REVIEW OF SCIENTIFIC INSTRUMENTS **78**, 123501 (2007)

# Fine positioning of a poloidal probe array

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(Received 30 April 2007; accepted 5 November 2007; published online 4 December 2007)

Multipoint detection is an essential requirement for investigating plasma turbulence which is a highly nonlinear phenomenon in space and time. We have fabricated an array of 64-channel poloidal probes surrounding the linear cylindrical plasma named LMD-U in order to study turbulence properties, particularly the nonlinear mode couplings, in the domain of poloidal wave number and frequency. However, misalignments of probe tips produce spurious modes, which do not exist in the real plasma, to distort the precise wave number measurements. The paper presents the description of the 64-channel poloidal probe array with means to adjust the probe positions, with discussion on the effects of the misalignments on the wave number measurements. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2818796]

## I. INTRODUCTION

It has been a well known fact that turbulence governs toroidal plasma confinement.[1] In spite of the importance of turbulence, fundamental processes to realize the turbulence state have not yet been fully understood, since it could be quite difficult to carry out the observation with sufficient spatiotemporal resolution in such high temperature plasmas. Thus, experiments on linear plasma devices or toroidal devices of low temperature become more attractive for investigating fundamental processes of turbulence,[2–6] e.g., intermittency, nonlinear mode couplings, cascade, etc., since such plasmas allow easy application of the Langmuir probes which are one of the most suitable diagnostics for physics experiments. Langmuir probes consist of small metal electrodes directly inserted into plasmas. They can measure density fluctuation from the fluctuation of the ion saturation current, when the electron temperature is considered to stay constant. A poloidal Langmuir probe array is one way to investigate the wave number and the frequency of the fluctuations (density and/or potential) simultaneously. A poloidal Langmuir probe array, named COURONNE, was fabricated and applied in many cylindrical linear devices, such as KIWI,[2,7] MIRABELLE,[8] and VINETA.[3,9,10] (A poloidal probe array was also applied in TJ-K torus.[11]) We have made a similar 64-channel poloidal Langmuir probe array surrounding the plasma cylinder of our linear machine, termed LMD-U. The purpose of this probe array is to obtain the two-dimensional power spectrum of the wave number and frequency, and to investigate the nonlinear couplings between waves in the domain of both wave number and frequency.

A slight misalignment of the probe array to the plasma center causes appearance of spurious modes, which prevent us from precise evaluation of wave numbers and nonlinear couplings between modes. The consequence of the spurious modes, which is caused by misalignments, is much more serious in measuring the bispectra in comparison with the case of quadratic correlations. This is because the spurious modes keep the phase of the original modes (with different poloidal wave numbers) and affect the statistical average of higher order correlations. Therefore, the probe array was equipped with several means to adjust probe positions to the plasma. In this article, we describe the array of 64-channel poloidal probes, and discuss the effect of misalignment on the wave number measurement by presenting the results before and after the adjustment.

## II. PROBE ARRAY IN LMD-U

A schematic view of the 64-channel probe array is shown in Fig. 1. The probe array consists of 64 probe units constructed separately in order to align the probe tips individually. Each probe unit consists of a tungsten rod with a diameter of 0.8 mm, a ceramic tube with outer/inner diameters of 2.0/1.2 mm, and a polyimide block [see Fig. 1(a)]. The ceramic tube covers the tungsten rod with exposing 3 mm length and this is the length of the probe tip. The polyimide block holds the ceramic tube. Sixty-four tungsten tips are aligned in the poloidal direction ($\theta$) with 3.9 mm spacing along a circle with a radius of $r_p$=40 mm. The direction of $\theta$ is shown in Fig. 1(b). Since there are 64 probe

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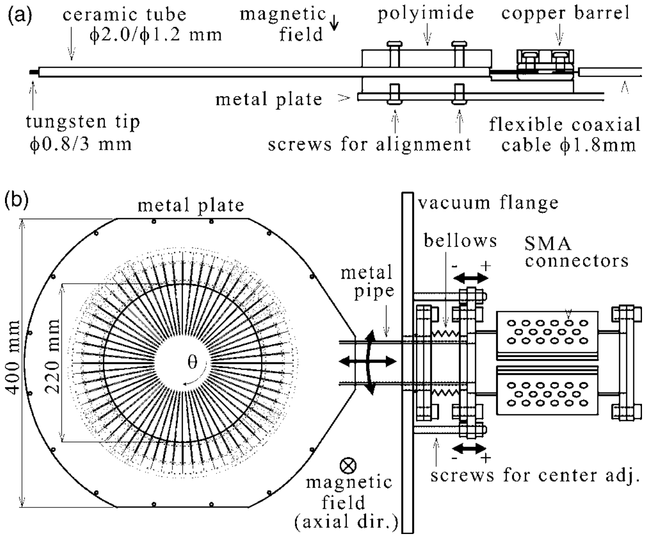

FIG. 1. (a) Schematic view of a single probe unit. Fine arrangement of the probe tips is available by two adjusting screws fixing the probe unit to a metal plate. (b) Schematic diagram of the 64-channel poloidal probe array. The probe array center is adjustable by changing the length of the bellows between the SMA connectors' box and the vacuum flange.

tips, the maximum measurable poloidal mode number is 32. Here, the poloidal mode number $m$ is related to the poloidal wave number $k$ by $m=r_pk$. Therefore, the wavelength resolution is $1/r_p=25\ \mathrm{m}^{-1}$ and the maximum measurable wavelength is $32/r_p=800\ \mathrm{m}^{-1}$. The poloidal flow direction of the fluctuation is measurable and is defined by the sign of the frequency $f$ (when $m\geqslant 0$ is defined), which corresponds to the sign of $\theta$.

The probe units are firmly fixed to a single metal plate (1.5 mm thick) with a hole with diameter of 220 mm, which is larger than the plasma diameter (~100 mm). In the alignment, the hole of the plate is closed with a metal disk graduated radially and azimuthally. After the probe tips are properly aligned according to this graduation, the probe units (the polyimide blocks) are fixed by two screws, the disk is removed, and the whole system is covered by another same metal plate to prevent the probe units from being damaged by the plasma (the distance between the two metal plates is 30 mm). By this method the misalignment of the probe positions (with respect to the reference location defined on the metal disk) is reduced to less than 0.1 mm. Thus, the noise produced in the poloidal mode number space is restrained as much as possible.

Even though the 64-channel probe array is placed accurately on the metal plate, the center of the probe array must be adjusted to coincide with that of the plasma column. In order to resolve a possible misalignment of the array with respect to the plasma center, the metal plate is made movable. The metal plate with a metal pipe of 60.5 mm outer diameter is jointed to the SMA connectors' box [see Fig. 1(b)]. The system of the probe array and SMA connectors' box are supported by the outer flange of a welded bellows with four screws. The probe tips are electrically connected, using the flexible coaxial cables (RG178B/U, outer diameter of 1.8 mm and 1 m length) passing through the pipe, to the SMA connecters. Coaxial cables are used to reduce the cross talks. The tungsten rod and the center conductor of the coaxial cable are connected by a copper barrel with two screws inside the polyimide blocks. The central position of the probe array can be controlled both horizontally and vertically and be adjusted to the plasma center by varying the shape of the outer flange of the bellows by the four screws on the upper and lower sides. There are scales along the screws to indicate the positions of the screws. The scales are graduated from −10 to +10 mm. The positive and negative directions are shown in Fig. 1(b). By observing from the outer end of the vacuum vessel, the probe center was revealed to match the center of the vacuum vessel when the positions of the upper/lower screws were −4/−6 mm. The probe center moves horizontally by changing the positions of all the four screws equally, and moves vertically (and slightly horizontally) by changing the lengths of the upper and lower screws unequally. Adjusting vertically is twice rougher than adjusting horizontally, since the distance from the SMA connectors' box to the probe center is twice longer than that between the upper and lower screws. It is necessary to keep the positions of the two screws of each pair (the upper and lower pairs) equal to prevent the probe array from tilting in the axial direction. (We can also revise the tilt in the case the array is tilting.) By this two-dimensional adjustable system, we can easily and flexibly apply the probe array symmetrically to the plasma column in order to measure the precise poloidal mode numbers of the plasma fluctuations, from the outside without breaking vacuum.

In the present experiment, the bias voltage applied on the probe tips is chosen to be −90 V for the measurement of ion saturation current. The current signals are led to $V$-$I$ conversion resistances with 20 Ω by coaxial cables with 1.5 m lengths. Since coaxial cables are used, the cross talk appears only from the probe units. The evaluated cross talk is $6\times10^{-6}$ in power from the neighboring probes, and much less from the others. This level revealed to be negligible by later discussion.

## III. EFFECTS OF MISALIGNMENT ON MEASUREMENTS

Here, we evaluate the effects of misalignments. The misalignments of probe tips and array should cause several nonideal effects leading to the false poloidal wave number measurements: the variation of the probe gain (depending on size and shape), the geometrical nonuniformity (or the deviation from the proper position of the individual probes), the shift of the probe array from the plasma center, and the tilt of the probe array in the axial direction.

Supposed that there is a test fluctuation symmetric around the plasma axis, the true fluctuation with a poloidal number $m$ can be expressed as $I(\theta,t)=I_0\cos(m\theta-\omega t+\varphi_0)$, where $I_0$ and $\omega$ represent the fluctuation amplitude and frequency, respectively, and $\varphi_0$ is the initial phase. Then, the observed fluctuation including the nonideal effects can be systematically written as

$$I=I_0(1+\delta_a)\cos[m(\theta+\delta_p)-\omega t+\varphi_0]. \tag{1}$$

Here, the nonideal effects can be regarded as the amplitude and phase distortions. In general, the parameters $\delta_a$ and/or $\delta_p$ can be expanded in the Fourier series as

$$\delta_{a,p}(\theta)=\sum_{m'=1}^{M/2}\hat{\delta}_{a,p}(m')\sin[m'\theta+\varphi_{a,p}(m')], \tag{2}$$

where $M$ is the number of the probes $M=64$ in our case. The major component of $\hat{\delta}$ should be $m'=1$ in the case of the center shift of the probe array, and $m'=2$ in the case of the tilt of the probe array, while $\hat{\delta}$ should be independent of $m'$, like a white noise, in the presence of the nonuniformity of the probes. The total intensity of the misalignment can be evaluated by Parseval's theorem $\langle\delta^2\rangle=M\langle\hat{\delta}^2\rangle/4$.

The effects of the amplitude distortion $\delta_a$ are evaluated by substituting Eq. (2) to Eq. (1). Ignoring the time variable $\omega t$ and the initial phase $\varphi_0$, Eq. (1) becomes

$$\frac{I}{I_0}=\cos m\theta+\sum_{m'=1}^{M/2}\frac{\hat{\delta}_a}{2}\{\sin[(m+m')\theta+\varphi_a(m')] - \sin[(m-m')\theta-\varphi_a(m')]\}. \tag{3}$$

Therefore, the amplitude distortion $\hat{\delta}_a$ with a mode number $m'$ provides spurious modes of $m\pm m'$ with the amplitude ratio $\hat{\delta}_a/2$ to the original mode intensity.

On the other hand, the effects of the phase distortion $\delta_p$ are more complicated. Assuming that the phase distortion should be expressed by a single poloidal mode $m'$ with amplitude $\hat{\delta}_p$, Eq. (1) becomes

$$\frac{I}{I_0}=\sum_{n=-\infty}^{\infty}J_n(m\hat{\delta}_p)\cos[(m+nm')\theta+n\varphi_p(m')], \tag{4}$$

by using the formula $\cos(A+B\sin C)=\Sigma_n J_n(B)\cos(A+nC)$, where $J_n$ is the Bessel function of the first kind. The term $n=0$ corresponds to the test fluctuation and $n\neq 0$ to the spurious mode components. The dominant terms of Eq. (4) are when $n=\pm 1$ and the ratio of the amplitudes to the test mode are both $m\hat{\delta}_p/2$ since $J_{-n}=(-1)^n J_n$, and $J_n(x)\sim(x/2)^n/n!$ (when $x\sim 0$ and $n$ is a natural number). Therefore, the phase distortion of the poloidal number $m'$ produces the major spurious modes of $m\pm m'$. In addition, the amplitude of the spurious modes becomes larger as the original mode number $m$ is higher. Thus, fine positioning of the probe array is essential for high $m$ measurements, which are necessary for exploring nonlinear high mode couplings and cascades to nonmode high $m$ regions.

## IV. COMPARISON BEFORE AND AFTER CENTER ADJUSTMENT

We explored the effect of adjusting the probe center. The experiment was performed in the LMD-U linear plasma device,[12] which has a cylindrical vacuum vessel with axial length of 3740 mm and inner diameter of 445 mm (at the probe array position, it has a 544 × 544 mm$^2$ rectangular space). A helicon plasma is generated by a double-loop antenna wound around a quartz tube with axial length of 400 mm and inner diameter of 95 mm. Straight magnetic field up to 0.15 T is generated by magnetic coils around the vacuum vessel. In the experiment, a typical discharge was performed by argon gas with pressure of 2 mTorr inside the quartz tube and the rf power of 3 kW. The typical electron temperature of the LMD-U plasma measured with a movable Langmuir probe was 3 eV. The electron density was calculated from the ion saturation current and temperature.

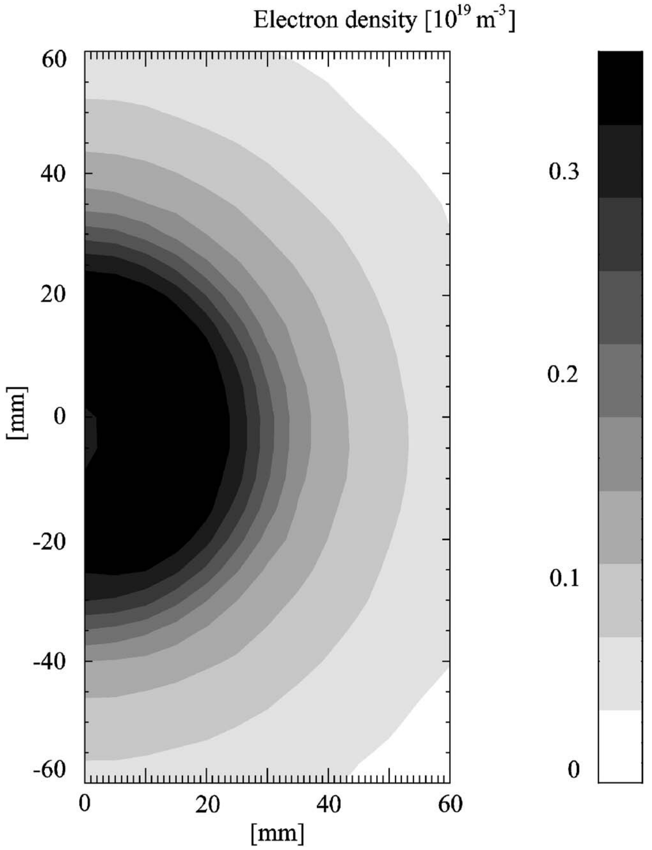

FIG. 2. Electron density profile of a typical LMD-U plasma measured with a two-dimensional movable probe. The LMD-U plasma has a cylindrical symmetric structure.

Figure 2 shows an example of a two-dimensional electron density structure measured with a two-dimensional movable probe.[12] From this observation, we confirm that, although only half sides of the plasma cross section are scanned, the electron density is considered to have cylindrical symmetry. It should also be noticed that the (concentric and circular) contour of the plasma density has a shift in the vertical direction in Fig. 2, by an amount of ~1.5 mm, with respect to the geometric center (origin of the axis in the figure) that is defined by the chamber. This small but finite shift of the plasma position may be due to, for instance, a displacement of an antenna with respect to the chamber or other similar reasons. Of course, this small shift [~O(mm)] does not affect the symmetry of the plasma column, since the plasma column (diameter of ~100 mm) is not limited by the chamber (diameter of 445 mm). The main impact of the small shift appears as a misinterpretation of the mode numbers of fluctuations, since the wavelength of microscopic fluctuations is shorter than plasma column. This is the reason why the accurate positioning of the probe array is essential.

The adjustment of the probe position with respect to the

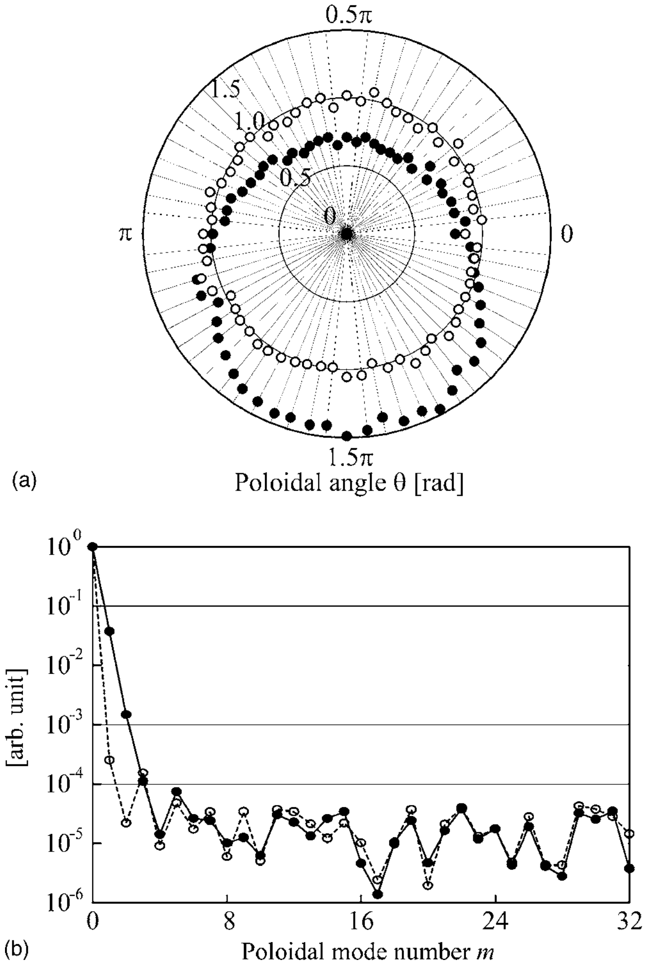

FIG. 3. (a) Polar plot of the time-averaged ion saturation current (arbitrary unit). Closed circles are before the center adjustment to the plasma axis, and open circles are after the center adjustment. (b) Fourier transformed expression of (a) in poloidal mode number space (arbitrary unit).

plasma column was executed by finding the position where the probe intensities become symmetric. Figure 3(a) shows the polar plot of the time-averaged ion saturation current measured by the poloidal probe array. The positions of the upper/lower screws around the bellows were −4/−6 mm, which were expected for the probe center to match the chamber center. Before the center adjustment, the intensities of the bottom were twice larger than those of the top. This asymmetry should be ascribed to the upward shift of the probe array from the plasma center. The positions of the upper/lower screws were moved to −5/−5 mm, which corresponded to 4 mm downward shift of the probe center. After the center adjustment, the intensities became almost symmetric. The remaining asymmetry may be caused by the individual difference in the probe gain or the amplitude distortion. Since the time-averaged intensity corresponds to the measurement of $m=0$, the noise produced by the geometrical nonuniformity or the phase distortion does not appear [see Eq. (1)].

Figure 3(b) shows the results of the Fourier transform on the time-averaged intensity to mode number space. The effects of the center shift and the probe gain (i.e., the surfaces of the tips and the radial positions) can be distinguished since the spurious modes of low mode numbers and the white noise of higher numbers stem from the center shift and the gain variation, respectively. After the center adjustment, the low mode number noise ($m'=1,2$) decreased significantly, while the white noise stayed almost the same. The spectral powers of $m'=1,2$ components became almost comparable to the white noise. Therefore, the effect of the center shift has been eliminated. By the same argument, the effect of the tilt of the probe array in the axial direction is negligible, since the $m'=2$ component is not remarkable.

The degree of the gain variation can be calculated by Eq. (3). Since the average of the white noise power $\langle(\hat{\delta}_a/2)^2\rangle$ is $2\times10^{-5}$, the degree of the gain variation should be $\langle\delta_a^2\rangle=M\langle\hat{\delta}_a^2\rangle/4=(3.5\%)^2$. The gain in ion saturation current mainly depends on the length of the probe tip and the circuit resistors. The latter is estimated as ~0.5% to be neglected here. Hence, the gain variation should mainly come from the accuracy in the fabrication the probes mounted on the plate, which is 0.1 mm in the probe length in this case. The value 3.5% corresponds to 0.11 mm variance in the probe length. This fabrication accuracy is consistent with the present gain variation. In addition, the cross talk level $6\times10^{-6}$ is smaller enough than the white noise level $2\times10^{-5}$.

Figure 4 shows the spatiotemporal behavior of the ion saturation current and the power spectra $S(m,f)$ before and after the center adjustment. The positions of the upper/lower screws were ±0/±0 mm before the adjustment and −5/−5 mm after the adjustment. Thereby, the probe center was adjusted horizontally for 5 mm. Here, each signal of ion saturation current is normalized by its temporal average $\langle I\rangle$. This normalization eliminates spurious modes produced by the probe gain or the amplitude distortion $\delta_a$. However, the phase distortion $\delta_p$ can produce the noise and it cannot be removed by normalization.

The spatiotemporal behavior after the center adjustment [Fig. 4(b)] shows a straight propagation with $m=3$ and $f=4.3$ kHz, while that before the center adjustment [Fig. 4(a)] shows a distorted signal, particularly at the poloidal angle around $\pi$. This distorted signal is produced by center shift by 5 mm with mainly $m'=1$, so that spurious modes produced by the phase distortion $\delta_p$ are seen at $m=2,4$ with the same frequency in $S(m,f)$ [Fig. 4(c)]. The spectral powers of these spurious modes are about 1/20 [$=(m\hat{\delta}_p/2)^2$] of the really existing $m=3$ fluctuation. This value is similar to the calculated value 0.04 from 5 mm center shift assumption. Figure 5 shows the power ratio of the spurious modes ($m=2,4$) to the real mode ($m=3$), when the probe center is shifted horizontally from 0 to 5 mm (the positions of the upper/lower screws from −5/−5 to ±0/±0 mm). The power ratio reduced according to the calculated ideal case with some offset. The offset occurs by the noise level or the broadband fluctuation components.

## V. SUMMARY

In summary, there are two kinds of the effects of misalignments of probes in the analysis of fluctuations, i.e., the amplitude and the phase distortions, to produce the spurious noise modes in wave number analysis. The 64-channel poloidal probe array can successfully eliminate the spurious

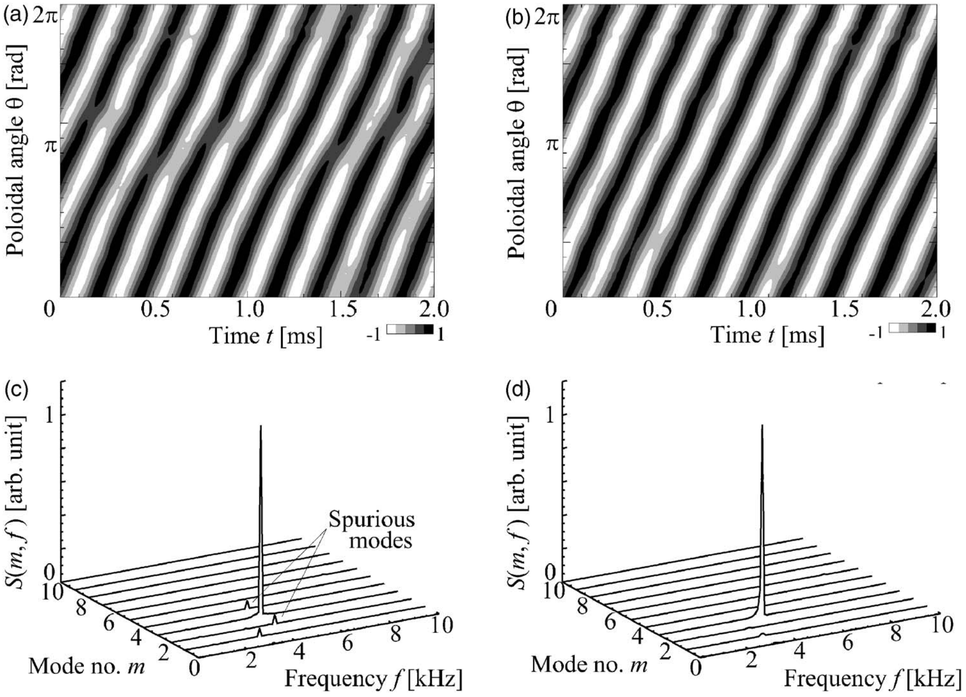

FIG. 4. Spatiotemporal behaviors of the ion saturation current fluctuations (a) before and (b) after the center adjustment. (c) and (d) are the power spectra $S(m,f)$ of (a) and (b), respectively. The strongest mode is $(m,f)=(3,4.3\text{ kHz})$, and the second mode $(m,f)=(1,3.1\text{ kHz})$ can be seen.

modes with low poloidal wave numbers by adjusting the position of the array to the plasma center. The range of mode numbers, which is subjected to pollution of spurious modes, is found important in studying the nonlinear interaction of excited instabilities.[13] Thus, the precise positioning of the probe array that is successfully explained in this article is inevitable for the study of nonlinear interactions. The argument presented here shows that the amplitude distortion caused by the individual difference in the probe gain can be easily eliminated by the normalization, while it is difficult to remove the phase distortion caused by the azimuthal misalignment of the probe tips. However, this article presents the formula to evaluate the noise level produced by the phase distortion for the wave number measurements. This kind of consideration on the effects of the probe misalignment is absolutely necessary for the precise wave number analysis for turbulence.

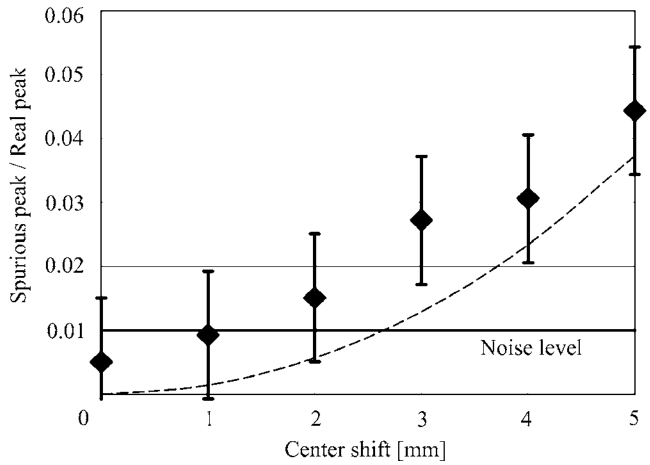

FIG. 5. Center shift of the probe array vs the power ratio of the spurious modes ($m=2,4$) to the real mode ($m=3$). The dashed line shows the calculated ratio in an ideal case. Signal-to-noise level is about 0.01.

## ACKNOWLEDGMENTS

This work was supported by Grant-in-Aid for Specially-Promoted Research of MEXT (16002005) (Itoh Project), by the collaboration programs of NIFS (NIFS07KOAP017) and RIAM, Kyushu University, and by Grant-in-Aid for Young Scientists (B) of JSPS (19760597).

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