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The experimental Greenwald density limit in tokamak *H*-mode is explained from the requirements that in the edge transport barrier the radial pressure gradient does not exceed the ballooning stability threshold and the plasma collisionality corresponds to the transition from the plateau regime of neoclassical transport to the Pfirsch–Schlüter one, where the edge temperature and plasma energy content decrease dramatically with increasing density. © *2009 American Institute of Physics*.
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The Greenwald density limit in tokamaks[1,2] remains one of the most puzzling phenomena in plasma physics. It provides a very laconic relation between the maximally achievable line averaged density $\bar{n}$ of charged particles and the averaged density of the electric current in the plasma,

$$\bar{n} \le n_{\mathrm{Gr}} \equiv I_P/(\pi a^2),$$

where $\bar{n}$ and n_{Gr} are measured in $10^{20}\ \mathrm{m}^{-3}$, the total plasma current I_P in *MA* and the separatrix minor radius a in *m*. Numerous attempts to explain this limit are based on the idea of a bifurcation in the balance between the power transported from the plasma core and lost from the edge by different mechanisms, e.g., heat conduction, convection, and impurity radiation. Normally this results in the absence of stationary states if some maximum plasma density at the edge is exceeded. However, in the high confinement *H*-mode the density limit does not lead to such a catastrophe but to a gradual deterioration of the confinement to its level in the low confinement *L*-mode. In this way the type I edge localized modes normally disappear and therefore by analyzing the density limit in *H*-mode, see, e.g., Ref. 3, the condition that the maximum plasma pressure gradient is below the ideal ballooning limit is often applied,

$$|d(nT)/dr| \le B^2\alpha_{cr}/(16\pi R q^2), \tag{1}$$

where r and R are the minor and major radii of the magnetic surfaces, B is the magnetic field, α_{cr} is the ballooning stability parameter, and q is the safety factor. In the edge transport barrier (ETB) we assume linear profiles of the plasma density and temperature, the same for electrons and ions,

$$n(r) = n_s + (n_b - n_s)(x/\Delta_n), \quad T(r) = T_s + (T_b - T_s)(x/\Delta_T).$$

Here $x=a-r$, n_s and T_s are the plasma parameters at the separatrix, n_b and T_b are their pedestal values, and Δ_n and Δ_T the widths of the ETBs in the density and temperature, respectively. In accordance with findings on diverse tokamaks, e.g., DIII-D,[4] we adopt that Δ_n is defined by the penetration depth of recycling neutrals. In diffusion approximation for neutral transport, see, e.g., Ref. 5, this corresponds to the condition

$$\int_0^{\Delta_n} n\sqrt{k_i k_{cx} m_i/T}\,dx \approx 1$$

with m_i being the ion mass, k_i and k_{cx} the ionization and charge-exchange rate coefficients for hydrogen isotope atoms, correspondingly. The width of the ETBs in the temperature profiles appear to be associated with other physical processes so that Δ_n and Δ_T are often different. Nonetheless for the present qualitative study we adopt $\Delta_n=\Delta_T$ and take into account that $T_s \ll T_b$. Then Eq. (1) results in

$$T_b\sigma_* \le \alpha_{cr}R/(16\pi)(B/qRn_b)^2, \tag{2}$$

where $\sigma_* \approx (2-\eta)\int_0^1[\eta+(1-\eta)\xi]\sqrt{k_i k_{cx} m_i/(T_b\xi)}\,d\xi$ and $\eta=n_s/n_b$. With the temperature dependences of k_i and k_{cx} from Ref. 6 one gets with an accuracy of 5% in the parameter range of interest, $0.3 \le \eta \le 1$ and $0.2 \le T_b \le 2$ keV,

$$\sigma_* \approx \sigma_0(T_0/T_b)^{0.4},$$

where $\sigma_0=3.6\times10^{-19}\ \mathrm{m}^2$ and $T_0=0.7$ keV. Thus, the ballooning condition (1) provides the upper limit for the plasma temperature at the ETB top,

$$T_b \le T_0^{-0.67}\left(\frac{\alpha_{cr}R}{16\pi\sigma_0}\right)^{1.67}\left(\frac{B}{qRn_b}\right)^{3.34}. \tag{3}$$

Suppose for a moment that the density limit corresponds to the transition in the ETB plasma from plateau to Pfirsch–Schlüter (PS) neoclassical regime, i.e., the collisionality $qR/\lambda_c=0.222$ (Ref. 7); here $\lambda_c=3T_b^2/(2\sqrt{2\pi}\Lambda e^4 Z_{\mathrm{eff}} n_b)$ is the mean free path length between coulomb collisions with Λ being the coulomb logarithm, e is the elementary charge, and Z_{eff} is the ion effective charge. Thus at this transition,

$$T_b = 2.74e^2\sqrt{\Lambda B Z_{\mathrm{eff}}}\sqrt{\frac{qRn_b}{B}}. \tag{4}$$

Being combined, Eqs. (3) and (4) result in

$$7.142(\Lambda B Z_{\mathrm{eff}} e^4)^{0.13}\left(\frac{\sigma_0}{\alpha_{cr}R}\right)^{0.435} T_0^{0.174} \le \frac{B}{qRn_b}. \tag{5}$$

For elliptic plasmas with elongation E we adopt according to Ref. 8 $\alpha_{cr}\approx 0.4\ s\,(1+E^2)$, where $s=d\ln q/d\ln r$ is the magnetic shear, and according to Ref. 9, $q\approx 6EBa^2/(RI_P)$, with R measured in *m* and B in *T*; the coulomb logarithm is a very weak function of the temperature and $\Lambda \approx 18$ will be used. With these estimates Eq. (5) results in the condition

$$n_b \leq 0.367 \frac{[sR(1+E^2)]^{0.435}}{(BZ_{\text{eff}})^{0.13}E} n_{\text{Gr}}. \quad (6)$$

The factor in front of n_{Gr} on the right hand side of Eq. (6) depends very weakly on the magnetic field, effective ion charge, and plasma elongation and a little bit stronger on the magnetic shear and major radius. For parameters typical at the ETB top in the tokamak JET,[10] $s=4$, $R=3$ m, $Z_{\text{eff}}=1.5$, $B=2.5$ T, and $E=1.6$, we get

$$n_b \leq 0.989 n_{\text{Gr}} \quad (7)$$

in astonishing agreement with experimental Greenwald density limit! Since without special means such as pellet[11] or impurity[10] injection the density profile is normally very flat in the core of H-mode plasmas and the limitation above holds also for the line averaged density $\bar{n}$.

Finally, we demonstrate that the energy confinement deteriorates fast if n_b exceeds n_{Gr}. Consider first the ion channel. In the ETB the ion heat conduction, interpreted from measurements,[12] can be well reproduced by the neoclassical one: $\kappa_\perp^i \approx \kappa_i^{\text{neo}} \sim n^\beta T^\gamma$, with (β,γ) smoothly changing from (1, 1.5) in the plateau regime to (2, −0.5) in the PS one.[7] From the ion heat balance in the ETB,

$$q_i \approx \kappa_\perp T_b/\Delta_T \approx \kappa_\perp T_b n_b \sigma_* \sim n_b^\beta T_b^\gamma T_b n_b \sigma_0 (T_0/T_b)^{0.4}, \quad (8)$$

one gets for a fixed density q_i of the ion heat flux

$$T_b \sim n_b^{-(\beta+1)/(\gamma+0.6)}.$$

This provides $T_b \sim n_b^{-0.95}$ in the plateau regime for $n_b \leq n_{\text{Gr}}$ and $T_b \sim n_b^{-30}$ in the PS one, where n_{Gr} is exceeded. Thus the H-mode density limit is not a bifurcation, which would result in a loss of the stationary state, but a transition to the situation where the edge temperature drops very fast with increasing density. The fact that events at the H-mode density limit start with a significant reduction in the pedestal ion temperature has been observed experimentally, see Fig. 6 in Ref. 13. Even in the H-mode the transport is anomalous beyond the ETB so that in the plasma core the temperature profile is stiff and the density is flat. Therefore the ion energy content $W \sim T_b n_b$ drops by a factor of 2 if n_b is ramped up above n_{Gr} by less then 3%.

The electron heat conduction $\kappa_\perp^e$ in the ETB exceeds significantly its neoclassical level. By reproducing experimental profiles it was obtained $\kappa_\perp^e \approx \kappa_\perp^i$ in Ref. 12 and $\kappa_\perp^e \approx \kappa_\perp^i/4$ in Ref. 14 where convective heat losses were accounted in the power balance. Thus the growth of the ion heat losses at n_{Gr} should lead to a significant drop of the overall plasma confinement. Moreover, electrons are cooled down through coulomb collisions with ions and their collisionality increases strongly for $n_b \geq n_{\text{Gr}}$: $\nu_* \sim n_b/T_b^2 \sim n_b^{61}$. As a result the anomalous electron heat transport generated through resistive drift instabilities,[15–17] typical at the plasma edge under the L-mode conditions, rises significantly and exaggerates the confinement deterioration initiated in the ion component.

The present approach to the density limit in the H-mode as a transition in the heat transport at the plasma edge is in line with that proposed in Ref. 5 for the density limit in the L-mode. The main difference is that in the former case the change in the neoclassical regime is of importance and in the latter one the anomalous transport is modified, from that driven by drift-Alfvèn (DA) to the one triggered by drift resistive ballooning (DRB) modes. The parametric dependencies of transport coefficients are very similar for plateau/DA and for PS/DRB regimes, correspondingly, and, therefore, scalings for the H- and L-mode density limits are also close each other.

Finally we want to stress the principal difference of our approach to the H-mode density limit from that proposed by Borrass, see Ref. 18 and his latter papers, where divertor detachment is considered as a triggering event. Note that Borrass' model essentially presumes Bohm anomalous transport in the scrape-off layer, being questionable under the H-mode conditions. Both approaches provide essentially different dependence of the density limit on the magnetic field that would allow to discriminate them experimentally.

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