Engineering Design of a Radiative Divertor For DIII–D*

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ABSTRACT

A new divertor configuration is being developed for the DIII–D tokamak. This divertor will operate in the radiative mode. Experiments and modeling form the basis for the new design. The Radiative Divertor reduces the heat flux on the divertor plates by dispersing the power with radiation in the divertor region. In addition, the Radiative Divertor structure will allow density control in plasma shapes required for advanced tokamak operation. The divertor structure allows for operation in either double-null or single-null plasma configurations. Four independently controlled divertor cryopumps will enable pumping at either the inboard (upper and lower) or the outboard (upper and lower) divertor plates. An upgrade to the DIII–D cryogenic system is part of this project. The increased capabilities of the cryogenic system will allow delivery of liquid helium and nitrogen to the three new cryopumps.

The Radiative Divertor design is very flexible, and will allow physics studies of the effects of slot width and length. The slot width is varied by installing graphite tiles of different geometry and can be accomplished in a shut down of less than 3 weeks. The change in slot length requires moving the structure vertically and could to be done in about 6–8 weeks. Slot lengths of 23, 33, and 43 cm have been chosen.

Radiative Divertor diagnostics are being designed in parallel to provide comprehensive measurements for diagnosing the divertor. The Radiative Divertor installation is scheduled for late 1996. Engineering experience gained in the DIII–D Advanced Divertor program form a foundation for the design work on the Radiative Divertor.

INTRODUCTION

The final design is in progress on a new divertor configuration for DIII–D called the Radiative Divertor Program (RDP) [1] (Fig. 1). The program will study the reduction in peak heat flux with creation of a radiating zone in the divertor area formed by puffing neutral gas into the scrape off layer. This will be accomplished in conjunction with particle control to limit the neutral gas from entering the plasma core. Particle control will be addressed in two ways: baffle structures to limit the transport of gases from the divertor region to the core; and density control by a divertor cryopump at each of the four strike points of a double-null divertor.

The RDP is designed for either single or double-null high triangularity plasma shape with a maximum plasma current of 3.0 MA. The baseline shape was chosen based on a systematic study of plasma shape and performance. The new divertor hardware enables continuing research toward the goal of DIII–D: integrated long pulse demonstration of well confined high-beta divertor plasma with non inductive current drive. The divertor hardware will provide the pumping and baffling required for the low density target plasmas of the advanced tokamak program, in addition to continuing the divertor research program [2].

The design of the Radiative Divertor utilizes engineering and technology developed in the successful DIII–D AdvancedDivertor Program (ADP) [3]. In the ADP, a toroidally continuous gas baffle, ring electrode, and cryocondensation pump enabled the demonstration of divertor pumping and density control in H–mode plasmas. The designs for plasma facing components, water cooled support panels, electrical insulation, and cryopumps from the ADP are heavily drawn upon in the new design.

MECHANICAL DESIGN

The in-vessel RDP hardware consists of six toroidally continuous baffles and four cryopumps with the top and bottom divertor structures nearly symmetric. Two of the inner baffles consist of graphite tiles mounted off the vessel wall. The other four baffles are created by mounting inertially cooled tiles onto water cooled support panels (Fig. 2). Either the private flux or outer baffle water-cooled structures in the upper divertor will be manufactured using a vanadium alloy. Within the pumping plenums created by the support panels are four toroidally continuous cryopumps, pumping all four strike points of a double-null divertor plasma. Three of the pumps will be new in the installation. The design of the system is modular to enable simple modifications of the slot length, the distance from the X-point to the target plate. The slot width is also easily changeable by installing a new set of graphite tiles. The design has been optimized to enable a variety of plasma shapes and flexibility in the design.

STRUCTURE

The main structural element of the RDP is four toroidally continuous water cooled support panels [4]. The design was chosen for its strength and reduction of electric potentials during disruptions. Although this results in large toroidal currents in the structure during disruptions, the structural loads resulting from these currents are easily accommodated

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Fig. 1. Radiative Divertor configuration in DIII–D shown with double-null plasma, with single-null capability also existing.

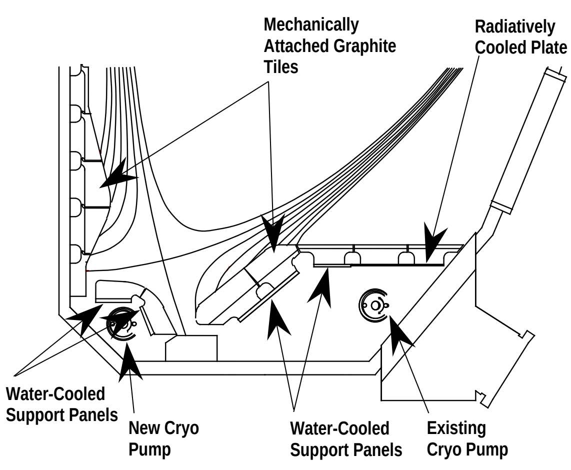

Fig. 2. Major hardware components of radiative divertor program.

in the design. The great hoop strength of the panels react the radial loads and a support system reacts the vertical loads into the vacuum vessel. In addition, modeling has shown that the toroidal currents close to the plasma during disruptions can help reduce the severity of the disruption.

The panels are connected to the existing air/water cooling system of the vacuum vessel providing water cooling during experiments and hot air during bakeout of the vacuum vessel. Inductive currents driven in the panels and vacuum vessel by the ohmic coils connected to a AC controller during machine bakeout allows the panels to reach 350°C while the vacuum vessel is at 400°C. During bakeout, the water in the panels is replaced with hot air which helps to distribute uniformily the heat in the vessel walls.

The maximum plasma that can be run with the RDP structure has a current of 2.8 MA. With the private flux baffle and pump removed and replaced with wall mounted graphite tiles, a 3 MA plasma can be run. The outer baffle and tiles are designed for 3 MA plasmas and the private flux baffle to 2.8 MA. Halo currents of 20% of the before disruption plasma current were used in design with a peaking factor of 2:1, peak to average ratio. Due to the design of the panels and supports, the local load governs the stress in the panel and thus the load with the 2:1 peaking factor locally gives loads equivalent to 40% of the predisruption plasma current. The halo currents will be monitored with a set of Rogowski loops, and if larger halo currents are measuted, a retrofit to strengthen the structure will be installed The halo current values are based on DIII–D experience of measured halo currents, and modeling of disruptions. The loads due to the halo currents are the largest seen by the structure.

The four water-cooled panels, 0.95 cm thick, are made of Inconel 625 with an internal water flow passage. The water flow is in the toroidal direction at a pressure of 0.4 MPa and is connected in parallel to a common manifold. Water velocity in the panels is less than 3 m/s with the manifold velocity <1.5 m/s. Total water flow in the system is 4 kg/s and the RDP system is capable of cooling the structure for 38 MW, 10 second single-null pulse in 14 minutes.

The continuous panels are comprised of 120 or 90 degree arcs, bolted and pinned together in the vessel. The toroidal length of a panel segment is governed by the maximum size fitting through the largest midplane port. The water connection between segments is made using a specially designed coupling that requires weld access only from the front surface to facilitate installation. The structure will be accurately aligned using special tooling plates.

The supports for the water cooled panel, made from Inconel 718, are designed to serve two functions: accommodate differential thermal growth and react disruption loads. They also serve as a current path for the halo currents from the structure to the vessel wall. The largest differential thermal growth occurs during baking when the transient temperature differences of ≤100°C are developed. Elastic bending of the supports allow the differential thermal growth; no sliding interfaces are used. The supports also react the loads resulting from halo currents flowing in the structure and provide a path for the current to flow into the vessel. Rigid bolted joints are used to prevent arcs and provide direct current paths.

Radiatively cooled plates provide the final closure for the pumping plenums between the toroidal rings and the outer vessel wall. There are 24 plates toroidally, each center supported. Diagnostic views for the lower and upper ports are provided through these plates by making holes in the edges of two neighboring plates. Eddy currents create the largest loads (1700 Nm) seen by these plates. The gaps around the edges of the plates are sealed to minimize leakage from the pumping plenums, but are electrically insulated to prevent toroidal currents from being driven in them.

TILES

The inertially cooled graphite tiles are mechanically attached to the support plates. A layer of flexible graphite (Grafoil®) is used as a compliant heat transfer interface between the tiles and support structure. The tile design utilizes the experience gained from the previous extensive engineering, analysis and testing effort [5] and in the successful operation of 1500 tiles in the divertor and first wall of DIII–D for the past 8 years. These inertially cooled tiles absorb energy during a shot and cool down to a temperature of 30°C in the 10 minutes between pulses, through the Grafoil®, to the water-cooled panels and vessel wall. Tile capability is 5 MW/m^2 for 5 s or 3.8 MW/m^2 for 10 s for ATJ graphite tiles with a 1200°C surface temperature limit. The stress allowables for graphite are not exceeded at these levels. Good edge alignment of the tiles is provided by the hold down design, clamping two adjacent tiles at their common poloidal edge with the same hardware. Edge alignment of 1 mm is achieved in the present divertor and shall be less in the RDP.

The tile thickness for the RDP ranges from 5 cm to 10 cm with lower limit set by thermal stresses in the tiles and upper limit by halo current induced stresses. The range in thickness allows for flexibility in the slot width and shape. The inner baffle is created by shaping the surface of four toroidal bands of tiles mounted to the vessel wall. The inner and outer divertor target plates are also mounted to the vessel wall. The tiles on the central and outer baffles are mounted on the water cooled support panels. Frictional force generated by the preload of the tile fasteners, reacts the poloidal component of the force resulting from halo currents. However, the force is proportional to the height of the tile and a shear key has been designed to react the loads for some of the taller tiles. The shear key is coupled back to the welded studs to react these larger loads.

CRYOCONDENSATION PUMPS

For the first time in a tokamak, the divertor pumping design will allow the study of inner versus outer strike point pumping. Four independently controlled cryocondensation pumps provide a pumping speed greater than 100,000 l/s to provide density control and low density target plasmas for rf injection. The existing pump remains in the same location and provides pumping for the outer lower strike point. Pumping at the other three strike points of a double-null discharge is provided by three new pumps of a design similar to that of the present pump [6].

The cryopump is toroidally continuous to minimize the potential for electrical breakdown in low density plasma and to utilize the hoop strength of the continuous ring. The pump surface is a 2.5 cm diameter tube cooled by liquid helium at 4.0 K. This helium tube is grounded only at the feedthrough and is electrically isolated from the surrounding nitrogen shields. A liquid nitrogen shield forms the main structural element of the pump, consisting of an 8 cm diameter tube with pumping apertures cut into one side. A radiation/particle shell surrounds the nitrogen shell to prevent the desorption of gases condensed on the nitrogen cooled surface. Description of the pump design, thermal analysis and testing results can be found in [7].

The compact area under the private flux baffle for the inner strike point pumps required some changes to the existing pump design for the supports and feedthroughs. A new support design to mount the pump to the vessel wall, limits the vertical movement of the pump while flexing radially for pump contraction (0.25 cm) during pump cool down. The support design change was necessary for the inner pumpts to simplify feedthrough design. The feed enters through a vertical port and the thermal contraction of the pump is accommodated by bending in the vertical section of the feeds. The feed design consists of concentric helium flow tubes surrounded by a liquid nitrogen cooled shell. The feed through design electrically isolates the feeds from the vacuum vessel to limit current flow in the lines.

The new feed design raised some concern about flow stability of two phase flow in a vertical column. A flow test was performed to verify the flow stability and pump performance with the vertical column. No detectable loss of performance was found in the testing.

New ex-vessel hardware is required to provide the additional cryogens to the pumps. Two new cryotstats will be installed in the machine hall containing heat exchangers to provide the subcooling for the liquid helium. The cryostats will be connected to the cryoplant with coaxial flexible transfer lines. The cryoplant is isolated from the machine by 30 kV dc breaks in the fluid lines. Because the cryopumps are regenerated between every discharge, a gas bag system will be installed to absorb and level out, the large transient gas load created. An upgrade to the distribution box for the cryoplant is also being designed and built to accommodate the extra pumps serviced by the system.

FLEXIBILITY

The RDP provides a comprehensive divertor research facility designed to be easily modified to study slot width, slot length, and divertor gas bag operation. The initial installation is a design with a 23 cm slot length (Fig. 3). Two other slot lengths (33 and 43 cm) and gas bag modifications are easily made with the addition of minimal hardware. Biasing of the SOL is accomplished with an add-on system.

Fig. 3. Flexibility of the Radiative Divertor Structure allows a change in slot length reutilizing many of the hardware components.

If the SOL characteristics change significantly with radiative divertor operation, the profile of the slot and its width is modified by changing a set of graphite baffle tiles. The initial shape of the surface is determined by DEGAS modeling [8], to limit the recycling of particles on the top of the baffle and to limit the particle flow back to the core. Should experimental results lead to the conclusion that a different shaped baffle surface would improve plasma performance, a new set of tiles can be quickly designed and installed. The installation of the tiles should take only one week. The rapid clean-up capability of DIII–D enables a return to plasma operations in just 1–2 weeks after installing the tiles for a total shut down time of ~3 weeks.

The effect of slot length on performance of a radiating divertor can also be studied. The length is changed by raising the structure vertically and adding new supports and water cooled rings. A 33 cm slot is formed by raising the private flux and outer baffle. A simple addition ring is added for the outer baffle. New tiles are required for all baffle surfaces except the inner which is raised one poloidal position. Two additional water-cooled rings are added to the 33 cm design to modify the structure for a 43 cm slot. The inner baffle tiles remain in the same position and again all new tiles are required elsewhere. A “gas bag” configuration can be created by removing water-cooled rings from the 43 cm design and adding additional supports. The cooled panels from the initial installation are used in all configurations. The slot length change requires a slightly longer shut down than slot width and is estimated to be 6–8 weeks.

VANADIUM ALLOY

As a part of the RDP, one of the upper divertor water cooled baffles will be manufactured from V-4Cr-4Ti vanadium alloys [9]. The purpose of using vanadium alloys is two fold: 1) begin the process of gaining materials processing “know-how” on the fabrication of full-scale vanadium alloy components and 2) demonstration of the in-service behavior in a tokamak of a vanadium alloy. Vanadium alloys are considered a leading candidate low-activation material for fusion power plants because of their low-induced radioactivity and rapid decay. Compatibility of vanadium alloys with the tokamak environment, particularly impurity pick-up and embrittlement, is a concern. The exposure of the vanadium alloy components will answer many of these compatibility questions.

In the area of design and manufacturing of components from vanadium alloys, little has been done particularly in the area of product form conversion and joining. The Radiative Divertor work is designed to develop preliminary engineering design data and manufacturing experience for vanadium alloys as a necessary first step towards the material qualification for reactor use.

The private flux or outer baffle water cooled panels will be chosen as the portion of the structure manufactured from vanadium alloys depending upon stress analysis being performed. The design of the vanadium panels will be nearly the same as the Inconel versions and is in progress. Production of approximately 800 kg of vanadium alloy, the largest single ingot of vanadium alloy produced, is in progress by Teledyne Wah Chang Albany. This ingot will be converted into sheet and plate to manufacture the components. Manufacturing R&D is being performed on resistance, inertial, electron beam, and stud welding to support this portion of the program together with other manufacturing processes and thermal treatments. The vanadium program within the

Materials Program of DOE Office of Fusion Energy is participating in the program by providing material for tests and R&D on base material properties and environmental effects.

As part of the program, samples and specimens have been and are being exposed in DIII–D to study the environmental effects of the tokamak. A set of long term (6–9 months) samples, both tensile and Charpy specimens, were placed in the divertor pumping plenum in February of 1995 with plans to remove them in late 1995. The environment for these samples is being monitored for temperature, pressure, and impurities. DiMES, Divertor material exposure sample system, has been and continues to be used for short term exposure of vanadium samples and specimens.

SUMMARY AND CONCLUSION

The Radiative Divertor Program creates a flexible divertor research facility for DIII–D that enables the continuing of the DIII–D program objectives, divertor and advanced tokamak research. The project is in the final design phase withmany hardware procurements in progress. Divertor baffles to assist in confining neutral gas in the divertor region along with active pumping at all four strikepoints are included in the design. A vanadium alloy will be used for fabrication of a portion of the upper divertor structure. Installation of the first phase is scheduled for completion in December of 1996

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