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LHDの統計的磁場領域がもたらす不純物制御の新展開
New Developments in Impurity Control Provided by Stochastic Magnetic Field Layer of LHD

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Stochastization of edge magnetic fields of magnetically-confined torus plasmas has been extensively studied not only for the ELM mitigation but also for the plasma detachment and the impurity transport. The ergodic layer of Large Helical Device (LHD) consists of stochastic magnetic fields with three-dimensional structure intrinsically formed by helical coils, while well-defined magnetic surfaces exist inside the last closed flux surface. Reduction of the parallel impurity transport, so called “impurity screening”, has been studied in LHD [1]. The theoretical modelling explains that the parallel momentum balance on impurity ions in the ergodic layer determines the impurity flow, which can be the key mechanism driving the impurity screening [2]. Recently, the carbon impurity flow in the ergodic layer was measured with a vacuum ultraviolet (VUV) spectroscopy. A close relation between the impurity flow and the impurity screening was experimentally verified by the comparison between the spectroscopic observations and the impurity transport simulation based on a three-dimensional simulation code, EMC3-EIRENE [3,4].

Space-resolved VUV spectroscopy using a 3 m normal incidence spectrometer has been developed to measure the impurity emission profile in the edge and divertor plasmas of LHD in wavelength range of 300 - 3200 Å [5]. The graphite divertor plate is the main source of carbon impurities which are uniquely the most abundant impurity in LHD. It has been experimentally demonstrated that the CIV emission is located in the outermost region of the ergodic layer because the ionization energy of 65 eV for C^{3+} ions is extremely low compared to the edge temperature of LHD plasmas. The experiment is attempted for hydrogen discharges with R_{ax} = 3.6 m, B_t = 2.75 T, $n_e = 6.0 \times 10^{13}$ cm^{-3} and P_{in} = 10 MW. Figure 1(a) shows a full vertical profile of C^{3+} impurity flow evaluated from Doppler shift of the second order of CIV line emission (2×1548.20 Å) at a horizontally-elongated plasma position of LHD. The observation range of the VUV spectroscopy is also illustrated in Fig. 1(b). Two arrows in Fig.1 (a) correspond to the observation chords located with two solid arrows in Fig.1 (b). The measured flow velocity in Fig. 1(a) is projection of the flow along the observation

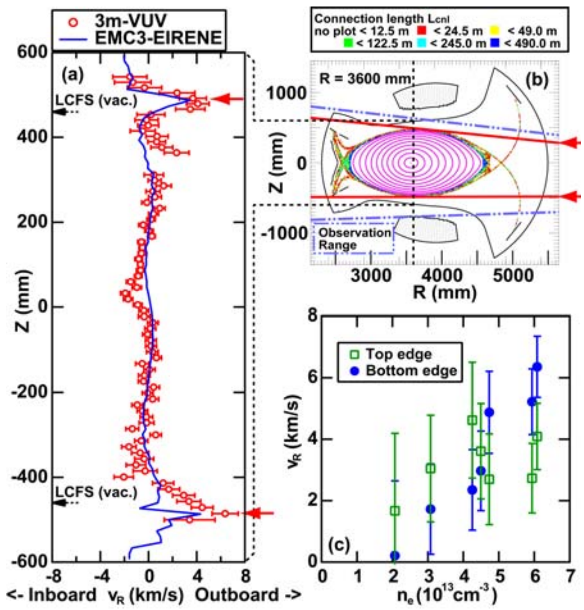

Fig. 1. (a) Vertical profile of C^{3+} impurity flow evaluated from Dopplar shift of the second order of CIV line emission (2 × 1548.20 Å) measured by VUV spectroscopy. A synthetic profile of the C^{3+} flow simulated with EMC3-EIRENE code is also plotted with solid line. (b) The observation range of the VUV spectroscopy. Two solid arrows in (a) correspond to the observation chords located with two solid arrows in (b). (c) Observed C^{3+} flow at the top and bottom edges of the ergodic layer as a function of density.

chord which can be approximately considered to be the direction of the plasma major radius. It is found that the flow direction is the same, i.e. the outboard direction, for both the top (Z = 480 mm) and bottom (Z = -480 mm) edges of the ergodic layer. Figure 1(c) shows the flow at the top and bottom edges of the ergodic layer as a function of density. It indicates that the flow velocity increases with the density. The carbon flow measured with spectroscopic method is compared with the impurity transport simulation based on EMC3-EIRENE code. The simulation is carried out under the same discharge condition as the result in Fig. 1(a). A synthetic profile of the simulated flow is also shown in Fig. 1(a) with solid line, which is obtained by integrating the Doppler-shifted CIV intensities along the observation chord. The excellent agreement between experiment and simulation in the present study concludes that the parallel flow in the ergodic layer can be well explained by the presently used theoretical modelling on the edge impurity transport. Therefore, the impurity parallel flow can be mainly determined by the momentum balance along the magnetic field line. In particular, the friction force between impurity and bulk ions and the ion thermal force driven by the ion temperature gradient are dominant terms in the momentum balance. The calculated friction force has the maximum value at both the top and bottom edges of the ergodic layer where the impurity parallel flow also takes the maximum value. The impurity screening driven by the friction force can be more effective at higher electron density range. The density dependence of the flow in the modelling can be also clarified by the experimental result shown in Fig. 1(c).

Figure 2 shows vertical profiles at the bottom edge of the ergodic layer of (a) CIV line intensity, (b) ion temperature, and (c) flow velocity derived from the CIV line for a hydrogen (H) plasma and a deuterium (D) plasma with a magnetic configuration with R_{ax} = 3.6 m and B_t = 2.75 T. As shown in the figure, the emission intensity is larger in the D plasma than that in the H plasma because the sputtering rate of carbon atoms from the divertor plates is larger in the D plasma. The ion temperature has no clear change between the H plasma and the D plasma. The flow velocity toward the outboard direction develops clearly with the maximum value at Z = -480 mm, which is a location close to the outermost region of the ergodic layer. This direction is same as the friction force in the parallel momentum balance calculated with EMC3-EIRENE. On the other hand, the maximum value of the flow velocity in the D plasma is clearly smaller than that in the H plasma, which indicates existence of some isotope effect on the impurity flow. The mass dependence of the thermal velocity of the bulk ions could be one of the reasons for the difference of the flow values between D and H plasmas when the friction force term is dominant in the momentum balance.

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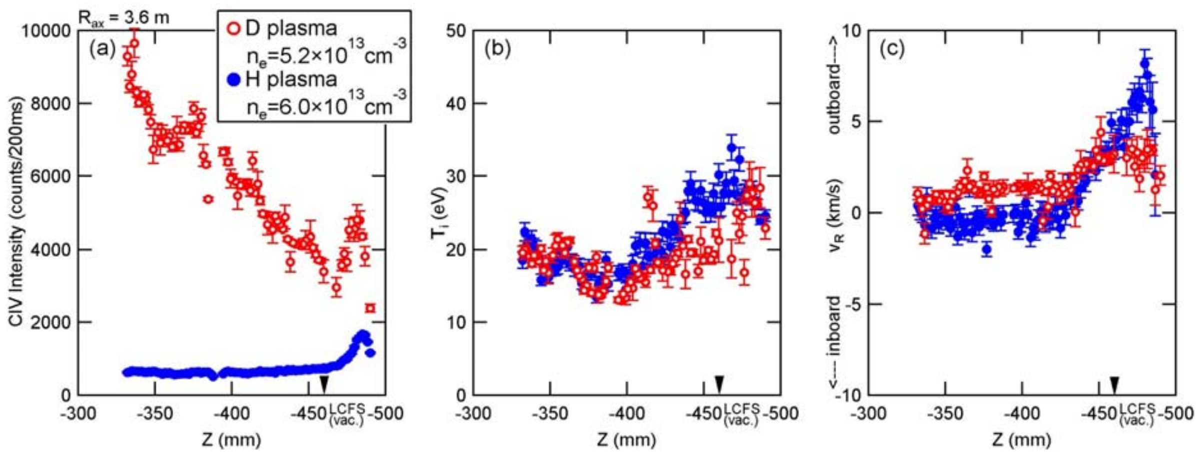

Fig. 2. Vertical profiles at the bottom edge of the ergodic layer of (a) CIV line intensity, (b) ion temperature, and (c) flow velocity derived from the Doppler profile of the second order of CIV line emission (2 × 1548.20 Å). Open and closed circles show the results from D and H plasmas, respectively.