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.

A.Messiaen[1], G.Mank[2], J.Ongena[1], B.Unterberg[2], P.Dumortier[1], D.Kalupin[1], M.Lehnen[2], V.Philipps[2], G. Van Wassenhove[1] and TEXTOR team[1, 2, 3]

Trilateral Euregio Cluster
[1] Laboratoire de Physique des Plasmas / Laboratorium voor Plasmafysica, EURATOM Association, B-1000 Brussels, Belgium
[2] Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association, D-52425 Jülich, Germany
[3] FOM Instituut voor Plasmafysica Rijinhuizen, EURATOM Association P.O.Box 1207, 3430 BE Nieuwegein, The Netherlands

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 τ_E, the peaking of the density profile γ_n and the plasma boundary characteristics expressed by the edge neutral pressure p_n, the recycling flux Φ_R, the particle confinement time τ_p and the exhaust efficiency η_{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 ($\tau_{RI}=KnP^{-2/3}$, K being a constant [5]) and the experimental β_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 τ_{RI} in the density range above the crossing points of τ_{RI} with the L-mode scaling up to the β_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 τ_{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 $f_{h,RI}=\tau_E/\tau_{RI}$ 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 $\tau_E=f_1(p_n)\tau_{RI}$ (1) with $f_1(p_n)\leq 1$. This edge pressure p_n is not closely related to the external fuelling flux Φ_{ext} (due to gas puff and neutral beam) but well to Φ_R. It results that Φ_R is also well correlated with $f_{h,RI}$ as shown in Fig.2b and that we have a relation similar to (1) linking τ_E with Φ_R and τ_{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 $f_{h,ITER\text{-}H98y2}$) 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 τ_{RI} and the SOC one by the L-mode scaling.

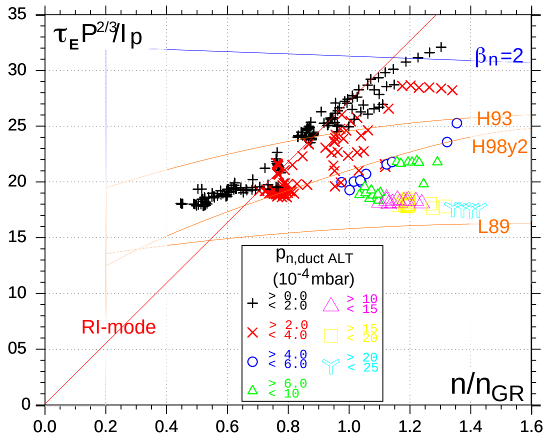

Fig.1 Normalised diagram of τ_E versus n/n_{GR} for auxiliary heated discharges (boronized wall with Neon injection). The symbols refer to different domains of edge neutral pressure.

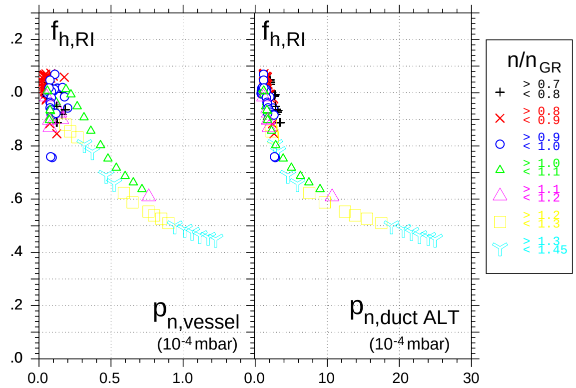

Fig.2a $f_{h,RI}$ as a function of p_n measured in the duct of the pump limiter or at the vessel wall. The symbols refer to different domains of n/n_{GR}.

Correlation of density profile peaking with the edge neutral pressure.
The density profile peaking γ_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 Φ_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 γ_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 $f\tau_p = N_{tot}/\Phi_R$ (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 $f\tau_p$ and to a decrease of η_{exh} when $f_{h,RI}$ increases as shown respectively on Figs. 4a and 4b. The use of $f\tau_p/(n/n_{GR})$ instead of $f\tau_p$ 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 Φ_R[1]. However the inverse is also true: a D gas puff flux (although always much smaller (<0.05) than Φ_R and not closely correlated with p_n) leads to an increase of p_n and Φ_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 Φ_R and p_n , 3) decrease of γ_n and 4) decrease of $f_{h,RI}$ (see e.g. Fig.5 of [1]). The

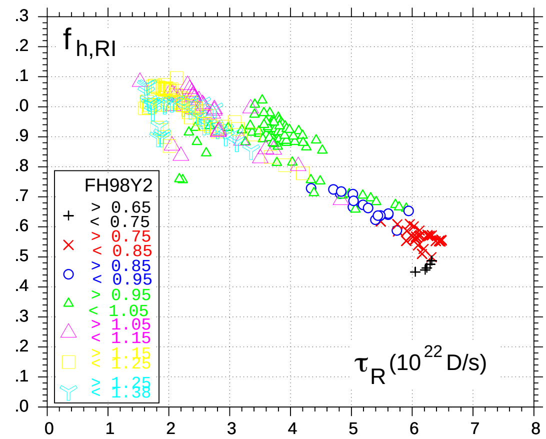

Fig.2b $f_{h,RI}$ as a function of the recycling flux. The symbols refer to different domains of $f_{h,ITER\text{-}H98y2}$.

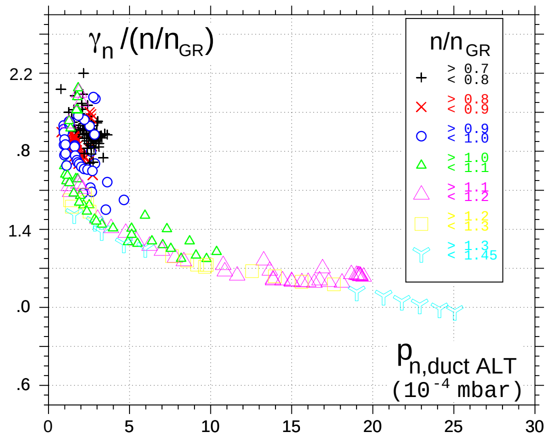

Fig.3a Normalised density peaking factor as a function of p_n with n/n_{GR} as parameter.

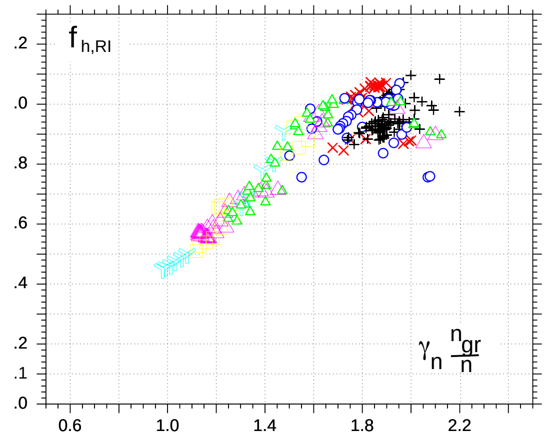

Fig.3b $f_{h,RI}$ versus $\gamma_n/(n/n_{GR})$ with n/n_{GR} as parameter (see table of symbols on Fig.3a).

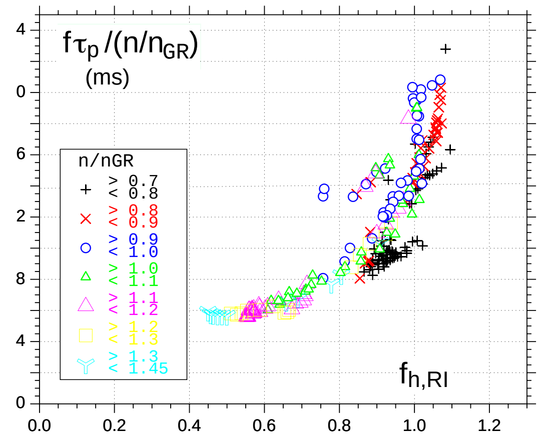

Fig.4a $f\tau_p/(n/n_{GR})$ as a function of $f_{h,RI}$ with n/n_{GR} as parameter.

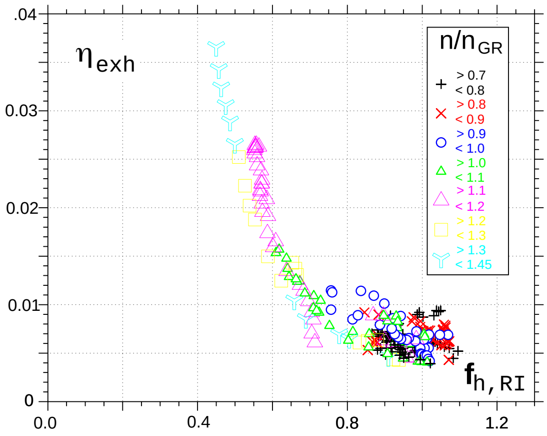

Fig.4b Exhaust efficiency of the pump limiter versus $f_{h,RI}$ for different domains of n/n_{GR}.

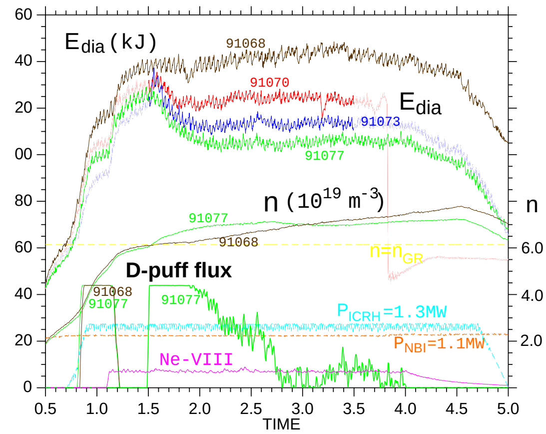

Fig.5 Time evolution of E_{dia}, n and D-puff flux for discharges with (91077) and without (91068) energy feedback control by the D-puff (from 1.5 to 4s). The E_{dia} signals for 2 discharges with other values of E_{ref} are added. The traces of ICRH and NBI power and of the brilliance of Ne-VIII (approximately 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 $n/n_{GR} \approx 1.3$ is reached. The increase of n is attributed to the rise of τ_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 $f_{h,RI}$, p_n, Φ_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.

shot	$f_{h,RI}$	p_n	Φ_R	$\gamma_n/(n/n_{GR})$	$f\tau_p/(n/n_{GR})$
91068	0.92	1.7	2.4	1.55	15.5
91070	0.83	2.5	3.0	1.44	12.6
91073	0.73	3.6	3.5	1.27	11.5
91077	0.66	5.0	3.7	1.25	10

Table 1 (p_n, Φ_R and $f\tau_p/(n/n_{GR})$ 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 Φ_R (and a rise of τ_p), followed by an increase of γ_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 τ_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 Φ_R, causes on the contrary an increase of plasma edge fluctuation [2,8] which results in an enhancement of Φ_R and consequently an increase of p_n and decrease of γ_n, edge Z_{eff}, τ_p and finally τ_E. The exact mechanism of this effect is still under investigation.

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