COLLECTIVE ACCELERATOR WITH VARIABLE ENERGY AND WIDE SPECTRUM OF ACCELERATED IONS.

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ABSTRACT

Experimental results on the slow cyclotron and space charge (plasma) waves excitation in intense relativistic electron beams (IREB) are presented. Large amplitude (10-50 MV/m) and low phase velocity (in order of 0.01 c) waves have been obtained. Collective ion acceleration results, which were recieved by using microsecond pulse duration electron beams are reported. A concept of a few stage collective accelerator with an energy and particle type control is also considered.

I. INTRODUCTION

The RF linacs are the most preferable accelerators for producing ions in the energy range of tens and hundreds MeV. However, there are two essential demerits which have to be taken into account when constructing and exploiting linacs, namely, the high cost of the RF supply system and the difficulty to control an energy and type of the accelerated ions in the wide range.

The collective methods of ion acceleration based on the utilization of intense relativistic electron beams may result in development of a new generation of ion linacs (so-called "collective linacs"). It is the most natural way to develop such collective linacs which are similar to the conventional RF linacs, but provide direct transferring a part of the IREB energy to the accelerated ions without using an expensive RF supply system. These linacs may be based on utilization of the slow cyclotron and plasma waves excited in the IREB. As it was shown in the early works [1],[2] the electric fields of the cyclotron and plasma waves are much larger than those in the conventional ion linacs. Moreover, intense ion beams with currents of 1-10 A may be accelerated by the cyclotron and plasma waves. But the most attractive feature of these waves is that their phase velocities may be controlled by a longitudinal magnetic field. The last peculiarity may be used for controlling an energy and a particle type in the wide range.

II. CYCLOTRON WAVE EXCITATION AND COLLECTIVE ION ACCELERATION

The slow cyclotron waves in the electron beams of a small power [3] or a high power, but a short pulse length [4] had been produced in early experiments by using of the radio-frequency supply from the external powerful generator and the helical guide, as an amplifier structure. In our experiments the intense relativistic electron beam propagates down a cylindrical copper passive cavity of H-type. The scheme of the experimental set up is shown in Fig.1.

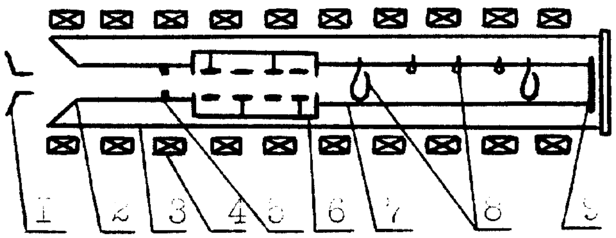

Fig.1. Experimental set up scheme: 1-cathode, 2-anode, 3 - vacuum chamber, 4 - magnetic coils of solenoid, 5 - diaphragm, 6 - cavity, 7 - collective acceleration channel, 8 - magnetic loops, 9 - IREB collector.

The H-cavity length is 0.34 m. The cavity involves 15 drift tubes, which have 4 cm in aperture and are installed with period of 2 cm. The electron beam propagation excites the large amplitude self-sustained RF oscillations in the cavity. The interaction between electrons and cavity fields results in the constrained generation of a slow cyclotron wave. It is found that the beam wave generation is also produced, when an equality between the structure period and the cyclotron wave length is not supported. The generation is occured in a wide magnetic field range from 0.4 T to 2.0 T. The phase velocity of wave is varied and controlled by value and distribution of magnetic field. When energy of electrons is about 500 keV and beam current equels approximetly 1 kA, it is excited a cyclotron wave with amplitude of about 10 MV/m and frequency of 667 MHz. Durations of the wave generation and the cavity oscillation process are about 0.5 - 1.0 mks (beam pulse duration equels 10 mks). A breakdown of the generation process is explained by arising of discharge in the cavity drift tube gap.

To test the effect of the collective ion acceleration by the cyclotron wave field it was proposed to use the collector plasma as ion source and to accelerate the ions opposite to the electron stream (Fig.1) [5]. In carried out experiments the protons were accelerated up to 1.5 MeV. The proton dynamics calculation showed that protons were accelerated up to 0.5 MeV in the acceleration channel and up to 1.5 MeV in the cavity. The current of accelerated protons was about 1 A. It was registered that the ion beam had a RF structure corresponded to the excited wave frequency.

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III. PLASMA WAVE EXCITATION

The problem of plasma wave excitation was solved in early experiments [2],[6]. The experiments of our colleagues [6] were conducted with using the annular IREB of energy 550 keV, current 4.5 kA and pulse duration 100ns. The experimental set up consisted of a disk-loaded waveguide and drift tubes of various diameters. Plasma waves were excited in IREB as a result of the interaction between the IREB and the waveguide. The waveguide had following parameters: relative phase velocity- 0.87, frequency of 3 GHz and shunt impedance of about 20 MOhm/m. The IREB was confined by the longitudinal magnetic field of about 0.7 T. The parameters of plasma waves were measured by magnetic loops mounted inside a drift tube.

The experimental results showed that the slow plasma waves of large amplitudes were excited. The measured values of phase velocities were 0.5 c, 0.27 c and 0.16 c (c- light velocity) when the diameters of drift tubes equaled 4cm, 7cm, and 8cm correspondingly. The estimates made for these cases gave the following values of electric field amplitudes: 4.5 MV/m, 20 MV/m and 50 MV/m. The lowest phase velocity was obtained when $I_b/I_L = 0.9$, where I_b - beam current and I_L - space charge limiting current. Consequent utilization of plasma waves for ion acceleration is advisable when initial energy of ions is sufficient high (about 20 MeV).

IY. ION ACCELERATOR CONCEPT WITH AN ENERGY AND PARTICLE TYPE CONTROL

The above experimental research has demonstrated out capabilities of collective ion acceleration by means of the intense electron beams. A rather low value of ion energy experimentally measured can be explained by using collector plasma, as a low energy ion source, and choosing a small value of the synchrotron acceleration phase to demonstrate collective acceleration physical effect. However, acceleration rate about 10 MeV/m can be taken for estimates, if electron beams with parameters described above is used. Energy and current of ions can be increased, if the independent ion injector is applied.

The phase velocity of the cyclotron wave moving together with ions is controlled by the external magnetic field B(z):

$$\beta_{ph} = 2\pi\beta\gamma mf/eB(z) \qquad (1)$$

e, m , β and γ are charge, mass, relative velocity and energy of electrons respectively, f - frequency of the propagating wave. The capture of ions with different mass and charge can be produced by varying of B_i (magnetic field in capture area). The output ion energy can be varied inversely B_0 (output magnetic field). The passive H-cavity has a line spectrum with lower frequency of 230 MHz. Cavity frequency, closely equel to f, can change according to excited mode and depends on the electron beam parameters. The collective ion accelerator concept with a velocity and mass control has been developed due to above factors.

The accelerator scheme is the same, as experimental set up scheme. The rather wide spectrum of ions, such as p, d, He^+, He^{++}, C^+, C^{++}, N^+, O^+ can be used for acceleration. Relation of magnetic fields is defined as

$$B_i / B_0 = (1 + ZeEl/W_i)^{1/2}, \qquad (2)$$

where Z - relative ion charge, E - accelerating electric field of wave, l -acceleration section length, W_i-injection energy. Maximum value B_i is limited by the technical capability (2.5 T for that experimental set up). Minimum value B_0 is determined by the electron beam equilibration (about 0.1 T). This magnetic field range is quite enough to capture and accelerate ions of the above spectrum. Using relation (2) one can produce estimates of the accelerator parameters for two boundery cases. The first case is the proton acceleration up to 21 MeV (W_i = 1.0 MeV). It may be obtained, if B_i= 1.0 T, B_0= 0.22 T and f = 667 MHz. In this case the most "fast" cyclotron wave (β_{ph}= 0.046-0.21) is creating. In the second case the acceleration of oxygen ions with mass-charge ratio of 16 is produced up to the same output energy and the slowest cyclotron wave (β_{ph}= 0.008-0.052) is used. It is occured, when B_i = 2.0 T, B_0= 0.31 T and f = 230 MHz. In both cases $\beta\gamma$= 2, l = 2m, E = 10 MV/m. In order to control the growth rate of wave and the output energy, the respective axial magnetic field distribution must be taken. In our experiments the longitudinal magnetic field gradient was exchanged by means of the solenoid coil commutation and the time displacement of the electron beam pulse relative to the magnetic field pulse. This method of the magnetic field distribution control was used successfully by ourself in the experiments on the collective ion acceleration and the microwave radiation [5],[7].

The output ion energy can be increased by increasing of wave amplitude and acceleration length. The ion energy is rised until 100 MeV, if E = 20 MV/m and l = 5 m.

The acceleration of ions up to hundreds MeV can be realized by using a few stage collective accelerator. For example let us consider a two-stage accelerator which can be based on scheme shown in Fig.2. The first stage consists of an ion injector, a high-intensity electron diode, a passive H-cavity and the first acceleration section. The first stage corresponds to above considered concept and can provide the ion acceleration up to 100 MeV. The second stage consists of an electron diode, a disk-loaded guide and the second acceleration section. The ions accelerated in the first stage are injected into the second stage through the hollow cathode tube of the second diode. The second stage is based on using the plasma waves and can produce a high gradient acceleration because very high fields were obtained in the above described experiments [6]. The phase velocity of plasma waves depends on the relation r/R, where r - beam radius and R -tube radius of acceleration section. In a magnetized electron beam its radius r is definded by the magnetic field value. Therefore, changing a distribu-

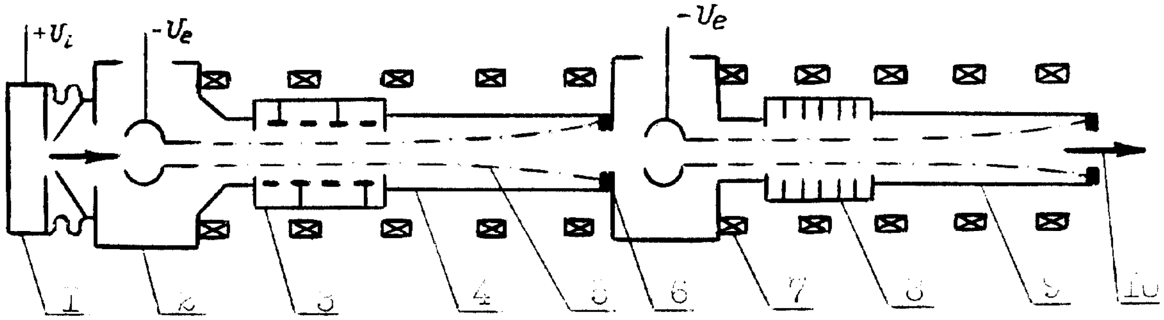

Fig.2. Few stage collective accelerator scheme: 1 - ion injector, 2 - electron diode, 3 - H-cavity, 4 - first acceleration section, 5 - electron beam, 6 - electron beam collector, 7 - magnetic coils, 8 - disk-loaded guide, 9 - second acceleration section, 10 - accelerated ion beam.

tion of the magnetic field one can vary the phase velocity along the acceleration section. This property provides a possibility to accelerate different type ions and to control their energies without overdesigning the accelerating structure. It should be pointed out that the higher is the injection energy of ions the more effective is the acceleration process. Therefore, the injection energy of protons chosen for the above considered example is quite high (1 MeV). In order to produce high energy ions, one can propose to use the resonance accelerating structure driven by an electron beam [8]. Such injector needs no RF supply system and may provide acceleration of intense ion beams. In this case a single requirement must be fullfilled, namely, the resonance structure frequency must be varied when the mass-charge ion ratio changes. The resonance structure may be driven at different frequencies depending on modulated beam frequency. The electron beam is modulated by means of two gaps coaxial resonator. This method has been described in the papers [8],[9]. According this method the operating frequency may be obtained by means of mechanical tuning the resonator and simultaneously supplying a negative bias to the cavity drift tube.

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