Compact Langmuir-probe/baffled-probe array for applications to edge-plasma and turbulence characterization in a stellarator

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Time series of electron temperature $T_e(t)$, electron density $n_e(t)$, and space potential $V_s(t)$ can be used for determining particle transport and energy transport induced by plasma turbulence. A Langmuir probe [1] can measure locally T_e, n_e, and V_s from the probe's current-voltage (I-V) characteristics. 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 $V_f = V_s - [(k_BT_e)/e]\ln[I_{e,sat}/(I_{i,sat} + I_{em})]$. 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 $I_{e,sat}/(I_{i,sat} + I_{em}) \approx 1$ 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 $I_{e,sat}/(I_{i,sat} + I_{em}) \approx 1$, and consequently $V_f(t) \approx V_s(t)$, can be attained by a non-emitting probe (I_{em}=0) by recessing the collecting surface behind a properly placed shield [3] to reduce the magnetic-field-aligned access of electrons so that $I_{e,sat} \approx I_{i,sat}$.

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 baffling results in equal electron and ion saturation currents, in which case space-potential fluctuations can be monitored in real time and with minimal plasma perturbation. Simultaneously-acquired Langmuir-probe and baffled-probe signals subtract to yield a time series proportional to the electron temperature. In this paper, the baffled probe's utility in individual and array applications are discussed with emphasis on a modification that offers compactness and fabrication simplicity. Probe shielding has been tested on the HSX stellarator [4] at the University of Wisconsin and on the WVU Q machine at West Virginia University. We document probe performance in low-temperature ($k_BT_e = k_BT_i$ = 0.2eV), low-density (n_e=10^9 cm^{-3}) alkali plasma and high-temperature (k_BT_e = 40eV, k_BT_i = 25eV), high-density (n_e=5×10^{11} cm^{-3}) stellarator plasma. A design is described for a compact array, consisting of a Langmuir probe and a baffled probe, for cross-correlating $V_s(t)$ and $T_e(t)$. This array can sample simultaneously in a single plasma region both $V_s(t)$ (with a shielded probe) and $T_e(t)$ (from subtracting a Langmuir probe's $V_f(t)$ from a shielded probe's $V_f(t)$).

Fig. 1 is a photograph of the compact array installed on the WVUQ machine. The alumina (Al_2O_3) probe stem, with 7.5 mm outer diameter, surrounds the 4.7-mm-diameter stainless steel tube that serves both as a Langmuir probe and as the baffle for the inner collecting probe tip, *i.e.*, the baffled probe. The slot width is 1.7 mm and the slot depth is 6.4 mm. The probe tip is stainless steel tubing having an outer diameter of 1.8 mm.

Fig. 2 displays amplitude spectra of floating-potential fluctuations obtained simultaneously in the WVUQ by the array's Langmuir and baffled probes. A factor-of-3 disparity in the spectra exists in the turbulent part of the spectrum, between 0.1 – 4 kHz. These measurements were acquired at a sampling rate of 0.2 Msamples/s.

Fig. 3 shows the baffled probe installed on the HSX stellarator experiment. 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-diameter 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 diameter piece. The exposed BN is 6 cm long and is supported by a stainless steel tube. This tube runs inside a bellows assembly outside the vacuum vessel and is held by a vacuum rotary feed-through, which is attached to a translation stage.

The hydrogen-plasma discharges produced by HSX are heated by 50 kW of 2nd harmonic (28 GHz at B = 0.5 T) electron cyclotron resonance heating (ECRH) power using a gyrotron. Typical center-crossing, line-averaged electron densities $\langle n_e \rangle$ range from 0.5 - 2.0 $\times$ 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% the central line-averaged densities, $k_B T_e \approx 40$ eV, and $k_B T_i \approx 25$ eV. Here, the edge refers to a region 90%-100% of the way to the separatrix from the magnetic axis. 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.

The baffled probe is swept +/- 800 V using an audio amplifier (nominally 1 kW) driving a step-up transformer. A number of *I-V* traces, shown in Fig. 4, were obtained for the baffled probe, located at the edge of the plasma, oriented at various angles with respect to the magnetic field. When the probe's collection surface points perpendicular to the magnetic field, the optimal value of probe orientation angle (at which $I_{e,sat} \approx I_{i,sat}$) can be reached.

Fig. 5 displays Langmuir-probe and baffled-probe amplitude spectra of floating-potential fluctuations, sampled at 5 Msamples/s using amplifiers with a four-pole filter at

800 kHz for the case of $<n_e> = 1\times10^{12}$ cm^{-3}, for different times. The spectra begin to diverge above 30 kHz, and are most disparate between 100 kHz – 400 kHz.

Our compact design for a baffled-probe array could be used, in principle, for cross-correlating $V_s(t)$ and $T_e(t)$ to get the cross spectrum and the cross phase. Tests of the baffled probe in HSX edge-plasma demonstrate that the probe, as built, survives many 50-ms-long, 40-eV discharges. Our demonstration that the electron shielding of the probe depends on probe orientation angle as expected and in a way that is similar to the dependence reported earlier for electrons characterized by k_BT_e = 0.2 eV, suggests that a compact array could be used successfully in stellarator plasma.

The deviation between the spectra of floating potential fluctuations obtained for the unshielded and shielded probe orientations) is consistent with electron temperature fluctuations being present, but insufficient as conclusive evidence. The ratio between the frequency range associated with these fluctuations in the HSX plasma and the frequency range associated with these fluctuations in the WVUQ plasmas is 150, which is approximately the same as the ratio between the ion-acoustic speeds in the two devices $(\sqrt{(m_{i,WVUQ}T_{e,HSX})}/\sqrt{(m_{i,HSX}T_{e,WVUQ})})$.

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References

[1] I. Langmuir and H. M. Mott-Smith, *Gen. Electr. Rev*. 26, 731 (1923).

[2] R. F. Kemp and J. M. Sellan, *Rev. Sci. Instrum*. 37, 455 (1966).

[3] I. Katsumata and M. Okazaki, *Jpn. J. Appl. Phys*. 6, 123 (1967); S. V. Ratynskaia, V. I. Demidov, and K. Rypdal, *Phys. Plasmas* 9, 4135 (2002); V. I. Demidov, S. M. Finnegan, M. E. Koepke, and E. W. Reynolds, *Rev. Sci. Instrum.* 74, 4558 (2003).

[4] F. S. B. Anderson, A. Almagri, D. T. Anderson, P. G. Matthews, J. N. Talmadge, and J. L. Shohet, *Trans. Fusion Tech*. 27, 273 (1995).

[5] M. E. Koepke, V. I. Demidov, S. M. Finnegan, and E. W. Reynolds, "Baffled-probe cluster for simultaneous, single-point monitoring of magnetized plasma fluctuations," Rev. Sci. Instrum., submitted.

Fig. 1: Photo of compact array installed on WVUQ.

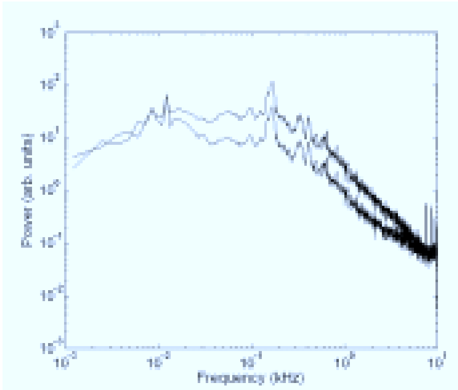

Fig. 2: Power spectrum of floating-potential fluctuations within WVUQ plasma edge. Upper (lower) trace is outer (inner) conductor. Note deviation in two spectra in the range of 0.05 KHz – 4 kHz. Scale-range: 10^{-3}-10^{3} (vert); 10^{-3}-10^{1} (horizontal).

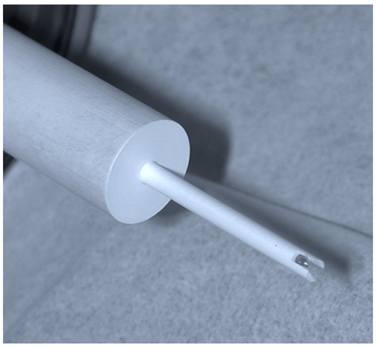

Fig. 3: Photo of baffled probe for HSX.

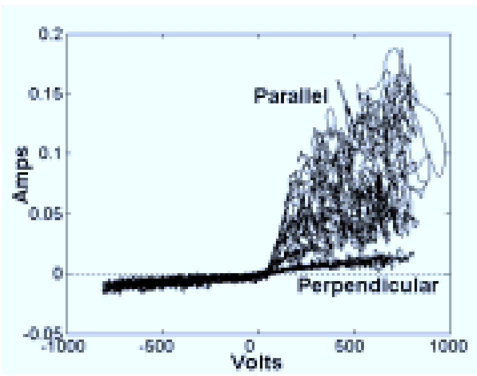

Fig. 4: *I-V* characteristics for various probe orientations, *i.e.*, for various degrees of electron shielding, in HSX.

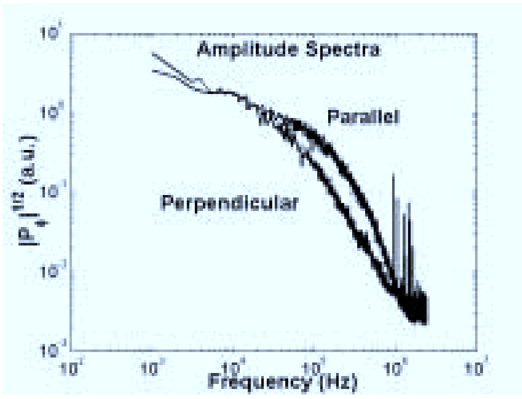

Fig. 5: Spectrum of floating-potential fluctuations within HSX plasma edge for $\langle n_e \rangle = 1.0 \times 10^{12}$ cm^{-3}. Note the deviation in the two spectra in the range 30 kHz - 800 kHz. Scale-range: 10^{-3}-10^{1} (vertical); 10^{2}-10^{7} (horizontal).