1.5 Enhanced production of runaway electrons during electron cyclotron resonance heating and in the presence of supersonic molecular beam injection in the HL-2A tokamak

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According to the Dreicer field theory, the production of runaway electrons is determined by \( \left( \frac{E}{E_0} \right) \), where \( E \) and \( E_0 \) are toroidal electric field and Dreicer field, respectively. And \( E_0 \) is proportional to \( \left( \frac{n_e}{T_e} \right) \), where \( n_e \) and \( T_e \) are electron density and electron temperature, respectively. Since \( \eta \) ( \( \eta \) is the plasma Spitzer resistivity and \( j \) the plasma current density),

\[ E - T_e^{-1/2} \] Then ( \( E/E_0 \) ) is determined by \( \left( n_e^{-1} T_e^{-1/2} \right) \), indicating that the higher density and higher electron temperature can avoid runaway electron generation. Accordingly, the production of runaway electrons should be suppressed during auxiliary heating phase or/and density growth phase. Experimentally, the suppression or mitigation of runaway electrons during wave heating has indeed been observed in some tokamak devices, such as RTP, FTU, JET, HT-7 and HL-2A. In the present paper, however, some anomalous experimental phenomena were observed during ECRH and in the presence of SMBI in the HL-2A tokamak. The production of runaway electrons during ECRH and in the presence of SMBI was not suppressed, on the contrary, enhanced evidently, although the electron temperature and density were increased obviously. In what follows, we will show that these anomalous experimental phenomena, in apparent contradiction with the Dreicer theory, can be attributed to the acceleration of the superthermal electrons created by the ECRH, leading to the runaway enhancement.

The detection of runaway electrons in the HL-2A tokamak is performed by means of the combination of hard X-ray (HXR) radiation and neutron emission, as shown in Fig. 1. The HXR radiation at energies above ~ 0.5 MeV is measured using two channel 476 x 76 NaI (TI) scintillator detectors shielded by lead. The two NaI(Tl) detectors are located in the equatorial plane and each detector aims at a fixed limiter to monitor the tangential emission of HXR in the motion direction of electron. The detection of neutron emission was performed by comparing the measurements of a set of \(^{235}\text{U}\) fission chambers (FC). FCI is sensitive both to neutrons and gamma rays, while FCI is only sensitive to gamma rays. At present, the central electron temperature during Ohmic heating (OH) phase in HL-2A is about 1 keV and ion temperature is less than 1 keV. Therefore, the fusion neutron number is negligible, and almost all the detected neutrons are photo-neutrons. Consequently, the fission chamber acts as a good tool for runaway electrons measurement. The HXR emission and photoneutron emission are used in this experiment for identifying the runaway electron production.

![Fig. 1. Schematic view of runaway measurement systems in HL-2A.](image)

An example is provided in Fig. 2, where the time evolution of the main parameters is plotted for ECRH discharge No. 6345. ECW power with 0.96 MW was launched into the plasma from 600 to 900 ms and a SMB was injected into the plasmas at 710 ms. During ECRH, on the one hand, the electron temperature \( T_e \) increases approximately from 0.8 to 1.5 keV and the intensity of soft X-ray radiation multiplies about factor of four. On the other hand, with the SMB injection the electron density increases gradually from 3.0 to \( 3.8 \times 10^{19} \text{ m}^{-3} \) and the electron temperature decreases slightly from 1.5 to 1.35 keV, as illustrated by curves (b) and (d) in Fig. 2.

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From Fig. 2 (f) and (g), it can be found that both the HXR radiation intensity and the neutron flux increase obviously after the SMBI. These evidences suggest that the production of runaway electrons is enhanced apparently during ECRH and in the presence of SMBI. Subsequently, the HXR radiation intensity and the neutron flux decline gently along with the termination of ECRH, which further shows that the runaway enhancement is related to the ECW power injection. To facilitate the understanding of runaway enhancement during ECRH, the SDD X-ray PHA system was employed to obtain the information of the superthermal electrons during ECRH. The evolutions of electron velocity distribution before, during and after ECRH are illustrated in Fig. 3. It can be seen that superthermal electron population violently bursts along with the ECW injection and the configuration of electron velocity distribution is changed obviously during ECRH phase in comparison with the OH phase. The "tail" of electron velocity distribution is elongated from 8 keV (OH phase) to 22 keV (ECRH phase without SMBI), then to 32 keV (ECRH phase with SMBI).

![Figure 2. Waveforms of ECRH discharge No. 6345.](image1)

![Figure 3. Time evolution of electron velocity distributions for No. 6345.](image2)

From the evolutions of plasma density and loop voltage, the evolution of the critical energy \( W_c \) for this discharge has been obtained. It indicates that the value of \( W_c \) increases rapidly with the ECW power injection and then decreases fleetly after the injection of SMB. Consequently, the value of \( W_c \) increases approximately from 15 keV (OH phase) to 35 keV (ECRH phase), then falls to about 25 keV (after SMBI). As shown in Fig. 3, the energy of superthermal electron tail during ECRH phase has extended above 30 keV. As a result, some of the superthermal electrons exceed the critical energy (25 keV) for runaway after the SMBI, and then these electrons will be turned into runaway regime under the acceleration of the toroidal electric field. Therefore, the production of runaway electron can be enhanced after the SMBI during ECRH phase. After the termination of ECW power injection, the HXR radiation intensity and the neutron flux begin to drop gradually due to the vanishing of ECRH produced superthermal electrons, i.e., the closing of ECRH shuts up the source of "seed" electrons for runaway. Therefore, the population of runaway electrons become smaller and smaller through runaway electron losses (e.g. due to magnetic field fluctuations or orbit drift).