Space-Charge Compensation Effects under Acceleration of Oppositely Charged Ion Bunches in UNDULAC-E *

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Abstract

This paper continues the study of an undulator linear accelerator with the plane electrostatic undulator and transverse RF field (UNDULAC-E). The process of acceleration of oppositely charged ions with the identical charge-to-mass ratio (H^+ and H^- or D^+ and D^-) in the single bunch is investigated. Analytical and numerical simulation results of intense H^+ H^- beam dynamics are presented.

1. INTRODUCTION

Study of a possibility to simultaneously accelerate positive and negative ions with the identicial charge-mass ratio in linear accelerators is of considerable interest. An idea of space-charge force compensation of an ion beam by means of oppositely charded ion beam aimed at increasing the current limit seems to be very attractive. Conventional schemes of ion focusing and acceleration are traditionally designed to accelerate ions with the same sign of charge. At the same time the current limit of the ion beam might be substantially increased by using space-charge compensation of positively (H^+, D^+) and negatively (H^-, D^- charged ions, being accelerated simultaneously. It may be possible if one succeed in providing a long-duration interaction between differently charged ions during the whole process of acceleration. In all the known RF accelerators (RFQ, APF, DTL, etc.) this opportunity is practically absent. Actually, in these structures an accelerating force is proportional to the charge sign of the accelerated particle, and oppositely charged ions are bunched in the different phases of the accelerating wave. Two bunches with positive and negative charges become separated (out of phase by π) and don't experience any strong interaction between each other, excluding the initial bunching portion when the synchronous phase is close to $\pi/2$. In this case a longitudinal separation of such bunches doesn't allow to achieve appereciable space-charge compensation.

Recently an idea to apply a combination of periodic undulator field and radiofrequency field for acceleration and focusing of low energy ions was put forward [1]. Such a linear undulator accelerator was called lineondutron. In case when electrostatic undulator is used it is suitable to call this accelerator "UNDULAC-E" (on the contrast to "UNDULAC-M" with magnetostatic undulator). For acceleration of ribbon beams the scheme of "UNDULAC-E" with the plane electrostatic undulator was suggested and studied in some details theoretically [2] and experementally [3]. So far the aspects of ion beam dynamics were investigated mainly in a single particle approximation. In this paper we will discuss the most interesting feature of undulator accelerator - simultaneous acceleration of oppositely charged ions.

A unique peculiarity of UNDULAC-E described here is that the accelerating force proportional to the particle sign squared is used. This force is produced by a combination of radiofrequency field and the periodic field of undulator. In other words, a change of particle velocity in average during the transit time of the RF-field period is proportional to $(ez/m)^2$, where z and m are the charge and mass of the particle. Thus under identical injection conditions it may be expected that capturing, bunching and acceleration of oppositely charged ion beams will occur in a similar way at the same synchronous phase. As the beams interact between each other, the opposite charges may exert forces that resist the charge separation. As a result if both beams have equal current, the space-charge forces will be eliminated or at least greatly weakened as compared with a single beam. Obviously, of principal significance in achieving the desired space-charge compensation is transverse dynamics of oppositely charged beams.

The general considerations discussed above will be demonstrated below.

2. DYNAMICS OF OPPOSITELY CHARGED IONS IN UNDULAC-E

Let us consider the motion of positive and negative ions with the same charge-to-mass ratio in UNDULAC-E with the plane electrostatic undulator. At first we neglect the space-charge field. The mechanism of acceleration and focusing is produced by a combined-wave field, resulted from a superposition of the first space undulator field harmonic and the zeroth space harmonic of the transverse RF field. Expressions for fields in the system involved are given in [4]. Higher space harmonics depending on the confiduration of electrodes may strongly effect the beam dynamics. Here as before we restrict our consideration by harmonics, following the fundamental ones.

All the harmonics in UNDULAC-E are non-synchronous with the beam. Such a non-synchronous interaction of the accelerated particle with the fields can be analyzed with the help of averaging method. In accordance with that, the trajectory of a single particle may be respresented as a combination of quick oscillations $\vec{r}(t)$ and slow variation $\vec{R}(t)$. After the procedure of averaging over quick ocsillations one may derive the expression for effective potential function describing the averaged particle motion:

$$U_{eff} = U_0 + \Delta U, \tag{1}$$

where

$$U_0 = \frac{1}{4} a_0^2 \cosh(2\rho/\beta_s) - \frac{1}{2} a_v a_0 \cosh(\rho/\beta_s) \sin\varphi + \frac{1}{4} a_v^2 ,$$

- the term due to fundamental field harmonics,

$$\Delta U = \frac{1}{36} a_0^2 g_3^2 \cosh\frac{6\rho}{\beta_s} - \frac{1}{4} a_v^2 f_2 \cosh\frac{2\rho}{\beta_s} \cos 2\varphi - \frac{a_v a_0}{4} \left(f_2 \cosh\frac{3\rho}{\beta_s} + \frac{f_2 g_3}{g} \cosh\frac{5\rho}{\beta_s}\right) \sin\varphi + \frac{5}{72} a_v^2 f_2^2 \cosh\frac{4\rho}{\beta_s}$$

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- an addition due to the second RF-field harmonic with the normalized amplitude f_2 and the third undulator field harmonic with the amplitude g_3. Here $a_v = eE_v\lambda/2\pi mc^2$ and $a_0 = eE_0\lambda/2\pi mc^2$ are the normalized amplitudes of the RF and undulator field harmonics, λ is the RF-field wavelenght, $\beta_s = D/\lambda$ is the synchronous particle velocity, D is the undulator period, $\varphi = \int d\xi/\beta_s - \tau + \tau_0$ - the slow phase in the combined-wave field, $\tau = 2\pi c/\lambda t$ the dimensionless time, $x = 2\pi Z/\lambda$ and $\rho = 2\pi Y/\lambda$ - the dimensionless longitudinal and transverse coordinates in the smooth appoximation. The equations of averaged longitudinal and transverse motion can be obtained by differentiation of (1). It is clearly seen from (1) that the potential function depends on the particle charge squared, i.e. averaged motion of positively and negatively charged ions occur similarly. It is important to note that both fundamental and higher space harmonics make simular averaged influence on differently charged ions.

Further for simplicity we let the higher harmonics alone. Near the injection plane (at $\rho/\beta_S << 1$) the equation of longitudinal particle motion can be written as:

$$\frac{d\beta}{d\xi} = \frac{b^2}{2\beta_s^2}\cos\varphi , \qquad (2)$$

where $b^2 = a_V a_0$. By the appopriate selection of the dependencies $a_V(\xi)$, $a_0(\xi)$ and $\varphi_S(\xi)$ one succeed in supplying effective bunching and acceleration for both positive and negative ions within the single separatrix. In its turn, the acceration rate is independent of the sign charge. The overlapping of positively and negatively charged buncnes in the longitudinal direction is complete. So longitudinal space-charge compensation under simultaneous acceleration of oppositely charged ions is taken place.

Let us consider next the transverse dynamics in UNDULAC-E with the plane undulator. From the expression (1) one may derive that the averaged transverse oscillations frequency ω_Y is:

$$\left(\frac{\omega_Y}{\omega}\right)^2 = \frac{a_0^2}{\beta_s^2} - \frac{a_v a_0}{2\beta_s^2}\sin\varphi \qquad (3)$$

The averaged trajectories of positively and negatively charged ions and their focusing conditions coincide with each other. In the meantime, quick transverse oscillations of different kinds of ions occur in anti-phase. The value of the quick oscillation amplitude depends on the sign of charge:

$$\tilde{\rho} = a_v \sin\tau + a_0 \cosh\frac{\rho}{\beta_s}\cos\int_0^{\xi}\frac{d\xi}{\beta_s} \qquad (4)$$

In practice the amplitudes of quick oscillations are comparable with the mean beam size. For the space-charge compensation to take place it is important that the transverse separation of the oppositely charged beams would not be large. In the case if such beams with the equal current and the same initial emittances and velocities are injected into the accelerating channel, one needs at least that the bunch center positions of two beams differ from each other not greater then by $2\tilde{\rho}$, where $\tilde{\rho}$ is defined by the expression (4).

The results of mutual space charge compensation depends primarily on the behaviour of bunch centers for each beam. Further the aspects of transverse stability for two-component ribbon ion beam were considered analytically using simple 1D model. The beams were assumed to be uniformly charged and have equal current value. The analysis of dispersion equation for this case showed that dipole resonancies resulted from the coherent build-up of the bunch centers of oppositely charged beams are absent in the presence of external focusing.

3. INTENSE H^+ H^- BEAM DYNAMICS SIMULATION

Accurate analysis of high-current beam dynamics taking into account space-charge effects can be made only by numerical simulation methods. Simultaneous acceleration of positive and negative hydrogen atoms in UNDULAC-E with the plane undulator had been studied with the help of program package BEAMPATH [5]. Computer simulation of two-component ion beam, consisting of H^+ and H^- was carried out by a macroparticle method (particle-in cell). The space-charge field was calculated from the Poisson equation in 3D region. In modeling H^+ H^- beam the distribution of the model particle charge, defining the mesh function of the charge density, and computation of space-charge forces as well as external forces were carried out taking into account the sign of ion charge. Uniform input distribution of H^+ and H^- in the transverse phase space of coordinates and velocities was utilized. On the period $\beta\lambda$ macroparticles were distributed uniformly without any energy spread. In the motion equations electrostatic and RF fields of UNDULAC-E were represented by the fundamental harmonics. The following characteristics of H^+ and H^- beam were analyzed on the output of the program: bunch center position, RMS deviation, phase length of the bunch, energy spread, plots of the beam phase space at the given point of the channel.

As an example, we carried out computer simulation of two-component ribbon beam dynamics in UNDULAC-E for a 150 MHz bunching section with the following parameters: the input energy 50 keV, output energy 300 keV, RF field amplitude on the axis 180 kV/cm, undulator field amplitude 65 kV/cm. Along the accelerator length the fundamental harmonic amplitudes were gradually growed and the synchronous phase was decreased by a linear law from $\pi/2$ to $\pi/6$. Input beam with a thickness of 2 mm, width of 40 mm and angle spread of ± 10 mrad was injected along the midplane. The numbers of posi-

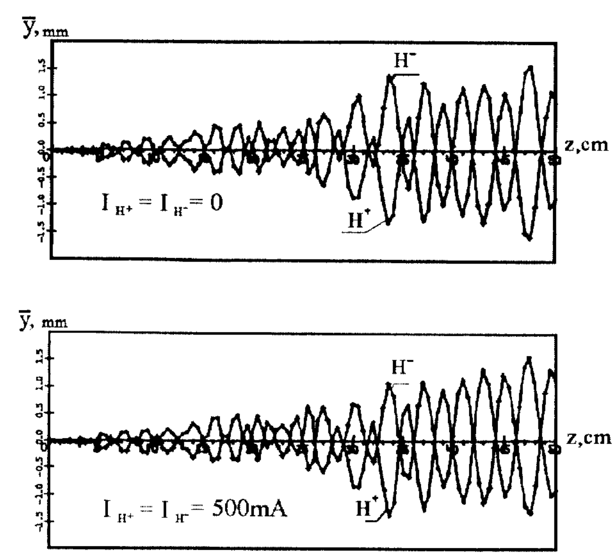
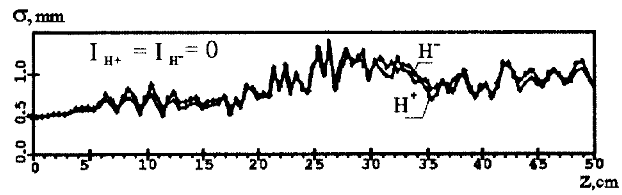


Figure 1. Bunch center position versus longitudinal coordinate when H^+ and H^- are simultaneously accelerated.

tively and negatively charged macroparticles were taken equal. The results obtained when the current of each H^+ and H^- beams equals zero were compared with the results when equal-current H^+ and H^- beams were accelerated. Fig.1,a and Fig.1,b show the bunch center position y along the section length when H^+ and H^- are simultaneously accelerated at $I_{H+} = I_{H^-} = 0$ and $I_{H+} = I_{H^-} = 500$ mA respectively. The evolution of root-mean-square deviation σ from the bunch center for both cases are presented in Fig.2,a and Fig.2,b.



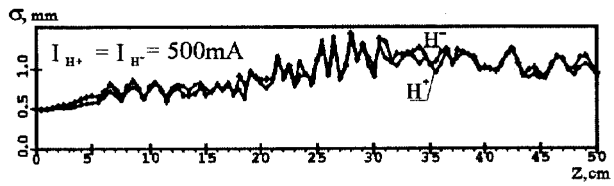


Figure 2. RMS deviation from bunch center versus longitudinal coordinate when H^+ and H^- are simultaneously accelerated.

It follows from Fig.1 and Fig.2 that the overlapping area of oppositely charged ions throughout their simultaneous acceleration is large enough. Therefore, although the bunch centers oscillate in anti-phase in the transverse direction, space separation of the most part of H^+ and H^- happens to be small. It illustrates the space-charge compensation effect.

4. CONCLUSION

Processes of transverse focusing, bunching and acceleration for two-component ribbon ion beam in electrostatic undulator linear accelerator (UNDULAC-E) have been studied. It is shown that in UNDULAC-E simultaneous acceleration of oppositely charged ions with the same charge-to-mass ratio in a single bunch (H^+ and H^- or D^+ and D^-) may substantially increase the overall intensity. It is proved that space overlapping of positively and negatively charged ion beams under their acceleration allows to obtain space-charge compensation. Space-charge compensation effect makes it possible to eliminate or at least to weaken the space-charge fields. It may result in forming the quasi-neutral ion beam. In this case ion beam dynamics in a single particle approximation are close to that obtained while taking into account self quasi-static fields. Numerical simulation results of intense H^+ and H^- beam dynamics confirm analytical estimates and assumptions.

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