Spectra from impurities in the Large Helical Device

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Abstract. Time dependent VUV and EUV spectra were measured in the Large Helical Device (LHD) and we have analysed the spectra. In the wavelength range of $\lambda = 90 - 130$ nm, CIII, OVI, H Ly$\alpha$, NeVII, NeVI, NeV lines are observed. We have derived electron temperature from CIII line ratios with the use of collisional radiative model. We have resolved the spectra into NeVII and NeVI lines and derived the ion ratios. In the wavelength range of $\lambda = 10 - 16$ nm, Xe spectra were measured with Xe gas puffing. The spectra from Xe ions near 13 nm are studied with theoretical calculations.

Key word: VUV spectra, EUV spectra, CIII, NeVII, Xe ions

PACS: 81V45, 82D05

1. Introduction

In low temperature plasmas such as divertor or process plasmas, emission from impurities is important for plasma diagnostics and plasma modeling. We observed VUV and EUV spectra from LHD and studied the behaviour of impurities. We made a collisional radiative model for carbon L-shell ions including both ionization/excitation and recombination processes. We studied dielectronic recombination processes to the excited states for carbon L-shell ions. We apply this model to the spectra measured in the LHD.

Emissions for heavy impurities are important for fusion plasma such as ITER and for the light sources of industrial lithography. Heavy impurities emit many lines and it is difficult to identify. We study Xe spectra emitted from LHD theoretically and experimentally.

2. Collisional radiative model of C$^{2+}$ ions including the dielectronic recombination to excited states

As recombination processes, dielectronic recombination (DR) is the important process for L-shell ions. However since the DR process is complicated relating to the autoionization states, the accurate data to the excited states have not been published so far. Therefore we have calculated the DR rates to each excited states of carbon atom and L – shell ions [1 - 3]. Data for dielectronic recombination (DR) to excited states are available up to $n = 6$ distinguishing the configuration, spin and terms of L-shell ions: C$^{+}$, C$^{+1}$ and C$^{+2}$. The DR data for rate coefficients are available in NIFS Database (http://dbshino.nifs.ac.jp). The DR rates remain large for highly excited states up to $n = 100$ where $n$ is the principal quantum number.

Using these data we have constructed the collisional radiative model (CRM) for carbon atom and ions. We study temperature dependence and density dependence of spectral lines with CRM. We derived effective ionization, recombination and emission rate coefficients which depend on the electron density as well as the electron temperature. Effective ionization
rate coefficient is increased by ladder-like excitation and ionization at high densities. Density effects begin from $10^{13}$ cm$^{-3}$ and saturate at $10^{18}$ cm$^{-3}$. Effective recombination rate coefficient is decreased by ladder-like excitation and ionization at intermediate density ($< 10^{16}$ cm$^{-3}$) and increased at high densities ($> 10^{18}$ cm$^{-3}$). Radiation loss rate coefficient (Watt cm$^{-3}$/ion/electron) in ionizing plasmas decreases at high densities. Radiation loss rate coefficient in recombining plasmas decreases at high densities for $T_e > 2$eV because the contribution of dielectronic recombination decreases [4].

A collisional radiative model for C$^{2+}$ ions including the levels up to n = 5 has been constucted. DR rates to the excited levels higher than n >5 are included to the level n=5 considering the density effect [4]. The effective emission rate coeffcieint of a line is written by

$$I_{ij} = A_{ij} (n_i/\Sigma n_k) / n_e \quad \text{(cm}^3\ \text{s}^{-1})$$

where $A_{ij}$ is the transition probability from i state to j state, $n_i$ is the population density of the excited i state, $n_e$ is the electron density. The population density of excited states $n_i$ can be expressed by the summation of the ionizing component (the first term) and recombining component (the second term) as,

$$n_i = a_i n(1s^22s^2) + b_i n(1s^22s)$$

where $n(1s^22s^2)$ and $n(1s^22s)$ are the population density of the ground state of C$^{2+}$ and C$^{3+}$ ions. In ionizing plasma, the lines in low levels are strong whereas in recombining plasma the lines in high levels are strong.

We have calculated the effective rate coefficients for CIII lines, I$_r$ (2s$^2$1S - 2s2p $^3$P, 977A) and I$_r$ (2s2p $^3$P - 2p$^3$P, 1175A) using our CRM. We studied the temperature and density dependences of line intensities [5]. Using the effective rate coefficients the intensity ratio of I$_r$ (2s$^2$1S - 2s2p $^3$P) / I$_r$ (2s2p $^3$P - 2p$^3$P) are calculated sown in Fig.1. Intensity ratios in ionizing plasma are smaller than one and those in recombining plasma are larger than one. We can distinguish ionizing and recombining plasma phases by the values of the intensity ratios of the two lines of C$^{2+}$ ions.

![Fig. 1(a) The intensity ratio I/I$_r$ of CIII lines in ionizing plasmas](image)
3. Time dependent VUV spectra from LHD

Time dependent VUV spectra (~1000Å) were measured for plasmas heated by ECH (Electron cyclotron heating) every 184 ms with 20ms exposure time for the shot #15080. The spectra from plasmas heated by NBI (Neutral beam injection) are also measured every 100ms with 33ms exposure time for the shot #28967. From the intensity ratios of CIII emission lines $I_t/I_r$ for #15080, the spectra can be classified as ionizing or recombining plasma. The intensity ratios are shown in Fig.2 (a). We obtain plausible electron temperatures $T_e$ from the CIII spectra; $T_e = 30 – 40$ eV for time sequence No. 3 - 5 (ionizing phase), $T_e = 2 – 3$ eV for No. 6 (recombining phase), $T_e \sim 0.1$ eV for No.7 (recombining phase). At the same time the spectra from hydrogen Lyman series intensity have been observed. We also derived electron temperature and density from the observed Lyman series intensity ratios of hydrogen ($n = 3 – 7$); $T_e = 0.4$ eV and $N_e = 10^{13}$ cm$^{-3}$ for No. 7 and $T_e = 0.3$ eV and $N_e = 10^{12}$ cm$^{-3}$ for No. 8. Those are also very low temperature. The observed spectrum at No.7 is shown in Fig.3.
Fig 2(b) Time dependent observed line intensities of CIII (left axis) and the intensity ratios (right axis) for the shot #28967.

For NBI (#28967) case, the carbon spectra are classified always as ionizing plasma (the intensity ratios are always below one) even after radiation collapse as shown in Fig.2(b). This is because NBI is still after the rapid cooling caused by radiation collapse. Electron temperature is estimated $T_e = 40$ eV for $t = 0.2$ - 0.8 sec, decreases to 20 eV during 0.8 – 1.1 sec before radiation collapse and goes down to $T_e \sim 3$ eV at radiation maximum phase at 1.3 sec. After radiation collapse, temperature drops to 2 eV.

We derived time dependent carbon ion density $N(C^+)\text{ }$from the intensity of CIII 977Å using the derived temperature and average electron density. The derived density of C$^+$ is...
constant during the heating phase and increases very rapidly during the radiation collapse and becomes again constant after the heating phase. Time dependent model calculation is in progress.

4. Spectra from Neon ions

We identify 2s - 2p fine structure transition lines from neon L-shell ions as a second order diffraction from the observed spectra for Ne VII \((2s2p^3 \, P_J - 2p^3 \, P_J', 6 \, \text{lines})\), Ne VI \((2s^22p \, P_J - 2s2p^3 \, P_J', 3 \, \text{lines})\), Ne V \((2s^22p^2 \, P_J - 2s2p \, P_J', 6 \, \text{lines})\), Ne IV \((2s^22p^3 \, S_J - 2s2p^3 \, P_J, 3 \, \text{lines})\) as shown in Fig.4(a). We calculate the intensities of Ne VII and VI lines by our collisional radiative model. Ion density ratios are derived comparing spectra and calculations. We find the ion densities of Ne \(^{6+}\) about equal to Ne \(^{5+}\). Fig. 4(a) shows the observed Ne ion spectra with identifications. The theoretical convoluted spectrum including NeVII and NeVI lines are shown in Fig.4(b).

**Fig4(a)** Observed spectra of Neon ions for the shot of #28967.

**Fig4(b)** Theoretical spectra of NeVII and NeVI lines.
5. Xe spectra from LHD

Extreme-ultraviolet (EUV) light sources from compact plasmas are now intensively studied for the next generation of lithography. The emission of multicharged Xe ions has strong emissions near 11 and 13 nm and these are attributed to transitions in Xe$^{10+}$. Better knowledge of this emission is important for EUV sources and for optimization of a 13.5nm EUV source. Recently EUV spectra from Xenon injected into LHD have been measured in the wavelength range 10 – 17 nm. We analyze the spectral lines near 13 nm. We compare the spectra with theoretical calculations and try to identify the spectral lines from Xe$^{10+}$ ions. We can make a benchmark test of computer codes using the observed spectral lines. This is important because the theory has not been extensively tested for such high- Z low-charge ions. We will study plasma conditions which give the best EUV emissions and make collisional radiative model for high- Z many- electron ions.

Xe gas was puffed into LHD plasma and the EUV spectra from Xe ions were measured. We used the spectra without Xe puffing to calibrate wavelengths of the lines of Xe ions. A 2m grazing incidence multichannel spectrometer SOXMOS[6] with 600 g/mm grating was used. The observed spectra with and without Xe gas puffing are shown in Fig.5. The measured line-width(FWHM) is $\Delta \lambda = 0.023$nm at 13.2nm (Fe XXIII line). Recently Churilov et al[7] in NIST measured Xe$^{10+}$ spectra from a low inductance vacuum spark and gave a list for observed lines with identification. Comparison with results for Xe$^{10+}$ spectra by Churilov [7] is shown in Fig. 6(a) and the intensities are quite different. In order to know the contribution of other charged ions than Xe$^{10+}$ we studied the time behaviour of line intensities. For the shot(#42801) where the spectra are obtained during 4 sec, the plasma collapse at 3.6 sec and electron temperature begins to decrease at 3 sec. Therefore the electron temperature at 4 sec is lower than the previous time. The emission from Xe ions is always the strongest at the late phase during the radiation collapse although the lines from FeXXIII and FeXXII decrease. We also measured spectra from different directions, from the center and from the edge of the plasma, to confirm the location of the emitting ions. It is found the Xe emission is emitted not from the center but rather spherical regions. These two phenomena suggest that the observed Xe emission comes from mainly from low charged ions.

Fig.5. Observed Xe ion spectra from LHD. The Solid line indicates the spectrum without Xe gas. Dotted and dashed lines indicate the spectra with Xe gas.
**Fig. 6(a)** Comparison of the observed spectra (solid line) and the spectra in Churilov et al.[7] (dotted line)

**Fig. 6(b)** Comparison of the theoretical spectra for Xe$^{10+}$ ions.
6. Theoretical Calculations for Xe$^{10+}$ ions

Since the electron configuration for Xe$^{10+}$ is complicated, it is difficult to obtain accurate theoretical atomic data. Sasaki [8] showed the spectra by collisional radiative model based on the atomic data calculated by Hullac code. We calculated atomic data with three different atomic codes; i) MCDF (Multiconfiguration Dirac-Fock) by Y.Ki. Kim [9] and by S. Frizsche [10], ii) Cowan (Multiconfiguration Hartee-Fock ) codes [11] in relativistic mode, iii) Hullac code [12]. The results are compared each other as well as Ref[7].

For a many electron system like Xe$^{10+}$ ions, configuration interaction by electron correlation is important. Configurations taken into account in our calculations are $4s^24p^64d^8$ (lower state) and $4s^24p^64d^75p^1$ (upper state) for MCDF code [9], $4s^24p^64d^{10}$ (lower state) and $4s^24p^64d^55p^1$, $4s^24p^64d^44f^1$, $4s^24p^64d^4f^1$ (upper state) for Cowan code [10] and $4s^24p^64d^8$, $4s^24p^64d^4f^1$, $4s^24p^64d^55s^1$, $4s^24p^64d^55p^1$, $4s^24p^64d^5d^1$, $4s^24p^64d^5f^1$ for Hullac code. The Fritsche’s MCDF code [11] includes more than 100 configurations. We obtain many transitions from the results of theoretical codes. Both wavelengths and transition probabilities $A_r$ can be compared.

Since it is difficult to compare the atomic data in detail for each line, we made a convoluted spectra with a Gaussian profile assuming the integrated line intensity is equal to theoretical value $gA_r$ (s$^{-1}$) where $g$ is the statistical weight of the upper level $i$ and $A_r$ is the transition probability from the upper level $i$ to the lower level $j$. The MCDF calculations include 421 lines and 589 lines respectively for the codes of reference [9] and [10]. The Cowan code calculation includes 195 lines. As seen in Fig.6 (b), the total convoluted spectra look similar and the strong peaks coincide with each other. However the detailed structure are quite different.

We compared the observed spectra with theoretical convoluted spectra based on the data by MCDF and Cowan codes. The agreements are not very good. However we can identify the strong lines with an error of 0.01nm (0.1A). The observed lines (number 1 and 8) at 13.066 and 13.839nm are always strong but the theoretical value of $gA_r$ is not large. The lines with the large theoretical $gA_r$ values are not always strong in measured spectra. One of the reasons is that the observed lines are emitted by excitation by electron impact or recombination. In order to analyze the intensities we need to make a collisional radiative model which includes all these processes. We will take into account the contribution of dielectronic recombination as well as recombination on the observed spectra; in the hope we can improve this agreement. There is a possibility that other ions than Xe$^{10+}$ contribute the observed spectra. We are now investigating this problem. We also would like to study the continuum emission near 13nm observed in the spectra which might be produced by free- free, free- bound and two photon emissions.

6. Summary

We analyzed impurity spectral emission quantitatively. Electron temperature is derived from the intensity ratio of CIII line intensities. After radiation collapse, low charged carbon ions are the dominant source of radiation in the case of #28967. The Electron UV Xe$^{10+}$ ion spectra from LHD near 13nm are measured. Theoretical calculations were performed and compared with observed spectra. It is difficult to identify the observed lines. We will study this difference in the future with a collisional radiative model. We will also investigate the possibility of the contribution of other charged ions. Strong emission is measured during radiation collapse or after radiation collapse. LHD spectra can give a bench - mark test of theoretical data for wavelengths of Xe ions. We are making a model for intensities of high Z ions with many electrons.

Acknowledgements

T.K thanks the support by EUV Leading Project in Osaka Univ.
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