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Influence of magnetic field induction on the energy of ions and injection processes of ionized flows of working substances in a plasma mass separator

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Abstract. The concept of plasma mass separation of substances in a configuration with a potential well implies the development of specialized plasma sources. The conversion of condensed matter into a low-temperature plasma flow and its further injection into the separation chamber is a crucial stage that largely determines the efficiency of the technological process. It is especially important if the aim of the concept is the separation of spent nuclear fuel (SNF). The energy distribution of charged particles at the starting point determines the trajectories of the separated elements in crossed E×B fields. In real experiments on the separation of substances, it is possible to use a plasma source in a fairly wide range of magnetic induction values up to 1400 G. In this paper, we present the results of studying the energy distributions of ions behind the anode plasma of a non-self-sustained arc discharge with a hot LaB_6 cathode and independent lead vapor injection.

Keywords: plasma separation, plasma sources, low-temperature plasma flow, energy distribution, multigrid probe, plasma jet.

1. Introduction

The concept of plasma mass separation is a promising method of processing materials [1]. The method is based on the conversion of a mixture of elements into a low-temperature plasma flow and their further separation in crossed E×B fields formed in plasma. Within the framework of this approach, the trajectory is determined by the charge-to-mass ratio at other equal parameters. The development of this concept and its main stages imply the need to conduct research in such areas as the conversion of matter into a plasma flow with certain parameters [2, 3], the formation of an electric field in the plasma (plasma environment is needed for volume charge compensation) [4], the collection of separated substances and the study of the mechanisms of deposition during particle energies up to 100 eV. One of the possible schemes for implementing this method is plasma separation with a potential well and injection of the working substance along magnetic field lines [5].

One of the primary factors that influences the efficiency of the concept is the initial dynamic characteristics of the particles. Thus, the energy distribution of the separated elements and the direction of injection significantly affect the scale of separation [6, 7]. When the flow is injected across the magnetic field lines, the energy distribution of charged particles directly affects the separation efficiency. Injection along the magnetic field lines makes it possible to avoid dependence on this distribution, but leads to the appearance of additional requirements on the value of the average energy and the energy distribution of charged particles.

So, the value of the average energy actually determines the size of the separation chamber along the axis of symmetry of the installation and establishes the efficiency of deposition. Within the framework of the concept with a potential well, in the first approximation, there are no axial forces acting on the separated particles.

The main purpose of this work is to study the energy distribution of plasma ions of working substances and to obtain its dependence on the magnetic field induction. At this stage, a non-self-sustained arc discharge with a hot cathode and independent injection of working substance vapors into the discharge gap is used as a plasma source. A multigrid analyzer was used as a diagnostic method [8]. This method has been repeatedly tested and all the mechanisms and sources of errors and the apparatus function are sufficiently studied [9].

2. The concept of plasma mass separation with a potential well

A schematic diagram of a plasma mass separator with a potential well is shown in Fig.1. Key elements: a plasma source, a background discharge for space charge compensation and a potential distribution formation system (end electrodes that initiate a reflex discharge), a substrate for collecting substances. As can be seen from the above diagram, there are no forces acting on the charged parts and changing their trajectories along the Z axis. That is why the coordinates of the substrate placement and its dimensions along the Z axis depend from the energy distribution of particles and the average energy value.

Spent nuclear fuel (SNF) is a possible mixture of substances which separation is nowadays relevant [10]. Silver and lead are used as model substances, which simulate the light and heavy components of SNF, respectively. The characteristic time scale of separation at a value of a radial electric field of 15 V/cm and a magnetic field induction of 1400 G for Pb is 44 μs (the time of flight to the substrate for Ag is 30 μs), which, taking into account the geometric factors of the setup, will make it possible to carry out separation with particles up to an energy of 100 eV.

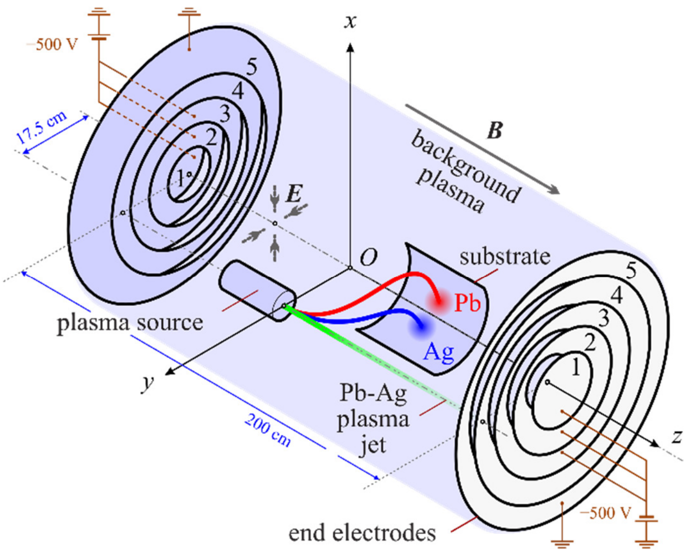

Fig.1. Scheme of the plasma mass separator.

It should be noted that plasma separation with a potential well and injection of working substances along magnetic field lines is possible at different values of the radial electric and axial magnetic fields [6]. This leads to the relevance of the study of energy distributions at relatively low values of magnetic induction (up to 150 G). The operation of the installation at low values of magnetic induction can in principle significantly reduce energy costs for the processing of materials.

3. Experimental setup

3.1. Plasma source

Fig.2 shows a scheme of the created plasma source device. The mixture of working substances is placed in a molybdenum crucible. The crucible is heated up to 1000–1450 °C by the induction method. The substance in the form of vapor enters the discharge gap and is ionized. The generated plasma penetrates into the separation chamber along the magnetic field lines through the cavity in the anode.

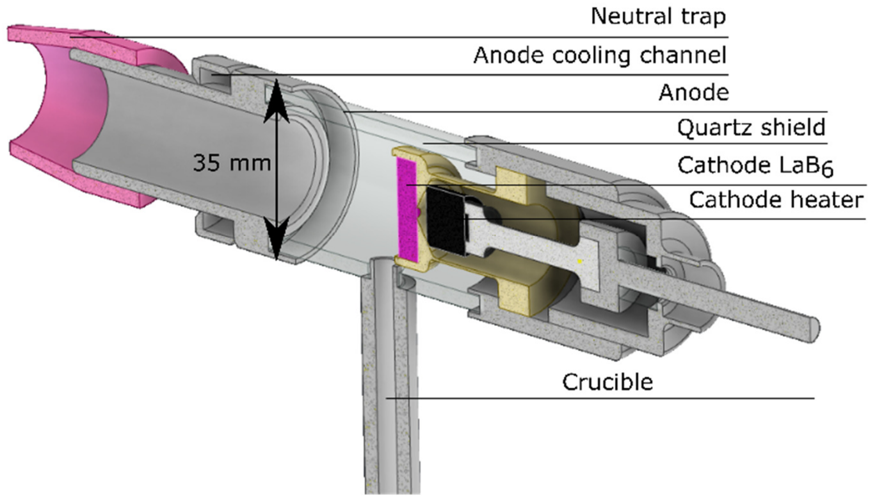

Fig.2. Scheme of the plasma source of model substances.

The diagnostics of the source parameters was carried out by the following methods: a double Langmuir probe for determining the plasma density, a single flat probe 40 mm in diameter for measuring the saturation current of ions in a plasma jet with a diameter of 20 mm, a multigrid analyzer for studying the energy distribution of ions, spectral diagnostics of optical radiation to control the plasma composition in flow during experiments on the separation of the mixture. The ion saturation current of a single flat probe placed at the output of the source characterizes the performance of the plasma source. At this stage, a productivity rate of 20 g/h was obtained, which corresponds to an ion current of 2.6 A at a discharge current of 120 A. With these parameters, the current-voltage characteristic is growing. The plasma concentration at the outlet of the source is about 10^{12} cm^{-3}. The main parameters of the plasma source during operation are shown in Table 1.

Table 1. Operating parameters of the plasma source

Parameter name	Value
Magnetic field induction	0–1400 G
Ion saturation current	2.6 A
Productivity rate (Pb)	20 g/h
Discharge current	120 A
Hot cathode	LaB_6 (~314 mm^2)
Crucible temperature	up to 1500 °C
Electron density (behind the anode)	~10^{12} cm^{-3}
Working substances	lead, silver

3.2. Experimental scheme and multigrid probe

On the current stage only lead plasma flow was studied. During experiments, a multigrid analyzer was installed along the path of plasma jet propagation coaxially to the axis of symmetry of the electrode system of the plasma source. Fig.3 shows the schematic diagram of the experiment. Within the framework of these studies, a scheme with two grids and a collector was used. Macor® acted as an insulator. The first grid and the body of the probe have ground potential, as well as the cathode of the plasma source. The main task of the input grid is to minimize the influence of the second (reflective grid) on the plasma jet. Reflective mesh potential is –100 V. A sawtooth analyzing signal with an amplitude of up to 110 V was applied to the collector. It should be noted that this approach makes it possible to measure the total energy, i.e. the sum of kinetic and potential energy relative to the ground potential. Discharge current of the plasma source in the experiment was 30 A at a potential difference of about 13 V, while the value of the saturation ion current in the region behind the anode was at the level of 400 mA.

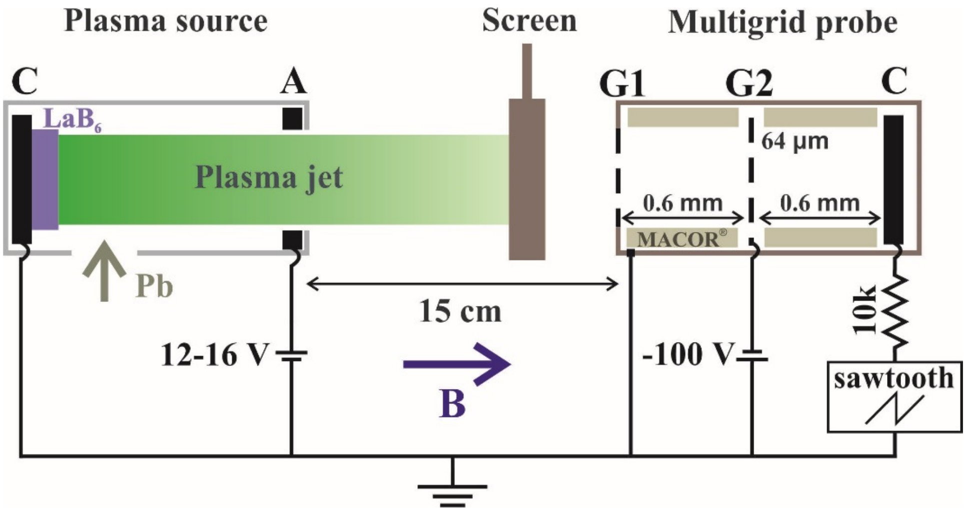

Fig.3. Scheme of the experiment.

4. Results and discussion

Typical energy spectra (the sum of kinetic and potential energies) at different magnetic field inductions are shown in Fig.4. Similar results of ion current measurement by the collector are shown in Fig.5. The most probable total particle energy takes values of 12–18 eV at FWHM from 6–9 eV.

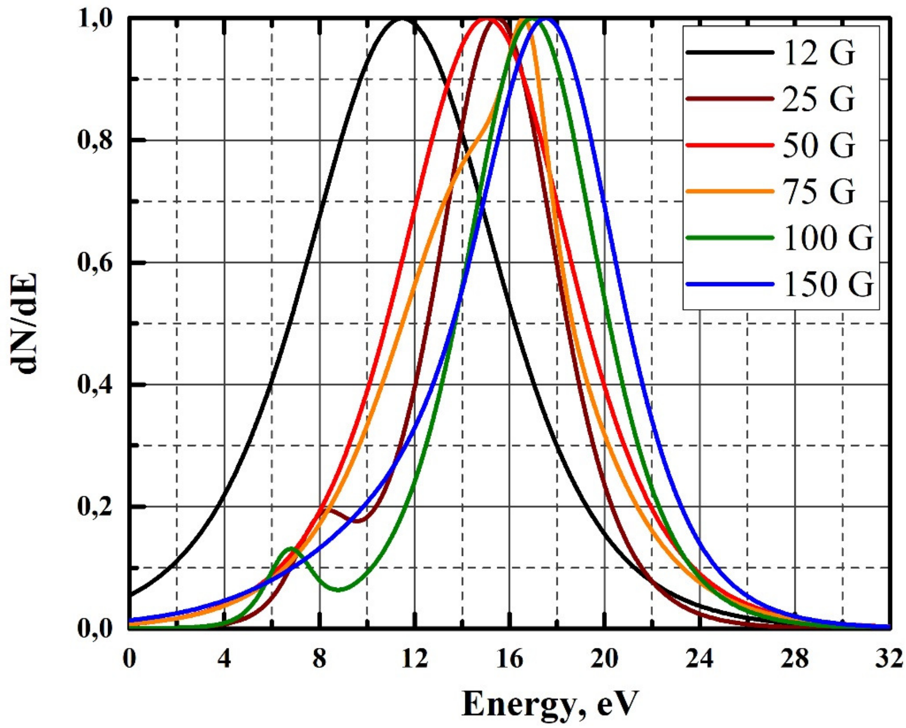

Fig.4. Dependence of the energy distribution of lead ions in a plasma jet on the magnetic field induction.

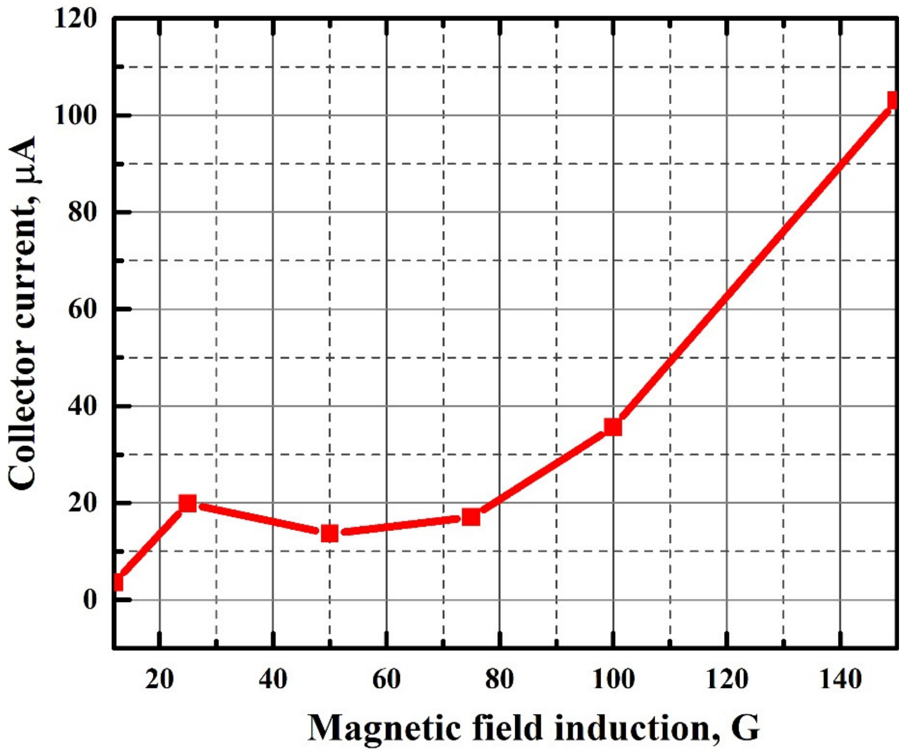

Fig.5. Dependence of the collector current of a multigrid analyzer on the magnetic field induction.

As can be seen from the presented data, an increase in the magnetic field induction leads to an insignificant increase in the most probable total particle energy and an increase in the collector current. These effects can be explained by the following hypothesis. An increase in the total energy occurs due to an increase in the potential energy, which depends on the plasma potential in the vicinity of the probe. An increase in the magnetization effect leads to focusing of the plasma jet, which leads to an increase in the collector current and a change in the plasma potential along the plasma flow propagation axis.

It should be noted that to test this hypothesis, additional studies of the potential distribution of the propagating plasma along the Z axis in the region behind the anode by the thermionic probe method are required [11].

5. Conclusion

The paper presents the results of measuring of the energy distributions of lead ions in a low-temperature plasma flow of a non-self-sustained arc discharge in a magnetic field. The most probable total particle energy takes values of 12–18 eV at FWHM from 6–9 eV. These results will be used to analyze the efficiency of extraction of ions from a plasma jet by a radial electric field and to refine the trajectories of particle motion in the separation chamber.

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5. References

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