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Characteristics of HCIs Produced at Kobe EBIS under Modulated Operation

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Abstract

The electron beam ion source (Kobe EBIS) has been developed to perform modification of surfaces using highly charged ions (HCIs) at the Kobe University, Japan. Recent study revealed that periodic intermission of electron beam improves charge state distribution of extracted ions. The period of intermission is in the order of 100ms and the width of beam-off time is 1ms or less. This operational mode (pulse mode) make it possible to produce Ar^{15+} to Ar^{17+} effectively, while the charge is limited less than 14+ under the ordinary operational mode with DC electron beam. A spike of HCIs with a peak current in the order of nA is also observed at each moment of electron beam off. The measurement of the time evolution of Ar^{16+} intensity around the timing of mode change revealed that the intensity of extracted Ar^{16+} changes slowly after mode change with a time constant of few seconds.

Introduction

Interaction of highly charged ions (HCIs) with solid surfaces causes modification of structure over the nanometer scale region of surface as well as emission of secondary particles and photons[1,2] as a consequence of potential energy release from HCI to surface (potential effect). Electron beam ion source (EBIS) has been developed to produce HCIs since around 1980[3,4]. The Kobe EBIS was developed to perform modification of surfaces using HCIs at the Kobe University, Japan.[5] We have revealed that the irradiation of various surface with HCIs brings electric and magnetic modification, and emission of Balmer light from a hydrogen atom desorbed from the surface.[6,7] For most of phenomena, degree of influence of potential energy increases with the charge state of incident HCI, for example, the intensity of Balmer light changes with the 4^{th} power of the charge state. Recent machine study on the Kobe EBIS revealed that periodic intermission of electron beam improves charge state distribution of extracted ions.[8] This finding is useful for studying potential effect in the interaction of HCI with surfaces because the potential effect is emphasized for the

irradiation with HCI in higher charge state. In the present paper, this operation is named as 'pulse mode' while ordinary operation as 'DC mode', and we will describe characteristics and advantage of pulse mode in detail.

Experimental

The Kobe EBIS consists of an electron gun, drift tubes, an electron collector, and a super-conducting magnet (3T) cooled by a closed cycle refrigerator.[5] The electron gun and collector are floated on negative high voltage in order to lower the electric potential of drift tube region (i.e. lower the kinetic energy of HCI extracted from the EBIS), which is essential to emphasize the potential energy effect of HCIs in the interaction with material surfaces. The drift tubes at room temperature are separated in 7 pieces (DT1 ~ DT7, from electron gun side to collector side), where potential barrier is realized applying higher potential to DT1 and DT7 under traditional operation. The length of potential well (DT2 to DT6) is 200 mm. The electron gun, drift tubes and collector are installed in a vacuum tube which is inserted in the super-conducting magnet with the bore size of 180mmϕ. The vacuum system is evacuated by a turbo-molecular pump, a titanium getter pump and a sputter ion pump. The ultimate pressure of the Kobe EBIS with the electron beam (~100 mA) is 2-3x10^{-8}Pa after bake-out procedure for 100 h at ~500 K.

The experimental apparatus for irradiation of samples with HCIs comprises the Kobe EBIS, beam transport and charge separating section with a sector magnet, and irradiation chambers. [7] The charge state distribution of HCIs extracted from the ion source was measured with a Faraday cup or a MCP detector at the irradiation chamber by scanning the coil current of the sector magnet.

The performance of the Kobe EBIS was improved by the modulation of electron beam emission. The modulation is periodic repetition of on/off of electron beam which is realized by on/off of anode voltage; the period is in the order of 0.1s and the width of beam off time is around 1ms. The response time of switching is ~100μs using a fast high-voltage amplifier (Matsusada Precision HEOPS-10P2). The emission current of 100mA is obtained at the anode voltage of 4 kV relative to cathode which is at -10 kV from the ground level. The collector is at 1.5 kV relative to cathode.

In the present experiment, data were obtained with the potential of DT7 at 0 V relative to the common potential of drift tubes (3 kV) except special cases (Figure 4) where DT7 potential was switched rapidly between certain voltage and zero, while DT1 is 200 V and DT2 to DT6 are 0 V through entire experiments. Since the duty ratio of modulation is almost 1, the intensity of highly charged ion beam extracted from the

EBIS can be monitored as DC current with an ordinary electrometer. On the other hand, time structure of each charge state in the ms range exhibits the evolution of charge state distribution. Then we observed the variation of the intensity of specific charge state at the time resolution of ~30 μs. In this time response measurement, ion beam current amplified by the MCP detector (gain is ~380) was converted to voltage using a current preamplifier (DL instruments 1211) at the conversion gain of 10^6 V/A, and measured with an oscilloscope (Tektronix TDS3032B).

Results and discussion

The charge state distributions of the extracted ions are shown in Figure 1 for both modes; (a) DC mode and (b) pulse mode. [8] The partial pressure of introduced Ar is $1x10^{-8}$ Pa. At the DC mode the ion current of higher charge state decreases with the charge number and diminishes for the charge states larger than 15+ (the peak around Ar^{15+} coincides with O^{6+} signal which was observed for the mass spectrum measured before introducing Ar gas). For the pulse mode, higher charge states up to Ar^{16+} are obtained and Ar^{17+} is also identified. The period of modulation is 400ms and the time width of electron beam off is 1ms for the Figure 1(b).

The time response of the intensity of extracted HCI beam of specific charge state (Ar^{16+}) is demonstrated in Figure 2. When the electron beam is turned off a strong spike appears, and the ion beam disappears immediately after the electron beam is turned off. After the electron beam is turned on, the intensity of Ar^{16+} gradually increases with the response time of ~10 ms and saturates toward an almost constant value (namely DC component). Figure 2(b) compares the intensities of the spikes and the DC component; the peak heights of spikes are ~40 times higher than the DC component. The width of the spike is ~100 μs which is close to the response time of the high-voltage amplifier applied to the anode. The spike indicates that the ions trapped by space charge potential of electron beam are released at once. Such burst signal has been observed in electron cyclotron resonance ion sources due to a similar mechanism; strong ion pulse with the width of 0.1~1 ms is generated when rf is turned off. [9,10]

Figure 3 shows the time response of the intensity of Ar^{16+} after switching the operational mode to the other one; Figure 3(a) for DC mode to pulse mode, and Figure 3(b) for pulse mode to DC mode. In Figure 3 the arrows indicate the timing of mode change and T_p represents the period of repetitive modulation (250 ms). Ion current steeply rises at the moment of beam-off and absolutely stays zero during beam-off time (~1 ms), then the rapid change of ion current will make upward/downward spike at each beam on/off timing as shown in Figure 2, however, such structures are smeared out in

Figure 3 due to the limited time response of the electrometer. As shown in Figure 2, the response time for the creation of Ar^{16+} is in the order of 10 ms, however, the fraction of Ar^{16+} among the HCIs stored in and extracted from the drift tube region changes over several seconds. This long time constant in transient response at the mode change suggests that it needs several second to reach equilibrium charge state distribution of trapped HCIs. It seems that some kind of memory effect works for this transient phenomena. The memory might be ions trapped by the magnetic field, which remain in the drift tube region even in the absence of electron beam.

We performed another experiment to observe pulsed ions released by abrupt changing of DT7 potential. Figure 4(a) is time response of extracted Ar^{16+} similar to Figure 2(a) for various values of DT7. DC component decreases with the height of DT7. In this experiment, DT7 and anode potentials were controlled as schematically shown in Figure 4(b). The potential barrier is set to zero for 1 ms, and electron beam is turned off at 0.25 ms after the recovery of the potential barrier. The electron beam remains off for 0.75 ms. The spike at the turning off of electron beam is observed only for DT7 = 0, that is, when the potential barrier is turned off the ions escaped from the drift tubes include those ions trapped by the space charge of electron beam.

Summary

Recent study on the performance of the Kobe EBIS revealed that periodic intermission of electron beam improves charge state distribution of extracted ions. The period of intermission is in the order of 100ms and the width of beam-off time is 1ms or less. This operation makes it possible to produce Ar^{15+} to Ar^{17+} effectively, while the charge is limited less than 14+ under the ordinary operational mode with DC electron beam. A spike of HCIs with a peak current in the order of nA is also produced at each moment of electron beam off. The measurement on the time evolution of the intensity of Ar^{16+} around the timing of mode changes revealed that the intensity of extracted Ar^{16+} changes slowly after mode change with a time constant of few seconds, while Ar^{16+} is created rapidly within a few tens ms after switching on. This means that it needs several seconds to reach equilibrium charge state distribution of extracted ions after the operational mode is changed.

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Figure Captions

Figure 1

Mass spectra of highly charged ions extracted from the Kobe EBIS for different operational modes; (a) DC mode and (b) pulse mode.

Figure 2

Time evolution of the ion current of Ar^{16+} during pulse mode operation. (a) and (b) are drawn for the same data with the same horizontal scale and different vertical scale.

Figure 3

Time response of the intensity of Ar^{16+} after switching the operational mode to the other one. (a) DC mode to pulse mode, and (b) pulse mode to DC mode.

Figure 4

Time evolution of the ion current of Ar^{16+} during pulse mode operation for various DT7 values, (a) is for the time span over several periods, and (b) is near the switching time of DT7 and anode voltage corresponding the moment indicated with a broken ellipse in (a).

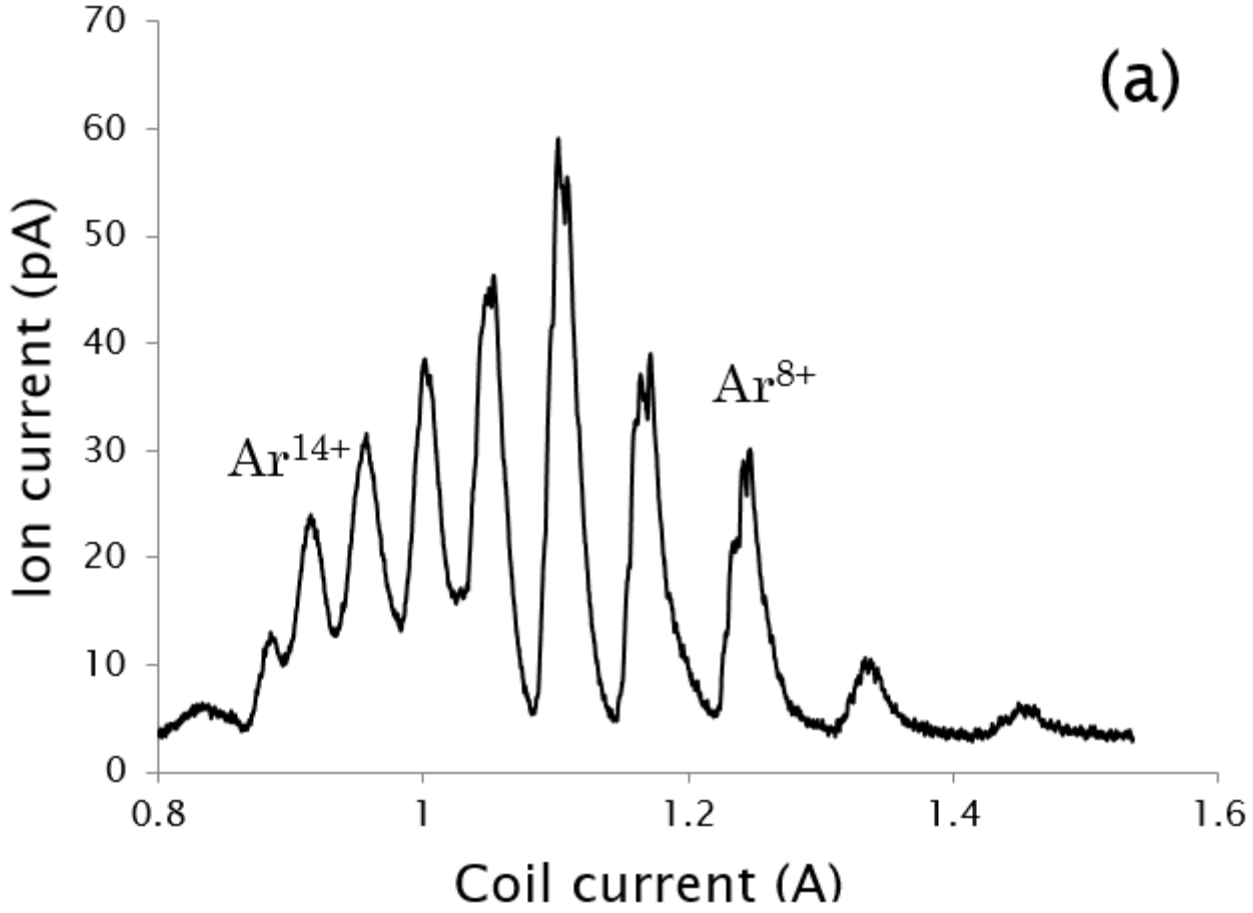
(a)
Ion current (pA)
70
60
50
40
30
20
10
0
0.8
1
1.2
1.4
1.6
Coil current (A)
Ar14+
Ar8+

Fig. 1(a)

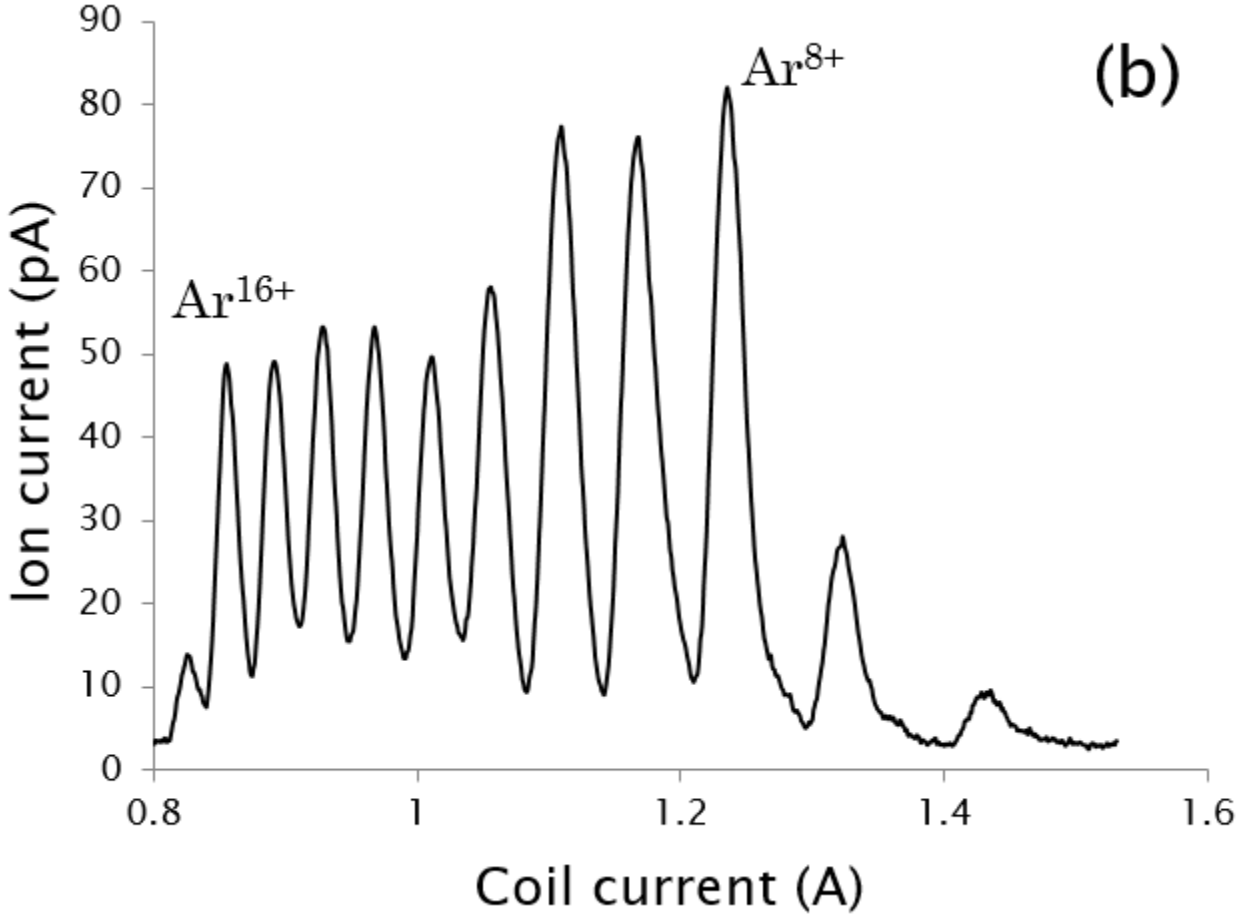
(b)
Ar^{8+}
Ar^{16+}
Ion current (pA)
Coil current (A)
0
10
20
30
40
50
60
70
80
90
0.8
1
1.2
1.4
1.6

Fig. 1(b)

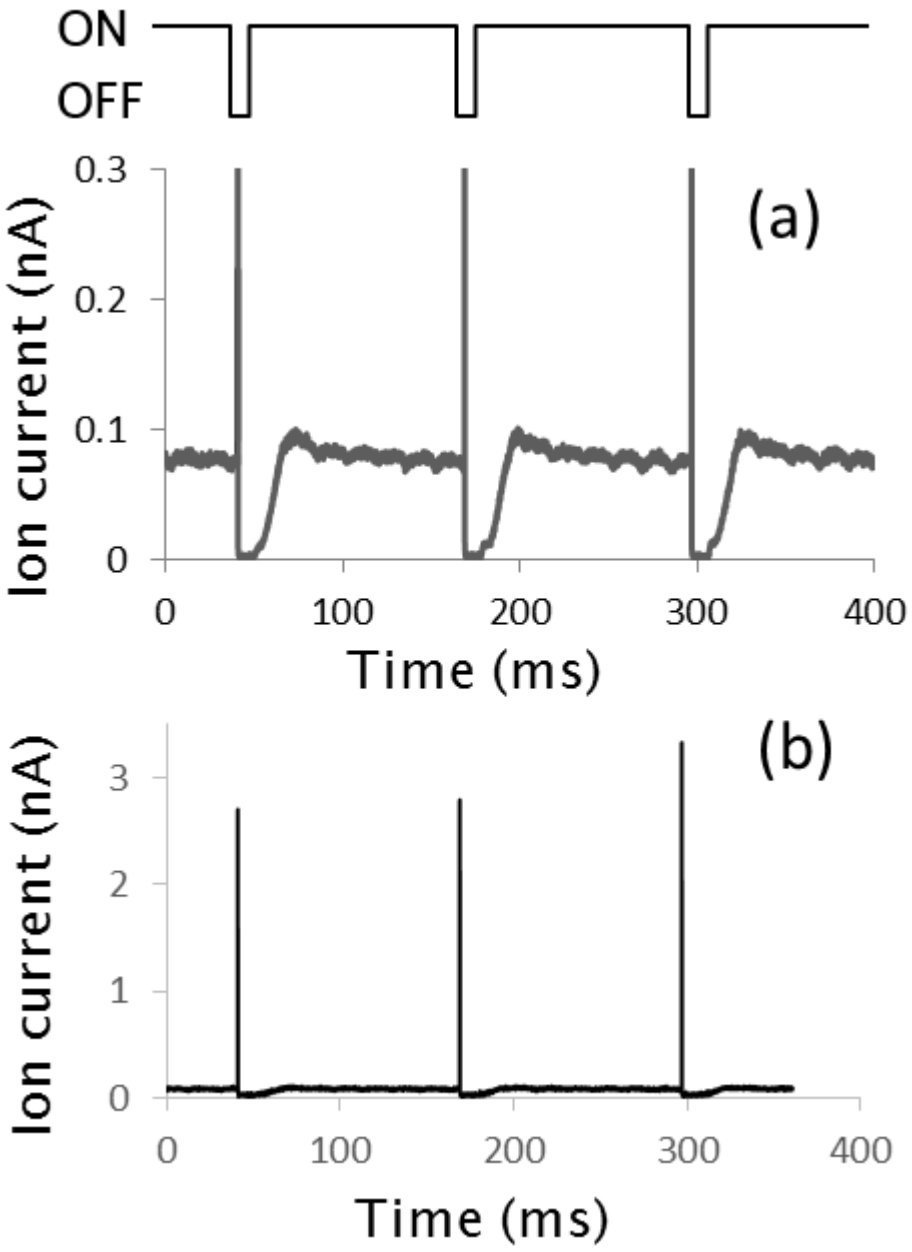
ON
OFF
0.3
0.2
0.1
0
Ion current (nA)
(a)
0
100
200
300
400
Time (ms)
3
2
1
0
Ion current (nA)
(b)
0
100
200
300
400
Time (ms)

Fig. 2

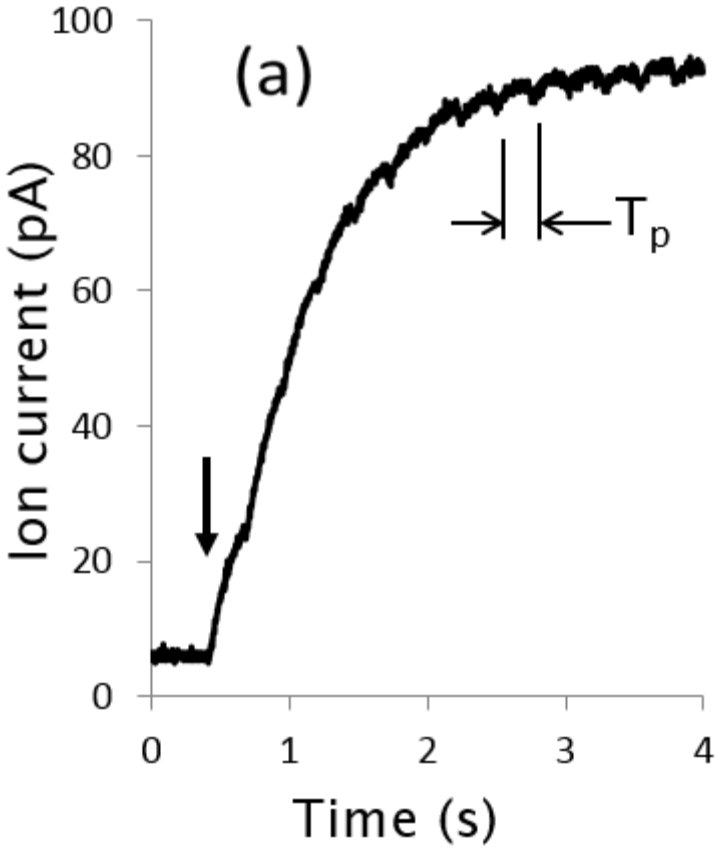

Fig. 3(a)

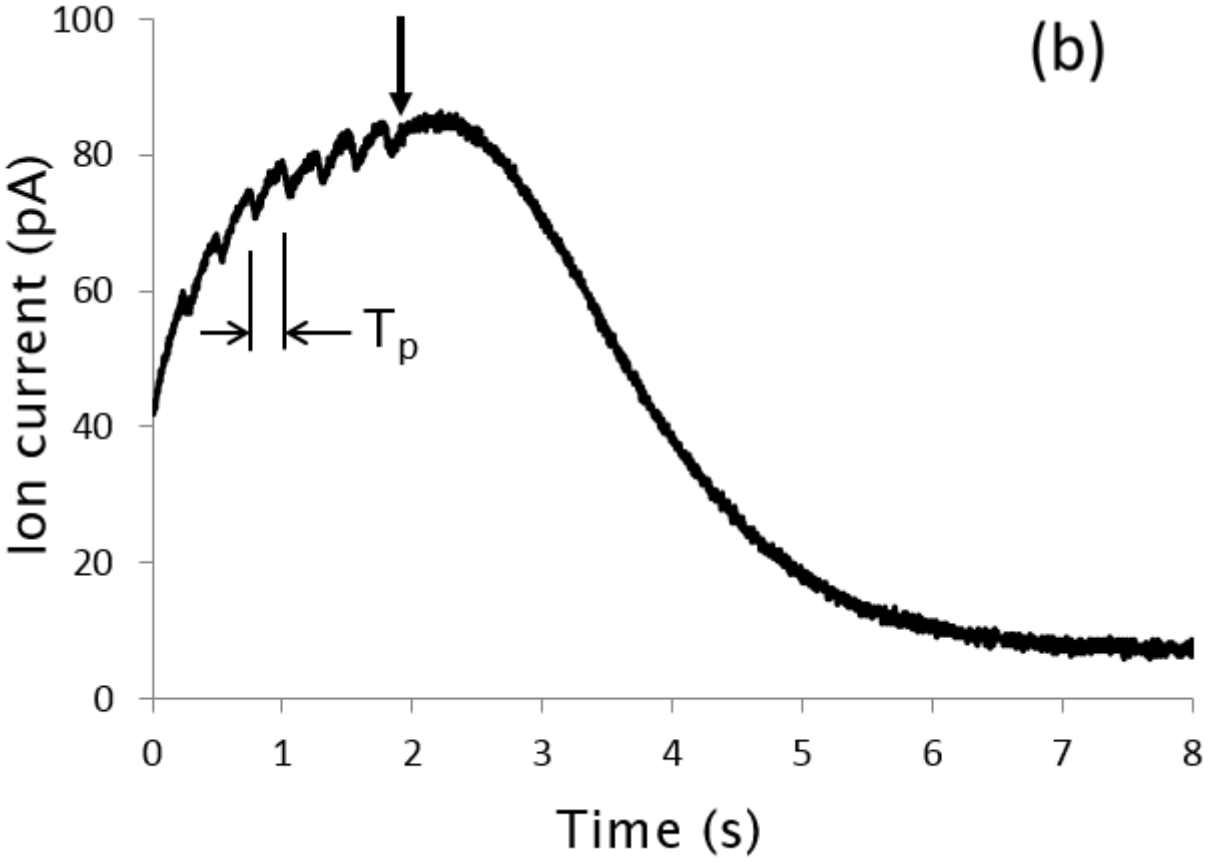

Fig. 3(b)

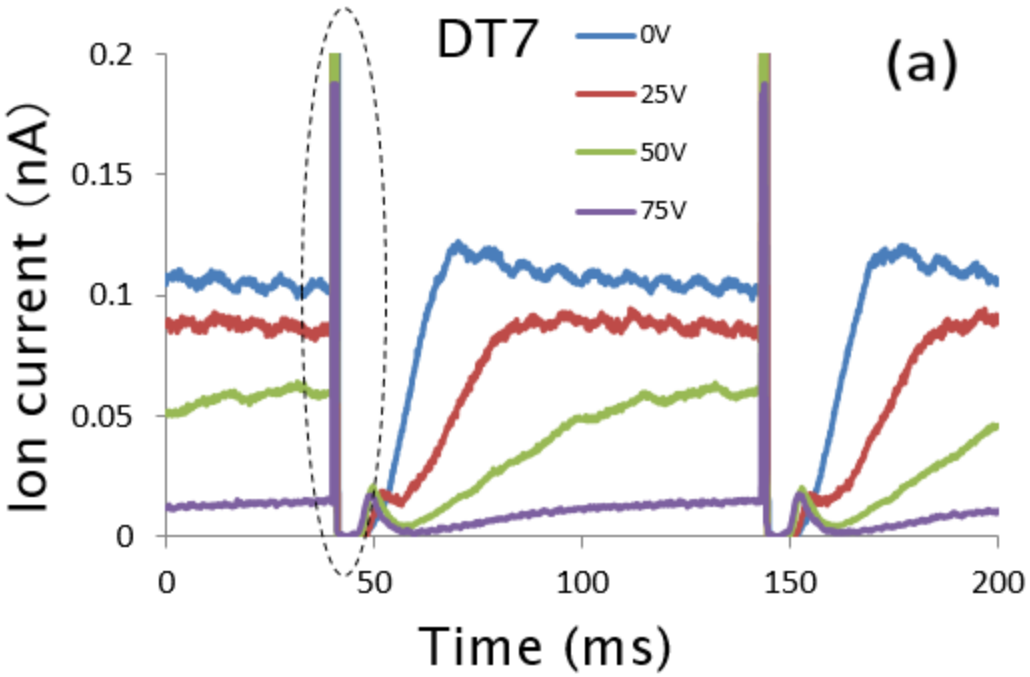
DT7
0V
25V
50V
75V
(a)
Ion current (nA)
0.2
0.15
0.1
0.05
0
0
50
100
150
200
Time (ms)

Fig. 4(a)

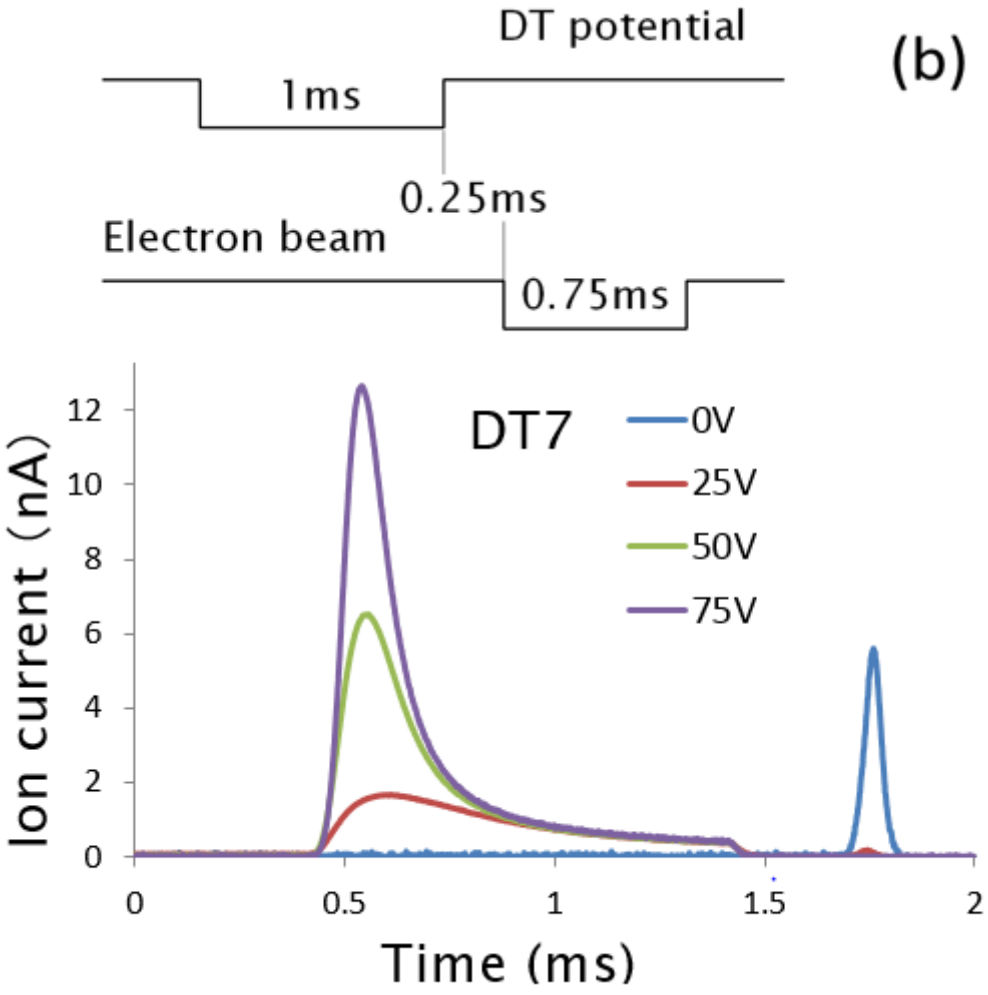
DT potential
(b)
1ms
0.25ms
Electron beam
0.75ms
DT7
0V
25V
50V
75V
Ion current (nA)
12
10
8
6
4
2
0
0
0.5
1
1.5
2
Time (ms)

Fig. 4(b)