Modeling of confinement degradation in Radiative Improved mode caused by strong gas puff

D. Kalupin[1], M.Z. Tokar[2], P. Dumortier[1], A. Messiaen[1], D. Reiser[2], S. Soldatov[3], B. Unterberg[2], G. Van Wassenhove[1], R. Weynants[1].

1. *Laboratoire de Physique des Plasmas / Laboratorium voor Plasmafysica, EURATOM Association, Ecole Royale Militaire, B-1000 Brussels, Belgium.*
2. *Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association, D-52425 Jülich, Germany.*
3. *Nuclear Fusion Institute, Russian Research Centre "Kurchatov Institute", Kurchatov Square 1, 123182 Moscow, Russia.*

Introduction. The gas puff is the simplest and most frequent method to fuel the plasma in fusion devices. It has however been found in many tokamaks such as JET, JT-60, DIII-D, ASDEX-U (Horton *et al* 1999, Petrie *et al* 1993, Suttrop *et al* 1999), that too strong a gas puff leads to confinement saturation followed by a decrease towards Low (L) mode. Experiments with different scenarios of gas puff have been recently performed on the TEXTOR-94 tokamak in discharges where seeding of neon triggered a transition from L to the Radiative Improved (RI) mode (Mank *et al* 2000, Unterberg *et al.* 2000). These experiments were aimed to attain plasma densities significantly exceeding the Greenwald density limit, n_{Gr} (10^{20} m^{-3}) = $I_P/\pi a^2$, where I_P is the plasma current (MA) and a the minor radius (m), with simultaneous sustaining of the improved confinement. It has been found that the maximum density at which the RI-mode is observed is then no longer imposed by a β_n limit but by a limit set by the fuelling rate for given wall conditions. The intense gas puff results in a moderate increase of the line averaged density characterized by a flattening of the density profile in which the edge plasma density rises noticeable faster the averaged one. At the same time the effective plasma charge, Z_{eff}, diminishes and rollover of the energy confinement towards L-mode occurs (Fig.1, solid curves).

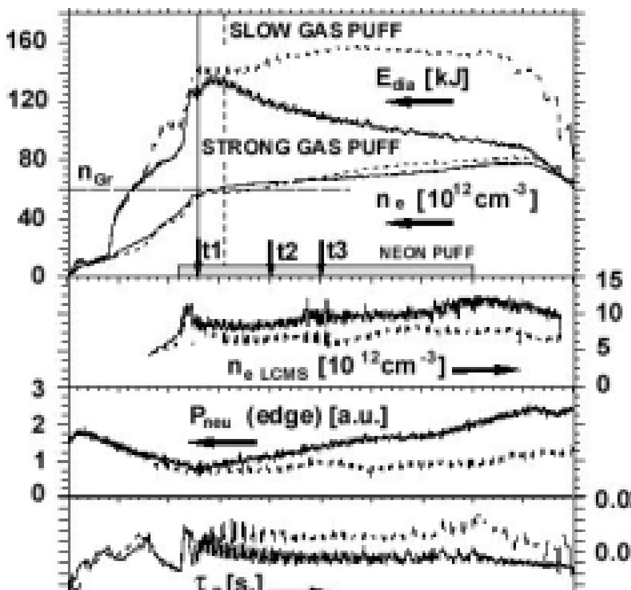

Fig.1 Two discharges differing by the gas puff rate: 88478 (dashed curves) – slow gas puff [$3*10^{21}$ part/sec], 88482 (solid curves) – strong gas puff [$8*10^{21}$ part/sec]. E_{dia} is the diamagnetic energy; n_e is the line averaged electron density; n_e(LCMS) is the electron density at the last closed magnetic surface; P_{neu} is the neutral pressure at the edge; τ_p is the particle confinement time; n_{Gr} indicates the Greenwald density limit; t1,t2,t3 are the times of the reflectometer measurements.

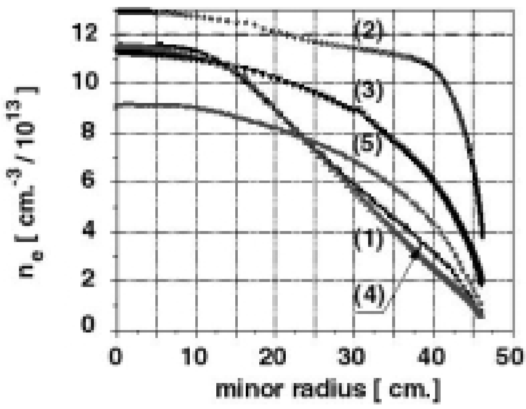

fig.2.1

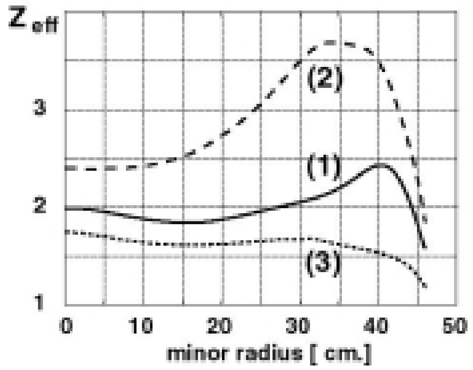

fig.2.2

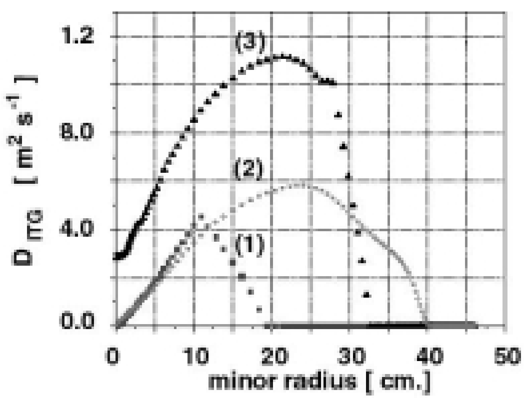

fig.2.3

Fig.2 Profiles of the electron density, Z_{eff} and the ITG-induced diffusion coefficient for the modelled discharges differ by the gas puff rate and the edge diffusion coefficient.

Conversely, a less intensive gas puff allowed to preserve the energy confinement of the H-mode or even higher quality and to maintain a peaked density profile being of principal importance for RI-mode performance. Simultaneously the averaged density was increased noticeably to a level exceeding n_{Gr} by 30% (Fig.1, dashed curves).

Modeling with the RITM-code of the effect of the different gas puff on the confinement. The rollover from the RI to the L-mode in the impurity seeded plasmas with a strong gas puff was modeled by the 1-D transport code RITM (Tokar 1994, Tokar *et al.* 2000). The anomalous transport coefficients in the plasma core include contributions from the Ion Temperature Gradient (ITG) and Dissipative Trapped Electron (DTE) instabilities. This model allows to reproduce the L-RI bifurcation with impurity seeding in good agreement with experimental observations. The calculations have been arranged in order to reproduce the experimental density profile and also to obtain Z_{eff} in accordance with the experimental value. The computations are done with a constant neon puff and with the ion temperature profile evolution taken from the experiment. Fig.2 shows the profiles of the electron density, Z_{eff} and ITG-induced diffusion coefficient for the calculations made with a various gas puff. The calculated density profile in the case of a slow gas puff (Fig.2.1, curve 1) reproduces well the experimental RI-mode density profile (Fig.2.1, curve 4) and has a steep gradient over a wide plasma zone. As a result, the ITG-mode is suppressed and the diffusion flow caused by this turbulence is reduced over 2/3 of radii (Fig.2.3, curve 1). The effective ion charge, Z_{eff}, (Fig.2.2 curve 1) is in the range 1.8-2.4. In the discharge shown in Fig.2.1 by the curve 2 the gas puff is increased by a factor of 3 with respect to the level assumed in the previous case. This results in a strong broadening of the density profile in rough agreement with the experimental behaviour. However, the increase in the edge density and its gradient significantly exceed the measured values (Fig.2.1 curve 5) and the density profile is too flat in the outer plasma region. Moreover, the increase of the gas puff results in a rise of Z_{eff} in the whole plasma column with respect to the level in the RI-mode (Fig.2.2 curve 2). This disagrees with experiment, which shows a significant decrease of Z_{eff} with the intense gas puff. Thus, the computations show that the effect of a strong gas puff can not be simulated by an increase of neutral particle influx alone, but that, additionally, the transport of charged particles should be increased. In the plasma core this occurs automatically because the broadening of density profile leads to a restart of the ITG induced transport (Fig.2.3 curve2). However, the charged particles can not leave the plasma since their diffusivity at the plasma edge is limited by the present edge transport model. Fig. 2.1 curve 3 shows the density profile computed under the assumption that, simultaneously with the intensification of the gas puff, the edge diffusion coefficient is increased by a factor of 4 with respect to the level assumed in two previous computations. In this case the flattening of the density profile occurs in agreement with the experimental observations (Fig.2.1 curve 5) without formation of an extremely high density and density gradient at the LCMS. Simultaneously the high edge diffusion allows more impurity ions to escape from the plasma and the Z_{eff} value reduces in the whole plasma (Fig.2.2 curve 3). Nevertheless there remains a difference of 20% in the line averaged densities between experimental and RITM-simulated density profiles. This discrepancy arises from the different values of the density at the LCMS, where the simulation assumes as boundary conditions fixed e-folding lengths for the densities and temperatures. We expect that a more sophisticated model for the scrape-off layer (SOL), taking into account ionisation of neutrals in the SOL, would improve numerical results.

Experimental confirmation of the increase in edge transport with strong gas puff.

The frequency spectra of the edge density fluctuation for the data set taken at a given magnetic field B_t=2.24T and plasma current I_p=380kA, were measured by a microwave reflectometer. (Dreval V. et al 1999) The position of the reflection layer estimated from the cut-off density, corresponding to the reflectometer frequency, is on the top and 2-3 cm inside the LCMS towards the plasma core. Figure 3 shows the correlation between the plasma edge parameters and the width of the auto-correlation function, Δ_{ACF}, relating to the wave lengths of fluctuations. The areas corresponding to the RI and L-mode are separated by the grey curve where the energy confinement time, τ, is 80% of that predicted by the RI-mode scaling $\tau_{RI} \approx k\bar{n}_{e0}(P_{tot})^{-2/3}$ (k ≈ 0.18, $\bar{n}_{e0}$ is the central line averaged density in $10^{20}m^{-3}$, P_{tot} is the total input power in MW). (Weynants *et al*. 1999, Messiaen *et al*. 1999). It is seen that Δ_{ACF} increases when the plasma edge parameters cross the grey curve going from the RI- to L-mode as a result of an intense gas puff. If one assumes that the plasma rotation does not change significantly in the considered sequence of discharges at the radii near the cut-off layer, then the$\Delta_{ACF}\sim\langle\lambda\rangle\sim 1/\langle k_\perp\rangle$, where λ is the wave length of turbulence, averaged over the frequencies and the reflecting volume, and $k_\perp$ is the poloidal component of the wave vector. As the diffusion coefficient is proportional to $1/k_\perp^2$ (Kadomtsev and Pogutse, 1971), Fig. 7 therefore suggests, in agreement with the RITM modelling, that anomalous transport in the plasma edge increases at the time of the confinement deterioration.

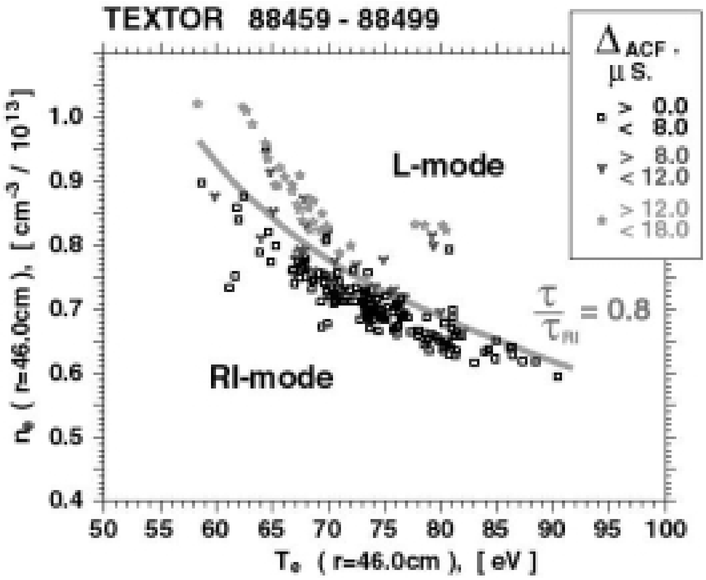

Fig.3 Variation of the auto-correlation function Δ_{ACF}, measured by reflectometer ($r \approx 44$ cm), with the plasma edge parameters and its correlation with the confinement performance.

Additionally, this increase of the edge particle transport is confirmed by the drop in the particle confinement time observed during intense gas puff (see Fig.1).

Conclusion

By the optimisation of the gas puff rate and wall conditions it is possible to achieve the H-mode or even higher quality of confinement in the RI-mode at densities well above the Greenwald density limit. Too strong a gas puff leads however to confinement degradation towards L-mode, apparently as the result of a significantly increased edge transport. The latter follows from the results of RITM-code modelling and is supported by changes in the density fluctuation spectrum measured by reflectometer. The loss of puffed impurities with increased edge transport results in a decrease of Z_{eff}. Both this and flattening of the density profile caused by the gas puff are crucial factors for the restart of ITG turbulence in a wide plasma zone with accompanying confinement degradation.

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