

Ion collection from Laser-induced Plasma by Applying Radio-frequency Voltage

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Ions were collected on the electrodes from a laser resonance photoionized plasma by applying 1.8MHz radio-frequency voltage to the electrode. It was demonstrated that the ions are collected in a shorter time at the same kinetic energy of the collected ions compared with ion collection by applying DC voltage to the electrode. A simple one-dimensional model was extended for prediction of ion collection times in the cases of applications of not only the DC voltage but also the radio-frequency voltage. The ion collection times estimated using the simple one-dimensional model agreed with experimental values in both cases of DC and radio-frequency voltages.

Keywords: Laser, Resonance Photoionization, Plasma, Ion Collection,
Radio-Frequency, Laser Isotope Separation

1. Introduction

In atomic vapor laser isotope separation (AVLIS), one isotopic species of a chemical element is photoionized by pulse lasers and these ions are extracted by applying an electric fields across a pair of collection electrodes as shown in Fig.1(a). The ions produced constitute a plasma with released electrons and electrostatic fields do not penetrate the plasma. The mechanism of ion extraction from the plasma was made clear in several investigations[1,2,3]. Now we can predict how the ions are extracted and collected by the electrodes[4]. Since efficient laser isotope separation requires a high density atomic vapor, dense plasma is produced. It takes a long time for ions in the high-density plasma to be collected at a fixed voltage applied to the electrode, and many ions flow through the collection electrodes and are not collected. On the other hand, the ions are collected in a shorter time if higher voltage is applied to the positive electrode. The

extracted ions impinge on the collector electrode and sputter the specified atoms which have already collected. The kinetic energy of the impinging ions corresponds to the applied voltage, and self sputtering yield grows with increasing kinetic energy of the impinging ions. Hence, higher potential application causes sputtering of more specified atoms on the collection electrode. Therefore, it is desirable that all ions are collected in a short time with low kinetic energy of the collected ions.

For improvement of ion collection, we tried using a positively biased wire electrode[5] shown in Fig.1(b). With this method, the ions are collected from the laser-induced plasma in a shorter time at the same kinetic energy or at lower kinetic energy in the same collection time compared with the conventional parallel electrode method.

In this paper, we attempted ion collection from laser-induced plasma by applying radio-frequency voltage as shown in Fig. 1(c). In this case, the ions are expected to be collected in a shorter time compared with the parallel electrode method because the ions are collected by both collector electrodes

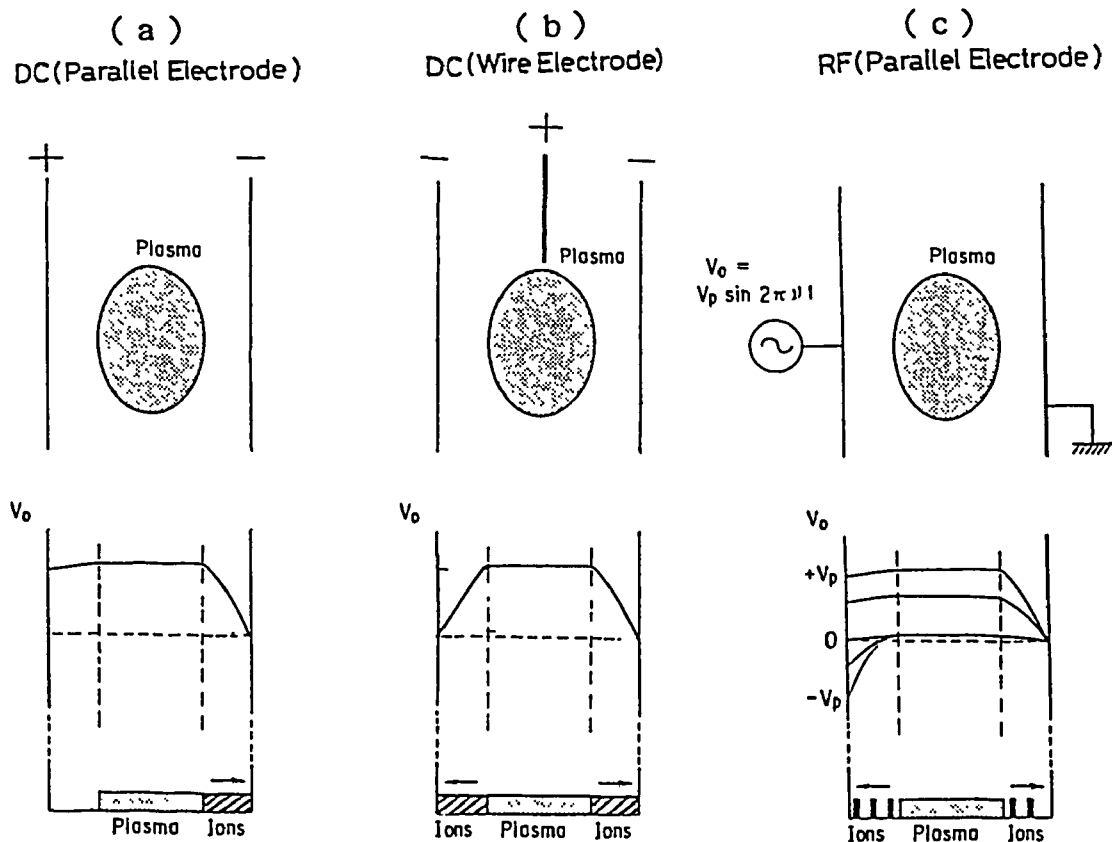


Fig.1 Three methods for ion collection from the laser induced plasma. Lower parts show the potential distributions during the ion collection.

in the same way as the wire electrode method. Moreover, compared with the wire electrode method, this method has an advantage that there is no need to install the wire electrode between the collection electrodes.

2. Experimental

The experimental apparatus is shown schematically in Fig.2. A gadolinium atomic beam was produced by electron beam heating. To remove the plasma contained in the atomic beam, negative potential of 200 V was applied to the elimination electrodes[6]. The atomic beam collimated by a slit of width 14 mm and length 80 mm entered the laser interaction region between the two collection electrodes. The space between the electrodes was 20 mm. The atomic beam flux was monitored by a quartz crystal sensor. Two Faraday cups were set at one collection electrode in order to measure the collected ions. The collection electrode has two rectangular holes. The holes were so long along the stream of the atomic beam that the ion currents detected by the Faraday cups were proportional to the total ion current collected by the collection electrodes. A stainless steel mesh having transparency of 80 % was

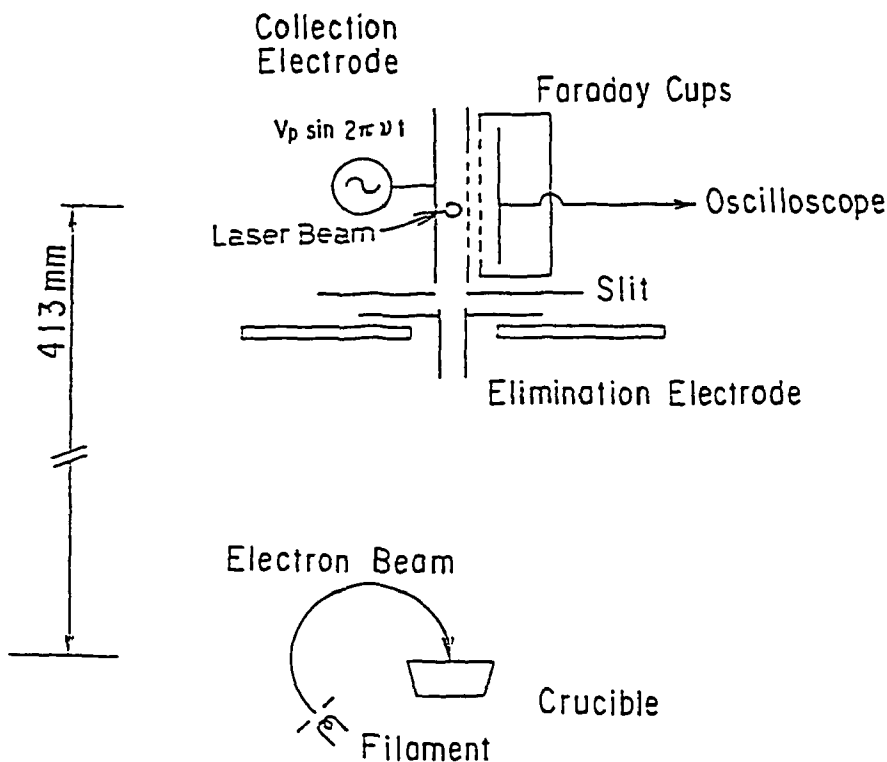


Fig.2 A Schematic view of the experimental apparatus.

spot-welded on the holes so as not to change the electric field between the collection electrodes.

Gadolinium atoms were ionized by the following two-wavelength two-step resonance photoionization[7] using two pulse dye lasers:

$$\lambda_1 = 441.1 \text{ nm} (533 \text{ cm}^{-1} (J=4) \rightarrow 23196 \text{ cm}^{-1} (J=5))$$

$$\lambda_2 = 376.2 \text{ nm}$$

where λ_1 is the first-step laser wavelength and λ_2 is the second-step laser wavelength. The pulse duration of the dye laser was about 10 ns and time intervals between the two output pulses of the lasers were adjusted to be about 20 ns. Radio-frequency voltage of 1.8 MHz was applied to the one collector electrode and another collector electrode was grounded. The ion currents in the case of the parallel electrode method were also measured for comparison.

3. Experimental results

Typical oscillograms of the ion currents measured with the Faraday cups are shown in Fig. 3(a). The peak RF voltage applied to the collector electrode was ± 140 V. All ions between the electrodes were collected by the collection electrodes within 18 μs . Assuming ions were collected at both electrodes, the initial ion density of the plasma was estimated to be

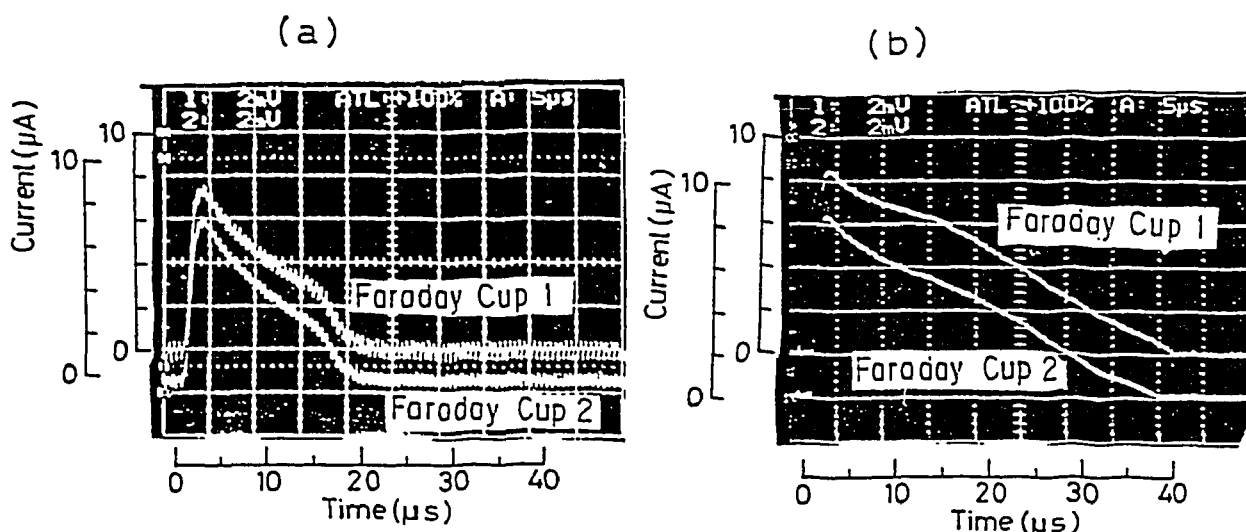


Fig.3 Examples of measured oscillograms of ion collection currents.

(a) Ion collection by RF voltage

(1.8 MHz, peak voltage: 140 V, initial plasma density: $3.5 \times 10^9 \text{ cm}^{-3}$)

(b) Ion collection by DC voltage

(100 V, initial plasma density: $3.8 \times 10^9 \text{ cm}^{-3}$)

$3.5 \times 10^9 \text{ cm}^{-3}$ from the integration of the ion current considering the transparency of the meshes. Figure 3(b) shows one example of the Faraday cup signals in the case of the DC parallel electrode method. The initial ion density was estimated to be $3.8 \times 10^9 \text{ cm}^{-3}$. In this case the ion collection time was $38 \mu\text{s}$.

In Fig.4, the collection times are shown by solid circles as a function of initial plasma density for three cases of RF voltage of $\pm 140 \text{ V}$ and DC voltage of 50 V and 100 V . The plasma density was varied by altering the atomic density at the laser interaction region. Solid lines show the ion collection times estimated with a one-dimensional model described in the next section.

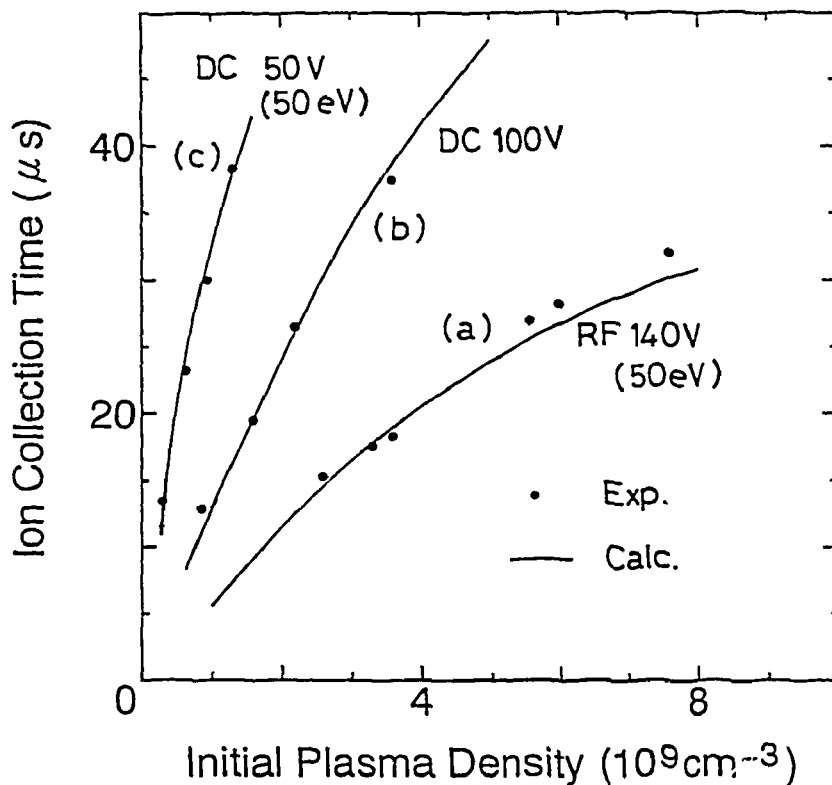


Fig.4 Collection time as a function of initial plasma density. solid circles are the experimental values. Solid lines are estimated values with a one dimensional model.

- (a) Ion collection by RF voltage (1.8 MHz, peak voltage: $\pm 140 \text{ V}$)
- (b) Ion collection by DC voltage (100 V)
- (c) Ion collection by DC voltage (50 V)

4. Extension of a simple one-dimensional model for application of radio-frequency voltage

In our previous papers[3,5], we showed that a simple one-dimensional model can predict the ion collection times for DC voltage applications of both the parallel electrode method and the wire electrode method. The one-dimensional model includes the following ion collection behaviors:

(1) The potential of the laser-induced plasma is slightly higher than that of the positive electrode.

(2) the plasma flows with the atomic beam.

(3) the plasma expands with the Bohm velocity ($V_e = 0.6(kT_e/M)^{1/2}$).

(4) the ions are extracted from the plasma at the rate of the space-charge-limited current and this ion extraction causes the retrograde motion of the plasma boundary from the electrode plate.

(5) the plasma boundary moves according to the difference between plasma expansion and reduction caused by ion extraction.

In the case of applying RF voltage, (2) and (3) hold as it is. If the ion current at the RF voltage application is known, plasma reduction due to ion extraction can be estimated and the simple one-dimensional model for RF voltage application can be made.

We estimated the ion current by simulating the moving ions between the plasma boundary and the collection electrode. Figure 5 shows one model of ion extraction from the plasma by applying the RF voltage. Emission surface corresponds to the plasma boundary emitting the ions. The RF voltage, V_0 , is $V_p \sin 2\pi\nu t$, where V_p is the peak voltage of RF and ν is the frequency. As shown in Fig.1(c), the plasma potential is expected to be equal to V_0 when $V_0 > 0$ V and 0 V when $V_0 < 0$ V. At each time step, positive charge is produced at the emission surface so that electric field at the emission surface may be 0 V/m. Each positive charge moves to the collection electrode in the electric field between the emission surface and the electrode. The electric field at each time step is obtained from Poisson's equation. Here, when $V_0 < 0$ V, $E = 0$ V/m because the plasma potential is 0 V. There is some places where electric potential is higher than V_0 due to positive charge between emission surface and the electrode. In this case the electron in the plasma will move to the place where $V > V_0$ and the potential will become V_0 and the electric field will be 0 V/m.. We continued the calculation until steady state is reached. The ion current density at the steady state, i , was found to be $AV_p^{3/2}/d^2$, where A is a proportional constant and d is distance between emission surface and the electrode. The A value determined from the calculation to be 0.49 times of that for DC parallel electrodes.

Thus, we can apply the simple one-dimensional model to RF voltage application. Moreover, kinetic energy of ion collected on the collection electrode was only about $V_p/3$ (eV).

The calculated ion collection times shown by solid lines in Fig. 4 agree with the experimental values for not only DC voltage method but also RF voltage method. This means that the simple one-dimensional model was extended for prediction of ion collection times in the cases of applications of not only the DC voltage but also the RF voltage.

In the case of RF voltage application of $V_p = \pm 140$ V, kinetic energy of collected ions is expected to be about 50 eV from the simulation, which was recently confirmed by measuring the kinetic energy [8]. In the case of application of DC voltage of 50 V, the energy of collected ions is 50 eV. Therefore, Fig. 5 shows that the ions are collected in a shorter time at the same kinetic energy of the collected ions compared with ion collection by applying DC voltage to the electrode.

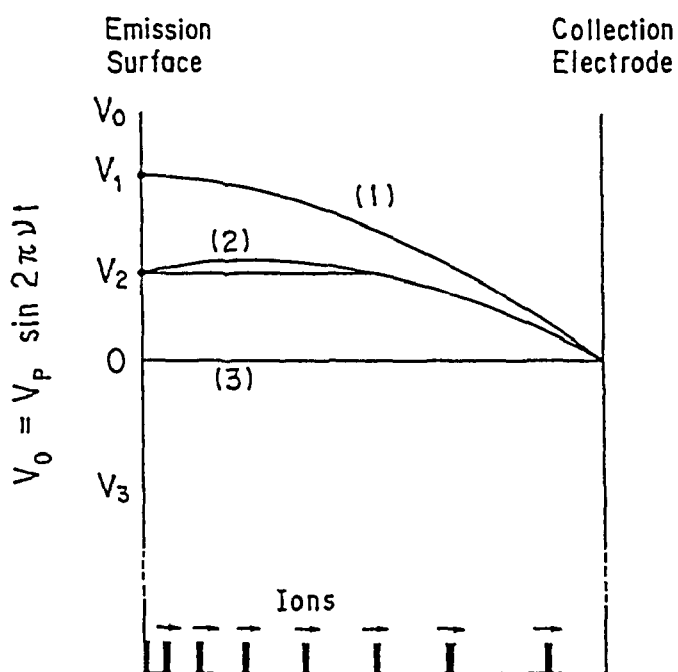


Fig.5 A model for calculation of current density of ions extracted by RF voltage.

- (1) Production of positive charge so that $E = 0$ V/m at the emission surface.
- (2) $E = 0$ V/m where $V > V_0$.
- (3) $E = 0$ V/m, when $V < 0V$.

5. Discussion

The experimental conditions described above are far from those of AVLIS plant. In order to know whether RF voltage method is effective or not, the ion collection times were estimated with the simple one-dimensional model under the following conditions that are considered to be close to AVLIS plant: (1) initial density of $^{235}\text{U}^+$ is $3 \times 10^{10} \text{ cm}^{-3}$. (2) width of the initial plasma is 3 cm. (3) distance of the collection electrodes is 5 cm. Figure 6 shows the possibility that with RF voltage method the ions are collected in a shorter time at the same kinetic energy than DC voltage methods of both the conventional parallel method and the wire electrode method.

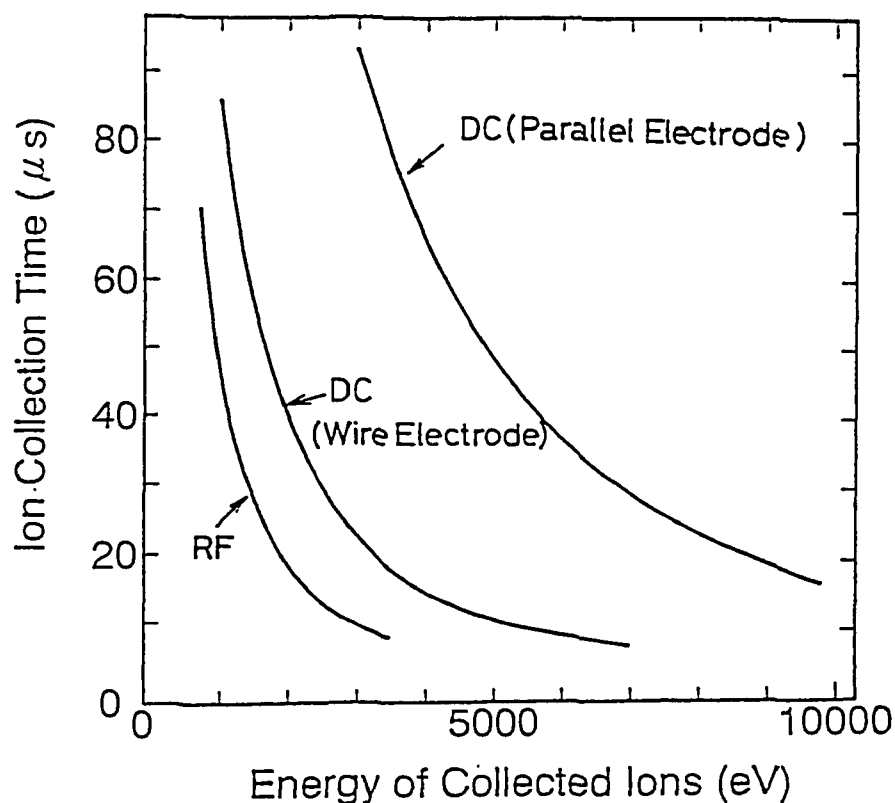


Fig.6 Estimated ion collection times of $^{235}\text{U}^+$ under the following conditions.
(1) initial density is $3 \times 10^{10} \text{ cm}^{-3}$.
(2) width of the initial plasma is 3 cm.
(3) distance of the collection electrodes is 5 cm.

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