RECENT PROGRESS ON CONFINEMENT IMPROVEMENT STUDY AND ION HEATING EXPERIMENTS IN LHD

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Experimental efforts have been extensively done in Large Helical Device (LHD) to find the key for confinement improvement like H-mode and ITB seen in tokamaks. In outwardly shifted configuration (R_{ax}=4.00m) having an m/n=1/1 rational surface at the ergodic layer an H-mode-like transition was obtained with rapid density rise and appearance of ELM-like Hα bursts, when the P_{NBI} was decreased from 8 to 5MW. A density window of 4-8x10^{13}cm^{-3} existed for the H-mode-like transition. The ELM-like Hα bursts may be drived by a pressure gradient at the 1/1 position. On the other hand, Ne and Ar discharges were adopted to increase the ion heating power per ion and to perform the density peaking. As a result, high ion temperatures up to 10keV were obtained with a large enhancement of toroidal rotation (~40km/s). A clear reduction of the ion thermal diffusivity was found in the Ar discharge with large toroidal rotations in comparison with the Ne discharge with a small toroidal rotation (<10km/s).
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1. INTRODUCTION

Confinement improvement in toroidal fusion devices is one of the most important key issues for future reactor design not only in tokamaks but also in helical devices. Extensive studies on the confinement improvement have been also done in LHD.

The control of edge particles is one of generally expected methods to make a sharp edge pressure gradient. The LHD has a natural open divertor configuration. In this configuration the edge pedestal, which is normally appeared in tokamak H-mode, was observed [1] with a confinement improvement from the ISS-95 stellarator scaling [2]. Active control of the edge particles has been tried using an m/n=1/1 island at the plasma edge produced by additionally supplied resonant magnetic field and a pump limiter with the same surface curvature as the 1/1 island structure, so called 'LID (local island divertor)' [3]. The energy confinement improvement after switching off H_2 gas puff, so called 'reheat-mode', has been studied in relation to edge particle confinement [4]. An H-mode-like discharge was observed in high-β plasmas (β~2%) with a low magnetic field (B_t<0.75T) at R_{ax}=3.60m (ι/2π (a)=1.56) [5]. The growth of m/n=2/3 modes appeared at the edge barrier region with the saturation of plasma performance. Recently, the H-mode-like discharge has been newly obtained in a full B_t field (B_t=2.5T) by shifting the R_{ax} outwardly (R_{ax}=4.00m) [6] with a rapid density rise and ELM-like Hα burst. The key parameters for the H-mode-like transition were controls of the edge 1/1 island position and the edge pressure based on the R_{ax} shift and an optimum choice of neutral beam heating power and electron density, respectively. The H-mode-like discharges recently observed in LHD are interpreted in the first half of this paper.

The confinement improvement has been also studied in the core region of LHD plasmas. An ITB-like centrally peaked electron temperature profile ($T_e(0)$≤10keV) was obtained at a radial position of ρ<0.3 in low-density ECH discharges of <0.5x10^{13}cm^{-3}. This electron-ITB is explained with formation of a radial electric field connecting to electron root [7]. This scenario was applied to additional ECH heating during NBI discharges and similar e-ITB profile was also obtained. On the other hand, a study on ion confinement improvement is considerably difficult in the present situation of high-energy (~180keV) negative-ion-based NBI heating, since the most of the input power is absorbed by bulk electrons and only 20-30% of the total P_{NBI} is absorbed by bulk ions. Neon and argon discharges were, then, tried to raise up a ratio of ion heating power to ion density, P_i/n_i. As a result, a high central ion temperature up to $T_i(0)$=10keV has been obtained with appearance of large toroidal rotation, whereas the $T_i(0)$ stayed around 2keV in H_2 discharges. The increment of the $T_i(0)$ was well correlated with the enhanced toroidal rotation. The high-ion temperature discharges are described in the latter half of this paper in relation to the ion confinement at plasma core.

2. IMPROVEMENT of EDGE CONFINEMENT

2.1 ERGODIC LAYER and EDGE ι/2π(a)

Magnetic surface structures in helical devices are generally characterized by the ergodic layer surrounding the core plasmas. The ergodic layer plays an important role for confinement properties in LHD (m/l=10/2, $R/\langle a_p\rangle$=3.5-4.1m/0.5-0.64m, B_t<3T, V_p=20-30m^3), because the thickness is much larger than ionization lengths of neutrals and the connection lengths of magnetic fields are long. The magnetic field structures of the ergodic layer are illustrated in Fig.1 for the cases of R_{ax}=3.60m (LHD standard configuration) and R_{ax}=3.90m (outwardly shifted configuration). The best confinement performance is obtained in the standard configuration of R_{ax}=3.60m.

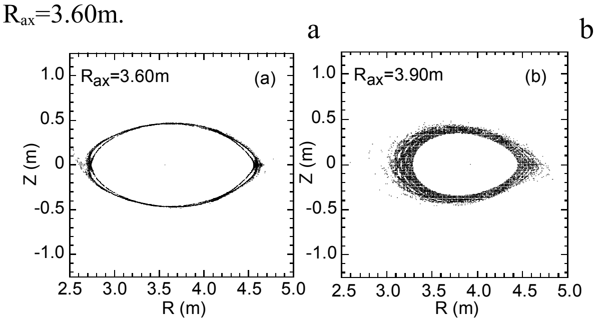


Fig.1. Ergodic layer structures at horizontal cross-section of R_{ax}=3.60m (a) and 3.90m (b)

Edge rotational transform at ρ=1 and averaged plasma minor radius in LHD are plotted in Fig.2 (a) and (b) as a function of magnetic axis position, R_{ax}. The edge rotational transform ranges in 0.7< ι/2π(a) <1.6. The 1/1 surface is located at ρ=0.88 in R_{ax}=3.60m and located at ρ =1.0 near R_{ax}=3.90m. The plasma size becomes small but the thickness of the ergodic layer becomes large, when the R_{ax} is shifted outwardly.

Figure 3 shows edge radial profiles of magnetic field connection length, L_c, and ι/2π at a horizontally elongated position in R_{ax}=3.90, 4.00 and 4.10m [8]. The thickness of the ergodic layer becomes large at the X-point and closes to 40cm (also see Fig.1(b)). The plasma boundary of LHD plasma is positioned inside the ergodic layer and movable according to the edge energy balance, although it is, of course, a strong function of the connection length. The positions of the 1/1 surface in R_{ax}=3.90 and 4.00m are located near the LCFS and inside of ergodic layer, respectively. No 1/1 surface exists in R_{ax}=4.10m. In the case of R_{ax}=4.00m, thus, it is understood that the pressure gradient at the 1/1 surface can be easily changed according to the input power and edge electron density.

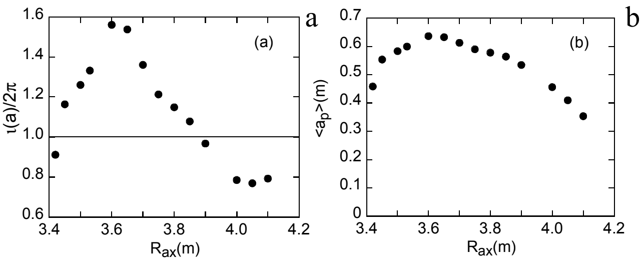


Fig.2. Edge rotational transform (a) and averaged plasma radius (b) against magnetic axis, R_{ax}

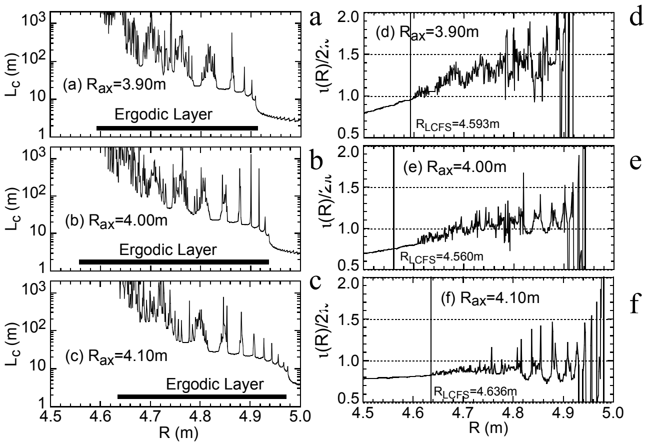


Fig.3. Edge profiles of magnetic field connection length ((a), (b), (c)) and rotational transform ((d), (e), (f)) at R_{ax}=3.90m, 4.0m and 4.1m, respectively

2.2 H-MODE-LIKE DISCHARGES

Experiments have been done for above-mentioned three configurations. The H-mode-like transition was found in R_{ax}=4.00m by changing the NBI input power and maintaining a relatively high density. No transition was observed in R_{ax}=3.90 and 4.10m. This result strongly suggests the importance of the 1/1 island at the plasma edge for the H-mode-like discharge.

Typical waveforms of the key signals are shown in Fig.4. One of three NBIs is turned off at t=1.25s. After turning off the NBI, the Hα emission quickly drops and the density gradually rises, showing a clear turning point. ELM-like bursts appear in the Hα signal. Similar bursts are also observed in an electrostatic probe on the divertor plate (I_{is}) and a magnetic probe (db/dt). The energy confinement in such an outwardly shifted configuration is always much smaller than predictions from ISS-95 scaling due to less central heat deposition of NBI. The energy confinement times obtained in the present discharge are 17ms (τ_{E_ISS95}=36ms) and 41ms (τ_{E_ISS95}=65ms) at t=1.2 and 2.0s, respectively. A clear confinement improvement is not observed at present.

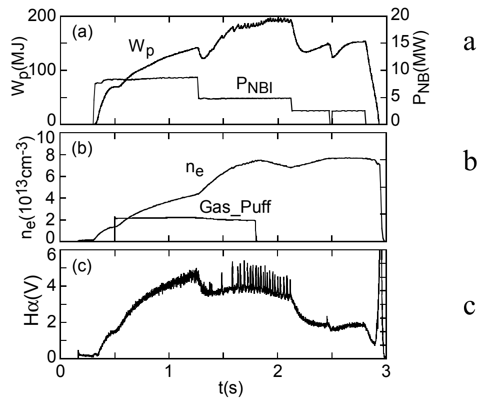


Fig.4. H-mode-like discharge after P_{NBI} decrease

Those signals during the H-mode-like phase are expanded in Fig.5. Reduction of the magnetic fluctuation is seen after the H-mode-like transition.

This H-mode-like feature, however, disappears after turning off the second NBI at t=2.1s. It strongly suggests that a relatively narrow power window exists for c

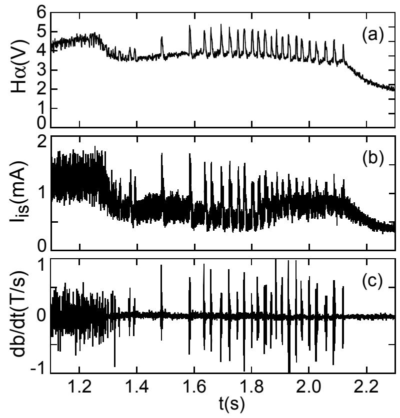
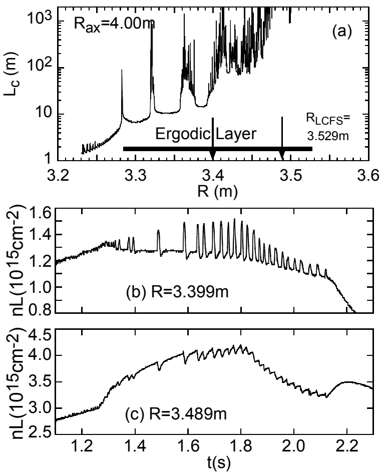


Fig.5. (a) Hα, (b) I_{is} and (c) db/dt during H-mode-like phase

appearance of the H-mode-like phase. In order to confirm the existence of power window the P_{NBI} was increased from one beam to two beams. The H-mode-like phase was also obtained only in a period during the two-beam heating.

In addition, the H-mode-like discharges cannot be obtained in low- and high-density ranges, appearing only in a density range of 4-8x10^{13}cm^{-3}. The existence of these power and density windows strongly suggests that the phenomenon is sensitive to edge plasma parameters around $\iota/2\pi(a)=1$ surface. The pressure gradient at the 1/1 island could be a driving force for the Hα bursts.

The edge density behaviors were analyzed from signals of multichannel interferometer, which measures vertical chord-integrated densities (n_eL) at vertically elongated plasma cross-section. Temporal behaviors of two chord-integrated densities from edge region at inboard side are traced in Fig.6 (b) and (c) with the connection length shown in Fig.6 (a). The ergodic layer becomes thick at the inboard side in such outwardly shifted configuration of R_{ax}=4.00m. Since the position of LCFS is R=3.529m, both signals shown in Fig.6 (b) and (c) indicate the density from the ergodic layer. Especially, one of the densities ((c): R=3.489m) is close to the LCFS. Relatively high density exists even in R=3.399m where the L_c is roughly



a

b

Fig.6. (a) L_c at vertical-inside of R_{ax}=4.00m and c

(b) (c) n L. Two arrows indicate positions of

100m.

The density bursts become remarkable in the inboard side as seen in Fig.6 (b) and can be well correlated with the Hα bursts. The density from R=3.489m in Fig.6 (c), however, indicates an inverse temporal behavior. A density collapse toward the plasma boundary from the inside is seen. It is calculated that the 1/1 surface in this position exists near R=3.46m located between two interferometer chords of R=3.399 and 3.489m. The position of the 1/1 surface may possibly correspond to the inversion radius of the density collapse. This density collapse appeared inside the ergodic layer suggests that the plasma in the ergodic layer having a relatively long L_c behaves like a core plasma with well-defined magnetic surface. It means that a perpendicular diffusion becomes important also in the ergodic layer, depending on the electron temperature.

3. ION HEATING EXPERIMENTS

3.1 ELECTRON-HEATING REGIME

The input power of the present LHD NBI is mainly absorbed by electrons, because the electron temperature of bulk plasmas ranges between 1/50 and 1/100 of the fast ion energy, and the critical energy, at which P_e becomes equal to P_i in slowing-down process of the beam energy, is expressed by 15*T_e. The input power into the bulk ions (P_i) deposited directly from the fast ions generally becomes only 10~20% to the total input power (P_{tot}). Therefore, all the NBI discharges in LHD stay in the electron-heating regime (P_i<P_e), where the ion temperature has remained in a range of T_e>T_i at present. Although the ion transport study in such an electron-heating regime is important, it is considerably difficult to evaluate the ion transport coefficient because of a large uncertainty on the ion heating power. Then, the ion transport was examined in ECH discharges where a pure electron heating is possible.

The ECH (82.7, 84 and 168GHz) was injected perpendicularly and strongly focused on the magnetic axis of 3.50m. The ECH power is deposited within ρ=0.1~0.15. High central electron temperature up to 10kev has been observed with appearance of a high central ion temperature of 2.2keV, which was measured from Doppler broadening of TiXXI x-ray line (2.61E) using a high-resolution crystal spectrometer [9]. This high $T_e(0)$ ECH plasma (P_{ECH}=700kW) was analyzed using TOTAL-code. The T_e and n_e profiles measured are shown in Fig.7. The electron temperature was extremely peaked at the plasma center. The ion temperature is calculated from the given T_e and n_e profiles with values of neo-classical χ_i. The result is traced by dashed line. The calculated $T_i(0)$ was 2.5keV and indicated a similar temperature to experimentally obtained $T_i(0)$. This result suggests that the ion transport in the ECH plasma is dominated by the neoclassical transport, at least, in the plasma center. The

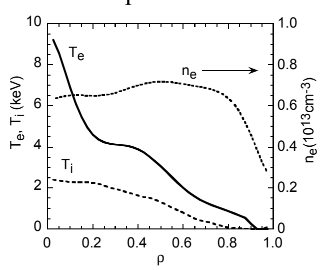


Fig.7. Experimentally obtained T_e (solid line) and n_e (dotted line) profiles Dashed line shows T_i calculated with neo-classical χ

experimentally obtained χ_e was roughly 5 times as large as the neoclassical χ_e.

3.2 ION-HEATING REGIME

In order to overcome above-mentioned situation of NBI discharges, recently, neon discharges have been tried [10]. The increase of P_i/n_i due to the n_i reduction was expected in the NBI neon discharge. A typical result on the ion temperature behavior from R_{ax}=3.53m configuration is shown in Fig.8(a). Here, the central ion temperature is measured from Doppler broadening of ArXVII (3.9492E) x-ray line [9]. A higher ion temperature is obtained in the Ne discharge with a flat top of 1s. The measured ion temperatures were plotted with values of the P_i/n_i (see Fig.8 (b)). A good correlation was obtained between the two parameters. The energy exchange time between electron and ion, τ_{ei}, becomes 3 times longer than hydrogen discharge. The value of τ_{ei} is 0.6s at 1×10^{13}cm^{-3} and 1.5s at 0.5×10^{13}cm^{-3}. These values are much larger than the energy confinement time (τ_E<0.1s). Then, the power input into ions from electrons can be ignored and the value of P_i/n_i becomes much important in addition to the ion confinement in such a low-density range.

Ne glow discharges were carried out for 8 hours overnight before daily experiments in order to decrease hydrogen neutrals. The Hα intensity further decreased during NBI discharges and roughly became half of that after He-glow discharges. Some amount of hydrogen was replaced by neon. As a result, a further density decrease became possible down to 0.2×10^{13}cm^{-3}.

Ar discharge was tried expecting a reduced edge recycling and a further decrease of ion density. The T_i measured during a steady phase of discharges is plotted against a density increment after the Ar puff, as shown in Fig.9 (a). The T_i plotted here is taken during a density decay phase at ~0.5s after the Ar gas was puffed. It is seen that the T_i increases with increasing Ar puff rate.

The radiation loss was calculated in steady plasmas using impurity transport code. The calculated Ar radiation becomes equal to the P_{NBI} (10MW) at 4×10^{13}cm^{-3}. The radiation loss is enhanced during a transient phase since all the particles deposited by the gas puff have to pass through the low-temperature region at the plasma edge. In addition, the density limit in LHD is given by a half value of the critical density where P_{rad} is equal to P_{NBI}. Therefore, the drop of T_i at 1.3×10^{13}cm^{-3} is quite reasonable. NBI deposition fractions are plotted in Fig.9(b) for He, Ne and Ar discharges. Those are considerably improved for higher Z discharges due to an increase of ion-ion collisional ionization cross section.

Typical waveforms of high-T_i discharges in R_{ax}=3.60m are traced in Fig.10. After the Ar puff the $T_i(0)$ quickly increases and reaches 7keV. The $T_e(0)$ is also high (~4keV). The $T_i(0)$ begins to decrease at t=1.7s with a small density reduction, whereas the $T_e(0)$ still keeps the high temperature. The reduction of Ar ions and the replacement to hydrogen are

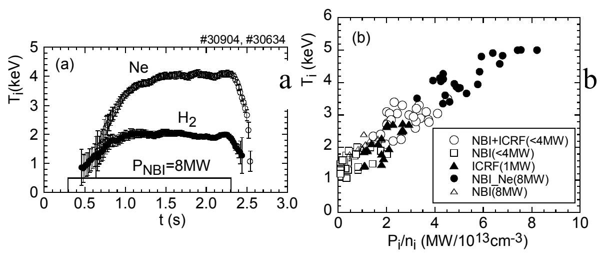


Fig.8. (a)H_2 and Ne discharges; (b) $T_i(0)$ against P_i/n_i

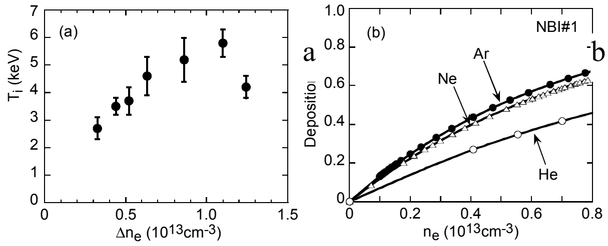


Fig.9. (a) $T_i(0)$ against density increment after Ar puff; (b) NBI birth deposition rate as a function of density

suggested. An interesting point in the Ar discharge is in the density profile and toroidal rotation.

The density profile became peaked in Ar discharges, as shown in Fig.11(a). In Ne discharges after Ne glow discharge cleaning, however, an extremely flat density profile was performed by the enhanced edge recycling of neon. It is reported that the inward velocity of impurities in LHD is

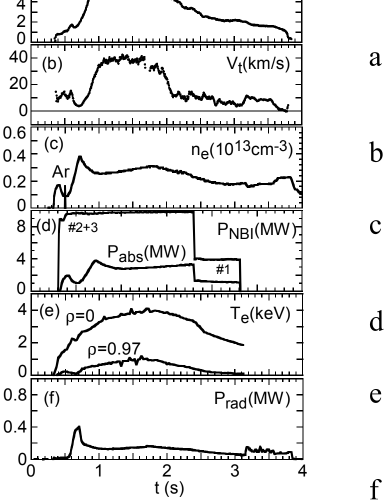


Fig.10. Ar discharge in R_{ax}=3.60m

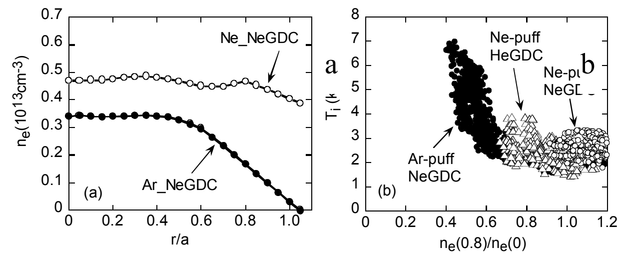


Fig.11. (a) $n_e(\rho)$ in Ne and Ar discharges; (b) $T_i(0)$ against edge density normalized by central density

proportional to their ionization stages, q_i [11]. This may be a main reason why the Ar discharge has such a peaked density profile in addition to the lower recycling rate.

From these experiments it became clear that the ion temperatures are sensitive to density profiles. The relation between ion temperatures and density profiles is plotted in Fig.11(b). The density peaking followed by the reduction of edge density at ρ=0.8 is well correlated with high values of ion temperatures, especially in the Ar discharge case.

Central toroidal rotations measured from Doppler shift of ArXVII were analyzed with the ion temperatures and density peaking. As a result, the rotations could be also well correlated with the density peaking and ion temperatures. For example, the rotation was smaller than 10km/s in the flat density profile of Ne discharges after Ne-glow cleaning and 30-40km/s in the peaked density profile of Ar discharges (see Fig.11(a)). The $T_i(0)$ was 2-3keV and 7keV for Ne and Ar discharges, respectively. The heat transport was analyzed between such two discharges. The central ion thermal diffusivity, χ_i, was 55m^2/s and 35m^2/s for Ne and Ar discharges, respectively, under assumption of pure Ne and Ar discharges. Here, it should be noticed that the ion density much decreases in these discharges and then, the analyzed χ_i becomes larger than that in hydrogen discharges (χ_i~2-5m^2/s). In the practical discharge the hydrogen ion density becomes still dominant and is estimated to be 2-3 times as much as the Ar ion density. Detailed analysis on the ion density is now being done. The obtained χ_i are, of course, much larger than the neoclassical values. Then, it is pointed out that the enhanced toroidal rotation followed by the density peaking may improve such an anomalous transport also in LHD. The toroidal rotation velocity of 40km/s corresponds to 30% of the Ar thermal velocity.

The toroidal rotation is mainly reduced by a parallel viscosity due to helical ripple mainly located at plasma outer half region. The density reduction at the plasma outer region leads to the reduction of the parallel viscosity and enhances the toroidal rotation. The recent theoretical analysis predicts the same rotation velocity as the experimentally obtained velocity of 40km/s, taking into account the density and temperature profiles.

CONCLUSIONS

H-mode-like and high-ion-temperature discharges in LHD were described suggesting possibilities of a comparative study with tokamak plasmas and a future direction of confinement improvement. From these studies it was suggested that controls of edge islands and ergodic layer, density profiles and toroidal rotation are, at least, key parameters for the future confinement improvement.

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ПРОГРЕСС В ИССЛЕДОВАНИЯХ УЛУЧШЕННОГО УДЕРЖАНИЯ И ЭКСПЕРИМЕНТЫ ПО НАГРЕВУ ИОНОВ НА LHD

С. Морита и др.

Значительные экспериментальные усилия на установке LHD были направлены на выяснение причин улучшения удержания в режимах, подобных H-моде или внутреннему транспортному барьеру (ITB), наблюдаемому на токамаках. Для смещённой наружу магнитной конфигурации (R_{ax}=4.00m), когда область вблизи рациональной поверхности *m/n*=1/1 была эргодизирована, наблюдался переход, подобный H-моде. Этот переход сопровождался быстрым нарастанием плотности и вспышками свечения линии H_α, подобными ELMам, наблюдался при уменьшении P_{NBI} от 8 до 5MW. Такой H-mode подобный переход наблюдался для плотности плазмы, лежавшей в диапазоне 4-8x10^{13}cm^{-3}. ELM –подобные вспышки H_α могли быть следствием градиента плотности вблизи поверхности 1/1. Другое направление исследований – разряды на неоне и аргоне, проводившиеся с целью увеличения мощности нагрева на ион и получения пикированных профилей плотности. В результате была получена высокая температура ионов (до 10 кэВ) с одновременным увеличением скорости тороидального вращения (~40km/c). Чёткое уменьшение теплопроводности ионов наблюдалось в аргоновых разрядах с большей скоростью вращения по сравнению с неоновыми разрядами, где скорость вращения была меньше (< 10 km/c).

ПРОГРЕС У ДОСЛІДЖЕННЯХ ПОЛІПШЕНОГО УТРИМАННЯ Й ЕКСПЕРИМЕНТИ ПО НАГРІВАННЮ ІОНІВ НА LHD

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Значні експериментальні зусилля на установці LHD були спрямовані на з'ясування причин поліпшення утримання в режимах, подібних H-моді або внутрішньому транспортному бар'єру (ITB), що спостерігається на токамаках. Для зміщеної назовні магнітної конфігурації (R_{ax}=4.00m), коли область поблизу раціональної поверхні *m/n*=1/1 була эргодизирована, спостерігався перехід, подібний до H-моди. Цей перехід супроводжувався швидким наростанням щільності і спалахами світіння лінії H_α, подібними ELMам, спостерігався при зменшенні P_{NBI} від 8 до 5MW. Такий H-mode подібний перехід спостерігався для густини плазми, що лежала в діапазоні 4-8x10^{13}cm^{-3}. ELM -подібні спалахи H_α

могли бути наслідком градієнта щільності поблизу поверхні 1/1. Інший напрямок досліджень – розряди на неоні й аргоні, що проводилися з метою збільшення потужності нагрівання на іон і одержання пікіруваних профілів густини. У результаті була отримана висока температура іонів (до 10 кэВ) з одночасним збільшенням швидкості тороідального обертання (~40км/с). Чітке зменшення теплопровідності іонів спостерігалося в аргонових розрядах з більшою швидкістю обертання в порівнянні з неоновими розрядами, де швидкість обертання була менше (< 10 км/с).