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ScienceDirect
Journal of Nuclear Materials 363–365 (2007) 770–774
journal of nuclear materials
www.elsevier.com/locate/jnucmat

The study of MARFE during long pulse discharges in the HT-7 tokamak

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Abstract

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 is summarized and studied in the HT-7 tokamak. MARFE during LHCD discharge often occurs at the value of $Z_{\mathrm{eff}}^{1/2} f_{\mathrm{GW}}$ in range of 0.6–0.9. These MARFEs generally appear to have the same characteristics as high f_{GW} density MARFEs and are locally stable throughout the LHCD pulse. The MARFE instability typically occurs at a fraction 33% of the n_{GW} density during LHCD discharge, and it can often terminate the long pulse discharges in the HT-7 tokamak.

PACS: 52.25.Fi; 52.35.Hr; 52.35.Py

Keywords: HT-7 tokamak; Limiter materials; MARFE

1. Introduction

The MARFE is a multifaceted asymmetric radiation from the edge. It is a poloidally asymmetric and toroidally symmetric intensified radiation band located at the inner side of the cross section. The formation of MARFE is related to the locally thermal imbalance along the magnetic field in the edge. The occurrence of MARFE often follows a precursor of the plasma density distribution and the impurities. In some case (related to the edge circumstance) the impurities become not even and aggregate in the inner side of the cross section, the increased radiation causes the thermal instabilities, so further impurities enter the area, with the accumulation of impurities in edge developed, the MARFE forms. Usually it leads to disruption or the plasma detachment respect to different conditions. Under some conditions, it can also cause the improvement of confinement in HT-7 tokamak [1]. These have been investigated in some articles from both theory and experiment and on some machine, such as TFTR, TEXTOR, and FTU. The critical condition for the onset of MARFE is different on different machine and for the different plasma parameters, wall-conditionings, and limiter materials [2–13].

HT-7 tokamak is designed mainly to study the long-pulse discharge physics [1–5]. The machine has make a lot of modifications to achieve long

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0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2007.01.196

durations such as the rf wall-conditioning, plasma density and displacement control, water cooling limiter, different limiter material such as the molybdenum and the graphite limiters [5]. Up to 2005, the duration of the long-pulse discharge has reached to 5 min with LHW current drive [4]. From the experience of the operation of long-pulse discharge, the physics at plasma edge is of great importance for the duration limit. In HT-7 tokamak, MARFE sometimes is observed in the late phase of the long-pulse discharge and it can lead to termination of the discharge.

In this paper, we summarized the MARFE phenomena under different conditions: the ohmic discharge with molybdenum poloidal limiter [1,2] and with graphite poloidal, toroidal and belt limiter [3,4]. The critical conditions for the formation of the MARFE and the MARFE behavior under long-pulse discharge are studied in this article.

2. Experimental setup

The HT-7 tokamak is a superconducting tokamak, reconstructed from the former Russia T-7 tokamak in 1994 [1]. The tokamak has major radius of 1.22 m, minor radius of 0.27 m. The limiters (a water-cooling double-ring graphite limiters in the toroidal, two poloidal limiters and one beta limiter [5]) are made of graphite at present, but there was only poloidal limiter made of molybdenum several years ago [1]. The maximum toroidal magnetic field is up to 2.5 T and provided by 24 superconducting coils. The OH transformer iron core can provide 1.7 Vs magnet flux. A low hybrid current drive was built to drive the long-pulse current and improve the confinement. The plasma current is up to 250 kA, the line-average density is 1–6 ($10^{13}/cm^3$).

The main purposes of HT-7 tokamak are to research the steady-state operation, the long-pulse discharge, the high performance discharge, and the RF heating. The diagnostic systems relevant to MARFE are as below (with Mo limiter and with C limiter respectively): (1) previous molybdenum limiter: the vertical 5-channel far-infrared (FIR) hydrogen cyanide (HCN) laser interferometer, a multichannel soft X-ray array, an electron cyclotron emission diagnostics, a 16-channel XUV bolometer array, an neutral particle analyzer (NPA), an electromagnetic measurement system, two multichannel H-alpha (D-alpha) radiation arrays (9-channels from the up and 35-channels from the down), 4-channel bremsstrahlung emission, 10-channel CIII line emission and an impurity optical spectrum measurement system (see Fig. 1); (2) present graphite limiter: a 16-channel XUV bolometer array, a 7-channel bremsstrahlung emission (Z1-7) to measure Zeff, two multichannel H-alpha (D-alpha) radiation arrays (ha1-35 and ph1-20), a multichannel soft X-ray array (46 channels), 10-channel CIII line emission, an impurity optical spectrum measurement system and the electron density profile measured by a vertical 5-channel far-infrared (FIR)

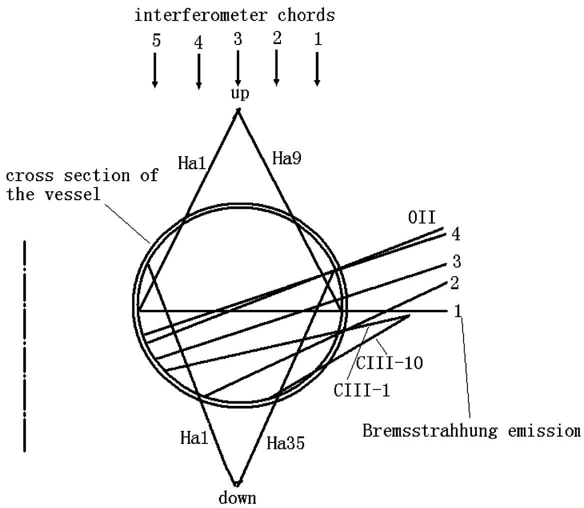

Fig. 1. The cross section distribution of the diagnostic chord signals with molybdenum limiter for the H-alpha (the up and the down), OII, CIII, Bremsstrahlung chord signals.

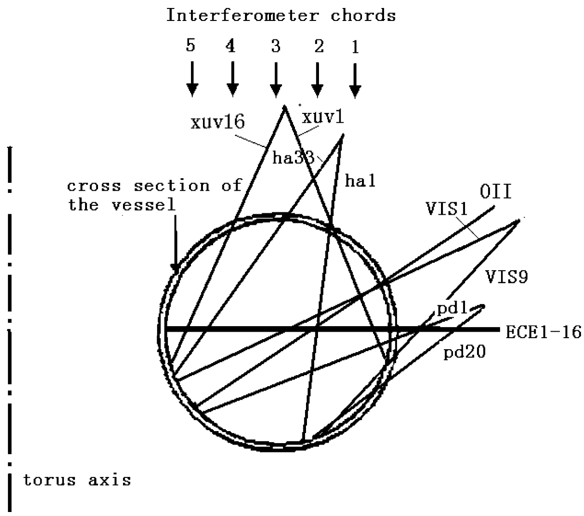

Fig. 2. The cross section distribution of the diagnostic signals with graphite limiter for the H-alpha, Pd (also H-alpha, but in different location), CIII, OII, SXA chord signals.

hydrogen cyanide (HCN) laser interferometer as shown in Fig. 2.

The occurrence of MARFE is observed through sudden modifications of some channel of radiation and optical spectrum signals and can be further testified by the distribution of the density and radiation.

3. MARFE with molybdenum and graphite limiters

The HT-7 molybdenum poloidal limiter was built in 1999 [1], which is not sufficient for the potential increase of discharge duration. To acquire longer duration, the new active-cooled toroidal double-ring doped graphite limiters were mounted in 2004 (Fig. 3). the new active-cooled toroidal double-ring doped graphite limiters were applied in 2004 (Fig. 3). The material is GBST1308 (1% B, 2.5% Si, 7.5% Ti) [5]. The limiters have high thermal conductivity up to 210 W/mK and good thermal shock resistance that can withstand 6 MW/m^2. The new graphite limiters were verified allowing longer duration and higher plasma parameter in the later experiment campaign.

The MARFE phenomenon under the new graphite limiter conditions was compared with before. The same behavior and the rule are testified, while the critical conditions go different due to the alteration of the edge plasma behavior and the density behavior for different limiter.

The typical MARFE phenomenon under the new graphite limiters conditions is showed in Fig. 4. The discharge is an ohmic shot before wall-conditioning, with the plasma current about 130 kA, the toroidal magnetic field 1.7 T, the loop voltage <3 V, the central chord density about $4.5 \times 10^{13}/cm^3$. The onset of MARFE is verified by the sudden change of the CIII signal and the increase of the edge density.

The critical conditions for the MARFE formation with the new graphite limiters are investigated and compared with the old ones as shown in Fig. 5 and Fig. 6.

As described in Fig. 5 the critical factor $Z_{eff}^{1/2} f_{GW}$ is 0.5–0.7 for molybdenum limiter and 0.9–1.2 for

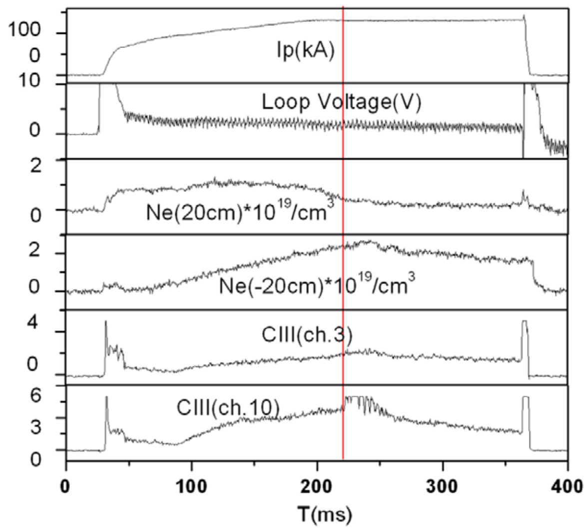

Fig. 4. The MARFE behavior under new graphite limiter conditions. From up to down: The signal is plasma current, loop voltage, electron line density at 20 cm, electron line density at −20 cm, CIII radiation signal at channel 3, CIII radiation signal at channel 10. Shot No. 66361.

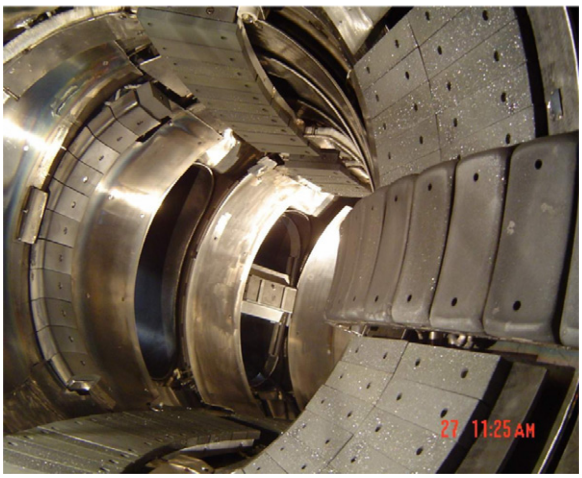

Fig. 3. The double-ring graphite limiters in the HT-7 tokamak.

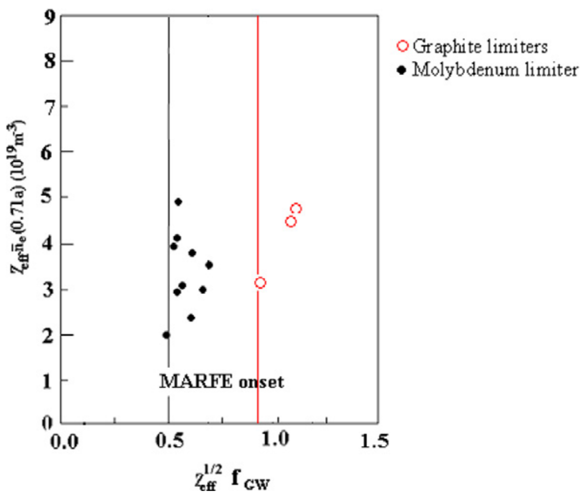

Fig. 5. The critical factor of MARFE onset is 0.5–0.7 for molybdenum limiter and 0.9–1.2 for graphite limiters.

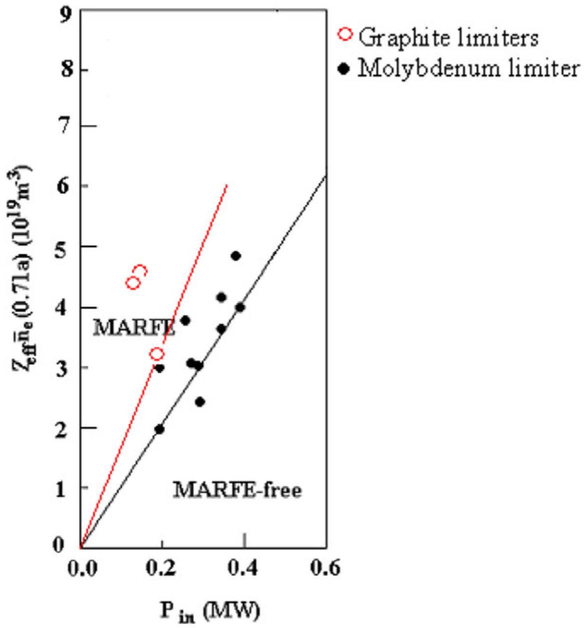

Fig. 6. The critical density is higher for graphite limiter than for molybdenum limiter.

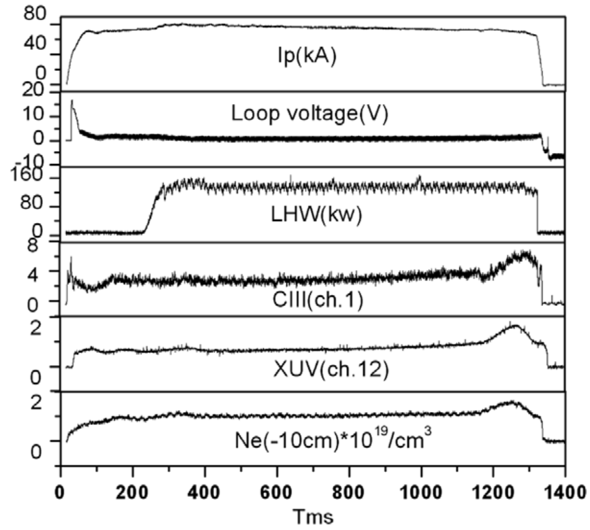

Fig. 7. The typical MARFE in LHCD discharge. Characterized by the sudden change of CIII signals. From up to down: plasma current, loop voltage, Low hybrid power, CIII radiation at channel 1, xuv radiation power, electron line density at −10 cm. Shot No. 74285.

graphite limiters. The Z_{eff} has been investigated to be 3–8 for molybdenum limiter and 1–4 for graphite limiters. The calculated results show that the MARFE can occurs just up the 25% Greenwald density with molybdenum limiter, while for graphite limiters, it occurs in 50–90% Greenwald density which hint that with the new limiters, the density control is more free than before. The result also show that the factor $Z_{eff}^{1/2}f_{GW}$ is descriptive both for low-Z_{eff} and high-Z_{eff} discharge. In Fig. 6, with the same ohmic power, the critical density is higher for graphite limiters, which implies a better edge plasma circumstance.

4. MARFE in the LHCD discharge

The low hybrid current drive method as an effective measure to maintain discharge has long been carried out for long-pulse discharge physics research on HT-7 tokamak, together with the modification of the hardware and the experience of the crew, up to 2005, the duration of the long-pulse discharge has been promoted to 5 min [4,5].

In the low hybrid current drive discharge, the MARFE is dangerous, it can lead to the termination of the plasma current. A typical MARFE in LHCD discharge is shown in Fig. 7, which terminated the discharge because of the emission loss of the energy.

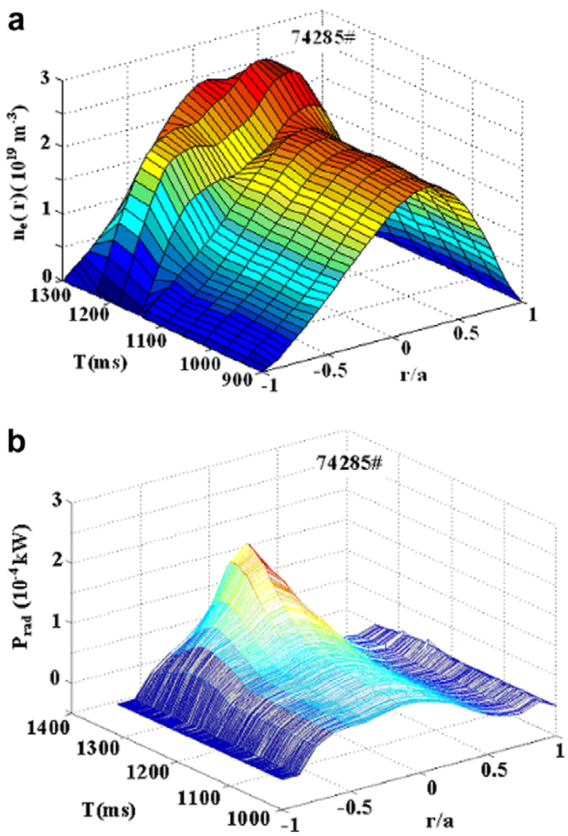

Fig. 8. The podensity (a) and radiation (b) change in the long pulse discharge.

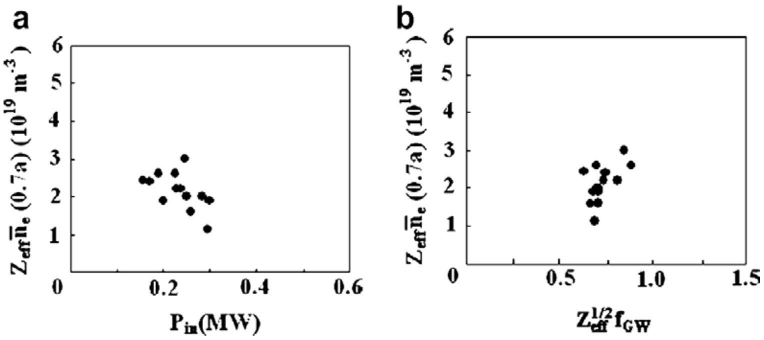

Fig. 9. The critical conditions that MARFE occurs in the LHCD discharge.

The occurrence of MARFE is characterized by the sudden change of the CIII emission and the modification of the density. In the Fig. 8, the increase of the density (a) and the radiation power (b) in the inner part of the cross section is obvious. The plasma parameter is as follows, the plasma current is 76 kA, the loop voltage is 0.7 V after the low hybrid wave, the density is $1.2 \times 10^{13}/\text{cm}^3$.

The critical condition for the formation of the MARFE in LHCD discharge is $Z_{eff}^{1/2} f_{GW} = 0.6 - 0.9$ (as shown in Fig. 9(b)). However, opposite to the ohmic discharge as shown in Fig. 6, the critical density decreases with the input power (see Fig. 9(a)) of LH wave.

5. Conclusion

The MARFE phenomena have been summarized in the HT-7 tokamak under different conditions. A key parameter $Z_{eff}^{1/2} f_{GW}$ is concluded to describe the critical condition that MARFE occurs, where the $f_{GW} = n_e/n_{GW}$ and the n_{GW} is Greenwald density.

Under the molybdenum limiter conditions, the MARFE occurs when $Z_{eff}^{1/2} f_{GW} = 0.5$–$0.7$, the $Z_{eff} = 3$–8 and $n_e > 25\%$ Greenwald density. Under the graphite limiters conditions, the $Z_{eff}^{1/2} f_{GW} = 0.9$–$1.2$, the $Z_{eff} = 1$–4 and the $n_e = 50$–90% of Greenwald density. The comparison of the two conditions gives the conclusion that the occurrence of the MARFE instability is more difficult with graphite limiters in the HT-7. The edge circumstance of the tokamak is improved, and the control of the density is more flexible.

MARFE phenomena is observed and studied in LHCD plasmas when the input power of LH wave $P_{LH} > 160$ kW and $q(a) \sim 6.5$ in the HT-7 tokamak. MARFE during LHCD discharge often occurs at the value of $Z_{eff}^{1/2} f_{GW}$ in range of 0.6–0.9. These MARFEs generally appear to have the same characteristics as high f_{GW} density MARFEs and are locally stable throughout the LHCD pulse. The MARFE instability typically occurs at a fraction 33% of the n_{GW} density during LHCD discharge, and it can often terminate the long pulse discharges in the HT-7 tokamak.

Acknowledgements

The author wish to thank all of the HT-7 team for the helpful work. This work is supported by the National Nature Science Foundation of China (Contract Number: 10005010) and partly supported by JSPS-CAS Core-University Program on Plasma and Nuclear Fusion in 2006.

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