High density Langmuir probe array for NSTX scrape-off layer measurements under lithiated divertor conditions[a)]

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A high density Langmuir probe array has been developed for measurements of scrape-off layer parameters in NSTX. Relevant scale lengths for heat and particle fluxes are 1–5 cm. Transient edge plasma events can occur on a time scale of several milliseconds, and the duration of a typical plasma discharge is ~1 s. The array consists of 99 individual electrodes arranged in three parallel radial rows to allow both swept and triple-probe operation and is mounted in a carbon tile located in the lower outer divertor of NSTX between two segments of the newly installed liquid lithium divertor. Initial swept probe results tracking the outer strike point through probe flux measurements are presented. © *2010 American Institute of Physics.* [doi:10.1063/1.3494381]

I. INTRODUCTION

In the National Spherical Torus Experiment (NSTX) the edge diagnostic coverage has traditionally been sparse, especially in the divertor region. Previously, the only method for divertor density, temperature, and particle flux measurements was through two flush-mounted Langmuir probes, based on a Tokamak de Varennes design,[1] and located approximately 12 cm apart. With the recent installation of the liquid lithium divertor[2] (LLD) at a major radius of 66–86 cm, it was desired to have much greater spatial resolution for edge temperatures and densities in order to characterize changes to edge profiles. The presence of transient edge events such as edge localized modes (ELMs) and scrape-off layer (SOL) turbulence motivates a triple-probe design to produce instantaneous temperature and density measurements. Engineering requirements constrain the available area for the array to a carbon gap tile between two LLD plates. The primary concerns for the survivability of the probe tips were the high heat flux, on the order of several $\mathrm{MW/m^2}$, and the high amount of evaporated lithium delivered to the area by the NSTX lithium evaporators. These requirements resulted in a final design with a 99 electrode probe array, arranged into three radial rows of 33 probes each.

II. DESIGN AND INSTALLATION

A. Physics design requirements

One of the primary concerns in probe design was the ability to capture phenomena at the scale length of the heat and particle flux gradients in the divertor region. Heat flux and density scale lengths on the order of 1 cm radially are common for NSTX discharges, and set the maximum probe size in this dimension.[3] Temporal resolution is set by time scales of transient events. Swept probes are able to provide full current-voltage (IV) curves that aid in characterization, but practical limitations on the sweep frequency mean that they are of less utility for measuring temperatures during an ELM or fast turbulence. Divertor D_α light measurements show that ELMs can occur over 2–5 ms, with fine structure filament effects occurring over ~100 μs,[4] and previous Langmuir probe data show turbulence on kilohertz to megahertz time scales,[5] faster than viable sweep frequencies. To address this, three sensors were constructed at each radial location to allow for triple-probe measurements, and a collaboration was established with the University of Illinois Urbana-Champaign to provide triple-probe circuitry.

B. Engineering requirements

The engineering constraints also provided stringent conditions for the probe design. Steady-state heat flux in NSTX to the plasma facing components can be substantial: 1–10 $\mathrm{MW/m^2}$, depending on the input power. Of novel concern in NSTX, a significant thickness (on the order of several micrometers) of evaporated lithium will be deposited on the probes. The evaporators used to coat the LLD are positioned at the top of the machine,[6] and also coat all of the surrounding surfaces. Elemental lithium is both conductive and corrosive, and the probe array and its supporting structures must be able to tolerate these lingering effects. Lastly, the spatial limitations of 2.5 cm toroidally, 10 cm radially, and 1.5 cm vertically for probes and wires precluded the use of many traditional assembly methods, such as securing wires with screws and mounting probes individually within the surface of the tile. After consideration of all these potential concerns, a design based on the MAST divertor probe array[7] was chosen and modified to meet the NSTX needs.

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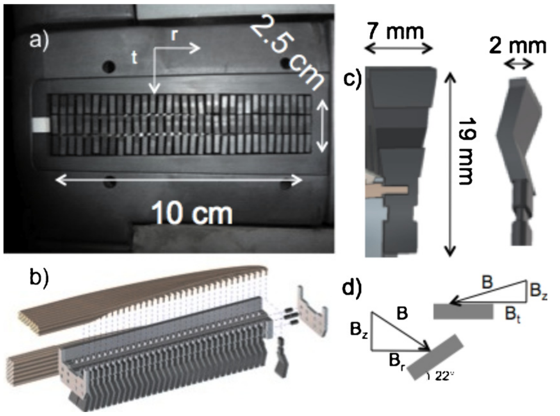

FIG. 1. (Color online) (a) Top view of assembled tile with 33 rows of triple-probe electrodes, as installed on NSTX. (b) Exploded schematic view of BN cassette, probe electrodes, and wires. (c) Front and side views of probe electrode, including signal wire location. (d) Magnetic field orientation with respect to poloidal and toroidal probe views.

C. Probe design and assembly

The resulting design is shown in Fig. 1. Tokai HK-6 graphite was chosen as the probe material for its thermal and electrical properties. Liquid lithium corrodes carbon, but previous experience had shown that existing divertor probes maintained their functionality even after a run year with several hundred grams of lithium evaporation. Probe spatial dimensions were optimized for resolution, resulting in a 2 mm radial × 7 mm toroidal rectangular electrode face. The probe bodies taper in the toroidal direction to allow mounting in a boron nitride cassette. A bend is also introduced into the probes in the radial direction to shield the cassette from direct plasma or lithium line-of-sight deposition. A schematic of an individual probe head is shown in Fig. 1(c).

In order to maximize probe tip density while still maintaining an arc-resistant distance between probes, a 0.5 mm gap was chosen. The existing flush-mounted NSTX probes used a 0.25 mm gap between probe and tile, which was sufficient to prevent lithium bridges from routinely shorting the probes.

The cassette consists of four pieces of boron nitride, a vacuum-compatible insulator more resistant to lithium corrosion than the Macor used on the MAST probes. Each cassette piece has slots to accommodate individual probe seating and secures them against motion in any direction. The 2 m, 24-gauge, copper signal wires are attached to small holes in the electrodes with graphite cement. The wires exit the bottom of the cassette for the middle row of probes, and through holes in the sides for the edge rows. The individual wires are covered with vacuum-compatible, temperature-resistant glass braid. Two boron nitride faceplates secured with stainless steel pins hold the assembly together. Fortafix adhesive applied to the wire exit holes provides an additional strain relief mechanism. The cassette is fitted with a boron nitride "keeper" interfaces with the carbon tile mount. Four carbon pins, also affixed with graphite cement, slide through holes in the front and back of the keeper to affix the cassette in place in the tile.

D. Installation

The mount is one of the gap tiles between the LLD plates, and sits on the first row of tiles directly outboard of the coaxial helicity injection gap.[2] Radially, it overlaps both the first row of carbon tiles and the LLD farther outboard. Due to changes in the LLD design, the tile had to be machined down 1/8 in. in height so as not to protrude into the plasma past the LLD front-face surface. Since the bottom of the tile could not be shaved, nor could the probe heads be shortened, the tile face was given sloped edges to interface with the LLD and allow the probes to maintain their height. The tile is secured to the NSTX copper passive plates that form the divertor substrate by means of stainless steel T-bars and bolts. The 99 wires are split into three branches and run under chamfers in the outboard tiles, passing under the outboard passive plate. From there, they are crimped to 4 m wires of the same material, but with a stainless steel braid along half the length to reduce noise pickup. The braided part is run along the toroidal direction to a vertical nipple, where the cable transitions to unshielded again for a drop to the feedthrough. Probe to feedthrough resistance measurements provide correction factors for circuit resistances. FARO arm measurements give the absolute position of the probes in the vessel. The initial electronics configuration, provided by UIUC, allows for four single swept probes, ten triple probes, and two each of parallel and perpendicular SOL current probes.[8] The wiring scheme at the electronics rack allows individual electrodes to be quickly reconfigured for maximum flexibility.

III. MAGNETIC FIELD REGIME

Langmuir probe ion saturation current is traditionally used to determine the plasma density, in the form $I_{+\mathrm{sat}} = \frac{1}{2} e n_i c_s A_{\perp \mathrm{probe}}$, where n_i is the ion density, taken to be the same as the electron density, c_s is the ion sound speed, and $A_{\perp \mathrm{probe}}$ is the probe area normal to the magnetic field, taken as the base area multiplied by the scalar product of the probe normal and total field angle, as shown in Fig. 1(d). Given this, the ion flux measured by a probe is then

$$\Gamma_{\mathrm{probe}} = n_i c_s = \frac{2 I_{+\mathrm{sat}}}{e A_{\perp \mathrm{probe}}}.$$

One of the caveats in the interpretation of flux comes from the toroidal magnetic field angle,[9] defined as arctan B_z/B_t and typically 3°–10° in the NSTX edge plasma, depending on discharge shape. Information on the field angle and strength is taken from the EFIT equilibrium reconstruction, which is determined by solution of the Grad–Shafranov equation. The Larmor radius of a 30 eV ion in a 0.6 T magnetic field (the typical value at the probe location) is 1.3 mm (hence ρ_e is 30 μm), on the order of the probe dimension d, while λ_D is 13 μm for a density of $1 \times 10^{19}/\mathrm{m}^3$. This gives the condition $d \geq \rho_i \gg \rho_e,\ \lambda_d$, placing the probes in a transitional magnetic field regime and making the effect of the field angle important. The 22° inclination of the outer divertor and the poloidal field angle, defined as arctan B_z/B_r

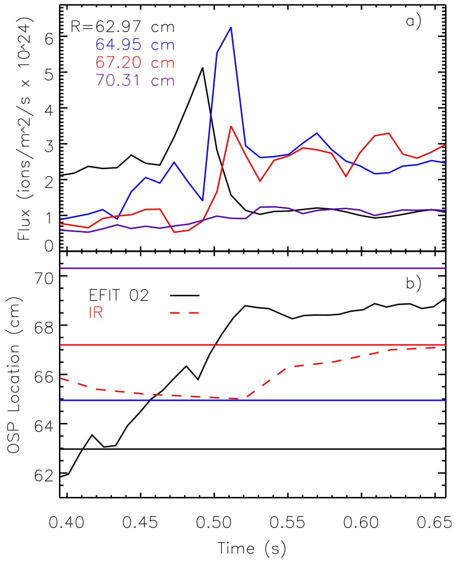

FIG. 2. (Color online) Strike point tracking by swept Langmuir probes during NSTX plasma shot 137610. (a) Flux from probes at four radial locations as the outer strike point sweeps. (b) Strike point location from EFIT magnetic and IR camera data, with probe positions indicated.

and typically 50°, also alter the effective area. Although the poloidal field magnitude ($\sim.1B_t$) is relatively weak, the probe radial dimension is comparably smaller, and thus the total field angle is used in the scalar product.

IV. INITIAL RESULTS AND DISCUSSION

The motion of the NSTX outer strike point can be observed by inferring that an increased $I_{+\mathrm{sat}}$ is due to an increased ion flux caused by strike point proximity. Figure 2 shows the ion flux measured by probes at various radial locations, with a corresponding graph of strike point location as indicated by magnetic and IR camera data. As the strike point moves in this discharge, each probe tip shows an increased flux as the strike point sweeps over it, and the measured flux reaches a stationary state when the strike point ceases its motion. The relative magnitudes of measured fluxes provide good agreement in strike point location with the other diagnostics, which can have a 1–2 cm uncertainty.

This method can be used to qualitatively provide comparisons with other diagnostics, but it does not take into account the systematic uncertainties that can affect the measured magnitude of probe current. Initial swept probe temperature and absolute density results resemble values previously observed by existing NSTX divertor Langmuir probes, but this discussion, along with triple-probe analysis, is reserved for future publications.

Of future concern is the effect of integrated lithium evaporation as the LLD is filled. Plasma interaction with the surface should clean transiently deposited layers, but large sustained depositions without plasma operations could cause coatings of several micrometers to develop, which could interfere with the penetration of ions or electrons to the probe face, potentially causing a loss of signal. To date, the probes have operated with minimal change in resistance after the evaporation of several hundred grams of lithium during NSTX operation, comparable to the amount deposited past year. This indicates that the probe baffling and design are effective even under sustained Li deposition. Future improvements to the system include instrumentation for all channels, as only approximately 40 of the 99 probe tips can be connected to the electronics at present.

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