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CARBON INFLUX FLOW RATE
IN AN OHMICALLY HEATED PLASMA
IN THE FM-1 SPHERATOR

BY

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PLASMA PHYSICS
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CARBON INFLUX FLOW RATE IN AN OHMICALLY
HEATED PLASMA IN THE FM-1 SPHERATOR

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ABSTRACT

The flow rate of neutral carbon atoms during the initial startup phase of an ohmically heated plasma in the FM-1 spherator was determined from the spatially resolved measurements of the carbon line radiation and independent measurements of spatial distribution of plasma density and electron temperature. This was accomplished by comparing the measured carbon line intensity with a numerical solution of time-dependent coupled differential rate equations for several carbon ionization states. The empirical flow rate of carbon atoms into the discharge, $\Gamma_{\text{flow}}(t)$, was found to be $\Gamma_{\text{flow}}(t) \approx n_e(t)/\tau_{\text{flow}}$, where τ_{flow} was 30-100 msec depending upon discharge conditions.

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1. INTRODUCTION

Recently there is considerable interest in the impurity influx of low Z impurities such as carbon and oxygen during the initial startup phase of ohmically heated plasmas in large toroidal plasma confinement devices. Several experiments in tokamak devices indicate that the initial plasma condition determines the final plasma parameters in the later part of the discharge [1,2,3]. In particular, the presence of small amounts of low Z impurities can significantly affect the startup conditions in a large tokamak [4]. Although the necessity and significance of quantitative measurements of the impurity flow rate into the discharge has been discussed [1,2], few experiments have been carried out to obtain the flow rate in toroidal devices.

In this paper, a method will be presented to obtain the impurity flow rate from spatially resolved measurements of the impurity line radiation and spatially resolved measurements of the electron density and temperature. Here, the analysis was carried out for carbon atoms, which is the main impurity species in an ohmically heated plasma in the FM-1 spherator.

The procedure of numerical analysis is as follow: The time-dependent differential rate equations for several carbon ionization states is solved by using the measured electron density and temperature with an adjustable parameter, the flow rate of carbon atoms into the discharge $\Gamma_{\text{flow}}(t)$. The calculated emitted line intensity of CII and CIII is found to be a sensitive function of the assumed flow rate of carbon atom. Thus by comparing the numerical results with

the absolute intensity as well as the time dependence of the line radiation, it is possible to obtain the carbon flow rate. As will be shown, the carbon impurity flow rate in the ohmically heated plasma in the FM-1 spherator is empirically given by $\Gamma_{\text{flow}}(t) \approx n_e(t)/\tau_{\text{flow}}$, where τ_{flow} is 30-100 msec depending upon plasma conditions. In Sec. II, the experimental arrangements will be discussed. In Sec. III, we present the numerical model that is used to determine the carbon flow rate. In Sec. IV, we examine the possible mechanisms that may dislodge carbon atoms from the wall or the limiter surface into the plasma and in Sec. V, we state our conclusions.

II. EXPERIMENTAL ARRANGEMENT

In the present experiment, the levitated superconducting coil was excited with 275 kAT. The ratio of the toroidal field current I_t to the ring current I_p was 1.0. The magnetic field strength in the plasma volume was 3.5 ~ 4.5 kG. The typical base pressure was less than 1.5×10^{-7} torr (by using 4000 l/sec oil diffusion pump). The plasma volume was $7 \times 10^5 \text{ cm}^3$ and the volume of the vacuum tank was $5 \times 10^6 \text{ cm}^3$. Hydrogen gas was used in the experiment in the range of filling pressured 0.2 - 3×10^{-5} torr. The preionized plasma was produced by applying microwave heating of 1 kW at 10.6 GHz with the pulse length of 200 ~ 500 msec. The plasma reached to the quasi-equilibrium stage of $n_e = 5 \times 10^{11} \text{ cm}^{-3}$ and $T_e = 5 \text{ eV}$ within the preionizing heating pulse. The ohmic heating current was produced by applying an inductive electric field in the poloidal direction just after the termination of the preionization pulse. The pulsed inductive current was about 150 kA with a one cycle period of 500 Hz.

The line average plasma density was measured by a 4mm microwave interferometer. Spatially resolved measurements of electron density and electron temperature were obtained by laser Thomson scattering. The Thomson scattering system was designed to measure the relatively low plasma density ($n_e \geq 2 \times 10^{12} \text{ cm}^{-3}$) with $T_e \approx 10 \sim 200 \text{ eV}$, by using high sensitivity photomultiplier tube RCA C31034A. The average electron temperature was also obtained from the line intensity ratio CIII 4647Å/CIII 2297Å and CIII 4647Å/CII 4267Å, which was generally in good agreement with the values obtained by laser Thomson scattering measurements.

The spatial distribution of the line intensity was measured by using a rotatable mirror in the vertical plane and an absolutely calibrated 50cm monochromator with a spatial resolution of less than 2 mm. The observed line intensity $I(\theta)$ at angle θ , was the integrated intensity along the optical path, namely

$$I(\theta) = \int i(\psi) dl,$$

assuming the line intensity is uniform over the same magnetic surface, where the natural toroidal coordinate [5] (ψ, χ, ϕ) is used. The local light emissivity $i(\psi)$ was calculated by an inversion technique similar to the Abel inversion in the cylindrical coordinate. In the present case, the integral interval is over the space between the surface of the levitated ring (ψ_{ring}) and the outside plasma edge (ψ_{edge}), while in the conventional cylindrical calculation the integration is usually done from $r = 0$ to r_{edge} . The accuracy of the present inversion is considerably better than that in the cylindrical case. This is especially true for the regions around the maximum signal.

In the experimental parameter range ($n_e = 2 \sim 5 \times 10^{12} \text{ cm}^{-3}$), $T_e = 2 \sim 50 \text{ eV}$, the time interval of the first half cycle of the ohmic heating pulse, i.e., ($\Delta t \leq 1 \text{ msec}$), the carbon atoms are ionized mainly to CII and CIII stage. Thus, the intensity of CII 4267Å and CIII 4647Å were used for the spatially resolved measurement; and the spatial average intensity of CIV 4658Å which was relatively weak, was used to check the consistency of the observations. The plasma particle confinement time was determined from the loss rate across the magnetic surface as measured by the flow rate of the plasma into the limiter, which was located just outside of the outermost stagnation surface.

Fig. 1 shows the time dependence of typical plasma parameters at the spatially maximum point for hydrogen discharge at a filling pressure of $2 \times 10^{-5} \text{ torr}$. Just after the termination of the pre-ionization pulse ($t = 0 \text{ msec}$) the plasma density and electron temperature were $n_e \approx 5 \times 10^{11} \text{ cm}^{-3}$ and $T_e \approx 5 \text{ eV}$. The plasma density and electron temperature increased up to $t = 0.5 \text{ msec}$ when the ohmic heating current was maximum, and then the electron temperature decreased and did not significantly increase during the second current maximum at $t = 1.5 \text{ msec}$ while the density increased slowly. It was observed that the line intensity of CII 4267Å and CIII 4647Å monotonically increased up to 1.5 msec. The particle confinement time obtained from the measurement of the plasma loss rate was 5 ~ 20 msec, depending on filling pressure.

Fig. 2 shows the radial profiles of light emissivity of the CII 4267Å, CIII 4647Å and H_β lines and also n_e , T_e radial profiles at various times after the start of the ohmic heating pulse. The

solid line corresponds to the calculated values of the local emissivity $i(\psi(r))$ from the measured profile $I(\theta)$ which is shown by the dotted line. For convenience; the horizontal scale is converted to the distance r from the surface of the ring at the horizontal plane instead of ψ -values or θ -values. The vertical scale is for $i(\psi(r))$. At early times in the discharge the H_β emissivity, electron density and temperature had very similar profiles while the CII and CIII profiles were relatively broader. At later times, as shown in Fig. 2b, the peak of the electron density profile was shifted towards the outside ($r \approx 7$ cm) with respect to the electron temperature profile while the CII and CIII light emissivity peaked in the vicinity of the peak electron density. (It was also noted that the impurity intensity increased toward the ring location; however, the T_e and n_e data was not available around $r \sim 4.5$ cm because of extremely low T_e for Thomson scattering measurement. Therefore, in the following we restrict ourselves only to the outside peak around $r \approx 7$ cm). This behavior was observed to exist up to $t \approx 1$ msec, when the profiles became broader (see Fig. 2c). The time sequence of the spatial profiles of the carbon line radiation may indicate that the observed CII and CIII line radiation is due to an influx of carbon atom from the wall and the limiter and is not due to the carbon present in the preionization state. If the carbon were uniformly distributed in the plasma, it is expected that the light emissivity would also peak at the electron temperature maximum for this range of T_e and n_e .

III. NUMERICAL MODEL

During the startup phase of an ohmically heated plasma, the discharge conditions vary so rapidly that the ionization rate to the higher ionization states is comparable to the rate of fractional change of the electron density and temperature. In this case the usual assumption of equilibrium between successive ionization states is not applicable. Thus, it is necessary to solve the time-dependent coupled differential equations for the population of carbon in successive ionization states. For the case of carbon impurities these equations are given by

$$\begin{aligned} \frac{\partial C_0(t)}{\partial t} &= -n_e(t) C_0(t) S_1(t) + n_e(t) C_1(t) \\ &\quad [\alpha_1 + \beta_1 n_e(t)] + \Gamma_{\text{flow}}(t) \\ \frac{\partial C_k(t)}{\partial t} &= n_e(t) C_{k-1}(t) S_k(t) \\ &\quad - n_e(t) C_k(t) [S_{k+1} + \alpha_k + \beta_k n_e(t)] \\ &\quad + n_e(t) C_{k+1}(t) [\alpha_{k+1} + \beta_{k+1} n_e(t)] - C_k / \tau_k. \end{aligned} \quad (1)$$

Here $C_k(t)$ is the carbon density of the k th ionization state, S_k is the ionization rate of the $k-1$ th state to the k th state, α_k and β_k are the radiative and three body recombination rates of the k th state to $k-1$ th state, and τ_k is the particle confinement time of carbon ions of the k th state. Ionization rate coefficient S_k and recombination rate coefficients α_k , β_k were calculated from the formula found in Ref. [6] and [7]. It is assumed that τ_k is equal

to the observed plasma particle confinement time ≈ 10 msec, which is obtained from the loss rate measurement. This assumption that the plasma confinement time is equal to the confinement time of carbon ions does not introduce a significant ambiguity in the present analysis except for the very high ionization states, since during the startup phase the ionization rate to the successive ionization states is much larger than the reciprocal of the particle confinement time. This is in contrast to the quasi-steady state in the latter part of the discharge where the particle confinement time is comparable to the ionization time constant.

It must be also mentioned that the above model describes impurity atom behavior where the ionization process is dominant, since only the interaction between ground states is taken into account. The present model may not be adequate in the case where the higher excitation levels are important such as the strong recombination from the higher ionization state to the lower state. The present model is applicable for the plasma with $T_e \geq 5$ eV, neutral gas density $n_0 \leq 10^{12}$ cm $^{-3}$, and $1 < n_e < 10^{13}$ cm $^{-3}$. An example of the necessity of including high excitation levels in the FM-1 spherator can be found in Ref. [8],

The initial conditions (at $t=0$) for the calculation were obtained from the measurements in the quasi-equilibrium state established during the preionizing microwave heating. For example, the initial carbon atom density was provided by the measurement of line intensity CII and CIII. As shown in Fig. 3, in the time-dependent calculation we have tried to obtain the best fit of the observed line intensity

$I_{CII}(t)$ and $I_{CIII}(t)$ by adjusting the flow rate function,

$$\Gamma_{flow}(t) = \Gamma_0 + n_e^p(t-t_0) [T_e(t-t_0)/T_e(t=0)]^q / \tau_{flow},$$

where we have assumed that the flow rate depends on the pth power of n_e and qth power of T_e , Γ_0 is the constant carbon influx flow rate which exists even during the preionization discharge, τ_{flow} is an adjustable parameter, and t_0 represents the time delay between the change of plasma condition and the time of carbon influx into the plasma (such as the time delay of carbon flow at the initial start around $t=0$ shown in Fig. 1). The emissivity of the CII 4267Å and CIII 4647Å were calculated by using the formula given in Ref. [9], where we also take into account forbidden transition according to Ref. [10]. For a hydrogen discharge at a filling pressure of 2×10^{-5} Torr., the carbon influx flow rate given by

$$\Gamma(t) = \Gamma_0 + n_e(t - t_0) / \tau_{flow}$$

$$\Gamma_0 = 2 \times 10^{12} \text{ cm}^{-3}/\text{sec}$$

$$\tau_{flow} = 100 \text{ msec}$$

$$t_0 = 0.1 \text{ msec}$$

yields the best agreement with the experimental results as shown in Fig. 3, where the result of the numerical calculation shown by black circles includes the ambiguity due to the laser T_e and n_e measurement and the observed light intensity of CII and CIII is shown by solid lines. The carbon influx rate is shown in Fig. 4, where the uncertainty due to the measurement of $n_e(t)$ and $T_e(t)$ is shown by the black points. The relatively low carbon influx flow rate

$2 \times 10^{12} \text{ cm}^{-3} \text{ sec}^{-1}$ during the microwave preionization discharge was drastically increased up to $4 \sim 5 \times 10^{13} \text{ cm}^{-3} \text{ sec}^{-1}$ within 0.5 msec. It may be pointed out that it is not so easy to choose a flow rate function which can provide an increase of CII and CIII intensity around $t = 0.4 \sim 1.0$ msec, while the electron temperature decreased drastically. In other words, if equilibrium is going to be established during $t = 0.4$ to 1 msec with a fixed flow rate, the line intensity of CII should increase and CIII intensity should reduce because of the decrease of T_e after $t = 0.4$ msec. A similar calculation carried out for a different filling pressure (0.5×10^{-5} Torr) yielded a flow rate time constant of 30 msec. It must also be mentioned that even in a non-ohmic heating case, such as neutral beam heating in the FM-1 spherator, the assumption $\Gamma_{\text{flow}}(t) \propto n_e(t)$ provided a good agreement with the observed carbon accumulation process [11].

It may be noted that the empirical flow $\Gamma_{\text{flow}} \approx n_e / \tau_{\text{flow}}$ with $\tau_{\text{flow}} \approx 30 \sim 100$ msec gives a reasonable estimate even in other toroidal plasma confinement devices. For example, such an empirical flow rate formula was found to fit the recent experimental results of the TFR group in the TFR tokamak device at Fontenay-aux-Roses [1,2].

IV. DISCUSSION

We now wish to examine the several possible mechanisms which may dislodge carbon atoms from the wall or the limiter surface into the plasma. These are:

(1) Diffused Plasma Bombardment on the Wall or the Limiter Surface.

The inverse of the observed flow rate time constant $1/\tau_{\text{flow}}$ where $\tau_{\text{flow}} \approx 30 \sim 100$ msec is about 10 ~ 30% of the inverse of the plasma confinement time $1/\tau$ where $\tau \approx 10$ msec. This indicates that the diffused plasma bombardment on the wall or the limiter surface could be a major source for carbon impurity flow. In order to study this possibility in detail we have carried out several procedures: (a) the limiter was inserted deeply enough to prevent the direct bombardment of plasma on the wall, (b) the surface of the limiter was polished to eliminate at least physically attached carbon molecules, and (c) clean discharge was carried out with the deeply inserted limiter position to clean the limiter surface. However, these studies did not show any positive indication of reducing the carbon impurity influx flow.

(2) Radiation Bombardment.

Since a large fraction of the plasma energy loss is due to the line radiation of impurity atoms, it can be expected that the photodesorption could be responsible for the impurity flux. By using the formula for population levels of the ionization state [9,10], we find that the radiation is about 1.2×10^{16} photons $\text{cm}^{-3} \text{sec}^{-1}$ at $n_e = 2 \times 10^{12} \text{ cm}^{-3}$, and carbon density, $n_c = 10^{11} \text{ cm}^{-3}$. Since the impurity atom flow rate is $4 \sim 10 \times 10^{13} \text{ cm}^{-3} \text{sec}^{-1}$, the required photodesorption efficiency to explain the observed influx is about $0.4 \sim 1 \times 10^{-2}$ atoms/photon.

Few experimental results are available for photodesorption efficiency and the Refs. [12] and [13] gives an efficiency of 8×10^{-8} to 5×10^{-3} molecules/photon, which depends upon the surface condition and the wavelength. Thus, it appears that even if we chose the highest value, 5×10^{-3} molecules/photon, the photodesorption process is barely enough to explain the observed influx flow rate.

(3) The Bombardment by Charge Exchanged Particles.

In order to estimate the charge exchanged atom flow rate due to the charge exchange process, it is necessary to obtain the neutral hydrogen atom density inside the plasma column.

The neutral hydrogen atom density was obtained from the measurement of the absolute intensity of H_{α} , H_{β} and a numerical calculation for several excited stages, which is similar to the model discussed in the carbon ionization state. This complicated procedure was required, since the hydrogen atoms have not reached the equilibrium stage so that the absolute intensity of H_{α} , H_{β} does not necessarily provide the hydrogen atom density.

(The details of this calculation will be published elsewhere).

It was found that the initial neutral density of $1.3 \times 10^{12} \text{ cm}^{-3}$ decreased slightly to $7 \times 10^{11} \text{ cm}^{-3}$ around $t = 0.3 \sim 1 \text{ msec}$.

According to the formula given in Ref. [14], the charge exchange time constant is expected to be about 0.1 msec for $n_e = 3 \times 10^{12} \text{ cm}^{-3}$, $T_i \sim 5 \text{ eV}$. Thus if the bombardment due to charge exchanged particles is responsible for the impurity flow rate, the efficiency

of impurity release due to this bombardment should be about $1-3 \times 10^{-3}$. In the literature no experimental result of carbon desorption due to gas bombardment is available. Further, this efficiency could be sensitive to the chemical status of carbon atom on the surface. However, judging from the available experimental result of ion bombardment on the gas absorbed surface [16] whose efficiency is about 0.2 - 1, this charge exchange particle bombardment process could provide sufficient carbon impurity influx.

In summary, it is extremely difficult to identify the exact cause of impurity influx. The radiation process might not be enough to explain the observed flow rate. A most likely candidate seems to be the charge exchanged particle bombardment. However, the plasma bombardment cannot be ruled out even though we did not observe positive indication of this process.

IV. CONCLUSION

The influx of the main impurity atoms in the FM-1 spherator (i.e., the carbon atoms) was investigated by comparing the measured radial and time dependent distribution of carbon light intensity, with those predicted from a numerical solution of the time-dependent coupled differential rate equations for several carbon ionization states using the measured radial profiles of n_e and T_e . It was found that an empirical flow rate $\Gamma_{\text{flow}} \sim n_e/\tau_{\text{flow}}$ with $\tau_{\text{flow}} = 30 \sim 100$ msec yielded the best fit between the experiment and numerical calculation. This is in agreement with the recent results obtained in other toroidal confinement devices such as the TFR device. Although our study of the origin of the impurity flow was not conclusive because of the lack of experimental data on the efficiency of various processes that could be responsible for dislodging carbon atoms from the wall or the limiter surface into the plasma, our present experiment appears to rule out the photodesorption process. A more likely candidate seems to be charge exchanged particle bombardment on the wall and the limiter. However, the plasma particle bombardment on the wall and limiter as a possible cause could not be ruled out entirely.

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Fig. 1. Time behavior of ohmic heating current, $T_e(t)$ at the maximum spatial point, $n_{e0}(t)$ at the maximum point, and average intensity of CII 4267Å, CIII 4647Å, and H β .

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763214
 Fig. 2a. Spatial distribution of CII, CIII, H_β and n_e , T_e at (a) $t = 0.4$ msec. Dashed lines are measured profile of $I(\theta)$ and solid lines are calculated $i(r)$.

Fig. 2b. Spatial distribution of CII, CIII, $H\beta$ and n_e , T_e at (b) $t=0.8 \text{ msec}$. Dashed lines are measured profile of $I(\theta)$ and solid lines are calculated $i(r)$.

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Fig. 2c. Spatial distribution of CII, CIII, $H\beta$ and n_e , T_e at (c) $t = 1.0$ msec. Dashed lines are measured profile of $I(\theta)$ and solid lines are calculated $i(r)$.

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Fig. 3. Comparison with numerical calculation and observed CII and CIII line intensity.

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Fig. 4. Obtained carbon flow rate $\Gamma_{\text{flow}}(t)$.