Experimental Study of the Runaway Current in the J-TEXT Tokamak

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Major plasma disruptions in tokamaks often generate runaway currents, which contain electrons with energies of several tens of megaelectron-volts (MeV). These currents can cause substantial damage when control is lost and the current hits the limiters or the vessel wall. The interaction between the runaway electrons and the impurities inside the plasma results in soft X-ray emission, which can provide detailed information about the runaway generation process and the confinement of runaway electrons. A vertical soft X-ray array at the top of Joint Texas Experimental Tokamak (J-TEXT) was used to study the runaway beams resulting from major disruptions. Runaway electron production and confinement of runaway current were observed by using soft X-ray images.

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I. INTRODUCTION

One of the serious issues for next-step tokamaks is the large runaway current caused by major disruptions [1, 2]. With the increase in the size and plasma parameters, future tokamaks face larger runaway currents due to the plasma disruptions. Additionally, the energy of the runaway electrons can be very high. A numerical simulation indicated that the runaway electrons in International Thermonuclear Experimental Reactor (ITER) might reach one hundred MeV. Because of the high-energy electrons, the runaway current can cause severe damage to the tokamak device if control is lost and hits the vessel wall. Hence, many methods, such as massive gas injection (MGI) [3] and resonant magnetic perturbations (RMP) [4], have been proposed to suppress the generation of the runaway electrons. The present expectation is that a significant (multi-mega-ampere) runaway current will form in ITER disruptions because these efforts cannot absolutely prevent the generation of runaway electrons [5]. Thus, additional available methods should be proposed to control and dissipate the runaway current, and a further understanding of the runaway current is required both from theoretical and experimental points of view.

Usually, runaway electrons are detected by measuring the hard X-ray radiation (HXR) or photo-neutron emissions [6–9]. The runaway electrons produce these two kinds of radiation when control is lost, and they hit the vessel wall; however, these are not a direct measurement of the runaway electrons. The runaway current produces an observable soft X-ray image by the excitation of impurity ions in the residual plasma. This image allows the runaway current to be investigated directly [10], and this technique has been proved in Joint European Torus (JET) [11,12].

Recently many experiments have been pursued toward further understanding of the runaway current in J-TEXT. This paper is organized as follows: the introduction to J-TEXT is presented in Section II, the behavior of the runaway current in J-TEXT is presented in Section III, and the analysis of the soft X-ray images of the runaway current is presented in section IV. Lastly, the summary is presented in section V.

II. EXPERIMENTAL SETUP

J-TEXT is a conventional tokamak with an iron core [13]. It has a major radius of R = 105 cm. The minor radius can be modified in the range from 25 cm to 29 cm by using a movable titanium-carbide-coated graphite limiter. The maximum toroidal magnetic field is \( B_T = 2.3 \) T. The maximum plasma current is \( I_P = 220 \) kA with a 400-ms pulse length. The line-averaged electron density is in the range of \( n_e = (1 \sim 4) \times 10^{19} \) m\(^{-3}\).

When runaway electrons strike the vessel wall, they will cause thick-target bremsstrahlung, which are hard X-ray emissions (E\( \sim \)0.5-5 MeV). In J-TEXT, three NaI detectors detect these HXRs. The detector array is
Fig. 1. (Color online) Schematic view of the sight lines of the soft x-ray detection array in the J-TEXT tokamak.

placed about 5 m from the vessel at the level of the vessel’s midplane. One detector is arranged in the electron forward direction, the second one is arranged in the radial direction, and the third detector is arranged in the electron reverse direction.

Most of the measurements reported in this paper were provided by the vertical soft x-ray detector array, which consists of a multi-channel photodiode array and provides 16 viewing lines [14,15]. The soft x-ray detector array was installed at the top of the vessel and a schematic view of the sight lines is shown in Fig. 1 [15]. It covered the minor cross section from $-15.3$ cm to $15.3$ cm, and has a spatial resolution of about 2 cm. The available energy range of the array is from 1 keV to 10 keV with a 12 µm Be foil in front of the array. The runaway electrons produce weak soft x-ray emissions by the interaction with the impurity ions in residual plasma, the energy of these soft x-rays is a few keV thus they can be detected by the array and provide a direct observation of the runaway beam.

III. BEHAVIOR OF THE RUNAWAY PRODUCTION DURING DISRUPTION IN J-TEXT

The reasons for plasma disruptions have been discussed in detail in many papers [1,2,16], and the mechanisms for runaway electron generation are well known: primary generation (Dreicer generation) create runaway seed electrons with high energy, and then the seed electrons are amplified by secondary generation (avalanche generation) [1, 16, 17]. Previous studies have indicated that a plasma disruption should produce a large number of runaway electrons as a consequence of the high electric field that is induced during the current quench phase [16]. The previous experiments have shown that disruptions in the J-TEXT tokamak can result in a runaway current plateau when the toroidal magnetic field is higher than 2.1 T [18].

A typical plasma disruption (shot #1017289) with a runaway current plateau is shown in Fig. 2. The pre-disruption plasma current was about 240 kA and resulted in a runaway current of about 80 kA, which was sustained for approximate 20 ms. During the disruption, a redistribution of the plasma current occurred, which usually flattened the profile and resulted in a decrease in the plasma inductance [19]; however, the plasma energy $E \sim \frac{1}{2}I_p^2L_p$ was a constant for this short period, so an increase in the plasma current took place in this phase (about 15% of the pre-disruption current). In addition a short-lived negative voltage spike arose in this phase, and it is a characteristic feature of plasma disruptions. The loop voltage at the plasma edge rose to 20 V as a result of a significant reduction in the plasma electron temperature (usually a drop to the order of 10 eV), and as a result of the heavy impurity concentration. During the current quench, the change in the force balance resulted in a compression of the plasma and pushed it toward the inner wall; sometimes, the control was lost and, the current hit the vessel wall and was terminated. In other cases (Fig. 2), the post disruption plasma was constrained well and the high loop voltage resulted in a large number of runaway electrons, which formed the runaway current plateau. The loop voltage started to fall to as low as zero as long as the plateau was formed because the runaway electrons had an extremely low electrical resistance.

In several large tokamaks, the runaway current accompanied by an HXR burst [11,20], but in the J-TEXT it is quite different; the HXR signal remains at noise level.