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Multifaceted asymmetric radiation from the edge along improved confinement mode in LHCD plasmas with graphite limiters on HT-7 tokamak

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Abstract. Multifaceted asymmetric radiation from the edge (MARFE) phenomena during lower hybrid current drive (LHCD) Experiments on the HT-7 superconducting tokamak are summarized in this paper. The best correlation has been found between the total input (ohmic + LHCD) power and the product of the edge line average density and Z_{eff}. Studies show that the critical density of MARFE onset is observed in the region of $Z_{eff}^{1/2} f_{GW} = 0.6$–$0.9$, where $f_{GW} = \bar{n}_e/n_{GW}$, (here $\bar{n}_e$ is the maximum line average electron density and n_{GW} is the Greenwald density). These MARFEs generally appear to have the same characteristics as high f_{GW} MARFEs and are positionally stable throughout the LHCD pulse. Improved confinement mode induced by a MARFE is observed, and it is maintained for about 65 ms. MARFE cools the plasma edge, and the electron density profile is observed to become more narrow and peaked.

PACS. 52.55.Fa Tokamaks, spherical tokamaks – 52.40.Hf Plasma-material interactions; boundary layer effects

1 Introduction

Confinement improvement and long pulse duration are the most important issues for tokamak research. The prerequisite of such studies is to drive the plasma current non-inductively by radio frequency (RF) waves. LHCD was investigated extensively in many fusion devices not only as a promising method of non-inductive current drive but also as a effective way to control plasma profile and to improve the confinement of plasma. Recently several distinctive phenomena related with plasma confinement were observed during LHCD. The confinement improvement during LHCD was observed in the modest density range ($n_e \leqslant 1.5 \times 10^{19}$ m^{-3}). When LHW is launched into the plasma, the density increases and the H_α from edge plasma decreases. It was found that the particle confinement time during LHCD is $\tau_P = 33$ ms, while $\tau_P = 15$ ms for similar shots of ohmic heating alone [1].

Nuclear fusion experiments have made rapid progress since the 1980s in many tokamaks using lower hybrid current drive (LHCD) [2]. The LHCD system on HT-7 is designed mainly for this purpose. It is also hopeful to achieve high performance for long pulse by means of LHCD. Up to 240 s of long pulse discharge [3] has been achieved by LHCD on HT-7 in 2004 that successfully demonstrated the reliability of LHCD technology. Recently, LHCD experiments have been carried out to achieve high performance for long pulse operation in the HT-7 superconducting tokamak. Multifaceted asymmetric radiation from the edge (MARFE) phenomena and an improved confinement mode induced by a MARFE are observed in LHCD plasmas, when $P_{LH} > 160$ kW and edge safety factor $q(a)$ is slightly less than 6.5. It is found that an improved confinement mode induced by a MARFE, characterized by an H_α line emission drop and the line-averaged density increase is triggered in the MARFE discharges. The MARFE event occurs at $t = 1120$ ms followed by L–H transition, and the improved confinement phase exists for about 65 ms from $t = 1140$ ms which is the onset of the L–H transition. The MARFE cools the plasma edge, and the electron density profile is observed to become more narrow and peaked. The LHCD plasmas have basically typical MARFEs and they show an improved confinement mode, but they are unique in that they appear at very low $\bar{n}_e$ values in HT-7 tokamak.

2 HT-7 superconducting tokamak device

The HT-7 tokamak [3] is a superconducting device with a circular cross section, which was rebuilt from the original Russian T-7 tokamak in 1994. It has a major radius of

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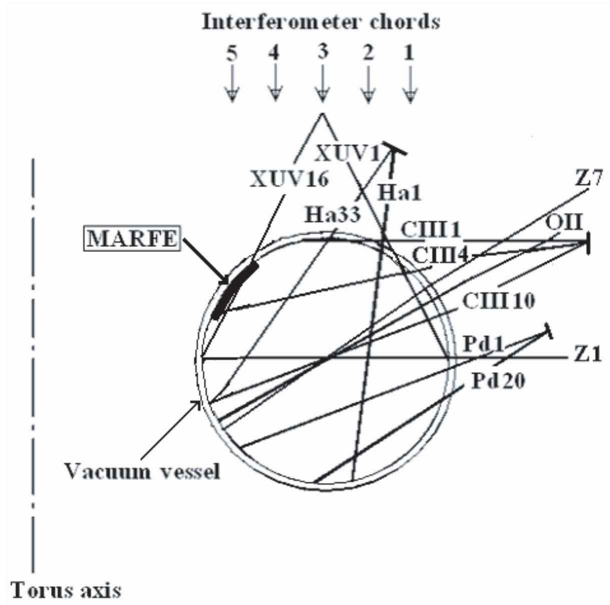

Fig. 1. A chord view of the vertical 5-channel HCN interferometer (from low field to high field at: +20 cm, +10 cm, 0 cm, –10 cm, –20 cm), 20-channel H_α emission (Pd1∼20), 33-channel H_α emission, 10-channel CIII emission, 7-channel bremsstrahlung emission ($Z = 1$–7), 16-channel XUV bolometer, one channel OII line emission chord in the HT-7 tokamak.

$R = 1.22$ m, minor radius of $a = 0.27$ m defined by one poloidal water-cooling limiter, a recently installed guard limiter to protect the LHCD antenna, one toroidal water-cooling belt limiter at the high field side and a modified set of actively cooled toroidal double-ring graphite limiters at bottom and top of the vacuum vessel, and a plasma up to 240 s long [3], has been achieved with new graphite limiters in HT-7 in 2004. There are two layers of thick copper shells, and between them 24 superconducting coils are located which can create and maintain a toroidal magnetic field (B_T) of up to 2.5 T. The HT-7 ohmic heating transformer has an iron core and it can offer a magnetic flux of 1.7 Vs at its maximum. A lower hybrid current drive (LHCD) system has been built for the HT-7 superconducting tokamak to deliver a 1.2 MW microwave power at a frequency of 2.45 GHz [4]. The main purpose of developing LHCD technology on HT-7 tokamak is to sustain long pulse discharge and to improve plasma confinement. A successful experiment with LHCD heating was carried out in the HT-7 superconducting tokamak in 2005. The HT-7 tokamak is normally operated with $I_P = 100$–250 kA, $B_T = 1$–2.5 T, line-averaged density 1–6 $\times 10^{19}$ m^{-3}. For recent experiments on the HT-7, shown in Figure 1, the following main diagnostics signals are effectively used in this paper: 16-channel XUV bolometer array to measure plasma radiation losses, a 7-channel bremsstrahlung emission ($Z = 1$–7) to measure Z_{eff}, a multichannel $H_\alpha(D_\alpha)$ radiation array, 10-channels CIII line emission, an impurity optical spectrum measurement system and the electron density profile is measured by a vertical 5-channel far-infrared (FIR) hydrogen cyanide (HCN) laser interferometer [5].

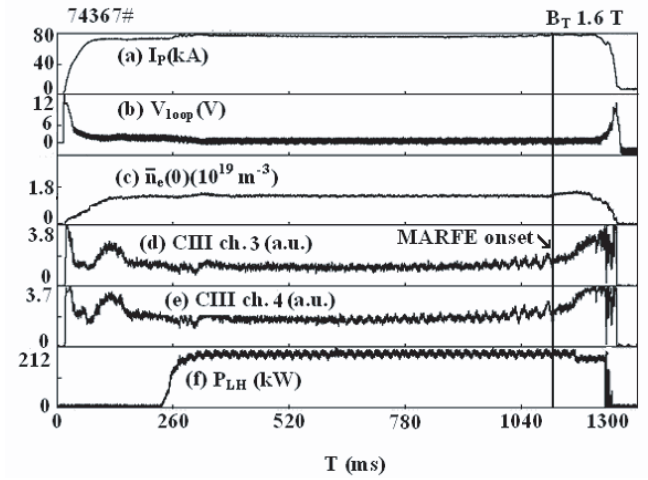

Fig. 2. Time traces of the (a) plasma current, (b) loop voltage, (c) central line-averaged density, (d) CIII emission from channel 3, (e) CIII emission from channel 4, (f) lower hybrid wave (LHW) power, P_{LH}(kW).

3 MARFE phenomena during LHCD plasmas on HT-7

The multifaceted asymmetric radiation from the edge (MARFE) [3,6–8] is a poloidally asymmetric but toroidally symmetric region of locally high density, low temperature plasmas located on the high field side, giving rise to strong radiation. MARFE phenomenon usually appears beyond a critical density in the tokamaks. In the HT-7 superconducting tokamak with molybdenum limiter [7], 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 [9] for circular plasmas: $n_{GW} = I_p/\pi a^2$, where n_{GW} is Greenwald density in units of 10^{20} m^{-3}) of each experimental campaign before wall conditioning. The occurrence and location of a MARFE is identified by different diagnostic systems as shown in the Figure 1. In the HT-7 tokamak high-Z_{eff} discharges with molybdenum limiter [7], it is found that the MARFE occurs at values of $Z_{eff}^{1/2} f_{GW} = 0.5$–0.7, where $f_{GW} = \bar{n}_e/n_{GW}$. In HT-7 with graphite limiters [3], the critical density of MARFE onset is observed in the region of $Z_{eff}^{1/2} f_{GW} = 0.9$–1.2.

Figure 2 shows the typical shot of experimental campaign 2005 (shot No. 74367) on HT-7 with LHCD, the plasma current about 76 kA, the loop voltage $V_{loop} < 3$ V, the toroidal field $B_T = 1.6$ T, $Z_{eff} = 5.8$, $R = 1.22$ m, $a = 0.27$ m and the line-averaged density $\bar{n}_e = 1.25 \times 10^{19}$ m^{-3} which refers to a Greenwald limit of $n_{GW} = 3.3 \times 10^{19}$ m^{-3}. A typical position of the MARFE on the HT-7 (shot No. 74367) is identified by visible CIII (channel 3, channel 4) line emission as shown in Figure 2. The

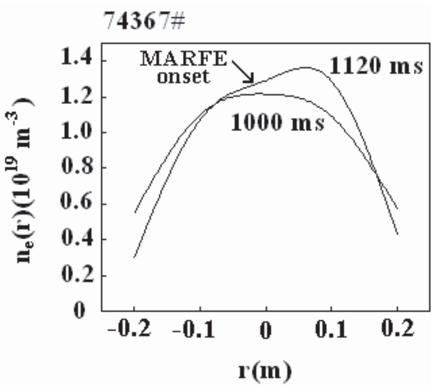

Fig. 3. Electron density profiles with LHCD.

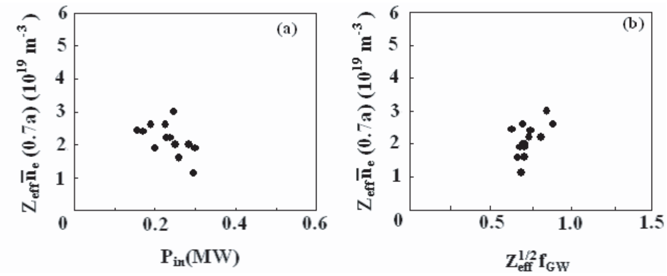

Fig. 4. (a) In LHCD plasmas, the dependence of critical value of the $Z_{eff}\bar{n}_e(0.7a)$ for MARFE onset and input power (ohmic +LHCD). (b) MARFE onset occurs at values of $Z_{eff}^{1/2} f_{GW} =$ 0.6–0.9, where $f_{GW} = \bar{n}_e/n_{GW}$, (here $\bar{n}_e$ is the maximum line average electron density and n_{GW} is the Greenwald density).

MARFE occurs in the plasma column (upper half) on the inner high field side. The MARFE onset is characterized by a sudden modification of visible CIII (channel 3, channel 4) line emission signals. It is clear that MARFE event occurs from $t = 1120$ ms suddenly as shown in Figure 2. Asymmetric and peaked density profile is observed (see Fig. 3).

Under total input injected power (ohmic +LHCD), the critical density for LHCD plasmas is shown in Figure 4a. The critical conditions for the occurrence of a MARFE in HT-7 can be deduced from the experimental data in Figure 4a for LHCD plasmas. The best correlation has been found between the total input power (ohmic+LHCD) and the product of the edge line average density $\bar{n}_e(0.7a)$, measured at the outermost interferometer channel at $r =$ 20 cm ($r/a \cong 0.7$, the minor radius $a = 27$–28 cm), and Z_{eff}. In the HT-7 tokamak high-Z_{eff} discharges, it is found that the MARFE occurs at values of $Z_{eff}^{1/2} f_{GW} = 0.6$–0.9 for LHCD plasmas as shown in Figure 4b.

The MARFE phenomenon usually develops before reaching the density limit [7]. It was found recently that MARFEs typically occur at a fraction, 50–90%, of the density limit on tokamaks [10]. It is found for LHCD plasmas in HT-7, that MARFEs typically occur at a fraction, 33%, of the density limit. However in the HT-7 tokamak the occurrence of a MARFE is not only correlated with the density but also with Z_{eff}. These MARFEs generally appear

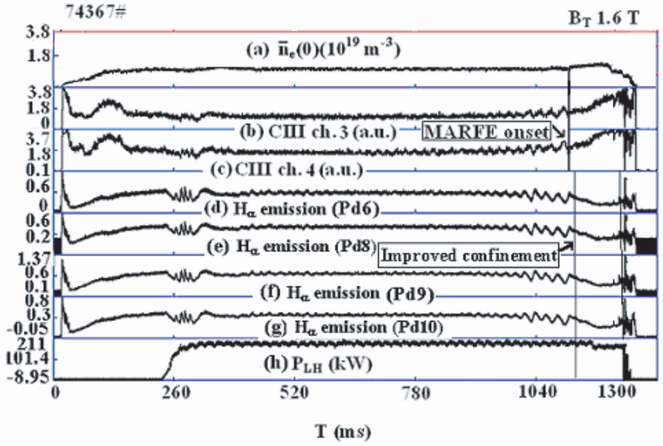

Fig. 5. The onset of a MARFE and the H-mode-like plasma in the HT-7: (a) line averaged electron density (vertical chord at $r = 0$ cm), (b) CIII emission from channel 3, (c) CIII emission from channel 4, (d-g) multichannel H_α emission (Pd6, Pd8, Pd9, Pd10), (h) lower hybrid wave (LHW) power, P_{LH}(kW).

to have the same characteristics as high f_{GW} MARFEs and are positionally stable throughout the LHCD pulse.

4 Improved confinement mode induced by a MARFE

The MARFE may lead to improved confinement by cooling the edge at some times. The observed sequence of events for the formation of the MARFE and subsequent evolution into a detached plasma is as follows [11]. As radiating impurities accumulate in the plasma edge, a poloidally uniform band of radiating impurities is formed; then, as the plasma density or impurity density is increased, the poloidally uniform band goes through a transition into a stable, poloidally asymmetric distribution of radiating impurities — the MARFE, still located in the plasma edge, which ultimately becomes highly localized in tokamaks. Then, as the plasma or impurity density is further increased, the impurities undergo a further transition back into a poloidally uniform band. Since the radiative cooling of the edge has been increasing with increasing density, in this final state the plasma is detached or nearly detached. Figure 5 shows that MARFE event occurs from $t = 1120$ ms. The improved confinement mode, which is characterized by multichannel H_α emission (Pd6, Pd8, Pd9, Pd10) drop and the line-averaged density increase, is observed clearly from $t = 1140$ ms in Figure 5, and it was maintained for about 65 ms. Figure 6 shows the electron density profiles at $t = 1120$ ms (before the event trigger) and $t = 1200$ ms (before the end of improved confinement mode). The density profile shows that the profile becomes narrow and more peaked. The confinement is improved and the density profile is clearly changed from the L-mode ($t = 1120$ ms) to the improved confinement mode $t = 1200$ ms). The plasma confinement parameters in the

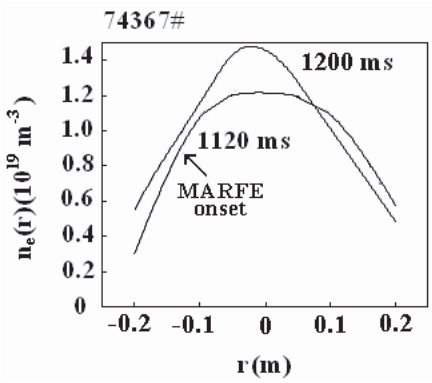

Fig. 6. Electron density profiles $n_e(r)$ by Abel inversion, at $t = 1120$ ms (before the event trigger) and $t = 1200$ ms (before the end of improved confinement mode).

experiment will be studied in detail with the optimized operation in the future.

5 Summary

Lower hybrid current drive (LHCD) experiments have been carried out to achieve high performance for long pulse operation in the HT-7 superconducting tokamak. Multifaceted asymmetric radiation from the edge (MARFE) phenomena and an improved confinement mode induced by a MARFE are observed in LHCD plasmas when $P_{LH} > 160$ kW and edge safety factor $q(a)$ is slightly less than 6.5. Studies show that the critical density of MARFE onset is observed in the region of $Z_{eff}^{1/2} f_{GW} = 0.6$–0.9. It is found for LHCD plasmas in HT-7, that MARFEs typically occur at a fraction, 33%, of the density limit. These MARFEs generally appear to have the same characteristics as high f_{GW} MARFEs and are positionally stable throughout the LHCD pulse. The MARFE cools the plasma edge, and the electron density profile is observed to become more narrow and peaked. However in the HT-7 tokamak the occurrence of a MARFE is not only correlated with the density but also with Z_{eff}.

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