EXTENDED PARAMETRIC STUDY OF THE RI-MODE ON TEXTOR-94

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The RI-mode discovered on the limiter tokamak TEXTOR combines *simultaneously* many features needed for a reactor grade plasma: (i) quasi-stationary discharges with density around the Greenwald density limit, (ii) confinement of the quality of ELM-free or ELMy H-mode, (iii) high beta for a circular cross-section machine, (iv) edge radiated power fractions up to 95% of the total input power (v) negligible effect of the seeded impurity on the fusion reactivity and (vi) high values for the figure of merit for ignition margin f_{L89}/q_a up to 0.8 at low q(a) operation. Stationary RI-Mode discharges with a flat top phase exhibiting all of the above mentioned features for over 7s, i.e. corresponding to 160 confinement times were obtained[1].

A striking property of the RI-mode is that its energy confinement is improving with increasing density (showing a totally different behaviour as the usual L-Mode or H-mode regimes)and reaches the confinement quality of the Elmfree H-mode (i.e. the enhancement factor ,with respect to the scaling ITER H93-P ,f_{H93} =1,or with respect to the scaling ITER H97-Elmy, f_{H97} =1.15-1.20) at the Greenwald density limit, i.e. for a Greenwald number $\bar{n}_{eo}/\bar{n}_{eo,Gr}$=1.The RI-Mode scaling

$$\tau_{RI} = (\bar{n}_{eo}/\bar{n}_{eo,Gr})\ \tau_{ITERH93-P}. \qquad (1)$$

has been proposed [2,3] which was well describing the experimental data in the available domain of line averaged density $\bar{n}_{eo}$, plasma current I_p and total applied power P_{tot}. No check of the scaling versus the toroidal field B_t,the small and large radii a and R was available.

The experimental conditions to observe the RI-mode on TEXTOR-94 have been identified[2].They are: the presence of co-injection in the heating scenario (at least 20 to 25% of P_{tot}), Deuterium injection into a deuterium target plasma (labelled D->D), large density (exceeding 70% of the Greenwald density limit $\bar{n}_{eo,Gr}$), an optimum horizontal position ,the injection of medium Z impurities [Ne, Ar] in order to obtain $\gamma=P_{rad}/P_{tot} > 50\%$.

Recent experiments have been performed on TEXTOR-94 in order to extend the parameter range under which the RI-mode is observed and to test the robustness of the proposed confinement time scaling and of the operational conditions necessary to obtain this mode.

1. Confinement and performances

RI-mode discharges have been performed (i) at lower current (Ip=250-300kA; i.e. at q(a) around 5) and with Neon injection and boronized wall heated by co-injection +ICRH with possible addition of counter-injection (up to balanced injection), (ii)with siliconized wall,the edge radiation being due to the sputtered Si [4] and to the possible addition of feedback controlled Neon injection. The confinement scaling of all these discharges follows quite accurately the above mentioned RI-mode scaling (1) as e.g. shown on Fig 1a for the case of low Ip discharges. For what concerns the operational limits RI-mode has been established up to $\bar{n}_{eo}/\bar{n}_{eo,Gr} = 1.2$ whereas the Beta limits correspond to approximately β_p=1.5 for sufficiently low Ip with respect to aB_t and, at large Ip, to β_n=2. Poloidal and toroidal beta scans are shown on Figs. 1b and 1c. A trial to higher beta values leads to rollover, confinement back transitions or disruptions. Note that stationary discharges close to these limits are possible [1,5].

Very recently experiments in a large domain of B_t have been performed: they show a lower B_t dependence as the one expected from the scaling ITER H93-P in (1) [5].

2. Influence of the heating scenario

In Ref. [6] it has been shown that Neon injection could improve the confinement of ICRF heated discharges but that the presence of at least 20-25% of co-injection was needed to reach the RI-mode performances. The role of the heating scenario has been further explored:

a) H->D co-injection (+ICRH) has also been compared with the usual D->D co-injection (+ICRH) heating scheme. Figure 2a shows the comparison of the two cases for identical NBI and ICRH heating powers and same density. The shown H->D discharge #74191 is the first one after a series of `D->D co-injection RI-mode shots in order to well differentiate the role of the heating method from the isotopic effect on the confinement. The isotopic ratio of hydrogen in the plasma $n_H/(n_H + n_D)$ ranges between 15 and 20% for the two discharges. As for the discharge with D->D injection a confinement transition is also observed for the one with H->D injection soon after the start of the Neon seeding but the confinement remains lower and its quality stays below the one of the Elming H-mode as indicated in the figure. This is also illustrated in Fig. 2b where f_{H93} is plotted versus $n_H/(n_H + n_D)$ for the discharges before and after the change of the injected species. The symbols differentiate the shots heated only by coinjection and those with the addition of ICRH. For all the shots the Greenwald number lies between 0.8 and 1.05. When $n_H/(n_H + n_D)$ increases during the series of H->D discharges due to the repeated H injection the confinement continues to deteriorate for the shots with combined coinjection+ICRH. This is probably due to the less efficient ICRH when the H concentration increases. The main difference for the beam heating characteristics at the change-over from H->D to D->D is the ratio E_c/E_b of the beam critical energy to the injection energy which is larger (by approximately a factor of 2.5) for the D->D case and which therefore leads to a larger fraction of the beam power coupled to the ions in this case. The ratio E_c/E_b for the H->D discharges increases slightly with larger $n_H/(n_H + n_D)$ but its value remains below the one obtained for the D->D case. Note that we have achieved similar RI-mode conditions for D->D beam heating with a large domain of variation of the ratio E_c/E_b by varying the beam energy [6]. In addition, a slight dependence on the isotopic composition of the plasma cannot be excluded. Notwithstanding their different values of f_{H93} the electron density profiles of the two shots of Fig. 2a are nearly identical with a same peaking factor but, on the other hand, both discharges have their confinement transition correlated with an increase of their peaking factors. Finally let us remark that H->D discharges have required a slightly larger horizontal shift towards outside than the D->D ones to obtain the shown transition (see discussion in section 3).

b) RI-mode performances in D->D balanced discharges (+ICRH) have been compared to the ones obtained with the usual heating conditions [D->D coinjection (+ICRH)]. Quasi-stationary conditions are also obtained with approximately the same confinement characteristics but for very different toroidal rotation velocities. An illustration of this is shown in Fig. 3a where after the onset of Neon injection (at 1.4s) the RI-mode transition is obtained with balanced injection (+ICRH). At 3s the counter injection is switched off and the RI-mode phase is further maintained by coinjection+ICRH with the same value of f_{H93}. The plasma energy content is lower in this last phase due to the reduced heating power. At 3.8s a ramping down of the plasma current Ip starts in order to obtain a soft landing of the discharge. As shown in Fig 3b stable RI-mode discharges with a confinement quality between Elmy and Elm-free H-mode have been obtained in a large domain of central toroidal velocity V_{tor} by changing the amount of counter-injection power. This indicates that the magnitude of V_{tor} does not play a determining role in the confinement improvement mechanism. More details about the measurements by CXES of V_{tor} and its radial profile can be found in Ref. [9].

3. Role of the plasma positioning with respect to the limiters

An important factor to obtain a stationary RI-mode discharge is the choice of the plasma horizontal position ΔH between the outer pump limiter ALT-2 and the inner bumper limiter.The optimal position ΔH, measured from the interferometric HCN data [7] and shown in Fig.3a, is different for balanced and co-injection. The "normal" positioning which corresponds to an equal heat load on the poloidal limiters when they are symmetrically inserted into the discharge is also indicated on the figure. The effect of the different positioning (and also of the different heating schemes) is to push the discharge more towards the outer or inner limiter as it is apparent on Fig. 3c. With co-injection the choice of the optimal ΔH for balanced injection would inhibit the large confinement transition and provoke MARFE appearance and the choice of the optimal ΔH for co-injection in presence of balanced injection would lead to non-stationary RI-mode phase with back-transition to L or sub L-mode confinement. The optimal position depends not only on the heating scenario but also on the plasma current and on the toroidal magnetic field value with no direct dependence of the edge q. It depends also to a less extent on the wall condition and on the type of seeded impurity. A too large outward shift leads to a back transition whereas a position more inwards than the optimal one leads to decrease of confinement and finally to Marfe formation. This seems to imply a leading influence of the plasma-wall interaction in these experiments as discussed in [8].

4. Conclusions and summary

We have shown that the extended RI-mode data base follows well the density and power dependence of the proposed scaling and that RI-mode discharges can be obtained as well with balanced injection. The presence of D->D injection and a careful horizontal positioning of the discharge are mandatory to reach the RI-mode performances.

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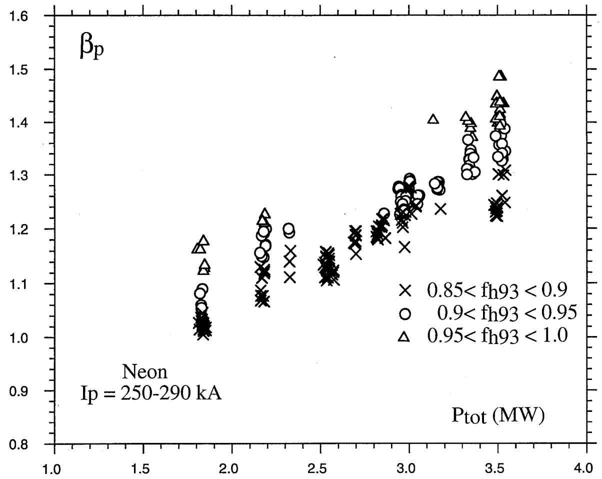

Fig. 1b) β_p versus P_{tot} at low Ip ($0.85< \overline{n}_{eo}/\overline{n}_{eo,Gr} < 1.15$)

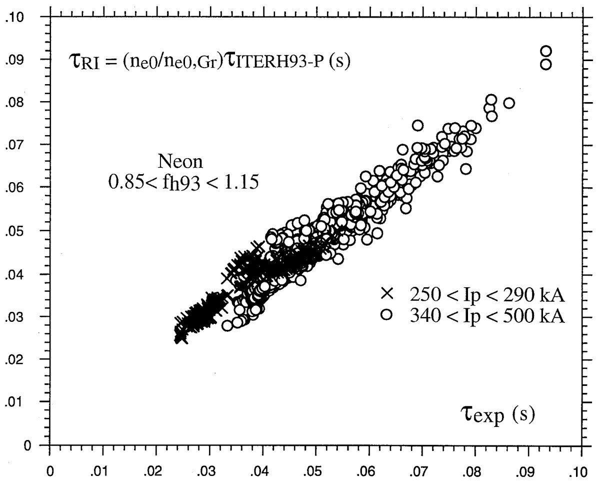

Fig. 1a) τ_{RI} compared to the experiment. confinement time τ_{exp} for the enlarged data base. (Neon, $1<P_{tot}<4.5$MW, $0.7< \overline{n}_{eo}/\overline{n}_{eo,Gr} <1.15$, B_t=2.25T).

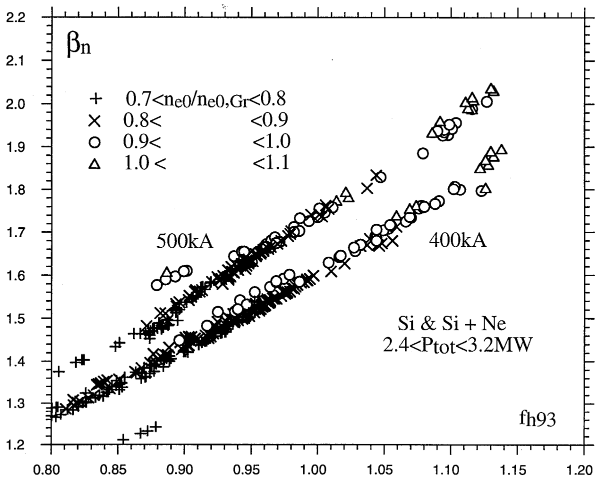

Fig. 1c) β_n versus f_{H93} at high Ip for siliconized wall conditions.f_{H93} is varied with the density ($0.7< \overline{n}_{eo}/\overline{n}_{eo,Gr} <1.1$).

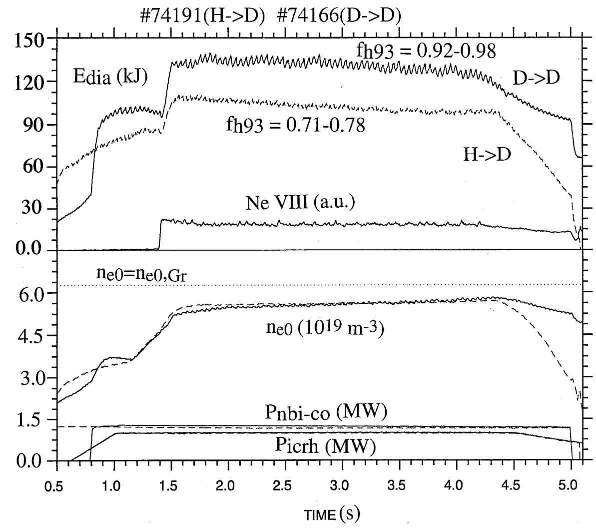

Fig. 2a) Comparison of D->D and H->D discharges. Are shown the diamagnetic energy E_{dia}, f_{H93}, the brilliance of NeVIII, the central line averaged density $\overline{n}_{eo}$ (with the position of $\overline{n}_{eo,Gr}$), $P_{nbi\text{-}co}$ and P_{icrh}.

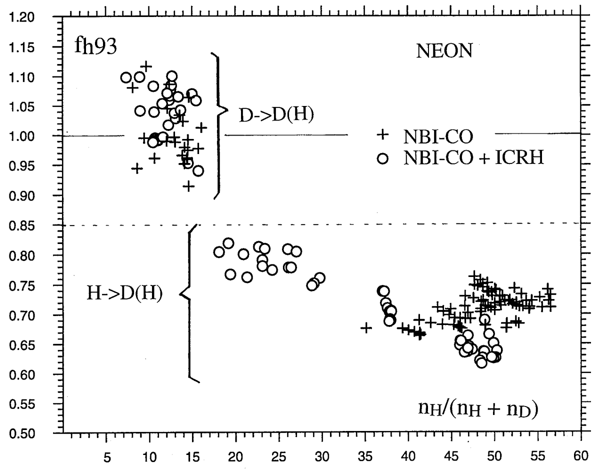

Fig. 2b) f_{H93} versus $n_H/(n_H + n_D)$ in a series of discharges first heated by D->D injection and later by H->D(H) injection .

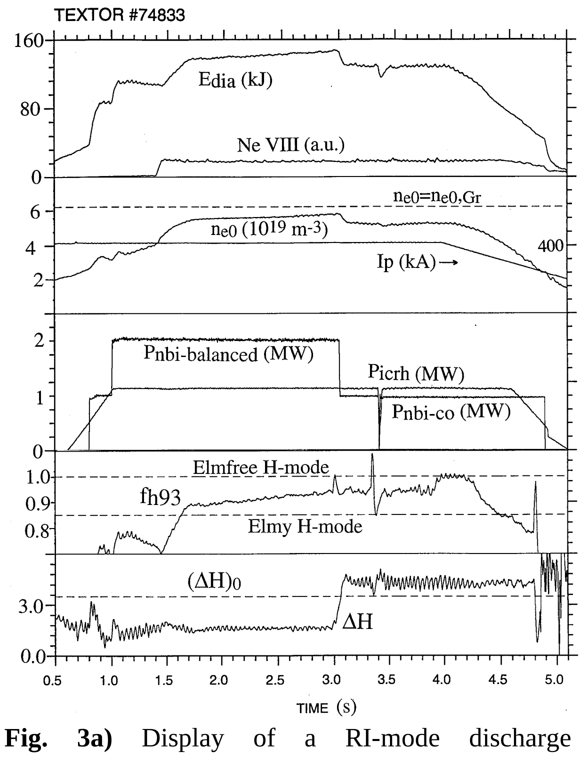

Fig. 3a) Display of a RI-mode discharge successively heated by balanced injection (+ICRH) and co-injection (+ICRH). There are shown E_{dia} , f_{H93} , the brilliance of NeVIII, $\overline{n}_{eo}$ (with the position of $\overline{n}_{eo,Gr}$) , $P_{nbi\text{-}co}$, P_{icrh} , Ip, and the horizontal position ΔH (with its "normal" value $(\Delta H)_0$)

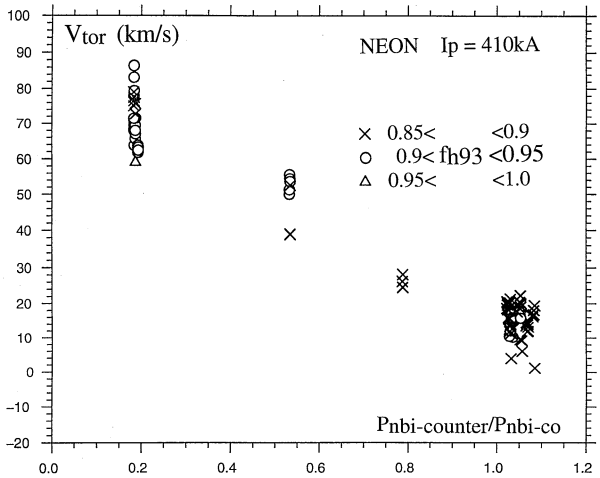

Fig. 3b) Central toroidal velocity V_{tor} as a function of the ratio $P_{nbi\text{-}counter}/P_{nbi\text{-}co}$ for a series of RI-mode discharges($0.85< \overline{n}_{eo}/\overline{n}_{eo,Gr} < 1.05$)

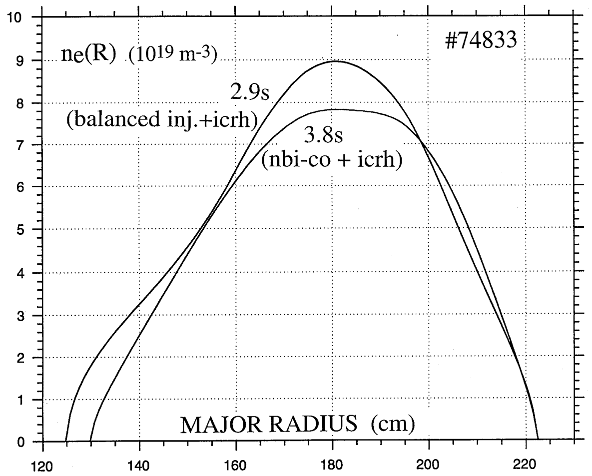

Fig. 3c) Radial electron density profiles of the discharge shown in Fig3a) at 2.9 and 3.8 s