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Long-pulse discharges by synergy of LHW and IBW heating in the HT-7 tokamak

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Abstract

In the HT-7 superconducting tokamak, long-pulse discharge was generated by synergy of high power LHCD (300–600 kW, 2.45 GHz) and high power IBW (200–350 kW, 27 MHz) heating. Recently, a new set of actively cooled toroidal double-ring graphite limiters at bottom and top of the vacuum vessel has been developed for long-pulse operation in the HT-7. Based on the understanding of plasma surface interactions, nearly full non-inductive current driven plasma ($I_p = 120$–180 kA, $B_T = 1.5$–2 T, $T_e(0) = 2$–4 keV, and $\langle n_e \rangle = 1$–$2.5 \times 10^{19}\,\mathrm{m}^{-3}$) was achieved with the operational pulse length of 1–10 s. For lower performance operation, more than 60 s of long-pulse plasma was obtained by the LHCD in 2003 on the HT-7 tokamak.

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Keywords: HT-7 tokamak; Ion Bernstein wave; Limiter; Long-pulse discharge

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1. Introduction

Enhanced performance discharge induced by lower hybrid wave (LHW) and ion Bernstein wave (IBW) synergy has been studied in the HT-7 superconducting tokamak since 2000 [1]. The local synergistic behavior of LHW and IBW was observed on PBX [2]. It was found that the hard X-ray bremsstrahlung emission from suprathermal electrons, generated with lower hybrid current drive, was enhanced during ion Bernstein wave power injection. By means of the improvement of heating system and hard X-ray diagnostics in the HT-7, the optimal profile of hard X-ray intensity has been achieved by the synergy effect [3,4]. High-performance plasma is produced with a broadened current profile and broadened ITB (internal transport barrier) on electron density and temperature profiles in the HT-7 [3,4]. This high-performance mode utilizing synergy effect of IBW and LHCD provides a new way to obtain steady-state operation in the advanced tokamak scenario [3].

In this paper, progress of long-pulse discharge and PSI issue towards the steady-state operation are

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discussed. The long-pulse discharge generated by synergy of high power LHCD (300–600 kW, 2.45 GHz) and high power IBW (200–350 kW, 27 MHz) heating is reported. MHD behaviors and thermal instabilities during long-pulse operation are summarized [5]. Nearly full non-inductive current driven plasma ($I_p = 120$–180 kA, $B_T = 1.5$–2 T, $T_e(0) = 2$–4 keV, and $\langle n_e \rangle = 1.0$–$2.5 \times 10^{19}\,\mathrm{m}^{-3}$) was achieved with the operational pulse length of 1 $\sim$ 10 sec. For lower performance ($I_p = 60$ kA, $T_e(0) = 0.5$–1 keV, $\langle n_e \rangle = 0.5$–$1 \times 10^{19}\,\mathrm{m}^{-3}$) operation, more than 1 min of long-pulse plasma was obtained by the LHCD (<200 kW) in 2003 on the HT-7 tokamak.

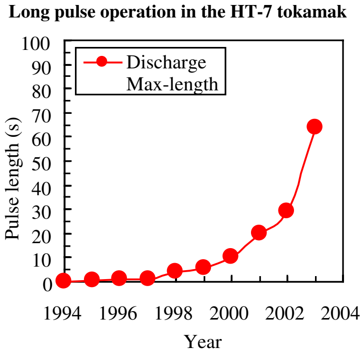
2. Experimental setup and PSI issue on HT-7 tokamak

The HT-7 machine is a superconducting tokamak, and it was rebuilt from the original Russian T-7 tokamak in 1994 [6]. It has a major radius of $R = 1.22$ m, minor radius of $a = 0.27$ m in the circular cross-section. There are two layers of thick copper shells, and between them are located 24 superconducting coils which can create and maintain a toroidal magnetic field (B_T) of up to 2.5 T. The HT-7 tokamak is normally operated with $I_p = 100$–250 kA, $B_T = 2$ T, line-averaged density 1–$5 \times 10^{19}\,\mathrm{m}^{-3}$, $T_e = 1.0$–3.0 keV, and $T_i = 0.5$–1.5 keV limiter configuration. A stainless-steel liner was installed in the vacuum chamber with a radius of 0.32 m [6]. The power for the ion cyclotron range of frequencies (ICRF) system was 0.3 MW with continuous wave (CW) capacity. The LHCD system consisted of a multi-junction grill, 1.2 MW of wave system with the frequency of 2.45 GHz and the power supply system with long-pulse length.

Based on the understanding of plasma surface interactions, several technical improvements have been made recently. The new GBST1308 doped graphite was used as limiter material [3]. It has high thermal conductivity up to 210 W/m.K. Its good thermal shock resistance can withstand 6 MW/m^2 high heat loads for 100 s. All carbon titles were coated with 100 μm SiC functional gradient coating [7], which was also used for the limiter and the Faraday screen of the IBW antenna. Fig. 1 shows poloidal limiters and a toroidal water-cooling belt limiter at high field side (developed in 2002), where a new set of actively cooled toroidal double-ring graphite limiters at bottom and top of the vacuum vessel has been developed and tested recently in 2004 for long pulse operation in the HT-7.

Twenty-four pieces of a ferromagnetic material–ferritic steel-have been installed inside the vacuum chamber, to be used as plasma facing components and for the reduction of the magnetic ripple in 2001 [3]. The ripple at the limiter radius is reduced from 4% to about 1.6%. The new CW LHCD system with 1.2 MW has been installed into the machine. The grill of the LHCD has been changed in 3 × 16 multijunction and coated with TiN film. The 1.5 MW ICRF system with a new antenna has been built. Two cryopumps with 10 m^3/l pumping speed were installed to enhance the particle exhaust. The rf wall conditioning technique has been well developed and routinely used in HT-7 tokamak since 1999. This technique is designed for future large superconducting devices in the presence of high magnetic field. The previous techniques consist of rf cleaning, hydrogen recycling and isotopic control, rf boronization and siliconization. The B/C:H and Si/C:H films show the higher adhesion, uniformity and longer lifetime of the plasma discharges than those obtained by normal GDC method. These rf coatings contribute to the significant reduction of the impurity radiation and edge recycling [3]. Fig. 2 shows the progress of long-pulse operation (up to $t = 64$ s) and related technologies in the HT-7 superconducting tokamak from 1994 to 2003. Steady-state high-performance plasma with new set of actively cooled toroidal double-ring graphite limiters is expected by LHCD and IBW synergy on HT-7 in the near future.

Fig. 1. Poloidal and toroidal water-cooling limiters in the HT-7 tokamak.



1994:First plasma
1996:Development of plasma control and diagnostics system
1998:Feedback control for plasma current, displacement and density
1999:RF wall condition
2000:Upgrade data acquisition & diagnostics
2001:Ferritic steel to reduce ripple loss; New LHCD antenna system
2002:Water cooling poloidal and belt graphite limiters

Fig. 2. Progress of long-pulse operation and related technologies in the HT-7 tokamak.

3. Long-pulse discharges

High-performance plasma is produced by the synergy between IBW and LHCD with a broadened current profile and broadened ITB on electron density and temperature profiles in the HT-7 [3,4]. The key issue for achieving high-performance discharge by using LHCD and IBW is to increase the high confinement volume. For this purpose, off-axis current drive is utilized to obtain an internal transport barrier structure beyond the half radius. The profiles of electron temperature and density were gradually broadened in the plasma core region up to about a half-minor radius [3]. The ITB-like profiles in both temperature and density were formed at the time around 1 s. At this time, a clear enhancement of the plasma performance was initiated. The electron temperature, store energy, and H-factor increased significantly while the plasma density was constant. A well-boronized wall kept a very low impurity radiation and a large pump remained the low recycling from the wall. The high confinement indicated by $\beta_N^* H_{89} > 3$ lasted for about 1.2 s, which is about 54 times of energy confinement time [3]. It is a challenge for high-performance steady-state plasmas due to several problems, such as MHD instability, high impurity radiation, and edge recycling [5]. In HT-7, the most dangerous MHD instability is the $m/n = 2/1$ resistive tearing mode, which is driven by the plasma current density gradient. The key points to get long duration of high confinement are controlling the edge transport, suppressing edge turbulence and keeping low impurity and wall recycling [5].

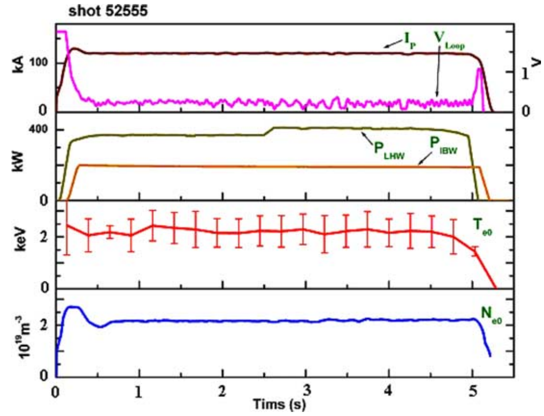


Fig. 3. Long-pulse high-performance discharge by synergy of LHCD and IBW heating.

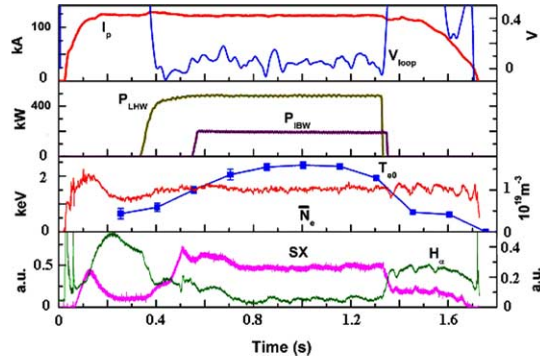


Fig. 4. Full non-inductive scenario under higher power of LHW (0.5 MW) and IBW (0.2 MW).

Edge plasma profile and its evolution were measured during the long pulse discharge [4]. The radiation and impurity behaviors were studied carefully [5]. MHD behaviors and thermal instabilities during long-pulse operation were studied in detail [5]. Based on the understanding of plasma surface interactions, nearly full non-inductive current driven plasma (I_p = 120–180 kA, B_T = 1.5–2 T, $T_e(0)$ = 2–4 keV, and $\langle n_e \rangle = 1.0$–$2.5 \times 10^{19}\,\mathrm{m}^{-3}$) was achieved with the operational pulse length of 1–10 s. Fig. 3 shows a typical long-pulse discharge by synergy of LHCD and IBW heating. The plasma current is 120 kA, the toroidal field is $B_T = 1.8$ T, major radius of $R = 1.22$ m, minor radius of $a = 0.27$ m, edge safety factor is about 4.6 with sawtooth-free, averaged electron density is $1.65 \times 10^{19}\,\mathrm{m}^{-3}$, center density is $n_e(0) > 2.1 \times 10^{19}\,\mathrm{m}^{-3}$, electron temperature $T_e(0) > 2.0$ keV, ion temperature $T_i(0) > 1.2$ keV. The injected power of LHW is about 0.4 MW, and the injected IBW power is 0.2 MW at radio frequency of 27 MHz. Confinement study shows that the energy confinement time is about 20 ms for sawtooth-free plasma, and $\beta_N^* H_{89} > 2$ is achieved and sustained for about 4.4 s which is about 220 times of energy confinement time. The loop voltage is about 0.25 V as shown in Fig. 3. The transport analysis shows that the LHW driven current is $I_{\mathrm{LHCD}} = 50$ kA, the bootstrap current is about $I_{\mathrm{BS}} = 46$ kA and the ohmic current is $I_{\mathrm{OH}} = 24$ kA. About 80% non-inductive current is generated by the synergy of LHW and IBW in the HT-7 long-pulse operation, where the fraction of bootstrap current f_{BS} is 38% and f_{LHCD} is 42%. Fig. 4 shows another shot with full non-inductive current discharge under higher power of LHW and IBW. The injected power of LHW is about 0.5 MW, and the injected IBW power is 0.2 MW at 27 MHz. The plasma current is 120 kA, the toroidal field is $B_T = 1.6$ T, averaged electron density is $1.0 \times 10^{19}\,\mathrm{m}^{-3}$, electron temperature $T_e(0) = 2.4$ keV. It is observed in Fig. 4 that there is no MHD and sawtooth behavior on soft X-ray signal, and a clear decrease in H_α radiation with improved confinement is obtained during the synergy. The loop voltage is nearly $V_{\mathrm{loop}} \sim 0$ V as shown in Fig. 4. The transport analysis shows that about 100% non-inductive current is generated by the synergy of LHW and IBW, it is one of candidates for advanced steady state operation in the HT-7. This scenario will be studied for long pulse operation with new set of actively cooled toroidal double-ring graphite limiters recently as

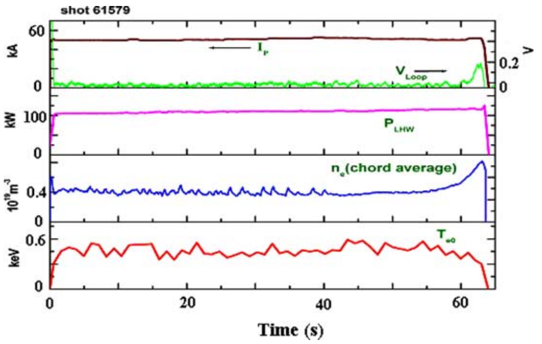


Fig. 5. Up to 64 s of long-pulse plasma by LHCD (0.1–0.2 MW) in the HT-7 tokamak.

shown in Fig. 1. Heat exhaust and particles control is essential in long-pulse discharges [5]. For lower performance ($I_p = 60\,\mathrm{kA}$, $T_e(0) = 0.5$–$1\,\mathrm{keV}$, $\langle n_e \rangle = 0.5$–$1 \times 10^{19}\,\mathrm{m}^{-3}$) operation, more than 1 min of long-pulse plasma was obtained by the LHCD (< 200 kW) in the HT-7 tokamak as shown in Fig. 5. Precursor of density increase from $t = 55\,\mathrm{s}$ to $t = 64$ s leads the rapid rise of loop voltage and a clear decrease in the electron temperature from $t = 60\,\mathrm{s}$ to $t = 64\,\mathrm{s}$, which terminated the discharge on $t = 64\,\mathrm{s}$ at final as shown in Fig. 5. New set of actively cooled toroidal double-ring graphite limiter is expected to take the important rule on heat exhaust and particles control for advanced steady state operation on HT-7 in the near future.

4. Summary

High-performance plasma is produced by the synergy between IBW and LHCD with a broadened current profile and broadened ITB on electron density and temperature profiles in the HT-7. The key issues for high performance steady-state operation is MHD instability, high impurity radiation, and wall recycling. Based on the understanding of plasma surface interactions, nearly full non-inductive current driven plasma ($I_p = 120$–$180\,\mathrm{kA}$, $B_T = 1.5$–$2\,\mathrm{T}$, $T_e(0) = 2$–$4\,\mathrm{keV}$, and $\langle n_e \rangle = 1.0$–$2.5 \times 10^{19}\,\mathrm{m}^{-3}$) is achieved with the operational pulse length of 1–10 s. Confinement study shows that $\beta_N^* H_{89} > 2$ is achieved and sustained for about 4.4 s which is about 220 times of energy confinement time. The transport analysis shows that about 80% non-inductive current is generated by the synergy of LHW and IBW in the HT-7 long-pulse operation, where the fraction of bootstrap current $\mathrm{f_{BS}}$ is 38% and $\mathrm{f_{LHCD}}$ is 42%. Heat exhaust and particles control is essential in long-pulse discharges. New set of actively cooled toroidal double-ring graphite limiter is expected to take the important rule for advanced steady-state operation on HT-7 in the near future.

Acknowledgments

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