Main features of self-consistent pressure profile formation

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In several works [1-3] it was shown that in tokamak plasma a self-consistent profile of normalized pressure exists, $P_N(r)=P(r,t)/P_0(t)$. Such a profile exists in the whole plasma area except the regions, where the transport barriers (ITBs) are formed. In these regions higher ∇P are permitted. The aim of this T-10 experiment is to show, how this phenomenon depends on plasma parameters.

1. Dependence $P_N(r)$ on plasma density. It is well known that in tokamaks the energy confinement time τ_E has different dependencies on plasma density $\bar{n}_e$: for low densities $\tau_E \sim n_e$, but for higher densities τ_E is practically independent on n_e. Different fluctuation spectra are seen in these two cases [4]. The T-10 tokamak experiments were performed in a wide $\bar{n}_e$ range: from the lowest possible value for given plasma current up to the density limit near to disruption (see figures 1 and 2).

Fig.1. OH. a) temporal evolution of line-averaged density and current; b) $P_N(r)$ for different time instants shown in a).
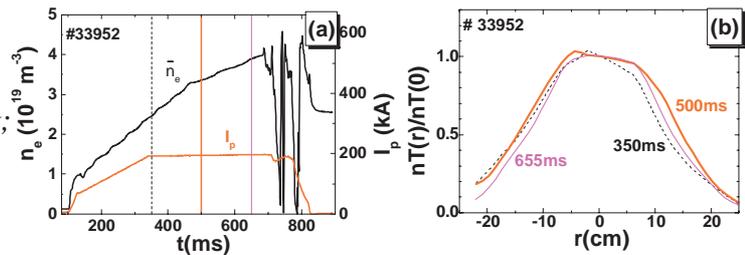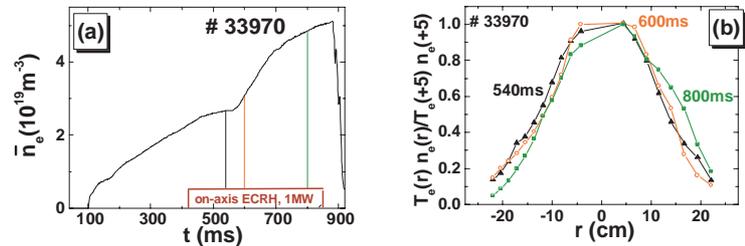

Fig.2. On-axis ECRH. a) time behavior of line-averaged density and EC power; b) $P_N(r)$ for different time instants.

Figures show that for all experiments we have the same $P_N(r)$ profile, which is independent on the type of instabilities.

2. Dependence $P_N(r)$ on the power deposition profile

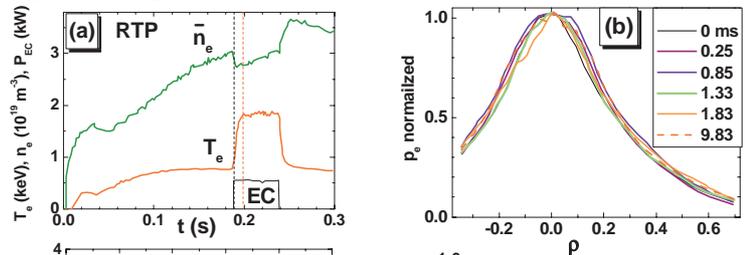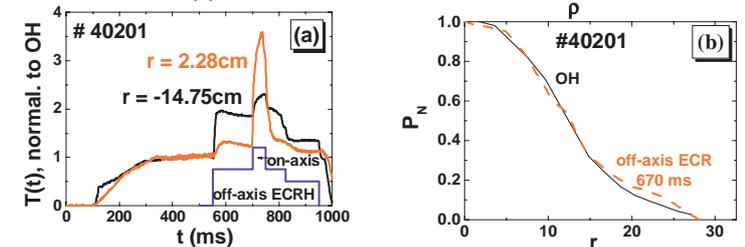*Fig.3. On-axis ECRH on RTP. a) evolution of T_e and n_e. b) $P_N(r)$ during first 10 ms of P_{ECRH}*

Fig.4. Off-axis + on-axis ECRH on T-10. a) time evolution of ECRH and central T_e (r=+2.28 cm) and near heating region (r= -14.75 cm); b) $P_N(r)$ for OH and ECRH.

One can see that $P_N(r)$ does not depend on the power deposition profile**,** and hence on the current density profile $j(r)$.

3. How quickly $P_N(r)$ is formed? As it can be seen from figure 3, $P_N(r)$ conservation is realized even after 0.25 ms, in time much shorter than $\tau_E=3$ ms for given case on RTP. For off-axis ECRH on T-10, the time resolution of reflectometer was 4 ms, and we can say that $P_N(r)$ is formed not longer than this value, which is less than $\tau_E=12$ ms.
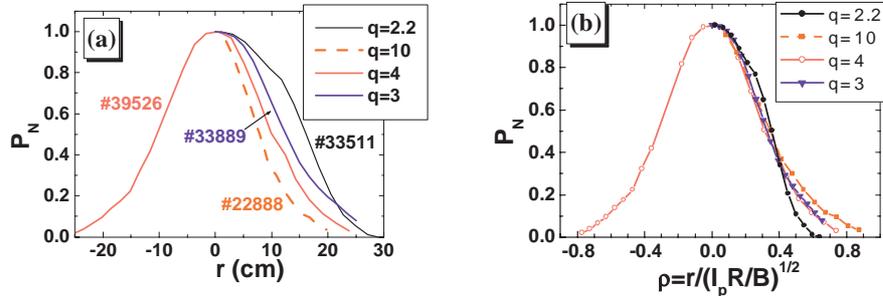

Fig.5. a) $P_N(r)$ for regimes with different edge safety factors q_L; b) the same curves as functions of normalized radius $\rho = r\left/\sqrt{I_p R/B}\right.$.

4. What is happen, when edge q_L is changed?

We can see from figure 5,a that $P_N(r)$ profiles are different under different q_L. Using simple scaling, we can gather all these profiles into the single: we have to normalize r to radius of any magnetic surface outside the plasma current $\rho = r\left/\sqrt{I_p R/B}\right.$, I_p is plasma current, R is major radius, and B is toroidal magnetic field. $P_N(\rho)$ profiles for strongly different q_L are combined, so this profile is practically standing for any regimes. However, for the lowest $q_L=2.2$ the profile in figure 5,b appears to be more steep. In this case the limiter interacts with the hot plasma region, and the discharge is near to disruption. The longest "tail" is seen for $q_L=10$, when the boundary conditions affect faintly, and plasma may have the most energetically advantageous $P(\rho)$ profile. So, we have an unexpected result: FWHM (full width at half maximum) of $P_N(r)$, Δ_{PN}, depends on $\sqrt{I_p}$, but does not depend on $j(r)$. Under ECRH, $j(r)$ profiles are changed in accordance with $j \sim T^{3/2}$, but $P_N(r)$ obeys the previous law. So, $P_N(r)$ is primary defined by the process of self-consistent profile formation.

5. Experiments with rapid plasma current ramp-up

In order to understand the mechanism of $P_N(r)$ formation for different I_p, experiments with rapid plasma current ramp-up were performed. We know, see figure 5 that for higher current the wider $P_N(r)$ has to be formed. How quick will be this transformation? Plasma current was ramped at stationary phase of discharge by 25% during 20 ms, while the current redistribution time was ~200 ms. During the first 50 ms no appreciable j increase expected in 1/3 plasma radius. Experiments were performed either in OH discharge, or when sawteeth were suppressed by off-axis ECRH. As we want to have temporal information about $P_N(r)$ evolution in this dynamic process, we will use the integral description: Δ_{PN}, but we have to be careful, because ITBs, if they exist, may influence this value.

Fig.6. OH+dI/dt. a) P_N for the time instant before dI/dt and 10 ms after it. b) temporal behavior of I_p, Δ_{PN} and phase reversing radius of sawteeth r_S.
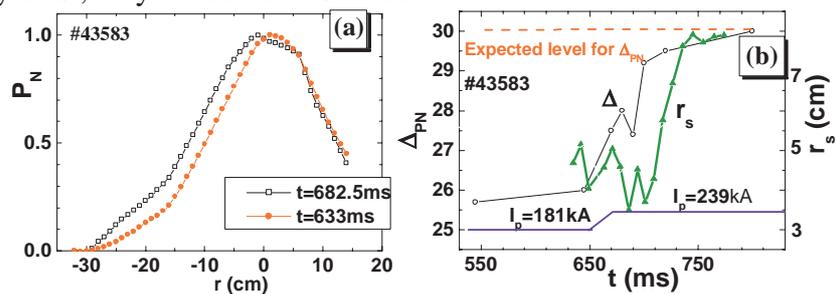
In OH, Δ_{PN} increase during I_p ramp-up occurs essentially faster than the penetration of additional Δj into the plasma core (even change of r_s in figure 6,b begins after $t>50$ ms), so it follows the total current value, but not the current density ptofile.
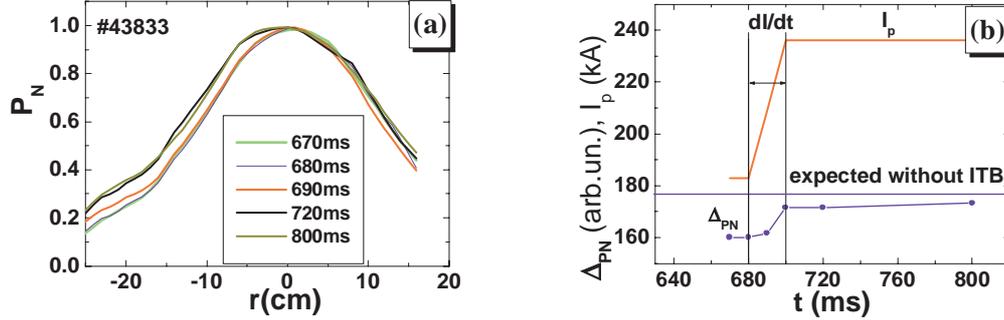

Fig. 7. Off-axis ECRH+dI/dt. a) $P_N(r)$ profiles for different time instants. b) Time change of current I_p and FWHM of normalized pressure profile Δ_{PN}.

In the case, when sawteeth are suppressed by off-axis ECRH, FWHM of $P_N(r)$ increases practically synchronous with I_p ramp, and much faster than the Δj penetrates into plasma core. This result may be explained only by change of equilibrium along the minor radius, as nothing more changes in the plasma core at that time.

6. ASTRA calculations

Using ASTRA code, we calculated $j(r,t)$ during and after current ramp-up. We found that the density of rational surfaces is a very sensitive factor to the plasma profile parameters. The density of rational surfaces $q=m/n$ was calculated under the assumption that numbers m and n are limited: m, $n\leq30$. The experimental $T_e(r,t)$ and $n_e(r,t)$ values were used in calculations.
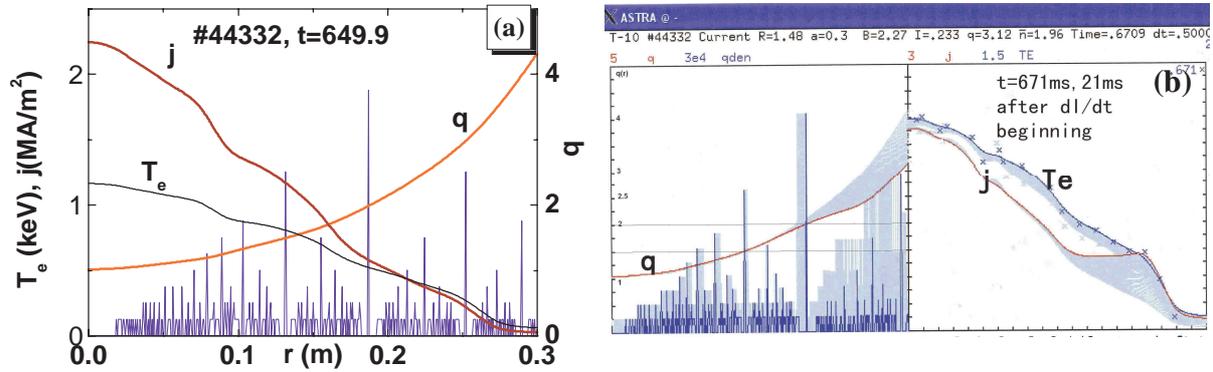

Fig.8. ASTRA calculations. q(r), j(r) and rational surface densities: a) before dI/dt; b) after the current rise; solid curves correspond to the end of current rump-up. The shadow reflects previous positions of curves from the beginning of the ramp-up.

As I_p rises, β_p diminishes and equilibrium along minor radius is changed. Shafranov shift decreases and rational surfaces are displaced to the plasma center. Simultaneously additional Δj penetrates into plasma, and external magnetic surfaces move outside. Density of rational surfaces decreases between these two regions. The changes inside 0.5 plasma radius take place in spite of the additional current still has not penetrated into this region.

$P_N(r)$ width in this experiment (figure 7) does not reach the value expected from scaling $\Delta_{PN}\sim \sqrt{I_p}$ (see figure 5) may be due to ITB formation in the inner plasma part. This is supported by experiment with the short on-axis ECRH at different phases of discharge (figure 9). We see that in the case of heating just after the current ramp-up, the effect of the temperature increase 2 times higher than without current ramp-up, and 2.4 times higher than

in OH case. Evolution of $T_e(r)$ shows that during the first 3 ms, T_e increases inside $r=\pm 6$ cm, and later inside $r=\pm 16$ cm, so ITBs are formed in experiment with current ramp-up.

Fig.9. a) Effect from the short on-axis ECRH in different conditions: OH, off-axis ECRH without current ramp-up and with current ramp-up. b) Changes of $T_e(r)$ during first 18 ms after on-axis ECRH start for the same regime as presented in figure 7.
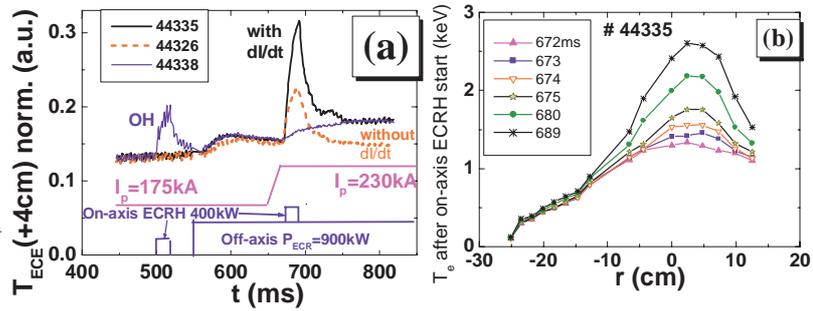
6. Discussion and conclusion

Two important effects take place in plasma: self-consistent pressure profile and ITB formation. This makes difficulties in the experimental data analysis. In figure 10 we presented schematically our idea of it: if ITB exists in plasma, in order to see self-consistent pressure profile, we need to exclude the ITB region and connect the ends of P_N profiles, lowering the inner part. Using the integral characteristics, like density peaking, one can do a mistake, if a pronounced ITB exists in plasma. If we isolate ourself from ITB effects, we can conclude from experiments described above that self-consistent pressure profile $P_N(r)$ is formed everywhere, except the ITB regions and does not dependent on the type of instability spectrum. Under rapid changes of external impacts, $P_N(r)$ rehabilitates itself in the time much shorter than the diffusion one. Under rapid change of current or $\beta_p \sim 1/I_p^2$, the width of $P_N(r)$ follows this change in spite of that in the inner part of plasma only equilibrium along minor radius is changed. So our conclusion is: the self-consistent profile links with plasma equilibrium.
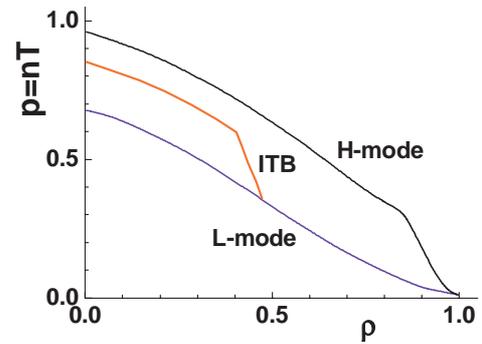

Fig.10

Scheme of pressure profiles with transport barriers and without them.

Effect of self-consistent profile will be in a tokamak-reactor (ITER) also. We have to take it into account. Only the ITB formation may help us to organize more peaked pressure profile in ITER.

References

[1] Yu.V. Esiptchuk and K.A. Razumova, Plasma Phys. Control. Fusion 28 1253 (1986)

[2] Yu.N. Dnestrovskij et al., Plasma Phys. Reports 31 529 (2005)

[3] K.A. Razumova et al., Plasma Phys. Control. Fusion 48 1373 (2006)

[4] V.A. Vershkov et al., Nucl. Fusion 45 S203 (2005)