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Modification of the electron energy distribution function during lithium experiments on the National Spherical Torus Experiment

M.A. Jaworski [a,*], M.G. Bell [a], T.K. Gray [b], R. Kaita [a], J. Kallman [a], H.W. Kugel [a], B. LeBlanc [a], A.G. McLean [b], S.A. Sabbagh [c], V.A. Soukhanovskii [d], D.P. Stotler [a], V. Surla [e]

[a] Princeton Plasma Physics Laboratory, United States
[b] Oak Ridge National Laboratory, United States
[c] Columbia University, United States
[d] Lawrence Livermore National Laboratory, United States
[e] University of Illinois at Urbana-Champaign, United States

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ABSTRACT

The National Spherical Torus Experiment (NSTX) has recently studied the use of a liquid lithium divertor (LLD). Divertor Langmuir probes have also been installed for making measurements of the local plasma conditions. A non-local probe interpretation method is used to supplement the classical probe interpretation and obtain measurements of the electron energy distribution function (EEDF) which show the occurrence of a hot-electron component. Analysis is made of two discharges within a sequence that exhibited changes in plasma fueling efficiency. It is found that the local electron temperature increases and that this increase is most strongly correlated with the energy contained within the hot-electron population. Preliminary interpretative modeling indicates that kinetic effects are likely in the NSTX scrape-off layer (SOL) plasma. The decrease in plasma fueling efficiency, increase in local temperature, and increase in hot-electron fraction are all consistent with an absorbing surface intercepting the SOL plasma.
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1. Introduction

Plasma wall conditioning and the plasma–material interactions have presented a significant challenge to fusion research for some time. Energy confinement time, stability and other metrics often improve with the application of various wall conditioning procedures. Boron is often employed for this purpose, but recent experiments have led to more wide-spread use of lithium as a wall-conditioning material. TFTR showed improvements in plasma performance by lithium conditioning of its graphite limiter [1]. CDX-U demonstrated energy confinement time increases with greater lithium coverage of its limiting surfaces in the form of both liquid and solid coatings [2]. FTU demonstrated improvements in performance with the usage of a liquid lithium limiter [3]. Many other experiments are also exploring this material in experiments detailed further in these proceedings. NSTX has also demonstrated plasma performance improvements with the application of evaporated lithium to its divertor and other plasma facing surfaces [4]. These studies all demonstrate modifications of the bulk plasma, but do not address the issue of how the wall conditioning is modifying the local plasma that is in direct contact with the plasma facing component (PFC).

The liquid lithium divertor (LLD) was installed and tested in NSTX in order to provide an initial assessment of a porous molybdenum plasma-facing component with evaporated lithium coatings and the associated plasma–material interactions (PMI) [5,6]. In addition to the extensive core diagnostics available on NSTX, new divertor diagnostics were installed alongside the LLD [7,8]. This work focuses on the Langmuir probes used to diagnose the near-surface plasma.

Langmuir probes provide a direct measure of the net current collected by a biased electrode in a plasma [9]. Although simple in implementation, relating the electron and ion currents to plasma fluid observables has remained an issue of debate. It is possible to formulate a theory describing the electron current channel based on transport arguments [10] although such theories have been criticized [9] due to reliance on anomalous cross-field transport terms. At present, the consensus is that the region of an *I*–*V* characteristic below floating potential can be utilized for the determination of a plasma electron temperature [11] This is referred to as the “classical” interpretation [12]. In general, this reveals a mere 5% of the electron distribution – the high energy tail. Without the ability to view the bulk of the plasma electrons, non-Maxwellian effects are not diagnosable with the

* Princeton Plasma Physics Laboratory, United States. Tel.: +1 609 243 2711.
E-mail address: mjaworsk@pppl.gov (M.A. Jaworski).

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classical interpretation potentially leading to erroneous measurements [13].

Indications of such effects are evident in experiment and kinetic simulations. Experimentally, comparisons have been made between divertor Langmuir probes and divertor Thomson scattering on ASDEX [14] and DIII-D [15]. On DIII-D, it was found that the Langmuir probes yielded consistently higher electron temperatures which would be expected if the classical interpretation were used in the presence of a high-temperature tail population [13]. In ASDEX, the probe-based electron temperature was found to be a factor of two greater than the laser scattering during quiescent plasma conditions. Additionally, the Thomson scattering on ASDEX gave some indications of non-Maxwellian characteristics. In simulations of charged particles in the SOL, non-Maxwellian EEDFs are a common feature. Independent simulations by Chodura [16] and Batishchev et al. [17] both show that sharp spatial gradients arising from a recycling boundary were found to give rise to non-Maxwellian distributions at a divertor target plate. In addition to gradient effects, electron interactions with neutrals and ions can lead to non-Maxwellian distributions [18].

This paper presents Langmuir probe measurements obtained during the recent LLD experiments on NSTX. The classical and non-local approaches to probe interpretation are both utilized and compared. This is the first time the non-local approach has been applied to Langmuir probes in the divertor of a toroidal device. The impact of the evolving surface of the LLD on the SOL plasma is measured with the use of these probes and a heuristic model is proposed to account for the observations in light of the kinetic treatments of the SOL. Finally, preliminary interpretative model simulations are shown which assess the degree of collisionality of the SOL and the likelihood of the hypothesis.

2. Theory

Standard practice in the interpretation of tokamak Langmuir probes has been to assume the existence of a single Boltzmann fluid [9–11] and fit the data to the following equation:

$$I_{pr} = I^{+}_{sat}\left[1 - \exp\left(\frac{V_{pr} - V_{fl}}{T_e}\right)\right] \tag{1}$$

where I_{pr} is the probe current, I^{+}_{sat} is the ion saturation current, V_{pr} and V_{fl} are the probe and floating potentials, respectively, and T_e is the electron temperature. One will notice, however, that Eq. (1) already has inaccuracies in that even though the electrons form the fluid under question, it is the *ion current* that is used in the fit, as opposed to the electron current as is the case with non-magnetized discharge probe interpretation [19,20].

One can determine if depletion of the plasma in the flux-tube attached to the probe is operating by considering the balance of fluxes into and out of that flux-tube. Define the fraction ϕ as follows:

$$\phi \equiv \frac{\Gamma_{\perp} A_{\perp}}{\Gamma_{\parallel} A_{\parallel}} \approx \frac{D_{\perp} L}{\bar{c}_e D_h^2} \tag{2}$$

where the flux, Γ is given in both perpendicular ($\perp$) and parallel ($\parallel$) directions across the respective areas, A. At the limit of electron saturation, the plasma supplies, in the parallel direction, the mean thermal velocity, $\bar{c}_e$. The length terms, L and $D_h = 2ab/(a+b)$ are the length of the flux tube and the "hydraulic" diameter (a term borrowed from hydrodynamics), respectively. The collection point is defined as having a rectangular cross section with side lengths of a and b. When the value of ϕ is much greater than one, then cross-field transport can supply more particles than are removed by the free-streaming parallel particle flux. In the case where ionizations are occurring inside the flux-tube, then an additional particle source is added to the numerator, relaxing the conditions on ϕ.

Table 1
Scale length estimation for the NSTX divertor plasma.

Method	n_e, m^{-3}	T_e, eV	λ_ϵ, m	λ_{pr}, m
Classical	1 (10^{20})	15	0.023	6 (10^{-4})
Non-local	1.4 (10^{20})	8	0.005	6 (10^{-4})

For Bohm-like diffusion [21] ϕ can be further simplified to the following:

$$\phi \approx 0.06 \frac{L}{BD_h^2}\sqrt{\frac{\pi m_e T_e}{8e}} \tag{3}$$

where B is the magnetic field strength in T, T_e is given in eV and the other terms are in SI units. This is a conservative approximation as the cross-field transport is often found to be in excess of Bohm transport [21,22]. In the case of the NSTX SOL, a typical connection length is 20 m, mean temperatures based on target data and upstream MPTS measurements are about 20 eV along a flux-tube and $B \approx 0.5$ T. The probes under consideration in this study are 2 mm × 7 mm in surface area but due to the field-line angle-of-attack, the projected dimensions are about 2 mm × 0.6 mm. For a probe of this size then we find $\phi \approx 20$. Considering the conservative nature of this estimate for the reasons above, one would not expect the flux-tube to suffer depletion effects.

In order to address the I–V characteristic in the region beyond the floating potential, a more comprehensive probe theory is sought. In certain circumstances, it can be shown that the non-local approach is usable [12,23–25]. Although the method is developed in these references, it is repeated here due to its relative novelty. The essence of this approach is that the energy scale length of the electrons, λ_ϵ, in the plasma is much larger than the spatial scale of the probe such that [24,26]:

$$\lambda_\epsilon = \left[\frac{4D_e}{\nu_e + \delta\nu_a + \nu^*}\right]^{1/2} > a\ln\left(\frac{\pi l}{4a}\right) \tag{4}$$

where a is a probe radius and l is a probe length (probe scale length is $\lambda_{pr} = a\ln(\pi l/(4a))$ [26]). The electron diffusion is given by $D_e = \nu\lambda/3$. The collision frequencies for electron–electron, electron–atom and electronic excitation are ν_e, ν_a and ν^*, respectively. Typical plasma parameters and probe dimensions are given in Table 1. The electronic excitation frequency is estimated by the electron–ion collision frequency for the present work. The term, $\delta = 2m/M$, is the electron–atom energy-transfer efficiency. In this instance, the kinetic equation for the distribution function can be simplified as a problem in spatial coordinates only [24]. The resulting solution for the electron current collected by the probe is given as follows:

$$I_e(U) = -\frac{8\pi e A_{pr}}{3m^2}\int_{eU}^{\infty}\frac{(W - eU)f(W)}{\gamma[1 + ((W - eU)/W)\psi(W)]}\mathrm{dW} \tag{5}$$

where A_{pr} is the probe area, m and e are the electron mass and charge, respectively, U is the probe potential, W is the energy, γ is a geometric factor and $\psi(W)$ is the "diffusion parameter". In the case of a magnetized plasma, the diffusion parameter is given as follows for a perpendicularly oriented probe [12,26]:

$$\psi_\perp = \frac{a\ln(\pi l/4a)}{\gamma R_{Le}(W, B)} \tag{6}$$

where $R_{Le}(W, B)$ is the electron Larmor radius. This equation is simplified such that a nominal value of the diffusion parameter is used at the Larmor radius corresponding to 1 eV such that $\psi(W) = \psi_0/\sqrt{W}$. An important consequence of having the full I–V characteristic available for interpretation is the ability to determine the plasma potential.

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