Ion Transport from Laser Induced Metal Plasma to Ion Extraction Electrodes

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Ion transport from a laser-induced metal plasma in a vapor to a cathode surface has been investigated experimentally using conventional parallel plate electrodes and a new conceptual electrode system, which consists of an anode and two cathodes, designated as “M-type electrodes”. Rapid ion transport is possible using the M-type electrodes compared with the parallel plate electrodes and there are two modes of ion transport. One is a mode similar to that seen for parallel plate electrodes, in which the bulk plasma upstreams with a velocity of 1,160 m/s during the ion extraction. The other is a special mode for the M-type electrodes, in which the plasma upstream stops at its origin and ions are transported to the parallel cathodes from both sides of the plasma.

KEYWORDS: ion transport, lasers, cathodes, anodes, ion extraction, metal plasma, mode, electrodes, electrode system

I. INTRODUCTION

In the last ten years, the atomic vapor laser isotope separation (AVLIS) technology has developed rapidly. In the AVLIS system, uranium metal (U) is evaporated in an electron beam evaporator. The $^{235}$U isotope can be separated by selectively collecting laser-ionized $^{236}$U$^+$ from a uranium vapor using an electrostatic field. Since this method has a large separation factor in principle, numerous efforts have been made to develop a commercial plant\textsuperscript{(1)-(4)}. Recent developments, especially regarding a pulse laser system with tunable dye lasers driven by copper vapor lasers of high power and high repetition frequency, are leading up to realization of a commercial plant for nuclear fuel\textsuperscript{(5)}.

A commercial plant requires an effective isotope extraction system. Ion density should be on the order of $10^{16}$ m$^{-3}$ with column size of about 0.05×0.05×2 m$^3$. Under these conditions, isotope ions and electrons undergo collective movement after their birth due to Coulomb force between particles, i.e. they act as a plasma. Therefore, investigations of the plasma behavior can give key information needed to develop an ion extraction system for a commercial plant.

Numerous experimental\textsuperscript{(6)-(12)}, theoretical\textsuperscript{(11)-(13)} and computational\textsuperscript{(14)-(16)} investigations have addressed the problem of an effective isotope extraction system. In ion extraction, the plasma is surrounded by biased electrodes, then ions are collected on the electrode surface of lower potential (cathode surface). In a commercial plant with conventional parallel plate electrodes, the ion extraction is mainly determined by ion diffusion from the bulk plasma to the sheath front because of a strong shielding effect of the plasma to potentials applied to the electrodes. The shielding effect results

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from formation of an ion sheath between the bulk plasma and the cathode. During the ion extractions, some actions take place as time passes, such as plasma rise with a velocity equal to that of the vapor, plasma expansion and plasma density decay due to ion diffusion by an ambipolar effect, and penetration of the ion sheath into the bulk plasma (7).

Rapid ion extraction provides the most desirable performance of the extraction system because of following two demands. One is to minimize loss of ions due to: (1) resonant charge exchange reaction between isotope ions and undesired neutrals, (2) ion diffusion to the electrode of higher potential (anode), and (3) outward loss of ions from interspace of the electrodes by the ion diffusion and the rising motion of bulk plasma. The second is to prevent deposition of undesired neutrals on the cathode surface by minimizing height of the electrodes, which height is mainly determined by the rise distance of the bulk plasma during the ion extraction.

Parallel plate electrodes are commonly used for an ion extraction systems (see Fig. 1(a)). This electrode system is suitable for investigation of the plasma behavior, because its configuration is simple, so that the plasma behavior can be recognized as one-dimensional motion in the horizontal direction for vertically infinite electrodes. Therefore, most previous works used this system (6)-(8)-(11)-(16). However, in this system, ion loss to the anode surface is very large due to large surface area facing the bulk plasma. The ion extraction time is also very long. To avoid these disadvantages, Tetsuka & Yamada have proposed new conceptual electrodes in 1990, which consisted of grounded parallel plate electrodes with a positively biased upper plate electrode (see Fig. 1(b) and (c)). These electrode systems are designated as “II-type electrodes” and “M-type electrodes” due to resemblance in their cross-sectional shapes to the letters “II” and “M”. Performance of the II-type electrodes has been reported (9). This system has improved the ion extraction time up to a factor of about 2.6 in comparison with the parallel plate electrodes. However, more advanced simulation technology (17) indicated that the applied potential to the electrodes was not effectively used to extract ions from the plasma, because a large distance between the anode and the plasma provides a lower potential difference between the plasma and the cathode (see Fig. 1(b)).

Ogura et al. (10) have also proposed a similar electrode system to the M-type electrodes and showed its effectiveness to improve the ion extraction time. They used a wire anode instead of the vertical plate anode of the M-type electrodes. However, a wire electrode would be mechanically weak under a hot condition (above 1,000 K) in a commercial plant, where the electrodes are attacked by chemically active uranium melt. Moreover, too small anode surface area compared with that of the cathode would lead to thick electron sheath formation between the bulk plasma and the anode, reducing the plasma potential (18).

When ions are transported from the bulk plasma to electrodes, ions move perpendicular to equipotential lines around the plasma. Then, ion transport in the M-type electrodes is somewhat more two-dimensional than that in the conventional parallel plate electrodes, as indicated from the equipotential lines shown in Fig. 1. We installed a set of the M-type (parallel plate) electrodes in a large-scale electron beam evaporator. A series of ion extraction experiments was performed and ion transport paths in these electrodes are discussed by comparing initial position of the plasma and distribution of collected ions on the cathode surface. Ion transport regimes are also pigeonholed by normalized plasma density \( \rho_0 \) and ion extraction time \( \tau \) (18).
II. EXPERIMENTAL ARRANGEMENT

Figure 2 shows a schematic diagram of the experimental setup. Optical system consists of a 0.8 J XeCl excimer laser, a pulsed dye laser and optics. The excimer laser light (308 nm) with a 30 ns pulse width is split into two paths. One is used to pump the pulsed dye laser providing a tuned 502.86 nm of 0.8 mJ laser light. The 308 and 502.86 nm laser lights are expanded and combined. This ionizing laser light is collimated by a slit with an aperture of 50×50 or 30×30 mm² so as to obtain a fairly uniform intensity distribution prior to entering the vacuum chamber.

Figure 3 shows a schematic inside the evaporator. The evaporator consists of a vacuum chamber, an electrode system, a box shaped carbon vapor shield, a copper crucible and an electron beam gun. The electron beam gun is a 180° bent-beam transverse type with a 140 kW (50 kV, 2.8 A) electric power source. The cross section of the beam on the evaporation surface is 2×150 mm². The electron beam power is 80~140 kW to allow vapor density changes. A weak magnetic field of 40~50 Gauss is impressed over the whole vacuum chamber to deflect the electron beam. The residual gas pressure is almost constant, 3~4×10⁻⁵ Pa, before and after the beam irradiation due to sufficient preheating of the target.

A desired vapor passes through the carbon vapor shield and the water-cooled copper collimator, which limits heat radiation from the evaporating surface. Between the collimators, which are grounded, electrodes to remove a vapor plasma are installed, their potential is maintained at −3 kV in all experiments. The vapor plasma and high-energy back-scattered electrons in the vapor, generated by an irradiation of the electron beam on the target, are removed.

The electrode system is schematically shown in Fig. 4(a) and (b). The vapor streams into the interspace of the electrodes and then is photo-ionized by the laser light. The cross section of the plasma is 50×50 or 30×30 mm², determined by the aperture. The gap of the two cathodes is set to 40 or 60 mm, depending on the plasma size, to fix the distance between the bulk plasma at birth and the cathode surface at 5 mm. The plasma-anode distance is less than 2 mm. In experiments using the parallel plate electrodes, the center electrode is removed. The cathode and anode configurations are defined by Fig. 4(c). The anode is grounded and the cathode is biased to a minus potential (0/~ system) throughout.
The vapor density was monitored by an EIES (Electron Impact Emission Spectroscopy, Leybold Inficon: Sentinel III). The density of the photo-ionized plasma was determined with a probe by comparing the density of the vapor plasma\(^{(29)}\). Collected ion distribution on the cathode surface was measured by seven Faraday cups (FC1~FC7), which were vertically installed on the back of the electrode center. They were biased to \(-1\) kV. Ion current of a FC was converted into voltage by a resistor of 10 kΩ, and this signal was picked up by an isolation amplifier (NF: 5323) and recorded in a hard disk of a work station (HP: 9000/300) through a 12 bit A/D converter (HP: 5183A). Between FCs and the electrode, a molybdenum mesh grid (ϕ: 0.05 mm, 50 mesh/inch) biased to \(-1.05\) kV was set to return secondary electrons to FCs. Number of incoming ions was conserved in a wave form of the FC’s ion current, so an integration of the wave form could give the amount of ions to provide a distribution of collected ions on the cathode surface. Currents of each electrode were measured by current probes (Sony-Tektronix: A6302+AM503) and recorded. An example of a set of current wave forms is shown in Fig. 5. The ion extraction time is defined as a time between birth of the plasma and time when the cathode ion current becomes zero.

A series of ion extraction experiments was performed using the parallel plate electrodes and the M-type electrodes. The experimental conditions are summarized in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Experimental conditions</th>
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<tr>
<td>Electron beam power</td>
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<tr>
<td>Type of electrodes</td>
</tr>
<tr>
<td>Height of ion extraction</td>
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<tr>
<td>Plasma size</td>
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<tr>
<td>Electrode gap</td>
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<td>Vapor density</td>
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<td>FC potential</td>
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<td>Grid potential</td>
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<td>Vapor plasma removal</td>
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† The anode is grounded (0) and the cathode is biased to a minus (−) potential.

### III. RESULTS AND DISCUSSION

#### 1. Regime of Ion Transport

When an electric field is applied to a low density plasma and the ion density is too low to shield the potential, the plasma cannot maintain its charge neutrality and disappears. Under this condition, ion extraction is determined by motion of individual ions driven by the electric field. Single particle kinetics can be used to describe the behavior. When the plasma density is very high, the potential difference between the anode and the cathode is shielded by a thin ion sheath compared with the size of the bulk plasma. In this
situation, the ion extraction is determined by ion diffusion from the bulk plasma to the sheath front. The ion transport regime relates these ion transport conditions, which depend on ion mass, applied potential to the electrode, electron temperature, plasma size etc.\cite{11} Okano\cite{12} has classified these ion transport regimes in simple forms using normalized parameters. They are $\xi$, $\kappa$, $\gamma$, $\delta$, $\alpha$, ion extraction time $\tau$, and plasma density $\rho$, which are expressed as:

\begin{align*}
\xi &= \frac{4}{3} \left( \frac{2}{eM} \right)^{1/2} e_0, \\
\kappa &= \left( \frac{4\sqrt{\pi} e_0}{9e} \right)^{1/2}, \\
\gamma &= \left( \frac{e}{M} \right)^{1/2}, \\
\delta &= T / \phi, \\
\alpha &= a / d, \\
\rho &= \frac{\rho}{\kappa \phi^{1/2} n}, \\
\tau &= \frac{\gamma T^{1/2}}{d \tau},
\end{align*}

where $e$: Electronic charge \\
$M$: Ion mass \\
e_0: Dielectric constant in vacuum \\
d: $a$ (vacuum gap, 5 mm) + $b$ (plasma thickness, 30 or 50 mm) \\
$T$: Electron temperature (0.1 eV) \\
n: Plasma density \\
$\tau$: Time ($t=0$ at birth of plasma) \\
\phi: Ion extraction voltage between the anode and the cathode.

The $\xi$, $\kappa$, and $\gamma$ are fixed parameters in this study with values of $6.6 \times 10^{18}$, 5,894, and 637. All values are expressed in MKSA units except for $T$ (eV).

As discussed by Yamada et al.\cite{8,9} and Okano\cite{12}, initial conditions of the plasma and the electrodes, especially dimensions of plasma and electrodes, plasma density and ion extraction voltage, determine the ion extraction process. Therefore, to specify the effects of the initial condition, $\rho_0$ is defined as $\rho$ at the birth of the plasma to classify the ion extraction process.

Regimes of ion transport can be classified into four using $\rho_0$. At $\rho_0 \ll \rho_i$, ions are transported by a single particle kinetic (SPK) regime, because space charge of ions is too small to shield the applied electric field. Here, $\rho_i$ is given as

$$\rho_i = \frac{9 \sqrt{2}}{4} \left( \frac{1}{1-\alpha} \right)^{d/12}. \quad (8)$$

When $\rho_i < \rho_0 < 1$ is satisfied, the ion transport is mainly determined by penetration of the ion sheath into the bulk plasma. This is called the Child-Langmuir (CL) regime. For $\rho_i > 1$, ion diffusion from the bulk plasma to the sheath edge mainly governs the ion transport. This regime is further classified into the quasi-Bohm (QB) regime at $1 < \rho_0 < \alpha^{-2}$, and the Bohm (B) regime at $\rho_0 > \alpha^{-2}$.

The results of experiments are summarized in a $\rho_0$-$\tau$ diagram as shown in Fig. 6. Scaling relations obtained by Okano\cite{12} and Yamada et al.\cite{9} for the parallel plate electrodes and the II-type electrodes, respectively, are also plotted in this figure. All results are pigeonholed into the CL regime or QB regime. At $\rho_0 = 1 \sim 2$, the scaling formula shown by the solid line has a shoulder. This is because approximations used to derive the scaling formula break down for $\rho_0 \approx 1$. Appearance of the shoulder has no physical meaning\cite{12}. However, this scaling gives nearly the same values even at $\rho_0 = 1 \sim 2$ with other computer simulation codes\cite{21}. Okano's scaling describes

![Fig. 6 $\rho_0$-$\tau$ diagram for parallel plate, II-type, and M-type electrodes](image-url)
our results gotten with the parallel plate electrodes well.

This diagram shows that the M-type electrodes can make the quickest ion extraction among these three types of electrodes. The results of the M-type electrodes are shifted down from the scaling relation. However, ρ−τ characteristics of the M-type electrodes are roughly parallel to those of the parallel plate electrodes. This means that the ion extraction behavior in the M-type electrodes can be estimated roughly with the simple one-dimensional consideration. We estimated τ for the M-type electrodes by Okano's scaling relation with a half plasma width, because the anode-cathode distance is just half of the parallel electrodes, e.g. b=25mm for the plasma cross section of 50×50mm². The results are plotted in the diagram by open circles. Relations between the original experimental data and the open circles are indicated by arrows. Each open circle shifts almost horizontally to the left from its original location. Physically, this shift to the left means that penetration of the ion sheath into the bulk plasma becomes stronger, i.e. the strong electric field on the shoulder part of the plasma plays an important role in the ion transport. This electric field is two times stronger than that of the parallel plate electrodes. Obviously, this strong electric field reduces the ion extraction time of the M-type electrodes compared with that of the parallel plate electrodes.

2. Ion Transport in the Parallel Plate Electrodes

Distributions of collected ions on the cathode surface for the parallel plate electrodes are shown in Fig. 7. Experiments were carried out at a constant plasma density of 1×10¹⁶ m⁻³. Depending on δ, the QB regime and the CL regime are seen. As δ increases, i.e. τ decreases, the ion distribution spreads to the upper part of the cathode.

The ion transport in the parallel plate electrodes is simulated by a two-dimensional plasma fluid code LASER[16]. The conditions of Fig. 7(a) were used as the simulation parameters. The results are shown in Fig. 8.

Figure 8(a) shows the initial equipotential lines. An ion sheath can be seen between the bulk plasma and the cathode. Since ions move perpendicular to the equipotential lines, ions are transported to the cathode from three sides of the square plasma. With time, the plasma region spreads upward and downward due to ion diffusion. The penetration of the ion sheath into the plasma region and the plasma upstream are reproduced. As shown in Fig. 8(c), later in the ion extraction, the equipotential lines become almost parallel to the electrodes, so that a more one-dimensional ion transport can be expected compared with the initial plasma condition. The simulation results are consistent with the measured ion distributions shown in Fig. 7 and the previous findings[7].

3. Ion Transport in M-type Plate Electrodes

Ion extraction experiments were carried out with conditions at the plasma density of
1 \times 10^{14} \text{ m}^{-3} \) and the plasma cross section of 50 \times 50 \text{ mm}^2 by changing the applied potential from 1 to 5 \text{kV}. The results are summarized in Figs. 9-12. Initial position of the plasma in the electrodes is shown on the right side of Fig. 12.

**Figure 9** shows wave forms of FC ion currents, where three phenomena can be seen. One is that the ion currents of the upper FCs, e.g. FC1\textendash}FC3, disappear as \( \delta \) decreases. The second is that the time, at which a peak of the wave form is seen, appears in order at \( \delta = 1 \times 10^{-4} \), but almost immediately at \( \delta = 2 \times 10^{-5} \). The third is that the FC ion currents of the lower FCs, FC5\textendash}FC7, increase as \( \delta \) decreases.

By assuming that the peak of the wave form in Fig. 9(a) appears when FC meets the densest part of the rising plasma\(^{(7)}\), we could estimate a rising velocity of the bulk plasma by measuring the time delay between the peaks. **Figure 10** shows the results and the drift velocity of 1,160 m/s is gotten. This velocity is reasonable for the bulk plasma upstream, because its drift velocity is equal to that of the vapor and the measured 1,160 m/s is close to the measured drift velocity of the vapor\(^{(21)}\).

As \( \delta \) decreases, *i.e.* the ion extraction voltage increases, the time delay between the peak points decreases. Time delay between the peak point of FC5 ion current and that of FC4 is shown in **Fig. 11**. A step-like decrease of the delay time can be seen at \( \rho_0 = 2 \). The delay time of 3 \( \mu \text{s} \) at \( \rho_0 = 0.78 \) is shorter than the ion extraction time of about 30 \( \mu \text{s} \) (\( \tau = 0.11 \)). Therefore, all wave forms in Fig. 9(c) indicate change in the density of the bulk plasma. This means that the rise motion of the plasma seen in Fig. 9(a) does not appear in Fig. 9(c).

The distributions of collected ions are shown in **Fig. 12**. At \( \rho_0 = 8.71 \) and 3.08, the ion distributions are wide. This indicates that a part of the plasma rises and enters into the interspace between the anode and the cathode. This interspace has the same conditions as the parallel plate electrodes. Modes of ion transport expected from this experiment are schematically shown in **Fig. 13**. For \( \rho_0 = 8.71 \) and 3.08, the ion transport from the
plasma to the anode is very similar to that of the parallel plate electrodes as shown in Fig. 13(b). Here, this type of ion transport is called the "mode of the Parallel Plate Electrodes (PPE mode)". The M-type electrodes work like the parallel plate electrodes with a stronger electric field. Because of the plasma upstream with a drift velocity over 1,000 m/s, the distribution of collected ions spreads widely, but the ion extraction time is short as shown in Fig. 6 due to the strong electric field.

As shown in Fig. 12(d) and (e), most of ions are collected by FC4~FC6 at $\rho_s=1.09$ and 0.78. During the extraction time of $\tau=0.11$ (30 ms) at $\rho_s=1.09$, the plasma can rise a distance of over 30 mm with a velocity of 1,160 m/s. However, the distributions of collected ions in Fig. 12(d) and (e) do not indicate the plasma rise. The time evolution of the FC ion current in Fig. 9 also does not indicate it. On the other hand, the distributions do show that the plasma exists at the initial position where it originated during the ion extraction. Ions are seen to be transported from this stopped bulk plasma to the cathodes. This ion transport mode is illustrated in Fig. 13(c). This mode is called the "mode of the M-type electrodes (MTE mode)".

In the $\rho_s-\tau$ diagram of Fig. 14, the results, in which the MTE mode is observed, are shown by the solid triangles and those of the PPE mode are shown by the open triangles. The MTE and PPE modes are clearly classified in the diagram. In the region below $\rho_s=1.6$, the MTE mode is observed. This region corresponds to the CL regime. This means that the MTE mode appears when penetration of the ion sheath into the bulk plasma is very strong. This classification is also seen in Fig. 11.
The PPE mode is seen in the region above $\rho_s \approx 1.6$, which corresponds to the QB regime. Therefore, the PPE mode is the mode when ion diffusion governs the ion extraction. In other words, the penetration of the ion sheath into the bulk plasma is weak. In this situation, the plasma density is high enough to shield the applied electric field even it is the strong electric field at the plasma shoulder. If once the plasma flows into the gap between the cathode and the anode, the plasma can keep rising, because the gap condition is the same as that of the parallel plate electrodes.

Distributions of collected ions were measured at a constant applied voltage of 5 kV by changing the plasma density from $1 \times 10^{15}$ to $1 \times 10^{16} \text{ m}^{-3}$. Figure 15 shows the results. The MTE ion transport mode is seen in all cases. At $\rho_s = 0.078$, a peak of the distribution is seen at FC4. At $\rho_s$ increases, $\tau$ also increases. However, the peak point lowers to FC5. These results show that the center of the distribution drops with time.

Faraday cup 4 (FC4) locates beside the shoulder part of the plasma, but the peak of the distribution is at FC4 in Fig. 15(a). While $\tau$ is small as 0.02, this distribution indicates that the plasma rises during the ion extraction. When $\tau$ is 0.10 (Fig. 15(c)), the distribution does not show the plasma rise motion. Therefore, Fig. 15 indicate that this plasma rise stops as $\tau$ becomes longer. In other words, the speed of the plasma upstream decreases with time, and finally the plasma rise stops or is reflected to downstream after an enough time.

The amount of ions, which is transported to the cathodes, is determined by both the ion diffusion from the bulk plasma to the ion sheath and the ion sheath penetration into the bulk plasma. The ion transports at the MTE mode are illustrated in Fig. 16(a)~(c). Figure 16(a) shows the ion transport before the plasma rise stops, which is seen at the initial stage of the ion extraction. The combination of the plasma rise and the strong electric field outside the plasma shoulder allows flow out of the largest ion flux from the plasma shoulder. Additionally, the electric field outside the plasma shoulder is spread widely. This enables a transport of a large amount of ion through the sheath outside the shoulder compared with that through the sheath beside the plasma. Therefore, the penetration of ion sheath into the bulk plasma is strongest at the plasma shoulder. Due to these two mechanisms, when the plasma disappears before the plasma rise stops, most of ions in the plasma are transported through the shoulder part of the plasma. Therefore, the peak of the distribution is seen at FC4.

The ion transport when the plasma rise stops is illustrated in Fig. 16(b). This situation appears at the later stage of the ion extraction. Due to the strong penetration of ion sheath into the bulk plasma at the plasma shoulder, the plasma shape changes from the square pillar to column. This mechanism also can be seen in the ion transport with the parallel plate electrodes (see Fig. 8(b) and (c)). Although the equipotential lines of Fig. 16(b) are rather parallel compared with those in
Fig. 16(a), the electric field in the ion sheath is strongest at the center of the plasma, not at the shoulder or the bottom of the plasma. The penetration of the ion sheath into the bulk plasma is strongest at the plasma center, i.e. at FC5. Moreover, when ions are reflected to downstream, this stream results in that the largest ion flux flows out from the lower side of the plasma (see Fig. 16(c)). Thus, the peak of the distribution can be obtained at FC5 as shown in Fig. 15(c) or Fig. 12(c), (d) and (e). This physical view can explain the measured distributions of collected ions on the cathode surface of the M-type electrodes in the MTE ion transport mode.

The mechanism to stop or reflect the plasma upstream was not clarified in this study. To stop the plasma upstream, an electric field, the direction of which is downward, is required in the plasma region not in the electron and ion sheaths. The electric field strength should be on the order of several hundreds millivolts or several volts per centimeter, because the kinetic energy of the plasma upstream of $1-2\text{ eV}$ must be canceled in the plasma region of a few centimeters' height. Our plasma fluid code LASER, in which magnetic field effects are ignored, can not represent the formation of the retarding electric field (the ion repelling phenomena). However, the one-dimensional three-velocities (1d3v) PIC-MCC plasma simulation code developed by Birdsall(23) can represent it(24), which code treats magnetic field effects. Therefore, the formation of this downward electric field is due to a magnetic field for bending the electron beam. Inapplicable to our case directly due to a different configuration of magnetic field and electrode but very interesting study has been performed by Stangeby et al.(25). He showed that a retarding electric field for drifting ions can be formed in a presheath around an electron sheath. Lower electron diffusivity across a magnetic field compared with that along a magnetic field provides a slight potential gradient in a plasma region to promote an electron collection (to repel ions) in front of an electron sheath. This retarding electric field for ions is formed for over a distance of electron-ion collision length (several tens' centimeters in our case). Therefore, there was a possibility that similar situation occurred in our case. Obviously, the overhead anode of the M-type electrodes plays a key role in the electric field formation. The reason is that the only this overhead anode can give a downward electric field to the plasma, while the configuration of the parallel plate electrodes can make only a horizontal electric field.

IV. CONCLUSIONS

Ion transport from the laser-induced metal plasma to a cathode surface has been investigated experimentally by using conventional parallel plate electrodes and the new conceptual electrode system, which consisted of an anode and two cathodes, the "M-type electrodes".

By a $\rho_0-\tau$ diagram, where $\rho_0$ is the normalized plasma density and $\tau$ is the normalized ion extraction time, we showed that a more rapid ion transport can be achieved by the M-type electrodes compared with the parallel plate electrodes and the II-type electrodes. Two modes of ion transport were found for the M-type electrodes. The first was a mode similar to the ion transport in the parallel plate electrodes, where the bulk plasma upstreamed with a velocity of $1,160\text{ m/s}$ during the ion extraction; this velocity equaled the vapor drift velocity. In this case, the M-type electrodes worked as parallel plate electrodes with a stronger electric field. The plasma density, however, was high enough to shield the applied electric field even if it was the strong electric field at the plasma shoulder. Once the plasma flowed into the gap between the cathode and the anode, the plasma could continue rising because the gap condition was same as that of the parallel plate electrodes. The second was an original mode of the M-type electrodes, where the plasma upstream stopped at the position of its birth and ions were transported beside the plasma. These modes could be classified in the $\rho_0-\tau$ diagram. We showed that the second mode appeared below $\rho_0 \approx 1.6$, where the penetration of the ion sheath into the bulk plasma mainly governed the ion extraction.
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