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POLE SHIELDS FOR THE 80 KEV
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Fabrication of New Magnet Pole Shields for the 80 keV Neutral Beam Lines for DIII-D*

H.J. Grunloh, C.B. Baxi, J.L. Busath, R.W. Callis, H.K. Chiu, M. DiMartino, R.M. Hong,
A.W. Hyatt, J.A. Leuer, W.C. Martin, E.E. Reis, R.H. Ryder, and R. Tao
General Atomics, P.O. Box 85608, San Diego, California 92186-5608

Abstract—In September 2003, a water leak emanating from a magnet pole shield in one of the 80 keV neutral beam lines halted DIII-D physics experiments. Investigation showed that impingement of the diverted charged particle beam on the copper shield plate initiated melting and a through-wall crack that propagated through a brazed stainless steel cooling line. A subsequent survey of all pole shields in the 4 neutral beam lines found that similar damage was present in 9 of the other 15 shields but to a lesser extent. The decision was made to arrest the crack propagation in damaged shields and to begin fabrication of new pole shields, which will be installed during the long torus opening of 2005-2006.

A summary is presented of the physical damage that was found in the shields and the assessments that were conducted to determine the cause of the damage. The custom tooling that was developed and then utilized inside the beam lines to arrest crack propagation in the shields is also presented. Modifications to the design of the shields were made to minimize stress concentrations and were implemented in the new pole shields. A novel technique was devised to fabricate the serpentine cooling tubes that are brazed into matching grooves in the shields. This presentation includes descriptions of the shield design modifications and the procedures that were employed to successfully complete the fabrication of the new pole shields.

Keywords—DIII-D, neutral beams, pole shield, bending magnet, crack initiation, crack propagation, crack tip drilling, magnetic fields, CNC machining, brazing, tube bending, stress concentration, fabrication technology

I. INTRODUCTION

In September 2003, during DIII-D physics experiments involving C-coil currents approaching 7 kA, a water leak was detected inside the 30-deg neutral beam line that terminated operations. The ensuing investigation determined that the leak was in the water cooling line imbedded in the right bending magnet pole shield serving the left 30-deg ion source. Both the right and left pole shields for this ion source were subsequently removed from the line, and inspection determined that the leak was caused by an abnormally high heat load near the center of the beam side of the pole shield. The high heat load caused severe material damage and local melting of the copper shield [Fig. 1(a)], which initiated a through-wall crack that propagated bi-directionally to a length of 4.13 in. (105 mm) until one crack front broke through the shield's brazed, imbedded stainless steel cooling tube [Fig. 1(b)]. Furthermore, the left pole shield was also found to be damaged in a similar fashion in the same location, but its through-wall crack had only propagated to a length of 2 in. (50 mm), its crack front not yet reaching the cooling tube. The damage zone, marked by a severe orange-

peel texture, on the beam-side surface of both shields was in an arc-shape, generally coinciding with the location and shape of the magnetically bent, charged particle beam adjacent to the pole shields during neutral beam operation. Beam impingement was thus suspected to be the cause of damage, and an inspection survey was conducted to determine the condition of the remaining 14 pole shields in DIII-D's four neutral beam lines. The survey determined that damage of the same type and location was present in nine additional shields, with surface melting evident on five shields and cracks present also in six shields. No damage was found in five shields.

Operation of the C-coil at record high currents approaching 7 kA coincided with the water leak. The greater than normal magnetic fields generated by the C-coils were first suspected to have caused the damage. Although the earliest magnetic field analyses showed that the high C-coil fields may have been capable of deflecting the beam sufficiently to have caused damage of the nature seen, this scenario did not bear out as more details were added to the analyses. Once factors were added for the magnetic shielding provided by the bending magnet itself and the interactions of the fields caused by the plasma and other coils, the analyses showed the effects of the C-coils were minimal if not negligible. No combination of coil effects could be found that would have caused the pattern of damage seen among all the pole shields.



Figure 1. The 4.13 in. 105 mm) through-wall crack in the right pole shield of the 30-deg left neutral beam line, as seen from (a) the beam side, and (b) the thermocouple side. Melting and severe surface damage can be seen accompanying the crack in (a), while crack propagation to the brazed cooling tube can see on the left in (b).

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As no operational root cause for the damage could be identified, limits were not placed on coil operations, but slightly reduced time-at-power limits were placed on the beams, and beam operation interlocks based on pole shield thermocouple data were instituted. Since the occurrence of the pole shield damage, visual inspections of the shields have been conducted regularly during vent periods and no further damage has been observed, even though the C-coils have been operated up to the near-7 kA range since that time.

II. IN-SITU CRACK REMEDIATION

The pole shields are oxygen-free high conductivity (OFHC) copper plates, 61.6 in. (1565 mm) by 28.0 in. (711 mm) by 0.5 in. (12.7 mm) thick, which are fastened to the vertical inner walls of the neutral beam bending magnet coils. The plates are water cooled by type 304 stainless steel tubing, 0.25 in. (6.3 mm) outside diameter by 0.020 in. (0.5 mm) wall, that are brazed into serpentine grooves milled into the back side (i.e., the side opposite the beam side) of each plate (Fig. 2). Thermocouples are attached to the back of each shield in nine locations. The thermocouples and their insulated lead wires are routed through grooves machined into the back surface of each plate and secured there by staked clips made of stainless steel.

Damage to the pole shields was present in each of the four neutral beam lines. Replacing damaged shields with new shields was an unfavorable option as the time required to fabricate all new shields was far greater than the length of the scheduled maintenance outage. Furthermore, replacing all pole shields would require at least partial disassembly of all four beam lines, a major undertaking. Instead, it was decided that crack growth in the shields with cracks should be arrested by drilling holes at the crack tips, and that temperature limits on the face of the shields should be established at levels below which analyses showed crack initiation or re-initiation would not occur. These temperature limits were derived based on thermal models of the shields and data monitored during beam shots from the thermocouples welded to the backs of the pole shields.



Figure 2. A newly fabricated pole shield is shown after successful brazing of the imbedded stainless steel cooling tube. Thermocouples have not yet been installed.

To drill holes at the tips of the cracks in the pole shields, a device had to be fabricated that could function within the 7-in. wide space between the pair of pole shields in a beam line. The device had to be capable of being accurately positioned to drill the crack tips, it had to bear its own weight so that the operator would not have to do so during drilling, and it had to administer some form of cutting fluid to cool the drill tip that was compatible with the vacuum restrictions applied to all work performed within a beam line. Personnel access to the pole shields was to be through a manhole port in the side of the neutral beam vacuum vessel near the bending magnet. Due to the severe space restrictions inside the beam lines, all work between the two pole shields would have to be performed using only a single hand and at arm's length.

The device that was produced was based upon a commercially available portable drilling machine. This apparatus uses a single compressed air supply to operate a suction mount in its base to bear its weight and secure its position on any smooth surface and to actuate an air cylinder that moves an attached drill chuck. Several significant modifications were made to the standard device to adapt it to its special purpose (Fig. 3). Because the overall height of the device was greater than 7 in. (178 mm), the air cylinder actuator assembly had to be shortened to produce a final maximum height of 6.5 in. (165 mm). A right-angle drill chuck attached to a flexible drive shaft was secured to the actuating head of the air cylinder. Drilling power was provided by a portable electric drill attached to the end of the flexible drive shaft. The end of a long 0.125 in. (3 mm) diam plastic tube was glued to the device's base plate at a location nearest the end of the drill tip. The other end of the tube was connected to a plastic catheter-type bag filled with alcohol. When in use, alcohol would drip from the end of the tube and be allowed to flow off the base plate to the pole shield, then onto the drill bit and into the hole being drilled. Little, if any, alcohol ever drained off the bottom of the pole shield as the alcohol evaporated before reaching this location.



Figure 3. The crack tip hole-drilling apparatus is shown installed between the pole shields of a neutral beam line. The drill and air cylinder actuator is seen at the bottom; the device is positioned from a temporary support (top) before the suction mount is actuated.

A support bracket with long slots and fastener holes was machined from a piece of aluminum angle. This bracket was attached to existing holes in the pole shields above the cracks. A copper tube, externally threaded a majority of its length, was added to the air inlet port of the drilling device. Two jacking nuts were threaded onto the copper tube before a quick-disconnect air line fitting was added to the end of the tube. The drilling device was then suspended from the fixed bracket by inserting the copper air tube through one of the slots in the bracket, with a jacking screw above and below the bracket (Fig. 3). Horizontal position of the drilling device was then adjusted by sliding the copper tube side to side within the slot in the support bracket, while vertical position was adjusted by turning the jacking screws on the threaded copper tube. A hand-held mirror or borescope was used to locate the crack tip as the drilling device was being positioned. The drill bit feed was controlled by a finger-actuated trigger on the device. All crack tips were drilled using a 0.25 in. diam bit, the largest size that could be made to work properly.

III. NEW POLE SHIELD FABRICATION

Numerous difficulties were encountered when the pole shields were originally fabricated in 1984-85. OFHC copper is so soft after annealing, a required step, that any handling of the plates after this point of the fabrication process often led to gross plastic deformation of the plate. The use of coiled copper refrigerator tubing was originally attempted but the tubing could not be made to lie perfectly flat within the machined grooves in the plates, which compromised the quality of the braze, and the dissimilar metal connections between the copper tubing and the stainless steel water supply lines inside the neutral beam lines leaked frequently. The tubing specification was then changed to type 304 stainless steel, seamless, 0.25 in. (6.3 mm) diam by 0.020 in. (0.5 mm wall) by 35 ft (10.7 m) long. Cleanliness of the plate and tubing had to be maintained stringently or else the pump down portion of the vacuum braze run would be prohibitively long. Staking the tubes in their machined grooves became essential as the tubing would otherwise float on the braze metal as it liquefied. The original tube staking was done with center punches but the punches would occasionally slip and puncture the tubing. Securing the thermocouple leads also became problematic in that the stainless steel sheet metal clips that were staked over the top of the leads in their grooves occasionally severed a lead wire as it was trapped in the bottom corner of its groove under the edge of the clip. Possibly the greatest problem, however, was the difficulty in fitting the serpentine-shaped tubes fabricated by a vendor specializing in tube bending into the mating groove in the pole shield machined by a vendor specializing in computer-controlled milling. Mismatches as small as a few thousandths of an inch in the geometries of the tubing and the grooves would cause the tubing to buckle out of its groove, making it extremely difficult, if not impossible, to stake properly into the plate.

Each difficulty in the original fabrication was addressed in the new fabrication. The 35-ft lengths of thin-wall, seamless stainless steel tubing were custom drawn to the dimensional specifications and meticulously cleaned on the inside and outside surfaces. To prevent deformation of the copper plates during handling, cast aluminum backing plates were fabricated

and pinned to the copper plates during all milling and staking processes, as well as during transport.

Attaining a precise match in the geometries of the tubes and their mating grooves in the plates was assured by linking the two fabrication processes. In effect, the bending of the tubes and the milling of the grooves in the copper were both governed by the same geometrical database. The coordinates of the geometrical shape of the tubes and their matching grooves were entered into a single file to be read by a CNC milling machine. That file was used to machine a tooling plate from a cast aluminum plate of the same dimensions as the pole shield plates. Holes were then machined in the tooling plate to position tube bending tools shaped like pulley spools with radii exactly matching the radii of each bend in the tube and matching groove in the plate. When the tooling was assembled onto the plate, the tubing was manually wound around the series of spools, one spool at a time, until all the tube bends had been made. The same geometrical database was then used to machine the serpentine tube groove in the copper shield plate. When a tube and a plate were finished, the tube could be immediately test fit into its matching groove. Four tubes and four pole shield plates were fabricated in this way and each fit was precise.

The braze metal used to attach the tubes to the copper shields was AWS BAg-8, an alloy composed of 72% silver and 28% copper, with a liquidus temperature of 1435°F (780°C). This braze requires that nickel be plated onto the stainless steel tubing prior to brazing to the copper. While the tubes were being plated, the copper shields were degreased, ultrasonically cleaned, and vacuum annealed. The heat treating was done to assure that no movement of the copper due to the release of residual stresses during the braze cycle would occur that would cause the stainless steel tubing to buckle out of its groove and produce voids in the braze joint.

The nickel-plated tubes were staked into the annealed copper shields using a new method. Rather than hand-staking the copper using a center punch to deform the walls of the groove around the tube, a staking tool was designed that shaved a thin strip of copper from the wall of the groove and bent it against the top side of the tube. Fig. 4 shows the results of the old and new staking methods. The new staking tool, designed to be held by the CNC mill that machined the shield plates, has a cutting end shaped like a crescent, with the ends of the crescent being the cutters and the distance between the cutters being slightly greater than the diameter of the tube. In the staking procedure, the CNC mill head, holding the staking tool, tracks along the centerline of the tube using the geometry from the original database, then pushes the staking tool down into the copper plate every 4 to 6 in. (100 to 150 mm), cutting and bending thin shavings over the top half of the tube. Since the cutters are never directly over the tube at any time, the risk of puncturing the tube is eliminated.

The vacuum brazing of the tubes into the shield plates was successfully accomplished. No voiding was seen along the braze interface of any tube, and more than ample tube surface area was covered by braze metal for heat transfer purposes.

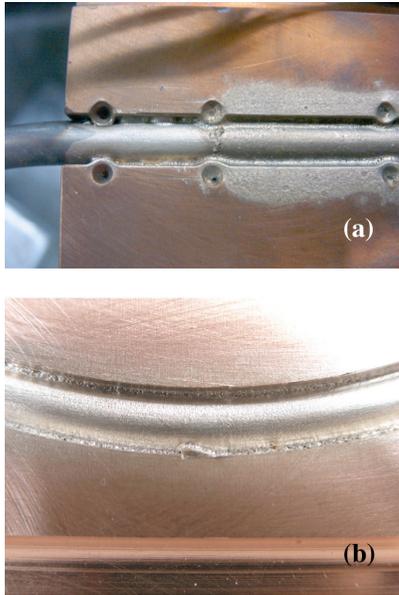


Figure 4. The old (a) and new (b) methods of staking the stainless steel cooling tube into its groove is shown. The old method used a hand-held center punch while the new method employed a CNC head-mounted crescent-shaped cutter.

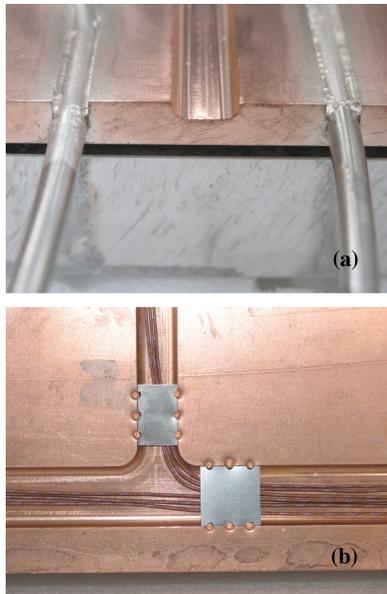


Figure 5. The profile of the thermocouple grooves were modified to reduce the stress concentration in their corners. The new groove corners are fully radiused (a), and the staked thermocouple lead clips (b) can no longer pinch or sever the leads.

Modifications were also made to the shape of the thermocouple grooves machined in the pole shields. Under severe, thermally induced stress, cracks had initiated in the pole shields at the stress concentration formed at the sharp bottom corners of the thermocouple grooves. In the new pole shields the bottom corners of all thermocouple grooves were fully radiused [Fig. 5(a)]. With no corners in the thermocouple grooves in which to pin a thermocouple lead, the risk of pinching and severing a thermocouple lead with a staked clip was eliminated [Fig 5(b)]. Recesses machined into the edges of the stainless steel clips prevented the clips from buckling as the staked copper deformed against the edges of the clips.

Thermocouple junctions were attached to the pole shields using the gas tungsten arc welding process. AWS BCuP-5, a silver-copper-phosphorus alloy, was used in stick form to deposit a molten metal bead onto the copper shield plate into which the thermocouple junction was inserted. Solidification of the bead fixed the thermocouple junction to the plate. Fig. 6 shows a thermocouple welded to a shield plate in the narrower, fully radiused thermocouple groove of the new design.



Figure 6. The thermocouple junctions are attached to the back of the pole shields using a gas tungsten arc welding process. The filler metal is a silver-copper-phosphorus alloy.

IV. CONCLUSION

Crack growth was arrested in cracked pole shields in DIII-D neutral beam lines by in-situ crack tip drilling using a specially designed drilling apparatus. Four new pole shields were successfully fabricated that incorporated changes designed to significantly reduce the difficulty of fabrication and lower the stress concentrations that contributed to crack initiation in the original pole shields. The four new pole shields were recently installed into the 210-deg beam line during DIII-D's long torus outage, replacing the four original shields that were damaged during experiments in September 2003. A second set of four new pole shields has since been fabricated and will be installed into the 150-deg beam line during the current outage.