Interaction of Runaway Electrons with Magnetic Field Ripple in the HT-7 Tokamak

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Abstract: The runaway electrons have been measured in combination with hard x-ray detectors and thermographic camera in the HT-7 tokamak. The dynamics of runaways in the core and edge regions is monitored simultaneously. The HXR signals monitor the lost runaways and the dynamics of runaways in the edge region. The maximum energy of runaways in the edge region could be blocked by the resonance of gyromotion with the *n*th harmonic of the magnetic field ripple. This resonance interaction creates a barrier to a further increase in the energy of runaway electrons.

1. Introduction

In tokamak plasmas, the plasma currents are usually driven by the electric field induced by the transformer principle. Electrons are accelerated by the electric field, but they experience friction also due to collisions with ions and other electrons. The friction is inversely proportional to the square of the electron velocity. A small part of the total electron population has a sufficiently large velocity to escape from the influence of the friction. Electrons that exceed the critical velocity (for which the collisional drag balances the acceleration by the field) are freely accelerated and can reach very high energies. These electrons are called runaway electrons.

The runaway electrons are investigated for several reasons. One of the outstanding problems of a tokamak fusion reactor is the possible damage caused by runaway electrons[1, 2]. The effect of the runaway electrons when they impinge on the vessel walls or plasma facing components is strongly dependent on the energy gained in the electric field. The knowledge of the energy that can be reached by runaway electrons constitutes an essential tool to estimate the effect. Another puzzle in plasma physics is the anomalous heat transport [3]. Transport induced by electrostatic fluctuations is inversely proportional to the particle velocity. Because of their large velocity, runaway electrons can be regarded as effectively collisionless, and the transport of runaway electrons is mainly determined by the magnetic perturbations. Therefore, runaway electron is effective test particle to probe the magnetic fluctuations[4, 5, 6].

Detecting of runway electrons is usually done by measuring hard x-ray radiation (HXR) when runway electrons are lost from the plasma and impinge on the vessel walls or plasma facing components[7]. A gamma-ray spectrometer system has been used to investigate the behavior of runways in the Frascati Tokamak Upgrade (FTU)

[8, 9]. The synchrotron radiation, originating from the movement of highly relativistic electrons in the toroidal direction, provides a tool to measure the runaway electrons inside the plasma.

The magnetic field ripple can play an important role on the runaways located in the edge region. The maximum energy of runaways in the edge region could be blocked by the resonance of gyromotion with the *n*th harmonic of the magnetic field ripple[10]. In order to obtain detailed information on the dynamics of runaway beam and interaction of edge runaways with magnetic field ripple simultaneously, the runaway electrons have been measured recently in combination with hard x-ray detectors and thermographic camera in the HT-7 tokamak [11]. The parameters of runaway beam in the core can be deduced from the IR pictures, and the interaction of runway electron with toroidal magnetic field ripple can be monitored by the HXR spectra.

After an introduction into the HT-7 machine and runaway electron diagnostics in Sec.2, the experimental results from typical runaway discharges are presented in Sec.3. Finally, a summary is presented in Sec.4.

2. Experimental setup

HT-7 is a medium sized tokamak with superconducting toroidal coils and water-cooled graphite limiters in circular cross section [12]. It has a major radius of R_0 = 1.22 m, minor radius of a = 0.27 defined by one poloidal water-cooling limiter, one toroidal water-cooling belt limiter at high field side and a new set of actively cooled toroidal double-ring graphite limiters at bottom and top of the vacuum vessel. There are 24 superconducting toroidal field (TF) coils, which can create and maintain a toroidal magnetic field (B_t) of up to 2.5 T. The Ohmic heating system has an iron-core transformer with 1.7 VS flux. Twenty-four pieces of a ferromagnetic material (ferritic steel) have been installed inside the vacuum chamber for the reduction of the magnetic filed ripple. The ripple at the limiter radius of 27cm is reduced from 4% to about 1.6% at B_t=2 T. The HT-7 tokamak is normally operated with I_p=100–200 kA, B_t=2 T, line-averaged density $\bar{n}_e$=(0.5~4)×10^{19}m^{-3}, T_e= 1.0–3.0 keV, and T_i = 0.5–1.5 keV in limiter configuration.

Three NaI scintillators (2″×2″) are arranged tangentially on the equatorial plane to monitor the HXR in the energy ranges of 0.5-7 MeV. Two NaI detectors are arranged in the electron approach direction with different position, and a NaI detector is arranged in the ion approach direction as shown in Fig.1. The hard x-ray system is used to follow the energy and the intensity evolution of the runaway electrons since their appearance in the discharge. Two branches are used for the data acquisition. One provides the HXR intensity with 2 ms time-resolution, the other one is the standard pulse height analyzer (PHA). The multi-channel analyzer (MCA) system can acquire data for 20 seconds with 10ms time resolution and with 512 channel resolution.

A thermographic camera is used for the detection of the synchrotron radiation originated from the runaway electrons. The IR camera with 320×240 pixels is sensitive in the wavelength range of 7.5-13 μm, and works in the snapshot mode with frame rates 50 frames s^{-1}. Figure 2 shows the schematic top view of HT-7 with experimental set-up for IR measurements. With a tangential viewing into the plasma in the direction of electron approach on the equatorial plane, the synchrotron radiation from the runaway electrons can be measured with a full poloidal cross section.

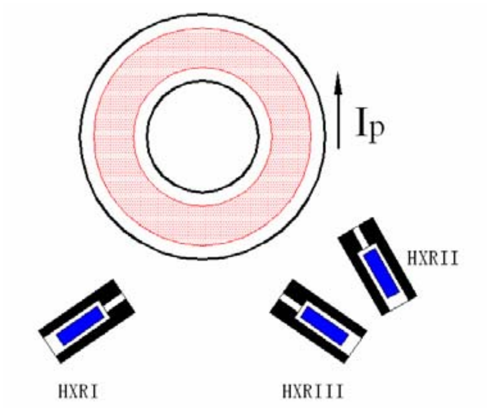

Fig.1. Schematic view of the tangential HXR diagnostics in the HT-7 tokamak.

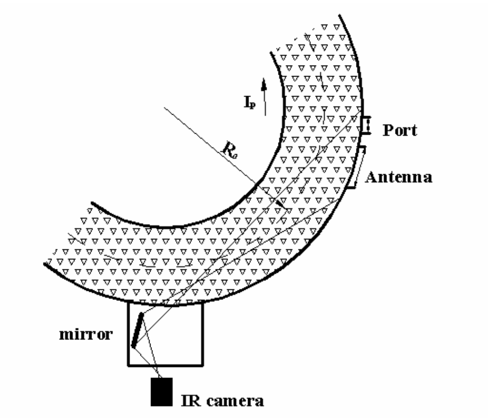

Fig.2. Schematic view of infrared measurement system in HT-7.

3. Experimental results

The runaway electrons speed up very quickly until the synchrotron radiation loss balances the energy gain in the electric field. The energy that a runaway electron reaches can be limited by the synchrotron radiation, the drift orbit shift, the flux swing, and the interaction with magnetic field ripple. In the present work, the resonance interaction of runaways with magnetic ripple is experimentally investigated by plasma current scan experiments in the HT-7 tokamak.

The toroidal magnetic field is generated by a finite number of coils. This slightly modulates the magnetic field and runaway electrons will experience this modulation at frequencies $\omega_{ripple} = nNc / R_0$. Runaway electrons accelerated by the electric field will experience a resonant interaction between their relativistic down-shifted cyclotron frequency ω_{ce} and the magnetic field ripple [10]. When a resonance occurs, the electrons are scattered in pitch angle θ, the power radiated per electron P will increase. Any pitch angle scattering process, increasing the energy perpendicular to the magnetic field and the power radiated by the electron, can create a barrier to a further increase in the runaway energy. A resonance occurs for $\gamma_{res} = eBR_0 / nNm_0c$ which corresponds to an energy $W_{\max}^{ripple}(MeV) = 0.511\frac{eB_tR_0}{nNm_ec}$. For typical HT-7 parameters, $W_{\max}^{ripple} = \frac{30}{n}(MeV)$. When the runaways accelerated in the toroidal electric field cannot cross a particular ripple resonance, they pile up at this resonance energy. The conditions under which the ripple mechanism can set a limit on the runaway energy have been investigated by a test particle model [13]. It is shown that, for a constant electric field, the strength of the resonance decreases with increasing harmonic number, for a given ripple amplitude, there is always a range of electric field values for which the interaction with the *n*th harmonic of the toroidal field ripple will create an upper bound on the runaway energy. So when the electric field is low, high harmonic number of ripple will be efficient in energy blocking. At higher electric field, the runaway electrons will cross this resonance until the interaction with lower harmonic number of ripple be efficient. Experimental evidence for efficient runaway-ripple interaction has been observed in several devices [10,13,14].

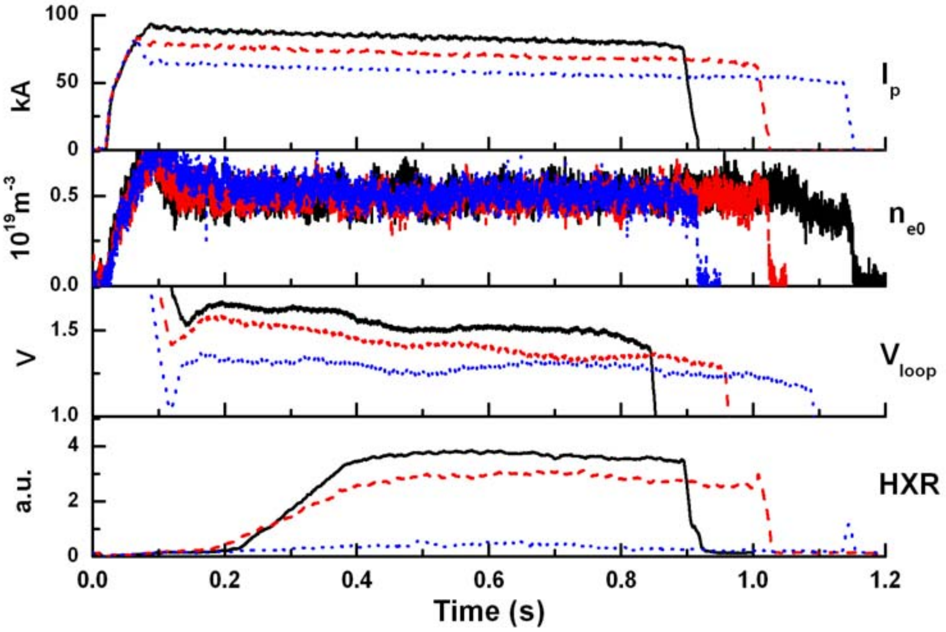

Fig.3 A serial of current scan discharges in the HT-7.

The experimental results presented in this paper were performed in current scan experiments at constant plasma density during runaway discharges. The density is about $0.5\times10^{19}\mathrm{m}^{-3}$, while the plasma current decreased from 80 kA to 60 kA with 10 kA step in a serial ohmic discharges as shown in Fig.3. For constant plasma density, the HXR flux is larger at higher plasma current due to higher electric field. This means the runaway population is larger.

In runaway discharge, the runaway electrons are being created in the startup phase. They become more and more energetic in the flat-top phase. With increasing time the energies of the HXR increase also, until for times above 0.6 s the bremsstralung spectrum stays constant. The HXR energy spectra at selected time internal (0.65 s-0.75 s) with different plasma current are shown in Fig.4. There are abnormal energy gap in the HXR spectra.

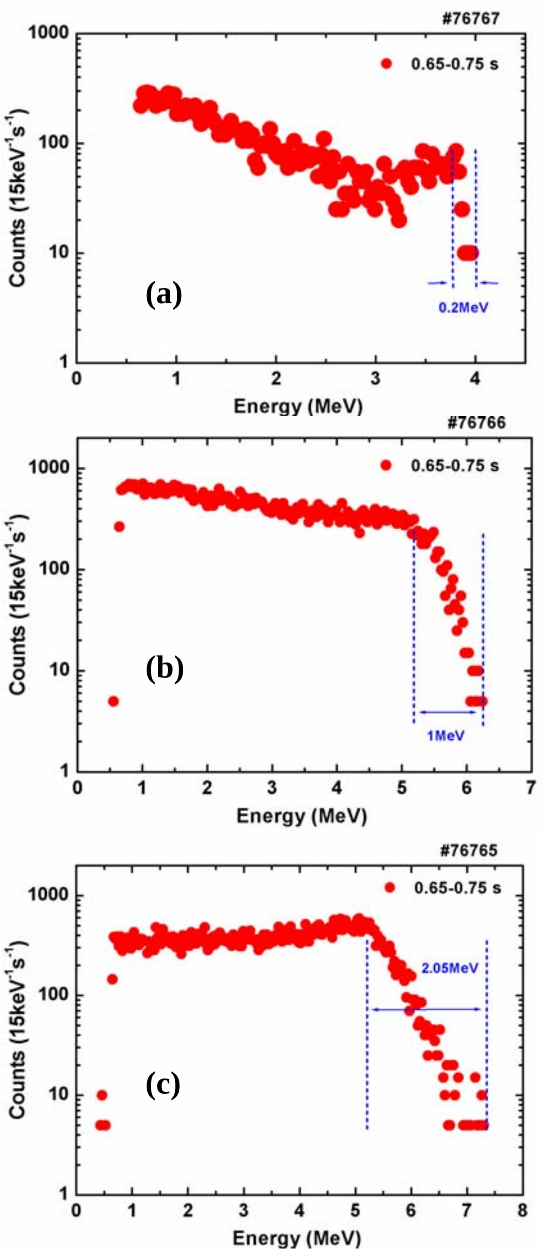

Fig.4 HXR spectra at 0.67s-0.75s for a serial current scan discharges. (a) HXR spectra at 0.65-0.75s for discharge #76767, (b) is HXR spectra at 0.65-0.75s for discharge #76766, (c) is HXR spectra at 0.65-0.75s for discharge #76765.

The runaway ripple interaction mechanism can quantitatively account for the observed energy limit of the runaways in HT-7. According to the IR signals, runaway electrons in the core have energy of above 20 MeV, while the energy limit of runaways in the edge is only several MeVs. The observed maximum energy of the runaways in the edge can not be directly loss of runaways from the core. A dramatic lowering of the energy stems from the gyromotion of the runaways with larger pitch angle. A very efficient mechanism to increase the pitch angle, and thus the synchrotron losses, which finally lead to the observed energy blocking of runaways, is the resonance of gyromotion with the *n*th harmonic of the magnetic field ripple [13]. It creates a barrier to a further increase in the runaway energy. Under different electric field value, the interaction of runaways with ripple has different harmonic number as the experimental results indicated. The energy limit of HXR spectra increases with increasing plasma current (loop voltage). The eighth harmonic resonance activity can quantitatively account for the observed energy limit in discharge No. 76767 as shown in Fig.4 a. The fifth harmonic resonance activity can quantitatively account for the observed energy limit in discharge No. 76766 as shown in Fig.4 b. The fourth harmonic resonance activity can quantitatively account for the observed energy limit in discharge No. 76765 as shown in Fig.4 c.

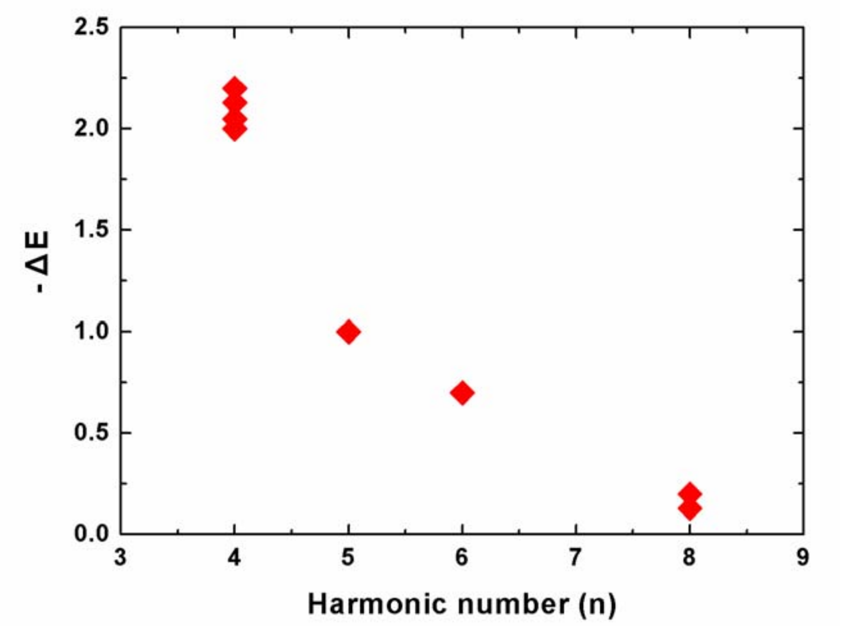

Fig.5 Resonance harmonic number n vs HXR spectra energy gap.

The value of energy limit is consistent with the resonance energy with harmonic number *n*. With decrease resonance harmonic number, the energy gap is larger. In another plasma density scan experiment at constant plasma current, similar results are derived. The energy gap at different harmonic number is shown in Fig.5. It is shown that, the strength of the resonance increases with decreasing harmonic number. At the 8th resonance interaction, the energy gap is only 0.2 MeV, while at the 4th resonance interaction, the energy gap increases to 2.05 MeV.

4. Conclusion

The anomalous energy gap in the HXR spectra can be well explained by the interaction of runaways with the *n*th harmonic of the magnetic field ripple. The resonance interaction could create an upper bound on the runaway energy in the low field side. Although the runaways has energy up to 26 MeV in the core, the edge runaway energy is blocked to a few MeV due to the strong interaction with magnetic field ripple. The additional barrier to limit the energy of runaways to a few MeV in the edge region is favorable for reducing the effect of runaways on first wall. This mechanism provides us a tool to control the energy of runaways for safer operation during disruptions.

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