Princeton Plasma Physics Laboratory

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DESIGN AND MANUFACTURE OF DIII-D NEUTRAL BEAM POLE SHIELDS WITH COPPER PLATES AND MOLYBDENUM INSERTS

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***Abstract*— The copper pole shields for the neutral beam lines that have been in service at DIII-D have experienced localized melting and fatigue cracks on the front faces which have migrated into the cooling tube grooves machined in the back of the copper plates, leading to water leaks. A solution was required for longer beam pulse lengths and higher beam power operation planned for DIII-D which was limited by the pole shield heat handling capability. An upgraded pole shield design was developed by the Princeton Plasma Physics Laboratory to handle these elevated and extended thermal loads.**

Since the heat flux on the pole shield is highly localized, the new design includes a permanent, actively cooled, copper plate with a cut out region for a segmented set of replaceable and serviceable molybdenum inserts positioned in the area of the maximum thermal loading. A ten-segment molybdenum insert configuration was designed to relieve high stresses resulting from uneven and large thermal loads, which can range as high as 1600°C. The inserts are designed with loose tongue and groove connections, which balance a reliable and sturdy fit-up while allowing for thermal expansion of the inserts without buckling or over-stressing. Ease of installation and maintenance of the inserts was another important design parameter.

Time-dependent finite element analyses were performed in ANSYS to simulate the thermal and heat transfer conditions that the pole shield would be exposed to. Multiple load cycles were run to verify that peak thermal conditions were fully ratcheted. Various temperature distributions with differing gradients were then resolved into peak stresses and strains via transient structural analyses.

Once the analyses converged upon an optimal design configuration, final details were worked out and design drawings developed. Final details of the pole shield assemblies include cooling lines, clamps, thermocouple grooves, and plasma spraying. Ultimately, two sets of complete pole shields (two plates with inserts comprise one set) were manufactured, delivered and accepted by General Atomics in San Diego. The project was completed on schedule and within the allocated budget. The pole shields have been installed for service during the next run cycle.

Keywords—Neutral beams pole shields; Molybdenum; high heat flux; transient analysis.

I. INTRODUCTION

Design of the DIII-D neutral beam includes two pole shields to protect ion separation magnets. The pole shields are placed on both sides of the neutral beam in front of each magnet. A schematic of the neutral beam design is presented in Fig. 1, with the pole shield location indicated.

Water cooled copper pole shields were used in DIII-D neutral beams' original design. These pole shields showed evidence of localized melting and fatigue cracks during operation with 2.6MW maximum power for 3 second pulses. New requirements for DIII-D call for neutral beam power up to 3.2MW for 6 seconds, increasing the thermal load on the pole shields. Thus, a redesign of the pole shields was needed to withstand the expected elevated heat loads. In addition, a key aspect of the new design would be one that could be maintained with relative ease with readily replaceable elements in situ.

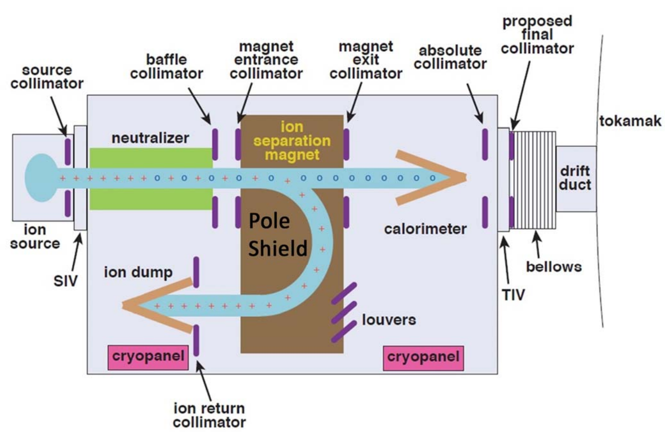

Fig. 1. DIII-D neutral beam schematic

II. NEW POLE SHIELD DESIGN

A. Thermal Loading

The new design of the pole shield is determined by the nature of the thermal load which is highly non-uniform in space and in time. According to the updated operational requirements[1], the length of the pulse increases to 6 seconds with a 12 minute repetition rate. Spatial distribution of the heat flux on the front face of the pole shield is presented in Fig. 2. This distribution was obtained analytically from a particle trajectory analysis for a 2.6MW pulse load. To simulate a 3.2MW load, this distribution was scaled up proportionally.

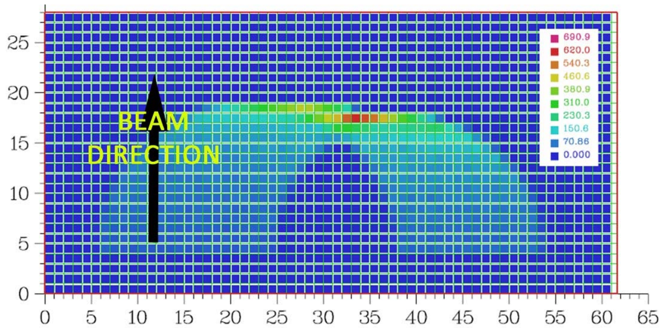

Fig. 2. Heat flux on the pole shield [W/cm^2] for a 2.6 MW pulse

B. *Design Concept*

The thermal load distribution presented in Fig. 2 shows a very high intensity hot spot (837 W/cm^2 for 3.2MW load) in the center of the pole shield with much lower values in surrounding areas. On the periphery of the pole shield, the heat flux values are very close to ambient. This type of thermal load distribution led to a new pole shield concept including an insert comprised of interlocking TZM molybdenum placed in the area of the hot spot. TZM molybdenum was chosen as the insert material because of its high melting temperature and structural strength. The new design of the pole shield is shown in Fig. 3.

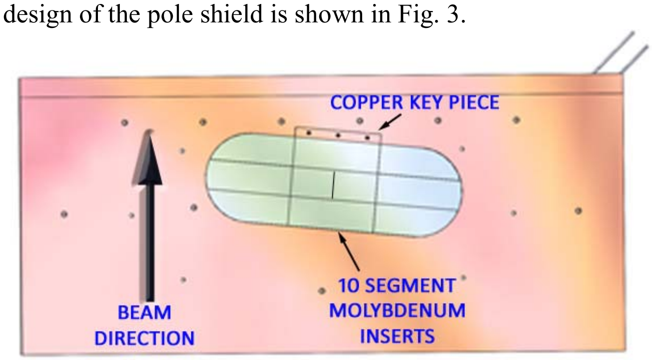

Fig. 3. Pole shield design with TZM molybdenum inserts

The conservative size of the molybdenum insert was defined by the requirement to accommodate the possibility of the two inch shift of the heat flux pattern in any direction. Initial numerical analysis showed that the high thermal gradients and the non-uniformity of the heat load and, consequently, the temperature distribution within the insert leads to higher stresses due to the differences in thermal expansion. Thus, the insert was split into ten separate segments. Segments of the insert were kept together and within the copper plate using a loose tongue and grove pattern. The gaps of 0.25 mm (0.01 inch) between molybdenum segments and of 0.635 mm (0.025 inch) between molybdenum and copper parts were designed to accommodate different thermal expansion and deformation of the parts. Details of tongue and groove patterns are presented schematically in Fig. 4. Application of the tongue and groove pattern allows streamlined assembly of the insert segments *in situ*. All molybdenum pieces are placed in sequence within the copper plate and the final assembly is locked by the copper key piece shown in Fig. 3. The key piece is fixed in the copper plate by three bolts. These three bolts are the only mounting hardware required to assemble the ten segments of the insert within the copper plate. The overall dimensions of the copper plate are approximately 1.56 meters by 0.7 meters. The nominal plate thickness is 12.7 mm.

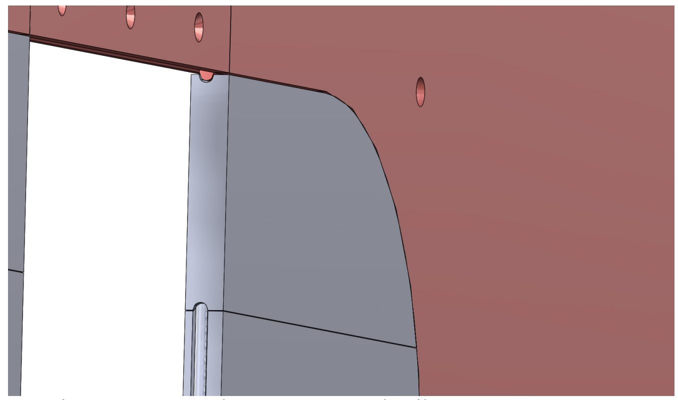

Fig. 4. Tongue and groove pattern details

A stainless steel water cooling tube and thermocouples are placed in grooves cut in the copper plate on the side opposite to the beam. These grooves create structurally weaker regions. It is worth mentioning that cracks on the original pole shields appeared near thermocouple grooves. To reduce the load on these weaker regions of the copper plate, cooling channels were moved to the perimeter of the copper plate, where the thermal load and gradients are smaller. The pulsed nature of the thermal load allowed for successful heat removal from the periphery during the cool down period due to the good thermal conductivity of copper.

III. Design Verification and Analysis

To verify the new pole shield design, three-dimensional numerical and finite element analyses were performed using ANSYS software. Initially, an unsteady three-dimensional flow and heat transfer analysis was performed using ANSYS-CFX. At this stage, flow and heat transfer analysis of the coolant flow was performed using computational fluid dynamics together with heat transfer analysis in the solid parts. Temperature distributions obtained at the initial stage were used in structural analysis using ANSYS Mechanical[2].

A. *Heat Transfer and Coolant Flow Analysis*

Conjugated heat transfer analysis was performed simultaneously in liquid coolant and solid parts, with a fluid-solid interface imposed on the internal cooling tube walls. Multi-block approach allowed creating a hexahedral mesh with boundary layers in the fluid near wall regions. A portion of the mesh shown in Fig. 5 shows the cross-section of the mesh near the coolant channel.

In the new design, gaps are assumed between the segments of the molybdenum insert, and also between the insert and the copper plate. This design feature, while advantageous from a structural perspective, creates additional thermal resistance between the insert and the copper plate, impeding heat transfer from the hot molybdenum insert to the copper and the coolant, during cool down phase. This effect was included in the analysis via solid-solid interfaces with thermal resistance. The conservative assumption was made that all segments of the insert and the copper plate are not touching each other, so the only mechanism of heat transfer is thermal radiation. Any actual contact between components would greatly enhance heat transfer and cool down.

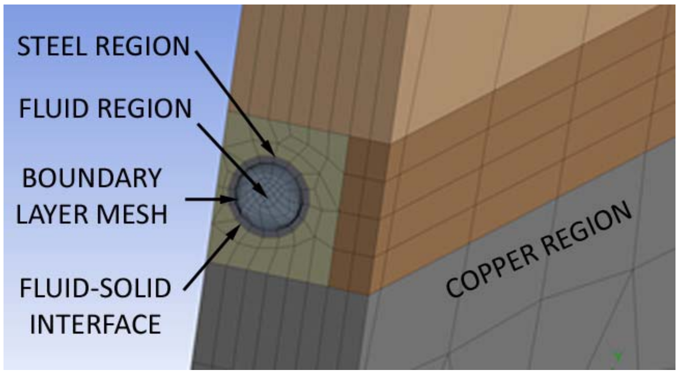

Fig. 5. Fluid and heat transfer analysis mesh details

The heat flux distribution presented in Fig. 2 was used as a boundary condition on the front face of the pole shield for a six second pulse. Radiative heat transfer conditions were used on both faces of the pole shield all the time in the form of the calculated heat flux, where local wall temperature and ambient temperature of 70°C were used as the temperatures on both sides of the interface. A relative emissivity value of 0.8 was used. The combined heat flux distribution of the front face during pulse is presented in Fig. 6. Coolant water velocity of 3.1 m/s and a temperature of 20°C were imposed at the inlet. At the outlet a constant pressure condition was imposed.

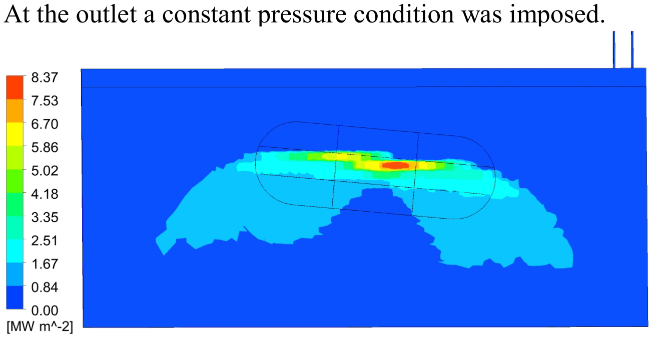

Fig. 6. Heat flux distribution on the front face of the pole shield

B. *Analytical Results*

Any damage of the cooling tube and/or water leakage leads to major failure of the pole shield. Thus, it is advantageous to move cooling channel areas away from the highly stressed areas near the molybdenum insert to the perimeter of the copper plate. Time variation of the peak pole shield temperature (Fig. 7) for the initial cooling channel arrangement (central cooling) versus perimeter cooling show that the effect of the cooling tube location is, in fact, very small. Furthermore, thermal analysis shows that no significant ratcheting occurs after the second pulse. Both of these findings are very beneficial for a robust pole shield design.

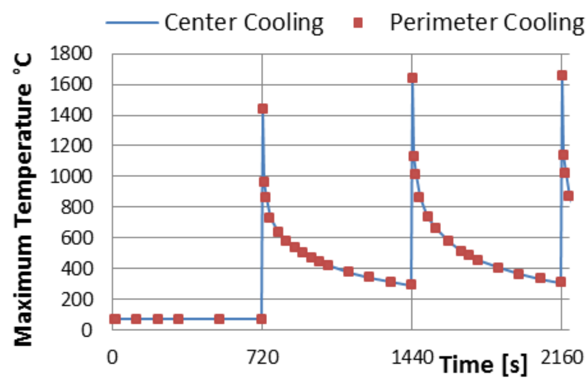

Fig. 7. Peak pole shield temperatures vs. time for central and perimeter cooling

The calculated temperature distribution on the front face of the pole shield, presented in Fig. 8, generally follows the distribution of the heat flux presented in Fig. 6. The effect of the gaps between the individual molybdenum insert pieces between each other and the copper plate are clearly evident. High temperature gradients exist especially at the central part of the insert. These temperature gradients can lead to excessive stresses. That was the reason for splitting the central segment of the insert from a single piece into two smaller pieces as can be seen in Fig. 3

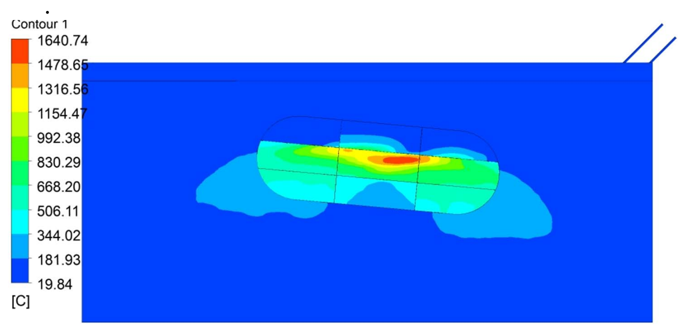

Fig. 8. Temperature distribution at the end of the second pulse

C. *Structural Analysis*

The structural finite element analysis was performed for all solid regions using the ANSYS mechanical solver utilizing a hexahedral mesh. A close-up of the mesh shown in Fig. 9 (similar to Fig. 5) shows the cross-section of the mesh near the coolant channel with one of the copper plate support bolts.

A constant pressure condition (0.5 MPa) was imposed on the inner cooling tube wall simulating coolant water pressure. The temperature distribution was interpolated on the structural mesh from heat transfer analysis at different time steps using ANSYS Workbench. The analysis allows movement of the insert segments inside the copper plate due to the gaps. The copper plate was supported on the sides and also with support bolts as shown in Figs. 9 and 10. Ten support bolts are located at the same positions as in the original pole shield design, thus the new pole shield can be directly connected to the corresponding existing holes on the magnet support structure in the neutral beam. However, numerical simulations with these ten supports showed excessive deformation of the copper plate in the plane normal to the pole shield exceeding the updated design requirements at the specified higher performance levels[1]. To reduce this deformation three additional support bolts were proposed and are marked with red circles in Fig. 10 for reference.

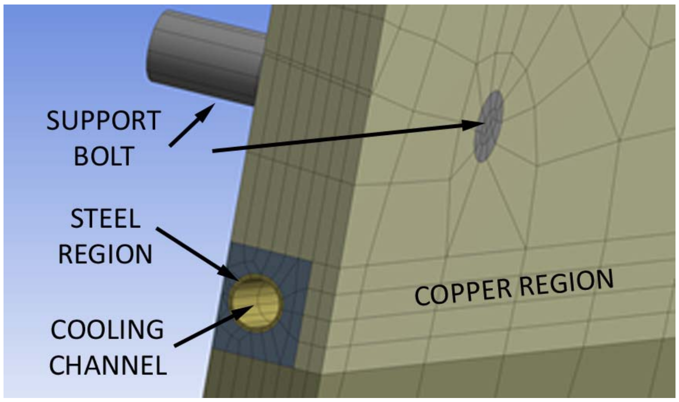

Fig. 9. Structural analysis mesh details

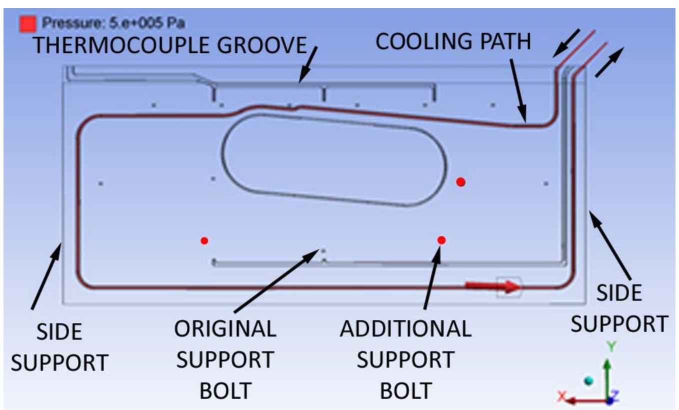

Fig. 10. Pole shield schematic showing support bolts, cooling path and thermocouple grooves

As stated previously, the baseline design of the TZM Molybdenum insert was comprised of nine interlocking segments resembling a tic-tac-toe board. After the initial rounds of structural analyses were completed, it was apparent that both the stresses and deformations of the insert exceeded the updated DIII-D requirements for successful operation. Thus, it was decided to split the center molybdenum tile into two equally sized halves. This allowed for greater insert flexibility to withstand the highly localized heat loads that were expected at the center of the insert. When the analysis was re-done with ten insert segments, the results indicated a significant reduction in both the peak stresses and deformation of the molybdenum to within allowable values.

Similarly, the copper plate also had to meet allowable stresses and deformations. The stress intensity in the copper plate at the end of the second (fully ratcheted) pulse is presented in Fig. 11. The calculated deformation of the copper plate is presented in Fig. 12. The results show a significant reduction of the copper plate deformation when three additional supports were added (as detailed in Fig. 10). For comparison, when only the original plate supports are used, the deformation ranges from -1.00 mm to 0.61 mm. With the addition of the three additional support bolts, the deformations are reduced to a range of -0.18 mm to 0.33mm.

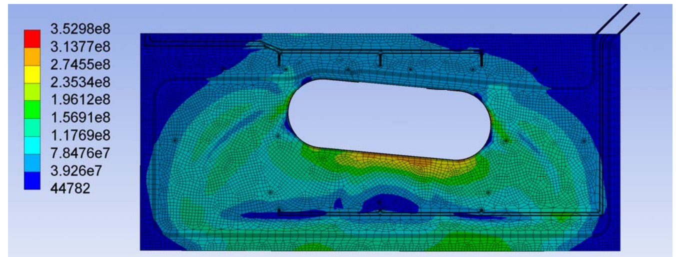

Fig.11. Stress intensity (MPa) in the copper plate after second pulse

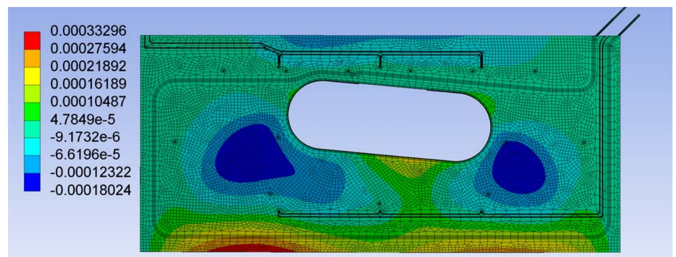

Fig.12. Copper deformation (mm) normal to plane of plate after second pulse (positive deformation is towards magnet)

The thermal and structural analyses confirm that the new design of the pole shield successfully meets all performance requirements. The ten-part segmented TZM Molybdenum insert resolves the peak stress level to below 500 MPa, which from a fatigue perspective, permits 6000 stress cycles[3]. The stresses are primarily compressive with the maximum principal stress not exceeding 150 MPa. Stresses on the stainless cooling channel pipe do not exceed an allowable of 275 MPa for a 30,000 cycle design life. Fatigue and yield limits in the copper are exceeded in the design; however, the ductile copper plates retain their function even if fatigue cracks form. The cooling tubes have been purposefully positioned away from the high copper stress and temperature regions. Tongue and groove retainers for the molybdenum tiles will perform adequately even with potential thermal fatigue cracking and expected plasticity.

IV. Fabrication

Once the analysis of the new pole shield design was complete, a Final Design Review (FDR) was held in June 2014 between PPPL and GA to confirm that all of the requirements had been met and that the fabrication phase could begin. The FDR was deemed successful and a complete fabrication drawing package was assembled for the purpose of soliciting bids from potential manufacturers. As the request for bids was issued, the criteria for the winner included the following:

- Precision machining of the copper plate including overall dimensions, and exact placement of the cooling channels, thermocouple grooves, tongue and grooving for the insert region, and mounting hole locations
- Precision machining of the TZM Molybdenum inserts including the ability to machine curves and tongue and groove edges in a material with brittle behavioral properties and a tendency to chip; knowledge of appropriate drill/machining procedures (bits, speeds, etc.) is essential
- Precise bending of a continuous 316 stainless steel cooling tube such that it will fit exactly in the cooling channels machined into the copper plates; no welded joints are permitted within the copper plate and a kinked bend would render the tube rejected
- Plasma/flame spraying with a pure copper mist fine enough to cover the embedded stainless steel cooling tubes within the copper plates; the plasma spray enables better heat conduction between the cooling tubes and copper plates; spray cannot be higher than the surface of the plate – for that reason there is a chamfered space in the copper plates that can be filled with the plasma spray

The successful bidder would be able to address all of the above criteria either in-house or through sub-contractors subject to PPPL approval. The award would be to build two sets of pole shield assemblies (two copper plates with molybdenum inserts per set – See Fig. 13 for orientation). Plus an extra set of molybdenum inserts was included as part of the job in the event that any issues were encountered during installation or initial operation.

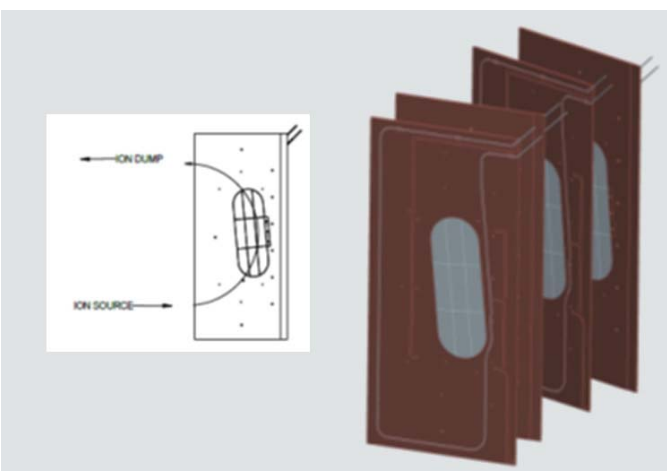

Fig. 13. Orientation of two pole shield sets

One of the special features of the new pole shield design was the forethought that went into the ease of assembly and ease of maintenance. With its active cooling, the analysis has shown that the copper plate should be able to sustain a long life. Given that the most difficult part of the pole shield installation is the mounting of the copper plate, the goal is that once it is mounted, the copper should not be expected to be removed for maintenance. Since the molybdenum insert pieces bear the brunt of the heat load, only those pieces will likely have to be maintained/replaced. Because of the tongue and groove assembly and the relative small size and weight of each piece, the molybdenum pieces can be maintained, as necessary, with relative ease. During a maintenance period, an individual can reach into the neutral beam and remove and replace insert pieces as necessary. The only attachment that requires a tool is the removal of the three cap screws that hold the copper insert cover in place (see Fig. 3).

Following the evaluation of all bidders, the award of the entire pole shield manufacturing job went to Martinez & Turek of Rialto, California. Martinez & Turek are familiar to both PPPL and GA, so there was great confidence that they could not only do the job, but deliver all components in a timely manner. The contract was awarded in late-July 2014.

In late-November 2014, 8 months after the collaboration agreement was signed between PPPL and GA, and 4 months after the contract was awarded, the manufacturing of all pole shield components was complete. Everything was shipped to GA for installation into DIII-D. All parties were extremely satisfied with the workmanship of received pole shield components. The copper plates (Fig. 14) and the molybdenum inserts (Figs. 15 and 16) all passed a thorough inspection.

Fig. 14. As-delivered copper plate with plasma sprayed 316SS cooling tubes and thermocouple grooves

Fig. 15. As-delivered TZM Molybdenum insert pieces

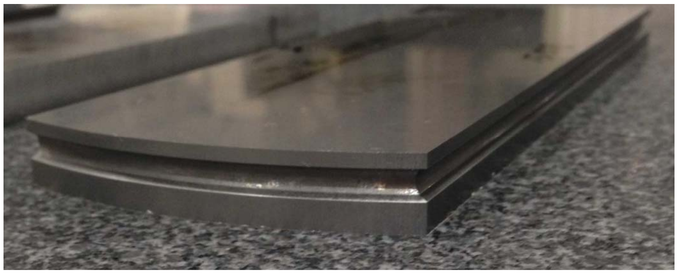

Fig. 16. Close up of tongue and groove detail along the edge of a TZM Molybdenum insert piece

In early 2015, during a scheduled machine outage, GA prepped and installed these pole shield assemblies in the DIII-D neutral beams. Fig. 17 shows one of the pole shields installed within the neutral beam. When operations resume later in 2015, the performance of these pole shields will be closely examined and compared to the predicted behavior.

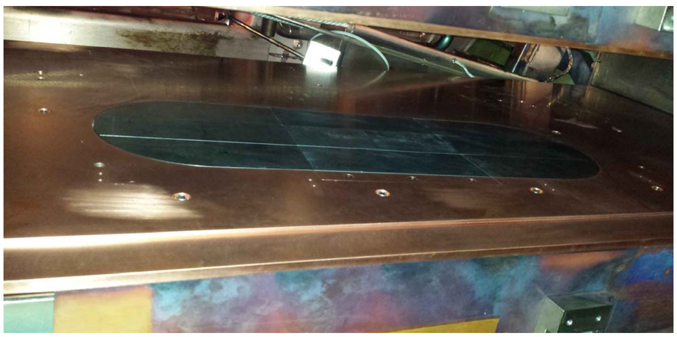

Fig. 17. A pole shield assembly installed in-place in one of the DIII-D neutral beams

V. SUMMARY

A Memorandum of Understanding[1] collaboration agreement between the Princeton Plasma Physics Laboratory and General Atomics to design, analyze, manufacture, and deliver two sets of neutral beam pole shields for DIII-D was signed in March 2014. By the end of November 2014, in approximately eight months, these pole shields were delivered to GA, where they were inspected and accepted.

The new pole shield design incorporates a set of ten TZM Molybdenum insert pieces in a copper plate with active cooling. Extensive thermal and structural analyses were used to confirm the feasibility of the design then optimize it. A contract was awarded to have these pole shield assemblies built to the required precisions specified on fabrication drawings. The pole shields have been installed in the neutral beams of DIII-D and their performance will be closely monitored.

ACKNOWLEDGMENT

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