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MARFE phenomena in the HT-7 tokamak ☆

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Abstract

Multifaceted asymmetric radiation from the edge (MARFE) phenomena on the HT-7 superconducting tokamak are summarized in this paper. The best correlation has been found between the total input ohmic power and the product of the edge line average density and Z_{eff}. The occurrence of MARFEs are strongly correlated with impurity density, and always occur at Z_{eff} =3–8 ohmic discharges. In the HT-7 tokamak high Z_{eff} discharges, it is found that the MARFEs usually occur at values of $Z_{\mathrm{eff}}^{1/2}\rho$ in the range of 0.5–0.7, where $\rho = \pi a^2 n_{\mathrm{e}}/I_{\mathrm{p}}$ (10^{20} MA^{-1} m^{-1}). In the case of good wall condition ($Z_{\mathrm{eff}} = 1$–2), the onset of MARFEs have not been observed before reaching the Greenwald density limit on the HT-7. Improved confinement mode induced by a MARFE is observed, and it is maintained for about 40 ms. MARFE cools the plasma edge, and the electron density profile is observed to become more narrow and peaked.

1. Introduction

It has been observed that an increase in the density in a tokamak beyond a certain limit produces a multifaceted asymmetric radiation from the edge (MARFE) [1]. MARFEs are axisymmetric, strongly radiating belt of short poloidal and radial extent located at the high-field edge of the plasma. The radial extent includes the scrapeoff layer (SOL) and extends to regions inside the divertor separatrix or limiter radius. A further increase in density usually leads to a disruptive collapse of the temperature profile, but under certain conditions evolves into a cool poloidally symmetric edge distribution in which virtually all of the plasma heating power is radiated and the plasma is detached from the limiter [2,3]. There has been a substantial theoretical effort to understand MARFE formation. It was recognized some years ago that thermal instabilities were associated with MARFE formation [4] and that the radiative condensation mechanism was responsible [5] for driving the instability. The importance of ionization [6] and recombination [7] effects on MARFE formation limits has been suggested. Poloidally symmetric and highly asymmetric thermal equilibria have been shown to exist for different values of the input to radiated powers [8].

Experiments in the TFTR tokamak [2,9,10] illustrated the sequence of MARFE formation and evolution to a detached H-mode-like plasma, a MARFE triggered at some position on the inner periphery of the minor cross-section of the plasma, it cools the plasma edge further causing the minor radius to shrink and the plasma to thus pull away from the walls and limiters. In the detached state the electron temperature and density profiles are narrower and ~100% of the input power is radiated away by impurities in the edge layer. In the TEXTOR tokamak, the MARFE generally leads to a disruption. In the FTU tokamak the onset of a MARFE

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always occurs before achieving the density limit [11]. The critical density for its onset is not a constant for the same magnetic field and plasma current, but depends on the vacuum vessel conditioning procedure and on the material used for the limiter surface [12].

In this paper, MARFE phenomena on the HT-7 superconducting tokamak are summarized. MARFE usually occurs in the case of high Z_{eff} value ohmic discharges before wall conditioning and/or the boronization on the HT-7. The location of a MARFE is identified by different diagnostic systems. In some cases, the MARFE may extend all around the poloidal cross-section, thus detaching the main hot plasma from the first wall. An improved confinement mode plasma induced by a MARFE is observed in the HT-7, the global particle confinement time increases 1.9 times, the energy confinement time increases 1.1–1.2 times. MARFE cools the plasma edge, so that the electron density and soft X-ray profiles becomes more narrow and peaked, the peaked density profile is observed.

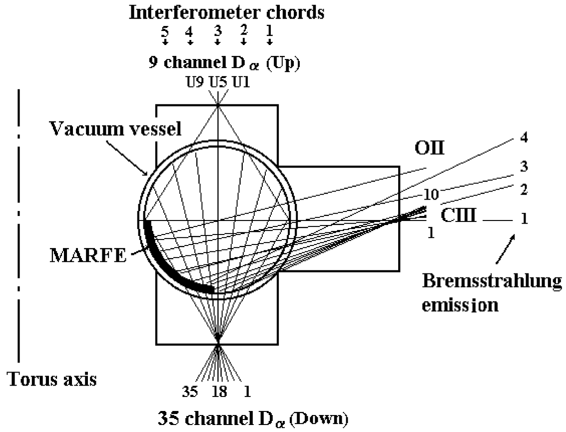

Fig. 1. A chord view of the vertical 5-channel HCN interferometer (from low field to high field at: +20 cm, +10 cm, 0 cm, −10 cm, −20 cm), 9 channel D_α emission (from up window), 35-channel D_α emission (from down window), 10-channel CIII emission, 4-channel bremsstrahlung emission measurements and one channel OII line emission chord in HT-7.

2. HT-7 superconducting tokamak

The Hefei Tokamak 7 (HT-7) machine is a superconducting tokamak [13], and it was rebuilt from the original Russian T-7 tokamak in 1994. The HT-7 tokamak has major radius of $R = 1.22$ m, minor radius of $a = 0.26$–0.28 m in circle cross section, the stainless steel vessel and the stainless steel liner, two fixed and two moveable stainless steel limiters (including a moveable pump limiter) with molybdenum tips. There are two layers of thick copper shells operated at $\sim$80 K, between them are located 24 superconducting coils which can create and maintain a toroidal magnetic field (B_T) up to 2.5 T. The HT-7 ohmic heating transformer has an iron core and can offer a magnetic flux of 1.7 Vs at its maximum.

The main diagnostics for recent experiments on the HT-7 are as follows: a vertical 5-channel far-infrared (FIR) hydrogen cyanide (HCN) laser interferometer (see Fig. 1) for measuring the electron density profile, a multichannel soft X-ray array for intensity measurement, an electron cyclotron emission diagnostic, a 16-channel XUV bolometer array to measure plasma radiation losses, a 3-channel soft X-ray spectrum analyzer, a 7-channel hard X-ray intensity and spectrum analyzer, a neutral particle analyzer (NPA), an electromagnetic measurement system, two multichannel H_α (D_α) radiation arrays, a 4-channel visible bremsstrahlung emission, diagnostic 10-channel CIII line emission and an impurity optical spectrum measurement system (see Fig. 1).

The first plasma was produced on the HT-7 tokamak in 1994. During the Spring experimental campaign in 1998, a feedback control system to simultaneously control plasmma current, density and displacement was developed and put into daily operation. Since 1998 the radio frequency (RF) wave boronization, a new technique for the superconducting tokamak wall condition, has been successfully developed on the HT-7 [14].

3. MARFE phenomena on the HT-7

Radiation of the plasma heating power uniformly to the first wall by a combination of bremsstrahlung from the plasma edge and line radiation from seeded impurities in a thin mantle at the edge is an attractive power exhaust solution for tokamak reactors. However, the observation of MARFE [1] constitutes a potential limitation to the ability to achieve a uniform radiative power exhaust. The MARFE can occur either in the equatorial plane or in the lower or upper half of the plasma column, but always on the inner side. The combination of signals from the horizontal and vertical arrays, measuring the emission from the plasma in the visible range, allows localization of the MARFE position. In some instances MARFEs lead to disruptions, and in others MARFEs cool the edge sufficiently to evolve into detached plasmas with a symmetric radiative edge which exhausts essentially all of the plasma heating power uniformly to the first wall [3].

In the HT-7, a MARFE usually occurs in the early ohmic discharges of each experimental campaign. In a typical shot with a MARFE event (see Fig. 2), the plasma current is about 100 kA, the loop voltage $V_{loop} \sim 3$ V, the toroidal field $B_T = 1.5$ T, $Z_{eff} = 6$–7, $R = 1.22$ m, $a = 0.28$ m, the electron temperature $T_e(0) = 400$–500 eV, the ion temperature $T_i(0) = 200$ eV,

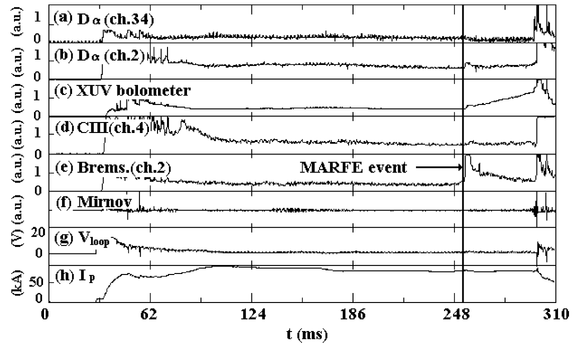

Fig. 2. Typical MARFE phenomena on the HT-7 superconducting tokamak.

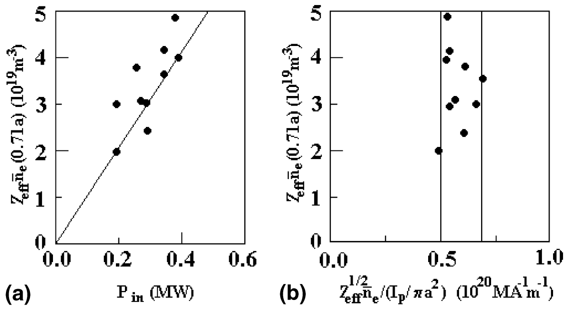

Fig. 3. (a) A dependence of critical value of the $Z_{\mathrm{eff}}^{1/2} n_{\mathrm{e}}$ (0.71a) just before the MARFEs onset and the input ohmic power on HT-7. (b) MARFE occurs at values of $Z_{\mathrm{eff}}^{1/2} n_{\mathrm{e}}$ in the 0.5–0.7 where $\rho = \pi a^2 n_{\mathrm{e}}/I_{\mathrm{p}}$ (10^{20} MA^{-1} m^{-1}).

the line average density is about 1×10^{13} cm^{-3}. A typical position of the MARFE on the HT-7 is identified by different diagnostic systems as shown in Fig. 1. The MARFE event occurs in the lower half of the plasma column on the inner high field side.

The MARFE onset is characterized by a sudden modification of all the signals. Fig. 2 shows a MARFE event from the D_α line emissions (asymmetrically channel 34 signal has no changing in Fig. 2(a), and channel 2 increasing in Fig. 2(b)), from the visible CIII line emission (channel 4 in Fig. 2(d)) and from the visible bremsstrahlung emission (channel 2 in Fig. 2(e)) together with the emission measured by a vertical center channel of the XUV bolometer system (Fig. 2(c)) on the HT-7 ohmic discharge. The increases at the edge radiation intensity not only come from the hot plasma but also include the contribution from MARFE plasma. The later can not be considered simply as the bremsstrahlung emission, the recombination and molecular visible emission could also contribute to the measured brightness. It is clear that there is no MHD precursor from the plasma current (Fig. 2(h)), the loop voltage (Fig. 2(g)) and the mirnov coil signals (Fig. 2(e)) before the event occurs.

The critical conditions for the occurrence of a MARFE in the HT-7 can be deduced from experimental data in Fig. 3(a). 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 $r = 20\,\mathrm{cm}(r/a = 0.71a$, $a = 28\,\mathrm{cm})$, and Z_{eff}. The occurrence of MARFEs strongly correlated with impurity density, it always occurs at $Z_{\mathrm{eff}} = 3$–8 ohmic discharges on the HT-7 tokamak. A review of early published data on MARFEs in tokamaks during strictly high density and low Z_{eff} ohmic operation [1], shows that the MARFE occurs at values of ρ in the 0.4–0.7 where $\rho = \pi a^2 n_{\mathrm{e}}/I_{\mathrm{p}}$ (10^{20} MA^{-1} m^{-1}). In the HT-7 tokamak high Z_{eff} discharges, it is found that the MARFE occurs at values of $Z_{\mathrm{eff}}^{1/2}\rho$ in the 0.5–0.7 (see Fig. 3(b)). It implies that the MARFE event can occurs not only at high density and low Z_{eff} conditions but also at low electron density and high Z_{eff} and neutral density conditions. The MARFE generally lead to a disruption and terminate the discharge as shown in Fig. 2.

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 [3]. 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. Fig. 4 shows the signals for D_α line emission (channel 1), visible CIII line emission (channel 5) and visible bremsstrahlung emissions (shot No. 24176#). It is clear that the MARFE event occurs from $t = 254.4$ ms in Fig. 4. Before the MARFE formation, there is an obviously precursor increase in the edge density and the visible bremsstrahlung emissions at $t = 251$ ms (Fig. 4(c)–(e)). Fig. 5 shows the central line average density, the vertical central soft X-ray signal, the central chord region D_α emission, OII line (441.8 nm) emission and CIII line (464.7 nm) emission of the outside channel No. 10 at low field side. It is observed that D_α line emission, OII and CIII radiation drop, and the central line average density, soft X-ray intensity increase simultaneously.

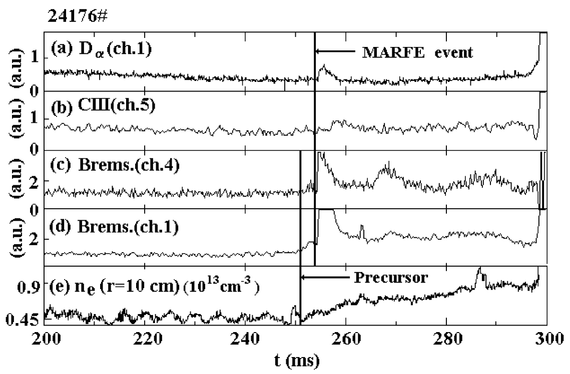

Fig. 4. The onset of a MARFE in HT-7: (a) D_α emission from channel 1 (to see Fig. 1), (b) CIII emission from channel 5, (c) bremsstrahlung emission from channel 4, (d) bremsstrahlung emission from channel 1 along a horizontal line of sight crossing the plasma center, (e) line average density at $r = 10$ cm chord.

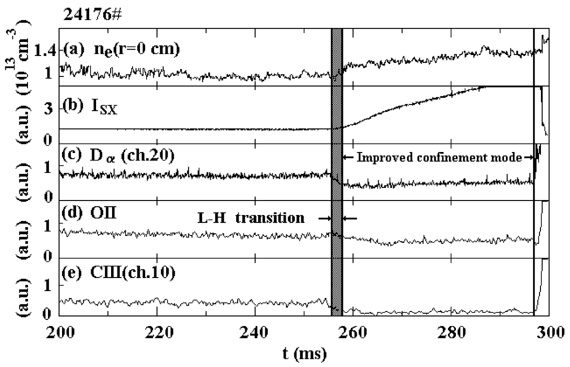

Fig. 5. The improved confinement plasma: (a) central chord average density, (b) central vertical chord soft X-ray intensity, (c) central chord region D_α emission, (d) OII line emission along a line of sight crossing the plasma center (to see Fig. 1), (e) CIII emission from channel 10.

The improved confinement mode, which is characterized by D_α line emission drop and the line average density increase, is observed clearly from $t = 257.8$ ms in Fig. 5, and it was maintained for about 40 ms. The global particle confinement time, which is calculated from $\tau_p = N/(S - dN/dt)$, increases 1.9 times, and the energy confinement time increases 1.1–1.2 times. The horizontal displacement measured by electromagnetic diagnostics shifts 2 cm from the initial equilibrium value $\Delta_{/\!/} = -2$ cm (inside) to a new equilibrium of $\Delta_{/\!/} = 0$ cm with respect to the center of the vacuum vessel. The precursor increase of 3.4 ms at the edge density (radiating impurities accumulate in the plasma edge) leads the event trigger. The relaxation time between MARFE event trigger and the L-H transition is about 1.4 ms, and the followed L-H transition time is 1.9 ms [15].

Fig. 6 shows the electron density profiles at $t = 240$ ms (before the precursor of the event trigger) and $t = 290$ ms (before the end of improved confinement mode). The confinement is improved and the density profile is clearly changed from L-mode ($t = 240$ ms) to H-mode like ($t = 290$ ms). Fig. 7 is the peaking factor of the electron density profile $n_e(0)/n_e(0.71a)$, it increases obviously from 2.1 to 3 after the transition, the electron density profile becomes more narrow and peaked (Fig. 7). The onset of MARFEs has not been observed in the discharge after wall conditioning and the boronization ($Z_{eff} = 1$–2), typically the ohmic discharge after boronization ($Z_{eff} = 1.5$) could achieve 1.2 times the Greenwald density limit without MARFEs on the HT-7.

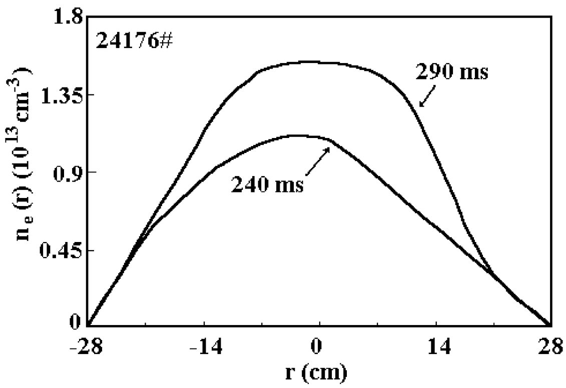

Fig. 6. Electron density profiles $n_e(r)$ by Abel inversion (at $t = 240$ ms and $t = 290$ ms).

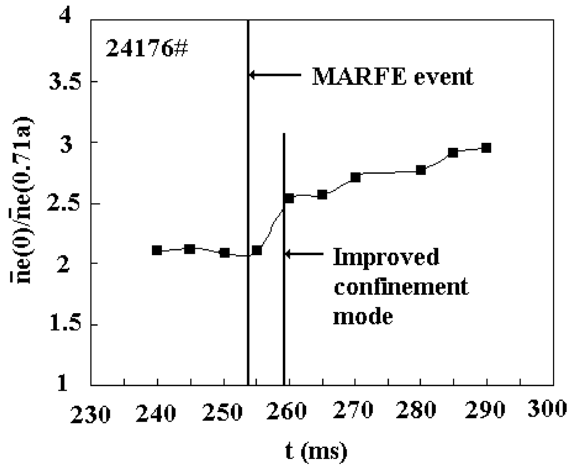

Fig. 7. The evolution of the peaking factor of the electron density profile.

5. Conclusions

In the HT-7 superconducting tokamak the onset of a MARFE usually occurs in the early ohmic discharges of each experimental campaign due to high impurity density. MARFE phenomena on the HT-7 tokamak are summarized in this paper.

The best correlation has been found between the total input ohmic power and the product of the edge line average density and Z_{eff}. The occurrence of MARFEs strongly correlated with impurity density, it always occurs at $Z_{eff} = 3$–8 ohmic discharges. In the HT-7 tokamak high Z_{eff} discharges, it is found that the MARFEs usually occur at values of $Z_{eff}^{1/2}\rho$ in the 0.5–0.7, where $\rho = \pi a^2 n_e / I_p$ (10^{20} MA^{-1} m^{-1}). In the case of good wall condition ($Z_{eff} = 1$–2), the onset of MARFEs have not been observed before reaching the Greenwald density limit on the HT-7 [16].

The MARFE induced improved confinement mode which is characterized by D_α radiation drop and the central line average density increase is observed, the global particle confinement time increases 1.9 times, the energy confinement time increases 1.1–1.2 times. The time sequence of MARFE formation and followed L-H transition is studied. The precursor increase in the edge density (radiating impurities accumulate in the plasma edge) start from $t = 251$ ms, and it leads the event trigger. The MARFE event occurs at $t = 254.4$ ms and the followed L-H transition happens from $t = 255.8$ ms to 257.7 ms, the improved confinement phase maintained for about 40 ms from $t = 257.7$ ms after L-H transition. MARFE cools the plasma edge, and the electron density profile is observed to become more narrow and peaked.

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