ACCELERATION OF IONS IN A HIGH-CURRENT RELATIVISTIC ELECTRON BEAM AT EXTERNAL INJECTION OF PLASMA

P.T. CHUPIKOV, N.P. DIKIJ, D.V. MEDVEDEV, I.N. ONISHCHENKO, YU.V. PROKOPENKO, S.S. PUSHKAREV

National Scientific Center "Kharkiv Institute of Physics and Technology"
(1, Academichna Str., Kharkiv 61108, Ukraine; e-mail: onish@kipt.kharkov.ua)

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Collective acceleration of ions and low-frequency modulation of a high-current relativistic electron beam (REB) at the plasma injection into the virtual cathode region has been studied experimentally. Ions were accelerated in the electrical field of an evolutional virtual cathode. A REB current modulation needed for the excitation of a space charge wave and the further acceleration of ions is caused by the periodic compensation of the virtual cathode field by plasma ions.

1. Introduction

Among several proposals of advanced methods of acceleration of charged particles, the concept [1] of using the high-gradient electric fields of a space charge excited in plasma or in a high-current REB is widely developed. Relating to the collective acceleration of ions in the field of a virtual cathode and a space charge wave originated in the high-current REB, a lot of theoretical and experimental investigations is overviewed in [2]. In particular, the important results on the ions acceleration have been obtained in the so-called Luce diode [3]. The current of a produced REB was above the limiting vacuum current in a drift tube, so a virtual cathode was formed there. The supplier of ions was plasma which was originated during the interaction of REB with a polyethylene insert in the central part of the anode. In modified Luce diode, a plasma anode is successfully used [4].

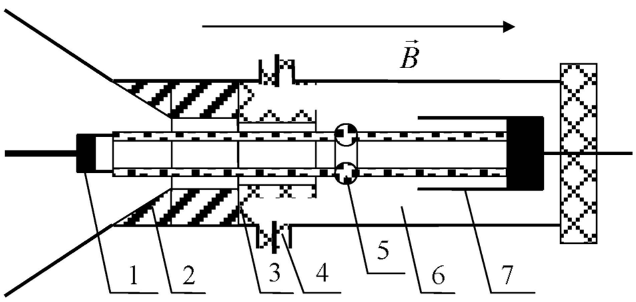

Fig. 1. Scheme of the ion accelerator; *1* – cathode; *2* – anode; *3*– dielectric insert; *4* – plasma guns; *5* – virtual cathode of REB; *6* – drift tube; *7* – Faraday cup

Contrary to the mentioned scheme of ion acceleration, in the present experimental work, first, the needed place of virtual cathode formation was predetermined by inserting an electrodynamics' peculiarity in the drift tube, and, second, plasma was injected from outside by 4 plasma guns into the virtual cathode region. Such a scheme allows controlling the virtual cathode formation, plasma parameters, and ions species. The measurements of the number and the energy of accelerated ions, the low-frequency spectrum, and the depth of temporal modulation were performed.

2. Experimental Setup

The experimental setup is based on a pulsed electron accelerator "Agat" using a Marx generator and a magnetically insulated diode which is capable to produce a high-current REB with an energy up to 280 keV, a current of 4.4 kA, and a pulse duration of 0.8 μsec. In Fig. 1, the scheme of a collective ion accelerator is shown, in which the source of ions is a plasma anode, and ions are accelerated by the electrostatic field of a space charge of the virtual cathode. The plasma anode is formed by a

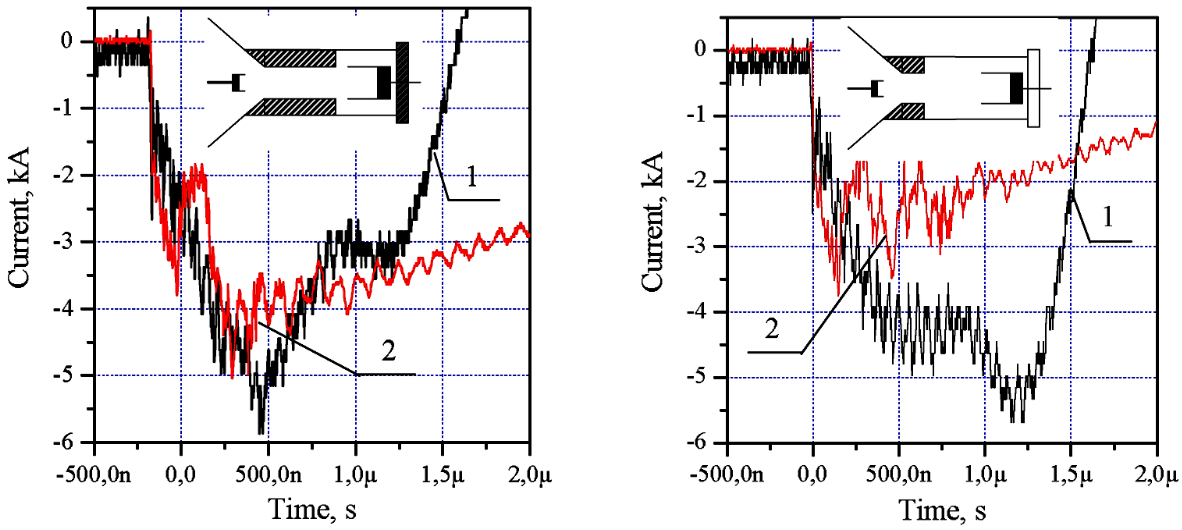

Fig. 2. Current oscillograms: *1* – input REB current; *2* – REB current on a Faraday cup; *a* – tube with a diameter of 41 mm; *b* – tube with diameter jump from 41 to 50 mm

synchronous operation of four plasma guns *4* of the Bostick type with plexiglas surface electric breakdown. The guns are placed azimuthally in the same plane on the periphery of cylindrical drift tube *6* near the place, where the diameter sharply increases and the virtual cathode is formed. To achieve the needed annular plasma configuration, the initial radial motion of neutral plasma from guns is changed by dielectric insert *3* placed in the region of plasma injection. Dielectric insert *3* forms a drift channel of neutral external plasma of the corresponding diameter specifying the direction of its motion along the force lines of an external magnetic field B.

In the absence of dielectric insert *3*, external plasma radially moving to the axis of the drift tube forms a planar plasma anode in the region between cathode *1* and virtual cathode *5*. In this case, the maximum collector REB current registered by Faraday cup *7* coincided with the maximum value of the diode current. This means that, at the transport of REB in the drift chamber with plasma, the virtual cathode did not appear.

The application of dielectric insert *3* has allowed to form the near-wall plasma anode by means of the radial injection of plasma. By changing the longitudinal size of the insert, the different operational regimes of the virtual cathode were realized. In experiments with a lengthy dielectric insert *3*, a pulse of the collector current on a Faraday cup corresponded exactly to the pulse of REB under the accelerator operation without an external plasma source. When insert *3* was shorter, the peak, whose amplitude was equal to the maximum value of the diode current, was observed on a collector current pulse. This fact allowed one to make a conclusion that, for this short time, the virtual cathode has disappeared.

3. Governing of Virtual Cathode Place

The conditions for the virtual cathode formation in the magnetically insulated diode were studied using the smooth cylindrical structure with a diameter of 41 mm (Fig. 2,*a*) and the structure with a diameter jump from 41 to 50 mm (Fig. 2,*b*). In the first case, the input REB current is lower than the limiting vacuum current, and, in the second case, it is above the limiting vacuum current corresponding to a larger diameter. In Fig. 2, the oscillograms of the REB current injected into a drift tube and the REB current on a Faraday cup are shown.

As seen from Fig. 2,*a*, in the first case, the REB current injected from the cylindrical cathode with a diameter of 31 mm and the emissive edge width of 0.1 mm is transported in the homogeneous constant magnetic field with an induction of 0.88 T practically without losses to the collector placed at the end of the drift tube. In the electrodynamics' structure with a diameter jump, the REB current on the collector is much less than the diode input current and corresponds to the limiting vacuum current in the drift tube with a diameter of 50 mm (Fig. 2,*b*). This proves the possibility to govern the place of the virtual cathode formation by means of a jump of the structure diameter.

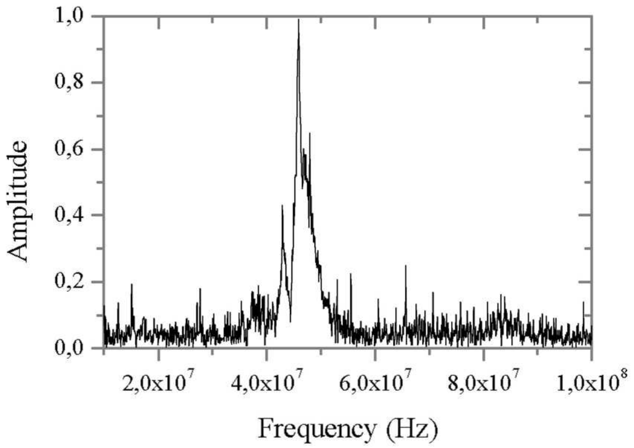

Fig. 3. Spectrum function of the low-frequency modulation of the REB current at the external plasma injection

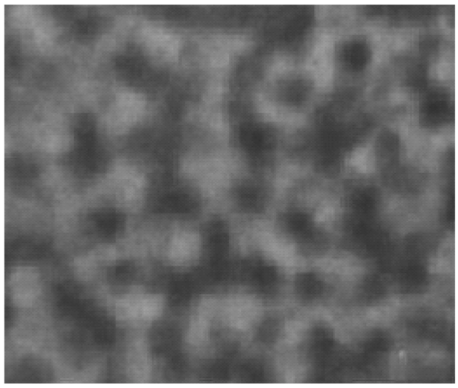

Fig. 4. Caverns on a cellulose nitrate target after the bombardment by heavy ions

4. Low Frequency Modulation of REB Current

The theoretical study [5] of the dynamic evolution of a virtual cathode in the presence of the outer injection of plasma has revealed two phenomena – the low frequency temporal modulation of the REB current and the plasma ions acceleration. It was explained by the periodically repeated compensation of the virtual cathode space charge by plasma ions and the virtual cathode restoring, when ions fly away by inertia. It should be noted that the low frequency temporal modulation of the REB current is one of the main constituents of the advanced method of charge particle acceleration [6, 7], in which the temporal and consequent spatial modulations of the REB current generate an intense space charge wave with high-gradient accelerating electric field. Accelerated plasma ions serve both the ion source and the injector. In our experiment, both mentioned physical phenomena are observed.

The time delay between pulses of the plasma gun current and the diode current are chosen so that the injection of REB into the drift tube corresponds to the instant of maximal plasma density arrival. The REB current modulation was determined from the current signal on a Faraday cup and from the X-radiation of relativistic electrons at their bombardment of a stainless steel target. An X-ray sensor [8] consisted of a polystyrene scintillator with a displaying time of (2.2±0.2) ns and a photomultiplier with a time resolution of 1.5 ns. The active units of the sensor were protected with lead. The signal from the sensor was registered by an oscillograph. When decreasing the dielectric insert length, the low frequency REB modulation was observed. In Fig. 3, the spectrum function of the REB current modulation at the outer plasma injection is shown. The modulation frequency was 46 MHz. At that, the maximum modulation depth was 10 %.

5. Ions Acceleration

The direct observations of accelerated heavy ions were made by using a track detector based on cellulose nitrate. In Fig. 4, the portrait of the ion flow that was observed by means of a microscope with the magnification factor of 970 is shown. The etching time of the detector had the duration of 2 min in a 10-% NaOH solution at a temperature of 60^{o}C. Accelerated protons were registered by using the nuclear reaction ^{11}B(p,α)^{8}Be with the observation of α-particles by a track detector.

To determine the kinetic energy of ions which were accelerated by the space charge field of a virtual cathode, we have used a magnetic analyzer, a time-of-flight analyzer, and the nuclear-physical method based on the nuclear reaction ^{11}B(p,α)^{8}Be with the detection of α-particles.

The magnetic reflecting system has the following parameters: the magnetic induction of 0.144 T; the length of the region of a homogeneous magnetic field was 40 mm; and the distance from the magnetic field to the screen was 40 cm. The detector made of cellulose nitrate was used as a screen. The width of a slot of the diaphragm was equal to 1 mm. For one-charge ions of carbon C^+, the deflection was (6.08±0.82) mm. Using these values, the calculated ion energy was (0.54±0.06) MeV. It is worth to note that this ion energy exceeds the energy (210±30) keV, which can be gained in the virtual cathode field. This evidences that the acceleration is caused not only by the potential well

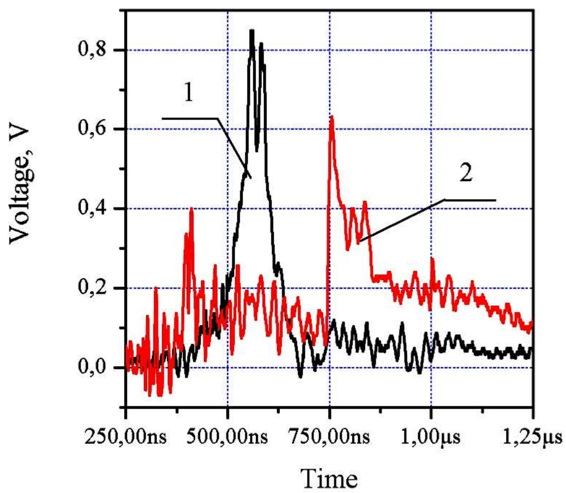

Fig. 5. Signals from the first (curve *1*) and the second (curve *2*) grid probes in time-of-flight measurements

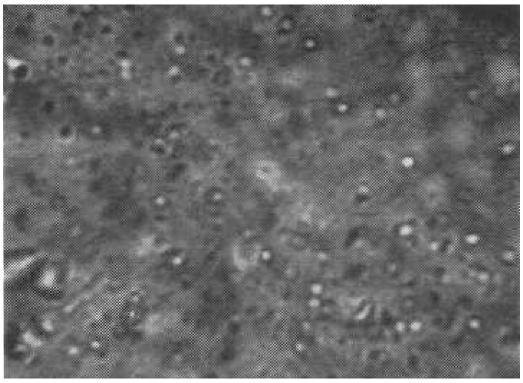

Fig. 6. Tracks of α-particles created in the reaction ^{11}B(p,α_1)^{8}Be in a mylar film of 10 μm in thickness

created by the space charge of the virtual cathode, but also by the dynamical behavior of the virtual cathode (its movement forward and the potential well oscillation in accordance to the theory [5]).

The scheme of time-of-flight measurements included two grid probes with cells of 0.8×0.8 mm^2 placed at the distance L=50 cm in the drift tube. At the exit of the accelerating section, REB was removed to the walls of the drift tube before the placement of the first probe. The signals from two probes were registered with an oscillograph and are shown in Fig. 5.

The velocity of ions was determined from the time delay between signals of two grid probes that are placed in space at a distance L. In our experiments, the time delay between pulses had the value within 180-200 ns that, for a distance between grids equal to 50 cm, corresponded to an ion velocity of 2.5×10^8 cm/s. Therefore, if the ions are one-charged ions of carbon C$^+$ (because plasma was produced by evaporating and ionizing plexiglas), they had an energy within 490 keV, i.e. in agreement with the energy of ions measured by a magnetic analyzer.

The estimations of the ion density $n_i = I_i/q_i S_{\rm col}\sqrt{2E_i/m_i}$ in a flow of ions with the charge q_i and mass m_i at the exit of the collective ion accelerator were based on the measurements of the ion energy E_i by a magnetic analyzer and the time-of-flight diagnostics and ion current I_i registered by a Faraday cup with the collector area $S_{\rm col}$. At that, electrons and protons were deflected by an additional transversal magnetic field. The fluence of ions $N/S_{\rm col}$ that have reached the collector was determined by the relation $N/S_{\rm col} = I_i\tau/q_i S_{\rm col}$, where N is the total number of ions; τ is the duration of an ion pulse on the half-level of the power. In addition, the fluence of ions was also determined by the direct counting of the tracks after the ions bombardment of the track detector.

In the Table, we show the results of studies of the flow of one-charged carbon ions C$^+$ accelerated by the space charge field of the virtual cathode.

Thus, on the output of the accelerator of ions, the flow of one-charged carbon ions C$^+$accelerated by the space charge field of the virtual cathode up to energies about 490 keV with a density of 6.3×10^6 cm^{-3}was formed. The fluence of ions on the collector during the ion pulse was within (5.1÷7.2)×10^7 particles/cm^2.

Nuclear-physical diagnostics in our experiment consisted in the irradiation of a target B$_4$C by protons accelerated in the dynamic virtual cathode field. In Fig. 6, we show the tracks in a mylar film of 10 μm in thickness, which were produced by α-particles created in the nuclear reaction ^{11}B(p,α)^{8}Be.

It is seen from Fig. 6 that the tracks of α-particles have almost the same diameter. This evidences the

Parameters of the flow of accelerated heavy ions

Energy, KeV	Current, mA	Pulse duration (3 dB level), ns	Collector diameter, mm	Density, cm^{-3}	Fluence, particles/cm^2	
					Calculated (from Faraday cup current)	Counted (from track detector)
490	160	50	30	6.3×10^6	7.2×10^7	5.6×10^7

monoenergeticity of α-particles. That is, the only one resonance corresponding to 162.8 keV takes participation in this nuclear reaction. The measured diameters of the tracks of α-particles were in the range 6–7 μm, and the density of tracks was $3{\cdot}10^4$tracks/cm^2, being a result of the target bombardment by 10^{13} protons per pulse. It is much more than the fluence of heavy ions and corresponds to a current of accelerated protons of 30 A at a pulse duration of 50 ns.

6. Conclusions

We have experimentally demonstrated the possibility to accelerate ions by the collective field of the space charge of the virtual cathode of a pulsed intense REB. The source of ions was plasma injected from external plasma guns into the virtual cathode region. For a tubular REB with an energy of 280 keV, current of 4.4 kA, pulse duration of 0.8 μs, diameter of 32 mm, and thickness of 2 mm, which was injected into the drift tube with a diameter jump from 41 to 50 mm, the 30-A ion current with a pulse duration of 50 nsec and an energy of ions of (0.54$\pm$0.06) MeV was obtained.

Simultaneously, due to the processes of periodic compensation of the virtual cathode space charge and the subsequent restoration of the virtual cathode, we have obtained the low-frequency modulation of a REB current. This important phenomenon can provide the creation of an intense traveling wave of space charge in REB [6] for the further high-gradient acceleration of ions. For this purpose, the REB current should be periodically modulated in space, e.g. by using a spatial periodic magnetic field [7].

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ПРИСКОРЕННЯ ІОНІВ В СИЛЬНОСТРУМОВОМУ РЕП ПРИ ЗОВНІШНІЙ ІНЖЕКЦІЇ ПЛАЗМИ

П.Т. Чупіков, М.П. Дикий, Д.В. Медведев, І.М. Оніщенко, Ю.В. Прокопенко, С.С. Пушкарьов

Резюме

Експериментально досліджено колективне прискорення іонів і низькочастотну модуляцію сильнострумового релятивістського електронного пучка (РЕП) при інжекції плазми в область віртуального катода. Іони прискорюються в електричному полі еволюційного віртуального катода. Модуляція РЕП, необхідна для збудження хвиль просторового заряду та подальшого прискорення іонів, створюється періодичною компенсацією поля віртуального катода іонами плазми.