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Plasma and Neutral Transport Study of Local Island Divertor Configuration in Large Helical Device Edge Region with 3D Monte Carlo Codes

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Abstract

Edge transport physics of the Local Island Divertor (LID) configuration in Large Helical Device (LHD) is studied with the 3D transport code package, EMC3-EIRENE [Y. Feng *et al*., Contrib. Plasma Phys. **44**, 57 (2004)] [D. Reiter, Technical Report Jul-1947, KFA Juelich, Germany (1984)]. Particularly, the behaviour of neutrals around the divertor region was investigated, where it was found that the resulting profiles of atom and molecular density as well as temperature are considerably different each other. The cause of these difference is discussed.

Keywords:

edge transport, 3D modelling, Monte Carlo, application of atomic/molecular data, Large Helical Device (LHD), Local Island Divertor (LID)

1. Introduction

Demands for edge transport modelling (plasma and neutrals) in magnetically confined devices such as tokamaks and stellarators have been increasing in order to interpret experimental results and to also predict relevant physics of upcoming devices like ITER. Much efforts has been paid for the works in the last decades, and the modellings, simplest in 1D along flux tubes and often in 2D in poloidal cut, have successfully applied for these purposes [1].

An assumption of an axisymmetry accepted widely so far in 2D tokamak computations, however, may have to be relaxed to cope with the observed toroidally asymmetric profiles, *e.g.* plasma or/and impurity deposition pattern on the divertor plates that might be attributed to any toroidal un-uniformity caused by gas puff, NBI, toroidal coil ripple etc. Yet in devices which inherently have a 3D magnetic structure such as stellarators or tokamaks with special configuration, *e.g.* W7-AS, W7-X, TEXTOR-DED and LHD, a 3D treatment is an only approach to an understanding of transport properties therein.

A 3D modelling of the edge transport taking into account recycling neutrals from wall and thus relevant atomic/molecular processes was first implemented in W7-AS with the codes, EMC3 [2] (plasma part) and EIRENE [3] (neutral part). The codes could successfully reproduce the experimental results and helped understanding well the transport physics that are sometimes unique to the 3D magnetic structure. The modelling has been extended to other machines, i.e. TEXTOR-DED [4] and W7-X [5], to predict the edge transport or to optimize the design.

The purpose of this paper is to implement the codes, EMC3-EIRENE, in the Local Island Divertor (LID) configuration [6] of LHD which also exclude any 2D approach due to its inherent 3D magnetic structure, and to demonstrate a feasibility of the codes with the configuration. In this paper, particularly the behaviour of neutrals is discussed.

2. Model of plasma & neutrals

EMC3 solves the standard plasma fluid equations [7] of conservation of mass, momentum and electron & ion energy, in steady state, with a Monte Carlo scheme [8]. EIRENE solves neutral kinetic transport equations with a Monte Carlo scheme [3]. Both codes work in almost arbitrarily complex 3D geometry of plasma and wall components. The codes are iteratively coupled each other via source/sink terms appearing in the plasma

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equations, i.e., particle source due to ionization, momentum and energy source/sink due to charge exchange (CX), dissociation and elastic collisions between ions and neutrals, respectively. At material surfaces, the Bohm condition is imposed for particle and heat flux of plasma, and the deposition pattern on the surfaces is obtained taking into account the incident angle of field lines. Recycling neutrals from the LID head (divertor surface) are released with weights being proportional to plasma particle deposition pattern. The released neutrals are atoms or molecules based on TRIM model assumed on the divertor surface of carbon with a recycling coefficient of 1. The neutrals experience following atomic/molecular processes [9] activated in EIRENE in the present computations. Among those, the most important processes are

Atoms(H)

$$e + H(1s) \rightarrow e + H^+ + e \text{ (ionization)}$$

$$p + H(1s) \rightarrow H(1s) + p$$

$$\text{(charge exchange + elastic component)}$$

Molecules(H_2)

$$e + H_2 \rightarrow e + H_2^+ + e \text{ (ionization)}$$

$$p + H_2 \text{ (elastic collision)}$$

H_2^+

$$e + H_2^+(v) \rightarrow e + H_2^{+*} \rightarrow e + H^+ + H(1s)$$

$$\text{(ionization).}$$

3. LID configuration

The magnetic field configuration together with the LID head and the baffle are shown in Fig. 1, in a poloidal cut at the center of the LID head. A magnetic island of $(m,n) = (1,1)$ is induced at the edge region, utilizing the separatrix as SOL to guide the plasma to the

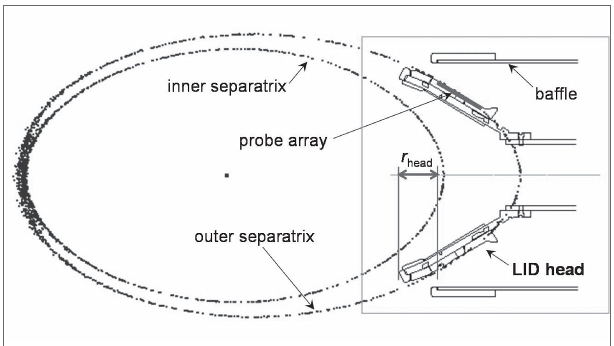

Fig. 1 Schematics of LID head and the pump duct together with the separatrix of $(m,n) = (1,1)$ island, at $\phi = 162^\circ$.

back side of the LID head, where the collected plasma is pumped out. The systems are movable separately in horizontal direction in order to adjust a pumping efficiency (particle collection efficiency).

4. Implementation

The present computations are corresponding to the shots 41691 and 41696: major radius of magnetic axis (R_{ax}) is 3.60 m, P_{NB} (input power) = 1.4 MW, r_{head} (LID head position) = −118 mm. Spatially constant cross field particle & heat diffusivities (D, χ_e, χ_i) are used in EMC3 to simulate an anomalous perpendicular transport. The values are set to best fit the measured radial profiles of density and temperature. For the shots in concern, those were selected as $D = 0.3\,\mathrm{m^2/s}$, $\chi_e = \chi_i = 0.8\ \mathrm{m^2/s}$, respectively, which are in agreement with the values estimated in Ref. [10]. In the present computations, the plasma parameters in the divertor regions were, on an average, found to be $T_e \sim T_i \sim 5$ eV and $n \sim 10^{20}\ \mathrm{m^{-3}}$. The estimated ion saturation current from these results were found in good agreement with the probe measurements.

5. Behaviour of neutrals

A high neutral compression in the divertor region is expected from the closed structure of LID head and the baffle. This is confirmed in Fig. 2, where atom and molecule densities around the divertor region are plotted in logarithmic scale normalized with maximum values of 3.3×10^{19} and $2.3 \times 10^{20}\ \mathrm{m^{-3}}$, respectively. In the figures, one sees the densities are higher inside the divertor than outside by at least one order. The atom density peaks near the divertor surface where the recycling is occurring, whereas the molecule density becomes higher deep in the pump duct, where there are more chances for atoms to recombine into molecules in course of surface reflections. The elastic collision, $p + H_2$, whose cross section becomes higher in lower temperature [11], pushes back these molecules into the duct. This is the reason why the molecule density decreases towards the divertor surface, as shown in Fig. 2(b).

Shown in Fig. 3 are the temperature profiles of atom and molecule, which were obtained by energy density ($\mathrm{eV/m^3}$) divided by particle density ($\mathrm{m^{-3}}$). Because of the very low particle density outside the divertor, i.e. the statistical error, the temperature there is not reliable, so that we will restrict our discussion only in the divertor region. It is seen that the atom temperature is rather high, about 4 eV almost throughout the pumping duct, while the molecule's is around 1 eV and decreases down to room (wall) temperature deep in the duct (note the

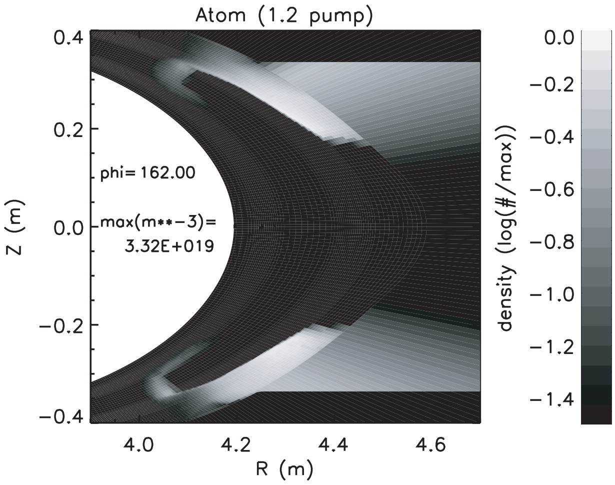

Fig. 2 (a) Atom density profile around the LID head, in logarithmic scale normalized to the maximum density of 3.3×10^{19} m^{-3}. The LID head is depicted with the black background.

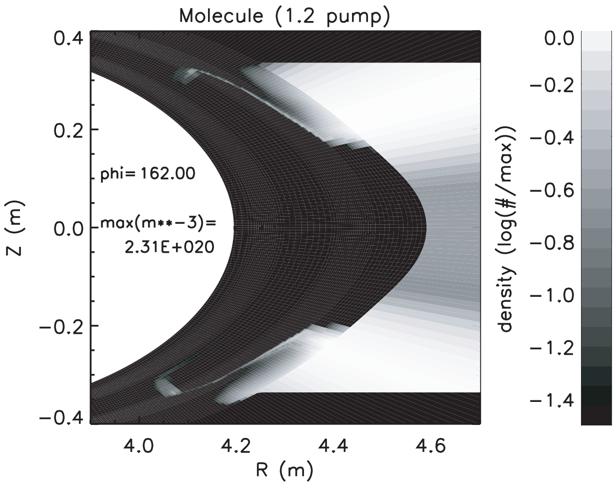

Fig. 2 (b) Same as Fig. 2 (a) but for molecule, normalized to 2.3×10^{20} m^{-3}.

different scale for each plot). The difference of the profiles deep in the duct is attributed to the reflection model at the material surfaces, in which the atom carries still significant fraction of incident energy after reflection, whereas the molecule is first accommodated in the wall then released with the wall temperature that is assumed to be room temperature.

Another reason for the difference is considered due to energy gain/loss channel with plasma. Atoms gain/loss energy through CX (plus elastic collision) and ionization. In the parameter range given above, mean free paths for the reactions are estimated as, $\lambda_{CX,elastic} \sim$ a few cm, $\lambda_{ion} \sim$ a few tens cm, respectively, so that CX is a dominant process of, probably, energy gain from plasma. The code results showed that practically the energy exchange is a net gain for atoms of 5 % of input power. For molecules, the processes are more complicated as shown in sec. **2**, and there are several channels of energy exchange that are also tightly linked with H_2^+. Although a dominant energy gain is the elastic collision which has almost same cross section as that of CX for atoms with the present parameter range, the reactions that produce H_2^+ take away some of the gained energy, which are then mainly given back to plasma (2.2.12, 2.2.11). The obtained proportion is, a gain for molecules of 3.5 % of input power, while loss for H_2^+ of 1.8 %, respectively. These are considered the reasons giving such differences in the temperature profiles in atoms and molecules. As a result, the neutral pressure of 1 to 5 Pa in the duct and a neutral compression ratio, $p_{0,div}/p_{0,sep} \sim 30$ ($p_{0,div}$ and $p_{0,sep}$ are neutral pressure at divertor and separatrix (upstream), respectively), are obtained in the configuration, that are comparable to the numbers achieved in various tokamaks with closed divertor configurations [12,13].

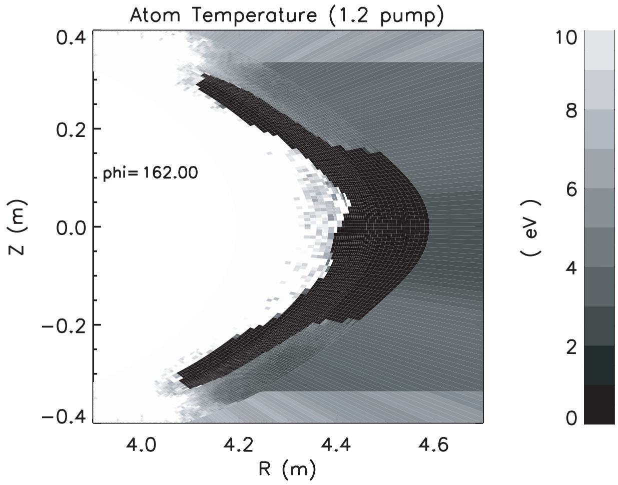

Fig. 3 (a) Atom temperature profile around LID head.

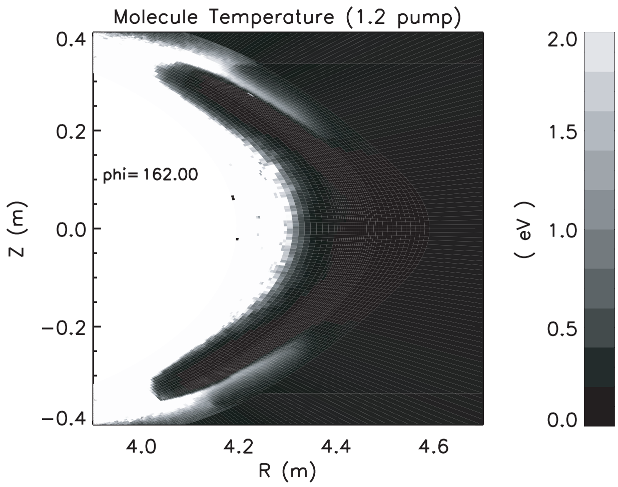

Fig. 3 (b) Molecule temperature profile around LID head.

The energy loss/gain discussed above is still small compared to that via electron (through ionization, excitation, dissociation) which is about 30 % of input power. But the former component is directly converted to the neutral energy (momentum) and it then affect neutral pressure in divertor region. This is an important process in terms of edge density control and also helium ash removal by pumping in fusion devices [14], not only in LHD but also for forth-coming machines like ITER.

The reflection model of molecules at the wall may have to be still improved with higher energy reflection coefficient as for atoms. Also an elastic collision between atoms and molecules would equilibrate the temperatures to some extent, which has not been taken into account in the present runs. These are the next step studies.

6. Summary

The 3D edge transport codes, EMC3-EIRENE, for plasma & neutrals, was successfully implemented in LID configuration of LHD. We particularly investigated neutral behaviour in this paper and found,

1. The closed divertor structure gives rise to high neutral density in the duct, giving pressure of 1 to 5 Pa and $p_{0,div}/p_{0,sep} \sim 30$.

2. Neutral density and temperature can differ significantly depending on the species (atoms and molecules) in the divertor region. The difference is attributed to the energy gain process from plasma and the wall reflection model for each species.

In order to give an accurate estimation of the neutral profile in divertor region that is important in terms of the edge density control by pumping, helium ash removal, chemical sputtering etc., the survey on the issue must be continued.

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