SPACE-CHARGE NEUTRALIZATION IN ION UNDULATOR LINEAR ACCELERATOR

E.S. Masunov#, S.M. Polozov,
Moscow Engineering Physics Institute (State University), Moscow, Russia

Abstract

RF undulator accelerator (UNDULAC-RF) is suggested as an initial part of high intensity ion linac. In UNDULAC ion beam is accelerated by the combined field of two non-synchronous harmonics. Accelerating force value 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. In this paper the process of acceleration and focusing the positive and negative charged ions is discussed.

INTRODUCTION

The designing low energy ion linac is a challenging task of contemporary acceleration physics. High intensity ion accelerators can be used for neutron generators, nuclear energetic, thermonuclear synthesis and other applications. In a conventional radio frequency (RF) linear accelerator (linac) the beam is accelerated by a synchronous wave of RF field. RFQ structures usually are used as an initial part of high current linac (buncher). In RFQ the transmission coefficient can be made large. But small size of beam cross-section and influence the space charge field are main factors of the particle losses in RFQ. An alternative method of acceleration in fields without a synchronous wave has been suggested and analytically studied in [1, 2]. New accelerator can be realized in periodical IH structure where a field has no spatial harmonics in synchronism with the beam. Transmission coefficient and accelerating gradient for low velocity ions are the same as in RFQ. The physical acceleration mechanism is similar to an inverse free electron laser [3, 4]. In our case, the accelerating force is driven by a combination of two non-synchronous waves (two undulators) in a periodical RF structure. The phase velocity of undulator wave must differ significantly from the beam velocity. A new linac based on this approach has been termed undulator linear accelerator (UNDULAC) [1]. There are three different types of undulator that can be used to design the required configuration of nonsynchronous fields: magnetic, electrostatic and RF undulator. It has been shown that one of the undulator must be only RF type and the second can be a magnetic, electrostatic (UNDULAC-E) or radio frequency (UNDULAC-RF) type [5].

High intensity ion beam can be accelerated in UNDULAC. 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: (i) to enlarge beam cross section and (ii) to use space charge neutralization. These methods will be studied analytically and verified by numerical simulation for UNDULAC-RF.

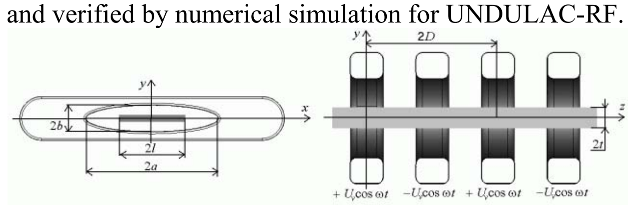

Figure 1: UNDULAC-RF for π mode.

HIGH INTENSITY SINGLE BEAM ACCELERATION IN UNDULAC-RF

One of the possible methods to increase beam intensity is enlarging the beam cross-section. Ribbon beams can be used for this purpose. The acceleration of ribbon beams is possible in UNDULAC-RF [2]. Such accelerator can be realized using an interdigital H-type periodic resonator which includes two rows of electrodes connected to the vanes (Fig. 1). The beam dynamics in UNDULAC-RF can be studied by means of traditional methods using the smooth approximation. From the equation of motion in averaged form, one can find the Hamiltonian of system. The beam bunching and accelerating in UNDULAC-RF were investigated analytically by means of this method [2]. It was shown that the frequency of ion beam bunching is equal 2ω, where ω is RF field frequency. The choice of the undulator field amplitude is not arbitrary because, simultaneously to acceleration, it must ensure transverse beam focusing. The optimal ratio of the amplitudes of the zero (E_0) and the first (E_1) harmonics of the RF field, (coefficient $\chi=E_1/E_0$), must be equal to 0.3–0.4. Particle losses due to longitudinal sliding will be small in this case. Transverse beam focusing can be realized in the UNDULAC-RF for all values of χ if the π mode of RF field is used.

The beam dynamics cannot be investigated completely using analytical methods only. Numerical simulation is necessary to verify the results of analytical study. In our case the BEAMDULAC code was used for beam dynamics simulations in UNDULAC-RF. This code utilizes the well-known cloud-in-cell (CIC) method for accurate treatment of the space charge effects.

The numerical simulation was provided for ribbon beam of deuterium D^- ions. Let us consider briefly the results of simulation in RF structure using π mode of RF field. The simulation was provided with next parameters: initial energy of deuterium ions W_{in}=100 keV (β_{in}=0.01), length of accelerator channel 2 m, accelerator channel cross-section size $2a\times2b$=0.8×20 cm^2, length of wave

#esmasunov@mephi.ru

λ=1.5 m. The limit zero harmonics amplitude of the RF field, E_0, was chosen equal 230 kV/cm, coefficient $\chi=E_1/E_0$ =0.3. In this case the output beam energy is equal 1 MeV. The numerical simulation of beam dynamics when a space charge field is taken into account shows that current transmission coefficient, K_t , is not exceeding to 85-90 % for beam size $2l\times2t$=5×0.3 cm^2 . The value of χ is equal to 0.3 and coincides with analytically founded value. In UNDULAC-RF the limit current I_{max}=0.2–0.25 A (see Fig. 2).

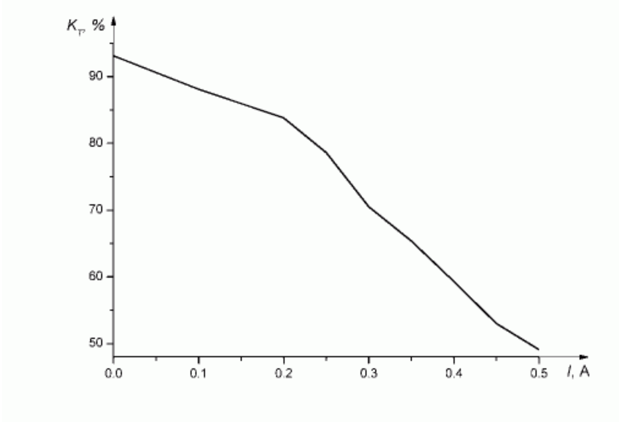

Figure 2: Current transmission coefficient of D$^-$ ion beam versus input beam current.

ACCELERATION OF DUAL BEAMS

The study of a possibility to simultaneously accelerate positive and negative ions with the identical charge-to mass ratio in linear accelerator represents a considerable interest. The beam intensity can be increased in linac by using space charge neutralization of positive and negative charged ions [6]. In a conventional RF linac (RFQ, DTL) the opportunity substantially to increase beam intensity is absent [7, 8]. Actually, in this structure an accelerating force is proportional to the charge sign of the particles, and oppositely charged ions are bunched in different phases of the accelerating wave. Two bunches with positive and negative charges become separated and don't overlap each other, excluding the initial bunching subsection. In this case the beam intensity can be doubled [8]. In undulator linear accelerator the accelerating force value 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 [9, 10]. The first numerical results of intense H$^+$, H$^-$ beam dynamics are present for UNDULAC-E [10]. In our case we will use the code BEAMDULAC-2B [11]. For two beams D$^+$ and D$^-$ dynamics in UNDULAC-RF was studied. The main goals of investigation were to verify the possibility of the simultaneous acceleration of positive and negative ions in the same bunch and to define the limit beam flux in this case. It is interesting also to investigate the influence of the space charge neutralization on the quality of dual beams.

Let us represent some results of dual beam dynamics simulation. The input and output normalised transverse emittances in (x,β_x) and (y,β_y) phase planes are shown at Fig. 3a and 3b. The output parameters of dual beams are shown for D$^+$ by blue points and solid black line and for D$^-$ by cyan points and dot black line. The initial beam transverse emittances are shown by red points and brown line. The oscillations of phase mass centre are plotted at Fig. 3c for both particle types. Figure also shows the borders of combined wave separatrix and reference particle phase variation. The output phase spectra for D$^+$ and D$^-$ ions are shown at Fig. 3d. The beam bunching is illustrated in Fig. 4 which shows the longitudinal beam emittance for different z coordinates. As it was proposed D$^+$ and D$^-$ ions are accelerating in the same bunch in UNDULAC. The phase trajectories for positive and negative ions are oscillating in different directions.

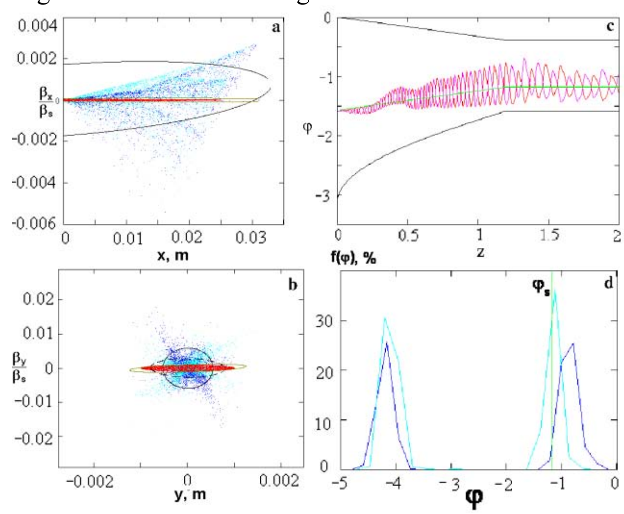

Figure 3: The results of the neutral dual beams dynamics simulation.

The numerical simulations shows that the output beam flux of neutral dual beams in UNDULAC-RF can be done very large (see Fig. 5a). The current transmission coefficient is not reduced with enlarging current for every beam in case when intensities of ion beams D$^+$ and D$^-$ are equal: $|I^{(+)}|$ = $|I^{(-)}|$. In this case total Coulomb field compensation is observed. The nonlinear Coulomb effects cause the decreasing of current transmission and beam emittance enlarging only when the current of every beam is larger than 4 A (see Fig. 5b).

It is interesting to study dynamics of quasi neutral dual beams when $|I^{(+)}| \neq |I^{(-)}|$. The transmission coefficient for D$^+$ ions, $K_t^{(+)}$, is larger in case when $|I^{(+)}| < |I^{(-)}|$. In dual beams the transmission coefficient for D$^-$, $K_t^{(-)}$, is equal approximately to transmission coefficient for a single ion beam D$^-$ with current $I=|I^{(-)}|-|I^{(+)}|$. The transmission coefficient increases for D$^+$ and decreases for D$^-$ with $|I^{(-)}| / |I^{(+)}|$ ratio enlarging and $K_t^{(+)}=K_t^{(-)}$ when $|I^{(+)}| \approx |I^{(-)}|$. This effect is observing when the both beam currents are not very large (see Fig. 6). It should be noted that beam with smaller current has the smaller output emittance.

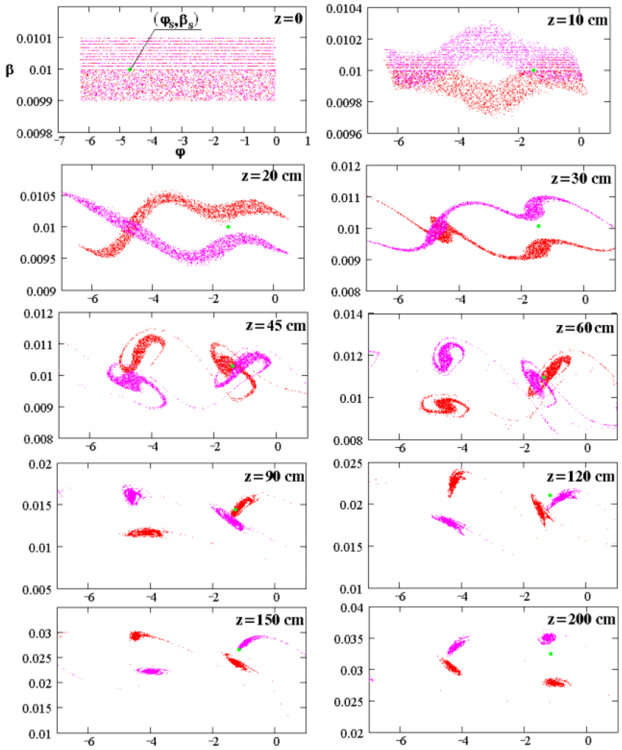

Figure 4: The bunching of the neutral dual beams.

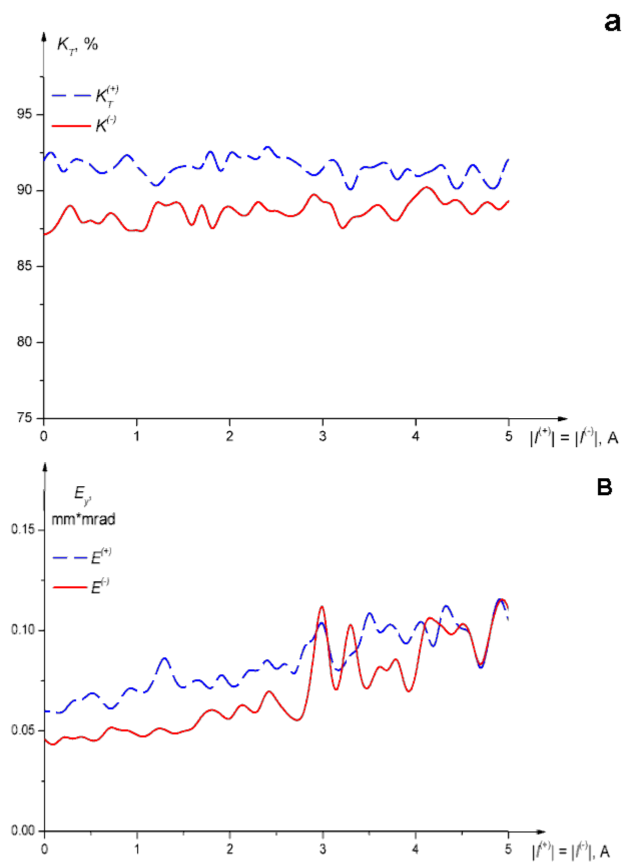

Figure 5: The current transmission coefficient (a) and transverse beam emittance (b) of neutral dual beams versus the input beam current.

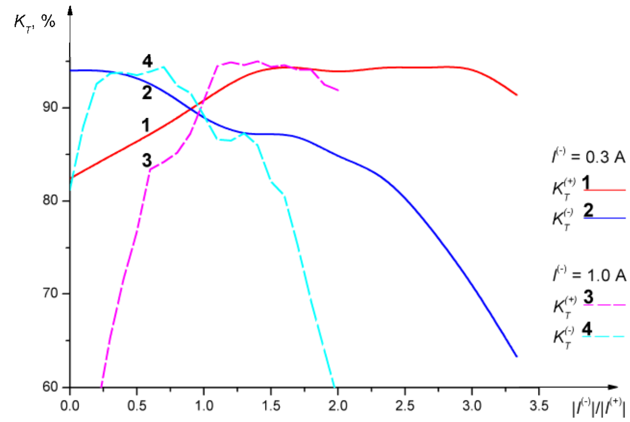

Figure 6: The current transmission coefficient as the function of $|I^{(-)}| / |I^{(+)}|$.

CONCLUSION

The dynamics of oppositely charged ion beams was studied in radio frequency undulator linac and the results of dual beams dynamics simulation are presented. The results of the numerical simulation coincide with the analytical investigation. It was shown the flux intensity of neutralized dual beams in UNDULAC-RF can be very large. In this case the current value of every beam will be limited practically by the beams intensity of the sources for positive and negative ions and RF generator power which must be larger the output power of the dual beams.

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