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Design and installation of a test helical divertor with a baffle structure in LHD

The helical divertor in the Large Helical Device (LHD) at the National Institute for Fusion Research (NIFS) in Toki, Japan was partially modified before the 2010 experimental campaign to demonstrate control of particles by using a baffle structure. This baffle structure consists of water-cooled divertor plates combined with baffle plates and a dome inside the private region of the divertor. The recycled neutral gas was successfully compressed in the modified divertor during discharges, and more than ten times higher pressure was observed there than in the unmodified divertor.

The control of neutral particles using a divertor is a crucial issue for a fusion reactor such as the force-free helical reactor (FFHR) [1]. Hydrogen isotopes, helium ash, and impurities must be pumped to sustain the burning fusion plasma. Closed divertor experiments have also been conducted in the Compact Helical System (CHS) [2], Wendelstein-7AS [3], and LHD [4] using a magnetic island. In LHD, a local island divertor (LID) experiment was conducted, and effective particle control was demonstrated [5]. Furthermore, the superdense core (SDC) plasma operational regime caused by the formation of an internal diffusion barrier (IDB) was obtained during high pumping operation using the LID [6]. However, the wetted area on the divertor head of the LID was so small that it could not be utilized during long-pulse operation in a high-performance plasma. The wetted area in the helical divertor, which is an inherent part of the heliotron magnetic configuration, is larger than that in the LID. However, the neutral pressure in the helical divertor only reaches about 0.01 Pa even during a high-density discharge in which the line-averaged density is higher than 10^{20} m^{-3}, and it is believed that the neutral pressure must be ten times higher for effective particle control using divertor pumping [7]. The relatively low neutral pressure in the helical divertor was considered to be caused by the three-dimensional (3D) plasma distribution in the divertor and the large volume of the vacuum vessel. Therefore it is necessary to install a baffle structure to compress neutral particles in the divertor region.

The baffle structure for the helical divertor was designed using a fully 3D neutral transport simulation [8] with the EIRENE code [9]. The code was applied to study the behavior of neutrals in the existing divertor configuration before the start of the design, and the results of the calculation were validated by comparing them to experimental results obtained by spectroscopic measurements [10].

The development of the plasma-facing components for the divertor was conducted using the electron beam irradiation device, ACT (Active Cooling Test stand) at NIFS, on the basis of a mechanically jointed water-cooled divertor plate used in the existing divertor [7, 11]. The divertor plate's temperature is considered to be highest during a steady-state discharge using 3 MW heating power, which is an experimental goal of LHD. In such discharges, the largest heat flux to divertor plates is estimated to be 1.5 MW/m^2, and the divertor plates were developed to tolerate this heat load. The design of the divertor and the development of the plasma-facing components were completed in 2008 [7], and two of ten torus inboard side divertors were modi-

In this issue . . .

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The Large Helical Divertor experiment has designed and installed a test helical divertor in LHD and operated it in the 2010 experimental campaign. In the new divertor, the plates face into the private region, and a protective dome is used to plug up the throat region. The divertor was designed to provide control of the neutral pressure during high-power neutral beam injection. During injection, the neutral pressure was an order of magnitude higher than in the unmodified divertor. After the 2011 campaign, this divertor design will be installed in an additional six toroidal sections of LHD. 1

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fied by installing the baffle structure before the 2010 experimental campaign to demonstrate neutral particle compression in the helical divertor [12].

Figure 1 shows a schematic view of both the existing and the modified divertor. In the existing divertor, the plasma-facing surfaces of the divertor plates face the main plasma. In the modified divertor, these surfaces face the private region which also contains the "dome" structure. Due to the changes of the divertor plates' angles and the installation of the dome, it was expected from the neutral transport calculations that the neutral pressure under the dome should be at least ten times higher than that in the private region in the existing divertor [7, 8], as shown in Fig. 2.

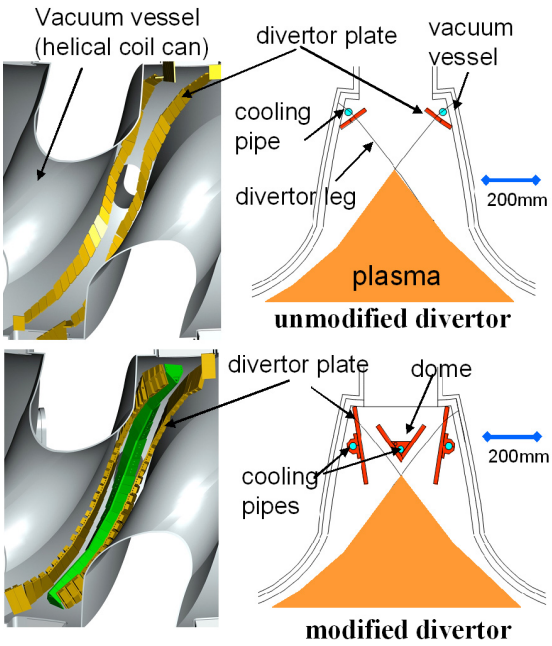


Fig. 1. Schematic views of an unmodified (top) and a modified divertor (bottom) in the torus inboard side. The right-hand figures are the cross-sectional views of the divertors in the equatorial plane. [12]

Figure 3 shows the modified divertor. One of the modified divertors provides armor to protect the vacuum vessel against the neutral beam (NB) used for plasma heating. The divertor plates and dome are made from isotropic graphite, and they are water cooled by mechanical jointing to water cooling pipes made of SUS316 [7, 11]. Carbon-fiber composite is applied to the divertor plates and dome components in the NB deposition area.

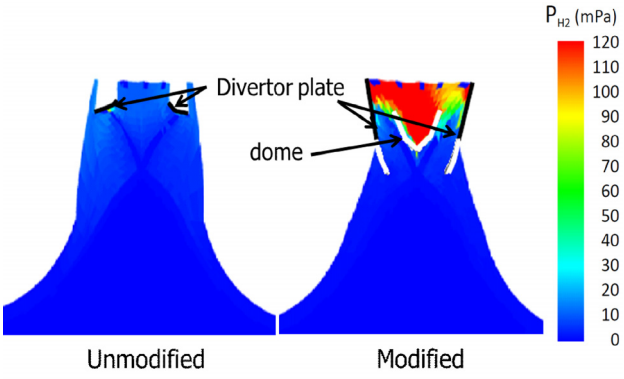


Fig. 2. Comparison of the neutral pressure in the divertor region of the unmodified and modified helical divertors.

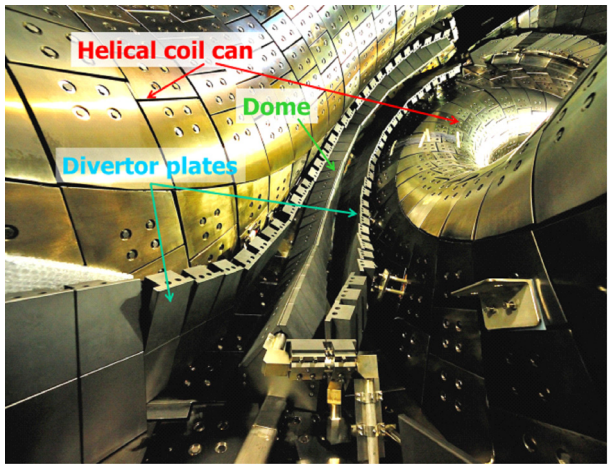




Fig. 3. Photographs of the modified divertor.

Figure 4 shows a CCD camera view of the modified divertor during a discharge. In the photo, H_α emission is intense in the region between divertor plates and dome, suggesting that neutral particles interact intensely with plasma in the region.

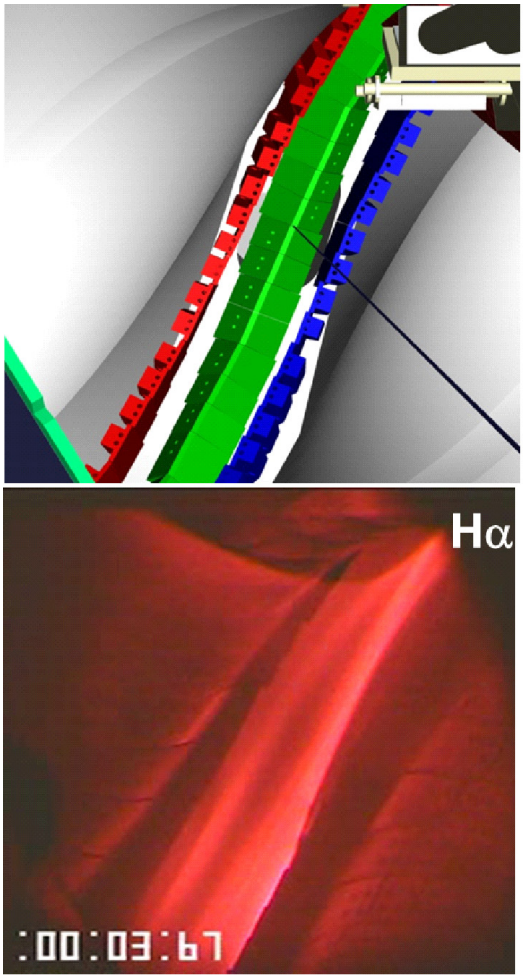


Fig. 4. Top: CAD data for the modified divertor. Bottom: CCD camera view of the modified divertor during a discharge with H_α filter.

To measure the neutral pressure in the modified divertor, three fast-ion gauges were installed under the dome. To compare the pressure in the modified and unmodified divertors, another fast ion gauge was installed in the torus inboard-side private region of an unmodified divertor. These fast ion gauges were calibrated using a cold cathode gauge and a capacitance gauge from 5×10^{-3} to 2 Pa.

Density ramp-up discharges were conducted in a standard magnetic configuration in which the magnetic axis radius is 3.6 m to compare the neutral pressures in the modified and the unmodified divertors. Figure 5 shows the time evolutions of plasma stored energy, line-averaged electron density ($n_{e,bar}$) in the center chord, and the neutral pressure near the equatorial plane in these divertors during a density ramp-up discharge. Hydrogen gas puffing was conducted during the discharge, and $n_{e,bar}$ increased to 7×10^{19} m^{-3}. The neutral pressures in both divertors increased with increasing $n_{e,bar}$, and the pressure in the modified divertor was more than 10 times higher than that in the unmodified divertor throughout the discharge. After the termination of the NB injection, the neutral pressure in the modified divertor decreased and become the same as that in the unmodified divertor. This result proves that neutral particle compression in the modified divertor works well.

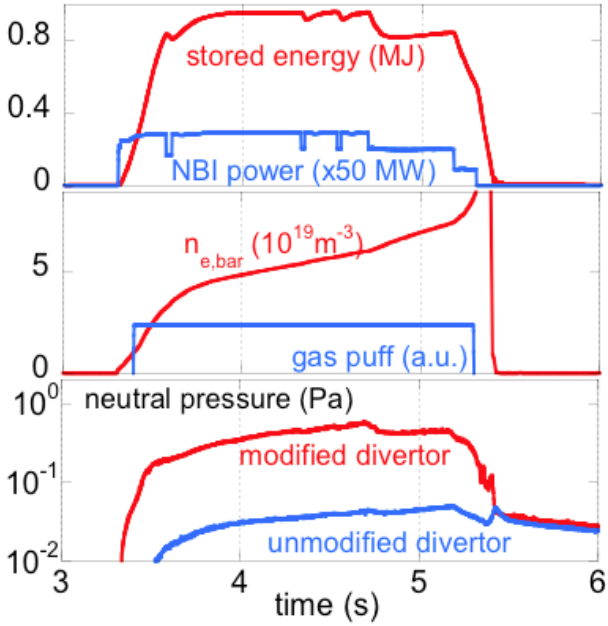


Fig. 5. Time evolutions of the stored energy and NB injection power (top), line-averaged density and fueling amount (middle), and neutral pressure in the modified and unmodified divertors (bottom) during a density ramp-up discharge.

No negative effects on the plasma operation caused by the installed baffle structure have thus far been observed. The initial result promises that an upgraded divertor system with pumps under the dome will provide efficient active particle control in LHD.

The 2011 experimental campaign began on 28 July without any additional modifications in the divertor region. After the campaign, starting in November, we are going to modify the divertor in another six toroidal sections and install in-vessel cryopumps under their domes.

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