Unbalance magnetron plasma source for ion mass-separator

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Abstract. The report presents the results of the preliminary studies characteristics of an unbalanced magnetron plasma source supplied with the transport system based on a curved magnetic field. The aim of these studies was to recognize if the system is suitable, in principle, for mass-separation of a multi-component plasma flow. The magnetron source has 50 mm diameter cathode manufactured of an alloy composed of Cu (64%), Pb (22.5%) and admixtures, about of 14% (Al, Zn, C). By means of an immersion time-of-flight spectrometer, a spatial distribution of ions of the cathode material was measured through the system output cross-section. Distribution of atom of these elements was measured here by the X-ray fluorescence spectrometry as well. Both methods showed that the ions of the lighter element (Cu) were concentrated in the inner part of the plasma flow deflected by the magnetic field while the distribution of the heavy element (Pb) was shifted toward the outer area of the flow. The similar effect was observed for each couple of the elements. Such a system is promising for use in plasma technology of reprocessing spent nuclear fuel, namely for separation heavy radioactive fission product from nuclear waste.

1. Introduction
Plasma techniques have long been used for various applications in nuclear researches. In particular, a few types of rotating magnetized plasmas are a convenient way to separate particles by mass. Namely, a concept of centrifugal confinement produced a set of the circular electrodes in a magnetized rotating plasma was proposed in paper [1]. Concept of a filter to separate particles of different mass using rotating plasma with both centrifugal and magnetic confinement was examined in paper [2].

The mass-separators mentioned above are based on magnetic system with straight field lines. Nevertheless, mass-separation effects from centrifugal force may be anticipated when a plasma flows along curved magnetic field lines. Various electro-magnetic guiding structure designs based on curved magnetic fields, for instance, are used frequently as filters to remove macroparticles from cathodic vacuum arc plasma jet. Recently, the present authors have suggested using a vacuum arc supplied with a transport system based on the curved magnetic field for mass separation a multi-component cathodic plasma flow [3,4].

It is interesting to perform the similar measurements with a plasma flow produced with a magnetron source because the source produces an intensive and stable plasma flow. The objective of the study is to find out whether it is possible to use such a system as an element of a technological system for plasma reprocessing of atomic industry waste [5].
2. Experimental details

2.1. Experimental setup

Experiments were carried out using a modified device similar to that described in [3,4], where the vacuum arc plasma source was substituted with a magnetron source. The schematic of the device is shown in figure 1. The discharge burned at the surface of 50 mm diameter and 4 mm thickness target as a cathode, the rear end of which was cooled with water. The target was made of a composite material consisting of light and heavy components, specifically, alloy of Cu ($m_{\text{Cu}} = 64$ amu) and Pb ($m_{\text{Pb}} = 204$ amu) with mass abundances of 64% and 22%, respectively, and the admixture (C –7%, Al, Zn – each about of 2%). The low-current (100 mA, 500 V) duty magnetron discharge was sustained with a dc power supply. To ensure the high ionisation degree in the plasma flow, a high power impulse magnetron sputtering (HiPIMS) was used [6]. The main pulsed discharge was initiated by means of application to the cathode a high voltage (~1500 V) pulse from a capacitor of 100 μF so that the discharge current length was of 3.5 ms and the average discharge current was about of 20 A. The grounded vacuum vessel was as an anode. The vessel was evacuated down to a residual pressure not

![Figure 1. Schematic diagram of the experimental setup. The setup is in the horizontal plane and is viewed from above. 1 – 5 are solenoids of the magnetic transport system; $z_s = 11$ cm, $x_{s1} = 15$ cm, $x_{s1} = 18$ cm, $x_{m1} = 24$ cm, $x_{p1} = 17$ cm and $x_{p2} = 28$ cm; inset B depicts the enhanced map of magnetic field line near the cathode, inset C depicts the probes holder and inset E depicts the ITOFS positions in the A – A plane.](image)
exceeding of $2 \times 10^{-3}$ Pa and the after that the working gas (Ar) was introduced into the vessel up to about $2 \times 10^{-2}$ Pa pressure, which was held constant. The pulse repetition rate was 10 pps; the current was measured with the Rogovski coil. A flow of metallic plasma was produced from the cathode surface and was guided through the working vessel by a transport system based on a curved magnetic field.

The magnetic field was formed with a set of magnetic solenoids, so that three of them (1, 2, 3 in figure 1) were co-axial to each other, and the co-axis of the other two (4 in the figure) was perpendicular to the axis of the former. In this series of experiments, the standard magnetic system was modified by introducing an additional solenoid 5. The characteristics of the solenoids, namely their inner ($d$) and outer ($D$) diameters and length ($L$), which are depicted in figure 1a, as well as the number of coils ($N$) and the solenoid currents ($I$) are shown in Table 1. Solenoids 1 and 2 were intended for magnetic stabilization of the discharge on the working surface of the cathode. Solenoids 3 and 4 were placed so that their magnetic field affects the structure of the total field in the travelling area of the cathodic plasma flow; hence it helped us to govern the flow magnetically. Solenoids 4 were supplied with currents of equal values but opposite polarity so that their magnetic fields were also oppositely directed. Solenoid 5 was designed to reduce the curvature of lines of the guiding magnetic field, hence to increase the centrifugal force providing the mass-separation effect.

The magnetic field configuration presented in this paper was calculated by a procedure similar to that applied in [3,4] and it was described previously in detail there, hence it is presented here briefly. The configuration was calculated by applying Biot–Savart’s law to an array of current carriers representing the magnetic solenoid coils used in the transport magnetic system. A code to set up the current carrier array and then to trace the magnetic field line is written using MATLAB™. A comparison of the calculated and measured magnetic fields in the reference points shows that they differ by less than 15% from each other. Figures 1 depicts a calculated map of the magnetic field lines at a set of the solenoid currents presented in the Table 1.

Due to the specific design of the device, the cathode axis was shifted relative to the common axis of solenoids 1–3 by $\Delta z = 30$ mm (see figure 1). As a result, the magnetic field lines passing through the cathode surface were deflected in the +Z direction. In the A–A plane, where the parameters of the cathode flow were measured, the field lines were directed almost perpendicular to their initial direction. The plasma flow propagating along the field lines was deflected in a similar manner. In this magnetic configuration, the field strength varies substantially as the plasma propagates from the cathode to the measurement area. The maximum field strength in the vicinity of the cathode was about 70 mT, and it drops with distance from the cathode so that in the A–A plane it was 2–3 mT.

To establish the effect of the magnetic field on the plasma components, take into account that the electron temperature in the magnetron plasma was of about 2 eV and the plasma density estimated from the Langmuir probes measurements was of the order of $10^{12}$ cm$^{-3}$. From these data one may estimate the electron Hall parameter in the plasma flow: $\omega_B \tau_{ei} >> 1$, where $\omega_B = eB/m = 10^{10} \times 3 \times 10^8$ c$^{-1}$ is the electron cyclotron frequency and $\tau_{ei} \approx 10^{-8}$ c is the electron-ion collision time. The similar estimation for ions shows that $\omega_B \tau_{ei} << 1$. Hence, a conclusion may be drawn that the plasma electrons

| $D$ (mm) | $d$ (mm) | $L$ (mm) | $n$ | $I$ (A) |
|---------|---------|---------|-----|--------|
| 1       | 240     | 180     | 85  | 1570   | 1.05  |
| 2       | 240     | 180     | 55  | 1100   | 1.05  |
| 3       | 240     | 180     | 55  | 1100   | 2.0   |
| 4       | 145     | 65      | 110 | 1270   | 1.4   |
| 5       | 240     | 180     | 220 | 1050   | 0.72  |
in the transport system are magnetized and the plasma ions are non-magnetized. This implies that the travel of a plasma flow through the system is governed by varying the magnetic field by the solenoids.

2.2. Langmuir probe measurements
We used a set of Langmuir probes as a diagnostic technique. The set consisted of eight identical pieces biased by −50V that provided operation of the probes in the ion current saturation mode. The probes were intended for measurement of the ion saturation current profile throughout the horizontal diameter of cross-section A–A of the plasma flow. For this purpose the probes were inserted at a holder, where they were spaced 15mm from each other and the holder was located as shown in figure 1. The probe had a tungsten wire of 10 mm length and 1mm diameter. The probe data were acquired by a computer. Shape of the probe signals were near the same as that of the discharge current (see figure 2), and the figure 3 presents the profile of probe ion currents across the horizontal diameter of the plasma flow cross-section on the A–A plane. One can see that there a maximum at the probes 4 and 5 is observed that corresponds to 21 – 24 cm distance from the Z-axis and the current decreases sharply at the plasma flow area approaching the rear vacuum chamber wall.

2.3. Mass spectrometer measurements
We used an immersion time-of-flight spectrometer (ITOFS) for measurement of the plasma flow mass composition at exit of the magnetic transport system. The detailed description of the spectrometer is presented in [7] and we describe it briefly. The plasma flow components are separated in the gap between the entrance grid and grid on the drift tube (see inset E in figure 1). These fine grids have a 100 μm mesh size that is close to the plasma Debye length; hence we suppose that the ion-electron separation occurs in the inter-grid gap. A high-voltage (-800 V) pulse of rectangular shape and 200 ns duration was applied to the drift tube that formed an ion bunch at the tube entrance. This bunch travelled through the tube and when passing the tube, the ions were separated by the time of flight \( \tau \) in accordance with parameter \( m/Z \). Thus, for ions of \( m_1 \) and \( m_2 \) masses and \( Z_1 \) and \( Z_2 \) charge states, the relation is valid as follows,

\[
\frac{\tau_1}{\tau_2} = \left( \frac{m_1 Z_2}{m_2 Z_1} \right)^{1/2}.
\]

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**Figure 2.** Wave forms of the discharge current (top trace) and voltage (bottom trace). Empty arrows point the instance of the mass-spectra and the Langmuir probe ion current measurements

**Figure 3.** Profile of probe ion currents at the instance \( t_0 \) across the horizontal diameter of the plasma flow cross-section on the A–A plane
After travelling the drift tube, the ions passed through the exit grid and were captured with the collector.

Figure 4 presents the ITOFS collector signals obtained at positions $x_{m1}$ and $x_{m2}$ on the A–A plane, depicted in figure 1, at the instant $t_0$, pointed in figure 2. One can see from figure 4 that the plasma flow ion compositions differ significantly in these positions. Namely, there are observed a few peaks corresponding to the main plasma component, $Cu^{+}$ and $Cu^{++}$ ions, as well as to the light ions $Ar^{+}$ ($m_{Ar} = 40$ amu) in position $x_{m1}$. As the ITOFS is displaced to position $x_{m2}$, then the $Cu^{++}$ and $Ar^{+}$ ion peaks disappear and a peak corresponding to the $Pb^{+}$ ions appears.

2.4. Measurements of ion component distributions in the plasma flow with X-ray fluorescence spectrometry

The separating characteristics of the magnetic transport system were determined from the distribution of the cathode material components in the A–A plane. To do this, a series of seven identical collectors fixed in a holder was placed in the A–A plane so that the holder was parallel to the X-axis (see figure 1) and placed in the plane XZ. The collectors were spaced by distances of 2 cm from one another along the X axis. Collector no. 1 was placed at a distance of 27 cm from the Z-axis, while collector no. 7 was placed at a distance of 15 cm from this axis. The collectors were 12 mm diameter polished discs from Ti foil faced the plasma jet. The collector surface was cleaned in a glow discharge and then irradiated by the plasma jet for 30 min. As a result, a metal film consisting of the elements of the cathode material formed on the surface of the collectors.
The elemental composition of the film was studied by means of electron probe X-ray spectrum analysis by using a JXA 8200 microanalyzer and an EX-84055MU energy dispersive spectrometer (JEOL Ltd., Japan). X-ray emission was generated by an electron beam with a 1 × 1 μm cross section and contains radiation of the elements of the cathode material (Cu, Pb and admixtures), as well as the substrate material (Ti) and gas admixtures (O₂, C, N₂). The data were used to determine the relative mass content of elements in the film as functions of the collector number, i.e., the collector position in the A–A cross section of the cathode jet.

The obtained distributions of the mass content ratios are shown in figure 5. It can be seen that the ratios of the heavy to light elements depend on the collector position. The ratios decreases with the collector number increases, i.e. as position of the collector is displaced towards the internal area of the curved plasma flow. This trend was observed both for the main components, Pb and Cu, and for admixtures as well (see figure 5). Thus, after the cathode jet has passed through the magnetic transport system, its components turn out to be spatially separated along the curvature radius of the jet.

3. Discussion and conclusions
First, note that as figure 4 shows, the working gas (Ar) is found in a minor amount only in the inner area of the curved plasma flow. Obviously, that is due to the low pressure of the working gas, and a conclusion may be drawn, as well, that the magnetron, in fact, operates in a HiPIMS mode. Furthermore, it is seen from the figure that a presence of a small amount of the Cu⁺⁺ ions is found only in the inner area of the flow. This finding implies that an electric field arises in the plasma flow that is due to the separation of magnetized electrons “attached” to the magnetic field lines and ions, which mainly follow the direction of the curvilinear magnetic field because of the relatively strong charge separation electric field. This field directed to the centre of curvature of the bent flow and it strongly affects the Cu⁺⁺ ions. The authors observed recently the similar effect in the curved plasma jet produced with a vacuum arc plasma source [8].

Finally, the results presented in figure 5 show that a significant enrichment of the outer area of the plasma flow with the massive ions is observed for any couple of the elements consisting the cathode material. This effect, obviously, is due to influence of the centrifugal force on the ions.

Thus, a conclusion may be drawn that the presented device, in principle, is promised as an ion mass-separator for any applications. For instance, it can be used in the plasma technology of reprocessing spent nuclear fuel, namely for separating heavy radioactive fission product from nuclear waste.

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