Stationary multifaceted asymmetric radiation from the edge and improved confinement mode in a superconducting tokamak

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Stationary multifaceted asymmetric radiation from the edge (MARFE) is studied by gas-puffing feedback control according to an empirical MARFE critical density ($\sim 1.8\times10^{13}\,\mathrm{cm}^{-3}$) in the HT-7 Ohmic discharges (where the plasma current I_p is about 170 kA, loop voltage $V_{\mathrm{loop}}=2-3$ V, toroidal field $B_T=1.9$ T, and $Z_{\mathrm{eff}}=3$–4). It is observed that an improved confinement mode characterized by D_α line emissions drops and the line-averaged density increase is triggered in the stationary MARFE discharges. The mode is not a symmetric "detachment" state, because the quasi-steady-state poloidally asymmetric radiation (e.g., C III line emissions) still exists. This phenomenon has not been predicted by the current MARFE theory.

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A multifaceted asymmetric radiation from the edge (MARFE), which is characterized by a poloidally asymmetric and toroidally symmetric band of cold and intense radiating plasma at the inner wall, has been observed on many tokamaks [1,2]. The local density and temperature in the MARFE has been measured experimentally [3]. It has been observed that in many cases MARFE's precede the density limit disruption. The critical line-averaged density of a MARFE instability onset is observed within a very wide region of densities on different tokamaks. A review of early published data on MARFE's in tokamaks during strictly high density and low Z_{eff} Ohmic operation [1] shows that the MARFE typically occurs at a fraction of 40–70 % of the Greenwald density limit n^{GW} [4]. In the TEXTOR-94 limiter tokamak, the highest critical density can be up to 130–200 % of the Greenwald limit by the controlled localized recycling [5]. In the Tore Supra superconducting tokamak [6], the critical density is only 12–22 % of the Greenwald limit. In the HT-7 superconducting tokamak, the averaged density of MARFE onset ($Z_{\mathrm{eff}}=3$–8 and 15–30 % of the Greenwald limit [7,8]) is also observed to be very low in the discharges of each campaign before the wall conditioning [9,10]. However, after rf boronization in the HT-7 [10], the MARFE onset density is more than 120% of n^{GW} [7,12]. With good wall conditioning (e.g., fresh siliconization and fresh boronization) in the TEXTOR-94 [11], the appearance of MARFE's has been postponed up to 170% of the Greenwald limit. The critical conditions for the occurrence of a MARFE may be correlated to the edge plasma parameters, because it is a localized instability within the edge region. It was evidence that the critical value of $n_e(0.7a)Z_{\mathrm{eff}}$ in the MARFE onset always correlated with the total input power which has been observed in the FTU [13] and the HT-7 limiter tokamak [7,12], where a is the radius of the plasma column. In the TEXTOR-94, dependence of the edge electron density ($r=a+1$ cm) on the heating power was also observed [14]. Therefore, it suggests experimentally the importance of impurity radiation and localized power balance in the MARFE formation.

The lifetime of MARFE's is observed in the time scales from about of the global particle confinement time τ_p (the "nonstationary" MARFE) to more than the several tens of τ_p (the "stationary" MARFE) [15]. Experimentally, the global particle confinement time is about 15–20 ms typically in the HT-7. In many cases, the nonstationary MARFE is a precursor of a major disruption, and it demonstrates a nonstationary behavior: moving along the inner wall of a tokamak, changing its size and brightness, disappearing, and appearing again naturally. However, the long-lifetime stationary MARFE's are usually produced in the tokamaks by a stochastic magnetic-field control [6] or a feedback-controlled gas puff [16]. The lifetime of stationary MARFE's (>215 ms) shows a quasisteady state in the HT-7 MARFE feedback experiments.

There have been several theories developed to explain MARFE formation and development [17–24]. MARFE's can occur when the plasma edge density is high and results from an imbalance between the power flowing along magnetic-field lines at the edge and the power lost locally due to radiation [17–23]. An increase in the density in a tokamak beyond a certain limit produces MARFE. And 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 [22]. In those models, the mechanisms responsible for the MARFE instability are impurity radiation [17–23] and/or localized recycling [5,24,25]. A distinction between these two driving mechanisms can hardly be made experimentally, because the release of carbon is connected to the hydrogen flux [25]. The MARFE instability can be affected by the localized recycling and hence the plasma-wall interaction [24]. The latest results on spectroscopic studies of stationary MARFE's in TEXTOR-94 indicated that the enhancement of the hydrocarbon emission confirms the increase of a plasma-wall interaction in the vicinity of the MARFE [15].

In this Brief Report, we present a stationary MARFE experiment based on the observation of multichannel D_α and C III line emissions in the HT-7: an improved confinement

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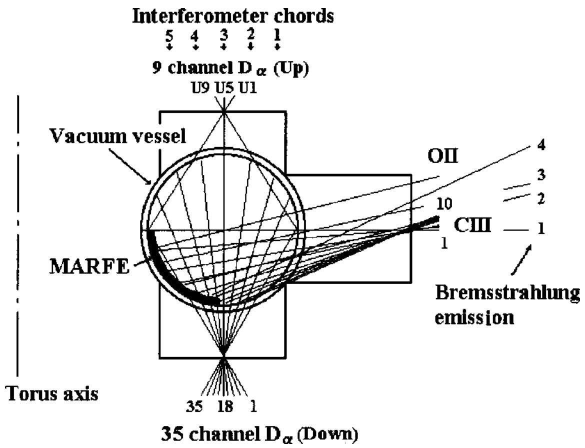

FIG. 1. A chord view of the vertical five-channel HCN interferometer (from low field to high field at +20, +10, 0, −10, and −20 cm), nine-channel D_α emission (Ch. U1–U9 from top window), 35-channel D_α emission (Ch. 1–35 from bottom window), 10-channel C III emission, four-channel bremsstrahlung emission measurements and one-channel O II line emission chord in the HT-7.

mode plasma exists in the stationary MARFE's which is produced by the feedback gas-puff method. It is clearly observed that the poloidally asymmetric C III line radiation state is a stationary state (∼215 ms), and the deuterium flux D_α suddenly drops for a phase of about 50 ms in all of the D_α channels in the stationary MARFE state. It is very interesting for understanding the mechanism of the MARFE instability. This result is repeatable in the HT-7 MARFE feedback experiments, and it is consistent with the results of low-density MARFE experiment in Tore Supra [6].

The Hefei Tokamak-7 (HT-7) is a superconducting tokamak [7]; it was reconstructed from the original Russian T-7 tokamak in 1994. 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. The HT-7 tokamak has a major radius of $R=1.22\,\mathrm{m}$, a minor radius of $a=0.26-0.28\,\mathrm{m}$ in the circular cross section, a stainless-steel liner, two fixed, and one movable stainless steel limiter with molybdenum tips. The operational temperature of the first wall T_w is about 80–130 °C in the HT-7 superconducting tokamak. There are two layers of thick copper shells in the HT-7, and between them are located 24 superconducting coils which can create and maintain a toroidal magnetic field (B_T) up to 2.5 T for steady-state operation. The technique of rf wall conditioning within a steady-state high toroidal magnetic field has been routinely used in daily experiments [9,10]. The HT-7 Ohmic heating transformer has an iron core and can offer a magnetic flux of 1.7 V s at its maximum. The main diagnostic system for this study (see Fig. 1) has been described in our published papers [8,26–28].

The improved confinement mode induced by a "natural" MARFE has been observed in the HT-7 tokamak [26]. Recently, stationary MARFE's with a long lifetime by the gas-puff feedback control was studied in the HT-7. Similar MARFE feedback (to control the critical C II or C III line radiation near the inner wall) experiments were also studied

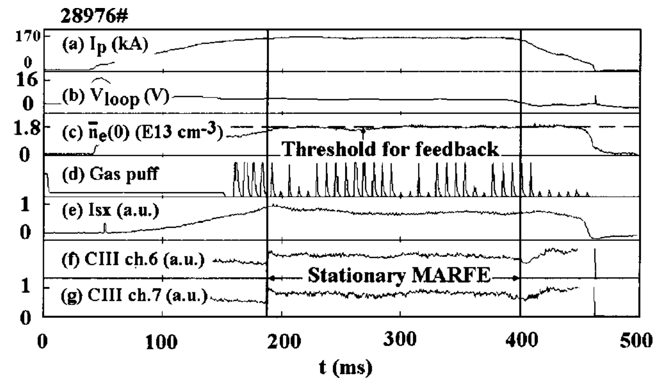

FIG. 2. A long lifetime stationary MARFE feedback experiment in the HT-7 limiter tokamak (shot no. 28976), where the MARFE threshold presetting is provided by the HT-7 MARFE onset database.

in the TEXTOR-94 [16]. An empirical threshold density, which is given from the HT-7 database of the MARFE onset (that work has been published in our works [7,8]) for each shot, is used to trigger a stationary MARFE as a critical density for feedback gas puffing in our experiments. The plasma current and displacement is also feedback-controlled in the HT-7 as mentioned above. Figure 2 shows typically a feedback gas-puff plasma for triggering the stationary MARFE in the HT-7 Ohmic discharge (shot no. 28976). The plasma current I_p is about 170 kA, loop voltage $V_{\mathrm{loop}}=2-3\,\mathrm{V}$, toroidal field $B_T=1.9\,\mathrm{T}$, $Z_{\mathrm{eff}}=3-4$ [9], $R=1.22\,\mathrm{m}$, $a=0.28\,\mathrm{m}$, electron temperature $T_e(0)=1.0-1.1\,\mathrm{KeV}$, ion temperature $T_i(0)=500-600\,\mathrm{eV}$, and the empirical MARFE onset density [see Fig. 2(c)] for feedback control in this shot is about $1.8\times10^{13}\,\mathrm{cm}^{-3}\sim26\%$ of the Greenwald limit n^{GW} ($6.9\times10^{13}\,\mathrm{cm}^{-3}$) as shown in Fig. 2(c). The stationary MARFE [see Figs. 2(f) and 2(g)] is produced for more than 215 ms by the MARFE feedback control, and its lifetime is terminated by the programming plasma current quench started at $t=400\,\mathrm{ms}$ in shot no.

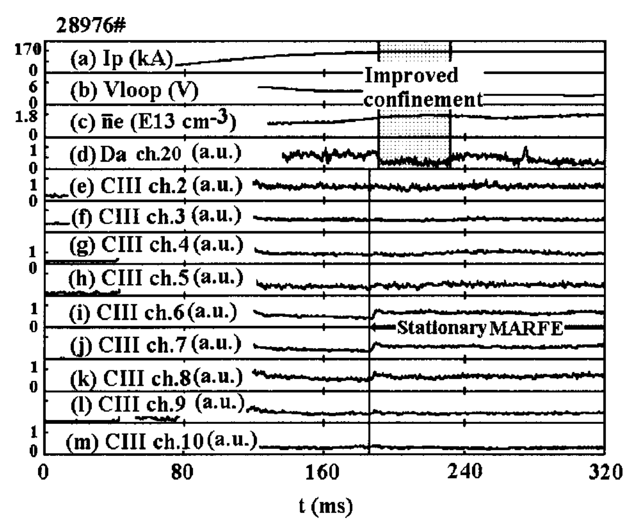

FIG. 3. Multichannel C III line measurements for confirming stationary MARFE state in the HT-7 Ohmic discharge (shot no. 28976).

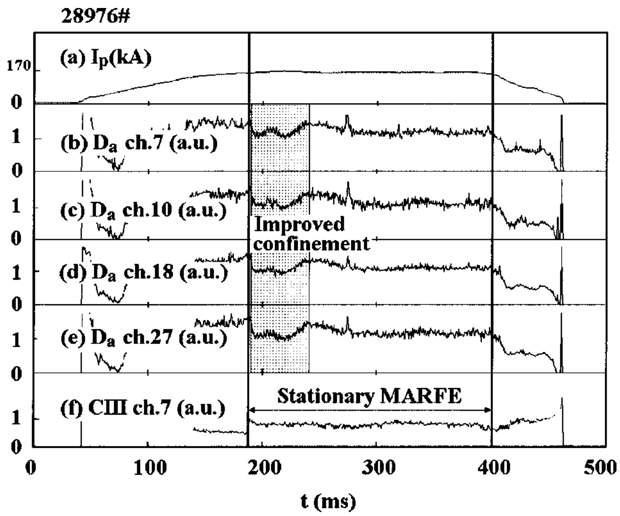

FIG. 4. Improved confinement mode in stationary MARFE (ICMISM) plasma indicated by the HT-7 multichannel D_α measurements (No. 28976).

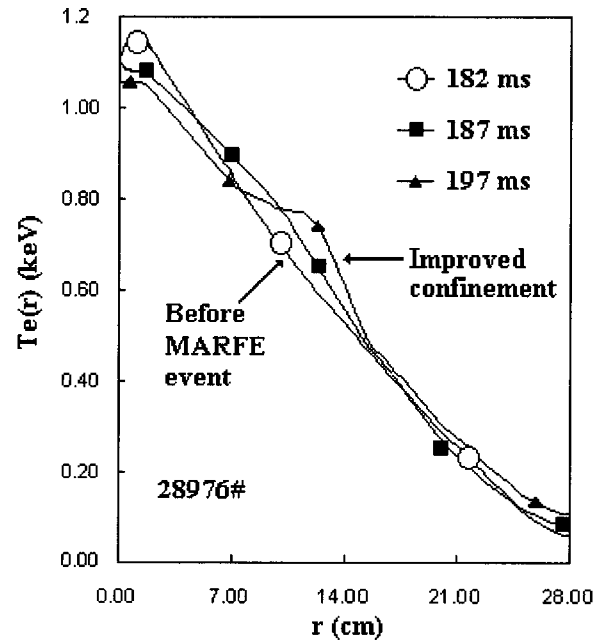

FIG. 5. Evolution of the electron temperature profiles around the occurrence of the event.

28976 of Figs. 2(a), 2(f), and 2(g). Figure 3 shows the multichannel C III measurements to identify the spatial and temporal evolution of the stationary MARFE in the HT-7. It is identified that a sudden modification occurs at $t=185$ ms in the channels from No. 5 to No. 8 of C III radiation as shown in Figs. 3(h)–3(k). The MARFE onset is also observed in a signal of the bremsstrahlung emission (Brems. Ch. 2, see Fig. 1), but it is not observed in the O II line emission for shot no. 28976. Figure 4 shows the multichannel D_α measurements (no. 28976), and it is observed that D_α emissions suddenly drop at $t=189$ ms in the all of D_α channels, which covers the whole region of MARFE plasma and MARFE-free plasma. It is a typical improved confinement mode [26] which exists for about 50 ms during the stationary MARFE [see Fig. 4(f)] discharge, and it disappears at $t=239$ ms in Fig. 4. The density profile is studied and shows that there is no obvious change in its profiles during the whole stationary state. However, the electron temperature profile (see Fig. 5) shows a weak internal transport barrier (ITB) at $r=0.5a$ in the improved confinement mode plasma. It was measured by a new ECE diagnostics [28]. The observation of the plasma profiles in this experiment is different from the "natural" result in Ref. [26] where the ITB localized at $r=0.35a-0.71a$ was observed in the electron density profiles during the improved confinement phase. The plasma confinement parameters in the experiment will be studied in detail with the optimized operation in the future.

The onset density of stationary MARFE is quite a bit lower than the Greenwald density limit in the HT-7 [8] and the Tore Supra superconducting tokamak [6]. It is known that density limits are distinguished in two ways. In the Ohmic and auxiliary heated discharges with low-Z impurities, the density is limited by a radiative collapse that leads to forming the symmetric radiation belt around the shrinking plasma. This density limit can be increased until the radiation power equals the total input power before triggering large-scale instabilities. This limit is well understood now. Another density limit is found to scale with the averaged current density in tokamaks for strong auxiliary heating by Greenwald *et al.* [4], and the MARFE instability is though to play a role in the destabilizing process of the discharge operated near the Greenwald limit [1]. However, a factor is that the MARFE onset density was widely observed from 12% to 200% of the Greenwald limit n^{GW} in tokamaks. Therefore, the mechanism research of the Greenwald limit and MARFE's is still important in plasma physics.

In summary, stationary MARFE's have been studied in the HT-7 MARFE feedback experiments since 1999. It is observed that the improved confinement mode can also be triggered in the stationary MARFE discharges by gas-puff feedback control. The lifetime of the improved confinement mode in stationary MARFE's (ICMISM) is about 40–100 ms in the HT-7 Ohmic discharge. The ICMISM is observed in the long-lifetime MARFE discharges with the high value of Z_{eff} (=3–8) and the low value of density (=15–30 % of n^{GW}) conditions. The occurrence and the disappearance of the ICMISM have not been well understood and controlled. The plasma confinement parameters in the ICMISM will be studied in detail with the operational optimization. The ICMISM plasma implies that the intense localized and global D_α recycling flux is not important in the development of stationary MARFE's experimentally, though the MARFE formation may be triggered by localized recycling or impurity radiation independently in current models. This phenomenon was not studied by the present MARFE theories.

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