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Radiation Loss by Impurities Measured from the Large Helical Device

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Abstract

We have analyzed impurity VUV emission lines quantitatively. Electron temperature is derived from the intensity ratio of C III lines. Radiation loss sources are identified using the spectroscopy and bolometer data in the case of radiation collapse caused by neon gas puffing. Time dependent radiation losses by impurity ions are derived.

Keywords:

VUV spectrum, impurity, radiation loss, Ne VII, C III, O VI

1. Introduction

In low temperature plasmas such as divertor or process plasmas, line emission from impurities is important for plasma diagnostics and plasma modeling. Most of the radiation losses are caused by VUV emissions from impurities. Therefore it is important to study VUV spectra quantitatively. Time dependent VUV spectra were measured in the LHD and are analysed with collisional radiative models for impurities. The Large Helical Device (LHD) is a high temperature laboratory plasma for fusion research in the National Institute for Fusion Science.

Time dependent C III, O VI, H Ly$_\alpha$, Ne VII, Ne VI, Ne V lines were observed in the wavelength ranges of $\lambda = 90 - 130$ nm. We have analysed these spectra using the collisional radiative models. The radiation loss from C III, O V, Ne VII and Ne VI ions are obtained from the VUV spectra. The time dependent radiation loss from neon L-shell ions are compared with bolometric measurements.

2. C III line intensity ratio

We construct a collisional radiative model (CRM) for C^{2+} ions including levels up to $n = 5$. Our CRM includes dielectronic recombination to excited states [1,2]. We derived the effective rate coefficients for the intensities of C III lines, I_r (2s^2 ^{1}S – 2s2p ^{1}P, 977 Å) and I_t (2s2p^{3}P – 2p^2 ^{3}P, 1175 Å) as functions of electron temperature and density. We study the temperature and density dependences of the line intensities using our CRM.

The C III line intensity ratios are substantially different for the ionizing or recombining plasma phases; the intensity ratio I_t (2s2p ^{3}P – 2p^{23}P)/I_r (2s^2 ^{1}S – 2s2p ^{1}P) is smaller than unity in an ionizing plasma and greater than unity in a recombining plasma as shown in Fig. 1. We compare the calculational results to the spectra measured in LHD for cases where the spectra may be classified as ionizing or recombining.

Observed spectra were taken for a plasma heated by ECH (#15080) and heated by Neutral Beam Injection (NBI) (#28967). In the case of #15080 C III spectra indicate a recombining plasma after ECH power off. For #28967 case, the carbon spectra always indicate an ionizing plasma despite rapid cooling caused by radiation collapse. Since NBI is still on after the radiation collapse, low temperature plasma is supposed to be made. The temperatures are derived from the intensity ratios as follows; $T_e \sim 40$ eV (t = 0.2 – 0.8 sec), $T_e \sim 40$ eV $\rightarrow$ 20 eV (t = 0.8 – 1.1 sec) $T_e \sim 3$ eV (max radiation, t = 1.3 sec), and then T_e drops to 2 eV (t = 1.4 – 1.7 sec). The waveform of the shot is shown in Fig. 2. Near the time of radiation collapse (Fig. 2), impurity line emission increases by more than a factor 4 as shown in Fig. 3.

3. Neon ion spectra and radiation loss by impurities at 1 sec

We have analysed the VUV spectra for a NBI heated (#28967) experiment with neon gas puffing which showed the radiation collapse. We derive the radiation loss rate by impurity ions and compared them with the bolometric measurement. The observed

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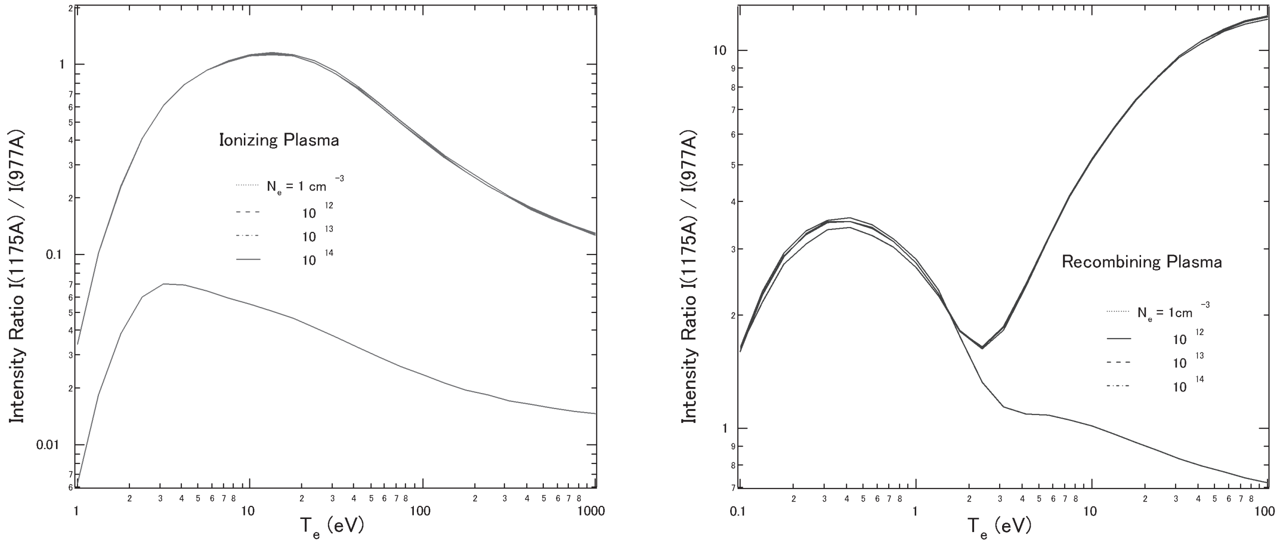

Fig. 1 Calculated intensity ratio of C^{2+} lines in ionizing (a) and in recombining plasma (b).

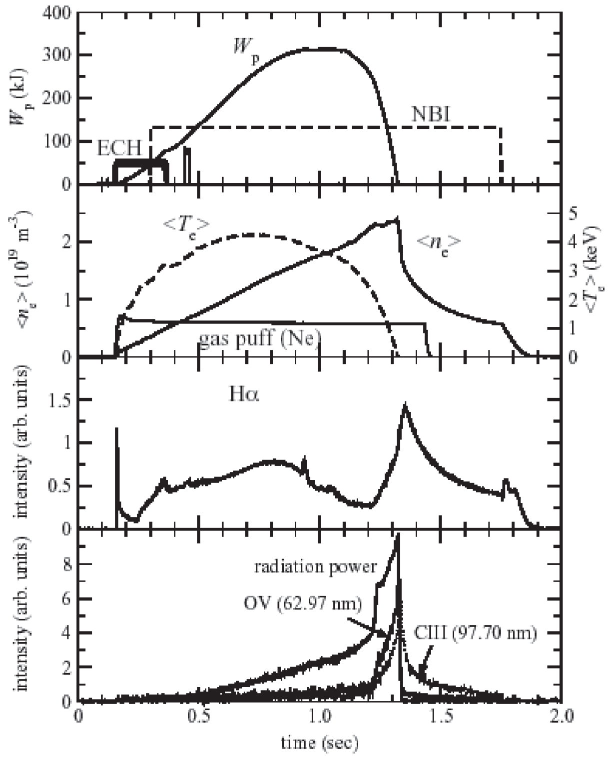

Fig. 2 The time history of plasma parameters for shot #28967.

VUV spectra at 1.0, 1.2 and 1.3 sec are shown in Fig. 3. We identify the 2s – 2p fine structure transition lines from the neon L-shell ions as second order spectra as shown in Fig. 4 (a); Ne VII (2s2p $^3P_J - 2p^2\ ^3P_{J'}$, 6 lines), Ne VI ($2s^22p\ ^2P_J - 2s2p^2\ ^2P_{J'}$, 3 lines) Ne V ($2s^22p^2\ ^3P_J - 2s2p^3\ ^3D_{J'}$, 6 lines), Ne IV($2s^22p^3\ ^4S_J - 2s^22p^4\ ^4P_{J'}$, 3 lines). We calculate the intensities of the Ne VII and VI lines by our collisional radiative model as shown in Fig. 4 (b). Ion density ratios are derived from comparison of the measured spectra and calculations. We find the ion densities of Ne^{6+} are about equal to that of Ne^{5+}.

The absolute neon ion density is derived from charge exchange spectroscopy (CXS) at $t = 1.0$ sec. The 5249Å line ($n = 11 - 10$) of Ne^{9+} is produced by the following charge transfer process with the hydrogen in the neutral hydrogen heating beam.

$$Ne^{10+} + H \rightarrow Ne^{9+}(n = 11) + H^+ \rightarrow Ne^{9+}(n = 10) + h\nu$$

The neutral hydrogen heating beam has 140 keV energy. The emission rate coefficient to produce Ne X 5249Å line by charge exchange is calculated by the ADAS code [3] as $\langle \sigma_{CX} v \rangle = 1.0 \times 10^{-8}\ \mathrm{cm^3 s^{-1}}$. State - selective charge transfer cross sections to high nl states are used to calculate the emission rate coefficients. The absolute density of Ne^{10+} ions is derived to be $N(Ne^{10+}) = 2.5 \times 10^{11}\ \mathrm{cm^{-3}}$ at the plasma center. We derive the absolute time dependent impurity radiation loss from the VUV spectra by using the absolute value of the neon ion density. Based on the density of Ne^{10+}, other neon ion densities are calculated for radial distributions by the MIST code [4] ; $N(Ne^{9+}) = 6.3 \times 10^{10}\ \mathrm{cm^{-3}}$, $N(Ne^{8+}) = 1.3 \times 10^{11}\ \mathrm{cm^{-3}}$, $N(Ne^{7+}) = 3.1 \times 10^{10}\ \mathrm{cm^{-3}}$, $N(Ne^{6+}) = 3.1 \times 10^{10}\ \mathrm{cm^{-3}}$, $N(Ne^{5+}) = 2.5 \times 10^{10}\ \mathrm{cm^{-3}}$ at the respective peak positions. The radiation loss rate coefficients of neon ions by ADAS code are $R(Ne^{9+}) = 10^{-26}\ \mathrm{W\,cm^3}$ at 1 keV, $R(Ne^{8+}) = 10^{-26}\ \mathrm{W\,cm^3}$ at 1 keV, $R(Ne^{7+}) = 5 \times 10^{-26}\ \mathrm{W\,cm^3}$ at 100 eV, $R(Ne^{6+}) = 10^{-25}\ \mathrm{W\,cm^3}$ at 100 eV, $R(Ne^{5+}) = 10^{-25}\ \mathrm{W\,cm^3}$ at 100 eV. Assuming $n_e = 10^{13}\ \mathrm{cm^{-3}}$ the radiation loss from the neon K-shell ions is $17\ \mathrm{kW\,m^{-3}}$ at 1 keV and the neon L-shell ions give $72\ \mathrm{kW\,m^{-3}}$ at 100 eV. This value can be compared with the bolometric measurement $65\ \mathrm{kW\,m^{-3}}$ at

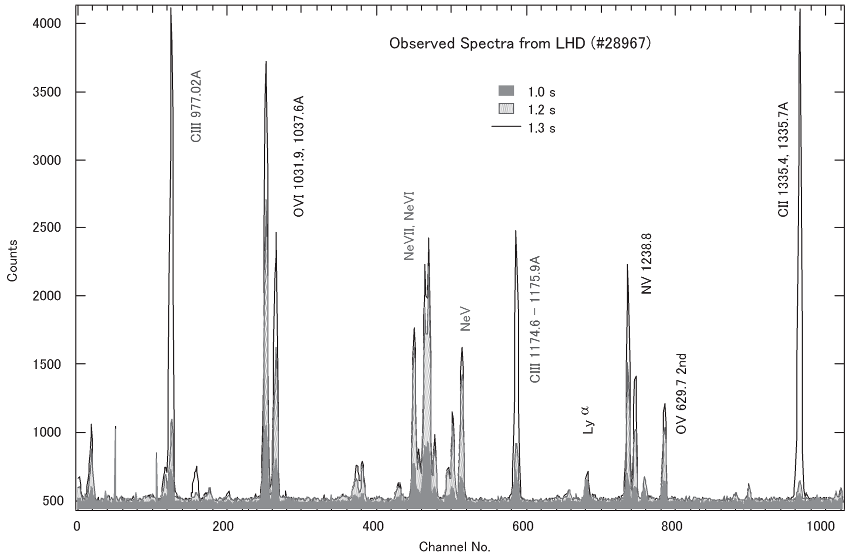

Fig. 3 Observed time dependent VUV spectra.

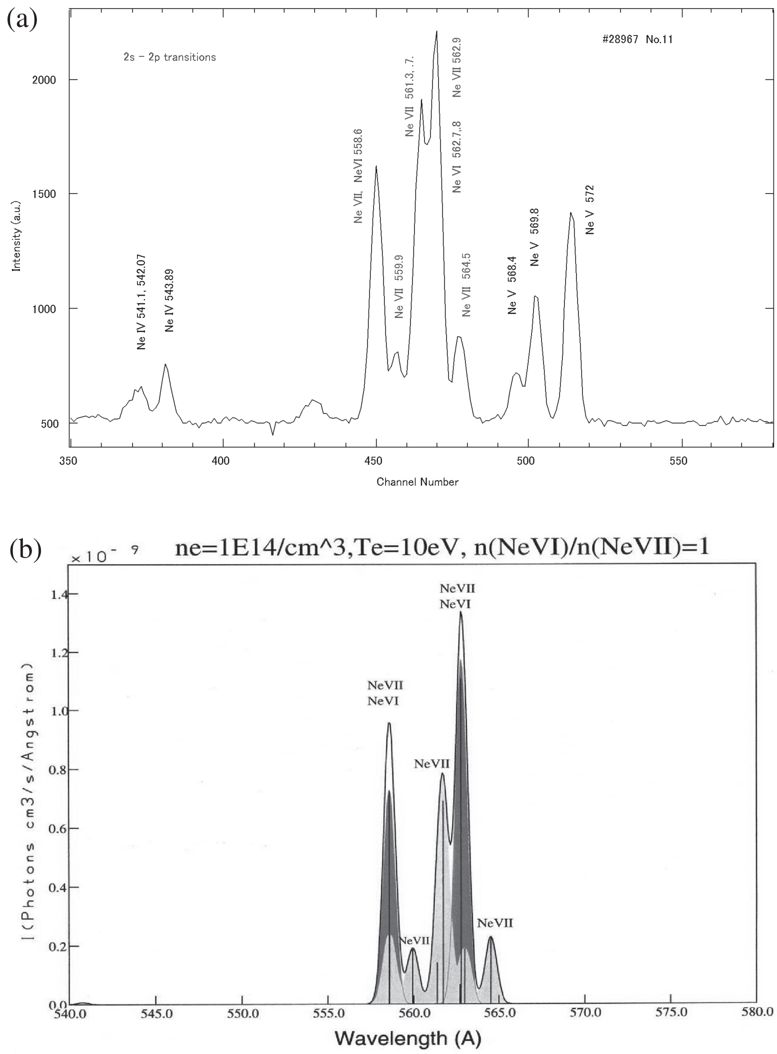

Fig. 4 Observed (a) and theoretical (b) spectra of NeVII and NeVI ions.

ρ = 0.9 for 1 sec in Fig. 5. Here, ρ is the distance from the plasma center normalized by the radius of the last closed magnetic surface.

4. Time dependent radiation loss by impurities

Since we obtained reasonable values for radiation loss of neon ions at 1 sec, we try to study the time variation of radiation loss by impurities using the time

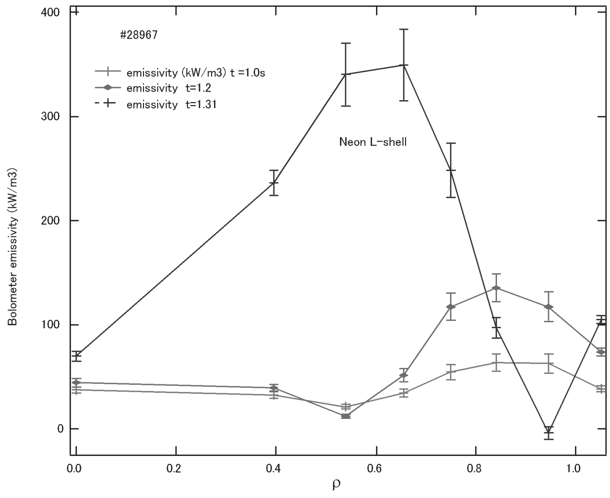

Fig. 5 Radial emission profile measured by bolometer.

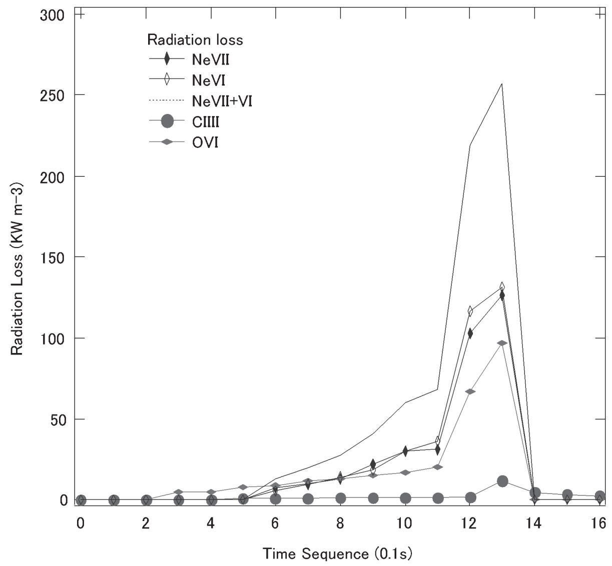

Fig. 6 Time dependent radiation loss from impurity ions.

dependent spectra. From the observed intensity of Ne VII 2s2p ^{3}P – 2p^2 ^{3}P at around 500 Å, the absolute intensities of other ions are estimated. With N(Ne^{6+}) = 3×10^{10} cm^{-3}, $n_e = 10^{13}$ cm^{-3} and effective excitation rate coefficients, $C_{eff}(561\,\text{Å}) = 2 \times 10^{-9}$ and $C_{eff}(564\,\text{Å}) = 7 \times 10^{-10}$ cm^3 s^{-1}, absolute observed volume emissivities are obtained to be $I(561\,\text{Å}) = 6 \times 10^{14}$ photons cm^{-3} s^{-1} and $I(564\,\text{Å}) = 2 \times 10^{14}$ photons cm^{-3} s^{-1}. The observed photon counts for Ne VII 561 Å and for Ne VII 564 Å at $t = 1$ sec are 2260 and 633 counts, respectively. From the C III 977.0 Å(2s^2 ^{1}S −2s2p ^{1}P) observed photon counts 1395 at $t = 1$ sec, the absolute volume emissivity I(C III977 Å) = 4.6×10^{14} photons cm^{-3} s^{-1} is derived using the intensity of neon emission lines. With $C_{eff}(977\,\text{Å}) = 6 \times 10^{-8}$ cm^3 s^{-1} and $n_e = 10^{13}\,cm^{-3}$, density of C^{2+} ions N(C^{2+}) = 7.6×10^8 cm^{-3} is obtained assuming the radial width of C^{2+} is the same as Ne^{6+}. From our collisional radiative model, the radiation loss from C^{2+} is obtained to be 0.8 kW m^{-3} and radiation loss of carbon L shell ions is 2.3 kW m^{-3}. Based on the radiation loss at $t = 1$ sec, the time dependent radiation loss for C^{2+} is derived from time variation of the VUV line intensity. From the O VI 1031 Å(2s ^{2}S – 2p ^{2}P) observed intensity at $t = 1.0$ sec, absolute volume emissivity I (O VI 1031 Å) = 6.6×10^{14} photons cm^{-3} s^{-1} is derived. With $C_{eff}(1031\,\text{Å}) = 1.3 \times 10^{-8}$ cm^3 s^{-1} and $n_e = 10^{13}$ cm^{-3} the density of O^{5+} ions, N(O^{5+}) = 7.7×10^9 cm^{-3} is obtained. Radiation loss of 8 kW m^{-3} from O^{5+} is derived. Radiation loss from the L-shell ions is estimated to be 16 kW m^{-3}. Based on the absolute values at 1 sec, we estimate the time dependent radiation loss of different ions using the time dependent line intensities as shown in Fig. 6. The radiation loss by Ne VII and Ne VI lines is 250 kW m^{-3} at 1.3 sec and this compares well with the bolometric measurement 320 kW m^{-3} within 30 %.

5. Summary

We analyzed the impurity spectral emission quantitatively. Electron temperature is derived from the intensity ratio of the C III line intensities. Radiation loss sources are identified using spectroscopy and bolometry in the case of radiation collapse caused by neon gas puffing. Time dependent radiation loss of impurity ions are derived from line intensities of impurities. Due to the large radiation loss by neon L-shell ions, temperature falls starting from the periphery leading eventually to the radiation collapse. After the radiation collapse, low charged carbon ions are the dominant source of radiation. We need more precise measurements for the radial distribution of electron densities and temperatures as well as line intensities, especially in the periphery region where the radiation loss is dominant. It is noted that reliable and comprehensive atomic data are important for such plasma diagnostics.

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