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Journal of Nuclear Materials 275 (1999) 95–100

journal of nuclear materials

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Feedback control of highly radiative plasmas in Tore Supra [1]

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Received 18 May 1998; accepted 10 March 1999

Abstract

The first Tore Supra experiment dedicated to plasma detachment is reported. A criterion of detachment is deduced from bolometric measurements. This criterion is used to feedback control gas injection and maintain plasmas attached. Due to changes in plasma properties when detachment is approached, the feedback loop is unstable. Nevertheless, radiated power is maintained almost constant at 85% of the total injected power during ohmic discharges. Feedback control of gas injection on radiated power during ICRH discharges is reported. It allows to maintain high radiated power (up to 80% of the total injected 8 MW power) and to reduce conducted power on the ergodic divertor tiles with a plasma edge temperature maintained below 15 eV. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

One of the major constraints of any next step tokamak will be the ability to sustain the level of power exhaust in steady-state conditions. To reduce the conducted power onto the limiter and divertor plates to manageable levels, the radiating power fraction ($\mathrm{Fr} = P_{\mathrm{rad}}/P_{\mathrm{tot}}$) has to approach unity. The edge radiation is essentially due to intrinsic or extrinsic (injected) impurities, when appropriate conditions are met at the edge, i.e. high density and low temperature (depending slightly on the radiating species). Radiative edge plasmas ($\mathrm{Fr} \sim 80\%$) have already been obtained at Tore Supra in the ergodic divertor (ED) configuration using neon injection. However, no feedback control was available at that time due to the lack of neon pumping. Now, a set of turbomolecular pumps has been installed on the low field side, outer pump limiter providing pumping of any gas including neon and argon and thus allowing to control the radiated power. In any case, an essential difficulty stems from the necessity of avoiding plasma detachment in order to maintain the ICRH coupling capability. Generally, ICRH power cannot be coupled after detachment [1], the antennae being located in between the ED modules. Therefore, feedback control of gas injection on edge plasma parameters or on radiated power is a key to avoid such a collapse and to stay at the onset of detachment. In this paper, the first experiments realised at Tore Supra dedicated to this plasma detachment control will be described. First, a criterion of detachment using bolometric signals will be defined. Then, this criterion will be used to feedback control gas injection and avoid any plasma detachment. Finally, an example of feedback control of gas injection on radiated power will be presented. This allows to maintain high radiated power (up to 80% of the total injected 8 MW ICRH power) and to reduce conducted power on the ergodic divertor tiles with a plasma edge electron temperature T_e maintained below 15 eV.

2. Definition of a detachment criterion

All experiments on plasma detachment control described in this paper are based on bolometric measure-

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[1] Presented at the 13th International Conference on Plasma–Surface Interactions in Controlled Fusion Devices, 18–22 May 1998, San Diego, CA, USA.

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ments. The bolometric system of Tore Supra consists of three cameras featuring 16 lines of sight. Each camera is located at a given toroidal position and two of them yield vertical lines of sight from top to bottom of the vessel, while the last yields ‘horizontal’ lines of sight. Signals from one of the vertical cameras are used for feedback control. Its measurements are covering the entire plasma volume. Data are measured every 8 ms and stored in the gas data acquisition system. The detachment process in the ergodic divertor configuration has a specific feature [2]. Generally, the radiative edge layer yields a prominent proportion from the low-field side, i.e. in the region which is closer to the ED modules. This can be understood in view of the connection patterns and of the physics of the radiation on open flux tubes [3]. As detachment occurs, one may expect that, due to the lowering of T_e, the ionisation length increases and radiative regions penetrate towards the plasma core. This is experimentally observed using the two outer bolometric lines of sight (BLS): when plasma detaches, BLS at the low field side plasma edge (BLS16) decreases whereas the adjacent BLS further inside the plasma (BLS15) increases. In Fig. 1, an example of such a behaviour is presented. In this experiment, the detachment is induced by a strong gas injection which increases the plasma average density $\langle n_e \rangle$ (see Fig. 2). The plasma edge density (n_{e_b}) measured by Langmuir probes located on the ergodic divertor neutraliser increases first more rapidly than $\langle n_e \rangle$ (for deeper insight, see Ref. [4]). Then n_{e_b} is shown to saturate before finally decreasing when the plasma detaches. After detachment, n_{e_b} experiences high level of fluctuations which produces a degradation of the ICRH coupling capability. This phenomenon is responsible for the loss of the ICRH coupling and can lead to a disruption.

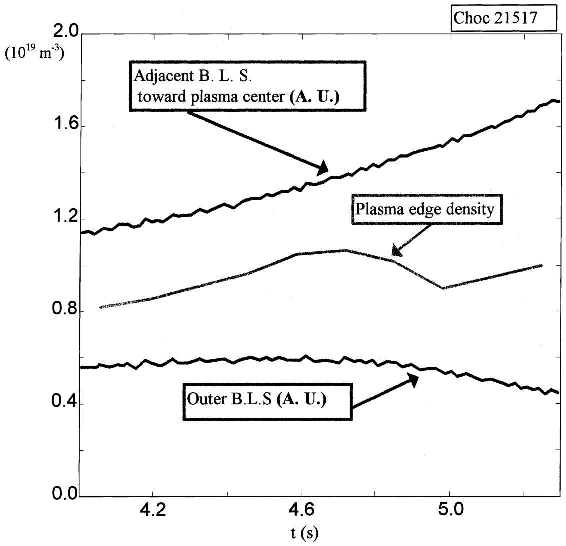

Fig. 1. Time evolution of two Bolometric Lines of Sight (BLS) during plasma detachment. The outer one (outer BLS) is viewing the low field side plasma edge, the other is adjacent to the previous one toward the plasma centre. Also plotted, time evolution of plasma edge density measured on one ergodic divertor neutraliser by a Langmuir probe.

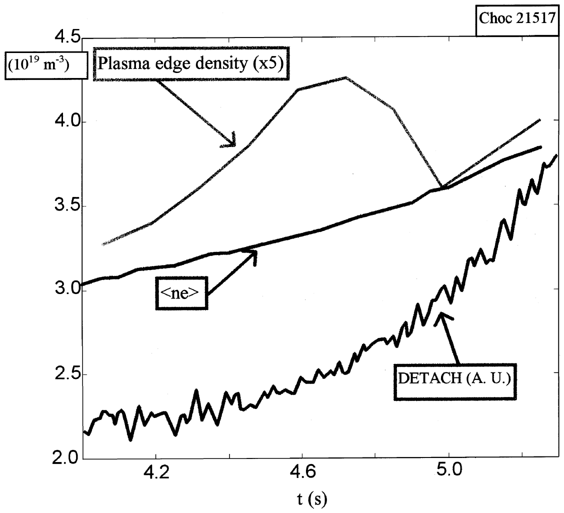

Fig. 2. Time evolution of the plasma average density and of the edge density measured by Langmuir probe on an ergodic divertor neutraliser. Also plotted DETACH criterion.

The detachment process in the ergodic divertor is complex [2] and displays specific variations depending on the physical characterisation of the involved flux tubes. These effects affect a plasma zone of a size which concerns only the two outer BLS. Nevertheless, the resolution of the bolometric camera (about 0.1 m) is sufficient to follow plasma detachment.

At 4.8 s, the outer BLS (BLS16) is decreasing and the adjacent BLS towards the plasma centre (BLS15) continues to increase. To characterise this evolution, a detachment criterion has been chosen which is the ratio of BLS15 over BLS16. In the following, this ratio is called DETACH. The time evolution of DETACH (see Fig. 2) is driven by gas influx and plasma edge density (n_{e_b}) . As shown previously n_{e_b} is decreasing after 4.5 s while DETACH is increasing. This illustrates the detachment characteristics in Tore Supra. The ‘progressive’ detachment may be used to induce a corrective action. Some other criteria have been tested using other BLS signals or a combination of them. For example, the derivative of BLS16 gives good results. However, to reduce the noise due to this calculation, a smoothing procedure has to be used which increases the time response of the feedback loop. That is why the raw signals are used rather than those obtained from derivatives.

In the example shown above, the ED titanium pumps are activated. Consequently, the recycling flux is not dominated by wall saturation and detachment can be controlled just by closing the gas injection valves. Indeed, n_{e_b} will then decrease due to particle sink effects and plasma will re-attach. This technique is used to control plasma detachment and is described in the following chapter.

3. Feedback control on detachment criterion

One example of a feedback using DETACH as a criterion is presented in Fig. 3. This feedback acts as a security ('passive' feedback). When DETACH becomes greater than the level predefined (2.6 in our case), the gas flow is stopped and DETACH recovers a lower level due to the pumping capability of the vessel. The DETACH setting of 2.6 was chosen from the analysis of previous shots.

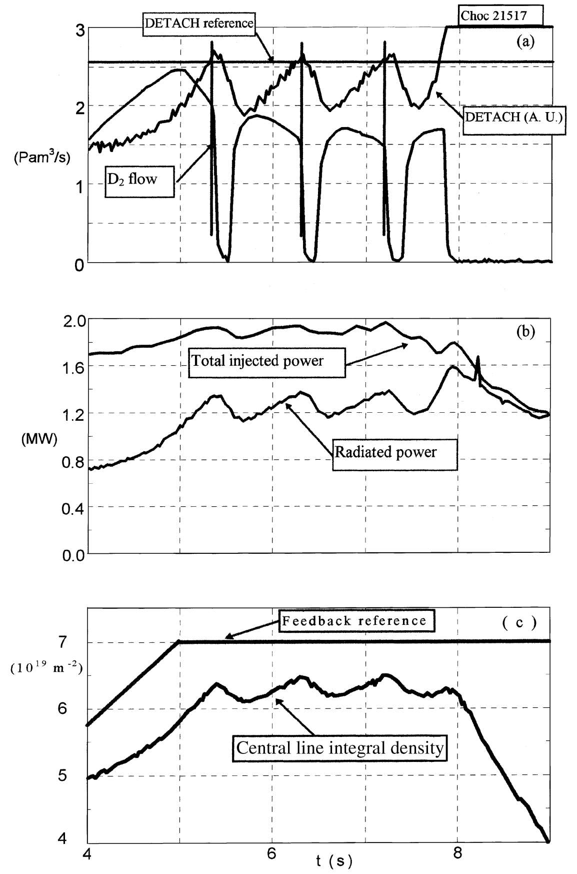

Fig. 3. Passive feedback control on detachment criterion (DETACH). Time evolution of: (a) DETACH and D_2 flow. Also plotted feedback control reference; (b) total injected and radiated power; (c) central line integral density and its feedback reference.

Before 5 s, DETACH is lower than 2.6 and gas injection is feedback controlled on the central line integral density with a feedback reference of 7×10^{19} m^{-2} (see Fig. 3(c)). To reach the target density, a strong D_2 gas injection of more than 2 Pa m^3 s^{-1} is needed (Fig. 3(a)). This leads to an increase of n_{e_b} and $P_{\rm rad}$, the radiated power of the plasma.

When DETACH is equal to 2.6, the gas injection valve is closed. Density feedback control is stopped as long as DETACH stays above 2.6. Due to the active pumping capabilities of the vessel, the density decreases as well as $P_{\rm rad}$ and DETACH. When DETACH becomes lower than 2.6, the density feedback control is activated again and the cycle described above starts again after a delay corresponding to the time constant of gas injection and pumping system. In the example of Fig. 3, every time DETACH reaches 2.6, plasma edge density begins to decrease: plasma is on the way to detachment. In spite of an overestimation of DETACH due to calibration problems on bolometric measurements, this simple technique allows to maintain the radiated power at an almost constant level (~73% of the total injected power). This level could be adjusted by increasing the threshold value of DETACH.

Another technique (called 'active' feedback) has been tested in which, after reaching the DETACH threshold value with density feedback control, the gas injection is controlled by feedback on the DETACH criterion itself. This active feedback technique is presented in Fig. 4. In Fig. 4(a), DETACH is plotted with its reference value and the D_2 flow. When DETACH reaches its reference, gas injection is stopped and the same behaviour as for passive feedback control is found.

It appears difficult to feedback control gas flow on the DETACH criterion. In both cases (active and passive feedback), oscillations of both DETACH and the density are observed.

In the case of the passive control, gas injection is controlled on the central line integral density. Gas flow (Φ) entering the edge plasma at time t is expressed by

$$\Phi(t) = K(n_{\rm r} - n(t - \tau)),$$

where τ is the time constant of gas injection system, $n_{\rm r}$ the reference density, n the measured density and K the control loop proportional factor.

The time evolution of the plasma linear density is then given by

$$\frac{dn}{dt} = F^{*}\Phi_{\rm r} - \frac{n}{\tau \rm pomp} + F^{*}\Phi(t), \tag{1}$$

$$\frac{dn}{dt} = F^{*}\Phi_{\rm r} - \frac{n}{\tau \rm pomp} + F^{*}H^{*}K(n_{\rm r} - n(t - \tau)), \tag{2}$$

where F is the plasma fuelling efficiency, $\Phi_{\rm r}$ the recycling flux coming from the walls and τpomp the time constant of the pumping system which can be the walls or an

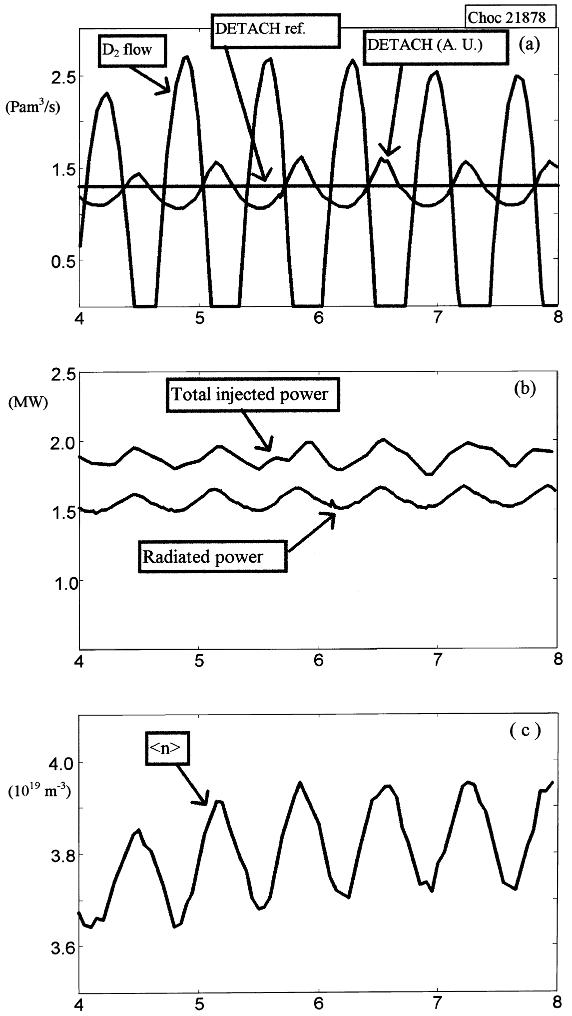

Fig. 4. Active feedback control on detachment criterion (DETACH). Time evolution of: (a) DETACH and D_2 flow. Also plotted, feedback control reference; (b) total injected and radiated power; (c) plasma average density.

external device. In expression (2), $H = 1$ if $(n_r - n(t-\tau)) < 0$ and $H = 0$ if $(n_r - n(t-\tau)) \geqslant 0$. Expression (1) was presented in Ref. [5]. Eq. (2) is only an extension of Eq. (1) to take into account the gas injection time constant.

As the density increases and the plasma reaches detachment, F becomes greater. This is shown in Fig. 5(a) where the fuelling efficiency is plotted against DETACH. From the attached plasma situation to detached one, F increases by a factor of 2 (from 9% to 18%).

The difference between Eq. (1) and Eq. (2) comes from the fact that in Eq. (2) the gas injection is forced by the feedback loop to increase the density towards the target density. This is not the case for Eq. (1) in which equilibrium states are described.

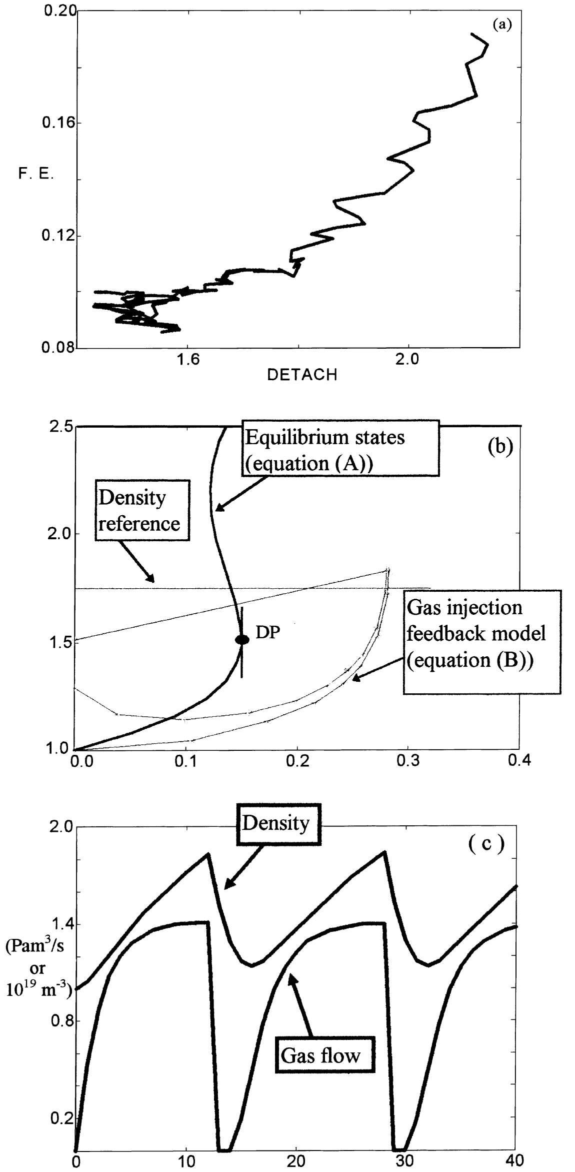

Fig. 5. (a) Fuelling efficiency as a function of DETACH for the time interval presented in Fig. 2; (b) density as a function of gas injection flow for the two equations presented in Section 3; (c) time evolution of density and gas injection flow for gas injection feedback model.

In Fig. 5(b), the density is plotted against gas injection Φ in the frame of the equations presented above. The curve labelled equilibrium states stands for Eq. (1). Note that plasma detachment appears in this case when the plasma density experiences a vertical tangent at point DP. The evolution of the density in the gas feedback controlled scheme is presented in the same drawing. The density increases with gas flow. All the points plotted now are out of equilibrium described by Eq. (1).

As the density increases and the plasma reaches detachment, F increases and the density experiences a vertical tangent. Gas injection does not stop when the density reaches the target density but only τ seconds after and target density is overreached. Then $\Phi = 0$ and the density drops due to wall pumping. In the drawing, the density drops almost vertically due to a very high particle sink. Feedback control starts (density is less than density target) and the cycle is repeated.

Density and gas injection behaviour versus time are presented in Fig. 5(c), where time is normalised to the pumping time constant of the device. These time evolutions compare well with those presented in Fig. 3(a) and (b) for passive feedback control.

DETACH is proportional to n and the above model describes the trends observed also in the active feedback control system (compare Fig. 5(c) and Fig. 4(a) and (b)).

The feedback loop is unstable and oscillations are obtained. This comes from the fact that the time constant of the pumping system of the vessel is much lower than the time constant of the gas injection system. When the density target is reached and gas injection is stopped, the plasma density decreases too much before gas injections starts again. Moreover, the proportionality factor of the feedback loop is constant. K is not decreasing with n to compensate for the increase of the fuelling efficiency when the plasma evolves towards detachment. This leads to a high injection flux close to the target density which is always exceeded.

Notwithstanding this difficulty, the technique allows to control the plasma radiated power at a value of around 85% of the total injected power.

The response of the BLS is strongly correlated to the plasma properties. The threshold of DETACH is not the same if the ED is not activated since the radiating zone is not located at the same place around the plasma. Moreover, if ICRH heating is used large perturbations of the BLS are observed and the DETACH criterion is not operational. For these reasons, new feedback control signals are under investigation at Tore Supra based on plasma edge measurements.

4. Feedback control on radiated power

Feedback control on radiated power is also available at Tore Supra. The key of this technique is to control the gas injection flow through a signal proportional to the difference between a radiated power reference and P_{rad}.

In part (a) of Fig. 6, the time trace of P_{rad}, estimated from a combination of raw data of bolometric arrays, and of the total injected power (P_{tot}) is 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 injection (τgas $\sim$ 200 ms) and to the global response of the plasma. At equilibrium, P_{rad} stays constant at 6 MW for more than 1 s 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. It has to be noted that without any neon injection and in the same condition, P_{rad} stays just above 4 MW. This corresponds to a radiated power only due to intrinsic impurities.

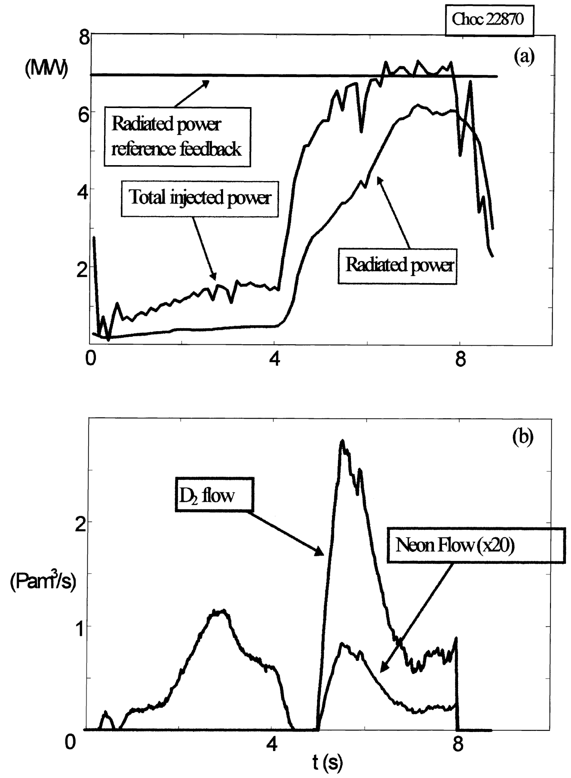

Fig. 6. Feedback control on the radiated power. Time history of: (a) total injected power (P_{tot}) and radiated power (P_{rad}); (b) D_2 and neon gas injected flux. (Feedback control on P_{rad} begins at 5 s.)

This high value of P_{rad} induced a significant decrease of the conducted power on the neutraliser plates of the ergodic divertor. Their temperature (T_{w}) drops to about 200°C. This temperature corresponds to an energy flux (Φ) of 400 kW m^{-2}. This T_{w} is very close to the working temperature of the vessel (T of baking = 160°C) while just before the neon injection T_{w} was at 500°C ($\Phi \sim 3.4$ MW m^{-2}). At the same time, the plasma edge temper-

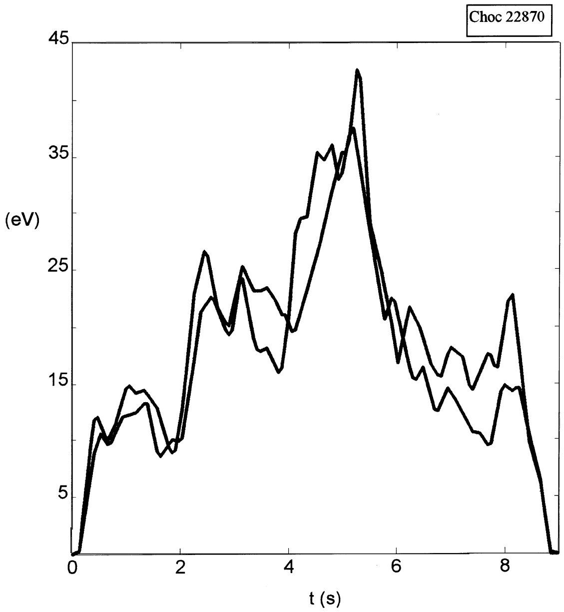

Fig. 7. Time evolution of plasma edge temperature. The two signals are measured with Langmuir probes and are located on two different ergodic divertor neutralisers.

ature (T_{e_b}) decreases as shown in Fig. 7. In this graph, two of the 14 T_{e_b} values measured by Langmuir probes on the ergodic neutralisers are presented. All the signals experience the same time evolution. After ICRH coupling, T_{e_b} increases from 35 to 40 eV which corresponds to a rather high plasma edge temperature when the ergodic divertor is operated. When D_2 + neon injection takes place, T_{e_b} decreases to 10–15 eV range. This value is comparable to temperatures obtained during detached ED and without additional heating.

5. Conclusions

In this paper, two different feedback controls of gas injection have been presented.

The first one is based on a bolometric criterion which is a ratio of two adjacent bolometric lines of sight viewing the low field side plasma edge. This criterion (DETACH) is compared to a threshold value and the result is used as a control parameter.

Then, a passive control can be implemented. If DETACH is smaller than a reference, gas injection is feedback controlled on the central linear density while, if DETACH is greater than this reference, gas injection is closed. In this case, due to passive and active pumping capabilities of the vessel, DETACH decreases and the cycle can restart. This allows the operations group of Tore Supra to avoid any plasma detachment and so DETACH can act as a safety parameter. Based on the same criterion, a proportional control loop can be used (active feedback). However, due to the chosen working point and to (i) the characteristic time constant of the gas injection, (ii) to the plasma response and (iii) to the variation of the gas fuelling efficiency with the degree of plasma attachment, the system is unstable and oscillations are obtained.

The second one is based on P_{rad} measurements. Gas injection is directly feedback controlled on P_{rad}. With this technique, constant high radiated power ($P_{rad} \sim 6$ MW e.g. 85% of the total injected power) has been obtained for more than 1 s. Gas injection is a mixture of D_2 and 2% of Ne. This leads to a decrease of the plasma edge temperature from 40 to 15 eV. At the same time, the wall temperature of the ergodic divertor neutraliser decreases from 500°C to 200°C corresponding to an energy flux reduction by a factor of 10 (from 3.4 to 0.4 MW m^{-2}).

References

[1] F. Nguyen et al., presented at 13th Int. Conf. on Plasma–Surface Interactions in Controlled Fusion Devices, May 1998, San Diego, CA, USA.
[2] P. Ghendrih et al., J. Nucl. Mater. 266–269 (1999) 189.
[3] P. Monier-Garbet et al., J. Nucl. Mater. 266–269 (1999) 611.
[4] B. Meslin et al., J. Nucl. Mater. 266–269 (1999) 318.
[5] T. Loarer et al., J. Nucl. Mater. 241–243 (1997) 505.