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DESIGN STUDY OF LHD HELICAL DIVERTOR AND HIGH TEMPERATURE DIVERTOR PLASMA OPERATION

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DESIGN STUDY OF LHD HELICAL DIVERTOR AND HIGH TEMPERATURE DIVERTOR PLASMA OPERATION

Abstract

The Large Helical device (LHD), now under construction is a Heliotron/torsatron device with a closed divertor system. The LHD divertor magnetic structure has been studied in detail. A peculiar feature of the configuration is the existence of edge surface layers, a complicated three dimensional magnetic structure. However it does not seem to hamper the expected divertor functions. As a confinement improvement scheme in LHD, we have proposed a high temperature divertor plasma operation in which a divertor plasma with a temperature of a few kev, generated by efficient pumping, leads to the confinement improvement.

1. Introduction

With the inherent advantage of the stellarator as an attractive steady state reactor, there has been growing interest in the sterallator. We are constructing a large superconducting Heliotron/torsatron device (B=4T,R=3.9m) , called the Large Helical Device (LHD), aiming at demonstration of attractiveness of the helical device at more reactor relevant plasma parameters [1]. A built-in divertor configuration exists for Heliotron/torsatron devices. This advantage has not been explored in any existing helical device and the LHD device will be the first helical device which will demonstrate various divertor functions such as impurity control and enhancement in the energy confinement. The LHD divertor configuration needs to be as flexible as possible so that one can accommodate a wide range of divertor operational scenarios. To this end, we have designed a large vaccuum vessel for installation of closed divertor chambers with reasonable size.

2. Features of the edge magnetic configuration

The magnetic topology and the associated divertor plasma behavior need to be understood theoretically before designing the LHD divertor system. A helical divertor magnetic configuration in LHD is depicted in Fig.1(a),(b). A closed surface region is surrounded by a stochastic region, generated by overlapping of the islands($n=10$) which somewhat naturally exist in the outer region. The field lines escaping from this region pass through thin curved surface layers before reaching the X-point and then the divertor plate. The existence of the edge surface layers is a peculiar feature of this type of helical divertor [2]. A surface layer consists of multiple layers , each of which again consists of multiple layers. Such a structure is generated by succesive folding and stretching processes as the field lines rotate poloidally. The former process occurs because the radial position of the X-point changes with poloidal angle as much as ~1/3 of the plasma radius. The latter is caused by the high local rotational transform and shear at the edge on the larger major radius side of the torus.

To study the structure of the divertor channel, the field lines are traced from the stochastic region until reaching a helical plane ($\theta=-[5\phi+\theta_0+0.1\sin(5\phi+\theta_0)]$) rotating with helical coils. In the real device, the divertor plates are located at $r=1.55$m near this plane. The effect of the perpendicular plasma transport is taken into account by field line tracing with a random walk process (at every 0.2 m step, positions of the field lines deviate by δ on the plane perpendicular to the field lines with random azimuthal angles). Puncture plots of the field lines on this plane are shown in Fig.1(c). A strong poloidal asysmetry is seen in the plots. A fine structure of the edge surface layer are clearly seen when they are traced exactly i.e. $\delta = 0$. With a ramdom walk process with $\delta = 1.2$mm,(which coressponds to an effective perpendicular diffusion coefficient of 0.5 m^2/s for a plasma with a temperature of 100eV, less than a typically observed edge value), the fine structure is smoothed out completely. We expect that distributions of the heat and particle flux fluxes on the plane in the LHD experiments are close to those with δ =1.2mm. Based on this estimate, the maximum heat flux on the divertor plate with a field line incident angle of 30° is expected to be ~5 MWm^{-2} for a standard 20 MW LHD discharge.

Divertor operation with a high density, cold divertor plasma [3,4], is suitable to reduce the impurity sputtering and to enhance the edge radiation, a promising boundary control which we plan to pursue in the LHD experiments. The vague boundary discussed above has a property of poor confinement and thus may serve to provide an edge cold radiative volume to reduce the heat flux on the divertor plate [4]. But it may in turn prevent formation of the H-mode edge temperature pedestal, which leads to improvement of the core energy confinement [5]. This has motivated us to propose a high temerature divertor plasma operation, discussed in section 3.

3. High temperature divertor plasma operation

A high temperature divertor plasma operation has been proposed to improve the energy confinement in helical devices as well as in tokamaks [6]. In this operational mode, the divertor plasma temperature is raised by efficient pumping in the divertor chamber. An elevated divertor temperature will lead to improvement of the core plasma, as observed in H-mode discharges.

The divertor temperature (T_{div}) is estimated by a power balance in the divertor channel. We consider a steady-state discharge which is heated (Q_{in}(input power)) and fuelled (Γ_{in}(particle flux)) by neutral beam injection alone, illustrated in Fig.2(a). We assumed that the pumping efficiency of the divertor is ξ , i.,e., a fraction (ξ) of the particles reaching the divertor plates (Γ_{div}) are pumped and the same amount of the particles need to be fuelled by the neutral beam injection i.e, $\xi \cdot \Gamma_{div} = \Gamma_{in}$. The injected power(Q_{in}) into the main plasma region flows into the divertor channel and at the sheath of the divertor plate, a power balance ($Q_{in} = \gamma \cdot T_{div} \cdot \Gamma_{div}$) is satisfied where γ is the heat transmission coefficient. From these relations, the divertor temperature is given as $T_{div} = (Q_{in} / \Gamma_{in}).\xi / \gamma$. For a parameter set (beam energy(Q_{in} / Γ_{in}) ~ 200kev, $\gamma \sim 10$, $\xi \sim 0.2$), T_{div} becomes as high as 4 keV, significantly higher than those observed at the pedestal of H-mode discharges.

We have studied high temperature divertor plasma ,i.e., collisionless divertor plasma in a one dimensinal model illustrated in Fig.2(b). Equal number of Ions and electrons with temperature T_0 are supplied between the divertor plates. Ions simply flow to the divertor plates. A negative electric potential is set up for the ambipolar flow condition and electrons with parallel kinetic energy less than the potential amplitude are trapped by the potential. The electron distribution functions in the divertor channel, calculated by a Fokker-Planck code [7] are shown for two different collisonalities. When the mean free path becomes much longer than $(M/m)^{1/2}.L$ (where M/m is the ion electron mass ratio and L is the distance between the divertor plates), the trapped electron density becomes nearly equal to the ion density even with a potential amplitude of $< eT_0$ and the average perpendicular energy of the trapped electrons is much greater than that of the parallel energy, as is shown in the case on the right-hand side of Fig.2c. On the other hand, for a less collisionless case (on the left-handed side of Fig. 2c), the potential amplitude is less than eT_0, but the temperature distribution is isotropic.

Such a collisionless effect become important for the energy balance with the secondary electron emission. At temperature above 100 eV, secondary electrons emitted from the divertor plate become a source of the cold particles, which lower the divertor electron temperature. This effect can be included in γ [8] and γ is 7.8 without secondary electron emission and is ~10 when the secondary emission rate is ~0.7. But when it exceeds ~0.7, γ increases rapidly and then saturates at ~23 because of the space charge limit. When divertor plasma electrons are collisionless, the secondary electrons emited from the divertor are first accelerated by the sheath potential and are barely trapped by the potentials. They eventually hit the divertor plate during the thermalization process. The parallel energy with which they hit the plates is ~0 and the perpendicular average energy is a fraction of the sheath potential in contrast to the conventional collisional sheath model where both average striking energys are equal to T_e (the electron temperature). Thus the collisionless effect reduces the cooling effect by the secondary electrons and hence γ substantially.

In this operation, a density profile is maintained by a combination of deep fuelling such as pellet or neutral beam injection and particle pumping. Thus the diffusion coefficient (D) and hence the particle confinement becomes important in determining the energy confinement. This is desirable for the energy confinement in LHD where high neoclassical ripple induced electron heat loss($1/\nu$-regime) tends to suppress the temperature gradient. However the effective D may not be high because the ions are confined by ExB drift (ν-regime). The radial electric field in such a plasma regime is positive and hence neoclassical outward impurity pinch [9] may prevent impurity contamination in the core plasma.

For this operation in LHD, we plan to install a cryopump system with overall pumping efficiency of ~20% in the divertor chamber. For a reactor design, we are trying to find divertor configurations which guide the heat and particle fluxes to a remote region, away from the main coil system, thereby making the particle pumping and the heat removal achievable.

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Figure Captions

Fig. 1

(a) Poloidal cross-sectional view($\phi = 0^\circ$) of the LHD helical divertor.

(b) Illustration of the LHD edge magnetic configuration($\phi = 18^\circ$).

(c) Puncture plots of the field lines on a helical plane ($\theta=-[5\phi+\theta_0+0.1\sin(5\phi+\theta_0)]$) in the divertor chamber(shown in Fig. 1(a)) for three different random walk parameters.

Fig. 2

(a) Simplified heat and particle balances in the high temperature divertor plasma operation. (ξ : pumping efficiency).

(b) A one dimensional model with a collisionless divertor plasma.

(c) Electron distributions in the model divertor (4b) at two different collisionarities, $\lambda_e / L = 36$ (the left-hand side) and $\lambda_e / L = 360$ (the right-hand side). Here λ_e is the electron mean free path at a temperature of T_0 and L is a half of the distance between the divertor plates. ($V_0 = (kT_0/m_e)^{1/2}$).

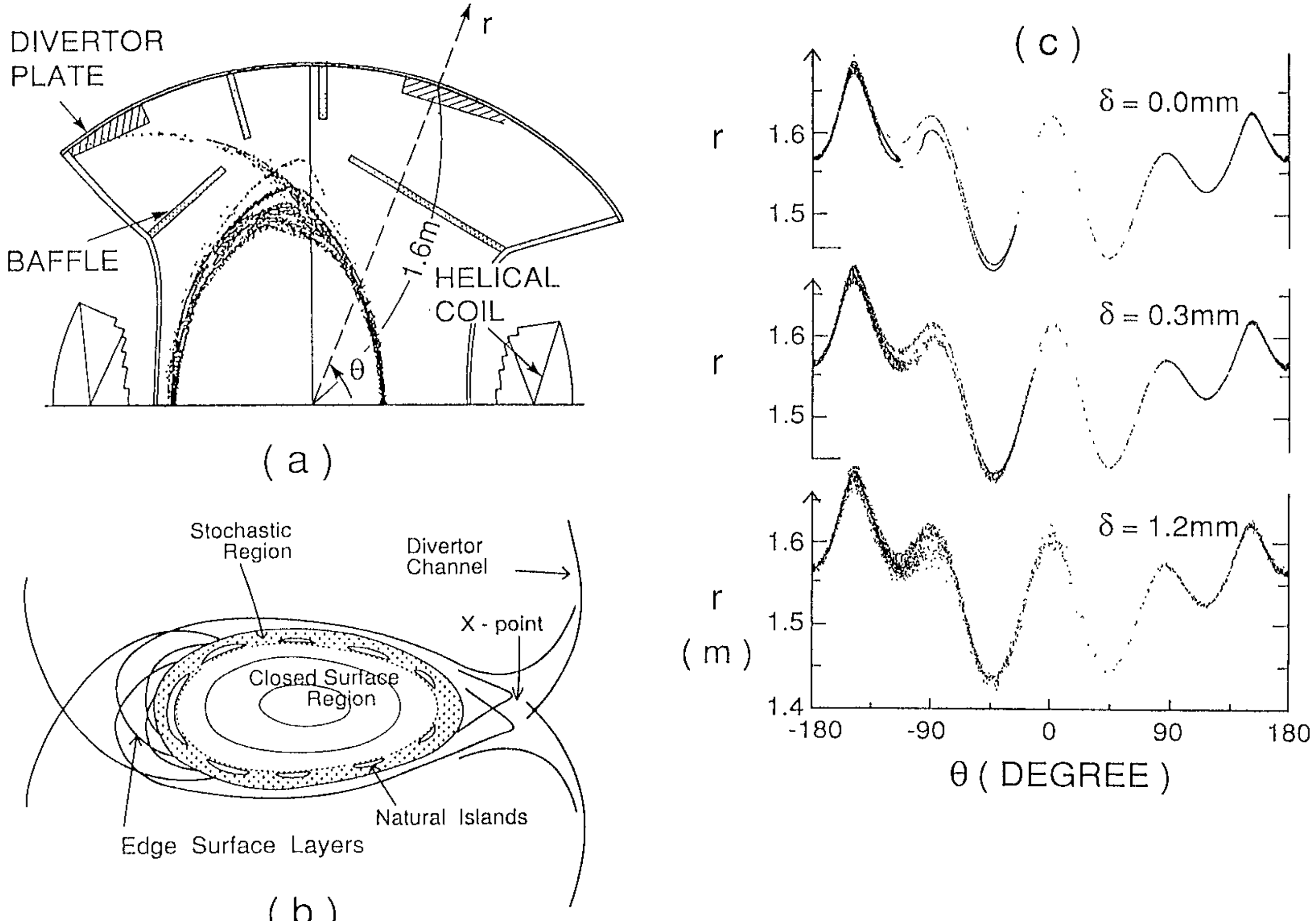DIVERTOR PLATE
BAFFLE
HELICAL COIL
r
1.6m
θ
(a)
Stochastic Region
Divertor Channel
X - point
Closed Surface Region
Natural Islands
Edge Surface Layers
(b)
(c)
δ = 0.0mm
δ = 0.3mm
δ = 1.2mm
r
r
r
(m)
1.6
1.5
1.6
1.5
1.6
1.5
1.4
-180
-90
0
90
180
θ (DEGREE)

Fig. 1

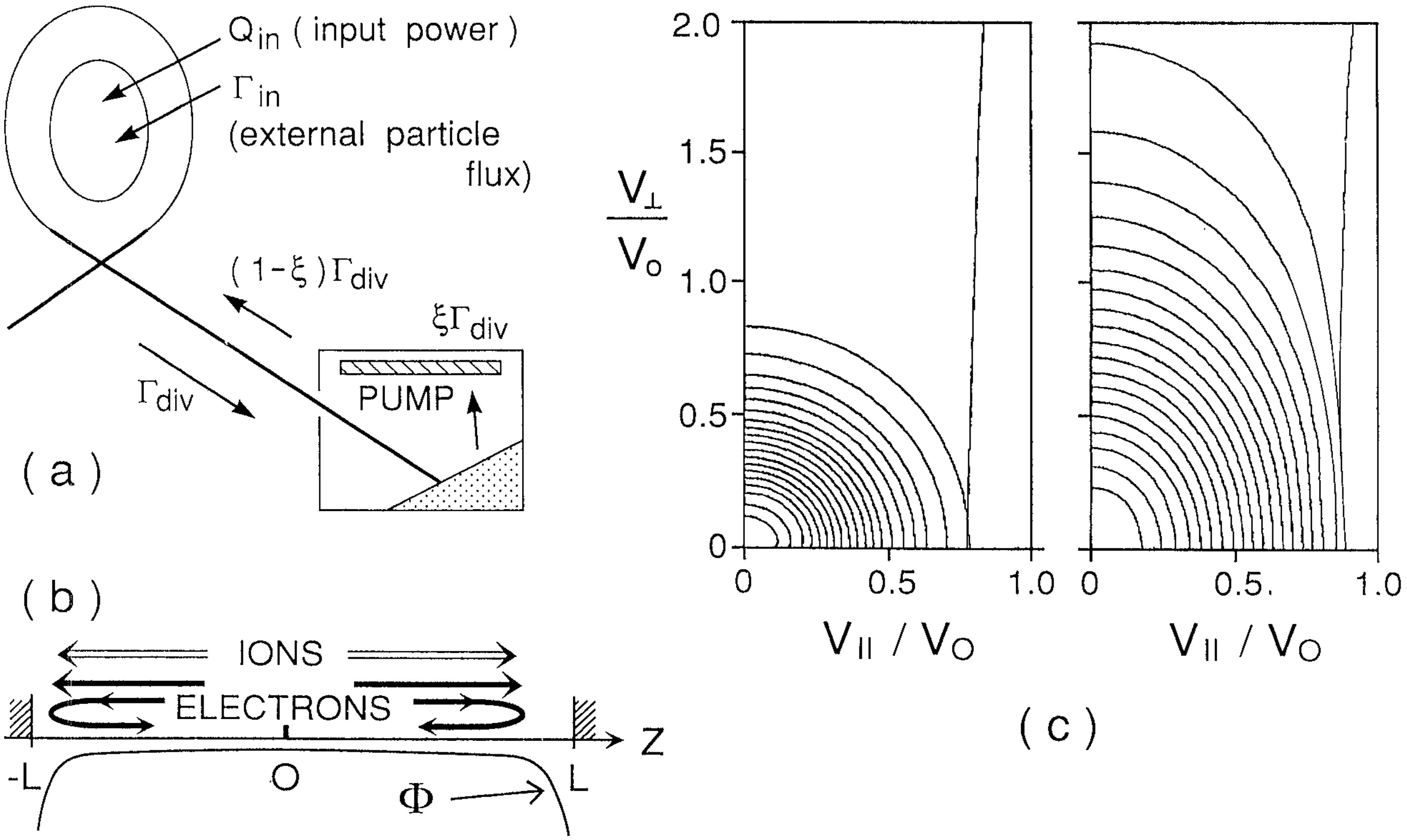Q_{in} (input power)
Γ_{in}
(external particle flux)
$(1-\xi)\Gamma_{div}$
$\xi\Gamma_{div}$
PUMP
Γ_{div}
(a)
(b)
IONS
ELECTRONS
Z
-L
O
L
Φ
$\frac{V_\perp}{V_o}$
2.0
1.5
1.0
0.5
0
0
0.5
1.0
$V_{\parallel} / V_O$
0
0.5.
1.0
$V_{\parallel} / V_O$
(c)

Fig.2

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