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Numerical predictions for the HT-7U divertor

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Abstract

HT-7U is a superconducting tokamak under construction in China. Its magnetically balanced double-null divertor is designed to accommodate the heat load due to a total heating power of 7.5 MW. In order to increase the degree of closure, the divertor structure is designed to consist of vertical targets, tightly fitting side baffles and dome baffles. To predict the details of the scrape-off layer and divertor plasma in different operational regimes and to assess the effects of the divertor geometry, two dimensional numerical calculations with the B2-EIRENE code package have been performed taking into account the real geometry of the HT-7U divertor. The results of the numerical predictions for the HT-7U divertor are to be described in this paper.

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1. Introduction

As the upgrade for HT-7 (a presently operating superconducting experimental device in circular and limiter configuration), HT-7U is designed to operate with shaped plasma cross-sections and in the magnetically balanced double null (DN) divertor configuration. The scientific mission of HT-7U is to explore the reactor relevant regimes with long pulse lengths and high plasma core confinement and to develop and verify solutions for power exhaust and particle control in steady operational state. To accomplish this aim, both its toroidal and poloidal coils will be superconducting magnets and the plasma current (1 MA) will be sustained over long periods of time $\tau_{pulse} = 60$–1000 s by lower hybrid waves. The DN divertor should be designed to accommodate the heat load due to the combined heating power of 7.5 MW in long duration discharges.

During the last decade, some expected benefits of a closed divertor have been confirmed by the experiments conducted on most existing divertor tokamaks (Alcator C-mod, ASDEX-U, DIII-D, JET and JT-60U, etc) [1]. These experimental devices have modified their divertors to increase the 'closure', i.e. to decrease the fraction of recycled neutrals escaping from the divertor region. The proven effects of the divertor geometry are considered in the design process of the HT-7U divertor. In order to increase the degree of closure, the divertor structure has to be designed to minimize its conductance for neutral leakage from the divertor region into the main chamber. So the divertor structure in HT-7U is deep and consists of inner and outer vertical target plates, tightly fitting side baffles and a dome baffle in the private flux region, which is close to the divertor concept developed by the ITER JCT [2].

The purpose of this work is to predict the details of the scrape-off layer (SOL) and divertor plasma in the different operational regimes and to assess the effects of the divertor geometry considered. Two-dimensional numerical calculations with the B2-EIRENE code package [3–5] have been performed taking into account the real geometry of the HT-7U divertor. The results of numerical predictions for the divertor are to be described in this paper.

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2. Simulation model

Tokamak plasma performance generally improves with increased shaping of the plasma cross-section. The poloidal field coil system of HT-7U has the capability to accommodate two different DN plasma configurations. One has a high elongation of up to 1.9, while the other has a modest elongation but with a largely increased plasma volume to make the most of the space available inside the vacuum vessel. Since during the preliminary phase HT-7U is planned to operate in the latter one, the work in this article is based upon the larger volume configuration with the major parameters shown in Table 1. Here $L_{\parallel}$ represents the magnetic connection length from the midplane to the outer divertor strike point. In this configuration, the divertor depth, i.e. the distance between the X-point to the outer target along the separatrix, is about 0.30 m.

The schematic HT-7U divertor geometry and the computational mesh used in the present study are shown in Fig. 1. The targets and baffles fit the magnetic geometry tightly to minimize the neutral back flow into the main chamber. The shape of the outer side baffle follows the magnetic flux surface which is at a distance of about 3.5 cm away from the separatrix, measured in the outer midplane. The magnetic equilibrium is generated by a free boundary equilibrium code EQ and is the basis of the numerical grid generation for the B2-EIRENE code package. The computational domain for the divertor predictive studies covers the whole SOL and both the upper and lower divertors. A small region of the plasma core periphery and the private flux region are also included. The whole computational domain is resolved into 120 poloidal divisions and 24 radial divisions.

Only hydrogen will be used as plasma species in present work and C is generated self-consistently by sputtering. For the standard operating scenarios (without impurity injection), we assume that 80% of the total power flows into the entire SOL. The anomalous perpendicular transport model used in the present study is constant in space, with the thermal diffusivities $x_{i\perp} = x_{e\perp}$ varying in the range 1.0–2.0 m^2/s and the particle diffusivity $D_{\perp}$ varying in the range 0.5–1.0 m^2/s. Ultra-long discharges will be achieved on the superconducting tokamak HT-7U, so the wall pumping effect is neglected and the recycling coefficient R is set to 1.0 for the divertor plasma facing components and the vacuum vessel wall.

Table 1
Major parameters of the HT-7U Tokamak

Major radius, R (m)	1.94
Minor radius, a (m)	0.48
Elongation at separatrix, κ_x	1.74
Triangularity at separatrix, δ_x	0.62
Plasma volume, V_P (m^3)	~15
Plasma surface area, A_P (m^2)	~49
Connection length, $L_{\parallel}$ (m)	~31

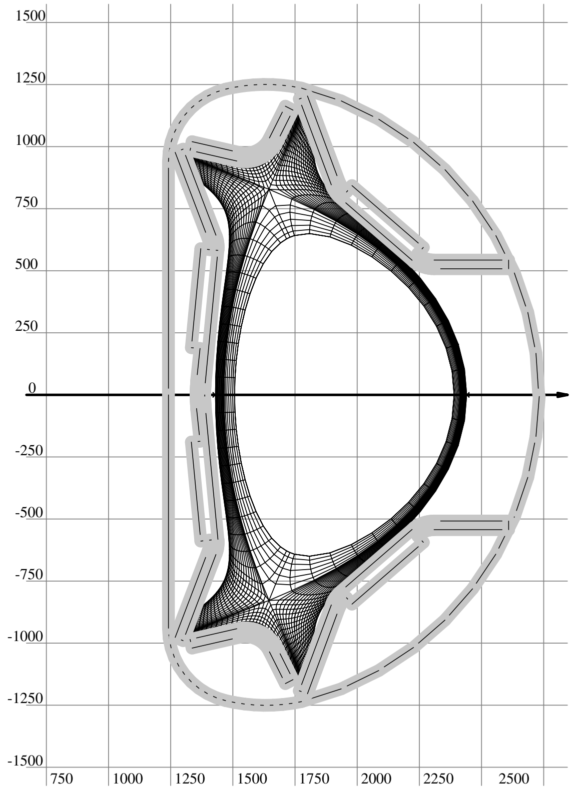

Fig. 1. The schematic HT-7U divertor geometry and the computational mesh.

3. Results of the B2-EIRENE prediction

3.1. Effect of the vertical targets

Vertical targets are adopted in the HT-7U divertor. The neutrals produced at the target plates are preferentially reflected towards the separatrix and hence ionization is enhanced near the vicinity of the separatrix. Fig. 2 shows the 2-D distribution of (a) the neutral density and (b) the ionization source (H^+ ions $m^{-3}\,s^{-1}$), where only the lower part of the whole computational domain is shown. Since the power is mainly conducted through the region close to the separatrix, this vertical geometry effect is beneficial to improve the power exhaust. As a result, the peak heat flux is reduced and the profile is broadened (partly due to the increase of the wetted area), in comparison with our previous modelling

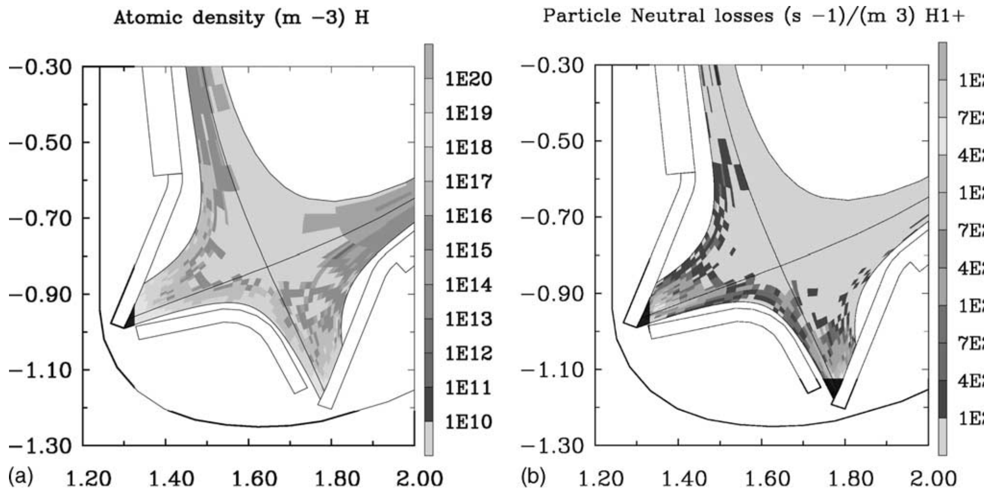

Fig. 2. The 2-D distribution of (a) the neutral density and (b) the ionization source (H^+ ions $m^{-3}\,s^{-1}$), showing the preferential reflection of neutrals towards the separatrix by vertical targets.

with divertor target plates normal to flux surfaces [6]. The broadened heat flux, the more peaked electron density and 'inverted' temperature profiles across the lower outboard divertor target are shown in Fig. 3(a). These anticipated profiles are the features of the vertical target geometry and have been found in most tokamaks operating with vertical divertors. Fig. 3(b) shows the typical profiles in [6] to illustrate the comparisons.

In the sheath-limited regime, however, since the divertor plasma is nearly transparent to neutrals, no intense neutral re-ionization takes place around the separatrix. Consequently, the temperature profiles become peaked and have high values at the separatrix, in contrast to the 'inverted' profiles at medium and high densities in vertical geometry.

3.2. Divertor operational regimes

To reduce the power load and erosion of the divertor target plates is the main issue in the design of the HT-7U divertor. Operating in the high recycling or detachment regime can effectively decrease the heat flux flowing to the target and make the electron temperature low at the target plate. Divertor regimes are very sensitive to the midplane separatrix electron density. For higher densities, the divertor has easier access to the high recycling

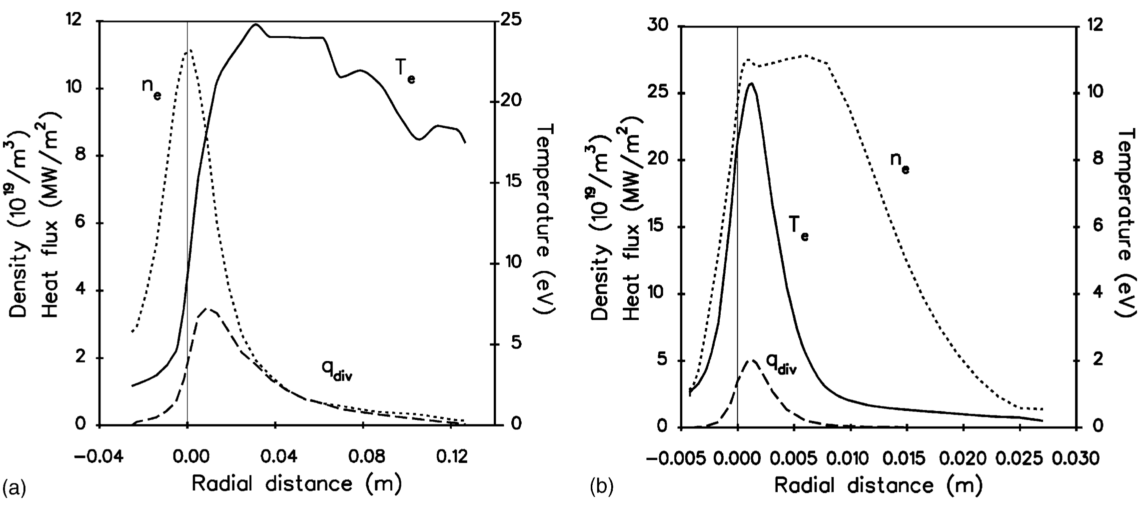

Fig. 3. Radial profiles across the SOL at the divertor target: (a) for the vertical target and (b) for the target plate normal to flux surfaces.

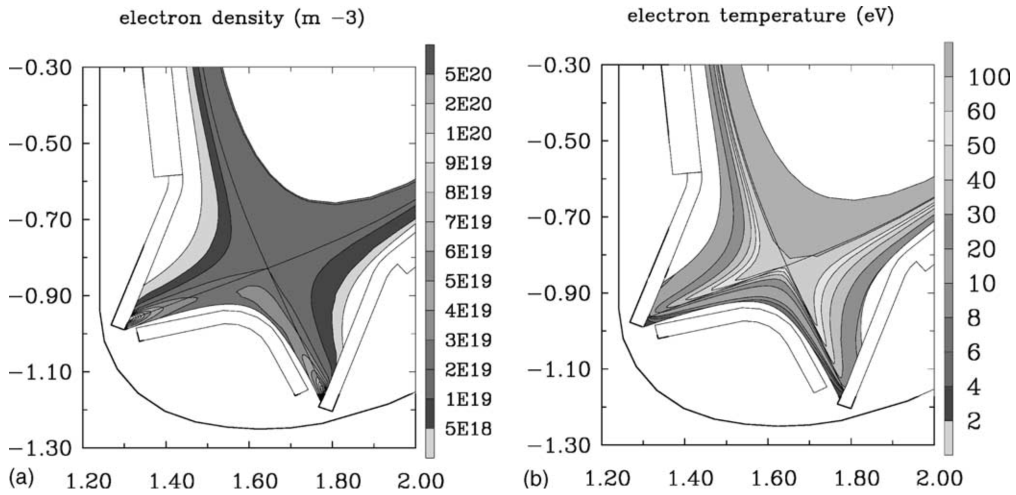

Fig. 4. Contours of (a) the density and (b) the temperature in the high recycling regime.

or detachment regime. According to the Greenwald limit, HT-7U will be able to run safely with the line average densities $\bar{n}_e$ up to 1.0×10^{20} m^{-3} in Ohmic discharges. But the efficiency of lower hybrid current drive (LHCD) requires operation at much lower density. To explore the possibility of achieving various operational regimes and to study the divertor behavior in these scenarios, a density scan has been carried out. In this scan, the midplane separatrix density $n_{e,\ sep}$ was varied while the SOL power was kept constant.

At a quite low density of about $n_{e,\ sep} = 0.7 \times 10^{19}$ m^{-3}, only the low recycling regime can be attained. In this regime, due to the high parallel heat conduction, the electron temperature shows little drop along the field lines and hence is as high as up to $\sim$120 eV at the lower outboard target. With low densities, recycling losses can be neglected, so the peak heat flux at the target is higher than 5 MW/m^2, which exceeds the engineering constrain.

As the midplane separatrix density is increased to the value of $\sim 1.1 \times 10^{19}$ m^{-3}, significant gradients of plasma profiles along the field-line can be observed, indicating the accession to the high recycling regime. At this density, however, the peak heat flux at the target is still higher than expected. To reduce the peak heat flux to lower than 3.5 MW/m^2, the midplane density $n_{e,\ sep}$ should be increased further to about 1.4×10^{19} m^{-3}. Considering the density limit required for non-inductive current drive efficiency, this result suggests that the operating window is rather narrow for the HT-7U divertor to perform in the high recycling regime. In this regime, due to the strong ionization sources from recycling neutrals, a plasma with high density and therefore low temperature is formed close to the plate as shown in Fig. 4, which reduces target sputtering and makes the Z_{eff} an ideal value of 1.4. In contrast to the low recycling regime, flow reversal of the hydrogen ions, which generally characterizes the high-recycling regime, is observed in a region close to the separatrix.

Our modelling indicates that, for HT-7U, the transition to power detachment occurs at the line average densities $\bar{n}_e \sim 7.8 \times 10^{19}$ m^{-3}, that is about 80% of the Greenwald limit and is much higher than the density limit posed by the LHCD efficiency. Consequently, additional approach such as gas puffing or impurity seeding should be adopted to attempt detachment. But the modelling results at this high density reveal the effect of the divertor geometry on detachment behavior. In this case, the electron temperature is low enough (<4 eV) throughout most of the inner target and even lower than 2 eV at the separatrix. Although the separatrix temperatures at the outer target become very small below 2 eV, the outer SOL remains at high temperature >10 eV and thus keeps attached. This may suggest that detachment in HT-7U starts from the separatrix due to the effect of the vertical divertor geometry. The result also indicates that complete power detachment is attained for the inner divertor, but partial detachment is attained for the outer divertor. It was observed in experiments that flow reversal disappears with divertor detachment. In our modelling, this flow disappears in the inner divertor, while in the outer divertor the reversal region shrinks but does not disappear, which might be attributed to the partial detachment.

4. Summary and conclusions

In order to increase the degree of closure, the HT-7U divertor structure is designed to be deep and well baffled. Its vertical target plates preferentially reflect neutrals towards the separatrix and hence are beneficial to improve the power exhaust. In the low recycling regime, the temperature is high and the peak heat flux at the target exceeds the engineering constrain. Performing in the high recycling regime leads to the peak heat flux below 3.5 MW/m^2 and makesthe Z_{eff} an ideal value of 1.4. The operating window, however, is rather narrow due to the density limit required for non-inductive current drive efficiency. To attempt detachment for the HT-7U divertor, additional approach such as gas puffing or impurity seeding should be adopted. The vertical divertor geometry also has effects on the detachment behavior.

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