Behavior of carbon impurity ions in radiation collapse in the Large Helical Device

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Abstract. We measured time-dependent EUV spectra to make a quantitative study of impurity spectral lines of C III, C IV and C V during radiative collapse in the Large Helical Device (LHD) at the National Institute for Fusion Science. We calculated the intensity ratios of spectral lines of C V and C III using our collisional-radiative model and compared to observed time-dependent intensity ratios. We find that intensity ratios of C V are affected by recombination at the end of plasma for an experiment showing radiation collapse; the population density of 2s3d 3P is increased by recombination.

1. Introduction

Plasma impurities are important from the viewpoint of energy balance and particle transport in plasma simulation or modeling of many kinds of plasmas, including fusion plasmas, astrophysical plasmas and industrial plasmas. Impurities play a key role for plasma evolution. We would like to know the absolute values of ion and electron densities, electron temperature, radiation power, etc. Spectroscopic measurements give a useful, quantitative way to study both plasma and impurity behavior. For that reason spectroscopy is a central technique for plasma diagnostics. In this paper, we present EUV spectra from fusion plasma experiments in the Large Helical Device (LHD), and study the behavior of impurities in representative cases showing radiation collapse.

Radiation collapse in a fusion machine is related to the problems of the density limit and the threshold temperature [1]. “Radiation collapse” occurs when the plasma temperature decays rapidly together with strong emission of radiation. It is related to the power balance between input power and emitted radiation power. Radiation collapse is thought to occur when the electron density increases and the electron temperature decreases, leading to a significant increase in radiation loss. Today this phenomenon is not understood quantitatively. The effect of the plasma electric field on radiation collapse was discussed recently [2]. In order to investigate how and why plasmas collapse, we measure time dependent impurity emission spectra and study the intensity ratios of carbon ions. In previous studies [3,4], we have measured the intensity ratios of carbon ions as plasma diagnostics to estimate the plasma temperature or density. In this paper we show some quantitative features of radiation collapse by comparing temporal behaviour of the intensity ratios of carbon ions with other measurement of plasma parameters.

2. Observed EUV spectra
We measured EUV spectra from LHD plasma with a grazing incident spectrometer SOXMOS [3] using a 133 mm$^2$ grating. Two different wavelength regions, 200 – 346A and 953 – 1232A were measured together every 20 ms as shown in Fig.1. These spectral ranges are chosen to measure the emission lines from carbon ions. The line intensity ratios can give useful information for plasma diagnostcs. In this paper we use the line intensity ratios to investigate the plasma state. The main observed line pairs used to obtain the intensity ratios are as follows; C V 227.18A(1s2s $^3$S – 1s3p $^3$P) and 248.6A(2s2p $^3$P – 1s3d $^3$D), C IV 312.4A(2s – 3p ) and 289.22A (2p – 4d), C III 977.02A (2s2 $^3$S – 2s2p $^3$P) and 1175.5A ( 2s2p $^3$P – 2p$^3$P), H I 1024A(1s – 2p) and 1215.7A(1s – 3p). Time-history comparisons suggest that the increase of radiation emission at the beginning is mainly from C IV lines and later from C V lines. [4]

We studied time dependent line intensity ratios of CIII and CV for a plasma with radiation collapse which happened in the experiment at NIFS-LHD shot number 55644. The time dependent spatial distribution of the electron temperature and density was measured by Thomson scattering [5] and the radiation power measured by imaging bolometers [1] in our experiments. The plasma was heated by Neutral Beam Injection (NBI) and a hydrogen gas puff was started at 0.5 s from the beginning of the plasma and continued until 1.1 s. The time history of the intensity ratios I(1175A)/I(977A) of CIII and I(248)/I(227) of CV is shown in Fig.2. Intensity ratios are almost constant during the heating until 0.94 s when the electron density begins to increase due to the gas injection. The intensity ratios increase from 0.94 s until 1.08 s. The electron temperature begins to decrease at 1.0 s and plasma decays before 1.2 s [4]. The lines from CV ions disappear after 1.18 s although lines from CIII are observed for a long time because the NBI heating continues and supports a low temperature plasma even after the radiation collapse. The low counting rates of CV lines before 0.3 s and after 1.2 s in Fig.2 (a) are probably noise due to low temperature.

Theoretical calculations for the line intensities are performed with the use of our collisional-radiative model for carbon ions. The intensity C V 227A is stronger than C V 248A in ionizing plasma because excitation from lower states is stronger to the level 1s3p than 1s3d. On the contrary the line CV 248.6A is stronger than C V 227A because recombination to 1s3d levels is larger than to 1s3p levels. The theoretical intensity ratios for a CV line pair I(248)/I(227) are shown in Fig.3 for ionizing, equilibrium and recombining plasmas as a function of electron temperature. The intensity ratios increase when recombination process increases.

The values of the observed line intensity ratios are around 0.7 during the heating. These small values indicate that the emission is produced by excitation in an ionizing plasma, and the electron temperature is estimated to be about 400 eV. After 0.94 s the intensity ratio increases rapidly and this indicates a contribution from recombination. We also estimated the temperature from another line pair (the intercombination line / resonance line pair of C V) for other experiments with Xe puffing and the derived temperature was about 200 eV. The radial position for 400 eV of our shot is $\rho = 0.95$ from the temperature distribution measured by Thomson scattering where $\rho$ is the scaled radius ($\tau = 1$ is the last closed magnetic surface). The spatial distribution of the radiation power measured by bolometer has a peak at $\rho = 0.94$. Therefore we assumed the electron temperature of C V region is the same as the peak region of the Radiation power measured by the bolometer. In Fig. 3 we plot the observed intensity ratios against the temperature derived from the bolometric measurement. This figure shows that the intensity ratios are larger at lower temperature. The intensity I(248) increases more rapidly than I(227) at lower temperature. This indicates that the recombination effect on the population density of the upper level 1s3d $^3$P of the line 248A is stronger than that of of 1s3p $^3$P of the line 227A. In order to explain the increase of the ratios quantitatively it is necessary that the ion ratio C IV/C V be about 0.95 – 0.98 which means the amount of H-like C is almost the same as He-like C. We made a time dependent theoretical calculation for carbon ions. It is found that the total radiation loss is mainly produced by excitation although the line CV 248A is also affected by recombination and the ion abundances are changing due to the recombination process.
Fig. 1 Observed spectra of carbon ions during the NBI heating (t = 0.9 s).

Fig. 2 The time history of the observed intensity ratios (filled circle) of (a) C V lines I(248)/I(227) and (b) C III lines I(1175)/I(977). The time evolution of two lines is also plotted. Radiation power measured by the bolometer is shown by a dotted line.

Fig. 3 The theoretical intensity ratios of CV I(1s2p – 1s3d)/I(1s2s – 1s3p) as a function of electron temperature (eV). The solid line indicates the case for ionizing plasma, the dot-dashed line for recombining plasma, the dotted line for equilibrium plasma conditions. The dashed line for the case the ion density ratio n(CVI)/n(CV) = 0.95. The observed values are shown by filled circles with the measured time.

3. Energy balance at radiation collapse
When we compare the radiation power measured by the bolometer and the energy input from NBI heating, the NBI deposition power is much larger. In our case (55644) the radiation power is less than 10% of the NBI deposition power. The radiation begins to increase at 0.94 s when the electron density begins to increase by gas puffing. However the electron temperature begins to decrease at 1 s. The radiation power has a peak at $\rho = 0.94$ which is the edge of the plasma, far from the center. How does the plasma cool? We consider the energy is lost by radiation at the edge of the plasma and the temperature at the edge decreases only gradually. The stored energy is measured by a coil called a diamagnetic loop. The stored energy of the plasma reached the maximum value (about 700 KJ) at 0.96 s and decays within 0.2 s. The stored energy begins to decrease at 0.964 s and the loss rate of stored energy increases for a time. At around $t = 1$ s, the stored energy is decreasing by about 500 kW which is almost the same as radiation power measured by the bolometer.

The peak emission observed by the bolometer is $\rho = 0.9$ at 0.96 s and the emission rate $Prad \sim 50$ kW/ m$^3$. At this position the electron temperature is 500 eV and the electron density is $6 \times 10^{13}$ cm$^{-3}$. The cooling time for this plasma $\tau = 3/2 n_e kT_e / Prad \sim 0.1$ s which is the same order of the decay time of the radiation collapse. We can consider the radiation loss at the edge is the origin of the collapse. However we do not yet know how the electron temperature at the center decreases.

4. Comparison with non-radiation collapse.
We also measured the spectra for a shot (55642) in which the plasma decays without radiation after the NBI heating terminates. The temperature and stored energy decay gradually over 0.4s. We derived the time history of the observed intensity ratios of carbon lines as in Sec.2. It is found that the behaviors of the intensity ratios are quite different from the case of radiation collapse. The intensity ratios of CV decrease rapidly although they increased in the case of radiation collapse. This means that the temperature where CV ions exist is increasing from our calculation shown in Fig.3. After the heating turns off, the plasma becomes smaller and the electron density increases according to the density measurement by Thomson scattering. Therefore it appears that CV ions move towards the center in the decay phase. However this phenomenon needs more careful analysis.

5. Summary and Discussion
We measured time-dependent spectra from carbon ions for shots with radiation collapse. The main part of the radiation loss is probably CIV and CV line emission from the time history of line intensities. Intensity ratios of CV and CIII indicate an increase of the recombination component after 0.92 s. We could explain the increase of CV lines by recombination processes from CVI to CV. However the main radiation is produced by excitation, not by recombination. We compared the time history of the intensity ratios for experiments with radiation collapse and non-radiative collapse. The intensity ratios for non-radiation collapse indicate an ionizing plasma, quite different from radiation collapse. We will study this difference further. We plan to extend our time-dependent model for carbon ions. We will also study radiation collapse caused by radiation from other elements such as neon, iron and xenon. We also would like to know why the central electron temperature decreases because of the radiation after 1 s.

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