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# Simulation of radiation losses using non-coronal model on HL-2A

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In this paper, the radiation losses of impurity on HL-2A have been simulated by assuming the profiles electron temperature and density and solving ionization rate equation under conditions of non-coronal radiation. The time required for an impurity species to establish equilibrium is proved to be sensitively dependent on the plasma electron temperature, and it is strongly correlated with the ionization state distribution during equilibrium establishment of impurity species. It is found from simulation results that the residence parameter plays an important role in the enhancement of radiation losses of plasma.

**Keywords:** ionization rate equation, radiation losses, radiated power coefficient, residence parameter

**PACC:** 5265

## 1. Introduction

The behaviour of impurity in tokamak plasma is exceedingly complex if the impurity transport and recycling from the walls are taken into account. Generally, there is not enough time for the impurity ions of plasma to reach their coronal equilibrium.[1−4] For example, in coronal equilibrium, negligible radiation is expected for beryllium (Be) above 10 eV, boron (B) above 20 eV, carbon (C) above 30 eV, and oxygen (O) above 40 eV, whereas significant radiation has been observed experimentally from these species with the core periphery and scrape-off layer (SOL) temperature typically greater than 40 eV. The non-coronal radiative rate coefficient is very important in radiation and divertor physics of plasma.[5] It has been adopted in some sophisticated codes, such as B2-Eirene,[6] IMPMC,[7] MCI[8] and DIVIMP.[9]

The main atomic processes of impurities included in the calculations are collisional ionization, radiative and dielectronic recombination. In this paper, by using a numerical and analytic method, the charge-state distribution of impurity from entering into plasma has been obtained. The complete set of ionization rate equations for each impurity (Be, B, C, O, Ne, Si and Ar) has been solved analytically; at the same time, the cooling rate of impurities in plasma has been calculated under conditions of non-coronal radiation.

The radiation losses of impurity have been simulated by assuming the profiles of electron temperature and density on HL-2A. It is indicated that the time required for a series of impurity to establish coronal equilibrium is sensitively dependent on the plasma electron temperature, and strongly correlated with the ionization state distribution during equilibrium establishment of impurity species. From simulation results, it is found that the residence parameter of impurities plays an important role in the enhancement of radiation losses of plasma.

## 2. The ionization rate equation and atomic processes

The interactions of electron with hydrogen atoms and ions in plasma are complicated by considering collision and radiative decay times; the techniques for treating such systems were first described by Bates and McWhirter.[10,11] The physical processes included are listed as follows: a. electron collisional ionization $K_{i,mn}$; b. radiative recombination $\beta_m$; c. three-body recombination $K_{r,mn}$; d. spontaneous radiative transitions $A_{mn}$; e. electron collisional excitation $K_{e,mn}$; f. electron collisional de-excitation $K_{d,mn}$; where $m$ and $n$ are principal quantum numbers. For the two-state terms, the initial state is the second number; the

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final is the first. This apparently backward notation allegedly has a mathematical origin.

A set of $m$ equations describes the balance between these processes which determines the density of the $m$th excited state of the atom, $N_m$:

$$\frac{\mathrm{d}N_m}{\mathrm{d}t} = -N_m\left[N_\mathrm{e}\left(K_{i,m}+\sum_{n>m}K_{\mathrm{e},nm}+\sum_{n<m}K_{\mathrm{d},nm}\right)+\sum_{n<m}A_{nm}\right]+N_\mathrm{e}\left(\sum_{n>m}N_nK_{\mathrm{d},mn}+\sum_{n<m}N_nK_{\mathrm{e},mn}\right)+\sum_{n>m}N_nA_{mn}+N_\mathrm{e}N_\mathrm{I}(\beta_m+n_\mathrm{e}K_{\mathrm{r},m}), \quad (1)$$

where $N_\mathrm{e}$ is the electron density and $N_\mathrm{I}$ is the density of ions corresponding to the atom under consideration ($m\to\infty$, effectively).

Neglecting physical processes c–f, we can write Eq.(1) as

$$\frac{\mathrm{d}N^q}{\mathrm{d}t} = N_\mathrm{e}\left[(\beta^{q+1}N^{q+1}-\beta^qN^q)-(K^qN^q-K^{q-1}N^{q-1})\right] \quad (2)$$

where $N^q$ is the ion density of $q$-th ionization state, $\beta^q$ is the recombination rate coefficient from $q+1$ to $q$, $K^q$ is the ionization rate coefficient from $q$ to $q+1$. This can be written in matrix notation as:

$$\frac{\mathrm{d}f}{\mathrm{d}t} = N_\mathrm{e}Af, \quad (3)$$

where

$$A=\begin{bmatrix} -K^0 & \beta^1 & 0 & \cdots \\ K^0 & -(K^1+\beta^1) & \beta^2 & \cdots \\ 0 & K^1 & -(K^2+\beta^2) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}, \quad (4)$$

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \begin{bmatrix} f^0 & f^1 & \cdots & f^q & \cdots \end{bmatrix}^\mathrm{T}, \quad (5)$$

and $f^q$ is the fractional abundance of the $q$-th ionization state $\dfrac{N^q}{N_\mathrm{I}}=\dfrac{N^q}{\sum\limits_q N^q}$, $N_\mathrm{I}$ is the impurity initial density.

The ionization rate Eq.(2) describes the net effect of the ionization and recombination processes. if the ionization rate $K^q$ and recombination rate $\beta^q$ of the impurity are known and the Eq.(3) is solved, we can obtain the charge state distribution $N^q$ and the fractional abundance $f^q$.

# 3. The radiated power, the cooling rate and average charge of impurities

## 3.1. The radiated power of impurities[12]

Impurities in plasmas give rise to line and recombination radiation in addition to enhancing the bremsstrahlung. The power $P_q$ radiated by a particular impurity species may be written as

$$P_q = \sum_q P_{q\mathrm{l}}+P_{q\mathrm{r}}+P_{q\mathrm{d}}+P_{q\mathrm{c}}+P_{q\mathrm{br}}, \quad (6)$$

where $P_{q\mathrm{l}}$ is the line radiation from impurities in the $q$-th state, $P_{q\mathrm{r}}$ is the radiative recombination radiation, $P_{q\mathrm{d}}$ is the dielectronic recombination radiation, $P_{q\mathrm{c}}$ is the charge-exchange recombination radiation, $P_{q\mathrm{br}}$ is the bremsstrahlung due to the impurities. We will now deal with these separately.

### 3.1.1. Line radiation

In the coronal model, excited ions are assumed to undergo instantaneous radiative decay. Thus the line radiation is given by the product of the ion abundances, the excitation rates, and the transition energies. We have

$$P_{q\mathrm{l}} = N_\mathrm{e}N_\mathrm{I}f^q\sum_{n=1}^{N}Q_{qn}\Delta E_{qn}, \quad (7)$$

where $N$ is the number of transition included (typically 1 – 10), $Q_{qn}$ is the excitation rate coefficient of

the $n$-th transition, $\Delta E_{qn}$ is the excitation energies of the $n$-th transition.

#### 3.1.2. Radiative recombination radiation

In this process, a free electron is captured by an ion. The kinetic energy of the electron and the potential energy of the recombined ion are radiated, on the average, we have

$$P_{qr} = N_{\rm e} N_{\rm I} f^q \alpha_{{\rm rr}_q} (\chi_{q-1} + \langle E_{\rm e} \rangle), \tag{8}$$

where $\chi_{q-1}$ is the ionization potential of the recombined ion, $\langle E_{\rm e} \rangle$ is the average kinetic energy of the recombining electrons.

#### 3.1.3. Dielectronic recombination radiation

When the energy of an electron is below the excitation threshold energy it can excite an ion and subsequently find itself with insufficient energy to escape from the ion's Coulomb field. If the excited electron decays radiatively (the stabilizing transition) then the colliding electron is captured. The resulting radiation is:

$$P_{q{\rm d}} = N_{\rm e} N_{\rm I} f^q \alpha_{{\rm dr}_q} (\chi_{q-1} + E_q), \tag{9}$$

where $E_q$ is the excitation energy of the resonant transition.

#### 3.1.4. Charge-exchange recombination radiation

The charge-exchange electron will be in an excited state immediately following the collision. The charge-exchange radiation calculation is exceedingly difficult. Nevertheless, when we assume that on collision the full ionization potential of the recombined ion is radiated, we find that this loss is less than the additional power radiated as a result of the altered charge-state distribution. Thus we have:

$$P_{qc} = N_{\rm e} N_{\rm I} f^q \alpha_{{\rm cx}_q} \chi_{q-1}. \tag{10}$$

#### 3.1.5. Bremsstrahlung

The additional bremsstrahlung power due to the presence of a particular impurity charge-state is

$$P_{q{\rm br}} = 1.53 \times 10^{-38} N_{\rm e} N_{\rm I} f^q T_{\rm e}^{1/2} (q+1)^2 \ \ {\rm Wm}^{-3}. \tag{11}$$

### 3.2. The cooling rate of impurities[13]

The cooling rate of impurities in the $q$th state can be written as

$$l_q = \frac{P_q}{N_{\rm e} N_{\rm I} f^q}. \tag{12}$$

Therefore, the radiated power coefficient may be written as:

$$L_Z(T_{\rm e}) = \sum_{q=0}^{Z} f^q l_q = \sum_{q=0}^{Z} \frac{P_q}{N_{\rm e} N_{\rm I}} \tag{13}$$

where $Z$ is the atomic number of impurity. With negligible transport effects, the radiated power density may be written as:

$$P_{\rm rad} = N_{\rm e} N_{\rm I} L_Z(T_{\rm e}). \tag{14}$$

### 3.3. The average charge of impurities[13]

The quantities $\langle Z \rangle$ and $\langle Z^2 \rangle$ are used to calculate the number of additional free electrons produced when impurities are ionized, and the enhancement of the plasma resistivity and bremsstrahlung are realized. We have, by definition,

$$\langle Z \rangle = \sum_{q=0}^{Z} f^q q, \tag{15}$$

$$\langle Z^2 \rangle = \sum_{q=0}^{Z} f^q q^2. \tag{16}$$

In addition, the plasma can be considered to be composed of an effective ionic charge $Z_{\rm eff}$, when calculating the resistivity and the total bremsstrahlung. For thermal hydrogen plasma, $Z_{\rm eff}$ can be written as

$$\begin{aligned} Z_{\rm eff} &= \frac{\sum\limits_{q=0}^{Z} q^2 N^q}{\sum\limits_{q=0}^{Z} q N^q} = \frac{\sum\limits_{q=0}^{Z} q^2 N^q}{N_{\rm e}} \\ &= 1.0 + \frac{N_{\rm I}}{N_{\rm e}} \sum_{q=0}^{Z} f^q q(q-1). \end{aligned} \tag{17}$$

The evolutions of radiated power coefficient $L_Z$ and average charge $\langle Z \rangle$ of carbon, as the function of residence parameter $N_{\rm e}\tau_{\rm ss}$, are presented in Figs.1(a), (b), where $\tau_{\rm ss}$ is the impurity residence time in the plasma.

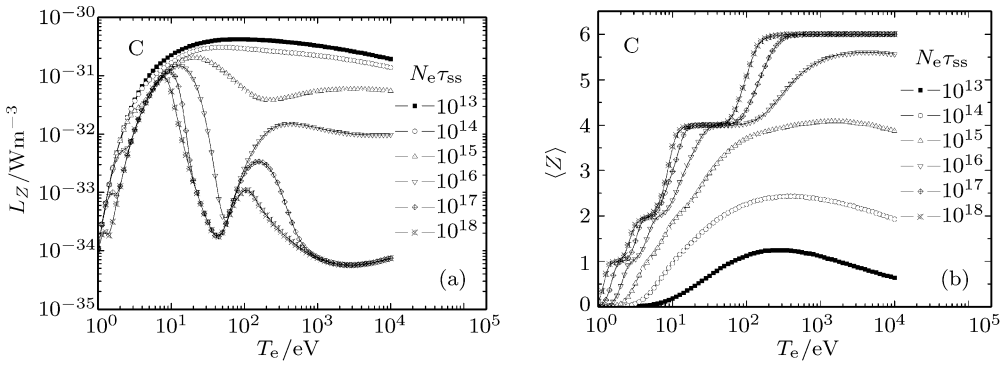



**Fig.1.** (a) The radiated power coefficient $L_Z$ of carbon for various values of $N_e\tau_{ss}$. (b) The average charge $\langle Z\rangle$ of carbon for $N_e\tau_{ss}$.

It is evident from the figures that the farther the impurities are from coronal equilibrium (i.e. small $N_e\tau_{ss}$ values) the flatter the radiation curves are: i.e. the closely packed ionization states, which are the strongest radiators, must be 'burnt-through' to reach the closed shell configurations. It follows that considerable enhancement of radiation, over that of steady-state, will usually occur only at temperatures in excess of that of the first radiation peak.

## 4. The application on HL-2A

In the discharge of HL-2A, the profiles of electron temperature and electron density are measured by electron cyclotron emission and microwave reflectometry respectively. Generally, they can be written as

$$T_e(r) = T_{ed} + (T_{e0} - T_{ed})\left[1 - \left(\frac{r}{a}\right)^2\right]^2, \quad (18)$$

$$N_e(r) = N_{ed} + (N_{e0} - N_{ed})\left[1 - \left(\frac{r}{a}\right)^2\right]^2, \quad (19)$$

where $a$ is the minor radius of plasma, $T_{ed}$ is the electron temperature of edge, $T_{e0}$ is the electron temperature of centre, $N_{ed}$ is the electron density of edge, $N_{e0}$ is the electron density of centre, $c$ is the impurity fraction. The profile of density of neutral impurity can be written as:

$$N_I(r) = \frac{c}{100} N_e(r). \quad (20)$$

Under the assumptions, the radiated power coefficient $L_Z$ and the radiated power density $P_{rad}$ have been calculated, and the results of carbon and oxygen are presented in Figs.2(a)–(d), and the effective charge $Z_{eff}$ is shown in Fig.3.

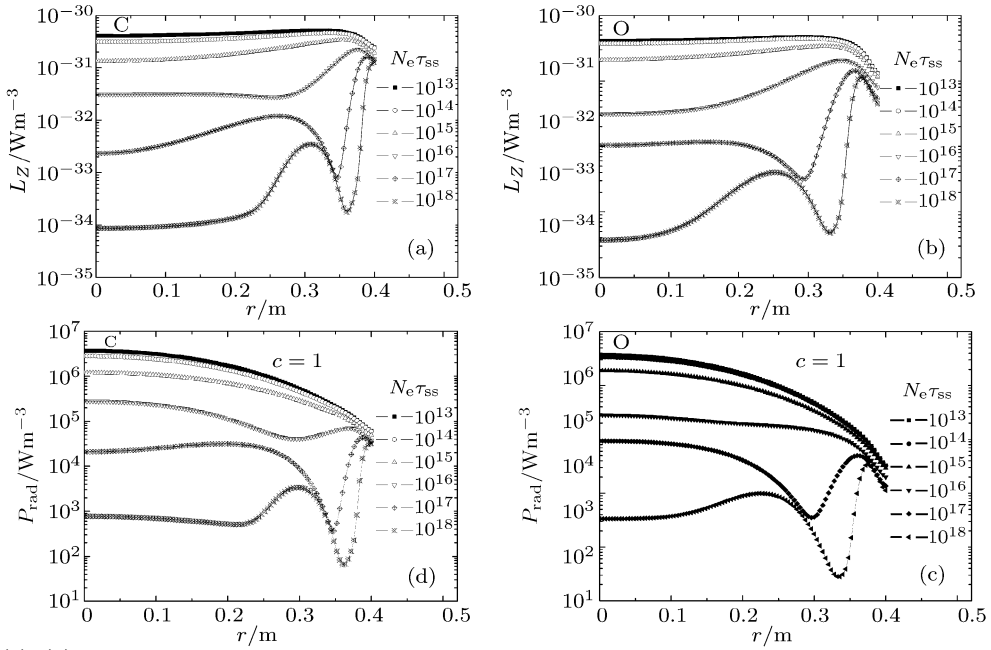



**Fig.2.** (a), (b) The radiated power coefficient $L_Z$ of carbon and oxygen for various values of $N_e\tau_{ss}$ on HL-2A. (c), (d) The radiated power density $P_{rad}$ of carbon and oxygen for various values of $N_e\tau_{ss}$ on HL-2A (i.e. $a = 0.4$ m, $T_{ed} = 10$ eV, $T_{e0} = 800$ eV, $N_{ed} = 0.5 \times 10^{19}$m$^{-3}$ and $N_{e0} = 3.0 \times 10^{19}$ m$^{-3}$).

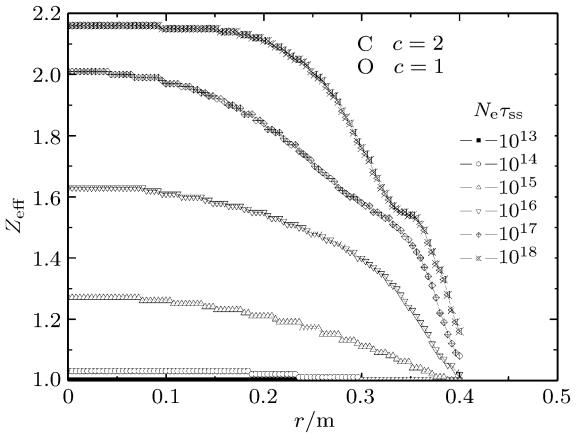



**Fig.3.** The effective charge $Z_{\rm eff}$ for various values of $N_{\rm e}\tau_{\rm ss}$ on HL-2A (i.e. $T_{\rm ed} = 10\,{\rm eV}$, $T_{\rm e0} = 800\,{\rm eV}$, $N_{\rm ed} = 0.5 \times 10^{19}\,{\rm m}^{-3}$, $N_{\rm e0} = 3.0 \times 10^{19}\,{\rm m}^{-3}$, carbon fraction 2% and oxygen fraction 1%).

# 5. Summary

The time that impurities must spend in plasma before reaching coronal equilibrium has been computed in a wide range of electron temperatures and impurity elements. The evolutions of the impurities during the non-coronal equilibrium phase have been presented and the radiated power coefficient, average charge and effective charge have been calculated as functions of electron temperature and residence parameter.

The local or transient radiation losses in plasmas can greatly exceed those in the coronal equilibrium. During non-coronal radiation, an impurity ion in the boundary has more electrons than it would have in equilibrium and therefore highly elevated levels of radiation can be found. Coronal equilibrium only represents a lower limit to the radiation level from an impurity. This is illustrated in Fig.1(a) for the case of carbon. The results can be parametrized by using a 'residence parameter' $N_{\rm e}\tau_{\rm ss}$. For example, at 30 eV, the rather low level of coronal radiation power for carbon can be enhanced by a factor of nearly 1000. This enhancement factor rapidly decreases with the period of time which the impurity is in the plasma and by $N_{\rm e}\tau_{\rm ss} \sim 10^{17}\,{\rm m}^{-3}{\cdot}$s.It has decreased by a factor of 30 from the peak value to $L_Z < 10^{-32}\,{\rm W}{\cdot}{\rm m}^{-3}$. In a word, the residence parameter is an important factor in the enhancement of radiation losses of plasma.

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