Plasma wall particle balance in TORE SUPRA

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Abstract:

A comprehensive study of the particle balance between the carbon wall and the plasma is presented. One finds that the effective particle content of the wall which governs the plasma equilibrium density departs from the deposited number of particles. This effect is dominant for the fully desaturated wall. A scaling law of the plasma density in terms of the wall effective particle content has been obtained. Moreover, the experimental data allows to estimate the plasma particle confinement time. Values ranging from 0.2 s to 0.5 s are found depending on the density. An analytical functional dependence of the particle confinement time is obtained.

1 - Introduction

The carbon environment of present Tokamaks, such as Tore Supra [1], leads to a complex problem of density control [2,3]. In a previous paper [4], a scaling of the plasma particle content is given in terms of the number of particles deposited in the wall $N_{deposited}$, the latter quantity being obtained by a shot to shot balance of the injected and pumped gas. Such a wall particle content is several orders of magnitude larger than the plasma particle content. It is therefore important to analyse what is the effective wall particle content which must be considered in the plasma-wall particle equilibrium description. Let us first recall the experimental procedure which was used (note that the series of shots is also that of [4]).

Before the beginning of a series of successive shots, the wall (saturated, mainly with D atoms) is cleaned by 60 hours of He glow discharges (I_{Glow}=3 A, filling pressure 0.3 Pa, wall temperature 170 °C). This procedure removes from the 90 m^2 of graphite coated wall a total quantity of gas of about 680 $Pa.m^3$ ($N_{pumped} \approx 3.6\ 10^{23}$ atoms or 400 saturated monolayers, i.e. a depth $L_{wall}(0) \approx 10^{-7}$ m, assuming a value of 0.4 for the atomic ratio D/C in the a:C-D layer). At the end of such a conditionning procedure, the residual pumped gas is mainly hydrogen diffusing from the bulk graphite, indicating that the wall pumping capability has reached its maximum value.

All shots of the series are identical D_2 ohmic discharges (I_p=1.2 MA, B_Φ=3.8 T, see Figure 1). The plasma is initiated on the limiter (outboard), a gas puff (0.5 $Pa.m^3/s < \Gamma_{puff} <$ 2 $Pa.m^3/s$ during 3 to 4 s) begins 0.75 s after the plasma start up. On the current plateau and 2 s after the end of the puff, the plasma is pushed onto the inner wall (at time t_0). This change in the plasma position causes a density decrease which magnitude is strongly correlated to the wall saturation status. During the whole procedure, the limiter ($S_{Limiter} \approx 0.5\ m^2$) and wall (only $S_{wall} \approx 10\ m^2$ is in direct interaction with the plasma, as deduced from the spatial repartition of the Hα emission) are then continuously filled from shot to shot by the injected gas. The series of shots ends by a density limit disruption which occurs when the global amount of deposited gas reaches 70 $Pa.m^3$. The latter value is to be compared to the 75 $Pa.m^3$ removed from the 10 m^2 wall by the glow discharges if we assume an homogeneous removal.

Our analysis of the equilibrium value of the plasma particle content (N_{plasma}) and of the saturation state of the surface is based on the following measured quantities defined in the following, $R_N(k)$, $\Delta N/N(k)$, $\tau_o(k)$, and $L_{wall}(k)$ over 18 shots (k is the number of the shot in the series). During the limiter phase (out), two quantities are used (Figure 1), the equilibrium plasma particle content (with no gas puff) $N^{\infty}_{p,out}$ and its ratio, $R_N(k)$, to the actual plasma particle content at the displacement time $N_{plasma}(t_0)$, $R_N(k) = N^{\infty}_{p,out} / N_{plasma}(t_0)$. After the swing to the inboard configuration (in), two other quantities are used, the time scale of the density change at time t_0, $\tau_o(k) = -1/(dN_{plasma}/(N_{plasma}dt))$, and the relative variation of the particle content at equilibrium $\Delta N/N(k)$, $\Delta N/N(k) = \left(N^{\infty}_{p,out} - N^{\infty}_{p,in}\right) / N^{\infty}_{p,out}$ where $N^{\infty}_{p,in}$ is the equilibrium plasma particle content (in the inboard configuration). The global wall content is described by a thickness $L_{wall}(k)$ of the monolayers which are still empty. This scale is computed by assuming that the deposited particles pile up in saturated monolayers starting from the maximum $L_{wall}(0)$, hence $L_{wall}(k) = L_{wall}(0)\left(1 - N_{deposited}(k) / N_{pumped}\right)$. Although this definition does not account for the actual distribution of the D atoms in the graphite, it gives a convenient measurement of the wall status.

2 - Qualitative description of the evolution of the wall status

Two time scales are found for the evolution of the wall status, $\tau_{lag} \approx 900$ s, the time lag between two shots, and $\tau_{shot} \approx 10$ s, the duration of the discharges in this series. For a given diffusion coefficient of the D atoms in the graphite, $D_{D:C}$, these times yield two length scales $L_{lag} = (D_{D:C}\,\tau_{lag})^{1/2}$ and $L_{shot} = (D_{D:C}\,\tau_{shot})^{1/2}$. The comparison of L_{wall} to L_{shot} and L_{lag} allows a qualitative interpretation of the changes observed in the wall status. On Figure 2, the characteristic time scale of the plasma particle pumping by the inboard wall, τ_o, is plotted versus the wall status given by L_{wall}. The series of shots starts from point A and goes to D (as the total amount of injected particles increases). Three regimes are identified, delimited by the points A, B, C and D.

Regime 1 : $L_{wall} \geq L_{lag} >> L_{shot}$ (from A to B).

The whole carbon surface (wall + limiter) appears as a quasi-infinite reservoir which is almost not modified by the quantity of matter trapped in the wall. The effective wall particle content seems to be dominated by the gas deposited at the very surface of the wall during the start up phase and the gas puff. The evolution of this quantity is small so that τ_o is almost independent of L_{wall}. Note that at the beginning of this regime both the limiter and the wall are completely desaturated. However from shot to shot the evolution of the limiter should be more rapid owing to the large ratio of the surfaces, $S_{Limiter} / S_{wall} \approx 0.05$.

Regime 2 : $L_{lag} \geq L_{wall} \geq L_{shot}$ (from B to C).
The increase in the slope of τ_o versus L_{wall} at point B is understood as a change in the wall status. Indeed the change in the wall particle content becomes relevant for two successive shots if the time lag between them is long enough to let the particles diffuse from the saturated layers (L_{wall}) to the surface and vice versa. One has therefore $L_{lag} \approx L_{wall}(B)$, which yields an estimate of $D_{D:C} \approx L_{wall}(B)^2 / \tau_{lag} = 2.8\ 10^{-18}$ m²/s (which lies in the range of values elsewhere published [5]). In this regime the effective particle content of the wall must now account for a slow build-up (between shots) of the particle content at the graphite surface.

Regime 3 : $L_{shot} \geq L_{wall}$ (from C to D).
At point C, the global wall particle content is such that $L_{wall} \approx 9\ 10^{-9}$ m. Using the value of $D_{D:C}$ to compute $L_{shot} \approx 5.5\ 10^{-9}$ m, one finds that $L_{wall}(C) \approx L_{shot} + L_{implant}$, where $L_{implant}$ is the implantation depth of 100 eV energy particles in graphite, $L_{implant} \approx 2\ 10^{-9}$ m. For the shots following that at C, one has $L_{shot} > L_{wall}$. The surface is almost completely saturated and the evolution time of L_{wall} becomes shorter than τ_{shot}. The characteristic time τ_o increases very rapidly from shot to shot while the wall content changes on a slower pace until the wall is completely saturated. In the present serie of shots, this regime is bounded by a density limit disruption occurs.

3 - Scaling of the plasma density with the effective wall particle content

In order to study the relations between the three quantities $R_N(k)$, $\Delta N/N(k)$ and $\tau_o(k)$ we consider a 0-D balance model between the plasma and the effective wall.

$$\frac{dN_{plasma}(k)}{dt} = -\frac{N_{plasma}(k)}{\tau_{plasma}(k)} + \frac{N_{wall}(k)}{\tau_{wall}(k)} \qquad (1)$$

In the inboard configuration, the reservoirs are characterized by different confinement times, $\tau_{plasma} = \tau^{in}_{plasma}$ and τ_{wall} for the plasma and the effective wall respectively. The equilibrium relations in the two configurations is straightforward to compute and yields :

$$N_{wall}(k)\,\frac{r_{transport}(k)}{N_{limiter}(k)} = 1 - \frac{\Delta N}{N}(k) \quad ; \quad r_{transport}(k) = \frac{\tau^{in}_{plasma}}{\tau^{out}_{plasma}}\,\frac{\tau_{Limiter}}{\tau_{wall}} \qquad (2)$$

The coefficient $r_{tranport}(k)$ is introduced for the sake of clarity and represents the ratio of the transport processes between the outboard and the inboard configurations. In the present study we assume that this ratio does not vary from shot to shot, i.e. that this ratio of the transport processes does not depend on the density.

In the following,unless specified, the plasma quantities refer to the inboard plasma and the wall content $N_{wall}(k)$ is the effective wall content (which is different from $N_{deposited}(k)$). On Figure 3, the plasma particle content N_{plasma} is given versus the parameter $[1 - \Delta N/N(k)] \propto N_{wall}(k)$. The latter quantity exhibits two phases, a decreasing phase over the very first shots and then a regular increase. Such an evolution is difficult to explain by a decrease of the inner wall content since the global amount of particles deposited on the wall increases steadily during these shots. We understand this initial decrease in terms of an increase of the limiter particle content until saturation (although a priori a decrease of $r_{transport}(k)$ cannot be dicarded, see equation (2)). However the most important features of this plot of the dependence of N_{plasma} versus N_{wall} is the accumulation point around point B and the regular increase of both N_{wall} and N_{plasma} from B to D. The accumulation point corresponds to the first regime where the effective wall content and hence N_{plasma} do not vary, while the transition from B to D, regime 2 and 3, is characterized by the increase of the effective wall content. The dependence of N_{plasma} versus N_{wall} can be fitted by (Figure 3) :

$$N_{plasma} = \left(N^{adjust}_{wall}\right)^{1/2}\left(N_{wall} - N^{critical}_{wall}\right)^{1/2} \qquad (3)$$

with $N^{critical}_{wall} = N_{limiter}\,\frac{0.51}{r_{transport}}$ and $N^{critical}_{wall}\,N^{adjust}_{wall} = \left(8.75\ 10^{20}\ \text{particles}\right)^2$

This fit is only relevant for points such that $\Gamma_{transport} / N_{limiter}$ is constant (plain markers on Figure 3). The exponent (1/2) is chosen in view of the plasma-wall fluxes given in the next section. A possible interpretation of the critical value $N_{wall}^{critical}$ is the low fuelling efficiency of the gas puff : only ≈ 20 % of the injected gas fuels effectively the discharge. The remaining 80% then lead to the minimum particle deposition on the wall during the start-up phase and during the gas puff.

4 - Dependence of the particle life time on the plasma density

From equation (1) it is possible to derive the characteristic time scale at time t_0 when the plasma is shifted to the inner wall. Using the equilibrium relations and the ratio $R_N(k)$, one finds :

$$\tau_{plasma}(k) = \tau_o(k)\left[1 - R_N(k)\left(1 - \Delta N/N(k)\right)\right] \qquad (4)$$

The dependence of τ_{plasma} is plotted on Figure 4 versus the plasma particle content N_{plasma} (plain markers refer to points such that $\Gamma_{transport} / N_{limiter}$ is constant). One readily recovers an increase of the particle life time with the plasma density. However this dependence is not Alcator like since a linear dependence would imply an offset in the plasma density. Using a simple model for the plasma screening [6] which gives the particle content of the discharge in terms of a balance between the plasma outflux and the neutral influx, one has :

$$\left|\Gamma_{plasma}\right| \approx D_\perp \frac{N_{plasma}}{V\lambda_I} \approx \left|\Gamma_{neutral}\right| \approx \frac{N_{wall}}{S\,\tau_{wall}} \qquad (5)$$

where V is the plasma volume, S the plasma surface and λ_I the ionization length. Assuming the plasma anomalous diffusion coefficient to be given by $D_\perp \approx a^2 / \tau_{plasma}$ where a is the plasma radius, and taking into account the dependence of λ_I on the plasma density, $\lambda_I \propto 1 / N_{plasma}$, one finds the following dependence of τ_{plasma} over the plasma density :

$$\tau_{plasma} \propto N_{plasma}{}^2 / N_{wall}$$

$$\tau_{plasma} \approx \tau_{adjust} \frac{N_{plasma}{}^2}{N_{plasma}{}^2 + N_{wall}^{adjust}\, N_{wall}^{critical}} \quad \text{with } \tau_{adjust} \approx 2.5\ \text{s} \qquad (6)$$

The time constant is adjusted so that the functional dependence obtained analytically fits the experimental points. The analytical dependence on N_{plasma} insures that $\tau_{plasma} \rightarrow 0$ when $N_{plasma} \rightarrow 0$ (no offset). Furthermore when $N_{plasma} >> \left(N_{wall}^{adjust} N_{wall}^{critical}\right)^{1/2}$ one finds that $\tau_{plasma} \rightarrow \tau_{adjust}$ a value which might seem too high in regard to the values of τ_{plasma} found in the literature (in [4] for instance) but which yields a reasonable mean value of the anomalous particle diffusion coefficient. Using the hereabove definition $\langle D_\perp \rangle \approx a^2 / \tau_{adjust}$, one finds for Tore Supra parameters $\langle D_\perp \rangle \approx 0.25\ m^2\ s^{-1}$. The latter value accounts for the very low diffusion coefficient in the bulk, typically $0.05\ m^2\ s^{-1}$ [7], and the large values of this diffusion coefficient at the very edge of the plasma, of the order of $5\ m^2\ s^{-1}$ [7].

The difference between the present values $200\ ms \leq \tau_{plasma} \leq 500ms$ with the value published in [4], $\tau_{plasma} \approx 200$ ms, stems from a different definition of the particle life time. Indeed, in [4] one refers to a life time of particles deposited at mid-radius by pellets while the present life time refers to a global profile relaxation.

The scaling law of the plasma density with the wall particle content is derived from equation (6). In a regime where τ_{plasma} does not depend on the plasma density, the plasma density must then scale like $(N_{wall})^{1/2}$ [8]. Such an interpretation should be tested with a similar experimental procedure but at higher plasma current. This will increase the plasma density limit and may enable to run plasma discharges in a regime with a saturated τ_{plasma}.

5 - Conclusion

The comprehensive study of the particle balance between the carbon wall and the plasma discussed in this paper is based on 18 identical and successive shots starting from a deeply desaturated wall. This well defined experimental procedure allows to determine several key features which control the plasma particle content. First, one finds that the effective particle content of the wall departs from the deposited number of particles. This effect is dominant for the fully desaturated wall and gradually falls out as the wall is saturated. The analysis of this evolution allows to compute a diffusion coefficient of D-atoms in desaturated graphite ($D_{D:C} \approx 2.8\ 10^{-18}\ m^2\ s^{-1}$).

The dynamical response of the plasma to a change of the plasma-wall particle balance (due to a swing of the plasma from the limiter (outboard) to the inner wall) is used to obtain a scaling law of the plasma density in terms of the wall effective particle content. Furthermore, the experimental data allows to estimate the plasma confinement time. Values ranging from 0.2 s to 0.5 s are found depending on the plasma density. A model of the particle flux balance between the plasma and the wall, together with the scaling of the plasma density with the wall content, gives a fit of the dependence of τ_{plasma} on the plasma density. The agreement found between the analytical functional dependence and the experimental estimation of τ_{plasma} gives us confidence to use the present procedure to more involved experimental situations, for instance with pellet injection or with the ergodic divertor perturbation [9].

References

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Figure captions

Figure 1 Schematic behaviours of gas puff (Γ_{puff}), plasma current (I_p) and particle content (N_{plasma}). Also indicated are the plasma position and the main quantities used in the data interpretation.

Figure 2 Shot to shot evolution of the decay time of the plasma particle content after the displacement versus the equivalent depth of desaturated graphite. The vertical bar indicates the location of the wall surface.

Figure 3 Shot to shot evolution of the (inboard) equilibrium plasma particle content versus the effective wall content ($\propto r_{transport} N_{wall} / N_{limiter}$). The solid line is the fit of the 2nd regime (eq.3).

Figure 4 Shot to shot evolution of the global particle replacement time versus the plasma equilibrium particle content. The solid line is the fit corresponding to eq.6.

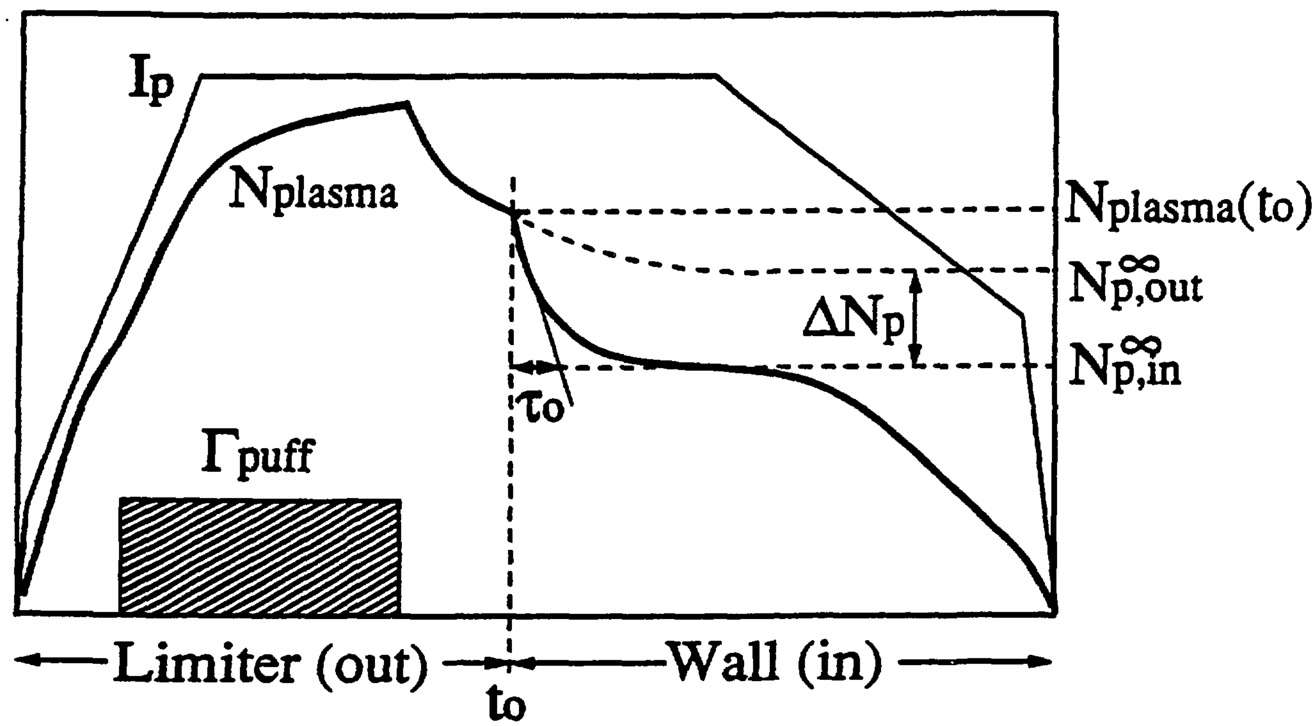
Ip
Nplasma
Nplasma(to)
Np,out∞
ΔNp
Np,in∞
τo
Γpuff
Limiter (out)
to
Wall (in)

Figure 1

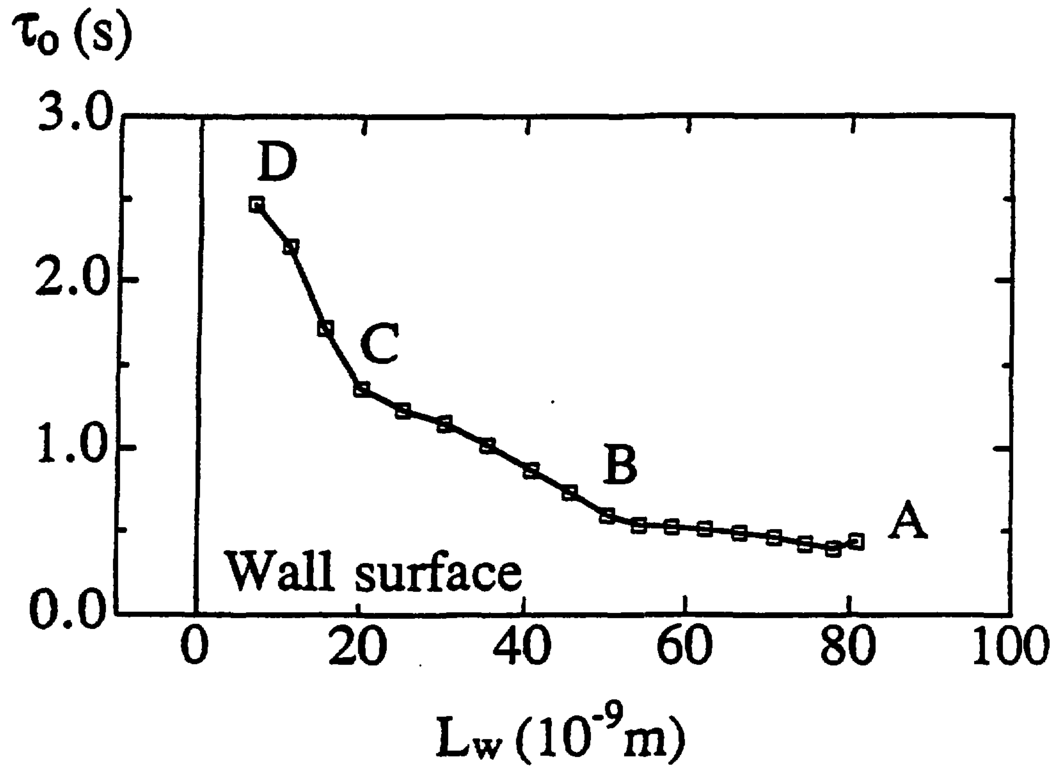

Figure 2

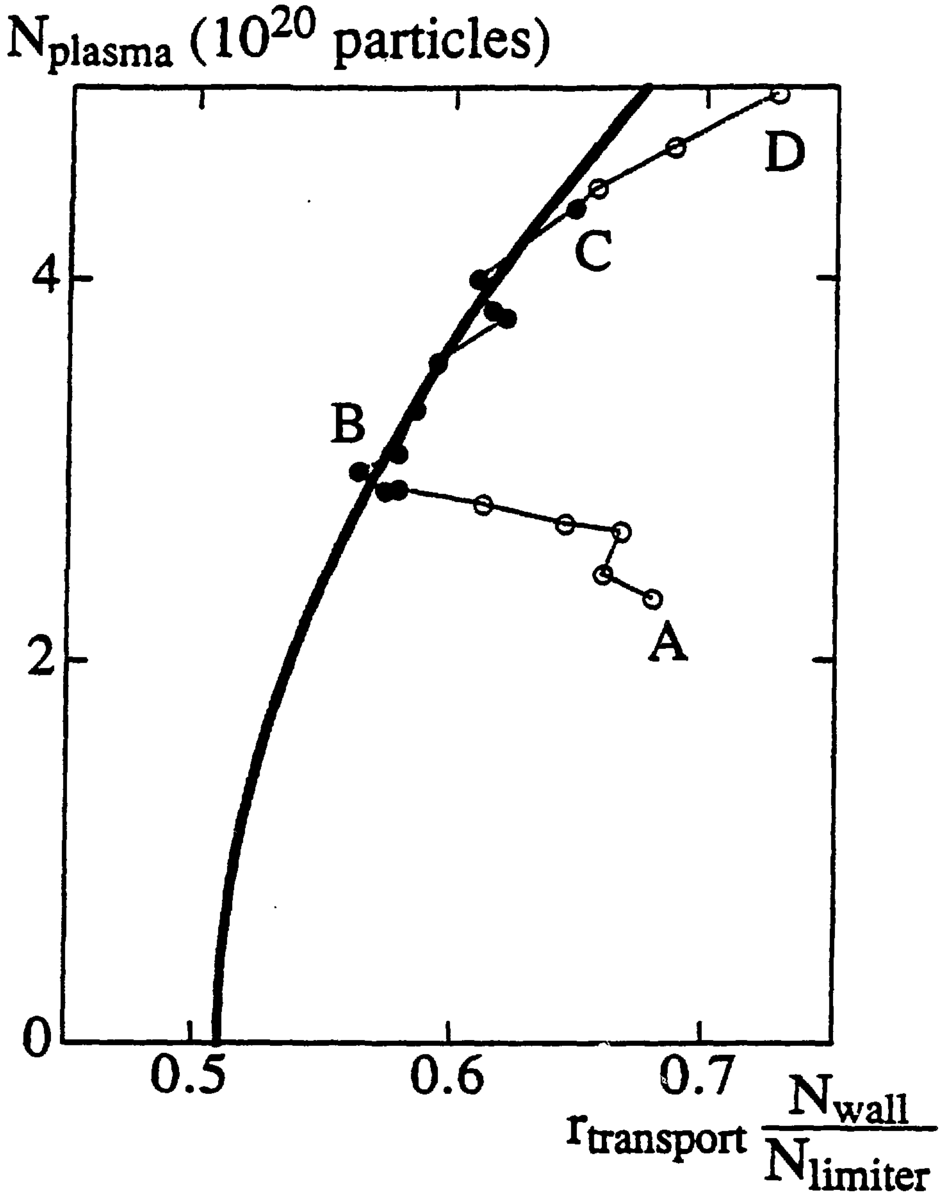
N_{plasma} (10^{20} particles)
4
2
0
0.5
0.6
0.7
$r_{transport} \frac{N_{wall}}{N_{limiter}}$
A
B
C
D

Figure 3

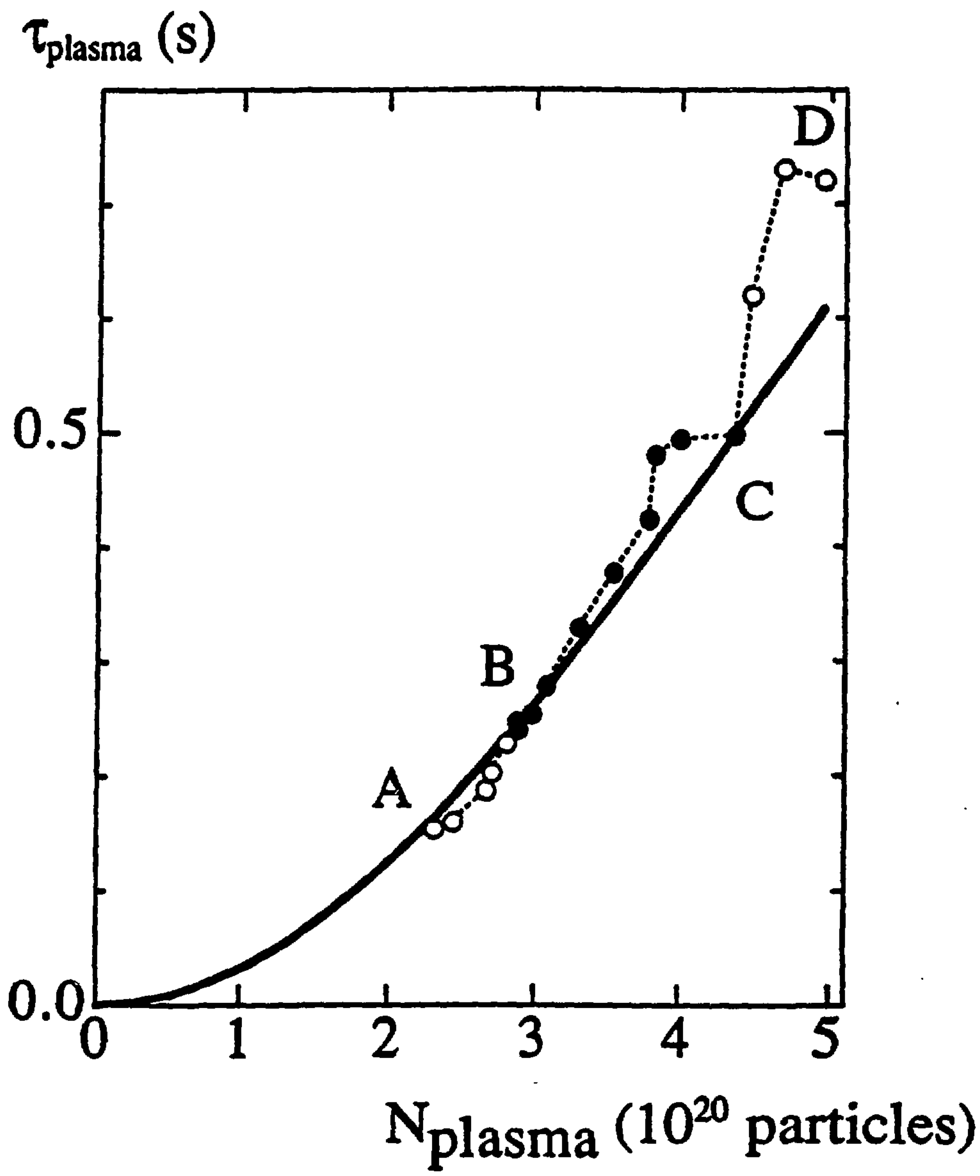

Figure 4