Influence of toroidal alfvénic instability on runaway electron generation in HL-2A tokamak

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Introduction

Runaway electron (RE) generation in the presence of electric fields is common in both laboratory and space plasmas [1]. In laboratory plasmas, much attention has been given to the highly relativistic RE beams that can be generated in tokamak disruptions. Such REs may damage plasma facing components due to their highly localized energy deposition. The potential for detrimental effects increases with plasma current. Therefore, understanding the processes that may eliminate RE beam formation is very important for future reactor-scale tokamaks with high currents, such as ITER [2]. In several tokamak experiments it has been observed that RE generation only occurs above a threshold toroidal magnetic field [3, 4]. While the origin of this threshold is uncertain, it has been linked to decreased relative magnetic fluctuation levels [4-6].

Observation of the high frequency mode

Recent work at the HL-2A tokamak has shown the presence of instabilities in the frequency range f ~ 80 − 150kHz, during disruptions deliberately triggered by the massive gas injection (MGI) of argon in an Ohmic discharge (Fig. 1(a)). The experiments were carried out with the following parameters: B_T=1.38T, I_P=150 kA, n_e=0.7-1×$10^{19}$$m^{-3}$, the number of injected Ar particles changing from 1×10^{20} to 10×10^{20}. The obvious high frequency mode has been observed in the magnetic pick-up coils with the sampling rate of 1 MHz (see Fig. 1(d)). This mode occurs at the beginning of the

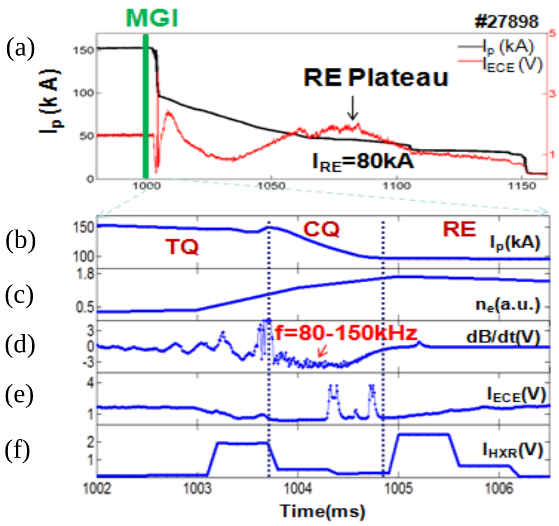

Figure 1: *(a) The fast shutdown experiment with long RE plateau by argon injection at the HL-2A tokamak. The current quench occurs at about 2.8 ms after triggering the MGI in shot 27898. (b) Time traces in the current quench phase showing plasma current I_P,(c) electron density n_e, (d) radiation of Electron Cyclotron Emission I_{ECE}, (e) magnetic turbulence dB/dt, and (f) hard x-ray radiation I_{HXR}.*

current quench(CQ) and lasts about 1ms. The mode number is n=1, and m=2 or 3. After the onset of the high frequency mode, large bursts on ECE singles present(see Fig. 1(e)), just prior to the runaway generation. Concerrently, the ECE radiation profile is peaked and moves outwards, as signified in the bursts of the hard X-ray radiation (Fig. 1(f)). The existence of the REs before the mode onset seems to be in accordance with the burst of hard X-ray in the thermal quench period (see Fig. 1(f)). The presence of these instabilities appears to be favorable in limiting the RE beam formation.

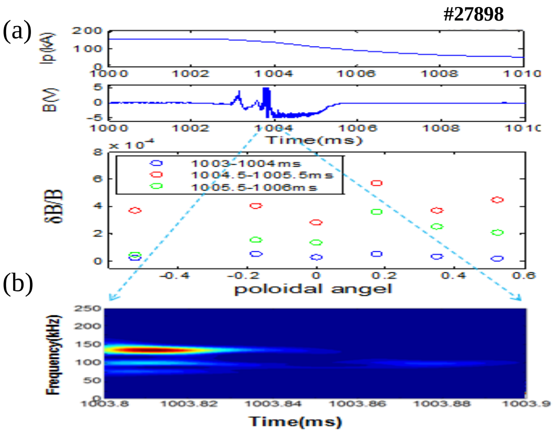

Figure 2: *High frequency mode during CQ before RE current. (a) the mode level;* (b) *spectrogram of Mirnov signal.*

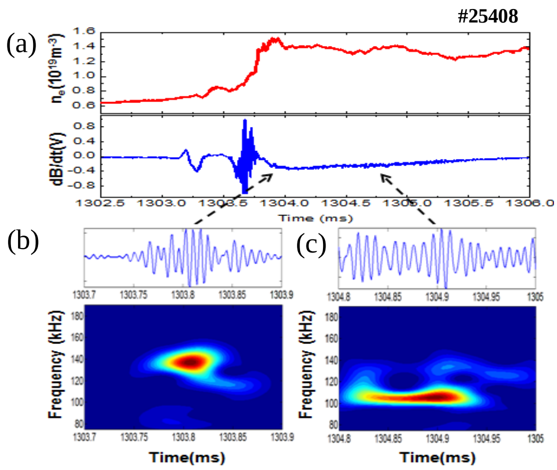

Figure 3: *(a) Time evolution of the electron density at the central and Mirnov signal with high frequency mode in shot 25408. (b) (c) The mode frequency changes with the n_e.*

Behavior of the mode frequency

The magnetic fluctuation level of the high frequency mode, $\delta B/B_T$, during the current quench is stronger than that at the beginning of the current quench, and then becomes weaker before RE generation (Fig. 2(a)). A typical frequency spectrum of high frequency mode is shown in Fig. 2(b). The spectrum shows that the frequencies of the mode form a wide distribution and most of the power is in the range from 80 to 150 kHz. Comparing the signals of different Mirnov coils distributed along the poloidal circumference of the liner shows that the magnetic turbulence is poloidally asymmetric (Fig. 2(a)). The mode level at the low field side is higher than that at the high field side. Poloidal asymmetry during the current quench could be an indication that the plasma is shrinking and moving inward [6].

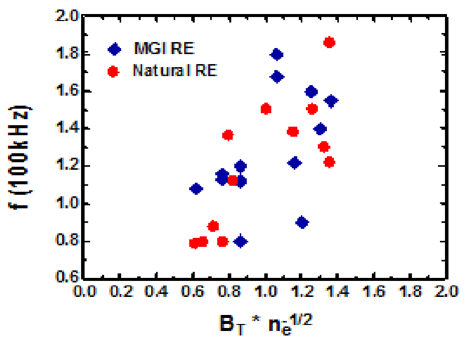

Figure 4: *Relationship between the RE current and the mode level $\delta B/B_T$.*

The High frequency mode is mainly attributed to background plasmas. Figure 3 shows the time evolution of the line-averaged electron density in the centre and Mirnov signal with high frequency mode. The mode frequency is higher at low density and decreases with the increase of n_e (fig. 3(b, c)), suggesting that the mode has the behavior of an Alfvén-like mode. The statistical analysis with a few MGI induced disruptions shots and natural disruptions shots both with RE plateaus was made to verify the relationship between Alfvén speed $V_A \approx B_T{*}n_e^{-1/2}$ and mode frequency. It is found that the mode frequency increases with plasma density and scales rougly with $n_e^{-1/2}$, consistent with the characteristic of the toroidal alfvén eignmode (TAE), as shown in Fig.4.

In order to prove this point, we have calculated the spectrum of Alfvén modes using the shear Alfvén dispersion relation [7]:

$$\begin{vmatrix} \Omega^2-\Omega_m^2 & (r/R+\Delta'+\sigma)\Omega^2+(r/R+\Delta'-\sigma)\Omega_m\Omega_{m+1} \\ (r/R+\Delta'+\sigma)\Omega^2+(r/R+\Delta'-\sigma)\Omega_m\Omega_{m+1} & \Omega^2-\Omega_{m+1}^2 \end{vmatrix}=0$$

The frequency is $f_{TAE}=\frac{nV_A}{2\pi(2m+1)}$. The comparison between the experimentally observed mode frequencies and the simulated ones are illustrated in figure 5 at two different densities during the CQ phase. Figures 5 (a) and (b) show that the measured frequencies are f≈130kHz and 60-100kHz at $n_e=1.1\times10^{19}m^{-3}$ and $1.8\times10^{19}m^{-3}$, respectively, which are in fairly agreement with the simualted gap frequecnies of the TAE modes, as depicted in figures 5(c) and (d). Therefore, the mode is an TAE mode.

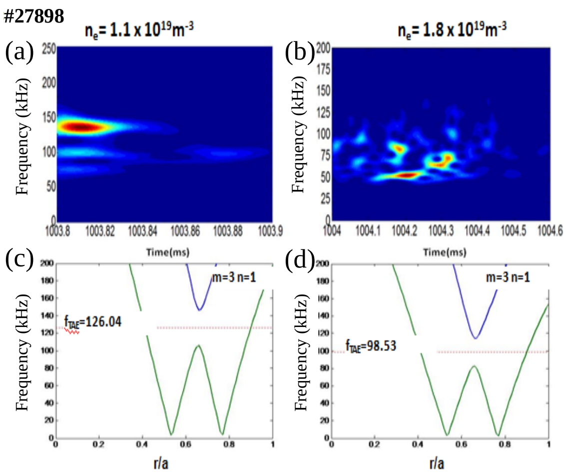

Figure 5: *Spectrograms (a) (b) and the Alfvén Spectrum simulations (c) (d) of thehigh frequency mode during the current quench phase with the different electron density in shot 27898.*

$\delta B/B_T$ dependence

It has been found that the $\delta B/B_T$ is associted with the amount of injected particle number (N_{inj}). Figure 6(a) shows the I_p of the three continuous shots with different N_{inj}. The parameters of all shots 25406, 25407 and 25408 are the same except for the N_{inj}, but the RE generation is totally different. The increasing N_{inj} of Ar leads to different kinds of disruption: internal reconnections events (IR); RE Tail (RET) and RE Plateau (REP). RET develops a small RE current tail, and REP has a RE plateau

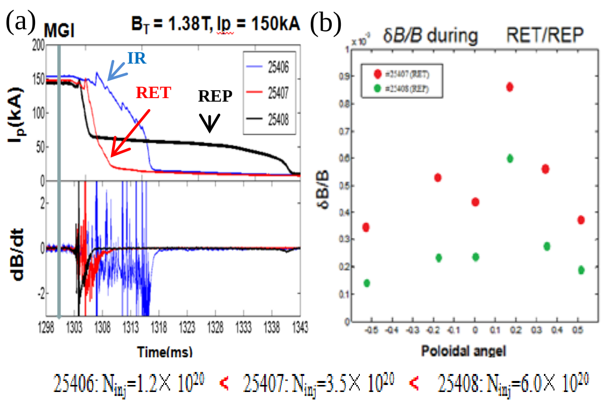

Figure 6: *(a) Time traces from three discharges in the CQ phase showing: plasma current IP and magnetic turbulence dB/dt in shots 25406, 25407 and 25408. (b) The mode level $\delta B/B_T$ during RET and REP cases.*

during the current quench. However, IR does not produce any RE current. Meanwhile, obvious magnetic instabilities are seen during CQ phase in signals from magnetic pick-up coils, shown in Fig. 6(a). The magnetic turbulence appears at IR case is obviously different from those of RET and REP, because the frenqucy(~20kHz) is quite lower than those of two others(~100kHz). It indicates the high frequency mode only occurs before the RE generation. Figure 6(b) compares the mode level $\delta B/B_T$ during RET and REP cases, respectively. The $\delta B/B_T$ of RET is about 1.5 times than that of REP. Anomalous RE losses with RET are therefore much larger than with REP.

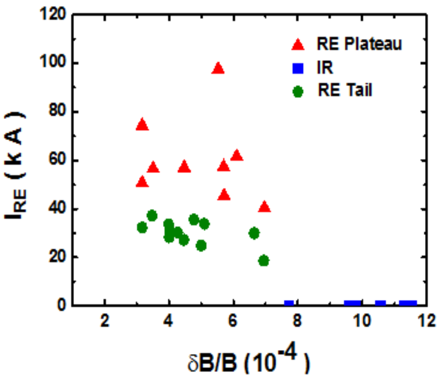

Figure 7: *Relationship between the RE current and the mode level $\delta B/B_T$.*

The satistic results of several discharges with three kinds of disruptions indicate that the runaway current I_{RE} varies with $\delta B/B_T$ during the current quench, shown in Fig. 7. The runaway current is invisible when the normalized magnetic fluctuation level exceeds the threshold of about 7.8×10^{-4}. The runaway plateau is easy to obtain on the condition of low $\delta B/B_T$. For shots with lower mode level than the threshold, it is found that the RE current decreases almost linearly with $\delta B/B_T$. It has been found that in case of small $\delta B/B_T$, the bursts in the ECE emission and subsequent radiation level in the hard X-ray are much weaker, and correspondingly, the RE current becomes larger. This result clearly indicates that this magnetic mode plays a scattering role on the RE beam strength and is the cause of the different observed RE current. The excitation of the mode might be driven by a steep spatial gradient of REs or whistling runaway ions form an invertedenergy distribution[7]. The magnetic perturbation associated with the instability is expected to scatter the runaway electrons and in certain cases may therefore stop beam formation.

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