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# Feedback Control Achievements and Endeavours in Tore Supra Plasma Wall Interactions Control

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## Abstract

Feedback control on the power exhaust repartition will be required in any reactor like tokamak experiments. A review of the experimental studies in Tore Supra is given, where many feedback options have been empirically tried to optimise the edge radiation while staying very close to detachment so as to still insure good ICRF waves coupling.

## Keywords:

ergodic divertor, radiative edge, detachment, plasma edge measurement, feedback control

## 1. Introduction

Control of plasma wall interaction is one of the most difficult challenges of controlled fusion research [1]. The constraints imposed on the wall components by the requirement of steady state operation are so severe (i.e. at the feasibility limit) that dedicated edge plasma conditions have to be provided. These conditions are subject to modifications that may stem from internally or externally imposed physical configurations. The time constants involved in the many phenomena display a wide spectrum from those originating from parallel transport in the edge ($10^{-3}$ s) to those linked to the wall physical conditions, that are generally considered as large ($10^{-1}$–$10^{2}$ s). The necessity to introduce feedback controls derives from the definition of target edge conditions of particle and heat exhaust, RF wave coupling, etc. The major difficulties to be encountered are the determination of the physics at stake, the capability to provide an adequate monitoring of the physics criteria, and finally the implementation of an effective action in due time.

In Tore Supra, a major effort has been concentrated on the control of the ergodic divertor conditions. The feedback control systems are essential in providing highly radiating layers at the very threshold of detachment, so as to ensure the coupling of ICRH, and good screening of the impurity influx. This paper will review various employed techniques, from deduction of the radiation front by bolometers, to monitoring of the edge electron temperature or the total radiation. Generally, the abrupt transition to plasma detachment should be prevented in Tore Supra as the coupling of ICRF waves cannot be achieved any more in such conditions.

The main action remains the gas injection, either of deuterium or impurities. The actual injection time constant cannot be decreased below 100 ms, which, appears somewhat marginal and needs a degree of anticipation in the analysis. The edge $T_e$ evolution, measured by Langmuir probe has proven to be the more efficient, due to a good definition of the "detachment diagram" knowledge.

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## 2. Physics Basis of The Feedback Control

Extensive studies in Tore Supra proved the ergodic divertor to operate in a very similar manner as the X point divertor [2]. A remarkable finding is that in the laminar zone, the existence of distinguishable flux tubes allows to apply the so called 2 points model [3] to relate upstream and downstream plasma parameters. Very similar "density regimes" have been found in Tore Supra ergodic divertor experiments [4]. Noteworthy, a strong non linear evolution of the electron density at the target nt as a function of the upstream density $n_u$ ($n_t \sim n_u^3$), while the target temperature displays an inverse evolution ($T_t \sim n_u^{-2}$), both at least in the high recycling regime. Any attempt to decrease too much the temperature will lead to detachment, where the target density decreases. Such an evolution is shown in Fig. 1 for one Tore Supra shot, in which the target parameters are measured with Langmuir probes, inserted within the divertor target plate.

It should be stressed here that the edge density decrease observed at detachment prevents the achievement of good ICRF waves coupling, whereas ICRH is the main auxiliary heating system in Tore Supra and the antennas are unavoidably within the divertor region in the ergodic divertor configuration.

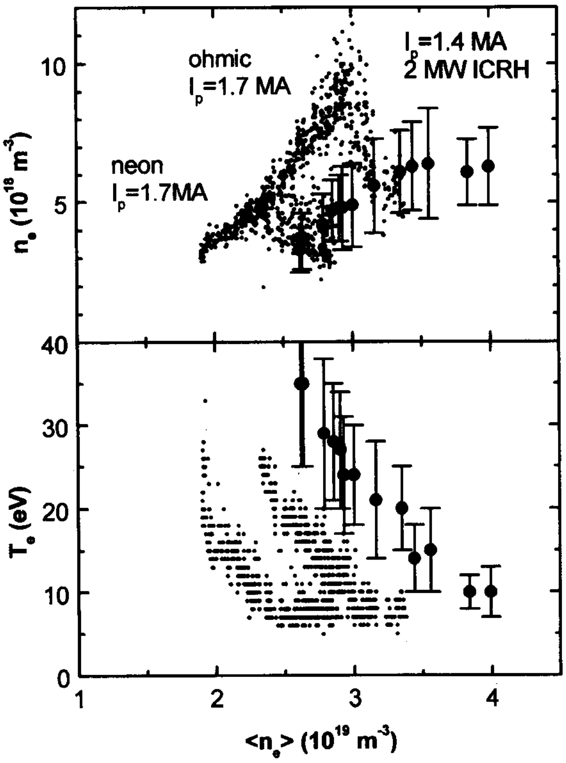


Fig. 1 Evolution of the target density and temperature as a function of the plasma average density for 3 conditions (neon injection: below and left; deuterium injection: up and middle, and with the adjunction of 2MW RF power: points with error bars)

On the opposite, the high recycling regime induces conditions which are very favourable to enhance the radiation losses inside the divertor region. It was shown in [5] that the radiation losses could be written:

$$P^{z}_{rad} = \sqrt{f_{screen}(Z_{eff} - 1)}\, n_t T_t R_z(T_t) \qquad (1)$$

where $P_{rad}$ is the total radiated power, $Z_{eff}$ the effective charge of the plasma bulk $f_{screen}$ the ratio of the impurity content in the edge and in the bulk and $R_z$, the radiation function as defined in [6]. The latter function varying rather slowly except very close to the radiation maximum (at about 7 to 20 eV, depending on the impurity species), it appears that the enhancement is in great part due to the increase of the screening of incoming impurities (itself a linear function of $n_t$).

## 3. Radiative Power Control in Tore Supra

This paragraph will review the various methods used in Tore supra to optimise the radiative losses at the edge. From the previous paragraph, it stems that the major actions to be promoted are an increase of the density and of the edge impurity content. Both of them can be achieved at the time only by gas injection. This kind of action proved to work efficiently; Yet, two questions were raised:

- the injection time constant (about 0.3 s due the injection tubes conductance) is rather long compared to some of the major physics constant for the plasma edge such as $\tau_{//}$ (= $L_c/C_s$, the parallel time constant about $10^{-2}$ s).
- the wall evolution with much longer time constant (10 s at least) will in the long run plays a dominant role through the recycling process, unless a efficient pumping is provided.

Concerning the criteria, 3 absolute measurements were used, the average density $<n_e>$, the total radiation $P_{rad}$ and the target electron density. Unfortunately, the relation of the former to edge parameters cannot be unequivocally deduced; the second proved to be difficult to deduce as radiation is non axisymmetric. The latter is subject to the well known difficulties encountered with Langmuir probes.

It is the reason why two relative criteria were also used. The ratio of the two outer bolometer line of sight could be used to monitor detachment processes [7], whereas, the degree of detachment parameter, deduced from the deviation of the edge density to the high recycling evolution [8] proved to be even more efficient [9]: in fact, the edge bolometers were affected by stray signals in the presence of ICRH.

### 3.1 Feedback on $<n_e>$ and control on $T_t$

A simple modification of the usual feedback algorithm allows to insure good RF coupling:

$$\Phi_{INJ} = \mathrm{GAIN}\times\left[n_{e,PROG}(t) - \bar{n}_{e,MEAS}(t)\right]\times S\left(T_e(t)\right). \quad (2)$$

Here, $S(T_e)$ is a factor that attenuates the gas flow in real time based on the instantaneous measurement of the divertor electron temperature. Above an upper threshold temperature $T_{e1}$ the factor equals unity, so the gas injection proceeds normally. Between $T_{e1}$ and a lower threshold temperature $T_{e2}$, the factor decreases linearly according to

$$S(T_e) = \frac{T_e - T_{e2}}{T_{e1} - T_{e2}}, \quad (3)$$

with the gas flow being completely cut off when $T_e \leq T_{e2}$. Here, the upper threshold was chosen to be $T_{e1}$=20 eV, and the lower value $T_{e2}$ = 14 eV. This guarantees that the edge will not fall out of the high recycling regime, and even with a disastrous event such as coupling failure, or excessive gas injection, there will be some margin for the edge to warm up and recover.

The ability of the program to respond to unexpected events has been shown and an example is given in Fig. 2.

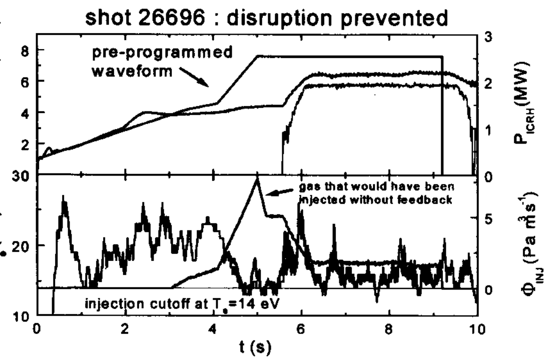


Fig. 2 Example of disruption prevention, where density is adapted to ensure good RF coupling, with a cut-off at $T_{e2}$ = 14 eV.

### 3.2 Feedbacks with security relying on the DoD

Instead of using a threshold value of $T_e$, it appeared even more accurate to use a criterion actually related to the detachment process. The DoD exhibits a large dynamic close to the detachment limit. Practically, the DoD is defined during the initial density ramp up. The fitted ion current: $J_{SAT,FIT} = f(\bar{n}_e)$ is calculated using data points whose corresponding temperature lies between two predefined values, 13 eV and 18 eV for the example shown here. The DoD is undefined until the temperature falls into this range. Once it is defined, the security routine is activated and attenuation of the gas flow begins at lower threshold $DoD_1$ and is cut off at upper threshold $DoD_2$, similar to the security on edge temperature described in the previous section. A linear fit of the DoD on $<n_e>$ proved to be sufficient.

This successful attempt allowed to achieve experiments in which optimum values of Te were searched. The DoD was efficient in avoiding to reach too low values and detachment. An example is given in Fig. 3. The reference value of temperature was set to 5 eV at the end of the ramp. The gas flow was attenuated

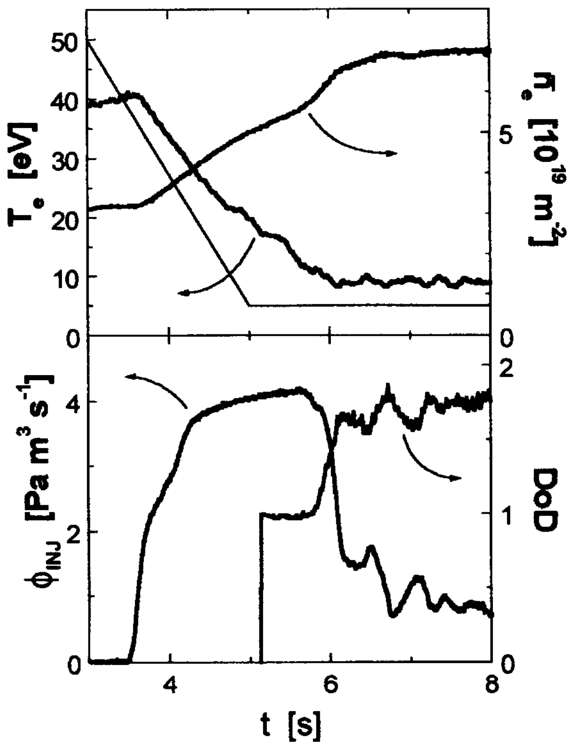


Fig. 3 Evolution of the linear density, the target electron temperature, the gas injection and the DoD. An edge temperature below 10eV is thus controlled.

starting at 6 s due to the increase of the DoD towards the cutoff value $DoD_2 = 1.9$. The gas flow was not totally stopped because the overall gain of the feedback loop was well adapted to these particular conditions, and the detachment was held stable until the end of the current plateau at 8 s, as evidenced by the flat line-averaged density.

### 3.3 Feedback on bolometric signals

In Fig. 4, the time trace of $P_{rad}$, estimated from a combination of raw data of bolometric arrays, and of the total injected power ($P_{tot}$) are presented together with the reference feedback value of the radiated power. In the first part of the discharge, before 4 s, gas injection is feedback controlled on the central linear density. Then, at 4 s, ICRH heating is coupled to the plasma leading to an immediate increase of $P_{tot}$ and $P_{rad}$. At 5 s, gas injection control is changed to feedback on radiated power. A gas mixture of about 2% of neon in deuterium was prescribed before the shot. $P_{rad}$ increases at 6 s, after a delay (almost 1 s) due to the time constant of gas At equilibrium, $P_{rad}$ stays constant at 6 MW and the radiated power fraction is then equal to 85%. This value of $P_{rad}$ is 1 MW lower than the target value of $P_{rad}$ due to a low proportionality factor chosen on the feedback prerequisite. This high value of $P_{rad}$ induced a significant decrease of the conducted power on the neutraliser plates of the ergodic divertor. An energy flux as low as 0.4 $MW.m^{-2}$ could be deduced from thermographic measurements [10].

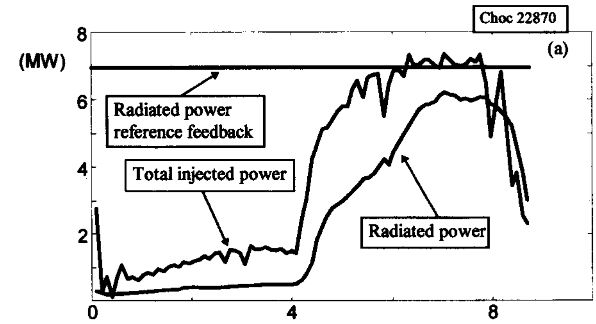


Fig. 4 Feedback on the total radiated power.

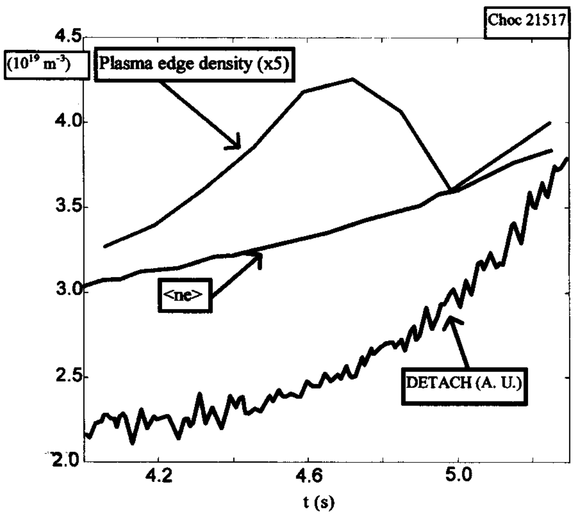


Fig. 5 Evolution of the edge and average densities and of the DETACH parameter as a function of time.

Yet, the difficulties related to the determination of an accurate radiation power prevented a confident use of such techniques. The detachment parameter based on the ratio of the two outer bolometer line of sights was also tested; In that case, the major problem was the too abrupt evolution of this parameter (called here DETACH). This is well displayed in Fig. 5, where the DETACH parameter evolves significantly only after the edge density already decreases. Thus, the control is obtained at the expense of strong modulations of both the radiation but also the density.

## 4. Conclusions

Feedback techniques applied to the complex question of radiating edge control show that strong improvements of performance through their implementation in spite of:

- rather long time constant for the gas injection
- difficulty in defining criteria.

Yet, absolute measurements can be replaced by ratios, related to "bifurcation physics" and proved (especially the degree of detachment DoD) to improve the control capability in edge radiation optimisation experiments.

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