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Abstract

A local island divertor (LID) has been proposed for the edge plasma control of the Large Helical Device (LHD), and its functions and effects on edge plasmas have been studied in detail. Although the LHD edge plasma will primarily be controlled by a closed full helical divertor, the LID will be used as an alternative. The advantage of the LID over the helical divertor is technical ease of the hydrogen pumping because of its toroidally localized recycling. A significant feature of the LID is high overall pumping efficiency of $\gtrsim$ 30%, which is the key in realizing high temperature divertor operation, leading to a significant energy confinement improvement.

1. INTRODUCTION

It is a major topic of research to control the edge plasma of the Large Helical Device (LHD) (B = 4 T, R = 3.9 m), which is a superconducting heliotron-type device under construction at NIFS [1,2]. The edge plasma control is important such as handling the heat and particle fluxes to the wall, and enhancing the core plasma confinement. The LHD edge plasma will primarily be controlled by a closed full helical divertor which utilizes a separatrix existing naturally at the edge of heliotron type configurations [3]. As an alternative approach, we also plan to use a local island divertor (LID) for the edge plasma control. We have studied the expected LID functions and its effects on edge plasmas, which are described in this paper. The LID experiment will provide us critical information on the edge plasma behavior in the LHD, and help us to optimize the design of the closed full helical divertor. It will also influence the divertor design of W7-X [4] and exploration of advanced divertor concepts.

2. PRINCIPLE AND FUNCTIONS OF LID

The LID is a divertor that uses an m/n=1/1 island, formed at the edge region, as depicted in Fig. 1(a). Since the core region is surrounded by the separatrix of the island, the outward heat and particle fluxes cross the island separatrix, and flow along the field lines to the back side of the island, where target plates are placed on a divertor head to receive the heat and particle loads [5]. The particles recycled there are pumped out by a pumping system. If the divertor head and a pumping duct leading to the pump are properly designed, a closed divertor system with overall pumping efficiency of $> 30\%$ can be obtained. Unlike the conventional pump limiters, blades of the divertor head are located inside the island, thereby being protected from the high outward heat flux from the core. Thus there is no leading-edge problem.

High efficient pumping is the key in realizing high temperature divertor operation, where the divertor plasma with a temperature of a few keV is produced, leading to a significant energy confinement improvement [3]. A closed divertor equipped with efficient pump such as the LID is ideal for this operation. A closed divertor also provides high plasma plugging efficiency required for the high recycling operation, where a low temperature and high density divertor plasma is produced for radiative cooling. Thus, these two operational modes can be realized in the LID, as in the closed full helical divertor [3]. These divertor functions allow the LID to pump out ionized impurities that are difficult to be pumped out in the presence of the magnetic field. Thus, a steady state LID operation with input power of ~500 kW can be used as an effective wall conditioning technique. One hour LID cleaning is expected to replace a few week conventional discharge cleaning.

3. MAGNETIC CONFIGURATION FOR LID

A copper coil system, as shown in Fig. 1(b), was demonstrated numerically to be able to generate a clean m/n=1/1 island at the edge. When a resonant perturbation field generated by two pairs of island control coils located above and below the torus is added to the standard LHD magnetic configuration, an m/n=1/1 island appears at $\iota\!\!\!-= 1$ surface, as shown in Fig. 2(a), together with m/n=2/1 islands, which appear due to the toroidal coupling at $\iota\!\!\!- = 0.5$ surface. Figure 2(b) shows, however, that the m/n=2/1 islands can be generated by another pair of island control coils. Thus, the m/n=2/1 islands are almost eliminated by a proper arrangement of the control coil currents, as shown in Fig. 2(c). One of the remarkable feature of this type configuration is a very sharp transition (within 2 mm in radial direction) from the closed surface to the open region. This is in quite contrast to the helical divertor with the transition width of ~50 mm. The connection length in this open region was calculated to be longer than ~750 m in the case of Fig. 2(c). This indicates that the length of the magnetic field lines in the open region is still long enough for the particles not to strike upon the vacuum vessel or the helical divertor plate immediately.

4. CONCEPTUAL DESIGN OF LID

To estimate the number of particles that strike upon the back side of the divertor head, we calculate the percentage P of the magnetic field lines that strike upon the target plate, among a total of 240 field lines, which circulates around the torus 15 times. The field lines start from the poloidally equally spaced points at distances of 4, 8 and 12 mm from the last closed flux surface (LCFS) and toroidally at the same angle as the center of the plate. This distance between the plate and starting points is the longest along the field lines. The perpendicular spreading of the starting points takes into account the perpendicular diffusion of the particle flux to some extent. Figure 3 shows the magnetic surfaces formed by these field lines, before they strike upon the plate, on the plane, whose normal direction is parallel to the direction of the helical coils at the outside (large major radius side) of the equatorial plane. The plate with the width of D is on this plane in our calculation. Figures 3(a), 3(b) and 3(c) show the magnetic surfaces obtained without and with the plates of D = 30 and 60 cm, respectively. The field lines pass through the plate and tend to circulate around the entire island flux surface when D = 30 cm, but almost all field lines strike upon the plate during the first island circulation when D $\geq$ 60 cm. Thus, P is almost proportional to D, and begins to saturate at D $\sim$ 50 cm. It reaches 90% at D = 60 cm.

The relation between P and N was also obtained with D = 40 cm. By increasing N from 0, it was demonstrated that N must be larger than 10 for realizing the large P. Then, the width of the gap between the pumping duct and divertor head, Δ, necessary for the high efficiency pumping, is obtained to be $\gtrsim$ 5 cm using the relation $\Delta \gtrsim \sqrt{2\pi \mathrm{RND}_\perp / \mathrm{v}_{//\mathrm{i}}}$ when N = 10, $\mathrm{D}_\perp$ =1 m^2/sec and $\mathrm{T_i}$ = 100 eV, since the particle flux diffuses radially during the toroidal circulation. Figure 4 shows the conceptual design, thus obtained, of a divertor head of ~60 × ~60 cm with the overall pumping efficiency of > 30%. Here, the solid and broken lines represent the magnetic field lines in the outer and inner parts of the island flux surface, respectively.

Optimization of the target plate shape, and design works of the pumping and cooling systems are under way. Through our physics and engineering design works of the LHD, we believe that the LID can function reliably and enhance the LHD plasma quality.

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FIGURE CAPTIONS

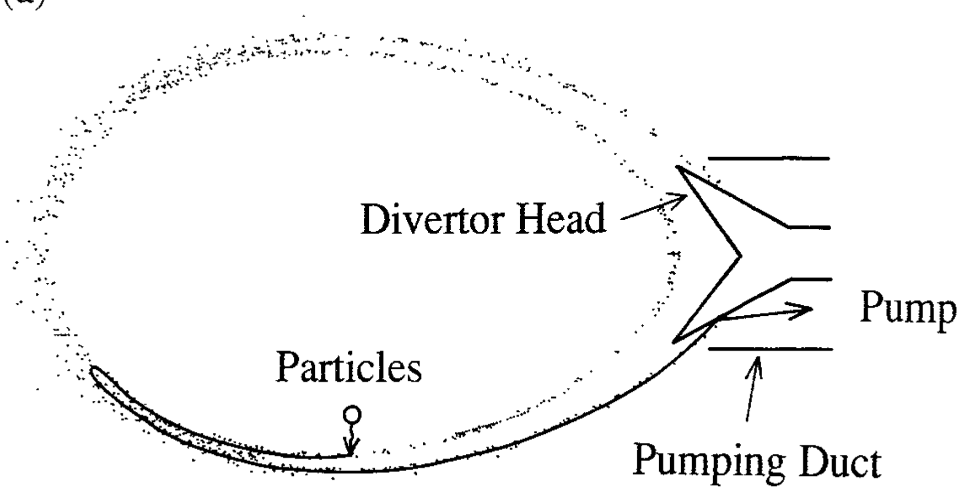
Fig. 1. (a) Schematic of the LID. (b) Island control coils for generating an m/n=1/1 island.

Fig. 2. Magnetic surfaces when resonant perturbation fields are added to the standard LHD magnetic configuration. The perturbation fields are generated by (a) adjacent two pairs of island control coils located above and below the torus, (b) another pair of coils, located toroidally at a right angle to those for (a) and (c) these three pairs of coils with a proper coil current distribution, respectively.

Fig. 3. Magnetic surfaces formed by magnetic field lines that start from near the LCFS and circulate around the torus within 15 times until they strike upon the target plates of (a) D = 0 (no plate), (b) 30 and (c) 60 cm, respectively.

Fig. 4. Conceptual design of a divertor head, viewed from a horizontal vacuum vessel port.

(a)


Divertor Head
Pump
Particles
Pumping Duct

(b)

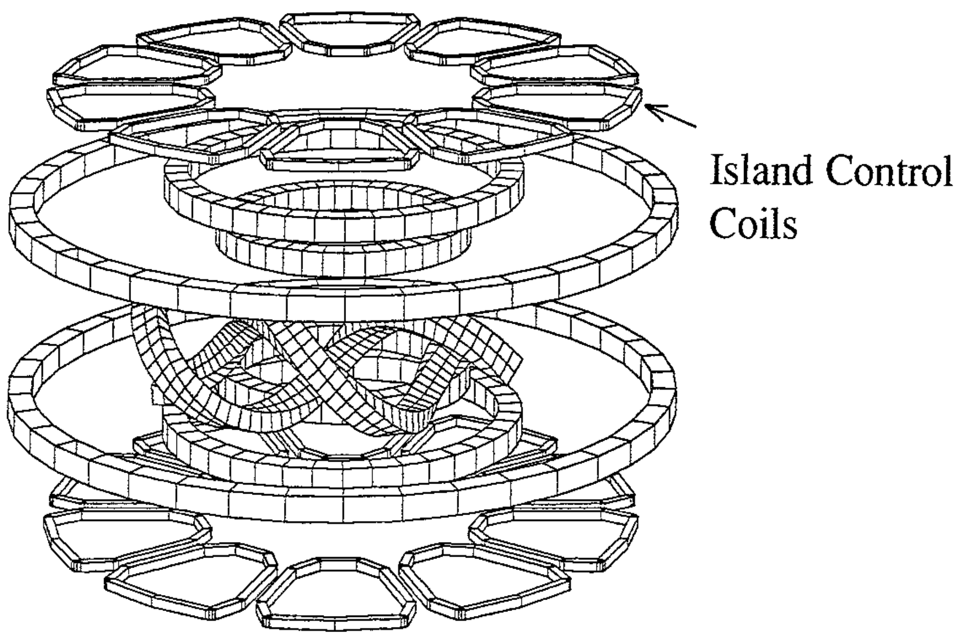

Island Control
Coils

Fig. 1

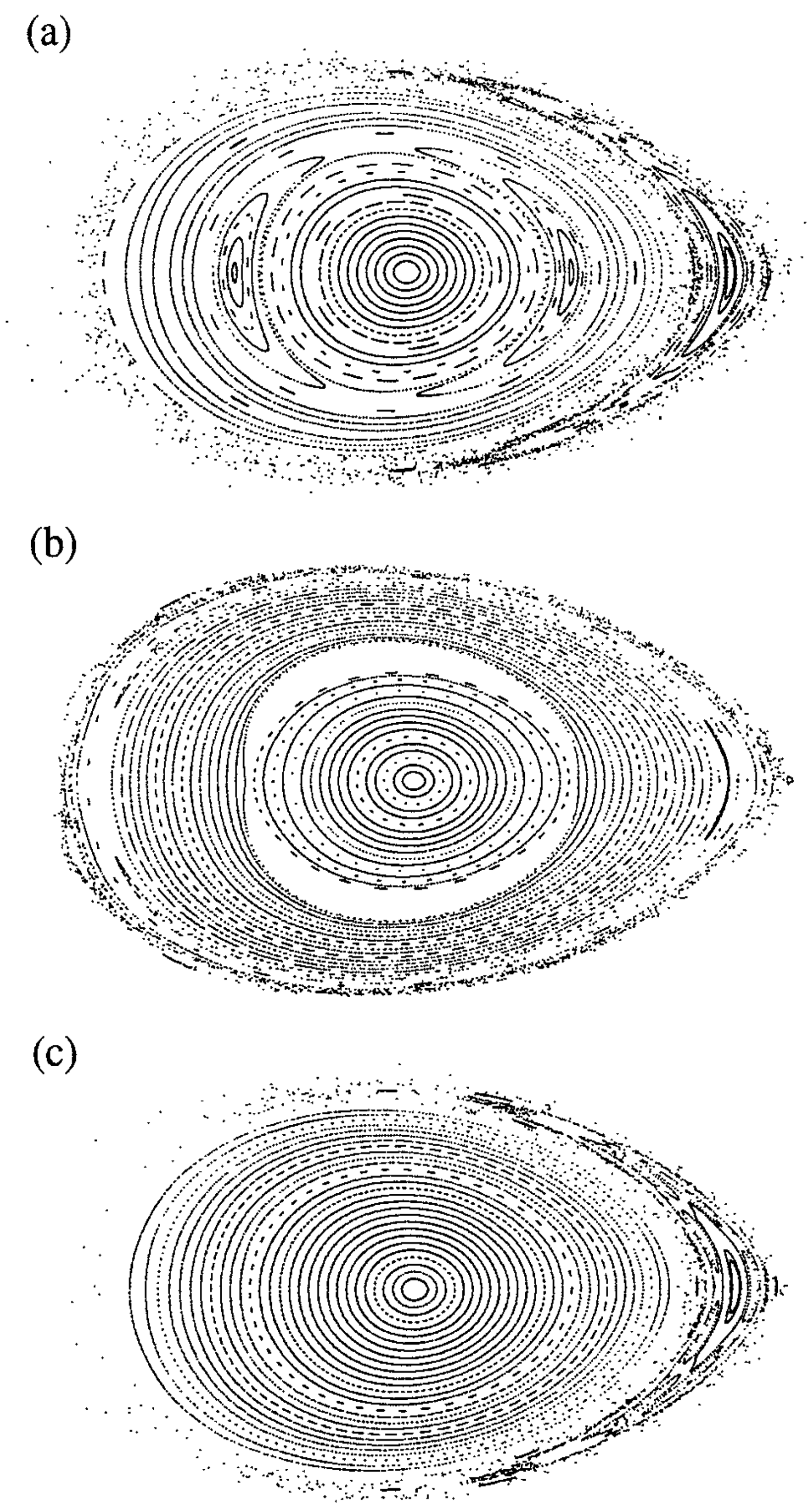


Fig. 2

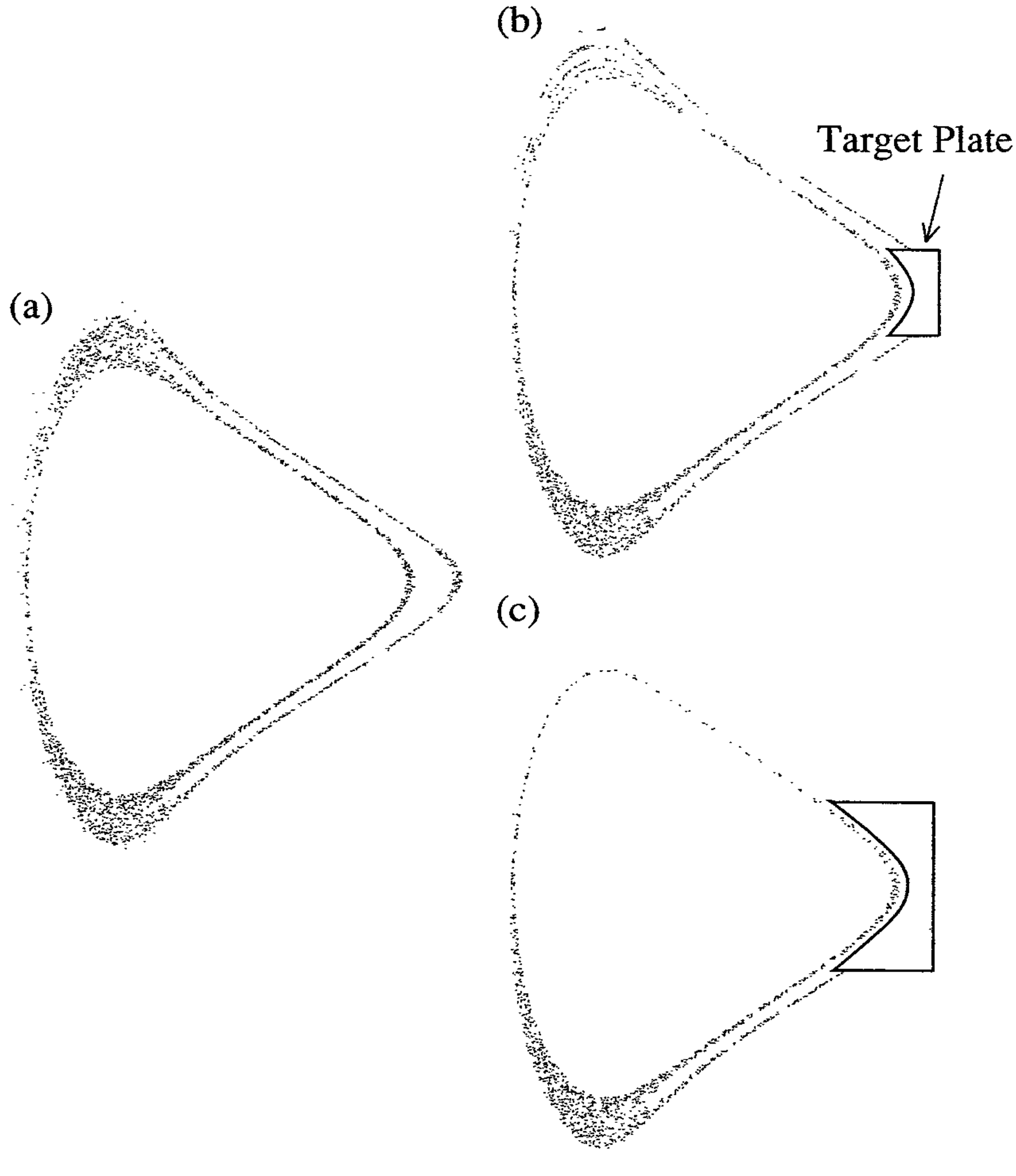


Fig. 3

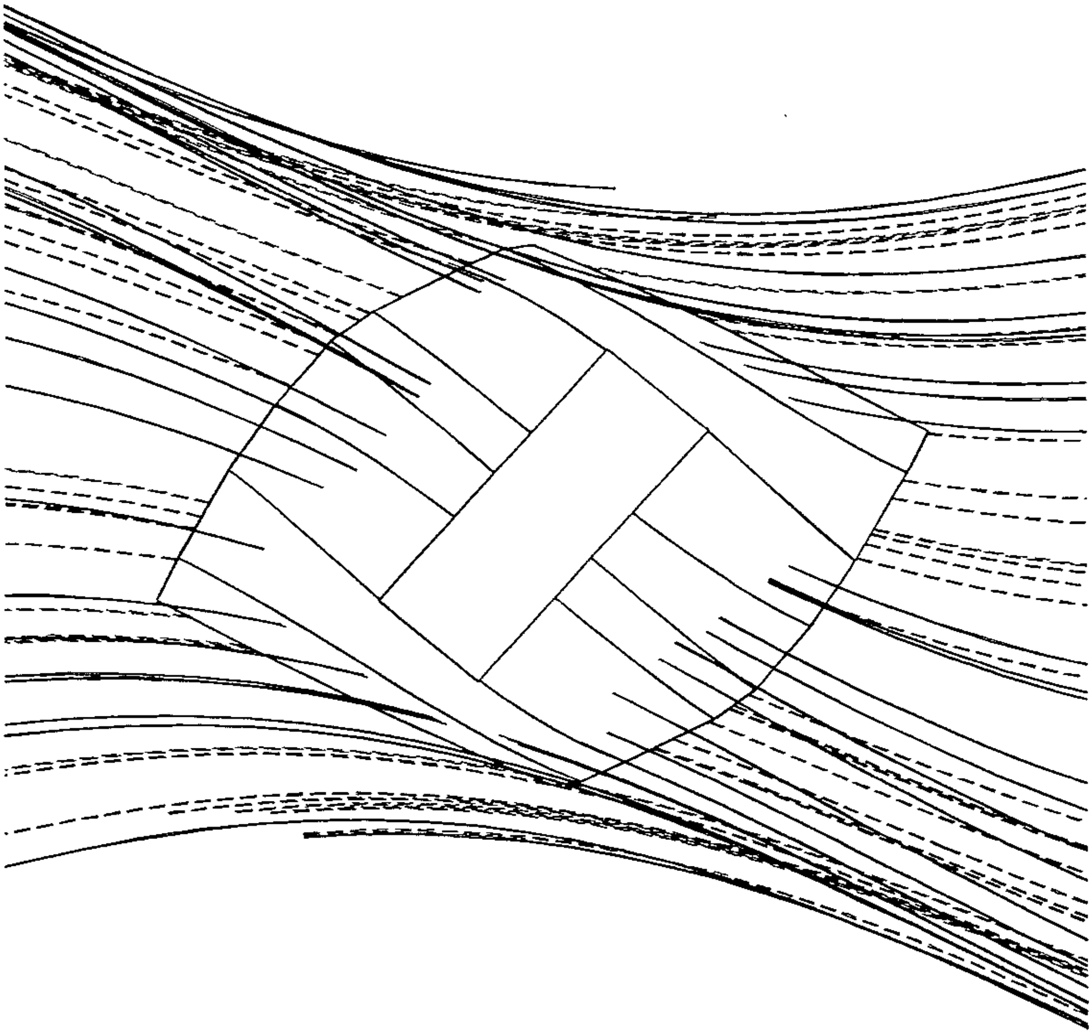


Fig. 4

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