# ION ACCELERATOR BASED ON PLASMA VIRCATOR

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Based on previous fundamental and experimental research [1, 2] the conception of a collective ion accelerator is proposed to be developed in the frameworks of STCU project #1569 (NSC KIPT, Ukraine) in coordination with the ISTC project #1629 (VNIIEF, Russia). The main processes of acceleration are supposed to be consisted of two stages. First one is the plasma assistance virtual cathode (VC) in which plasma ions are accelerated in a potential well of VC. Along with ion acceleration the relaxation oscillations, caused by diminishing the potential well due to ion compensation, arise that provides the low-frequency (inverse ion transit time) temporal modulation of an intense relativistic electron beam (IREB) current. At the second stage temporally modulated IREB is injected into the spatially periodic magnetic field. The further ion acceleration is realized by the slow space charge wave that arises in IREB due to its simultaneous temporal and spatial modulation.
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## 1 INTRODUCTION

Acceleration of ions in the potential well of the VC space charge [I], and in the field of a space charge slow wave, which arises in IREB due to its modulation both in space and time are the physical processes that allow to develop the conception of a collective accelerator with high acceleration gradient and intense current. Its possible applications are the followings:
- electronuclear method of energy production (energy amplifier) [3], ion deep implantation [4], material modification with ion beams [5]. Besides the ion beams, generated on the accelerator proposed, can be used for the following goals: nuclear transmutation purposes, radioactive scrap demolishing, research on inertial thermonuclear fusion, radiation damage imitation, electron - ion beam transportation, etc.

In the present paper the preliminary investigations of a two-stage scheme of collective ion acceleration that uses consecutively both mechanisms [1] and [2] are represented. At the first stage VC with plasma assistance is used. Plasma ions are accelerated by the VC electric field and along with this ions IREB are modulated in time by means of repeated compensation of VC space charge. At the second stage IREB modulated at low frequency (determined by ion transit time), are injected into a drift chamber with a spatially periodic magnetic field [6], where the spatial modulation of IREB takes place. In the drift chamber the preliminary accelerated in a VC region are being accelerated by a slow wave of IREB space charge to the energy determined by the residence time in Cherenkov synchronism with the wave.

## 2 PRELIMINARY RESULTS [6]

### 2.1 Simulation

We represent the results of theoretical consideration of the low-frequency (LF) modulation of IREB current at ion acceleration by VC with plasma presence. In the scheme under consideration two goals are gained: the ion acceleration up to energies of the order of the initial energy of the IREB particles and the LF modulation of the IREB current, which is necessary for the subsequent excitation of the slow wave during the beam injection into a spatially modulated magnetic field. To elucidate a mechanism for LF modulation of the IREB and to determine its characteristic frequencies, we developed a numerical model that adequately describes the experiment. The self-consistent dynamics of the ion flow and the VC, which is formed by the IREB, is studied by the particle-in-cell method in an electrostatic approximation.

For the simulation of axisymmetric annular beams we used a planar model. The two-dimensional calculations used a 32x32 grid. We assumed the following boundary conditions: the potential vanished at both the side boundaries and the left (entrance) boundary, and the right boundary was open. Thin symmetrical electron and ion beams were injected into the system from the left.

The transverse sizes of the beams (which correspond to the beam diameters in the axisymmetric statement of the problem) and their thickness, the initial electron and ion energies, as well as the injection currents could be independently varied in the calculations. We assumed that electrons were magnetized and moved only along the magnetic field lines, whereas the ion motion was two-dimensional.

The calculations were performed with the following model parameters: injection electron current $J$ 50-500 A/cm, ion current 0-50 A/cm, initial electron energy 200-500 keV, initial ion energy 50-100 keV, ion mass was 25-30 electron masses, the beam width (diameter) 0-3 cm, and the system length 7 cm.

*Calculation results:*

In the absence of ions, we observed VC formation accompanied by the high-frequency (HF) modulation of the reflected and transmitted currents. When the ion current was injected near the axis of the system, this effect was similar up to the ratio of the ion- to electron currents equal to 0.25. When the ion-beam "radius" was larger than the electron-beam "radius" *(Ri/Re* = 3.5), we observed LF modulation of both the transmitted and reflected electron current even for the ratio of the ion- to electron currents equal to 0.1. When the LF modulation of IREB takes place, the transverse ion motion plays an important role in VC dynamics. Moving in the two-dimensional potential well produced by the electron beam, the ions accelerate along the axis and, at the same time, displace toward the axis; as a result, they are focused behind the VC. When a sufficient amount of ions is accumulated, the neutralization of the IREB space charge causes the VC to displace inward the chamber and then to disappear. In this case, the entire electron-beam current flows through the system. The ion acceleration by the VC field and their arrival into the IREB ceases. Then, the previously accumulated ions drift into the chamber, and the VC is restored at the left end of the chamber. Further, this process repeats. The estimates show that the frequency of the LF beam modulation is of the order of the frequency of the transverse ion oscillations in the VC field.

In the second stage of the accelerator, when the IREB with the LF-modulated density enters the spatially periodic magnetic field, spatial modulation of the beam along the drift chamber occurs. As a result of the spatial and temporal modulation, a slow wave is formed in the beam. The phase velocity of this wave is $v_{ph,} = \omega_m / k_m$, where $\omega_m$ is the time-modulation frequency, and $k_m = 2n/L$ is the wave number of the spatial beam modulation *(L* is the period of the external magnetic field). As follows from this relationship, for the synchronism between the wave and accelerated ions to be maintained, it is necessary that either the spatial period of the magnetic field or the modulation frequency $\omega_m$ should be increased.

We consider the magnetic field in the form

$$H_r = hI_1(k_m r)\sin(k_{mz} z),$$
$$H_z = H_0 + hI_0(k_m r)\sin(k_m z),$$

where $I_{0,1}$ are the modified Bessel functions. The current of the annular beam at the entrance of the system is harmonically modulated in time. Then, for the accelerating field near the axis, we obtain the following expression:

$$E_z = (J\alpha k_m h/2vH_o)\sin(\omega_m t - k_m z)$$

where $J$ is the electron-beam current, $v$ is the electron-beam velocity, and $\alpha$ is the amplitude of the time modulation of the beam. As follows from the latter expression, the accelerating-field amplitude is proportional to the product of amplitudes of the magnetic field and beam current modulation and linearly depends on the beam current.

### 2.2 Experiment

The experiments were carried out in the AGAT accelerator, which is a microsecond diode with a magnetic insulation [7]. The accelerator produced an annular electron beam with the following parameters: $E$ = 280 keV, $J$= 3.5 kA, $\tau$ = 1 $\mu$ s, and the beam energy 350 J. The beam was injected into a drift chamber 4.9 cm in diameter which was placed in an external magnetic field of 4-4.5 T. In the first acceleration stage, the acceleration is related to the formation of the VC near the diode in the regime of the overlimiting IREB current. We studied experimentally the conditions of the VC formation and measured both the space and time distributions of the electric potential in the drift chamber for different values of the beam diameter, gas pressure, and external magnetic field. It was found that, when the magnetized IREB with a current higher than the limiting current was injected into the drift chamber filled by a gas at a pressure of $2\times10^{-5}$ - $4\times10^{-4}$ Torr, the relaxing VC was formed near the anode. Simultaneous measurements were made by a set of the capacious probes located along the drift chamber. The dimensions of the region occupied by the VC were determined by comparing the signals from the probes located at distances of 3, 5, 7, and 11 cm from the cathode. It was shown that, at a distance of 3 cm from the cathode, the potential is higher than the voltage applied to the diode. As the distance increases, the potential drops rapidly, and then, at a distance of 11 cm, it becomes constant. The magnitude of magnetic field in the region of the IREB injection was chosen such that a portion of the beam escapes to the walls of the chamber. Thereby, a plasma was produced near the anode; in the experiment, this plasma acted as an ion source. The maximum ion current was observed for $H\alpha / H_0$ = 0.6, where $H\alpha$ is the magnetic field near the anode, and $H_0$ is the guiding magnetic field.

In the experiments, we studied the structure of ion pulses for different geometry of the diode and also for different values of the electron beam diameter, magnetic field magnitude and gradient, and gas pressure. To measure the ion-beam parameters, we used collimated and wide-aperture collectors, negatively biased Faraday cylinders, Rogowski loops, magnetic analyzer, and track detectors made from the cellulose nitrate. It was found that the accelerated ions appeared behind the VC when the injection current $J$ was either comparable or higher than the limiting current. The ion current reaches its maximum of 200 A when the radius of the beam propagating through the drift chamber is 14 mm. When the injection current is smaller than the limiting current, the ion current was noticeably smaller. Most of the nitrogen ions of the wall plasma, which were accelerated by the potential well of the VC, had energies of the order of 300 keV. From the energy spectrum and potential distribution, we found that ion energy was governed by the depth of the potential well of the VC.

In the VC regime, we observed LF modulation of the electron beam; the modulation characteristics were determined from the measurements of the bremsstrahlung X radiation and beam-collector current and from the signals of the magnetic loop probes installed along the drift chamber. From the correlation analysis of the measured signals, we could determine the fluctuation parameters. It was found that the frequency spectra of the signals, which were measured by three independent diagnostics, coincide quite well over the entire transportation channel. The LF fluctuations of the electron current were quite regular and were observed over all the IREB-transportation channel. The frequency spectrum has a maximum at a frequency of 20 MHz; the modulation amplitude reaches 40%. As follows from the above theoretical analysis, the transverse oscillations of ions in the VC field are responsible for LF modulation.

In the second acceleration stage, the spatial modulation of the beam was produced by the periodic magnetic field. The space-modulation period was chosen such that the slow wave in the IREB was synchronized with the accelerated ions. Spatial modulation occurred during IREB propagation in the external magnetic field through a set of iron and aluminum coils placed around the circular waveguide. In the experiments, the modulation amplitude *h,* which dependeds on the coil thickness, could be varied within 12-40%. The modulation period could be either constant or increasing along the system; the space periods were chosen in such a way that the ions were accelerated continuously and synchronously in our system. We studied the acceleration of the ion beam that was preliminarily accelerated in the first accelerator stage. The maximum energy of the nitrogen ions reached 1.5 MeV after passing five space-modulation periods whose length was changed from 6 to 7.8 cm. The current of the accelerated ions was 20 A; the pulse duration was 400 ns.

The experimental study of the time modulation of the REB current revealed an increase in the time-modulation frequency during acceleration: as the beam propagated through the modulated magnetic field, the maximum of the frequency spectrum of LF fluctuations of the REB current shifted to higher frequencies (from 20 to 60 MHz). This increase in the time-modulation frequency during the acceleration process causes a corresponding increase in wave phase velocity, which enables ion acceleration even when the space-modulation period is constant. A more complete understanding of this effect requires further study.

## 3 PLANNED INVESTIGATIONS

The further investigations are determined in the proposals of the projects that are purposed for physical investigations and elaboration of the recommendations on the construction of intense ion accelerator of a new type, based on the vircator with a plasma anode and space-periodic magnetic field.

The main important problems, which are supposed to be solved in the frame of project #1569 [8] are the followings:

- theoretical study and numerical simulation of the mechanism of low-frequency modulation of the REB current and the dependence of LF modulation frequency on the REB parameters, the current of accelerated ion flow and the geometry of system;
- theoretical study of the maintenance of synchronism conditions for the charge density wave of REB and accelerated ions of various kinds by changing the period of a magnetic field or modulation frequency, research of radial and phase stability of ions in field of acceleration;
- a choice of geometry of the high current diode and, accordingly, IREB configuration in the field of acceleration and drift space;
- experimental research of modes and parameters of the non-stationary ion flow;
- investigation of conditions of ion trapping with the help of compulsory creation and configuration of a dense plasma bunch with a necessary ion structure;
- study of dynamic characteristics of the virtual cathode and parameters of ion flow at the output of the first step of acceleration at presence of a focusing magnetic field of a various configuration and amplitude;
- elaboration of the diagnostic equipment for determination of final and intermediate parameters of accelerated ion currents and diagnostics of a slow wave of REB spatial charge;
- experimental research of spatial - temporary characteristics of high current REB depending on REB and plasma parameters;
- investigation of energy gain by ions in dependence on the length of the second section with a spatially periodic magnetic field;
- determination of the REB configuration optimum from the point of view of efficiency of ion acceleration and their radial and longitudinal stability.

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