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Generation of high-power submillisecond metal ion beams

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The possibility of using one grid electrode in the form of a part of a sphere for extraction from a free plasma boundary and focusing of metal ions is shown for the first time using titanium ions as an example to form a pulsed beam with a duration of 500 μs and a power density reaching 10^5 W/cm^2. The results of studying the influence of the amplitude of the accelerating voltage in the range of 9−30 kV and the size of the grid cells on the efficiency of space charge neutralization and ion beam focusing are presented.

Keywords: metal ions, vacuum arc plasma, submillisecond beams, high power density.

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Charged particle beams and plasma flows are being used more and more widely to modify the properties of various materials and coatings. Pulsed energy processing of the surface of solids holds a special place among ion-plasma material treatment techniques. Nano- and microsecond electron [1–3], ion [4], and laser [5] beams with a high power density modify various metals and alloys owing to extremely high rates of heating and subsequent cooling of near-surface layers to a depth ranging from several micrometers to several tens of micrometers. Ion implantation is an alternative method of beam modification of metals and alloys [6,7]. The study of features and trends of modification of metal and alloy properties under common ion implantation demonstrated that its practical applicability is limited. The primary limitation stems from the smallness of the projective range of ions (and, consequently, the insignificant thickness of an ion-implanted layer).

New methods of high-intensity implantation with ion beams of a low energy and high power density have been developed in recent years. These methods were found to provide ion implantation to a depth of several tens of micrometers under an ion irradiation fluence of $10^{19}-10^{21}$ ion/cm^2 [8]. In certain promising applications, the advantages of high-intensity low-energy ion implantation, which penetrates deep under the surface of a material, are offset by heating of the entire sample to high temperatures that have an adverse effect on the material microstructure.

The method proposed in [9] is aimed at preserving the advantages of high-intensity low-energy ion implantation while obviating the high-temperature degradation of microstructure of an irradiated target. It essentially consists in the use of ion beams of a microsecond or submillisecond duration with a power density ranging from several tens to several hundred kilowatts per square centimeter in high-intensity implantation. Pulse-periodic implantation with such ion beams provides pulsed heating of a local region near the surface with subsequent rapid transfer of heat deeper into the target material. This helps achieve a high temperature in the ion-implanted layer while limiting the heating effect in the bulk of the irradiated material. A high temperature in the near-surface layer coupled with a high ion current density facilitate radiation-enhanced diffusion of implanted atoms that is needed to achieve ion implantation at depths exceeding considerably the projective range of ions.

Continuous vacuum arc discharge plasma appears promising for application in sources of metal ions generating beams of a high pulse and mean power. The authors of [10] were the first to produce low-energy ion beams of a high pulse and mean power using vacuum arc discharge plasma with plasma-immersion extraction of ions and their subsequent ballistic focusing by a one-grid spherical electrode with a rejection system for the microdroplet fraction and pulse-periodic filling of the beam drift space with plasma for space charge neutralization. The feasibility of generation of pulse-periodic ion beams with a pulse duration of 2–8 μs at a rate of 10^5 imp/s with an ion current density up to 1 A/cm^2 under negative bias potentials up to 3 kV in amplitude was demonstrated. Negative effects associated with the formation of a virtual anode in experiments with a pulse duration increased to 30 μs were suppressed successfully with the use of an additional thermionic electron source [11].

Below we report the results of an experimental study into the feasibility and certain patterns of generation of pulse-periodic beams of titanium ions of a submillisecond duration from vacuum arc plasma with a power density up to 100 kW/cm^2.

A complex for ion-beam and ion-plasma treatment of materials was used in this study. Pulse and pulse-periodic beams of titanium ions were shaped using a modified „Raduga 5"ion and plasma source [12]. The plasma flow was produced by a continuous vacuum arc discharge with an arc current of 160 A. A „solar eclipse"system, which was tested successfully in [10,13], was used instead of a shutter-type plasma filter to remove the microdroplet fraction from plasma.

A system for extraction of ions from a free plasma boundary and their focusing by a single grid electrode in the form of a part of a sphere 120 mm in radius with an equipotential space for ion beam transport and focusing have been used for the first time to shape an ion beam with a high pulse power density. The diagram of the experiment is shown in Fig. 1. Classical ion sources (including those based on pulse or continuous vacuum arc plasma) often utilize a three-electrode system, which prevents the penetration of plasma electrons from the beam drift space into the accelerating gap, to prevent overloading of a pulse voltage generator. In the present study, we examine the feasibility of shaping of a high-power long-duration beam of titanium ions by a one-grid electrode. Three grid electrodes with the following cell sizes were used in experiments: 0.5, 1, and 1.4 mm. A disk electrode, which prevented direct propagation of vacuum arc discharge macroparticles from the working cathode surface to the beam focusing region, was aligned with the center of the focusing electrode. Ion extraction was performed under an anode bias potential of 9–30 kV.

Figure 2 illustrates the results of examination of the influence of accelerating voltage on the distribution of ion current density over the beam cross section for a grid electrode with a cell size of 0.5 mm. The maximum ion current density achieved at an anode (and, consequently, plasma) potential amplitude of 9 kV is about 2.75 A/cm^2. The distribution of current density over the cross section turned out to be rather narrow. When the voltage was raised further to 16 kV, the maximum current density increased to 3.25 A/cm^2. This was accompanied by a slight broadening of the distribution of current density over the beam cross section. A further increase in the accelerating voltage led to a reduction in the maximum ion current density at the beam center.

In the course of extraction of ions and their injection into the drift space, efficient neutralization of the beam charge is initially performed by vacuum arc plasma pre-injected into the drift space. The neutralization time is specified by the removal of plasma ions from the beam. Just as in the case of shaping of high-intensity low-energy metal ion beams [11], this time does not exceed several microseconds. At the first stage, the density of ions, which were accelerated in the charge separation layer, entering the drift space is almost an order of magnitude lower than the density of electrons in plasma. This ensures a fine degree of neutralization of the ion beam charge both near the grid electrode and at a considerable distance from it in the drift space (under the condition of focusing with a proportional increase in the ion density). However, when the charge separation layer (within which ions are accelerated) forms near the grid electrode, the inflow of plasma supplying electrons to the drift space ceases. In the case of shaping of long pulses, the production of electrons is sustained primarily by ion-electron emission from structural elements of the beam shaping system, generation of plasma via ionization of residual atmosphere atoms, or additional injection of electrons from the thermionic emitter into the ion beam drift space.

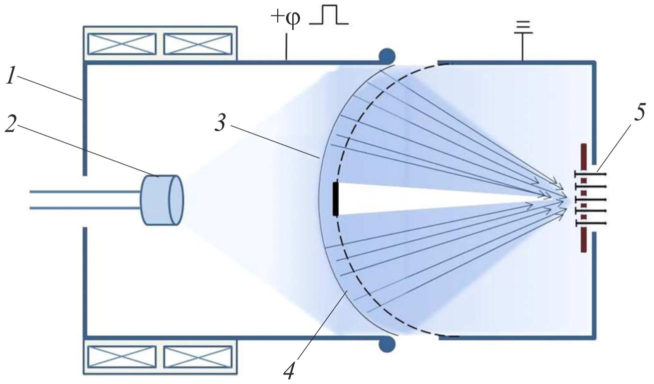

Figure 1. Diagram of the experiment. *1* — Anode, *2* — cathode, *3* — ion-emission boundary of plasma, *4* — charge separation layer, *5* — collectors of a sectioned Faraday cylinder.

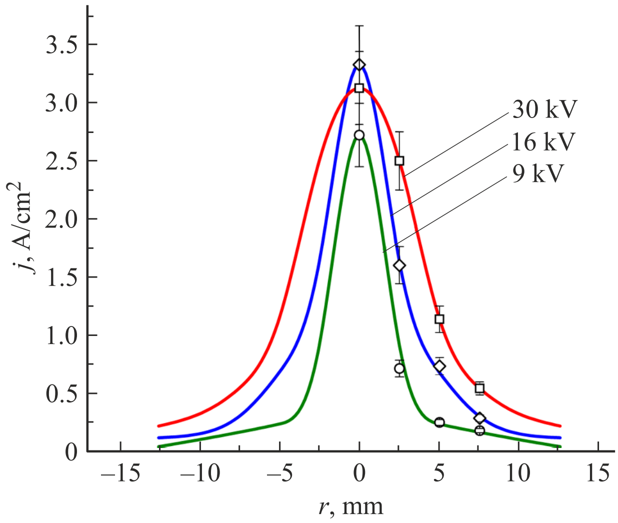

Figure 2. Distributions of ion current density over the beam cross section for a shaping system with a grid electrode with a cell size of 0.5 mm at a continuous arc discharge current of 160 A under an accelerating voltage of 9–30 kV.

Five collectors with an area of $2 \times 2\,mm^2$ spaced 2.5 mm apart were used to examine the distribution of ion current density in the focal plane. Signals from three collectors and the accelerating voltage sensor were fed simultaneously to a four-beam oscilloscope.

Oscilloscope records illustrating the variation of current densities at three collectors (one of them was mounted at the center, and the other two were located at distances of 2.5 and 5 mm from the system axis) revealed that the current density under an accelerating voltage of 16 kV remains roughly the same with insignificant modulation within the duration of a pulse (Fig. 3, *a*). This modulation became slightly more pronounced at an increased accelerating voltage of 25 kV (see Fig. 3, *b*). The current

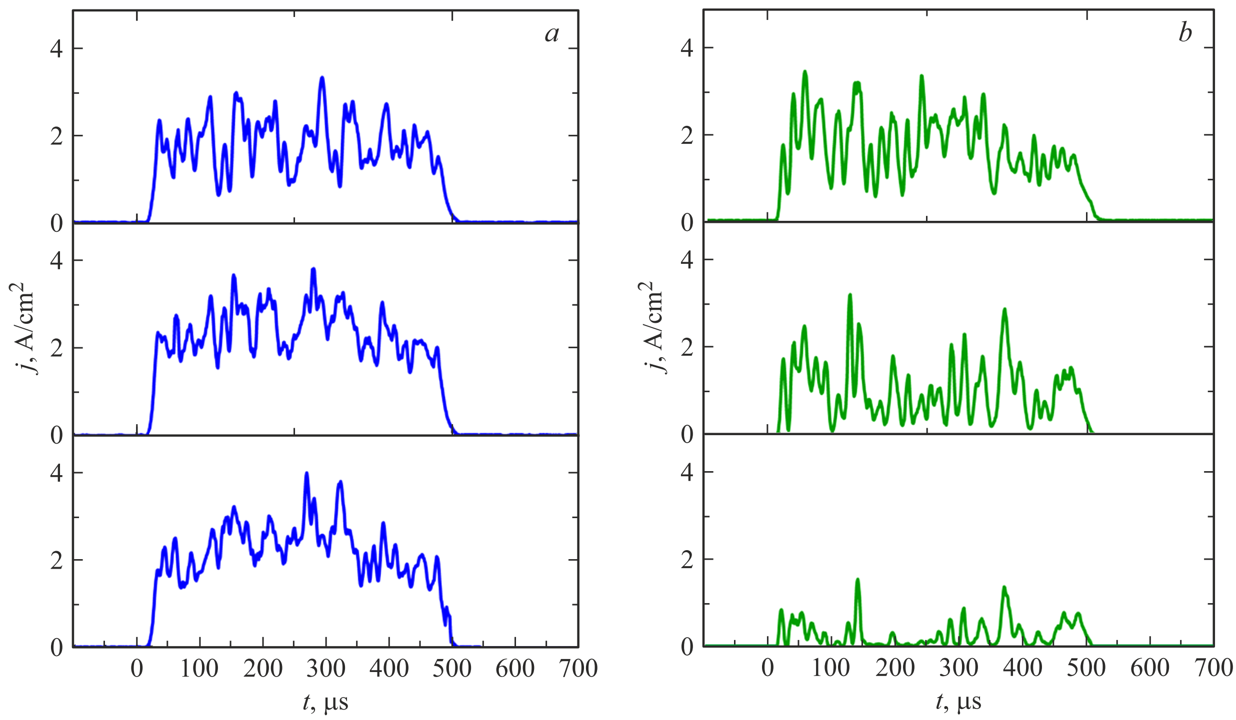

Figure 3. Oscilloscope records of the ion current density at collectors at the beam center for an accelerating voltage amplitude of 16 (*a*) and 25 kV (*b*).

density at the central collector decreased dramatically in this case. A considerable reduction in the current density was also observed at the second collector. These variations of the distribution of ion current density over the beam cross section with increasing accelerating voltage may be attributed to a reduction in the efficiency of neutralization of the beam space charge. In its initial state, the beam focusing and transport system is an equipotential space. The grid electrode violates the equipotentiality condition of the drift space and allows electrons to escape into the accelerating gap. The electric field of the accelerating gap penetrates into the drift space through grid cells and extracts electrodes, thus exerting an adverse influence on neutralization of the beam space charge. As the accelerating voltage amplitude increases, the process of electron escape from the drift space intensifies; the quality of focusing deteriorates under the influence of the intrinsic ion charge, and the distribution of current over the beam cross section indicates that a solid beam transforms into a hollow one. A less efficient neutralization of the beam space charge is also the likely cause of reduction of the maximum ion current density observed at an increased accelerating voltage of 0,5 kV for a grid electrode with a grid cell size of 0.5 mm (Fig. 2).

A similar pattern was noted in shaping of a high-intensity ion beam by a grid electrode with a radius of 65 mm and a grid cell size of 1.4 mm. Under an accelerating voltage of 5 kV, the current pulses at collectors had a current density maximum at the center with an amplitude up to 0.7 A/cm^2. When the accelerating voltage amplitude increased to 25 kV, the ion current density dropped almost to zero, while the oscilloscope records for the second and the third off-axis collectors displayed current densities up to 0.25 A/cm^2 with periodic modulation to zero throughout the entire pulse duration. Beam modulation may be induced by the periodic formation of a virtual anode.

Thus, it was demonstrated that a continuous vacuum arc discharge with a current up to 160 A combined with an axially symmetric focusing system in the form of a grid electrode have the capacity to shape pulsed beams of titanium ions with a submillisecond pulse duration and a power density as high as 100 kW/cm^2 at accelerating voltages up to 30 kV. It was found that the grid electrode structure has a significant effect on the processes of space charge neutralization and, consequently, on ballistic focusing of a high-power ion beam.

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Conflict of interest

The authors declare that they have no conflict of interest.

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