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Fabrication and Installation of the DIII–D Radiative Divertor Structures*

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Abstract — Phase 1A of the Radiative Divertor Program (RDP) is now installed in the DIII–D tokamak located at General Atomics. This hardware was added to enhance both the Divertor and Advanced Tokamak research elements of the DIII–D program. This installation consists of a divertor baffle enveloping a cryocondensation pump at the upper outer divertor target of DIII–D. The divertor baffle consists of two toroidally continuous Inconel 625 water-cooled rings and a toroidal array of discontinuous radiatively-cooled plates. The water-cooled rings are each comprised of four quadrants, mechanically formed, chem.-milled, and resistance and TIG welded Inconel 625 panels. The supports attaching the panels to the vessel wall are designed to accommodate the differential thermal expansion between the rings and vessel during bake and to react the electromagnetic loads induced during disruptions. They are made from either Inconel 625 or Inconel 718 depending on the stress levels predicted in Finite Element Analysis. Gas seals are designed to limit the leakage from the baffle chamber back to the core plasma to 2,500 ℓ/s and incorporate plasma sprayed alumina to minimize currents flowing through them.

The bulk of the water-cooled ring fabrication was performed by a vendor, however, the final machining of penetrations in the conical ring for diagnostic access was performed in-house using a unique machining configuration. This configuration, and the machining of the diagnostic cutouts is described. Graphite tiles were machined from ATJ graphite to form a smooth plasma-facing surface.

The installation of all divertor components required only four weeks. This divertor installation included electro-discharge welding studs, accurately locating the supports using a toroidally continuous tooling plate and local fixtures, and mounting the structures. Tooling was used during ex-vessel test assembly to greatly simplify the installation process. This process is reviewed.

INTRODUCTION

The installation of the first phase, 1A, of the Radiative Divertor in DIII–D is now complete and will provide particle control for high triangularity, Advanced Tokamak discharges. The new hardware will allow the demonstration of divertor heat flux reduction through divertor radiation while having a minimum effect on the core confinement. This divertor modification is a key element in the research towards solving the divertor heat flux issue and provides important data for ITER and other future fusion devices. This initial installation is only the first installment of a comprehensive system that will provide baffling and pumping at all four divertor legs of a double null high triangularity discharge in DIII–D.

Initial results from early experimental campaigns have been successful and are encouraging. Initial measurements indicate that gas puffing reduces the divertor heat flux and when used in combination with the cryocondensation pump, the core density decreases.

Detail design has commenced on Phase 1B of the project with manufacture and installation scheduled for 1999. The installation of Phase 1C is scheduled for 2001.

DESIGN

The Phase 1A divertor structure consists of an outer baffle comprised of two toroidally continuous Inconel 625 water-cooled rings of sandwich construction with internal water channels. The toroidally continuous design was chosen for its inherent strength and its ability to resist the large toroidal currents induced during a disruption. Resistance seam welding is used for structural integrity while TIG welding creates a helium leak tight part. Twenty-four discrete, radiatively cooled, Inconel 625 plates are located between the outermost ring and vessel wall and complete the outer baffle. These plates are designed to be removed easily to allow access to the outer cryopump, vessel ports, or other under-baffle components and diagnostics. Fig. 1 shows the primary components of the Radiative Divertor.

Vertically stiff yet radially flexible supports made from Inconel 718 with 15 degree toroidal spacing, transmit the loads from the rings to the vessel wall. These supports allow for radial thermal expansion of the toroidally continuous rings experienced during the 400°C bake. The bolted supports also provide a connection path for halo currents to the vessel.

During operations, water reaches the divertor rings via a manifold that enters the vacuum chamber through an

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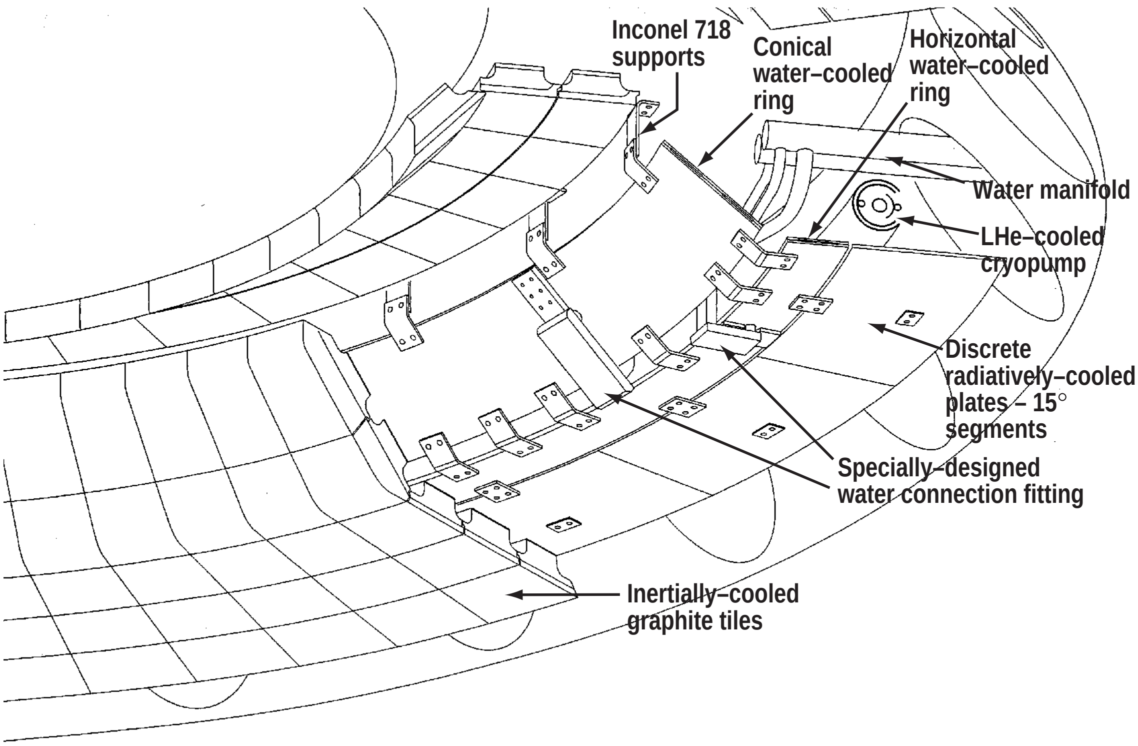

Fig. 1. Primary components of the Phase 1A Radiative Divertor.

electrically isolated bellows feedthrough. Individual tubesfor the inlet and outlet flow for each ring branch off of a common distribution box which is bolted to the vessel ceiling. Additional tubes have been run for the future installation of the private flux baffle rings. This routing will eliminate the need to lower the outer baffle rings to gain weld access to the distribution box when the private flux water lines are installed. During high temperature bakeout, the water is removed from the cooling circuit and replaced with air which helps distribute the heat resulting from the inductive bake.

To prevent the backstreaming of particles and leakage from the pumping plenum, an effort is made to reduce the conductance of leakage paths leading from beneath the baffle to the plasma chamber. Gas seals are used to minimize the leakage due to gaps between components. Hydroformed 1.5 mm thick Inconel sheets with plasma sprayed alumina edges are used between the two water-cooled rings of the outer baffle. They are attached to the brackets connecting the two rings together which provides periodic support and preload to the seal. The alumina insulation is used solely to minimize induced currents from flowing through the thin sheet metal, thereby reducing the loads and preventing melting. Twenty-four seals are installed end to end creating a continuous closure. Similar seals are utilized between the outermost cooled ring and the radiatively cooled plates as well as between the 24 radiatively cooled plates themselves and between the discrete plates and the vessel wall.

FABRICATION, ASSEMBLY, AND INSTALLATION

The first fabrication step involved the laser cutting of the arc segments and frustum flat patterns from 4.76 mm annealed sheet stock. Next, the flat patterns were roll formed to the proper conical shape. The internal water channels were then created by chemically milling 1.27 mm deep by 63.5 mm wide slots into each sheet. Two sheets were then faced together so the slots in each created a channel. Spot welds held the sheets together until the resistance seam weld was performed around the perimeter near the panel edge for structural integrity. In addition to the perimeter weld, the conical panel also has two welds between its side-by-side channels, running the entire quadrant for additional structural support. A V-groove TIG weld was then performed at the edge of the panel to create a helium leak tight channel. The quadrants were then re-rolled to eliminate any distortion induced by the welding processes. Tubes were welded into each end of the quadrants which allow water to flow into and around the rings via inlet/outlet boxes and jumpers.

While the work described above was performed at an outside vendor, additional work remained after the rings were received at General Atomics. The conical ring required a number of Ø6.35 cm penetrations through the water channels along with the match drilled and line reamed holes for the pins at the quadrant ends. This was accomplished by setting the proper ring diameter and holding it in place with temporary “spokes” welded across the assembly. The conical ring, small diameter up, was mounted on a large optically leveled tooling plate. A theodolite mounted at the theoretical ring center was used to locate the toroidal positions of the large penetrations. The machining was accomplished through the use of a unique mill configuration. A conventional mill was tilted at a 50° angle relative to the horizontal by bolting the mill to a large custom fabricated steel base. This base was in turn anchored into the concrete floor in the DIII–D building high bay. The cutting head was removed from the mill and remounted on the mill's X-Y table. This arrangement allowed the machining to be performed in one plane, perpendicular to the conical surface. A Ø6.35 cm Rotobroach® was used to cut through both skins of the water-cooled ring. A special two-point cutting tool was used to spot face a Ø8.89 cm hole through the skin nearest the mill. Because of the high torque needed to cut the large diameter holes and the mill's low horsepower motor, a frequency modulator was wired to the motor to reduce the cutting speed of the mill to 10 rpm. A total of 11 large diameter penetrations and 32 match drilled and line reamed holes were machined in the conical ring. After the chips and cutting fluid were thoroughly cleaned from the panels, machined water jumpers were inserted and welded into the panel.

After a series of helium leak checks, a pressure test, and a vacuum furnace bake, the parts were prepared for installation. A toroidally continuous tooling set and discrete fixtures were used to temporarily assemble the quadrants into rings at their proper diameters as well as to locate the ring positions relative to one another. The amount of work done inside the vessel was reduced by simplifying the installation. To accomplish this, almost 800 threaded studs, used to attach supports, brackets, and graphite plasma facing surfaces to the rings, were electro-discharge welded to the rings while they were outside the vessel. Also, fixturing was used to accurately locate and attach as much bracketry as possible to the panels prior to their in-vessel installation. After the graphite tiles were test fit on the rings to ensure proper fit, the rings were ready for installation in DIII–D.

While the ex-vessel work took place, in-vessel preparation was carried out in parallel. This consisted of electro-discharge welding studs to the vacuum chamber to accommodate the support brackets. Location of the stud positions was accomplished through the use of the tooling ring and fixtures which allowed the stud positions to be transfer punched directly to the vessel wall. After the studs were located and welded, the radial location of the brackets was set using additional fixturing. The brackets were then bolted in place. The water manifold was pre-assembled outside the vacuum vessel, brought in through the entrance port and fed out of the feedthrough port and bolted to the vessel flange via an electrically isolated bellows feedthrough. The rings were assembled in the vessel, pinned and welded together, raised to the ceiling, and bolted in place. The water lines were then welded to the rings through inlet/outlet boxes and the flow path completed through the welding of the jumpers between ring segments. The entire system was helium leak checked and the tiles were installed to complete the installation which is shown in Fig. 2.

INITIAL OPERATIONAL RESULTS

Commissioning of the upper divertor has begun with an unoptimized upper single null plasma. Fig. 3 shows a comparison of a shot with the cryocondensation pump warm (92044-dashed) to a shot after the pump was cooled (92062-solid). With an operational cryocondensation pump, the core density decreases, the electron temperature increases, and the β_N•H (normalized plasma pressure multiplied by the H–mode confinement improvement factor) remains about the same for the case with the pump cold. The upper divertor D_α (deuterium neutral recycling) and midplane pressure (not shown) also decrease dramatically. Even with limited initial operating time, the “figure of merit” density control parameter, $\eta \equiv n_e (10^{19} m^{-3})/I_P(MA)$, achieved has been about 2.5 [1].

FUTURE PLANS

Final design of Phase 1B of the Radiative Divertor Program is now in progress. This phase consists of the fabrication and installation of vanadium alloy water-cooled rings forming a divertor baffle around a cryocondensation pump at the upper inner strikepoint location of DIII–D. The early 1999 installation of this baffle will complement the outer baffle by providing pumping to either or both legs of high triangularity discharges and will be the first demonstration of the use of low-activation alloys in a tokamak. To accomplish this installation, fabrication techniques are being developed for the vanadium alloy (V-4Cr-4Ti). To date V-4Cr-4Ti has been electron beam and resistance welded to itself, friction

Fig. 2. Completed installation of Phase 1A RDP in upper outer corner of DIII–D.

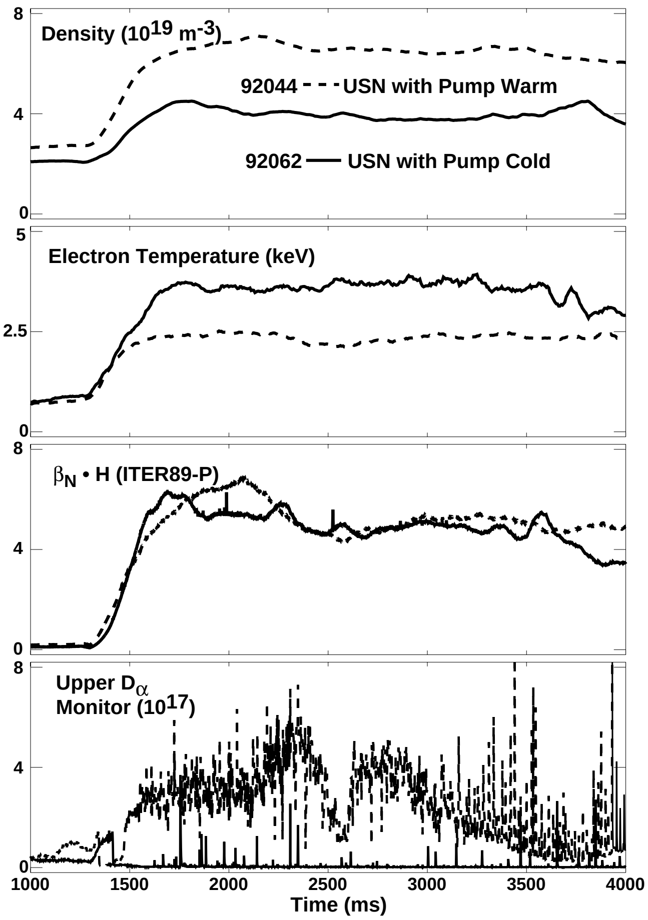

Fig. 3. Initial results showing density control and recycling reduction with no change in normalized confinement with the upper divertor pump (solid-pump cold, dashed-warm).

welding has been used to attach studs to plate, and inertia welding has been used to make bimetallic welds between vanadium alloy and Inconel 625 bars. In addition Inconel 625 has been successfully explosion bonded to vanadium in plate and cylindrical configurations [2]. A small scale vanadium alloy prototype incorporating all of the necessary fabrication methods is being designed and will be built prior to the fabrication of the divertor rings. Upon completion of Phase 1B, the design, fabrication, and installation of Phase 1C, consisting of a private flux baffle enveloping a new cryopump and an outer divertor baffle surrounding the ADP cryopump in the bottom of DIII–D, will commence. Fig. 4 shows the progression of the RDP.

CONCLUSION

The first phase of the Radiative Divertor Program has been successfully installed and encouraging operational results have been obtained. The next phase of the Radiative Divertor is in the final design stage and manufacturing methods are being developed for the fabrication of a vanadium alloy divertor structure. These

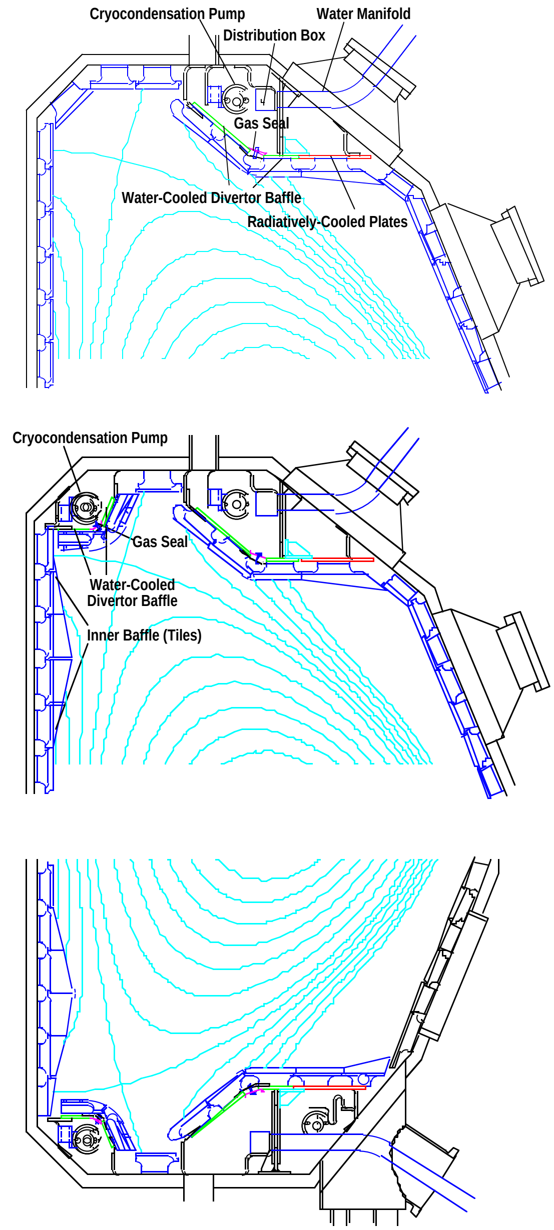

Fig. 4. Phased approach to the RDP installation. (a) Phase 1A installed 1997, (b) Phase 1B adds private flux baffle, and (c) Phase 1C adds inner and outer lower baffle structures.

elements will work together to help further develop the radiative divertor concept and demonstrate the fabrication and use of a low activation material in a tokamak environment.

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[1] S.A. Allen, *et al.*, “Effects of divertor geometry and pumping on plasma performance on DIII–D,” unpublished.

[2] J.P. Smith, et al., “Metallurgical bonding development of V-4Cr-4Ti alloy for the DIII–D radiative divertor program,” unpublished.