Three different simple detector manipulators for spatial measurements in a plasma discharge device

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Simple and convenient novel manipulators with two dimensions and three dimensions were demonstrated for measuring various parameters directly in a cylindrical vacuum chamber. Examples of experimental data are presented to prove the usefulness of the systems in a plasma device. Three different mechanisms with neither internal driving nor differentially pumped systems for achieving varying degrees of accuracy were proposed: In one of the two three-dimensional driving systems, detectors were introduced along the axial direction with an arbitrary rotation with respect to the axis by the use of two small-diameter bellows. The other system allowed motion along the radial direction with the capability of arbitrary rotation by small-diameter bellows. In the two-dimensional system, detectors could be scanned vertically using a sliding flange in addition to a radial motion mechanism. [DOI: 10.1063/1.1556949]

I. INTRODUCTION

In measuring various parameters in vacuum chambers, it is often crucial to have two-dimensional (2D) and three-dimensional (3D) profiles. However, direct spatial measurement access is usually limited by boundary conditions, such as geometry access constraints in the form of ports, vacuum and measuring systems, magnets, etc. Therefore, the installation of a complex or an expensive instrument often needs to be considered. In plasma fields, for example, a one-dimensional (1D) profile measurement needs only a simple driving system (linear motion) utilizing a bellows or a gauge port without a bellows if a pipe is attached to detectors and passed through the gauge port smoothly without air leakage. However, for 2D and 3D measurements, special care must be taken. In principle, there are two types of moving systems (and sometimes a combination of the two) that are located outside or inside a chamber; e.g., a large-sized bellows (outside type) or a driving stage[1] (inside type) installed in a vacuum for moving detectors in two or three dimensions. These are generally complicated, difficult to handle, and expensive. Furthermore, for the outside type, if the displacement perpendicular to the axis is relatively large compared to the diameter of the bellows, it will suffer from considerable stress since a large twisting of the bellows is expected. For the inside type, the harsh conditions of the plasma environment, such as high vacuums and strong magnetic field effects, must be considered, in addition to physical disturbances of the plasma by this system.

Of course, one simple way of making 2D measurements is to use a supporting pipe that is passed through a gauge port with an O ring, and bent by 90° with detectors at the end of the chamber. This setup can provide 2D information when the pipe is rotated. If, in addition, the end section near the detectors can be stretched perpendicularly with respect to the axis, 3D measurements may also be obtained.[2] A simple angular motion with a small size was proposed using a spherical body,[3,4] and motion in the radial direction using a simple spring for 3D measurements was also presented.[5] However, it is still desirably to further develop various 2D and 3D driving systems, or manipulators (depending on the objectives), by means of a simple method.

In this article, we present novel 2D and 3D driving manipulators, i.e., three different mechanisms developed for making measurements in a cylindrical plasma discharge chamber, that are simple, convenient, and inexpensive. Section II briefly describes the experimental setup used in the plasma fields for the 2D and 3D systems. In Sec. III, two 3D driving mechanisms are presented, with an example of experimental data that was obtained in a plasma, to prove the usefulness of the driving systems. Note that there are two types of angular motion: A rigid sealing surface with the use of bellows, e.g., Refs. 6–8, and a sliding bearing seal, i.e., a pivot within the seals,[3,4] sometimes with the use of differential pumping. In our case, a simple bellows-based design without differential pumping was used: In one of the large systems with two small bellows, the use of a supporting pipe, 0.8 cm outer diameter (o.d.) prevents drooping of the 1-cm-o.d. pipe with detectors, leading to good positioning. On the other hand, larger size shafts (2.54 cm and 1.9 cm o.d) with two ball bearings are used in another system to provide rigidity.[8] Our small-type 3D system is handy and convenient to use, and can be tilted with the use of a small bellows to ~50°. This is larger (smaller) than the value of 34° presented in Ref. 3 (Ref. 4 of 60°) with a sliding bearing seal. Finally, a large 2D system used in a plasma experiment as an example is described in Sec. IV. This system meets the requirement of detector directivity, since motion in Cartesian coordinates must be employed in order to avoid an angular motion. Although there is a long sliding seal (the use of one O ring) with neither a differential pumping system nor

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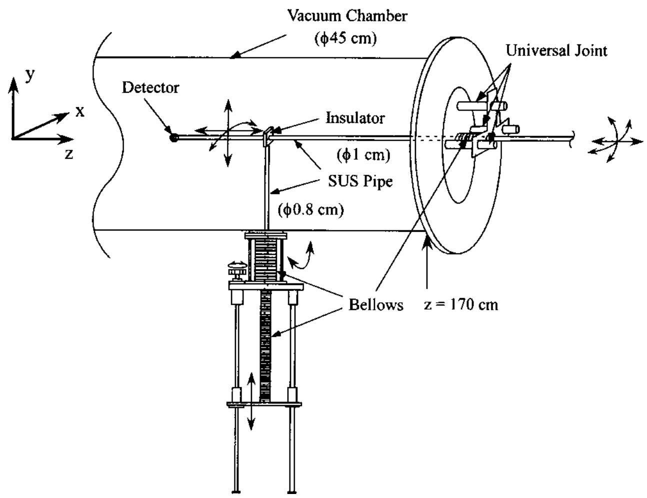

FIG. 1. Schematic view of 3D moving system using end and bottom flanges.

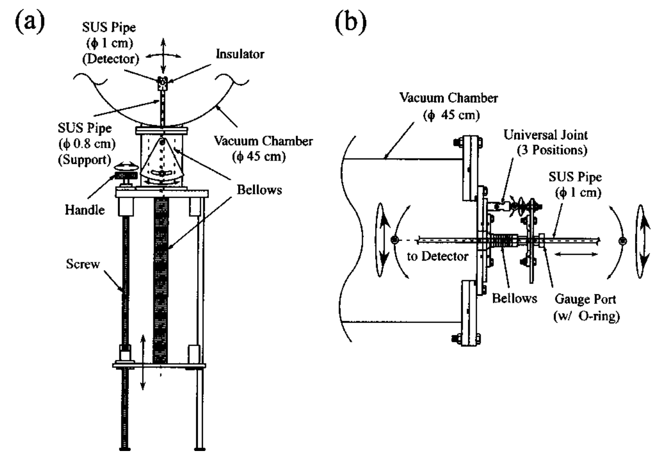

FIG. 2. Detailed cross-sectional views of Fig. 1: (a) (x, y) plane and (b) (y, z) plane.

double O rings, an appreciable increase in pressure was not found in our experiment during sliding motion.

II. EXPERIMENTAL SETUP

The experimental system[9,10] for 2D and 3D measurements is as follows: Argon plasma was produced in a linear device by a four-turn spiral antenna connected to a rf power supply: <1 kW input power with a typical frequency of 7 MHz. Here, the device is 45 cm in diameter and 170 cm in axial length, and the magnetic field coils surrounding the vacuum chamber generated various field configurations with fields typically in the region of 0.5 kG. The base vacuum pressure in this device was $\sim 10^{-6}$ Torr without a baking system, and the fill pressure was $P_0 = 0.3$–30 mTorr in our experiment, without any appreciable leak. The system used neither differential pumping systems nor double O rings in the driving systems. Here, the acceptable leak rate was less than $<10^{-4}$ Torr·1/s for driving systems in our measurement. This value can be evaluated from the fact that the effective speed of the exhaust is estimated to be $\sim$400 1/s with a turbomolecular pump (pumping speed is 1000 1/s), and the acceptable increase in pressure is much less than 10^{-6} Torr.

Langmuir probes for plasma density and temperature measurements, and magnetic probes for magnetic field measurements were used to determine the plasma conditions in 2D and 3D spaces. The former probes have no directivity, but the latter ones do, i.e., they have three components. This needs to be considered in a driving system and will be discussed in the next section.

III. THREE-DIMENSIONAL MEASUREMENT SYSTEMS

A. Use of end and side bottom flanges

Figure 1 shows a schematic diagram of a drive detector in the 3D direction introduced from the end of the cylindrical chamber. Here, the moving direction of the detectors is not orthogonal to the (x, y, z) coordinates: There are one linear motion and two degrees of freedom of rotation using the three bellows and universal joints at the end flange. The two bellows for this rotation mechanism have 3.3 and 9.4 cm o.d. and are attached to the end and side bottom flanges, respectively. A more detailed system is depicted in Fig. 2(a): (x, y) plane and in Fig. 2(b): (y, z) plane. As shown in Fig. 2(b), a stainless-steel pipe, 1 cm o.d., with detectors set on the left-hand side front, is introduced from the right-hand side in a linear motion by a motor. A Viton O ring, 0.9 cm inner diameter (i.d.) is used at the gauge port, and the pipe surface is lubricated with grease (Silicone Grease™) to ensure smooth motion. Using a bellows and with the help of universal joints at the end flange, angular rotation is realized with respect to the axis. The pipe with detectors is droopy in the case of deep insertion of up to 170 cm long from the right-hand-side flange. In order to avoid this droopy condition, a supporting pipe, 0.8 cm o.d., is inserted from the bottom side flange [Figs. 1 and 2(a)], which is 80 cm away from the end flange [Fig. 2(b)] in the axial direction. At the top end of the supporting pipe in Fig. 2(a), there is a hole in the insulator material to receive a pipe with detectors. The larger bellows, 9.4 cm o.d., allows rotation of the supporting pipe in the (x, y) plane as mentioned earlier, and the smaller one, 3.6 cm o.d., at the lower side allows vertical motion, i.e., y direction [see vertical motion of a stage using a handle, as shown in Fig. 2(a)]. Although the manual manipulation of the detector position is done in this system, extending automatic 3D positioning with stepping motors is possible, in principle, using computer control.

Figure 3 shows an example, using this system, of a contour plot of the z component of the excited magnetic field (rf component) with plasma density $n_e \sim 10^{12}$ cm^{-3} in the divergent magnetic field (see Ref. 11 for more details). In this experiment, an rf wave with a frequency of 15 MHz was excited using a loop antenna, 30 cm in diameter, as shown in Fig. 3, and four measuring lines, i.e., continuous data, on the lines by magnetic probes. These are shown as dotted lines in Fig. 3. Here, $z = 0$ cm is set to the window surface on the left-hand side facing the vacuum chamber. Using this system, three components of the excited magnetic field were measured successfully in the 3D geometry to derive contour maps,[11] and the angle effect was negligible. In Fig. 3, for example, the maximum tilt angle θ_{max} of the probes with

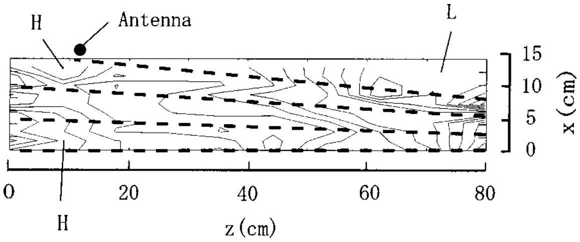

FIG. 3. Typical example of contour plot [logarithmic scale in (x, z) plane] of amplitude B_z excited by a loop antenna, 30 cm in diameter, derived from magnetic probe data using the 3D scanning system in Fig. 1. Here, measuring lines are indicated by dotted lines, and H and L denote high and low amplitudes, respectively, compared with those in the neighboring region. In this experiment, plasma density n_e is $\sim 10^{12}$ cm^{-3} in the divergent magnetic field.

respect to the main z axis is 4.8°, and then the mixing of the three components is expected to be small since $\cos\theta > 0.997$ and $\sin\theta < 0.084$. Needless to say, there is no problem regarding the tilting angle for the case of the detectors without directivity, such as Langmuir probes in the plasma field.

B. Use of side flange

Using a small side flange 8 cm in diameter, a handy 3D measuring system was developed, as shown in Fig. 4. Similar to the system described in Sec. III A, one linear motion and two degrees of freedom of perpendicular motion were possible using a small bellows with 3.6 cm o.d. A tilting angle with respect to the main axis (x direction) could be changed by up to ±25°, and full rotation in the (y, z) plane was done for measuring various parameters flexibly in the 3D space [see arrows and bolt holes (every 30°) in Fig. 4(a)]. Same as the case of Fig. 2(b), a Viton O ring with 0.9 cm i.d. was used at the gauge port and sometimes the pipe surface was lubricated with grease to ensure smooth motion. Here, apart from the nondirective detectors, for the case of a large tilting angle, we must be cautious in estimating signals from directional detectors, and a calibration of each component for deriving the real values is necessary. In our experiment, this system was used successfully for the local measurement of plasma parameters by a Langmuir probe (no directivity) near the ten concentric electrodes.[12]

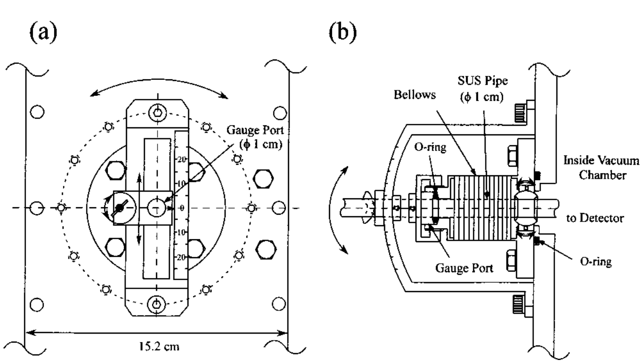

FIG. 4. Detailed cross-sectional views of 3D moving system using a small side flange: (a) (y, z) plane and (b) (x, y) plane.

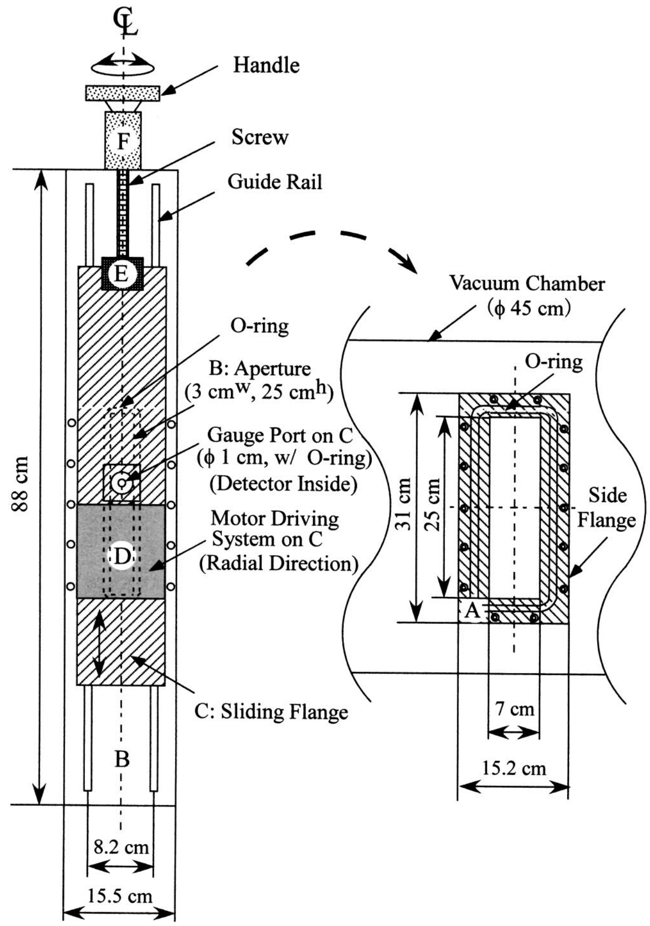

FIG. 5. Schematic view of 2D moving system using a sliding side flange [(y, z) plane].

IV. TWO-DIMENSIONAL MEASUREMENT SYSTEMS

Using a larger side flange, 15.2 cm (z direction) ×31 cm (y direction), located at $z = 60$ cm, a 2D orthogonal measuring system has been developed, as shown in Fig. 5. (Here, the initial idea came from Ref. 13.) The long flange B (left-hand side in Fig. 5) was attached to side flange A with an O ring (right-hand side in Fig. 5) using ten bolts (M6 size), and on flange B, there were two guide rails, e.g., so-called slide guides, on which flange C could slide vertically (y direction). Here, the distance (gap) between the surfaces of flanges B and C was very carefully kept constant at ~0.5 mm in order to have no air leaks and no strong friction forces for the case of vertical motion (no twisting of an O ring). In flange B, there was an aperture shaped like a racetrack, which was 3 cm wide (z direction) and 25 cm high (y direction), and a Viton O ring with an i.d. of 15.9 cm was placed on the groove, which was located outside the aperture. The detectors with a pipe (1 cm o.d.) passing through a gauge port on flange C could be moved vertically up and down by ±12 cm using a handle attached to flange B, as shown at the top of Fig. 5: The handle and flange C were connected through a screw and a screw nut (see E and F in Fig. 5). For radial motion (x direction), a motor driving system, denoted by D, was installed and attached to flange C. Here, a Viton O ring, 0.9 cm i.d., was used at the gauge port, and the pipe

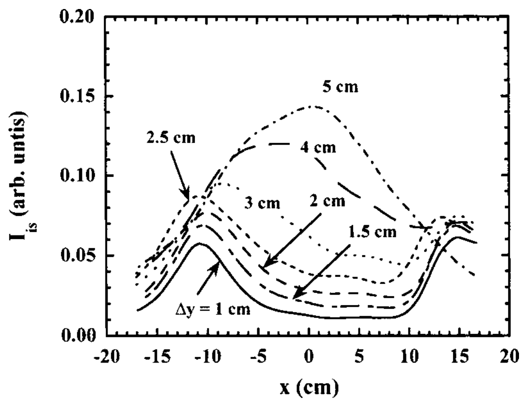

FIG. 6. Typical example of radial profiles of ion saturation current I_{Is}, obtained while changing the distance Δy between the plate and the plasma ($P_0 = 0.3$ mTorr and $V_b = -50$ V), using the 2D system in Fig. 5.

surface (sliding surface) was lubricated with grease to produce smooth motion in the radial (vertical) direction.

Figure 6 shows an example of the radial (x direction) profiles of ion saturation current, I_{Is}, as a function of the distance Δy between the plate and the plasma ($P_0 = 0.3$ mTorr and bias voltage $V_b = -50$ V on this plate). Here, the biased plate was a square 20 cm$\times$20 cm and had 0.1 cm thickness on the (x, z) plane. Its surface was 5 cm lower in the central axis of the vacuum chamber, i.e., $y = -5$ cm (see Ref. 14 for more details). In this experiment, $I_{\mathrm{Is}} = 0.1$ corresponded to $n_e = 2\times10^9$ cm^{-3} if the electron temperature was constant at 5 eV. Although a discrete Δy was described in Fig. 6, continuous changes in Δy were possible in addition to the x direction.

The present system solved a problem that persisted in a previous experiment,[15] where insufficient 2D measurements were obtained with a 1D driving system (x direction) for detectors: It was difficult to acquire 2D data correctly since the bias plate itself had to be moved vertically, which influenced plasma performance, i.e., plasma parameters changed depending on the bias plate position. In this present system, probes could be moved in the 2D direction without changing the bias plate position. In addition, it was shown that orthogonal 2D motion, which resulted in no problems for the detectors in terms of directivity, as was mentioned earlier, was successfully executed without any appreciable air leakage (the increase in pressure was much less than 10^{-6} Torr during slow vertical movement of less than cm/s). If linear motion capability in the z direction were to be added using the same method as that mentioned herein, this system could easily be extended to the 3D orthogonal system along with computer control of the detector position.

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[1] H. Pfister, W. Gekelman, J. Bamber, D. Leneman, and Z. Lucky, Rev. Sci. Instrum. **62**, 2884 (1991).
[2] R. L. Stenzel, J. M. Urrutia, and C. L. Rousculp, Phys. Fluids B **5**, 325 (1993).
[3] A. M. Ferendeci, J. Phys. E **6**, 816 (1973).
[4] D. Leneman and W. Gekelman, Rev. Sci. Instrum. **72**, 3473 (2001).
[5] G. Braught, H. Pfister, and J. Wachtel, Rev. Sci. Instrum. **64**, 3270 (1993).
[6] S. H. A. Begemann and J. Eilander, J. Phys. E **4**, 660 (1971).
[7] J. Eilander, H. H. Feijen, S. B. Luitjens, and E. P. Th. M. Suurmeijer, J. Phys. E **9**, 814 (1976).
[8] E. E. Scime, J. L. Kline, D. Mathess, and C. Weber II, Rev. Sci. Instrum. **73**, 1970 (2002).
[9] S. Shinohara, N. Matsuoka, and Y. Yoshinaka, Jpn. J. Appl. Phys., Part 1 **38**, 4321 (1999).
[10] S. Shinohara, S. Takechi, N. Kaneda, and Y. Kawai, Plasma Phys. Controlled Fusion **39**, 1479 (1997).
[11] S. Shinohara and A. Fujii, Phys. Plasmas **8**, 3018 (2001).
[12] S. Shinohara, N. Matsuoka, and S. Matsuyama, Jpn. J. Appl. Phys., Part 1 **8**, 1154 (2001).
[13] S. Takamura, Y. Yoshida, and T. Okuda, Phys. Fluids **28**, 1516 (1985).
[14] S. Shinohara, S. Matsuyama, and O. Kaneko, Thin Solid Films **407**, 209 (2002).
[15] S. Matsuyama, S. Shinohara, and O. Kaneko, Trans. Fusion Technol. **39**, 362 (2001).