Loss of Pre-disruptive Runaway Electrons by Magnetic Perturbation and Its Effect on Plasma Disruption

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\textbf{Abstract.} It is observed that a loss of pre-disruptive runaway electrons can induce a rapid radiative cooling of the plasma, by generating the impurity cloud from the first wall. The synchrotron infrared image showed that the loss of runaway electrons occurs from the edge region when a resonant magnetic perturbation is applied on the plasma. When the impact of the runaway electrons on the wall is strong enough, a sudden drop of the plasma temperature occurs with the characteristic plasma behaviors such as the positive spike and following decay of the plasma current, \textit{D}\textit{\alpha} spike, big magnetic fluctuation, etc. The visible images at this runaway spike showed an evidence of the generation of impurity cloud and the following radiative cooling. Considering the localized feature of the runaway orbits, a localized impact on the runaway orbit could induce the radiative cooling of the plasma, without global destruction of the magnetic structure up to the core.

1. Introduction

In a recent study in Korea Superconducting Tokamak Advanced Research (KSTAR) on the behavior of runaway electrons near ohmic plasma disruptions \cite{1}, it was observed that the loss of pre-disruptive runaway electrons frequently precedes the abrupt drop of the plasma temperature, i.e., the thermal quench, suggesting a close relationship between the behavior of runaway electrons and the disruption procedure. In one of the typical low-q disruptions, the runaway electrons localized on the \(q=2\) drift surface, which could be identified from the \(m/n=2/1\) magnetohydrodynamics (MHD) pattern in the photoneutron signal, are observed to be expelled from the confinement making a typical two-stage thermal quench \cite{2-4} trace. The first feature of the observation, the localization of runaway electrons on the rational \(q\) drift surfaces has been found not only in KSTAR, but in various devices such as TEXTOR \cite{5,6}, EAST \cite{7}, and J-TEXT \cite{8}, thus believed to be one of the general features of runaway electrons. The second feature, the two-stage thermal quench could be explained with the impurity influx model \cite{4}, where the first stage attributes to the particle loss in an ergodized magnetic structure, and the second stage to the radiative cooling by the massive influx of impurities generated by the heat flux on the first wall during the first stage. In order to generate the collective neutral impurity atoms 'impurity clouds', those can penetrate and cool down the plasma on a timescale of a few hundred microseconds, a localized impingement of energetic particles on the first wall is necessary to evaporate massive impurities in a small area with a neutral pressure much higher than the plasma pressure.

Based on this model, the strong correlation between the loss of runaway electrons and the energy loss during the first stage of the thermal quench observed in KSTAR suggests that the impingement of the runaway electrons on the first wall can generate impurity clouds thus can induce the fast radiative cooling, known as the second stage of the thermal quench. One special feature of the radiative cooling induced by the loss of runaway electrons would be that the localized impact on the runaway orbit could induce it when the runaway electrons are
localized on a certain drift surface, while an ergodization of magnetic structure up to the core is essential for runaway-absent plasmas. In order to investigate the possibility of the runaway-induced radiative cooling, plasma behaviors were observed while removing pre-disruptive runaway electrons artificially by generating perturbed magnetic field structure near the plasma edge. Experimental methods and observation results in KSTAR tokamak are reported here.

2. Experiments

2.1. Experimental Methods

KSTAR is a superconducting tokamak with the plasma size of 1.8m in major radius and 0.5m in minor radius [9,10]. Owing to the field error correction (FEC) coils installed in the vacuum vessel of KSTAR [11], mainly being used for the suppression of edge localized modes during H-mode plasma operations [12], a resonant magnetic perturbation (RMP) field can be applied on the edge of the plasma. FEC coils consist of three poloidal loops (top, middle, and bottom FECs) and 4 toroidal loops, thus can provide n=1 and n=2 toroidal modes with different toroidal phases between poloidal FEC coils. Figure 1 shows Poincaré plots of magnetic field structure in vacuum condition without RMP current (Figure 1 (a)) and with the RMP current of 4 kA \cdot turn in n=1 toroidal mode (Figure 1 (b)). Stochastic magnetic structure is formed on the edge region of plasma by RMP thus a loss of runaway electrons through the ergodized field is expected when they had located in this region.

![FIG. 1. Poincaré plots of vacuum field (a) without RMP and (b) with RMP current of 4 kA \cdot turn in n=1 toroidal mode.](image)

Plasma behaviors were observed while applying RMP on the plasmas containing pre-disruptive runaway electrons. Previous studies [13-16] predict that the rapid loss of runaway electrons will occur when the magnetic perturbation \( \delta B/B \) becomes larger than \( 10^{-3} \) at the runaway locations, starting from the edge region of the plasma as increasing the RMP current. Main diagnostic to detect runaway loss was Cherenkov neutron detector (CND) [17], which was proven to be very effective in detecting photoneutrons generated by the runaway electrons hitting the first wall. The infrared (IR) and Visible cameras [18,19] were used to check the distribution of the runaway electrons in the plasma before the loss, and to find the evidence of the runaway-induced radiative cooling, respectively.
2.2. Location of Runaway Electrons

In the previous study [1], the location of runaway electrons could be identified by the MHD pattern in the neutron signal, which was in phase with m/n=2/1 tearing mode, concluding they were locating on the q=2 drift surface as a form of ‘runaway snake [5,6]’. Synchrotron radiation image obtained by the IR camera frequently shows the evidence of the runaway localization on the rational q drift surface. Figure 2 shows IR images of synchrotron radiation emitted by runaway electrons in a plasma shot #15603. At t=2.0s (Figure 2 (a)), a ring-shaped IR image is formed near the plasma edge where the q=2 and q=3 magnetic surfaces are located. EFIT-calculated locations of q=2 and 3 surface at this time were r/a=0.75 and 0.93, respectively. This ring shape near the plasma edge is the most common runaway distribution found in KSTAR, which is beneficial for the runaway removal experiments using RMP. At t=6.6s of the same discharge (Figure 2 (b)), the locations of the q=2 and 3 surface were changed to r/a=0.24 and 0.46, respectively. It is noted that the runaway distribution is changed into coaxial shape, i.e., one ring containing a central spot, following the shape of changed magnetic surfaces. This characteristic ‘ring’ or ‘coaxial’ shape of IR images supports the idea that runaway electrons are located mainly on the rational q drift surfaces, changing the position or the shape according to the evolution of the magnetic field structure during a discharge.

![IR images of synchrotron radiation emitted by runaway electrons in plasma shot #15603 at (a) t=2.0s and (b) t=6.6s.](image)

2.3. Soft Loss of Runaway Electrons

Figure 3 shows an example where the runaway loss occurred by RMP. In this shot the RMP current was applied in n=1 mode on the top row of coils. The RMP current was slowly increasing with the rate dI_{RMP}/dt=1 kA · turn/sec and a sudden loss of runaway electrons was detected by CND at t=3.92s when the RMP current reached I_{RMP}=2.9 kA · turn. During the runaway loss a slight decrease in the plasma current of about 1.5 kA was detected possibly due to the loss of runaway current. One of the typical features of the runaway loss is the temperature decrease measured by the electron cyclotron emission (ECE) radiometer, mainly
due to the removal of suprathermal effect in the ECE measurement, which could also be identified during a ‘natural’ disruption [1]. In this shot ECE temperature near the edge was about 0.85 keV before the runaway loss and a decrease of about 0.35 keV occurred by the loss. Although there was no clear evidence of radiative cooling induced by the runaway impact could be found, a slight increase of the Dα signal indicates that there was an impact of runaway electrons on the first wall when the loss was occurring. No clear magnetic fluctuation was detected during the loss.

![Plasma parameters during the loss of runaway electrons in shot #16117.](image)

**FIG. 3.** Plasma parameters during the loss of runaway electrons in shot #16117.

![IR images of synchrotron radiation in shot #16117.](image)

**FIG. 4.** IR images of synchrotron radiation in shot #16117 (a) before, (b) during, and (c) after the runaway loss.

Figure 4 shows the IR images of runaway distribution (a) before, (b) during, and (c) after the runaway loss. It could be identified that runaway electrons were locating from the core to the edge before the runaway loss occurred. EFIT calculation shows q=1, 2, and 3 are located at r/a=0.01, 0.66, and 0.84, respectively at this time. During the runaway loss (Figure 4 (b)), the size of IR emitting area was reduced, shrinking to the core region. It is interesting to note that parts of the runaways were still remaining in the plasma making a crescent-shaped IR emission on top of the main emitting area. This crescent IR image also supports the assumption that runaways are located mainly on a certain narrow orbit, not in a continuous
distribution across the plasma. After the total loss of the runaways on that orbit, no longer the crescent IR image could be found (Figure 4 (c)). Judging from the size change of the IR emission and also from the location of the crescent IR image, it seems only the runaway electrons on the \( q=3 \) drift surface was removed by RMP. It also confirms the previous prediction \([13-16]\) that the runaway loss will rapidly occur from the edge region when the magnetic perturbation reaches a certain level.

2.4. Runaway Spike

Figure 5 shows another example where the runaway loss occurred by RMP. The RMP current was applied in \( n=1 \) mode on the top row of coils, same configuration with the previous example, and was slowly increasing with the rate \( \frac{dI_{RMP}}{dt} = 1.4 \text{ kA} \cdot \text{turn/sec} \). In this shot the behavior of runaway electrons can be classified in several phases.

a) Runaway electrons were generated in the early phase of the discharge. Slow increase of the neutron signal is observed during \( t = 0.7 - 1.5 \text{ s} \).

b) Runaway electrons were stably confined in the plasma without a noticeable neutron signal change during \( t = 1.5 - 2.6 \text{ s} \). No effect of RMP is observed.

c) Slight increase and small perturbation in the neutron signal is found from \( t = 2.6 \text{ s} \), when the RMP current reaches \( I_{RMP} = 2.1 \text{ kA} \cdot \text{turn} \). It seems RMP started to affect the transport of the runaway electrons from this phase. Still no noticeable effect can be found in other plasma parameters.

d) Sudden increase of the runaway loss which can be identified from the burst of neutron signal occurred from \( t = 3.0 \text{ s} \), when the RMP current reached \( I_{RMP} = 2.8 \text{ kA} \cdot \text{turn} \). The plasma showed similar behavior with the one during the ‘soft loss’ in the previous example, e.g., slight decrease of the plasma current, significant decrease of the plasma temperature, slight increase of the \( D\alpha \) signal, etc.

e) Very strong neutron spike was generated at \( t = 3.36 \text{ when the RMP current reached } I_{RMP} = 3.3 \text{ kA} \cdot \text{turn} \). Positive spike and decay in the plasma current, abrupt drop in the plasma temperature, sudden and strong increase in the \( D\alpha \) signal, and a big magnetic fluctuation were followed right after the neutron spike. More exactly, the neutron spike started at \( t = 3.36615 \text{ s} \) lasting for about 300 microseconds, and the abrupt temperature drop initiated at \( t = 3.36695 \text{ s} \), about 800 microseconds after the initiation of the neutron spike. In order to discriminate from the soft loss before the neutron spike, the runaway loss in this phase can be called as ‘runaway spike’.

f) Neutron signal disappears and the plasma recovers from the impact of the runaway spike. The plasma temperature, which had dropped to a few hundreds of eV, recovered to the value before the runaway spike in about 50 ms. The plasma current, which had been 610 kA before the runaway loss could not fully recover even after the temperature recovery and saturated to the level of about 520 kA, meaning the runaway current of about 90 kA was lost by the runaway spike.

Figure 6 shows the visible images of the plasma near the runaway spike. Figure 6 (a), (b), and (c) are three consecutive frames before, during, and after the neutron spike, respectively, and Figure 6 (d) shows the plasma image after the runaway spike event. In Figure 6 (a), when the soft loss was occurring, radiation noises on the camera pixel are found as an evidence of the impingement of runaway electrons on the first wall. In Figure 6 (b), the radiation noise is dramatically increased as an evidence of the runaway spike. This frame also includes the localized emission of reddish glow near the upper outboard region of the plasma, strongly suspected as an evidence of the impurity cloud. In the next frame (Figure 6 (c)), bright emission of the visible light all over the plasma column is found due to the radiative cooling.
At this time the sudden drop of the plasma temperature was observed in the ECE measurements. Note that there is no radiation noise anymore indicating the runaway loss is completed. Figure 6 (d) shows the plasma recovering from the runaway spike meaning that the magnetic structure of the core region was not destructed by the RMP application or the runaway spike.

![Graph](image)

**FIG. 5.** Plasma parameters during the loss of runaway electrons in shot #12870.

![Images](image)

**FIG. 6.** Visible images of the plasma near the runaway spike: (a), (b), and (c) are three consecutive frames before, during, and after the neutron spike, respectively, and (d) shows the plasma image after the runaway spike event, at t=3.5s.
2.5. Summary and Discussion

It is observed that the loss of runaway electrons can be induced by applying RMP, with the characteristic plasma responses such as the decrease in the plasma current, increase in the temperature and D$\alpha$ signal, etc. Synchrotron IR image showed the runaway loss was occurring from the edge region of the plasma. When this ‘soft loss’ is occurring by RMP, the plasma behavior is basically the same with the one during the first stage of the thermal quench in a natural disruption, in terms of the removal of suprathermal effect in the temperature measurement by the loss of runaway electrons in the plasma.

When the impact of the runaway electrons on the wall is strong enough, a sudden drop of the plasma temperature occurs with the characteristic plasma behaviors such as the positive spike and following decay of the plasma current, D$\alpha$ spike, big magnetic fluctuation, etc. Observation results during this ‘runaway spike’: a) temporal coincidence of the neutron spike and the localized impurity glow in the visible image, b) the neutron spike followed by the temperature drop in 800 microseconds, which can be interpreted as a time necessary for the impurity cloud to penetrate to the core, and c) temporal coincidence of the temperature drop and the strong emission of visible light, supports the impurity influx model as a possible cause of the plasma behaviors. This runaway spike phase is analogous to the second stage of the thermal quench in a natural disruption, in terms of the rapid radiative cooling of the plasma induced by the impurity influx. The only difference of the runaway spike from the conventional impurity influx model is that it is the runaway electrons that hits the first wall and makes an impurity cloud, instead of thermalized electrons. Considering the localized feature of the runaway orbits, it can be deduced that a localized impact on the runaway orbit can induce the radiative cooling of the plasma, without global destruction of the magnetic structure up to the core, which can be supported by the observation of the plasma recovery after the RMP application or the runaway spike.

3. Conclusion

It is shown that a sudden temperature drop by the radiative cooling can be induced by the loss of the runaway electrons confined in the plasma. Due to the localized feature of the runaway electrons on a certain orbit, it is possible to induce the radiative cooling only with the localized impact on the runaway orbit, contrary to the conventional concept that a global destruction or the ergodization of the magnetic surface to the core is essential to induce such a cooling. Even though the radiative cooling induced by the runaway loss does not necessarily lead to the termination of the discharge, it can give a bad impact on the machine integrity by making a damage on the in-vessel material, or by giving a heavy electromagnetic load on the vessel. Or, there is a possibility that the runaway loss accelerates a disruption process through the radiative cooling, otherwise the impact on the machine could be much milder. Therefore, it would be important to remove pre-disruptive runaway electrons in the plasma as well as the post-disruptive runaway electrons to avoid a bad impact on the machine integrity during a hard disruption.
Appendix 1: References


