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Plasma density behavior with new graphite limiters in HT-7

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Abstract

A new set of actively cooled toroidal double-ring graphite limiters has been developed in HT-7 superconducting tokamak for long pulse operation. Significant progress of long pulse operation with the graphite limiter is achieved in HT-7. The operation parameter space is expanded largely, and the edge recycling, plasma density and impurity can be easily handled. The extension of operational region and density behavior with graphite (C) limiters have been studied in this paper. Under the same injected power, the critical density of MARFE onset with the new C limiter is much higher than the previous Mo limiter. A moveable graphite limiter has been developed in order to investigate the local recycling and density limit behavior in HT-7 tokamak, which shows that the recycling is low while plasma is shifted outwards, is high for inwards shift.

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Keywords: Graphite materials; Density limit; Limiter materials; MARFE; Wall recycling

1. Introduction

Many machines were operated with the mixed carbon material for long pulse operation, ultimately steady-state. The graphite-based first wall components have been designed and tested to sustain particle and heat exhausts under steady-state conditions in Tore Supra. HT-7 is a superconducting tokamak [1] with the limiter configuration designed to operate with high power and long duration discharge. In past operations with the Mo limiter, due to energetic particles bombardment and overheating problem, the plasma discharge was usually terminated by the very strong hard X-ray radiation, hot spot and high-Z impurities. In order to alleviate the above problems, a new set of actively cooled toroidal double-ring graphite limiters (see Fig. 1) has been developed on HT-7 in 2004. The doped graphite GBST1308 with the dopant concentration of 1% B, 2.5% Si, 7.5% Ti was used as limiter material [2,3]. Its good thermal shock resistance can withstand 6 MW/m^2 high heat loads for long pulse operation. Very stable and reproducible discharges were obtained with significantly increased density and a large increase of the available pulse length, as compared to Mo limiters. Up to 240 s of long pulse discharge has been achieved by lower hybrid current drive with new graphite limiters in the HT-7 in 2004. The operation parameter space is largely expanded,

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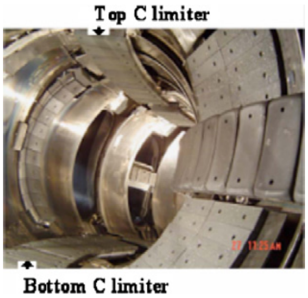

Fig. 1. The actively cooled toroidal double-ring graphite limiters at the bottom and top of the vacuum vessel on HT-7.

and the edge recycling, plasma density and impurity can be easily handled. The operational regime and density behavior with new graphite limiters were studied in this paper. The density limit and MARFE phenomenon high-density operation were compared between new graphite (C) limiter and previous molybdenum limiter in HT-7.

2. Experiment setup

HT-7 has a major radius of $R = 1.22$ m, minor radius of $a = 0.27$ m in the circular cross section. The new GBST1308 doped graphite was used as limiter material. All carbon tiles were coated with 100 μm silicon carbide (SiC) functional gradient coating. A new set of actively cooled toroidal double-ring graphite limiters at the bottom and top of the vacuum vessel was developed recently, as shown in Fig. 1, for long pulse operation, up to 240 s of long pulse plasma has been achieved in the HT-7 in 2004. Recently, a moveable graphite limiter is developed in order to investigate the influence of the density limit with different horizontal plasma position in the HT-7 tokamak as shown in Fig. 2.

Fig. 2. A photo of moveable limiter with graphite tip.

3. High-density operation

In the HT-7 tokamak, the density limit appeared to be connected with the impurity content and the edge parameters, and the best results were obtained with very clean plasmas and the peaked electron density profiles. The HT-7 tokamak is normally operated with $I_P = 100$–250 kA, $B_T = 1$–2.5 T, line-averaged density 1–6×10^{19} m^{-3}. The first plasma was produced on the HT-7 in 1994, and the operation region of the HT-7 Ohmic discharges were limited by the wall condition and the HT-7 controlling system before 1997 as shown in Fig. 3. During the Spring experimental campaign in 1998, a feedback control system to simultaneously control plasma current, density and displacement was developed and put into daily operation. Fig. 3 shows the Hugill plot of the data taken during this phase, together with the HT-7 experimental limit corresponding to an inverse slope $n_e R q_a / B_T = 1.61 \times 10^{20}$ Wb^{-1}: this line also represents the Greenwald limit $n_e/J = 1$, where n_e and J are measured in units of 10^{20} m^{-3}and MA/m^2, respectively. In Fig. 3, the solid points (at the high-density region and the high-current low-q_a region) were achieved by the RF boronization and the RF siliconization, respectively, in 1999. During the Spring experimental campaign in 2004, the new graphite limiters has been developed as shown in Fig. 1, for long pulse operation in the HT-7. Fig. 3 shows the Hugill plot of the data taken during this phase, along with the previous molybdenum limiter at a range of $B_T = 1$–2.5 T. In Fig. 3, the extended high-density region at the low-q_a was achieved. It was clear that the new C limiters extended both the operational parameter space as shown in Fig. 3 and discharge length on the HT-7 tokamak. From closer inspection of the data, it turns out that the density profiles at higher current were systematically broader than those at low current as shown in Fig. 4.

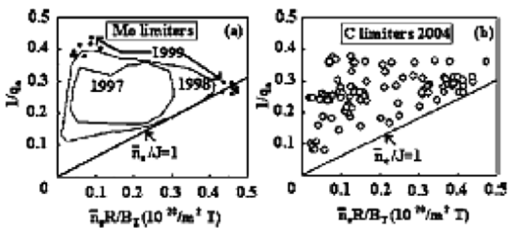

Fig. 3. Hugill plot for HT-7 superconducting tokamak with: (a) molybdenum and (b) graphite limiters.

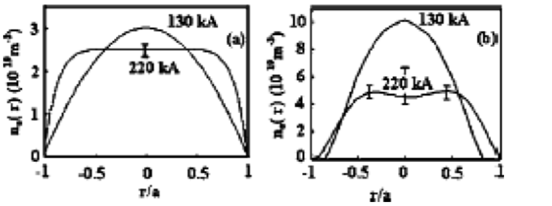

Fig. 4. Electron density profiles at same toroidal field ($B_T \sim 2$ T) with: (a) molybdenum and (b) graphite limiters.

The density limit appeared to be connected with the edge parameters in the HT-7. The density profile with C limiter was studied to compare with previous Mo limiter. Fig. 5 shows the peaking factors $n_e(0)/n_e(0.7a)$ (where $n_e(0)$ is the line average density, measured at the central interferometer channel at $r = 0$ cm), for different averaged density conditions, and the higher density always correlated with the peaked profile in the HT-7. Comparing with the previous molybdenum material limiter, it is observed that the peaking factor of the electron density profile is weakly proportional to the line average density with the graphite limiter. Fig. 6 shows the peaking factor of the density profiles for different plasma currents, and the peaked profiles were obtained at high-current range of $I_P = 120$–220 kA. Comparing with the Mo limiter data, higher density and its peaked profile were achieved on high plasma current discharges by new graphite limiters, which led to extension of the operational region, as shown in Fig. 3.

In order to investigate the influence of the plasma position on the density limit, we reduced the plasma minor radius to $a = 25$ cm by inserting a moveable graphite limiter. The horizontal plasma position was then changed from discharge to discharge. The plasma position control signal was generated

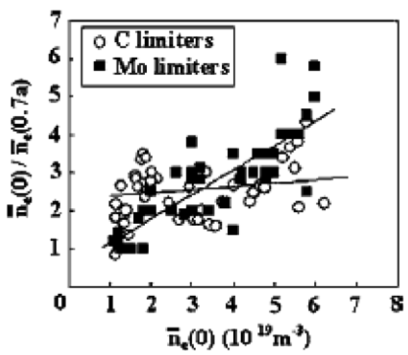

Fig. 5. Peaking factor $n_e(0)/n_e(0.7a)$ with different line-averaged density conditions in the HT-7 C and Mo limiters.

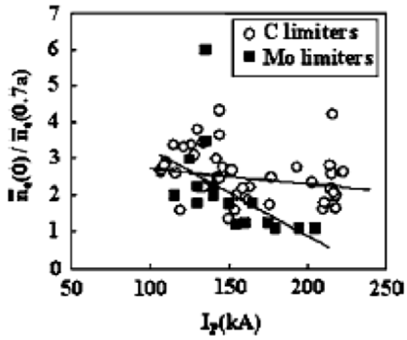

Fig. 6. Peaking factor $n_e(0)$ $/n_e(0.7a)$ of the density profiles with different plasma current I_P in the HT-7 C and Mo limiters.

by magnetic diagnostics. For these ohmic discharge series the toroidal plasma current was $I_P = 100$–105 kA, which refers to a Greenwald limit of $n_e^{GW} = 5.210^{19}$ m^{-3}. The density was increased by normal gas puffing, up to a disruption. For a typical plasma position the time traces of the density and Hα intensity are shown in Fig. 7. It can be seen that the density exceeds the predicted Greenwald limit at $t > 205$ ms considerably. The Hα intensity is found to increase until $t = 294$ ms, when a density limit instability approaches which leads to the disruption. In Fig. 8(a), it is shown that a higher density could be reached if the plasma is moved several cm towards the LFS. The Greenwald number is shown for each discharge, which is the density normalized

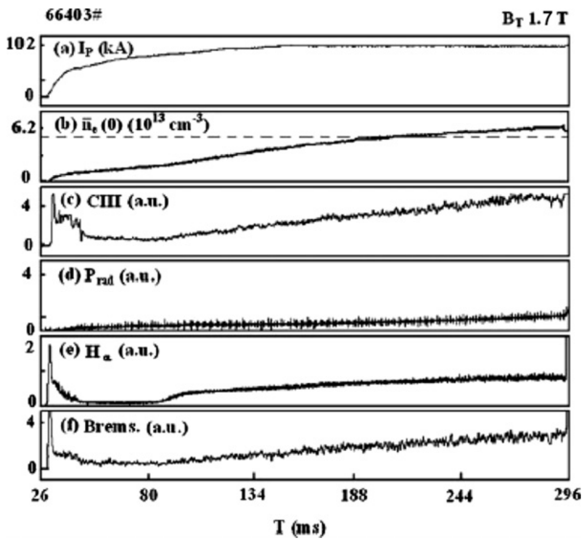

Fig. 7. Time traces of the (a) plasma current; (b) central line-averaged density. The horizontal dashed line shows the Greenwaldlimit; (c) CIII emission; (d) radiative power; (e) Hα intensity; and (f) bremsstrahlung emission, from the HFS for a discharge which is positioned 2.25 cm outwards.

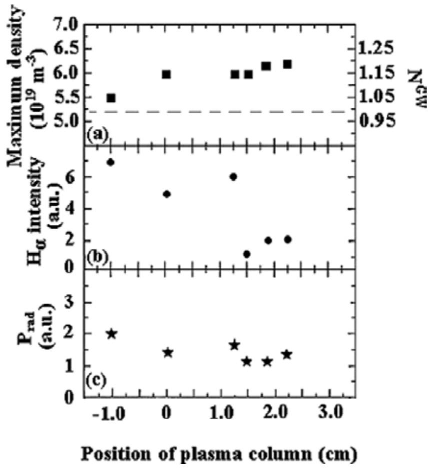

Fig. 8. (a) The maximum density or Greenwald number scales with the horizontal position of the plasma column. An inward shift is represented by a negative plasma position, (b) the recycling properties, deduced from the Hα intensity, and (c) the total radiative power with the horizontal position of the plasma column just prior to the maximum density and the MARFE instability.

to the Greenwald density. For these set of discharges a maximum Greenwald number, $N_{GW} >$ 1.2, was achieved, when the plasma column was repositioned more than $\Delta// = +2.25$ cm outwards. The discharges, which had been moved towards the HFS at $\Delta// = -1$ cm, disrupted near the predicted Greenwald limit $N^{GW} = 1.05$.

In order to investigate the influence of the recycling on the density limit the hydrogen flux was derived from the Hα radiation measurement. Hence, the Hα radiation intensity provides information on the global neutral flux and the local recycling on the HFS. The temporal evolution of the hydrogen flux is observed for different horizontal plasma positions. Jump in Hα intensities signals observed on TEXTOR-94 at near Greenwald density has not been found in the HT-7 tokamak. A threshold in the hydrogen flux for the development of radiation instability was studied. These hydrogen fluxes at Greenwald limit are shown in Fig. 8(b) as a function of the horizontal plasma position. It can be observed that the Hα intensities taken at the time when the density reached the Greenwald limit are lower for outward shifted plasmas than for discharge inward shifted in Fig. 8(b). Thus, the localized particle recycling affects the density limit, and the central averaged density can be increased to higher values by keeping the recycling at a low level. The experimental result in HT-7 well reconfirms the observation in TEXTOR-94.

4. MARFE

The multifaceted asymmetric radiation from the edge (MARFE) is poloidally asymmetric but toroidally symmetric regions of locally high-density, low temperature plasmas located on the high field side, give rise to strong radiation. The MARFE phenomenon usually appears beyond a critical density in the tokamaks. In the HT-7 superconducting tokamak with the molybdenum limiter, the onset of a MARFE usually occurs in the early Ohmic discharges ($Z_{eff} = 3$–8 and 15–25% of the Greenwald density limit scaling for circular plasmas) of each experimental campaign before wall conditioning. Fig. 9 shows the typical shot of experimental campaign 2004 (shot no. 66361) on HT-7 with graphite limiters, the plasma current about 130 kA, the loop voltage $V_{loop} \sim 3$ V, the toroidal field BT = 1.7 T, $Z_{eff} = 2.5$, and the line-averaged density about 4.5×10^{19} m^{-3}. The MARFE occurs in the plasma column on the inner high field side. The MARFE onset is characterized by a sudden modification of visible CIII line emission signal. It is clear that MARFE event occurs from $t = 220$ ms suddenly as shown in Fig. 9.

In HT-7 graphite limiters, the critical density of MARFE onset is observed in the region of $Z_{eff}^{1/2} f_{GW} = 0.9$–1.2, where $f_{GW} = n_e/n_{GW}$. Under the same injected power, the critical density with the C limiter is much higher than the Mo limiter. The best correlation has been found between the total input Ohmic power and the product of the line average density, measured at the outermost interferometer channel at $r = 20$ cm, and Z_{eff}. In the HT-7

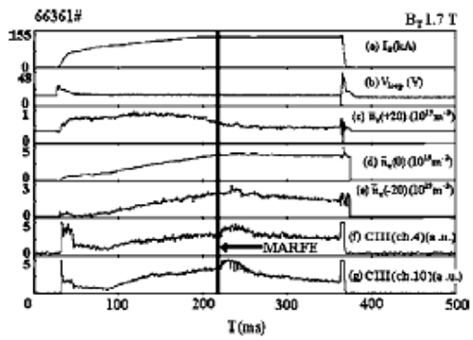

Fig. 9. The onset of a MARFE in the HT-7: (a) plasma current, (b) loop voltage, (c) line-averaged electron density (vertical chord at $r = +20$ cm), (d) line-averaged electron density (vertical chord at $r = 0$ cm), (e) line-averaged electron density (vertical chord at $r = -20$ cm), (f) CIII emission from channel 4, and (g) CIII emission from channel 10.

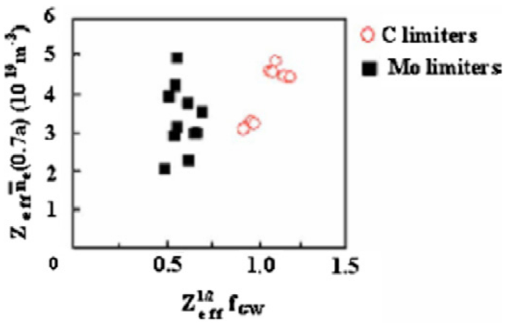

Fig. 10. MARFE occurs at values of $Z_{\mathrm{eff}}^{1/2} f_{\mathrm{GW}}$ in the range of 0.9–1.2 on new graphite limiters.

tokamak high-Z_{eff} discharges, it is found that the MARFE occurs at values of $Z_{\mathrm{eff}}^{1/2} f_{\mathrm{GW}}$ in the range of 0.5–0.7 with the molybdenum limiter. The critical factor of MARFE onset is 0.9–1.2 with graphite limiters as shown in Fig. 10. It implies that the MARFE event can occur only at high-density and low input Ohmic power discharges with graphite limiters.

5. Conclusion

A new set of actively cooled toroidal double-ring graphite limiters has been developed in the HT-7 superconducting tokamak for long pulse operation. Significant progress of long pulse operation with a graphite limiter is achieved in the HT-7. An extended operational region is obtained with new C limiters. High-density plasma behaviors and the high-density operation region were studied in the HT-7 superconducting tokamak with new graphite limiters. The density profile with the C limiter was studied to compare with the previous Mo limiter. The peaking factor of electron density profile is weakly proportional to the line average density with C limiters. In the HT-7, the best correlation has been found between the total input Ohmic power and the product of the edge line average density and $Z_{\mathrm{eff}}^{1/2}$.

A moveable graphite limiter has been developed in order to investigate the influence of the horizontal plasma position on the density limit in the HT-7 tokamak. The recycling and density limit behavior has been studied in this Letter, which shows that if plasma is shifted outwards the recycling is low, for inwards shift is high. A maximum Greenwald number, $N_{\mathrm{GW}} > 1.2$, was achieved, when the plasma column was repositioned more than $\Delta// = +2.25$ cm outwards. The localized particle recycling affects the density limit, and the central averaged density can be increased to higher values by keeping the recycling at a low level.

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