Observation of asymmetric radial profile of tungsten ions in low ionization stages located in edge plasmas of Large Helical Device

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Tungsten is regarded as a leading candidate material for the plasma facing components in ITER and future fusion reactors. Considering transport processes of tungsten impurity in ITER, firstly neutral tungsten atoms are released from the divertor plates, then tungsten ions at lower ionization stages are transported in the edge plasmas, and finally tungsten ions at higher ionization stages are distributed in the confinement region. To understand behaviors of the tungsten impurity ions, diagnostics for line emissions from tungsten ions have been intensively conducted, such as visible spectroscopy for neutral tungsten atoms around 4000 Å and extreme ultraviolet (EUV) spectroscopy for tungsten ions at higher ionization stages around 15-70 Å [1,2]. However, tungsten ions at lower ionization stages have not been measured except for several cases of vacuum ultraviolet (VUV) spectroscopy in basic plasma experiments even though it is necessary for accurate evaluation of tungsten influx and comprehensive understanding of the tungsten impurity transport in high temperature plasmas [3,4]. In the present study, VUV spectra of emissions released from tungsten ions are measured in the Large Helical Device (LHD) for exploration of tungsten lines at low ionization stages which will contribute spectroscopic studies of edge plasmas in ITER and other tungsten-wall machines.

LHD is a superconducting heliotron device with the major/minor radii of 3.6/0.64 m, the plasma volume of 30 m^3, and the toroidal magnetic field of 3 T in the standard configuration [5]. Tungsten ions are introduced in the LHD plasma by injecting a tungsten impurity pellet which consists of a small piece of tungsten wire covered by a polyethylene or carbon tube. The length and diameter of tungsten wire is 0.6 mm and 0.15 mm, respectively. Owing to the advantages of steady-state current-free helical systems, the LHD plasma can be sustained even though substantial amount of tungsten atoms are injected [6]. Figure 1(a) illustrates the top view of the instruments together with the optical axis of the VUV spectrometer and the incident orbit of the impurity pellet. A 3m normal incidence VUV spectrometer (McPherson model 2253) is installed on an outboard midplane diagnostic port which is the same as the impurity pellet injector [7,8]. A back-illuminated CCD detector (Andor model DO435-BN: 1024 × 1024 pixels) is placed at the position of the exit slit of the spectrometer. A high wavelength dispersion of 0.037 Å/pixel enables measurements of the Doppler profiles of the impurity lines in the working wavelength range of 300-3200 Å. Time resolutions are 50 ms for the "full-binning" measurement in which all 1024 vertical pixels are replaced by single channel and the spatial resolution is entirely eliminated and 100 ms for "space-resolved" measurement in which the wavelength-dispersed image of the VUV emission is projected on a corresponding vertical position on CCD through a space-resolved slit mounted between the entrance slit and the grating. Figure 1(b) illustrates the vertical view angle of the VUV spectroscopy and the pellet orbit on the horizontally-elongated cross section of the magnetic field in LHD.

Figure 2 shows VUV spectra in the wavelength range between 600 to 705 Å in the time frame just after the tungsten pellet injection in hydrogen discharge in LHD. The plasma was initiated by the electron cyclotron heating, and three neutral hydrogen beams based on negative ion sources with total port-through power of 8 MW were injected. Central electron density, $n_e(0)$, and temperature, $T_e(0)$, just before the pellet injection was 2×10^{13} cm^{-3} and 3 keV, respectively. Bright WVI lines with 5d-6p transitions located at the wavelengths of 605.926 Å, 639.683 Å, and 677.722 Å have been observed. They are the first observation of line spectra from tungsten ions in low ionization stages in fusion plasma experiments.

We also succeeded a measurement of the vertical profile of the emission intensity of the WVI line. Figure 3(a) shows a typical temporal evolution of $n_e(0)$ and $T_e(0)$. At the pellet injection, $n_e(0)$ increases and $T_e(0)$ decreases. Figure 3(b) shows a temporal evolution of the intensity of the second order of WVI 639.683 Å line measured using a 20 cm normal incident VUV spectrometer [9]. A large emission is observed at the same time of the pellet injection, which is an emission from the pellet ablation cloud. Figure 3(c) shows a vertical profiles of WVI 639.683 Å line in time frame just after the pellet injection. The emission

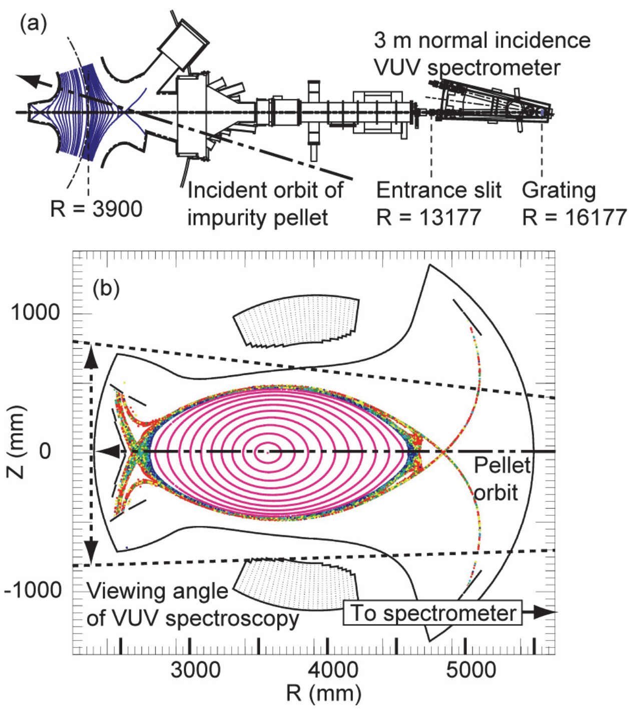

Figure 1. Schematic drawing of VUV spectroscopy in impurity pellet injection experiments. (a) Top view of the instruments together with the optical axis of the VUV spectrometer and the incident orbit of the impurity pellet. (b) Vertical viewing angle and the pellet orbit on the poloidal cross section of the magnetic field in LHD.

profile consists of two components; one is emissions from a pellet ablation cloud located at the vertical center of the plasma and the other is emissions from the plasma confinement region. The enlarged figure for this time frame around the signal level of the emission from plasma confinement region is shown in Fig. 3(d). The positions of the last closed flux surface (LCFS) in the vacuum magnetic field and an edge boundary denoted as a_{99} which is the effective minor radius in which 99% of the plasma kinetic energy is confined are shown together. The profile has a vertical asymmetry that the signal intensity in the lower half is significantly larger than that in the upper half. This asymmetry with an intensity peak close to the lower edge of the plasma is more obvious in the time frame 100-200 ms after the pellet injection as shown in Fig. 3(e). Mechanisms forming the asymmetrical profile of WVI line should be investigated in

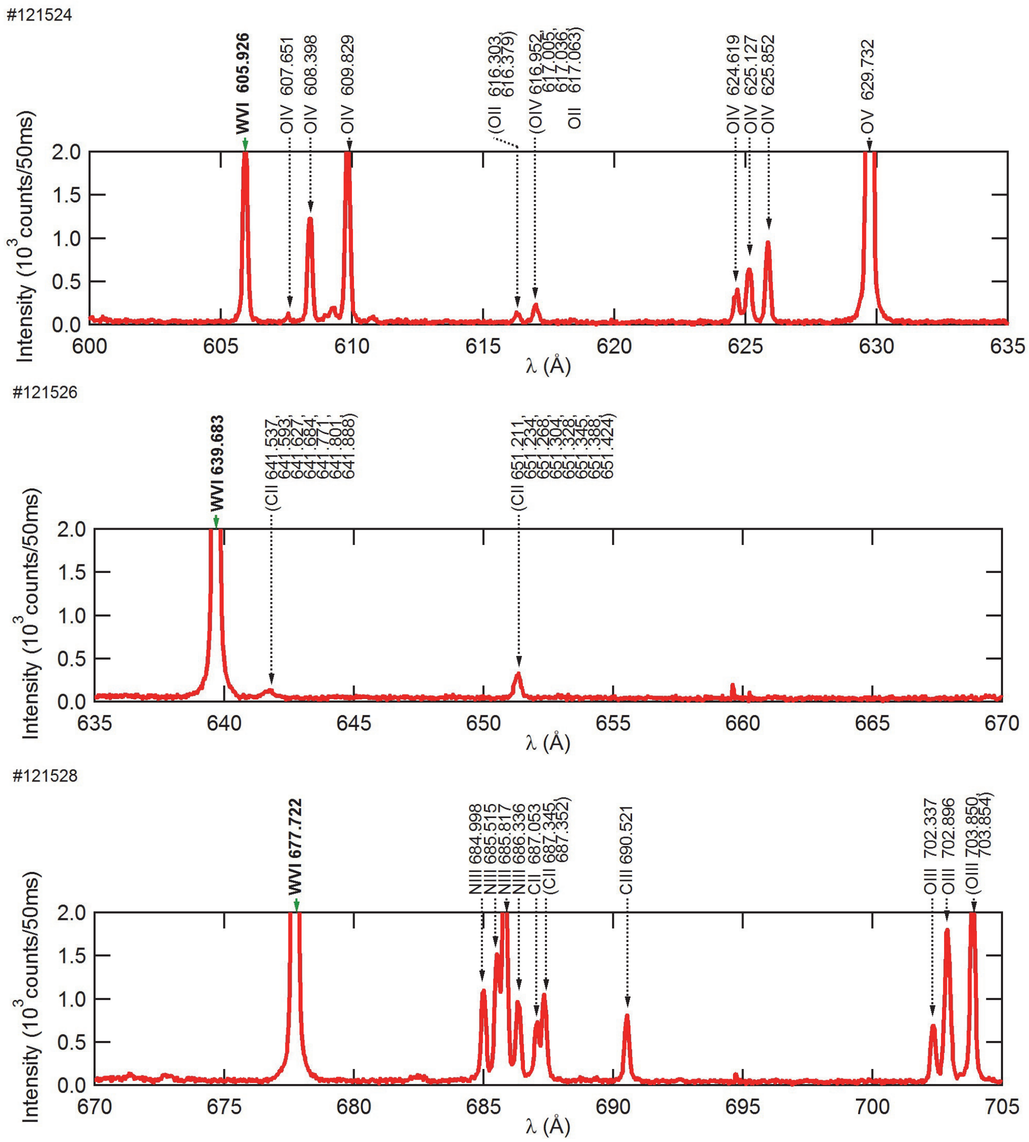

Figure 2. VUV spectra in the wavelength range between 600 to 705 Å measured using the 3 m normal incidence VUV spectrometer in the time frame just after the tungsten pellet injection.

future studies. Candidate factors responsible for the asymmetry include a thick stochastic magnetic field layer called "ergodic layer" located outside the core plasma of LHD, because it has been observed that intrinsic impurities located in the ergodic layer have asymmetrical profiles [10].

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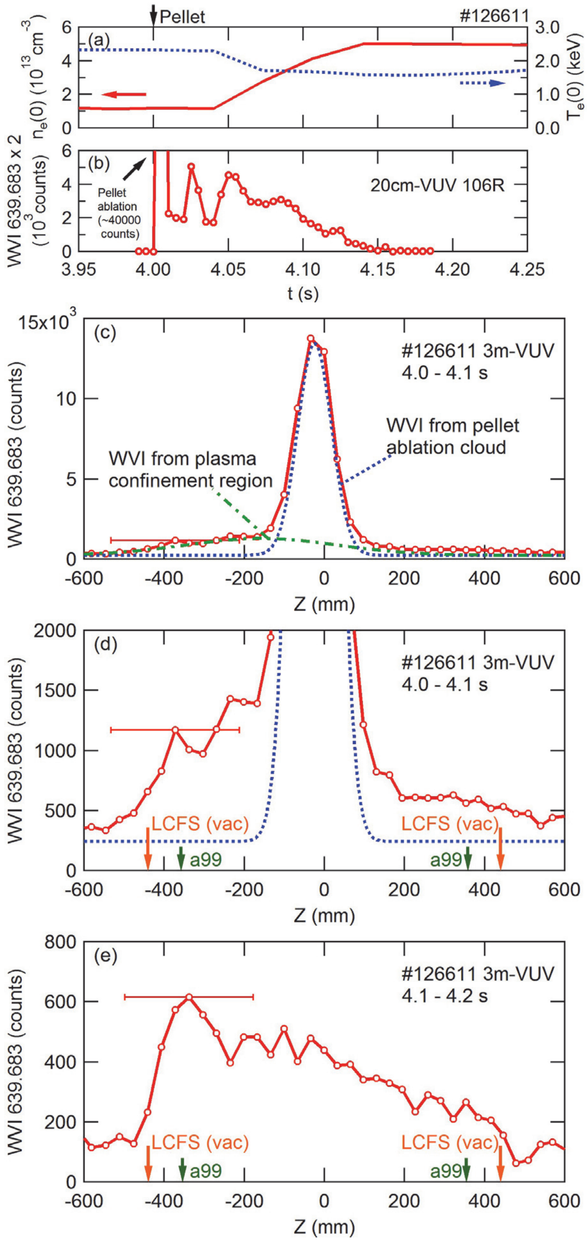

Figure 3. Temporal evolutions of (a) central electron density and temperature with tungsten pellet injection and (b) intensity of WVI 639.683 × 2 Å line. Vertical profiles of WVI 639.683 Å line in time frames (c) 0-100 ms after the pellet injection, (d) the enlarged figure for the same time frame around the signal level of the emission from plasma confinement region, and (e) 100-200 ms after the pellet injection.