Research on the effect of resonant magnetic perturbations on disruption limit in

J-TEXT tokamak

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Abstract. The effect of resonant magnetic perturbations (RMPs) on high density limit and low- q limit discharges is studied in J-TEXT tokamak. It is found that a moderate amplitude of applied RMPs increases the density limit and delays the disruption, and the disruption precursor is suppressed with a slight reduction in toroidal plasma rotation. A too large amplitude of RMPs, however, leads to a lower density limit and an earlier disruption. For the optimal RMPs amplitude, the disruption is delayed by about 150 ms. For low- q discharges, the applied static RMP can either lower the limit of the edge safety factor q_a from 2.15 to nearly 2.0 or sustain stable plasma discharge with $q_a = 2.1$, and the disruptive precursor is also suppressed.

1. Introduction

The feasibility and economics of a tokamak as a fusion reactor are strongly influenced by the occurrence of disruptions—rapid loss of all or a large fraction of the magnetic and thermal energy of the plasma column [1]. It is observed that many disruptions are preceded by the precursor MHD instability, a period of rotating magnetohydrodynamic (MHD) activity with low poloidal and toroidal mode numbers [2, 3]. Near the disruption limit, the precursor MHD activity grows quickly and causes the disruption in several ms [1]. For example, the maximum current limit in a tokamak is set by the tearing-kink instability (usually $m = 2$, $n = 1$), which grows and disrupts the plasma when edge safety factor q_a approaches 2 [4], where m and n are the poloidal and toroidal mode numbers. While for given plasma current and minor radius, there is a maximum plasma density (namely density limit) that can be sustained [5], also set by a disruptive MHD-initiated instability.

Experiments had been performed in the past to control the precursor MHD activity and hence to avoid or delay the disruption by using resonant magnetic perturbations (RMPs). In 1970s, the disruptive instability was avoided by using the resonant-helical-field (RHF) in PULSATOR-I [6]. Later on, stabilization of disruption precursor had been extensively studied in other devices [7-9], and it was observed that RMPs can effectively reduce the width of magnetic islands [7, 8], and plasma stabilization had also been achieved by rotating RMPs [9]. In 1990s, RMPs feedback control had been used in the DITE tokamak for the stabilization of disruption precursors, and the disruptive density limit was significantly increased [10]. Recently, DIII-D and RFX-mod experiments have demonstrated stable tokamak operation at very low values of the edge safety factor q_a near and

below 2 via RMPs feedback control of MHD stability [11, 12]. In addition, it has been observed in TEXTOR that the threshold of the MARFE onset in the NBI heated plasmas is increased by making more homogeneous plasma recycling at the plasma edge by applying a 1 kHz ac magnetic field perturbation at the high field side (HFS) [13]. These studies develop a flexible method to control disruption precursors.

Most of the precursor MHD instability before disruption is verified to be the tearing mode (TM) [1], hence it is important to control the precursor TM for the disruption mitigation/avoidance. Previous experimental studies showed that RMPs can suppress rotating TM effectively, accompanied by a plasma rotation reduction [14-17]. Theoretical analysis developed by Fitzpatrick [18, 19] reveals that the applied RMPs contribute a net stabilizing and braking effect on the TM and plasma rotation, respectively. The analytical results are confirmed by recent experimental and numerical studies in J-TEXT [16, 17, 20], which also indicate that RMPs can completely suppress the TM with partial rotation reduction. Further numerical modeling shows that a smaller amplitude TM can be suppressed more easily by RMPs [16], agreeing with Fitzpatrick's theory and suggesting that it is possible to take advantage of RMPs to control the precursor TM for disruption mitigation. In Fitzpatrick's analytical results the stabilizing and braking terms are [18]

$$\Delta'_{\text{RMP}} = A_1 \left(\frac{W_{\text{vac}}}{W} \right)^2 \cos \Phi, \quad (1)$$

$$T_{\text{zEM, RMP}} = A_2 W_{\text{vac}}^2 W^2 \sin \Phi, \quad (2)$$

respectively, where Δ'_{RMP} parameterizes the effect of RMPs on TM stability, $T_{\text{zEM, RMP}}$ is the electromagnetic torque exerted by RMPs, W_{vac} is the vacuum magnetic island width and represents the amplitude of RMPs, W is the actual magnetic island width, Φ is the phase difference between magnetic island and RMPs, and A_1 and A_2 are constant parameters related to plasma equilibrium. The time integration of equations (1) and (2) reveals a net stabilizing and braking effect by the applied RMPs [19, 20]. The mechanism for the stabilization of TM by the RMP was described by Hender and Fitzpatrick [14, 18]: Due to the electromagnetic force applied from the RMP, the TM rotation becomes non-uniform in a period, rotating faster in the half period when $\pi < \Phi < 2\pi$ but slower in another half period when $0 < \Phi < \pi$. On the other hand, the RMP has a stabilizing (destabilizing) effect on the TM when $\Phi > |\pi/2|$ ($\Phi < |\pi/2|$). The non-uniform rotation leads to the TM (or magnetic island) to stay for a longer time in the half period when the RMP is stabilizing ($\Phi > |\pi/2|$), so that on the average the RMP has a net stabilizing effect on the mode. Such an effect is larger if the island width W is smaller, as can be seen from Eq. (1). Therefore, in order to suppress the precursor TM with less rotation braking, for given amplitude of RMPs the island width W should be as small as possible, so as to ensure a larger stabilizing effect while a weaker braking effect. For satisfying this requirement, it is better to apply the RMPs in the early growth phase of the precursor TM when the island width is small.

Motivated by the above understanding of the RMP effect on TM dynamics, experiments have

been carried out in J-TEXT tokamak to study the RMPs effect on high density limit and low- q limit discharges, as reported in this paper, to control the disruptive precursors for disruption mitigation. In these experiments, the static RMPs are applied before the growth of precursor TM in both density limit and low- q discharges. As a result, the density limit is increased and the low- q limit is lowered, and the disruption is delayed, because the precursor TM is completely suppressed with a slight rotation reduction, as expected [14, 18]. The experimental setup and results are presented in section 2, and the discussion and summary are given in section 3.

2. Experiment results

2.1. Experimental setup

J-TEXT is a circular, medium sized, limiter tokamak with a major radius (R_0) of 1.05 m and a minor radius (a) of 0.25-0.3 m [21]. Recently, J-TEXT had been equipped with 12 in-vessel saddle coils located at four toroidal locations as shown in figure 1(a), which can generate either static or rotating RMPs [22]. In the present experiments, the coil system is set to only produce static RMPs, dominated by a resonant $m/n = 2/1$ component with its radial magnetic field b_r of the strength 2.5 Gs per kilo-ampere of coil current at plasma edge ($r = a$). The electron density is measured with seven-channel far-infrared (FIR) HCN interferometer, which views the plasma vertically at $R = 1.0, 1.05, 1.1, 1.15, 1.2, 1.25$ and 1.3 m [23] as shown in figure 1(b). The electron density provided by the channel at $R = 1.05$ m is used to interpret the experimental results in the context. The MHD activity is measured by the poloidal and toroidal Mirnov arrays as well as the locked mode detectors (figure 1(a)), which consist of two saddle coils installed at two opposite toroidal locations outside the vacuum vessel, and the difference between two saddle coil signals gives the perturbations with odd toroidal mode number ($n = 1, 3, 5, \dots$). The edge toroidal rotation of CV impurity is measured by a multi-channel spectrometer [24].

Figure 1. (a) Structure and layout of the DRMP coils, poloidal Mirnov array, toroidal Mirnov array, and locked mode detector on the J-TEXT tokamak [22]. (b) Diagram of seven-channel FIR HCN interferometer system for electron density measurement, which views the plasma vertically at $R = 1.0, 1.05, 1.1, 1.15, 1.2, 1.25$ and 1.3 m on the low-field side (LFS).

For the experimental results presented below, two kinds of plasma conditions are adopted, and the corresponding plasma parameters are as follows unless otherwise noted: (I) *density limit condition*, major/minor radius (R_0/a) is 1.05 m/ 0.255 m, plasma current $I_p = 140$ kA, toroidal

magnetic field $B_t = 1.6$ T, the safety factor $q_a = 3.55$ at the plasma edge, the central chord line-averaged electron density at $R = 1.05$ m is ramped up in the range $3\text{--}6 \times 10^{19} \text{ m}^{-3}$ until disruption, and the Greenwald density limit is $n_G = I_p/\pi a^2 = 6.85 \times 10^{19} \text{ m}^{-3}$. (II) *low-q limit condition*, major/minor radius (R_0/a) is 1.05 m/ 0.255 m, the central chord line-averaged electron density at $R = 1.05$ m is around $1.0 \times 10^{19} \text{ m}^{-3}$, the toroidal magnetic field $B_t = 1.35\text{--}1.55$ T, the plasma current is ramped up from 180 kA to 215 kA after reaching its flattop, and the edge safety factor is lowered from $q_a = 2.65$ to 1.95. For all cases reported in this paper, an $m/n = 2/1$ TM grows quickly when approaching the high density or low-q limit, and it rotates in the counter- I_p direction with a frequency decreasing from 10 kHz to 2 kHz. The central plasma rotation is observed to be in the electron diamagnetic drift direction.

2.2. The effect of RMPs on density limit

A typical example of the density limit discharge is shown in figure 2 for shot 1033264 without the application of RMPs. The effective charge Z_{eff} is about 2.5 (figure 2(b)) measured by the spectrometer system. In the experiments, electron density is kept increasing by gas puffing. During the interval of $t < 0.32$ s, the line-averaged electron density n_e keeps increasing to $4.6 \times 10^{19} \text{ m}^{-3}$ (figure 2(a)), and there is a magnetic fluctuation with a frequency about 10 kHz (figure 2(b) and 1(d)). This magnetic fluctuation is found to be an $m/n = 2/1$ TM [25]. The toroidal rotation of CV impurity is $V_{\text{CV}} = -10$ km/s, here V_{CV} is the toroidal rotation at the radial location $r = 0.75\text{--}0.85a$, and the negative value of V_{CV} indicates the rotation in the counter- I_p direction. During the interval of $0.32 \text{ s} < t < 0.33 \text{ s}$, n_e is further increased to $4.7 \times 10^{19} \text{ m}^{-3} = 0.68 n_G$, and the magnetic fluctuation grows to an amplitude of more than 15 Gs as shown by the magnetic perturbation $\delta B_\theta^{n=1}$ in figure 2(b). Meanwhile the frequency of the precursor TM decreases from 10 kHz to 1 kHz, and mode locking and disruption happen shortly afterwards as shown by figure 2(d). And V_{CV} changes from the initial value of -10 km/s to a positive value in the co- I_p direction (figure 2(c)), which is similar to previous observation in mode penetration experiments in COMPASS-C [14]. In J-TEXT, the precursor TM is usually observed before density limit disruption, and the density limit is found to be less than $0.7n_G$.

Figure 2. Typical density limit disruption in J-TEXT. Time traces of (a) plasma current I_p (blue curve) and line-averaged electron density $\bar{n}_e$ (red curve), (b) effective Z_{eff} (blue curve) and $n = 1$ magnetic perturbation $\delta B_{\theta}^{n=1}$ (red curve), (c) toroidal rotation of CV impurity V_{CV} and (d) wavelet power spectrum of Mirnov signal.

Figure 3. Influence of static RMP on density limit. Time traces of (a) static RMPs current I_c , (b) line-averaged electron density $\bar{n}_e$, (c) plasma toroidal rotation of CV impurity V_{CV} , (d) $n = 1$ magnetic perturbation $\delta B_{\theta}^{n=1}$ for shots 1033264, 1033265 and 1033268, and detail evolution of $\delta B_{\theta}^{n=1}$ for shot (e) 1033265 and (f) 1033268.

In the following experiments, the static RMPs are applied before the onset of the precursor TM as shown in figure 3. The case without RMPs (shot 1033264) is also shown there for comparison. The static RMPs coil current (I_c) is turned on at $t = 0.26$ s, then ramping up to 2 kA in 0.02s for shot 1033265 and to 3.5 kA in 0.02s for shot 1033268 (figure 3(a)), respectively. During the application of a weaker static RMPs in shot 1033265, the core line-averaged electron density increases to $n_e = 5.05 \times 10^{19} \text{ m}^{-3} = 0.74n_G$, and then disruption happens at $t = 0.36$ s. When looking into the time evolution of $\delta B_{\theta}^{n=1}$ in figure 3(d) and 3(e), it is found that $\delta B_{\theta}^{n=1}$ is less than 2 Gs before disruption. In addition, the toroidal rotation V_{CV} decreases slightly from -10.5 km/s to -9.4 km/s before disruption. Compared to the case without RMPs (shot 1033264), for $I_c = 2$ kA the limit density is increased by 7.5% with the time of disruption being delayed by 30 ms. The amplitude of precursor TM is substantially suppressed, and the plasma rotation is reduced little. When a larger amplitude of static RMPs are applied for shot 1033268 with $I_c = 3.5$ kA at the flattop, the core density is further increased to $n_e = 5.25 \times 10^{19} \text{ m}^{-3} = 0.77n_G$, and the disruption occurs at $t = 0.38$ s. The time evolution of $\delta B_{\theta}^{n=1}$ in figure 3(d) and 3(f) show that there is no precursor TM until disruption, indicating that it is completely suppressed. Besides, toroidal rotation V_{CV} decreases from -10.1 km/s to -7.2 km/s. Comparing to the case without RMPs, the limit density is increased by 12% with the time of disruption being delayed by 50 ms. For both cases with RMPs, the disruptions are eventually caused by field penetration.

Figure 4. Effect of RMP amplitude on density limit. Time traces of (a) static RMPs current I_c , (b) plasma current I_p , (c) line-averaged electron density $\bar{n}_e$, (d) the locked mode detector signals b_r and (e) plasma toroidal rotation of CV impurity V_{CV} for shots 1033299 (blue), 1033285 (red), 1033287 (pink) and 1033289 (black).

The results shown in figure 3 verify that the static RMPs effectively suppress the precursor TM, increase the limit density and delay the occurrence of disruption for tens of *ms*. RMPs with a too strong amplitude, however, decreases the limit density and leads to earlier occurrence of disruption, as shown in figure 4. The static RMPs coil current (I_c) is 3 kA for shot 1033299, 3.5 kA for shot 1033285, 4 kA for shot 1033287, and 4.5 kA for shot 1033289. The disruption occurs during the ramp down phase of plasma current for shot 1033299. The density is $n_e = 5.1 \times 10^{19} \text{ m}^{-3}$ when the plasma current is 90 kA ($n_G = 4.4 \times 10^{19} \text{ m}^{-3}$), transiently exceeding the Greenwald limit. For shots 1033285, 1033287 and 1033289 shown in figure 4, field penetration occurs as indicated by the rapid growth of locked mode detector signal b_r (figure 4(d)). As a result the large magnetic island first causes the density to decrease [26], and then the current quench occurs 10-30 ms later. The time interval between these two time points are shadowed and marked by Δt_1 , Δt_2 and Δt_3 respectively ($\Delta t_1 = 35 \text{ ms}$). The plasma rotation is slightly decreased during the suppression phase of precursor TM with a rotation reduction $\Delta V_{CV} \sim 3 \text{ km/s}$, and plasma rotation reversion to the co- I_p direction after field penetration [14]. The results of figure 4 are summarized in table 1. RMPs results in lower limit density when $I_c > 3.5 \text{ kA}$. In table 1 the density for shot 1033299 is the maximum value during the flat-top of plasma current but not the one during the ramp down phase of plasma current. The wavelet power spectra of the Mirnov signal for these four shots are shown in figure 5, which shows that the precursor TM is partially suppressed for shot 1033299, completely suppressed for shots 1033285, 1033287 and 1033289.

Table 1. Summary of the parameters for the 4 shots corresponding to figure 4.

parameters shot No	$I_c(\text{kA})$	$n_e(\times 10^{19} \text{m}^{-3})$	n_e/n_G	Disruption time (s)	$V_{CV}(\text{km/s})$		
					Initial	During suppression	After penetration
1033299	3	5.7	0.83	0.57	-11.3	-8.1	2
1033285	3.5	5.15	0.75	0.45	-9.5	-6.8	11.4
1033287	4	4.4	0.64	0.36	-9.6	-5.9	11.5
1033289	4.5	3.5	0.51	0.28	-9.8	-4.6	12.7

Figure 5. Corresponding to figure 4, wavelet power spectrum of Mirnov signal for shots (a) 1033299, (b) 1033285, (c) 1033287 and (d) 1033289 are shown together with RMPs current I_c .

Figure 6. Ratio between n_e and Greenwald density n_G (red circles) and the disruption time (blue squares) versus static RMPs current I_c .

Systematical experiments have been carried out by keeping the background plasma parameters to be the same, while only the amplitude of static RMPs are changed by scanning I_c from 1 kA to 4.5 kA. In figure 6, n_e/n_G and the disruption time are shown as a function of I_c . The density is usually limited to $n_e < 0.68n_G$ and disruption happens at $t < 0.33$ s without the application of static RMPs. Both the limit density and disruption time linearly increase with I_c for $I_c \leq 3$ kA. Static RMPs increase the limit density to more than $0.8n_G$, and the disruption is delayed by 30 ms to 100 ms for $I_c = 3$ kA. However, even stronger RMPs do not lead to a further increase in the limit density

but a decrease in it with an earlier disruption. The limit density decreases from about $\sim 0.8n_G$ to $0.5n_G$ when I_c increases from 3 kA to 4.5 kA. It should be noted that the intrinsic 2/1 error field in J-TEXT is measured to be 0.3 Gs at the plasma edge $r = a$ [27], being much weaker than applied static RMPs (ranging from 2.5 Gs to 11 Gs), and the toroidal phases of intrinsic error field (317°) and static RMPs (290°) are close. Therefore, the increased limit density is not due to the correction of error field. The maximum density is obtained due to the presence of static RMPs with an appropriate amplitude ($I_c = 3$ kA).

2.3. The effect of RMPs on low- q limit

Similar to the results presented in section 2.2, static RMPs are also applied in the low- q discharges. In order to approach the low- q limit, the plasma current is ramped up slowly for 100 ms after reaching its first flat-top at $I_p = 180$ kA. The experimental results without RMPs are shown in figure 7 with the toroidal magnetic field $B_t = 1.55$ T and 1.35 T for shots 1037639 and 1037647, respectively. It is seen that disruption does not happen for shot 1037639 with minimum $q_a = 2.2$, and there is no obvious precursor TM in $\delta B_\theta^{n=1}$. While for shot 1037647, disruption happens when q_a approaches 2.15. The time evolution of $\delta B_\theta^{n=1}$ reveals that an $m/n = 2/1$ precursor TM is excited just before the disruption, and the mode frequency is around 10 kHz, being similar to that of density limit discharges. In J-TEXT, the precursor 2/1 TM is often observed in low- q limit disruption, and the limit q_a is found to be around 2.15-2.2.

Figure 7. Typical low- q discharges in J-TEXT. Time traces of (a) plasma current I_p (solid curves) and toroidal field B_t (dashed curves), (b) edge safety factor q_a , (c) $n = 1$ magnetic perturbation $\delta B_\theta^{n=1}$ for shots 1037639 (blue) and 1037647 (red), and (d) wavelet power spectrum of Mirnov signal for shot 1037647.

Figure 8. Influence of static RMP on low- q discharge. Time traces of (a) edge safety factor q_a , (b) static RMP current I_c and (c) $n = 1$ magnetic perturbation $\delta B_\theta^{n=1}$ for shots 1037647, 1037645 and 1037649.

Figure 8 shows the effect of static RMPs on low- q discharges for shots 1037645 and 1037649. The static RMPs is applied when q_a decreases to 2.2 with $I_c = 2$ kA at the flat-top. Compared to the case without RMPs (shot 1037647), disruption does not occur for shot 1037645 with a lower q_a , $q_a = 2.1$. For shot 1037649, disruption happens until q_a approaching 2.0. The evolution of $\delta B_\theta^{n=1}$ just

before disruption shown in figure 8(c) reveals that the precursor TM is also completely suppressed. The results shown in figure 8 reveal that static RMPs can lower the low- q limit from 2.15 to 2 and suppress the precursor TM. Additional studies have also been carried out to look into the effect of RMPs amplitude, it is found that lowest q_a , $q_a = 2$ is approached for $1 \text{ kA} \leq I_c \leq 2.5 \text{ kA}$, while stronger RMPs trigger the disruption at higher q_a . However, the $q_a = 2$ limit has never been overcome. The required amplitude of RMPs to complete suppress precursor TM for low- q discharges is smaller than that of density limit discharges, since the $q=2$ is closer to plasma edge in this case.

3. Discussion and summary

The effect of resonant magnetic perturbations (RMPs) on high density limit and low- q limit discharges is studied in J-TEXT tokamak. It is found that a moderate amplitude of applied RMPs increase the density limit from less than $0.7n_G$ to more than $0.8n_G$ for $I_c \leq 3 \text{ kA}$, and the disruption is delayed by about 30 ms to 100 ms. The disruptive precursor is suppressed with a little change in toroidal rotation. A too large amplitude of RMPs with $I_c > 3.5 \text{ kA}$, however, leads to a lower density limit and an earlier occurrence of disruption. For the optimal RMPs amplitude with $I_c = 3 \text{ kA}$, $n_e = 0.83 n_G$ is achieved, and the disruption is delayed by about 150 ms. The toroidal plasma rotation of CV impurity decreases a little during the suppression phase of precursor TM with $\Delta V_{CV} \sim 3 \text{ km/s}$. For low- q discharges, the applied static RMP can either lower the edge safety factor q_a from 2.15 to nearly 2.0 or sustain stable plasma discharge with $q_a = 2.1$, and the disruptive precursor is also suppressed.

These experimental results are consistent with the mechanism of TM stabilization by static RMPs described in section 1. In the high density limit and low- q limit discharges on J-TEXT tokmark, the disruptions are caused by the growth of the TM and subsequent mode locking, similar to the observations from other tokmarks. A moderate amplitude of RMP delays the disruption because it has a stabilizing effect on the rotating TM, as seen from the experimental results. A too large amplitude of the RMP, however, will lead to field penetration (locked mode) and therefore an earlier disruption, even if the precursor TM is stabilized.

The studies presented in this paper reveal several features and possible applications of externally applied RMPs. Firstly, the optimal amplitude of RMPs to obtain the maximum density or minimum q_a is not zero, indicating that a finite amplitude of error field (or RMPs) is in fact stabilizing in these cases. Secondly, together with the disruption prediction system, static RMPs can be utilized for delaying the disruption, to allow more time ($\sim$ tens - 100 ms) for disruption mitigation by using, e.g., massive gas injection. Thirdly, as static RMPs can effectively suppress the rapid growth of TM instability, it might also be able to suppress the growth of NTM (neoclassical TM) [28] seed island if RMPs is applied in its early growing phase. Fourthly, the amplitude of RMPs to excite field penetration in density limit discharge is lower than the error field penetration threshold observed in J-TEXT before [25], indicating that the field penetration threshold depends on other plasma parameters in addition to the plasma density.

RMPs has been used to suppress the runaway electron beam on TEXTOR [29, 30], and it is also proposed for runaway mitigation on ITER [31, 32]. It is possible to both delay the disruption and suppress the runaway electron by applying an appropriate waveform of RMPs.

It should be noted that the static RMPs are applied much earlier before the growth of precursor TM in our experiments, because the magnetic feedback has not been utilized in the presented experiments. In addition, during the application of static RMPs, a discharge with higher and stable electron density has not been tried except for shot 1033299, and this will be carried out in the future experiment.

In summary, static RMPs are used to influence the disruption limit and control disruption precursors in both density limit and low- q limit discharges in J-TEXT Ohmic plasmas. The major results are as follows:

- (1) A moderate amplitude of applied RMPs increases the density limit and delays the disruption. The disruption precursor is suppressed with a slight reduction in toroidal plasma rotation. A too large amplitude of RMPs, however, leads to a lower density limit and an earlier disruption. For the optimal RMPs amplitude, the disruption is delayed by about 150 ms.
- (2) By applying a moderate amplitude of RMPs, the edge safety factor q_a is lowered from 2.15 to 2.0.
- (3) Precursor 2/1 TM is effectively suppressed for both density limit and low- q limit discharges.
- (4) The toroidal plasma rotation V_{CV} is slightly decreased in the suppression phase of precursor TM with $\Delta V_{CV} \sim 3 \text{ km/s}$.

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