# Flight-type-probe for Measuring the High Density and High Temperature Plasmas

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**Abstract:** The flight-type-probe (FTP) for measuring the high density and high temperature plasmas is proposed. The FTP is designed as a compact magnetic and/or an electrostatic probe, which travels with a fast speed through the core plasma, in order to measure the core plasma parameters simultaneously. The obtained information signals are transmitted by the rf signal from the core plasma side towards the observer during the flight and/or stored in the compact CPU elements buried in the FTP for the analysis after the flight.

**Key words:** flight-type-probe (FTP), magnetic probe, electrostatic probe, fast speed, measuring core plasma, rf signal, compact CPU

## I. INTRODUCTION

An electrostatic probe is a simple and convenient diagnostic tool for measuring the plasma density and temperature with high spatial and time resolutions. In low temperature plasmas, many kinds of electrostatic probes are widely used for measuring the plasma to clarify the mechanism thereof. In the hot and dense fusion plasma, however, the application of the electrostatic probe is limited to such a localized region as the scrape off layer (SOL), since the conventional probe would be destroyed in the core plasma region due to the great heat damage and/or the electromagnetic force during the plasma disruption. For the measurement of plasma parameters of high density and high temperature plasmas nowadays, indirect methods using electromagnetic waves, charged particle beams and spectroscopic methods are available. However, the spatial resolutions of these active and passive diagnostic methods are not good since it is so difficult to identify the original location generating signals. Furthermore, since these signals may often contain complex physical quantities related to passive and active lights it is difficult to analyze and to identify the precise plasma parameters.

In order to make the best use of the electrostatic probe having a high spatial and time resolution, we consider a flight-type-probe (FTP), in which the probe circuit and memory elements are installed in a capsule to be thrown into the core hot plasma from one side port with a fast speed. This is intended to prevent the probe from melting due to the hot plasma. The measurement is completed during the flight of the FTP and the data acquired are transmitted to observers outside observers by rf signals and/or are saved in the memory elements of the FTP to be analyzed after reproduction [1].

As early as the 1970s the current profile, which is an indispensable quantity in tokamaks, could not be measured in large tokamaks. In such a small tokamak as MINIMUK with the relatively low temperature and weak density plasma, however, the current profile in the core plasma has been successfully measured with a high spatial and time resolution by the magnetic probe

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whereby the mechanism of MHD instability has been precisely clarified [2]. Later, the current profile in the large tokamak could be measured by the spectroscopic method using the fast beam probe with the principle of Zeeman effect [3] and with the motional Stark effect [4] and with the soft X ray emission [5]. However, the instrumentation of these diagnostics is large and the performance is complicated.

If not only the magnetic probe but also the electrostatic probe can be inserted into the hot plasma, the capability of the diagnostic tool must be enhanced to clarify various plasma parameters with a higher spatial and time resolution. Development of the computer memories and the CPU capability has become remarkable recently. For example, the areas of the CPU and the memory have become as small as a pin like elements, which has made it possible to manufacture moble telephones. The development of memory content has greatly progressed in the last fifteen years. In 1990 only the 128 kB memory could be stored on 8 inch (19.6 × 19.6 cm) floppy disks, however, nowadays the 512 MB memory can be stored at the size of 1.5 × 1.0 cm chips in mobile phones. The performance of the FTP is imagined as an ultra-miniature mobile telephone being thrown into the hot plasma. If the size of the probe including the data acquisition system is packed in such a small region, the probe technique can be used for the measurement of the core plasma. It should be noted that before damage of the probe, the operation of FTP should be finished quickly. This corresponds to technical extension from the Reciprocating Langmuir Probe (RLP) [6] and from the rocket-borne electrostatic probes in space plasma [7]. In space plasmas, the Langmuir probe with the probe circuit and the amplifier is on board the rocket and the information signals are received by observers on the ground [8], however, the weight and the data acquisition system are too large and complicated to be used as the FTP.

In this paper, the hardware of the FTP is shown and the possibility of measuring plasma parameters using it in the core plasma is discussed.

## II. DESIGN OF FLIGHT-TYPE- PROBE

### A. Performance of the FTP

The RLP cannot be used in the whole region of the core plasma since it would be so troublesome for the housing surrounding the signal cables to be immersed in the core plasma. This would disturb the plasma and would suffer from much heat damage and would melt the RLP substance itself. In the case of FTP, this fear is avoided since the FTP has no support structure. The schematic performance of the FTP is shown in Fig. 1, where the FTP is injected with a fast speed from one side-port, crossing the total region through the core plasma to reach another side-port with a shock absorber. The dimension of the FTP is made as small as 1 cm and the probe pin for the electrode is about 1 mm in length. The probe circuit and the CPU system are installed in a so reduced localized region that is buried in the insulating material like the boron nitride or the macor-H. Several types of the FTP are prepared and the special launcher chamber room for the FTP is equipped, which is controlled in a high vacuum condition being separated from the atmospheric room by the gate valve. When the FTP is used, both gate valves of A and B are opened and the FTP is injected towards the core plasma. The process is remote controlled automatically. During the flight of the FTP signals from the core plasma, which are mainly a voltage drop due to the probe current from the core plasma, are received by the FTP and are stored in the CPU memory and/or are immediately transmitted by the rf signal. The probe circuit must be triggered by the remote signal. After the flight, both gate valves are closed and the FTP is taken out for the analysis. Several kinds of manufactured FTP's manufactured are injected to observe the plasma parameters across the core plasma step by step using the launching mechanism, which is either a pellet type injector [10] or a rail gun type [11]. It is necessary for the FTP not to rotate against the magnetic field while measuring the ion temperature by the magnetic probe and by the differential double probe. The rail gun has the merit of keeping a constant angle without any rotation after injection.

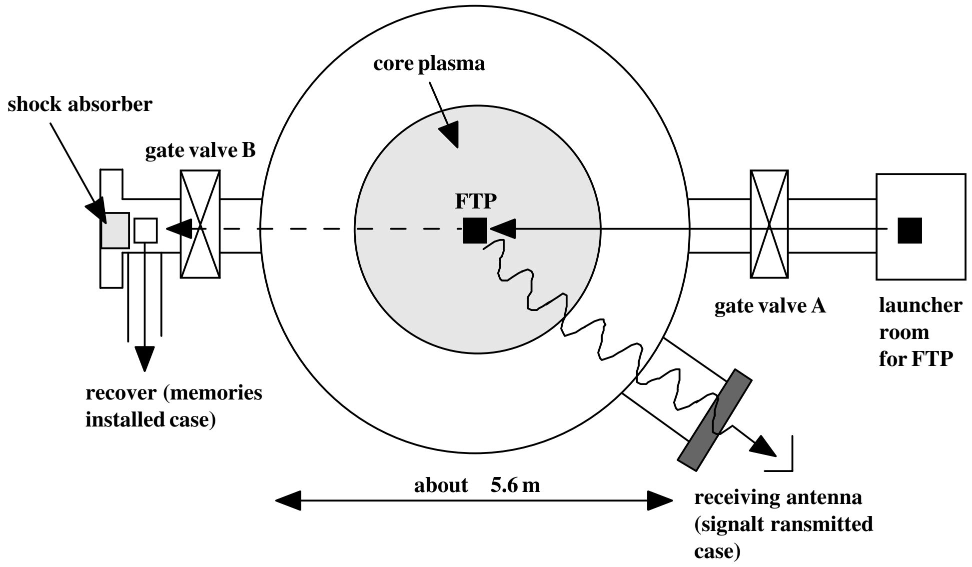

**Fig. 1** Schematic design of the performance of the flight type probe (FTP), where the scale of plasma is assumed as that of ITER [9].

### B. Structure of the FTP

Detail structures of the FTP are shown in Figs. 2 and Fig. 3. We consider two types of the FTP. One type is used to measure the current profile as shown in Fig. 2, which is denoted by MPRF-1. The other type is denoted by EPCPU-1 as shown in Fig. 3 and is used to measure the electron temperature Te, the ion temperature Ti and the floating potential $V_f$.

In the MPRF-1, the magnetic probe and/or Hall element for x, y and z direction measures the poloidal magnetic field $B_\theta(r)$, which gives the current profile J(r) in the core plasma of tokamaks. For the measurement of $B_\theta(r)$ we use the conventional magnetic probe technique with several turns coils and/or the Hall element. The voltage generated in the loop circuit of the magnetic probe and/or the Hall element is picked up through a finite resistance. The voltage signals of $I_1$, $I_2$ and $I_3$ are superimposed on the carrier wave of the crystal oscillator and are transmitted toward the observer outside the chamber, where we can acquire the data in real time. For the crystal oscillator, the voltage controlled is available due to the transmission of the signal, which is named as the voltage controlled crystal oscillator (VCXO). The candidate of this is, for example, ECCM7 of the Ecliptek corporation, the scale being 3.2 × 2.5 × 0.7 mm and the frequency of the carrier wave is 13.5 MHz. This element can operate at the atmospheric pressure below 85 °C [12].

In the EPCPU-1, the triple probe and the differential double probe are installed with the probe circuit. The triple probe is used for measuring the electron temperature $T_e(r)$ and the floating potential $V_f(r)$, which are obtained by applying a constant bias voltage. For the measurement of $V_f$ we follow the procedure of JFT-2M, in which we observe the higher voltage across the detective resistance [13]. The differential double probe is used for measuring the ion temperature $T_i(r)$. For the measurement of $T_i$ we follow the differential double probe (DDP) technique in which we can measure $T_i$ by observing the ratio of the ion saturation current between two probe pins [14]. The real data of $T_i$ using the DDP has been successfully obtained in JFT-2M [15]. If we expect to measure the higher ion temperatures, a high voltage may be preliminarily charged in a condenser of the probe circuit before the flight since scale large batteries cannot installed in the FTP. The information signals are stored in a compact CPU elements, which includes the voltage exchanger circuit, A/D transformer with small batteries having about 5 volts and the memory elements. For detecting the initial state of measurement, an external trigger to the thyristor switch and/or the signal for leaving the contact must be received by an antenna from outside the chamber as shown in Fig. 3. In the measurement of the DDP it is necessary to use two insulating amplifiers to detect the voltage drop due to the fact that in the A/D transformer the voltage is measured against the common standard level. These elements have recently been highly integrated to a small region with a high spatial resolutions [16]. For example, since the measuring points are 100 and a sampling time of 0.01 sec of the signal is necessary for the measurement of the spatial profile, then the necessary memories are estimated to be 1 kB per 1 channel. In the MPRF-1, 3 channels and 8 channel signals in the EPCPU-1, then the total memory may be lower than 10 kB, which could be fully installed in the reduced size FTP volume of about S= 2000 mm$^3$ (12.6 × 12.6 × 12.6 mm) [17]~[18]. The proposed CPU is MSP430F149 of Texas Instruments, which is 9 mm × 9 mm size and can operate with a voltage of 1.83 ~ 3.6 V including the A/D and the CPU elements [19].

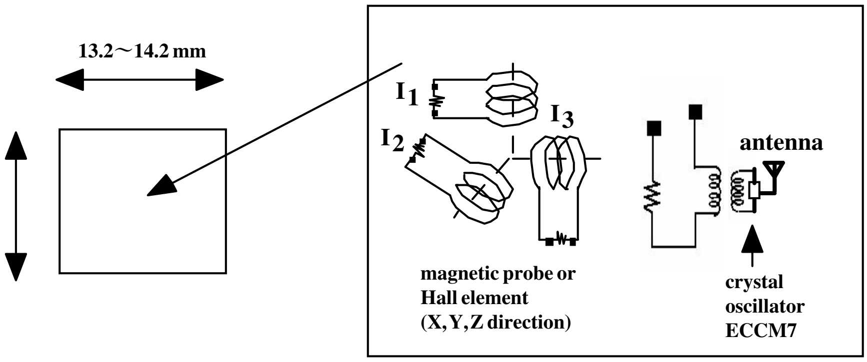

**Fig.2** The magnetic probe and the rf signal transmission (MPRF-1) of the FTP.

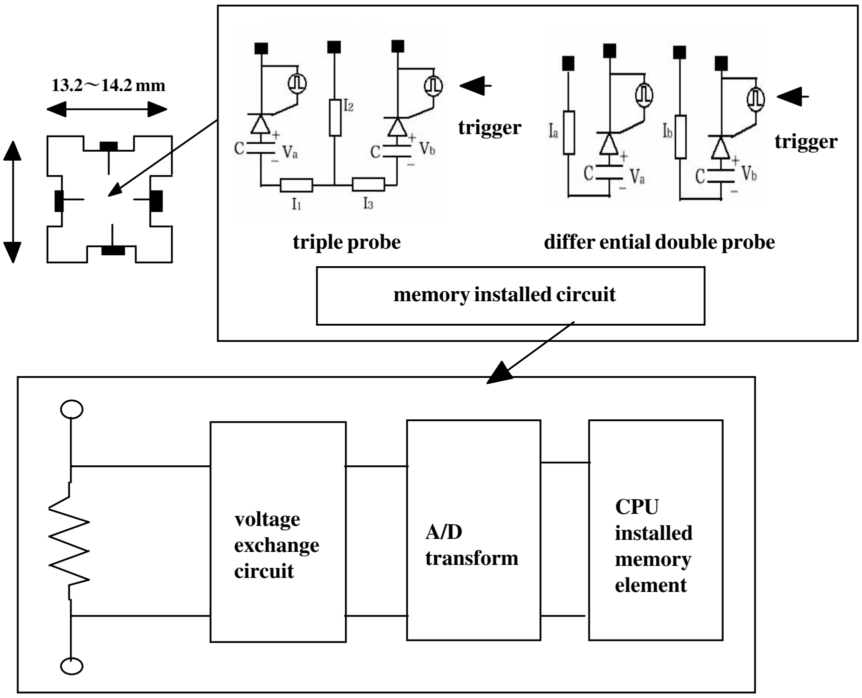

**Fig. 3** The electrostatic probe installed in the CPU memory (EPCPU-1) of the FTP which contains the triple probe, the differential double probe and the CPU memory.

### C. Method to draw out the data

How can we best draw out the data when the measurement of the FTP is performed ? Some kinds of advanced data acquisition are necessary in the FTP. In the case of the MPRF-1, since the data are transmitted during the flight and the measurement is made in real time, the some kinds of the receiving instruments including software to convert the real profile are necessary. The procedure is controlled by the acquisition system at the observer.

In the case of EPCU-1, since the data are analyzed after recovery, one of the possible methods of drawing out the data is sending the data by the infrared rays inserting a small LD in the circuits, which is almost same as the remote control switch in a television.

### D. Estimation of heat load

The FTP must travel through the core plasma quickly before being melted. We can estimate the temperature rise T of the FTP using the following equation of thermal conduction :

$$\frac{\partial T}{\partial t} = \frac{\lambda}{c\rho}\nabla^2 T, \tag{1}$$

where $\rho$ is the density , c is the specific heat, and $\lambda$ is the thermal conductivity. We consider the FTP as a spherical object with radius $r_0$ with a uniform temperature of 0 °C. When the surface temperature of the object is suddenly brought to $T_0$, the time and space distribution of the temperature in the object is obtained as

$$T = T_0\{1 - \frac{2r_0}{\pi r}\sum_{s=1}^{\infty}\frac{(-1)^{s+1}}{s}\exp[-(\frac{\lambda}{c\rho})(\frac{s\pi}{r_0})^2 t] sin\frac{s\pi r}{a}\} \tag{2}$$

from eq.(1), where s is integer. The temperature rise in the object is limited by the width of $r_c=2\pi/[\lambda t/(c\rho)]^{1/2}$, where the distance is estimated from the surface. We consider the temperature distribution of the object from eq. (2); then, the surface temperature of the FTP becomes

$$\frac{dT_0}{dt} = \frac{q - W}{4.18\sqrt{(\pi\lambda c\rho)t}} \tag{3}$$

from the energy conservation law, where q is the heat power density flowing into the object and $W=\sigma T^4$ is the black-body-radiation loss of the object, where $\sigma$ is the Stefan-Boltzmann constant. The value of q is expressed as $q = \gamma T_e J_{is}$, where $T_e$ is the electron temperature, $J_{is}$ is the ion saturation current density, and $\gamma$ is the heat transmission rate which is given by

$$\gamma = \frac{2.5T_i}{T_e} + \frac{2}{1-\delta_e} - 0.5\ln[2\pi\frac{m_e}{m_i}\{1 + \frac{T_i}{T_e}\frac{1}{(1-\delta_e)^2}\}] \tag{4}$$

where, $m_e$ is the electron mass, $m_i$ is the ion mass, $T_i$ is the ion temperature and $\delta_e$ is the secondary electron emission rate [20]. The value of W is expressed as $W=\sigma T^4$, where $\sigma$ is Stefan-Boltzman constant as $5.672 \times 10^{-12}$ $\mathrm{Wcm^{-2}K^{-4}}$. The equation of (1) is solved by the numerical integral using the fifth order Lunge-Kutta method. We assume that $J_{is}$ is presented by the ion saturation current $J_{is}=0.61env_{thi}$, where e is the electronic charge , n is the plasma density and $v_{thi}$ is the ion thermal velocity. Furthermore, we assume the density and temperature profiles such as ; $n=n_{e0}(1-(r/a)^2)^2$, $T_e=T_{e0}(1-(r/a)^2)^2$ and $T_i=T_{i0}(1-(r/a)^2)^2$, where a is the radius of plasma. We consider the ITER scale tokamak as the typical plasma parameter of the core plasma, such as $n_{e0}=1 \times 10^{14}$ $\mathrm{cm^{-3}}$, $T_{e0}$= 10 keV, $T_{i0}$= 10 keV, a =200 cm, and the mass number A=2 (deuterium).

Equation (3) is numerically solved with the fifth-order Lunge-Kutta method. We denote the coordinates as follows: x is major radius direction and y is the displacement from the equatorial plane. The FTP travels at the velocity $v_0$ in the x direction, apart from y from the equatorial plane; at which point t becomes $(x+a)/v_0$. When the FTP travels at the velocity of $v_0$ below 10 km/s, which is the maximum velocity of flying objects shut by the rail gun, the estimated temperature of $T_0$ is given in Figs. 5 (a) and (b) for the tungsten electrode at y/a = - 0.7 and for the macor-H insulator at y/a = - 0.8. It is seen that the surface of the FTP melts when the FTP travels near y = 0 and $v_0$ is so small. However, the FTP would not melt at $v_0$ = 8 km/sec and y/a = - 0.8 at the final stage of the flight (x/a = 1), since the melting points of tungsten and macor-H is 3683 K and 2173 K, respectively. It would be possible to measure the plasma parameters in this situation, since we consider the measurement with the FTP in the region of the internal transport barrier [21]. For various y/a values corresponding to the barrier region, $T_0$ as a function of x/a is shown in Figs. 6 (a) and (b). It is seen that the surface of the FTP would not be melted when the FTP travels at y/a < - 0.66 for tungsten and y/a < -

0.76 for macor-H with $v_0$= 8 km/ at the final stage of the flight (x/a = 1). We define $T_{0m}$ as the maximum surface temperature of the FTP when the FTP travels from x = -a to x = a. The calculated $T_{0m}$ are shown in Figs. 7 (a) and (b) for various values of $v_0$ and y/a. It is seen that the maximum surface temperature of the FTP would not reach melting point when the FTP travels at y/a < -0.68 for tungsten and y/a < -0.78 for macor-H with $v_0$ > 4 km/s.

When the thickness of tungsten and macor-H is larger than rc, the temperature rise in the inner box of the FTP having the crystal oscillator and the CPU elements is smaller than 0.1 K. For example, when $v_0$ = 10 km/s, $r_c$ = 2.1 mm for tungsten and $r_c$ = 0.8 mm for macor-H at t = 2a/$v_0$. Thus, the crystal oscillator and the CPU elements can keep the operation stable.

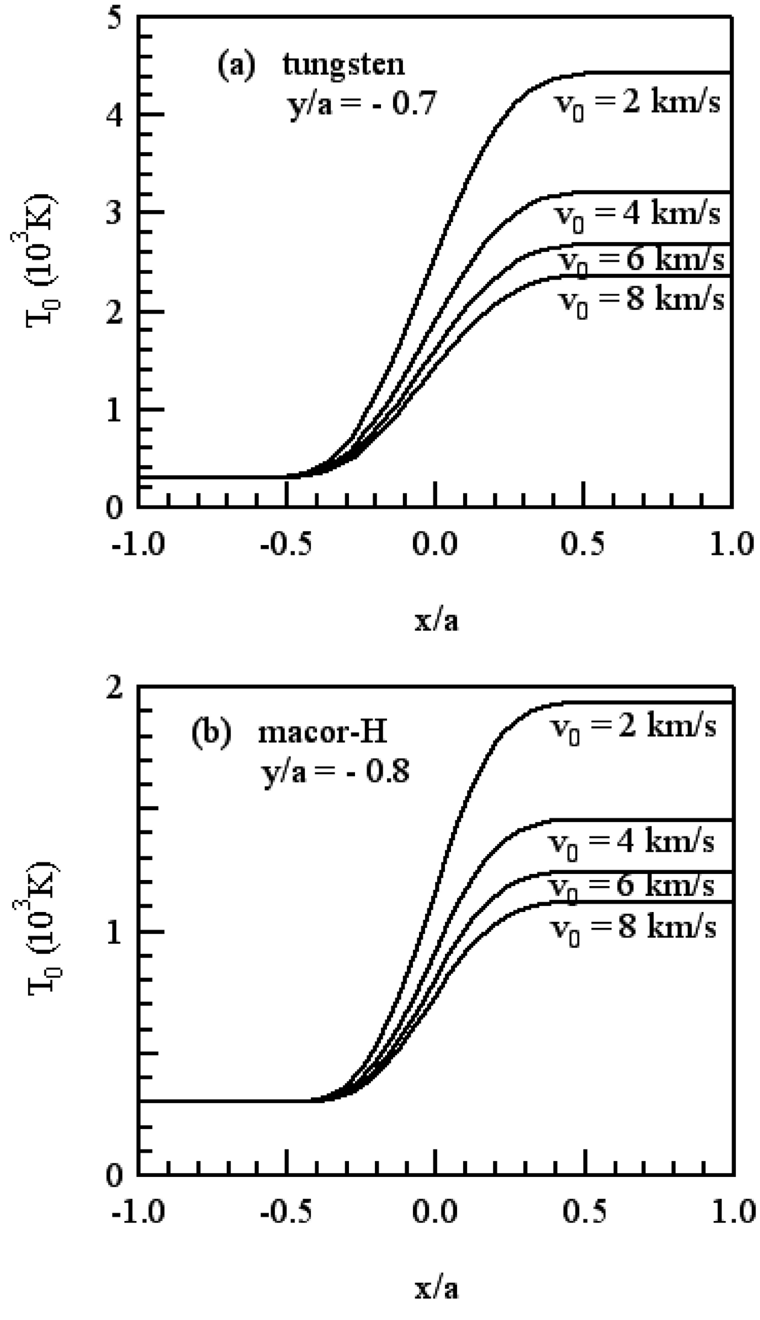

**Fig. 5** Calculated surface temperature increases of (a) the tungsten plate and (b) the macor-H plate as a function of x/a for various flight velocities, where A = 2, $n_{e0} = 1 \times 10^{14}$, $T_{e0}$ = 10 keV, $T_{i0}$ = 10 keV, and $\delta_e$ = 0.2.

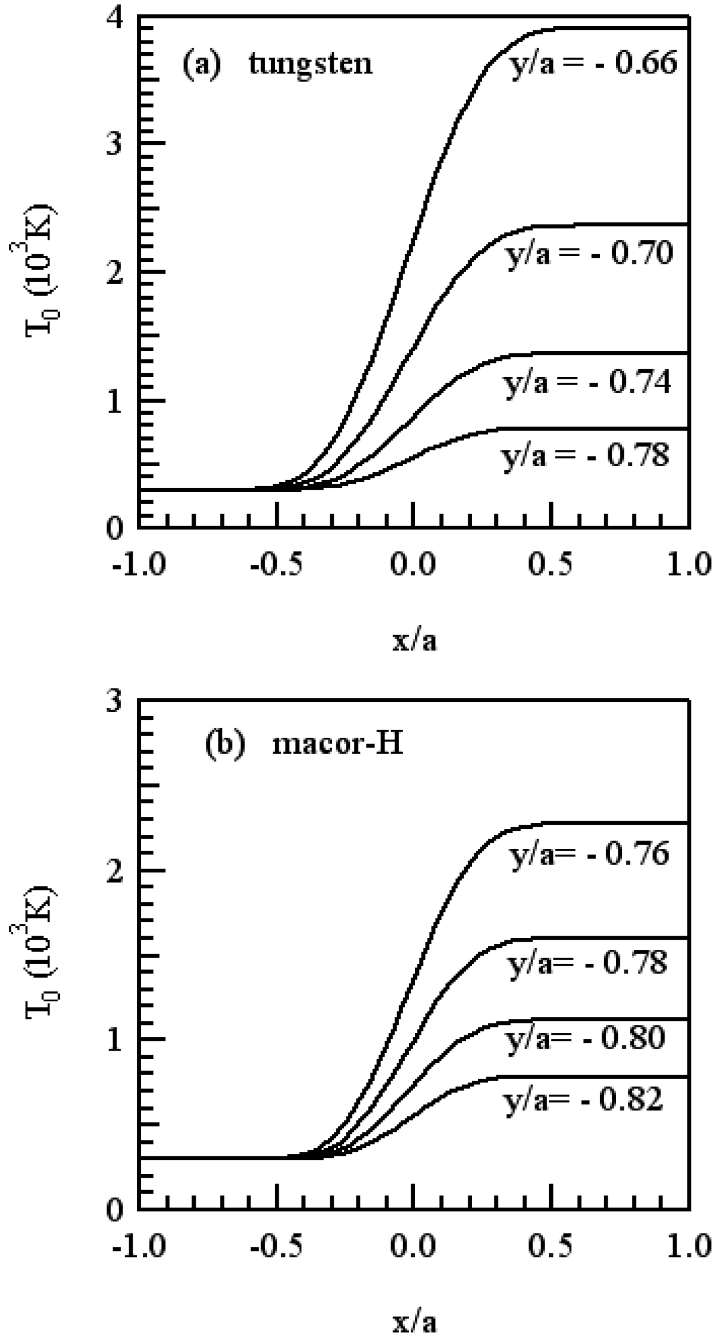

**Fig. 6** Calculated surface temperature increases of (a) the tungsten plate and (b) the macor-H plate as a function of x/a for various y/a values, where the flight velocity is 8 km/s, A = 2, $n_{e0} = 1 \times 10^{14}$, $T_{e0}$ = 10 keV, $T_{i0}$ = 10 keV, and $\delta_e = 0.2$.

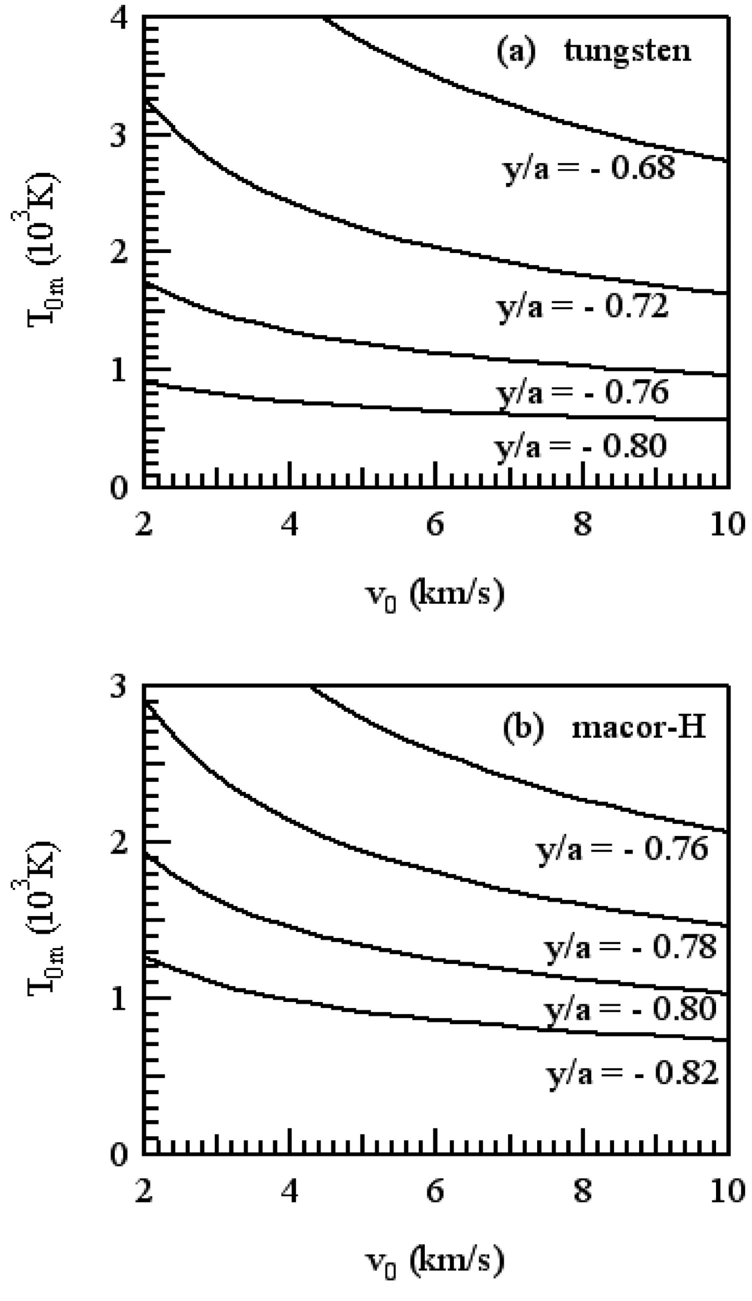

**Fig. 7** Calculated maximum surface temperature increases of (a) the tungsten plate and (b) the macor-H plate as a function of flight velocity for various y/a values, where A = 2, $n_{e0} = 1 \times 10^{14}$, $T_{e0}$ = 10 keV, $T_{i0}$ = 10 keV, and $\delta_e = 0.2$.

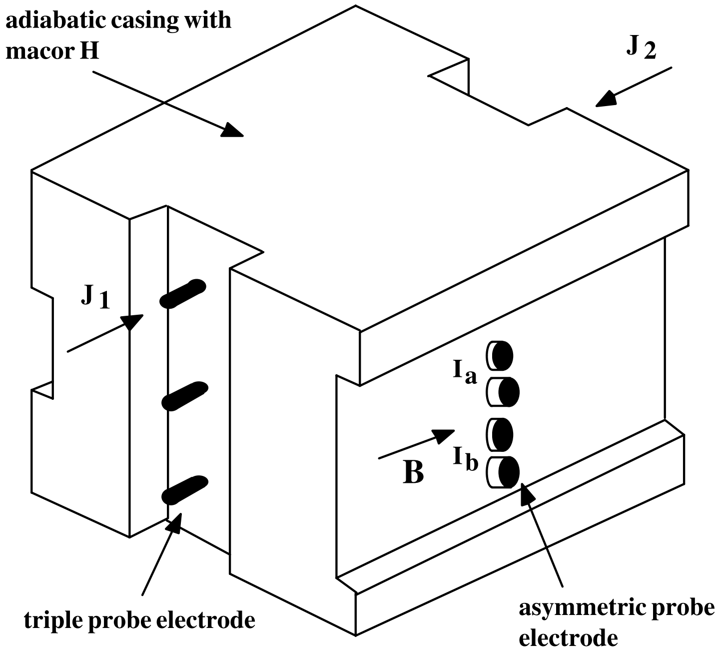

Fig. 4 Bird's-eye view of the EPCPU-1 of the FTP.

## III. OBSERVATION METHOD

Figure 4 shows the bird's-eye view of the FTP. This is the case of the EPCPU-1, where the triple probe and the differential double probe are buried in the low conductive insulator (macor H). All the electrodes made of high conductive material (tungsten) are placed in the shadow region in considering of the sheath effect. If we observe the current $J_2$, which is the current flowing anti-direction of the magnetic field line, we can also estimate the flow velocity. The size of this probe must be as small as possible to avoid the disturbance to the core plasma Three currents $I_1$, $I_2$ and $I_3$ in Fig. 2, which would be inductively excited in the loop coils when the plasma current flows in tokamak, generate voltages across the detection resistance during the flight and excites the crystal oscillator accompanying the rf signal, whose signal is simultaneously transmitted to the observer. The frequency of the oscillator is proportional to the excited voltage. The current of the MPRF-1 is superposed on the rf signal and we can estimate from this current the magnetic field profiles in the r, $\theta$ and z directions, these the values reflecting the poloidal magnetic field. When the Hall element is used for the detection of the poloidal magnetic field, some kinds of battery must be equipped inside the FTP.

Denoting $I_a$ and $I_b$ for both currents in Fig. 4 we can evaluate $T_i$ as

$$T_i[eV] = 9.57\times 10^7 \frac{(ZBL_p)^2}{A}(\frac{rI_a - I_b}{I_a - I_b})^2 \qquad (5)$$

where Z is charge state, B is magnetic field $L_p$ is the length of the differential double probe to the toroidal direction and A is the atomic number. The voltage is either positively or negatively biased in stationary state. It should be noted that the probe direction must be exactly in parallel to the magnetic field for the precise measurement of the ion temperature.

Using the value of $T_i$ and $V_f$ we refer to a more exact expression of the space potential as

$$V_s = V_f + \frac{k}{e}T_e \ln[\exp(-\frac{1}{2})\sqrt{(\frac{m_e}{2\pi m_i})(\frac{T_e}{T_i + T_e})}], \qquad (6)$$

where the value of $T_i$ is measured by the DDP while $V_f$ and $T_e$ are measured by the triple probe. Since the floating potential is equal to the space potential for the emissive probe, if one more circuit including the emissive probe having the heating coil can be installed inside the EPCPU-1, we can measure the space potential directly. From the value of $V_s$, the radial electric field in plasma is evaluated by the relation of $E_r = -\partial Vs/\partial r$, which may be useful to study the H mode physics in the core plasma.

If the current $J_1$- $J_2$ is obtained, the information of $nkT_e$ and $nkT_i$ as well as the information of the flow can be obtained. Even if $T_e$ and $T_i$ are not available to be measured due to the difficulty in voltage biasing, since the value of $J_j$(j=1.2) must be a function of $nkT_e$ and $nkT_i$ we can estimate $T_e$, $T_i$ and n as well as the flow where $J_1$ and $J_2$ are the currents parallel and anti-parallel currents to the magnetic field as shown in Fig. 4, respectively.

If we can observe the density and the potential fluctuations by the EPCPU-1 of the FTP, the study of the plasma transport must be advanced. In JFT-2M, where the transport has been investigated by using RPL [22], the use of FTP extends the measurement area over the whole region including the hot core plasma.

## IV. DISCUSSION AND CONCLUSIONS

When we first considered the first time the idea of the FTP about 20 years ago, when the current profile could not measured in the large tokamak, then we designed the scale of the FTP is as large as a golf-ball which was too large to apply to be applied to the tokamak. However, the development of the memory storage has recently been developed to a greater degree of density. The scale of the memory density has been increased by $10^4$ times in the last fifteen years. This development makes it possible to realize such a mechanism as the FTP for the first time.

The flight mechanism is the rail gun type or the pellet injection. If an easier mechanism of the flight as well as the probe circuits is developed the FTP will be easily manufactured and the application to the large machine must become more convenient.

The installment of the global positioning system (GPS) would assure the FTP exact location, since the objective of the FTP is to know the exact profile of the plasma parameter exactly. However, it is not always necessary to equip the FTP with the GPS system, in the FTP since if the FTP can catch at the opposite port successfully the time behavior of the current would reflect the information of the position exactly.

Some kinds of condenser do not operate in some low pressure conditions, and when an over-voltage is applied to them the electrolytic liquid included will flow out. Therefore, the area of the condenser may be placed in an isolated pressurized box. Since some kinds of ferrite must be included in the component of the CPU, a small Hall current may be generated in the circuit during the flight and the data would be damaged. It is necessary to remove such effects before manufacturing the FTP. If a timing device is necessary, it is possible to install this with small coils and resistors.

In conclusion, we have proposed a flight-type-probe for the measurement of high density and high temperature plasma in the core of fusion machines. If we can manufacture the compact FTP including the probe circuit and CPU memory with highly integrated way for the FTPs to fly with a speed of more than several km/sec keeping the angle of the electrode constant to the magnetic field, the FTP would survive in the hot plasma and yield the profiles of poloidal magnetic field, electron and ion temperatures, floating potential and fluctuations satisfactorily with a high spatial resolution. The use of FTP in hot and dense plasmas will open the frontier of the hot plasma confinement study.

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