Study of an Anomalous Pinch Effect in the T-11M Tokamak

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Abstract. The peaked density profiles $n_e(r)$ are typical for tokamaks with ohmic heating. This contradicts to the fact that the sources of plasma – gas puffing and hydrogen recycling are localized in plasma periphery. Usually one try to resolve this contradiction by assumption of impurity accumulation or development of neoclassical Ware pinch or by supposition of its version - turbulence-driven particle pinch. In the T-11M experiments with Li-limiter, where impurity effects were excluded and plasma collisionality was rather high ($\nu^* \approx 0.5$), the peaked density profiles $n_e(r)$ have been observed also and this seems to be an evidence of plasma density accumulation (anomalous pinch effect). The measurements of $n_e(r)$ were carried out with help of five-channel jump-free Cotton-Mouton interferometer (polarimeter) using the conventional Abel-procedure. The $n_e(r)$ profiles can be approximated by set of parabolas: $n_e(r) = n_e(0)\cdot(1- r^2/a^2)^{\alpha}$. The alpha parameter was an indicator of profile peaking and varied in range from 0.3 to ≈1.5. The analysis of experimental results showed that the formation of bell-shaped profile $n_e(r)$ with $\alpha \approx 1.5$ in condition of internal gas puffing can take place only under strong plasma influx from the periphery to the plasma center (along the gradient of $n_e(r)$) with velocity about of 3-4 m/s, which is 3-5 times more than assumed velocity of neoclassical Ware pinch. This effect does not depend on plasma purity and it is observed both with lithium and graphite limiters. Visible anomalous pinch effect increased following the growth of n_e. Any assumptions about influence of direct flux of neutral atoms on creation of $n_e(r)$ profile are eliminated thereby. The development of convective transport processes from the periphery to the plasma core seems to be the most probable reason of peaked profiles $n_e(r)$ generated in conditions of a peripheral source.

1. Introduction

It is known, that the typical profiles of electron density $n_e(r)$ in tokamaks with ohmic heating have a bell-shaped form with a maximum in the center, while hydrogen puffing and recycling are usually produced in plasma column periphery. Taking into account that free paths of cold hydrogen neutrals ionization and their charge-exchange length are usually much less than plasma minor radius, one can expect that source of charged particles flux to plasma will be localized in plasma periphery within mean square of hydrogen charge-exchange and ionization free paths. Formation of the bell-shaped profile $n_e(r)$ obviously contradicts to these common conceptions.

Usually one tries to remove this contradiction by assumption or accumulation of impurities near plasma column axis or development of neoclassical Ware pinch. However in a number of cases [1-4], when the influence of impurities could be neglected, the velocity of plasma movement to the plasma core required for the explanation of observed profiles $n_e(r)$, should be several times higher than a possible velocity of a neoclassical pinch. As soon as the phenomenon is observed in collisionless region, where a collisionality is $\nu^* = 10^{-1}$-10^{-2} [1], it could be considered as an anomalous form of pinch effect.

In the Li limiter experiments on the T-11M tokamak (B_T=1 T, R/a= 0.7/0.2 m, J_p=100 кA, $t_{shot} \leq 300$ ms [5]) the parameter of collisionality was approximately $\boldsymbol{\nu}^* \sim 0.5$ or higher (close to "plato" regimes). Also, in our experiments, Z_{eff} was equal to 1.1±0.1**,** and the influence of impurities on the density profile could be neglected. However, similar "bell"-shaped $n_e(r)$ profile is formed when n_e is growing up which is a direct evidence of the plasma pinching even at relatively high collision frequency. The estimated lower level of observed pinch velocity is 4±1 m/s, which is 3-5 times higher than possible neoclassical value. The investigation of this phenomenon is the main goal of the present work.

2. Experimental.

A main distinctive feature of experiments on the T-11M tokamak was the use of lithium limiter instead of conventional graphite one. It provides an operation with suppressed hydrogen recycling from the vacuum vessel walls. Moreover, the present design of the lithium limiter provides quasi-stationary plasma discharge mode with very pure hydrogen plasma [5], when the limiter temperature and main plasma parameters were almost constant during the time interval a few times more than the energy confinement time τ_E. One of the typical shot is presented in Fig. 1 [5], where the waveforms of total current $J_p(t)$, loop voltage $U_p(t)$, total radiation flux from the plasma center – MRL(t), mean electron density $N_e(t)$, limiter temperature $T_{lim}(t)$, parameter $Z_{eff}(0)/q(0)$ and electron temperature $T_e(t)$, are shown. The most important feature of such T-11M regimes is constancy of parameter $Z_{eff}(0)/q(0) \approx 1$, which was calculated by standard method from measurements: $T_e(0)$ from SXR, and loop voltage $V_p(t)$. If we assume from saw-teeth activity, that q(0) is equal 1, Z(0) should be close to 1 as well, which gives an evidence of quite clean hydrogen plasma in the plasma core.

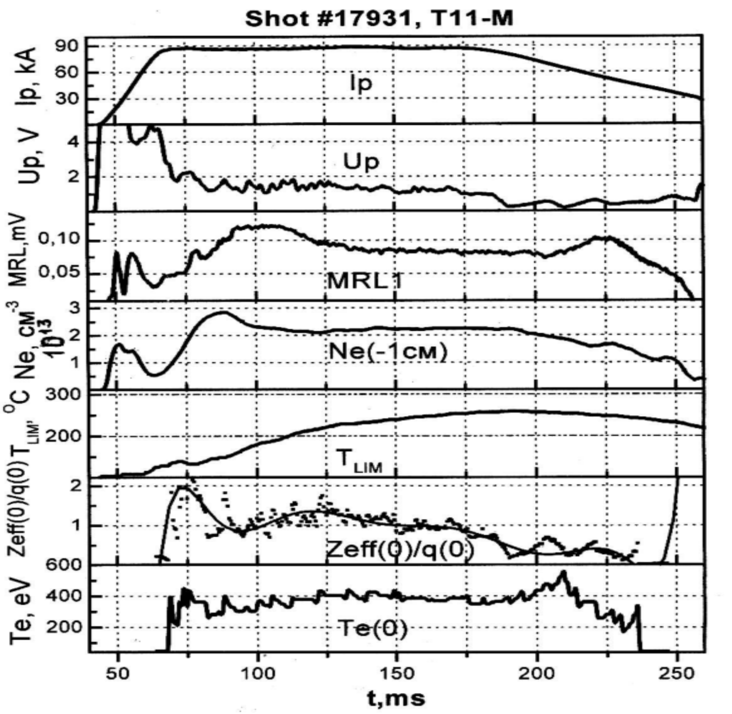

Fig. 1. Waveforms of plasma main parameters in the experiments with liquid Li limiter.

The low level of hydrogen recycling is a common feature of all discharges with Li limiters and the first wall covered by lithium. The main reason of recycling decrease is an effective absorption of hydrogen isotopes D^+ and H^+ at the wall. The low recycling requires the increase of gas puffing. If you switch off gas puffing, you can see a density collapse with characteristically time close to the particle confinement time τ_p**.** Sometimes, we used this feature of T-11M discharge for the upper estimation of τ_p.

The hydrogen (deuterium) puffing was implemented in the limiter region. The main sources of hydrogen influx: puffing, recycling and release from the lithium surface during the heating of Li limiter (dotted line) were localized in limiter region.

It is well known, that intensities of hydrogen spectral lines are proportional to total hydrogen influx into the plasma. Hence it could be monitored by observation of hydrogen lines. The intensity of H_γ line as indicator of total influx of hydrogen is shown in Fig.2b. The absolute calibration (in electrons) was made by comparison of H_γ intensity and the derivative dN_e/dt measured during the shutdown of the gas puffing (Fig.2b). From the evolution of H_γ emission and of the total number of charged particles $N_e(t)$, an average particle confinement time τ_p could be estimated. This value increases from 10 to 40 ms during the discharge (Fig.2e).

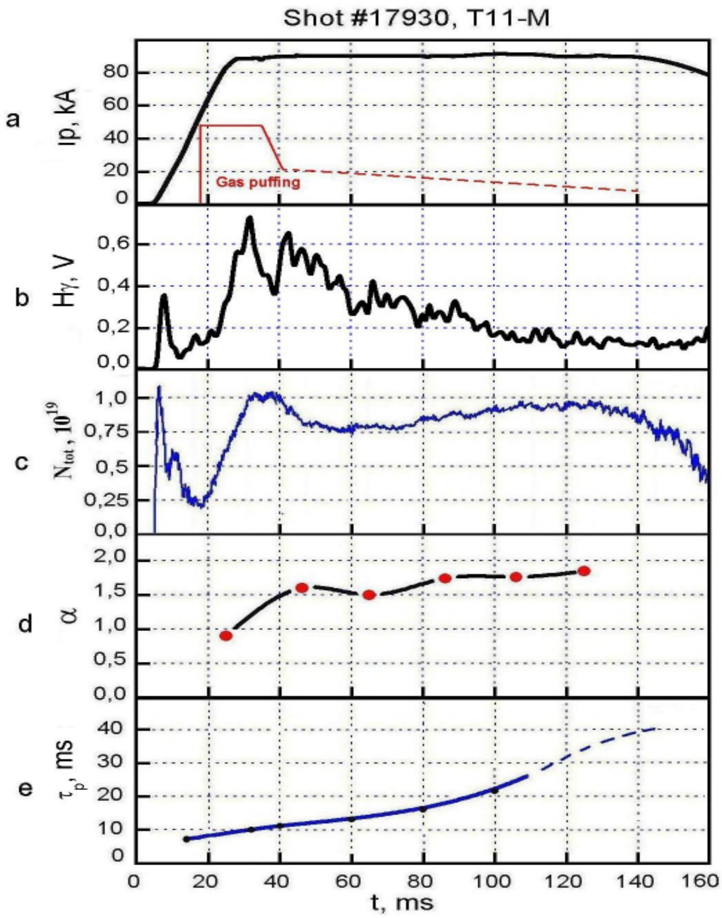

Fig. 2. The evolution of $J_p(t)$, H_γ emission, the total number of electrons, α–factor and average particle confinement time τ_p.

Unfortunately, since all these measurements are not absolutely correct, since we do not take into account the lithium influx to plasma column during the discharge. However, this influx is quite small and constant during the discharge, relying on the behavior of lithium emission. It does not affect considerably the measurements of τ_p in initial and middle stages of the discharge. But in the final stage, when intensity H_γ drops down, the influence of lithium could be remarkable. This uncertainty is shown in Fig.2e by the dotted line. The energy confinement time in quasi-stationary phase of the discharge is $\tau_E \sim$ 7-10 ms.

3. Measurements of electron density

The measurements of electron density were carried out with the help of five-channel jump-free Cotton-Mouton interferometer (polarimeter) [6]. The instrument measures the phase difference between an ordinary (**E**||**B**) and an extraordinary (**E** $\perp$ **B**) waves passed through the plasma along the same five (-13 cm, -5 cm, -1 cm, +7 cm and +11 cm) vertical chords. When simultaneously probing plasma by an ordinary and an extraordinary waves, the phase difference between them after passing through the plasma is determined by the expression (for the vertical central channel) [6, 7, 8]:

$$\Delta\Phi_{o,e}(\omega,x) = \frac{\omega}{c}\cdot\int_l \Delta\eta_{o,e}(\omega,x,z)dz \approx 2.45\cdot 10^{-11}\cdot\lambda^3\cdot B_T^2(x)\cdot\int_l n(x,z)dz, \quad (1)$$

where $\Delta\eta_{o,e}$ is the difference between the refractive indices for the ordinary and extraordinary waves and λ is the wavelength of the probing wave. Here, we take into account that, for a tokamak, the poloidal field is $B_{pol} \le 0.1\cdot B_T$, and the total magnetic field **B** is replaced with the toroidal magnetic field B_T. By properly choosing the wavelength, the phase shift in the plasma can be made less than 2π. In particular, for the T-11M tokamak, the probing radiation wavelength must be no longer than 2.2 mm. In our experiments, we used a microwave oscillator with a wavelength close to 2 mm. Detailed information on the operating principles of the polarization interferometer and on scheme of measurements is given in [6].

In multi-channel measurements, the numerical solution of the equation for evolution of a state of polarization of a probing wave in plasma has been used, in order to take into account the influence of Faraday effect on plasma density measurements [9]. The method applied for the numerical solution is described in [10].

The profiles $n_e(r)$ were reconstructed using conventional Abel inversion procedure [11]. In Fig. 3, an example of time evolution of reconstructed profiles is presented. The profiles were approximated by a set of parabolas: $n_e(r) = n_e(0)\cdot(1- r^2/a^2)^\alpha$. Thus, the parameter α is the profile peaking factor. During the plasma shot it increased from $\alpha \approx 0.3$ to a quasi-stationary value $\alpha \approx 1.5$-1.7 (Fig.1). This peaking of density profile is clear visible in the Fig. 3.

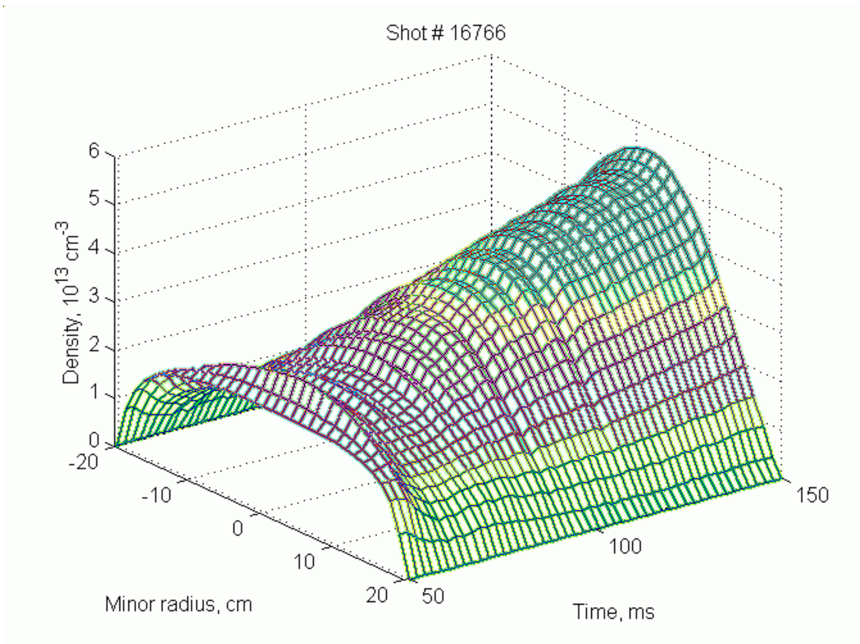

Fig. 3. Time evolution of density profile for shot #16766.

As we can see from the Fig. 2d, the value of $\alpha \approx 1.5$ is reached in the process of gas puffing and it is remained almost constant during the quasi-stationary phase. This time evolution is consistent with the global tendency of α variation versus the electron density (Fig. 4). It seems to be that this dependence of α versus electron density is universal. We can see from the Fig. 4, that it does not depend on the kind of impurity (carbon, lithium). It is possible that the dependence is result of some dramatical evolutions, which takes place in plasma column when n_e is approaching to the Greenwald limit.

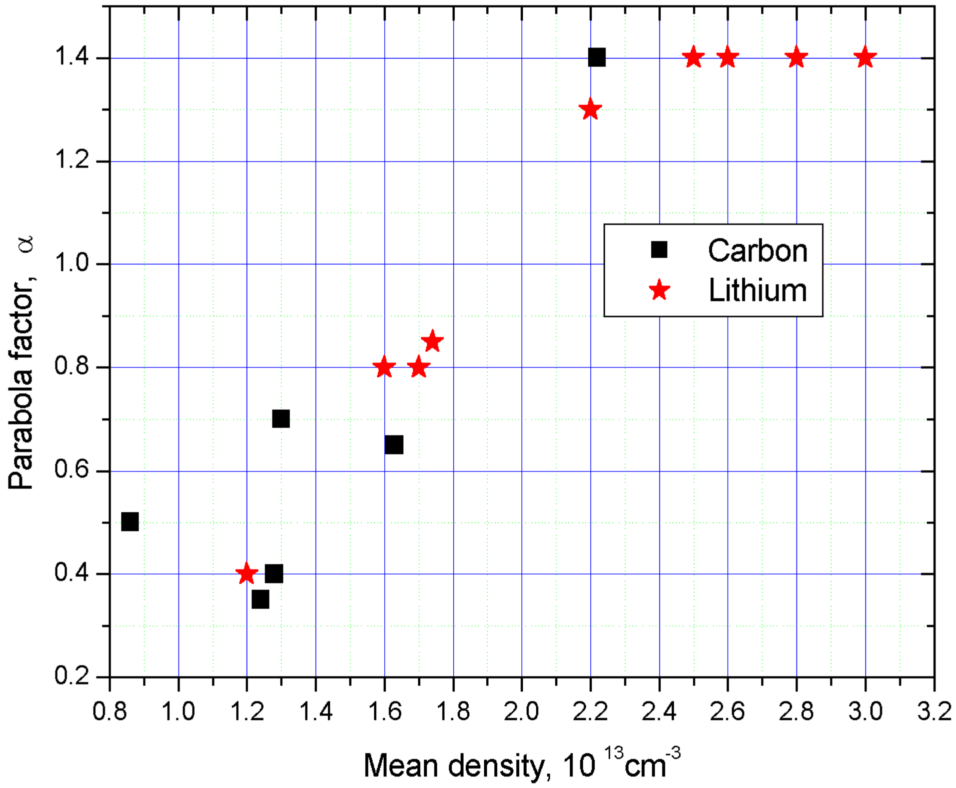

Fig. 4. Parabola factor α versus mean density in shots with Li- and C-limiters.

4. Discussion

What processes are responsible for the formation of peaked $n_e(r)$ profile, if the main sources of the influx of hydrogen are localized in plasma peripheral?

The penetration of hydrogen atoms into the plasma core was modeled by the Sigma+ code [12], which has been corrected to actual τ_p values in the T-11M (in the original version $\tau_p=2\tau_{Ee}$). It was shown, that more than 80% of neutral flux should be localized in the region r/a>0.8. Note, that almost total lithium light emission (and obviously lithium ionization) is localized in the same layer with thickness of 4-5cm. Only 1% of the total flux of hydrogen atoms could penetrate into the region r/a < 0.5. That means, the total source of injected electrons is localized in the region r/a > 0.8 and compensates plasma diffusion losses in quasi-stationary situation. We have to suppose, that formation of bell-shaped profile $n_e(r)$ in regimes with $\alpha \approx 1.5$ (Fig. 4) can take place under strong plasma influx from periphery to the center (along the gradient $n_e(r)$), compensating the main diffusion loss. If we suppose this flux in the form: $2\pi r n_e(r) V_r$, it should be equal to $2\pi \cdot r \cdot D \cdot dn_e(r)/dr$ and hence, $V_r = D \cdot \frac{d(\ln(n(r))}{dr}$, where D is the plasma diffusivity, and V_r is plasma convective transport velocity to the center. The experiments with low hydrogen recycling demonstrated, that the shape of $n_e(r,t)$ profile remains almost constant even during the density collapse. That might be considered as an evidence of D-constancy across plasma column. If we suppose, that D is constant in region r/a=0.8 and in region of highest $n_e(r)$ gradient (0.5-0.6 = r/a) and take into account that τ_p = 20±5ms (Fig. 2e), the velocity V_r in this region could be calculated. It is of 3-4 m/s, which is 3-5 times more than the assumed velocity of neoclassical Ware pinch in the actual conditions of the T-11M with $\nu* \approx 0.5$. This effect could not be explained by central impurity accumulation, since otherwise it should be accompanied by increase of Z_{eff} in the center up to the value of ~10 contradicting to the observed value 1 (Fig.1). The effect does not depend on the plasma purity, as could be derived from Fig. 4. It is observed both in conditions of lithium and graphite limiter. In the last case the radiation losses of plasma center increase almost by an order of magnitude higher in comparison to the lithium one. The effect rises with the growth of n_e (above 0.4 n_{eG} level). Any assumptions on the influence of the direct influx of neutral atoms on the creation of $n_e(r)$ profile are eliminated thereby.

The development of convective transport processes from the periphery to the plasma core seems to be the most probable reason of peaked profiles $n_e(r)$ generated in conditions of a peripheral source, originating from the increase of density n_e towards the Greenwald limit.

4. Conclusions

In the T-11M experiments with Li-limiter in quasi-stationary regimes, where impurity effects were excluded and plasma collisionality was rather high ($\nu^* \approx 0.5$), the peaked density profiles $n_e(r)$ have been observed, which seems to be an evidence of plasma density accumulation (anomalous pinch effect). The analysis of experimental results showed that the formation of peaked profile $n_e(r)$ in condition of internal gas puffing can take place only under strong plasma influx from the periphery to the plasma core (along the gradient of $n_e(r)$) with the velocity of 3-4 m/s, which is 3-5 times higher than the assumed velocity of neoclassical Ware pinch. This effect does not depend on plasma purity and it is observed both in conditions of lithium and graphite limiters. The visible anomalous pinch effect increases in following the growth of the n_e. The development of convective transport processes from the periphery to the plasma core seems to be the most probable reason of peaked profiles $n_e(r)$ generated in conditions of a peripheral source, originating from the increase of density n_e above the 0.4 n_{eG} level.

Acknowledgments

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5. References

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