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Transport simulation analysis of peripheral plasma with the open and the closed LHD divertor
開／閉LHDダイバータ配位における周辺プラズマ輸送シミュレーション解析

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Simulation modeling of the ergodic and divertor plasmas of the Large Helical Device (LHD) and its application to analysis of neutral particles, plasma, and impurity transport is presented. EMC3-EIRENE simulation with a new calculation mesh system is employed to evaluate effects of different divertor configurations: the open and the closed divertor. Effects of gas pumping were investigated to understand recycling. Difference of particle source which compensates the gas pumping is elucidated. Particle deposition in the core by NBI and palette causes significantly lower electron density in divertor regions than gas puffing. Impurity accumulation and impurity screening in the ergodic region were investigated and differences caused by the configurations are evaluated. The closed configuration causes large impurity accumulation but the impurity screening effect suppress the accumulation at the same level of as the open configuration.

Divertor configuration of Large Helical Device (LHD) has been modified to the closed one to control neutral transport and achieve efficient pumping. Evaluation of its effects on the plasma is an argent issue. Different configurations lead to different transport and recycling and therefore investigations of global transport in realistic configuration are essential for understanding and control of the plasma. We employ EMC3-EIRENE code [1,2], which is a fluid code with Monte-Carlo technique and has the capability of resolving perpendicular transport across a magnetic field line in 3D space.

The peripheral plasma of the LHD has been model by EMC3-EIRENE code and simulation studies have been performed [3-5]. Modeling of LHD peripheral plasmas by fluid-description of parallel transport and diffusive terms of perpendicular transport are discussed in Ref. [3]. Extension of the simulation model to the closed divertor configuration [6] is realized effect of different divertor configurations on neutral gas pressure is investigated in Ref. [5]. We modeled a 1/20 toroidal block of the LHD plasma. The simulation region consists of plasma and vacuum regions and they cover every cross section of the vacuum vessel. The plasma mesh system of EMC3 covers the peripheral plasma which has long connection length, roughly >10m. The core region is excluded from the simulation and modeled as boundary conditions at the last closed flux surface (LCFS). The magnetic axis is located at R_{ax}=3.6m and the vacuum field, i.e., zero beta value, is employed to make the mesh.

Cryopumps have been installed under the dome structure of the LHD and evaluation of their efficiency started in the 2013 experiment campaign. In order to know the effect of the gas pumping, we carried out simulations with pumps. We introduced pumping panels with zero reflection probability on the backside of the dome plates. We ignore the effect of wall-pumping to focus on the pumps. Particle source and sink must be balanced in the simulation box, and therefore we model two types of sources: gas-puffing and core fueling. In the actual device, both of them exist in a discharge, but we employ the two extreme conditions of 100% gas-puffing and 100% core fueling. The gas puffing is implemented as an increase of recycling flux from the divertor plates in the code. Approximately 20% of neutral gas input is pumped out in both cases. That rate is roughly the maximum performance of the pumps determined by geometrical factors. Simulation parameters are as follows: input power, P=8MW, perpendicular particle and heat transport coefficients, D=1m^2/s, $\chi_e=\chi_i$=3m^2/s, electron density at LCFS, $n_e=2\times10^{19}$/m^3.

Neutral gas pressure distribution in the closed configuration is given in Fig.1: (a) no pumping, (b) pumping and gas-puffing and (c) pumping and core fueling. The most obvious difference between them is the significant reduction of the pressure when the source is core fueling. That change is linked to the boundary condition of electron density. The core fueling increases the LCFS density directly if the perpendicular transport coefficient D is constant. The density is fixed as a boundary condition and therefore ionization source in the ergodic/divertor regions must be reduced. The difference between no pumping and pumping with gas-puffing is not clear in pressure distribution except under the dome, where the pressure is reduced to approximately 1/5.

Figures 2(a) and (b) show distribution of electron density and temperature along z=0 line for three cases; without pump (red line), with pump and gas-puffing (green line), and with pump and core fueling (blue line). The gas-puffing condition causes almost the same plasma distribution as without the pump. That is a reasonable result because neutral particles pumped out are injected again and therefore the recycling flux does not change to sustain the same electron density at the LCFS. On the other hand, the core fueling condition causes significantly lower density and higher temperature by a factor of two in the outer region, R>4.6m. This is understood by increasing the plasma source in the core and decreasing recycling flux.

Figures 2(c) and (d) show distribution of H_2 molecules and H atoms. The difference between conditions without pump and with gas-puffing is not significant. Molecule and atom densities increase a little in this case, but how the density increases depends on measurement position. In fact, we observe an opposite result at a different position. This subtle difference arises from the different distribution of the neutral source. The change caused by core fueling is clear and not dependent on the measurement position. Molecule density decreases due to less recycling. Since the electron density becomes low, molecules can penetrate deeper into the ergodic plasma, and that causes increase of molecule density in the inner ergodic region, R<4.8m. The atom density and the total ionization source decrease.

We carried out a series of simulations in both configurations with carbon impurity. Gas pumping is switched off. We use a constant chemical sputtering yield, 1%, independent of plasma parameters and surface temperature. A sputtered carbon particle is a neutral atom and traced until it is ionized in the plasma. The impurity ion of each charge state is solved by fluid equation and the impurity temperature is the same as ion temperature.

Figure 3 shows density distribution of carbon ions in low and high-density plasma with the same heating power. The carbon density is significantly reduced near the core in the high-density condition. That reduction is called “impurity screening” [4] in the ergodic region. The dominant forces acting on an impurity ion are friction force and thermal force. The former is proportional to particle parallel flux of the background plasma and normally has the direction toward divertor plates. The latter is proportional to temperature gradient of the plasma and normally has the direction toward upstream, i.e., the ergodic region. Flow distribution of impurity ions is determined by the balance of these forces in the plasma.

The sputtering yield is fixed in simulations and therefore the amount of the erosion is proportional to the plasma flux on divertor plates. The impurity source in the plasma becomes large for high-density plasma and large carbon density is observed in divertor leg regions in our simulation. The impurity transport in the ergodic region is dominated by the force balance, as we mentioned. The closed configuration causes larger impurity generation due to large particle flux, but the transport toward the core region can be at the same level as the open configuration when the impurity screening occurs.

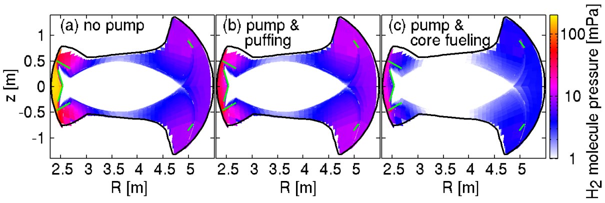

Fig. 1: Distribution of H_2 molecule pressure of the closed divertor configuration.

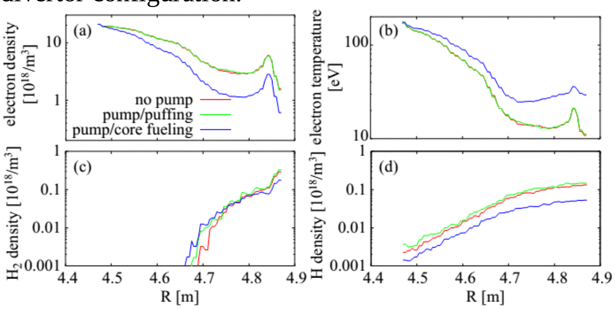

Fig. 2: Distributions of (a) electrons density, (b) temperature, (c) H_2 molecule density, and (d) H atom density along z=0 line on the horizontally elongated plane.

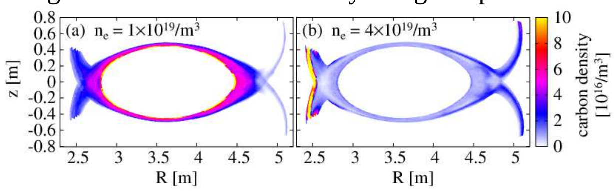

Fig. 3: Density distribution of carbon ions: (a) n_e=1×10^{19}m^3 (b) n_e=4×10^{19}m^3 at the LCFS. All the charge states of carbon are included.

References

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