Particle collection by the Ergodic Divertor of Tore Supra: high recycling and partially detached plasmas.

A. Azéroual, B. Pégourié, E. Chareyre, R. Guirlet,
J.P. Gunn, T. Loarer, P. Ghendrih and G. Granata

Association Euratom-CEA sur la Fusion Contrôlée,
Centre d'Etudes de Cadarache, F-13108 St Paul lez Durance.

1) Introduction:

The detached plasma regime is envisaged as an operating condition for next step tokamaks. In this regime, the edge incident ion flux decreases dramatically and goes down to nearly zero on the wall. A proposed method of pumping is to capture backscattered neutrals due to atomic processes, namely FC (Franck Condon) dissociation and CX (charge exchange), with a dedicated vented structure. This solution has been tested with the Ergodic Divertor (ED) of Tore Supra. In this configuration, the field lines connect to neutralizers located between the divertor current bars (7 neutralizers per module - 6 identical modules distributed toroidally around the vacuum chamber). These neutralizers are vented structures which are semi-transparent to neutrals and can be used for particle pumping. A comprehensive set of diagnostics has been installed: 14 Langmuir probes poloidally and toroidally distributed, pressure gauges in the modules plenum and D_α measurements along the neutralizer located in the equatorial plane. The results for quasi-steady state operation (>2s) have been presented in ref.[1]. In the present study, we analyse transient experiments performed for density scan studies and concentrate on high recycling and partially detached plasmas. The investigated range of parameters is $2.5\div4.5\times10^{19}m^{-3}$ for the volume-averaged density and $1.5\div6$MW for the total power, with a radiative fraction varying from 40 to 90%. Under these conditions, the neutral pressure in the divertor plenum ($5m^3.s^{-1}$ of pumping speed) increases with density and total power and is about $2\div9\times10^{-2}$Pa for the high recycling regime and $1.5\div3.5\times10^{-2}$Pa for semi-detached plasmas. The corresponding domain of edge density (temperature) is $1.0\div2.510^{19}m^{-3}$ ($15\div30$eV) and $0.5\div1.5\times10^{19}m^{-3}$ ($8\div15$eV), respectively. For known density and temperature profiles at the edge, two quantities are sufficient to describe the neutral recirculation and particle balance: the pressure in the ED plenum (which characterizes the particle collection) and the distribution of the D_α emission line in front of the neutralizers (which characterizes the ion source due to recycling). Their behaviour during the high recycling and semi-detached phases is described in the next two sections. The multi-1D model presented in ref.[1] is used to interpret the measurements. Scaling laws of the edge parameters and pressure in the pumping chamber with volume-averaged density and total power are given in the last section.

2) Particle collection during the high recycling and semi-detached phases:

All the discharges used for this study have been performed with a density ramp-up. They begin in the high recycling regime and are terminated by a semi-detached phase. The ED is activated during the whole discharge. An illustration is shown on Fig.1a and 1b where the plasma current (I_p), the volume-averaged density ($<n_e>$), the probe saturation current (J_{sat}) and the safety factor at the edge (q_a) are displayed versus time. The pressure measured in the ED plenum (Π_{exp}) is shown on Fig.2a. The different phases can be clearly identified on the trace of the probe saturation current. Before t≅2s and after t≅10s, the condition for the ED resonance (q_a=3±0.3) is not satisfied. The neutralizers are not wetted by the plasma outflux and J_{sat}≅0.

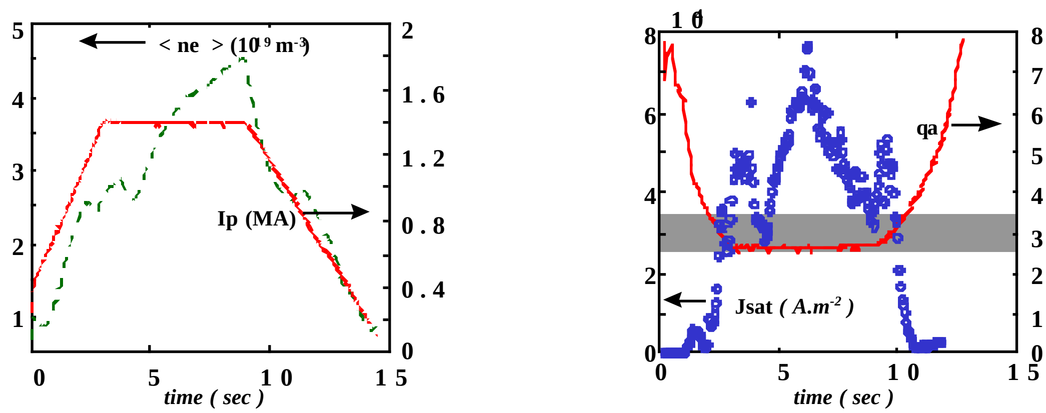

Fig.1: (a) *<ne>, Ip vs. time* **(b)** *Jsat, qa vs. time*

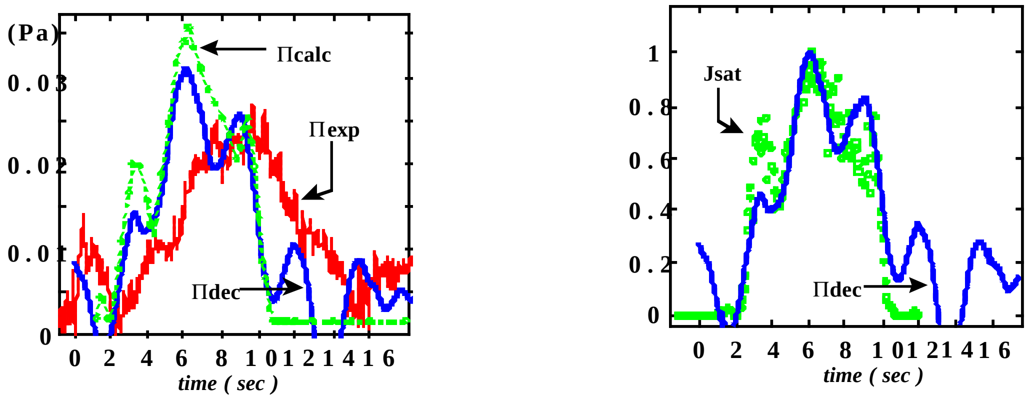

Fig.2: (a) *Πexp, Πdec, Πcalc vs. time* **(b)** *Normalized Jsat, Πdec vs. time*

Until t≅6s ($<n_e>$≅$4.5\times10^{19}m^{-3}$), the discharge is in the high recycling regime and J_{sat} increases rapidly with $<n_e>$. For t>6s, the discharge enters the semi-detached phase and J_{sat} decreases abruptly until the loss of the ED resonance where it vanishes. The volume-averaged density at which the transition between the two regimes occurs varies from shot to shot (between 2.7 and $3.7\times10^{19}m^{-3}$). Its precise value depends on the radiative fraction and total power coupled to the plasma. The trace corresponding to Π_{exp} displays less clear features. To interpret it, one must account for the propagation time of the pressure front in the tube which links the pressure gauge to the ED plenum (τ≅2s for D_2 with a tube of 4.5m long and ∅≅1.5×10^{-2}m). Due to this long response time, the pressure signal is significantly distorted. This is shown on Fig.2a where the latter, deconvoluted from the time constant of the tube (Π_{dec}), is displayed versus time. The corresponding simulated pressure (Π_{calc}) is also plotted, which shows a good agreement with Π_{dec}. A remarkable point is that Π_{dec} remains always proportionnal to J_{sat}, even during the semi-detached phase. This is shown on Fig.2b where the normalized Π_{dec} and J_{sat} are plotted versus time. This similarity is not surprising since the lowest edge temperature obtained when operating the ED is ≅6÷8eV, which is too high for volume recombination to take place. But that stresses the fact that, to satisfy the particle control requirements, the ED must be operated in the high recycling regime, at least at this level of power coupled to the plasma (P_{tot}≤6MW).

3) Partial detachment of the ion source:

The second point to investigate for consistently modelling the particle balance is the ion source, which can be characterized by the D_α light distribution. The absolute brightness of the latter is measured along four lines of sight (L_1 to L_4) at 1, 2.4, 4 and 7cm of the neutralizer surface, respectively. When the plasma edge transits from the high recycling to the semi-detached regime, the peak of D_α emission shifts from L_1 to L_3 [5]. An example is shown on Fig.3a and 3b where the edge temperature ($T_e(a)$), density ($n_e(a)$) and the D_α measurements ($L_{1\div4}$) are plotted versus time. For t<2s, the ED resonnance condition is not fulfilled and the neutralizers are not wetted by the plasma outflux ($T_e(a)$≅$n_e(a)$≅0).

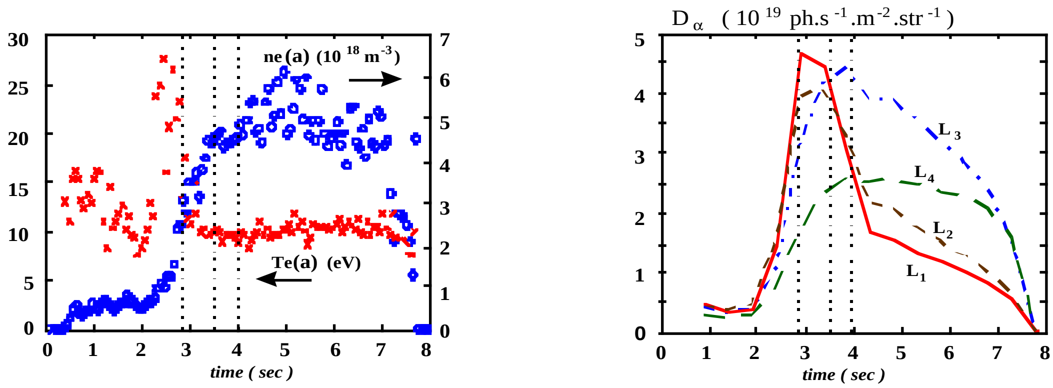

Fig.3: (a) *$n_e(a)$, $T_e(a)$ vs. time* ***(b)*** *D_α brightness vs. time*

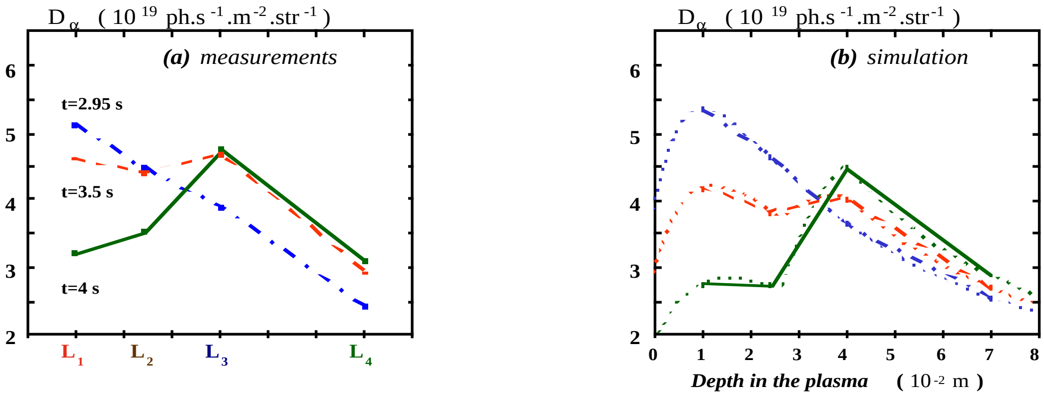

Fig.4: *D_α brightness vs. distance from target*

Partial detachment occurs at the beginning of the current plateau (t≅2.8s): $T_e(a)$ drops abruptly from 30 to ≅10eV when $n_e(a)$ slowly increases to saturate at $\cong 5\times10^{18} m^{-3}$. Just after the detachment, the brightness measured on the two lines L_1 and L_2 drops to stabilize at 1/3 of its initial value. Three radial profiles of the D_α light are displayed on Fig.4a for t=2.95, 3.5, and 4s (indicated by dotted lines on Fig.3a and 3b), showing the shift of the light emission. Simulations have been done by coupling the calculation of the ionization rate with a collisional-radiative model [2] (the molecular ions contribution is neglected). The measurements can be fitted by the appearance of a drop in the temperature profile: in the closest 3cm to the neutralizer surface, the electron temperature decreases from 15eV to 9eV between t=2.95 and 4s, but remains unchanged outside this region. No major changes are required in the shape of the density profile. Results are displayed on Fig.4b where the calculated D_α profiles (dotted lines) are plotted with the corresponding synthetic signals (thick lines) for comparison with Fig.4a. The agreement is satisfactory (within 20%) for the shape of the profiles as well as for their magnitude. During the transition, the ion source distribution follows the appearance of the step in the temperature profile and the neutral penetration increases accordingly: from λ≅2cm for fully attached plasmas (t=3s) to ≅8÷10cm when detachment arrises (t>7.5s). The corresponding screening factor ($e^{-\delta/\lambda}$, where δ≅12cm is the thickness of the stochastic region) increases then from 2×10^{-3} to 0.2÷0.3.

4) Edge parameters and exhausted flux in the high recycling regime:

For practical purpose, it is useful to know the dependence of the edge temperature and density on the main control parameters of the discharge (e.g. P_{tot} and $<n_e>$). This has been done in the high recycling regime (more promising for particle pumping) for which it has been established [3] that the edge density was varying as the cubic power of the volume-averaged density: $n_e(a)[m^{-3}] \approx 2.1\times10^{17} < n_e > [10^{19} m^{-3}]^{3.4}$. Taking advantage of the moderate variation of the radiative fraction in this regime, one can write $P_{tot} \propto P_{cond} \approx n_e(a)\cdot T_e(a)^{3/2}$, which yields for the edge temperature: $T_e(a)[eV] \approx 1.1\times10^{2} < n_e > [10^{19} m^{-3}]^{-2.3} \cdot P_{tot}[MW]^{2/3}$. For given P_{tot} and $<n_e>$, one can then estimate what would be the exhausted flux by using the proportionality between the pressure in the modules plenum and the saturation current $J_{sat} \approx n_e(a)\cdot T_e(a)^{1/2}$, which yields: $\Pi[Pa] \approx 3\times10^{-3} < n_e > [10^{19} m^{-3}]^{2.3} \cdot P_{tot}[MW]^{1/3}$ (With no pumping. For limiter discharges, a similar scaling law for Π has been reported in ref.[4].) The exhausted flux per module can then be written: $\Gamma_{pomp}[Pa\cdot m^3 \cdot s^{-1}] \approx \Pi[Pa]\cdot S\cdot C/(S+C)$, where S is the effective pumping speed and $C \cong 4.8 m^3.s^{-1}$ is the molecular conductance of the neutralizers slots.

References:

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