Use of the correlation between the confinement and the edge neutral pressure for the feedback control of the plasma energy in the RI-mode of TEXTOR-94.


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Introduction.
The use of impurity seeding in presence of a freshly siliconized or boronized wall with a careful control of the edge neutral pressure has allowed to obtain high performing discharges at densities exceeding substantially the Greenwald density limit in TEXTOR-94 [1,2,3]. This paper enlightens the strong correlation existing in the high density regime on TEXTOR between the energy confinement $\tau_E$, the peaking of the density profile $\gamma_n$ and the plasma boundary characteristics expressed by the edge neutral pressure $p_n$, the recycling flux $\Phi_R$, the particle confinement time $\tau_p$ and the exhaust efficiency $\eta_{exh}$ of the pump limiter ALT–II. The paper also shows that the gas puff flux, although much smaller than the recycling flux can act on the energy confinement and can be used for the feedback control of the plasma beta instead of using the auxiliary power, as done before in TEXTOR [4].

Correlation of the energy confinement with edge neutral pressure and recycling flux.
The global energy confinement behaviour at high density is illustrated on Fig. 1 in the normalised diagram introduced in Ref. [5] showing $\tau_E P^{2/3}/I_p$ ($\propto \tau_E/\tau_{L\text{-mode}}$) versus $n/n_{GR}$, $P$ being the total heating power, $I_p$ the plasma current, $n$ and $n_{GR}$ respectively the line averaged and Greenwald densities. A set of data obtained with neon seeding in a freshly boronised machine and with heating by combined co-injection and ICRH is displayed. The loci of the L-mode scaling ITER-L89, the H-mode scalings ITER-H93 (ELM-free) and ITER-H98y2 (elmy), the RI-mode scaling ($\tau_{RI} = K n P^{-2/3}$, $K$ being a constant [5]) and the experimental $\beta_n$ limit [6] are also shown. The symbols refer to different intervals of edge neutral pressure $p_n$. Strikingly, the data points corresponding to the lowest $p_n$ range are following the RI-mode scaling $\tau_{RI}$ in the density range above the crossing points of $\tau_{RI}$ with the L-mode scaling up to the $\beta_n$ limit where confinement rollover or back-transition occur due to MHD activity [6]. When $p_n$ increases the confinement decreases progressively towards the L-mode scaling. This shows again [5] that the $\tau_{RI}$ scaling describes the optimum confinement performance only obtained if $p_n$ is sufficiently low. Furthermore the relation between the confinement degradation with respect to the RI-scaling $f_{\tau_{RI}=\tau_{RI}} = \tau_E/\tau_{RI}$ and $p_n$ is roughly independent of the density and of the radiating impurity (Ne with boronized wall, Si with siliconized wall). This is shown in Fig. 2a using as measurement of $p_n$ the mean pressure in the ducts of the toroidal pumped limiter. The achieved confinement is thus $\tau_E = f_\tau(p_n) \tau_{RI}$ (1) with $f_\tau(p_n) \approx 1$. This edge pressure $p_n$ is not closely related to the external fuelling flux $\Phi_{ext}$ (due to gas puff and neutral beam) but well to $\Phi_R$. It results that $\Phi_R$ is also well correlated with $f_{\tau_{RI}}$ as shown in Fig.2b and that we have a relation similar to (1) linking $\tau_E$ with $\Phi_R$ and $\tau_{RI}$. A local pressure measurement at the vessel gives qualitatively the same results, as shown on Fig.2a. Fig. 2b, obtained for the same data set as Fig2a, also indicates that good
confinement quality (here expressed by $f_{h,RI}$) can be maintained at large density even if a significant degradation with respect to the RI-mode scaling takes place.

The same correlation applies also for Ohmic conditions: the degradation from IOC to SOC is also accompanied by an increase of $p_n$, the LOC and IOC conditions are described by $\tau_{RI}$ and the SOC one by the L-mode scaling.

Correlation of density profile peaking with the edge neutral pressure.

The density profile peaking $\gamma_n$ (ratio of central to volume averaged density) is also strongly correlated to $p_n$ through the relation $\gamma_n = f_2(p_n) n/n_{GR}$ (or to $\Phi_R$ by a similar relation) which has been checked in a large $n/n_{GR}$ (from 0.7 to 1.8) and $I_p$ (from 0.25 to 0.5 MA) domain. As shown on Fig 3a this means that $\gamma_n$ decreases when $p_n$ rises for given $n$ and $I_p$ and increases with the ratio $n/I_p$ for a given $p_n$. It results that $f_{h,RI}$ is related to the density peaking through the ratio $\gamma_n/(n/n_{GR})$ as shown in Fig. 3b. Presently the origin of the confinement improvement of the RI-mode is precisely attributed to the stabilisation of the ITG modes resulting from the steepening of the density profile in presence of impurities [7,8].

Particle confinement time and exhaust efficiency of the pump limiter ALT-II.

Other effects correlated with the increase of $p_n$ are (i) the decrease at a given $n$ of the product $f_{r_p} = N_{tot}/\Phi_R$ (where $N_{tot}$ is the total number of D ions and $f$ is the deuterium fuelling efficiency which has to be measured directly [9]) and (ii) the increase of the exhaust efficiency $\eta_{exh} = \Phi_{pump,ALT}/\Phi_R$ of the pumped limiter ($\Phi_{pump,ALT}$ is the flux pumped by ALT-II). This leads to an increase of $f_{r_p}$ and to a decrease of $\eta_{exh}$ when $f_{h,RI}$ increases as shown respectively on Figs. 4a and 4b. The use of $f_{r_p}/(n/n_{GR})$ instead of $f_{r_p}$ approximately takes into account the $n$ and $I_p$ dependences.

Causality and feedback control of plasma energy by means of gas puff.

Both causalities are possible in the link between $p_n$ and the confinement. A decrease of core confinement (due e.g. to MHD) can be causal and leads to larger $p_n$ and $\Phi_R$[1]. However the inverse is also true: a D gas puff flux (although always much smaller (<0.05) than $\Phi_R$ and not closely correlated with $p_n$) leads to an increase of $p_n$ and $\Phi_R$ and can be the cause of loss of core confinement. The time sequence of events for this last case is: 1) Start of D puff, 2) increase of $\Phi_R$ and $p_n$, 3) decrease of $\gamma_n$ and 4) decrease of $f_{h,RI}$ (see e.g. Fig.5 of [1]).
Fig. 2b \( f_{h,RI} \) as a function of the recycling flux. The symbols refer to different domains of \( f_{h,ITER-H98Y2} \).

Fig. 3a Normalised density peaking factor as a function of \( p_{n} \) with \( n/n_{GR} \) as parameter.

Fig. 3b \( f_{h,RI} \) versus \( \gamma_{n}/(n/n_{GR}) \) with \( n/n_{GR} \) as parameter (see table of symbols on Fig. 3a).

Fig. 4a \( f_{\tau_{p}}/(n/n_{GR}) \) as a function of \( f_{h,RI} \) with \( n/n_{GR} \) as parameter.

Fig. 4b Exhaust efficiency of the pump limiter versus \( f_{h,RI} \) for different domains of \( n/n_{GR} \).

Fig. 5 Time evolution of \( E_{dia} \), \( n \) and D-puff flux for discharges with (91077) and without (91068) energy feedback control by the D-puff (from 1.5 to 4s). The \( E_{dia} \) signals for 2 discharges with other values of \( E_{ref} \) are added. The traces of ICRH and NBI power and of the brilliance of Ne-VIII (approximately common for the 4 discharges) are added.
best proof of this causality is its use for the feedback control of the plasma energy. Theresults of such an experiment are shown on Fig.5. The complete time evolution of two discharges are shown. These discharges are heated by co-injection + ICRH and a first gas puff controlled by density feedback brings the density n near \(n_{GR}\). At 1.1s neon is injected and soon after the RI-mode transition occurs. The brilliance of a NeVIII line is used for its feedback control until 4s. For the discharge #91068 no energy feedback is applied and the density continuously increases up to the ramp-down of \(I_p\) at 4.5s where \(n/n_{GR}=1.3\) is reached. The increase of n is attributed to the rise of \(\tau_p\) with n which leads to a density runaway process. A feedback control of the plasma energy is applied to the second discharge (#91077) from 1.5 to 4s. For this purpose the opening of a second D gas inlet valve is controlled by the difference \(E_{dia}-E_{ref}\) where \(E_{dia}\) is the diamagnetic energy and \(E_{ref}\) the preset value of the energy (in this case 105kJ), such that the D puff flux increases with \(E_{dia}\). One observes that \(E_{dia}\) is reduced by the gas puff to \(E_{ref}\) and maintained to this value. Note that as a result of this feedback the density is also better controlled. The energy traces for two others values of \(E_{ref}\) (115 and 125kJ) are given during their feedback phase. In table 1 are shown for the 4 considered discharges the corresponding mean values of \(f_{hRI}, p_n, \Phi_R, \gamma_n/(n/n_{GR}), \tau_p/(n/n_{GR})\) during the energy feedback period. These quantities evolve as indicated in the Figs. 1to 4.

<table>
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<th>shot</th>
<th>(f_{hRI})</th>
<th>(p_n)</th>
<th>(\Phi_R)</th>
<th>(\gamma_n/(n/n_{GR}))</th>
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**Table 1** (\(p_n, \Phi_R\) and \(\tau_p/(n/n_{GR})\) are respectively expressed in \(10^{-4}\) mb, \(10^{22}/s\) and ms)

**Discussion.**

If D puff tends to degrade confinement, medium Z impurity puffing (as Ne, Ar or Si) has an opposite effect due to its influence on the transport in the confined plasma. Its effect belong to the first causality discussed above: neon puffing results in an immediate decrease of \(\Phi_R\) (and a rise of \(\tau_p\)), followed by an increase of \(\gamma_n\), increase of \(E_{dia}\), and decrease of \(p_n\). The present interpretation is that neon injection starts its effect by cooling the edge of the confined plasma with as a result the increase of \(\tau_p\) followed by a larger peaking of the density profile. As stated before this peaking together with the increase of edge \(Z_{eff}\) by the neon seeding leads to the stabilisation of the ITG modes. The D puffing flux, although much lower than \(\Phi_R\), causes on the contrary an increase of plasma edge fluctuation [2,8] which results in an enhancement of \(\Phi_R\) and consequently an increase of \(p_n\) and decrease of \(\gamma_n\), edge \(Z_{eff}\), \(\tau_p\) and finally \(\tau_E\). The exact mechanism of this effect is still under investigation.

**References**

8. D. Kalupin et al., this conference.