Fluctuations-Based Calibration of Probe Radial Position in Linear Magnetized Plasmas

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To properly study plasma fluctuations and to develop new plasma processing technologies, precise calibration of probes is required. We exploit plasma fluctuations properties to develop a novel simple method for calibrating the radial position of a probe in a linear magnetized plasma device. We determine the probe radial position with respect to the plasma column axis by using a previously calibrated reference probe. This study provides the experimental evidence that plasma fluctuations can be used not only to investigate plasma physics but also to determine the radial position of probes.

Keywords: magnetized plasma, probe, calibration, radial position, high-frequency, fluctuations, coherence

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An understanding of turbulence and fluctuations-driven transport mechanisms remains crucial for improving plasma confinement in fusion devices [1]. Furthermore, neoclassical and anomalous transport also affect the development of advanced plasma processing technologies. In this broad context, diagnostics with high spatial resolution are needed to correctly characterize the plasma properties and the parameters required to infer heat and particle fluxes. However, the installation of diagnostic instruments can be challenging. For instance, a key practical difficulty is the precise calibration of the radial position of newly installed probes. Probes are among the most widely used diagnostics due to their relative simplicity and ability to provide reliable measurements.

In low-temperature devices such as the Plasma Assembly for Nonlinear Turbulence Analysis (PANTA), electrostatic probes are extensively used. In PANTA, numerous important results have been obtained in the investigation of plasma fluctuations using various probes configurations [2]. In particular, the study of high frequency fluctuations in linear devices, usually characterized by short spatial wavelength, requires an accurate determination of the probe radial position.

In this work, we present a novel method for calibrating the radial position of a newly installed electrostatic probe in magnetized plasma systems. The method is applicable to any probe, provided that the position of a reference probe has been accurately determined through prior calibration. The technique exploits density fluctuations properties, derived from ion saturation current (I_{is}) measurements. Cross-spectral densities of the I_{is} signals from the two probes are calculated using Fourier transform, and then compared through coherence analysis. In other similar studies, cross correlation analysis was already used to infer the origin region of elongated plasma structures and the relative position of two probes [3].

In a linear device such as PANTA, it is convenient to define the probe location in terms of its radial position r relative to the center of the plasma column. In most cases, probes can be radially movable with respect to the axis of the cylindrical vessel after manual calibration. However, depending on the operation conditions, the plasma column is not always centered with respect to the vacuum vessel.

This experiment was carried out on the linear magnetized plasma device PANTA to determine the radial location of a new radially movable Langmuir probe (LP). The magnetic field strength was set to 0.09 T, the RF input power was set to 3 kW, and the initial neutral gas pressure was set to 0.1 Pa.

PANTA is equipped with a poloidally arranged 64 channels Langmuir probe array. Significant progress in the study of plasma instabilities has been achieved using this diagnostics [4, 5]. Each channel is located at a fixed radial position of 4 cm from the center of the array. After installation, the array was centered with respect to the plasma column by analyzing the poloidal plasma density profile [6]. One of the 64 channels was selected as reference probe to calibrate the newly installed LP.

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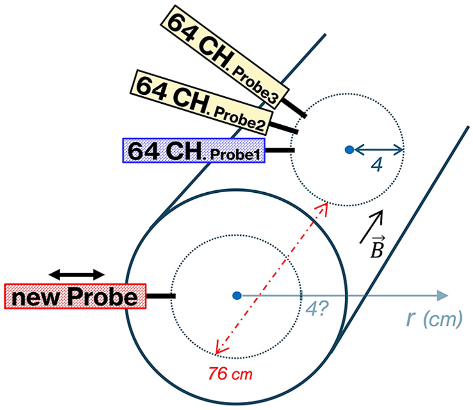

Fig. 1. Schematics of the calibration setup along the plasma column. In red, the new installed LP. In blue, the reference channel in the 64 channels poloidal probe array, at the same poloidal angle as the new LP.

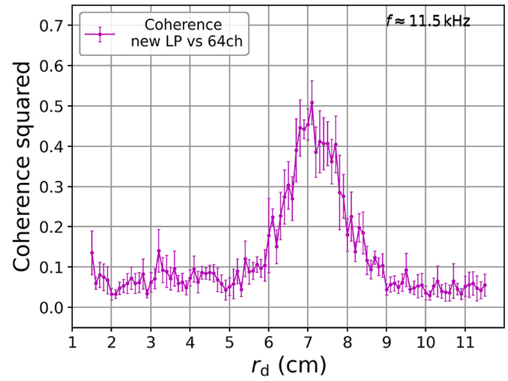

Fig. 3. Coherence radial profile for the fluctuation at approximately 11.5 kHz in the CSD between the new installed LP and the reference channel in the 64 channels poloidal array signals. The error bars indicate the standard deviation of the coherence obtained by varying the number of FFT points in the Welch method.

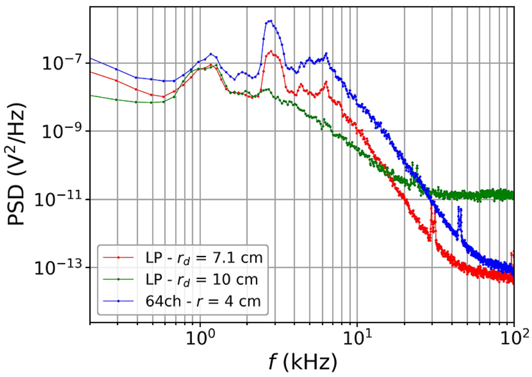

Fig. 2. Auto-power spectral densities of the Ion saturation current of a new LP at two dial locations r_d, and of one channel in the 64 channels array fixed at $r = 4$ cm (blue). Frequency resolution of these PSD is 100 Hz.

The reference probe and the new LP share the same poloidal angle. Their relative distance on the axis is approximately 76 cm (Fig. 1). Ion saturation current I_{is} was measured across the plasma radius using the new LP to be calibrated, and simultaneously by the reference probe in the poloidal array at its fixed radial position of 4 cm.

Cross-spectral density (CSD) analysis was performed between the reference probe signal and the signals acquired by the new LP at all radial positions. Figure 2 shows the auto-power spectral DENSITY (PSD) of the ion saturation current measured by the reference probe at $r = 4$ cm (blue), along with the auto-power spectral densities obtained by the new LP at two different radial positions $r_{d.}$ The position r_d is determined by the dial on the body of the probe. Similarities are observed between the PSD of the reference probe signal and the new LP signal when the dial position of the new LP is set to $r_d = 7.1$ cm (red). In particular, three coherent spectral peaks in the 1–10 kHz range can be noticed in both PSD.

The linear relationship between the signals measured by the two probes and its radial dependence were further examined through coherence analysis. This method allows the investigation of fluctuations at specific frequencies, whereas cross-correlation includes contributions from the entire time-domain signal. Consequently, coherence results are not affected by the different radial propagation of the various device-scale low-frequency modes observed in Fig. 2. Figure 3 shows the squared coherence $C(f,r)^2$ radial profile for fluctuations at approximatelty 11.5 kHz. It is defined as

$$C(f,r)^2 = \frac{|P_{xy}(f,r)|^2}{P_{xx}(f,r) * P_{yy}(f,r)}, \quad (1)$$

where $P_{xy}(f,r)$ is the CSD between the two probe signals, and $P_{xx}(f,r)$ and $P_{yy}(f,r)$ are the corresponding auto-PSD of the reference probe signal and the new LP signal, respectively.

Coherence analysis was conducted at a fluctuations frequency of approximately 11.5 kHz, since the shorter temporal and spatial scales of HIGH-FREQUENCY turbulence provide enhanced spatial resolution for probe calibration. Under these conditions, the coherence attains its maximum when the radial positions of the two probes are identical. As shown in Fig. 3, the coherence increases sharply as the new LP approaches the dial position $r_d = 7.1$ cm. This results indicates that the LP dial position of 7.1 cm corresponds to the plasma radial position r of 4 cm, where the reference probe in the 64 channel probe array is fixed.

In conclusion, plasma fluctuations properties were used to precisely calibrate the radial position of an electrostatic probe in the magnetized plasma device PANTA. This method simplifies probe installation and calibration and may be broadly applicable to both laboratory plasma studies and plasma processing technologies.

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