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ABSTRACT

We propose a combined use of a Pockels electro-optic sensor with a pickup loop coil (Bdot probe) for the measurement of magnetic fluctuations in plasmas. In this method, induced fluctuating voltage on the coil loop is converted into an optical signal by a compact electro-optic sensor in the vicinity of the measurement point and is transferred across optical fiber that is unaffected by electric noise or capacitive load issues. Compared with conventional Bdot probes, the electro-optic Bdot probe (1) is electrically isolated and free from noise pickup caused by the metallic transmission line and (2) can be operated at a higher-frequency range because of the smaller capacitance of the operation circuit, both of which are suitable for many plasma experiments. Conversely, the sensitivity of the current electro-optic Bdot probe arrangement is still significantly lower than that of conventional Bdot probes. A preliminary measurement result with the electro-optic Bdot probe showed the detection of a magnetic fluctuation signal around the cyclotron frequency range in the RT-1 magnetospheric plasma experiment.

I. INTRODUCTION

The measurement of magnetic fluctuations is important in numerous plasma experiments.[1–6] Magnetic fluctuation probes (Bdot probes)[7] have been extensively used as a standard diagnostic tool for this purpose. The fundamental principle of the Bdot probe is to measure the induced voltage on a pickup coil loop placed in a temporary changing magnetic field according to Faraday's law. A typical Bdot probe consists of a pickup coil loop, a metallic signal transmission line with electric shielding, and a data recording instrument. One of the key issues in the measurement with a Bdot probe is to accurately transfer the induction signal to the final measuring instrument through the transmission line. Despite the relatively simple measurement principle, this is not always straightforward especially in plasma experiments that are frequently conducted in a severe noise environment caused by, for example, high-power RF waves, pulsed operation of high current sources, and radiation emitted from plasmas themselves. Fluctuations caused by these effects may be picked up as noise signals on the metallic transmission line. Particularly, when the recording device is operated at a distant location from the plasma for avoiding electric and radiation noise, signal transmission over a wide frequency range also can be a difficult task. In general, the existence of measurement instruments or large volume metallic components close to the experiment is not preferable because they could disturb ambient electromagnetic field lines. To meet experimental requirements under these restrictions, numerous schemes, such as shielding of the transmission line with appropriate grounding, differential measurement technique,[5] DC cut using a transformer, and impedance conversion using amplifiers,[1] have been developed for the reliable operation of Bdot probes for plasma studies.

Here, we propose a combined use of a Pockels electro-optic sensor and a Bdot coil loop for the measurement of local magnetic fluctuations in plasmas. The Pockels effect[8] is an electro-optic effect and has been utilized for the direct measurements of electric fields, such as microwaves and high-voltage phenomena.[9–15] In the field of plasma physics, examples of successful electric field measurement using electro-optic sensors include the validation of anomalous resistance brought on by the chaotic motion of charged particles,[10] diagnostics in an ion thruster,[11] and direct detection of ion cyclotron heating waves.[13] In this study, we expanded the use of Pockels sensors for magnetic measurements in plasmas. By combining the Pockels electro-optic modulator with a Bdot probe,[16] signals induced by the magnetic fluctuations in plasma are converted into light signals near the signal source and are easily transferred at a long distance using an optical fiber. This allows us to measure magnetic fluctuations with high noise immunity, which can be a useful tool for plasma diagnostics. In the following sections, we describe the measurement principle, calibration results, and preliminary measurement of plasma fluctuations using an electro-optic Bdot probe.

II. MEASUREMENT PRINCIPLE AND CALIBRATION

When electric fields are applied, some materials show a change in the refractive index n through the variation of the polarization state. Among these electro-optic effects, the variation of n is proportional to the applied external electric field strength E in the Pockels effect. The Pockels effect is used for various scientific applications, not only for electric field measurements but also for light modulators and polarization control of light beams. In a waveguide-type Pockels sensor, which is favorable in terms of miniaturization with circuit integration, a micro-waveguide is installed on the $LiNbO_3$ substrate, and electric field information is collected by interfering with the light waves traveling through the two channels [routes 1 and 2 in Fig. 1(a)].[17,18] The refractive index n for laser light traveling in each of waveguides 1 and 2 is written as

$$n_1 = n_{10} + a_1 E \quad \text{and} \quad n_2 = n_{20} + a_2 E, \tag{1}$$

using constant coefficients a_1 and a_2. Here, n_{10} and n_{20} are the values of the refractive index when $E = 0$. When used as a Pockels voltage sensor, the electric field is related as $E = V/d$, where V is the applied voltage between the waveguide electrodes with a distance of d, as shown in Fig. 1(a). When laser light with an electric field component of $P_{\text{in}} \sin(\omega t)$ is equally divided and injected into two waveguides as shown in the figure and extracted as

$$P_{\text{in}} \sin(\omega t + \phi_1)/2 \quad \text{and} \quad P_{\text{in}} \sin(\omega t + \phi_2)/2, \tag{2}$$

they interfere to produce an output light signal of

$$P_{\text{out}} = [1 + \cos(\phi_2 - \phi_1)] P_{\text{in}}/2. \tag{3}$$

Figure 1(b) shows the relationship between the phase difference $\phi_2 - \phi_1$ and the intensity of the output light signal. Because the phase difference is written as

$$\phi_2 - \phi_1 = \frac{2\pi L}{\lambda}(n_1 - n_2), \tag{4}$$

using the common length L of the waveguides and laser wavelength λ, we have

$$\phi_2 - \phi_1 = \frac{2\pi L}{\lambda}[(a_1 - a_2)E + n_{10} - n_{20}], \tag{5}$$

which shows a linear relationship between the variation of phase difference and electric field, $\Delta(\phi_2 - \phi_1) \propto \Delta E$. For small signal measurements, the operating point is often set to $\phi_2 - \phi_1 = \pi/2$ or $3/2\pi$

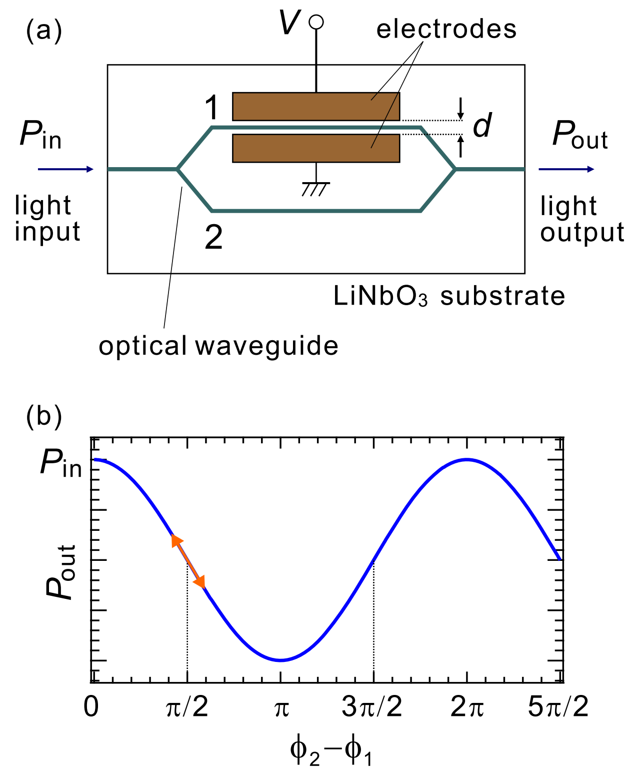

FIG. 1. (a) Construction of a waveguide-type electro-optic sensor and (b) an output laser light signal after interfering light beams extracted from two waveguides.

as indicated in Fig. 1(b) to maximize the sensitivity and to keep the linearity of the sensor.[18] In measurement conditions in the present study, the value of E is small enough so that the response of P_{out} for E is well approximated by a linear relationship [schematically shown as an arrow in Fig. 1(b)].

Figure 2(a) is a diagram of the electro-optic Bdot probe used for the plasma fluctuation measurement. The fluctuating voltage on the Bdot probe loop induced by the magnetic variation is converted into an optical signal by the Pockels electro-optic sensor. We used a single-turn loop pickup coil ($2b = 30$ mm in diameter) suitable for the measurement of high-frequency fluctuations. The main elements of the electro-optic sensor system consist of an electrostatically shielded reflection-type Pockels voltage sensor (Seikoh Giken ES-2005), a laser light source (wavelength $\lambda = 1.57$ μm and optical output power 14 dBm, ID Photonics CoBrite DX1-L-H01-FA), and a biased InGaAs fiber-optic detector (DC to 15 GHz, Newport 818-BB-35F). Each of these components is connected with an optical fiber via a circulator as shown in the figure. The output light signal P_{out} is converted into electrical signal V_{out} and recorded by a 500 MHz oscilloscope (Rohde & Schwarz RTM3004) with an input impedance of 50 Ω.

The sensitivity of the electro-optic Bdot probe was calibrated using a reference magnetic field generated by (A) a single-turn loop coil and (B) a Helmholtz coil. A reference field was generated by these coils connected to a function generator with twisted cables and a 50 Ω coaxial cable. The calibration coil current I_c was

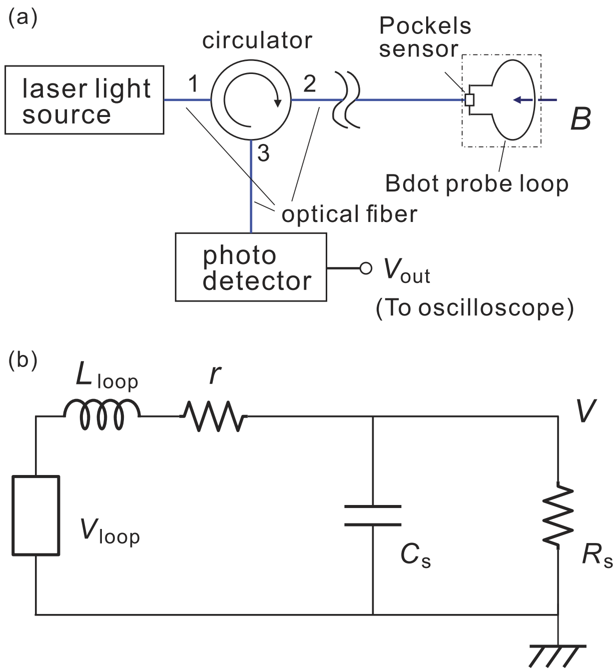

FIG. 2. (a) Schematics of electro-optic Bdot probe including the Bdot probe loop and Pockels sensor and (b) its equivalent circuit.

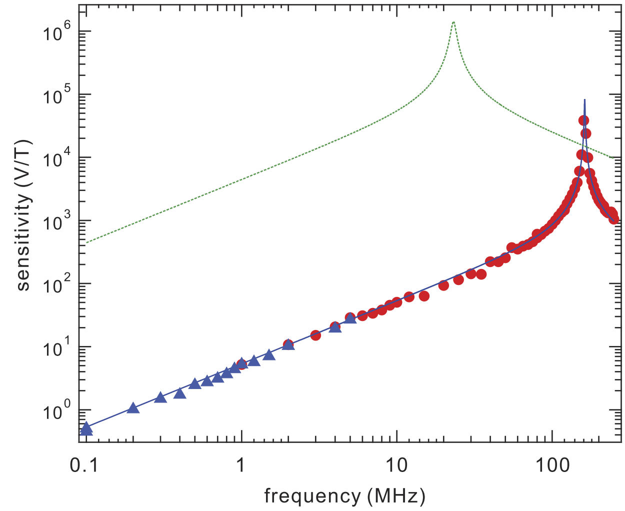

FIG. 3. Comparison of measured and calculated sensitivity of electro-optic and conventional Bdot probes for a normalized fluctuating magnetic field strength in a unit of tesla (T). Triangles (obtained with a Helmholtz coil) and circles (obtained with a single loop) show measured frequency dependence of the electro-optic Bdot probe. The solid line is the expected frequency dependence of the electro-optic Bdot probe obtained using the intensity of the produced voltage calculated using (7) and the sensitivity of the photodetector measured at $f = 1$ MHz. For comparison, the sensitivity of a conventional Bdot probe with a metallic transmission line of a similar length of 5 m is plotted as a dashed line.

monitored with a 1 GHz current transformer (Tektronix CT-1). The magnetic flux produced by (A) the single-turn loop that intersects the Bdot probe loop was numerically calculated. To validate the flux calculation, we also used (B) the Helmholtz coil to generate another reference magnetic field for a low frequency range below $f = 2\pi\omega = 5$ MHz. The coil current I_c that generates a magnetic field $(4/5)^{3/2}\mu_0 N I_c/R$ of the Helmholtz coil was monitored using Tektronix CT-1, where R is the coil radius, N is the turn number, and μ_0 is the permeability of free space. These two calibration results are displayed as circles (calibration coil A, single-turn loop) and triangles (calibration coil B, Helmholtz coil) in Fig. 3. Measurements of induced voltage conducted with the Helmholtz coil and the single loop showed a good agreement in an overlapping operation frequency range between 1 and 5 MHz, demonstrating the consistency of the numerical flux computation for the single-turn loop coil.

The electric circuit of the Bdot probe loop combined with the Pockels sensor [Fig. 2(a)] may be approximated as an equivalent circuit shown in Fig. 2(b). Because of the waveguide electrode structure, the Pockels sensor has a capacitance C_s and resistance R_s. When a Bdot probe with N turns and a single loop area of S interlinks a fluctuating magnetic field $B(t)$, the induced voltage on a loop is

$$V_{\text{loop}} = SN\frac{dB}{dt}. \tag{6}$$

Relationship between the output signal $V(\omega)$ and the local magnetic field $B(\omega)$ in the frequency space is given using the Fourier transform of the circuit equation[2] as

$$\frac{V(\omega)}{B(\omega)} = SN\frac{\omega^2\left(L_{\text{loop}}/R + rC_s\right) + i\omega\left[(1 + r/R_s) - L_{\text{loop}}C_s\omega^2\right]^2}{\left[(1 + r/R_s) - L_{\text{loop}}C_s\omega^2\right]^2 + \omega^2(L_{\text{loop}}/R_s + rC_s)^2}. \tag{7}$$

When the internal resistance r of the loop is negligible, this equation is simplified to

$$\frac{V(\omega)}{B(\omega)} = SN\frac{\omega^2\left(L_{\text{loop}}/R_s\right) + i\omega\left[1 - L_{\text{loop}}C_s\omega^2\right]^2}{\left[1 - L_{\text{loop}}C_s\omega^2\right]^2 + \omega^2(L_{\text{loop}}/R_s)^2}. \tag{8}$$

Furthermore, in the low frequency limit of $\omega \ll 1/\sqrt{L_{\text{loop}}C_s}$ and $\omega \ll R_s/L_{\text{loop}}$, a well-known expression of the Bdot probe signal amplitude ($\propto \omega$) is obtained.

In Fig. 3, we compare the calculated sensitivity of the electro-optic Bdot probe with the measured sensitivity. The circles and triangles in the figure depict the aforementioned sensitivity of the electro-optic Bdot probe measured with the setup in Fig. 2(a). In the current setup, the pickup coil is made of a single-turn loop coiled in $2b = 30$ mm in diameter using a 50 Ω semirigid coaxial cable with a center conductor diameter of $2a = 0.203 \pm 0.013$ mm [Fig. 4(b)]. We measured that $L_{\text{loop}} = 98$ nH, $C_s = 11$ pF, and $r = 1.2$ Ω. Here, the self inductance of an N turn loop of radius b and wire radius a is approximated as[19]

$$L_{\text{loop}} = \mu_0 N^2 b\left[\ln\left(\frac{8b}{a} - 2\right) + \frac{1}{4}\right] \tag{9}$$

and is 94.4 nH for the aforementioned values, which showed a consistent agreement with the measured value of L_{loop}. In Fig. 3, numerical results calculated with the relationship between $B(\omega)$ and

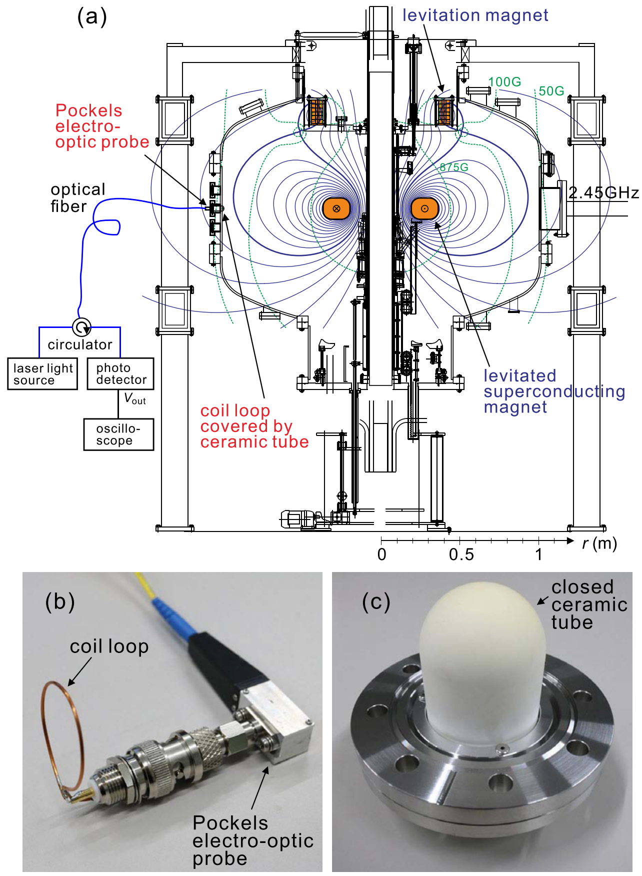

FIG. 4. (a) Cross section of the RT-1 experiment including the positioning of measurement point with the electro-optic Bdot probe, (b) construction of the probe using a coil loop, Pockels electro-optic sensor, and grounded-type vacuum feedthrough, and (c) installed probe structure covered by a protective ceramic tube.

$V(\omega)$ in (7) using the measured values of $L_{\rm loop}$, C_s, and r are also plotted as a solid curve including the efficiency of the photodetector in Fig. 2(a) to convert the optical signal to $V_{\rm out}$. Reasonably excellent agreement between the measured (circles and triangles) and calculated (solid line) values indicates that the equivalent circuit in Fig. 2(b) with the aforementioned component values is an appropriate model for the electro-optic Bdot probe system. The magnetic sensitivity exhibits linear dependence below ∼100 MHz and has an LC resonance peak at $f_{\rm LC}$ = 159 MHz in the present configuration.

For comparison, the calculated sensitivity of a conventional Bdot probe with a metallic coaxial cable of 5 m in length (C = 500 pF) is also plotted in Fig. 3 as a dashed line. The sensitivity of the current electro-optic Bdot probe setup is much lower than that of conventional Bdot probes, which may be improved by using a new stable laser system in the future. Because the higher bandwidth is mainly caused by the smaller capacitance, on the other hand, with the electro-optic Bdot probe, we can measure fluctuation activities in a higher frequency range below the resonance frequency.

III. MEASUREMENT OF PLASMA FLUCTUATION

To demonstrate the operation of the electro-optic Bdot probe system for magnetic fluctuation measurement in plasma, we installed the probe at the RT-1 "laboratory magnetosphere" (levitated dipole) experiment[20,21] as shown in Fig. 4. In the dipole magnetic field configuration, the fluctuation activities of plasmas are a subject of great interest because fluctuations play crucial roles in the self-organization processes of plasmas through wave particle interactions. As illustrated in Fig. 4(a), we positioned a coil loop at the edge of the confinement region inside the vacuum chamber of RT-1 on the equator of the device (i.e., the same vertical position as the levitated superconducting coil). The loop was covered by a protective ceramic tube and was connected to a Pockels electro-optic probe located at the atmosphere side through coaxial vacuum feedthrough. The fluctuation signal was converted into an optical signal and sent to a photodetector, as shown in

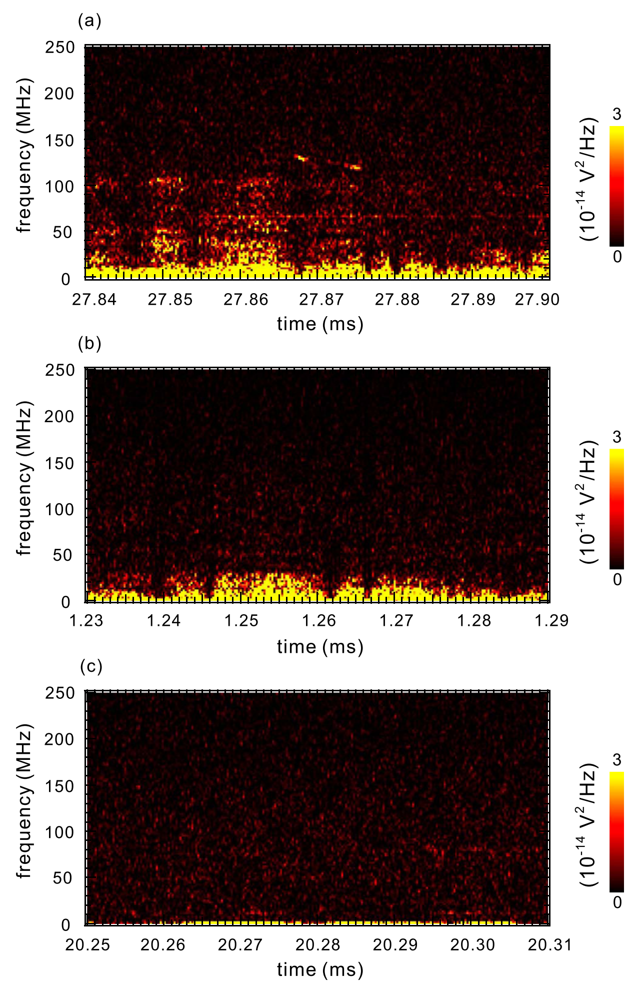

FIG. 5. Frequency power spectrum of magnetic fluctuations measured using the electro-optic Bdot probe in RT-1 for (a) high-β and (b) low-β plasma generation cases. (c) Measurement outcome with a conventional Bdot probe with the high-β operation case.

the diagram in Fig. 2(a). The output signal from the photodetector is measured using an oscilloscope with a sampling frequency of 500 MHz.

Figure 5 displays a typical frequency power spectrum measured using the electro-optic Bdot probe for the high-β plasma operation of RT-1. The plasma was generated by electron cyclotron resonance heating (ECH) with a 2.45 GHz microwave of 10 kW. The working gas was helium. A typical electron density at the edge confinement region was 1×10^{16} m^{-3}. At the position of the Bdot probe loop located at the edge confinement region, the electron cyclotron frequency was f_{ce} = 140 MHz. The fluctuations that appear in the frequency range of 1–10 MHz are most likely caused by unstable laser intensity delivered into the Pockels sensor. In a condition with a lower filling gas pressure and an increased hot electron component of high-β plasma in (a) of the figure, the fluctuation activities were seen at frequency ranges comparable with and below f_{ce}. Because these fluctuations were not detected in a low-β operation by increased neutral gas pressure in (b) while maintaining a similar noise environment, we conclude that they are magnetic signals related to plasma activities induced by the significant ratio of hot electron components produced by ECH. Fluctuation activities with a different behavior were also reported in the previous study at RT-1 with different diagnostics[22] below the electron cyclotron frequency. As a comparison with conventional Bdot probe diagnostics, in Fig. 5(c), we performed an identical measurement by swapping the electro-optic sensor system to the conventional metallic coaxial cable with 5 m, the same length as the optical transmission line. We could not locate the fluctuation activities in a frequency range comparable with f_{ce} in this conventional B dot probe system. The stray capacitance of the measurement line was C = 570 pF, and the LC resonance frequency for this case with the same coil loop was f_{LC} = 22 MHz, which was much below f_{ce}. This demonstrates one of the benefits of the electro-optic Bdot probe measurement.

IV. CONCLUSION

In summary, we proposed and demonstrated a combined use of a Pockels electro-optic sensor with a Bdot probe as a new diagnostics tool for magnetic fluctuations in plasmas. Compared with conventional Bdot probes, the benefits of the electro-optic Bdot potential are (1) greater noise immunity and (2) broader frequency bandwidth. (1) Because the optical fiber-based transmission line is electrically isolated, the system is free from the electric noise pickup induced by the metallic transmission line while positioning the data recording equipment at a distant location from the pickup loop, which is ideal for various plasma experiments. (2) Additionally, because we can drastically reduce the capacitance that couples with coil loop inductance in this system, we can measure magnetic fluctuation activities in a higher frequency range below the resonance frequency. On the other hand, because the sensitivity of the present electro-optic Bdot probe setup, ~50 V/T at 10 MHz, is still significantly lower than that of conventional Bdot probes, further advancement is required on this point. The first investigation using the electro-optic Bdot probe for plasma fluctuation measurements successfully demonstrated the detection of electromagnetic activity of the magnetospheric plasma of RT-1.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

H. Saitoh: Investigation (lead); Visualization (lead); Writing – original draft (lead). **M. Nishiura**: Conceptualization (equal); Resources (equal); Writing – review & editing (equal). **T. Nakazawa**: Investigation (equal); Writing – review & editing (equal). **J. Morikawa**: Conceptualization (equal); Investigation (equal); Writing – review & editing (equal). **Z. Yoshida**: Conceptualization (equal); Investigation (equal); Methodology (equal); Writing – review & editing (equal). **R. Osawa**: Investigation (equal); Resources (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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