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Radiation loss in a compound plasma system with high and low temperature regions

Cheng Fa-Yin(程发银)[a)†], Tomonori Takizuka[b)],
Nobuhiko Hayashi[b)], and Shi Bing-Ren(石秉仁)[a)]

[a)] *Southwestern Institute of Physics, Chengdu* 610041, *China*

[b)] *Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Ibaraki* 311-01, *Japan*

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A code has been developed for calculating the non-coronal radiation of impurity in a compound plasma system which consists of high and low temperature regions. The radiation loss of impurity carbon in this system is calculated and analysed. The cooling rate in this system is smaller than that in a homogeneous plasma system due to the particle exchange between the two regions of the system. The volumetric radiation is much bigger in the low temperature region than in the high temperature region because of the relatively low temperature and high electron density, despite the much smaller volume.

Keywords: plasma, non-coronal radiation
PACC: 5265, 5225V, 5220F, 5225P

1. Introduction

Impurity radiation plays a major and probably dominant role in energy loss especially for the dense and cold divertor plasma and the detached plasma. This radiation loss is expected to reduce the heat load on the divertor plates in fusion reactors. There are many kinds of impurities in tokamak plasma: low-Z intrinsic species such as beryllium, boron, carbon and oxygen and other extrinsic impurities such as neon and argon specifically introduced to enhance the radiation loss. The impurity radiation in a core plasma is often evaluated with a coronal equilibrium model. In a coronal equilibrium the radiation losses are negligibly small for beryllium at an electron temperature T_e above 10eV, for boron at T_e above 20eV, for carbon at T_e above 30eV and for oxygen at T_e above 40eV.[1] However, significant radiation levels from these species have been observed in a periphery region and scrape-off-layer (SOL) region at a temperature typically greater than 40eV. This is because the impurity charged states are not in the coronal equilibrium. Under such a non-coronal condition, the fractions of the impurities in all the charged states are calculated by the rate equations, and then the radiation loss is calculated by using the cooling rate of the respective charged state. The reason for the increase of non-coronal radiation in a peripheral plasma is as follows. The charged impurities are lost fast from the plasma and the new impurity source is supplied to this region. The charged states of impurities, therefore, do not reach their coronal-equilibrium ones. These impurity ions capture more electrons than those in the coronal equilibrium, and resultantly emit the higher radiation power. Accurate knowledge of the non-coronal radiation of impurities under the edge plasma condition is required both for an accurate assessment of the feasibility of reducing the heat load on divertor target plates and for the analysis of present experiments in which impurity radiation in the plasma edge and divertor plasma plays an important role.

In this paper, we study the non-coronal radiation loss in a compound plasma system, which consists of high and low temperature regions. The calculation model and the code for the non-coronal radiation in a compound plasma system are introduced in Section 2. Section 3 presents calculation results of radiation loss by impurity carbon. In Section 4, we summarize the results and discuss problems to be solved in future.

†E-mail: chengfy@swip.ac.cn

2. Calculation model

2.1. Rate equations for a homogeneous plasma system

We calculate the impurity densities n_k ($k = 0, 1, \ldots, z$) for all charged states of impurities with a charge number z by solving the rate equations of the system, which are described as[2,3]

$$\frac{\partial n_k}{\partial t} = v^{\mathrm{i}}_{k-1} n_{\mathrm{e}} n_{k-1} - (v^{\mathrm{i}}_k + v^{\mathrm{r}}_k) n_{\mathrm{e}} n_k + v^{\mathrm{r}}_{k+1} n_{\mathrm{e}} n_{k+1} - \frac{n_k}{\tau^{\mathrm{loss}}_k} \quad (k = 1, 2, \ldots, z), \tag{1}$$

$$n_0 = n_{\mathrm{tot}} - \sum_{k=1}^{z} n_k, \tag{2}$$

where v^{i} and v^{r} in Eq.(1) represent the ionization and recombination rates, respectively, which are calculated by using the average-ion model developed by Hulse.[4,5] We assume here the conservation of total density of impurities n_{tot}, and obtain the density of neutral impurity n_0 by Eq.(2). The parameter τ^{loss}_k denotes the loss time of impurity in the kth charged state. It must be noted that for fully striped particles ($k = z$ in the above equations) the ionization rates v^{i}_z are automatically set to be zero. Furthermore when $k = z$, the recombination terms v^{r}_{k+1} are also zero.

Because the ionization to a higher charged state needs a higher plasma temperature, the locations of highly charged-state ions in a peripheral plasma are farther from the solid surface than those of lower kth ions, and the transportation of higher kth ions to the solid surface needs a longer time. In order to simulate these features we introduce a simple model of the loss time in Eq.(1): $\tau^{\mathrm{loss}}_k = \tau_0 (1 + k)^{\alpha}$.

2.2. Rate equations for a compound plasma system

Now we consider a compound plasma system with high and low temperature regions. This compound system represents the peripheral plasma region in a magnetic confinement system, such as a tokamak. This system can be applied to the following cases: (I) core peripheral plasma as a hot region and SOL plasma as a cold region. (II) SOL plasma as a hot region and divertor plasma as a cold region. The rate equations newly include the particle exchange term between the two regions. This particle exchange corresponds to the cross-field transport in the case (I) while it corresponds to the parallel transport in the case (II). The rate equations of this compound plasma system are described as

$$\frac{\partial n^{(\mathrm{l})}_k}{\partial t} = v^{i,(\mathrm{l})}_{k-1} n^{(\mathrm{l})}_{\mathrm{e}} n^{(\mathrm{l})}_{k-1} - (v^{i,(\mathrm{l})}_k + v^{\mathrm{r},(\mathrm{l})}_k) n^{(\mathrm{l})}_{\mathrm{e}} n^{(\mathrm{l})}_k + v^{\mathrm{r},(\mathrm{l})}_{k+1} n^{(\mathrm{l})}_{\mathrm{e}} n^{(\mathrm{l})}_{k+1} - \frac{n^{(\mathrm{l})}_k}{\tau^{(\mathrm{l})}_k} - \frac{n^{(\mathrm{l})}_k - \beta n^{(\mathrm{h})}_k}{\tau^{\mathrm{ex}}_k}, \tag{3a}$$

$$\frac{\partial n^{(\mathrm{h})}_k}{\partial t} = v^{i,(\mathrm{h})}_{k-1} n^{(\mathrm{h})}_{\mathrm{e}} n^{(\mathrm{h})}_{k-1} - (v^{i,(\mathrm{h})}_k + v^{\mathrm{r},(\mathrm{h})}_k) n^{(\mathrm{h})}_{\mathrm{e}} n^{(\mathrm{h})}_k + v^{\mathrm{r},(\mathrm{h})}_{k+1} n^{(\mathrm{h})}_{\mathrm{e}} n^{(\mathrm{h})}_{k+1} - \frac{n^{(\mathrm{h})}_k}{\tau^{(\mathrm{h})}_k} - \frac{n^{(\mathrm{h})}_k - (1/\beta) n^{(\mathrm{l})}_k}{\tau^{\mathrm{ex}}_k}, \tag{3b}$$

where the charged state k takes the number from 1 to z.

In these equations, τ_k denotes the loss time from the system, and superscripts (h) and (l) represent high and low temperature regions, respectively. Parameter β which is the ratio of the volume in the high temperature region to that in the low temperature region ($V^{(\mathrm{h})}/V^{(\mathrm{l})}$) is introduced here so that the particle exchange between the two regions does not change the total number of the kth impurity particles. Similar to the loss time in a homogeneous plasma system, the exchange time between the high and low temperature regions of the compound plasma system is assumed to be a function of charged state k: $\tau^{\mathrm{ex}}_k = \tau^{\mathrm{ex}}_0 (1 + k)^{\alpha}$.

In order to maintain the particle balance, we assume that all the particles lost from the system (from both cold and hot regions) are recycled and supplied to the low temperature region as neutrals. This situation is described by the following equations:

$$\frac{\partial n^{(\mathrm{l})}_0}{\partial t} = v^{\mathrm{r},(\mathrm{l})}_1 n^{(\mathrm{l})}_{\mathrm{e}} n^{(\mathrm{l})}_1 - v^{i,(\mathrm{l})}_0 n^{(\mathrm{l})}_{\mathrm{e}} n^{(\mathrm{l})}_0 - \frac{n^{(\mathrm{l})}_0 - n^{(\mathrm{h})}_0}{\tau^{\mathrm{ex}}_0} + \sum_{k=1}^{z} \frac{n^{(\mathrm{l})}_k}{\tau^{(\mathrm{l})}_k} + \sum_{k=0}^{z} \frac{n^{(\mathrm{h})}_k}{\tau^{(\mathrm{h})}_k}, \tag{4}$$

$$n^{(\mathrm{h})}_0 = n_{\mathrm{tot}} - \sum_{k=0}^{z} n^{(\mathrm{l})}_k - \sum_{k=1}^{z} n^{(\mathrm{h})}_k, \tag{5}$$

where n_{tot} is the total impurity density of the system.

Equations (3a), (3b) and (4) together with the restrict condition Eq.(5) are solved, and the density distribution of all charged states are obtained. Then the cooling rate of impurity in either region can be calculated by using the radiation coefficient p_k[6]

$$L = \sum_{k=0}^{z} (p_k n_k) \Big/ \left[n_{\mathrm{e}} \sum_{k=0}^{z} n_k \right]. \tag{6}$$

2.3. Numerical method

In this work, we solve the rate equation by using a full-implicit time difference scheme. The time discretized rate equations can be easily solved by using the lower/upper triangular matrix decomposition (LU decomposition) method. The initial conditions are as follows: the neutral impurity density in the low temperature region is $n_0(0) = n_{\rm tot}$, both the densities of charged impurities ($k = 1, 2, \ldots, z$) in the low temperature region and the densities of all charged state impurities ($k = 0, 1, \ldots, z$) in the high temperature region are set to be zero. We can obtain the impurity distribution for all charged states in the two regions at the time $t' = t + \Delta t$ by solving the time discretized rate equations. When the time has progressed long enough, we obtain the steady-state solution to the rate equations of the compound plasma system. We calculate the cooling rate for this steady state by using Eq.(6).

For accuracy, the time step Δt should be smaller than the characteristic time of ionization and recombination. Generally, under the tokamak edge plasma condition (electron density is in a range of $10^{19} - 10^{20}{\rm m}^{-3}$, electron temperature is less than 200eV), the minimal ionization time is about 10^{-6}s, the minimal recombination time is about 10^{-3}s, so in this work we choose the time step as $\Delta t = 10^{-7}$s.

3. Calculation results

In this section we calculate and analyse the radiation losses of impurity carbon.

Consider a compound system consisting of high and low temperature regions in the case (II), i.e. SOL and divertor regions, and in either region the plasma is assumed to be homogeneous, the particle exchange time between the two regions is a function of charged state of the impurity: $\tau_k^{\rm ex} = \tau_0^{\rm ex}(1+k)^\alpha$, and here we let the parameter $\alpha = 0.5$. In the low temperature region, the plasma temperature is given in a range of 5eV to 20eV, the electron density $n_{\rm e}^{(\rm l)}$=$10^{20}{\rm m}^{-3}$, and the particle loss time being 1/10 of the particle exchange time ($\tau_{\rm loss}^{(\rm l)}/\tau_{\rm ex}^{(\rm l)} = 1/10$). In the high temperature region, the plasma temperature is given in a range of 50eV to 200eV and we fix the ratio of $T^{(\rm h)}/T^{(\rm l)} = 10$ in any case. The electron density in the high temperature region is set to be $n_{\rm e}^{(\rm h)} = 10^{19}{\rm m}^{-3}$ so as to satisfy the pressure balance: $n_{\rm e}^{(\rm h)}T^{(\rm h)} = n_{\rm e}^{(\rm l)}T^{(\rm l)}$. Contrary to the case of the low temperature region, we assume the particle loss time in the high temperature region to be infinite. Furthermore, we assume the volume of the high temperature region to be 10 times that of the low temperature region ($V^{(\rm h)}/V^{(\rm l)} = 10$), which is typical of SOL and divertor regions in a tokamak edge plasma.

Figures 1 and 2 show the cooling rate of carbon in the low and high temperature regions of a compound plasma system, respectively. For comparison, we also calculate the cooling rate of carbon in a simple plasma system by solving the rate equations described in Eq.(1). Figures 3 and 4 show the results in a simple system, which are obtained under the similar calculation condition to those in the low and high temperature regions of the compound plasma system, respectively, i.e. with the same values of parameter $n_{\rm e}\tau_{\rm loss}$ in a simple system, $n_{\rm e}^{(\rm l)}\tau_{\rm loss}^{(\rm l)}$ in a low temperature region, and $n_{\rm e}^{(\rm h)}\tau_{\rm ex}$ in a high temperature region.

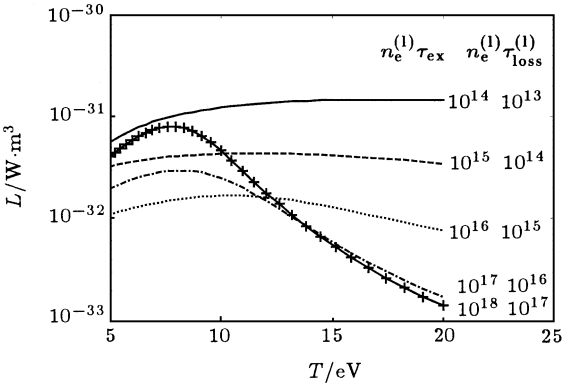


Fig.1. Cooling rate L of impurity carbon in the low temperature region of a compound plasma system as a function of plasma temperature T.

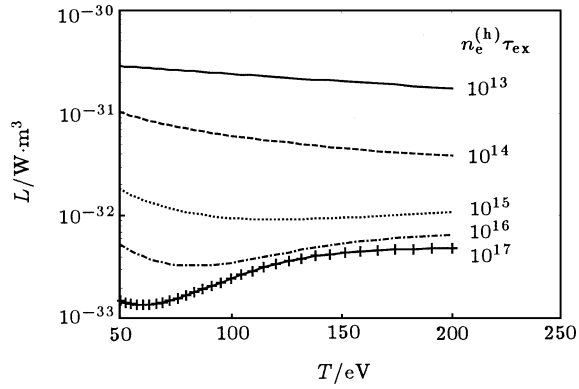


Fig.2. Cooling rate L of impurity carbon in the high temperature region of a compound plasma system as a function of plasma temperature T.

From Figs.3 and 4 we can see that the cooling rate of impurity decreases with the increase of $n\tau$ value for the simple plasma system, which is consistent with the

results in Refs.[7,8]. The coronal radiation ($n\tau \to \infty$) in this situation can only represent the lower-limit of impurity radiation. However, radiation in the compound plasma system is very complex compared with that in the simple system. We can see from Fig.1 that when the temperature is lower than a certain value (about 13eV here), the radiation of impurity at first decreases with the increase of $n\tau$, and then increases with it. Figure 5 shows the relationship of cooling rate with parameter $n\tau$ in the low temperature region of the compound plasma system at a temperature of 8eV. For a small $n\tau$ value, a large number of ions in highly charged state are supplied from the high temperature region in an exchange process, hence the radiation loss decreases with the increase of $n\tau$. With further increase of $n\tau$ value, the average charge state of impurity decreases, and the resultant radiation loss increases with it and approaches the coronal radiation loss.

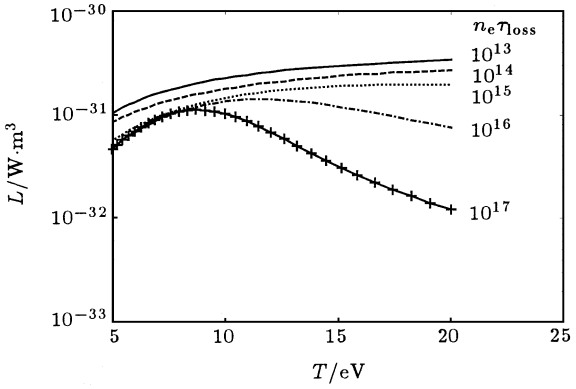


Fig.3. Cooling rate of impurity carbon in a homogenous plasma system which is under the similar calculation condition to that in Fig.1.

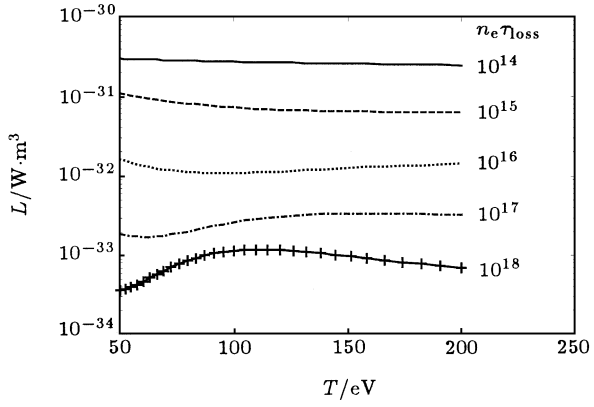


Fig.4. Cooling rate of impurity carbon in a homogeneous plasma system which is under similar calculation condition to that in Fig.2.

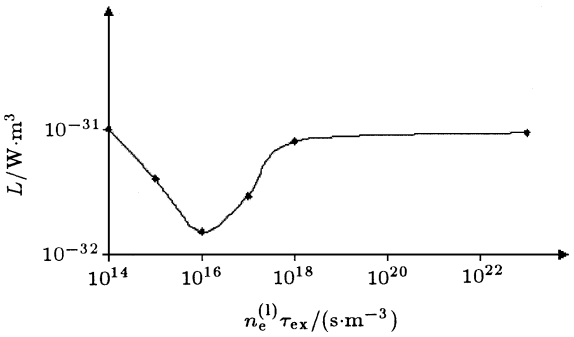


Fig.5. The cooling rate L changes with the parameter $n_e^{(l)}\tau_{ex}$ in the low temperature region of a compound plasma system. The temperature in this region is 8eV.

Figure 6 shows the ratio of volumetric radiation loss in the low temperature region to that in the high temperature region $(PV)^{(l)}/(PV)^{(h)}$. From this figure we can see that despite the much smaller volume of the low temperature region, the volumetric radiation in it is much bigger than that in the high temperature region; in particular, when $n\tau = 10^{16}\mathrm{s\cdot m^{-3}}$ and temperature T_e is less than 10eV, the ratio of volumetric radiation in these two regions becomes more than 100.

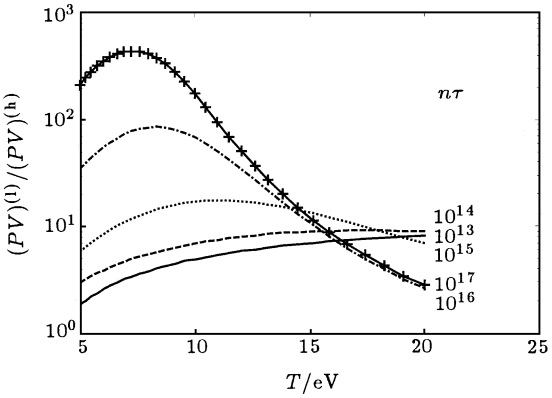


Fig.6. Ratio $(PV^{(l)}/(PV)^{(h)}$ of the volumetric radiation loss in the low temperature region to that in the high temperature region of a compound plasma system as a function of the temperature T in the low temperature region.

4. Summary and discussion

A non-coronal impurity radiation code which uses an average-ion model has been developed. The radiation loss of carbon in a compound plasma system has been calculated and analysed. This compound system consists of a low temperature region and a high temperature region, which is a model for the divertor plasma and the SOL plasma. It can be seen from the calculations that the cooling rate of carbon in this compound plasma system is smaller than that in a homogeneous plasma system: that is to say, using a

simpler model will often result in an overestimated radiation loss of impurity. Furthermore, through comparison, we have found that the volumetric radiation loss in the low temperature region is much bigger than that in the high temperature region despite its volume being much smaller. This is the reason why we can reduce the heat load of the target plate by introducing some impurities into the divertor chamber.

The carbon impurity population in present tokamak plasma is affected significantly by the hydrocarbon species.[9] Therefore the densities of hydrocarbon impurities should be included in the rate equations for the accurate estimation of the cooling rate by carbon impurities. The model used here to calculate the radiation loss is simple to some extent. The behaviour of ion transport in plasma is not completely described. More detailed calculation of the non-coronal radiation will be necessary. A Monte Carlo calculation such as the personal-made IMPMC[10] is a solution, but this exceeds the range of the present work. However, the simple calculation like the present work is significative both for the understanding of the characteristics of non-coronal radiation itself and for the experimental analysis.

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References

[1] Pitcher C S and Stangeby P C 1997 *Plasma Phys. Control. Fusion* **39** 779

[2] Suzuki A, Takizuka T, Shimizu K, Hayashi N, Hatayama A and Ogasawara M 1997 *J. Comput. Phys.* **131** 193

[3] Li Q L, Zheng Y Z, Cheng F Y, Deng X B, Deng D S, You P L, Liu G A and Chen X D 2001 *Acta Phys. Sin.* **50** 507 (in Chinese)

[4] Hulse R A 1983 *Nucl. Technol. Fusion* **3** 259

[5] Marchand R, Lafortune S and Bonnin X 1993 *Comput. Phys. Commun.* **76** 203

[6] Zhang L Z, Yu W, Wang J L, Han L and Fu G S 2001 *Chin. Phys.* **10** 639

[7] Post D E 1995 *J. Nucl. Mater.* **220–222** 143

[8] Shimada M, Nagami M, Ioki K, Izumi S, Maeno M, Yokomizo H, Shinya K, Yoshida H, Brooks N H, Hsieh C L, Groebner R and Kitsunezaki A 1982 *Nucl. Fusion* **22** 643

[9] Chen Y P, Zhou G C and Wu J S 2003 *Acta Phys. Sin.* **52** 421 (in Chinese)

[10] Shimizu K, Kubo H, Takizuka T, Azumi M, Shimada M, Tsuji S, Hosogane N, Sugie T, Sakasai A, Asakura N and Higashijima S 1995 *J. Nucl. Mater.* **220–222** 410