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Three-dimensional transport of neutral particles in the CHS edge region

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Abstract. We used Monte Carlo simulation code DEGAS and studied the neutral particle behavior in the Compact Helical System (CHS) three-dimensionally. In contrast to other helical devices, the CHS plasma in the standard configuration has contact with the inner vacuum vessel wall like the material limiter used in many Tokamaks and the neutral recycling becomes dominant there. As the intensity of neutral recycling changes also along toroidal direction, we extended our previous simulation model geometry three-dimensionally and compared the results of these models. We found the variation of the gap between the vacuum wall and main plasma enhanced toroidal transport of hydrogen molecules and atoms. As the formation of the edge transport barrier (EBT) discovered recently in CHS is characterized by a clear drop in Hα emissions, it is interesting to study the relationship with the profile of atomic/molecular hydrogen and the Hα emission profile. We estimated emission not only from excited hydrogen atoms but also from dissociated molecules with a collisional radiation model. We found that our Hα detector signal in CHS mostly came from excited atoms and that the emission profile largely changed with the ETB formation.

1. Introduction

Improvement of plasma confinement such as the H-mode is one of the most urgent issues in fusion research. The edge transport barrier (ETB) discovered recently in the Compact Helical System (CHS) [1] is characterized by a clear drop in Hα emissions. As Hα emission intensity is often used as the measure of recycling particle flux, particle confinement seems to be improved. Quantitatively, however, this conclusion must be checked carefully, since Hα emission has a deep relationship with the profile of atomic/molecular hydrogen, which is so complicated that their experimental study is difficult in helical systems such as CHS.

In order to study the neutral particle behavior in CHS, we have used the Monte Carlo simulation code DEGAS [2]. The two-dimensional axial-symmetric model and its preliminary results have already been reported in [3]. In this work, we expand the simulation model into three dimensions to include the toroidal behavior of neutral particles [4], and compare the results for plasma conditions with/without ETB.

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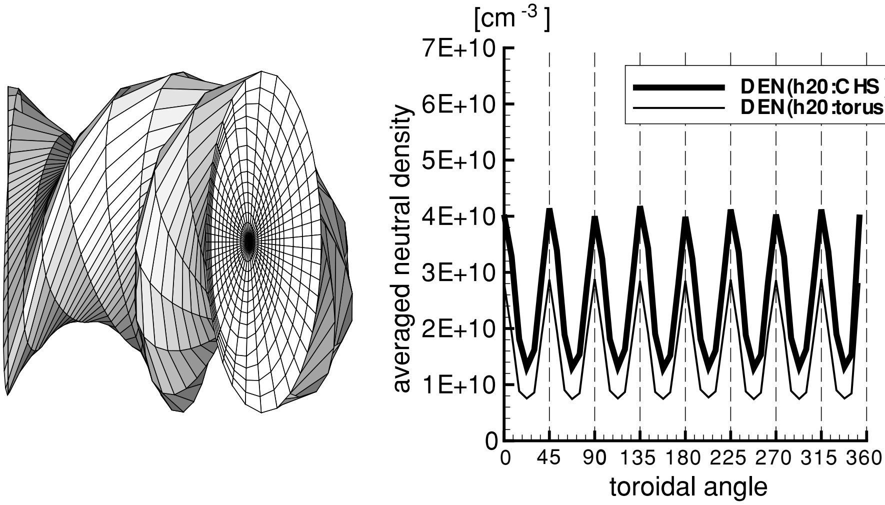

(a) (b)

Figure 1. (a) Three-dimensional simulation geometry for CHS and (b) comparison of the toroidal variation of molecular hydrogen density for 'CHS' and 'torus' geometries.

2. CHS model geometry

In contrast to other helical devices such as the Large Helical Device (LHD), the CHS plasma in the standard configuration has contact with the inner wall like the material limiter. Moreover, the gap between the vacuum wall and main plasma varies along the toroidal direction. For example, at the toroidal cross section with toroidal angle $\phi = 0°$, where magnetic surfaces are elongated vertically, core plasma has contact with the chamber wall inside of the torus major radius direction and the neutral recycling becomes dominant there. However, at the other toroidal cross section with $\phi = 22.5°$, a partial magnetic limiter configuration is established and there exists no direct contact between the main plasma and the wall material.

Using the KMAGN code, we computed the 10 magnetic surfaces at 48 toroidal cross sections, and drew 45 iso-poloidal lines from magnetic axis. We used intersection points in magnetic surfaces and these lines as grid points. In the vacuum region between the last closed flux surface (LCFS) and the chamber wall, we extrapolated three other radial meshes. So our full three-dimensional calculation geometry for CHS is divided into 45 poloidal zones, 13 radial zones, and 48 toroidal zones (see Fig. 1).

Plasma parameters such as electron density and temperature in these zones are determined on the basis of CHS plasma measurement data. Experimental data are mostly obtained one-dimensionally. So, homogeneity on magnetic surfaces are assumed. This must be checked in future work, especially near and outside of the LCFS.

As the intensity of neutral recycling changes also along the toroidal direction, we set eight neutral particle sources at the inner wall of vertically elongated toroidal cross sections, since CHS helical coils have toroidal periodicity of $m = 8$. There is no sink of neutral particles in this model, so we chase neutral particle flights until they are ionized in core plasma. The total intensity of sources are estimated from the particle confinement time.

3. Results

Experimental information on neutral particles is obtained through Balmer line emission (mainly Hα). Until now, we had no Hα detectors at the source (vertically elongated) cross section of CHS. As neutral particles entering into core plasma are soon ionized, neutral particles existing at other toroidal cross sections are transported through the gap between the vacuum wall and main plasma. Our Hα data may suffer the effect of this transport. We found that the toroidal variation of this gap enhanced the transport of hydrogen molecules and atoms. In Fig. 1(b), we compare the toroidal distribution of molecular hydrogen density for 'CHS' geometry and 'torus' geometry. The latter is equivalent to axial-symmetrical geometry with the same cross section as that of CHS at the toroidal angle $\phi = 0°$. As the gap between the vacuum wall and main plasma is kept narrow for 'torus', neutral density between neutral source section is smaller than 'CHS' geometry. If the poloidal extension of the effective recycling region is large, however, the chance for neutral particles to be transported poloidally becomes larger and the difference between 'CHS' and 'torus' may be smaller. So the precise modeling of the recycling region is important [3].

According to the collisional radiation (CR) model [5, 6], the population density of an excited level with principal quantum number p is given by

$$n(p) = R_0(p) n_i n_e + R_1(p) n_H n_e + R_2(p) n_{H_2} n_e \tag{3.1}$$

where population coefficients (R_0, R_1, R_2) can be calculated by Sawada code [5]. They are less dependent on plasma density ($n_e = n_i$) and the weak increasing function of T_e. The first term of the right-hand side of (3.1) is the contribution from recombining ions. In the CHS edge parameter region, R_0 is much smaller than R_1 or R_2 and this term can be negligible. Since the molecular hydrogen density is much larger in the recycling region than atomic density, we must estimate Balmer series emission not only from excited atoms (i.e. the second term of (3.1)) but also from dissociating molecules (i.e. the third term).

In Fig. 2, we calculate the Hα emission profile from the atomic hydrogens profile with the CR model. The two cross sections correspond to those where Hα detectors (indicated as 2O, 2O-3, and O-4) are set down. In these cross sections, Hα emission from molecular hydrogens is much smaller than that from atoms and more localized near LCFS, since the penetration length of molecules is much smaller. When ETB is established, the plasma density profile becomes broader and neutral penetration into plasma is inhibited. So the peak of the Hα emission profile drops and the emission area also shrinks not only radially but also poloidally. In particular, the emission profile of Hα from molecular hydrogens becomes very narrow.

The reason for the drop in measured Hα signal is still unclear. The change of emission profile (reduction of emission area, total peak intensity, and so on) along the detector line of sight must be studied more carefully. Unfortunately, in our Monte Carlo simulation, the number of test particles is not sufficient especially at the region where neutral density is low and test particles rarely visit. Due to this reason, there exist noisy peaks of Hα emission inside of the LCFS in Fig. 2. Increasing the number of test particles will reduce these statistical errors. More accurate estimate of drop with Hα signals with ETB formation is left for future work.

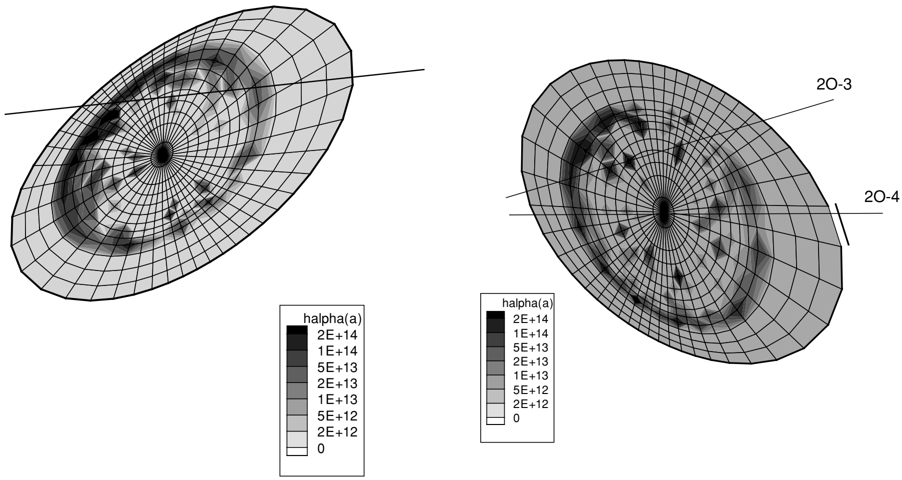

Figure 2. Hα line intensity profiles calculated from DEGAS simulation results with CR model. (a) Cross section where 2O detector locates and (b) 2O-3 and 2O-4 detectors. Straight lines in the figure are the line of sight of the detectors.

4. Conclusions

The obtained results are summarized as follows.

• Neutral particle density is strongly localized near the recycling region. The complex three-dimensional shape of the vacuum vessel and the LCFS have a large effect on the toroidal transport of neutrals.

• In CHS edge plasma, Hα emission is mainly from atomic hydrogen deeply penetrated into core plasma.

• With the formation of ETB, neutral penetration into plasma is inhibited. So the emission profile of Hα, especially from molecular hydrogens, becomes narrow.

Acknowledgement

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