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Excitation of Internal Kink Instability during Off-Axis Electron Cyclotron Heating in the DIII–D Tokamak

K.L. Wong,[1] M.S. Chu,[2] T.C. Luce,[2] C.C. Petty,[2] P.A. Politzer,[2] R. Prater,[2] L. Chen,[3] R.W. Harvey,[4] M.E. Austin,[5] L.C. Johnson,[1] R.J. La Haye,[2] and R.T. Snider[2]

[1]*Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543.*
[2]*General Atomics, P.O.Box 85608, San Diego, CA 92186.*
[3]*Department of Physics, University of California, Irvine, CA.*
[4]*CompX, Del Mar, CA.*
[5]*University of Texas, Austin, TX*

Experimental evidence is reported of an internal kink instability driven by a new mechanism: barely trapped suprathermal electrons produced by off-axis ECH/ECCD [1] in the DIII–D tokamak. It occurs under some conditions in beam-heated plasmas with an evolving safety factor profile q(r) when q_{min} approaches 1. This instability is most active when ECH is applied on the high-field-side of the flux surface. It has m/n=1/1 with a bursting behavior. In positive magnetic shear plasmas, this mode becomes the fishbone instability usually driven by deeply trapped energetic ions via precessional resonance. This observation can be qualitatively explained by wave-particle interaction with the barely trapped suprathermal electrons produced by off-axis ECH. It is a very special situation where the diamagnetic drift velocity and the precession velocity of the barely trapped suprathermal electrons at the q=1 surface are parallel to those of the deeply trapped energetic ions so that they can resonate with the same 1/1 mode and drive it together. The instability cannot exist in plasmas with $q_{min} > 1$. When there is a q=1 surface in the plasma, the instability may be avoided by placing the ECH location far enough from the q=1 surface.

The 110 GHz ECH experiment was carried out in the DIII–D tokamak with the following parameters: $B_T = -1.77$ T, $I_p = 0.89$ MA, R = 1.76 m, a = 0.62 m, $q_{95} = 6.06$, q_{min}~1, $\rho_{q_{min}}$~0.2 which is near the flux surface where peak wave power absorption occurs. The wave absorption occurs near the second harmonic resonance layer ($\omega = 2\ \omega_{ce}$) which is on the high field side of the magnetic surface. The electron temperature profile in the plasma core is measured by the 32 channel electron cyclotron emission (ECE) system at the second harmonic frequency. The results are in good agreement with measurements from Thomson scattering.

2.5 MW of deuterium neutral beam from a single source is injected into DIII–D early at t = 0.5 s to produce the negative central shear (NCS) plasma [2]. 1.1 MW of 110 GHz microwave power from two gyrotrons is injected at t = 1.2 s. At t = 1520 ms, the plasma q profile has strong negative central shear (NCS) with q(0) = 2.6, q_{min} ~ 1.0 , and bursts of MHD activities start to appear in ECE, soft X–ray and Mirnov loop signals. In most of the cases, the frequency is fixed at a value near 10 kHz which is close to the toroidal rotation frequency at the q=1 surface measured by charge-exchange recombination spectroscopy (CER). This is consistent with the toroidal mode number n = 1 determined by the toroidal array of Mirnov loops.

We analyze the ECE data with the singular-value-decomposition (SVD) technique. The deviation of the electron temperature from the average temperature, δT_e, is analyzed. Fig. 1(a) and Fig. 1(b) show the results for the time interval t = 1.5–1.6 s when there is 1.1 MW of ECH power from two gyrotrons. The topos (spatial eigenfunction) clearly shows a m=1 structure (m is the poloidal mode number). The chronos (temporal eigenfunction) exhibits the growth and decay of the mode. Each burst correlates with a drop in the central electron temperature as detected by ECE measurements shown in Fig. 1(c). These are m/n = 1/1 modes. Stability analysis by the GATO code (contains no energetic particles) shows that the 1/1 ideal mode is stable for this plasma equilibrium. The existence of the 1/1 mode suggests the presence of energetic particle (ions and electrons) drive. There is an intrinsic uncertainty of order 0.1 in the MSE measurement of q(r) [2]. Should q_{min} fall below 1.0, these would be double kink modes.

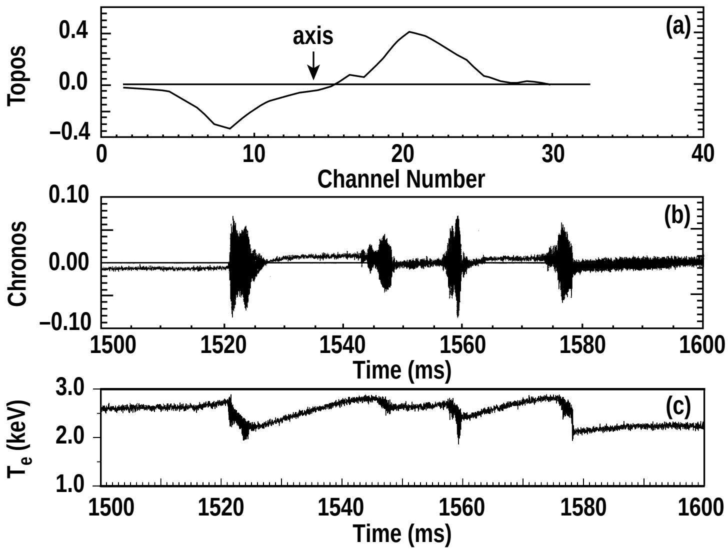

Fig.1. Results from SVD analysis of ECE data from 1500–1600 ms. (a) Topos showing m =1 structure. (b) Chronos of the m=1 mode showing the bursting behavior. (c) Dips in central electron temperature (ECE) that correlate with the MHD bursts.

The plasma q profile evolves with time during the shot. After t = 1.72 s, q(0) drops to a value near q_{min} which is close to 1.0, and MHD bursts can appear between sawtooth crashes. The plasma equilibrium is analyzed with the EFIT code, and the results are used by the GATO code for stability analysis. The 1/1 mode is marginally unstable in this case and the mode structure is obtained. From the plasma displacement ξ on the midplane, we calculate the topos by $\delta T_e = \xi\, dT_e/dr$. The result is in qualitative agreement with experimental observations.

Fishbone instabilities in tokamaks are m=1 internal kink modes driven by deeply trapped energetic ions via precessional resonance. The energetic ion pressure gradient is the source of free energy for this instability. The beam deposition profile peaks near the magnetic axis and the mode propagates poloidally parallel to the ion diamagnetic drift velocity ($k_\theta \parallel v_{di}$) and toroidally parallel to the precession velocity $\langle v_\phi \rangle$ of deeply trapped ions which is in the same direction as the plasma current. Since effective energy exchange during wave-particle interaction requires that the particles resonate with the wave, one would not expect electrons and ions to resonate with the same mode and drive it together because they usually drift in opposite directions due to their opposite electric charges.

During off-axis ECCD experiments, a small number of suprathermal electrons are preferentially heated by obliquely propagating waves. In our analysis, the bulk of the electron distribution function f(v) is represented by a Maxwellian $f_m(v)$, and the suprathermal electrons are those in the tail of f(v) which deviates from $f_m(v)$. We use the TORAY-GA ray tracing code [3] to calculate the wave absorption profile and the CQL3D Fokker-Planck code [4] to calculate the bounce-averaged electron distribution function. Detailed analysis was carried out for shot 96163 where the resonance layer was placed at the high field side of the flux surface. The calculated wave power deposition peaks near ρ=r/a=0.16, so does the suprathermal electron energy density. On this flux surface, calculations show that 1.4% of the electrons are suprathermal electrons with 7.9% of the total electron energy; 0.27% electrons have energy above 36 keV and they possess 3.4% of the electron energy. The calculated population of barely trapped electrons with energy above 36 keV has hollow profiles as shown in Fig. 2. Therefore, in the region where the energetic trapped electron density gradient is positive, the diamagnetic drift velocity of these electrons is parallel to that of the energetic ions produced by neutral beam injection. The precessional direction of the trapped electrons on the outboard side (θ<90°) is opposite to that of the deeply trapped ions; it reverses direction at θ>90° because the vertical component of the poloidal magnetic field reverses sign. For barely trapped electrons, the precessional direction averaged over the entire orbit is parallel to that of the deeply trapped ions because they spend more time on the inboard

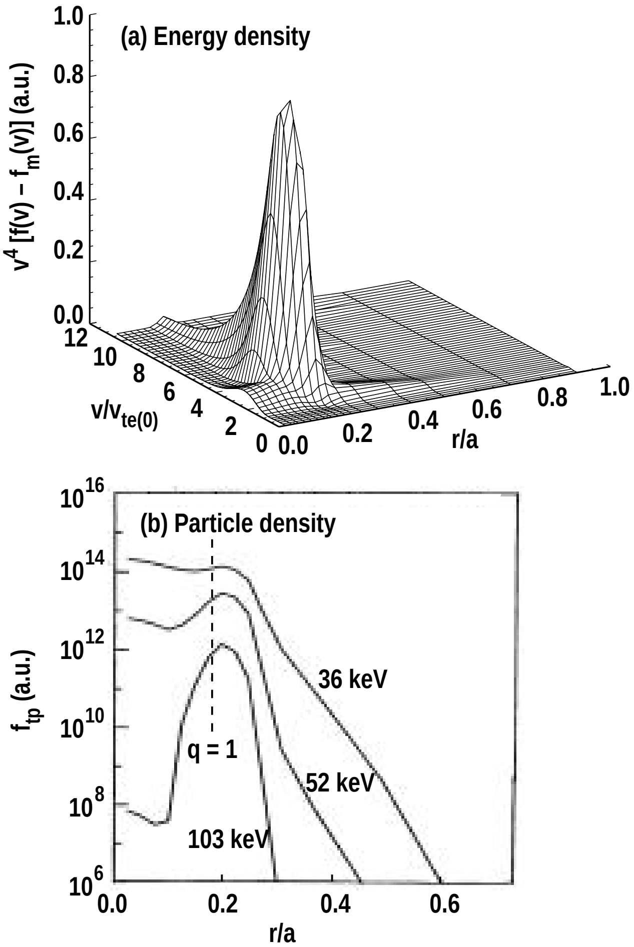

Fig. 2. Suprathermal electron distribution (calculated from the CQL3D code).

(θ>90°) side so that this part of the orbit is weighted more. Due to this drift-reversal effect, the barely trapped suprathermal electrons in the same energy range as the fast ions from neutral beam injection can resonate with fishbone modes. The hollow pressure profile of these electrons provide the free energy from the electron channel to assist the drive. Since the m=1 internal kink mode is the most common precursor of sawtooth events, it is usually near marginal stability just prior to sawtooth activities, and this is the time that the electron drive is most likely to be noticeable.

The best way to confirm the above interpretation is to investigate the instability variation with the poloidal location of the heating. Let θ_{res} denote the poloidal angle coordinate of the electron cyclotron wave absorption point. θ_{res} is zero when the heating takes place on the outer midplane and increases along a flux surface to π on the inner midplane. The data presented so far come from the shot with $\theta_{res} \sim \pi$ (shot 96163). This is the shot in which the m=1 internal kink instability is most active and the sawtooth instability appears earliest in time. By variation of the microwave injection angle and small changes in the magnetic field, θ_{res} is varied from π to π/2 in the experiment, and it is found that the instability becomes progressively weaker and the sawteeth appear later in the discharge. This trend is true not only for NCS target plasmas; it is also true for plasmas with positive central shear as depicted in Fig. 3 which shows that the number of 1/1 bursts which appear before the first sawtooth crash increases with θ_{res}. The q-profiles for these shots at the time of interest are quite similar; they all have positive central shear with $q_{min} = q(0) \sim 1.0$. However, no two plasma shots are identical; there are minor differences in q(r) as well as in other plasma parameters. In order to establish the effect of suprathermal electrons, we have to rule out the effect from the energetic ions whose population is proportional to $S_n/\langle n_e \rangle$ – the neutron emission rate divided by the plasma density. By comparing shots with different 1/1 activities and θ_{res}, we found 14 pairs of

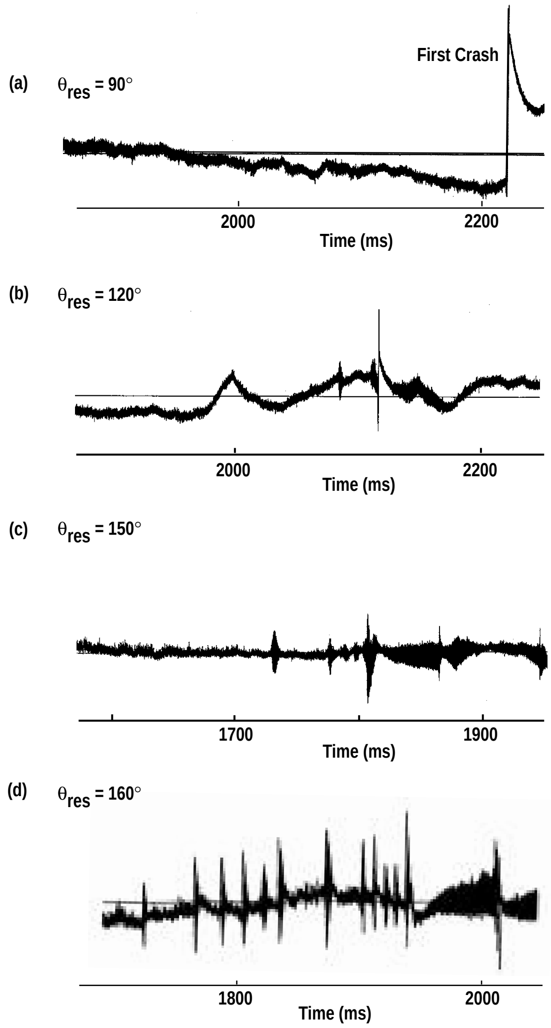

Fig. 3. Results from SVD analysis of ECE data showing variation of the the m/n=1/1 internal kink activity with the poloidal location of the second harmonic electron cyclotron resonance. Only one gyrotron is used in this sequence of shots.

shots where in each pair, the shot with stronger 1/1 activity has equal or slightly smaller value of $S_n/<n_e>$ so that the difference in the 1/1 activity is not due to the energetic ions. A clear trend emerges from this ensemble: the shot with the larger 1/1 activity always has the larger θ_{res}. This is a strong indication that barely trapped suprathermal electrons take part in driving the 1/1 mode. $S_n/<n_e>$ is about the same in the top three panels of Fig. 3; it is 25% higher in the bottom panel and the similarity between this figure and Fig. 1 of Ref. [5] becomes easy to understand: they are the same fishbone modes with different driving mechanisms. The modes observed in PDX are driven purely by deeply trapped energetic ions while the excitation of the modes shown in Fig. 3(d) here is aided by barely trapped suprathermal electrons. They appear just before the sawtooth crash when the m=1 internal kink is near marginal stability.

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