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Fast reciprocating probe assembly for the Hanbit magnetic mirror device

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A fast reciprocating probe assembly (RPA), which can scan a long length up to 100 cm (with maximum velocity of 136 cm/s), is fabricated to measure basic plasma parameters during a plasma discharge time (~500 ms) in the Hanbit magnetic mirror device. The probe driving mechanism consists of two steps of movements; first a slow movement to set the probe at a standby position, and then a fast one to measure plasma parameters within an adjustable time interval. Both movements are driven by only a pneumatic system. This is a distinctive feature of the probe drive system that has advantages of a simple driving mechanism and an easy adjustment of the fast stroke length for the wide range. The probe head is fabricated as a modular type for easy replacement. Performance test results and initial measurements from the fabricated RPA will be discussed. © *2000 American Institute of Physics.* [S0034-6748(00)04905-4]

I. INTRODUCTION

Recently, fast reciprocating probe assemblies (RPAs) have been used for measuring plasma parameters in several tokamaks.[1–4] In these RPAs, a step motor for slow movement and a pneumatic cylinder for a fast one were used as the probe drive system except for the case of the TEXTOR,[4] in which two road-type cylinders for slow and fast movements were used.

Under the high magnetic field environment (a few tesla), a pneumatic RPA for both the slow and fast movements is recommended. Hence, we designed and fabricated a fully pneumatic driven RPA for the Hanbit magnetic mirror device.[5] The probe drive system was remotely controlled by two sequential trigger signals from an external signal generator, and the elapsed distance of the probe (including its moving speed) was measured with a position transducer. Two performance tests of the probe drive system and the initial measurement by the probe in the RF Test Facility (RFTF) device[6] were carried out in order to prove the utility of the probe assembly.

In this article, the main components of the RPA are described in Sec. II, and performance tests of the probe drive system (such as the reproducibility of the prepositioning and the vertical vibrations) and the initial measurements by the probe in the RFTF device are presented in Sec. III. Finally, the discussion is given in Sec. IV.

II. PROBE DESCRIPTION

A. Probe drive system

The main drive components of the fast RPA consist of a pneumatic cylinder, five solenoid valves, three optical limit switches, and bellows sectors. Total length of the probe assembly is 197 cm and its stroke is 120 cm. Figure 1(a) shows the images of the left and right side views of the fabricated RPA.

The pneumatic cylinder is a road-less type (SMC cylinder, model: MY 1M32-1200AH-Z73), its maximum allowable pressure is 0.8 MPa. There are two piston chambers on the right and left sides of the piston in the cylinder. In each chamber, working gas from the gas reservoir is drawn in or exhausted through each port. The slide table on the cylinder moves along the guide rail due to the pressure difference between two chambers. The probe is fastened to the slide table. The solenoid valves are composed of a main solenoid and four additional solenoids. The main one is a closed center type (SY7320) and it controls the initial position and moving direction of the slide table. The additional one is a single type (VF3130) that has a speed control valve controlling the speed of the motion. The optical limit switch is an inductive proximity type (Autonics, model: PR12-4AO), and it optically senses the probe position and then generates a trigger signal to stop the probe at the required position within allowable deviation. Two optical limit switches are located at two end positions to set a length of the fast scanning by the probe and an optical limit switch is located at a standby position to set the probe at an initial position for the desired measurement. The bellows unit is used as the transfer unit of the probe assembly, and it is composed of eight bellows sections, seven stainless rings, and two end flanges. Each bellows sector is a welded type (o.d.∅57.15 mm, i.d.∅38.1 mm, $L=35.4$ cm) and is made of SUS 304. Stainless steel rings were welded between two bellows sectors in order to connect each bellows sector, thus the bellows was one unit having the long strokes of 120 cm. Seven pairs of plates were fastened to the seven rings. The plate has a ball bearing (NTN, No. 694). The bearing supports bellows sectors and

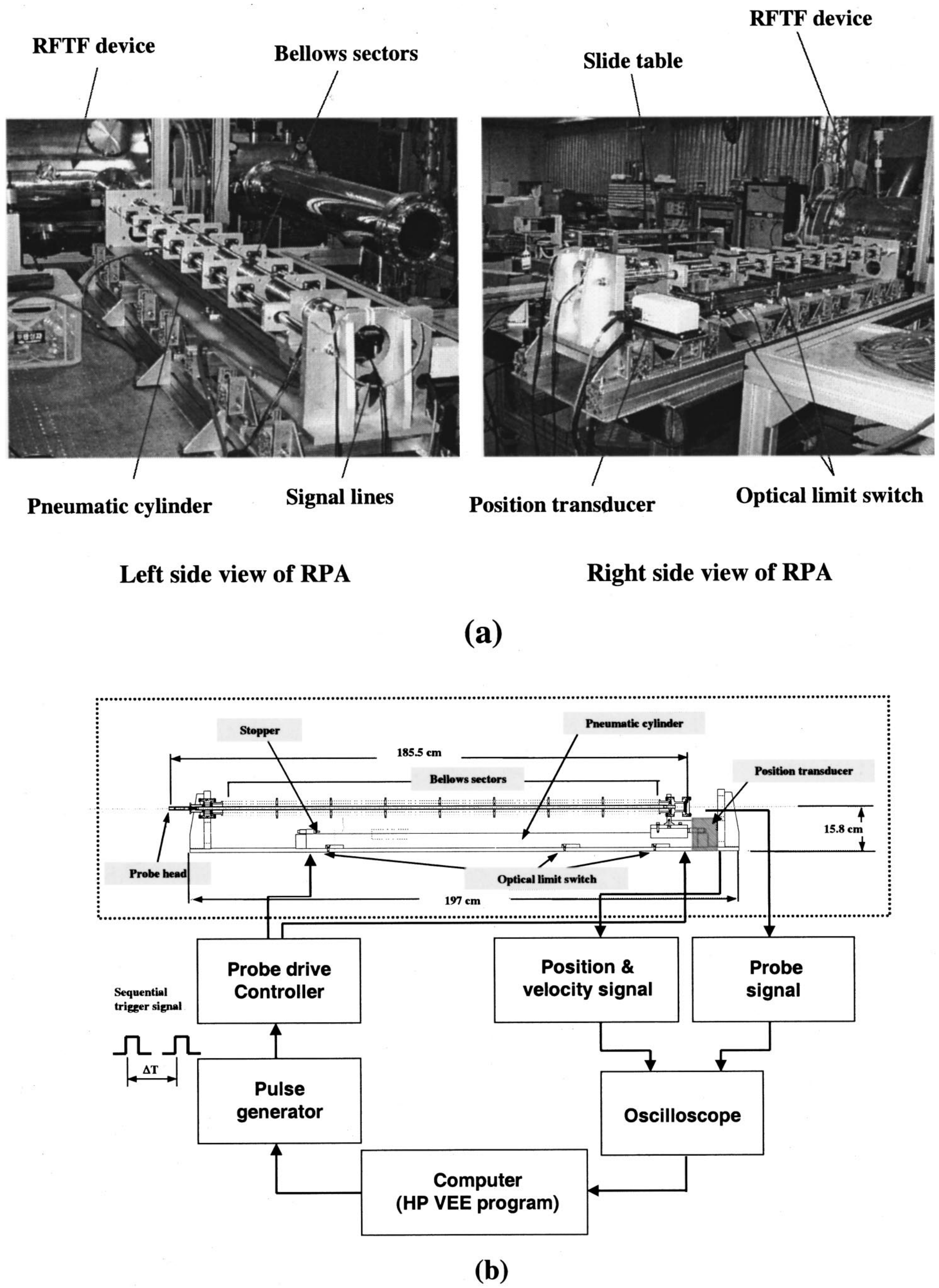

FIG. 1. The fabricated reciprocating probe assembly: (a) images of the left and right side views and (b) the schematic diagram of the probe drive and data acquisition system.

guides movement of bellows along two side-guiding rods (length of 182 cm). Four Vespel guide rings (o.d.∅25 mm, i.d.,∅12.7 mm) were fastened to the inner wall of four rings in order to reduce a horizontal/vertical vibration and to minimize a drag force during the probe movement. Also an additional pair of stainless steel strings between two bellows sectors minimize the damage of the bellows unit due to the unequal tension on each bellows sector when the bellows unit is compressed or extended.

Two acetal stoppers were located at the forward and backward end points in order to stop the probe assembly and also to reduce the mechanical shock due to the momentum change of the probe. For monitoring the elapsed distance and the moving speed of the probe, a position and velocity transducer (Celesco Transducer Products, Ins., DV301) was used in the RPA. The transducer has two sensors; a plastic-hybrid precision potentiometer for sensing position and a tacho generator for sensing velocity.

The probe drive and the data acquisition systems are set as shown by the schematic diagram in Fig. 1(b). The probe drive controller, which controls the slow and fast movements, is composed of the sensing and controlling parts. In the circuit, the sensing part receives the signal from limit switches and the controlling part controls solenoid valves, adjusting flow rate of the working gas. The sensing part was optically isolated with the controlling part in order to prevent the signal from picking up an unwanted noise. The drive controller is operated manually by pushing two buttons in the

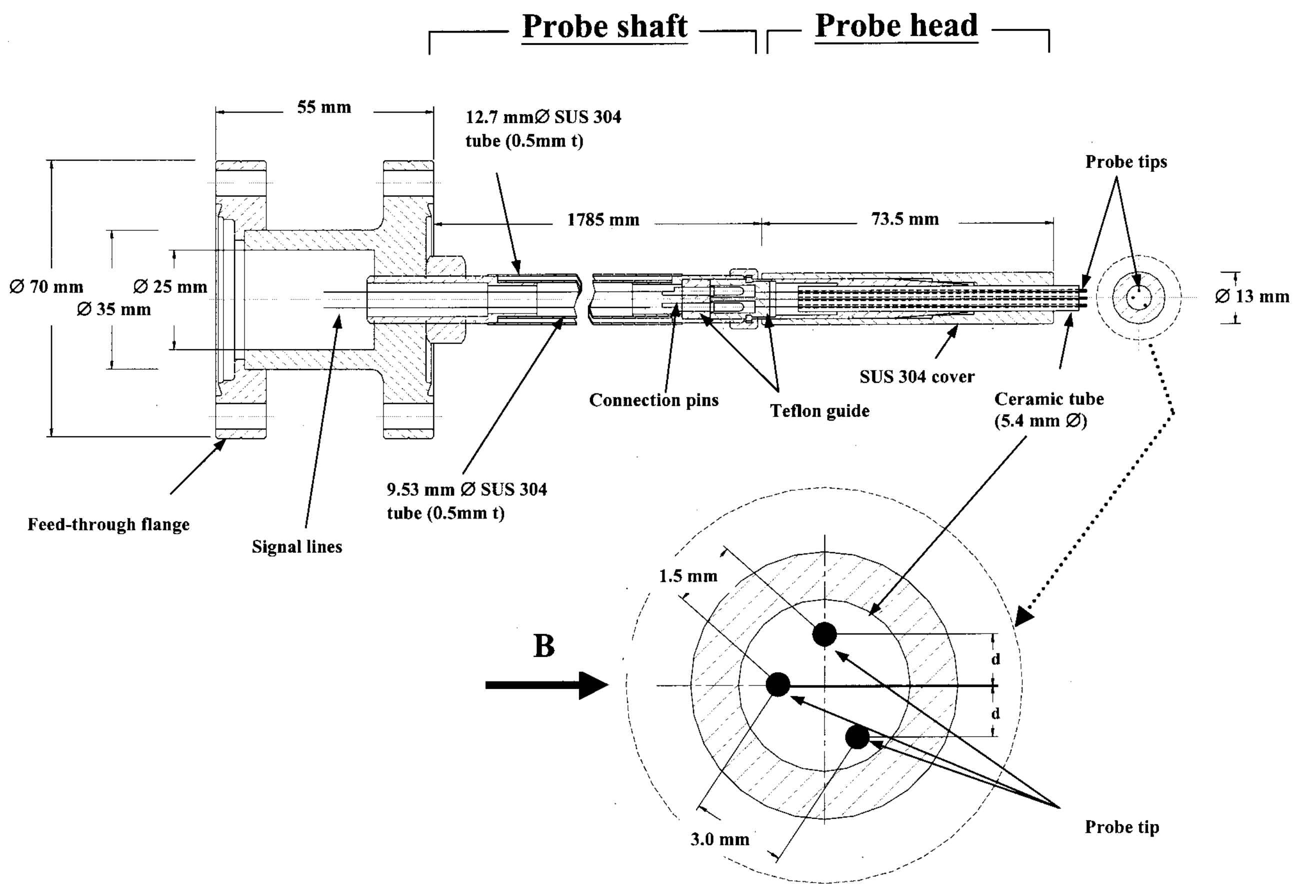

FIG. 2. The probe head used as a triple probe and probe shaft of the reciprocating probe assembly. B indicates the applied magnetic field direction.

front panel, and also is operated remotely by the trigger signal (pulse shape with duration time of 5 μs and amplitude of $V_{pp}=5$ V). Two sequential trigger signals with a time interval ΔT (from a pulse generator) are used to activate the slow and fast movements of the RPA. An HP VEE program controls the value of ΔT and the data acquisition. The oscilloscope (TDS 420A, bandwidth of 200 MHz) receives the signals (1000 samples) from the drive system and the probe, and transfers the digitized data to a PC to be stored or analyzed.

B. Probe assembly

The probe head (used as a triple probe) consists of outer cover, insulator tube, and probe tip as shown in Fig. 2. Stainless steel tube (o.d.∅13.0 mm) was used as outer cover. A ceramic tube with six holes (o.d.∅5.4 mm) was used as an insulator. A probe tip was made of a 1.0 mm∅molybdenum wire (length=4.5 mm). The probe shaft has a coaxial structure (length of 175 cm), which consists of an outer SUS tube (o.d.∅12.7 mm, $t=0.5$ mm) and an inner SUS tube (o.d.∅9.53 mm, $t=0.5$ mm) as shown in Fig. 2, in order to minimize a vertical vibration during the probe movement. The modified circular connector (four contacts) installed inside the probe shaft was used for connecting the probe tips and lead lines from the feedthrough as shown in Fig. 2. Thus, it is an advantage that only the probe head is easily

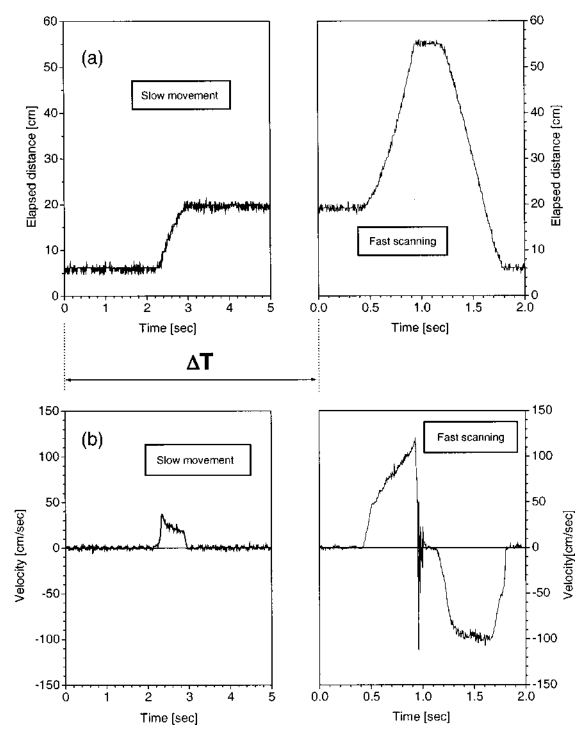

FIG. 3. The typical motion characteristics of the reciprocating probe assembly: (a) elapsed distance vs time and (b) its moving speed vs time ($P_{inlet}=7.6$ kgf/cm^2). ΔT is a time interval between two sequential trigger signals, which are controlled by the HP VEE program.

TABLE I. The measured values of the standby position in the slow movement of the probe for two different preset positions.

Trial No.	Measured value of case 1 (cm)	Measured value of case 2 (cm)
1	44.49	16.70
2	44.49	16.71
3	44.52	16.59
4	44.54	16.47
5	44.53	16.59
6	44.52	16.70
7	44.56	16.70
8	44.51	16.58
9	44.50	16.57
10	44.54	16.58

disassembled from the probe shaft when the probe tip needs to be modified or replaced. That is, several interchangeable probe heads (used as a triple probe, a Mach probe, or an emissive probe) can be installed to measure plasma parameters. Additionally, another bypass port for prevacuum and a gate valve were prepared between main vacuum chamber (for plasma production) and the probe assembly for fast replacement of the probe head during operation of the plasma device.

III. EXPERIMENTAL RESULTS

A. Performance test of the probe drive system

For an inlet pressure of the working gas ($=7.6$ kgf/cm^2), the typical time characteristics of the RPA using only a pneumatic system in the slow movement (for setting the probe at the standby position) and in the fast one are shown in Figs. 3(a) and 3(b), respectively. In the probe movement, the maximum velocity is 136 cm/s, and average velocities are 82.3 cm/s (fast one) and 21.3 cm/s (slow one). The time interval ΔT was set as 1–5 s in this experiment. The characteristics of the RPA (such as the position reproducibility, the vertical vibrations of the probe shaft, and the velocity of

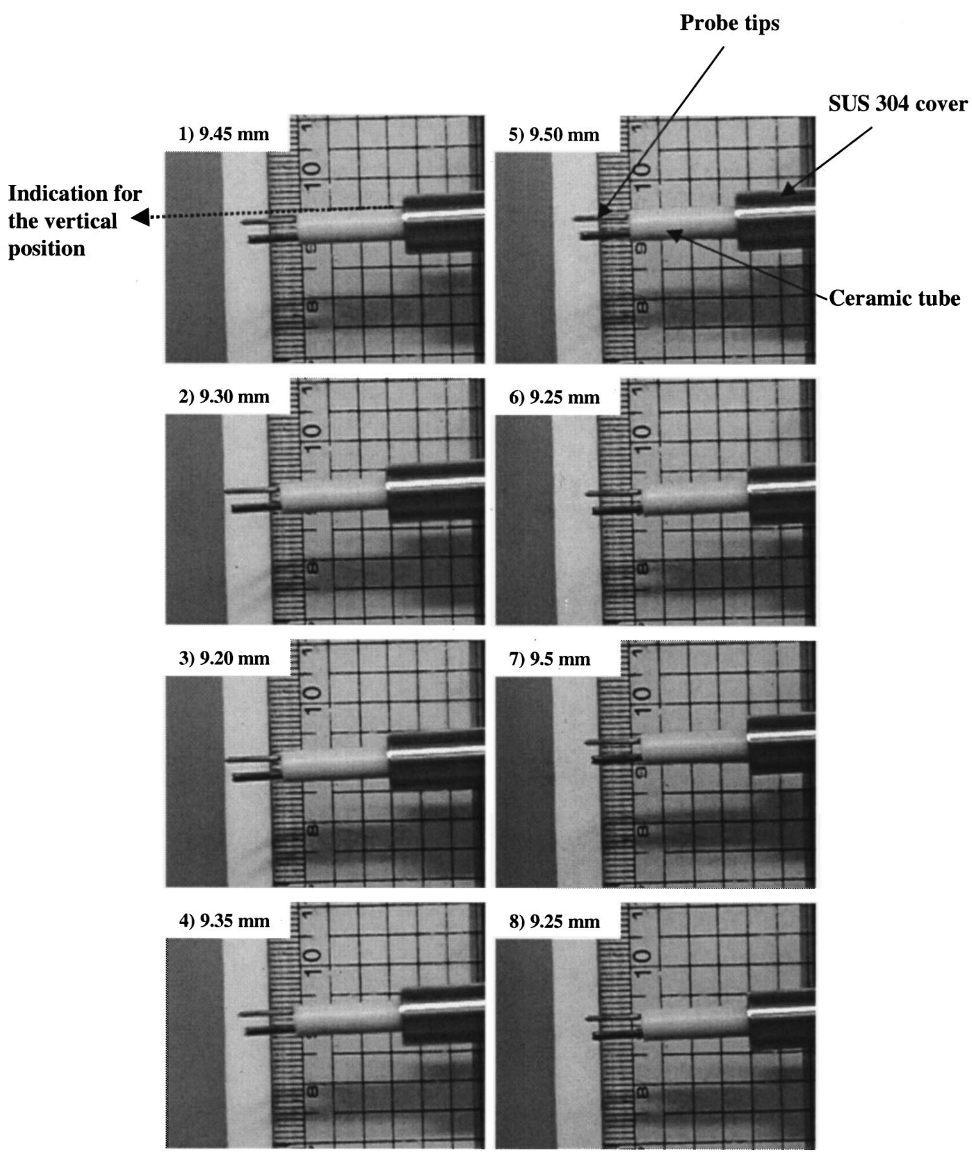

FIG. 4. Sequential images that demonstrate the vertical vibration of the probe shaft in the fast movement, which is taken by a strict camera; $P_{\mathrm{inlet}}=7.5$ kgf/cm^2. The time sequence is from (1) to (8).

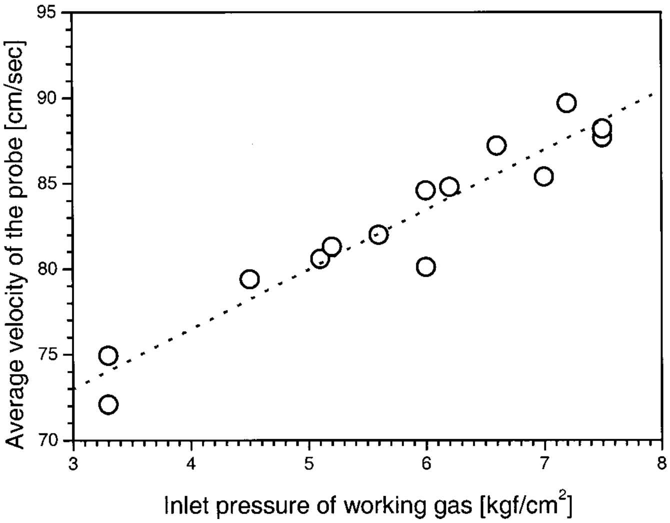

FIG. 5. Average velocity of the probe in the fast movement vs inlet pressure of the working gas.

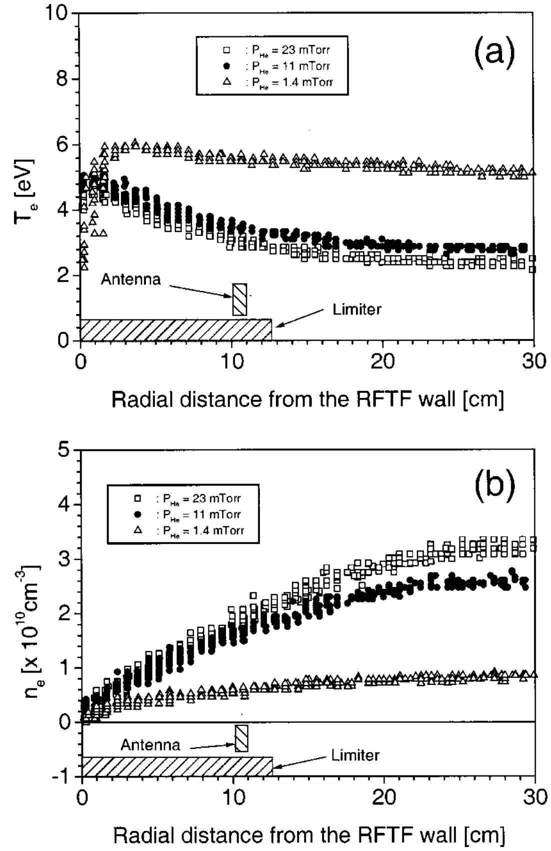

FIG. 6. Profiles of basic plasma parameters measured by the probe (triple probe) in the RFTF device: (a) plasma density and (b) electron temperature for the plasma discharge conditions of P_{rf}=600 W and P_{He}=1.4, 11, 23 mTorr.

the probe) was investigated n order to prove the utility of the probe drive system.

In order to test the position reproducibility of the RPA, the slow movement for setting the probe at the standby position, which was preadjusted, was carried out. The measured values of the position are 16.62±0.08 and 44.52±0.02 cm for two different presetting positions as presented in Table I. From two results, it is confirmed that the position reproducibility of the probe drive system is reliable within the spatial deviation of 1%. In this case, the probe velocity (maximum value) was est at 30 cm/s by adjusting the speed control valve in the solenoid valve. It was an optimal value for obtaining the best reproducibility of the standby position.

When the probe assembly arrives at the forward end position, the vertical vibration of the probe shaft must be small in order to perform more accurate measurement. For the probe stroke of 100 cm with average velocity of 82 cm/s, the maximum width of the vertical vibration of the probe shaft is $\Delta y = \pm 1.25$ mm, which is acquired from eight sequential images as presented in Fig. 4. Thus, it can be estimated that the spatial resolution (due to the vibration of the probe shaft) is less than 2 mm in the probe measurements.

During the fast movement of the probe, the moving velocity was measured for the inlet working gas pressure range of $P_{inlet} = 3-7.5$ kgf/cm^2 (within the allowable maximum pressure). The maximum velocity can be reached up to 136 cm/s near the forward end position. The average velocity during fast scan is increased as the inlet pressure becomes higher, and the measured value is 70–90 cm/s as shown in Fig. 5.

B. Initial measurements

The initial measurement of plasma parameters was carried out in the RFTF device that had been used for the study on the ICP (inductive coupled plasma) phenomena in our laboratory. The device has a total chamber length of 150 cm and a chamber diameter of 60 cm, which are the same dimensions as those of the Hanbit central cell. There is a double half-turn antenna (38 cm diam) between a pair of circular limiters (35 cm diam) installed in order to produce rf plasma ($f = 4$ MHz) in the device. After the probe assembly was installed in the RFTF device, an additional pressure regulator was used to compensate for the forward force of the vacuum on the RPA. The probe (used as a triple probe) scanned the spatial range from the edge to the center of the device during 350 ms in the radial direction.

The radial profiles of the electron temperature (T_e) and the plasma density (n_e) were measured under experimental conditions with the working pressure of helium gas (P_{He}) varied as 1.4–23 mTorr. In this experiment, the input rf power (P_{rf}) was 600 W. In order to minimize the rf effect on the measurement, the low pass filter (Mini-Circuits, Model: BLP-1.9) was used. A typical result is presented in Fig. 6. The electron temperature profiles show that uniform distributions ($\Delta T_e/(T_e)_{min} \leq 0.3$) appear in the broad region (within limiter diameter) and the uniform region becomes broader as P_{He} decreases. The value of T_e is decreased from 5.1 to 2.3 eV, but n_e is increased from 0.8×10^{10} to 3.3×10^{10} cm^{-3} in the center with increasing P_{He}. Additionally, the radial profiles were obtained when the magnetic field ($\mathbf{B}_{axial}$) was applied to the rf plasma (P_{He}=23 mTorr and P_{rf}=600–650 W) in the axial direction. The magnetic field was generated by two electromagnets (with the Helmholtz configuration), and it varied from 0 to 220 G (I_{mag} =255 A). In this measurement, the Larmor radii were esti-

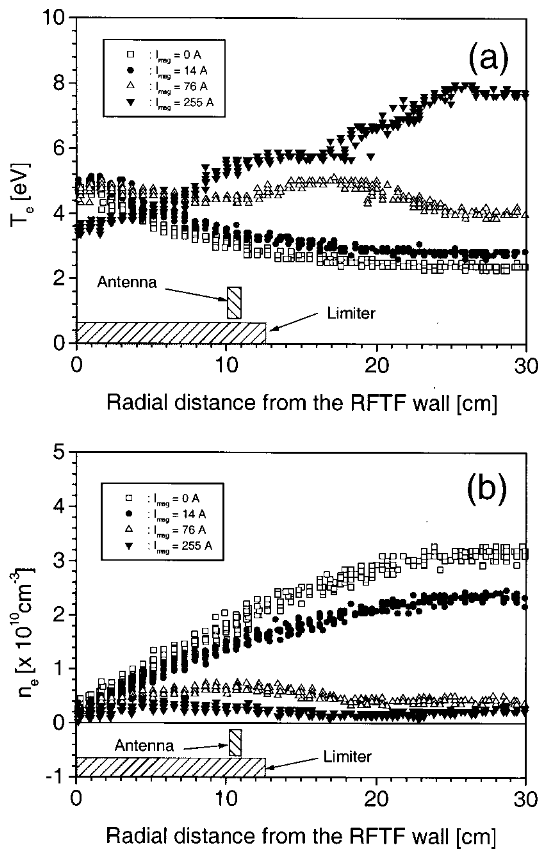

FIG. 7. Profiles of basic plasma parameters measured by the probe (triple probe) in the RFTF device for $B = 0-220$ G (axial magnetic field): (a) plasma density and (b) electron temperature for the plasma discharge conditions of $P_{rf} = 600-650$ W and $P_{He} = 23$ mTorr.

mated to be $r_e \sim 0.3$ mm, $r_i \sim 6.6$ mm ($\mathbf{B}_{axial} = 220$ G), and the diameter of the probe tip is $a_p = 1.0$ mm and $r_e < a_p < r_i$. Thus, the probe was biased by a significant negative voltage ($V_{bias} \sim -80$ V) in order to use the interpretation of the probe characteristics in a nonmagnetized plasma.[7] The measured profiles are presented in Fig. 7. The density profile shows that the value of n_e is remarkably dropped (from 3.2×10^{10} to 0.4×10^{10} cm^{-3}) and the broad and small dip appears in the center region when $\mathbf{B}_{axial}$ is higher than 66 G ($I_{mag} = 76$ A). Also, it becomes more uniform as $\mathbf{B}_{axial}$ increases. The electron temperature profile shows that the value of T_e in the center is increased from 2.3 to 7.9 eV as $\mathbf{B}_{axial}$ increases and a broad hump appears in the center region when $\mathbf{B}_{axial}$ is higher than 66 G ($I_{mag} = 76$ A). The hump moves to the center as $\mathbf{B}_{axial}$ increases.

In the initial measurement, the obtained profiles show that the spatial resolution of the profiles was less than 4.5 mm. The length of the probe tip used in the experiment mainly restricted the resolution. Thus, it can be estimated that measured profiles have resolutions of less 4.5 mm in the radial and vertical directions, including the resolution due to the vibration of the probe shaft. Also, both profiles, which were measured during the injection and ejection of the RPA, were similar within 5% differences.

IV. DISCUSSION

The reliable reproducibility of the standby position was confirmed from the result that its spatial deviation was less than 1%. A vertical vibration of the probe shaft during the fast stroke was less than 1.25 mm for the stroke of 100 cm. The maximum velocity of the probe was achievable up to 136 cm/s for the long stroke of 100 cm. Thus, the performance test results for the driver system (using only a pneumatic cylinder) of the RPA were satisfactory. In the initial measurement by the probe in the RFTF device, radial profiles (electron temperature and plasma density) with the spatial resolution of 4.5 mm was obtained during 350 ms. The resolution was mainly restricted from the length of the probe tip that was used in the experiment, and will be improved by modifying the probe tip. In conclusion, it is expected that basic plasma parameters (with high spatial resolution) will be measured by the RPA during the plasma shot in the Hanbit magnetic mirror device.

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