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Feedback control on edge plasma parameters with ergodic divertor in Tore Supra

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Abstract

In order to control highly radiative plasmas with the ergodic divertor, feedback procedures based on real time Langmuir probes measurements have been implemented in Tore Supra. The prediction of the detachment density threshold, which leads to disruption, is a major experimental difficulty. On the other hand, it has been observed that the edge electron temperature limit, measured by probes, is quite reproducible in many different operating scenarios. Therefore, feedback procedures on the edge electron temperature have been developed to control the gas injection. When the plasma reaches detachment, the fuelling efficiency abruptly increases and the feedback loop can become unstable. A detachment criterion, defined as the ratio of the saturation current of the probes scaled from the high recycling regime phase to its current value, has been used to manage detached plasmas. These techniques have been successfully applied in Tore Supra discharges with ergodic divertor for the study of edge density regimes and plasma detachment in ohmic, ICRH heating, and impurity seeded experiments. © 2001 Published by Elsevier Science B.V.

Keywords: Feedback control; Detachment; Density limit

1. Introduction

Controlling plasma–wall interaction is one of the major issues toward steady-state operation in magnetic confinement devices. The ergodic divertor of the superconducting tokamak Tore Supra is dedicated to the organisation of the interaction [1]. Six octopolar current coils, regularly distributed toroidally on the low-field side of the vessel, generate helical magnetic perturbations that are resonant at the plasma edge. Outermost magnetic surfaces are thus destroyed and a stochastic layer is created. This low confinement region, dominated by parallel transport and atomic processes, acts both as a strong impurity screener and as a stable radiator [2]. In the next step devices, highly radiative plasma regimes are considered to be a good solution to reduce the excessive conducted power on plasma facing components. In this context, discharges that radiate a large fraction of the total power have been investigated. High level of radiation is reached when appropriate conditions are met at the edge of the plasma: adequate concentration of intrinsic or extrinsic (injected) impurities, high electron density and low electron temperature. Therefore, to increase the radiated power fraction, one has to increase the density and lower the edge temperature (by gas puffing) or inject impurity. The control of such discharges through the usual gas injection feedback on line-averaged density is troublesome because it is very difficult to predict the density threshold that leads to disruption. This threshold depends very sensitively on several factors such as the amount of neutral gas, the radiating impurity content and the amount of injected power. In the other hand, edge density regime studies [3], with divertor probes, has revealed some reproducible features in the behaviour of some edge parameters.

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Like in axisymmetric divertors, three edge density regimes have been identified. At low core density a linear sheath-limited regime is observed for which the edge electron density has a linear dependence on the core density. During this phase the radiated power is usually less than 50% due to the low density and to the high temperature in the divertor volume. At intermediate core densities, the edge density increases rapidly with the core density, obeying approximately a cubic law while the edge electron temperature drops to the neighbourhood of 10 eV: this is the conduction or high-recycling regime. As the core density is further increased in response to gas injection, the edge density suddenly drops whilst the edge electron temperature remains in the 10 eV range (to compare to 1–5 eV in typical axisymmetric divertor). This is the detached regime in which the power is mostly radiated (85–95%). The detachment phase is generally followed by a radiative limit disruption. A too high line-averaged density reference value is mostly at the origin of the disruption either because of a bad estimate of the density threshold or because of an unexpected decrease of the threshold (loss of ICRH power coupling). If the density threshold varies with the operating scenario, the edge electron temperature, on the other hand, tends to stay constant around ~10 eV when the plasma moved to detachment regime. According to these observations, new feedback controls of the density, that allows one to monitor the state of the edge plasma in order to avoid disruption and handle plasma in a particular edge regime, have been implemented in Tore Supra [4].

2. Real-time Langmuir probe measurement at Tore Supra

2.1. Divertor Langmuir probe system

Tore Supra ergodic divertor is equipped with 14 CFC graphite domed probes (hemispherical, 5 mm diameter) installed between the fingers of some of the vented neutraliser plates. The probes are biased in single probe mode with respect to the machine ground. Current–voltage characteristics are swept out in 1 ms. Standard analysis techniques of strongly magnetised probes are applied, meaning that finite Larmor radius or sheath effects are neglected and a hard ion current saturation is assumed [5]. This kind of analysis can lead to an overestimation of the electron temperature when T_e approaches 100 eV, which is not a concern in our case for the relevant physics of highly radiating plasma that occurs at low edge T_e (~10 eV). Two of the 14 probes may be selected to obtain an I–V characteristic every 8 ms for which analysis is performed in real time just after each acquisition. The calculated density and temperature of both probes are transmitted to the reflected memory via a SCRAMNet card where they can be accessed by other control units [6] (Fig. 1).

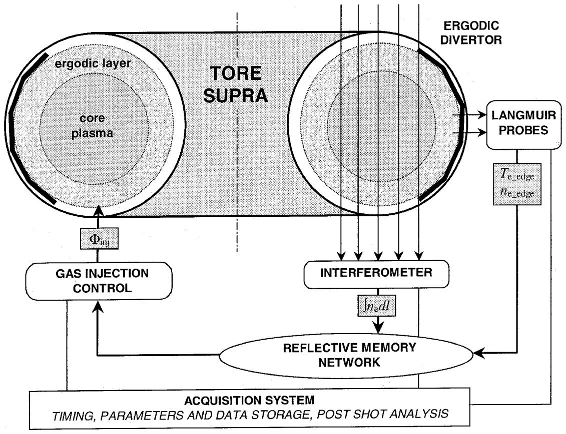

Fig. 1. Principle of the Tore Supra plasma density control system and feedback loop that can be used to control the gas injection by reacting upon the line-averaged density (interferometry), the edge density and the edge temperature (Langmuir probes).

2.2. Measurement reliability issues

Edge temperature and density signals calculated in the Langmuir probe diagnostic unit are then smoothed in the feedback algorithm using a sliding average method in order to reduce the intrinsic probe measurement noise and the potentially ICRH induced one. The averaging time window duration is of the order of the gas injection system time constant (~50 ms). The probes are placed in isolated locations on different divertor neutraliser plates, so they are subject to poloidal and toroidal asymmetries. Furthermore, temporal variations in the magnetic equilibrium cause the flux deposition patterns to sweep over the probes. For example, during current ramp-up, when the safety factor reaches 80–90% of its nominal value for resonance with divertor, plasma begins to strike the divertor plates and the Langmuir probes record the passage of several high-temperature spikes before the equilibrium is reached. They correspond to the deposition of hot flux tubes, fed directly by parallel transport from hot plasma originating in the ergodic layer, as opposed to cold flux tubes fed by cross-field diffusion and characterised by short connection length to the wall. To minimize the influence of the ergodic structure of the edge, probe signals are averaged from two carefully chosen probes.

3. Feedback control on edge parameters

Usually the gas injection is proportional to the instantaneous difference between a pre-programmed reference density and the measured density, with the system response controlled by a pre-programmed multiplicative gain:

$$\Phi(t) = G(t) \times [n_e l_{\mathrm{REF}}(t) - n_e l_{\mathrm{MEAS}}(t)]. \tag{1}$$

At low density the fuelling efficiency, defined as the rate of increase of the central density with respect to the gas injection rate, is very low in the range of 1%, due to the screening property of the divertor. During density ramp-up, the fuelling efficiency abruptly increases when the edge temperature comes close to ~10 eV (up to 20%) as the ionisation mean free path of the deuterium atoms through the cold edge increases [7]. If the gain waveform of the feedback loop is not properly set, the large gas influx required to raise the density in the beginning may lead at higher density to excessive core fuelling, uncontrolled density rise and radiative limit disruption. Since the central density limit is very difficult to predict, this method inexorably involves some trials and some disruptions when highly radiative regimes are to be explored. Feedback on bolometry signals has been attempted in the past [8] but Langmuir probe signals appear more promising to solve this problem.

3.1. Feedback on line-averaged density with security on edge temperature

The edge electron temperature is a good candidate to manage the problem of density limit since its value at detachment is reproducible in many operating scenarios (10 ± 2 eV). A simple modification of the feedback algorithm permits this feature to be used. When the high recycling regime is entered the usual gain is multiplied by an attenuation factor as a function of the temperature, in order to attenuate the gas injection as the fuelling efficiency increases and to cut off the gas injection when detachment is reached:

$$\Phi(t) = G_{n_e l}(t) \times S(T_e(t)) \times [n_e l_{\mathrm{REF}}(t) - n_e l_{\mathrm{MEAS}}(t)]. \tag{2}$$

Above an upper threshold temperature T_{e1} the factor equals unity, so that the gas injection proceeds normally. Between T_{e1} and a lower threshold temperature T_{e2} the factor decreases linearly according to

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

and below T_{e2} the gas flow is completely cut off. Thereby, independently of the pre-programmed core density reference value, the feedback loop can prevent the excessive cooling of the edge that leads to density limit disruption and maintain the high recycling regime, which is thought to be optimal. The experiment displayed on the Fig. 2 shows the ability of the program to control the edge temperature and respond to unexpected events. The plasma current is $I_p = 1.5$ MA, the toroidal field $B_T = 3.14$ T and 1.5 MW of ICRH is requested. In this typical scenario for ICRH power coupling, the security is switched on at $t = 3$ s. At that time, the edge temperature T_e is below T_{e2} and gas injection is immediately stopped. When ICRH power is coupled, the conducted power into the edge increases and T_e slowly increases. At $t = 4$ s, the density reference is ramped up while the T_e threshold reference values are ramped down. The gas injection is still inhibited by the security until T_e rises above a lower threshold value. Then, T_e is maintained between the two threshold values by the attenuation algorithm as the pre-programmed density value is actually far above the density limit. Despite the loss of ICRH coupling when the plasma reaches detachment limit, the gas injection is controlled and density limit disruption is avoided.

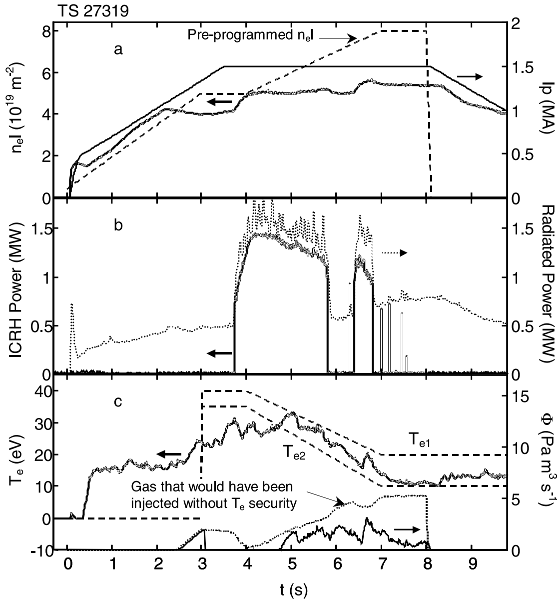

Fig. 2. Example of feedback control on line-averaged density with security on edge temperature. (a) Plasma line-averaged density $n_e l$ (central chord), pre-programmed $n_e l$ reference waveform (dashed line), and plasma current I_p as a function of time. (b) ICRH and radiated power. (c) Measured edge temperature T_e pre-programmed temperature threshold T_{e1} and T_{e2} waveforms (dashed curves), gas injection Φ and gas flux that would have been injected without T_e security (dotted curve).

3.2. Feedback on line-averaged density with security on the degree of detachment (DoD)

In deuterium discharges, once detachment begins, the probe temperature levels off and remains independent of the core density and thus cannot be used to control detached plasmas. In contrast, a sudden drop of the probe ion saturation current is observed. This dynamics is exploited through the definition of the degree of detachment (DoD). Defined as the ratio between a theoretical ion current, extrapolated to high density from the high recycling regime, and the measured ion current:

$$\mathrm{DoD} = \frac{I_{\mathrm{SAT,SCALED}}}{I_{\mathrm{SAT,MEAS}}} \tag{4}$$

the DoD equals unity in the high recycling regime and increases non-linearly during detachment. The JET definition is based on a simple two-point model that predicts $I_{\mathrm{SAT}} = c\langle n_e l\rangle^2$ for constant input power in the high recycling regime [9]. Such an expression is too sensitive to be reliably applied in real time to experimental data, so a linear fit of experimental data points in the high recycling regime has been chosen to extrapolate I_{SAT} above the high-recycling regime. The scaled ion current $I_{\mathrm{SAT,SCALED}} = f(n_e l)$ is calculated from the average value of data points whose temperature lies between two predefined values T_{e1} and T_{e2} (13 and 18 eV for the examples shown in Figs. 3 and 4) according to the following formula:

$$I_{\mathrm{SAT,SCALED}}(t) = \frac{\sum_{i\leqslant t \& T_{e1}\leqslant T_e\leqslant T_{e2}} I_{\mathrm{SAT,MEAS}}(i)}{\sum_{i\leqslant t \& T_{e1}\leqslant T_e\leqslant T_{e2}} n_e l_{\mathrm{MEAS}}(i)} \times n_e l_{\mathrm{MEAS}}(t). \tag{5}$$

The DoD is undefined until the temperature falls into this range and typically reaches values between 2 and 2.5 at the density limit. Easily adapted for real time calculation, this method is very robust since the computed value of the DoD is not too sensitive to the choice of T_{e1} and T_{e2} as far as they correspond to high recycling regime temperatures. Once the DoD is defined, a security algorithm (similar to the one previously described) begins to attenuate the gas flow at lower threshold DoD_1 and cuts off at threshold DoD_2. In Fig. 4, we report a shot for which the DoD was used to prevent a disruption. In this ohmic discharge, the plasma current is $I_p = 1.4$ MA and the toroidal field $B_T = 3.03$ T, the threshold values for the security function are $\mathrm{DoD}_1 = 1.2$ and $\mathrm{DoD}_2 = 1.8$. At $t = 5$ s, a density ramp is requested and the gas injection increases driving the line averaged density upwards and cooling the edge. At $t \sim 6$ s, the DoD is defined as T_e enters the domain of definition of the DoD. Half a second later, a spike in the DoD curve is observed corresponding to the penetration of the fast scanning probe into a flux tube that is connected to one measuring probe. At $t \sim 7$ s, the DoD rises and the characteristic increase of fuelling efficiency that coincides with the beginning of detachment is clearly observed. The gas flow is strongly attenuated by the DoD security algorithm and the system reaches equilibrium. The plasma is detached and controlled in a steady state.

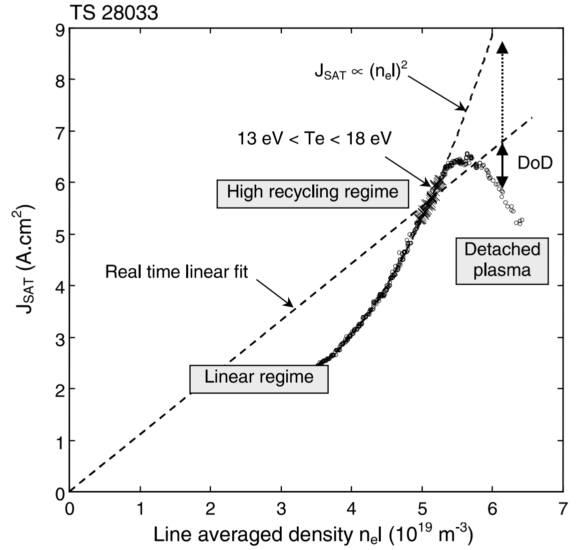

Fig. 3. Edge density regimes with ergodic divertor and DoD definition. The ion saturation current density J_{SAT} is traced as a function of line-averaged density $n_e l$. The crosses are the data points used for the linear fit, they correspond to data points for which the edge temperature lies between 13 and 18 eV.

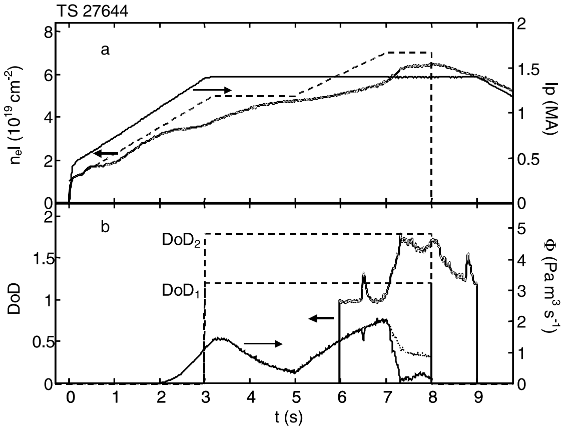

Fig. 4. Application of the security on the DoD. (a) Plasma line-averaged density $n_e l$ (central chord), pre-programmed $n_e l$ reference waveform (dashed curve), and plasma current I_p as a function of time. (b) DoD (computed from measurements), pre-programmed threshold DoD_1 and DoD_2 waveforms (dashed curves), gas injection Φ and gas flux that would have been injected without DoD security (dotted curve).

3.3. Feedback on edge electron temperature with security on the DoD

Since the edge temperature appears to be a critical control parameter of the discharge it is natural to use it for feedback control instead of line-averaged density:

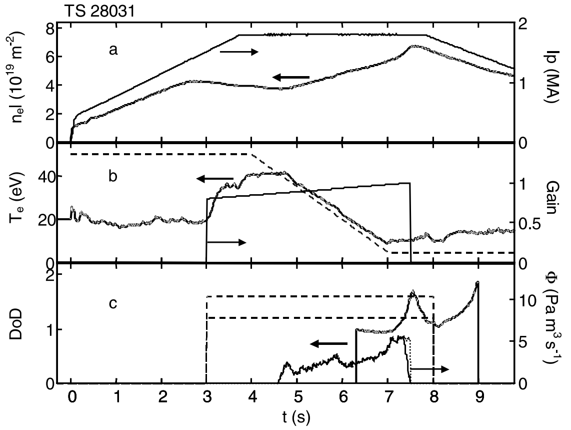

Fig. 5. Example of feedback control on edge temperature with security on DoD in an ohmic discharges at high current (1.8 MA). (a) Plasma line-averaged density $n_e l$ (central chord) and plasma current I_p as a function of time. (b) Edge temperature, pre-programmed edge temperature reference waveform (dashed curve), and proportional gain of the feedback loop. (c) DoD, pre-programmed threshold DoD_1 and DoD_2 waveforms, gas injection Φ and gas flux that would have been injected without DoD security (dotted curve).

$$\Phi = G_{T_e}(t) \times \lfloor T_{e,\mathrm{MEAS}}(t) - T_{e,\mathrm{REF}}(t) \rfloor. \qquad (6)$$

This has been performed successfully in a large number of shots in ohmic, ICRH heating, and impurity-seeded experiments with deuterium and helium plasmas. In the example shown on the Fig. 5, a high current plasma, $I_p = 1.8$ MA, is slowly driven from linear regime to detachment. The edge temperature T_e follows accurately its reference curve until plasma begins to detach at $t \sim 7.3$ s. Then the DoD security comes to life and attenuates the gas flow to keep plasma under control. The detached plasma is maintained during 0.5 s. It should be noted that the T_e gain has been cut off at $t = 7.5$ s in order to give the pumps and wall time to absorb some of the excess gas and move away from density limit before current ramp down. That explains the absence of gas injection when the DoD drops back below its higher threshold value.

4. Discussion

The experiments reported here belong to the last campaign of the ergodic divertor in Tore Supra (year 1999). The upgrade of the tokamak (CIEL project) which consists of the installation of new first wall components, designed to sustain high power load in a steady state (up to 15 MW of conducted power) is currently underway. Plasma–wall interactions will take place at the so-called Toroidal Pumped Limiter (LPT) that is fully equipped with a set of Langmuir probes [10]. As the edge physics in limiter mode is different to that of a divertor mode, the feedback techniques presented here will not be relevant. However one can imagine to control the incoming flux on the limiter tiles and neutraliser plates using real-time Langmuir probe measurements, as a security, in complement to the infrared cameras. The power load measured by the probes could be attenuated whenever it reaches design limit values with an algorithm similar to the one we used for the DoD. In addition, in axisymmetric divertor experiments, these feedback techniques on edge temperature and DoD could be profitably implemented for ELM-free regime studies (RI modes, ITB) since the edge physics is very similar [11].

5. Conclusion

The implementation of real-time Langmuir probe measurements in gas injection feedback procedures has greatly improved the control of the plasma close to the density limit in ergodic divertor discharges of Tore Supra. The probe temperature signal, exploited in a security algorithm combinable with any other feedback control, has permitted to avoid density limit disruption. Similarly, the degree of detachment, computed from the probe ion saturation current, has permitted to handle detached deuterium plasmas. Finally, proportional feedback on edge temperature has been successfully applied to explore plasma edge regimes. These new operational tools, extensively used in many different scenarios during the ergodic divertor last campaign, have significantly increased the efficiency of the experiments.

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