THE STATE OF DEVELOPMENT OF THE LINEAR ION ACCELERATOR WITH RF FIELD EXCITATION USING DOPPLER EFFECT

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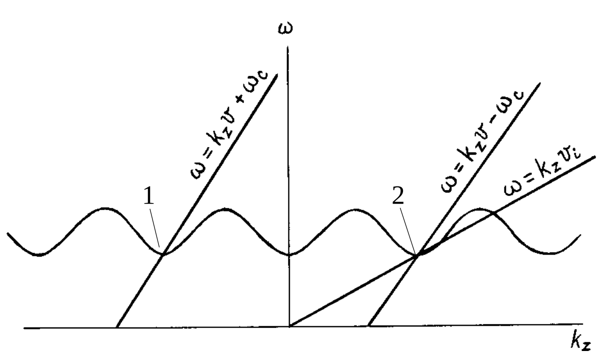
Abstract

An intense ion accelerator has been proposed and now is being developed in which accelerating and focusing electric fields in a slow wave structure are excited by an intense electron beam using anomalous and normal Doppler effect. The results of theoretical studies and computer simulations show the advantage of this acceleration method. A project and technical documentation of an experimental accelerating installation are worked out. At the moment the accelerator-injector "URAL-5" of energy 5 MeV is in operation; preliminary experiments on a small installation have been carried out; experimental investigations of an accelerating RF resonator model (in 1:1 scaling) are performed; the accelerating test installation is being manufactured.

1 INTRODUCTION

In a two-beam electron-ion accelerator it is possible for the driver electron beam to excite RF fields in an ion linear accelerator that are accelerating and focusing at the same time. A considerable gain may be obtained in the current of accelerated ions and in the acceleration rate. Ref. [1] outlines the concept and theory studies of a two-beam high current ion accelerator based on the Doppler effect. According to this concept, an intense electron beam injected along the accelerator axis together with the accelerated ion beam generates accelerating and focusing RF fields in the spatially periodic accelerating structure of a linear accelerator. RF fields are excited by the interaction of E-beam with transverse fields of any space harmonic due to cyclotron instability under anomalous Doppler effect (ADE) or normal Doppler effect (NDE) whereas the ions are accelerated by the longitudinal field of the same harmonics or another one, corresponding to the Cherenkov resonance. (See the Fig. where the periodic curve show the dispersion curve of the spatially periodic accelerating structure, point 1 corresponds to the NDE for electrons, and point 2 corresponds to the ADE for electrons and Cherenkov resonance for ions accelerated. Here ω is the wave frequency, k_z is the wave number, v is the electron velocity, v_i is the ion velocity, ω_c is the electron cyclotron frequency).



Such acceleration scheme is the intermediate or hybrid ones between conventional and collective accelerators (e.g., [2,3]) using well investigated and technologically elaborated electrodynamic structures of the former and accelerating/focusing high gradient RF fields of the latter. The preliminary investigations [1] show the new type of accelerators to be promising due to expected considerable accelerating fields (10^5-10^6 V/cm) and simultaneous phase and radial stability of accelerated ions. (Fields of order of 10^5 V/cm were obtained in suitable experiments [4]). This concept may perhaps provide the ground for creation of ion accelerators with acceleration rate of order of 10 - 100 MeV/m, 10-100 MeV energy and 1-10 A current. The tolerance system for them may be conceptually similar to one for classic accelerators and powerful electron RF devices (i.e., practically feasible). To realize of such accelerators we provide research and development activities including theoretical and experimental investigations, design and construction of an accelerating installation.

2 THE EXPERIMENTAL ACCELERATING STAND

The Experimental Accelerating Stand (EAS) is intended to prove the workability of a new promising type of ion accelerators and to optimize their parameters. The intense electron beam propagating along the installation axis in the resonant magnetic field with the given value and distribution over the length will excite focusing and accelerating fields in the EAS due to the anomalous Doppler effect. To save money we can use the operating linear proton accelerator "URAL-5" of 5 MeV energy and 30 mA current as an injector. If a more powerful injector is available the current in the EAS may exceed 3 A. The EAS is described in details in Ref.1. The accelerating section is designed on the basis of the H-type resonator with drift tubes on meeting suspenders (such accelerators are designed successfully at the KIPT). The resonator length is 161 cm, the operation frequency is 148.5 MHz, the calculated accelerating field is 56 kV/cm. Electron injector utilizes the electron gun with the transverse compression of the beam and the supply unit of a powerful klystron of industrial production. The electron beam energy is 350 keV, the current is 150 A, the time duration is 2.5 μs. A proton beam from the "URAL-5" is injected along the axis into accelerator structure of the EAS through a central hole in a cathode of the electron gun, and pass through the H-type resonator to have an additional acceleration to 8 MeV. Accelerating and focusing RF fields are excited by the electron beam upon the anomalous Doppler resonance conditions. The solenoid creates a resonance space-changed magnetic field (it can be at the entrance 609 Gs and at the exit 439 Gs).

At the moment the accelerator-injector "URAL-5" of energy 5 MeV is in operation; preliminary experiments on a small installation have been carried out; experimental investigations of an accelerating RF resonator model (in 1:1 scaling) are performed; the accelerating test installation is being manufactured.

3 TWO SECTIONS, TWO-BEAM ION ACCELERATOR

In connection with a development of this accelerator, it seems reasonable to use an energy stored in electron transverse motion in the 1st section for wave excitation at NDE in the 2nd one [1]. It is interesting to investigate this process in details. With this aim in view, we consider consecutive self-consisted excitations of two acceleration sections by a relativistic electron beam under ADE and NDE conditions (ADE• NDE). So, we suppose an electromagnetic structure consist of two sections in which slow electromagnetic waves could be excited. These structures are placed in an external DC magnetic field; in general case, the intensity of this field is different for 1st and 2nd sections. Along the axis of this structure an electron relativistic beam is injected. At the 1st section entrance, the beam electrons are monoenergetic and have only longitudinal velocity component. The beam velocity, magnetic field intensity, structure parameters are chosen for excitation of the main mode at ADE in 1st section, and at NDE in 2nd one.

Field excitation process under ADE or NDE conditions in a resonator of H-type with drift tubes has a very complicated nature. Specifically, at a slow wave excitation, longitudinal retarding and bunching of the beam particles is obeying not only to the force $\vec{F} \sim \vec{v}_{\perp} \times \vec{H}$ but also to the non-uniformity (along the radius) of the longitudinal electric field. However, this effect does not change qualitatively the character of ADE instability; namely, at the saturation stage the beam stay uniform and it has monoenergetic values of transverse and longitudinal momenta [1].

As for dynamics of beam particles and wave amplitudes at the consecutive excitation of waves under NDE, one should noted that it is more complicated. At NDE instability the beam electrons are being bunched as in longitudinal direction so in transverse one. The electrons can be intermixed in the cross-section and in the longitudinal phase. The dispersion of transverse momenta of the beam particles can be achieved the initial values of momenta at the entrance of the 2nd section. In the longitudinal direction, bunching of the particles will be occurred too, and dispersion of longitudinal momenta values can be of order of transverse ones.

We assumed that frequencies of waves excited in 1st and 2nd sections are equal: $•_1 = •_2 = •$. At the fixed frequency, for the ADE resonance: $\omega = k_z v - \omega_c^{(1)}$ (see above the Fig.), and for the NDE resonance: $\omega = -k_z v + \omega_c^{(2)}$; the magnetic field in 1st section $H_0^{(1)}$ and in 2nd section $H_0^{(2)}$ should be satisfied to the relationship $\omega_c^{(2)} = \omega_c^{(1)} + 2\omega$ (• $<< k_z v$, • $<< •_c$).

The equations describing the dynamics of the beam particles and wave amplitudes was written separately for 1st section and 2nd one.

Now let us eliminate the rather complicated calculations and consider the main results. We have obtained numerical estimations of the maximum amplitude of electromagnetic wave excited in 2-nd section at normal Doppler effect and also a value of dispersion of longitudinal electron's momenta. Substituting parameters of the EAS (as a 1st section) into the corresponding expressions, we obtain for the 2nd section $E_z \approx 20$ • V/• m. This amplitude saturation is reached at the distance from the entrance of 2-nd section equal to the inverse spatial increment: $L_{sat} \approx 40$ cm. It should be mentioned that the above evaluation corresponds only to the wave amplification regime. Using the regime of wave generation in a resonator of high shunt impedance, it should lead to increasing of the wave amplitude in 2-nd section up to value, comparable with the amplitude of accelerating field in 1-st section. Then, we obtain in the 1-st section (at ADE) E_z = 60 kV/cm and in the 2-nd one (at NDE): E_z = 40 kV/cm. This allows to excite 1st and 2nd section of the two-beam ion accelerator using the same electron beam.

Growth rate and maximum wave amplitude can be enlarged, if perpendicular velocity of the beam electrons be increased at the entrance of the 2nd section. In this case, efficiency of field generation at NDE (being proportional to square of perpendicular velocity of the electrons) increased too. For this aim, in the space between 1-st section exit and 2-nd section entrance the axial magnetic field can be adiabatically increased along coordinate z from H.. to H... From conservation law of magnetic moment of electrons $\mu = mV_{\perp}^2 / 2H_0$ it follows that transverse velocity of electrons at the entrance of the second section increases to the value:

$$V_{\perp}\left(z_{2i}\right) = \left[H_{02}/H_{01}\right]^{1/2} V_{\perp}\left(z_{1e}\right)$$

Accordingly, radius of electron cyclotron orbit decreases to $r_{\perp} = V_{\perp}/\omega_c$ that facilitates the electron beam transport through the drift tubes of the 2nd section.

Let the intensity of guiding magnetic field in the 2-nd section is twice of that in the 1-st section (the frequency is doubled as well). The resonance conditions take the form (here we suppose that phase velocity, as well as longitudinal velocity of electrons, are approximately equal for both sections):

for the 1-st section $\omega_1 = k_{z1}v - \omega_{c1}$,

for the 2-nd section:

$$\omega_2 = 2\omega_1 = -k_{z2}v + \omega_{c2} \approx -2k_{z1}v + 2\omega_{c1}.$$

In this case we obtain $\beta_{\perp}^{2}$• 0.12, • • 1.8 %, and E_z• 60 kV/cm. This example demonstrates the opportunity of using of the 2-nd section for the further acceleration of ions in two-beam ion acceleration.

It should be mentioned that in this approximation (of the fixed resonance conditions) the efficiency can not exceed the value of order of 1 %. It will be considerably higher in case of resonance adjustment by means of specially profiled magnetic field.

4 RESULTS OF RESEARCH AND DEVELOPMENT

1. The physical concept of the two-beam high-current ion accelerator based on Doppler effect is well grounded. This concept may provide the ground for creation of ion accelerators with 10 - 100 MeV energy, 1 - 10 A current, and 10 - 100 MeV/m rate of acceleration.

2. The project of the EAS is developed. The EAS is intended to prove the workability of this type of ion accelerators and to optimize their parameters. The main EAS parameters are calculated to accelerate protons from 5 MeV initial energy to 8 MeV final energy. The accelerating section is designed on the basis of the H-type resonator with drift tubes on meeting suspenders. The operating linear proton accelerator will be used as an injector.

3. The set of nonlinear self-consistent equations has been elaborated for wave excitation by an electron beam in case of AED and NED in a H-type accelerating structure both for amplification and generation regimes.

4. The theoretical investigation and computer simulation have been fulfilled. For the experimental setup the planned accelerating gradient of order of 60 kV/cm can be achieved. Initial efficiency of order of 1% will become higher with keeping resonance by means of specially profiled magnetic field.

5. The method of stationary magnetic field synthesis with required dependence on longitudinal coordinate was realized. Thus it is used the regularization method developed by Acad. A.N. Tikhonov for solution of (so named) incorrect inverse problems. By this method the calculation of the solenoid for creation of a non-uniform resonant magnetic field in the EAS is accomplished.

6. Theoretical investigations and computer simula tions of ion acceleration in a two-beam elfectron-ion accelerator were curried out. Detailed studies of ion acceleration dynamics and its radial focusing have been realized. Computer simulations of ion acceleration and focusing have been accomplished for wide set of parameters including the main EAS parameters. Coulomb interaction of accelerated ions is taking into account by "large particle" simulation method (see this Conf. Proc.). The ion limit current about 3 A have been determined.

7. We have investigated the problem of field excitation in two sections of a two-beam ion accelerator under consecutive anomalous and normal Doppler effect conditions. For the EAS parameters in the case of two sections we obtain in the 1-st one (at ADE) E_z = 60 kV/cm and in the 2-nd one (at NDE): E_z = 40 kV/cm (and E_z = 60 kV/cm in case of magnetic field increasing, Ch.3).

These estimations demonstrate the opportunity of using of the 2-nd section for the further acceleration of ions in two-beam ion acceleration.

9. At present, the accelerator-injector "URAL-5" of energy 5 MeV is in operation; preliminary experiments on a small installation have been carried out; experimental investigations of an accelerating RF resonator model (in 1:1 scaling) are performed; the accelerating test installation (the EAS) is being manufactured.

8. The investigations carried out show this acceleration method to advantage and lead to the expediency of the research and development continuation.

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