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HIGH HEAT FLUX LANGMUIR PROBE ARRAY FOR THE DIII-D DIVERTOR PLATES

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GENERAL ATOMICS

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ABSTRACT

Two modular arrays of Langmuir probes designed to handle a heat flux of up to 25 MW/m^2 for 10 second exposures have been installed in the lower divertor target plates of the DIII-D tokamak. The 20 pyrolytic graphite probe tips have more than 3 times higher thermal conductivity and 16 times larger mass than the original DIII-D isotropic graphite probes. The probe tips have a fixed 12.5 deg surface angle to distribute the heat flux more uniformly than the previous 6 mm diameter domed collectors and a symmetric "rooftop" design to allow operation with reversed toroidal magnetic field. A large spring-loaded contact area improves heat conduction from each probe tip through a ceramic insulator into a cooled graphite divertor floor tile. The probe tips, brazed to molybdenum foil to insure good electrical contact, are mounted in a ceramic tray for electrical isolation and reliable cable connections. The new probes are located 1.5 cm radially apart in a staggered arrangement near the entrance to the lower divertor pumping baffle and are linearly spaced 3 cm apart on the shelf above the in-vessel cryopump. Typical target plate profiles of J_{sat}, T_e, and V_f with 4 mm spatial resolution are shown.

I. INTRODUCTION

The Langmuir probe is perhaps the oldest and most widely used diagnostic in plasma physics [1]. A Langmuir probe consists of a biased collector in electrical contact with ionized plasma. The current to the collector is monitored as the collector is biased from ion saturation into electron collection. The interpretation of the current (I) versus Voltage (V) data can be complicated by several factors, especially in a magnetic field, and these issues have been addressed by many authors [2–7]. Generally, a good collector design has a well-defined collection area even after many exposures to plasma particle and heat flux and does not overheat during use. Typical analysis of the I/V characteristic directly yields the electron temperature (T_e), ion saturation current (I_{sat}), and floating potential (V_f) which then yields electron density (n_e).

Langmuir probes have been implemented in most fusion energy research experiments and, specifically, in the boundary and divertor of tokamaks [2–4]. Langmuir probe data is very useful as a boundary condition for numerical models of the divertor plasma in tokamaks [8] because the measurements include non-linear neutral recycling and impurity radiation effects which are difficult to model. In DIII-D, Langmuir probes have been mounted in graphite tiles at three of the four divertor strike points to monitor plasma wall interactions [9,10] and in fast reciprocating mechanisms [11,12] where boundary plasma profile measurements are desired. The fixed location probes are subject to relatively lower heat flux levels for longer exposure times (seconds) while exposure times for reciprocating probes are short (milliseconds) due to very high heat fluxes in the edge and core plasma. The heat flux levels flowing along the magnetic field inside the tokamak are considered to be high because most material components exposed to this level of heat flux would be destroyed very quickly ($\ll$1 second) by either melting, sublimation, or shattering from thermal shock unless they are carefully designed and made using special materials. As part of the divertor redesign in the DIII-D tokamak [13], the heat flux and pulse length capabilities of the divertor targets were significantly improved. As part of this upgrade effort, the Langmuir probes mounted in the lower divertor plates were redesigned [14] to optimize both the heat flux and pulse length capabilities of the probe tips. Our goals for the new design were to improve the spatial resolution of the measurements on the divertor floor, increase reliability of the vacuum hardware, enhance thermal performance of the probe tips, preserve the ability to easily interpret the I/V data, and reduce maintenance requirements inside the DIII-D vacuum vessel.

II. COLLECTOR MATERIAL — PYROLYTIC GRAPHITE

All plasma touching materials in DIII-D are made of graphite to reduce atomic line radiation in the core plasma, to provide good thermal shock properties for the plasma contacting surfaces, and to preserve the original surface contours of components evenly to distribute heat flux. It was desired that the new fixed probe array handle the expected surface heat flux of 25 MW/m^2 for 10 s exposures without exceeding the surface temperature limit of 1600°C to avoid thermionic emission of electrons. For a passively cooled design such as this, the material below the heated surface should be thick enough so the heat pulse does not reach the back surface during the 10 s exposure. The pyrolytic graphite used for the probe tips has very good heat conduction (K ~ 350 W/m-K @RT) within the AB planes (see figure 1) and these planes have been aligned with the toroidal direction (i.e., along the dominant direction of the incident heat flux for most conditions) and extend as far as possible below the tile surface. In tokamaks, the toroidal direction is the long way around the torus and the radial direction is along the major radius of the torus. Although carbon fibers have even better thermal conductivity along the fiber (1D), the thermal mass of the exposed fibers is much less than the mass of the probe tip. Pyrolytic graphite, a material equivalent to stacked planes (2D) of high thermal and electrical conductivity material, has a larger effective thermal mass than the fibers: there are more thermal pathways into the bulk material. This extra thermal mass and the partial surface area exposure result in a lower surface temperature.

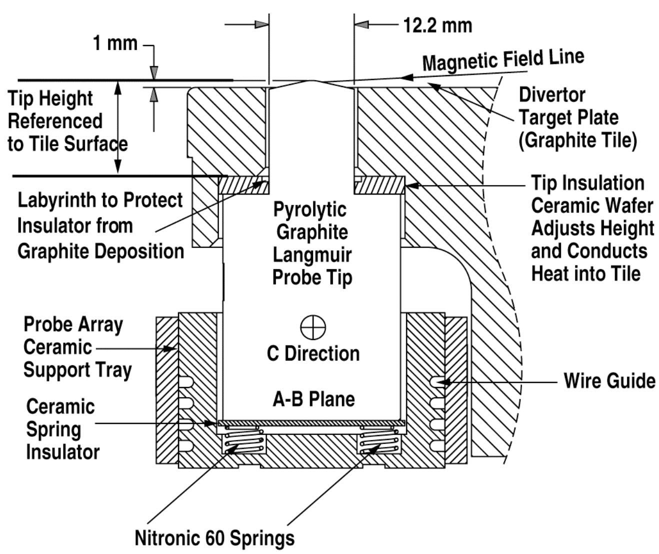

Fig. 1. Cross section of rooftop probe tip mounted in a DIII-D divertor tile viewed from the radial direction. The toroidal magnetic field is in the plane of the paper (AB plane).

III. COLLECTOR THERMAL DESIGN

Figure 1 shows the main features of the probe tip design. Since only half the rooftop is exposed to heat flux, the 2D spreading of heat reduces the surface temperature below that of an infinite slab (the standard for passive cooling) for pulse lengths of 10 s. Figure 2 shows the results of finite element thermal modeling for the rooftop probe tip and two other reference cases exposed to 25 MW/m^2 for 10 seconds. The surface temperature of the rooftop design stays well below the graphite sublimation temperatures seen for the infinite slab. The shoulder below the tile surface, which allows the heat flux to again spread sideways into a larger mass after about 2 seconds, has the effect of reducing the surface temperature by about 500°C at the end of the exposure. The results shown in figure 2 demonstrate that (1) the magnitude of this heat flux is high enough to sublimate even a high thermal conductivity material like pyrolytic graphite in less than 6 seconds and (2) that the high heat flux probe tip design keeps the temperature low enough to avoid detrimental effects such as thermionic emission and sublimation.

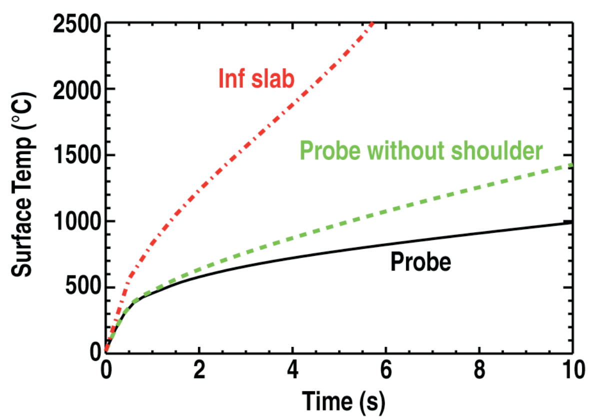

Fig. 2 Thermal analysis, including thermally dependent material properties of pyrolytic graphite, is shown for three cases exposed to 25 MW/m^2 incident heat flux for 10 seconds.

The tips have fixed angle of incidence with the incoming heat flux similar to the currently used JET design [15]. This feature distributes the heat flux much more evenly and results in a peak heat flux that is 30% less than the previous domed tips. The sides of the rooftop are angled to distribute the heat flux incident on the sides of the collector to more than one AB plane.

The tips are thicker in the C (radial) direction below the tile surface for increased mass and larger thermal contact area with the cooled divertor tile. Figure 3 shows the relationship of the probe tip array to the lower divertor. The 11 floor probes were staggered as shown in figure 4(a) to minimize the radial separation and maximize the probe tip mass. The nine shelf probes are linearly distributed every 3 cm to cover a larger radial range. Both probe assemblies are subjected to frequent baking to 350°C for tokamak wall conditioning.

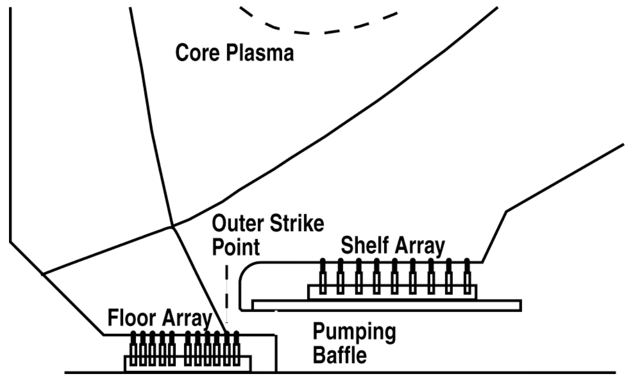

Fig. 3. Cross section of the upgraded DIII-D Lower divertor and Langmuir probe arrays. The radial direction is from left to right.

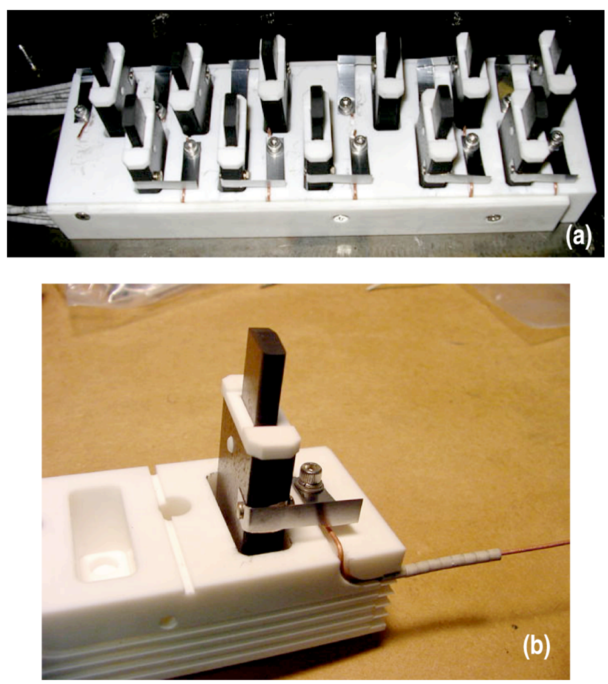

Fig. 4. (a) Langmuir probe floor array from above before installation of the divertor tiles. The toroidal direction is from lower to upper in the picture along the long dimension of the tips. (b) Individual collector showing pyrolytic graphite to molybdenum braze connection, glidcop wire connector, and wire guide along the side of the ceramic tray (insulated cover removed).

IV. DATA INTERPRETATION AND TIP GEOMETRY

In order to more easily interpret the probe data, the probe collector tips need to have a well-defined current collection area along the field. Probes with small angles of incidence with the magnetic field lines show variations of the effective collection area with bias voltage [16] as the sheath around the tip expands (mostly) across the field. There are also ion gyroradius effects that tend to increase the effective dimensions of the probe tip across the magnetic field. Therefore, the probe geometry should be designed such that the dimensions of the probe tip across the magnetic field are large enough to neglect these effects. A steeper angle of incidence with the field results in less sensitivity to these cross-field effects.

The desire to have a well-defined area has resulted in a requirement that the angle of the collection surface with the incoming magnetic field be greater than approximately 10 deg for typical conditions [17] and that the dimensions of the probe tip be large compared to the ion gyroradius. For our design of 12.5 deg and the typical tile surface magnetic field line angles of 0–6 deg, this angle criterion is always satisfied. For the height of 1 mm, the ion gyroradius criterion is met for ion temperatures typically expected for the divertor plasma (<40 eV) and magnetic fields of 2 Tesla.

To summarize the angle considerations, the 12.5 deg chosen for the tip angle is: (1) a fixed angle to distribute the heat flux uniformly, (2) as low as possible to reduce the incident heat flux, and (3) high enough (typically >10 deg) to clearly define the collection area as the geometric projected area over the expected range of conditions.

Further away from the strike point, the magnetic field line angle with the tile surface becomes steeper and the projected collection area increases. This effect partially compensates for the decreased plasma flux at locations further into the scrape-off layer. To accommodate reversed magnetic field operation, the tips must be symmetric in the toroidal direction resulting in the "rooftop" shape (figure1). Additionally, the projected area was chosen such that the available 4 Ampere power supplies are sufficient for expected ion saturation levels. The tip leading edge is recessed in the tile to avoid normal incidence heat flux.

The height and position of the probe tip is referenced to the tile. The insulator thickness is used to adjust the 1 mm height within 3% and to keep the tips centered and electrically isolated from the tiles. Ceramic inserts on the side of the collectors keep the tips from tilting radially and touching the tiles.

V. RELIABLE ELECTRICAL CONNECTIONS

Reliable electrical connections are very important because the Langmuir probes are inside the vacuum vessel and only accessible once a year. For good electrical contact, the pyrolytic graphite tips were brazed to flexible molybdenum foil across all the AB planes [figure 4(b)]. The thermal expansion of the pyrolytic graphite matches molybdenum in the higher expansion C direction. The flexible molybdenum foil is clamped to a captured 1 mm glidcop [18] wire by a spring-loaded connector. All the probe tip wires are compactly routed along the side of the ceramic mounting tray. The glidcop center conductor of a commercially available beaded cable [19] (with braided stainless steel sheath) is used to connect the probe tip to the vacuum feed through. Each cable is terminated in a vacuum compatible BNC connector that plugs into an isolated feed through at the vacuum vessel wall. The wires and ceramic trays that support the probe tips remain in place during tip replacement to avoid disturbing the cables and feed through connections.

VI. EXPERIMENTAL MEASUREMENTS

The probe tips have performed well during plasma operations in DIII-D. The I/V characteristics are very clean, never exhibit arcing even during edge localized modes (ELMs) and appear to show good ion saturation (figure 5). The 4 mm wide, 1.5 cm spaced collectors in the floor array provide good resolution for the 5–10 cm decay lengths typically seen near the entrance to the divertor pumping baffle. This array requires only a 2 cm strike point sweeps to obtain the 4 mm resolution desired for observing smaller (6–10 mm) target plate structures resulting from resonant magnetic perturbations. The nine probes in the shelf array (3 cm radial spacing) provide coverage for divertor physics experiments using a variety of plasma shapes. The 4 mm width of the tips gives us excellent spatial resolution and profile continuity when overlapping measurements are obtained with strike point sweeping (figure 6).

One drawback of the fixed angle rooftop design is that the projected area varies with the magnetic field direction. For typical conditions the area can vary by 50% across the divertor floor. Area calculations are done for each probe tip using the EFIT [20] magnetic equilibrium to get the projected area for each time of interest.

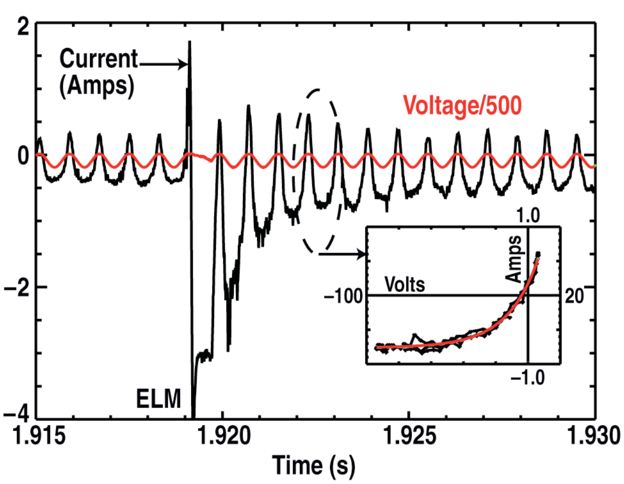

Fig. 5. Raw data from the rooftop probes shows collector current and voltage as a function of time during an ELM. The inset I/V characteristic shows good ion saturation.

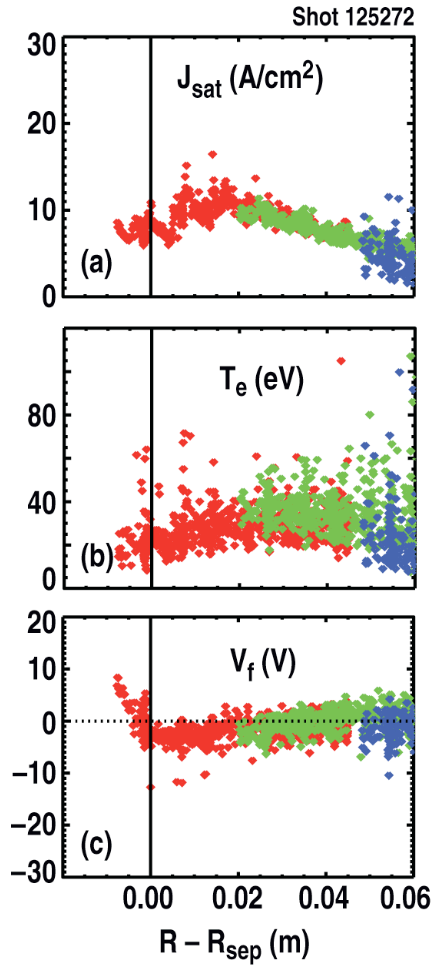

Fig. 6. Profiles of the measured (a) particle flux, (b) electron temperature, and (c) floating potential on the divertor shelf from four probes (color online) during a divertor strike point sweep for (L-mode) shot 125272. The horizontal axis is the probe location (m) normalized to the moving strike point position ($R-R_{sep} = R_{probe}-R_{separatrix}$).

REFERENCES

[1] L. Tonks and I. Langmuir, Phys. Rev. **34**, 876 (1929).

[2] G. F. Matthews, Plasma Phys. Control. Fusion **36,** 1595 (1994).

[3] S. Pitcher, P. C. Stangeby, Plasma Phys. Control. Fusion **39**, 779 (1997).

[4] P. C. Stangeby, *The Plasma Boundary of Magnetic Fusion Devices*, P. Stott and H. Wilhelmsson eds., Inst. of Physics Publication (Taylor & Francis, 2000).

[5] F. Chen, "Electric probes," in *Plasma Diagnostic Techniques*, R. H. Huddlestone and S. L. Leonard eds. (Academic Press, New York, 1965) chapter 4.

[6] P. C. Stangeby, J. Phys. D: Appl. Phys. **18**, 1547 (1985).

[7] J. A Tagle, P. C. Stangeby, S. K. Erents, Plasma Phys. Control. Fusion **29**, 297 (1987).

[8] R. Maingi, J. G. Watkins, M. A. Mahdavi, L. Owen, Nucl. Fusion **39**, 1187 (1999).

[9] D. A. Buchenauer, W. L. Hsu, J. P. Smith, D. N. Hill, Rev. Sci. Instrum. **61**, 2873 (1990).

[10] J. G. Watkins, D. A. Buchenauer, T. N. Carlstrom, J. W. Cuthbertson, D. N. Hill, R. A. Moyer, M. Ulrickson, J. Nucl. Mater. **241–243**, 645 (1997).

[11] J. G. Watkins, J. Salmonson, R. Moyer, R. Doerner, R. Lehmer, L. Schmitz, D. N. Hill, Rev. Sci. Instrum. **63**, 4728 (1992).

[12] J. G. Watkins, J. Hunter, B. Tafoya, M. Ulrickson, R. D. Watson, R. Moyer, J. W. Cuthbertson, G. Gunner, R. Lehmer, P. Luong, M. Mascaro, J. I. Robinson, Rev. Sci. Instrum. **68**, 373 (1997).

[13] P. M. Anderson, Q. Hu, C. J. Murphy, E. E. Reis, Y. Song, D. Yao, Fusion Engin. Design **82**, 1756 (2007).

[14] D. Taussig, J.G. Watkins, R. Boivin, Proc. IEEE 22nd Symp. on Fusion Engineering, 2007, Albuquerque, New Mexico, CD-ROM, http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?isnumber=4337855&arnumber=4337938&count=98&index=82

[15] R. J. Monk, "Langmuir Probe Measurements in the Divertor Plasma of the JET Tokamak," EFDA JET Report JET-IR(96)02.

[16] M. Weinlich, A. Carlson, Phys. Plasma **4,** 2151 (1997).

[17] A. Carlson, V. Rohde, M. Weinlich, ASDEX Upgrade Team, J. Nucl. Mater. **241–243**, 722 (1997).

[18] glidcop – Oxygen Free High Conductivity copper dispersion strengthened with alumina power – Insulator Seal Incorporated (MDC) – ISI part # 9943000.

[19] Insulator Seal Incorporated (MDC) – 1/8 inch vacuum coax cables with BNC termination – part number # – 9931305 modified for custom length.

[20] L. L. Lao, J. R. Ferron, R. J. Groebner, W. Howl, H. St. John, E. J. Strait, and T. S. Taylor, Nucl. Fusion **30**, 1035 (1990).

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