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Abstract

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Langmuir probes are commonly used to diagnose plasmas in the edges of magnetic confinement devices. Recent upgrades to the divertor of NSTX have created the opportunity to augment the existing diagnostic systems with a new 99 Langmuir probe array in the divertor floor of the machine. The probes consist of a set of flush-mounted probes with three electrodes at each radial location (spanning 2.4 cm) and 33 rows in the radial direction covering 10 cm.[1]. Myriad issues are typically met when using flush mounted probes in a magnetic confinement device such as non-saturation of the ion current[2], and reduced electron current collection[3] in addition to more mundane probe problems such as perturbation of the local plasma[4] and plasma fluctuations on time-scales shorter than a typical sweep such as those caused by plasma turbulence[5]. A common method of overcoming the temporal resolution issues of swept probes is the use of the triple Langmuir probe method[6]. This method is subject to the same issues facing swept probes and interpretation methods range from application of simple triple probe equations[7] to inclusion of multiple correction functions[8, 9].

In addition to the usual Langmuir probe results, recent work has highlighted the importance of currents within the scrape-off-layer of the plasma. Takahashi, *et al.* recently showed that a current spike preceded ELM events in DIII-D[10]. In addition to the suggested relationship with ELMs, scrape-off-layer currents could strongly influence the dynamics of liquid metal plasma facing components[11] of concern on NSTX. The present work describes the implementation of a set of electronics capable of monitoring single- and triple-Langmuir probes as well as a number of scrape-off-layer currents (SOLC) with the dense probe array.

The electronics system was constrained by available resources to provide signal acquisition for 40 analog channels. The chosen implementation of signal types is to diagnose 10 triple-Langmuir probes, four swept-Langmuir probes, three "parallel" scrape-off-layer current monitors and one "perpendicular" current monitor. Parallel SOLC are those which form a closed loop from inboard to outboard divertor legs through the machine structure. Perpendicular SOLC are those which form a closed loop within the PFC material and plasma[12].

The full potential of the array is realized through a patch-panel system in the instrumentation rack. Using a set of interconnect cables, any given electrode can be connected to a given signal from the electronics allowing the operator a wide degree of flexibility in measurements. In the initial operation of the system, four triple-Langmuir probes have been paired with the swept probes to determine the accuracy of the various models and inter-

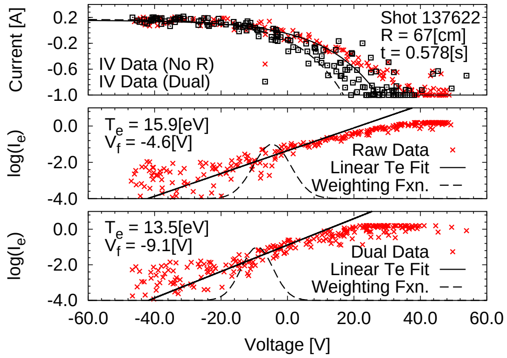

FIG. 1: Comparison of single and dual probe method for the same electrode. A reduced set of points is shown for clarity

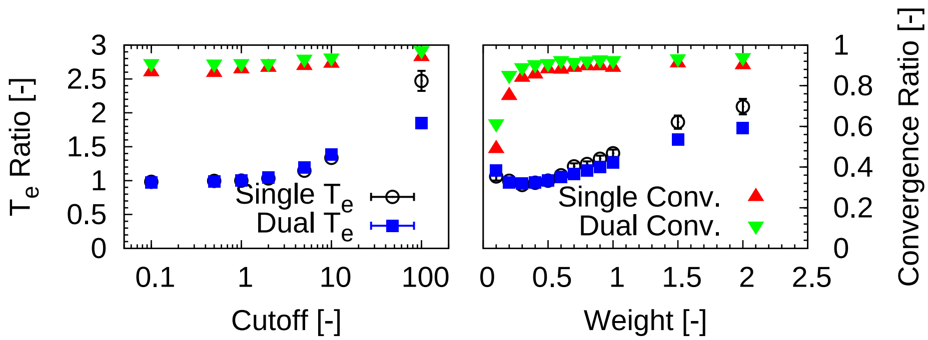

FIG. 2: Result of variation in weight function width and value of cutoff. Weight and cutoff given as multiples of T_e and ion current standard error, respectively. Each data point represents an ensemble of 500 sweeps. The T_e ratio is the ratio of the calculated temperature at the present value of weight/cutoff vs. the temperature calculated at the reference weight/cutoff (0.5/1.0 respectively). Identical symbols used on both subfigures.

pretations of the signals. The swept probes throughout this work are swept at 103Hz and ±50V. The radial separation between a single probe and its triple-probe mate is 2.5mm.

Each electrode signal from the vessel is paired with a return conductor that provides a vessel ground reference. In the case of parallel SOLC measurements, the current passing from the electrode to this return conductor through a small shunt resistor (5 Ω) is measured. In the case of the perpendicular SOLC, the current is measured from one electrode to another electrode in the array through a similar shunt resistor. All external signal wires consist of shielded-twisted pair to minimize external inductances as well as noise.

Each triple-Langmuir probe is biased by an individual circuit board which contains a regulated, isolating DC-DC power supply (MuRata ULE 48/1.25) and necessary signal conditioning electronics. The power supply provides a constant bias of 48V between electrodes 1 and 3 of the "standard" triple-probe circuit[8]. The signal conditioning uses an AD629 instrumentation amplifier which separates the triple-probe board from ground references via a large internal impedance ($> 100\,\mathrm{k}\Omega$ overall circuit impedance). The three signals digitized from each board are the floating potential measurement, the potential of the positively biased electrode and the current flowing through the circuit. The acquisition system samples all 40 analog channels at 250 kSamples/s/ch simultaneously.

Manual analysis of the data is not feasible given the volume of data present. Efforts have been made to create a standardized interpretation of each swept probe characteristic of this system. The use of such a large sampling rate with respect to the sweep frequency results in roughly 1000 data points per sweep. The algorithm developed results in a fitted characteristic of the type described as follows:

$$I_{probe} = I_{sat}\{1 - exp[(V - V_f)/T_e]\} \tag{1}$$

where I_{probe} is the current to the probe, I_{sat} is the ion saturation current, V is the electrode voltage, V_f is the floating potential, and T_e is the electron temperature given in eV. The algorithm applies an iterative process to determine the characteristic. A linear fit is applied to the data surrounding the floating potential with a Gaussian weighting function of width determined by some multiple of the temperature. It is found that in low density plasmas, perturbations in the ion current can cause large changes in the calculated temperature (100eV vs. 20eV in some cases). A cutoff selectively removes data prior to temperature determination. The cutoff level is defined by the mean maximum current plus a multiple of the standard error[13] over the lowest 5% of the voltage sweep. Once T_e is determined by linear fit, the floating potential is redetermined and the process is repeated. Problems in the data can cause the algorithm not to converge and when this occurs, appropriate data are generated for later inspection. Figure 1 shows an example data analysis set. Figure 2 shows the effect of both weighting function and cutoff as compared to arbitrarily chosen reference values of each. The relative flatness in the dual-probe method (described below) indicates that some of the non-linear behavior shown in ref. [4] is removed consistent with that work.

Figure 1 indicates that the ion current saturates. In the plasmas measured by the probe

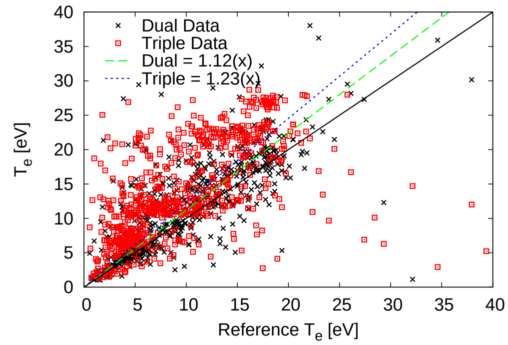

FIG. 3: Comparison of temperature calculations for dual and triple probe methods as compared to circuit resistance corrected single probe calculation.

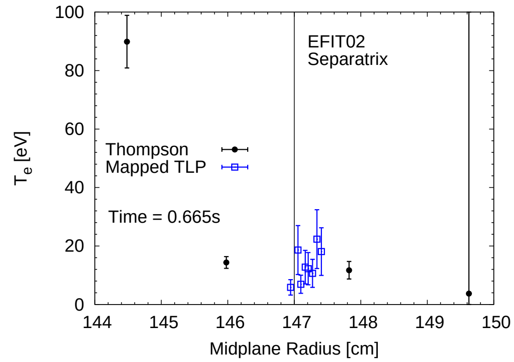

FIG. 4: Comparison of mid-plane Thompson measurements with triple-Langmuir probe results as mapped with magnetics data for shot 137603, time indicated. All probe locations are mapped based on the strike point and the probe array end-point position.

array so far, the Debye length is of order 10 microns placing the operation of the probe in the thin-sheath regime. Inclusion of 2D magnetic sheath effects, such as those in ref. [14], amount to a 10% alteration in current collection area. As such, further evaluation of 3D sheath effects is not found necessary for these plasmas. Likewise, finite Larmor radius corrections are impossible to evaluate with the current data set and laid aside for a future study.

An option for measurement made possible by the electronics is the use of a “dual probe” method where the floating potential measured on the adjacent triple probe is subtracted from the bias on the swept probe to account for fluctuations and plasma perturbation effects similar to the pin-plate probe[4]. Figure 1 shows a comparison of the raw IV characteristic and the resulting analysis against the dual probe method with circuit resistance corrections as well.

Although there are a number of correction functions available for the interpretation of the triple-Langmuir probe signal[8, 9], these are not generally applicable and it is not *a priori* known how necessary any corrections will be. Instead, the simple analysis is applied where T_e $(V_1 - V_f)/ln(2)$ and comparison is made to the single probe measurements for T_e.

In order to produce significant statistics on the three methods (single-, dual-, and triple-probes) 10 similar discharges were analyzed. Sweeps were taken during plasma current flat-top with strike-point control to eliminate gross variations over the course of a single sweep. The final data set consists of 1245 data points for the four pairs of probe sets. The reference T_e is calculated by the single probe method above (chosen due to the relative familiarity of the diagnostic) after taking into account known circuit resistance. Figure 3 shows a subset of the final data set for clarity. It is found that on average, the dual- and triple-probe methods produce temperatures 12% and 23% higher, respectively, than the reference single-probe. Although not shown in fig. 3, the average decrease in temperature when correcting for circuit resistances is 20%. Based on the data scatter, the precision of the simple triple-probe method is calculated to be roughly 45% on any given measurement. Application of correction methods such as those found in ref. [8] and [9] do not improve the scatter or mean offset.

The nearest independent T_e diagnostic available for comparison is Thompson scattering at mid-plane. Magnetic reconstruction allows the mapping of the probe signals to the mid-plane location, though there is some uncertainty in this process due to the coarseness of the grid (position resolution is estimated at ≈1 cm at the strike point). Nevertheless, the entire probe set is mapped according to the strike-point mapping and compared to measurements there for the same time slice, shown in Fig. 4. It is seen that at the very least, the temperature at the divertor target does not exceed the mid-plane temperatures by a significant amount using the nominal magnetics data. Improved modeling methods are planned in the future to create a more complete picture of the SOL plasma based on all available diagnostics.

The 99 Langmuir-probe array on NSTX has been diagnosed and operated successfully during the 2010 run campaign. The implemented system allows a high degree of flexibility in measurement location and type. A standardized interpretation has been implemented for the Langmuir probes providing a comparison to dual- and triple-probe methods. On average, all three temperature calculation methods yield results within 25% of one another. Upon mapping to mid-plane, the calculated temperatures are not inconsistent with those measured by Thompson scattering.

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