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Japan Atomic Energy Research Institute

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The global particle balance of ohmically heated divertor discharge in JT-60 tokamak has been investigated by using gas-flow, plasma density and H_α radiation measurements. The total number of ionization events was estimated by using a simple expression of H_α radiation profile, and the fueling efficiency was determined from the time derivatives of electron density before and after the gas feed termination. The global particle confinement time derived from the particle balance equation decreased about 130 ms to 60 ms with the averaged electron density in the range of $(1-3.6)\times10^{19}/m^3$. The recycling coefficient approached unity as the averaged electron density increased, but it didn't exceed unity. The resultant effective particle confinement time corresponding to the decay time of the electron density increased 0.5 s to 1.6 s in the electron density investigated. These results showed that the plasma density could be controlled by the gas injection in the ohmically heated divertor discharge.

Keywords: Tokamak, Divertor, Particle Balance, H_α Radiation, Particle Confinement Time, Particle Fueling, Recycling Rate, Plasma Density Control

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* On leave from Energy Research Laboratory, Hitachi Ltd.

大型トカマク装置JT－60のジュール加熱ダイバータ放電における粒子バランス

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（1986年2月21日受理）

プラズマ粒子の時間変化を表わす方程式を用いて，JT－60のジュール加熱ダイバータ放電における粒子バランスを検討した。H_α線の放射強度分布は，プラズマ断面内の異なる3箇所を垂直に見込むフォトダイオードの測定値を簡単な数式にフィットすることにより求めた。リサイクリングによるプラズマ粒子の供給量は，Johnson等によって計算された1 H_α線放出当りの電離割合とH_α線の放射強度分布から決定した。注入ガスのうちプラズマになる割合は，プラズマ電流一定期間の途中でガス注入を止めた放電を用い，ガス注入停止前後の電子密度の変化率から算出した。これらの結果から得られた粒子閉じ込め時間は，電子密度が$(1-3.6)\times10^{19}/m^3$の範囲で増加する時130 msから60 msまで減少した。リサイクリング率は，電子密度の増加とともに1に漸近するが，1を超えなかった。電子密度の減衰時定数に対応する実効的粒子閉じ込め時間は，電子密度とともに0.5 sから1.6 sまで増加した。これらの結果から，ジュール加熱ダイバータ放電では電子密度はガス注入により十分制御できることが分った。

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1. Introduction

As experience with large auxiliary heated tokamak devices has grown, the plasma density control has become more important to prevent major disruption by suppressing the density increase resulting from the neutral beam injection acting as an additional plasma source, and to provide high heating efficiency by maintaining the most suitable density for RF heating over the discharge period. In order to fully control the plasma density, it is required to grasp the behavior of charged and neutral particles in the plasma and its periphery.

The study of the particle behavior has been performed on numerous tokamaks[1-4] with or without divertor. Their studies have made it clear that the refueling by the hydrogen gas neutralized at the divertor plates plays an important role for the particle balance in the divertor configuration, while in the limiter configuration the particle dynamics is dominated by recycling at the limiter and wall. The plasma density was satisfactorily controlled by gas injection in the small and medium size tokamaks due to low recycling or refueling rate. In the recent limiter experiments of JET and TFTR, the electron density has remained constant without any additional gas during the current flat-top due to high recycling at the limiters. This implies that it is impossible to control the plasma density via the gas injection. On the contrary, in the divertor discharge, it is expected that the plasma density can be controlled by the gas injection since the divertor discharges require the gas injection several times the limiter one due to lower refueling rate. Therefore, it is worthy to examine the particle behavior in the divertor discharge of the reactor grade tokamak.

The present paper deals with the particle behavior in ohmically heated divertor discharge of JT-60. In sec. 2, plasma configuration and instruments are described. The poloidal asymmetry of H_{α} radiation ascribed to the divertor action is treated by a simple model in sec. 3. The measurement techniques to obtain fueling efficiency and global particle confinement time are discussed in sec. 4, and the results are presented in sec. 5 with a discussion of the plasma density control.

2. Experimental Arrangement

2.1 Plasma configuration

JT-60 is a large hydrogen tokamak with a compact poloidal divertor on the outer equatorial plane. The first phase of ohmically heated plasma experiments was carried out in both the limiter and divertor configurations.[5] The circular limiter discharge was formed at a major radius of 3.04 m with a minor one of 0.91 m by the limitation of molybdenum toroidal limiter coated with titanium carbide. The divertor plasma with the minor radius of 0.85 m was formed by shifting the major radius outward to 3.15 m during the plasma current ramp up phase in the limiter discharge. In the divertor discharge, the clearance between the first wall and the separatrix magnetic surface was maintained above 2.5 cm to provide the sufficient particle and energy flux into the divertor chamber.

The ohmically heated divertor discharges were mainly studied in the ranges of the plasma currents 0.5 to 1.5 MA and the line averaged electron densities $(0.7\text{-}3.7)\times10^{19}/m^3$. Hydrogen gas was injected towards the vacuum vessel center with a 30° angle from the equatorial plane at a single toroidal location from 2 s before breakdown to the end of the plasma current flat-top period. The plasma density increased gradually during the gas injection without its steady state.

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2.2 Instruments

Line integrated electron density along a vertical chord at a outer position about 10 cm away from the plasma center on the mid-plane was measured by a 2 mm microwave interferometer system. By assuming the electron density profile $n_e = n_o[1 - (r/a)^2]$ where n_o is the central electron density and a is the minor radius, the line averaged electron density and total number of electrons in the main plasma were determined.

The photodiode with the bandpass filter of which the central wavelength and the FWHM of the transmission profile were 656.3 nm and 10 nm, respectively, was used to measure the absolute intensity of H_α radiation. The H_α radiations along the vertical chord were observed at three positions on a poloidal cross section where the distances from the torus center were 2.54, 3.04 and 3.56 m in the major radius direction.

Gas injection was monitored by a capacitance diaphram manometer mounted on the gas injection port. Since its output signal was the pressure at the monitor position, the gas injection rate was estimated by using the previously calibrated relation between the measured pressure and the gas injection rate.

3. H_α Radiation Profile in Poloidal Cross Section

The toroidal symmetry of H_α radiation is expected except the vicinity of gas injection port because main plasma doesn't directly touch the first wall at the main chamber in the divertor discharge, while poloidal asymmetry of that appears due to intense refueling at the divertor side. The H_α radiation profile was numerically calculated[6)] by linking the neutral particle transport code using

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Monte-Carlo method and the line radiation calculation code based on collisional-radiative model[7]. In the calculation, two neutral particle sources were taken into account in addition to the gas injection. One is the desorption of working gas absorbed on the first wall, and the other is the refueling gas localized at the divertor side. A proportion of their neutral particle flux was determined by fitting the calculated values of H_α radiation intensity to the experimental results obtained from three photodiodes. A contour map of the H_α radiation intensity in the poloidal cross section thus calculated is shown in Fig. 1.

Since Monte-Carlo calculation requires considerably more time to determine a single H_α radiation profile, it is desirable to approximate its profile with a simple formula. As seen from the figure, nearly all the H_α radiation occurs in a edge region of the main plasma, and its intensity monotonously increases in the major radius direction except the vicinity of the entrance to the divertor chamber, which tendency agrees well with the visible TV image viewing vertically the main plasma. Therefore, the H_α radiation profile in the poloidal cross section should be expressed by the product of conventional axisymmetric distribution, $\phi_1(r)$ and non-linear one in the major radius direction owing to the refueling, $\phi_2(R)$ as follows:

$$\phi(r,R) = N_o \phi_1(r) \phi_2(R) \qquad - (1)$$

where N_o is a constant with the dimension of photons/m^3s. We take the following simple expression with a maximum near the plasma periphery as an axisymmetric distribution.

$$\phi_1(r) = 1 + A(r/a)^m - (1 + A)(r/a)^n \qquad -(2)$$

where A is a constant, and m and n are even indexs. According to the calculation code mentioned above, the H_α radiation profile has a maximum at $r/a = 0.92$ with the FWHM of about 0.15a in the typical divertor discharge of 1 MA, and the ratio of the maximum value to the H_α radiation intensity at $r/a=0.6$ is about 20. In the results reported here, the coefficient A and indexs m and n are fixed to 500, 8 and 24, respectively, so that the axisymmetric distribution function expresses the results of the calculation code.

Non-linear distribution because of the refueling may be expressed by the following function which monotonously increases up to a asymptotic value 1+B in the range of $R>Rp-a$:

$$\phi_2(R) = 1 + \frac{B[1+(R-R_p)/a]^4}{[1+(R-R_p)/a]^4 + C} \qquad -(3)$$

where Rp is the major radius, B and C are constants.

The number of photons incident on a photodiode is given by using the H_α radiation profile as follows:

$$I = \int \phi(r,R)T(\Delta\Omega/4\pi)dV_s \qquad -(4)$$

where T is transmission through a bandpass filter and window, $\Delta\Omega$ is the solid angle viewing the active area of the photodiode and V_s is the plasma volume in a viewing cone of the photodiode. Unknown parameters in the H_α radiation profile function can be determined from the measured counts of three photodiodes viewing the different vertical chords in the main plasma.

The coefficients B and C in the non-linear distribution obtained from above argument were 13±4 and 1.4±0.2, respectively, independent of the electron density and plasma current. The resulting ratio of the peak values of the H_α emitting shell at the inner and outer sides in the major radius direction, which characterizes the degree of the poloidal asymmetry, scatters in the range of 8-20. This scattering by a factor 2.5 yields an error of 15% in the global particle confinement time. This indicates that the total number of H_α emission is relatively insensitive to the radiation profile in the poloidal cross section.

Figure 2 shows three experimental values measured by photodiodes and two line integrated H_α radiation profiles along the major radius direction for the divertor discharge of 1 MA. A solid line was calculated by using the simple formula of the H_α radiation profile. A broken line indicates the detailed calculation result. Two curves agree fairly well except the divertor side. Considering the fact that the total number of H_α emission is insensitive to the radiation profile, we can sufficiently apply a simple expression (eq.(1)) as a H_α radiation profile irrespective of the discrepancy at the divertor side. The underestimation of the global particle confinement time by use of this approximation is at worst 10%.

4. Fueling Efficiency and Particle Confinement Time

Figure 3 shows a schematic particle flow pattern for the divertor configuration in JT-60. Plasma fueling is accomplished via gas injection and refueling of the hydrogen gas neutralized at the divertor plates. Neglecting the impurity contribution to the total number of electrons by the fact that the effective ion charge derived

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$$\frac{dN_e}{dt} = \eta N_Q + N_I - \frac{N_e}{\tau_p} \qquad - (5)$$

where N_e represents the total number of electrons in the main plasma, η is the fueling efficiency corresponding to the probability that an injected atom contributes to the formation of the main plasma, N_Q is the injection rate of hydrogen atoms, N_I is the total ionization rate of recycled neutrals and τ_p is the global particle confinement time in the main plasma.

Assuming that the particle confinement time and the total ionization rate depend on only the electron density, we can use eq.(5) before and after gas feed termination to give

$$\eta = [(\frac{dN_e}{dt})_{before} - (\frac{dN_e}{dt})_{after}]/N_Q \qquad - (6)$$

By using the discharges which the gas injection is terminated during the steady state plasma current as shown in Fig. 4, therefore, the fueling efficiency can be obtained from eq.(6).

The total ionization rate is obtained by integrating the product of the number of H_α photons emitted and the number of ionization events per a H_α photon over the plasma volume. According to results analyzed using the transition rate equations for atomic levels of hydrogen by L. C. Johnson et al.[8)], the ionization-per-H_α ratio is nearly independent of electron temperature above 20 eV. Therefore, we only take the density dependence into account by expressing it as follows:

$$\varepsilon(r) = 70 - 1.6 \times 10^{-39}(n(r) - 1.9 \times 10^{20})^2 \qquad - (7)$$

where n(r) is the electron density at the radius r. Considering that the toroidal symmetry of H_α radiation is maintained in the divertor discharge, we can calculate the total number of ionization events from the H_α radiation profile mentioned above and the ionization-per-H_α ratio by the following equation.

$$N_I = \int \phi(r,R)\,\varepsilon(r)\,dV_p \qquad - (8)$$

where Vp is the plasma volume.

Since the total number of electrons and its time derivative are estimated from the time evolution of the line averaged electron density, the global particle confinement time is obtained by rewriting eq.(5).

$$\tau_p = N_e/(\eta N_Q + N_I - \frac{dN_e}{dt}) \qquad - (9)$$

Once the particle confinement time is known from eq.(9), we can obtain the recycling coefficient and the effective particle confinement time characterizing particle behavior. The charged particles transported to the divertor chamber through the scrape-off layer are neutralized at the divertor plates, of which a fraction is refueled into the main plasma. Since the total number of the refueling particles is equivalent to the ionization rate, the recycling coefficient is given by

$$R = N_I/(N_e/\tau_p) \qquad - (10)$$

The effective particle confinement time corresponding to the lifetime of recycling particles is related to the particle confinement time via the recycling coefficient:

$$\tau_p^* = \tau_p/(1 - R) \qquad - (11)$$

5. Results and Discussions

Figure 5 shows fueling efficiencies versus the line averaged electron density for various plasma currents in both the divertor and limiter discharges. In the divertor discharges, the fueling efficiency is independent of the electron density and plasma current in the range of $(1.2\text{-}3.2)\times10^{19}/m^3$, and its average value is approximately 0.25. The fueling efficiency for the limiter discharge is greater by a factor of 1.3 to 1.5 than that of the divertor discharge in the density range investigated. This difference could be ascribed to the presence of the scrape-off layer in which the ionized atoms are transported to the divertor chamber.

The results of a series of measurements for the particle confinement time versus the line averaged density are shown in Fig. 6. All the values quoted were taken during the plasma current flat-top. As seen from the figure, the particle confinement time monotonously decreases about 130 ms to 60 ms with the averaged electron density in the range of $(1\text{-}3.6)\times10^{19}/m^3$. This implies that plasma recycling shell gradually moves towards the plasma edge. Similar phenomenon has already been observed in higher electron density region in the medium size tokamaks[1),9)].

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The absolute values of particle confinement time contain the systematic error besides an experimental error of about 15% for different discharge conditions. The systematic error is due to the uncertainty of the estimations of the H_{α} radiation profile described above and the parasitic light reflected on the inner wall of H_{α} emission measuring port. The parasitic light intensity was calculated by using the reflectivity[10] of the same machined and pickled surface as that of the H_{α} emission measuring port, which was 65±10% of the H_{α} light detection intensity. This estimation error resulting from the treatment of diffusely reflected light introduces the systematic error of about ±30%. Therefore, the global particle confinement time has the total systematic error in the range of -20 to 40%.

The recycling coefficient and the effective particle confinement time were calculated by using the same data set as that applied to obtain the particle confinement time. Figure 7 shows the recycling coefficients plotted to the line averaged electron density for various plasma currents. The recycling coefficient approaches unity as the averaged electron density increases in the range of $(1\text{-}3.6)\times10^{19}/m^3$, but it doesn't exceed unity. This means that the plasma density can be controlled by the gas injection in the ohmically heated divertor discharge. As a consequence, the effective particle confinement time corresponding to the decay constant of the electron density as shown in Fig. 8 could be obtained. Contrary to particle confinement time, the effective particle confinement time increases 0.5 s to 1.6 s in the electron density range investigated, and moreover, it slightly depends on the plasma current. These tendencies can be explained by the fact that the probability that the particle escapes from the recycling loop by trapping into the divertor plate and the first wall increases with the impacting energy of particles. When the electron density is constant, the particle energy flowing into the divertor chamber increases with the plasma current. The resultant higher trapping efficiency makes the effective particle confinement time lower. For the constant plasma current, higher recycling in front of the divertor plate resulting from the electron density increasement decreases the impacting energy, so that the effective particle confinement time increases with the electron density.

We can discuss the plasma density control by using the particle balance equation and the results described above. In steady state of the electron density, $\frac{dN_e}{dt} = 0$. Then, the gas injection rate required to maintain the electron density at a constant value is given by

$$Q = N_e/(\eta\tau_p^* n_Q) \qquad - (12)$$

where n_Q is the number of atoms included in 1 Pa m^3. The result obtained by the same data set as that used in the preceding paragraph is shown in Fig. 9. The gas injection rate in the steady state has a tendency to saturate with about 6 Pa m^3/s.

The response speed of the plasma density control is given by n_e/τ_p^* where n_e is the averaged electron density becuase the effective particle confinement time is equivalent to the time constant when the plasma density decays. As seen from eq.(12), that is proportional to the gas injection rate required to maintain the steady state of the electron density considering that the fueling efficiency is independent of the electron density. This means that the response speed of the density control scarcely depends on the electron density in the range of $(1-3)\times10^{19}/m^3$. The resultant response speed of the density control is about $2 \times 10^{19}/m^3$ s for the plasma current of more than 1 MA. This value is sufficient to produce the target plasma for additional heating with the electron density of $(3\text{-}5)\times10^{19}/m^3$ during the plasma discharge of 10 s.

The neutral beam injector is a plasma fueling source with high efficiency. In JT-60, the total number of particles injected by neutral beam heating device amounts to about 2×10^{22} atoms during a 10 s discharge, which corresponds to the gas injection rate of about 16 Pa m^3/s. Since the maximum value of the gas injection rate required to maintain the plasma density steady state is about 6 Pa m^3/s, in the full power heating the disruption at high density may occur due to the rapid density increase. To avoid this situation, it may be necessary to close the divertor chamber to reduce the refueling.

Acknowledgements

We thank all the members of the JT-60 Project who have long dedicated themselves to the construction of JT-60.

Our thanks are also due to the JT-60 operation team who conducted the first operation of JT-60 and contributed to implement the present series of experiments. We also thank Dr. S. Mori for his major role in initiating the JT-60 Project. We are grateful to Drs. K. Tomabechi, M. Yoshikawa, T. Iijima for their continued leaderships and supports. Drs. Y. Shimomura, S. Seki, M. Nagami, M. Azumi and Experimental Group cooleagues are gratefully ackowledged for their continuous discussions.

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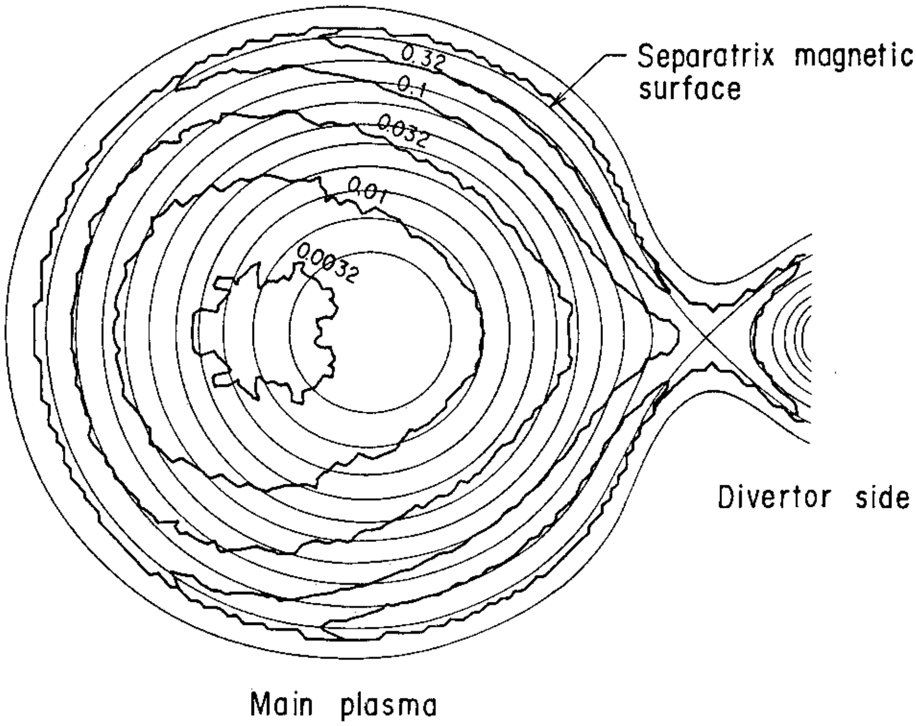

Fig. 1 Two dimensional H_α radiation profile in the poloidal cross section obtained by using the neutral particle transport code and the line radiation calculation code.

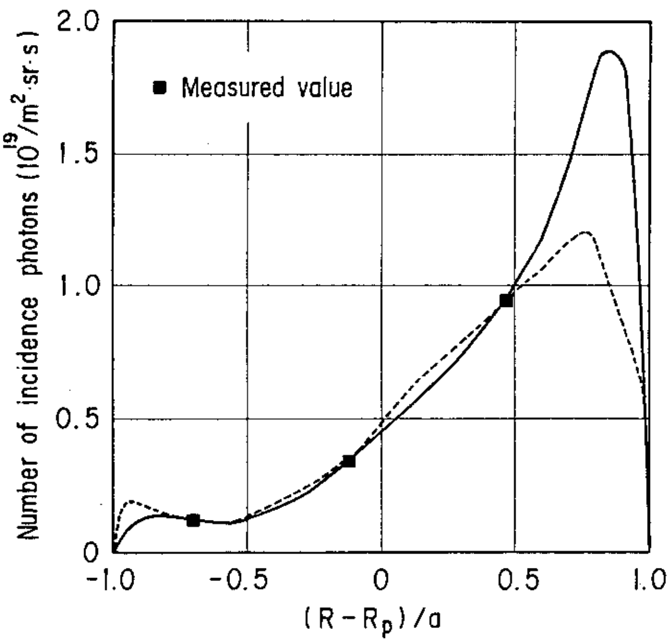

Fig. 2 The H_α radiation intensity integrated along the vertical chord as a function of the radius in the major radius direction. A solid line was determined by fitting three measured values (■) to the simple formula for the H_α radiation profile, and a broken line was calculated by using the neutral particle transport code and the line radiation calculation code.

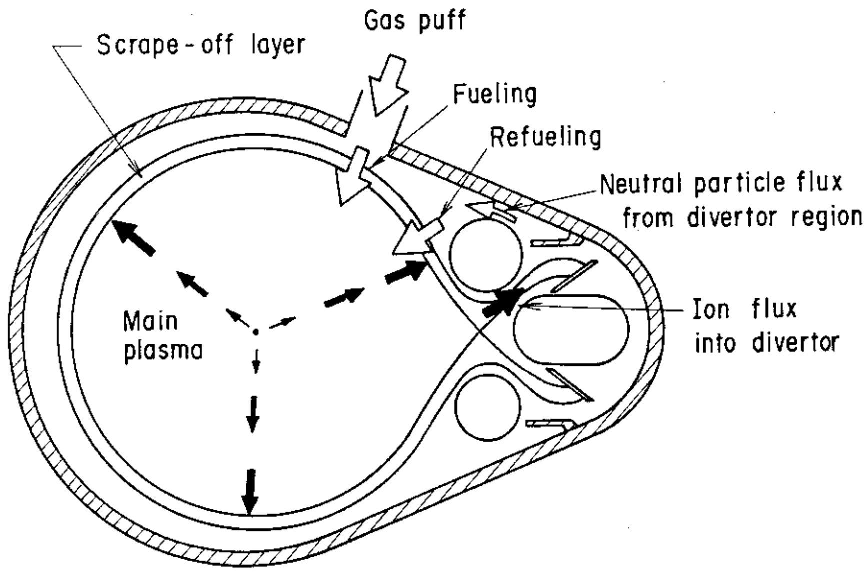

Fig. 3 A schematic particle flow pattern for the divertor configuration.

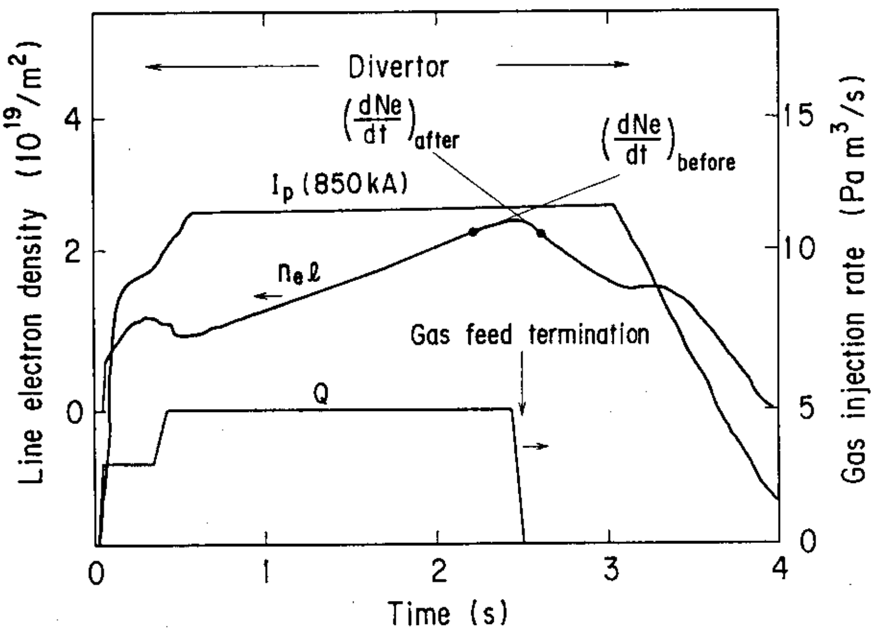

Fig. 4 An explanatory diagram of determining the fueling efficiency from the time derivatives of electron density before and after gas feed termination during the plasma current flat-top.

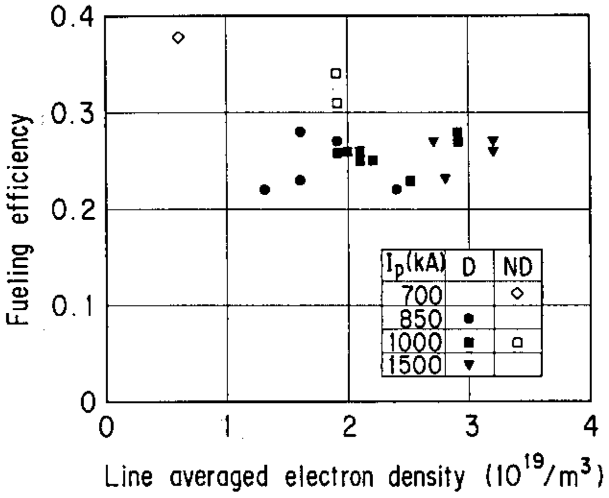

Fig. 5 The fueling efficiency versus the line averaged electron density in both the divertor and limiter discharges.

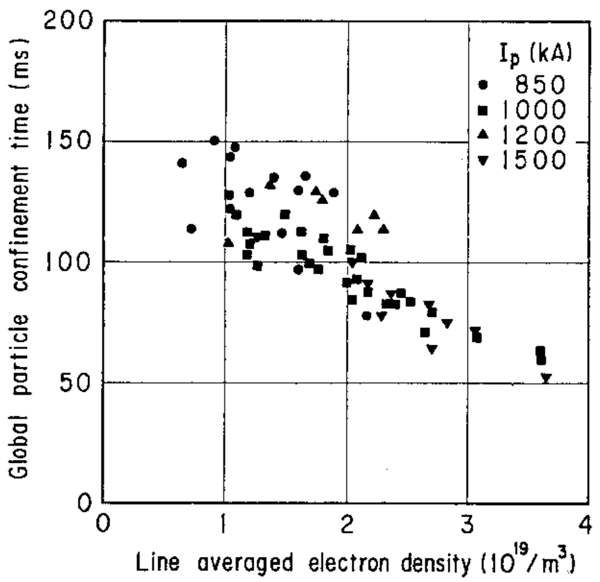

Fig. 6 The global particle confinement time versus the line averaged electron density in the divertor discharges.

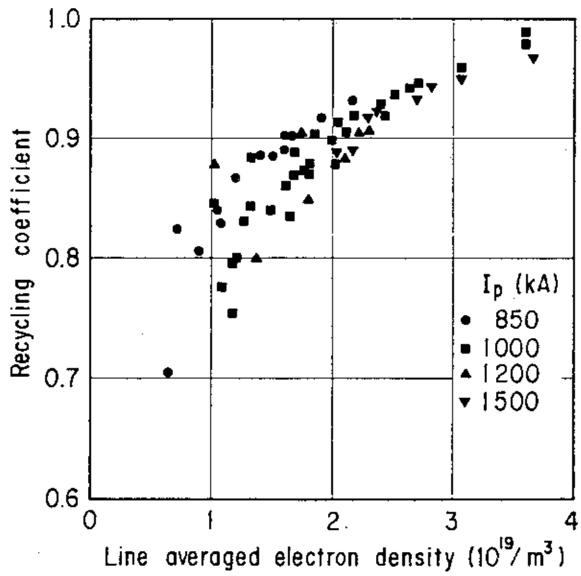

Fig. 7 The recycling coefficient plotted to the line averaged electron density in the divertor discharges.

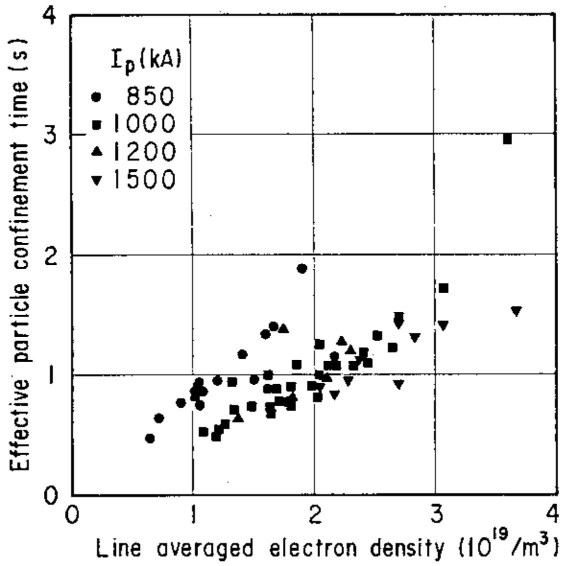

Fig. 8 The effective particle confinement time plotted to the line averaged electron density in the divertor discharges.

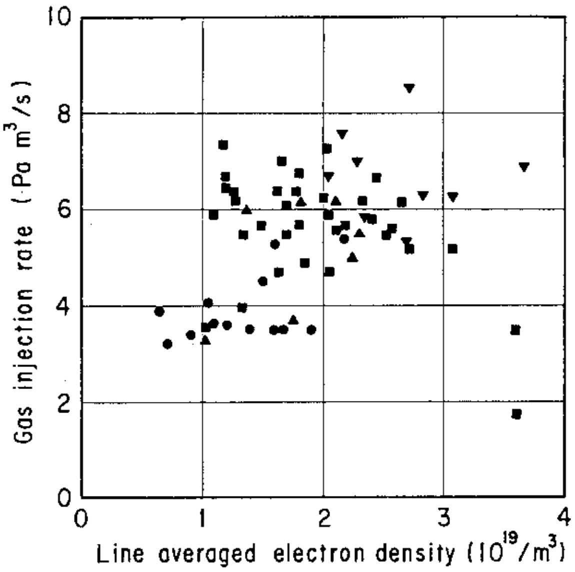

Fig. 9 The relation between the gas injection rate required to maintain the electron density steady state and the line averaged electron density.