RF DISCHARGE DYNAMICS WITH PASSING OVER L- AND H-LIKE MODE STATES IN THE URAGAN-3M TORSATRON

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In the l=3 Uragan-3M torsatron a hydrogen plasma with the density $\overline{n}_e \sim 2\times10^{12}$ cm^{-3} is produced and heated by RF fields in the $\omega \lesssim \omega_{ci}$ range of frequencies with using a frame-like antenna. Time variations are considered of (1) density $\overline{n}_e$ and electron cyclotron emission at different values of the RF power fed to the antenna; (2) fast ion generation and loss; (3) edge electric field E_r and edge turbulent transport. Obtained results are of importance for (1) subsequent production and heating of denser plasmas; (2) understanding of processes resulting in the observed transition to the H-like confinement mode.

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INTRODUCTION

In the l=3 "Uragan-3M" (U-3M) torsatron with an open natural helical divertor the plasma is produced and heated by RF fields in the Alfven range of frequencies, $\omega\lesssim\omega_{ci}$ [1]. Enclosure of the whole magnetic system into a large vacuum chamber and the plasma production and heating technique result in distinctions of discharge development during the RF pulse and after its termination.

The time evolution of plasma parameters is considered where the RF power is transmitted to the plasma by means of an unshielded frame-like antenna with a comparatively long wavelength spectrum [2].

Behaviors of the line-averaged electron density $\overline{n}_e$ and electron cyclotron emission (ECE) from the central plasma are compared at different levels of the RF power P fed to the antenna. The link has been established between the value of $\overline{n}_e$ and the level of ECE.

Two groups of ions with different temperatures are observed in U-3M: the lower temperature (tens eV) and higher temperature (300…600 eV) ones [3, 4]. In the optimum conditions for plasma heating the more energetic ion content ($\gtrsim$500 eV, fast ions, FI) increases [5]. With this, a short-time enhanced FI outflow to the divertor (burst of FI loss) occurs at a certain $\overline{n}_e$ value.

With the power P high enough, the FI burst triggers a bifurcation of the edge E_r toward a more negative value with a stronger radial E_r shear and, consequently, a stronger shear of the poloidal flux $E\times B$. This results in suppression of the edge turbulent transport with indications of confinement improvement to occur (the H-like mode). With the density $\overline{n}_e$ changing after discharge ignition, two H-mode states separated by an enhanced edge turbulent transport (the L-like state) are realized.

The results having been obtained are of interest for (i) target plasma formation to produce and heat a denser plasma in U-3M by means of another, shorter wave antenna; (ii) understanding of processes being determinative in the H-like mode formation in U-3M.

1. EXPERIMENTAL CONDITIONS

The U-3M device (fig. 1) is an l=3/m=9 torsatron with R_0=100 cm, $\overline{a}\approx$12 cm, $\iota(a)/2\pi \approx 0.3$. The magnetic field $B_\phi\lesssim$1 T is produced with the helical coils only. The whole magnetic system is enclosed into a large, 5 m diameter vacuum chamber, its volume, 70 m^3, being 200 times larger than the confinement volume. So, an open natural helical divertor is realized. The fuelling gas (hydrogen) is leaked into the chamber continuously at the pressure $p\sim10^{-5}$ Torr.

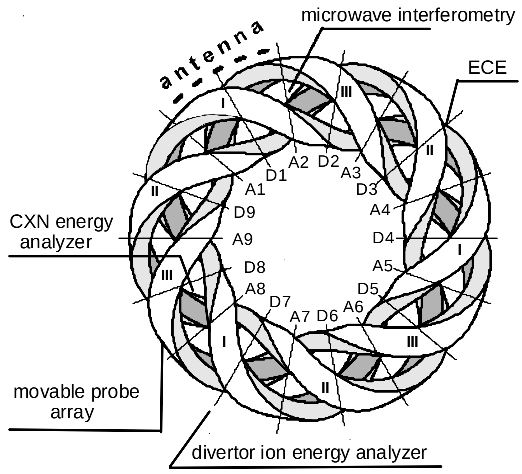

Fig. 1. U-3M helical coils I, II, III. Indicated are symmetric poloidal cross-sections A1, D1, A2, D2,…, A9, D9 in helical periods 1, 2, …, 9. respectively. The antenna is placed under the coils I and III between A1 and A2 (marked with dashes) with the leads in D1 on the low field side

The plasma with $\overline{n}_e$ units 10^{12} cm^{-3} is RF produced and heated at the frequency $\omega\lesssim\omega_{ci}$, with the local Alfven resonance (LAR) condition $N_{||}^2=\varepsilon_1$ being fulfilled for wavelengths $\lambda_{||}$ excited by the antenna where $N_{||} = k_{||}c/\omega$, $k_{||}=2\pi/\lambda_{||}$, $\varepsilon_1 \approx \omega_{pi}^2/(\omega_{ci}^2- \omega^2)$. Parallel with the linear Alfven heating, turbulent heating also takes place. The RF power is transmitted into the plasma by means of a twisted unshielded frame-like antenna [1, 2] (Fig. 2). The calculated spectrum of parallel wavelengths $\lambda_{||}$ generated by the antenna [2] covers 40…400 cm with the maximum generation at $\lambda_{||}^{max} \approx 80$ cm.

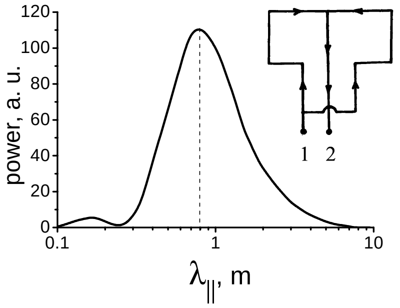

Fig. 2. Schematic representation of the antenna. 1, 2, connections to the oscillator. Calculated spectrum of generated parallel wavelengths $\lambda_{||}$ [2]

The parallel component of the RF antenna current excites mainly slow modes of the Alfven wave [6]. In the operating regime B_ϕ=0,72 T, $\omega/2\pi$=8.8 MHz ($\omega=0{,}8\omega_{ci}(0)$). The calculated $\lambda_{||}$ spectrum in Fig. 2 corresponds to the resonance densities $n_i \approx (0{,}07…7)\times10^{12}$ cm^{-3} with n_i = 1.8×10^{12} cm^{-3} for $\lambda_{||}^{max} \approx 80$ cm.

Two groups of ions, lower temperature (T_{i1}, tens eV [3]) and higher temperature ones ($T_{i2} \approx 300…600$ eV [4]) are formed during the heating. A possible reason for the T_{i2} group to arise turbulent processes could be [7].

Measurements are carried out of the density $\overline{n}_e$, the intensity of 2nd harmonic ECE from the central region ("radiation temperature"), the CXN flux Γ_n with different perpendicular energies $W_\perp$, the FI component (>500 eV) in the diverted plasma flow (DPF; a grid analyzer with retarding potential). Spatial distributions close to radial ones of mean and fluctuating edge parameters are studied with the use of movable Langmuir probes.

In the typical operating regime ($P \approx 130$ kW, the RF pulse length 40 ms) the electron temperature in the central region as estimated from ECE amounts $T_e(0) \sim 500…700$ eV.

2. DENSITY AND RADIATION TEMPERATURE EVOLUTION AT DIFFERENT VALUES OF RF POWER

It follows from Fig. 3 that within comparatively low values $60 \lesssim P \lesssim 80$ kW the $\overline{n}_e$ rise after discharge ignition is slowed down near $\overline{n}_e \approx 2\times10^{12}$ cm^{-3} ("$\overline{n}_e(t)$ bend"). As P increases, the maximum $\overline{n}_e \approx 6\times10^{12}$ cm^{-3} shifts toward the end of RF pulse. The maximum level of ECE is reached in the $\overline{n}_e(t)$ bend. An ECE drop with a further density rise ($\overline{n}_e > (2…3)\times10^{12}$ cm^{-3}) indicates plasma heating reduction due to LAR shift to the periphery.

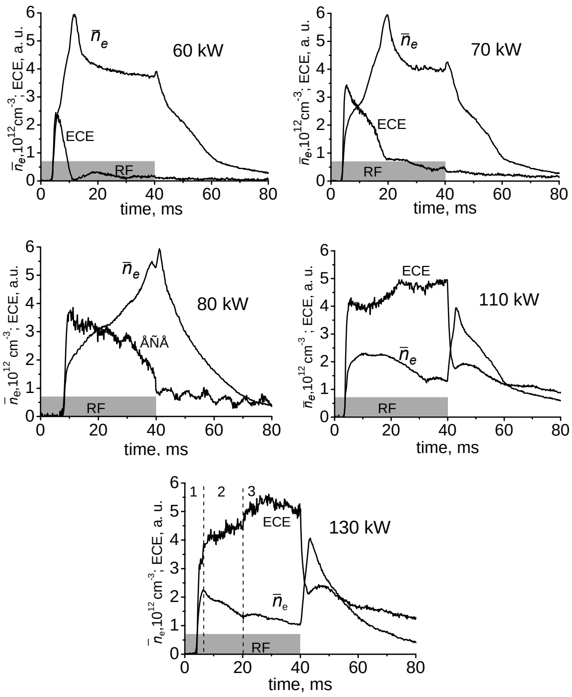

Fig. 3. Time behavior of density $\overline{n}_e$ and 2nd harmonic ECE at different values of RF power fed to the antenna. Vertical dashed lines separate phases 1, 2, 3 of discharge evolution

At P>80 kW the density achieves $\overline{n}_e \approx 6\times10^{12}$ cm^{-3} no more, starting to decay before the end of RF pulse the faster the higher P is. At P>100 kW the maximum density becomes $\overline{n}_e^{max} \approx 2\times10^{12}$ cm^{-3} in the active stage ($\overline{n}_e$ bend). After RF switched off $\overline{n}_e$ rises again during ~3 ms, and after reaching $\overline{n}_e \approx 4\times10^{12}$ cm^{-3} decays finally with a characteristic time of ~15 ms. With $\overline{n}_e \leq 2\times10^{12}$ cm^{-3} a high level of ECE is kept over all the RF pulse, thus evidencing the optimum density for heating.

At $P \approx 130…150$ kW, where the value of $\overline{n}_e \approx 1.2\times10^{12}$ cm^{-3} is attained in the slow density decrease (the time of decay ~10 ms), some indications of the H-mode transition [8, 9] occur. These are [10, 11] a suspension of the $\overline{n}_e$ decay, speeding up of both ECE and plasma energy content W_{dia} rise. Most distinctly, these effects are displayed at $P \approx 130$ kW. The H-mode transition is caused by the edge E_r shear strengthening and suppression of the edge turbulent transport (see Sec. 4).

We name the initial stage of the discharge up to $\overline{n}_{em} \approx 2\times10^{12}$ cm^{-3} ($\overline{n}_e$ bend) as phase 1 (Ph1), the stage of the density decay to the minimum $\overline{n}_e \approx 1.2\times10^{12}$ cm^{-3} and the H-mode transition as phase 2 (Ph2), and the subsequent state with the H-mode to the end of RF pulse as phase 3 (Ph3; see Fig. 3 at $P \approx 130$ kW).

At higher power values, P>100 kW (see Fig. 3) in Ph2, the rate of the $\overline{n}_e$ decay to the minimum and H-mode transition increases with power so that the Ph2 length reduces. This dependence is consistent with the universal generality, power degradation of confinement [12].

At P>80 kW a short-time ~3-fold increase $\overline{n}_e$ after RF switched off (see Fig. 3) is explained [7] by plasma flows reduction due to cooling, while the electron temperature remains sufficiently high for some time to ionize the neutral gas entering from the free volume of the chamber.

3. BEHAVIOR OF FAST IONS AND THEIR LOSS. THE LINK BETWEEN FI LOSS AND H-MODE TRANSITION

More energetic ions from the T_{i2} group (FI) seriously affect plasma characteristics in U-3M. In particular, the FI direct loss results in the DPF up-down asymmetry [13]. The relative FI content increases with the RF power [5].

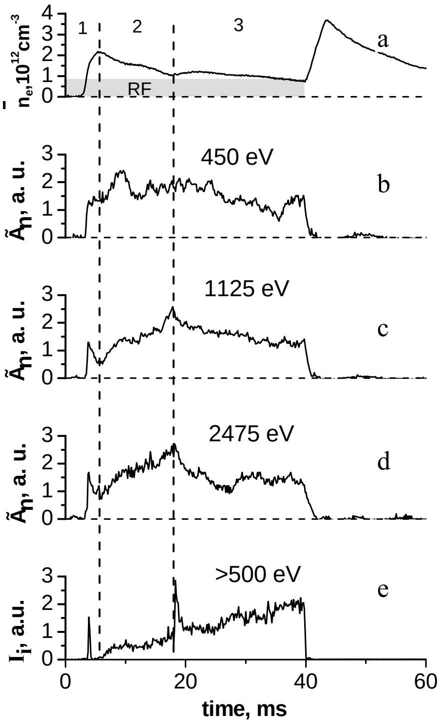

Fig. 4. Time behavior of (a) density $\overline{n}_e$; (b, c, d) CXN flux Γ_n with different perpendicular energies; (e) ion current I_i to the analyzer collector at U=500 V

The time evolution of the CXN flux Γ_n with different energies $W_\perp$ (Fig. 4) displays variation of the concentration of ions with such energies in the confinement volume. At $W_\perp$<500 eV (see Fig. 4,b) the behavior of $\Gamma_n(t)$ does not exhibit any distinctions correlating with $\overline{n}_e(t)$. However, at $W_\perp \gtrsim 500$ eV in Ph2 $\Gamma_n(t)$ changes in antiphase with $\overline{n}_e(t)$ (see Fig. 4,c,d), attaining a maximum at the minimum $\overline{n}_{e2} \approx 1.2\times10^{12}$ cm^{-3}, where the H-like mode transition occurs. In Ph1 with $\overline{n}_e$ increasing, Γ_n also passes over a maximum at $\overline{n}_{e1} \approx \overline{n}_{e2}$.

It is shown in Fig. 4,e how the FI outflow to the divertor changes in time (ion current I_i to the analyzer collector at the retarding voltage U = +500 V). In Ph1 at $\overline{n}_e = \overline{n}_{e1}$ and in the end of Ph2 ($\overline{n}_{e2} \approx \overline{n}_{e1}$) a short-time (hundreds μs) enhanced FI outflow to the divertor occurs, indicating a manifold rise of the FI loss (burst of FI loss). The burst amplitude increases with RF power [10, 11] and exhibits a resonance-like behavior depending on B_ϕ at a fixed P (Fig. 5, measured in Ph1).

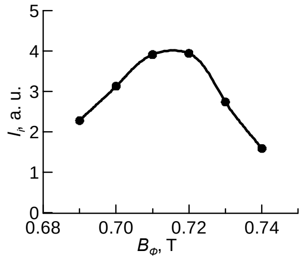

Fig. 5. Fast ion burst amplitude I_i versus toroidal magnetic field strength B_ϕ (measured in Ph1)

The synchronism of density decay termination at $\overline{n}_{e2} \approx$ 1,2×10^{12} cm^{-3}, the rise of ECE and W_{dia} in the end of Ph2 – start of Ph3, on the one hand, and the FI content passing over a maximum and the burst of FI ion loss, on the other hand, suggests an idea that the H-like mode is triggered by the non-umbipolar FI loss.

4. TIME EVOLUTION OF EDGE E_r AND E_r EFFECT ON TURBULENT TRANSPORT

Qualitatively, the effect of the E_r shear amplification in the H-like mode transition is demonstrated by comparison of edge floating potential profiles $V_f(h)$ close to radial ones (Fig. 6; h is the probe distance from the minor vertical exis when moving 1 cm over the midplane) before (t < 0) and after (t > 0) the transition (t = 0 corresponds to the moment of the Ph2–Ph3 transition with the burst of FI loss).

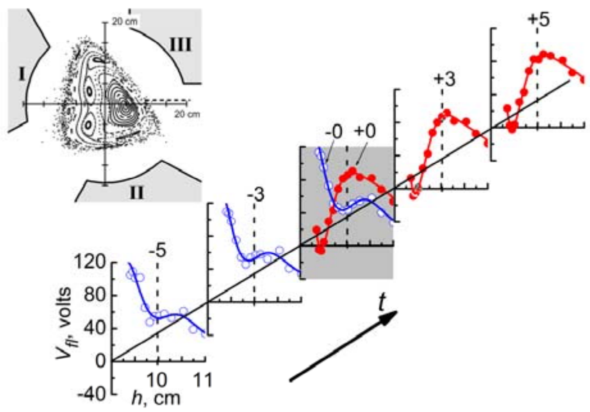

Fig. 6. Mean edge floating potential V_f versus distance h as measured at different moments t (indicated in ms) before (t<0) and after (t>0) transition (t=0). The plots measured 25 μs before and 25 μs after FI burst maximum (shaded) are marked as -0 and +0, respectively. Vertical dashed lines indicate LCFS position. In the insertion the line of probe movement is marked by dashes

The value of $|V_f|$ near the LCFS ($h = h_0 \cong 10$ см) increases with probe displacement toward both $h < h_0$ and $h > h_0$, while $\min(V_f)$ shifts inside the boundary. $E_r \approx -dV_f/dh$ becomes more negative, with E_r shear increasing. A rough estimation yields $E_r \approx -20$ V/cm in Ph2 and $E_r \approx -100$ V/cm in Ph3.

Similar to other 3D systems [9] and tokamaks [14], the radial shear of the mean flow $E\times B$ with negative E_r is formed at the plasma boundary prior to the transition. The presence of a pre-transitional lower edge E_r is connected with the maximum ("hump") of the electrostatic potential arising near the LCFS due to formation of the "radial sheath" ($\Delta \lesssim 1$cm) and the "ion halo" [15].

In Ph1 a lower level of $\tilde{\Gamma}$ and a stronger E_r shear also set in with the burst of FI loss at $\overline{n}_{e1} \approx \overline{n}_{e2}$. This short-time (2…3 ms) H-like mode state is terminated at $\overline{n}_{em} \approx 2\times10^{12}$ cm^{-3} ($\overline{n}_e$ bend) by a sudden, bifurcation-like reduction of $|E_r|$ and E_r shear with a $\tilde{\Gamma}$ rise and consequent $\overline{n}_e$ decay due to increase of plasma loss (Ph2). In this sense, we may say about a short-time H-like mode state to occur in Ph1 too. Here, however, the burst of FI loss in itself can arise at the same density $\overline{n}_{e1}$ even at a lower power, P<100 kW, though with a smaller amplitude where no H-mode occurs. This is an evidence of the FI burst being a primary effect relative to the H-like mode transition.

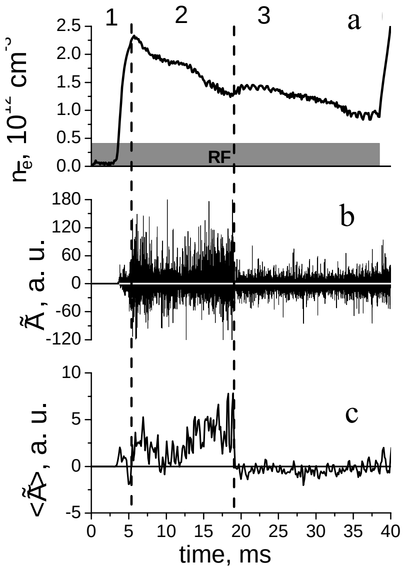

Fig. 7. Time behavior of (a) density $\overline{n}_e$, (b) edge radial turbulent flux $\tilde{\Gamma}$ (probe position h = 10.5 cm) and (c) its value averaged over 1 ms intervals $<\tilde{\Gamma}>$

The changes in E_r are momentarily displayed in the value of the edge turbulent flux $\tilde{\Gamma}$ (Fig. 7). A time correlation is well seen between the level of edge turbulent transport (a surface process) and plasma confinement (a volume characteristic defined here by the rate of $\overline{n}_e$ decay). In Ph3 (H-like mode) $<\tilde{\Gamma}>$ practically vanishes with suspension or deceleration of the density decay.

SUMMARY AND DISCUSSION

♦ Within $60 \lesssim P \lesssim 80$ kW a cold plasma with $\overline{n}_e \approx (4…6)\times10^{12}$ cm^{-3} is produced in U-3M. At P>100 kW the maximum density becomes $\overline{n}_{em} \approx 2\times10^{12}$ cm^{-3} with a high $T_e(0)$ which is kept over all the RF pulse. Such a discharge can be used as a target to produce and heat a denser plasma (up to 10^{13} cm^{-3}) by exciting the fast mode of the Alfven wave by a shorter wave antenna with azimuthal currents [16].

♦ In the typical operating regime ($P \approx 130$ kW), processes developing in the active stage can be divided in two groups by the time scale of their variation.

To the *slower processes* (units – 10 ms) the density decay in Ph2 from $\overline{n}_{em} \approx 2\times10^{12}$ cm^{-3} to $\overline{n}_{e2} \approx 1.2\times10^{12}$ cm^{-3} (see Fig. 3,e) is related, first of all. With this, the FI content increases (units ms) attaining a maximum at $\overline{n}_e = \overline{n}_{e2}$ (see Fig. 4,c,d), with the plasma energy content W_{dia} and ECE also growing monotonously. Taking account of the FI content increasing with power [5], optimum conditions for FI generation are supposed to be realized at the combination $\omega/2\pi = 8.8$ MHz, $B_\phi = 0.72$ T and $\overline{n}_e \approx \overline{n}_{e2}$, with increasing RF power fraction deposited in the plasma (a specific "coupling resonance", see also [17]). On the other hand, the rise of this fraction results in a stronger confinement degradation and density decrease.

Against a background of slower processes preparing the "coupling resonance" with maximum FI content, *faster processes* (tens – hundreds μs) arise, which determine the H-like mode transition in itself. The transition is triggered by the burst of FI loss (~500 μs, see Fig. 4,e). The burst initiates the edge E_r bifurcation to a more negative value with the E_r shear amplified (~50 μs, see Fig. 6). The stronger E_r shear suppresses the edge turbulence [18] and turbulence-induced anomalous transport $\tilde{\Gamma}$ (see Fig. 7). The time of the $\tilde{\Gamma}$ drop is ~100 μs.

The E_r bifurcation triggered by the ion orbit loss is considered in [19].

♦ Similar to other devices [9, 14], in U-3M a characteristic form of the edge potential profile has been already formed before the H-transition (see Fig. 6) and, probably, results from the non-ambipolar ion orbit loss [15]. With the transition, the edge E_r becomes stronger, with the potential well shifting inside the LCFS.

♦ Triggered by a single burst of FI loss, the H-like mode state persists for a comparatively long period without recovering the pre-transitional higher level of the edge turbulence (see Fig. 6). It looks as if the discharge went from one quasi-steady (L-like) state to another (H-like) state.

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ДИНАМИКА ВЧ-РАЗРЯДА С ПРОХОЖДЕНИЕМ L- И H-ПОДОБНЫХ СОСТОЯНИЙ В ТОРСАТРОНЕ УРАГАН-3М

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В трехзаходном торсатроне У-3М водородная плазма с плотностью $\overline{n}_e$ ~2×10^{12} см$^{-3}$ создаётся и нагревается ВЧ-полями в области частот $\omega\lesssim\omega_{ci}$ с использованием рамочной антенны. Рассмотрены изменения во времени: 1) плотности $\overline{n}_e$ и электронного циклотронного излучения при различных значениях ВЧ-мощности, подводимой к антенне; 2) генерации быстрых ионов и их потерь; 3) краевого электрического поля E_r и краевого турбулентного переноса. Полученные результаты важны для последующего получения и нагрева более плотной плазмы и понимания процессов, приводящих к переходу в Н-подобную моду удержания.

ДИНАМІКА ВЧ-РОЗРЯДУ З ПРОХОДЖЕННЯМ L- ТА H-ПОДІБНИХ СТАНІВ У ТОРСАТРОНІ УРАГАН-3М

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У тризаходному торсатроні У-3М воднева плазма зі щільністю $\overline{n}_e$ ~2×10^{12} см$^{-3}$ створюється і нагрівається ВЧ-полями в області частот $\omega\lesssim\omega_{ci}$ з використанням рамкової антени. Розглянуті часові зміни: 1) густини $\overline{n}_e$ та електронного циклотронного випромінювання при різних значеннях ВЧ-потужності, що підводиться до антени; 2) генерації швидких іонів та їх втрат; 3) крайового електричного поля E_r та крайового турбулентного переносу. Одержані результати важливі для подальшого створення та нагріву більш щільної плазми і розуміння процесів, що призводять до переходу в Н-подібну моду утримання.