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Study of runaway electron behaviour during electron cyclotron resonance heating in the HL-2A Tokamak*

Zhang Yi-Po(张轶泼)†, Yang Jin-Wei(杨进蔚), Liu Yi(刘 仪),
Song Xian-Ying(宋先瑛), Yuan Guo-Liang(袁国梁), Li Xu(李 旭),
Zhou Yan(周 艳), Zhou Jun(周 俊), Yang Qing-Wei(杨青巍),
Chen Liao-Yuan(陈燎原), Rao Jun(饶 军), Duan Xu-Ru(段旭如),
Pan Chuan-Hong(潘传红), and HL-2A Team

Southwestern Institute of Physics, P O Box 432, Chengdu 610041, China

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During the current flat-top phase of electron cyclotron resonance heating discharges in the HL-2A Tokamak, the behaviour of runaway electrons has been studied by means of hard x-ray detectors and neutron diagnostics. During electron cyclotron resonance heating, it can be found that both hard x-ray radiation intensity and neutron emission flux fall rapidly to a very low level, which suggests that runaway electrons have been suppressed by electron cyclotron resonance heating. From the set of discharges studied in the present experiments, it has also been observed that the efficiency of runaway suppression by electron cyclotron resonance heating was apparently affected by two factors: electron cyclotron resonance heating power and duration. These results have been analysed by using a test particle model. The decrease of the toroidal electric field due to electron cyclotron resonance heating results in a rapid fall in the runaway electron energy that may lead to a suppression of runaway electrons. During electron cyclotron resonance heating with different powers and durations, the runaway electrons will experience different slowing down processes. These different decay processes are the major cause for influencing the efficiency of runaway suppression. This result is related to the safe operation of the Tokamak and may bring an effective control of runaway electrons.

Keywords: runaway electron, electron cyclotron resonance heating, runaway suppression, suppression efficiency

PACC: 5240M, 5270, 5255G

1. Introduction

Electron cyclotron resonance heating (ECRH) by means of electromagnetic waves in the electron cyclotron frequency range and its low harmonics has become a well established and widely used approach to heat plasmas in toroidal magnetic confinement devices for fusion energy application. The good coupling effect of an electron cyclotron (EC) wave (ECW) to plasma and the relatively small loss of wave energy during its propagation have been duly recognized. Localized on/off-axis heating can be realized easily by stirring the antenna and adjusting the toroidal magnetic field to a suitable value, and thereby the profiles of electron temperature and plasma current density can be changed. This is beneficial to the control of magnetohydrodynamic (MHD) instability and the formation of reversed shear configuration, and then high confinement mode can be achieved.[1] In the last ten years, the ECRH system has been widely adopted in a variety of experimental research, including absorption of ECW, electron cyclotron current drive (ECCD) and suprathermal electron generation,[2] stabilization of soft x-ray sawtooth and MHD modes, transport study with heat pulse propagation analysis, and the effects of ECRH on runaway electron behaviour.[3−6]

In Tokamak plasmas, the plasma current is usually driven by the toroidal electric field induced by the transformer in principle. The electrons in Tokamak plasmas are accelerated by the inductively applied electric field E and slowed down by collisions with other particles. This process is expressed through the following equation[2]

$$m_{\mathrm{e}}\frac{\mathrm{d}v}{\mathrm{d}t} = eE - \nu_{\mathrm{e}} m_{\mathrm{e}} v, \tag{1}$$

where m_{e} and e are electron mass and charge, respectively, v is the electron speed and $\nu_{\mathrm{e}} = e^4 n_{\mathrm{e}} \ln \varLambda / 4\pi\varepsilon_0^2 m_{\mathrm{e}}^2 v^3$ (n_{e} and $\ln\varLambda$ are electron density and the Coulomb logarithm, respectively) is the electron collision frequency. Equation (1) shows that de-

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†Corresponding author. E-mail: zhangyp@swip.ac.cn

spite collisional deceleration, an electron will be continuously accelerated and eventually becomes runaway when

$$eE > \nu_{\mathrm{e}} m_{\mathrm{e}} v. \tag{2}$$

Subsequently, one can obtain a critical electron speed v_{c}, a critical energy W_{c} and a critical electric field E_{D}.[7] Since the discovery of the phenomenon is usually credited to Dreicer,[8] the critical electric field is called the Dreicer field.

$$v_{\mathrm{c}} = \left(\frac{e^3 n_{\mathrm{e}} \ln \Lambda}{4\pi\varepsilon_0^2 m_{\mathrm{e}} E}\right)^{1/2}, \tag{3}$$

$$W_{\mathrm{c}} = \frac{e^3 n_{\mathrm{e}} \ln \Lambda}{8\pi\varepsilon_0^2 E} \approx 0.21 n_{\mathrm{e},19} \frac{\ln \Lambda}{E(\mathrm{V \cdot m^{-1}})} \ \ (\mathrm{keV}), \tag{4}$$

$$E_{\mathrm{D}} = \frac{e^3 n_{\mathrm{e}} \ln \Lambda}{4\pi\varepsilon_0^2 m_{\mathrm{e}} v^2} \approx 0.13 n_{\mathrm{e},19} \frac{\ln \Lambda}{T_{\mathrm{e}}(\mathrm{keV})} \ \ (\mathrm{V \cdot m^{-1}}), \tag{5}$$

where $n_{\mathrm{e},19}$ and $T_{\mathrm{e}}(\mathrm{keV})$ are the electron density in units of 10^{19} $\mathrm{m^{-3}}$ and the electron temperature in units of keV, respectively. Owing to the fact that the critical velocity cannot exceed the speed of light, when

$$E \le E_{\mathrm{c}} = \frac{e^3 n_{\mathrm{e}} \ln \Lambda}{4\pi\varepsilon_0^2 m_{\mathrm{e}} c^2} \approx 0.0015 n_{\mathrm{e},19} \ln \Lambda \ \ (\mathrm{V \cdot m^{-1}}), \tag{6}$$

the electron cannot be accelerated, that is, runaway generation does not occur.

Runaway electrons are produced due to two mechanisms when $E > E_{\mathrm{c}}$:[9] (i) the primary or Dreicer mechanism and (ii) the secondary or avalanche mechanism. In the primary mechanism runaway electron generation is due to diffusion of electrons in the velocity space from the thermal into the runaway region. According to Dreicer field theory, the production of runaway electrons is determined by E/E_{D}. From Eq.(5), it is found that E_{D} is proportional to $n_{\mathrm{e}}/T_{\mathrm{e}}$. Since $E = j\eta$ (j is the plasma current density and η the Spitzer resistivity), $E \sim T_{\mathrm{e}}^{-2/3}$. Then E/E_{D} is determined by $n_{\mathrm{e}}^{-1} T_{\mathrm{e}}^{-1/2}$, which shows that higher density and higher temperature would suppress runaway electron generation. This information offers us a method for runaway suppression: increasing the electron temperature by additional plasma heating is capable of suppressing runaway generation. The secondary mechanism of runaway generation, pointed out by Sokolov,[10] is caused by close collisions of existing high energy electrons with thermal ones. Therefore, 'seed' electrons, i.e., high energy runaway electrons, are the necessary condition for the avalanche process. In the present machines with plasma currents of about 1 MA the avalanche amplification of runaway electrons gives a factor of $\sim \exp(2) \approx 5$ but in ITER the amplification factor is very large, $\exp(50)$.[8] Therefore, secondary avalanching will play an important role in next-step Tokamaks; however, the Dreicer source of runaway electrons remain the dominant source in current Tokamaks.[11]

Electrons which exceed a critical velocity are accelerated freely and turn into a runaway regime. Since these electrons are non-collisional in practice, they continue to gain energy (up to tens of MeV) from the toroidal electric field until synchrotron radiation losses become sufficiently large.[12] Under this circumstance, high energy runaway beams can be formed and they constitute a serious threat to Tokamak vessel structures,[13] especially for future large-size devices (e.g., ITER). For this reason, runaway electron control is a crucial issue in the endeavour to achieve safe Tokamak operation.

An important aspect of runaway dynamics is its sensitivity to the actual value of the toroidal electric field. Any sudden reduction of the electric field below the critical value may lead to a quenching of the runaway population and energy, as its free energy source is removed. Since ECRH is expected to reduce the value of the electric field by increasing electron temperature, ECRH possesses the essential element for controlling the runaway population and energy. The experiments in RTP[4] have demonstrated that ECRH can be used to ameliorate or to avoid the current quench of a major disruption by plasma resistivity control (via electron temperature increase). The suppression of runaways in the ECRH plasmas has been observed in FTU, too.[5,6] It has been found that runaway electrons could be quenched by reducing the toroidal electric field to near or below the threshold electric field.

In the present paper, we investigate the behaviour of runaway electrons during the flat-top of ECRH discharges in the HL-2A Tokamak and examine the dependence of the suppression efficiency on ECRH power and duration. The remainder of this paper is organized as follows: the experimental set-up is presented in Section 2. In Section 3, experimental evidence of runaway electron behaviour in ECRH discharges under different conditions (ECRH power and duration) is shown, coupled with a discussion on the correlation of the suppression efficiency with the ECRH power and duration. Finally, the experimental results are discussed and some conclusions are drawn in Section 4.

2. Experimental set-up

HL-2A is a medium-size Tokamak with a closed divertor chamber on the basis of the original ASDEX main components. HL-2A can be operated in double null, single null and limiter configurations. It has a major radius of $R_0 = 1.65$ m, a minor radius of $a = 0.4$ m. There are 16 toroidal field (TF) coils, which can create and maintain a toroidal magnetic field (B_T) up to 2.8 T. Three motor generators (MG) are used for its power supply system. Two MGs with a total released energy of 500 MJ are used to power the TF coils and another MG with an output power of 125 MVA is used to power the poloidal field system. The Ohmic heating system has an air-core transformer with 5.0 VS flux. An EC power up to 2.0 MW at 68 GHz is available presently in the HL-2A Tokamak. The ECRH system is composed of four subsystems. Each subsystem includes a gyrotron, a transmission line, and a launcher. The output of each gyrotron is a horizontal linear polarization Gaussian beam and its purity is up to 98.4% after matching the optical unit. ECWs are transmitted in HE_{11} mode in the corrugated waveguide. Each transmission system can propagate a 500 kW wave and the transmission efficiency is as high as 90%. The four transmission lines have been aligned carefully. The Gaussian beam is injected into plasma from the low-field side (LFS) in fundamental O mode. The steerable mirrors in the launcher can be rotated to choose the angle of injection in the toroidal and poloidal directions between 0° and 30°. It is possible to explore the on-axis and off-axis plasma heating over half of the plasma radius and the ECCD. The location of the Gaussian beam waist is 580 mm from the centre of the plasmas and the beam radius is 37 mm in the centre of HL-2A, which is compliant with the requirements of the plasma heating experiments.

The detection of runaway electrons in the HL-2A Tokamak is performed by a combination of hard x-ray radiation (HXR) and neutron emission. The measurement of HXR (0.5–5 MeV) from thick-target bremsstrahlung produced by runaway electrons hitting the first wall (FW) is implemented by using two $\phi 76 \times 76$ NaI(Tl) scintillators which are 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 advanced direction of the electron. The distance between the NaI(Tl) detector and the limiter is about 4 m. The HXR detection system is used to follow the intensity evolution of the lost runaway electrons. The detection of neutron emission is performed by using a set of fission chambers. At present, the central electron temperature during the Ohmic heating phase in HL-2A is about 1 keV and the ion temperature is less than 1 keV. Therefore, the fusion neutron number is negligible, and almost all detected neutrons are photoneutrons. The photoneutrons are produced by photo-nuclear reactions, when the energy of hard x-ray photons created by energetic runaway electrons hitting the FW exceeds some threshold energy. Consequently, the fission chamber acts as a well tool for runaway electron measurement.

In addition, a silicon drift detector (SDD) x-ray pulse height analysis (PHA) system is used to measure the x-ray spectra in the energy range 1–50 keV.[14] The SDD detector is shielded by a lead housing and views the plasma through the equatorial diagnostic port to detect the vertical radiation of fast electrons. The system provides the time evolution of x-ray spectra and their three-dimensional figure with 128-channel resolution and 10-ms time resolution.

In addition, the following HL-2A diagnostics is applied for the analysis: electron temperature measurements with electron cyclotron emission (ECE) diagnostics, electron density measurements with the HCN interferometer, and plasma loop voltage measurements with magnetic probe.

3. Experimental results

The experiments were done in deuterium target plasmas with the following typical plasma parameters: plasma current I_P = 280–300 kA, toroidal magnetic field on the axis $B_T = 2.4$ T and central line-averaged electron density $\overline{n}_e = (1.5\text{–}2)\times10^{19}$ m^{-3}. In the case of ECW heating at 68 GHz with $B_T = 2.4$ T, the resonance layer is located in the plasma centre, i.e., the ECRH is on-axis heating. In the discharges reported in this paper, the EC waves are injected during the flat-top of the discharge and the EC input power (P_{EC}) ranges from 0.3 MW to 1.6 MW.

3.1. Suppression of runaways by ECRH

In an accelerating electric field the runaway electrons are sped up until the energy they gain is balanced by the collisional and synchrotron losses. Since the energy source of runaway electrons is the toroidal electric field, the fall in the electric field will result in a fall in the runaway energy. When the electric field is below the threshold value for electrons to become runaway, the synchrotron and collision losses will exceed the energy gain from the toroidal electric field, and hence the runaways can be suppressed.

A typical runaway suppression discharge is illustrated in Fig.1, where the time evolution of the main plasma parameters is plotted for ECRH discharge No. 6287 ($P_{\rm EC}$ = 1.2 MW). The runaway electrons are built up since the start-up phase due to low plasma density and high plasma loop voltage. During ECRH (0.6–0.9 s), the electron temperature $T_{\rm e}$ at plasma midplane obtained from ECE diagnostics increases

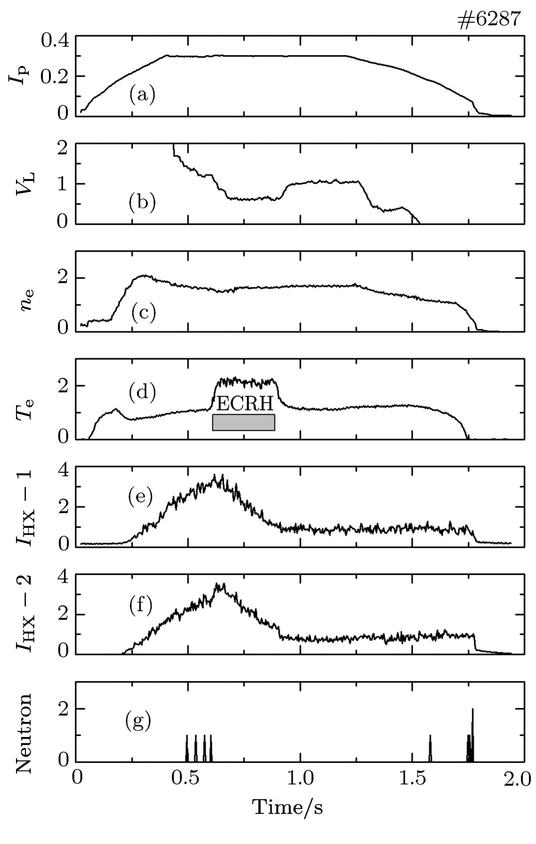

Fig.1. Waveforms of ECRH discharge No. 6287: (a) plasma current in units of MA, (b) loop voltage in units of V, (c) central line-averaged electron density in units of 10^{19} m^{-3}, (d) electron temperature at plasma midplane in units of keV, (e) and (f) HXR emission intensity in arbitrary units, (g) neutron count (accumulation counts per 1 ms). The shaded area in (d) indicates the time interval in which ECRH is applied.

approximately from 1.0 keV to 2.3 keV, the plasma loop voltage ($V_{\rm L}$) decreases approximately from 1.2 V to 0.6 V, and the intensity of HXR decreases evidently to a very low level. Though the pre-heating plasma situation ($T_{\rm e}$, $V_{\rm L}$) recovers after EC power termination, the HXR intensity still stays at a low level. These results indicate that the population or energy of runaway electrons decreases obviously during ECRH. The phenomenon during ECRH can again be identified from the neutron detection as shown in Fig.1(g). Photo-neutron emission is direct evidence that the energy of runaway electrons can be as high as 2.2 MeV, if neutrons are caused by D(γ, n)-reaction, or even higher than 6.8 MeV, if they are a result of ^{97}Mo(γ, n)-reaction. Therefore, it can be inferred that the energy of the runaways before ECRH is more than 2.2 MeV. Following ECW injection, the neutron count falls sharply to zero, implying that the energy of runaways is less than 2.2 MeV. Since the neutron flux is due to photo-nuclear reactions, the fall in neutron flux during ECRH phase demonstrates a decrease in runaway electron energy.

It is widely accepted that under the given plasma conditions there is a certain plasma resistivity η and a critical energy for runaway generation. When the energy of an electron exceeds that energy, the electron will gain more energy from the accelerating electric field E and travel to the runaway regime. The η can be written as

$$\eta \approx 5 \times 10^{-5} \frac{Z_{\rm eff} \ln \varLambda}{T_{\rm e}^{3/2}}, \tag{7}$$

where $Z_{\rm eff}$ is the effective charge. Therefore, the increase of $T_{\rm e}$ due to ECRH leads to a decrease in η and hence a fall in E. On the other hand, from Eq.(4) it follows that the reduction in E during the ECRH phase will lead to an increase in $W_{\rm c}$. The behaviour of runaway electrons during ECRH is attributed to two aspects: one is that the suprathermal electrons can turn into runaway electrons; the other is that runaway electrons are already present during ECRH. As is known, the interaction of EC waves with the resonance electrons during ECRH will produce a large number of suprathermal electrons.[2,15] If the energy of these electrons is greater than $W_{\rm c}$, the runaway production will be enhanced, otherwise, it will be suppressed due to a fall in the accelerating electric field. The time evolution of x-ray spectra before, during and after ECRH obtained by the SDD PHA system is shown in Fig.2. Because the ratio of peak counts to background counts, p/b, is very high in the measurements of energy spectra for mono-energy x-ray reference sources such as $M_{n\kappa\alpha}$ (5.894 keV), $M_{o\kappa\alpha,\kappa\beta}$ (17.44, 19.63 keV), $p/b \geq$ 400–3000, these spectra can be regarded roughly as electron velocity distributions.[16] During ECRH, it can be found that the spectra have been broadened and the the cut-off energy of the spectra became larger, which demonstrates that the high-energy component in the electron velocity distribution has been enhanced during ECRH. From Fig.2, it is seen that the energy of the suprathermal electron tail during ECRH is less than 40 keV. According to the evolution of plasma parameters (n_e and E) and Eq.(4), the time evolution of W_c of this discharge can be obtained. The evolution is plotted in Fig.3. For the data in Fig.3, $\ln\varLambda = 17$, the electric field inferred from the loop voltage ($E \cong V_L/2\pi R_0$) and estimation value for the central electron density have been used. Figure 4 also reveals that W_c increases approximately from 40 keV (pre-heating phase) to 90 keV (ECRH phase). As a result, the runaway production is suppressed sufficiently when the energy of the suprathermal electron tail is less than W_c, and therefore no runaway electrons are generated any more during ECRH. On the other hand, the energy of the existing runaway electrons is determined by the balance between the acceleration by the electric field and the energy loss (synchrotron radiation loss and collision loss). The fall in the plasma loop voltage due to ECW heating breaks the balance, which can lead to a sharp decrease in the energy of energetic runaway electrons.

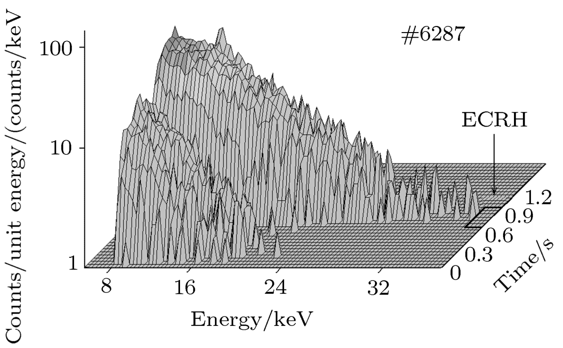

Fig.2. Time evolution of electron velocity distribution of ECRH discharge No. 6287 measured by SDD at the midplane.

The measurements discussed above show a dramatic reduction in the HXR intensity and neutron emission flux associated with ECRH. A theoretical investigation of the energy of the runaway electron response to the toroidal electric field change during ECRH confirms that these observations must be attributed to the fall of the electric field when the plasma is heated by ECRH. It is observed that the results of runaway electron behaviour during ECRH as described in this section are similar to the evidence in FTU.[5,6] That is, ECRH restrains the runaway electrons through the drop in the loop voltage, which in turn is due to the increase of electron temperature. In addition, the behaviour of runaway electrons in the presence of auxiliary plasma heating has also been examined in JET[17] and HT-7.[18] Intriguingly, a similar result was also obtained that additional heating quenches the runaway electrons by way of reducing the toroidal electric field to a level below the threshold electric field. It should be noted that study of the discharge set gives rise to the realization that the efficiency of runaway suppression by ECRH is obviously affected by two factors: ECRH power magnitude and ECRH duration. The following paragraphs present a detailed account of findings.

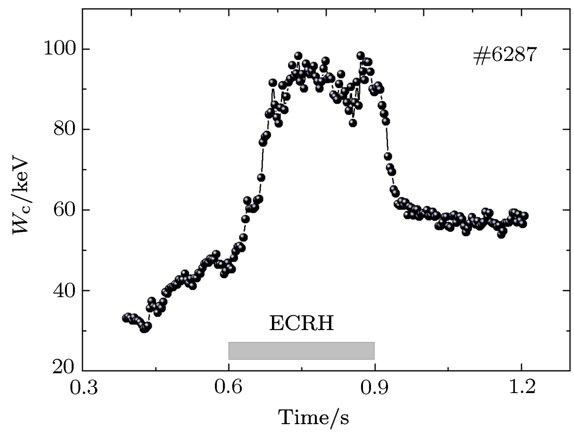

Fig.3. Time evolution of the critical runaway energy of ECRH discharge No. 6287. The shaded area indicates the time interval in which ECRH is applied.

3.2. Effect of ECRH power on suppression efficiency

An investigation into the set of discharges conducted in the HL-2A Tokamak reveals that the efficiency of runaway suppression by ECRH is obviously determined by the level of heating power and the drop level of the electric field during ECRH.

Figure 4 illustrates the three basic types of behaviour that can be found following EC wave injection and the associated electric field fall. In this figure, the time traces of HXR intensity and neutron counts are shown for three ECRH discharges with different levels of ECRH power. The main plasma parameters of the three discharges are approximately identical ($I_\mathrm{p} = 0.3$ MA, $\overline{n}_\mathrm{e} = 1.5 \times 10^{19}$ m^{-3}). In discharge No. 6027 ($P_\mathrm{EC} = 1.3$ MW), the V_L falls sharply to $\sim$0.5 V following EC wave injection into the plasma, the intensity of HXR drops rapidly to a very low level and thus the neutron flux drops to zero. Moreover, they do not recover at all when the pre-heating plasma conditions (T_e and V_L) are restored. All this evidence indicates that runaway electrons are well suppressed during ECRH. As for the second discharge (No. 6225: P_{EC} = 1.0 MW), partial runaway mitigation is observed. The V_L falls to 0.7 V due to EC wave injection. The intensity of HXR decreases to half the level of the pre-heating phase during ECRH, but it starts to increase progressively when the EC power is switched off. The flux of neutrons is suppressed completely during ECRH. Similarly, the neutron flux recovers gently after the termination of EC power. From these experimental results, it can be inferred that only partial runaway electrons are suppressed by ECRH when the power of ECRH is not sufficiently high; this group of electrons has a higher energy and their energies are reduced to the lower level. These results are consistent with the HT-7 ones in which runaway electrons were suppressed by using LHCD.[18] The recovery of HXR intensity and neutron flux implies that runaway electrons are recovered after the end of ECRH. The rebuilding of runaways is attributed to the fast electron seed population and the surviving low energy runaway seed population. Furthermore, the comeback of V_L due to the termination of ECRH will accelerate these fast electrons into the runaway regime. In the instance of discharge No. 6082 (P_{EC} = 0.3 MW), the suppression efficiency is very low. It appears that the energy and number of runaway electrons has not almost been affected by the ECRH power (0.3 MW).

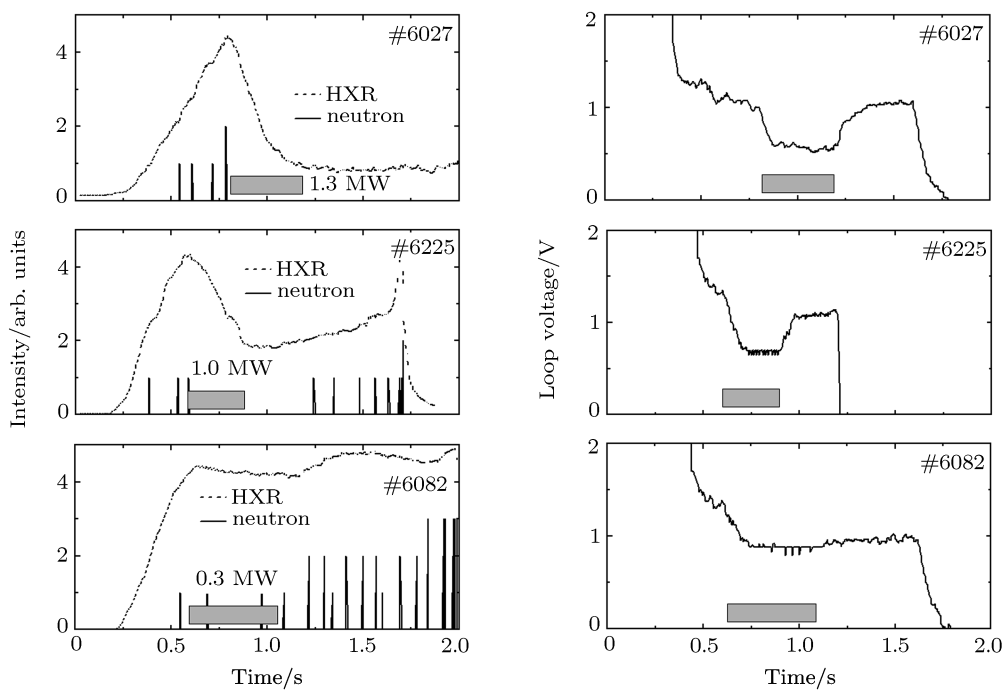

Fig.4. HXR intensity and neutron count time traces (pictures on the left) and the loop voltage vs. time (pictures on the right) for three ECRH discharges with different levels of runaway quenching and ECRH applied power (1.3 MW, 1.0 MW and 0.3 MW, respectively, in discharge No. 6027, No. 6225 and No. 6082). The shaded areas in the figures indicate the time interval in which ECRH is applied.

In order to illuminate the relation between the efficiency of runaway suppression and the power of applied ECRH, the electron temperature increment $\Delta T_e/T_e^b$ (ΔT_e is the electron temperature increment and T_e^b the electron temperature before ECRH) vs. the ECRH power, the remnant percents of the loop voltage V_L^a/V_L^b (V_L^a is the loop voltage during ECRH and V_L^b the loop voltage before ECRH) vs. the ECRH power and the remnant percent of the HXR intensity I_{HX}^a/I_{HX}^b (I_{HX}^a is the HXR intensity during ECRH and I_{HX}^b the HXR intensity before ECRH) vs. the ECRH power are analysed statistically, as shown in Figs.5(a), 5(b) and 5(c), respectively. From these figures, it is found that the values of $\Delta T_e/T_e^b$ increase with ECRH power while the values of both V_L^a/V_L^b and I_{HX}^a/I_{HX}^b decrease with increasing ECRH power. As mentioned above, the energy of runaway electrons is strongly sensitive to the value of the toroidal electric field. To suppress runaways, the residual electric field must be lower than the threshold value for electrons to run away, causing accelerating electric field to fail in maintaining the energy balance of the runaways. Therefore, a higher power is more beneficial to enhance the efficiency of runaway suppression.

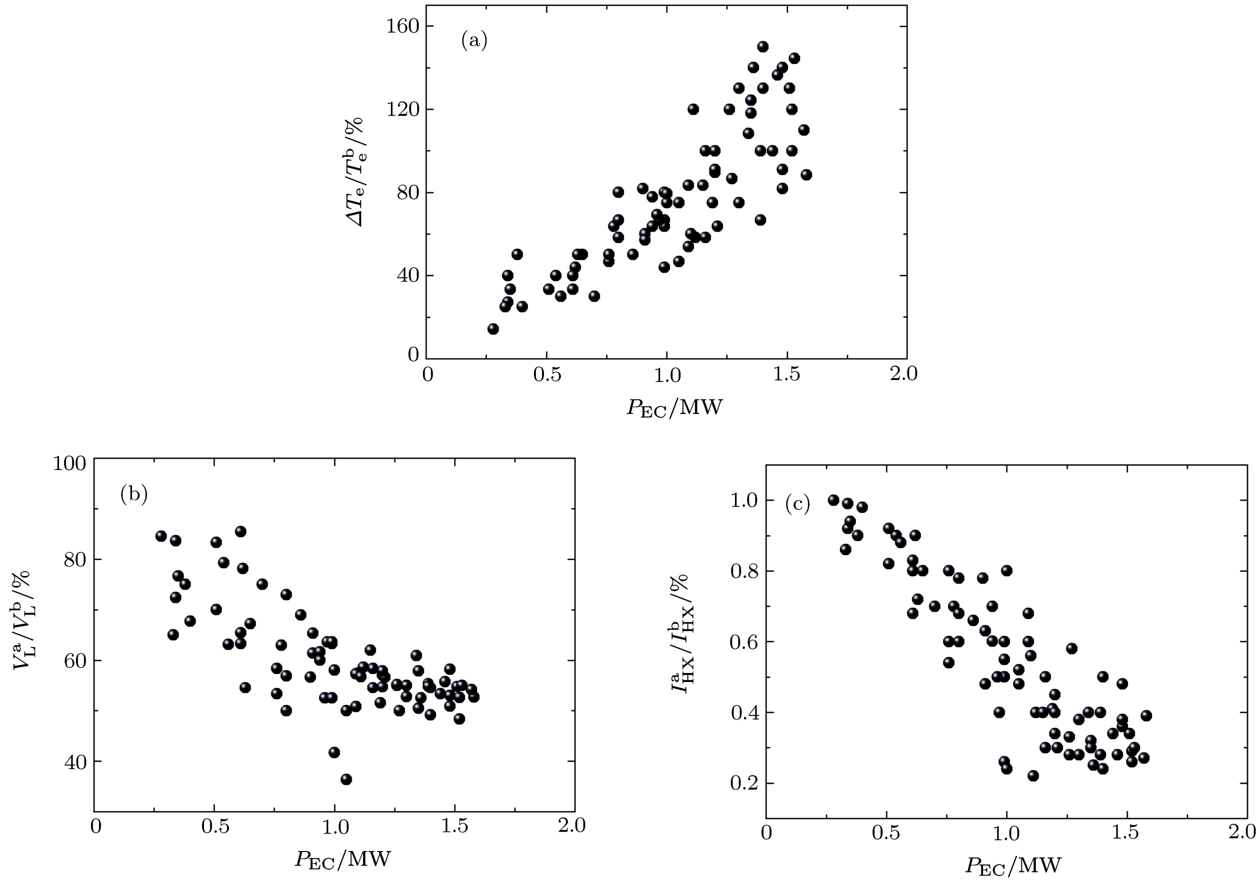

Fig.5. Statistic analysis: applied ECRH power vs. electron temperature increment percents $\Delta T_e/T_e^b$ (a), remnant percents of loop-voltage V_L^a/V_L^b (b) and remnant percents of HXR intensity (c). ΔT_e is the electron temperature increment and T_e^b the electron temperature before heating. V_L^a is the loop voltage during ECRH and V_L^b the loop voltage before ECRH. I_{HX}^a is the HXR intensity during ECRH and I_{HX}^b the HXR intensity before ECRH.

3.3. Effect of ECRH duration on suppression efficiency

Figure 6 shows the two typical types of behaviour in the two ECRH discharges under the same EC power (P_{EC} = 1.0 MW) but with different durations. The main plasma parameters of the discharges are the same (I_p = 0.3 MA, $\overline{n}_e = 1.6 \times 10^{19}$ m^{-3}). It is observed that the duration of the applied EC power is capable of influencing clearly the efficiency of runaway suppression. For discharge No. 6161, both the intensity of HXR and the neutron flux fall evidently to a lower level during ECRH (0.6–1.0 s, duration 0.4 s). Furthermore, after the termination of EC power, they do not recover any more. These indicate that the runaway electrons are suppressed well down by ECW heating. As for the other discharge (No. 6055: ECRH interval 0.8–0.85 s, duration 0.05 s), there is a slight fall in the HXR intensity during the ECRH phase; however, the HXR intensity quickly recovers to the pre-ECRH level after the termination of ECRH. Moreover, the neutron radiation flux maintains a high level. Consequently, from these experimental results, it can be inferred that the efficiency of runaway suppression in this ECRH discharge is very low.

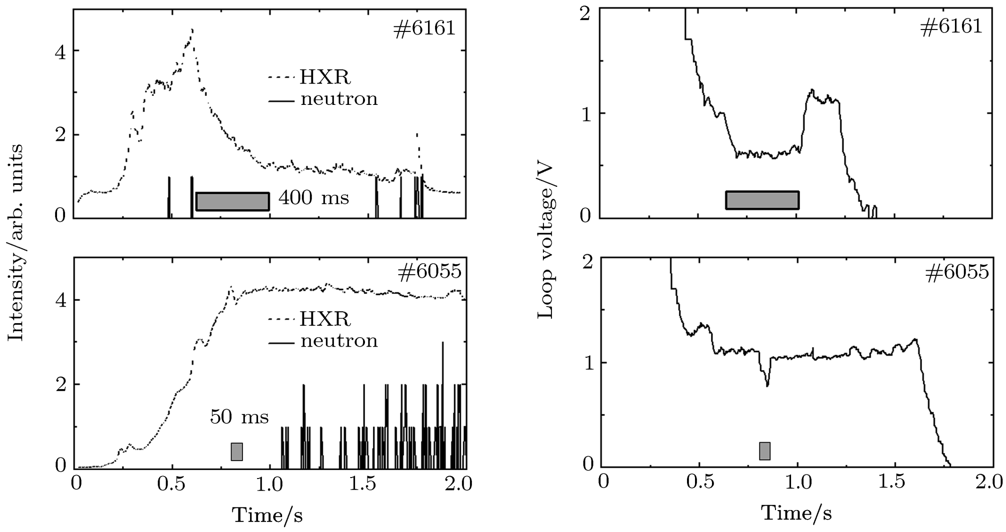

Fig.6. HXR intensity and neutron count time traces (pictures on the left) and the loop voltage vs. time (pictures on the right) for two ECRH discharges with different levels of runaway quenching and ECRH duration (50 ms and 400 ms in discharge No. 6055 and No. 6161, respectively). The shaded areas in the figure express the time intervals in which ECRH is applied.

From the comparison between discharges No. 6161 and No. 6055, it can be found that high power ECRH (when, accordingly, the resulting electric field drops) does not guarantee the disappearance of all the runaway electrons. This phenomenon is related to the slowing down process of runaway electrons.[11] To illustrate this point, a test particle model[19] is employed to estimate the energy decay time of existing runaway electrons during ECRH. The test particle model takes into account the acceleration in the toroidal electric field, collisions with the plasma particles and the deceleration due to synchrotron radiation losses. Typical HL-2A plasma conditions in these experiments have been assumed: $I_{\rm p}$ = 300 kA, $B_{\rm T}$ = 2.4 T, $\overline{n}_{\rm e} = 1.5\times10^{19}$ m^{-3}, $V_{\rm L}$ = 1.2 V, and EC waves are injected into plasma at 0.6 s. As an approximation, the estimation of the runaway energy at 0.6 s ($\varepsilon_0\sim5.0$ MW) has been achieved on the basis of the test particle model. Due to the suprathermal electron avalanche during ECRH (the tail energy is less than 40 keV, as shown in Fig.2), the accelerating electric field E during ECRH must be lower than the critical electric field $E_{\rm D}$ ($E_{\rm D}\geq0.083$ V/m, according to Eq.(5)) for suprathermal electrons in order to annihilate the runaway electrons. Figure 7 shows the calculated energy decay time for runaway electrons in the HL-2A Tokamak when ECRH is applied, as a function of E ($E<0.083$ V/m) during the heating phase. From Fig.7, one can find that the slowing down time of the runaway energy is proportional to the value of the residual electric field. Therefore, ECRH with longer duration is more beneficial to enhance the efficiency of runaway suppression.

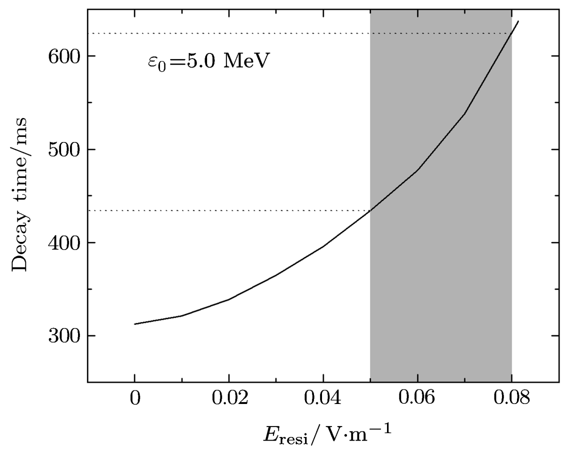

Fig.7. Estimated electron energy decay time vs. residual electric field value, $E_{\rm resi}$, during ECRH. HL-2A Tokamak plasma conditions: $I_{\rm p}$ = 300 kA, $B_{\rm T}$ = 2.4 T, $\overline{n}_{\rm e} = 1.5\times10^{19}$ m^{-3}, $V_{\rm L}$ = 1.2 V, and EC waves are injected into plasma at 0.6 s. Initial energy of runaway electron, ε_0 = 5.0 MeV. The shaded area expresses the main range of the residual electric field during ECRH in these experiments. The two horizontal dashed lines indicate the range of the runaway energy decay time corresponding to the main range of the $E_{\rm resi}$-values.

The calculated results shown in Fig.7 can explain the runaway electron behaviour during ECRH presented in this paper. The drop in the plasma resistivity due to ECRH results in a fall in the accelerating electric field. Therefore, the runaway electrons are slowed down in the residual electric field, leading to a decrease in the energy of runaway electrons and, if sufficiently large, to runaway suppression. The ECRH with higher power will give rise to a lower residual electric field (as shown in Fig.4). The decay process of runaway electrons in a lower residual electric field needs less time. Thus, runaway electrons during ECRH at different powers show different behaviours due to the different decay times (as shown in Fig.4). Similarly, the runaway electrons during the ECRH with different durations will experience different decay times. During ECRH with a long duration (such as discharge No. 6161), since the duration of the ECRH is greater than the slowing down time of runaway electrons, the energy of the runaway electrons has been sufficiently slowed, and thus, the runaway electrons can be fully suppressed during ECRH. However, during ECRH with a short duration (such as discharge No. 6055), some runaway electrons still remain in the runaway region while their energy has not been suppressed enough due to the short decay time, and therefore the runaway electrons quickly recover to the pre-ECRH level after the termination of ECRH (as shown in Fig.6). During ECRH with different powers and durations, the runaway electrons will experience different slowing down processes. These different decay processes are the major reason for influencing the efficiency of runaway suppression.

4. Conclusion and discussion

In the present paper, the behaviour of high energy runaway electrons during the flat-top phase of ECRH discharges has been investigated in the HL-2A Tokamak. The drop in the plasma resistivity due to ECRH results in a fall in the accelerating electric field, causing a decrease in the runaway energy as well as the runaway population, up to runaway suppression. A theoretical investigation of the runaway electron energy response to the toroidal electric field change during ECRH confirms that these observations must be attributed to the fall of the electric field when the plasma is heated. From the study of the set of above-mentioned discharges, it has been observed that the efficiency of runaway suppression by ECRH is largely affected by two factors: ECRH power magnitude and duration.

The effect of ECRH power magnitude on suppressing efficiency can be comprehended as follows: there is a positive correlation between electron temperature and ECRH power. ECRH with higher power will give rise to a lower residual electric field. The slowing down process of runaway electrons in a lower residual electric field needs less time. To suppress the runaway electrons using ECRH with higher power needs less time. Therefore, ECRH with higher power is more beneficial to enhance the efficiency of runaway suppression.

However, a high power ECRH does not guarantee the vanishing of all the runaway electrons. This question is related to the effect of ECRH duration on suppression efficiency. The calculated results shown in Fig.7 reveal that the slowing down time of the runaway energy is proportional to the value of the residual electric field. During ECRH with a long duration, the slowing down time of runaway electrons is such a long one that the energy of the runaway electrons has been suppressed sufficiently. However, during ECRH with a short duration, the runaway electrons still remain in the runaway region while their energy has been slightly reduced due to the short slowing down time. Therefore, ECRH with a longer duration is more beneficial to enhance the efficiency of runaway suppression.

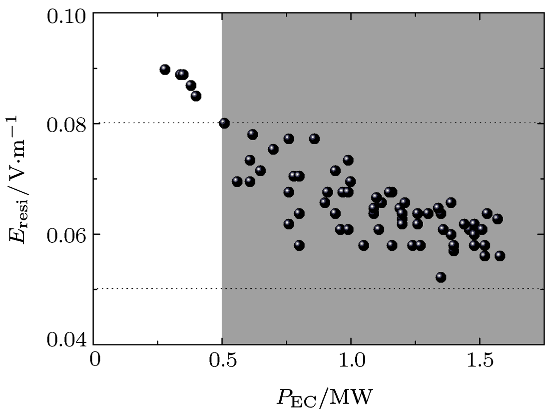

Fig.8. Residual electric field $E_{\rm resi}$ during ECRH vs. applied power for the selected set of HL-2A ECRH discharges. The shaded area expresses the applied ECRH power $P_{\rm EC} > 0.5$ MW. The two horizontal lines indicate the main range of the $E_{\rm resi}$-values during ECRH in these experiments: 0.05 V/m$< E_{\rm resi} < 0.08$ V/m.

Figure 8 shows residual electric field $E_{\rm resi}$ during ECRH vs. applied power for the selected set of HL-2A ECRH discharges. From Fig.8, it can be found that $E_{\rm resi} < 0.08$ V/m when $P_{\rm EC} > 0.5$ MW and the majority of the $E_{\rm resi}$-values are located in a range (indicated by the two horizontal lines in Fig.8): 0.05 V/m$< E_{\rm resi} < 0.08$ V/m. The calculated energy decay times for runaway electrons in the residual electric field corresponding to the shaded area range from

430 ms to 620 ms (as shown in Fig.7). Therefore, to completely suppress runaway electrons by means of the actual ECRH system in the HL-2A Tokamak, the ECRH power and duration must exceed 0.5 MW and 430 ms, respectively.

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