Tokamak Plasma Self-Organization and Possibility to Have the Peaked Density Profile in ITER

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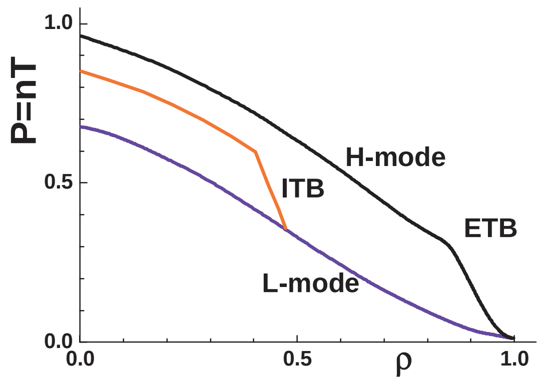
Abstract. The self-organization of a tokamak plasma is a fundamental turbulent plasma phenomenon, which leads to the formation of a self-consistent pressure profile. This phenomenon has been investigated in several tokamaks with different methods of heating. It is shown that the normalized pressure profile has a universal shape for a wide class of regimes in case the normalized radius $\rho=r/(I_pR/kB)^{1/2}$ is used. The consequences of this phenomenon are discussed.

1. Introduction

Extrapolations from present tokamaks to future fusion devices like ITER are often based on formal scalings, which express the energy confinement time as an empirical function of (sometimes a large) number of parameters. Then the scaling laws are only valid within the used ranges of the various parameters and often under the assumption that only one parameter in the equation is varied at the same time. ITER will operate in a plasma parameter range well outside that of today tokamaks, and it is obvious that there is not a single physical process that determines plasma behavior and confinement. Hence, if we want to predict the ITER parameters reliably the main physical processes that determine plasma confinement and transport behavior should be understood. One of the main processes in turbulent plasma is its self-organization. Under changing external conditions, various types of instabilities with different amplitudes are naturally excited in the plasma, and they subsequently influence the transport coefficients. This permits plasma to build the most stable energy profile, i.e. a self-consistent plasma pressure profile, $p(r)$, (r is a local minor radius). The self-organization occurs in all plasma regions, except in regions where the plasma turbulence is suppressed. Here the self-regulation cannot be realized and more steep pressure gradients are permitted. These are the so-called transport barriers. The self-organization and transport barriers are the two main factors that determine the shape of $p(r)$ profile. If we understand the physics of these processes it is possible to understand how they will work in the ITER case.

At the T-10 tokamak, the self-consistency of the plasma pressure profile was investigated in terms of the normalized plasma pressure, defined as $p_N(r) = p(r,t)/p_0(t)$ [1-3]. The T-10 tokamak (major and minor radii R =1.5 m, a_L= 0.3 m, circular cross section) features only ECR heating. Therefore, the ion temperature is usually smaller than the electron temperature: $T_i< T_e$. Hence, most the experiments mainly relate to the electron component of $p_N(r)$. For $T_e(r)$ measurement 2nd harmonic electron cyclotron emission is used (about 20 points along the plasma diameter). The plasma density profile is measured by an 8-channel radio-interferometer as well as a 7-channel laser interferometer. Additionally, in the outer 2/3 of the plasma radius an AM-reflectometer is used.



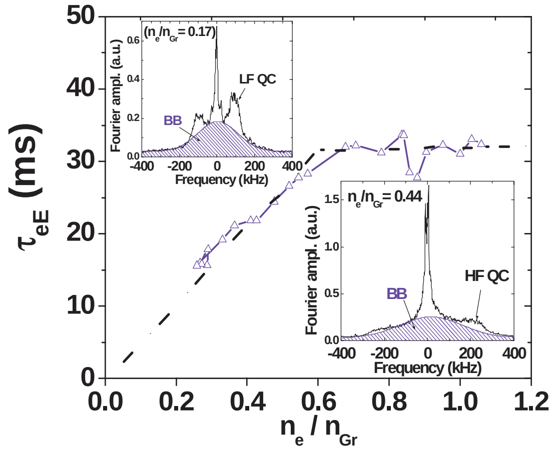


FIG. 1. Scheme of pressure profiles with internal (ITB) and external (ETB) transport barriers and without them (L-mode).

FIG. 2. The energy confinement time vs the average plasma density, normalized on the Greenwald density limit [21]. Insertions show the typical density fluctuation spectra for low and high densities [7]; QC – quasi-coherent, BB – broadband.

In order to understand in how far T-10 results are similar to those at other tokamaks and plasma conditions, also results from different devices: RTP, TEXTOR, JET have been used. In all three devices $T_e(r)$ and $n_e(r)$ are measured by Thomson scattering. TEXTOR and JET have also ion heating, and in these tokamaks, $T_i(r)$ is measured by CXRS. In all experiments shots without internal transport barriers (ITB) were selected in order to separate two phenomena: self-consistent plasma pressure profile and ITB formation. ITBs have a tendency to form near the rational surfaces with low m, n numbers in the 'gap' without rational surfaces [4-6]. The relative width of this gap increases with decreasing tokamak aspect ratio A. Hence, for T-10 with A=5, the ITB effects are less pronounced than for JET with A=3.5. It would also be possible to subtract the ITB region, using the scheme, given in [3] (see also figure 1), but this procedure would make the analysis less reliable.

2. Survey of the results on the pressure profile self-organization, obtained at T-10

In T-10, the following characteristics of pressure profile conservation have been observed:

2.1. Dependence of $p_N(r)$ on the averaged plasma density. In many series of T-10 experiments it was observed that $p_N(r)$ does not depend on the plasma density, $\bar{n}_e$, neither, when $\bar{n}_e$ is changed from shot to shot nor when it is dynamically changed during a discharge [3]. This fact is surprising if one realizes that the electron energy confinement time in tokamaks, τ_{eE}, has different dependencies on the plasma density n_e: for low densities ($n_e/n_{Gr}<0.5$) $\tau_{eE} \sim n_e$, but for higher densities ($n_e/n_{Gr}>0.5$) τ_{eE} is practically independent from n_e (fig. 2) Additionally, density fluctuation spectra measured by correlation reflectometry exhibit quite different spectra for low and high densities [7]. In the first case, beside the "broadband" part of spectrum a "quasi-coherent" maximum with frequency in the range 70 – 120 kHz is seen, which has been attributed to an ion temperature gradient mode. A density increase leads to a considerable change in the fluctuation spectrum: the low frequency maximum disappears and new, higher frequency maximum 150 - 250 kHz, appears, attributed to the Trapped Electron Mode. From this it is concluded that ***$p_N(r)$* *is independent on the dominant type of plasma drift wave instability.***

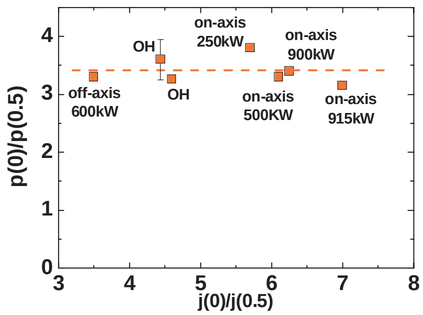


FIG. 3. Dependence of the pressure peaking on the current density peaking calculated by Spitzer's law $j \sim T_e^{3/2}$.

2.2. Dependence of $p_N(r)$ on the power deposition profile

It was further observed in T-10 that $p_N(r)$ does not depend on the deposition profile and power level of ECRH [1-3]. By locally heating electrons the T_e profile and, hence, the current density $j(r)$ profile ($j \sim T_e^{3/2}$) are changed. However, $p_N(r)$ is unchanged due to a simultaneous change in the plasma density profile $n_e(r)$. Hence, ***$p_N(r)$* is independent on *$j(r)$*** (see fig. 3).

2.3. Dependence of $p_N(r)$ on the q_L. Experiments have revealed that $p_N(r)$ depends on the relation between the plasma current I_p and the magnetic field B. The higher the q_L value, the narrower is the pressure profile. It was demonstrated that $p_N(r)$ is independent on I_p, B, and the tokamak geometry, if instead of r the dimensionless radius $\rho=r/(IR_0/kB)^{1/2}$ is used. Here k is elongation parameter. This formula permits to compare different tokamak results for regimes without pronounced ITB. In fig. 4 this is shown for regimes in T-10 with different q_L. The different profiles can be combined into a single one, if ρ instead of r is used. Analysis of TEXTOR shots with different methods of heating: NBI or NBI+ ICRF shows that normalized pressure profile is the same as for the T-10 OH shots. (fig. 5) The comparison of $p_N(\rho)$ profiles for different tokamaks is presented in fig. 6. The errors in this figure arise not only from the usual error bars in the $n_e(r)$ and $T_{e,i}(r)$ measurements, but are also due to the method of p normalization. In fig. 5 the $p(r)$ normalization was performed in plasma centre. This was possible because sawteeth in the various discharges were small. The existence of weak ITBs near main rational surfaces and some other effects, like MHD islands, could also lead to some spreading of results. Nevertheless, a reasonable coincidence is observed between the results of the small circular tokamak RTP and the large elongated JET tokamak. (A similar result was reported two decades ago [1] for the relatively small and circular tokamaks of that time). Similar features of pressure profile consistency were observed in the strongly shaped tokamak TCV, where k was up to 2.8, and both limiter and divertor configurations were used [8]. So, it can be concluded that the self-consistent pressure profile is a common feature of tokamak plasmas. ***The scaling $\rho=r/(I_pR/kB)^{1/2}$ allows us to describe the self-consistent pressure profile for tokamaks with different geometries.*** Note that pressure profile consistency (the same $p_N(r)$ for different regimes) has also been observed in devices with different magnetic configurations, like stellarators [9, 10]. So, we can conjecture that the self-consistent pressure profile is a common phenomenon for the turbulent plasmas in magnetic field.

3. Time of $p_N(r)$ restoration

In order to understand the physical mechanism of $p_N(r)$ conservation, the question: *how quickly does it realize?* needs to be answered. Does it take place on a current reconstruction, heat diffusivity, or inertial time scale? In fig. 7 the results of Thomson scattering measurements of $p_N(r)$ in RTP are presented. All $p_N(r)$ profiles are basically the same, which implies that $p_N(r)$ shape conservation is established during a time $t_c<0.1\ \tau_E$ (τ_E=3 ms in the given experiment). Off-axis heating experiments in T-10 have led to a similar conclusion. However, a lower $n_e(r)$ time resolution in the T-10 measurements [2] gives an upper limit $t_c<0.3\tau_E$ (τ_E=12 ms for given discharges).

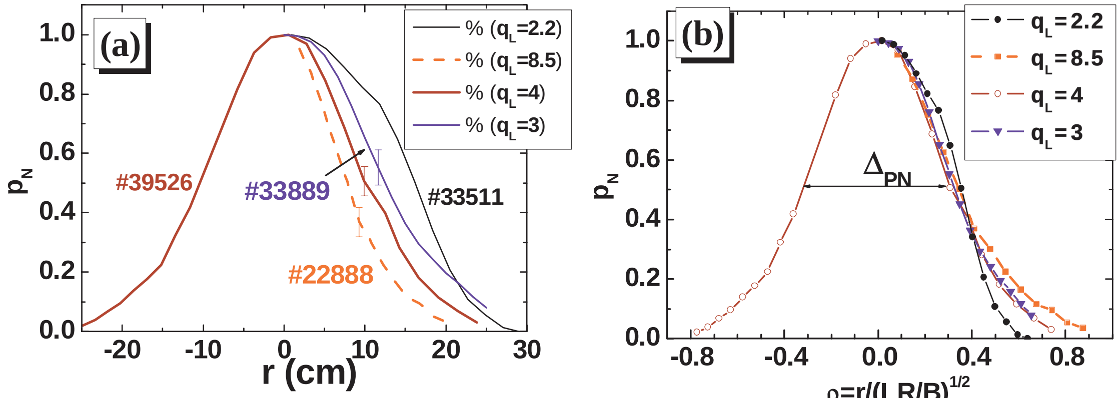


FIG. 4. Pressure profiles in T-10 ohmic discharges. á) $p_N(r)$ for regimes with different edge safety factor q_L; b) the same curves as a functions of normalized radius ρ

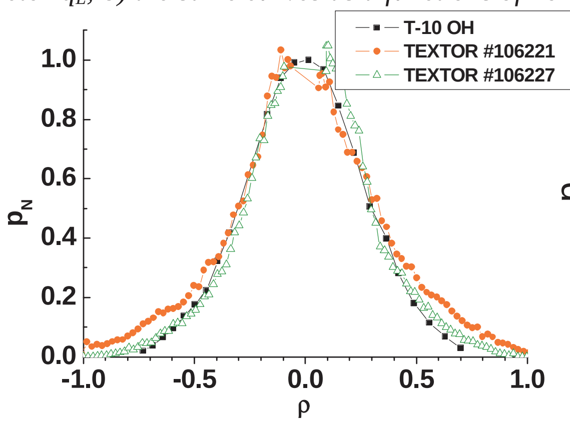


FIG. 5. Normalized pressure profiles for two TEXTOR shots: #106221 I=240kA; B=2.5T; P_{NBI}=1.02MW; P_{ICRH}=1.425MW; # 106227 I=240kA; B=2.5T; P_{NBI}=1.05MW; P_{ICRH}=0; and for T -10 ohmic shot.

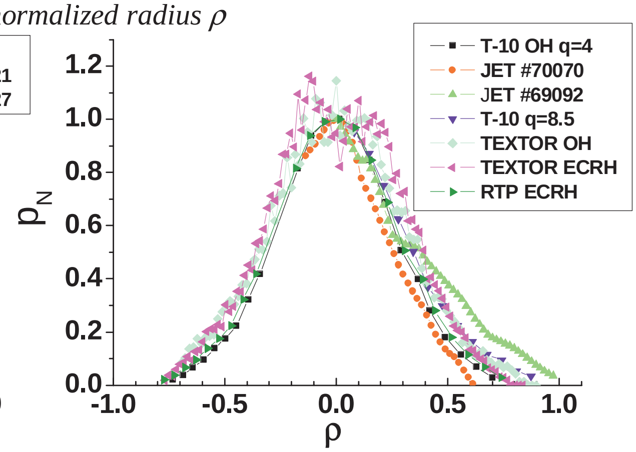


FIG. 6. Comparison of normalized pressure profiles $p_N=p(r)/p(0)$ on normalized radius for T-10, JET (# 70070, [22], # 69092, [23] , TEXTOR and RTP.

Taking into account the information that the $p_N(r)$ shape does not depend on $j(r)$, but instead on the total plasma current, experiments with rapid current ramp up were performed at T-10. It can be expected that if the plasma current is rapidly increased, the changes in the $p_N(r)$ profile may appear earlier than the additional Δ*j* will penetrate into the bulk plasma. The plasma current was ramped up by 25% in 20 ms during a stationary phase in both OH and off-axis ECRH discharges. (In the latter case the sawtooth relaxations were suppressed). The current equilibration time was about 200 ms; therefore, during the first 50 ms no appreciable *j* increase is expected inside radii $r < 1/3a$. Results of experiments are presented in figs 8 and 9.

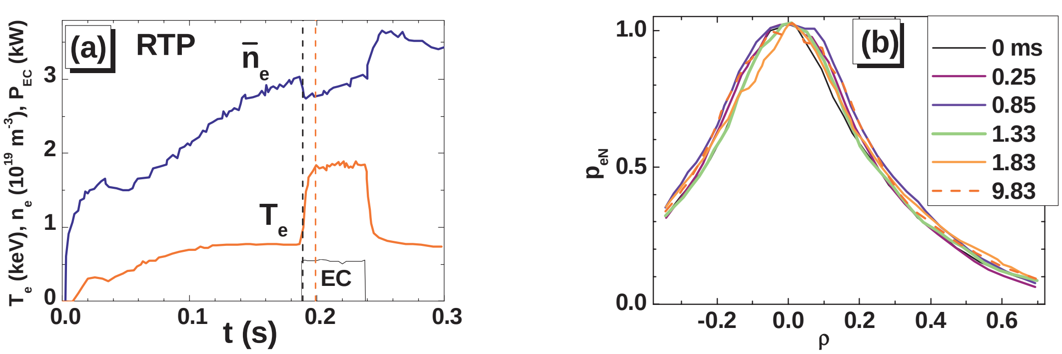


FIG. 7. Fast establishment of self-consistent pressure profile in RTP. a) line-averaged density and central electron temperature; b) normalized pressure profiles.

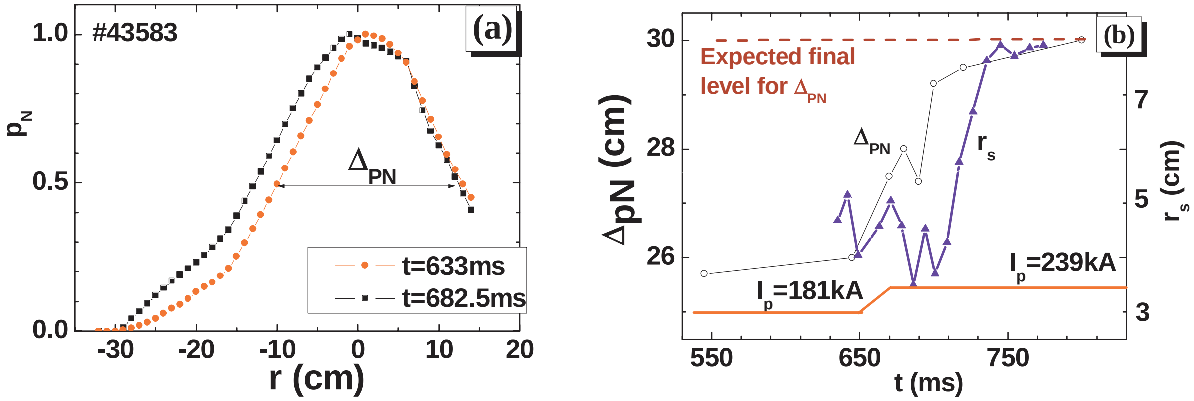


FIG. 8. Ohmic discharge with current ramp-up in T-10. a) p_N for the time instant before dI_p/dt (circles) and 10 ms after it (squares); b) temporal behaviour of current I_p, FWHM of normalized pressure profile Δ_{PN} and sawteeth inversion radius r_S.; B=2.33 T, q_L=3.9 – 3.0.

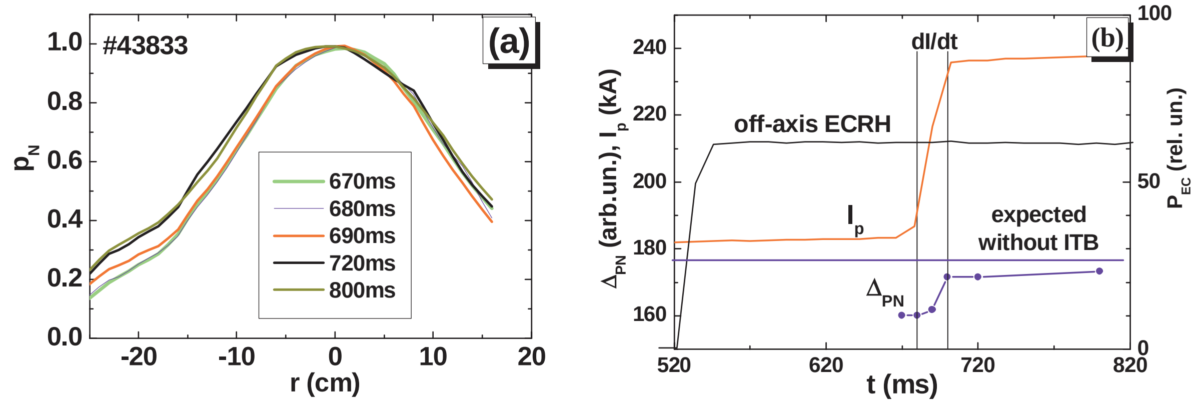


FIG. 9. Discharge with current ramp-up and off-axis ECRH. Absorbed power P_{ECR} =0.5 MW, P_{ECR}/P_{OH} = 4; a) $p_N(r)$ profiles for different time instants; b) time evolution of current I_p and FWHM of normalized pressure profile $\Delta_{PN.}$

The full width of $p_N(r)$ at half maximum (FWHM), denoted as Δ_{pN}, starts to increase practically at the same time as the current ramps up, and increases within the experimental accuracy synchronously with the current increase. The change in the sawtooth inversion radius starts 50 ms later. So, Δ_{pN} follows the total current value, but not the current density profile. The formation of a self-consistent pressure profile during a very fast time, in which the additional current cannot penetrate into the bulk plasma both in OH and OH + off-axis ECRH experiments can be explained only by a ***change of equilibrium***, as no external impacts influence the plasma core on that time scale.

4. What normalized profiles are stiff: pressure or temperature?

In several papers [11-13] it was reported that in tokamak regimes with high average density, the temperature profile is conserved under NBI heating. This effect is called temperature profile "resilience" or "stiffness". In the case of $T_N(r)$ conservation, the pump-out effect is also absent. So, the pressure profile is not changed too. If we deposit the power locally, directly to the electron component, then T_e in this region increases and pump-out will compensate its increase in the $p(r)$. If the power deposition is non-local and particle balance is very active, like in the NBI case, the pump-out may be lacking. Thus the $T_N(r)$ has to be conserved (because of transport coefficients change). So, we can conclude that ***$T_e(r)$ conservation effect is a particular case of pressure profile consistency***, when the pump-out is absent.

5. Conclusions and consequences

The main results of the experiments are the following:

1. The normalized pressure profile $p_N(r)$ shape is independent on the dominant type of instability.
2. The shape of the $p_N(r)$ profile depends on the total current as $I_p^{1/2}$, but it does not depend on the current density profile shape $j(r)$. Using the dimensionless radius $\rho=r/(I_pR/kB)^{1/2}$ the same $p_N(r)$ is found for tokamaks with different dimensions and geometry.
3. The adaptation time of $p_N(r)$ to perturbations is much smaller than the energy confinement time.
4. The self-consistent normalized pressure profile links to the equilibrium in the turbulent tokamak plasma. The Grad-Shafranov equation gives a relation between the plasma current and the plasma pressure profile, but it does not determine this profile. The pressure profile is determined by transport coefficients. A turbulent plasma has a possibility to change its transport coefficients in a wide range, so it has the possibility to organize the profile in such a way to be the most energetically advantageous. Such a balanced pressure profile will be the most stable and will have the best confinement, but external impacts prevent the plasma to be quite stable. It is the pressure profile that is regulated (neither the temperature nor density profile separately). From conclusion 2 above and the pressure driven character of the process it can be posed that the plasma behaviour is determined by MHD processes. Theoretical attempts to find this optimal $p(r)$ profile were reported in [14-16].

Consequence 1. *The best confinement is obtained in the OH case, where the power deposition profile has the possibility to redistribute itself in the best way*. The heating deposition profile for the classic ohmic process is $P(r,t) \sim T_e^{3/2}$; the pressure $p= n_eT$. If $n_e(r,t)/n_e(0,t)=[T_e(r,t)/T_e(0,t)]^{1/2}$, the P(r) and $p(r)$ profiles will be similar, and P increase will not distort the pressure profile, and will not lead to the transpot coefficient increase. In tokamaks with moderate aspect ratio (A= 4–5), this is indeed the case $n_e(r,t)\sim T_e(r,t)^{1/2}$. In tokamaks with low A, the neoclassical effect in the electron conductivity yields more peaked $T_e(r)$ and more flat $n_e(r)$ profiles. This redistribution will lead to higher transport coefficients for higher P_{OH}. We suppose that off-axis heating will increase τ_{eE} in this case.

Consequence 2. *A random deposition profile of auxiliary heating worsens the plasma confinement.* If the deposition profile of auxiliary power is not adjusted with the $p_N(r)$ profile then the total confinement will be worse in comparison to the OH case. The plasma tries to redistribute the auxiliary power to adjust to the $p_N(r)$ profile by quickly changing its transport coefficients. The density pump-out effect is the result of $p_N(r)$ profile conservation in the presence of electron heating (for example, ECR heating).

Consequence 3. *Anomalous velocity of hot/cold pulse propagation*. When it is tried to increase ∇p by local heating or cooling, the transport coefficients will quickly adapt to redistribute the input power as dictated by $p_N(r)$ profile conservation. This will increase the velocity of the hot/cold pulse propagation in comparison with the OH case, as is usually seen in experiments. The diffusion equation cannot be used in transient tokamak processes, since the transport coefficients can be rapidly changed by dozens times. [17].

Consequence 4. *Impossibility of density peaking in ITER.* In recent years several authors [see, e.g. 18, 19] have tried to find a possibility to organize a peaked electron density profile in ITER (along with a peaked temperature profile). The authors suppose that this can be achieved by making sure that the neutrals from the heating beams penetrate deep enough into

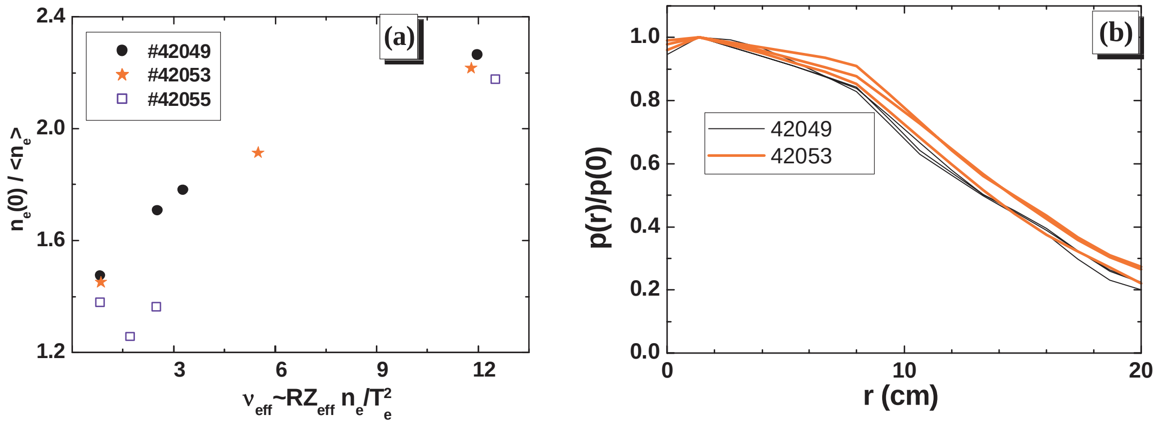


FIG. 10. T-10. a) Dependence of density peaking on the effective collisionality ν_{eff} under on-axis ECRH; b) Normalized plasma pressure profile for the different phases of the same shots with various EC powers; I_p=200 kA, B=2.4 T, measured absorbed power P_{ECR} =1.6 MW, P_{ECR}/P_{OH}=18.

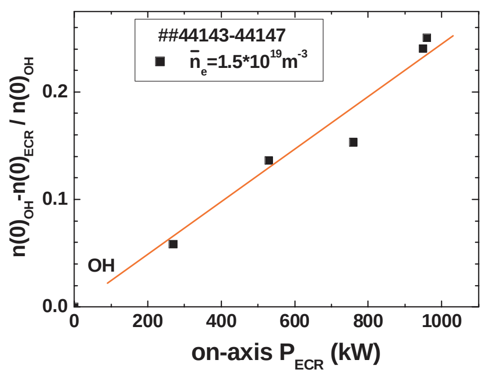


FIG. 11. Dependence of pump-out effect on the heating power in shots with on-axis ECRH only; I_p = 200 kA, B=2.4 T.

the plasma. Based on the particle balance and ionization rate they try to find regimes with deep penetration of an ionization source (neutrals) to the plasma core. From the mentioned ionization-diffusion model it is concluded that the plasma density peaking has to increase with an effective collisionality $\nu_{eff}=\nu_{ei}/\omega_{De}$ decrease, where ν_{ei} is the ion-electron collision frequency and ω_{De} is the electron diamagnetic drift frequency. However, as was shown above, in turbulent plasmas self-organization processes are very important. They are more powerful and faster than diffusion mechanisms, and they will lead to the formation of a self-consistent normalized pressure profile ($p_N(r)$).

In fig. 10 the dependence of the density peaking $n_e(r)/<n_e>$ on the collisionality, ν_{eff} ~$RZ_{eff}\, n_e/T_e^2$ is presented for on-axis ECRH shots. All shots have no pronounced ITB and the same I_p/B. Peaking of n_e decreases with decreasing ν_{eff}, which is in contrast to the findings in [18, 19], and $p_N(r)$ remains to be the same [20]. This profile may be changed only if ITB or ETB are formed.

Figure 11 presents the dependence of the central density decrease under on-axis ECRH. We see that the density decrease during heating is proportional to the ECRH power P_{ECRH}. By such a way the plasma compensates the local T_e increase in order to keep $p_N(r)$ constant (the density pump-out effect).

One could hope for a peaked density profile in the case of strong off-axis heating [2], but this is not practical in a reactor case. The thermonuclear power from α-particles will be deposited mostly in the plasma core; therefore it is impossible to deposit comparable external power at the plasma periphery. Of course, the ratio between $T(r)$ and $n_e(r)$ may depend on the radial distribution of ionization sources, but it is known that the $T(r)$ profile in a reactor will be peaked. Hence, due to self-consistency of the pressure profile, the density profile has to be flat. This has to be taken into account, when trying to predict future ITER parameter profiles. Only the formation of ITBs in specific regions may help us to organize more peaked pressure profiles in ITER.

Acknowledgments

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