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High Performance Discharges around Operational Limit in HT-7

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Abstract: Efforts have been made on HT-7 tokamak for extending the stable operation boundaries. Extensive RF boronization and siliconization have been used and wider operational Hugill diagram was obtained. Transit density reached 1.3 time of Greenwald density limit in ohmic discharges. Stationary high performance discharge with q_a=2.1 has been obtained after siliconization. Confinement improvement was obtained due to the significant reduction of electron thermal diffusivity χ_e in the out region of the plasma. Improved confinement phase was also observed by LHCD under the density range 70%~120% of Greenwald density limit. The weak hollow current density profile was attribute to off-axis LHW power deposition. Code simulations and measurements showed a good agreement of off-axis LHW deposition. Supersonic molecular beam injection has been successfully used to get stable high-density operation in the range of Greeenwald density limit.

Key Words: Tokamak, Wall coating, operational limit, Lower hybrid current drive, Greenwald density.

1. Introduction

It is important for tokamak operating around the operation boundaries, especially on the density limit. In order to achieve the required fusion yield, future large tokamak needs to operate at high density. Almost every kind of H-modes becomes largely degraded when plasma density approaches Greenwald density limit [1]. The discharges make a serious transition from type I ELMs to type III ELMs, to L-mode and finally to a density disruption in some large tokamaks [2]-[3]. It is still unclear how to maintain the high confinement phase in a stationery way around the operational boundaries, such as low q and high density.

Efforts have been made on HT-7 tokamak for extending the stable steady-state operation boundaries. Extensive RF boronization [4] and siliconization [5] have been used and wider stationary Hugill diagram was obtained. High-density discharges under different operational conditions were emphasized, especially on the lower hybrid current driven plasma. Stable discharges with a plasma density above Greenwald density limit have been obtained. Low q ohmic discharges were tried by using RF wall conditioning technique. Higher plasma performance was obtained after RF siliconization due to the significant reduction of oxygen content and reduced radiation loss. Plasma performance improvements obtained by LHCD and supersonic beam gas puffing were realized under either boronized or siliconized wall.

2. Low q operation by RF siliconization

The target plasma for silicon coating was produced by injection of ion cyclotron resonant frequency (ICRF) waves into tokamak. The pre-filled gases mixed by helium and silane (SiH_4) were easily breakdown by RF waves. Since the high energy impacting ions produced by RF waves hit and deposit to the wall, the quality of silicon film is much better than that obtained by GDC procedure. Plasma performance quickly improved after each siliconization. Lower q_a and wider stable operation region were achieved compared with RF boronization. Higher electron temperature was obtained for the same plasma current and density in tokamak discharge. Oxygen content dropped by a factor of two after siliconization and gradually recovered after 150 shots, while carbon radiation reduced by more than three times and kept at very low level even after 300 shots. XPS analysis to the bombarded film showed that a large amount of SiC was formed.

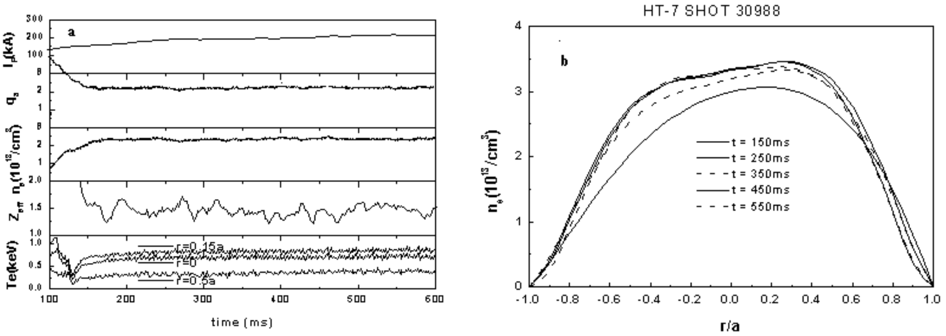

Fig. 1 A typical shot after RF siliconization. B_T=2.0, a=28.5cm, R=122cm.
(a) Main waveform (b) density profiles at different time.

Fig.1a is a shot after 30 minutes RF siliconization. A stationary discharge with plasma current 210kA and edge safety factor close to 2 lasted for more than 600ms and good plasma performance was obtained. Z_{eff} dropped to 1.5 and edge hydrogen recycling was low. A weak hollow and wider density profiles was formed shown as in Fig.1b. There was a sharp density gradient at a normalized minor radius 0.8.

Transport code has been used to calculate electron thermal diffusivity and plasma radiation power. Fig.2 shows that χ_e decreases dramatically in the out half of the plasma and radiation power is only 15% of ohmic power. The sharp density gradient at r/a=0.8, low radiation power and low edge hydrogen recycling make the energy confinement time increase about 50% and particle confinement time increase by a factor of three.

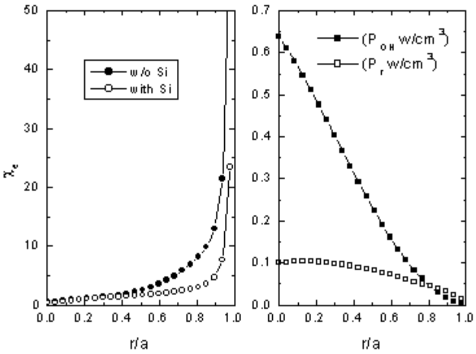

Fig.2 χ_e, ohmic heating and radiation power profiles

3. High density operation by LHCD

Since the density limit of lower hybrid wave accessibility, current drive efficiency will drop when density increases. It is very difficult to get good current drive effects above the density limit. LHCD experiments have carried out in HT-7 on several subjects during past few years and good confinement has been obtained in low-density level [6]. Very good LHCD results have been obtained on FTU tokamak in high-density condition [7]. The normalized density is still under 50% of Greenwald limit even with the high toroidal field (7 T) and LHCD frequency (8GHz). Under high plasma density condition, the LH waves can not be fully absorbed in the plasma center, a large fraction of non-inductive current will be driven in the outer region of plasma. High-density LHCD experiment was properly arranged under weak LH wave absorption dormant scenario in HT-7. The Stix-Golant accessibility limit, $n_{||\ \mathrm{acc}}$, typically varied between 2.8 and 3.8 when the density changed from 3 to $6.0\times10^{19}\mathrm{m}^{-3}$. The phase shift of the grill was set to 110 degree, which made $n_{||}$ to be 2.9. The accessibility limit is not fully satisfied here when plasma density is higher than $3\times10^{19}\mathrm{m}^{-3}$.

LH wave was injected during the current flat top when the density was about $1.5\times10^{19}\mathrm{m}^{-3}$, where LH wave could reach plasma center. When the input LHW power was close to the H-mode power threshold, the improved confinement phase started shortly after LHW injection. A strong gas puffing was applied and density increased until the plasma disruption. The improved phase started shortly after injection of LH waves, indicated by the drop of H_α radiation. Fig.3 shows that the duration with a densities higher than 90% Greenwald limit ($\sim6\times10^{19}\mathrm{m}^{-3}$) remains more than 5 times longer than τ_E^L (about 18ms). For normal discharge with current flat top, it was difficult for the density to pass through Greenwald limit with strong gas puffing. It would be disrupted when density approached the density limit. It could be maintained without disruption when density was between 75% to 90% of Greenwald density limit.

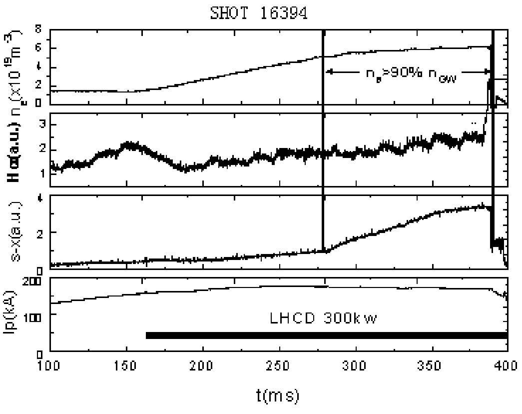

Fig.3 Shot 16394. B_T=2.0T, P_{LHCD}=300kW

Plasma current, toroidal magnetic field, LH wave launching spectrum and density were scanned to try finding the solution to operate in a quasi-steady-state condition without disruption. Fig.4 shows the relation between the normalized line averaged density and edge safety factor. It clearly shows that the higher the safety factor, the higher of the plasma density can be reached. This is because higher magnetic field gives better confinement of energetic electrons generated by LHCD. The launching spectrum of the LHCD grill was normalized with the accessibility condition. When the $n_{||}$ was close to the accessibility condition, the highest plasma density could been reached without disruption. The steady state LHCD operation at the density around Greenwald density limit and the solution to avoid the disruptions when normalized density passed unity are still under investment in HT-7 experiments.

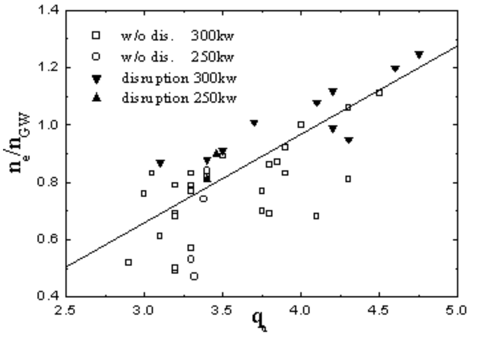

Fig.4 The relation between density and q_a

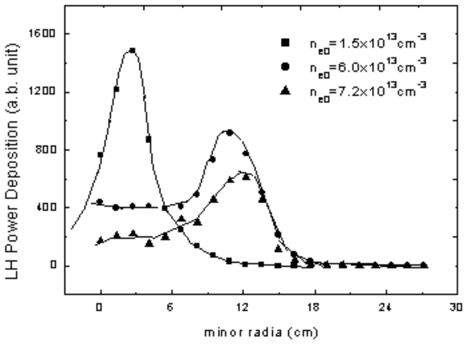

Fig.5 Calculated LH power deposition profile

The ray tracing and the wave diffusion/Fokker-Planck (WD/FP) codes were used to simulate the wave propagation and deposition processes. The caculations showed that an off-axis LH wave power deposition was formed as indicated in Fig.5. The weak absorption and multi-pass of LH waves were dominated here. When a certain of fraction of the plasma current (50% to 8% for the line average density $1.5\times10^{13}cm^{-3}$ to $5.8\times10^{13}cm^{-3}$) was non-inductively sustained by the low hybrid waves, the hollow current density profile was formed and the magnetic shear was reversed at the normalized plasma radius of 0.4 to 0.5. A peak of hard x–ray radiation with bulk energy of 80 keV was observed from the chords between r = 7 cm and 14cm, where were between normalized radii 0.25 to 0.5. Hard x-ray measurements showed a good agreement with the code simulations. The off-axis non-inductive current profile by LHCD improved and sustained the confinements for 5 times longer than τ_E^L with a plasma density $6\times10^{13}cm^{-3}$, which was about 90% of Greenwald density limit.

4. Supersonic Beam Injection

Fueling tokamak plasma under steady state with deep penetration depth is also one of the topics on the HT-7 tokamak. According to aerodynamic principle, Laval nozzle is a suitable device to produce supersonic molecular beam with high puffing speed. Experiments have demonstrated that is a more effective fueling method than the normal gas puffing [8]. Two Laval nozzles have been installed in the HT-7 superconducting tokamak. One is in the high field-side and another is located in the low field-side. Ddeuterium and helium working gases were used. Plasma density can be easily controlled by pulsed high-speed molecular beam that comes from the Laval nozzle. The speed of the hydrogen beam was about 0.4~0.8km/s inside plasma. With penetration depth up to the half of minor radius, the density peaking factor was almost same with that obtained by off-axis pellet injection. Figure 6 shows a typical shot by

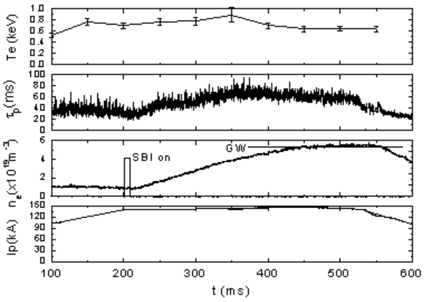

Fig.6 A typical shot of SBI. B_T=2.0T

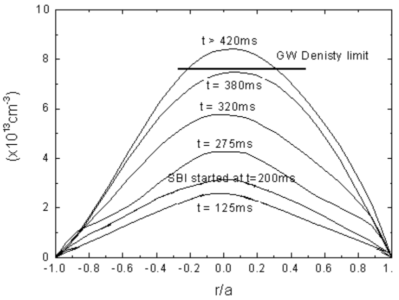

Fig.7 Density profiles during SBI of OH shot

supersonic beam injection (SBI). The line averaged density increased immediately after switching on the SBI, approached the density limit much faster than the gas puffing and stayed on the density limit level for more than 100ms. The impurity fluxes, Z_{eff} and electron temperature changed a little. The recycling was not as high as the case with strong gas puffing. The radiation power slightly increased but was still as low as 50% of input power. The particle confinement time increased by a factor of two. Fig.7 shows the density profile at different time before and after SBI. After t=420ms, the density profile kept unchanged and lasted for 100ms until the shut off the SBI. The high fueling efficiency of SBI, up to 60%, was obtained. The penetration and transport of neutral hydrogen with SBI have been measured and analyzed.

5. Summery

It is important for tokamak operating around the operational boundaries, especially on the density limit. Efforts have been made on HT-7 tokamak for extending the stable steady-state operation boundaries. Extensive RF boronization and siliconization have used and wider stationary Hugill diagram was obtained. High performance discharges have been obtained after siliconization. Edge safety factor could been maintained at 2.1. Improved confinement phase was also obtained by LHCD with the density range of 70%~120% Greenwald density limit. Off-axis LHW power deposition was contributed to the weak hollow current density profile. Code simulations and measurements showed a good agreement of the off-axis LHW power deposition. Supersonic molecular beam has been successfully used to get stable high-density operation around Greeenwald density limit.

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