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Density peaking in TCV and JET H-modes

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1. Introduction

Extensive analysis of the experimental data of JET H-mode plasma using interferometry and Thomson scattering measurements shows that the density peaking factor n_0/<n> strongly depends on the effective collisionality $\nu_{eff} \approx 10^{-14} RZ_{eff} n_e / T_e^{\,2}$. Scalings [1] derived from these experiments predicts a peaked density profile in ITER H-mode plasmas, which should result in higher performance (higher bootstrap current and fusion reaction rate). One of the main difficulties of an extrapolation of JET data towards reactor conditions is that the majority of H-mode shots were obtained with dominant NBI heating, while the few H-modes in the database with only ICRH have low β_N~1 (due to lack of available power), significantly below the ITER targets (β_N~2). However theory predicts a strong TEM destabilization [2] in case of dominant electron heating, which may result in density profile flattening by the appearance of an outward convective particle flux. In contrast to this expectation, purely electron heated H-modes [3] with β_N=2 and T_e/T_i~2 have recently been obtained on TCV, using 3rd harmonic ECRH, showing that significantly peaked density profiles can persist in electron heated plasmas at reactor relevant values of β_N, lending support to the predictions in [1].

2. Density profile peaking.

The density gradient in stationary state may be written in the following form:

$$\frac{\nabla n}{n} = \frac{1}{D}\left(\frac{\Gamma}{n} + V_{ware} + C_{Te}\frac{\nabla T}{T} - C_q\frac{\nabla q}{q}\right) \qquad (1)$$

where D is the diffusion coefficient (anomalous and neoclassical), Γ is the flux associated with the particle source, V_{ware} is the neoclassical Ware pinch, C_{Te} is the termodiffusion coefficient, C_q is the turbulent equipartition (TEP) term coefficient, the latter two being of anomalous origin. The source is provided by the NBI fuelling and to the penetration of edge neutral particles to the core by a sequence of charge exchange events.

3. Density profiles in JET H-modes

About 300 JET H-mode shots performed between 1998 and 2004 were thoroughly analysed using LIDAR Thomson scattering and interferometer SVD-I inverted [4] profiles. Both methods are in satisfactory agreement. It was found that density peaking n_0/<n> strongly correlates with the effective collisionality ν_{eff} (Fig. 1) and to a lesser extend with the NBI particle source term expressed as $\Gamma_{NBI}/(\chi n_e)$, where χ is the effective heat diffusivity. No correlations with l_i, β_N, q_{95}, $\nabla q/q$, ρ^*, L_{Te} or L_{Ti} were found.

Beam fuelling can be responsible only for a fraction of the density peaking, since the correlation is seen only for a relatively high total beam power and H-modes with only ICRH heating have also significantly peaked density profiles (blue stars in Fig.1).

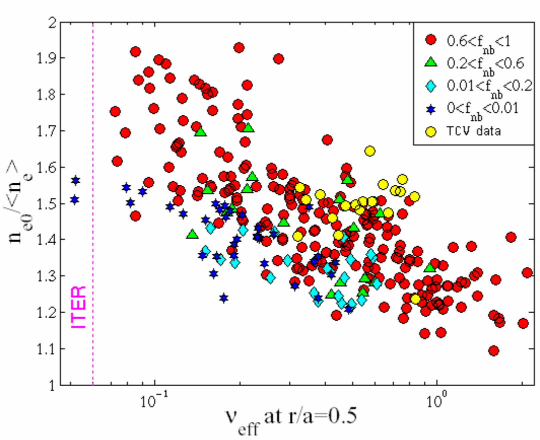

Fig.1 Density peaking versus effective collisionality in JET H-modes, resolved by the fraction of NBI heating, $f_{nb}=P_{NB}/P_{tot}$. Purely electron heated TCV points are also included

The contribution from edge fuelling calculated using the DOUBLE neutral transport code was found to be negligible [5]. Also, experiments with helium plasmas have the same peaking factor as deuterium plasmas, despite having a much lower core penetration of neutrals because the lower cross section for double charge exchange.

If we attempt to explain density peaking as resulting only from the Ware pinch, then, to explain the observed density gradient lengths $\frac{\nabla n}{n} \sim 1m^{-1} = \frac{V_{ware}}{D}$ for V_{ware}~0.05m/s (typical) and thermal diffusivity χ~1m^2/s, $\frac{\chi}{D}$ should be of order 20, which is far beyond the expectations (χ ~1.5D) for turbulent transport [2].

Hence we conclude that density peaking on JET is mostly due to an anomalous pinch. Extrapolation from a recent study of a combined database of JET and AUG plasmas leads to an expectation given by $n_0/<n>$~1.45 for ITER [6]. For temperature profiles as predicted for the inductive scenario [7] a peaking factor $n_0/<n>=1.5$ results in a 30% increase in fusion power for a given average density and β [1].

A weakness of extrapolations based on the existing database is that most JET H-modes are dominantly NBI heated. Besides the issue of fuelling, this also leaves an uncertainty about the effect of heating the ions, rather than, as with auxiliary and alpha particle heating in ITER, the electrons. Drift wave turbulence theories [2], backed up by observations [8], lead to an expectation of possible strong density flattening due to TEM in the presence of strong electron heating, which would make extrapolations from ion heated regimes useless. Source-free ICRH shots in JET have only β_N~1, which is much below reactor relevant values and may be not appropriate for the reactor predictions.

4. Density profiles in TCV H-modes.

The TCV (Tokamak à Configuration Variable) has a powerful ECRH system, consisting of 6 gyrotrons at 83GHz used for second harmonic heating, and 3 recently installed 118GHz gyrotrons for 3rd harmonic (X3) heating. Only X3 heating (about 1.5MW) can be used in H-mode due to relatively high densities which are normally above the cut-off limit for X2.

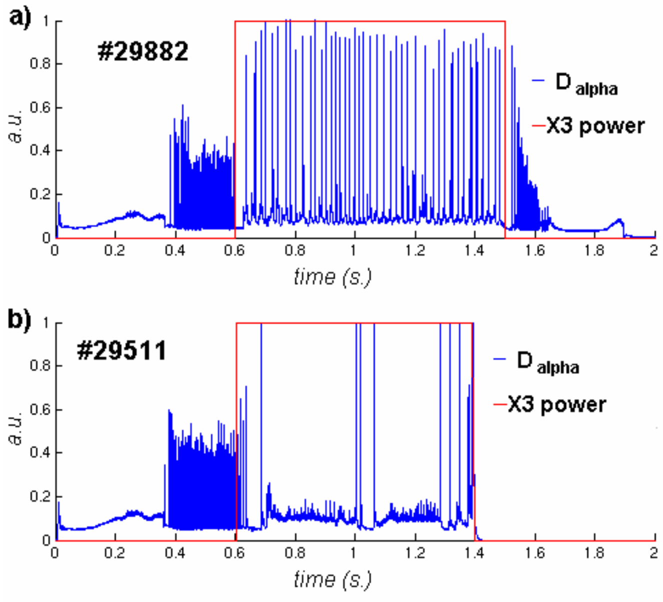

Fig 2: X3 heated H-mode scenarios
a) with giant ELMs
b) with stationary ELM-free phases

RF heated H-mode scenarios start with an Ohmic H-mode target with I_p~400kA, κ~1.75 in a single null divertor configuration. Applying 1.35 MW X3 heating power raises $T_e(0)$ from 0.8 to 2.4 keV and usually causes a change of ELM type from relatively small ELMs to giant ones (Fig 2a). In some cases the large ELMs are stabilized during the heating phase (Fig 2b), yet the plasma remains in quasi-steady state. In both cases the ECH heated plasma have β_N~2 and T_e/T_i~2.

From Fig.3 we see that during ECH the density profile flattens modestly in the presence of giant ELM phase and remains the same as in the Ohmic target for ELM-free shots. The corresponding values of density peaking $n_0/\langle n\rangle$ (was calculated from Thomson scattering measurements, averaged over a plenty of laser pulses) are 1.5 and 1.65, normalized density gradient length at the mid-radius R/L_n ~3.6 and ~4.3 for ELMy and ELM free plasmas respectively.

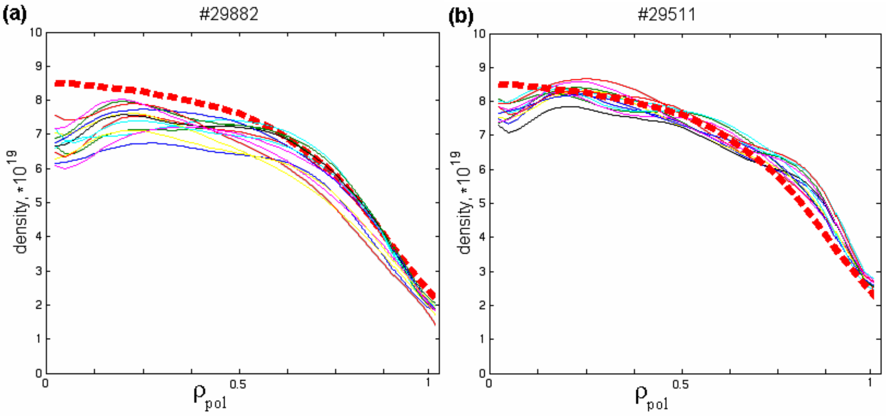

Fig 3: Multiple TS measurements of density profiles during X3 heating for ELMy (a) shot and ELM-free(b) shot. Red dashed line – density profile in an Ohmic H-mode plasma

The loop voltage drops by a factor of 2 when additional heating is applied, while χ and $1/\tau_e$ increase only slightly (about 20%). As for JET, peaking in these plasmas cannot be explained by the Ware pinch, unless very low values of D/χ are assumed. To maintain density gradient $\frac{\nabla n}{n} \sim 5m^{-1} = \frac{V_{ware}}{D}$ with typical V_{ware}~0.3m/s, D would have to be about $0.06m^2/s$ i.e. 50 times less than χ.

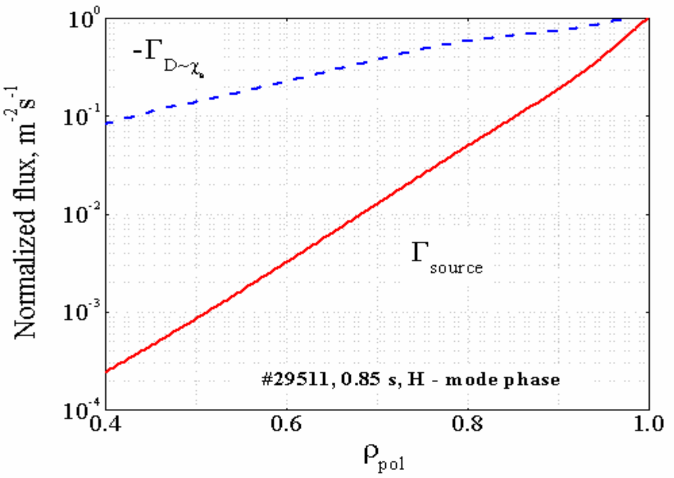

Fig. 4: Kn1D simulation of edge neutrals flux and comparison with particle diffusion flux for X3 heated H-mode plasma on TCV.

Since no NBI heating is used on TCV, edge neutrals are the only possible particle source. The one dimensional kinetic transport code Kn1D was used to estimate the importance of edge neutrals for the density peaking. Results are illustrated on Fig. 4, with the red line representing the edge neutral inward flux and the blue dashed line the diffusive outward particle flux with the assumption $D(\rho) \approx \chi_e(\rho)$. The source is renormalized such as to balance inward and outward fluxes at the LCFS without a convective flux. One can see that the edge neutral flux is too small by 2 orders of magnitude at mid-radius and hence cannot be responsible for the gradients, even in the vicinity of LCFS.

5. Conclusions

Due to the negligibility of the particle source and the neoclassical pinch we may conclude that density peaking in TCV X3 heated H-mode is clearly anomalous. It is purely electron heated, has a reactor relevant β_N~2 and contrary to the predictions [2], only a modest core flattening observed in the ELMy case.

In comparison to big machines, TCV has very low electron-ion coupling, hence quite high Te/Ti value. This is much more favourable conditions for TEM destabilizing, but even in that extreme case of electron heating no pump-out is observed. So profile flattening in ITER plasma is much less probable.

Values of density peaking and normalized density gradient at mid-radius are within the range found on JET for the same values of ν_{eff} or slightly higher (Fig 1) supporting an expectation of a peaked density profile in ITER despite the absence of a core particle source. From other hand we don't see any dependence of the peaking factor on ν_{eff} at the TCV experiments, probably due to lack of the experimental statistics.

6. Acknowledgement.

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7. References

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