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Investigation of the effect of electron cyclotron heating on runaway generation in the KSTAR tokamak

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ABSTRACT

Wave enhanced runaway generation is expected to play an important role in the conversion of plasma current into runaway current during major disruptions. The fast electrons created by electron cyclotron heating (ECH) were used to study this issue in KSTAR. It is found that the fast electrons driven by ECH can enhance runaway production in the flat top phase with high loop voltage. The runaway current in disruptions was not enhanced by the ECH produced fast electron population due to the strong magnetic fluctuations which inhibited the generation of runaway electrons. It is found that a complete loss of existing REs during thermal quench has occurred in KSTAR limiter configuration discharges.

1. Introduction

One of the outstanding problems of tokamak fusion reactors is the possible damage caused by runaway electrons (REs) [1,2]. The high electric fields induced during the current quench phase of a tokamak disruption can generate a large number of REs [2,3]. REs with the energy of the order of several tens MeV transfer their energy to the wall and may cause damage to plasma facing components. RE formation is a serious concern because of the large RE amplification (knock-on avalanche) could result in ∼10 MA runaway current in ITER [4]. The study of REs generation during disruptions and during rapid shutdowns is an active area of research in present tokamaks. The avoidance and mitigation of REs by massive gas injection, magnetic perturbation, and RF heating have been extensively investigated in tokamak plasmas [5–16]. Experiments have been pursued toward understanding the physics of RE production, transport, and amplification during disruptions.

REs are generated when the electron energy exceeds a critical energy at which the electric field driving force on the electrons is equal to the minimum frictional drag force in the plasma. There are, generally, three mechanisms for RE generation: primary generation (Dreicer generation), secondary generation (avalanche generation) and hot tail generation [4,17,18]. Dreicer generation, which is caused by diffusion into the runaway region of velocity-space due to long-range Coulomb collisions, can produce REs both in low density steady-state discharges and in disruptions. The secondary generation process occurs when there are some high-energy REs (multi megaelectronvolts) already in the plasma. These electrons can collide with thermal electrons and move them into the runaway region through large angle Coloumb collisions. The knocked out electrons, in turn, can collide with other electrons and, therefore, an avalanche of REs is triggered. Hot tail runaway generation is caused by incomplete thermalization of the electron velocity distribution during rapid plasma cooling [4,18]. This mechanism is caused by the fact that the collision frequency decreases with increasing velocity, so that the energetic particles in the tail of the initial Maxwellian need a longer time to slow down than the low-energy part of the velocity distribution. These energetic particles are left as a hot tail of the mainly cool post-thermal quench electron distribution in a transient period. When the runaway threshold velocity decreases due to the increasing electric field, a part of the hot tail can be converted into REs. The hot tail runaway generation process is often observed in fast shutdown experiments with killer pellet injection [19]. It is an important RE mechanism in tokamak disruptions if the thermal quench phase is sufficiently fast. In a disruption, the Dreicer and the hot tail processes are the primary runaway mechanisms, which create a runaway seed population that is amplified by the avalanche mechanism. The avalanche factor in disruption is about 6 at present KSTAR experiment.

Another important runaway generation process is wave enhanced runaway generation. The presence of waves could greatly enhance the runaway production because the quasi-linear diffusion of electrons by waves can enhance the flow in velocity space

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across the critical velocity for runaway generation [20–22]. The enhancement of REs by waves in flat-top phase has been observed in ATC, JFT-2, HT-7, FTU and HL-2A [16,22–25]. The enhancement of runaway production by wave-driven fast electrons has been identified during disruptions in FTU [26]. The fraction of the pre-disruption plasma current converted to runaway current reached values as high as 80% of the pre-disruption current due to the acceleration of the fast electrons (previously created by the lower hybrid waves) into the runaway regime during the disruptions.

The characteristics of electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) to deposit power or current in a localized controllable way make these techniques applicable to plasma startup, heating, generation, and maintenance of desired current profiles and stabilization of magnetohydrodynamic (MHD) instabilities [27]. It was found that high power ECH can quench the runaway population by reducing the toroidal electric field below the threshold electric field [15]. The ECH has been used as a promising technique to avoid or postpone disruptions by stabilizing MHD activities [28]. While ECH can produce a fast electron population which is prone to enhance runaway generation, it is desired to identify the role played by ECH produced fast electron tail on runaway generation in disruption. The behavior of REs with ECH has been investigated in the KSTAR tokamak. In Section 2 the experimental conditions and diagnostics are presented. The behaviors of REs in flat top phase and in plasma disruptions are described in Section 3. Finally Section 4 contains the conclusions.

2. Description of experiment

The Korea Superconducting Tokamak Advanced Research (KSTAR) system is a full superconducting, medium-sized tokamak device [29]. The mission of the KSTAR project is to perform high beta, long-pulse fusion research contributing to the establishment of scientific and technological bases for a future energy source. The KSTAR tokamak machine parameters include a major radius of $R = 1.8$ m, minor radius of $a = 0.5$ m, and the main operation goal parameters are plasma current $I_P = 2.0$ MA, $B_T = 3.5$ T, and pulse length $t = 300$ s. The KSTAR has 16 superconducting toroidal field (TF) coils and seven pairs of superconducting poloidal field (PF) coils, a vacuum vessel with thermal shields, and a cryostat. The superconducting magnet material of all the TF, PF coils 1–5 are Nb_3Sn while the PF 6 and PF 7 coils are NbTi. These are the same magnet materials as in the International Thermonuclear Experimental Reactor (ITER) coils. Therefore the TF and PF magnet coils could simulate the ITER magnet systems and many parts of the startup and the operation scenarios have relevance to ITER. The first plasma was achieved successfully in June 2008. An ECH power of 300 kW at 110 GHz was available during the KSTAR 2010 experimental campaign. The wide of ECH beam launched into the plasma is about 5.8 cm, which is much smaller than the minor radius of plasma. In this experiment, the ECH was launched with radial arrangement for heating.

A 280 GHz single-channel horizontal millimeter-wave interferometer system was installed for plasma electron density measurements in KSTAR. The electron temperature was measured by an ECE radiometer which covered the frequency range of 110–196 GHz with 1 GHz steps. Two x-ray imaging crystal spectrometers (XICS) for the measurements of profiles of the ion and electron temperatures, rotation velocities, and impurity charge-state distributions have been developed [30,31]. Neutrons from photonuclear and fusion processes were monitored by a high sensitivity ^{3}He detector and a small fission chamber. The measurement of REs was performed by the hard x-ray radiation (HXR) detectors. The HXR (0.5–10 MeV) was measured by two NaI(Tl) scintillators which were arranged tangentially on the equatorial plane.

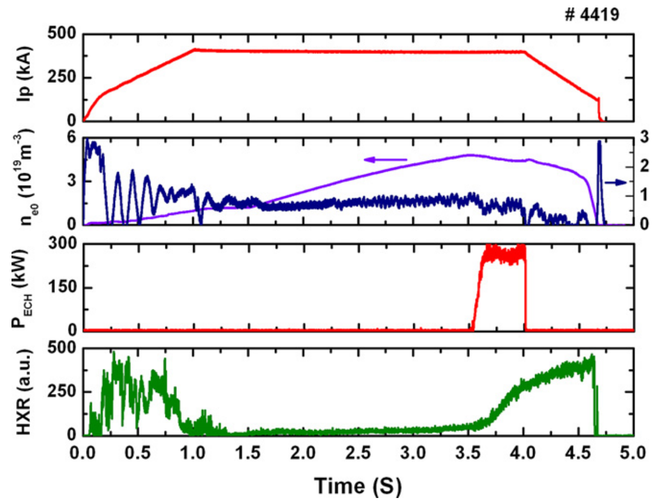

Fig. 1. Waveforms of an ECH discharge. The ECH power was switched on to trigger hot tail runaway generation by seeding a fast electron population.

3. Experimental results

The effect of ECH produced fast electron population on the runaway generation has been investigated with limiter configuration in KSTAR. Opposite to the formation of a hot tail in fast plasma cooling, ECH could produce a fast electron tail. The ability of ECH to enhance the runaway production during the flat-top phase is illustrated in Fig. 1. The plasma current was about 400 kA and the line integrated electron density was about 4.5×10^{19} m^{-3}. The REs were produced in the initial phase due to a low electron density as indicated by a high HXR flux. The HXR emission resulting from the thick target bremsstrahlung emission when REs are lost from the plasma and impinge on the first wall provides information on the generation, loss, and energy content of REs. The HXR flux decreased to negligible level in the following phase due to the increase of density. When the density ramped up to 4.5×10^{19} m^{-3} at 3.5 s, about 260 kW ECH power was switched on. The HXR flux increased significantly after the switch on of the ECH power. The ECH was terminated at 4.0 s, while the HXR flux kept increasing up to the end of discharge. The enhancement of REs was due to the creation of a fast electron population by ECH. There has no any fast electron monitor in KSTAR, the energy distribution of fast electron is not available. We can only give some qualitative discussions on the fast electron tail. Although the ECH mainly increase the perpendicular energy of resonance electrons, the collisional drag force experienced by these fast electrons will decrease due to the increase of electron total energy. This will result in further increase of electron parallel energy due to the acceleration in the electric field. Since the ECH power was limited, the loop voltage drop was limited. The loop voltage only dropped from 0.86 V to 0.63 V due to the limited ECH. With high loop voltage, the fast electron tail will extend to higher energy by electric field acceleration. The collisional drag force experienced by fast electrons decreases with the increase in the electron velocity. In high loop voltage environments, the superthermal electron tail is prone to be converted to REs since the energy of superthermal electron tail may be comparable to the runaway threshold energy. The ECH experiment in flat top phase identified the fact that a part of the ECH produced fast electron population was converted to runaway electrons because the limited ECH power makes the loop voltage remain high.

Since the loop voltage during disruption is quite high, it was expected that the fast electron tail would enhance runaway production during disruptions. The waveforms of a typical natural disruption with ECH are shown in Fig. 2. The plasma current was about 350 kA, the line integrated electron density was about