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3D Monte Carlo simulation for H-alpha Spectra observed in Compact Helical Systems

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Neutral particle behavior and H alpha emission spectrum in Compact Helical System (CHS) are simulated with Monte Carlo code DEGAS. In this work, we include the detector information into mesh model data and effect of chamber wall shape is examined. Which pathway generating H(n = 3) has main contribution in H alpha spectra is also studied.

Keywords: DEGAS, CHS, Warp boundary, H-alpha spectra, molecular dissociation

1. Introduction

Development of heat flux reduction method on divertor plate is an important issue for the future fusion reactor design. One of most promising scenario is to establish so-called detached plasma, whose electron temperature is kept below 1[eV] by powerful gas puffing. This scenario is applied to Tokamak reactor design such as ITER. In detached situation, neutral particles are expected to experience not only transport but also atomic/molecular process such as dissociation, ionization, and so on. So monitoring and control of neutral particles are very important tasks.

Experimentally, the neutral behavior is often monitored with H alpha emission intensity and spectrum. H alpha line emission results from radiative decay of exited hydrogen atoms from the principal quantum state $n = 3$ to $n = 2$. The line intensity is the measure of density of H($n = 3$) and its wavelength spectra reflects the velocity distribution of hydrogen atoms. However, due to limited ports and channels, cross check of observed spectrum with numerical simulation results is indispensable. Moreover, there are some groups of neutral particles with different velocity distribution and it is difficult to decompose observed spectrum uniquely and to determine the elementary process which produce each neutral particles groups, since some group has the similar characteristic energy.

On the other hand, simulation with Monte Carlo code such as DEGAS [1] can trace each neutral groups' behavior and estimate their contribution to H alpha spectra component, provided that reasonable simulation model (3 dimensional mesh geometry, back ground plasma parameter, neutral source, etc.) is given. In the previous study [2], DEGAS neutral transport simulation code (ver.63) has already been applied to complicated edge region of Compact Helical System (CHS) and given us neutral particle information. It also contains the routine to treat various H-alpha emission processes, and spectra profile to be compared with experimental data is also obtained. However, information on edge plasma parameters is practically insufficient in CHS and appropriates assumptions are made for 3-D simulation and simulation models themselves must be improved with observation data.

In this work, we include the detector information into mesh model data for CHS, and calculate H-alpha chordal intensity and spectra. In CHS standard magnetic configuration, neutral sources is localized poloidally and toroidally and visible detector is located near one of them. So in order to improve toroidal mesh resolution, model geometry is changed from full tours to a quarter sector [3], and effect of chamber wall shape is also examined. Which pathway generating H($n = 3$) has main contribution in H alpha spectra is also studied.

In section 2, we explain device parameter and new simulation model geometry of CHS briefly. In section 3, we present some simulation results on H alpha emission profile. Section 4 shows contribution of various pathways generating H($n = 3$) to H alpha spectrum. Section 5 is the summary.

2. Model geometry

CHS is a heliotron device with major radius of 1 [m] and minor radius of 0.2 [m]. The pole number of the helical field coil is $\ell = 2$ and toroidal periodic number is $m = 8$. Profiles of plasma density and temperature are measured with YAG Thomson scattering. The Li-beam probe is also used to edge plasma measurement [4].

In order to study with DEGAS, core plasma and "vacuum" region is divided into 45 zones poloidally and into 13 zones radially. Nine radial zones are determined by using KMAGN code [5]. Other four zones are interpolated between the chamber wall and the Last Closed Flux Surface (LCFS). In the previous

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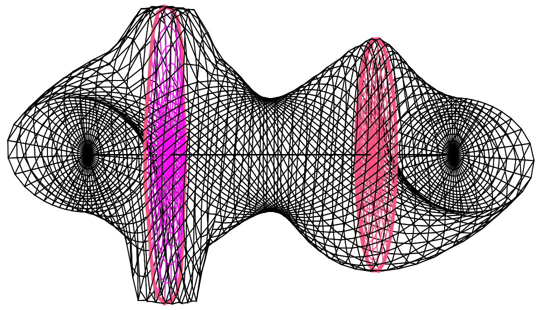
study[2], in order to construct the 3 dimensional mesh (called here as FULL), toroidally 48 cross sections are selected for full torus ($\phi = 0 \sim 360$[deg.]) and $\Delta\phi = 7.5$[deg.]. There isn't any sink of neutral particles in this model, so we chase neutral particle flights until they are ionized in core plasma.

About 30 optical fibers for visible light detector array in CHS [6] are set on vertical elongated cross section (toroidal angle $\phi = 0$ [deg.]) through a large vertical port, whose diameter is 30[cm]. In this cross section, the CHS plasma boundary in the so-called standard configuration, where magnetic axis exists at $R_{ax} = 92.1$[cm], is limited by the chamber wall inside of the torus major radius direction and the neutral recycling occurs there.

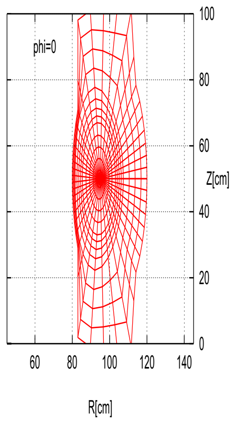
The FULL model does not consider this port duct and, since toroidal extension of the port is about 4.5[deg.], it is difficult to modify model geometry to include exactly the port shape. In this paper, simulation domain is restricted to a quarter sector of a torus and divided to 40 zones like Fig.1. Toroidal domain is from $\phi = -22.5$[deg.] to $\phi = 67.5$[deg.]. Since CHS helical coils have toroidal periodicity of $m = 8$, this domain corresponds to two toroidal pitches. Toroidal boundary at $\phi = -22.5$[deg.] and $\phi = 67.5$[deg.] is set as "Warp" boundary. A particle which crossed $\phi = -22.5$[deg.] section is moved artificially to another boundary at $\phi = 67.5$[deg.] and reinjected so as to keep relative velocity direction with the helical structure of chamber and LCFS.

In this new model (called here as DUCT2), a vertical port is included at the toroidal cross section with toroidal angle $\phi = 0$[deg.] (Fig. 1(b)) and another vertically elongated section at $\phi = 45$[deg.] (Fig. 1(c)) remain to be the same as the old models in order to compare the effect of a port duct.

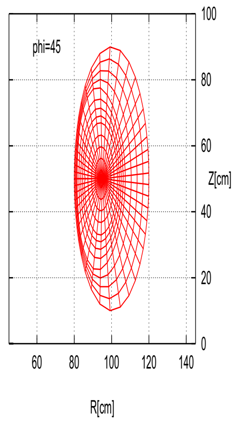
Plasma boundary is limited by inner wall of vertically elongated toroidal cross sections ($\phi = 0$ and 45[deg.]). So we set 2 neutral particle sources and the total intensity of sources is reduced by a factor of 0.25 compared with FULL model. CHS has two NBI beam lines and they could become high energy neutral source. But in present simulation, we consider only recycling at the chamber wall as the neutral source.



(a) Global Frame

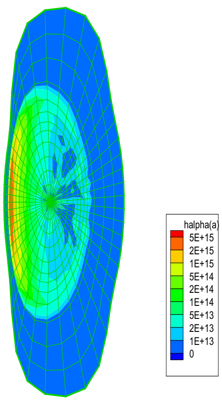


(b) Duct section

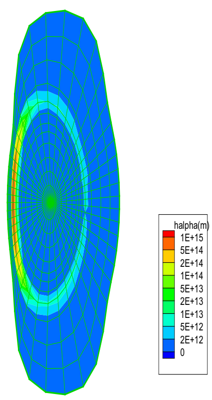


(c) No duct section

Fig. 1 Calculation geometry for the DEGAS simulation. Core plasma and vacuum region is divided into $45 \times 13 \times 40$ zones.



(a) From H



(b) From H_2

Fig. 2 H-alpha emission on toroidal angle $\phi = 0$ [deg.] cross section for standard configuration of CHS. Magnetic axis exists at $R_{ax} = 92.1$[cm] and chamber walls at the equator plane exist at $R = 80$ and 120[cm].

3. H alpha chordal integrals

In the previous study [7], it was found that in the edge region of CHS, H alpha emission from atomic hydrogen is dominant. Contribution from molecular hydrogen is limited only around the last closed flux surface (LCFS), where n_{H_2} is still large. This is shown in the Fig.2. Hydrogen molecules are launched at inner wall source as recycling and most of molecules are dissociated to two hydrogen atoms by the collision with core plasma. As some atoms have large energy from Frank Condon process, they can penetrate deeply into core plasma and emit H alpha line after electron impact excitation. (see Fig. 2(a).) As

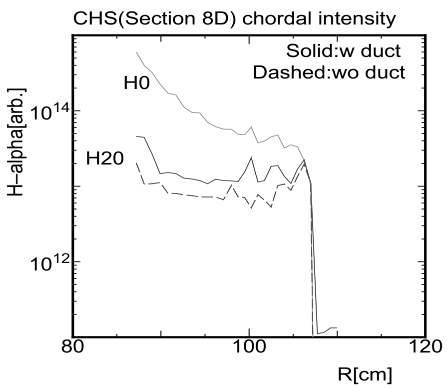
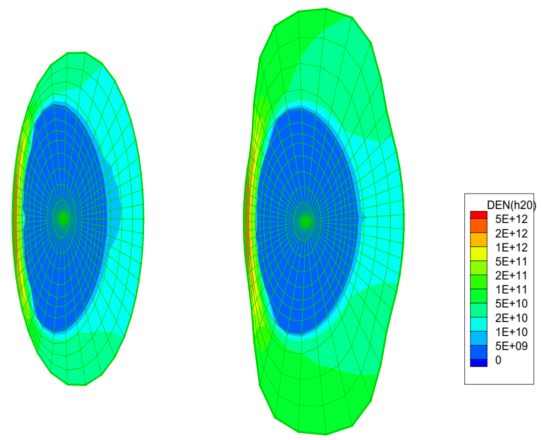


Fig. 3 H alpha chordal integrals in CHS. H alpha from atomic contribution (2(a)) is denoted with "H0" and shows no difference between duct section (Fig. 1(b)) and no duct section (Fig. 1(c)). H alpha from molecular contribution ("H20" and Fig. 2(b)) shows slight difference.



(a) No duct section

(b) Duct section

Fig. 4 Hydrogen molecular density on no duct section (Fig. 1(c)) and duct section (Fig. 1(b)) for standard configuration of CHS.

transport of hydrogen molecules in poloidal and radial direction is hindered by core plasma, they move along toroidal direction and spread to all vacuum domain. At LCFS, these molecules are easily dissociated and contribute H alpha emission by producing excited atoms directly.(see Fig. 2(b).)

Experimental data on H alpha emission profile is obtained as chordal integrals for visible light detector array. Figure 3 shows the simulation result of H alpha chordal integrals. Horizontal axis is major radius (R) and contributions from hydrogen atoms and molecules are plotted separately. Simulation result seems to agree well with experimental data, although increase at $R < 90$[cm] and decrease at $R > 107$[cm] are somehow steeper. As emission intensity is dominated by hydrogen atomic contribution especially at torus inside, the existence of a port duct has no significant effect on H alpha chordal integrals. However molecular contribution shows slight difference for no duct section (Fig. 1(c)) and duct section (Fig. 1(b)). So H alpha spectrum shape may need to be studied more carefully.

Figure 4 compares hydrogen molecular density contours for no duct section ($\phi = 45$[deg.], Fig. 4(a)) and duct section ($\phi = 0$[deg.], Fig. 4(b)). As neutral particles entering into core plasma are soon ionized and can not move long distance, their toroidal transport through the gap between chamber wall and core plasma determines the neutral density profile. If a viewing port duct is included, there might exist leakage of neutrals toward the viewing port. In fact, poloidal transport of hydrogen molecules is a little enhanced and their contribution to H alpha emission also increases due to this geometrical effect.

4. H alpha spectrum

H alpha line results from radiative decay of exited hydrogen atoms from the principal quantum state $n = 3$ to $n = 2$. Since there are many pathways to generate H($n = 3$), many groups of H($n = 3$) with different density and characteristic energy exist and contribute H alpha spectrum. In this section, which pathway is important is studied. DEGAS ver.63 used here considers 10 pathways [8].

Figure 5 shows the spectra calculated with present CHS mesh model (DUCT2) and detector sight line of $\phi = 0$[deg.] and $R_{det} = 85.0$[cm]. Similar results for divertor simulator MAP–II [9] has already been reported in [10]. Compared with MAP–II, there are two new pathways which have large contribution in CHS. One (green line in the figure) is H2+DI($e + H_2^+ \rightarrow H + H^+ + e$), and another (blue line) is H2DS($e + H_2 \rightarrow 2H + e$). These pathways produce hydrogen atoms in grand state. Since CHS edge plasma has higher density ($\sim 10^{13}$[cm^{-3}]) compared with MAP–II, these atoms are easily excited to $n = 3$ with electron impact and contribute H alpha emission.

Figure 6 shows the simulation result for $R_{det} = 107.0$[cm]. As shown in previous section, whereas electron impact excitation of hydrogen atoms is dominant in H alpha emission in inside channel, contribution of hydrogen molecular dissociation becomes large in outside channel. In this figure, contribution of pathways H2+DI and H2DS decreases significantly compared with $R_{det} = 85.0$[cm]. Contribution reduction of pathways with hydrogen molecules and molecular ions is rather small. So dominant pathways are H2DE($e + H_2 \rightarrow H(n = 3) + H^+ + 2e$,black) and H2+DI($e + H_2^+ \rightarrow H(n = 3) + H^+ + e$,yellow).

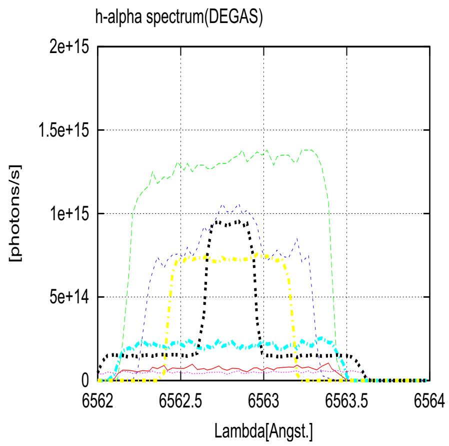


Fig. 5 H alpha spectrum for CHS inner sight at $R_{det} = 85$ [cm].(Black:H2DE, Green:H2+DI, Blue:H2DS)

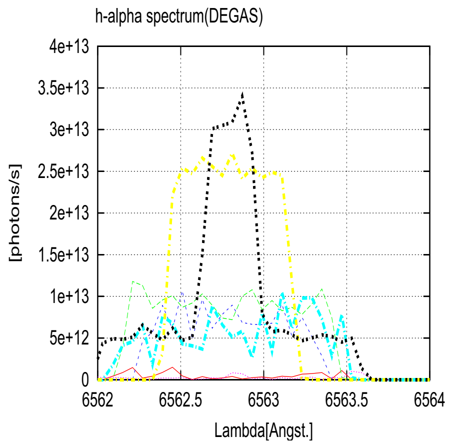


Fig. 6 H alpha spectrum for CHS outer sight at $R_{det} =$ 107 [cm].

Considering atomic/molecular data, there might exist another fast pathway to produce hydrogen atom (H_2+$H_2^+ \rightarrow H$+H_3^+) which is not included in present DEGAS code [8]. Produced atoms with this pathway stay at ground level, since H_2 has lower energy than electrons. So in order to contribute to H alpha emission, electron impact excitation will be necessary. H_3^+ behavior and contribution to H alpha spectra is left for future improvement of simulation code.

By summing up of all pathway contribution, H alpha spectra shape is obtained. One example for center sight line is shown in Fig.7. Global shape of calculated spectrum well agrees with experimental data for this this sight line ($R_{det} = 97$[cm]). But similar simulation result for $R_{det} = 107$[cm] is is somehow different. As shown in Fig. 6, atomic contributions such as H2+DI and H2DS decreases, spectra shape for outer sight line is expected to become narrow and the tail component of spectra is to be small. But no experimental observation of such a change was reported. One possibility

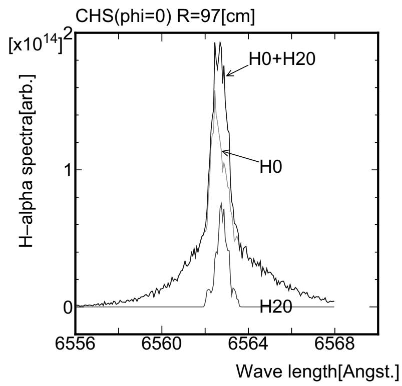


Fig. 7 H alpha spectrum for CHS center sight line at $R_{det} = 97$ [cm]. Three lines show contributions from atom, molecule, and their summation.

is the neutral source with NBI. In this simulation, we consider only recycling at inner wall. But there exist high energy ion produced by NBI heating. If these ions experience charge exchange with penetrated atoms, high energy atoms will be born. Although number of these atoms is small, they might contribute to H alpha spectrum tail.

5. Summary

Obtained results in this paper are summarized like the following.

- CHS 3D mesh model for DEGAS simulation is reconstructed and toroidal resolution is improved with “Warp” boundary condition.
- There is good agreement between experiment in CHS and DEGAS simulation on H alpha chordal integrals profile.
- Effect of a port duct on simulation result is not so large, especially for H alpha emission profile.
- There exist a few dominant pathways to produce excited H atoms which depend on detector sight line. High energy atom contribution to H alpha spectra profile seems to be underestimated in present simulation.

In order to compare simulation results and experimental observation quantitatively, more detail modeling of neutral source and improvement of statistical accuracy will be needed. These are left for the future work. Comparison with simulation results of other codes with different atomic/molecular/surface data base will also be an important task.

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