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Reduced effective ionic charge and enhanced plasma performance in the HT-7 tokamak

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Abstract

Many technical improvements were achieved recently in the HT-7 superconducting tokamak, such as ICRF boronization, new water cooling graphite limiters which is instead of molybdenum limiter, and application of ferritic steel for reducing the magnetic ripple, and so on. The global impurity content and impurity components were measured and studied by using of spectroscopy diagnostics in the HT-7 tokamak. Experimental results of the effective ionic charge Z_{eff} and impurity behaviors before and after technical improvements mentioned above are compared in this paper. It is observed that the integrated plasma performance is enhanced while the global impurity content and Z_{eff} drops with these technical improvements. Steady state plasma with higher performance and 5-min long pulse plasma were obtained.

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Keywords: Graphite limiter; Ferritic steel; Boronization; Spectroscopy; Impurity

1. Introduction

Steady state operation with high performance is a crucial issue for fusion plasma research. In order to achieve the required fusion yield and to operate effectively, future tokamak needs to operate under steady state condition with high performance. The various improved confinement modes are obtained in different machines [1–3]. It is relative to the first wall materials and plasma impurity contents from the wall materials. The study of the contamination of tokamak plasma by impurities is also an important aspect of fusion research. The performance of future burning plasma reactors will rely on maintaining plasma with a modest effective ionic charge ($Z_{\mathrm{eff}} \leqslant 2$), in order to minimize fuel dilution and central plasma radiation from impurities and bremsstrahlung. So research and development of plasma facing components to obtain clean plasma is very important to achieve not only high performance but also steady state operation.

HT-7 is a medium-sized superconducting tokamak. Its longest pulse is more than 300 s, which provides a good condition for PSI research. Its main purpose is to explore high performance plasma operation under steady state conditions. The parameters of the machine are: $B_{\mathrm{T}} = 2.5$ T, $I_{\mathrm{P}} =$ 100–250 kA, $R = 1.22$ m, $a = 0.27$ m, line-averaged

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density $n_e = 1–5 \times 10^{19}\ m^{-3}$, $T_e = 1.0–3.0$ keV, $T_i = 0.5–1.5$ keV. A 1.2 MW lower hybrid wave current (LHCD) system with the frequency of 2.45 GHz and a 0.3 MW ion cyclotron range of frequencies (ICRF) system with continuous wave (CW) capacity were equipped. More than 30 diagnostics were installed and operated in accommodation with requirements of steady state operation with high performance. During past several years some technical improvements had been made. In this paper, the technical improvements and enhanced plasma performance with reduced global impurity content are summarized.

2. Spectroscopy diagnostics for PSI study on HT-7

Several spectroscopy diagnostics equipped on HT-7 tokamak for PSI and steady state operation studies are shown in Fig. 1. In this paper, the key diagnostic is the 7-channel visible bremsstrahlung for effective ionic charge Z_{eff}. The effective ionic charge of plasma is given by $Z_{eff} = \frac{\sum_i n_i Z_i^2}{\sum_i n_i Z_i}$ where i are the ionic charge states, n_i (n_e) is the ion (electron) density and Z_i is the ionic charge. $Z_{eff}(r)$ can be derived from the radial profiles of visible bremsstrahlung, electron density and electron temperature. $Z_{eff}(r)$ measured at a wavelength over a spectral range of $\Delta\lambda$ (Å) is given by $Z_{eff}(r) = \frac{\lambda T_e^{1/2}(r)\xi_{brem}(r)\exp[12400/\lambda T_e(r)]}{9.5\times 10^{-20} g_{ff}\Delta\lambda[n_e(r)]^2}$, where n_e (m^{-3}) and T_e (eV) are the electron density and temperature of the plasma, respectively g_{ff} is the temperature averaged Gaunt factor (weakly dependent on T_e and Z_{eff}). For a central chord averaged $\overline{Z}_{eff}(0)$, it is given by $\overline{Z}_{eff}(0) = \sqrt{\overline{T}_{e0}} \times \int_{-a}^{a} \frac{d\xi_{brem}(r)}{d\lambda} dr \Big/ \left(\frac{1}{2a}\int_{-a}^{a} n_e(r)dr\right)^2$, where $\overline{T}_{e0}$ is central chord-averaged electron temperature, and a is plasma minor radius. In general, to estimate of the impurity content i.e. Z_{eff} levels, the central chord averaged $\overline{Z}_{eff}(0)$ can be adopted.

Hα photodiode array is employed to study the global particle confinement. One array is for the wall and another is for the toroidal limiter. Ten-channel visible spectroscopy is for the carbon impurity behaviors by monitoring the radiation profile of CIII. Rotating mirror monochromator diagnostic is employed to study the impurity transports by taking radiated profiles simultaneously of two ionization states for one kind of impurity. Two sets of UV and VIS monochromators are for monitoring the evolutions of OII and OV radiations with the discharge time. Optical spectroscopy multichannel analyzer (OSMA) is employed to take the whole spectrum from UV to VIS regions and provide H/H + D ratios by spectral line shape analysis.

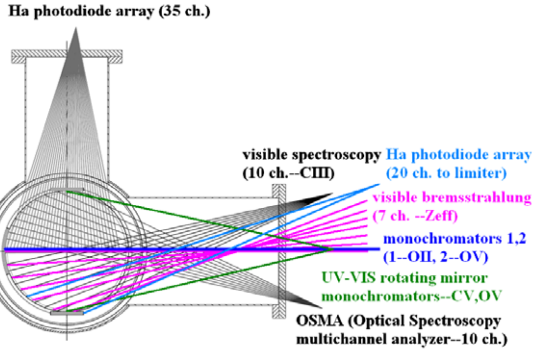

Fig. 1. Spectroscopy diagnostics for PSI studies on HT-7.

3. Plasma-facing components in the HT-7 tokamak

HT-7 is a superconducting tokamak with the limiter configuration designed to operate with high performance long duration discharges. In the past with a smaller and discrete molybdenum limiter as shown in Fig. 2, the plasma discharge was usually terminated by the very strong hard X-ray radiation, hot spot and high-Z impurities radiation duo to energetic particles and overheated problem. To meet the requirements of high performance and long duration operation, several technical improvements have been made. Carbon base material including B-, Si-, and Ti-doped graphite has also been success-

Fig. 2. Smaller and discrete molybdenum limiter employed before the year of 2000.

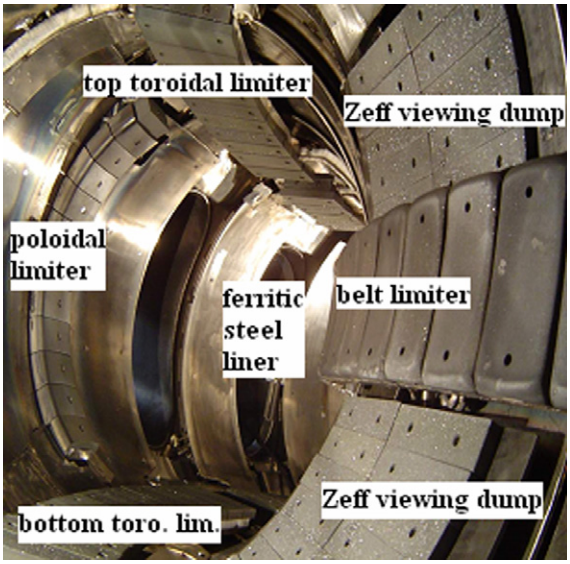

Fig. 3. The poloidal and toroidal water cooling graphite limiters in the HT-7 tokamak.

fully developed and tested. The new GBST1308 (1%B, 2.5%Si, 7.5%Ti) doped graphite with high thermal conductivity up to 180–240 W/m K has been used as the main limiter material [4]. All tiles of limiter were coated with above 100–200 μm SiC gradient coatings [5]. Its good thermal shock resistance can withstand 6 MW/m^2 high heat loads for 100 s. Fig. 3 shows poloidal limiters, a toroidal water cooling belt limiter at high field side and a set of actively cooled toroidal double-ring graphite limiters with Cu alloy heat sink at bottom and top of the vacuum vessel in 2004 for long pulse steady state operation in the HT-7. The main limiter has a minor radius $r = 27$ cm which is smaller than old molybdenum limiter 28.5 cm to protect the first wall and control impurities. The wide SOL provides a good protection for stainless steel liner from energetic ions bombardment. The total surface area of the limiters is about 2.35 m^2 with coverage of more than 20% of the plasma-facing surface. Two extra cryopumps with 10 m^3/s pumping speed which is matched to new graphite limiter were installed in order to enhance the particle exhaust. By using of new graphite limiters the capability of heat loading, heat exhaust and particle exhaust are enhanced. The Z_{eff} drops as shown in Fig. 4. It mostly owes to that high-Z impurities problem caused by local overheating have been alleviated with new graphite limiters.

In the campaign 2001, 24 pieces of ferritic steel boards named GYJ060 (8%Cr + 2%W + 0.2%V + 0.06%Ta + Fe remainder) ferromagnetic material were installed on the low field side in inside the vacuum vessel of HT-7. The experimental results show that the ripple of magnetic field had been reduced at the limiter radius ($r = 27$ cm) from 4% to less than 1.6%, and the serious impurity problem during Ion Bernstein Wave (IBW) heating had been solved with reduction of fast ion losses [6]. In the HT-7 campaign 2003, ferritic steel liners were installed to cover most area of the inner surface facing the plasma for purpose of more reduction of the magnetic ripple. It is observed that the Z_{eff} drops dramatically in auxiliary heating and current driven plasma discharges (see Fig. 4). It ascribes to reduced fast particle loss during the auxiliary heating and reduced high energetic runaway electrons during LHCD [4].

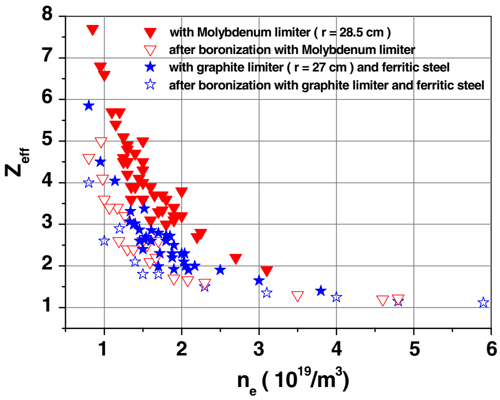

Fig. 4. The Z_{eff} before and after using graphite limiters and ferritic steel.

4. ICRF boronization

ICRF boronization is an effective way and powerful tool to suppress impurity for the future fusion devices in the presence of permanent toroidal magnetic field [7]. The analysis results of the B/C:H and Si/C:H films obtained by ICRF boronization or siliconization show the higher adhesion, uniformity and longer lifetime than those obtained by normal GDC method. It leads to reduced carbon and oxygen impurity influxes (see Fig. 5). Carbon impurity influx decreased by a factor of 3 after boronization and by a factor of 2 after siliconization. Oxygen impurity influx decreased by a factor of 5 after boronization and siliconization. It shows that ICRF boronization or siliconization are more efficient to reduce the oxygen impurity because of oxygen

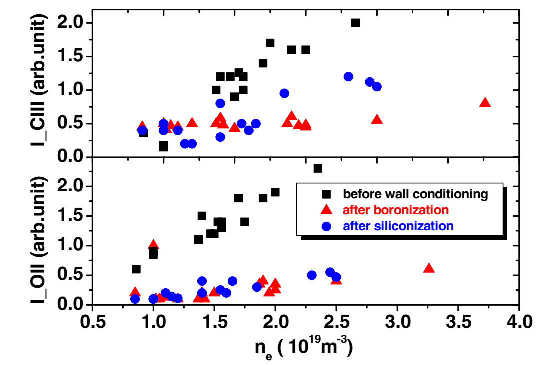

Fig. 5. The line emissions of carbon and oxygen impurities before and after boronization (siliconization).

getting of fresh boron or silicon films, and it also shows that Z_{eff} drops greatly in Fig. 4. Figs. 6 and 7 are the spectrum before and after ICRF boronization. Figs. 6 and 7 shown that not only the light impurities (C, O etc.) radiation is decreased but also

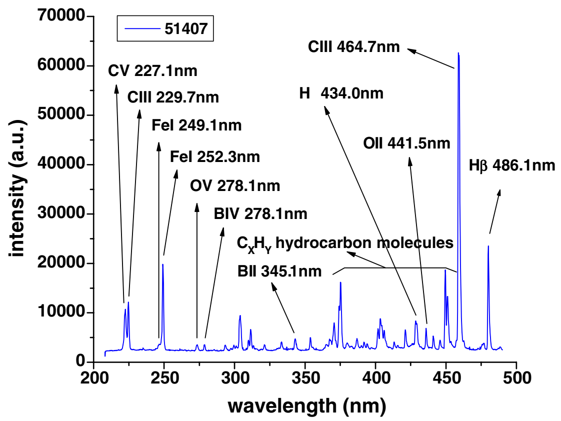

Fig. 6. The OSMA spectrum before boronization.

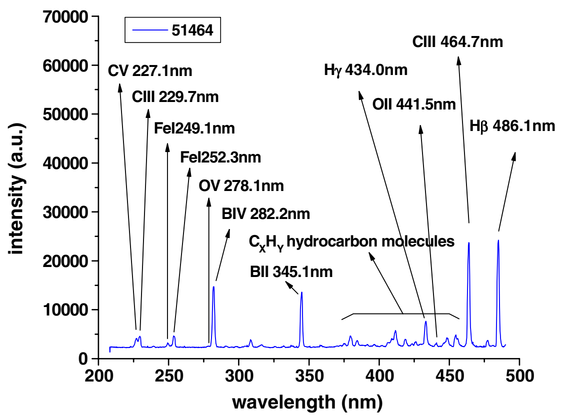

Fig. 7. The OSMA spectrum after boronization.

the metallic impurities (Fe etc.) and C_xH_y hydrocarbon molecule band radiations is significantly decreased. Effects of improvement of energy and particle confinements and extended operational region could be seen as well [8]. The improved effects of ICRF boronization were also demonstrated on ICRF heating and LHCD discharges, especially on LHCD discharges. During LHCD discharge in the HT-7 tokamak, Z_{eff} is observed to be increased by LHW typically from 3.5 to 6 before the boronization. After ICRF boronization Z_{eff} dropped by a factor of 2, and it changed from 1.5 to 2.5 by LHW. A higher current driven efficiency η_{CD} was achieved because of the important role of Z_{eff} for the current driven efficiency [7].

5. High performance and long pulse discharges

Significant progress in achieving high performance discharges under the quasi-steady-state condition in the HT-7 superconducting tokamak has been made after making technical improvements described before. Experiments have demonstrated that IBW can control the electron pressure profile by localized electron heating via electron Landau damping and improve the plasma confinement as well as induce H mode as shown in Fig. 8. Improved energy and particle confinements exist simultaneously in this kind of plasma discharges. It shows that τ_e was improved by a factor of 1.2–1.5 and τ_p was improved by a factor of 2–4. The efficiency of heating is about $\Delta T_e \sim 1$ keV and $\Delta T_i \sim 0.3$ keV at $n_e \sim 1.3 \times 10^{19}$ m^{-3}. Electron density rose by a factor of 2 and was peaked companying with the decreased Ha signals [9,13].

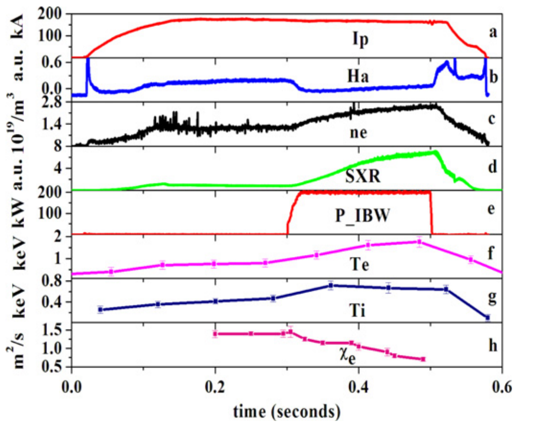

Fig. 8. H mode discharge induced by IBW heating in the HT-7 tokamak.

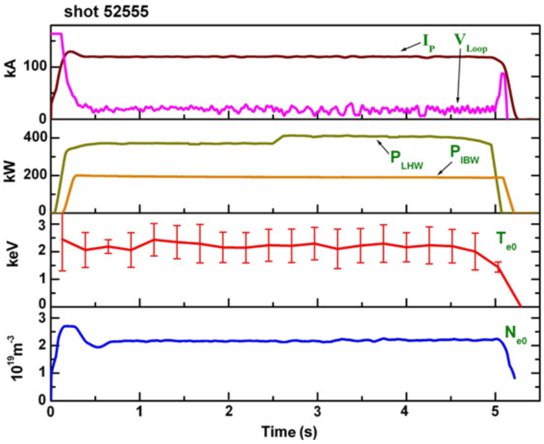

Fig. 9. Long pulse high performance discharge by synergy of LHCD and IBW heating.

The features of IBW in controlling electron pressure profile can be integrated into LHCD plasmas to tailor the current density profile and avoid MHD instability to achieve a high performance plasma discharges under a quasi-steady-state condition as shown in Fig. 9. The duration at the normalized performance of H89 * $\beta_N > 2$ has been extended to 4.4 s, longer than $220\tau_E$. The transport analysis shows that the LHW driven current is 50 kA, the bootstrap current is about 46 kA and the ohmic current is 24 kA. More than 80% non-inductive current was generated by the synergy of LHW and IBW, where the fraction of bootstrap current is 38% and fraction of LHCD current is 42%. It was found that these discharges formed an internal transport barrier at the footprint of the minimum q of a negative shear configuration. This status was kept in the time scale much longer than the energy confinement time and current diffusion time, implying the existence of a sustained current of steady-state high performance plasma [10–13].

A reproducible long pulse plasma discharge with plasma current $I_p \sim 50$ kA, central electron temperature $T_e(0) \sim 1.0$ keV and central electron density $n_e(0) \sim 0.75 \times 10^{19}\ \mathrm{m}^{-3}$ was obtained by LHCD ($P_{LHCD} < 200$ kW) with a duration of >300 s in the HT-7 tokamak. The new graphite limiters qualify the requirements of higher performance long duration operation. The longest plasma discharge was 306 s as shown in Fig. 10. Precursor of discharge termination is still electron density uncontrollable caused by the enhanced recycling of global particle and impurity particles. And it shows that the time gotten to electron density uncontrollable is much longer than that without the actively

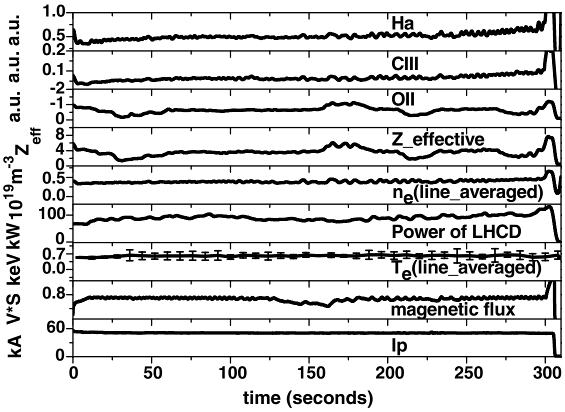

Fig. 10. Up to 306 s of long pulse plasma discharge driven by LHCD in the HT-7 tokamak.

water cooling graphite limiters. It owes to the improved capability of heat loading, heat and particle exhaust and reduced impurity content.

6. Summary

Steady state operation with higher performance was studied with many technical improvements on HT-7 superconducting tokamak. (1) The experiment results shown that ICRF boronization or siliconization can reduce carbon and oxygen impurities influxes, and it was more efficient to reduce the oxygen impurity influx. Significant suppression of metallic impurities and C_xH_y hydrocarbon molecules band is observed, and it leads the Z_{eff} drop obviously. Particle and energy confinements were improved simultaneously, and operational region was extended. (2) With application of new graphite limiters and ferritic steel, the Z_{eff} drops dramatically because the new graphite limiters provide a good protection for wall from energetic ions bombardment and fast particle loss reduction with reduced magnetic ripple. (3) By means of actively water cooling graphite limiters and matched cryopumps, the capabilities of heat loading, heat and particle exhaust were enhanced a lot. After these technical improvements the Z_{eff} drops and the integrated plasma performance is enhanced. Steady state plasma with higher performance and 5-min long pulse plasma were obtained.

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