STRUCTURAL DESIGN OF THE DIII–D RADIATIVE DIVERTOR

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GA–A22445

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GA PROJECT 3990
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Structural Design of the DIII–D Radiative Divertor*

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The divertor of the DIII–D tokamak is being modified to operate as a slot type, disipative divertor. This modification, called the Radiative Divertor Program (RDP) is being carried out in two phases. The design and analysis is complete and hardware is being fabricated for the first phase. This first phase consists of an upper divertor baffle and cryopump to provide some density control for high triangularity, single or double null discharges. Installation of the first phase is scheduled to start in October, 1996. The second phase provides pumping at all four divertor strike points of double null high triangularity discharges and baffling of the neutral particles from transport back to the core plasma. Studies of the effects of varying the slot length and width of the divertor can be easily accomplished with the design of RDP hardware.

Static and dynamic analyses of the baffle structures, new cryopumps, and feedlines were performed during the preliminary and final design phases. Disruption loads and differential thermal displacements must be accommodated in the design of these components. With the full RDP hardware installed, the plasma current in DIII–D will be a maximum of 3.0 MA. Plasma disruptions induce toroidal currents in the cryopump, producing complex dynamic loads. Simultaneously, the vacuum vessel vibrations impose a sinusoidal base excitation to the supports for the cryopump. Static and dynamic analyses of the cryopump demonstrate that the stresses due to disruption and thermal loadings satisfy the stress and deflection criteria.

1. INTRODUCTION

The Advanced Divertor Program (ADP) for the DIII–D tokamak was initiated in 1989 to study enhancement of plasma performance that can be achieved by controlling plasma density and the recycling of impurities to the plasma by divertor pumping and biasing. The program has been extrememely successful. The knowledge gained in the ADP is presently being applied to a divertor modification, the Radiative Divertor Project (RDP), which will provide particle pumping and density control in high triangularity, single or double null tokamak discharges. The RDP also will allow the study of dissipating divertor power by radiation, distributing the power over a larger area while pumping away the neutral particles. Dissipative divertor research is being conducted now in the existing open ADP divertor but gas puffed in the divertor region to enhance radiation sometimes ends up in the plasma core, degrading the quality of confinement. The RDP is designed to limit this core fueling by providing tighter baffles in the divertor region, and the neutral gas is better entrained in the divertor slots.

The RDP hardware consists of inner, private flux, and outer baffle plates in both the top and bottom of the machine (Fig. 1). Three new cryopumps are to be installed to complement the existing ADP pump. The lower baffles and cryopumps are shown in Fig. 1 and are nearly symmetrical about the mid-plane of the tokamak. Experiments and modeling have formed the basis for the new design. Modeling codes, benchmarked with experiments, have helped define the shape of the baffles to entrain the gas in the divertor. The core ionization is anticipated to be reduced by a factor of nine with the addition of the baffle structures. The four divertor pumps installed under the outer and private flux baffles, provide 100 m^3/s of pumping speed to a double null high triangularity discharge, removing neutral gas and particle impurities from the scrape off plasma. The four cryopumps will provide the capability to study inner versus outer strike point pumping for double null plasmas.

Installation of the RDP hardware has been separated into two phases as schematically shown in Fig. 2. The first phase will be completed in December of 1996 and the second phase installation in 1998. The design and analysis for the RDP has
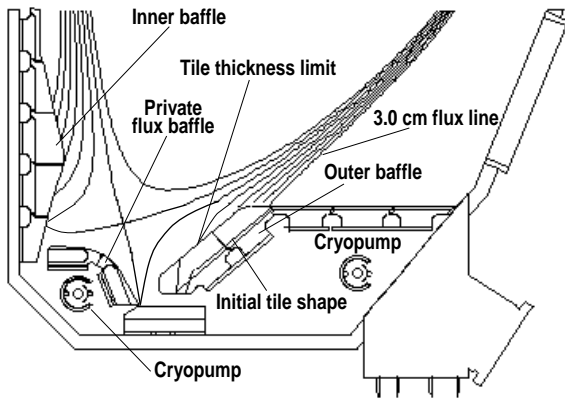
Fig. 1. Cross section of lower RDP structure. Limits of the tile thickness are shown with flux lines.

Phase One–Upper Pump
Open Lower Divertor

Full RDP Installation

Fig. 2. The Radiative Divertor installation in DIII–D (a) Phase 1 with upper outer baffle and cryopump. (b) The full RDP installation with active pumping and baffling at all four strike points.

been completed and hardware is being fabricated for the first phase.

Flexibility is a key feature of the RDP design. The ability to modify the structure easily as the understanding of the physics evolves has been accounted for in the design. Studies on the effects of varying the slot length and width of the divertor can be easily accomplished with the design of RDP hardware. The slot width is changed by installing a new set of graphite tiles of different size while the slot length can be changed by raising the structural panels and installing longer supports and additional tiles. Slot lengths of 23, 33, and 43 cm have been selected for these studies.

The cryopumps are also toroidally continuous to prevent electrical breakdown in the low density plasma underneath the baffle plates. The design, analysis, and operation of the existing cryopump and its support systems are presented in Refs. [1–2]. The baffles on the inner wall are thick tiles fabricated from graphite mounted to the inner wall of the vacuum vessel.

2. DESIGN DESCRIPTION

The baffles consist of inertially cooled graphite tiles mounted to water cooled support panels. The graphite tiles are of the same design developed for
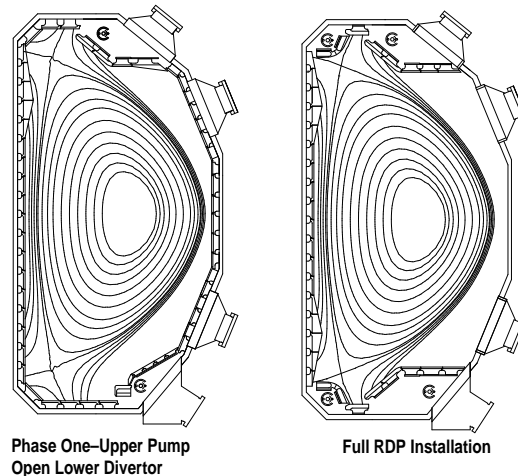
the existing divertor targets that have operated successfully since 1987 [3]. The water cooled panels are torroidally continuous, the design chosen for its hoop strength and reduction of electric potentials during disruptions. The water-cooled baffle rings are attached to the vessel with a set of supports spaced every 15 degrees. Inconel 625 material was selected for the baffle plates, with Inconel 718 alloy required for the supports. More detail on the design can be found in Ref. [4].

The new cryopumps are of the same basic design as the existing pump, a toroidally continuous liquid helium cooled pumping surface surrounded by a liquid nitrogen cooled shield. The small area under the private flux baffle, however, required a more compact support design to limit the vertical deflections and stresses due to disruption loads and provide radial flexibility for thermal contraction of the pump. The cryopump design with its supports and feedlines is shown in Fig. 3. The coolant feed lines utilize a vertical port and require special supports to react dynamic loads on the 2 m long vertical run of concentric tubing.

Upgrades to the cryosystem hardware are required to supply cryogens to the new cryopumps. Two new cryostats will be installed to sub-cool the liquid helium prior to entrance into the pump. A new distribution box at the DIII–D cryoplant will be installed to service the additional coaxial flexible
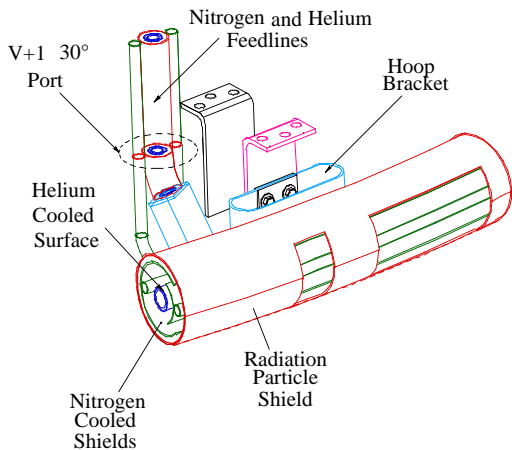
Fig. 3. Cryopump design, with supports and feedlines.

transfer lines. When the full system is installed, additional compressor capacity will be required.

3. STRUCTURAL ANALYSIS

Static and dynamic analyses of the baffle structures, new cryopumps, and feedlines were performed during the preliminary and final design phases. Disruption loads and differential thermal displacements were accommodated in the design of these components. With the full RDP hardware installed, the maximum plasma current in DIII–D is 3.0 MA with disruption induced loads scaled to this plasma current. The maximum differential thermal displacement of the vessel and RDP structural components occurs during baking of the machine to 400°C. While all the components reach nearly the same final temperature, the heating and cooling rates of the elements are different and a temperature difference of 100°C is developed. The differential thermal growth is accomodated by elastic bending of the supports. The cryopump sees a maximum temperature difference while the pump is cooled to liquid nitrogen and helium temperatures, with smaller differences during baking.

The structural design of the baffle plates is governed by the forces induced by halo currents which have been measured on DIII–D [5]. Toroidal currents also flow in the toroidally continuous structural plates due to disruptions, but are significantly

smaller than and tend to counteract the halo current forces. The asymmetric halo current induced loads on the divertor structure are based on a 2:1 peak to average factor of a total halo current equal to 20 percent of the 3.0 MA plasma current [6]. The finite element stress analysis of these components therefore required modeling a 180 degree segment of the structure to evaluate the stresses and deflections. Of particular concern was the global offset of the structure and the resultant support stresses caused by the asymmetric loads. The maximum offset of the structure in the radial direction was 0.58 mm and was in the location of the maximum load. The global offset of the model was small, 0.06 mm, measured by the toroidal displacement 90 degrees away from the peak load.

Detailed stress analysis of the baffle plates was performed using a structural model of a 15 degree sector of the water cooled panels and supports. The model of the panels included plate elements simulating the individul sheets of the panels and the structural welds holding the panels together. The peak halo current induced loading was applied in the analysis and the local stresses in the welds and sheets were determined along with the local deflections of the panels. A stiffening ring was added to the structure to limit the vertical deflections of the outermost water cooled ring.

In evaluating the dynamic effects of the loads on the water cooled panels, recent experimental results on DIII–D were considered. The new measurements have shown that the halo current asymmetries remain at a toroidal location for less than 2 ms, while axisymmetric halo currents have a rise-decay time over 15 ms [6]. Since the fundamental frequency of the baffle structure is 104 Hz, a dynamic load factor based on spectra-response curves ranges from 0.6 to 1.0 for the asymmetric and symmetric load cases respectively. Static stress analyses of the baffle structures were performed conservatively using a dynamic load factor of 1.0 for peak loads in all load cases. The stresses and deflections of the baffle structures and their supports are less than the allowable values.

Plasma disruptions also induce toroidal currents in the cryopump, producing complex dynamic loads. Simultaneously, the vacuum vessel vibrations impose a sinusoidal base excitation to the supports for the cryopump.

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Dynamic stress analyses of the inner and outer cryopumps and feedlines were performed with beam and spring-mass models using the COSMOS code [7]. The frequency analysis of the spring-mass model showed the helium line and supports have a frequency of 66 Hz and the fundamental frequency of the nitrogen system is 210 Hz. The beam and spring model was used to evaluate the dynamic stresses in the various components of the pump and feedlines due to the disruption currents driven in the pump.

In addition, the vacuum vessel oscillates vertically at 21 Hz due to a vertical disruption event. Although the maximum amplitude of the motion at the center of the floor of the vessel is at most 2.3 mm for a 3.0 MA disruption, the effect of this motion on the cryopump system needed to be determined. The maximum differential displacement calculated between the helium line and nitrogen shield is 7 mm at a support. The helium spring support can displace only about 2.5 mm before bottoming-out. Therefore, there will be some impact forces developed which will change the response of the system. To investigate the structural effects of the support springs impacting during maximum disruption conditions, a spring-mass-gap model was utilized. The results from this analysis showed that a maximum impact force of 818 N acting over 2 ms would occur at a worst case support location. Since there was concern that this impulse may cause cracking of the insulating ceramic ring interfacing with the helium line, an impact test was performed using prototypes. The theoretical impulse was duplicated closely using a calibrated hammer striking the center of the helium support which was held in place by a segment of the helium line. Inspection of the ceramic rings after several strikes showed no damage to the ceramic rings had occurred and the design verified.

4. CONCLUSIONS

Fabrication of hardware for Phase I of the RDP is nearing completion and installation will be completed by the end of 1996. Both the Phase I and II hardware will provide enhanced density control of the plasma. The new baffle structures will control the flow of neutral gas in the divertor region, thereby increasing the power radiated in the divertor slots. Studies of the effects of varying the slot length and width can easily be accomplished with the design of the RDP hardware.

The RDP structure was evaluated using both static and dynamic analyses. Halo current induced loads were critical for the baffle structure, while loads from toroidally induced currents coupled with vessel motion were most significant for the cryopump.

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