Letter

Enhancement of runaway production by resonant magnetic perturbation on J-TEXT

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Abstract
The suppression of runaways following disruptions is key for the safe operation of ITER. The massive gas injection (MGI) has been developed to mitigate heat loads, electromagnetic forces and runaway electrons (REs) during disruptions. However, MGI may not completely prevent the generation of REs during disruptions on ITER. Resonant magnetic perturbation (RMP) has been applied to suppress runaway generation during disruptions on several machines. It was found that strong RMP results in the enhancement of runaway production instead of runaway suppression on J-TEXT. The runaway current was about 50% pre-disruption plasma current in argon induced reference disruptions. With moderate RMP, the runaway current decreased to below 30% pre-disruption plasma current. The runaway current plateaus reach 80% of the pre-disruptive current when strong RMP was applied. Strong RMP may induce large size magnetic islands that could confine more runaway seed during disruptions. This has important implications for runaway suppression on large machines.

Keywords: runaway electron, disruption, resonant magnetic perturbation

(Some figures may appear in colour only in the online journal)

1. Introduction

The prevention and mitigation of damage due to disruptions are essential to the reliable operation of International Thermonuclear Experimental Reactor (ITER) due to the high thermal and poloidal magnetic energy content of the plasma [1–3]. Both heat loads and electromagnetic force have been mitigated using a moderate amount of massive gas injection (MGI) of impurities in current machines [4, 5]. It is generally thought that the heat load and halo current reduction capabilities of MGI shutdown will scale well to ITER. The required Rosenbluth density for the complete suppression of runaway electrons (REs) has not yet been reached. MGI prior to current quench is estimated to be insufficient to completely suppress REs by collisions in ITER disruptions. A severe consequence of a disruption on ITER could be the generation of a 10 MA RE beam with energies of several tens of MeV that could damage the vacuum vessel and the structure of the machine if it hits the wall unmitigated [6]. The avoidance and mitigation of REs during disruptions are critical issues for ITER.

It has been proved that magnetic perturbation can be a potential tool for the suppression of REs [7–10]. Externally applied magnetic perturbation has been used to reduce the runaway avalanche
during disruptions on JT-60U and Tokamak Experiment for Technology Oriented Research (TEXTOR) [7, 11]. The experiment conducted on JT-60U showed that when the magnetic perturbation with $mn = 3/2$ mode is strong enough, the runaway avalanche can be suppressed during disruptions. Resonant magnetic perturbation (RMP) with $n = 1, 2$ has been applied on TEXTOR disruption plasmas [11]. The disruptions with a stable runaway current plateau were initiated by moderate Ar MGI. The runaway plateau was shortened and decreased when RMP with $n = 1$ or $n = 2$ was powered during disruptions. This indicates that the runaway avalanche was suppressed by RMP.

The effect of RMP on runaway production during disruptions was investigated on J-TEXT. In this letter we report that the first experimental observations suggest that runaway suppression by RMP may not hold in general. It is shown that runaway production could be enhanced by the application of RMP.

2. Experimental setup

J-TEXT is a conventional tokamak with an iron core [12]. It has a major radius of $R = 105$ cm. The minor radius is $25.5$ cm. The maximum toroidal magnetic field is $B_T = 2.3$ T. The maximum plasma current is $I_p = 220$ kA with 600 ms pulse length. The line averaged electron density is in the range $n_e = (1−5) \times 10^{19}$ m$^{-3}$. A MGI valve has been developed for the study of fast shutdown experiments [13]. The MGI valve is located at the bottom of port 9, and about 0.5 m away from the plasma boundary. The penetration process of the gas jet from the plasma boundary to the core was monitored by a fast frame camera with tangential view. Soft x-ray (SXR) was used to monitor the formation of a runaway beam during disruptions [14]. The lost REs were monitored by hard x-ray (HXR) diagnostics. In-vessel RMP coils were developed to study the effect of RMP on the plasma response on J-TEXT [15]. The RMP coils are located at the low field side. The in-vessel RMP coils can induce $mn = 2/1$ or $mn = 3/1$ dominated magnetic perturbation by changing the connection of the power supply. In this experiment, $mn = 2/1$ dominated magnetic perturbation was applied. The line averaged RMP coils could be energized to 6 kA, which produced a 15 Gs $mn = 2/1$ mode. The relative perturbation of 6 kA RMP was about $\delta B/B_T = 6.8 \times 10^{-4}$ with $B_T = 2.2$ T.

3. Experimental results

In this experiment, the target ohmic plasmas with circular cross section had toroidal magnetic field $B_T = 2.2$ T, the plasma current was $I_p = 180$ kA, and the line averaged electron density was about $n_e = 1.0 \times 10^{19}$ m$^{-3}$. The edge safety factor $q_0$ was about 4. The disruption was initiated at 0.4 s by the injection of argon atoms via the MGI valve. Reproducible runaway current plateaus were deliberately generated by $5 \times 10^{10}$ argon atom injection.

The effect of RMP with $mn = 2/1$ mode ($m$ and $n$ are the poloidal and toroidal mode numbers, respectively) on runaway current generation was investigated on J-TEXT with internal RMP coils. The typical waveforms of the argon induced runaway current plateau are shown in figure 1. The plasma was disrupted in 2 ms due to the argon injection. According to the measurements using a fast frame camera with a filter, it was found that the gas jet reached the plasma boundary in 1 ms. The cold front induced by the gas jet penetrated from the plasma boundary to the $q = 2$ surface where it initiated MHD activities and resulted in thermal quench (TQ). The current quench started at 2.5 ms with about 100 MA s$^{-1}$ quench rate. Above 100 V a loop voltage was produced during the current quench phase. At about 67 kA a runaway current plateau was formed by this scenario. The runaway current plateau lasted about 15 ms. The runaway beam was monitored by SXR during the runaway current plateau phase since SXXs are dominated by the interaction between REs and impurities. The runaway current was lost to the first wall at the end. The amplitude of the runaway current plateau formed by this scenario was in the range 60−100 kA with constant Ar injection. With the same plasma parameters and an equal amount Ar injection, a 60 ms RMP pulse with a 5 Gs ($\delta B/B_T = 2.3 \times 10^{-4}$) $mn = 2/1$ component was applied 20 ms before the firing of the MGI. The waveforms of the discharge are shown in figure 2. A significant reduction in the runaway current plateau and the runaway current length was observed with the application of RMP. The small amplitude of the SXR during the runaway current plateau indicates that the runaway current is also lower. The amplitude of the runaway current plateau decreased to about 35 kA. The length of runaway current plateau decreased from 10 ms to about 6 ms. This indicated that RMP has the ability to suppress runaway generation during disruption, as demonstrated on several devices [7, 11]. Induced RMP can enhance the runaway loss rate.

When the amplitude of RMP was increased to a higher level, the runaway current was enhanced instead of suppression. The typical waveforms of the enhancement of the runaway current plateau by strong RMP are shown in figure 3. With the same plasma parameters and equal amount of argon injection, 60 ms RMP with 10 Gs ($\delta B/B_T = 4.5 \times 10^{-4}$)
m/n = 2/1 component was applied 20 ms before the firing of the MGI. The argon MGI that induced disruption was initiated at 2.5 ms with similar current quench rate, soon followed by a high runaway current plateau. The enhancement of SXR emissions during runaway current plateau indicates that the runaway current is significant. The runaway current plateau reached 145 kA, which is about 80% of the pre-disruption plasma current.

The amplitude of the RMP with m/n = 2/1 mode was scanned in the range 4–13 Gs to study the effect of RMP on runaway production. The conversion efficiency of the predisruptive plasma current into runaway current with RMP is shown in figure 4. With 4–8 Gs RMP, there is a trend that the runaway plateaus are reduced by the application of RMP. Although there are two shots with complete runaway suppression at 8 Gs RMP, most of them are partial runaway suppression. When the applied m/n = 2/1 RMP increased to above 10 Gs (δB/Br = 4.5 × 10⁻⁴), the runaway current plateaus roll over to higher amplitudes. The largest runaway current is much higher than that without the application of RMP.

The conversion of predisruptive plasma current into runaway current is usual in the range of 30%–60% in an ohmic target without the application of RMP. This is consistent with other machines. With moderate amplitude of RMP (m/n = 2/1) the conversion of predisruptive plasma current into runaway current decreased to below 30% due to the partial suppression of the runaway avalanche process. While the maximum runaway current conversion efficiency up to 80% was reached when 10–13 Gs m/n = 2/1 magnetic perturbation has been applied during the disruption phases. The relative perturbation of RMP is about δB/Br = (4.5–5.9) × 10⁻⁴.

4. Discussions

Runaway production is determined by the primary generation process, hot tail generation process and secondary generation process [6]. The primary generation and the hot tail processes act as the runaway seed, which is amplified by the secondary process. The avalanche gain scales as the exponential of the initial plasma current, exp(2.5Ip (MA)) [5]. In this experiment the factor that affected the amplitude of the runaway current plateau was the confinement of the runaway seed population.

In ohmic target disruptions with the same predisruptive plasma current, the conversion efficiency of predisruptive plasma current into runaway current mainly depends on the plasma current quench rate, which determines the amplitude of the toroidal electric field. The high loop voltage may result in higher primary generation rate. The loop voltage is measured by an external flux loop, which would not capture significant changes in the internal electric field that may occur during the TQ. A comparison of the current quench rate and
the amplitude of the loop voltage for different RMP amplitudes is shown in figure 5. It is found that both the initial disruption time and the initial current quench rate were not affected by the application of RMP. The disruption time is determined by the amount of Ar injection. The time traces of current quench overlap very well before the formation of the runaway current plateau. This indicates that RMP has no effect on the current quench rate, even with the strongest RMP. Since the initial current quench rate is almost the same, the behavior of the loop voltage before the formation of the runaway current plateau is also similar. Surprisingly, the amplitudes of the runaway current plateaus are different with the same plasma current derivative. For the target No. 1039533, the loop voltage increased to about 130 V. After the formation of the runaway current, the loop voltage decreased to a low level due to the replacement of ohmic plasma current by the runaway current. With the partial suppression of runaway generation in discharge No. 1039527, the high loop voltage persisted for a longer time due to the lower runaway current. For discharge No. 1039535 the time trace of the loop voltage before it reach the top is same as that without RMP. The amplitude of the loop voltage is lower than that without RMP or with moderate RMP. The formation of a runaway current at an early time indicates a better confinement of runaway seed with strong RMP field.

The confinement of runaway seed in the magnetic islands can provide a possible explanation for the enhancement of a runaway plateau with strong $m/n = 2/1$ RMP. The REs can be confined well by the large magnetic islands as observed on TEXTOR-94 [16]. The RE seed can be confined well by the intact magnetic islands during disruptions. The typical Poincaré section of the magnetic islands in the presence of the 4 kA $m/n = 2/1$ mode dominated RMP is shown in figure 6. It is based on the vacuum field calculation. In the plot shown in figure 6, mixed topological structures are observed: a large intact area at the $q = 2$ surface and a series of stable magnetic islands embedded in the stochastic layer at the boundary. The rapid TQ will result in a large population of runaway seed. The runaway seed could be lost rapidly in stochastic magnetic field. With moderate RMP amplitude, the stochastic magnetic field contributes to the runaway seed loss rate significantly. Thus the runaway plateau is lower. With increasing RMP amplitude, larger magnetic islands could be formed near the resonant surface inside the plasma in post-TQ plasmas. The runaway seed that remained in the magnetic islands are less sensitive to the magnetic turbulence due to the good topological structures. Therefore, more runaway seed can survive and lead to a higher runaway current plateau.

The NIMROD (non-ideal MHD with rotation, open discussion) extended MHD code [17] was used to model the effects of applied 3D fields on RE confinement in DIII-D plasmas. In these simulations, a TQ was initiated by the deposition of argon impurities, resulting in Ar radiation cooling. During the MHD evolution, drift-orbits for a test population of REs were calculated to determine the confinement of the REs as the flux surfaces were destroyed during the TQ phase. A detailed description of the model used, including the incorporation of impurity radiation and RE test particles into NIMROD can be found in [18], in which several simulations of Alcator C-Mod, DIII-D and ITER plasmas were presented showing the effects of plasma shape, impurity deposition profile, and machine size on RE confinement. Further DIII-D simulations [19] demonstrated a correlation between the NIMROD RE confinement results, and the experimentally measured RE current amplitude over a set of diverted DIII-D
discharges terminated by Ar pellet injection. Although [18, 19] did not present results in which 3D fields were applied prior to the TQ, the results of three such DIII-D simulations are shown in figure 7. In these simulations, RMP fields were applied corresponding those produced by the DIII-D I-Coils (two rows of six internal coils) [20] carrying 4 kA of current. Magnetic fields with \( n = 1, n = 2 \) and \( n = 3 \) symmetry were applied in the three cases, respectively. It was found that in no case did the application of RMP fields enhance the loss of REs during the TQ, and in some cases the confinement of REs was improved. The application of RMP fields altered the toroidal spectrum of unstable modes in such a way that a larger region of closed flux in the core survived the destruction of flux surfaces during the TQ. With the application of strong \( m/n = 2/1 \) RMP, more runaway seed can survive and be amplified by the avalanche process, which led to a higher runaway current plateau. The control of edge localized modes by RMP is a routine method in large scale machines. The application of RMP in an edge localized mode mitigation scenario may have an important effect on runaway production during disruptions. It may result in the enhancement of runaway production when the magnetic islands are formed by RMP in post-TQ phase.

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