NEUTRALIZED ION BEAM DYNAMICS STUDY IN UNDULAC-E

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Abstract

The undulator linear accelerator using electrostatic undulator (UNDULAC-E) is suggested as an initial part of high intensity ion linac [1]. In UNDULAC ion beam accelerating and focusing are realized by of the combined field of two non-synchronous harmonics. Indeed, the main factor limiting beam intensity in ion accelerator is a space charge force. There exist, at least, two ways to increase ion beam intensity: to enlarge the beam cross section and to use the space charge neutralization. The ribbon ion beam dynamics in UNDULAC-E was discussed in [2]. Accelerating force value in UNDULAC is proportional to squared particle charge and oppositely charged ions with the identical charge-to-mass ratio can be accelerated simultaneously within the same bunch and the beam space charge neutralization can be realized. These methods will be studied analytically and verified by numerical simulation for UNDULAC-RF in this paper.

INTRODUCTION

As it is well known, the space charge is the main factor limiting the beam intensity in ion buncher and low energy accelerators. There are two ways to increase ion beam intensity: (i) to enlarge beam's cross section and (ii) to use space charge neutralization. The aperture of accelerator and the necessary RF potential on electrodes should be enlarged in first case. The ribbon ion beam acceleration can be used as an alternative method of beam current enlarging [1].

In RFQ or 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 [3]). 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.

In a conventional RF linac the beam is accelerated by a synchronous wave of the RF field. An alternative method of ion acceleration in electromagnetic fields without a synchronous wave was presented in [2, 4]. Some analytical studies have already been published in [4]. 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 [5]. It should be noted that the ribbon ion beam can be accelerated in UNDULAC-RF or UNDULAC-E. 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 [6].

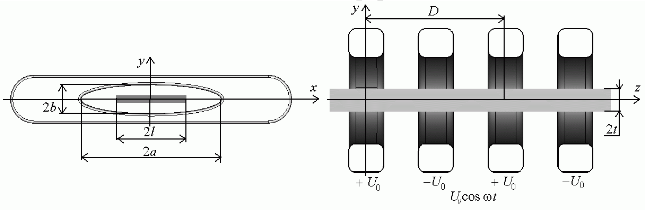

Figure 1: The scheme of UNDULAC-E.

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

$$\frac{d\beta}{d\tau} = \left(\frac{e\lambda}{2\pi mc^2}\right)^2 \frac{E_0 E_1}{\beta} \sin 2\varphi \quad , \tag{1}$$

and for UNDULAC-E

$$\frac{d\beta}{d\tau} = \left(\frac{e\lambda}{2\pi mc^2}\right)^2 \frac{E_0 E_0^o}{2\beta} \cos\varphi \quad . \tag{2}$$

Here β is the ion velocity, $\tau = \omega t$ 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 [7]. The results of the simulation of two beam dynamics in UNDULAC-RF are discussed detail in [8]. 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. The current transmission coefficient abruptly decreases and the beam emittance enlarges in case then 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.

D$^-$ ION BEAM DYNAMICS SYMULATION IN UNDULAC-E

The results of numerical simulation of deuterium D$^-$ ion beam dynamics were discussed in [2]. 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. 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^2). The current transmission coefficient is K_t=75% in this case. 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.

NEUTRALIZED ION BEAM DYNAMICS IN UNDULAC-E

The study of dynamics for dual deuterium D$^+$ and D$^-$ beam was done using the code BEAMDULAC-2B. Let us represent some results of the simulation of two beam dynamics. Figure 2 shows the longitudinal phase-spaces for different z coordinate and illustrates the beam bunching. It was shown that D$^+$ and D$^-$ ions are accelerating within the same bunch in UNDULAC-E 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 (see Fig. 3a). 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. 3b). 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 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.

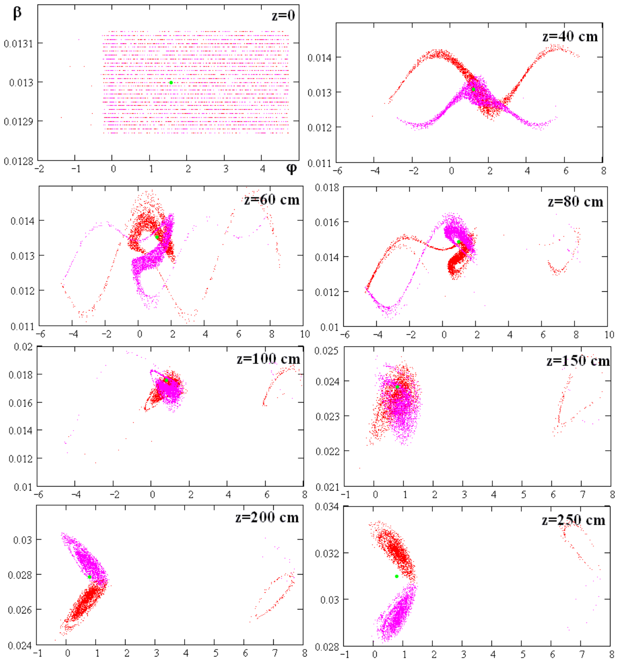

Figure 2: Dual beam bunching in UNDULAC-E.

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. 4, $|I^{(+)}||$=1 A). 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 ($\leq$ 20 %).

Next it is interesting to study the beam dynamics when D$^+$ and D$^-$ ion fluxes are equal $|I^{(+)}|\approx |I^{(-)}|$ and the transverse emittances are differs. It was shown that the current transmission coefficient is not reduced but the output emittance is enlarging (see Fig. 5, $|I^{(+)}|\approx|I^{(-)}|\approx$1A, $E_y^{(+)}(z=0)=1\pi$ mm·mrad). The current transmission coefficient sufficiently reduced for ions having largest input emittance in case when $E_y^{(-)}(z=0)>6\cdot E_y^{(+)}(z=0)$.

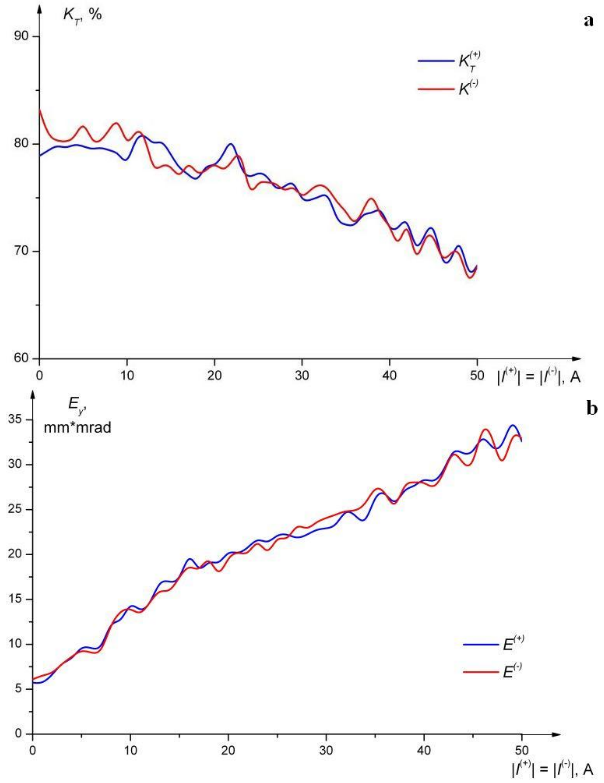

Figure 3: Current transmission coefficient (a) and the transverse beam emittance (b) versus the total initial beam flux.

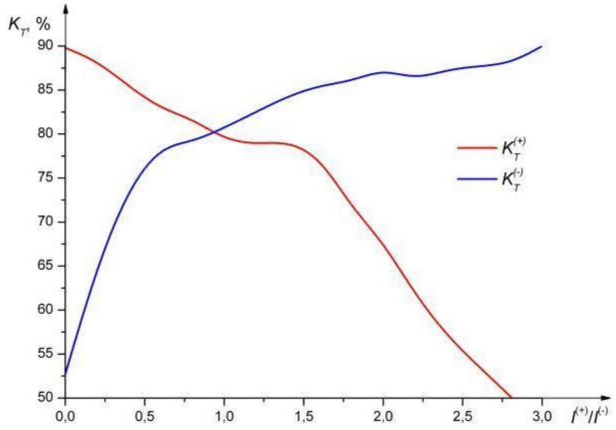

Figure 4: Current transmission coefficient when $|I^{(+)}|\neq|I^{(-)}|,|I^{(+)}|=1$ A

CONCLUSION

The effect of beam space charge neutralization in UNDULAC-E linac was discussed. The analysis of dual beam dynamics shows that the flux limit of D^+ and D^- the ion beam can be increased significantly by using space charge neutralization. It was shown that the beam space charge neutralization is not totally. The particles in phase space are moving in opposite directions and only centers of bunches are overlapped all time. The nonlinear Coulomb field effects are observed for other particles. It is provides to the beam transverse emittance enlarging and beam halo form (see Fig. 5 for example). These nonlinear effects are very interesting and should be studied in detail.

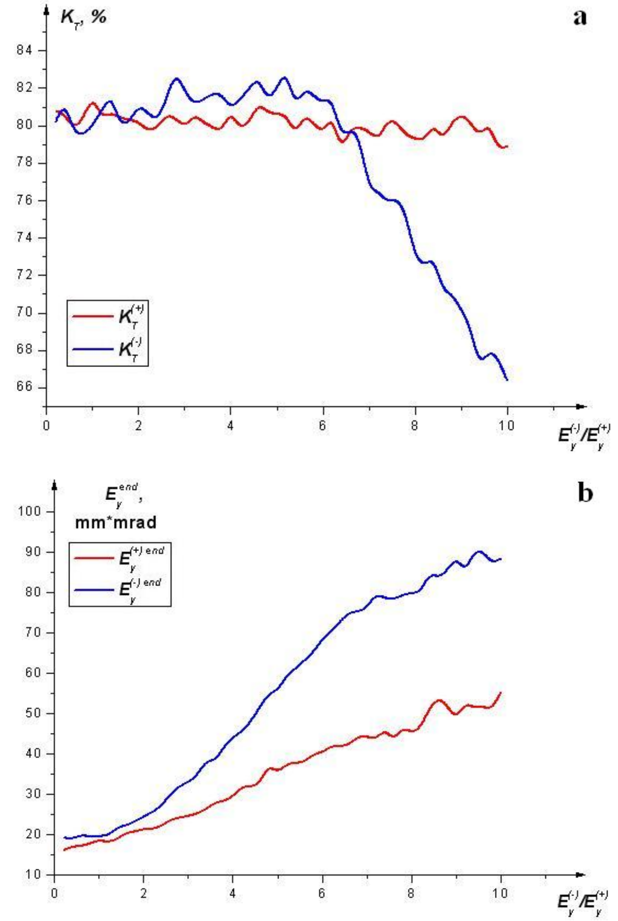

Figure 5: Current transmission coefficient (a) and output transverse emittance in (y,β_y) plane (b) versus initial beam emittances ($|I^{(+)}|\approx|I^{(-)}|\approx1$A, $E_y^{(+)}(z=0)\neq E_y^{(-)}(z=0)$, $E_y^{(+)}(z=0)=1\pi$ mm·mrad)

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