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Impurity generation and suppression during IBW heating in HT-7

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Abstract

Impurity production during high power ion Bernstein wave (IBW) heating has been a persistent problem when the input RF power is above 100 kW, resulting in a substantial increase in the radiated power. The core electron temperature drops quickly by a factor up to 3 within 20 ms, which is partially caused by fast particle loss induced by high toroidal magnetic ripple. By using the 24 ferritic boards, which makes the reduction of ripple amplitude from 4% to 1.6%, high quality water-cooled graphite limiter, the new IBW antenna and RF boronization, the impurity generation, especially high-*Z* impurity was almost disappeared. Z_{eff} increased a little with 300 kW, changed from 1.1 to 1.24. The radiated power was reduced to only one-third of the RF power, essentially solving the impurity problem during IBWH. Both electron and ion temperatures were increased during IBW heating. Very good heating efficiency has been obtained.

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Keywords: Plasma–wall interactions; Ion Bernstein wave; Boronization; Ripple loss; Impurity generation and suppression during IBW heating in HT-7; Ferritic steel

1. Introduction

Ion Bernstein wave (IBW) heating in tokamak is based on the fact that the finite larmor radius waves in the ion cyclotron range of frequency (ICRF) excited from the low field side of machine can penetrate to the hot plasma core without strong attenuation until the waves approach the harmonic cyclotron layers. The strong ion heating could be realized when the wave passes the resonant layers, where strong ion cyclotron damping happens. Good ion heating results by IBW were observed on JIPP-IIU [1–3], PLT [4], PBX [5] and Alcator-C [6]. Some theoretical work and simulation codes were developed during past decade [7–10].

IBW heating was also investigated in HT-7 superconducting tokamak for deuterium plasma during the past few years. The good results have been observed only with an input power up to 150 kW before 2001 [11]. The impurity problem during IBW heating was similar with ICRF heating and in some case even more serious, which was happened in DIII-D [12]. Due to the electrostatic property of IBW, it may be causing edge potential change through observed edge electron heating which tends to cause more global impurity release than that observed in ICRF heating. From the sheath physics point of view, the antenna surfaces, particularly the Faraday shields, would be bombarded by the sheath-accelerated ions causing an impurity problem. The resulting sputtering leads not only to the direct impurity influx, but also re-ionization of the sputtered material and self-sputtering at both limiter and Faraday shield surfaces with an associated increase in yield.

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2. Impurity generation during IBW heating

Before 2000, the main limiter was made of molybdenum, which was set at $r = 28.5$ cm. The IBW antenna was made of stainless steel. The position of the faraday shielding was $r = 30$ cm. The toroidal magnetic ripple at the limiter position was about 5.1%. The good IBW heating were only observed at a power below 150 kW. When the power was beyond 150 kW, plasma performance degraded due to the impurity radiation. As the input RF power was above 100 kW, the high-Z impurity influx was observed during IBWH in most conditions. The metal lines, such as Fe, Mo, were observed, resulting in a substantial increase in radiated power. The radiated power was usually from 50% to 100% of the input power. Z_{eff} increased from 3 to 5.6 with an input power up to 350 kW. The core electron temperature, which was measured by fast ECE, dropped quickly by a factor up to 3 within 20 ms. There were a few possible impurity source, which could contribute to the high radiation losses, such as the impurity came from Mo limiter, from Faraday shields of the IBW antenna, the impurity from the wall which induced by the energetic particle loss from ripple.

The power scanning experiments have been done which try to find which one is the main reason. Fig. 1 shows the power scan results. When the input power is over 150 kW, Mo impurity is has similar trend as Z_{eff}. The metal impurity radiation is the main contribution to the Z_{eff} for the RF power above 150 kW.

Since the IBW antenna current flows along the magnetic field lines, the induced RF electric field has a large parallel electric field component. A roughly estimate, Ez value is about 500 V/cm with a RF power of 100 kW on HT-7. This parallel electric field in the relatively low-frequency operating regime of IBWH may enhance the strong antenna-plasma interaction. This RF generated electric field is higher for higher RF power, which will induce more serious plasma antenna interaction. From the experience of ICRF heating, full metal antenna is not a good option from the plasma-antenna interaction. Graphite protector of the antenna and other technologies used in ICRF heating might be helpful in IBW heating.

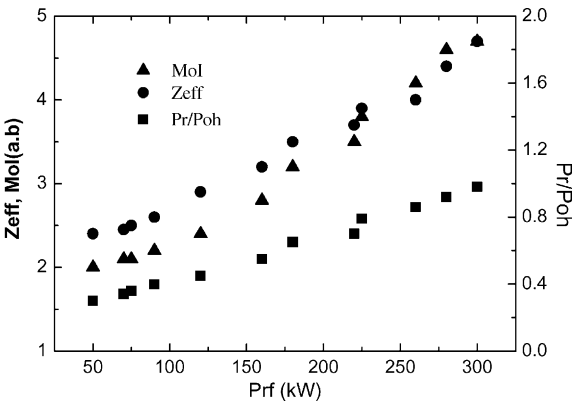

Fig. 1. The results for the power scan $B_T = 1.8$ T, $f = 30$ MHz. The solid circle represent the Z_{eff}, the triangle is the MOI line intensity. The square is the ratio between total radiation power P_r and ohmic heating power P_{oh}.

3. The way to reduce the impurity

The new GBST1308 (1%B, 2.5%Si, 7.5%Ti) doped graphite was used as limiter, the protector and the Faraday shields material of IBW antenna. The limiter radius was set at $r = 27$ cm to increase the space between plasma and the IBW antenna. The doped graphite has high thermal conductivity up to 210 W/m K. Good thermal shock resistance can withstand 6 MW/m^2 high heat loads for 30 s. All graphite materials were coated with 100 μm $SiC + B_4C$ coating. This mixed $SiC + B_4C$ coatings are very effective to reduce the chemical sputtering and suppress the radiation-enhanced sublimation. The central conductor and the back plate of the antenna were coated with TiN, which was used to reduce the chemical sputtering. Two cryo-pumps with 10 m^3/s pumping speed were installed to control particle exhaust.

After using the new graphite limiter, plasma performance was improved significantly. Plasma current can be easily controlled in the range of 200–250 kA, density $3–4 \times 10^{19}$ m^{-3}, which was very difficult to be obtained with Mo limiter. Electron temperature could exceed 1.5 keV for the ohmic heated plasma. The edge recycling could be easily handled. The energy confinement time in ohmic heated plasma increased by a factor of 30–50% for the similar plasma current and density. The impurity influx was dropped by a factor of 2 with the input RF power of 200 kW. The plasma can be easily heated up to RF power of 220 kW and sustained for nearly 500 ms. Before the modification, the good heating phase lasted for only 150 ms with the RF power below 120 kW since the impurity accumulation gradually increased and terminated the heating phase due to the increase of the radiation power.

When the IBW power was above 250 kW, the quick drop of electron temperature still happened. The electron temperature increased within first 200 ms and then quickly dropped. The spectroscopy measurement showed that it was due to the quickly increase of the metal radiation which comes from the wall. This indicates that the metal impurity is closely related to the energetic particle loss produced by the high power IBW heating. The possible reason is the high magnetic ripple at the edge.

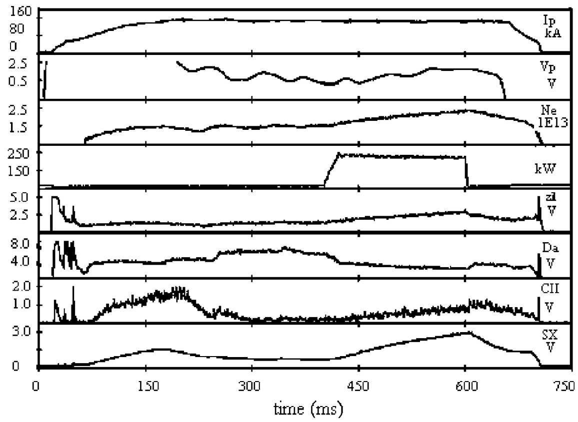

Fig. 2. The typical shot after installing FS. $B_T = 2.1$ T, $P = 240$ kW, $f = 27$ MHz.

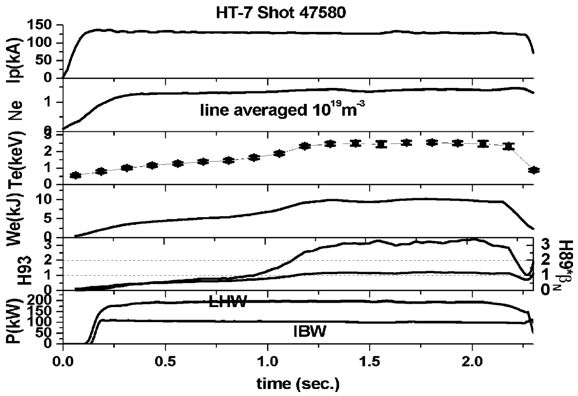

Fig. 3. Steady-state H-mode with IBW and LHCD. $B_T = 1.8$ T, $f = 27$ MHz.

Twenty-four pieces of the ferromagnetic material – ferritic steel board (F82H: 8%Cr + 2%W + 0.2%V + 0.06%Ta + Fe remainder) have been installed. The ripple at the limiter radius ($r = 27$ cm) is reduced from 4% to less than 1.6%.

With the ferritic steel boards, the problem of the fast temperature drop has been partially solved. The dominant impurity is not the wall material. With cryo-pump activating, the edge recycling can be controlled. Fig. 2 shows the plasma behavior after installed ferritic steel boards and cryo-pumps. The waveforms from top to bottom are plasma current I_p, loop voltage V_p, line averaged density n_e, IBW power, bremsstrahlung radiation Z_1, edge D_α radiation, CII and soft X-ray signals. The loop voltage and bremsstrahlung radiations increase a little due to the increase of the density. The edge recycling does not increase even the density keeps increasing. The carbon line increases a little. The serious impurity problem has been solved. The slow impurity accumulation still exists which mainly comes from the carbon.

4. The main results for suppressing impurity

RF wall conditioning techniques have been well developed and routinely used in HT-7 tokamak during past few years [13,14]. RF boronization [15] has been demonstrated to be the best coating techneque to suppress impurity and to obtain the best IBW heating results in the HT-7. By using the RF boronization, the impurity generation, especially high-Z impurity was almost disappeared. Z_{eff} increase a little with 300 kW, changed from 1.1 to 1.24. The radiated power was reduced to only one-third of the RF power, essentially solving the impurity problem during IBW heating in the present power level. Both electron and ion temperature increased during IBW heating. Very good heating efficiency has been obtained with 350 kW IBW heating.

Both on-axis and off-axis electron heating were realized by proper arrange the target plasma parameters. Plasma has been dramatically heated by IBW up to 2.8 keV. Maximum increment of electron temperature was about 2 keV. The impurity problem, which happens after 200 ms with IBW, was nearly disappeared. The heating factor reached $9.4\ \mathrm{eV} \times 10^{13}\ \mathrm{cm}^{-3}/\mathrm{kW}$. The maximum input RF power was 350 kW, which reached the limitation of generator. The fast increase of electron temperature and the slow increment of ion temperature gave the evidence that the electron heating was formed by electron Landau damping.

After RF boronization, when the input power is above 140 kW, H-mode has been obtained. Both energy and particle confinements have been improved. Steady-state H-mode with 43 times of energy confinement time has been obtained by IBW heating alone. H_{93} is about 0.94. Edge shear flow has been changed and turbulence has suppressed to a very low level.

By combining LHCD and IBW, the duration of H-mode reached 1.2 s, which is about 53 times of energy confinement time with electron temperature of 2.4 keV and ion temperature of 1.3 keV shown in Fig. 3. There is very little impurity accumulation during 2.5 s, which is above 100 times of energy confinement time.

5. Summaries and conclusion

Impurity production during high power IBW heating has been a persistent problem in the HT-7 superconducting tokamak due to the reasons of using Mo limiter, high magnetic field ripple and the stainless steel antenna. As the input RF power exceeded 100 kW, the high-Z impurity influx problem was observed during IBWH in most conditions. The serious impurity is due to the fast particle loss induced by the high magnetic ripple, metal radiation loss came from strong interaction between metal antenna, limiter and plasma.

Efforts for reducing the impurity have been made step by step. By using the doped graphite limiter, plasma performance has been significantly improved. The impurity influx, mainly the metal impurity, was dropped by a factor of 2 with the input RF power of 200 kW. The plasma can be easily heated up to RF power of 220 kW and sustained for nearly 500 ms. When the IBW power was above 250 kW, the quick drop of electron temperature still happened. The reason is the fast particle loss due to the large magnetic field ripple (5.1%). By installing the ferritic steel boards and reduce the limiter minor radius from $a = 28.5$ to 27 cm, The ripple at the limiter radius ($r = 27$ cm) is reduced from 4% to less than 1.6%. The serious impurity problem for the input RF power above 220 kW has been solved. The slow impurity accumulation still exists which mainly comes from the carbon. By using the two cryo-pupm, the particle exhaust capacity increased nearly two times. The recycling increase accompanied with high power IBW heating was disappeared. The recycling can be easily controlled.

By using the graphite IBW antenna protector and Faraday shields, applying RF boronization, the impurity problem generated with high power IBW heating was almost disappeared. Z_{eff} increase a little with 300 kW, changed from 1.1 to 1.24. The radiated power was reduced to only one-third of the RF power, essentially solving the impurity problem during IBWH at the present power level. Both electron and ion temperatures increase during IBW heating. Very good heating efficiency has been obtained with 350 kW IBW heating. A boronized wall prevented the further impurity accumulation and the large pumping kept the recycling at a very low level. By combining IBW and LHCD, ELM-free limiter H-mode discharges with $H_{93} > 1$, $\beta_N^* H_{89} > 3$ have been obtained that lasted for 53 times of energy confinement time.

Acknowledgements

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