Quasi-Periodic Mitigation of Runaway Electron Beam via Interaction with Kinetic Instabilities in the QUEST Spherical Tokamak

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Runaway electron (RE) driven kinetic instabilities have been observed in the QUEST spherical tokamak. A strong correlation between decay of the plasma current and activity of kinetic instabilities was first found with quasi-periodic behaviour during current quench. An efficient mitigation of RE by interaction with kinetic instabilities was experimentally demonstrated.

Keywords: runaway electron, kinetic instability, current quench, RE mitigation, spherical tokamak

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An intense toroidal electric field is produced during plasma current quench (CQ) in tokamaks. This field can promote electrons to runaway electrons (RE), and an excessive RE population can excite kinetic instabilities typically in the ion cyclotron frequency to whistler mode frequency range depending on the plasma parameters of magnetic confinement devices. These kinetic instabilities are expected to cause pitch-angle scattering of RE and elevate the critical electric field for avalanche generation of RE [1]. Therefore, they are of great interest to mitigate the RE beam during disruptions. The RE driven kinetic instabilities have been measured in several tokamaks [2–5] and spherical tokamaks [6, 7]. The resulting non-linear evolution of the kinetic instabilities in phase space is identifiable through frequency chirping. Fruitful kinds of kinetic instabilities behaviour in a wide frequency range from 3 to 250 MHz were observed in QUEST using high-frequency magnetic pickup coils located on the center stack and coils mounted in a fast reciprocating probe on the low field side [6]. The fast oscillations of the intensity of hard X-rays with kinetic instabilities was first found in QUEST by measuring fluctuations of the intense hard X-rays emissions using a scintillator sensor with a light decay constant of 2.1 ns, verifying the interaction of kinetic instabilities and fast electrons [6]. The kinetic instabilities can cause pitch-angle scattering of RE as shown in several simulations [1, 8], and resulting effects were partly indicated in the experiments through spikes in electron cyclotron emissions (indicative of increased perpendicular components) and reduced tail in the parallel energy spectrum obtained from hard X-rays measurements [5]. A correlation between kinetic instabilities activity and RE loss was also observed [5]. In this report, we first show a strong correlation between kinetic instabilities activity and the global plasma current (RE beam), which again supports a significant impact of kinetic instabilities on RE beam mitigation.

The data used to study a visible correlation between plasma current and kinetic instabilities have been collected on QUEST. These experimental sequences consist of a non-inductive plasma current start-up by electron cyclotron heating and current drive (ECH/ECCD) [9]. Figure 1(a) shows a representative discharge, where plasma current I_p is driven by ECCD from 2.06 to 3.46 s with slight assistance from the inductive loop voltage generated by the ramp-up of the poloidal fields for equilibrium. The spikes in I_p are often observed in these non-inductive start-up discharges on QUEST, which have been categorised into three types of sudden events so far [10]. After the termination of ECH/ECCD, sudden events disappear, and a smooth I_p follows until 3.80 s. Subsequently, as the center solenoid coil current was gradually ramped down from 3.80 through 3.95 s, I_p rapidly decayed primarily due to the imbalance in the equilibrium state. During CQ, a positive loop voltage of 0.3 V is induced that hinders the decay of I_p. The induced toroidal electric field also accelerates electrons to high energies of up to 500 keV in QUEST. Magnetic pickup coils data was recorded during CQ to be later processed to obtain spectrograms of magnetic fluctuations. In these spectrograms, many modes with characteristic chirping towards higher frequencies are visible as shown in Fig. 1(b). They range from a few 10 to 100 MHz in frequency, and from a few 10 µs to several 100 ms in duration. Among the shots analysed, about 1 in 10 exhibits sequences

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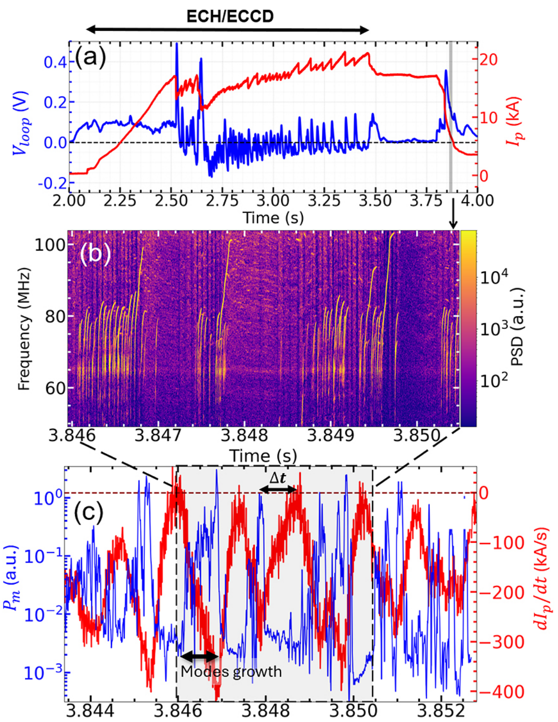

Fig. 1. (a) Waveforms of plasma current and equatorial loop potential for shot #54085. The CQ time interval shown in Fig. 1(c) is highlighted in gray. (b) Spectrogram of magnetic fluctuations of the sequence of short modes bunches. (c) Modes intensity parameter P_m and dI_p/dt during the sequence.

of short 10–100 μs modes activity bunches spanning several 100 ms. These features of the spectrograms are used to study the correlation between modes activity and variations of I_p during CQ. Modes activity during these sequences is quantified by the modes intensity parameter P_m, defined by the following formula for the time point corresponding to an interval $[t, t+\delta t]$:

$$P_m([t, t+\delta t]) = \frac{\int_t^{t+\delta t} \int_{49\text{MHz}}^{101\text{MHz}} \text{PSD}(f, t')\, df\, dt'}{\max_{\text{spectrogram}}(\text{PSD})}. \quad (1)$$

P_m is plotted together with the time derivative of the plasma current dI_p/dt in Fig. 1(c).

A quasi-periodic behaviour of modes intensity is visible, and for each quasi-period, the increase of dI_p/dt in the negative direction is observed together with the growth of the modes. Namely, while dI_p/dt is always negative during CQ, its ramp-down speed "$d|I_p|/dt$" is accelerated when the modes appear and decelerated when the modes disappear. The delay between the peak of mode activity and the following upward peak of dI_p/dt is estimated at Δt = (580 ± 100) μs for the analysed shots. This time would be associated with the time taken for the electron distribution to become unstable for the modes again.

Figure 2 shows the relationship between $d|I_p|/dt$ and P_m during 3 cycles of the quasi-periodic behaviour, defined between successive minima of $d|I_p|/dt$. The correlation seen in Fig. 1(c) is more clearly visible. The higher P_m becomes,

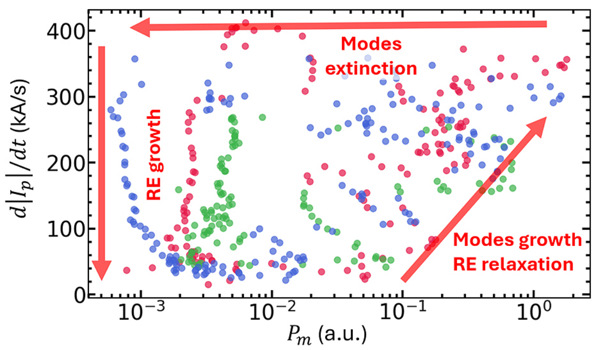

Fig. 2. $d|I_p|/dt$ vs. P_m for 3 cycles (red, green, blue) between local minima of $d|I_p|/dt$ on the time interval 3.846–3.85024s (indicated with dashed lines in Fig. 1(c)).

the more $d|I_p|/dt$ increases. Because most of I_p is carried by RE during CQ (electron density is much less than 10^{17} m^{-3}, which is the lowest value measurable at present in QUEST), variation in dI_p/dt strongly reflects the RE population and its energy. Thus, the acceleration of I_p decay speed coinciding with modes growth indicates that the RE driven current (or RE beam) is mitigated through interaction with the kinetic modes. This is also visible from the observation that $d|I_p|/dt$ again slows down after the modes disappear. In other words, disappearance of the modes enables re-generation of the RE beam via the toroidal electric field during the CQ period.

The variation of dI_p/dt correlated with modes activity is first shown. Pitch-angle scattering by the modes causes changes in the orbits of RE, and consequently leads to enhanced loss of RE to the wall. Improvements in plasma parameter measurements and an upgrade of the unique energetic particle probe [6] to assess the pitch-angle distribution of the RE beam will be pursued on QUEST. In addition, suppression of RE generation, as suggested by [1] is also of great interest. Experimental clarification of these effects and their relevance to a fusion reactor remains to be investigated in the future.

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