

Experimental Progress on HT-7 Superconducting Tokamak in 1998

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1. Introduction:

The steady-state tokamak operation and high performance plasma under non-inductive current drive are one of the most important issues for the tokamak fusion research. The various improved confinement modes are obtained in different machines [1]-[3]. How to make these modes work under steady state is still unsolved. HT-7 is a mid-size superconducting tokamak. Its main purpose is to explore steady-state tokamak operation with advanced modes. The parameters of the machine are as follow. $B_T = 2.5T$, $I_p = 100\sim 250kA$, $R=122cm$, $a = 30cm$, line average density $n_e=1\sim 5\times 10^{19}m^{-3}$, $T_e = 1.0 keV$, $T_i = 0.5 keV$, $\tau_E = 15ms$ and plasma duration time is about 3~5 seconds. A stainless steel liner was installed in the vacuum chamber with the radius of 0.32m. 24 large windows give very good accessibility to the diagnostics and wave systems. 1.2MW Lower Hybrid Wave Current (LHCD) system is tested with 10 seconds pulse length. The power for the ICRH system is 0.3MW with CW capacity. 1MW ECRH system is still under construction. More than 20 diagnostics were installed on the machine. A new feedback control system was installed in 1998. The machine is normally running for $I_p=150kA$, $B_T = 2T$, $a = 28.5cm$, with Mo limiter configuration. The LHCD experiments were successfully carried out in the expected manner. The plasma confinement was improved by LHCD. The full wave current lasting for 3.5 seconds was obtained. Since the presence of permanent toroidal field, ICRF conditioning has been routinely used during experiments, which has proved to be a very effective and powerful way for the impurity cleaning, boronization and recycling control. Very strong wall isotope exchange capability of deuterium RF conditioning was demonstrated. The long pulse length discharges were carried out with the pulse length up to 5.7 seconds. The MHD instability suppressing by LHCD and I_p modulation [4], the error field, lower loop voltage start-up, pellet injection, supersonic beam gas filling, as well as ICRF experiments were carried out. Some interesting results were obtained in the past year that will be described in the following sections.

2. High density LHCD experiments

The quasi-steady state ($t_H > 10 \tau_{Eoh}$) H-mode with a plasma density of 60% Greenwald density limit was obtained by the injection of LH Heating and LHCD in HT-6M tokamak [5]. The same method was used on the HT-7. Under high plasma density condition, the LH waves could not be absorbed in the plasma center, so a large fraction of non-inductive current is driven in the outer region of plasma. By proper choosing the plasma parameters, the weak absorption dominant condition could be satisfied. LHCD system consists of a multijunction 2x12 grill with a changeable $n_{||}$. The frequency is 2.45GHz. The magnetic field was 1.9T and plasma density is about $3\sim 6.0\times 10^{19}m^{-3}$. By enhanced ICRF boronization and helium discharge, a very good wall condition and high plasma performances were achieved. LH wave was injected to the plasma flat top and the density increased more than two times by the strong gas puffing. The H_a dropped that indicated the particle confinement time increased. The store energy increase by nearly a factor of three and the energy confinement time is about nearly two times higher than the L-mode scaling. The H-phase at the 75% Greenwald density limit remains as long as 5 times of energy confinement time. To invest the density limit that LHCD H-phase could sustain, wide plasma parameters

were scanned and plasma current was ramped down shown as figure1. The plasma confinements began to decline when the density accessed the Greenwald density limit. And plasma was disrupted at the 1.25 Greenwald density limit. The ray tracing and the wave diffusion/Fokker-Planck (WD/FP) mode were used to understand the wave deposition mechanism. When a certain of fraction of the plasma current (50% to 10% for the line average density $1.0 \times 10^{13} \text{cm}^{-3}$ to $4.5 \times 10^{13} \text{cm}^{-3}$) is non-inductively sustained by the low hybrid waves, the hollow current density profile was formed and the magnetic shear is reversed at the normalized plasma radius of 0.2~0.4. The off-axis non-inductive current profile by LHCD improved the confinements and sustained the reversed magnetic shear for more than 180ms which is about 10 times longer than the energy confinement time. When the $N_{||}$ is close to the accessibility condition, the highest plasma density could achieve without disruption. The higher the safety factor, the higher of the plasma density achieved shown as figure1 (b) and (c)

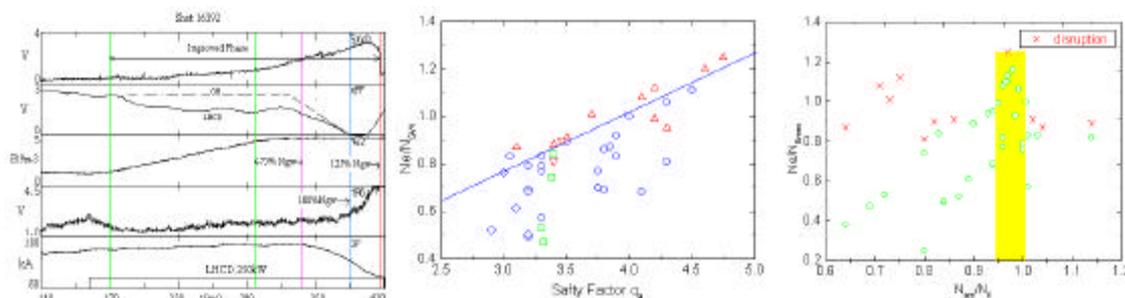


Fig. 1a High density H-mode by LHCD. Fig.1b The highest density with q_s (Δ) disruption shots. Fig. 1c The density dependence on the launching spectrum.

3. IBW heating

Ion Bernstein Wave (IBW) heating is an ion-cyclotron-resonance-frequency heating concept which using the directly launched IBW to carry RF power deep into the dense plasma core. Theory and experiments have showed the advantage of IBW heating in different tokamaks [6]-[7]. IBW heating was also investigated in HT-7 superconducting tokamak deuterium plasma with an injecting power up to 300kW. The RF frequency was 24 ~ 30 MHz and toroidal field was chosen to make the Ω_H layer located in the center region of the plasma. The bulk electron temperature shows a significant rise with heating factor, $\Delta T_e \times n_e / P_{RF}$, of $10.4 \text{ (eV} \cdot 10^{13} \text{cm}^{-3} / \text{kW)}$. The direct electron heating via electron Landau damping from IBW was observed (Fig.1a). By proper choosing the heating mechanism, both particle and energy confinement times were increased. The electron-heating mode was used to get high electron temperature for high Lower Hybrid Current Drive (LHCD) efficiency. An internal transport barrier shown as figure 2b and peaked density profile was attribute to the good confinement during IBW heating.

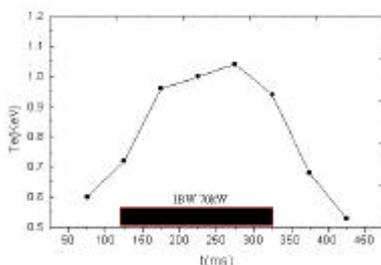
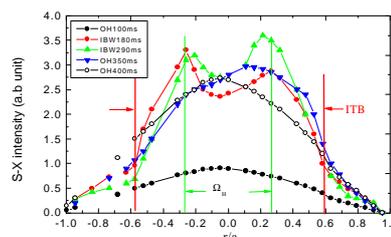


Fig. 2a Director electron heating by IBW



(b) ITB and Ω_H observed by s-x ray diode array

4. ICRF conditioning:

ICRF boronization has been successfully tested in the first time on tokamak. This new technique has demonstrated itself the high efficient, fast and easy controllable method for the future large device like ITER, especially for the superconducting tokamak. The high-energy ions and the mechanism of ICRF plasma make the film highly adhesion, hard amorphous, deep penetration depth, and uniform both in thickness and the toroidal directions. By choosing the proper RF conditioning parameters after RF boronization, the hydrogen recycling and H/(H+D) ratio could be easily handle. Comparing with the common boronization method, it shows much better film properties, such as high ratio of boron to carbon and longer lifetime. Its influence to plasma performance gives better results. The nontoxic and nonexplosive solid carborane ($C_2B_{10}H_{12}$) powder was used for the boronization material. The ion cyclotron resonant layers were clearly seen, shown as in figure 3.

X-ray photoelectron spectroscopy was made on the films. The B/C ratio varied from 2.8~3 for a depth of 250nm for all the sample materials. Analysis of B/C coating showed that it consisted of a fine amorphous C/B: H film with very strong adhesion to the first wall. Figure 4 shows the film structure on the graphite base material. Even after 250 shots with ICRF and LHCD (about 400 kW RF power), 11 of the total samples showed the nearly the same structure with fresh films except thickness shown as figure 4b. One sample had the clear damage spots, which were bombarded by energetic electron and ions. The lifetime of the coating was 1500~2000 shots.

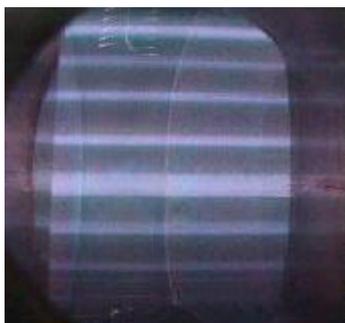


Fig.3 The ICRF resonant layers could be clearly seen.

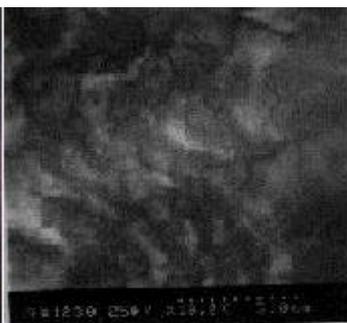


Fig. 4a Fresh film on C Sample material.



Fig. 4b Boron film after 250 shots which still looks good.

5. Pellet and supersonic beam injection:

Both hydrogen and deuterium pellets were fired to the plasma with the speed of 0.5~1.2 km/s. The different size pellets were chosen according to the different plasma conditions. Very peak density profile was obtained after the injection of the pellet under normal ohmic discharge. Up to four pellets were injected to the same shot. Each pellet makes the density increase about 50%. Figure 5 shows an ohmic shot with two pellets case. The pellets could penetrate to the plasma center and plasma performance improvement was obtained, which is indicated by suppressing MHD, peak density profile, the reduction of Z_{eff} , store energy increase, energy and particle confinements improving and hollow temperature profile.

The fueling tokamak plasma in more efficient way is very important for fusion research. According to aerodynamic principle, Laval nozzle is the key device to produce supersonic molecular beam, which is more effective fueling method than the normal gas puffing. The Laval nozzle has been installed in the HT-7 superconducting tokamak with the diameter on the throat section of the Laval nozzle as 1 mm and the

diameter on exit section as 10 mm. The experiments have been carried out. The density of plasma could easily be controlled by pulsed high-speed molecular beam that comes from the Laval nozzle. The speed of the hydrogen beam is about 0.4~0.8km/s inside plasma that is mainly depend on the temperature of the injection gas and the plasma condition. With penetration depth up to 15cm, the density peaking factor is almost same with the one achieved by pellet injection. The improvements for both energy and particle confinements were made by molecular beam injection. The fueling efficiency of about 60% demonstrates that it is a useful tool for the steady-state tokamak operation. The penetration and transport of neutral hydrogen have been measured and analyzed. Figure 6 is a typical shot by supersonic beam injection (SBI).

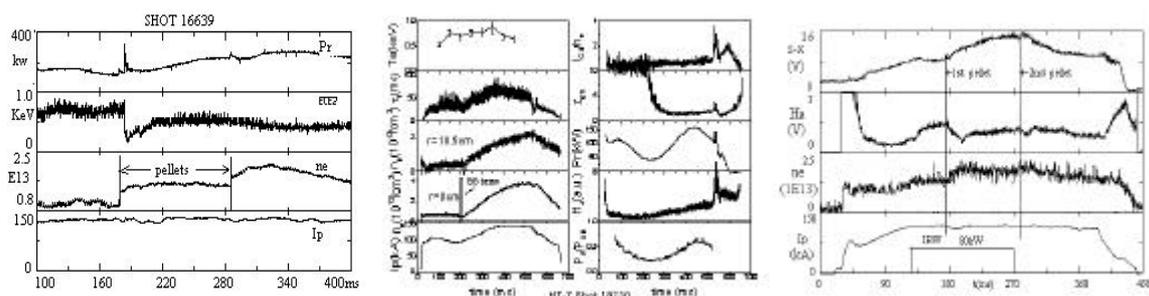


Fig.5 multi-pellet injection on OH shot. Fig.6 Typical shot for SBI. Fig.7 Shot with IBW and pellets

6. The improved plasma performances by combining IBW and other techniques

IBW heating was also combined with pellet injection and LHCD experiments, which also shows its unique merit. By proper timing the pellet and IBW, PEP like reversed shear configuration was obtained. The fueling efficiency is higher than the normal ohmic pellet injection. The super-thermal electrons were suppressed by applying IBW into LHCD plasma. Higher current driven efficiency and confinements were observed which is partially belonging to the synergy between IBW and LHCD.

7. Conclusion The quasi-steady state ($\tau_H > 10 \tau_{Eoh}$) H-mode was obtained with very high plasma density by LHCD. The line average density range during improved confinement phase is about $4.5 \sim 6.0 \times 10^{13} \text{cm}^{-3}$ which is in the range of Greenwald density limit (75~120% of Greenwald density limit). Steady state full LH wave current drive has been achieved for more than 3 seconds. The good plasma condition is obtained by ICRF boronization, which makes Z_{eff} close to 1.0. High-density shots are obtained by two different fueling methods: multi-pellet injection and supersonic beam injection. The later shows a high fueling efficiency that could be used for steady-state operation. IBW heating was carried out mainly on the electron heating mode. Very high heating factor was obtained. The synergy between IBW and LHCD has been tested and some interesting results have been obtained.

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