TRANSITION TO THE IMPROVED CONFINEMENT MODE IN TORSATRON U-3M IN RANGE OF RARE COLLISION FREQUENCIES

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Transition to the mode of improved plasma confinement in U-3M facility earlier was discussed in works [1-3]. In these studies discussed the various processes in the confinement volume and in the peripheral plasma that accompany the transition process. Study of plasma confinement and process of transition into the mode of improved confinement just at rare collisions between plasma particles is very important because future fusion reactor based on a toroidal magnetic trap will operate under plasma parameters with rare collision frequencies ("banana" mode). The peculiarity of experiments on torsatron U-3M is that they are conducted at small density $\overline{n}_e \le 2\times10^{12}$ cm^{-3} and, thereby, the frequency of collisions in the confinement area is in the "banana" mode [4]. And herewith, time of collisions is essentially smaller (up to several orders for electrons and up to the order for ions) than the lifetime of plasma particles. It ensures maxwellization of distribution function and possibility to compare the obtained results with data from other experiments. The objective of this work is to study the main regularity of transition into the mode of improved confinement. Also it is interesting to compare the results with data from other facilities.

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1. EXPERIMENTAL CONDITIONS AND RESULTS

In torsatron U-3M (l = 3, N = 9, R = 1 m, $a \approx 0.10$ m, $B_\phi \approx 0.7$ T, rotational transformation angle $\iota/2\pi \le 0{,}4$) hydrogen plasma is generated and heated using RF-frame-antenna on $\omega \approx 0.8\omega_{Bi}$ frequency [5], where ω_{Bi} is ion cyclotron frequency. Typical feature of the magnetic system of U-3M facility is allocation of helical winding inside the vacuum volume of 70 m^3 much bigger than the volume of the confined plasma and presence of natural helical divertor.

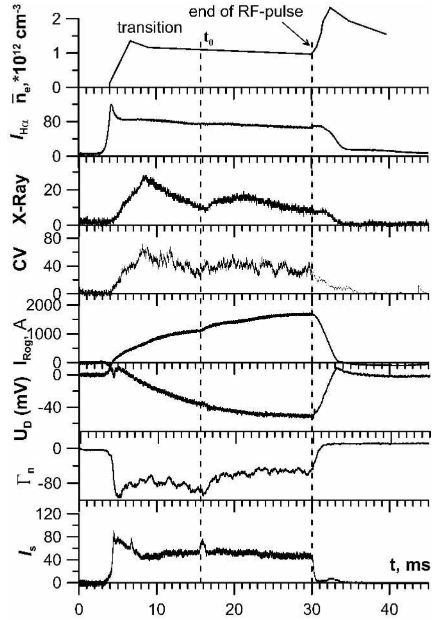

Fig. 1. Temporal behavior of main parameters of discharge that is registered in this experiment

Temporal behavior of the main plasma parameters measured in this experiment is given in the Fig. 1: $\overline{n}_e$ – average plasma density, intensity of line glow $I_{H\alpha}$, R_x – intensity of the soft X-Ray radiation, I_{CV} – glow of carbon line CV (λ = 2271 Å), I – longitudinal plasma current, U_D – signal from the diamagnetic coil, intensity of flow of charge atoms Γ_n with energy of 1575 eV and ion saturation current I_s from Langmuir probe that is allocated outside the confinement area. Vertical dotted lines mark the times of transition into the mode of improved confinement and the time of RF-pulse end.

It is clear, that the time of transition into the mode of improved confinement is clearly observed on plasma current behavior ($\partial I/\partial t$ is changing) and signal from Langmuir probe. Effect from change of plasma confinement is clearly observed on behavior of plasma current of high-energy charge exchange of atoms, X-Ray signal and glow of CV line. At the same time, plasma density, glow of H_α and signal from diamagnetic loop have slight reaction to this transition.

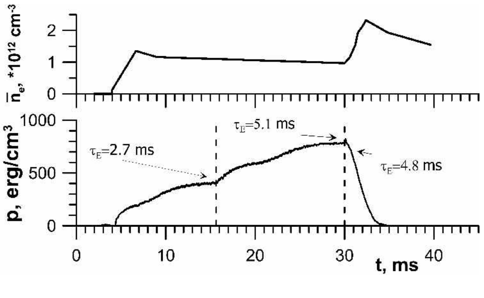

Fig. 2. Temporal behavior of plasma pressure calculated from diamagnetic measurements, $p=n_eT_e+n_iT_i$, where T_e and T_i – electron and ion temperatures, $\overline{n}_e$ – average plasma density

Fig. 2 gives temporal behavior of plasma pressure calculated from diamagnetic measurements, $p=n_eT_e+n_iT_i$, where T_e and T_i – electron and ion temperatures, $\overline{n}_e$ – average plasma density. From Fig. 2 it is clear that plasma pressure increases rapidly in the moment of transition. From the equation of power balance

$$\frac{3}{2}\frac{\partial}{\partial t}pV+LI\frac{\partial I}{\partial t}+\frac{3}{2}\frac{pV}{\tau_E}+\Omega I^2=W\,, \quad (1)$$

where τ_E – energy lifetime of plasma, V – volume of confinement area, L – inductance of plasma filament, I – longitudinal plasma current, Ω – plasma resistance, it appears that during rapid change of input power W in the time t

$$\tau_E=-\frac{p(t)}{\left.\frac{\partial p}{\partial t}\right|_t+\frac{LI}{V}\left.\frac{\partial I}{\partial t}\right|_t+\varepsilon\frac{\partial n}{\partial t}}\,. \quad (2)$$

Here ε – energy spent on dissociation, ionization of plasma.

In the time of transition into the mode of improved confinement $t = t_0$ consider that input power didn’t change after transition and till the end of RF-pulse, the following ratio is fair

$$\frac{1}{p}\left(\left.\frac{\partial p}{\partial t}\right|_{t_0}+\frac{LI}{V}\left.\frac{\partial I}{\partial t}\right|_{t_0}\right)=\frac{\tau_{E2}-\tau_{E1}}{\tau_{E2}*\tau_{E1}}\,. \quad (3)$$

If to assume that τ_{E1} is energy lifetime before the transition, τ_{E2} – after transition and in the moment when the energy content of plasma goes to the station ($\partial p/\partial t \to 0$), then, in terms of our experiment

$$\frac{\tau_{E2}}{\tau_{E1}}=\frac{p_2+\frac{L}{2V}I_2^{\,2}}{p_1+\frac{L}{2V}I_1^{\,2}}=1.9\,. \quad (4)$$

Here, p_1, I_1 and p_2, I_2 are pressure and current in plasma before and after the transition at the end of RF-pulse, respectively. Using expressions (3) and (4), considering the smallness of $L\sim10^{-6}$, it is easy to obtain τ_{E1} = 2.7 ms, τ_{E2} = 5.1 ms. After the end of RF-pulse, the value τ_E was determined by plasma pressure drop [6] and by expression (2). The value τ_E came to 4.8 ms. Proximity of values τ_E and τ_{E2} indicates that our assumption on constancy of power implemented into plasma during pulse duration is fair. The implemented power was

$$W=\frac{3}{2}\frac{p_2V}{\tau_{E2}}+I_2^{\,2}\Omega\approx 9\text{ kW}. \quad (5)$$

Change of expression (1) for power balance in comparison with [6,7] due to the fact that in modes with bootstrap-current at rather big value of $\beta=\frac{8\pi P}{B^2}$ the energy, stored in the magnetic field of plasma current $LI^2/2$ is comparable and even exceeds the energy content of plasma. In the present experiments $\frac{LI^2}{2PV}=2\beta\frac{R}{a\iota^2}\leq 0.6$.

The existing stellarator scaling ISS95 [8] gives value of energy confinement time for plasma parameters in the investigated mode $\tau_E^{ISS95}\approx 1{,}9$ ms.

Reactor scaling LHD [9] forecasts $\tau_E^{LHD}\approx 3.4$ ms. It is clear that experimentally obtained values of τ_E before the transition into the mode of improved confinement are between data of these scalings $\tau_E^{ISS95}<\tau_{E1}<\tau_E^{LHD}$. After the transition the energy confinement lifetime is τ_{E2} = 5.1 ms > $\tau_E^{LHD}\approx 3.4$ ms.

The transition into the mode of improved confinement took place at $\overline{n}_e\approx 1.1\times10^{18}$ m^3. The value of power per one particle in time of transition was $W/V\overline{n}_e\approx 0.4\times10^{-19}$ MW/particle that matches the results obtained on other stellarators (Liven' – 2 [10], CHS [11]). Data which is given according to results of experiments on these stellarators shows that in the time of transition into the mode of improved confinement $W/V\overline{n}_e$ = (0.2…0.32)$\times10^{-19}$ MW/particle. It should be noted that experiments on U-3M differ essentially from experiments of L-2 and CHS. The difference is in both in the parameters of the discharge, and the parameters of the magnetic system. The plasma density in U-3M is almost one order lower than in L-2 and CHS, and because of this the transition into the improved confinement takes place in “banana” area. Besides, U-3M is a three-thread torsatron with natural helical divertor unlike two-thread L-2 and CHS, where open divertor is absent.

The conducted experiments showed that transition into the mode of improved confinement occurs at rather wide range of changes of initial conditions of the charge. Puffing of working gas was changed in the range of p_0 = (0.6…1.1)$\times10^{-5}$ Torr, anode voltage on the output lamp of RF-generator change as U_A = 7.5…8.5 kV. At the same time, in the moment of transition the plasma parameters also changed in a wide range $\overline{n}_e$ = (0.9…1.25)$\times10^{12}$ cm^{-3}, plasma current I = 900…1100 A, gas-kinetic plasma pressure p = 380…420 erg/cm^{-3}.

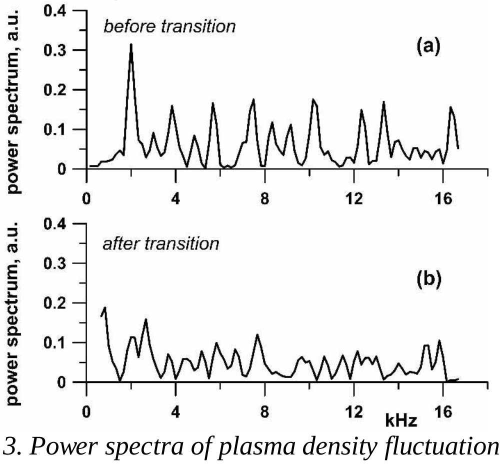

Fig. 3. Power spectra of plasma density fluctuations in the confinement volume before and after transition to the improved confinement

Evidently, the process of restructuring the plasma pressure profiles during the process of transition into the mode of improved confinement can be associated with the change of plasma turbulence. In our experiments we conducted the study of fluctuations of plasma density in the confinement volume in the frequency range of 1…20 kHz. The results are given in the Fig. 3. It is clear that after the improvement of plasma confinement the fluctuation level of plasma density decreases in almost 2 times and the frequency spectrum of fluctuations changes at the same time.

Fig. 4 (a, b) shows the temporal behavior of the averaged current (current fluctuations are averaged) close to the moment of transition into the mode of improved confinement. It is clear that before the change of the current derivative is the time period of 130 μs is observed, where current changes abruptly its behavior. Apparently, this is a transit period during which the profile *p*(r) restructuring occurs.

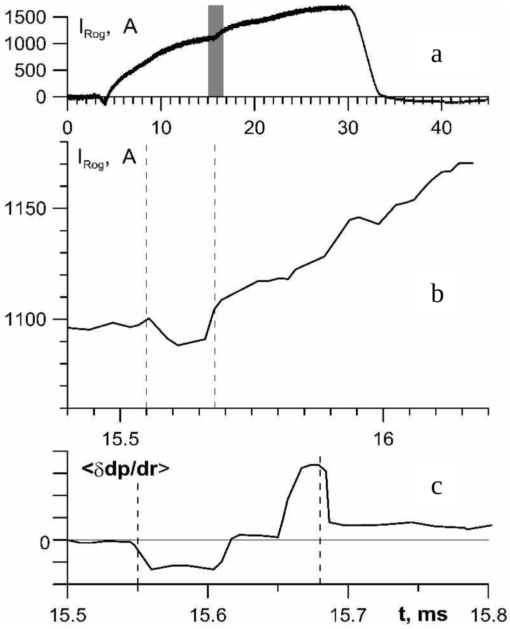

Fig. 4. The temporal behavior of the averaged current (current fluctuations are averaged) close to the moment of transition into the mode of improved confinement. Also changing of profile p(r) is presented

As it was shown in the work [12], the calculation of bootstrap-current in U-3M is similar to calculations for tokamak. According to neoclassical theory [13]

$$j_{\parallel} = j_{BS} + \sigma_{\parallel} E_{\parallel} \ , \qquad (6)$$

where j – is longitudinal current density, $j_{BS} \approx \sqrt{\frac{R}{r}} \frac{c}{B\iota/2\pi} \frac{\partial p}{\partial r}$ - is bootstrap-current density, $\sigma_{\parallel}$ - longitudinal conductivity, $E_{\parallel}$ – longitudinal electric field. From (5), considering that $E_{\parallel}$ does not depend on *r*, it is easy to obtain an expression that coincides with the famous expression of electrical engineering

$$L\frac{\partial I}{\partial t} + I\Omega = U \ . \qquad (7)$$

Here, L – inductance of plasma filament $\Omega = \frac{R}{\int_0^a \sigma_{\parallel}\, rdr}$ - resistance of plasma filament and $U = \frac{2\pi R}{\int_0^a \sigma_{\parallel}\, rdr} \int_0^a j_{BS}\, rdr$.

The expression that describes the change of gradient of plasma pressure in conditions of transition into the mode of improved confinement according to the expression (6) for fast changes of current, has the following form

$$\tau \frac{\partial I}{\partial t} = 2\pi \frac{c\sqrt{R}}{B} \int_0^a \frac{\partial p}{\partial r} \frac{r^{1/2}}{\iota/2\pi} dr \,, \qquad (8)$$

where τ=L/Ω. Temporal behavior of the plasma pressure gradient $\left\langle \delta \frac{\partial p}{\partial r} \right\rangle = \int_0^a \frac{\partial p}{\partial r} \frac{r^{1/2}}{\iota/2\pi} dr$ in the process of transition into the mode of improved confinement, is given in the Fig. 3 (c). It is clear that decrease of plasma pressure gradient is observed in the initial period of transition stage. However, later the increase of pressure gradient occurs. Velocity of the heat wave is $a/\tau_E^e \approx 10^2$ m/s (τ_E^e - energy lifetime in electron channel). As we can see in the Fig. 4, the time of pressure profile change is less than 30 ms. During this period of time, the pressure profile can be changed on average less than on 0.3 cm. Such a small profile change can result in essential change of τ_E only if changes occur on plasma edge.

2. CONCLUSIONS

1. Transition into the mode of improved plasma confinement is observed in experiments on torsatron U-3M at low plasma density ($\bar{n}_e \le 1{,}2\times10^{18}$ m^{-3}) and rare frequencies of collisions, which is illustrated by single-stage change of energy life time.
2. During the transition the energy life time changes on this mode from τ_E = 2.7 ms to τ_E = 5.1 ms with constant power introduced into plasma. The improvement of energy life time reaches value of 2 times.
3. Power density per one particle in the time of transition makes $W/\bar{n}_e V$ = 0.4×10^{-19} MW/particle and is in the range which is the same for other facilities (L-2, CHS) that conduct experiments at plasma density $\bar{n}_e \ge 1\times10^{19}$ m^{-3}. It's evidence of the universality of processes that result in transition into the improved mode for facilities with different parameters and methods of plasma heating.
4. The process of transition into the mode of improved confinement lasts for about 130 μs and is related to the processes in the area of plasma confinement, understanding of which requires further studies.
5. Decrease of density fluctuation level in almost 2 times is observed in the low-frequency range 1…20 kHz in confinement region.

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ПЕРЕХОД В РЕЖИМ УЛУЧШЕННОГО УДЕРЖАНИЯ В ТОРСАТРОНЕ У-3М В ДИАПАЗОНЕ РЕДКИХ ЧАСТОТ СТОЛКНОВЕНИЙ

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Переход в режим улучшенного удержания в торсатроне У-3М ранее обсуждался в работах [1-3]. Будущий термоядерный реактор будет работать в режиме редких частот соударений, вот почему изучение работы торсатрона У-3М, где реализован такой режим, несомненно, полезно. Особенностью экспериментов в торсатроне У-3М является то, что они проводятся при небольшой плотности $\leq 2\times10^{12}$ см$^{-3}$, благодаря чему и реализуется "банановый" режим в [4]. Время столкновений частиц в такой плазме существенно меньше (до нескольких порядков для электронов и до порядка для ионов), чем время жизни частиц плазмы. Это обеспечивает максвеллизацию функции распределения и возможность сравнить полученные результаты с данными других экспериментов. Целью данного исследования является изучение основных закономерностей перехода в режим улучшенного удержания. Также интересно сравнение с данными других установок.

ПЕРЕХІД В РЕЖИМ ПОКРАЩЕНОГО УТРИМАННЯ В ТОРСАТРОНІ У-3М В ДІАПАЗОНІ РІДКІСНИХ ЧАСТОТ ЗІТКНЕНЬ

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Перехід в режим покращеного утримання в торсатроні У-3М раніше обговорено в роботах [1-3]. Майбутній термоядерний реактор буде працювати в режимі рідкісних частот зіткнень, ось чому вивчення роботи торсатрона У-3М, де реалізовано такий режим, безсумнівно, корисно. Особливістю експериментів у торсатроні У-3М є те, що вони проводяться при невеликій щільності $\leq 2\times10^{12}$ см$^{-3}$, завдяки чому і реалізується "банановий" режим в [4]. Час зіткнень часток в такій плазмі істотно менше (до декількох порядків для електронів і до порядку для іонів), ніж час життя частинок плазми. Це забезпечує максвеллізацію функції розподілу і можливість порівняти отримані результати з даними інших експериментів. Метою даного дослідження є вивчення основних закономірностей переходу в режим покращеного утримання. Також цікаве порівняння з даними інших установок.