On the High Density modes of operation in W7-AS

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It has been found in W7-AS, that strong fuelling at the beginning of the discharge in divertor configurations results in an increase of the line-average density (up to $3.5 - 4 \cdot 10^{20} m^{-3}$) accompanied by a flattening of the density profile in the core and pedestal formation at the edge [1-3]. As a result, the confinement time is considerably improved compared with the so-called normal confinement regime(NC). This improvement is accompanied by radial electric field formation at the plasma edge (up to ~ 100V/cm) and the suppression of the MHD activity.

In this paper a plausible explanation of the high-density H-mode regime formation (HDH mode) in W7-AS is suggested. It is shown that the transition can be associated with the edge transport barrier formation caused by a strong gas puffing at the plasma edge at given input power. In contrast to tokamak plasmas, a primary factor which initiates the ETB in W7-AS is an excessive fuelling rate which drives a steep edge density gradient [4] . This happens when the fuelling rate $\left(\frac{\partial n}{\partial t}\right)_{source}$ prevails over the diffusivity at the edge:

$$\left(\frac{\partial n}{\partial t}\right)_{source} > D\frac{\partial^2 n}{\partial x^2} \qquad (1)$$

Here D is the anomalous radial diffusivity at the plasma edge. Estimates show that in helias stellarator plasmas even a moderate fuelling rate ($\sim 2 \cdot 10^{21} \sec^{-1}$) allows one to overcome the diffusivity effects and to build up a steep density gradient. The temperature profile does not change very much probably because the plasma cooling is compensated by of the thermal conductivity decrease ($\chi \propto a^2 / \tau_E \approx a^2 / \sqrt{\bar{n}}$). It is worthwhile to mention that this type temperature behaviour differs from tokamak plasmas, where the temperature usually drops during the puffing [5].

The results of the steeper gradients is to produce a radial electric field which causes sufficient poloidal rotation and shearing flow eventually leading to suppression of ion turbulence. As a result the density gradient increases further until the turbulent transport drops down to the subdominant (neo-classical) level.

$$D \cong D_0\left(1+\frac{\alpha}{1+\mu\left(E_r^{/}\right)^2}\right)+D_{neo-cl.} \qquad (2)$$

When the ion interchange mode dominates transport at the edge, the required value of the radial field shear E_r' is:

$$BE_r'/c > \gamma_{ITB} \qquad (3)$$

where γ_{ITB} is the growth rate for ITG linear mode and, α, μ are some constants.

The density profile evolution has been simulated numerically by solving the density equation for given sources, describing the NBI and puffing.

$$\frac{\partial n}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma)=S_n+\left(\frac{\partial n}{\partial t}\right)_{puff} \qquad \Gamma=-D_n\frac{\partial n}{\partial r}+nV \qquad (4)$$

Here the source S_n is associated with the NBI heating and the pinch term in form $V = const.(1-r/a)$, a is the minor radius. Fig. 1a shows the density profile evolution for different puffing rates.

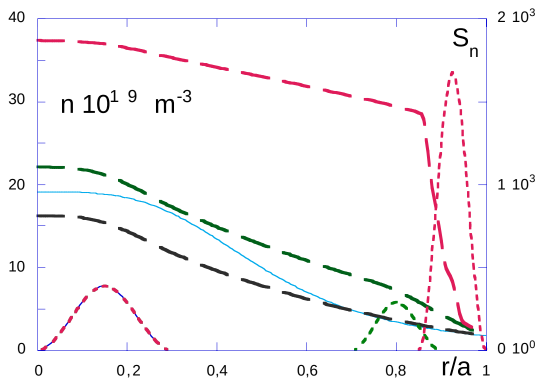

Fig. 1a Density profiles for moderate (green) and strong (red) puffing rates (shown at the edge two distributions by dashed lines).NBI source is also shown in the centre. Strong puffing corresponds to peaked density profile at the edge, S in units $10^{19}\,\mathrm{sec}^{-1}$

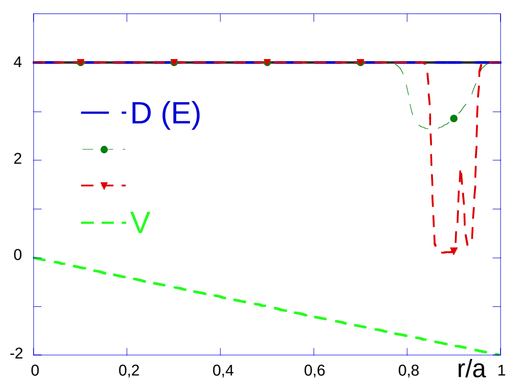

Fig. 1b. Diffusion D(E)/D(0) for the same puffing rates as in la. At a strong puffing rate the strong reduction of D is seen. The green line indicates the chosen pinch velocity model.

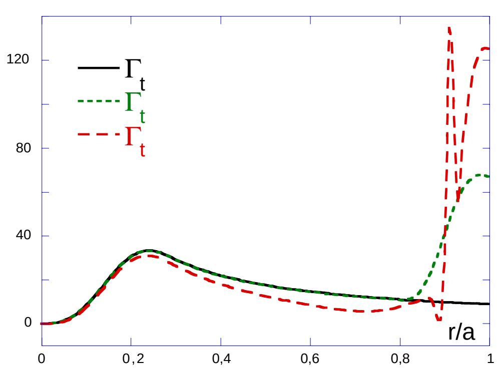

Fig. 1c. Profiles of the particle flux corresponding to the different puffing rates.

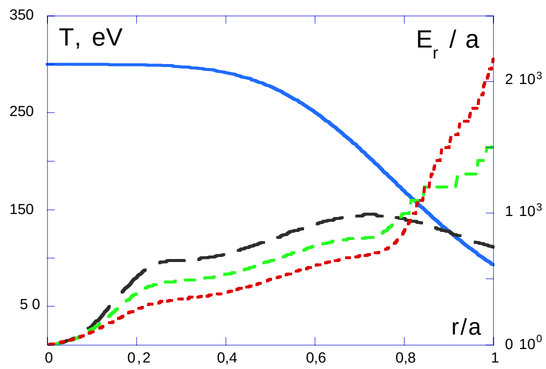

Fig. Id The radial electric field profiles corresponding to the different puffing rates.

At some puffing rate value ($\sim 1.5 \cdot 10^{21} s^{-1}$) the shear of the radial electric field becomes sufficient to suppress the edge turbulence. When it occurs, the edge transport barrier does not require any further strong puffing and can be maintained self-consistently. Then, the otherwise subdominant neo-classical (Phirsch-Schlueter) transport dominates in the edge region. Calculations have been done for W7-AS parameters. In Fig. la one can see a considerable increase of the pedestal, and hence, average density in case of strong puffing source. Fig. 1b shows how the diffusivity coefficient drops at the edge due to the increase of the electric field, shown in Fig. 1d. The radial distribution of the radial fluxes of particles is shown in Fig.1c. The maxima of this fluxes (diffusive and convective) are localised at the source positions.

The critical average density required for transition can be estimated from the energy and particle balance at the plasma edge. Further we will mainly follow [7] in our analysis of the stability of the steady-state solutions of the balance equations:

$$-D(n,T)n' + nV = \Gamma \quad (5)$$

$$-\chi(n,T)T' + \frac{5}{2}T \cdot \Gamma = P/S \quad (6)$$

where the particle flux, Γ, is given by a diffusive term with the Pfirsch-Schlueter diffusion coefficient, $D \propto n/B^2 T^{1/2}$ and a flow term with velocity V, defined as $V(r) \approx (1 - r/a)V_0$, where $V_0 \approx 0.003 m/s$. The heat flow P across a surface of area S is given by a conduction term with conductivity $\chi(n,T)$ and a convection term. In steady state, Γ and P balance the particle fuelling and input power. The electron and ion temperatures are assumed equal. The prime in eqs.5, 6 denotes the radial derivative. Here we suggest that the neutral-affected zone, of width λ, is small compared with the minor radius, a, which allows one to consider a simplified 1-D geometry. In this case the heat flow P and the particle flux Γ can be taken constant across the edge region and are treated as the control variables. The boundary conditions for equations (5-6) are determined for simplicity by specifying some small boundary density value (e.g. $5 \cdot 10^{18} m^{-3}$) and assuming that the heat is carried to the wall by particles reaching the edge, $T \approx P/S\Gamma$ (it can be shown that the results are insensitive to this assumption). Assuming that density in the region λ characterizes the volume average density one can plot contours of average densities in the P(MW), $\Gamma(10^{20} m^{-3}/s)$ plane (see Fig.2) It is clear that the contours of constant density depend on both power and particle flux.

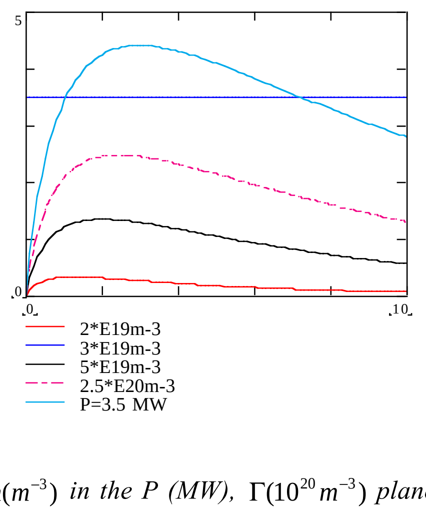

Fig. 2 Contours of constant density $n(m^{-3})$ in the P (MW), $\Gamma(10^{20} m^{-3})$ plane. Straight line corresponds to 3.5 MW thermal power.

That means that in order to maintain a given density there is a critical power which must not be exceeded at a given temperature. At a given critical power, there are two values of particle flux for a given density. Both are stable equilibria. It is seen in Figure 2 that exceeding the critical power leads to an unavoidable increase in density, reminiscent of the density increase observed in H modes. Fig. 3 shows a plot of density against particle flux at a fixed power of

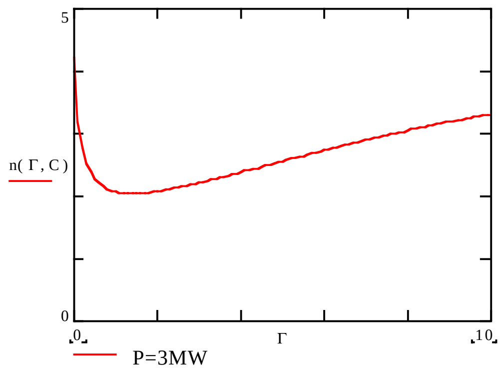

Fig. 3 Variation of density $n(m^{-3})$ *with particle flux for the input power of 3MW in the model with classical diffusion coefficient at the plasma edge.*

3MW and there are two solutions at a density $\sim 2.3 \cdot 10^{20} m^{-3}$, a high particle flux, low confinement solution with a low edge temperature, and a low particle flux, high confinement solution with a high edge temperature. It is tempting to identify these two solutions as NC and HDH modes of operation. The scaling of this critical density as a function of impurity content can be found by deriving asymptotic solution for density in case of low and high value of the particle flux. At low Γ, the inward pinch and the outward diffusion balance, so that from equation 5 it followes:

$$D\frac{\partial n}{\partial x} \approx nV, \quad x = r/a \tag{7}$$

which becomes $n' \propto B^2 V \sqrt{T}$ and with negligibly small edge density yields:

$$n(\lambda) \approx const_1 \cdot aB^2 V \sqrt{T/S\Gamma} \tag{8}$$

The density becomes large at low Γ because the resulting high temperature leads to a low diffusion coefficient whilst the pinch velocity is maintained constant. At high Γ, on the other hand, the outward diffusion balances the inward flux of neutrals,

$$D\frac{\partial n}{\partial x} \approx \Gamma \tag{9}$$

so that $nn' \propto B^2 \Gamma \sqrt{T}$ and hence

$$n(\lambda) \approx const_2 \cdot \sqrt{a} B (P\Gamma/S)^{1/4} \tag{10}$$

The density becomes larger at high Γ because of the strong particle source. As was shown in [7], an approximate solution for the average density can be constructed as the sum of the asymptotic limit for,

$$n \approx const_1 \cdot aB^2 V \sqrt{T/S\Gamma} + const_2 \cdot \sqrt{a} B (P\Gamma/S)^{1/4} \tag{11}$$

The critical density occurs when $\partial n / \partial \Gamma \approx 0$, that is when $\Gamma \propto B^{4/3} \cdot (PVa^2/S)^{1/3}$ which leads to the density

$$\bar{n}_{cr}(10^{20} m^{-3}) \approx Const. B_T^{4/3} P_{MW}^{1/3} (a/R)^{1/3} V_{m/s}^{1/3} \tag{12}$$

where $Const. \approx 2.5$ and for W7-AS parameters (*R=2m, a=0.16m P= 3MW , V=10m/s*) the critical density is $\bar{n}_{cr} \approx 1.6 \cdot 10^{20} m^{-3}$. The critical density measured experimentally in W7-AS for 2MW input power corresponds to $\approx 1.8 \cdot 10^{20} m^{-3}$ and for 3.5 MW $\approx 2.2 \cdot 10^{20} m^{-3}$ [2, 3].

Let us summarise. According the model presented here, strong fuelling brings about a strong density gradient at the edge, which triggers the formation of the edge transport barrier. In contrast to a tokamak, the barrier formation is not due to an increase of power, but the density at the edge. This has been checked in a numerical model, applied to W7-AS. The existence of the edge transport barrier and higher average density makes the difference between NC and HDH modes. Transition occurs when the pedestal or average plasma density exceeds some critical value. This critical value can be derived from the energy and particle balance at the edge, where the transport coefficients depend on the plasma parameters in such a way that bifurcation can occur. The bifurcation occurs between two stable solutions, which are characterised by different values of the particle flux and energy confinement time. The scaling analyses shows that the threshold average density required for transition increases with power and minor radius.

References

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