Utility of a baffled Langmuir probe for applications to edge plasma and turbulence characterization in stellarator plasma

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(Presented on 19 April 2004; published 5 October 2004)

Baffles are obstacles that shield plasma electrons from being collected by a floating probe by virtue of a small electron gyroradius compared to a large ion gyroradius. A baffled probe floats at space potential if the baffling results in equal electron and ion saturation currents. With such a probe, potential fluctuations can be monitored locally with minimal plasma perturbation. The performance is documented in the edge of a stellarator plasma. © *2004 American Institute of Physics.*
[DOI: 10.1063/1.1788858]

I. INTRODUCTION

Time series of electron temperature $T_e(t)$, electron density $n(t)$, and space potential $V_s(t)$ are used for determining particle transport and energy transport induced by plasma turbulence. A Langmuir probe[1] can measure these quantities locally. To obtain the time series $V_s(t)$, one can monitor the probe's floating potential $V_f(t)$, related to $V_s(t)$ according to $V_f = V_s + [(k_B T_e)/e]\ln[I_{e,\text{sat}}(I_{i,\text{sat}}+I_{\text{em}})]$. Here, k_B is Boltzmann's constant, e is elementary charge, subscripts "e,sat" and "i,sat" stand for electron saturation and ion saturation, respectively, and I_{em} is emitted current of an incandescent, electron emitting probe tip. Emissive probes[2] have the advantage that $V_f(t) \approx V_s(t)$ since $I_{e,\text{sat}}/(I_{i,\text{sat}}+I_{\text{em}}) \approx 1$ for sufficiently large values of I_{em}. Unfortunately, a probe's perturbation to the plasma increases as I_{em} increases. By sacrificing larger signal for smaller perturbation, the condition $I_{e,\text{sat}}/(I_{i,\text{sat}}+I_{\text{em}}) \approx 1$, and consequently $V_f(t) \approx V_s(t)$, can be attained by a nonemitting probe ($I_{\text{em}}=0$) by recessing the collecting surface behind a properly placed shield[3–5] to reduce the magnetic-field-aligned access of electrons so that $I_{e,\text{sat}} \approx I_{i,\text{sat}}$. Experiments are reported here that allow the performance of one such shielded Langmuir probe, the so-called baffled probe, to be evaluated in the edge region of the plasma produced in the helically symmetric experiment (HSX) stellarator at the University of Wisconsin.[6] Specifically, the capability of a baffled probe to measure dc and ac values of space potential and electron temperature is tested.

II. EXPERIMENTAL APPROACH

Figure 1 shows the baffled probe installed on HSX. The outer diameter of the boron nitride (BN) stem is 2 mm. The slot width is 1 mm and slot depth is 2 mm. The 0.75-mm-diam tungsten tip is recessed back 1 mm from the far end of the BN baffles. The 2-cm-long stem is turned down from a 12.6-mm-diam piece. The total length of exposed BN is 6 cm and is held by a stainless steel tube. This tube runs inside a bellows assembly outside the vacuum vessel and is held by a vacuum rotary feedthrough, which is attached to a translation stage.

The hydrogen–plasma discharges produced by HSX are heated by 50 kW of second harmonic (28 GHz at $B=0.5$ T) electron cyclotron resonance heating power using a gyrotron. Typical central line-averaged densities $\langle n_e \rangle$ range from 0.5 to 2.0×10^{12} cm^{-3}. Central electron temperatures, measured by Thomson Scattering, are on the order of 500 eV for these discharges. From earlier Langmuir probe measurements, edge densities are less than 50% of the central line-averaged densities, $k_B T_e \approx 40$ eV, and $k_B T_i \approx 25$ eV. With these parameters, ion and electron gyroradii are approximately $\rho_i \approx 1.4$ mm and $\rho_e \approx 40$ μm, respectively. Many discharges, each lasting 50 ms, are required to obtain radial scans with Langmuir probes, or to investigate several rotational orientations of the baffled probe.

III. dc PERFORMANCE OF THE PROBE IN HSX

The baffled probe is swept ±800 V using an audio amplifier (nominally 1 kW) driving a step-up transformer. A

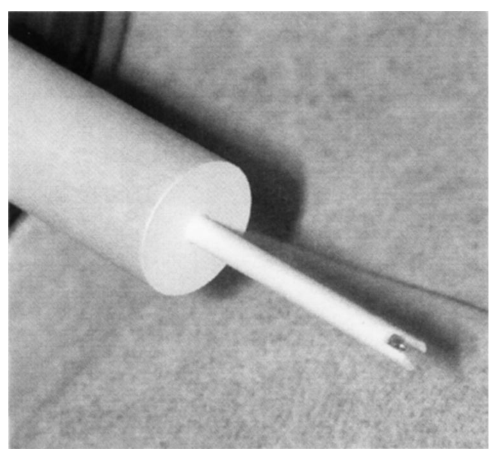

FIG. 1. Photo of baffled probe for HSX.

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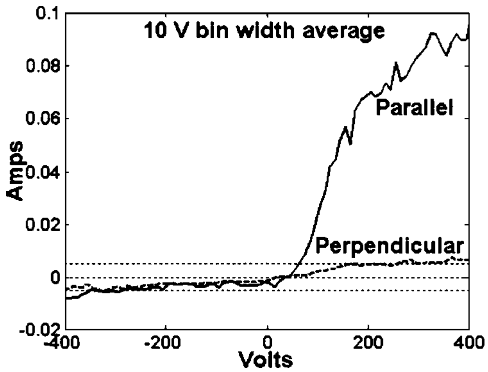

FIG. 2. Smoothed $I-V$ traces for perpendicular and parallel probe orientations.

number of current–voltage ($I-V$) traces were obtained for the baffled probe at line-averaged densities of $\langle n_e \rangle = 1 \times 10^{12}$ cm^{-3}, located at the edge of the plasma, oriented at various angles with respect to the magnetic field. Previous edge measurements with Langmuir probes at these plasma parameters show that $I_{i,\mathrm{sat}}$ fluctuates at amplitudes as large as 40% and the rms amplitude of V_f is as large as 20 V. Because of these large fluctuation amplitudes, Fig. 2 plots the perpendicular and parallel baffled probe sweeps with a 10 V binned average applied to smooth the sweep curves. $I_{e,\mathrm{sat}}$ is reduced by baffling since the effective cross section of the probe for collecting electrons decreased from approximately 1.5 mm^2 to practically zero. Note that V_f is approximately the same for both orientations, in contrast to exhibiting the expected shift of $[(k_B T_e)/e]\ln[I_{e,\mathrm{sat}}/I_{i,\mathrm{sat}}]_{\mathrm{parallel}}$, as discussed earlier.

At $\langle n_e \rangle = 1 \times 10^{12}$ cm^{-3}, there is evidence that a population of superthermal electrons exists in HSX,[7] which would severely complicate the interpretation of the probe measurements. As density is increased to $\langle n_e \rangle = 2 \times 10^{12}$ cm^{-3}, the evidence for the superthermal electron population is significantly reduced. To compare these two cases, floating potential was measured at a few radial locations, for both the perpendicular and parallel orientations. Figure 3 shows the results, indicating there is an unexpectedly small difference

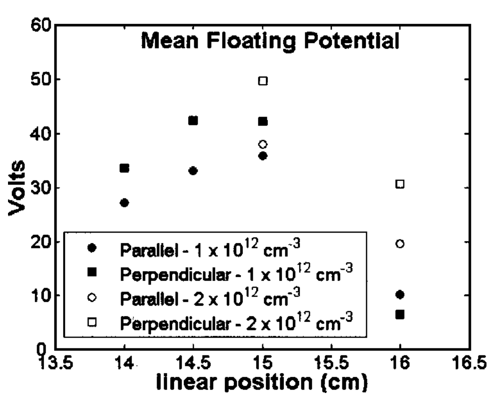

FIG. 3. Radial profile of time-averaged (mean) floating potential of probe at edge of HSX plasma. The separatrix is about ≈ 15 cm: (filled symbols) $\langle n_e \rangle = 1 \times 10^{12}$ cm^{-3} where the first three pairs are consistent with $\mu_e = 0.2$, smaller than expected, and the last pair is consistent with $\mu_e = -0.1$, opposite to the expected sign: (open symbols) 2×10^{12} cm^{-3}, where each pair is consistent with $\mu_e = 0.3$, again smaller than expected.

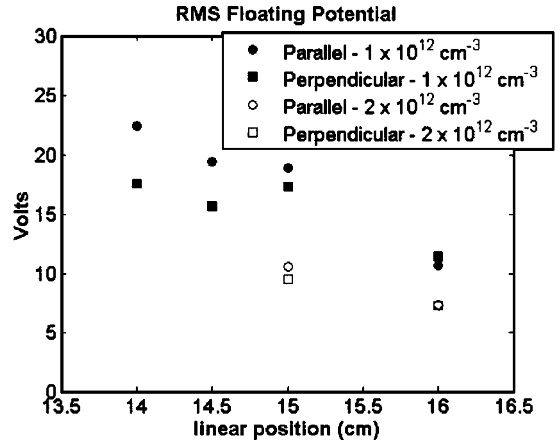

FIG. 4. RMS amplitude of floating potential in HSX. Same symbols as Fig. 3.

between the floating potential in the two orientations, based on $[I_{e,\mathrm{sat}}/I_{i,\mathrm{sat}}]_{\mathrm{parallel}} = 10$, so $[\mu_e]_{\mathrm{parallel}} \equiv \ln[I_{e,\mathrm{sat}}/I_{i,\mathrm{sat}}]_{\mathrm{parallel}} = 2.3$, and $k_B T_e = 40$ eV. On this linear slide position scale, the separatrix is estimated to be at ~ 15 cm, and the magnetic axis ~ 7 cm.

IV. ac PEFORMANCE OF THE PROBE IN HSX

Figure 4 shows rms amplitude of floating potential fluctuations in the perpendicular orientation for the high and low density cases. It would appear that for both cases, the fluctuation levels are reduced when baffling is employed. Figure 5 displays power spectra, sampled at 5 MHz, using amplifiers with a four-pole filter at 800 kHz for the low density case, at perpendicular and parallel orientations. The spectra are similar for the high density case. The spectra begin to diverge above 30 kHz, and are most disparate between 100 and 300 kHz.

V. OVERALL PERFORMANCE

Tests of a baffled probe in plasma having $k_B T_e = 40$ eV demonstrate that the probe, as built, survives many 50-ms-long discharges. The shielding of the collecting probe tip from electrons characterized by $k_B T_e = 40$ eV is shown to depend on probe orientation angle as expected and in a way

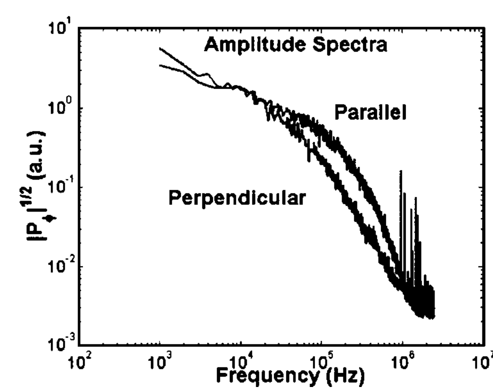

FIG. 5. Amplitude spectra of floating-potential fluctuations within HSX plasma edge for $\langle n_e \rangle = 1.0 \times 10^{12}$ cm^{-3}. Note the deviation in the two spectra in the range 30–800 kHz.

that is similar to the dependence reported earlier[5] for $k_B T_e = 0.2$ eV. The difference in the probe's floating potential in HSX for parallel and perpendicular orientations implies $\mu_e < 1$ for the parallel orientation, which is smaller than the $\mu_e \approx 2$ expected from either the modeled value or measured value of $\ln[I_{e,\mathrm{sat}}/I_{i,\mathrm{sat}}]$.

The deviation between the spectra of floating potential fluctuations obtained for the parallel and perpendicular orientations of the baffled probe is consistent with electron temperature fluctuations being present, but insufficient as conclusive evidence. An array of perpendicular-oriented and parallel-oriented baffled probes,[8,9] sampling the same plasma region, could monitor both $V_s(t)$ [i.e., $V_f(t)$ of the perpendicular-oriented probe] and $T_e(t)$ [from subtracting $V_f(t)$ of a parallel-oriented baffled probe from $V_f(t)$ of a perpendicular-oriented baffled probe].

ACKNOWLEDGMENTS

This work is supported by the Department of Energy and the National Science Foundation.

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