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Effect of Direction of Magnetic Field and Probe Surface on Measurement of the Electron Density by Electron Density and Temperature Probe

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Abstract**—**The electron density and temperature probe (EDTP) was proposed by Oyama and others instead of a Langmuir probe that is the conventional measurement tool of an ionosphere measurement. The EDTP is the most reliable instrument to measure the electron density and temperature of the ionosphere. The EDTP sweeps high frequencies which were applied to a probe and measures the resonance frequency of a plasma in the electron density measurement. The plasma of ionosphere is influenced by the magnetic field of the Earth. Therefore, the electron density varies by the relationship between the plane of the probe and the directions of the magnetic field. We generated a plasma in the space plasma chamber and changed the magnetic field of the chamber using a Helmholtz coil. In this study, we investigated the effects that are caused by the electron density in the direction of the magnetic field. As a result, we found the electron density become very high when the magnetic field was applied to the direction of the front of the disk probe.

Keywords**—**Microsatellite, ionosphere, Electron Density and Temperature Probe, electron density and electron temperature.

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I. INTRODUCTION

THE first investigators who observe the ionosphere using rocket were Reifman and Dow. They measured the electron temperature of ionosphere plasma using the Langmuir probe which was installed in the V-2 rocket in 1947. [1],[2].

Recently, the ionosphere observation technique utilizing microsatellites has been proposed to study the mechanism of the ionosphere change. However, using Langmuir probes for conventional ionosphere measurement has two big problems when using microsatellites. The first problem is that satellite potential easily changes when a sweeping voltage is applied to the DC probe. The second problem is that the electrode contamination affects the measurement.

Therefore, new observation techniques were proposed to perform the exact ionosphere observation using microsatellites. Electron Temperature Probe (ETP) was invented by K. Hirao and others. The probe was free from the influence of the electrode contamination and showed the sufficient results when installing in many rockets and satellites.

The ETP can measure an electron temperature of the ionosphere precisely and can be implemented on microsatellites due to its small size and light weight. Also, Oyama and others added a function to measure the electron density on ETP. However, the measured result of electron density using EDTP is easily affected by geomagnetic field and the direction of the electrode. We investigated the influence of the direction of the magnetic field to the electron density measurement by EDTP.

II. THE BASIC THEORY OF ELECTRON DENSITY AND TEMPERATURE PROBE

In this section, we describe the theory of EDTP. **Figure 1** The EDTP system shows the EDTP system. The EDTP has a disk-shaped probe which formed by combining the semicircles. One of the semicircular probes measures a floating electric potential, and other probe measures the voltage when high frequency voltage is added to the probe. The EDTP can measure electron temperature and the electron density of the plasma. Each measurement method is described below.

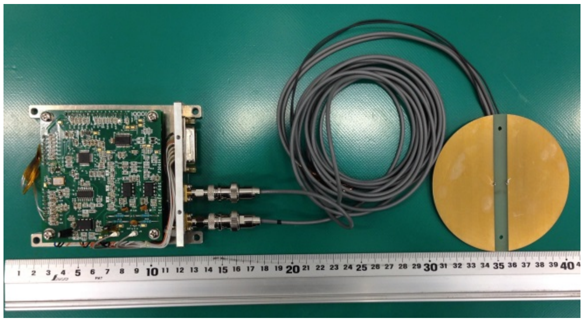

Figure 1 The EDTP system

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A. Electron Temperature Measurement Principle

The electron temperature probe (ETP) was first invented by Hirao and Miyazaki in 1970's and later improved by Hirao and Oyama in Japan [3],[4]. The ETP can measure the electron temperature with high precision, and the measurement is not influenced by the electrode contamination effect. The probe has been installed in 5 Earth-orbiting scientific satellites [5]-[10]. Also, the ETP was deployed for the sounding rocket use in Germany, India, Canada, USA and Brazil.

In the ETP, the high-frequency sinusoidal voltage is applied to a probe. **Figure 2** shows the principle of ETP probe. The current-voltage (I-V) characteristic curve shifts to the negative potential when the sinusoidal signal is superposed on the voltage which is applied to the electrode. This frequency should be fairly lower than the electron plasma frequency, and higher than the ion plasma frequency of the ambient plasma. The shift of the I-V characteristic curve depends on the amplitude of the sinusoidal wave. The probe current is expressed as

$$\begin{aligned} I_p(V + a\sin\omega t) &= I_{es}\exp(-e(V + a\sin\omega t)/kT_e) - I_i \\ &= I_{es}\exp(-eV/kT_e)\exp(-ea\sin\omega t/kT_e) - I_i \end{aligned} \tag{1}$$

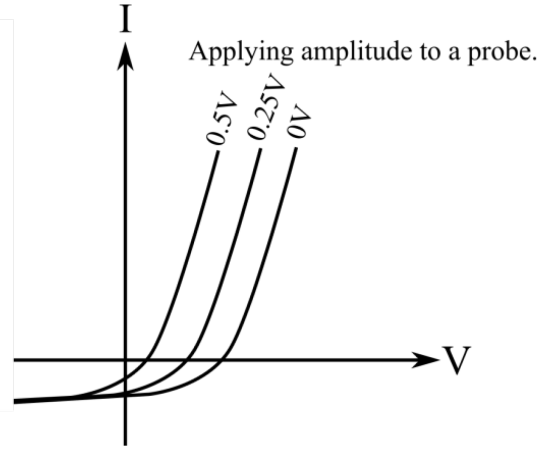


Figure 2 Principle of ETP probe

where I_p is the probe current, a is the amplitude of the sinusoidal wave, ω is angular velocity, t is time, I_{es} is the electron saturation current, e is the electric charge, I_i is ion current, k is the Boltzmann constant, and T_e is electron temperature. Then, the total probe current has both the DC component and the oscillating AC component. If we filter out the oscillating AC part, the probe current becomes

$$I_p(V) = I_{es}exp(-eV/kT_e)I_0(ea/kT_e) - I_i \tag{2}$$

where I_0 is the zero-order modified Bessel function. When the probe current $I_p(V)$ is zero, the applied probe voltage is called the floating potential. The floating potential V_{fa} for the DC part can be obtained as

$$V_{fa} = -(kT_e/e)\ln[I_i/\{I_{es}I_0(ea/kT_e)\}]. \tag{3}$$

The floating potential V_f without the added sinusoidal oscillating voltage is calculated as

$$V_f = -(kT_e/e)\ln(I_i/I_{es}). \tag{4}$$

Then, the floating potential shift ΔV_{fa} when sinusoidal oscillating voltage with amplitude a is applied can be calculated from Eq. (3) and Eq. (4) as

$$\Delta V_{fa} = V_{fa} - V_f = -(kT_e/e)\ln[I_0(ea/kT_e)]. \tag{5}$$

When applying another amplitude of $2a$, the floating potential shift ΔV_{f2a} is expressed as

$$\Delta V_{f2a} = V_{f2a} - V_f = -(kT_e/e)\ln[I_0(e2a/kT_e)]. \tag{6}$$

Then, the electron temperature T_e can be calculated from the output voltage of the EDTP.

In addition, T_e also can be calculated from following equation where R indicates the ratio between two floating potential shifts.

$$\begin{aligned} R &= \Delta V_{f2a}/\Delta V_{fa} \\ &= \ln[I_0(e2a/kT_e)]/\ln[I_0(ea/kT_e)] \end{aligned} \tag{7}$$

B. Electron Density Measurement Principle

The principle of the electron density measurement is based on the impedance probe which is developed by Oya and Obayashi [11]. The first experiment of the impedance probe called the gyro-plasma probe was carried out by using a rocket in 1965. In the EDTP we detect the variation of the DC probe voltage due to a sweeping frequency signal with amplitude a, which is applied to a feeding capacitor which transmits the signal to the probe electrode. The DC voltage changes depend on the antenna impedance, which varies with the input signal frequency and the capacitance of the feeding capacitor.

The impedance shows the sheath resonance (SHR) and the upper hybrid resonance (UHR). The SHR occurs at the frequency where the antenna impedance goes to zero. The UHR occurs at the frequency where the antenna impedance becomes infinite. The UHR frequency f_{UHR} is the function of plasma frequency (f_P) and the electron gyro frequency (f_c) expressed as

$$f_{UHR}^2 = f_P^2 + f_c^2. \tag{8}$$

The accurate electron density (N_e) is deduced from the UHR frequency as

$$N_e = (4\pi^2 m_e \varepsilon_0/e^2)[f_{UHR}^2 - (eB/2\pi m_e)^2]. \tag{9}$$

where m_e, ε_0, and B are the mass of electrons, the vacuum permittivity, and a magnetic field respectively.

C. System Configuration

The schematic diagram of the EDTP is shown in **Figure 3**. The EDTP has two semicircular planar probes which are placed on the same plane with a 10 mm gap. The sinusoidal wave is applied to only the probe A from the direct digital synthesizer (DDS). The diameter of the probe is 100 mm.

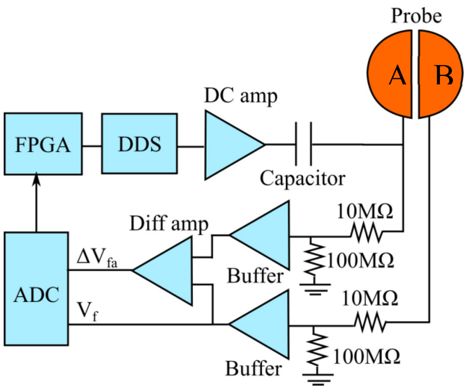


Figure 3 The schematic diagram of the Electron Density and Temperature Probe

Figure 4 shows the input and output signals of EDTP. The upper graph shows the signal applied to the probe, and the lower panel graph shows the output signal of floating potential shift.

The electron temperature measurement mode requires signals with constant frequency and two different amplitudes. The DDS signal generator first produces a constant frequency signal of 200 kHz for 0.8 seconds with amplitude changing from 0 V to 0.5 V to 0.25 V to 0 V for the electron temperature mode operation. Subsequently, in the electron density measurement mode, the DDS produces a swept-frequency signal from 100 kHz to 10 MHz with the constant amplitude (0.5 V) for the next 1 second. Then the sequence of signals is fed to the probe electrode through a 200 pF capacitor. The EDTP can measure the electron density and electron temperature which are in the ranges of 10^3-10^6 cm^{-3} and 1000-3000 K, respectively.

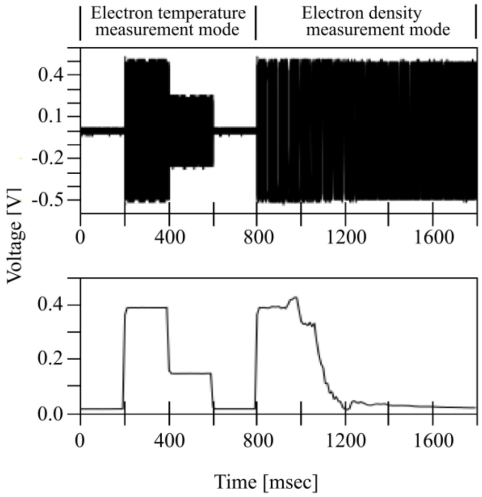
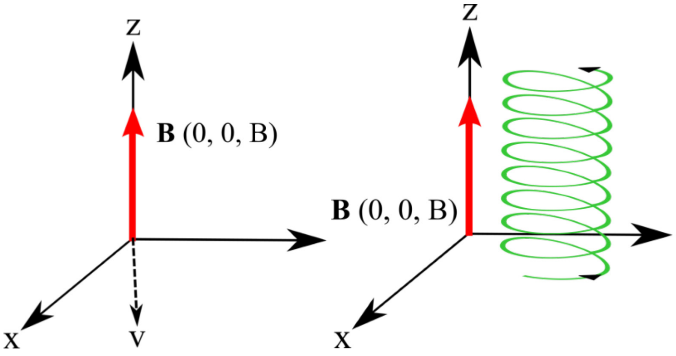


Figure 4 The input and output signals of the EDTP

III. THE EFFECT OF MAGNETIC FIELD

We explain what kind of influence an electron in the plasma comes under by a magnetic field. We consider an example of the magnetic field on the z-axis direction in the **Figure 5**. An electron that moves along the z-axis direction is not affected by the magnetic field (B) at all because the Lorentz force does not work in the direction of the line of magnetic force. However, the moving electrons in the x and y direction (v) that are perpendicular to the magnetic field are affected by the Lorentz force. Therefore these electrons perform the right-handed circular motion around a magnetic force line. This phenomenon is called the cyclotron motion of an electron. The actual electrons of plasma move in various directions because an electron has plural ingredients of x, y and z. Therefore, the electron performs the spiral exercise to the line of magnetic force direction in the **Figure 5 (b)**.



(a) (b)

Figure 5 (a) An electron moves along z-axis. (b) Right-handed circular motion around magnetic force line

IV. EXPERIMENTS AND RESULTS

A. Experiment Conditions

Using the Large Space Plasma Simulation Chamber, we set the EDTP system. The inside of the space chamber is made into a vacuum state of about 2×10^{-6} Pa, then the chamber is filled with gaseous nitrogen to restore internal pressure to about 2×10^{-3} Pa. The plasma generator varies its supplied current from 0.1 A to 0.05 A to 0.03 A sequentially to change the electron density. Then, the magnetic field inside the space chamber is changed by using the Helmholtz coil to measure the effect of the direction of magnetic field. We applied the eight different magnetic field conditions as follows:

- Non-magnetic field
- Earth magnetic field
- 50000 [nT] to the x-axis direction
- 50000 [nT] to the $-x$-axis direction
- 50000 [nT] to the y-axis direction
- 50000 [nT] to the $-y$-axis direction
- 50000 [nT] to the z-axis direction
- 50000 [nT] to the $-z$-axis direction

The magnetic field conditions are shown in **Figure 6**. The surface of the EDTP probe is parallel to the X-Y plane and parallel and perpendicular to the Z axis. The origin of the magnetic field is at the center of the chamber.

Also, we use a spherical probe to study the characteristics of the circular disk probe during the experiment. The spherical electrode is less influenced by the magnetic field because the amount of magnetic flux on the surface of the probe is not affected even if the direction of the magnetic field changes. Therefore, we can measure the influence of the magnetic field on the circular disk probe by comparing the spherical electrode and the circular disk electrode. We changed a forming condition of the plasma into three conditions in each direction of the magnetic field. **Figure 7** shows each probe and magnetic field directions in the chamber. The direction of the circular disk probe surface turns to the source of the plasma.

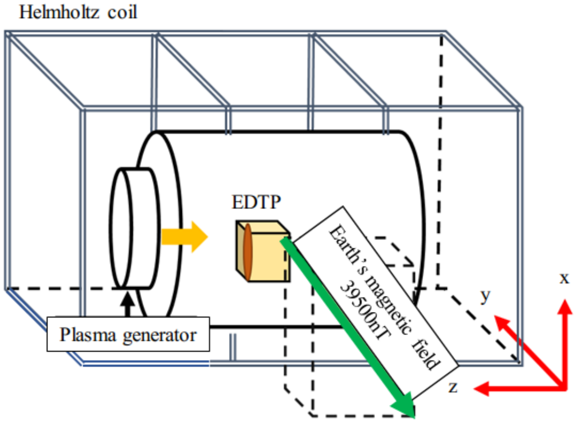


Figure 6 Experiment concept using space chamber to validate the proposed EDTP

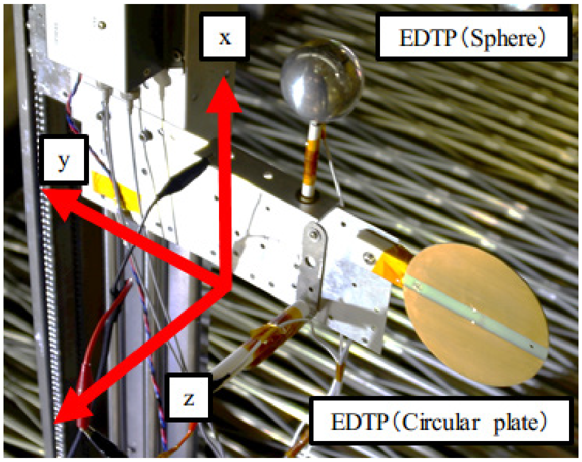


Figure 7 Each probe and magnetic field direction in the chamber

B. Results

Figure 8 shows the result of the electron density, which is measured using the disk probe and the spherical probe at each condition. In the measurement, except the magnetic field of the $-z$ direction case, there was no big difference on a disk-formed probe and a spherical probe. When adding the magnetic field on the $-z$ direction, the result of the electron density in the plate probe was higher than that of z-direction, but the result of the spherical probe decreased. The **Figure 9** shows the influence of the magnetic field in the disk probe. When we applied the z-axis direction of the magnetic field, electrons in the chamber gather around the plasma generator and the back side of the disk probe in cyclotron motion. The electron density of the z-axis case is the highest of the four cases; x-axis, $-x$-axis, y-axis and $-y$-axis. The chamber is a cylindrical object which has the length of the z-axis direction is longer than those of the x-axis and y-axis. Electron density decreases in four cases because more electron collides with the wall of the chamber in these cases than in the case of the z-axis. Also, the disk probe does not measure electrons of the back side of the probe. When the direction of the magnetic field is the $-z$-axis, electrons move from the plasma generator to the back of the chamber. In addition, the many electrons have motion component in $-z$-axis direction because the electron is emitted from the plasma generator in a beam shape. Therefore, the electron density is the highest of all cases because the electron at the surface of disk probe increases. **Figure 10** shows the case of the spherical probe in the direction of the magnetic field of the z-axis and the $-z$-axis. The movement of electrons is the same as that of the disk probe case. In the case of magnetic field of the z-axis, electrons of the back side of the probe is increase. The disk probe cannot measure electrons of the back side of the probe. However, the spherical probe can measure these electrons. Therefore, the electron density by the spherical probe is higher than the disk probe.

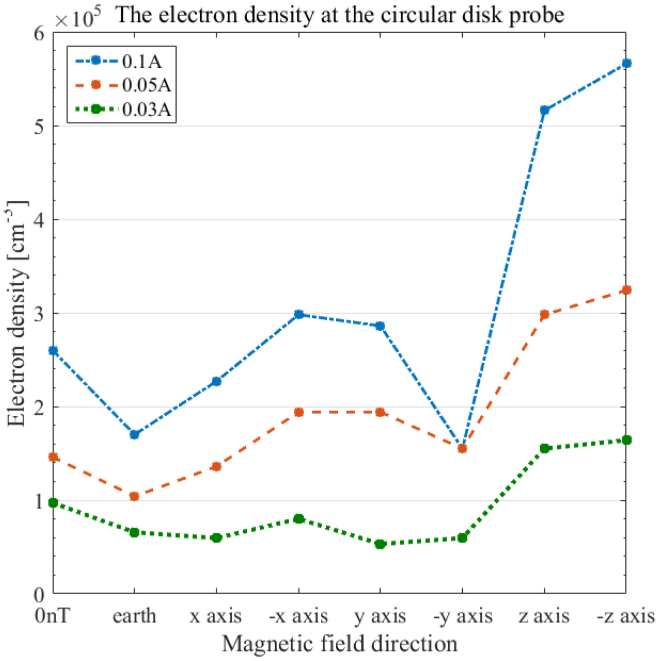


Figure 8 The electron density on each condition

In the case of the magnetic field in the $-z$-axis, electrons of the front side of the probe is increase, and the electrons of the back side of the probe decrease. Therefore, the electron density measured by the spherical probe is lower than the measurement by the disk probe. We compare each magnetic field in the spherical probe. The electron density in the magnetic field of the $-z$-axis is considerably lower than the magnetic field of the z-axis. This result shows that the decrement of electrons in the back side of the probe is bigger than the increase of electrons in the front of the probe.

However, it is difficult to conceive electrons considerably decrease on the back side of the probe because electrons spread to the back side of the chamber. We consider the cause that the electron density of the spherical probe is decreased in the magnetic field of the $-z$ direction.

We used UHR for a calculation of the electron density, which is calculated from an inductance L_p of the plasma and a capacitance C of the sheath. UHR is expressed in the next expression.

$$\omega_{UHR} = \frac{1}{\sqrt{L_p C}} \tag{10}$$

When electron density increases, also the UHR increases. The condition of increment at the UHR is the L_p or the C decrease. When the electron density increases, the L_p decreases by the next expression.

$$L_p = \frac{l}{S}\left(\frac{m_e}{n_e e^2}\right) \tag{11}$$

where S is the cross-sectional area of the plasma.

The plasma makes a sheath which is about ten times larger than the Debye length around the probe. This sheath forms a capacitor C between the probe and the plasma. The distance between electrons is reduced by the increment of the electron density. Therefore, the increment of the electron density causes the increment of the C because a Debye length and a width of a sheath of the plasma get shortened.

In the disk shape probe, the electron that hit on the front part of the probe is increased by the magnetic field of the $-z$ direction. We consider the high electron density was measured because the decrement of L_p by the increment of an electron flow is bigger than the increase of C by a decrease of sheath width. In the spherical probe, the electron density of the front part of the probe is similar to the disk shape probe. Consequently, we have concluded that the decrease of the electron density of the spherical probe in the magnetic field of the $-z$ direction may have been caused by the decrease of a capacitor C of a spherical probe surface and the increase of the inductance L_p of the plasma by electrons of the back side of the probe.

It is not realistic to measure C and L_p directly using this hypothesis. There is another experiment that changes the direction of the disk probe variously and compares each probe. By this experiment, we can confirm the influence from electrons to the front and the back side of probe.

V. CONCLUSION

The electron density and temperature probe (EDTP) presents a useful ionosphere condition data about the Langmuir probe obtained using the conventional technique in the ionosphere observations. However, the electron density measurement of the EDTP by a disk probe depends on the characteristic of electron distribution because the electron in the ionosphere is affected by the Lorentz force of the magnetic field of the earth. We measured the electron density by the EDTP at the plasma which was affected by a variety of the magnetic field direction. As a result, the electron density has increased when the magnetic field has the front direction of the disk probe ($-z$ axis direction). The reason for this is a decrease of a plasma inductor (L_p) by the magnetic field of $-z$ axis direction. When the Lp decreases, the electrons from the plasma generator move to the $-z$ axis direction, and the UHR shifts to the high frequency direction.

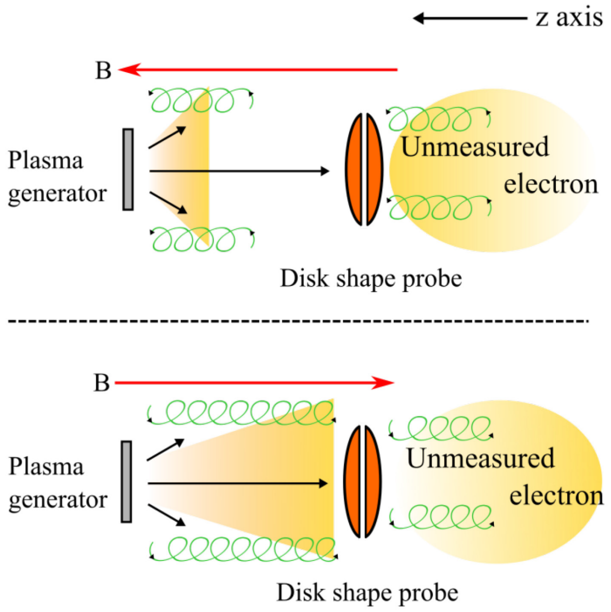


Figure 9 Effect of the magnetic field in the disk probe

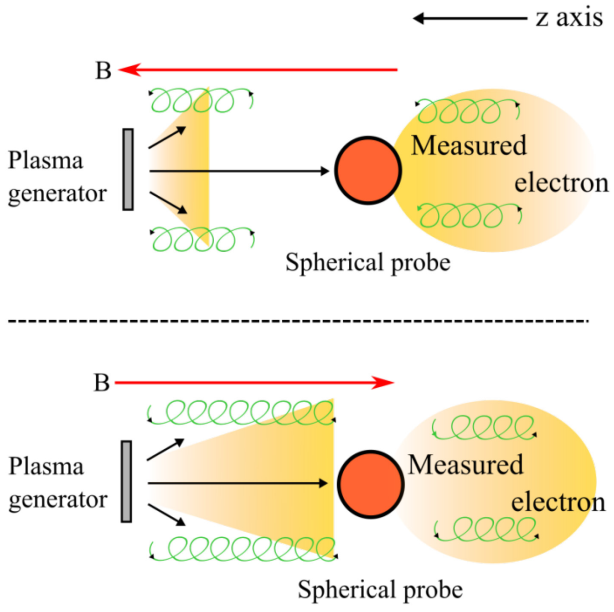


Figure 10 Effect of the magnetic field in the spherical probe

The sheath capacitor (C) increases because the sheath width became narrower according to approach of the electron. The reason for this is a decrease of a plasma inductor (L_p) by the magnetic field of $-z$ axis direction. When the Lp decreases, the electrons from the plasma generator move to the $-z$ axis direction, and the UHR shifts to the high frequency direction. The sheath capacitor (C) increases because the sheath width became narrower according to approach of the electron. The decrement of L_p is bigger than the increase in the C. Therefore, an electron density increased. We plan to inspect the relationship of the direction of the magnetic field, the electron transfer and the disk probe of the EDTP in next experiment.

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