NUMERICAL SIMULATION OF 3D ION RIBBON BEAM DYNAMICS IN RF UNDULATOR LINAC

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The ion ribbon beam can be bunched and accelerated in linear accelerator with RF undulator (UNDULAC-RF). The acceleration and focusing of beam are realized without using a synchronous wave in such an accelerator. The results of numerical simulation of 3D self-consistent ribbon ion beam dynamics are presented. The limit current and current transmission coefficients are calculated.

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1. INTRODUCTION

The ribbon ion beam acceleration is one of possible methods of beam current increasing. The linac called Ribbon Radiofrequency Focusing (RRF) accelerator [1] and some types of linear undulator accelerators [2] were proposed for this goal. The ribbon ion beam can be accelerated in linear undulator accelerators with electrostatic undulator (UNDULAC-E) [2,3] and radio-frequency undulator (UNDULAC-RF) [4]. The bunching, acceleration and focusing can be realized in the undulator linac without using the RF field synchronous space harmonic. The accelerating force is to be driven by a combination of two non-synchronous waves (two RF field space harmonics of periodical resonator, Fig.1) in UNDULAC-RF and by a combination of RF field space harmonic and space harmonic of electrostatic undulator field in UNDULAC-E.

2. 3D DYNAMICS FOR UNDULAC-RF

The investigation of beam dynamics in undulator linacs can be done using both the analytical methods and the numerical simulation. The results of such investigations are considered in. [2,3].

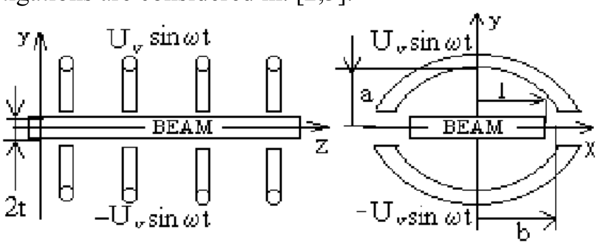

Fig. 1. The plane structure of UNDULAC-RF

UNDULAC-RF was studied using analytical averaging methods in. [4]. The Hamiltonian form of the motion equation was obtained by this method. This equation includes the effective potential function U_{eff}, depending only on the particle phase in the combined wave field and slowly varying transverse coordinates. The acceleration, transverse focusing conditions and the coupling between transverse and longitudinal motions can be studied using U_{eff}. The analytical study was done in assumption that the beam interacts with only two space harmonics of RF field. It was shown that the ribbon ion beams can be accelerated in UNDULAC-RF using the transverse or longitudinal RF field with $\mu = 0$ and $\mu = \pi$ modes. The rate of energy gain in UNDULAC-RF is proportional to $\sin(2\varphi_{v,s})$ but not $\cos(\varphi_{v,s})$ as in conventional accelerators. This peculiarity provides formation of two bunches on one RF field period. The rate of an energy gain in UNDULAC-RF using $\mu = \pi$ RF field mode is two times higher as for RF field with $\mu = 0$ mode. The analytical study of particles longitudinal motion shows that the optimal ratio of RF field harmonics amplitudes $\chi = E_1 / E_0$ is realized in UNDULAC-RF. This ratio is equal 0.3-0.4 for UNDULAC-RF using $\mu = \pi$ mode and 0.6-0.7 for $\mu = 0$ mode. The influence of fast oscillations of RF field is the lowest at these χ values. The transverse focusing conditions can be obtained by means of effective potential function. It was shown that the transverse focusing is realized independently of χ value for UNDULAC-RF using $\mu = \pi$ mode RF field. This result shows an advantage of this type of undulator linac from RRF accelerator. It should be noted that $\chi \approx 10$ value is necessary to obtain the effective focusing in the RRF accelerator [1]. The amplitudes of RF field harmonics must be equal for effective transverse focusing in UNDULAC-RF using epy $\mu = 0$ mode RF field ($\chi \approx 1$). However the smaller χ values can be used in UNDULAC-RF with the $\mu = 0$ mode RF field. The effective potential function has a local maximum in this case and a cross-section of ion beam will have a hollow form. The acceptance of UNDULAC channel and frequencies of phase and transverse oscillations can be obtained by means of the effective potential function.

The undulator linac includes two sections for beam bunching and acceleration. The synchronous phase of the combined wave $\varphi_{v,s}$ will decrease linearly and amplitudes of RF field harmonics increases as a sine in the first part (buncher). In the second part (accelerator) the amplitudes of harmonics and $\varphi_{v,s}$ are constant. It is shown that the current transmission coefficient K_t for UNDULAC-RF with $\mu = \pi$ mode RF field is equal to 90...95% and 85...90% for $\mu = 0$ mode.

The investigation of beam dynamics in smooth approximation does not take into account the fast oscillations of a particle velocity and phase. That is why the numerical simulation of the beam dynamics in a full polyharmonic field is necessary to find the optimum accelerator parameters. An influence of a space charge field on the beam dynamics can also be studied by means of this model.

3. UNDULAC-RF USING LONGITUDINAL RF FIELD (π MODE)

The numerical simulation was done for ribbon beam of deuterium ions with the following parameters: initial velocity of deuterium ions W_{in}=150 keV (β_{in} =0.013), accelerator channel length 2.5 m, accelerator channel cross-section size $2a\times2b$=0.8×20 cm, wave length λ =1.5 m. The effective amplitude of combined wave was chosen constant and equal $E_{eff} = \frac{e\lambda}{2\pi W_0 \beta} E_0 E_1 = 30$ kV/cm and the output beam energy equal to 1.3...1.5 MeV for this amplitude. It should be noted that for the ion beam under acceleration in smooth approximated field the current transmission coefficient may be as high as K_t=90...95% for the beam with the initial size $2l\times2t$=10×0.4 cm^2. The loss of particles takes place due to not optimum synchronous phase and RF field amplitude functions.

The current transmission coefficient is appreciably reduced if the beam dynamics simulation is done for the fast oscillating RF field. The current transmission coefficient is equal to 75...80% for the paraxial injected beam ($2l\times2t$=1×0.04 cm^2) and the optimum value of χ is 0.3...0.4 (see Fig.2, curve 1) that coincides with the analytically founded value. This ratio can be easily realized. It was found that K_t significantly decreases if the beam size is larger than the critical value (along $2l\times2t$=5 ×0.3 cm^2). The size of accelerator channel can be reduced to $2a\times2b$=0.7×10 cm. The particle loss is caused by fast oscillations of particle phases and longitudinal velocities. The figure 2 (curve 2) shows the current transmission coefficient versus χ with the initial beam size equal $2l\times2t$=5×0.3 cm^2. It is clear that K_t does not exceed 60 % in this case. It can be shown that K_t decreases with the large initial RF field amplitude $E(z=0)$: K_t=50% if $E_{0,1,in}=0,2E_{0,1,max}$ (see Fig.2, curve 3). The optimal length of bunching section equals to the accelerator half length.

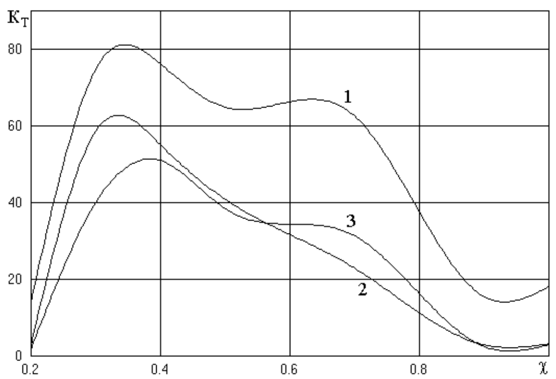

Fig.2. Current transmission coefficient versus ratio of RF field space harmonic amplitudes χ

Numerical simulation of beam dynamics in the full RF field and in the space charge field shows that the limiting current in UNDULAC-RF is lower than the analytically predicted value and its value is I_{max}=0.2...0.25 A (limiting current density J_{max}=0.12 A/cm^2) with $2l\times2t$ =5×0.3 cm^2.

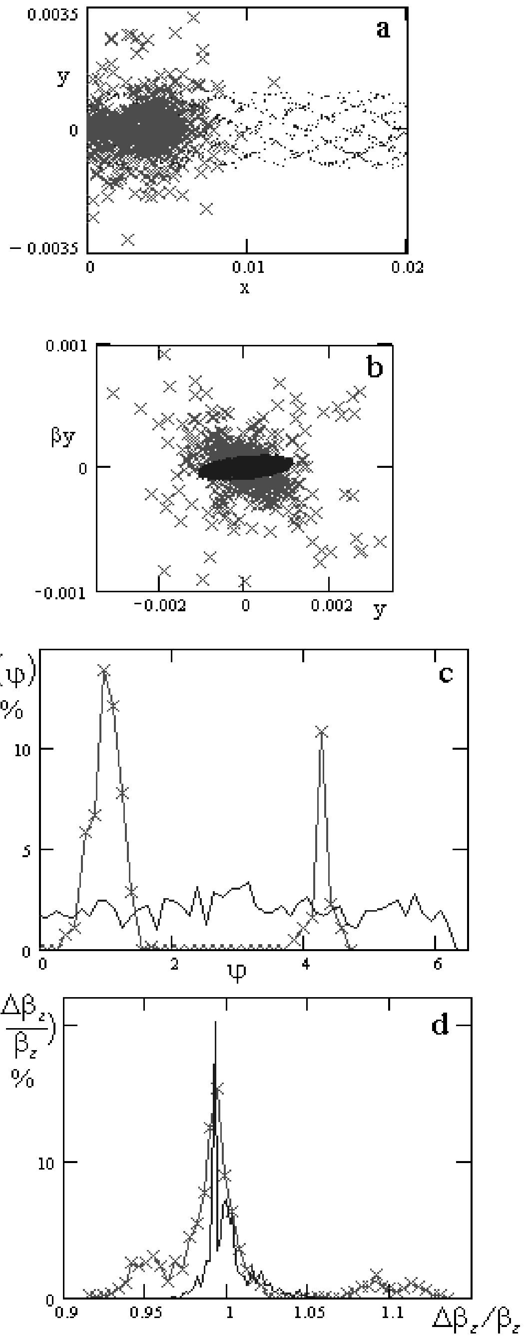

Fig.3. Initial and output beam cross-section (a), normalized transverse emittance E_y (b), phase (c) and energy (d) spectra. ("points" – initial values, "×" – output)

The initial and output beam cross-section (a), normalized transverse emittance ε_y (b), phase (c) and energy (d) spectra are plotted on figure 3. This figure illustrates the two bunches formation on one RF field period. The output normalized emittance is two times lager than the initial one. The limit initial emittance is equal ε_y=0,7π mm·mrad, ε_x=30π mm·mrad, ε_φ=25 keV·mrad.

4. UNDULAC-RF USING TRANSVERSE RF FIELD (π MODE)

The parameters of simulation are the same for UNDULAC-RF using transverse and longitudinal RF field for $\mu = \pi$ mode. In smooth approximation the current transmission coefficient is equal 75...80% for UNDULAC-RF using transverse RF field. It is higher than one for longitudinal RF field. The optimal RF field harmonics amplitudes ratio is equal 0.35 (see Fig.4, curve 1) and bunching section length is equal to the half of accelerator length too. The limit initial beam size is bigger than for UNDULAC-RF using longitudinal field: $2l\times2t=7\times0{,}3$ cm. The current transmission coefficient is equal 65% (see Fig.4, curve 2) for this initial beam size. The limit current equals 300...350 mA for this type of undulator linac. In a buncher there are no loses due to a phase motion and all loses are caused by transverse motion. The transverse emittance increases 3-4 times and increases the transverse particles velocity and beam size. The halo is not forming. The limit initial emittance ε_y is significantly smaller that for UNDULAC-RF using longitudinal field: ε_y=0.06π mm·mrad and ε_x=45π mm·mrad, ε_φ=25 keV·mrad.

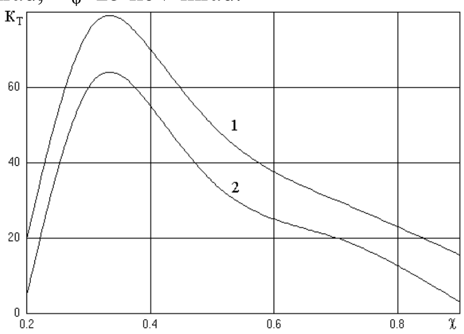

Fig.4. Current transmission coefficient versus ratio of RF field space harmonic amplitudes χ

5. UNDULAC-RF USING LONGITUDINAL AND TRANSVERSE RF FIELD (0 MODE)

The numerical simulation of ribbon ion beam dynamics in the polyharmonic field of UNDULAC-RF for $\mu = 0$ mode RF field shows that the current transmission coefficient is very low. The simulation in the smooth approximated field shows that the current transmission coefficient equals 85...90% for the paraxially injected beam. If the simulation is done a polyharmonic field, K_t decreases to 55...60% for paraxial injected beam. For larger beam cross-sections the current transmission coefficient reduces to 30...35% (UDULAC-RF using longitudinal field) and to 5...10% (using transverse field). These results are in conformity with the analytical investigation which was done earlier [5]. It should be noted that the transverse focusing is provided by the first RF field harmonic only for this type of UNDULAC-RF. The optimum value of the combined wave effective amplitude is equal to $E_{eff} = 20$ kV/cm and the output energy equals to 0.9...1.1 MeV. The limiting current was not calculated for this type of undulator linac because the current transmission coefficient is low.

6. CONCLUSIONS

The results of numerical simulation of beam dynamics in the UNDULAC-RF accelerator are discussed. It was shown that the UNDULAC-RF using $\mu = \pi$ mode RF field is more preferable for the further design. The ribbon beam of deuterium ions can be bunched and accelerated to the output energy of 1...1.5 MeV with a limiting current up to 350 mA and the current transmission coefficient K_t=65% in this type of undulator linac. It is supposed that the coefficient of current transmission can be increased by means of numerical optimization of the synchronous phase function and the RF field harmonic amplitude variation.

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ТРЕХМЕРНОЙ ДИНАМИКИ ЛЕНТОЧНОГО ИОННОГО ПУЧКА В ЛИНЕЙНОМ ВЫСОКОЧАСТОТНОМ ОНДУЛЯТОРНОМ УСКОРИТЕЛЕ

Э.С. Масунов, С.М. Полозов

Ленточный ионный пучок может быть сгруппирован и ускорен в линейном высокочастотном ондуляторном ускорителе (UNDULAC-RF). В UNDULAC-RF ускорение и фокусировка происходят при отсутствии в системе синхронной с пучком гармоники. Было проведено численное моделирование самосогласованной трехмерной динамики ленточного ионного пучка в UNDULAC-RF. Определен предельный ток пучка и максимальный коэффициент токопрохождения.

ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ТРИВИМІРНОЇ ДИНАМІКИ СТРІЧКОВОГО ІОННОГО ПУЧКА В ЛІНІЙНОМУ ВИСОКОЧАСТОТНОМУ ОНДУЛЯТОРНОМУ ПРИСКОРЮВАЧІ

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Стрічковий іонний пучок може бути згрупований і прискорений у лінійному високочастотному ондуляторному прискорювачі (UNDULAC-RF). У UNDULAC-RF прискорення і фокусування відбуваються при відсутності в системі синхронної з пучком гармоніки. Було проведено чисельне моделювання самоузгодженої тривимірної динаміки стрічкового іонного пучка в UNDULAC-RF. Визначено граничний струм пучка і максимальний коефіцієнт струмопроходження.