

Study on Acceleration Processes of an Inductive Plasma Accelerator by Three-axis Magnetic Field Measurements

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Abstract: Distributions of magnetic field and that of induced current in the acceleration phase of the RIPAL are investigated. The RIPAL expels plasma utilizing electromagnetic induction, the distributions of the magnetic field and induced plasma current are crucial factors. In order to conduct three-dimensional measurements of magnetic field, a three-axis magnetic probe was fabricated. The distributions of the magnetic field and that of induced plasma currents in the acceleration phase were obtained successfully using the probe. As a result of that, the time-evolution of the distributions of the induced plasma currents with changing mass flow rate of propellant (Xenon) were revealed, and the value were $O(1000A/m^2)$.

Nomenclature

B	= magnetic field
B_{coil}	= applied magnetic field by an acceleration coil
B_{ind}	= induced magnetic field in plasma
j	= induced plasma current
E	= electric field
n	= the number of turns of a coil
S	= cross section of turns of a coil
r	= coordinates
W	= weight function
e	= Napier's constant

I. Introduction

Electric propulsion has been used for a variety of deep space missions¹⁾²⁾. It has high specific impulse (~ 10 km/s) which enables high payload mass-fraction. In the recent years, deep-space explorations, including piloted missions, or cargo missions using high-power (100 kW-class) electric propulsion are planned³⁾. In order to develop it, there might be two approaches. The first one is to scale-up the conventional thrusters, i.e. ion thrusters, Hall thrusters and MPD thrusters⁴⁾⁵⁾⁶⁾⁷⁾⁸⁾. They demonstrate high specific impulse (3000 $\sim$ 5000 s) and efficiencies (~ 50 %) in ~ 10 kW-class operation. Their lifetime is, however, limited by erosion of electrodes due to direct contact with plasmas. This problem will become crucial in the future space missions, such as manned explorations. The second is realizing electrodeless thrusters. Until today, several concepts of electrodeless electric propulsion are proposed, for instance, the VASIMR⁹⁾, the FARAD¹⁰⁾, the HDLT and the electrodeless helicon thruster developed in the HEAT project¹¹⁾¹²⁾. Electrodeless thruster is no longer limited their lifetime by erosion of electrodes, and they need no neutralizers or hollow cathodes. As a candidate of an electrodeless thruster, we are proposing a concept of the RIPAL; Radio-frequency Inductive Plasma Accelerator with Low aspect plasma¹³⁾¹⁴⁾. It generates radio-frequency (RF) plasma and accelerate it by Lorentz body force which is a product of an interaction between magnetic field and induced plasma current. The most unique point of the RIPAL is ionization and acceleration is conducted in the same region. This provides us with two benefits. The first one is to reduce plasma losses on the walls in the thruster structure. This may contribute to achieve high thrust efficiency. The second one is ease of exhausting heat. Especially in the acceleration phase, the distributions of magnetic field and induced plasma currents are important for performance of the RIPAL because plasma is accelerated by electromagnetic force. In this work, distributions of magnetic fields are obtained by a magnetic probe, and that of induced plasma currents.

II. Description of the Concept

A schematic of the thrust generation processes of the RIPAL is shown in Fig.2. They are mainly divided into two phases; (1) the plasma generation phase and (2) the acceleration phase. In plasma generation phase, Xenon gas is fed in the grass cylinder. Then RF power is input the excitation coil wound around the grass cylinder and it cause RF (13.56 MHz) discharge. In the acceleration phase, alternative current (~ 100 kHz) in the acceleration coil placed in the bottom of the grass cylinder applies alternative magnetic field $\mathbf{B}_{\text{coil}}$. Because of the applied magnetic field $\mathbf{B}_{\text{coil}}$, plasma currents $\mathbf{j}$ is induced as the time-variation of the magnetic field $\frac{\partial \mathbf{B}}{\partial t}$ is reduced. By the Lorentz force $\mathbf{f} = \mathbf{j} \times \mathbf{B}$, which is the production of the interaction between $\mathbf{j}$ and $\mathbf{B}$, plasma is expelled in quasi-neutral state. The RIPAL generates thrust continuously by repetition of those two phases.

III. Experimental setup

A. Vacuum facilities

A picture of the vacuum facilities used in this work is shown in Fig. 1. All experiments shown in this paper was conducted in this vacuum chamber whose size is 1.4 m in diameter and 3.0 m long. It has two cryopumps which can pump 12,000 L/s and 10,000 L/s nitrogen, respectively. In this work, the former one which is capable of pumping 12,000 L/s nitrogen was only used. The background neutral pressure in experiments were less than 1.5×10^{-2} Pa.

B. The Components of the 1 kW-class RIPAL

In this work, the 1 kW-class RIPAL is used as preliminary experiments. A schematic representation of the 1 kW-class RIPAL is shown in Fig. 2. It is mainly composed of three parts; an excitation coil, an acceleration coil and some permanent magnets. In this work, we employed Xenon gas as a propellant of the RIPAL. Xenon gas is fed from the inlet port in the PTFE plate at the bottom of the cylinder (160 mm in inner diameter and 120 mm long). Around the grass cylinder, the excitation coil is wound at the position of $x = 70$ mm. It is a three-turns coil composed of copper wire ($\phi 2$ mm). In order to ionize Xenon gas, RF (13.56 MHz) power is input into the excitation coil through a matching box. The input power is up to 400 W, and the maximum value 400 W was used in the all experiments conducted in this work. The acceleration coil is a ten-turns coil attached on the PTFE plate, at the position of $x = -20$ mm. It is a component of a pulse generation circuit, and this circuit resembles to that of pulsed inductive thrusters (PITs). In this work, as preliminary experiments to confirm electromagnetic acceleration of the plasma in the RIPAL, the pulse generation circuit was installed instead of a RF power source. The circuit has a capacitor of 400 nF, high voltage

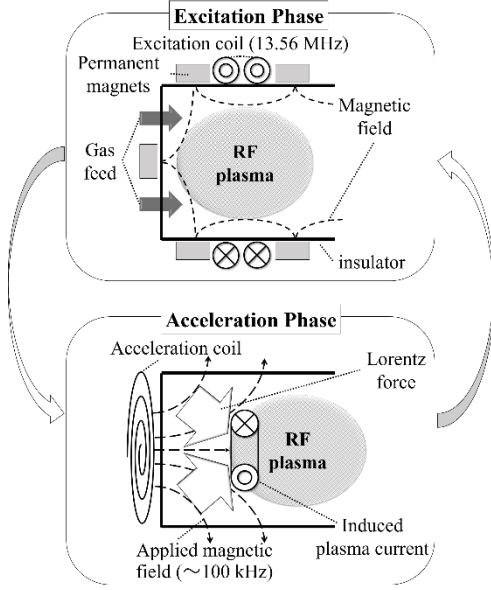


Figure.1. The concept of the RIPAL.

power supply and a semiconductor switching device (IGBT). The capacitor is charged with 1000 V by the high-voltage power supply (the energy of 288 mJ). This circuit can generate alternative current of ~60 kHz, ~180 A at the peak value. For confinement of the plasma and efficient acceleration, several block-type permanent magnets (20 mm×8.4 mm×4.2 mm) are installed on the side of the glass cylinder and a ring-shaped permanent magnet (60 mm in outer diameter × 32 mm in inner diameter × 7 mm in height) at the center of the acceleration coil on the PTFE plate.

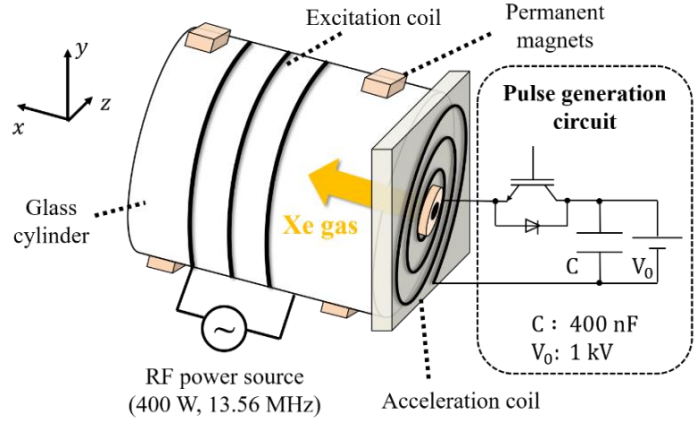


Figure 2. A schematic of the 1 kW-class RIPAL. It is an experimental model of the 100 kW-class RIPAL. Acceleration coil is connected with a pulse-generation circuit.

C. Magnetic probe

In order to measure time-variations of the distributions of magnetic field, a magnetic probe for three-axis measurement was fabricated. A picture of the magnetic probe is shown in Fig. 3. At the probe tip, it has a 6-mm alumina cube with gutters, 1 mm in depth, in its each side. Enamel copper wire (Ø0.2 mm) is wound around the cube in the gutters, forming three pairs of seven turns coil. The lead wires are twisted to reduce pickups by magnetic fluctuation at the part and led in the ceramic tube (3 mm in inner diameter and 40 mm long). The probe tip and ceramic tube is placed in a Pyrex glass tube. The glass tube is the size of 10 mm in outer diameter, 8 mm in inner diameter and 300 mm long, and protects the coils from electrical noise and thermal damage.

The probes utilize the faraday law;

$$\text{rot} \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}. \quad (1)$$

we can derive the integral form of Eq.1 by surface integral on the cross section of each coil using Stokes's theorem;

$$V_{\text{ind},i} = -n_i S_i \frac{\partial B_i}{\partial t} \quad (i = x, y, z). \quad (2)$$

$V_{\text{ind},i}$ can be obtained by measuring the voltage between two lead wires for each i . This raw signal was recorded by an 8-bit oscilloscope.

IV. Method and Data analysis

A flowchart of data analysis is shown in Fig. 5. As we obtain $V_{\text{ind},i}$, the magnetic field can be derived as follows;

$$\mathbf{B}_i(\mathbf{r}, t) = -\frac{1}{n_i S_i} \int_0^t V_{\text{ind},i}(\mathbf{r}, \tau) d\tau \quad (3)$$

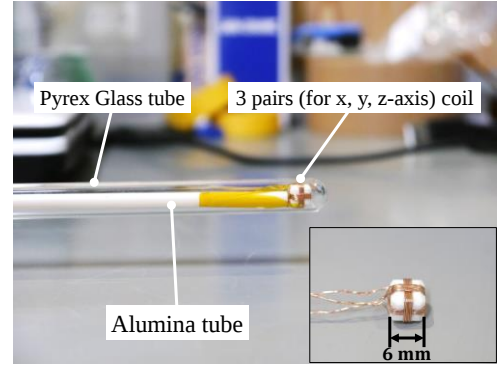


Figure 3. A photo of the three-axis magnetic probe.

Therefore, the magnetic field is derived by time-integrate $V_{\text{ind},i}(t)$ numerically. In this work, the time variation of the magnetic field in plasma was obtained when the pulse generation circuit was discharged in the $x - y$ plane at $z = 0$ mm. An example of measuring point is shown in Fig. 4. It shows the case of a 100 points measurement; 10 points (along the direction of x) $\times$ 10 points (along the direction of y). In this work, however, the number of measuring points are 400 points (20 points $\times$ 20 points). The interval of a point and the next is 6 mm. Magnetic field measurements were conducted two times at each point, and the signals were averaged.

In case the distributions of magnetic field on $x - y$ plane were obtained, we can calculate the z -axis component of induced plasma current j_z by the Ampère's circuital law;

$$\mathbf{j}(\mathbf{r}, t) = \frac{1}{\mu_0} \text{rot} \mathbf{B}. \quad (4)$$

In the process of deriving distributions of induced current, the values of $\text{rot} \mathbf{B}$ were averaged as weighted by the following two-dimensional weight function;

$$W(r, a, R) = \left(1 + \frac{ar^2}{R^2}\right)^{-1} \quad (5)$$

to improve S/N ratio. In this work, $a = e - 1$ and $R = 10$ mm was adopted, and the FWHM of weight function is 20 mm at that condition.

In the acceleration process of the RIPAL, there are some key parameters to realize efficient inductive acceleration of plasma. Among them, the electroconductivity of the plasma is one of the most important. High electroconductivity helps to generate large value of induced plasma current $\mathbf{j}$, and leads large value of Lorentz force. In this work, we changed the electroconductivity indirectly by changing mass flow rate of Xenon gas in 0.64, 0.91, 1.1 mg/s, and measured the induced plasma current in each condition.

V. Results

A. Time variation of magnetic fields

A typical raw signal obtained by the three-axis magnetic probe is shown in Fig. 6. The pulse generation circuit was discharged at Time = 0 μs . It shows signals from each coil on the tip of the magnetic probe could be obtained successfully. Then we can derive the time-variation of magnetic field from Eq. (3). In the numerical time-integration process, however, pickup noise included in raw signals cause drifts to the results of the integration. In this work, they are removed by FFT (Fast Fourier Transfer) analysis, and the signals of interested frequency band (35 – 100 kHz) were extracted. The typical time-variation of magnetic field is shown in Fig. 7. The typical variation of the value of the magnetic field in two times measurement was $\sim 3\%$ at the first peak.

B. Time variation of distributions of magnetic field

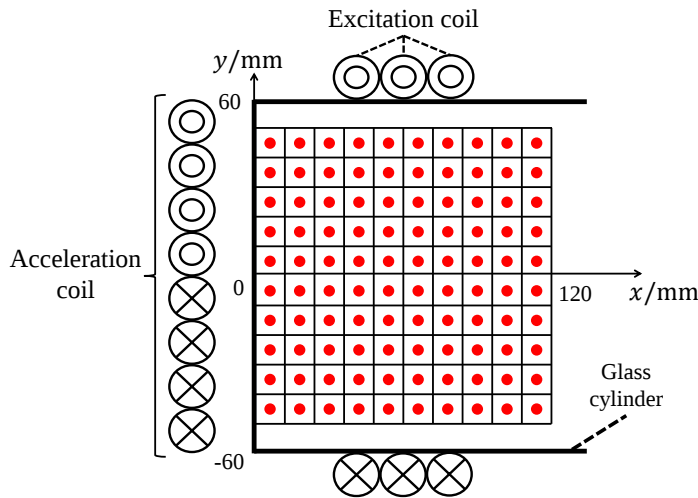


Figure 5. An example of the measuring points. It shows the case of 100 points measurement.

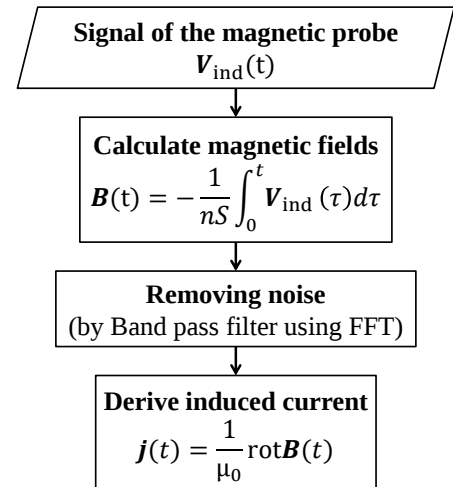


Figure 4. A flow chart of data analysis.

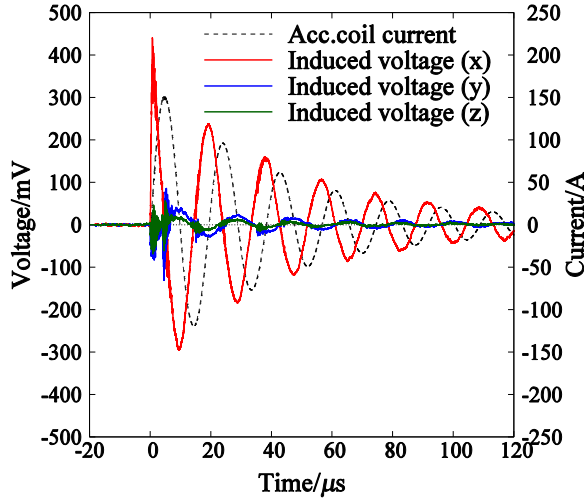


Figure 6. A typical signal of the magnetic probe.

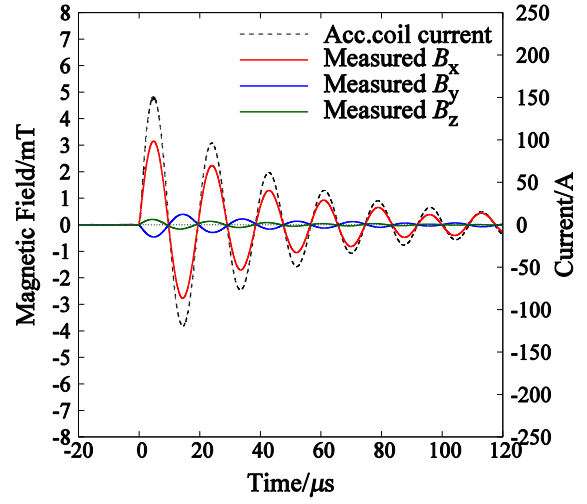


Figure 7. Time-variation of the magnetic field.

Conducting the 2-D measurements in the $x - y$ plane, the distributions of magnetic field were revealed. Time-evolution of distributions of magnetic field are shown in Fig. 8. The mass flow rate of Xenon gas was 0.91 mg/s when this data was obtained. This figure shows the distributions of

$$\mathbf{B} = \mathbf{B}_{\text{coil}} + \mathbf{B}_{\text{ind}}, \quad (6)$$

and they in the acceleration phase of the RIPAL are almost symmetrical.

C. Time variation of distributions of induced current

Using the distributions of the magnetic field, the distributions of induced plasma current was derived by Eq. (4). Figure 9 shows that in the condition of mass flow rate of Xenon was 0.91 mg/s. The order of the value of the induced plasma currents is 1000A/m², which corresponds to the result of the numerical simulation¹⁴. The distributions, however, are different from the view point of its symmetry.

VI. Conclusion

In this work, the distributions of the magnetic field in the acceleration phase of the RIPAL were measured by the three-axis magnetic probe. Using that data, the time-evolution of the distributions of induced plasma current were derived. The order of the value was $O(\sim 1000 \text{ A/m}^2)$.

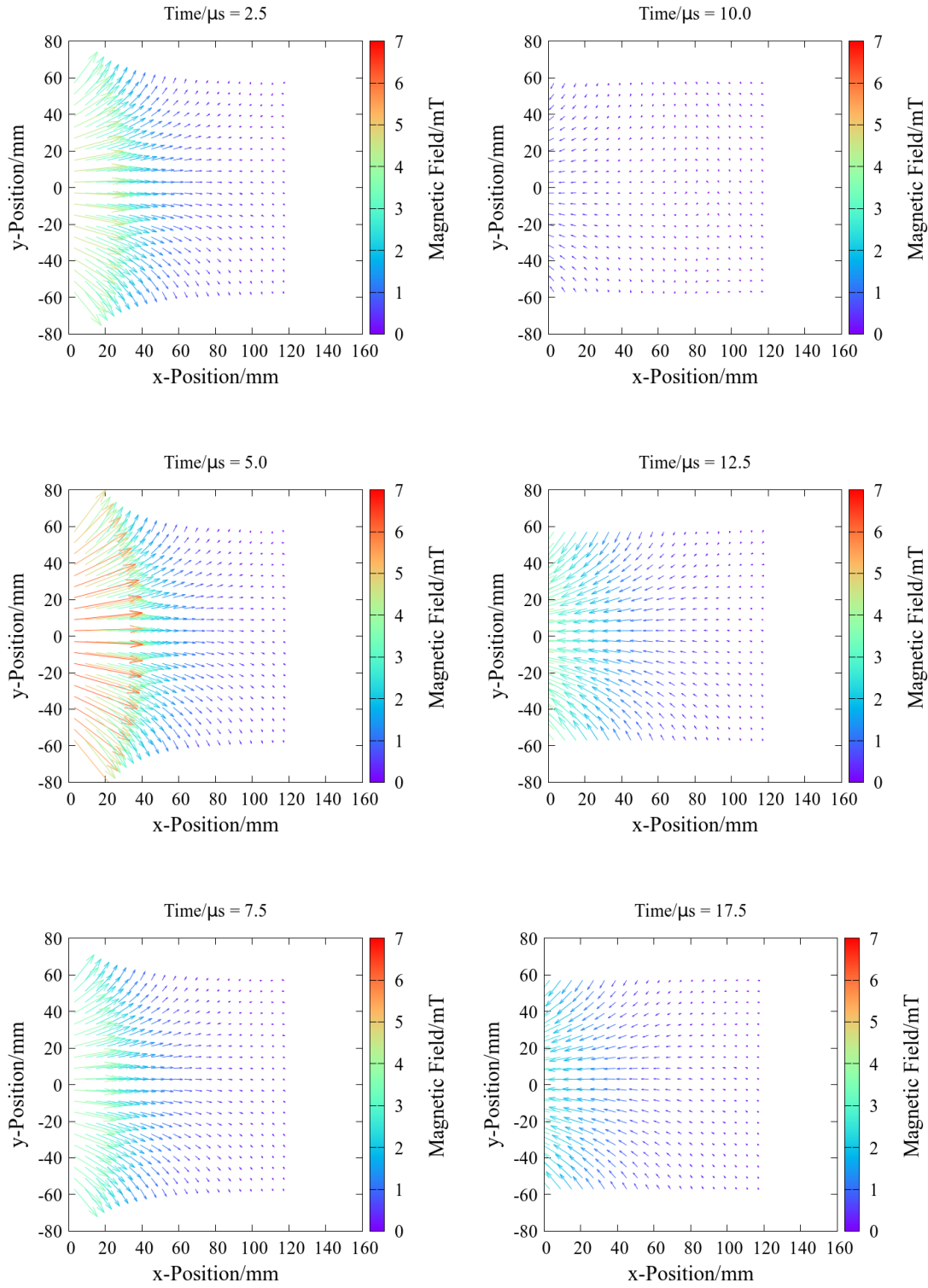


Figure 8. Time-evolution of the distributions of the magnetic field. The Xe mass flow rate was 0.91mg/s.

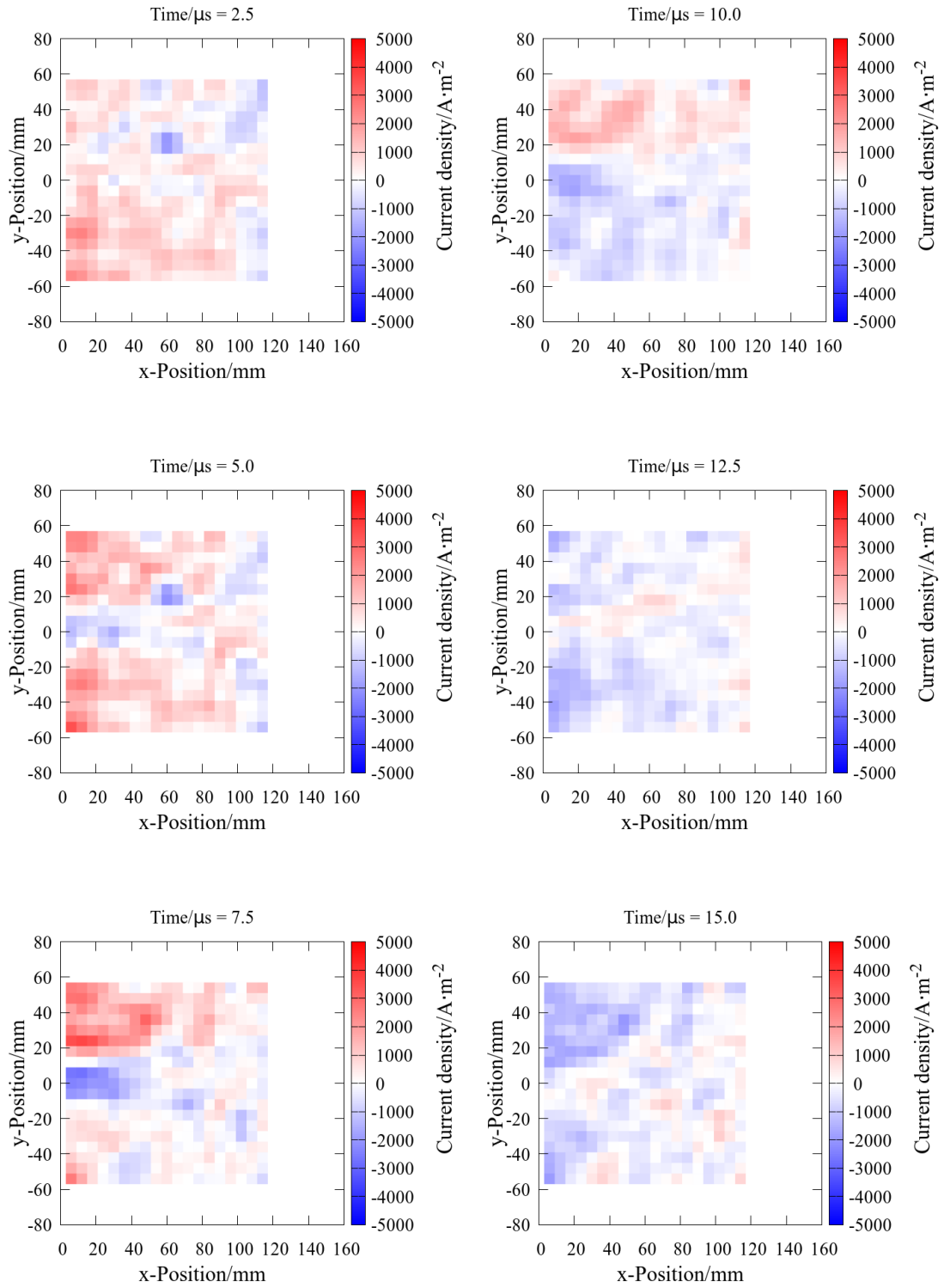


Figure 9. Time-evolution of the distributions of the induced plasma current. The Xe mass flow rate was 0.91mg/s.

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