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# Pumping Characteristics of the DIII–D Cryopumps*

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## *Abstract*

Beginning in 1992, the first of the DIII–D divertor baffles and cryocondensation pumps was installed. This open divertor configuration, located on the outermost floor of the DIII–D vessel, includes a cryopump with a predicted pumping speed of 50,000 ℓ/s excluding obstructions such as support hardware. Taking the pump structural and support characteristics into consideration, the corrected pumping speed for $D_2$ is 30,000 ℓ/s [1]. In 1996, the second divertor baffle and cryopump were installed. This closed divertor structure, located on the outermost ceiling of the DIII–D vessel, has a cryopump with a predicted pumping speed of 32,000 ℓ/s. In the fall of 1999, the third divertor baffle and cryopump will be installed. This divertor structure will be located on the 45° angled corner on the innermost ceiling of the DIII–D vessel, known as the private flux region of the plasma configuration. With hardware supports factored into the pumping speed calculation, the private flux cryopump is expected to have a pumping speed of 15,000 ℓ/s.

There was question regarding the effectiveness of the private flux cryopump due to the close proximity of the private flux baffle. This led to a conductance calculation study of the impact of rotating the cryopump aperture by 180° to allow for greater particle and gas exhaust into the cryopump's helium panel. This study concluded that the cost and schedule impact of changing the private flux cryopump orientation and design did not warrant the possible 20% (3,000 ℓ/s) increase in pumping ability gained by rotating the cryopump aperture 180°.

The comparison of pumping speed of the first two cryocondensation pumps with the measured results will be presented as well as the calculation of the pumping speed for the private flux cryopump now being installed.

## I. INTRODUCTION

During the past 10 years, the DIII–D tokamak has had three major in-vessel divertor hardware upgrades, the last of which is currently being installed. Throughout these years, divertor physicists have studied the experimental data gathered from edge and scrape off layer plasmas that have been biased, baffled, cryopumped, and radiatively dispursed near the outer strike point locations. The data is analyzed to evaluate divertor geometry and cryopump performance. This paper summarizes the DIII–D divertor installation history and briefly describes the characteristics of the divertor performance provided by the cryopumps, all from an engineering perspective.

## II. DIII–D DIVERTOR HISTORY

A divertor system was installed in DIII–D between 1989 and 1992 under the Advanced Divertor Program (ADP) [2]. During the first phase of the ADP installation, a torodially continuous gas baffle structure was located on the lower outer floor (Fig. 1). A torodially continuous, biasable electrode ring was also installed at that time. In the second phase of the ADP program, a torodially continuous cryopump was installed under the gas baffle structure.

The next major in-vessel DIII–D divertor upgrade was the Radiative Divertor Program (RDP). Beginning in 1992, this program's original goal was to install three additional DIII–D divertor structures, two on the inner most wall of the

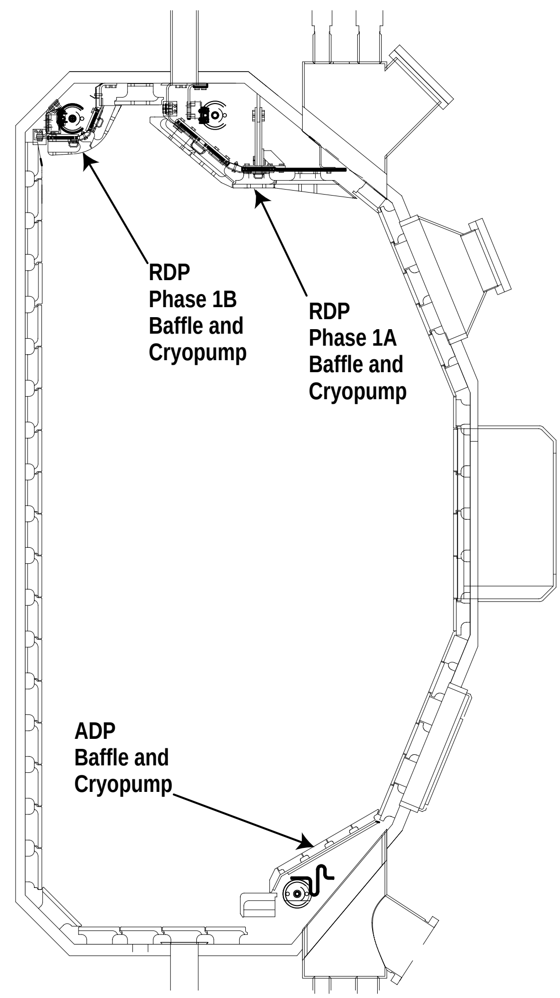


Fig. 1. DIII-D vessel cross section with the Advanced Divertor and the Radiative Divertors.

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vessel in the private flux region of the plasma, the third on the outboard ceiling. Also, the ADP baffle structure was to be replaced with a more closed divertor configuration. This upgrade was slated for completion in early 1997. These four divertors would have transformed DIII–D into a tokamak with more tightly baffled, or closed, divertors both on the floor and ceiling of the vessel, allowing for experiments utilizing double null, high-triangularity advanced tokamak plasma shapes [3]. Also included in the original RDP program was the development of Vanadium alloy (V-4Cr-4Ti), a promising low-activation material, to be used in the upper private flux region baffle structure. In later experimental years, the divertor slot lengths were to be modified from the original installation slot length of 23 cm to 43 cm, then to 33 cm. Many papers in the fusion physics, engineering, and materials development communities have been published describing this divertor configuration [7,11–13].

In 1995, there was a programatic shift in the RDP not to install all of the baffles simultaneously. It was stated that this new, more-closed divertor will not allow the large range of plasma shapes studied in the present (circa 1994) DIII–D in-vessel configuration [3]. The RDP installation was redefined into the Phase 1A, Phase 1B, and Phase 2 RDP installations. Phase 1A RDP installation (upper outer cryopump and closed baffle) was installed in 1996. The Phase 1B RDP installation will be completed by end-of-year 1999. As part of the Phase 1B RDP planning, the upper private flux region baffle would be made of Vanadium alloy. However, the fabrication development for the alloy required further investigation. Therefore, the upper private flux region baffle structure is made of Inconel 625, just as the other baffle structures. Phase 2, which included the installation of the floor private flux plasma region baffle as well as the installation of the various slot length baffles in future years, has been delayed indefinitely.

## III. DIVERTOR DESIGN SUMMARY

The ADP baffle is a radiatively cooled structure located on the lower outer corner of the DIII–D vacuum chamber [4]. There are 24 individual plate assemblies installed side-by-side to form a ring (Fig. 2). Between the pumping aperture of the baffle and the baffle main chamber is a toroidally continuous biasable electrode ring [5]. The baffle structure and the electrode ring were used for one year of operation before a toroidally continuous cryopump was installed [6]. Previous to the installation of this first-of-a-kind liquid helium cryopump, various design studies were conducted, including heat and particle loading calculations, thermal and structural analyses, cryogenic system design, full-scale hardware mock-up and cryogenic testing, and voltage transient analysis.

The RDP baffle structures are different from their ADP predecessor in that they are water-cooled (Fig. 3). Installed in the outboard ceiling corner of the DIII–D vessel, the Phase 1A RDP structure consists of two water-cooled rings, each

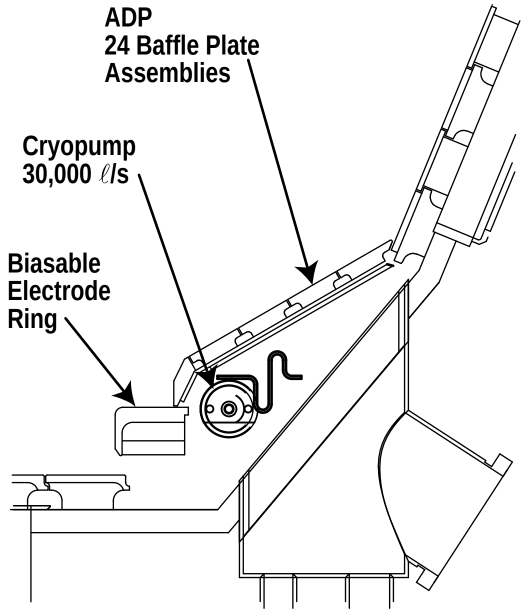


Fig. 2. DIII-D Advanced Divertor Program cross section.

having four 90° baffle sections. The four sections were carried into the DIII–D vessel, welded in the vessel to form continuous rings and installed [7]. There are radiatiavely cooled plates outboard of the water cooled baffle rings. The plates are 15° segments that were bolted into place after the water cooled rings were installed. This baffle also houses a torodially continuous cryopump that was installed at the same time as the baffle structure.

During the RDP Phase 1B installation, two sets of three 120° private flux plasma region baffle sections were carried into the vessel and welded into rings [8]. Unlike the outboard RDP structure, the private flux region baffle consist only of water-cooled baffle structures (Fig. 4). Thus, the structure has

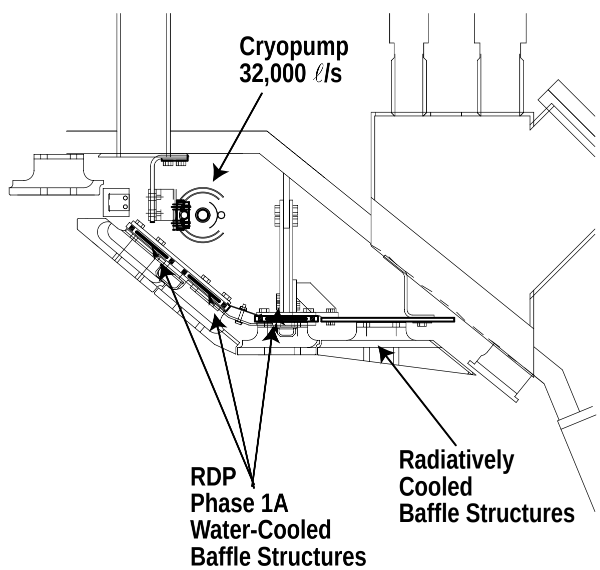


Fig. 3. DIII-D Radiative Divertor Program Phase 1A installation cross section.

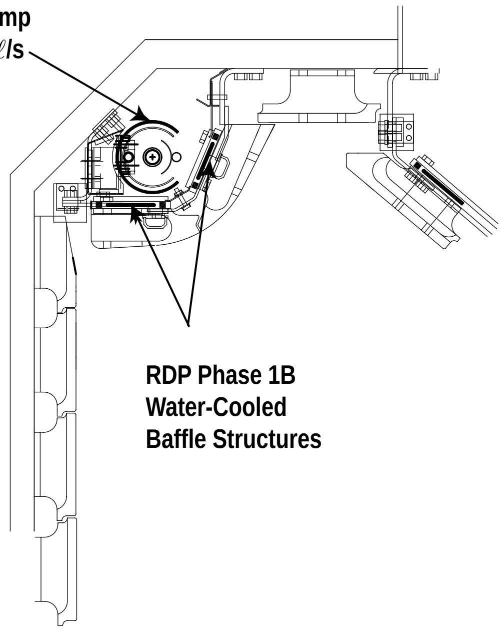


Fig. 4. DIII-D Radiative Divertor Program Phase 1B installation cross section.

much less under the baffle volume for gas storage during experiments. This baffle structure also had a cryopump installed at the same time it was installed.

All of the DIII–D divertor hardware was designed for easy in-vessel installation. For example, the Phase 1A fabrication of many cryopump components began 13 months prior to cryopump in-vessel installation, with material procurement beginning four months prior to any fabrication. Once the in-vessel portion of the installation began, it took only 12 days to complete. As stated in [9], most present day tokamaks require hands on maintenance for PFC installation or replacement. This is certainly true of the DIII–D divertor hardware. So, while there was an effort to make the in-vessel installation quick and easily performed, there was no attempt to design components that could someday be tested for remote maintenance capability.

## IV. DIVERTOR PERFORMANCE SUMMARY

The ADP divertor installation allowed for experimentation in the divertor electrical bias mode or the divertor baffle mode [4]. When biasing, an external 1 kV power supply provided up to 20 kA of current into the plasma scrape off layer. Biasing experiments studied particle transport, stability limits, and current drive.

After the ADP outboard floor installation, experiments proved that gas puffing with deuterium and neon at the plasma strike point reduces the peak heat flux to the target plate by radiating the energy over a larger area [3]. Thus, the RDP divertor and cryopump structures were designed for installation to provide greater baffling capability during gas puffing as well as to provide low density target plasmas for electron cyclotron heating. In order to perform gas puffing experimentation, capillary tubes were installed in-vessel to inject, or puff, deuterium and various other gases into the divertor strike point regions to perform puff and pump experiments.

All of the divertors were structurally designed to withstand induced loads from halo currents generated from a 3.0 MA plasma. The halo currents were estimated to be 20% of the plasma with a 2:1 peaking factor applied [10]. The divertors were also designed to accommodate the differential thermal expansion between the DIII–D vessel and the divertors during vessel baking. To date, the divertors have performed as designed, surviving all disruption events and baking cycles.

The cryopump was designed for a power load of the following: steady-state heat load (~10 W), neutrals particle loading (~35 W), and inductive heating (~30 W average) for a total duration of 13 s, including E-coil ramp, breakdown, plasma current ramp, and a 9.27 s current flat top [11]. The cryopumps are different sizes and have different pumping speeds (Table 1). The pumping speeds are dependent upon the baffle pressure. The greater the gas pressure is under the baffle, the greater the pumping speed (until the cryopump helium surface becomes saturated). The pumping rate of each cryopump is varied by moving the outer separatrix toward or away from the cryopump entrance [3].

There was a possibility that the pumping speed of the inboard ceiling cryopump could be limited during operation due to the restrictive conductance path of the private flux baffle and its support hardware. A conductance sensitivity study was done to evaluate the effectiveness of the cryopump to determine if the cryopump pumping aperture should be rotated 180° towards the baffle opening. Simplified series and parallel conductance paths were added for an overall conductance value (Fig. 5). The difference in the simplified calculations is the inclusion of the parallel conductance paths of $C_3$ and $C_4$. The results showed that the conductance could be increased by 20% (from 15,000 ℓ/s to 18,000 ℓ/s). This calculation was initiated by the divertor physics group and was done shortly after the final engineering design review for the private flux region cryopump was completed. By this time in Phase 1B of the RDP, hardware fabrication had begun with a completed design. The cost and schedule impact to change the cryopump orientation by 180° outweighed the calculated 20% increase in pumping capability.

Table 1. Cryopump sizes and pumping speeds

| Cryopump Location | Radius m (in) | Calculated Pumping Speed**(a)** ℓ/s |
|---|---|---|
| ADP (outboard floor) | 1.86 m (73.2 in) | 30,000 |
| RDP Phase 1A (outboard ceiling) | 1.59 m (62.5 in) | 32,000 |
| RDP Phase 1B (inboard ceiling) | 1.12 m (43.91 in) | 15,000 |

**(a)**2 mTorr baffle pressure

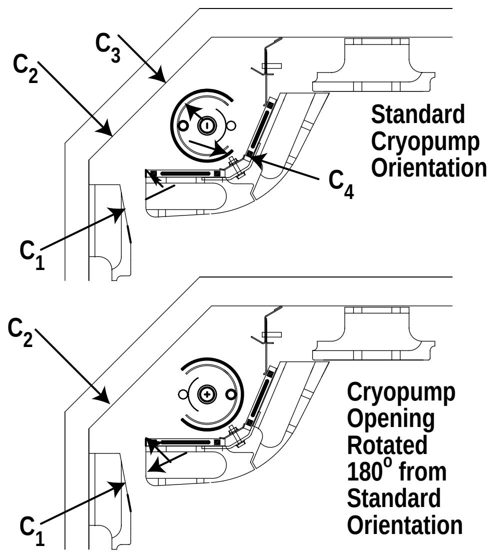


Fig. 5. DIII-D Phase 1B private flux region cryopump conductances for different cryopump orientations.

## V. CONCLUSION

DIII–D divertor development, including the installation of divertor hardware, has been a dynamic program for the past ten years, both from engineering and physics perspectives. The various divertor geometries have provided much flexibility to the divertor physicists for experiments including divertor plasma biasing, baffling, cryopumping, and radiative dispursion. Overall, the divertor structures have allowed for greater plasma density control and helium exhaust. The divertor baffle structures and cryopumps have proven their successful design with years of operations. Most recently, calculations for the cryopump have shown that some of the divertor hardware orientations may be optimized in a future installation for maximum performance. Or, as stated in [9], the future of divertor hardware could include radical new ideas such as liquid metal divertors.

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