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ScienceDirect
Fusion Engineering and Design 82 (2007) 1756–1761
Fusion Engineering and Design
www.elsevier.com/locate/fusengdes

Design, fabrication and installation of the lower divertor for DIII-D

P.M. Anderson [a,*], Q. Hu [b], C.J. Murphy [a], E.E. Reis [a], Y. Song [b], D. Yao [b]

[a] *General Atomics, P.O. Box 85608, San Diego, CA 92186-5608, USA*
[b] *Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) Hefei, Anhui Province, PR China*

Received 27 July 2006; received in revised form 1 February 2007; accepted 5 February 2007
Available online 4 May 2007

Abstract

The geometry of the DIII-D tokamak lower divertor was recently modified to improve tokamak plasma density control during operation in a high triangularity double-null configuration. The primary component of the lower divertor is a toroidally continuous flat cooling plate that was fabricated by the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). Three rows of graphite tiles are mechanically attached to the plate to shield it from plasma impingement. The plate is water-cooled for heat removal between shots and is heated to 350 °C with hot air and inductive current during vessel baking. The divertor plate is supported 100 mm from the vacuum vessel floor to allow for cryo-pumping. The vacuum tight 90° plate sectors were positioned and welded together inside the vessel forming a toroidally continuous ring. Plasma facing tile designs have evolved from previous installations. To limit erosion caused by plasma impingement on sharp edges, the through tile-face bolt holes were eliminated from graphite in areas of high heat flux. Upgraded floor tiles were installed to improve the target for the plasma strike point for outer leg pumping. Thermal analysis was done for the Union Carbide ATJ grade graphite divertor shelf and vessel floor tiles and results are presented.

Keywords: Divertor geometry; Thermal analysis; DIII-D; Divertor plate; Plasma facing

1. Introduction

The new lower divertor of the DIII-D tokamak was designed for improved density control of a balanced double-null high triangularity tokamak plasma configuration. The new divertor replaced the smaller advanced divertor (AD) installed in 1990. Installation of the new lower divertor was completed in March 2006. In addition to the graphite tiles covering the new divertor shelf, tiles for the vessel floor and lower three rows of the center-post were redesigned for improved performance.

* Corresponding author. Tel.: +1 858 455 4748; fax: +1 858 455 4190.
E-mail address: anderson@fusion.gat.com (P.M. Anderson).

0920-3796/$ – see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.fusengdes.2007.02.008

The physics specified requirements included a maximum heat flux of 13.2 MW/m^2 peak for 10 s shots followed by 600 s cool-down. Reduced tile gaps of 0.6 mm and tile edge height alignment of 0.1 mm were also specified. Tiles designated for high heat flux areas were not allowed to have bolt access holes. A maximum panel heat load of 54 MJ (27 MJ to any one tile row) per shot was specified. The divertor panels were designed for a halo current of 30% plasma current with 2:1 toroidal asymmetry. The physics requirements were based upon projected future operations.

Using the physics requirements as a foundation, complementary engineering requirements were developed. The engineering requirements specified a minimum water flow rate of 0.07 l/s (1.2 GPM) through each of six water channels to achieve desired cooling between shots. [Measured water flow through each channel was ≈0.35 l/s (6 GPM).] Panel flatness was also specified to achieve the tight tile edge-to-edge alignment.

The previous lower advanced divertor or AD ring was built in 1990 and was successfully used until 2005. Between 1998 and 2000, two additional divertors [inner and outer upper radiative divertors (RD)] were installed in DIII-D. These divertors have many similarities but also have differences as shown in Table 1.

2. Cooling panel design

Initially, two prototype panels were designed and built to test and refine manufacturing methods. These prototype panels tested welded joints, flatness control and tile fastening methods. Lesson learned from these panels were instrumental in the successful fabrication of the four production divertor panels. The new divertor ring is comprised of four 90° sectors or panels. Two sectors constitute one 180° cooling circuit. Ninety degree sectors were determined to be the largest able to fit into the vessel through available openings. Each cooling panel sector consists of two stainless steel plates with water passages milled 1.3 mm deep on one side of each plate and then spot-welded together with the water passages facing each other. The 316 stainless steel was chosen over other available grades of stainless steel due to low magnetic permeability after welding and machining.

Through all machining and welding, plate and panel flatness were tightly controlled (Fig. 1), as a flat final product was necessary (within 2 mm over entire panel) for tile alignment. Through plate holes for bolting of tiles were required every 5° [Fig. 1(b)], and these allowed additional clamping during plate and panel machining, enabling greater flatness control. (Produc-

Table 1
General Atomics DIII-D divertor history

	Thickness (mm)	Water channel	Construction	Panel/seal weld	Vacuum surface	Cooling path/section length	Fabrication issues
Inconel 625, flat ring AD outer floor (1990)	19	Machined and welded one side	Machined with welded cover plate	TIG/TIG	Machined	180°/90°	Conical distortion due to single side machining and welding. Weld porosity due to Inconel cleaning problems
Inconel 625, conical and flat ring outer RD ceiling (1996)	9.5	Chemical mill	Back-to-back welded	Spot/TIG	Mill finish	360°/120°	Vendor delivery issues. GA completed fabrication
Inconel 625, conical and flat ring inner RD ceiling (1999)	9.5	Chemical mill	Back-to-back welded	Overlap spots/TIG	Mill finish	360°/120°	No major problems
316 Stainless steel, flat ring lower floor (2006)	15.2	Machined one side	Back-to-back welded	Spot/TIG	Electro-polished	180°/90°	Material flatness thick spot welds. Weld shrinkage