GA–A25823

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JUNE 2007

GENERAL ATOMICS

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This is a preprint of a paper to be presented at the 22nd IEEE/NPSS Symposium on Fusion Engineering 2007, Albuquerque, New Mexico on June 17–21, 2007 and to be published in the *Proceedings.*

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Work supported by
the U.S. Department of Energy
under DE-FC02-04ER54698 and DE-AC04-94AL85000

GENERAL ATOMICS PROJECT 30200
JUNE 2007

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Improved Langmuir Probe Array for DIII-D

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***Abstract*—Langmuir probes are commonly used plasma diagnostics measuring localized floating potential, electron temperature, particle flux, and electron density. A major upgrade of DIII-D's lower divertor required an improved design of Langmuir probe arrays to accommodate the higher heat fluxes incident on the new divertor plasma facing components. It was also advantageous to decrease the linear spacing between electrodes and to improve the ease of maintenance.**

The new electrode design distributes the heat flux almost uniformly over its surface because of the fixed angle roof-top shape. The advanced design features 16x increased thermal mass half the peak heat flux. Thermal coupling of the probe to the surrounding tile was greatly enhanced by increasing the thermal contact area. A novel probe mounting system has the entire probe array supported in a single tray.

After an annual operational period, the probes yielded reliable data and showed little or no erosion.

Keywords: DIII-D; Langmuir probe array; divertor; tokamak

I. INTRODUCTION

Langmuir probes are commonly used plasma diagnostics measuring localized floating potential, electron temperature, particle flux, and electron density. They typically consist of electrodes slightly protruding into the plasma and driven with an oscillating potential. The resulting electrical current data is then analyzed to infer the aforementioned plasma properties. DIII-D utilizes numerous types of Langmuir probes [1–3], but this paper will be concerned with the new fixed tile Langmuir probes in the lower divertor region.

The DIII-D tokamak underwent major hardware upgrades during a special 12-month maintenance period starting in April 2005 [4,5]. These upgrades were implemented to enable DIII-D to meet new operational physics requirements allowing for high triangularity, high performance plasmas. This effort included a major rework of the lower divertor to facilitate an improved pumping geometry and to accommodate the more demanding operational conditions that impose higher heat fluxes upon the divertor region graphite armor tiles.

The DIII-D tokamak has approximately 50 fixed-tile Langmuir probes throughout the vacuum vessel. The probes are embedded within the tokamak's 5 cm thick graphite tiles and the probe tips protrude slightly through holes in the tiles. The probe tips, particularly those located in high heat load regions, are eroded by the plasma over time. Higher probe tip temperatures result in higher erosion rates. The probe tips are carefully shaped to provide a good compromise in operational characteristics. Design considerations include: low operational temperature and erosion; consistent signal strength for various magnetic field line impingement angles and eroded probe geometry; reduced thermal load and adequate heat sinking; mechanical integrity of the surrounding graphite tile; and ease of installation and maintenance.

The need for a new set of the Langmuir probes for the reworked lower divertor presented the opportunity to redesign the Langmuir probe system for improvements in performance and functionality. Implementation of a more closely spaced array allows for higher spatial resolution of the plasma measurements. The higher probe count and the more complex mounting of the new high heat flux divertor tiling system required an improved Langmuir probe system to ease installation and periodic maintenance. The higher impinging heat fluxes require probes with higher power capabilities.

II. PREVIOUS DESIGN

The previous design of the Langmuir probes is shown below in Fig. 1. The probe is 6 mm in diameter with a 5 mm spherical radius domed tip protruding 1.0 mm. The probe is made of pyrolytic graphite [6] brazed into an inconel mount. The assembly is mounted directly into the tile with alumina ceramic insulators and a crimped electrical connection to the ceramic-insulated coaxial cable. These probes have worked well in DIII-D but are not compatible with the new lower divertor power handling requirements.

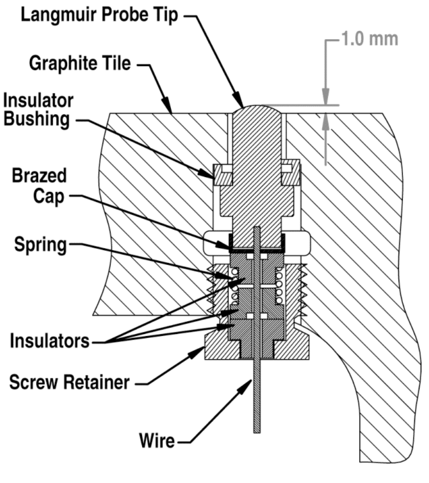

Figure 1. Cross-sectional rendering of previous Langmuir probe design.

The low thermal mass, small strike area, and insufficient heat sinking to the tile preclude them from use in the higher heat flux regions of the new lower divertor. The high heat loads in the new divertor would cause excessive probe tip temperatures leading to thermionic emission from the probe, tip surface, premature tip erosion, and possibly melting of the brazed joint.

The direct into-tile mounting system would also be problematic if used in the new divertor. Removing a tile containing a Langmuir probe lifts the attached probe cabling. If the cabling runs underneath adjacent tiles, those tiles must also be removed until enough cable slack is obtained to access and detach the probe from under the tile. If the removed adjacent tiles also have Langmuir probes or other diagnostics in them, the effort causes a chain reaction of tile and cable removal that significantly increases the labor burden and risk of damage. Additionally, the tiles for the new lower divertor have a more complex mounting system requiring a more labor intensive installation and removal procedure; therefore, it is highly desirable to avoid any unnecessary tile removal and reinstallation in the new design. With the increased number of probes in the new arrays, the previous Langmuir probe mounting system would impose a significant maintenance hindrance if implemented on the new lower divertor. These thermal and mechanical limitations required a new and improved Langmuir probe design for the upgraded lower divertor.

III. IMPROVED LANGMUIR PROBE DESIGN

The three primary goals of the improved Langmuir probe system are an increased heat load capability, closer probe spacing, and simplification of maintenance.

To improve the heat load capability, the probes are designed with high thermal conductivity material, increased thermal mass, improved thermal coupling to the tiles, and lower and more evenly distributed impinging heat flux. Fig. 2 shows the exposed portion of the Langmuir probe tip. The 12.5 deg sloped rooftop tip shape results in a more evenly distributed projected heat flux which effectively halves the peak heat flux density from that of the domed shape. The probes are made of pyrolytic graphite which has an anisotropic layered structure. It has very high thermal conductivity, about 300 W-m/ K in two dimensions (the AB plane) and a very low thermal conductivity, 3 W-m/ K, in the C direction. The heat flux strikes the probe mostly in the toroidal (B) direction with a small radial and vertical component. The probe material is oriented such that the C direction is in the tokamaks radial direction. This allows for faster spreading of heat into the probe mass. The toroidally symmetric rooftop shape of the probe tip allows for similar performance of the probe tips for both clockwise and counterclockwise toroidal field direction. Small chamfers on the sides of the rooftop allow for the slight amount of off-toroidal (C direction) heat flux striking the probe sides to distribute into multiple pyrolytic graphite layers instead of only a single layer. The top of the tip is rounded to decrease the projected area's sensitivity to erosion.

Heat impinging on the rooftop quickly disperses along the AB plane and into the large thermal mass of the probe body. The probe body mass was maximized within the constraints of the array spacing and tile structure. This resulted in an improved thermal mass that is 16x higher than the previous design.

The probes are required to survive 2.5 kW/cm^2 of heat flux on the exposed area for 10 s while maintaining a temperature under 1600°C, above which thermionic emission would be problematic.

Time dependent computational thermal analysis was performed to optimize the roof-top geometry and thermal mass. Peak temperature, energy distribution, and thermal stresses were analyzed to find the optimal geometry. Within a 10-s timeframe, heat flow into surrounding bodies, such as the tiles, springs, and tray holder, is insignificant compared to the internal heat flow of the pyrolytic graphite probe, so for the analysis objectives stated above only the pyrolytic graphite probe and impinging heat flux needs are included in the analysis. The results, shown in Fig. 3, yield a peak temperature of about 1500°C after 10 s and a minimum 8-fold thermally induced material stress factor-of-safety (FOS).

Thermal stress analysis was also performed on the tiles to verify that the Langmuir assembly penetrations and cutouts would not cause tile failure. Great care was taken in the design to minimize the amount of tile erosion and eliminate features that may concentrate stress. The analysis showed the tiles would survive all planned operational loads.

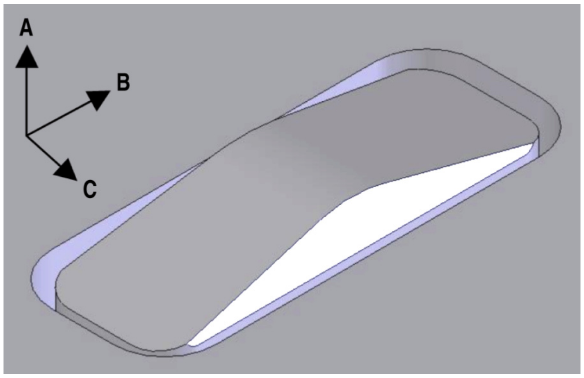

Figure 2. Rendering of an improved Langmuir probe's rooftop-shaped 12 mm x 4 mm probe tip protruding 1 mm through a DIII-D graphite armor tile. The orientation is such that the A, B, and C directions correspond to the tokamak's major vertical, toroidal, and radial axis, respectively.

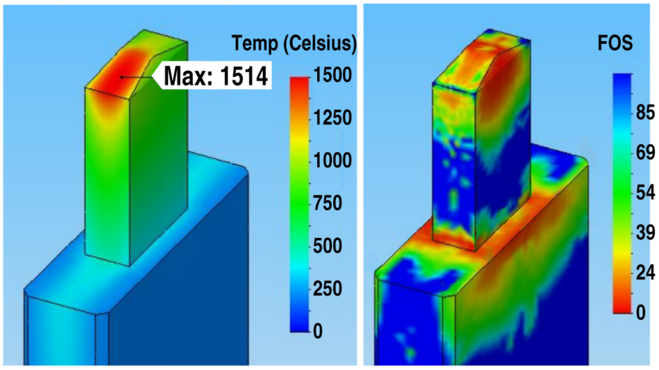

Figure 3. Computational analysis for probe tip exposed to 2.5 kW/cm^2 heat flux for 10 s. (a) Temperature distribution (b) factor of safety (defined as the material yield strength divided by the induced stress).

For easier maintenance and improved reliability of the electrical contacts, the Langmuir array is designed with the capability of removing the tiles while leaving the Langmuir probe array and cables intact and undisturbed. The design is based around the ability to install tiles over an array of probes set into an electrically insulating ceramic (Macor) tray, as illustrated in Figs. 4 through 6. The tray constitutes the primary support structure of each array. The individual probes are spring loaded for mating to a reference surface within the tiles. Fig. 5 shows the cross-sectional rendering of the probe mounting method and the subset of parts that make up each array element.

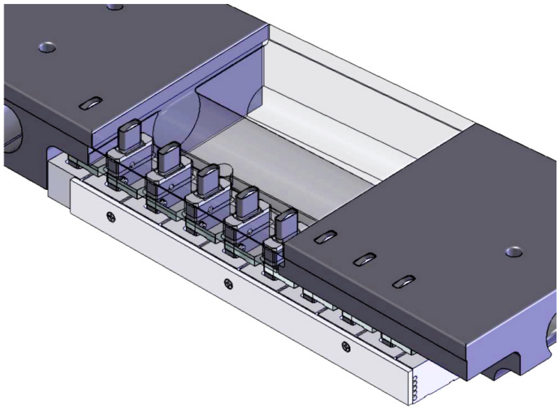

Figure 4. Rendering of the improved Langmuir probe array as implemented on the divertor shelf plate. The array spans three tiles, with the middle tile rendered as semi-transparent.

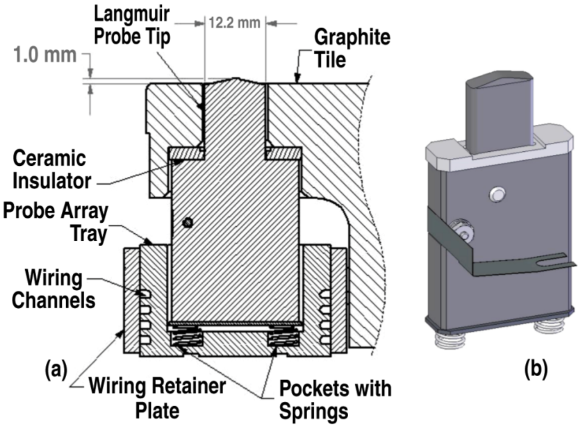

Figure 5. (a) Cross-sectional view of probe assembly mounted in a shelf tile. (b) Shows a single probe element and hardware without the tray and tile.

Tokamak operations may cause the tiles to slightly shift position independently of each other. Because the Langmuir probe arrays span more than one tile, each probe must have space within the tray to move with the tiles. The tray design allows each probe freedom to move 1 mm in any direction. This feature also aids in alleviating forces due to the different thermal expansions of the tray, probes, vessel floor, and tiles during operation and vacuum vessel bakeout.

The probe to tile surrounding clearance is 0.5 mm at the penetration in order to minimize erosion of the tile surfaces surrounding the penetrations. This tight clearance is maintained with an electrically isolating but thermally conducting ceramic spacer at the top of the probe shoulder that constitutes the primary mating surface and also serves to thermally couple the probe to the tile. Two cylindrical ceramic buttons also center and isolate the probe within the tile. The pockets within the tile are machined with chamfers to guide the probes into the tight tolerance openings as the tile is lowered during installation.

Another thermal consideration is that the probes have a minimum of 15 minutes for cool-down between the tokamak plasma shots to avoid temperature ratcheting on subsequent shots. Thermal analysis showed that the ceramic spacer provided more than sufficient thermal coupling of the graphite probe to the cooled tile. Thermal contact resistance dominated this analysis, thus re-emphasizing the importance of maximizing the contact area.

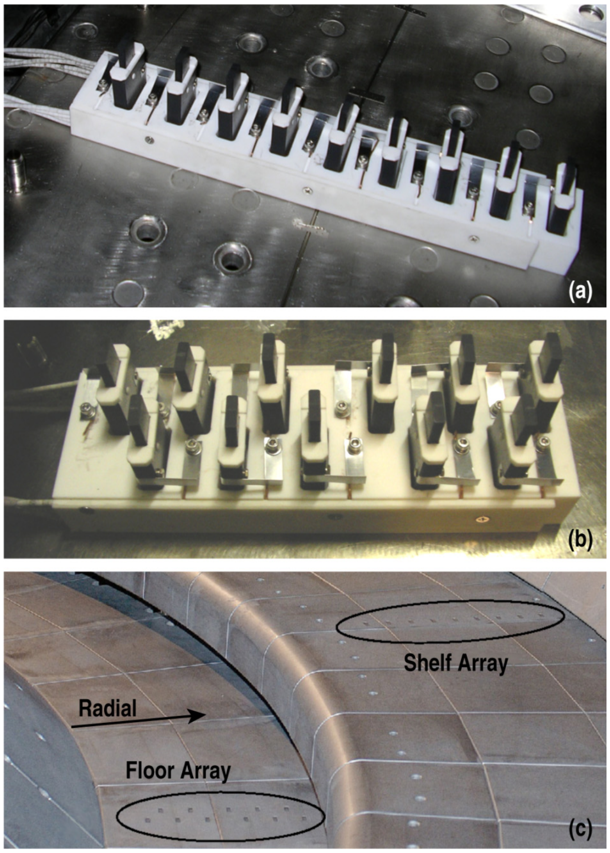

Figure 6. (a) The divertor shelf plate array prior to tile installation. (b) The staggered floor array. (c) The DIII-D lower divertor region with Langmuir probes and tiles.

The probe cabling and connections are designed for compactness and ease of maintenance. The cable conductors are ceramic particle strengthened copper (Glidcop®) wires for improved mechanical strength. These wires are captured along the length of the tray until they exit the back of the tray assembly and continue with alumina beaded insulation and stainless over-braid. This configuration greatly reduces the bulk of the cables under the tiles, allowing for less tile material removal and, thereby, improved tile integrity. The copper wires are each clamped with a single screw to a molybdenum strip that is brazed along the edge in the C-direction to the pyrolytic graphite probe. With the tile removed, this screw is the only fastener retaining an individual Langmuir probe in the array assembly, thereby facilitating quick and simple probe replacement without disturbing the cables or any of the other probes. The molybdenum strip is bent such that it allows movement of the probe and minimizes self induced vibration from forces due to the interaction of the oscillating Langmuir drive current and the tokamak's toroidal magnetic field. Molybdenum was chosen for its good electrical conductivity and matched thermal expansion coefficient with the pyrolytic graphite (C direction).

As shown in Fig. 6(c), the probe arrays are installed at two locations in the lower divertor: on top of the divertor shelf plate and on the vessel floor. The very different tile designs and attachment schemes on the plate and floor required slightly different implementation of the Langmuir probes. There is room within the floor tiles to stagger the array, thus allowing for closer array spacing.

The shelf plate mounted array, Fig. 6(a), has an inline array of 9 probes spaced 2.8 cm apart in the tokamak radial direction and the floor array, Fig. 6(b), has 11 probes space 1.5 cm apart. All the parts in the two probe array assemblies are identical except for the ceramic tray that simplifies the design and lowers manufacturing costs.

IV. CONCLUSION

The improved Langmuir arrays were successfully installed and utilized during tokamak operations for 2006 and 2007. Thus far, the arrays have performed well with no significant probe tip erosion, no overheating, and no probe-tip to tile arcing during operation. The arrays continue to provide DIII-D scientists with reliable high spatial resolution data advancing their understanding of tokamak divertor physics.

ACKNOWLEDGMENT

This work supported by the U.S. Department of Energy under DE-FC02-04ER54698 and DE-AC04-94AL85000. The authors would like to acknowledge our appreciation of C.J. Murphy and P.M. Anderson of General Atomics for their supporting design and thermal modeling of the tiles. We also thank C. Kunz of Sandia National Laboratories for his assistance in assembly and installation.

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