ION BEAM INTENSITY INCREASING IN UNDULATOR LINEAR ACCELERATORS

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Abstract

The undulator linear accelerator (UNDULAC) was suggested as an initial part of high intensity ion linac [1, 2]. Ion beam is accelerated by the combined field of two non-synchronous space harmonics in UNDULAC. The space charge force is the main factor limiting beam intensity. There exist two ways to increase ion beam intensity: (i) to enlarge the beam cross section and (ii) to use the space charge neutralization. The high intensity ribbon ion beam can be accelerated in UNDULAC [3]. Accelerating force value in UNDULAC is proportional to squared particle charge and oppositely charged ions can be accelerated simultaneously within the same bunch and the beam space charge neutralization can be realized.

INTRODUCTION

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 facilities as neutron generators, accelerating driven systems or medical isotopes breeders. 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 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 [1-3].

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.

The idea of beam space charge neutralization by means of electron cloud was proposed and analytically studied in [4, 5]. 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 (see for an example [6]). More interest results were analytically shown and experimentally verified by number of research groups [7-10] for bunched and continuous proton and ion beams. The ionized residual gas influence was studied in the all noted experiments. In was shown that the influence of ionized gas can provide to beam emittance decreasing.

The term "funneling" we can find in 30 years old reports [11, 12]. The LAMPF DTL linac long time works in LANL uses funneling (but not use this term) [13, 14]. The previously accelerated to 300 MeV H^+ and H^- were injecting in last section of LAMPF linac and simultaneously accelerated up 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 were proposed later in LANL [15] and Frankfurt University [16] using RFQ or magnetic quadrupole lenses [17]. A number of RFQ linacs using funneling was studied and constructed in Frankfurt University [18-20]. The funneling is used to increase the total beam current in these linacs. The four stage funneling scheme was presented in [18]. As it is clear the funneling method can be used for positive (or negative) ion beam acceleration only using frequency multiplying. The linac with very high current can be used for fusion technologies facilities or spallation neutron sources (see for example [21]).

Other bunching and acceleration mechanism can be realized in case when the positive and negative ions were accelerated in RFQ simultaneously. It was shown by numerical simulation [22] that the total beam flux is lower and beam transverse emittance decreases in case of simultaneously acceleration of H^+ and H^- ions. The decreasing of output beam flux seems very strange and can be caused by specific model used for simulation. The space-charge forces in this model was 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 was simplified by following only the positive ions.

The results of experiential study of simultaneously acceleration of O^+ and O^- ions were represented in [23]. It was shown that the total beam flux can be sufficiently (approximately 1.8 times) increased using funneling method. The 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 ions) become separated and weakly interact with each other after the initial part of the buncher and full 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 [24-26]. Note that the simulation results [24] 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 was calculated by superposition that is not all correct for two beam acceleration because the beams of oppositely charged particles are overlapping.

ION BEAM ACCELERATION IN UNDULAC

An alternative method of space charge neutralization can be realized if the oppositely charged ions will bunch in the same phase. In undulator linear accelerator (UNDULAC) the ion beam is bunching and accelerating in electromagnetic fields without a synchronous RF field spatial harmonic [1-2]. Some analytical studies of beam dynamics in UNDULAC have already been published in [2, 27]. 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 accelerating 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. Three different types of undulators that can be used to design the required configuration of accelerating fields: magnetic, electrostatic and RF undulator. 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. 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 [28]. 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.

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. 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 spatiality. As two examples, the equation of motion in UNDULAC-RF is

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

and for UNDULAC-E

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

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 spatial harmonics in periodical resonator, E_0^o is the amplitude of electrostatic undulator field.

ION BEAM DYNAMICS SIMULATION IN UNDULAC

The results of numerical simulation of deuterium D^- ion beam dynamics were discussed in [3] for UNDULAC-E and in [28] for UNDULAC-RF. It was shown that the limit ribbon beam current for the UNDULAC-E is higher (0.8-0.9 A and 0.3-0.35 A comparatively) and the rate of energy gain is smaller (500 keV/m and 800 keV/m) than for the UNDULAC-RF. The accelerators consisted of two sub-sections: the first for beam bunching and the second for acceleration. The current transmission coefficient is equal K_t=80% for UNDULAC-E and 90 % for UNDULAC-RF.

The simulation of dual beam dynamics study was provided using especial version of BAEMDULAC code. This code is developing in MEPhI to study the beam dynamics in linear accelerators and transport lines since 1999. 2D and 3D versions were developed for axisymmetric structures and for ribbon beams respectively. The equation of motion for each particle is solved in the external and the inter-particle Coulomb fields. The well-known cloud-in-cell (CIC) method is utilized for an accurate treatment of the space charge effects. To determine the potential of the Coulomb field, the Poisson equation is solved on the grid with the 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 a rectangular or a circular cross-section. This allows consideration of the shielding effect, which is sufficiently important for transverse focusing of ribbon beams. The fast Fourier transform (FFT) algorithm is used to solve the Poisson equation. The obtained Fourier series for the space charge potential can be analytically differentiated, and thus each component of the Coulomb electrical field can be found as a series with known coefficients. In our code, the space charge field can be calculated with the same precision as the Coulomb potential without numerical differentiation. The external fields in BEAMDULAC code can be represented by means of three different methods: analytically, as a series of spatial harmonics and in “real field” which can be defined on 2D or 3D grid by electrodynamics simulation codes or experimental measurements. Time is used as an independent variable and standard fourth-order Runge-Kutta method is applied for integration of the equation of motion.

Especial code version BEAMDULAC-2B allows to study the simultaneous motion of positive and negative ions, mainly it leads to an improved computation of the dual beam Coulomb field. The Poisson equation is solving using the conventional FFT algorithm: the distribution of particles on 3D grid is calculated first. Then the Fourier series coefficients for charge are defined and the algebraic equations connecting Fourier coefficients for the charge and the potential are solved on the grid. The final stage is the Fourier synthesis of the Coulomb potential and its differentiation to find the space charge field components. In the case of the beam containing oppositely charged ions, the Fourier coefficients for both types are added and Fourier synthesis is performed normally. The modification of space charge distribution calculation and noted algebraic equation was provided for two-component ion beam self-consistent dynamics simulation.

The results of the simulation of dual deuterium D^+ and D^- beam dynamics in UNDULAC-RF are discussed detail in [30] and for UNDULAC-E in [31]. 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. It is clear from figure 1 when the results of beam dynamics in UNDULAC-E simulation are presented.

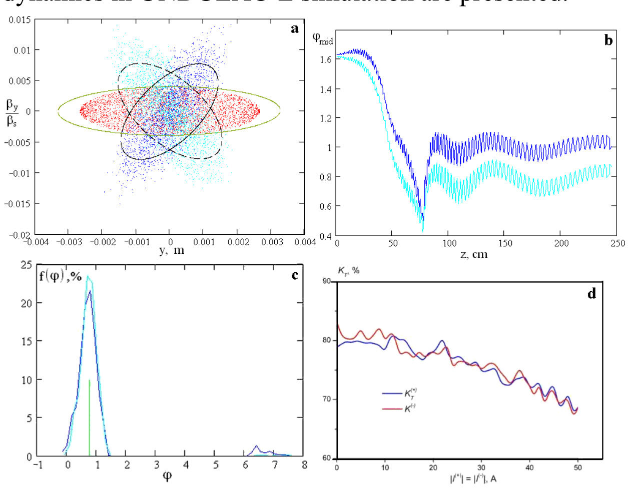

Figure 1: The input and output normalized transverse emittance in (y,β_y) plane (a), the oscillations of phases for mass centre (b), output beam phase spectra (c) and current transmission coefficient versus initial beam flux (d) for D^+ and D^- dual beam in UNDULAC-E (blue points and lines for D^- ions and cyan for D^+).

The current transmission coefficient abruptly decreases and the beam emittance enlarges in case then every beam current is larger than some value, although the total Coulomb field compensation is taken place. The analysis of numerical simulation results shows that the nonlinear Coulomb effect is primary cause of this two beam instability. The limit flux value is very high: about 4 A for UNDULAC-RF [30] and 20 A for UNDULAC-E [31] (Fig. 1d). Note that this flux 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.

CONCLUSION

The methods of ion beam intensity increasing using dual beam acceleration were discussed. The review of these methods was represented. The numerical model for dual beam dynamics study was described. Some results of effect of beam space charge neutralization in UNDULAC were discussed.

REFERENCES

[1] E.S. Masunov. Sov. Phys. – Tech. Phys., 1990, Vol. 35 (8), p. 962.
[2] E.S.Masunov, S.M. Polozov. Technical Physics, 2005, Vol. 50, No. 7, p. 112.
[3] E.S. Masunov, S.M. Polozov. NIM A, 2006, 558, p. 184.
[4] S. Hamphries et al. IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, 1979, p. 4220.
[5] T. Waiss et al. Proc. of EPAC'1988, p. 535.
[6] S. Robinson. Proc. of PAC'1993, p. 2641.
[7] T. Waiss et al.. Proc. of EPAC'1990, p. 809.
[8] X. Fleury, J-L. Lemaire. Proc. of EPAC'1998, p. 1300.
[9] A. BenIsmail et al. Proc. of LINAC'04, p. 324.
[10] J. S. Pennington et al. Proc. of PAC'07, p. 3675.
[11] R.II. Stokes, G.N. Minerbo. Proc. of PAC'1985, p. 2593.
[12] K. Bongardt, D. Sanitz. HIIF, GSI 82-8 (1982), p. 224.
[13] D.C. Hagerman et al. Proc. of PAC'1973, p. 905.
[14] D.C. Hagerman et al., Proc. of PAC'1981, p. 2910.
[15] F. W. Guy, R. H. Stokes. Proc. of PAC'1989, p. 833.
[16] W. Barth, A. Schempp. Proc. of PAC'1991, p. 3076.
[17] J.E. Stovall et al. NIM A, 278, Issue 1 (1989), p. 143.
[18] A. Schempp et al. Proc. of LINAC'98, p. 424.
[19] A. Schempp et al. Proc. of PAC'03, p. 2823.
[20] A. Schempp et al. Proc. of IPAC'10, p. 759.
[21] Y. Senichev et al. Report ESS01-119-L, 2001.
[22] K.R. Crandall. Proc. of PAC'1991, p. 401.
[23] J.X. Fang et al. Proc. of LINAC'02, p. 335.
[24] Q.Z. Xing et al. NIM A, 538 (2005), p. 143.
[25] Y. Oguri. NIM A, 373 (1998), p. 175.
[26] A. Durkin et al. Proc. of APAC 2001, p. 400.
[27] E.S. Masunov. Technical Physics, 46, (2001), No. 11, p. 1433.
[28] E.S. Masunov, S.M. Polozov. Phys. Rev. ST AB, 11 (2008), 074201.
[29] E.S. Masunov, S.M. Polozov. Problems of atomic science and technology, Series "Nuclear Physics Investigations", 2004, 1 (42), p. 134.
[30] E.S. Masunov, S.M. Polozov. Problems of Atomic Science and Technology, Series "Nuclear Physics Investigations", 2008, 5 (50), p.136.
[31] E.S. Masunov, S.M. Polozov. Problems of Atomic Science and Technology, Series "Nuclear Physics Investigations", 2010, 2 (53), p.118.