is limited by value 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. The current transmission coefficient and transverse emittance in (y,β_y) plane versus beam flux are shown in Fig.5. The beam loses are increase with flux enlarging. Its interesting that loses is caused by beam emittance enlarging. It may be said that the UNDULAC channel dynamics acceptance can be defined.

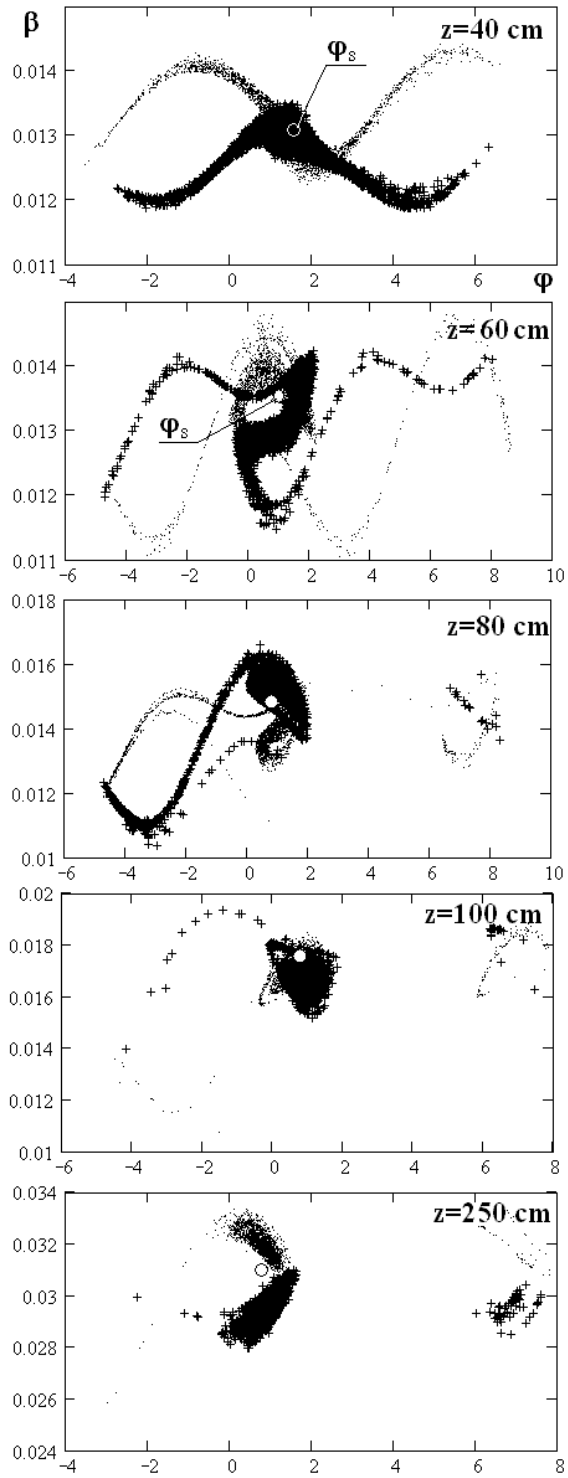

Fig.4. Dual beam bunching in UNDULAC-E

It is interesting to study the dynamics of dual beams when $|I^{(+)}| \neq |I^{(-)}|$. The transmission coefficient for D^+ ions, $K_t^{(+)}$, is larger in case when $|I^{(+)}| < |I^{(-)}|$ (see Fig.6, $|I^{(+)}|$=1 A (a) and $|I^{(+)}|$=10 A (b)). The transmission coefficient of D^- ions, $K_t^{(-)}$, in the dual beam is approximately equal to the transmission coefficient for the single D^- beam with current $I=|I^{(-)}|-|I^{(+)}|$. The current transmission coefficient of D^+ ions increases and $K_t^{(-)}$ 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 D^+ and D^- are closely, if the currents of D^+ and D^- differ insignificantly (≤ 20%).

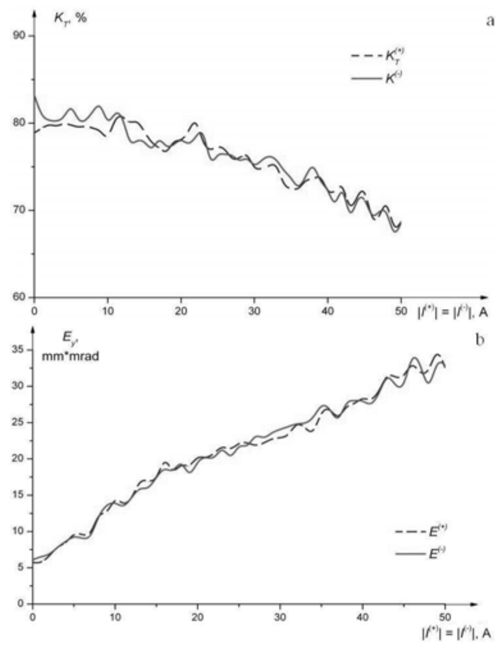

Fig.5. The current transmission coefficient (a) and the transverse beam emittance (b) versus the total initial beam flux

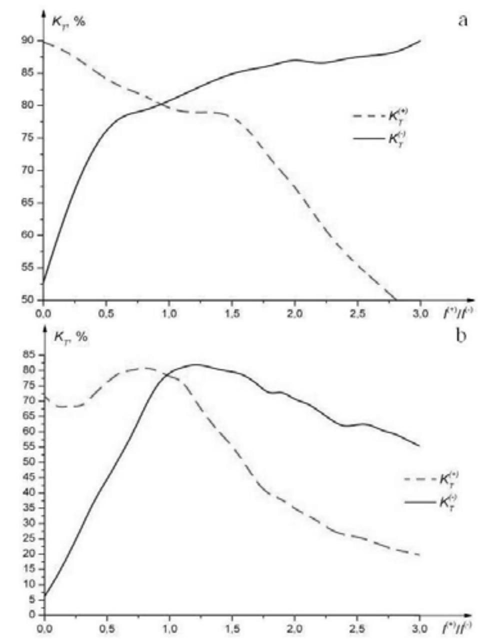

Fig.6. The current transmission coefficient when $|I^{(+)}| \neq |I^{(-)}|$, $|I^{(+)}|=1$ A (a) and $|I^{(+)}|=10$ A (b)

CONCLUSIONS

The effect of beam space charge neutralization in UNDULAC-E linac was discussed. The analysis of dual beam dynamics showed that the flux limit of D^+ and D^- the ion beam can be increased significantly by using space charge neutralization.

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НЕЙТРАЛИЗАЦИЯ ВЛИЯНИЯ ОБЪЕМНОГО ЗАРЯДА ПУЧКА В ЛИНЕЙНОМ ОНДУЛЯТОРНОМ УСКОРИТЕЛЕ С ЭЛЕКТРОСТАТИЧЕСКИМ ОНДУЛЯТОРОМ

Э.С. Масунов, С.М. Полозов

Одной из основных задач ускорительной физики является повышение интенсивности ионных пучков. Ранее для ускорения таких пучков был предложен линейный ондуляторный ускоритель (ЛОУ). В ЛОУ ускоряющая сила возникает в результате воздействия на пучок двух несинхронных пространственных гармоник поля. В частности, в ЛОУ с электростатическим ондулятором используется основная гармоника ВЧ-поля и поле электростатического ондулятора. Сила, действующая на частицу, в ЛОУ пропорциональна квадрату заряда иона, что дает возможность совместного ускорения положительно и отрицательно заряженных ионов в одном сгустке. В данной работе представлены результаты аналитического и численного исследования нейтрализации влияния объемного заряда пучка в ЛОУ с поперечным электростатическим ондулятором.

НЕЙТРАЛІЗАЦІЯ ВПЛИВУ ОБ'ЄМНОГО ЗАРЯДУ ПУЧКА В ЛІНІЙНОМУ ОНДУЛЯТОРНОМУ ПРИСКОРЮВАЧІ З ЕЛЕКТРОСТАТИЧНИМ ОНДУЛЯТОРОМ

Е.С. Масунов, С.М. Полозов

Одним з основних завдань фізики прискорювачів є підвищення інтенсивності іонних пучків. Раніше для прискорення таких пучків був запропонований лінійний ондуляторний прискорювач (ЛОУ). У ЛОУ прискорювальна сила виникає в результаті впливу на пучок двох несинхронних просторових гармонік поля. Зокрема , у ЛОУ з електростатичним ондулятором використається основна гармоніка ВЧ-поля й поле електростатичного ондулятора. Сила, що діє на частку, у ЛОУ пропорційна квадрату заряду іона, що дає можливість спільного прискорення позитивно й негативно заряджених іонів в одному згустку. У даній роботі представлено результати аналітичного й чисельного дослідження нейтралізації впливу об'ємного заряду пучка в ЛОУ з поперечним електростатичним ондулятором.