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Characteristics of Runaway Plasmas in JT-60U

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1. Introduction

It is well known that relativistic runaway electrons can be generated during a tokamak disruption [1], and the plasma facing components would be damaged if the localized and intense irradiation of runaway electrons occurs. In order to mitigate the post-disruption runaway electrons with good controllability, experiments has been carried out with external actuators such as impurity pellet injection [2]. On the other hand, it has been pointed out that the current quench time is extended by the appearance of runaway electrons [3]. This fact suggests that runaway electrons can be used to mitigate or avoid the current quench when the safe and reliable control of runaway electrons is available. Standing on such a point of view, the experiment for avoiding the current quench by runaway electrons has been carried out. To study the dynamics of runaway electrons precisely, a new active and direct diagnostic concept using the laser inverse Compton scattering has been proposed [4].

2. Mitigation of post-disruption runaway electrons by external actuator

A series of impurity neon pellets (2.1 mm cube, ~700 m/s, low field side injection [5]) were injected into an Ohmic hydrogen discharge (I_p=0.85 MA, B_t=3.73 T, a~1 m, R_p~3.5 m, $n_e(0)$~1x10^{19} m^{-3}, $T_e(0)$~2.3 keV) as shown in Fig.1. The 1st pellet works as a killer pellet to cause an intentional disruption accompanied by a runaway plasma where most of the plasma current was driven by the runaway electrons. Then, six successive neon pellets were injected into the runaway plasma. For the 2nd to 4th pellets injection, we found the prompt exhaust of the runaway electrons and the reduction of runaway plasma current without large amplitude MHD activities. These effects are indicated by the increase in the photo-neutron signal S_{neut} and the decrease in dI_p/dt, as shown in Fig.1.

Figure 2 shows a possible explanation for basic behavior of the runaway plasma current by the balance of the avalanche generation of runaway electrons and their slowing down predicted by the Andersson-Helander (A-H) model [6], including the combined effect of collisional pitch angle scattering and synchrotron radiation. In Fig.2, $\tau_{\mathrm{Ip\text{-}decay}}$ is defined by $I_p/(-\mathrm{d}I_p/\mathrm{d}t)$ and τ_{eff} is defined by $-1/\tau_{\mathrm{eff}}=1/\tau_s-1/\tau_{\mathrm{rad}}$, where τ_s is the generation time of the avalanche process and τ_{rad} is the slowing down time by the A-H model. The $\tau_{\mathrm{eff\text{-}Wr}}$ is the value with different energy of the runaway electrons W_r. It is suggested that the impurity pellet injection reduces W_r in a stepwise manner such as from 14.3 MeV to 12.2 MeV and from 12.2 MeV to 10.2 MeV.

3. Mitigation and avoidance of current quench by runaway electrons

Figure 3 shows a comparison between normal disruptions with and without runaway current tail. It is seen that the current quench time was extended in the case with a runaway current tail.

Figure 4 shows waveforms of the experiment for the avoidance of the current quench by runaway electrons. An impurity neon pellet (2.1 mm cube, ~120 m/s, high field side injection [7]) was injected as a killer pellet into hydrogen discharges (I_p=1 MA, B_t=3.73 T, a~0.86 m, R_p~3.3 m, $n_e(0)$~1x10^{19} m^{-3}, T_e^{ECE}(r/a~0.2)~2~5 keV) during the period with the ECRF injection (110 GHz, O-mode) [8,9]. The ECRF injection angle was adjusted so that the ECRF power was deposited around the center of the pre-disruption plasma. For the case of P_{ECRF}~3 MW, the current quench was avoided presumably due to relatively high T_e after the pellet injection. While the T_e decreased afterwards, runaway electrons appeared since t~12.88 s.

These runaway electrons reinforced the discharge to survive against the low T_e of less than several tens eV and additional impurity pellet injection at t~13.13s, as shown in Fig.5. As a result, the robust discharge was obtained, and thus the plasma current was maintained and terminated as programmed.

4. Diagnostics of runaway electrons by laser inverse Compton scattering

Energy and spatial distributions of runaway electrons can be known by the measurement of the X-rays by inverse Compton scattering. For instance, in case of the head-on collision of the relativistic electrons and the YAG laser photons (λ=1.06 μm), the expected energy of scattered photons is ranged between 1.8 keV~45 keV for W_r of 10 MeV~50 MeV. The diagnostics development including an innovative technique of the pulse X-ray imaging spectroscopy is now in progress.

References

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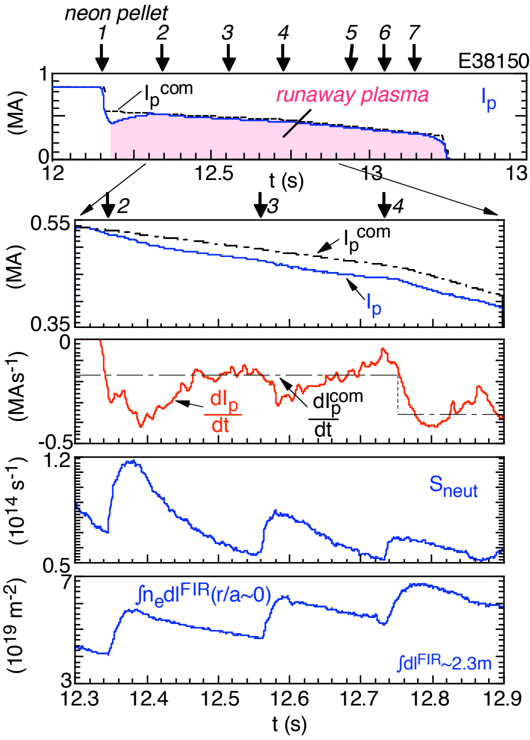

Fig.1 Waveforms of the experiment for mitigation of the post-disruption runaway electrons. Impurity (neon) pellets are injected into the runaway plasma.

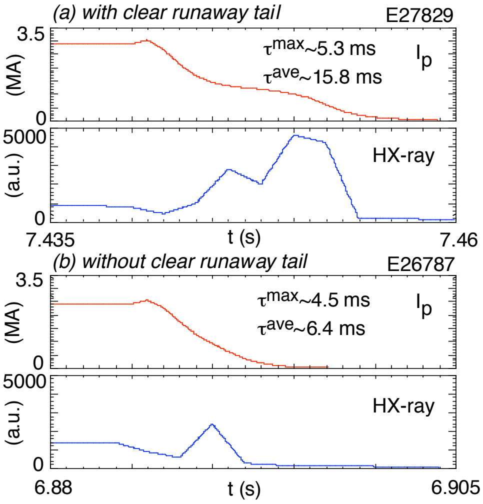

Fig.3 Waveforms of normal disruptions: (a) with a runaway current tail, and (b) without a runaway current tail. The τ^{max} is the maximum current decay time defined as $dI_p/(-dI_p/dt)^{max}$, where $(-dI_p/dt)^{max}$ is the maximum current quench rate, and the τ^{ave} is the averaged current decay time for 100% current drop derived from the period between 80% to 20% of pre-disruption plasma current.

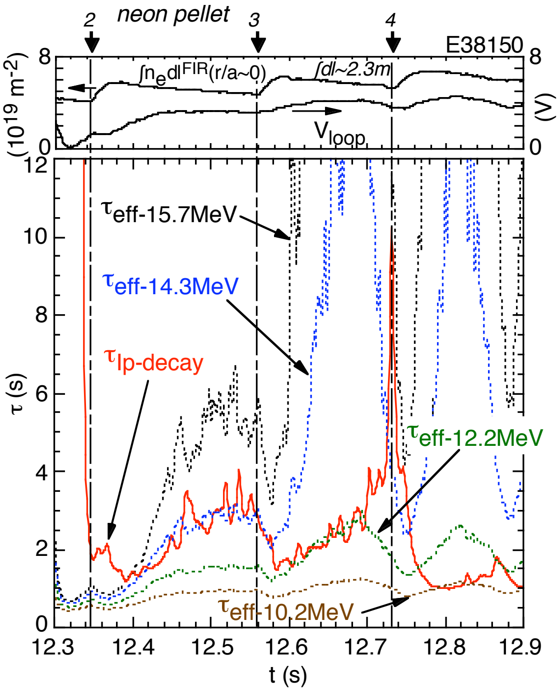

Fig.2 The decay time of the runaway plasma current $\tau_{\text{Ip-decay}}$, and the effective time constant $\tau_{\text{eff-Wr}}$ which shows the balance of the generation and slowing down of runaway electrons.

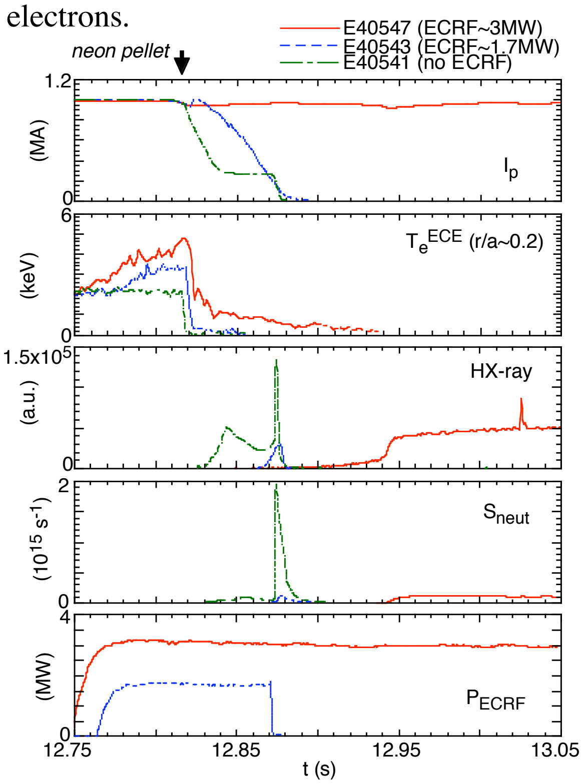

Fig.4 Waveforms of the experiment for the avoidance of the current quench by runaway electrons. The combination of the impurity (neon) pellet injection and the ECRF injection is utilized.

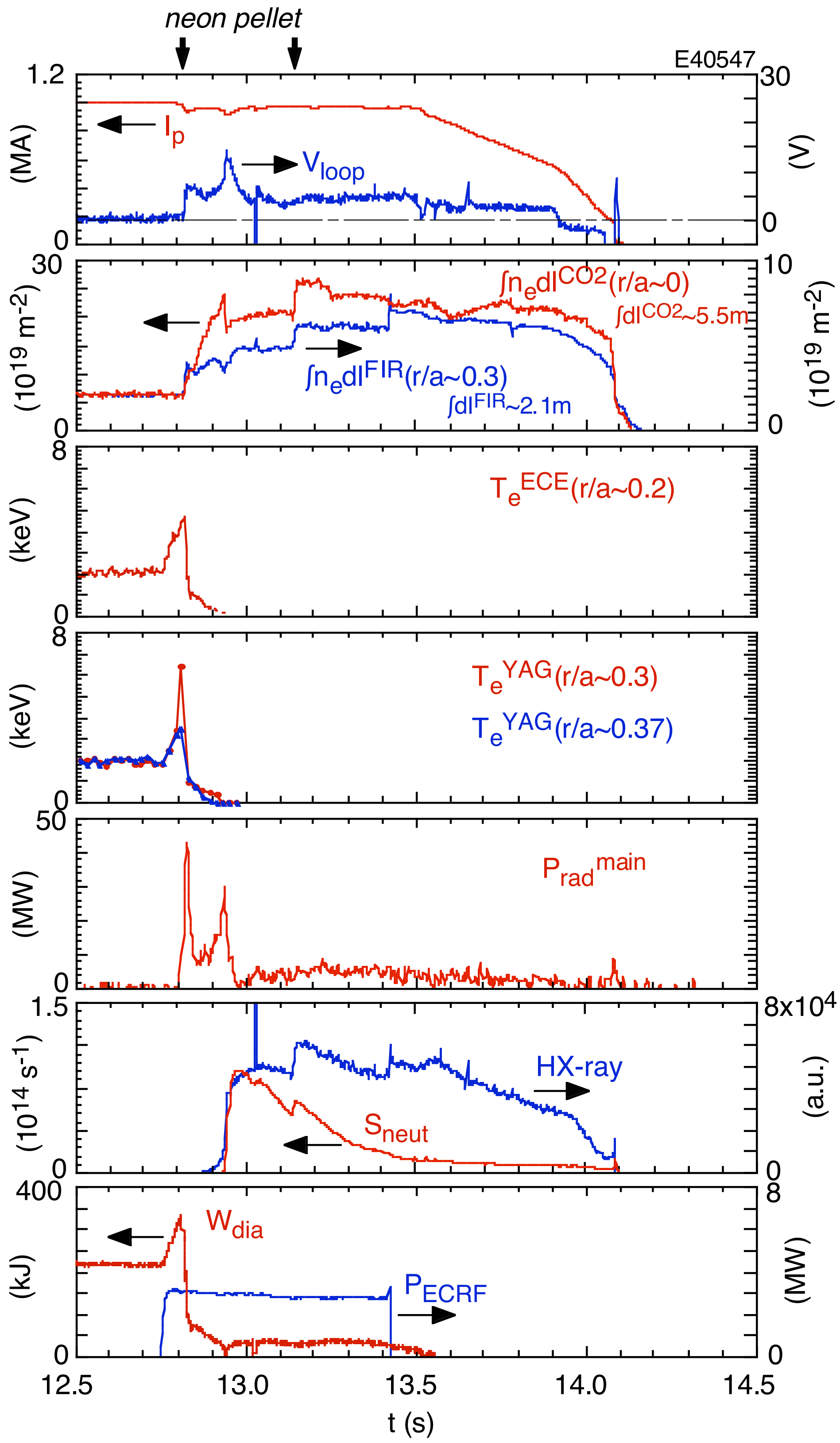

Fig.5 Waveforms of the discharge with avoidance of the current quench. The discharge is reinforced by runaway electrons, and this discharge is robust enough to survive under the impure and low electron temperature conditions. The plasma current was maintained and terminated as programmed.