IONS ACCELERATION IN A TEMPORARY AND SPATIALLY MODULATED INTENSE REB

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The conception, proposed by Lymar, Khizhnyak, and Belikov, to use collective electromagnetic fields of space charge excited in high-current relativistic electron beam (REB), modulated in time and space, have been experimentally investigated. At plasma assistance the low frequency oscillations of 46 MHz are excited in the overcritical REB. The flow of C^+ ions accelerated by the space charge field of virtual cathode up to 500 keV with density of 6×10^6 cm^{-3} was formed. The fluence of ions on the collector during the ion pulse has the value 5×10^7 particles/cm^2. The periodic magnetic field with 12% modulation was created by a sequence of aluminum and iron rings. After acceleration in the section with temporary and spatially modulated REB ions achieved energy 1.5 MeV and ion current 1 A.

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1. INTRODUCTION

The idea to create the space charge slow-wave arising at temporary and spatial modulation of REB and use it for ions acceleration was stated by Khizhnyak et al [1]. One of the first attempt to perform state-of-art experiment has been made in [2]. This work pursues the object to continue these researches and clarify acceleration mechanisms.

In the first section of the proposed ion accelerator the collective fields are formed when an intense REB with the current that exceeds the vacuum limiting current is being injected into the drift chamber and thus virtual cathode appears. Plasma source in the vicinity of virtual cathode (VC) gives two virtues: firstly, acceleration of plasma ions to the energy compared to the electron beam energy and thus realization ion injector, needed for the second section of ion accelerator; secondly, compensation the virtual cathode by plasma ions occurs periodical because its compensation allows ions to run away and the compensation process can repeat again. The periodic compensation should lead to the temporal modulation of electron beam current at low frequency (LF). In the second section temporary modulated intense REB is being modulated additionally in space during its motion through the spatially periodical magnetic field. Such double modulated REB can be considered as a slow space charge wave whose phase velocity can be resonantly adjusted to ions velocity by means of frequency or/and spatial period variation [1,2].

The pulsed electron accelerator produces REB with parameters: energy 280 keV, current 4.4 kA, pulse duration 0.8 μsec. VC in magnetically insulated diode was realized by means of sharp change of drift chamber diameter from 40 mm to 50 mm. The outer plasma source consisted of 4 plasma guns for radial injection into VC region to obtain accelerated ions and low frequency REB modulation. The plasma density was 10^{12} cm^{-3}.

At plasma assistance the low frequency oscillations of 46 MHz are excited in the high-current REB. At the exit of the first section the flow of C^+ ions accelerated by the space charge field of virtual cathode up to energy 490 keV with density of 6×10^6 cm^{-3} was formed. The fluence of ions on the collector during the ion pulse has the value 5×10^7 particles/cm^2.

The periodic magnetic field was created by a sequence of aluminum and iron rings. The periodic magnetic field with 12% modulation was obtained. After additional acceleration in the second section ions energy 1.5 MeV and ion current 1 A were achieved.

2. THE FIRST SECTION WITH EXTERNAL PLASMA SOURCE

The structures with virtual cathode are successfully applied in collective accelerators of charged particles [3, 4]. Such structure serves as the first section of two-sectioned collective ion accelerator (Fig. 1) based on joint temporary and spatial modulation of REB. In such accelerator the ions are accelerated by a field of space charge slow wave generated in electron beam at its temporary modulation by virtual cathode with plasma and spatial modulation by spatially periodic magnetic structure. The mechanisms of the REB low frequency by the field of virtual cathode that experiences periodical compensation by plasma ions at low frequency were studied theoretically and numerically [5, 6].

For REB producing the high-voltage pulse of Marx generator with the amplitude of 280 V is supplied to the magnetically-insulated diode on electron accelerator "Agat". The cylindrical cathode has diameter of 31 mm and depth of an emission edge of 0.1 mm. The entrance diameter of cylindrical anode with 40 mm allows to take the electron beam current of 4.4 kA. The inside diameter of transport electron cylindrical liner is equal 50 mm and the limit vacuum current is 3.4 kA for it. The jump of electrodynamics' structure provides the formation of virtual cathode [7].

The electron beam was transported in a longitudinal external magnetic field of the solenoid with inductance of 810 μH. Magnetic field value of 1.33 T that was produced by the system of external magnetic field formation. The time period of the external magnetic field was of 11.4 ms. In the cathode region the induction value of magnetic field has value 60% from induction value inside the solenoid. Such configuration of the magnetic field formed the electron cylindrical beam with diameter of 32 mm and wall thickness of 3 mm in the liner. In our system the limiting current of electron beam is 3.4 kA.

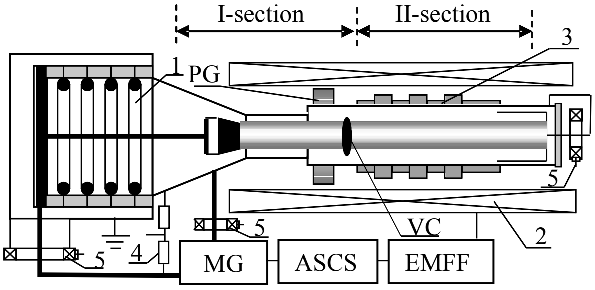


Fig.1. Scheme of collective ion accelerator MG-Marx generator; ASCS–accelerator starting and control system; EMFF-external magnetic field formation; VC-virtual cathode; PG-plasma gun; 1 – magnetically-insulated diode; 2 – solenoid; 3 – aluminum and iron rings; 4 – high-voltage resistive divider; 5 – Rogovsky coil for Faraday cup current measuring

In the first section of the collective ion accelerator, where ions are pre-accelerated by an electrostatic field of a space charge of virtual cathode. Ions are extracted from plasma cloud formed by an external plasma source. The second consequence of plasma assistance was a low frequency modulation of REB current due to periodic compensation with plasma of VC space charge.

The plasma cloud was formed at synchronous switching of four plasma guns. Plasma guns were placed in the same plane on peripherals of the cylindrical drift chamber. For tubular configuration of plasma flow the dielectric insert was placed in the region of plasma injection. The dielectric insert forms a tubular flow of external plasma along force lines of an external magnetic field.

At the absence of the dielectric insert plasma moving radially to the drift chamber axis forms a planar plasma anode. In this case the maximum REB current at the collector was registered that was almost equal to maximum diode current. It means that at REB transporting in the drift chamber with plasma filling the virtual cathode did not appear.

The cylindrical dielectric insert has allowed to form near-wall plasma tubular column. By change of longitudinal size of the insert the different operational regimes of the virtual cathode were realized. In experiments with a lengthy dielectric insert a pulse of the collector current on Faraday cup coincided to the pulse of REB without external plasma. When the insert was shorter current pulse on the collector the peak was observed (Fig.2, (3)) whose amplitude was equal to maximum value of the diode current. It allowed to make a conclusion that for this short time interval VC disappeared.

3. LF-MODULATION OF REB

The operation of accelerator comes to switching in series pulses of magnetic field, plasma gun, and diode. In Fig.2 the oscillograms of current pulses of plasma gun (1), diode (2), and Faraday cup (3) are shown. The time delay between pulses of currents of the plasma gun and diode are chosen so that injection of REB corresponds to the moment of steady state of plasma density.

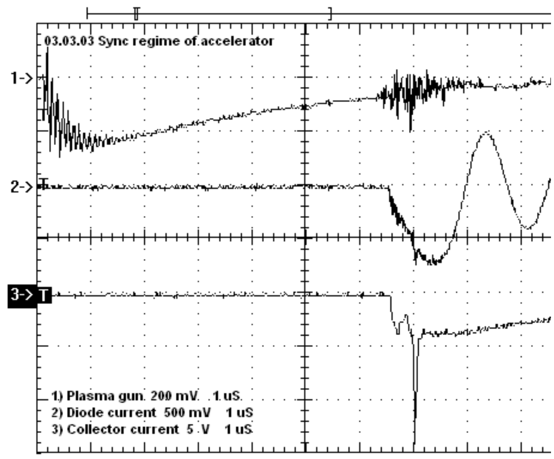


Fig.2. Time evolution of plasma gun, diode and collector currents

Peak on the oscillogram of the current of Faraday cup (3) corresponds to short-time disappearance of the VC due to its charge compensation by plasma ions. The time of 480 ns from the beginning of Faraday cup current pulse to peak appearance is determined by the time of motion of plasma ions from the plasma source to the region of the virtual cathode.

Due to VC space charge compensation by plasma ions, then relaxation and repeated ones REB experience temporal modulation with frequency equaled inverse ion time flight.

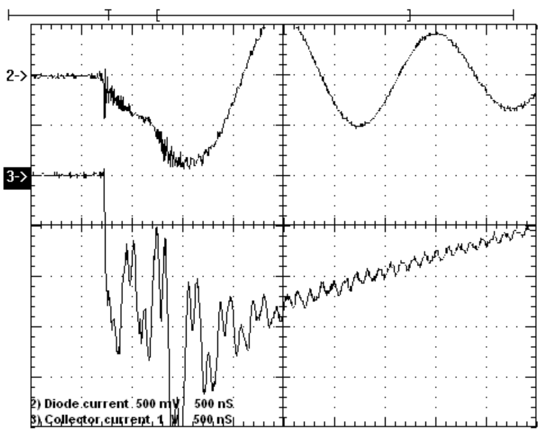
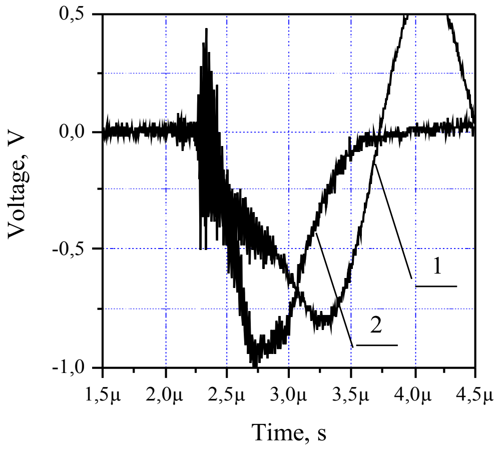


Fig.3. Low frequency modulation of REB

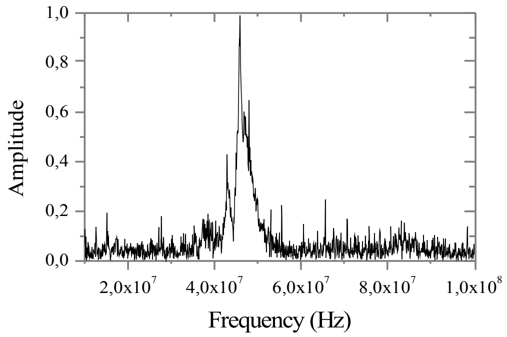
In Fig.3 the oscillograms of diode and Faraday cup currents are shown. The lower oscillogram shows the low frequency temporary modulation of REB current obtained with a short length of the dielectric insert.

The modulation frequency of 46 MHz at modulation depth 10% were observed in experiments.

Additional confirmation of low frequency REB modulation was modulation of X-radiation on the same frequency. The REB produced the X-radiation at bombardment of the target from stainless steel. X-radiation registration technique used here is shown in paper [8]. In Fig. 4 the results obtained at presence of plasma from the external source are shown.



a



b

Fig.4. Pulses of input diode current (1) and X-radiation (2) (a), and spectrum function of X- radiation (b) with external plasma

The duration of REB current was equal to pulse duration of the X-radiation and had value 0.8 µs close to REB current duration. In Fig.4,b the spectrum function of the X-radiation is shown with the maximum in the region of 46 MHz.

4. ENERGY OF IONS ACCELERATED BY A SPACE CHARGE FIELD OF VC

For ions detection we used cellulose nitrate film that was bombardment by ion flow. Ions tracks were obtained after etching of the track detector in 10% NaOH solution at temperature 60 C during 2 minutes. The images were observed by using the microscope.

For determination of ions energy, which were preaccelerated by space charge field of VC in the first section of the accelerator, magnetic analyzer was used. Kinetic energy of ion is determined by the relation

$$W = \frac{1}{2m}\left(\frac{\delta L}{l} qB_{\perp}\right)^2, \qquad (1)$$

where m, q, are mass, charge of the ion, δ is the cross-sectional size of transversal magnetic field $B_{\perp}$, L is the distance between the magnetic field and screen; l is the deflection of ion from the initial direction, which is registered on the screen. In our experiments the screen was made from the cellulose nitrate that was also the track detector of ion flow.

In our experiments the deflection system was used with following parameters: $|B_{\perp}|$=0.144 T; δ =40 mm; L=40 cm. The width of the slot diaphragm placed before transversal magnetic field was equal 1 mm. For one-charge ions of carbon C^+ the deflection l was 6.08± 0.82 mm. Accordingly to (1) the estimated ion energy is $E \approx$ 0.54±0.06 MeV.

Time-of-flight diagnostics were used for research of ion velocity at exit of the first section of accelerator In Fig. 5 the pulses registered by two grid probes of the time-of-flight diagnostics.

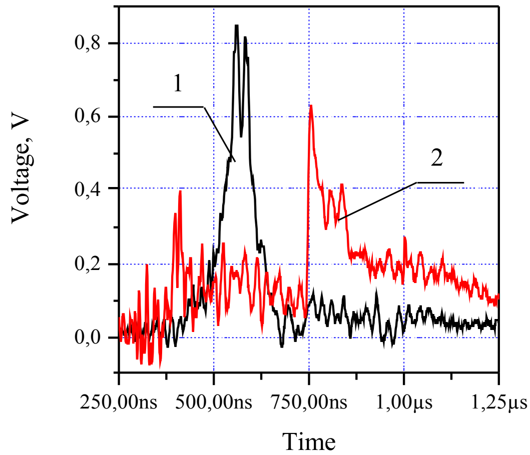


Fig.5. Pulses from first (1) and second (2) grid probes of the unit for time-of-flight measurements

The time delay between pulses had the value within 180...200 ns. For the distance between grids 50 cm it corresponded to ions velocity (2...2.5)×10^8 cm/s. If ions were one-charged ions of carbon C^+ (because plasma was produced by evaporating and ionizing of plexiglas) their energy was within 330...490 keV. The maximum value of determined energy of ions was in agreement with the energy measured by magnetic analyzer. Excess of ions energy above energy of REB electrons testifies about presence of the movement of negative potential well created by the space charge of VC. In the case, when the potential well and the ions are moved in the same direction, the ions obtain additional energy. The registered energy spread of one-charged carbon ions is probably caused by the complicated self-consistent dynamics of the space charge potential of VC.

The estimations of ion density in ion flow $n_i = I_i / q_i S_{col} \sqrt{2E_i / m_i}$ with the charge q_i and mass m_i at the exit of the first section of the collective ion accelerator were based on measurements of ion energy E_i by magnetic analyzer and time-of-flight diagnostics and ion current I_i registered by the Faraday cup with the collector square of S_{col}. The fluence of the ions N/S_{col} that have reached the collector was determined by the relation $N/S_{col} = I_i\tau / q_i S_{col}$, where N is total number of ions; τ is the duration of ion pulse on half-level of power. Besides, the fluence of ions was also determined by the straight counting of the slides of ions bombardment of the track detector. In the Table the research results of the flow of one-charged carbon ions C^+ pre-accelerated by the space charge field of virtual cathode are shown. The ions were extracted from plasma produced by REB bombardment of the special dielectric (plexiglas) insert in the drift liner near the virtual cath**ode location.**

		Energy, keV	Current, mA	Pulse duration, nsec	Ion density cm^{-3}	Fluence, ions/cm^2	
						Collector current	track detector
First section		500	200	50	$6{,}3\times10^8$	$8{,}8\times10^9$	$(5{,}6\pm0{,}5)\times10^9$
Second section	N=5	680	1600	60	$4{,}3\times10^9$	$8{,}45\times10^{10}$	–
	N=9	1500	1000	40	$1{,}8\times10^9$	$3{,}52\times10^{10}$	–

5. THE SECOND SECTION WITH PERIODIC MAGNETIC FIELD

In collective ions accelerator being developed the spatial modulation of REB is provided by the periodic magnetic field of the second section. From synchronism condition of a slow wave of space charge in REB and accelerated ions the period of the external magnetic field should be $L = v_i / f$, where v_i is the velocity of ions pre-accelerated by space charge field of virtual cathode, and f is the frequency of temporal modulation of REB in the first section. In our experiments the first section of the ions accelerator provides the temporal modulation of REB with frequency 46 MHz and the energy of accelerated carbon ions C^+ 500 keV. Period of the external magnetic field should be L = 6 cm.

The section of modulated magnetic field with period of L is created by alternating iron and aluminum rings, which are placed on the external surface of the drift liner. The modulated structure of the external magnetic field H_0 = 4.4 kOe consists of N=5 periods of iron and aluminum rings with the longitudinal size of each 3 cm. The radial thickness of aluminum ring is 1 cm and iron one is 0.5 cm. In Fig. 6 the distribution of the external magnetic field along the liner of ions transporting is shown.

It is seen that in the part with metal rings magnetic field with 12% modulation as a whole twice less comparatively to magnetic field of solenoid. Period of magnetic field is determined by metal rings period. Maximum corresponds to Al-rings and minimum corresponds to Fe-rings.

Propagating inside drift tube (diode anode) tubular REB becomes modulated too. The form of REB tube alog the axis was determined by means of portrait prints of REB on the metallic plates placed at different distances from cathode. As it is seen from Fig. 7 REB is modulated with increasing thickness of REB tube. However electrons didn't follow magnetic field lines.

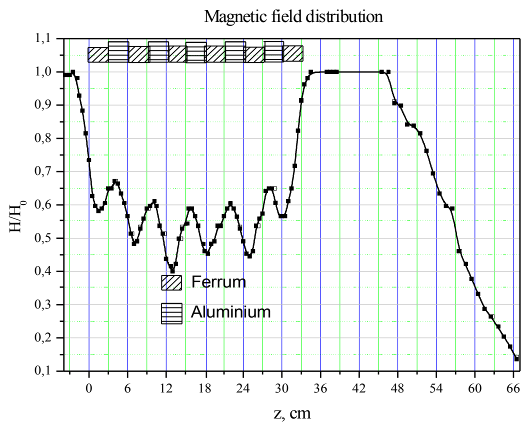


Fig.6. Magnetic field distribution along drift tube

In the second section ions gained additional energy due to acceleration by space charge slow wave. It is concluded from the results of ions energy and current measurements represented in Table (second line). Ions achieved energy 680 keV and current 1,6 A.

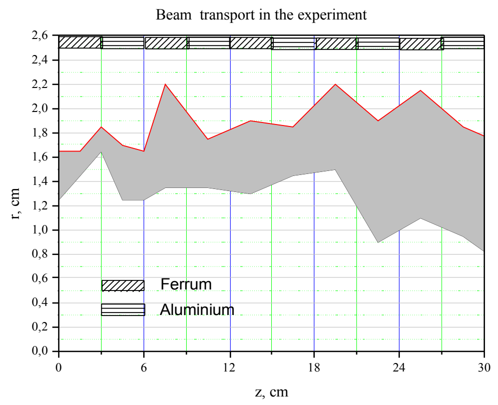


Fig.7. Picture of REB propagation in drift tube

To prove the resonant character of accelerating by traveling slow wave the length of the second section was increased twice and modulation period was made variable. Successive N=9 periods were equal to 6 cm, 6cm, 7cm, 7cm, 8cm, 8cm, 9cm, 9cm, 10cm. Magnetic field distribution for this case is shown in Fig. 8.

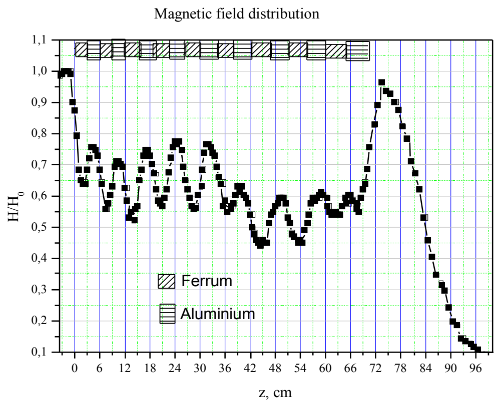


Fig.8. Magnetic field distribution along drift tube at twice enlarged second section

Results of ions acceleration in enlarged section are represented in Table (third line). Energy of ions at exit was 1,5 MeV, ion beam current 1 A. Ion beam duration was one order less comparatively to REB pulse duration.

6. CONCLUSIONS

In the first section of collective ion accelerator the low frequency REB modulation and the pre-acceleration of ions were realized using an external plasma source. The low frequency was observed on Faraday cup current and on the spectrum of X-radiation. The modulation frequency was near 46 MHz. Pre-accelerated ions had energy 540 keV, registered by track detector (cellulose) and measured by magnetic analyzer and flight-of-time analyzer. In the second section consisted of 9 variable length periods of magnetic field, ions gained energy up to 1.5 MeV, current 1 A, pulse duration 40 nsec.

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УСКОРЕНИЕ ИОНОВ В СИЛЬНОТОЧНОМ РЭП, МОДУЛИРОВАННОМ ВО ВРЕМЕНИ И ПРОСТРАНСТВЕ

П.Т. Чупиков, Д.В. Медведев, И.Н. Онищенко, Б.Д. Панасенко, Ю.В. Прокопенко, С.С. Пушкарев, А.М. Егоров

Экспериментально исследована предложенная Хижняком и др. концепция использования коллективных электромагнитных полей пространственного заряда в сильноточном РЭП, модулированном во времени и пространстве. Наличие виртуального катода и плазменного источника позволили промодулировать РЭП на частоте 46 МГц и ускорить ионы C^+ до 500 кэВ. Во второй секции, состоящей из 9 переменных периодов магнитного поля, эти ионы ускорялись до энергии 1.5 МэВ при токе 1 А.

ПРИСКОРЕННЯ ІОНІВ В СИЛЬНОСТРУМОВОМУ РЕП, МОДУЛЬОВАНОМУ В ЧАСІ ТА ПРОСТОРІ

П.Т. Чупіков, Д.В. Мєдвєдєв, І.М. Онищенко, Б.Д. Панасенко, Ю.В. Прокопенко, С.С. Пушкарьов, О.М. Єгоров

Експериментально досліджена запропонована Хижняком і інш. концепція використання колективних електромагнітних полів просторового заряду в сильнострумовому РЕП, модульованому в часі та просторі.

Наявність віртуального катоду та плазмового джерела дозволили промодулювати РЕП на частоті 46 МГц і прискорити іони C^+ до 500 кеВ. В другій секції, що складається із 9 змінних періодів магнітного поля, ці іони досягали енергії 1.5 МеВ при струмі 1 А.