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Design and Analysis of the DIII–D Radiative Divertor Water-Cooled Structures*

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ABSTRACT

The Radiative Divertor is a major modification to the divertor of DIII–D and is being designed and fabricated for installation in late 1996. The Radiative Divertor Program (RDP) will enhance the dissipative processes in the edge and divertor plasmas to reduce the heat flux and plasma erosion at the divertor target. This approach will have major implications for the heat removal methods used in future devices. The divertor is of slot-type configuration designed to minimize the flow of sputtered and injected impurities back to the core plasma. The new divertor will be composed of toroidally continuous, Inconel 625 water-cooled rings of sandwich construction with an internal water channel, incorporating seam welding to provide the water-to-vacuum seal as well as structural integrity. The divertor structure is designed to withstand electro-magnetic loads as a result of halo currents and induced toroidal currents. It also accommodates the thermal differences experienced during the 400°C bake used on DIII–D. A low Z plasma-facing surface is provided by mechanically attached graphite tiles. Water flow through the rings will inertially cool these tiles which will be subjected to 38 MW, 10 second pulses. Current schedules call for detailed design in 1996 with installation completed in March 1997. A full size prototype, one-quarter of one ring, is being built to validate manufacturing techniques, machining, roll-forming, and seam welding. The experience and knowledge gained through the fabrication of the prototype is discussed. The design of the electrically isolated (5 kV) vacuum-to-air water feedthroughs supplying the water-cooled rings is also discussed.

INTRODUCTION

The Radiative Divertor Program (RDP) is a major modification to the DIII–D divertor which will enhance the dissipative processes in the edge and divertor plasmas to reduce the heat flux and plasma erosion at the divertor target. The RDP incorporates a double null, slot-type divertor configuration which allows for the operation of single or double null plasma shapes. The divertor is designed to accommodate highly triangular plasmas ($\delta \geq 0.8$) to support Advanced Tokamak studies. Particle and density control is provided by four cryocondensation pumps, one existing ADP pump [1], and three new pumps [2]. The general arrangement of the top/bottom symmetric divertor is shown in Fig. 1.

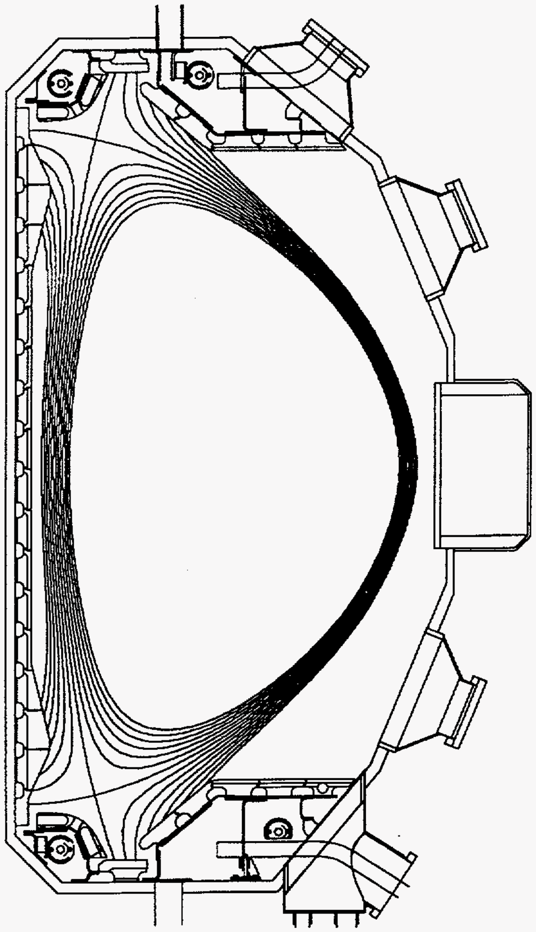

Fig. 1. General configuration of the Radiative Divertor in DIII–D.

The divertor is designed to be flexible, allowing for variations in the slot width as well as slot length. The slot width can be changed in a matter of weeks by exchanging different height graphite tiles on the divertor structure. The slot length change requires approximately two months to move the structures vertically and add additional water-cooled rings. The initial installation will have a slot length of 23 cm, with the option to lengthen the slot to 33 cm or 43 cm.

DIVERTOR STRUCTURE

A. Design

The divertor structure consists of private flux and outer baffles, each comprised of two toroidally continuous Inconel 625 water-cooled rings of sandwich construction with an

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internal water channel(s). The toroidally continuous design was chosen for its inherent strength, although large toroidal currents are induced during a disruption. The private flux baffle rings consist of 120° sectors, bolted and pinned together at the ends for alignment and reaction of loads in hoop. The outer baffle rings consist of 90° sectors also bolted and pinned at the ends. The internal water channel is created using two 4.76 mm thick sheets, each with a 1.27 mm deep by 63.5 mm wide slot milled into it. The two slots are then faced together and resistance seam welded around the perimeter to create a helium leak tight channel. In addition to the perimeter weld, the outer conical panel also has two welds between its channels, running the entire quadrant for additional structural support. Twenty-four discrete, radiatively cooled, Inconel 625 plates between the outer ring and vessel wall complete the outer baffle. These plates are designed to be removed easily to allow access to the outer cryopumps, vessel ports, or other under-baffle components and diagnostics. Fig. 2 shows the primary components of the RDP.

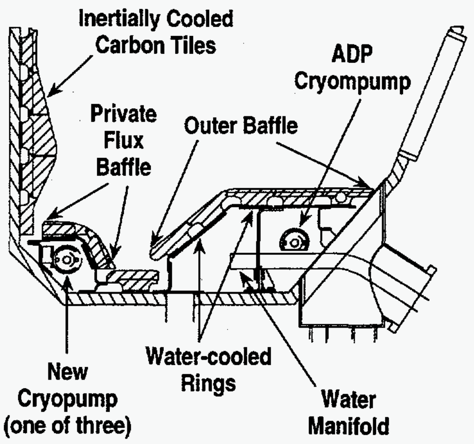


Fig. 2. Primary components of the Radiative Divertor.

Vertically stiff yet radially flexible supports made from Inconel 718 and spaced every 15 degrees toroidally transmit the loads from the rings to the vessel wall while allowing for radial thermal expansion experienced during the 400°C bake seen by the toroidally continuous rings. The bolted supports also provide a connection path for halo currents to the vessel.

To prevent the backstreaming of particles and leakage from the pumping plena, an effort is made to close conductance paths leading from beneath the baffles to the plasma chamber. To seal the gap between the two rings of the outer baffle, two 15 degree, overlapping sections of insulating material, Mica Mat®, are riveted together along with a thin strip of metal which is spot welded to the brackets connecting the two rings together. This provides periodic support and preload to the seal. Twenty-four seals are installed end to end creating a continuous closure. The same concept is also used to seal the private flux baffle. Similar seals are utilized between the 24 radiatively cooled plates.

B. Analysis

The RDP is designed to withstand loads from both halo currents flowing in the structures and induced toroidal currents, with the halo current loads being the largest. The private flux baffle is designed for electro-magnetic forces from halo currents equivalent to 20% of a 2.8 MA plasma current with a 2:1 peak-to-average toroidal peaking factor, while the outer baffle criteria is 20% of a 3.0 MA plasma current with the same peaking factor. The difference arises from the largest plasma which can fit with the private flux baffle installed; with this baffle, a 3.0 MA plasma can be run.

Finite element analyses were performed independently on the private flux and outer baffles. The global displacement, maximum deflections, and maximum stresses in the rings from non-symmetric halo current loads were determined by creating one hundred and eighty degree models and applying appropriate pressure loads to the rings and supports. The global offset was 2.5 mm in the radial direction. The maximum stresses in the private flux baffle are 138 MPa and 207 MPa in the outer baffle structure. The maximum vertical deflections observed were 0.76 mm and 1.40 mm in the private flux and outer baffles, respectively. The deflections are minimized to prevent the graphite tiles from becoming over stressed.

To more accurately determine the local stresses in the supports and in the connection between the support and the ring, finer mesh, 30 degree models were created. Information from these models allowed for a support and joint design which reduced local peak stresses by spreading them out over a larger area. Peak stresses in the support due to non-symmetric halo current loads were 462 MPa, below the 620 MPa allowable.

During bakeout, when inductive currents are driven in the vacuum vessel and in the continuous rings for resistive heating, a maximum transient temperature differential of 100°C is observed between the rings and vessel wall. This differential growth is accommodated by elastic bending of the supports. The maximum stress in any support due to this thermal differential growth was found to be 724 MPa, below the 1,240 MPa allowable.

COOLING DESIGN AND CAPACITY

The primary purpose of the Inconel rings is to provide inertial cooling for the graphite tiles which provide a low Z plasma-facing surface. To provide the necessary coolant flow, the four RDP rings on the floor or ceiling are connected in parallel to a common water manifold operating at an inlet pressure of 0.4 MPa. A concentric flow feedthrough is used to pass the water through the vessel port flange. The concentric tubes then separate into two Ø50 mm od tubes, the inlet and outlet manifolds, within the vessel port, and run side-by-side into the vessel. Each ring is fed from the Ø50 mm inlet manifold by its own smaller feed tube. The water passes through these tubes to a combination inlet/outlet box, through a section of the ring (120° for the private flux baffle rings, and 90° for the outer baffle rings), through a jumper box which connects the ring sections. The water makes one toroidal pass and exits from the ring through the inlet/outlet box, to the manifold and out of the vessel. Toroidal runs of the feed tubes within the vessel allows the tubes to bend, accommodating the thermal expansion differential between the rings and the manifolds and vacuum vessel. The inlet/outlet and jumper boxes are designed so all welding can be performed from the top side for ease of assembly. Fig. 3 shows the in-vessel routing of the water feed tubes.

A detailed analysis of the RDP cooling system has been performed and operational limits established. First, a flow analysis was performed for the entire RDP cooling loop, including feedthroughs. For given system pressure drop and average water temperature rise constraints, mass flow rates, channel velocities, and head losses were determined for each ring. Different combinations of the input power, pulse length, and repetition rate were then used to calculate the system performance. Other assumptions used were: a single null plasma configuration; 70% of the 38 MW injected power reaching the scrape off layer; 1.9 MW to the divertor strike plate; a line radiator at the x-point with 45% of the radiated power reaching the divertor structures (55% radiates to other areas); the water channels equally absorbing the radiated power. The inner conical ring is the limiting component and requires an 18 minute repetition rate for a 20°C average temperature rise. The system capabilities have been determined for a 0.16 MPa pressure drop, the present operating pressure drop for the DIII–D vacuum vessel water system. This pressure drop produces channel velocities of 2.1–2.5 m/s. The DIII–D water system has a pressure capability of 0.45 MPa, but a limit of 3 m/s water velocity in the channel is reached at a $\Delta P = 0.24$ MPa, at which the limiting repetition rate is reduced to 14 minutes for 38 MW injected power.

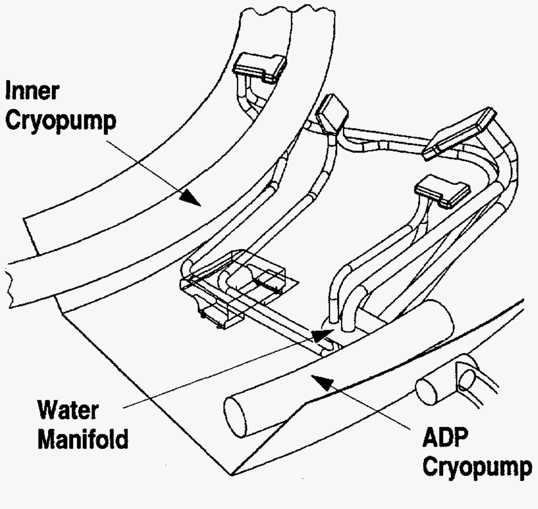


Fig. 3. In-vessel routing of RDP feed tubes (water-cooled rings not shown).

WATER FEEDTHROUGH

The electrically isolated, vacuum-to-air feedthrough for the water manifolds provided a unique challenge. The size of the inlet and outlet tubes needed to be small enough to fit through the vessel port while large enough to accommodate the system volumetric flow rates. Disassembly of the feedthrough must be accomplished without cutting welds should a leak occur. To meet these design constraints a concentric flow concept was incorporated. The feedthrough is electrically isolated from the vessel by a ceramic d.c. break and bellows combination to eliminate currents circulating through the water lines to the vacuum vessel.

The feedthrough consists of a Ø50 mm inlet tube running concentrically within a Ø64 mm outlet tube. To allow removal of a 5 kV electric d.c. break and bellows combination, the feedthrough was designed to be disassembled without cutting welds through the use of a series of Conflat® flanges, Fig. 4. The ceramic break and bellows has a Conflat® flange welded to each end. The Ø64 mm water tube coming from inside the vessel is welded to a flange with its knife edge outside the bolt circle. This prevents entrapment of the copper gasket. A flange on thefront makes two simultaneous seals, to the flange attached to the bellows and to the flange welded to the Ø64 mm tube. A final flange welded to the ex-vessel Ø64 mm water tube is bolted on the front side, making the water connection. To minimize the amount of cross leakage between the inlet and outlet flows, a small slip sleeve connects the two mating ends of the Ø50 mm inlet tube.

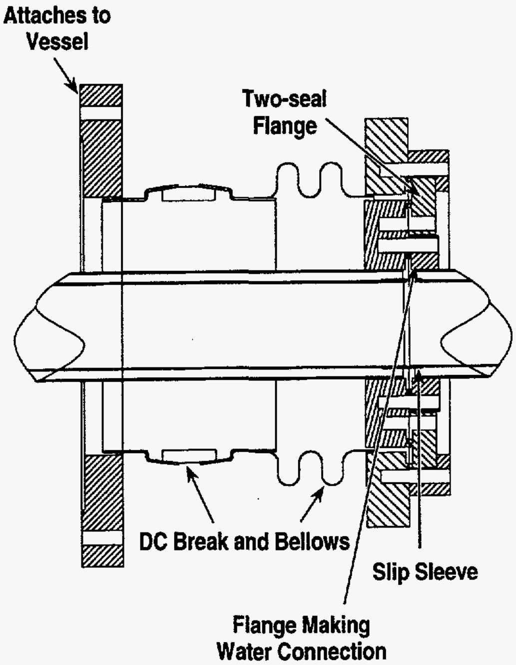
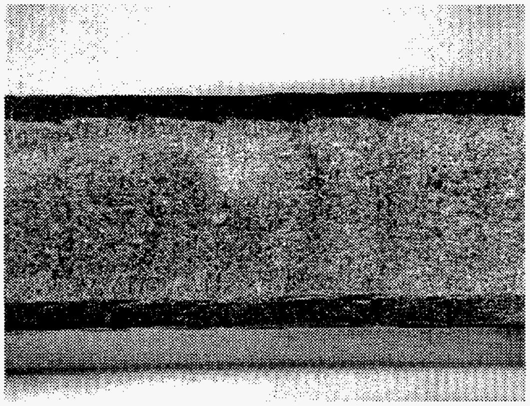


Fig. 4. Design of 5 kV electrically isolated water feedthrough.

PROTOTYPE DEVELOPMENT

The welding was the primary uncertainty in the manufacture of the RDP structural panels. Machining, whether conventional milling or chemical milling, and roll forming are both well established manufacturing methods. Resistance seam welding is also a well established manufacturing method (the DIII–D vacuum vessel corrugated water channels were created using this process), but resistance seam welded parts of this thickness is less common. In addition, the effect of all these processes together and the resulting distortion was an unknown. The first step was to verify if a resistance seam weld with a 6.35 mm nugget diameter could be obtained when joining two 4.76 mm Inconel 625 sheets. Two vendors were successful, creating welds larger than the required 6.35 mm and subsequent examination of the welds by radiographic and metallographic techniques showed them to be crack and void free. Fig. 5 shows a micrograph of a sample weld.

Transverse



Longitudinal

Fig. 5. Inconel resistance weld for water cooled panels.

Two separate prototypes were contracted for fabrication to gain valuable knowledge and experience with the combined manufacturing processes. A specification for the fabrication of the structures was written. Similar approaches to the manufacture of the parts are being used with differences in the order of manufacturing steps. A comparison of the quality of the final parts will be made upon their completion and the information used to select a contractor for the full production.

DIAGNOSTIC VIEWS

The new divertor structures block some of the existing diagnostic views. To accommodate these views, some diagnostics will be relocated, while local cutouts in the water-cooled rings have been made to accommodate others.

Views were provided for all vertical ports in the center of the floor and ceiling to allow diagnostic view access. Diagnostics such as Divertor Interferometer and Divertor Reflectometer extend vertically through these ports to view the divertor plasma. For these views, a small cutout was made in the inboard portion of the outer conical ring for both upper and lower divertors in six locations. In these locations the water channel was interrupted necessitating a jumper tube welded into the back side of the panel to restore flow passage. Conductance from beneath the baffles back to the plasma chamber through these cutouts is reduced through the use of simple concentric tubes limiting the conductance aperture but allowing for differential thermal growth between the rings and the vacuum vessel.

CONCLUSIONS

The Radiative Divertor Program provides a mechanically robust design which accommodates halo current and induced toroidal current loads and will not limit future long pulse, high energy input operations. It will validate the concept of a slot type radiative divertor and provide physics data important for the development of divertors for future devices. The prototype panels are scheduled to be completed in early October, 1995. The final design phase has begun with installation scheduled to begin in late 1996.

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