TAE during minor disruptions in the SUNIST spherical tokamak

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Abstract. Toroidal Alfven eigenmodes (TAEs) excited in purely ohmically heated plasmas without any auxiliary heating have been identified for the first time in the SUNIST spherical tokamak. The TAE modes are observed during minor disruptions and have a frequency range of 150-500 kHz. The mode structure analysis indicates the existence of both $m/n = -3/-1$ and $-4/-1$ harmonics, propagating in the electron diamagnetic direction in the laboratory frame of reference. These TAEs appear simultaneously with the generation of runaway electrons in the current quench phase, accompanying with the density sweeping during the minor disruption. Driving mechanisms and potential applications of these TAEs are discussed.

1. Motivation

Toroidal Alfven eigenmodes (TAEs) driven by fast particles are of particular importance for future burning plasma devices, where energetic particles will be abundantly produced by fusion reactions1. As shown in experiments on the tokamaks TFTR2 and D-IIID3 , TAEs are the most dangerous from the point of view of fast particle redistribution and losses. Furthermore, TAEs were first predicted theoretically to be excited by energetic particles4, extensive efforts for exciting TAEs have been made in tokamak plasmas in order to understand the mechanisms. In present tokamak experiments, the destabilization of TAEs has been widely investigated in different devices using super-Alfvenic ions generated by auxiliary heating systems such as neutral beam injection and ion cyclotron resonant heating5, 6 and active excitation by saddle coils7. As we know, the excitation of TAEs depends on the energy of the particles rather than the mass, so that energetic electrons can also drive these unstable TAEs. Fast electron driven TAEs were first seen on Compass-D with electron cyclotron heating only8 and on Alcator C-mod with lower hybrid current drive during the plasma current rising9. Runaway electrons (REs) are also a source of energetic particles and are naturally supposed to be able to excite TAEs. However, the TAE related to REs are rarely reported. Although Alfve-type oscillations excited by REs have been observed in the ohmic regime of TUMAN-3M tokamak [S.V. Lebedev, L.G. Askinazi, I.A. Balachenkov, A.A. Belokurov, V.A. Kornev, A.S. Tukachinsky, N.A. Zhubr, in 43rd EPS Conference on Plasma Physics, Vol. 40A (2016) p. P5.036.], they are not TAEs. Magnetic fluctuations in the frequency range $f \simeq 60$–260 kHz during disruptions without runaway plateaus have been observed in TEXTOR tokamak10. Later theoretical studies suggested that such magnetic fluctuations may be TAE driven by REs11, but no clear experimental evidences have been given. In this letter, we present the first experimental observation of TAEs accompanied by the bursts of REs during minor disruptions of purely ohmically heated plasmas without any auxiliary heating in the SUNIST spherical tokamak.

2. The Experimental Results

SUNIST is a small spherical tokamak (ST) with major radius R=0.3 m and minor radius a=0.23 m. The experiments discussed here were performed in ohmic plasmas with plasma current Ip=40 kA, toroidal magnetic field Bt=0.15 T. The line-averaged density measured by a 94 GHz microwave interferometer was in the range of 0.2-6×1018 m−3. The hard x-ray (HXR) detected by cadmium-zinc-telluride (CdZnTe) with a narrow collimating aperture was used to estimate the energy of REs.

Owing to the ST configuration, ohmic discharges of SUNIST are seldom terminated by one major disruption. The plasma current often decreases in a stepwise form caused by a sequence of minor disruptions. During these minor disruptions high-frequency magnetic fluctuations are observed from the signals detected by an array of high-frequency magnetic probes sampled at 15MHz12. As shown in Fig. 1, a kind of high frequency MHD modes occur during each minor disruptions which all have significant runaway plateaus. The frequency range of these modes is 150-500 kHz. Their toroidal and poloidal mode numbers are $n = -1$ and $-4 \leq m \leq -3$, respectively, as shown in Fig. 2. The mode structure analysis indicates the co-existence of $m/n = -3/-1$ and $-4/-1$ harmonics, propagating toroidally opposite to the direction of plasma current and poloidally in the electron diamagnetic drift direction in the laboratory frame of reference.

There are several minor disruptions in one discharge shown in Fig. 1. It can be found that the mode frequency is higher at low density and vice versa, suggesting that the modes may be Alfven-type modes. In order to verify it, a statistical analysis with about 200 shots was made. Fig. 3 illustrates that the observed mode frequency scales linearly with the TAE frequency $f_{TAE}=v_A/4\pi qR$, where $v_A=B_t/\sqrt{(\mu_0 \rho)}$ is the Alfven velocity, ρ is the mass density, q is the safety factor and R is the major radius. In the calculations, the line-averaged density and the on-axis toroidal field are used to estimate the Alfven velocity, and the safety factor is estimated by mode numbers. The scatter of data points in Fig. 3 is mainly due to the variation of the size of plasma column on which the line-averaged density is depended. Therefore, these high frequency MHD modes should be TAEs.

The GTAW code13 was employed to calculate the frequency and mode structure of Alfven eigenmodes in SUNIST equilibrium. Figure 4(a) shows that a mode with f=200 kHz is just within the $n = -1$ TAE gap due to the coupling of the $m = -3$ and $m = -4$ harmonics. The radial structure of the mode is plotted in Fig. 4(b), which shows the $m = -3$ and $m = -4$ harmonics are dominant. These dominant harmonics can also be seen in the contour plot of the radial displacement of the mode on the poloidal plane in Fig.4(c). Moreover, Figure 4(c) shows that this TAE mode exhibits a ballooning-like structure5, 14 , i.e., the displacement on the low field side is stronger than that on the high field side. This character is consistent with the poloidal variation of measured magnetic field fluctuations, which is given in Fig. 4(d).

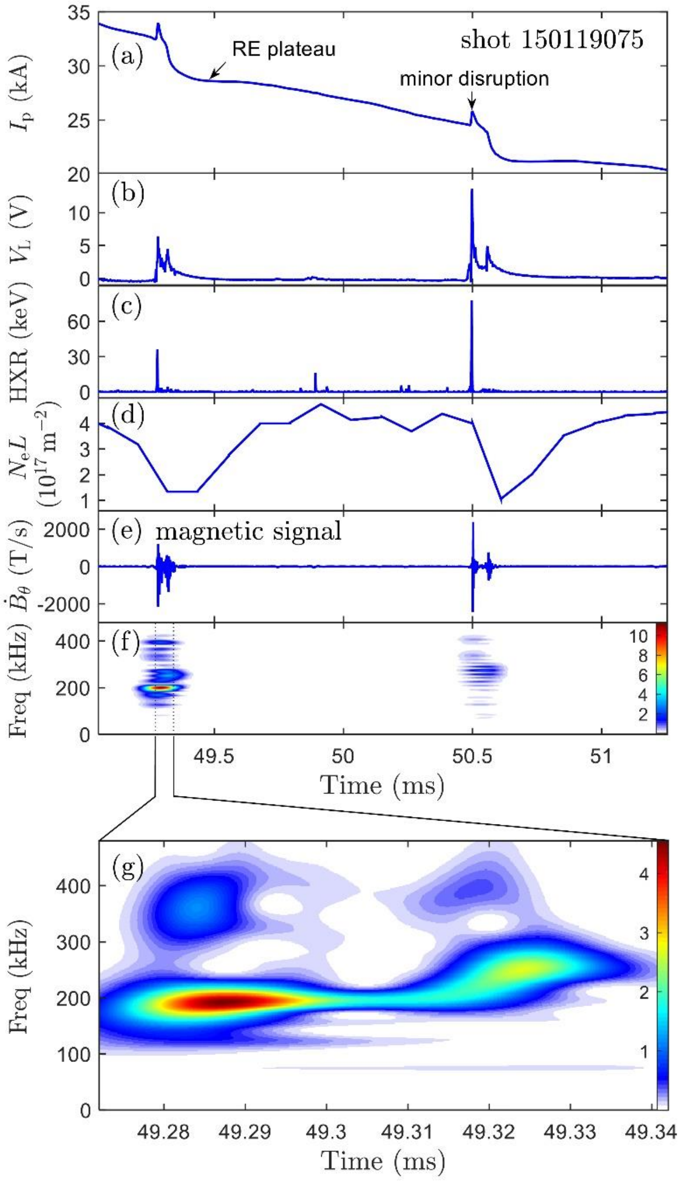

FIG. 1. Time evolution of (a) plasma current, (b) loop voltage, (c) hard x-ray (HXR), (d)line-averaged electron density, (e) magnetic probe signal, (f) the spectrogram of a magnetic probe signal and (g) detail of the spectrogram of a magnetic probe signal in a minor disruption.

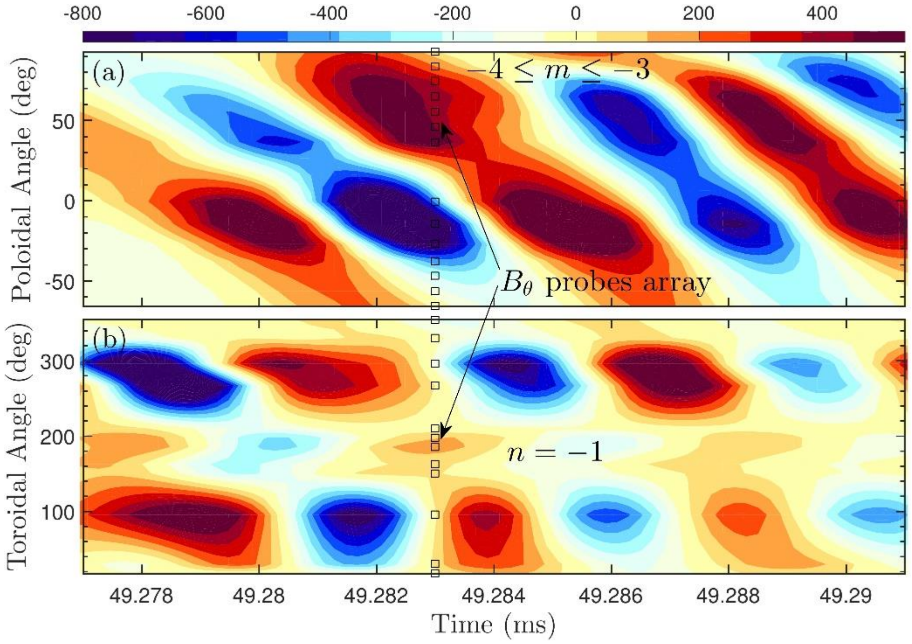

FIG. 2. Poloidal and toroidal mode numbers of MHD instabilities at TAE frequency range (30-300 kHz).

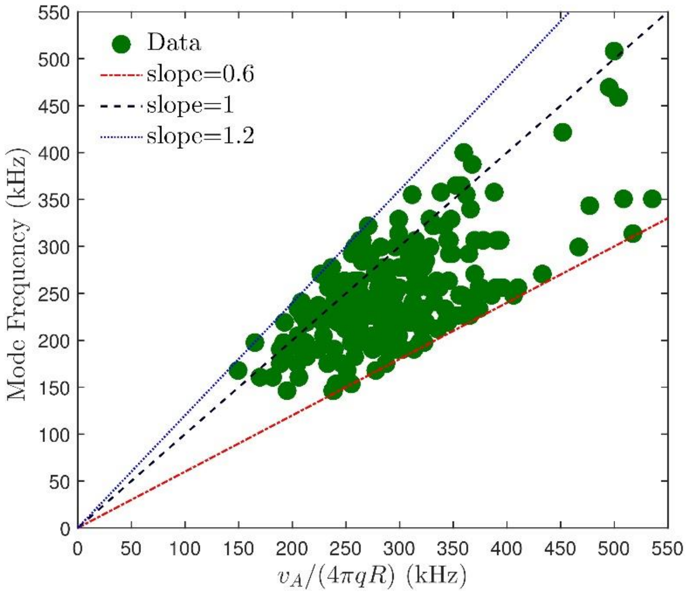

FIG. 3. Comparison of the observed mode frequencies during minor disruptions with the expected TAE frequencies.

The dependence of the impedance of antennas with BN limiters on toroidal field is shown in *FIG. 4*. It is obvious that the dependence becomes much weak when the antennas are shielded. This suggests an over protection by the BN limiters. A compromise between the protection and the coupling should be found. Until now, the data points of the impedance curve are not enough to find resonances of specific modes.

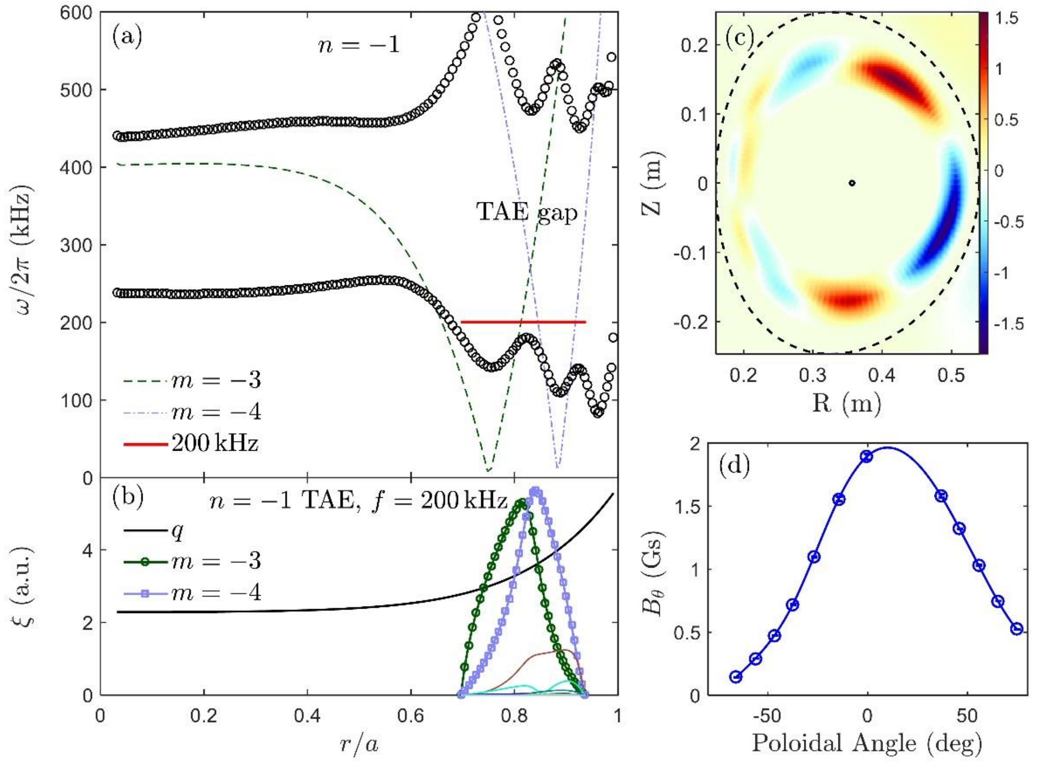

FIG. 4. (a) The n = −1 Alfven continuum calculated with an estimated q prole showing that the 200 kHz mode lies in the TAE gap. Also plotted are the m = −3 and m = −4 Alfven continua in the cylindrical geometry limit. The red line denotes the radial range used in the numerical calculation, which is chosen in order to avoid the continuum resonance. (b) Radial prole of the safety factor and radial structure of the amplitude of the n = −1 TAE mode at f = 200 kHz. (c)Two-dimensional structure of the real part of radial plasma displacement of the n = −1 TAE mode. (d) Measurement of the poloidal variation of the mode amplitudes for the TAE. Here, 0°is at the outer midplane, and positive angles correspond to the upper part. The equilibrium is for SUNIST shot 150119075 at 49.29 ms.

3. Discussion

TAEs observed in SUNIST are excited at the moment of minor disruptions in pure ohmic regimes, when energetic REs can be generated. Given that fast ions are practically absent in the ohmic plasmas of SUNIST, and the measured mode rotation direction is in the electron direction in the lab frame, energetic REs generated during minor disruptions are considered to be a possible driver of TAEs due to a resonant interaction of REs with the precession drift frequency $\omega=\omega_d$, where ω is the mode frequency and ω_d is the processional drift frequency of REs15. Considering the experimentally measured TAE frequency in the SUNIST case, the expression for the averaged RE energy that would match the precession drift resonance condition is approximately $T_h(\mathrm{keV}) \sim 2\pi f_{TAE} B_t R_r/(|n|q)$, where T_h is the energy of the resonant REs, f_{TAE} is observed TAE frequency, B_t is the toroidal field on axis, R is the major radius, n is the toroidal mode number, q is the safety factor associated with the resonant surface localized at the small radius r. Taking, $f_{TAE} \sim 200$ kHz, $B_t = 0.15$ T, $R = 0.3$ m, $r = 0.15$ m, $n = -1$, $q = 3.5$ for SUNIST shot 150119075 at 49.29 ms, $T_h \sim 2.4$ keV. Considering the sampling effect of collimated CdZnTe detectors and the broad energy spectrum of REs, the HXR burst shown in Fig. 1(c) implies the existence of a large amount of REs with energy in the vicinity of Th. The resonance condition for RE driven TAEs appears to be satisfied for these experimental conditions for SUNIST shot 150119075 accompanying with the change of the electron density. It is noted that the density sweeping during the minor disruption is important for matching the resonant condition. In Fig. 1(g), when the density decreases continuously, the TAEs are excited twice, with different frequencies corresponding to different density. On the contrary, although there is another HXR burst with energy 16 keV for SUNIST shot 150119075 at 49.89 ms shown in Fig. 1(c), the resonance condition for RE driven TAEs may not be satisfied since the electron density is nearly unchanged. After all, that REs drive TAEs wave-particle resonance in the precession frequency is just a preliminary conjecture. Other possible mechanisms are still open for interpolating the experimental observations.

Recently in the MAST [M. Gryaznevich, private communication.] and J-TEXT [Z. Y. Chen, private communication.], there were also observed some high frequency Alfven-like MHD oscillations during minor or major disruptions. All of these indicates there should be some stories between Alfven instabilities and disruption/RE. However, the driving mechanisms of these TAEs are still open. For example, another possible mechanism might be the distortion of the electron distribution function due to the generation of REs near the trapped to passing boundary, where the bounce frequency of electrons can be resonant with TAEs [F. Zonca, private communication.].

The experimental data presented here identify a TAE in the ohmic plasmas of SUNIST. The TAE is observed during minor disruptions with RE plateau. The measured mode frequency is consistent with the calculated TAE frequency, while the mode propagates in the electron diamagnetic drift direction. From the wave-precession drift resonance mechanism, the excitation condition of TAE is calculated and can be satisfied in the SUNIST spherical tokamak. However, the mechanism of TAEs excitation by runaway electrons is still an open question. More theoretical and experimental efforts are needed to interpret these observations.

4. Acknowledgements

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