Role of the equilibrium and perturbative central current density in sawtoothing and non-sawtoothing discharges in KSTAR

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Abstract

The recent experiment [1] on excitation of the m/n=3/3 mode with a current blip induced by ECH and successive evolution to the m/n=2/2 and m/n=1/1 mode in the core of the sawtoothing discharge in KSTAR suggests that the central safety factor (q_0) may have to change from below ~1 (before crash) to slightly above ~1(after crash). This interpretation is consistent with the q profile condition for MHD simulation necessary for the growth of higher order modes which require q_0 slightly above ~1 until the 1/1 mode becomes dominant [2]. Experimental observation of a long lived higher order mode in non-sawtoothing discharge (presumably q_0>1) is consistent with the fact that the q_0 has to be below ~1 to support the growth of the m/n=1/1 mode and subsequent crash.

Introduction

The classical magnetohydrodynamic (MHD) instability, "sawtooth oscillation", in the core of tokamak plasmas is initiated by the m/n=1/1 kink mode instability driven by an excess core current density [3] in the core. It is believed that the explosive growth of this instability leads to a burst of the m/n=1/1 mode through magnetic reconnection and the core pressure within the q=1 surface is transported to outside of the q=1 layer in a fast time scale (i.e., reconnection time scale) while the growth of the kink instability is in a slow time scale. A decade later the discovery of sawtooth event, experimental measurements of the central safety factor, q_0 confirmed that the measured value of q_0 remained close to ~0.75 before and after the crash [4, 5]. This suggests that the core current density remains mostly unchanged while the core pressure (density and temperature) is removed in a magnetic reconnection time scale (~hundred μs). Very little change in core current density casted a doubt on theoretical understanding of the sawtooth crash physics and the driving mechanism of the m/n=1/1 kink instability. This experimental confirmation puzzled the community but the controversial issue has been forgotten for long time. Note that there are other experiments that the results are contradicting with these two measurements. The measurement of the higher order modes (m/n=2/2, 3/3, etc.)

induced by the electron cyclotron heating (ECH) in the core of sawtoothing plasmas (presumably q_0<1) in KSTAR provided a promising new avenue to revisit this problem, since such higher order modes can have a growth rate only for q_0 slight above ~1 and the m/n=1/1 mode can be dominant when q_0 is below ~1. This is consistent with the previous theoretical understanding of the sawooth oscillation. Furthermore, a similar experiment in a non-sawtoothing discharge (i.e., presumably q_0 is slightly above ~1) sustained a long lived higher order mode for more than ~tens of sawtooth period. This observation further supports that the q_0 remains above ~1. In conclusion, experimental excitation of the higher order mode driven by ECH and its time evolution support the required conditions of q_0 value; 1) In non-sawtoothing plasmas, excitation of the higher order mode and its sustainment when the q_0 is maintained above ~1. 2) In sawtoothing discharges, excitation of the higher order mode after the sawtooth crash supports the hypothesis that q_0 is above ~1 and subsequent evolution to the m/n=1/1 mode and following crash suggest that the q_0 has to be below ~1 before the crash.

Generation and evolution of the higher order modes

KSTAR is a medium size tokamak with major radius R_0=1.8m and minor radius a=0.5m. The plasma parameters used in this paper are as follow: the average electron density$\langle n_e \rangle \sim 3\times10^{19}$m^{-3}, the electron temperatureT_{e0}= 3–3.8 keV at the plasma center, and the elongation factor of the last closed flux surface = 1.5–1.54. In this experiment (#9214), low confinement mode (L-mode) plasma was heated by neutral beam injection (100keV, 1MW) and ECH/CD (170 GHz, 0.7 MW) at the toroidal magnetic field 2.95T. After the plasma current ramp-up (I_p=700kA), the ECH/CD vertical position was linearly scanned from Z=0 to 16cm at the center in 4s while maintaining the plasma shape and position. The toroidal injection was fixed at 7˚in the co-current direction. The observed MHD modes are mainly from the high resolution (space and time) 2-D ECEI system. The ECEI system on KSTAR was developed for visualization of MHD instabilities in 2010. This first ECEI system with the dual arrays provided simultaneous 2-D images of Te fluctuations on the high field side (HFS) and low field side (LFS) at the same toroidal location with spatial resolution ~1–2cm and time resolution ~1–2us. In the 2013, another ECEI system with a single array has been installed at a different toroidal location [6]. The two ECEI views having different fixed toroidal locations were placed radially adjacent to each other so as to provide radially continuous quasi-3D images. Three different mode patterns are m/n= 1/1, 2/2 and 3/3 as the vertical position of the ECH/ECCD is moved from the core to inside edge of the inversion radius [1]. This observation was studied theoretically and confirmed that the required q_0 is slightly above ~1[2].

Study of the equilibrium q-profile condition for higher order mode

In order to have a systematic comparative study of the time evolution of q_0 based on the growth and decay of the higher order mode, an example of time evolution of the m/n=3/3 mode for one sawtooth period (~10 ms) is illustrated in Fig. 1. In Fig.1a, the time trace of the core T_e (black) demonstrates a high frequency oscillation (~17kHz), intermediate oscillation frequency (~11.4kHz) and slower oscillation (~5.7kHz) as the core temperature is increased before the crash. Here, the m/n=3/3 mode is excited after the crash and this mode slowly transforms into the m/n=2/2 mode and then it finally transforms to the m/n=1/1 mode before the crash. The blue time trace in this figure represents the time evolution of the electron temperature at outside of the inversion radius. A sudden rise of the T_e due to the fast crash is followed by an exponential

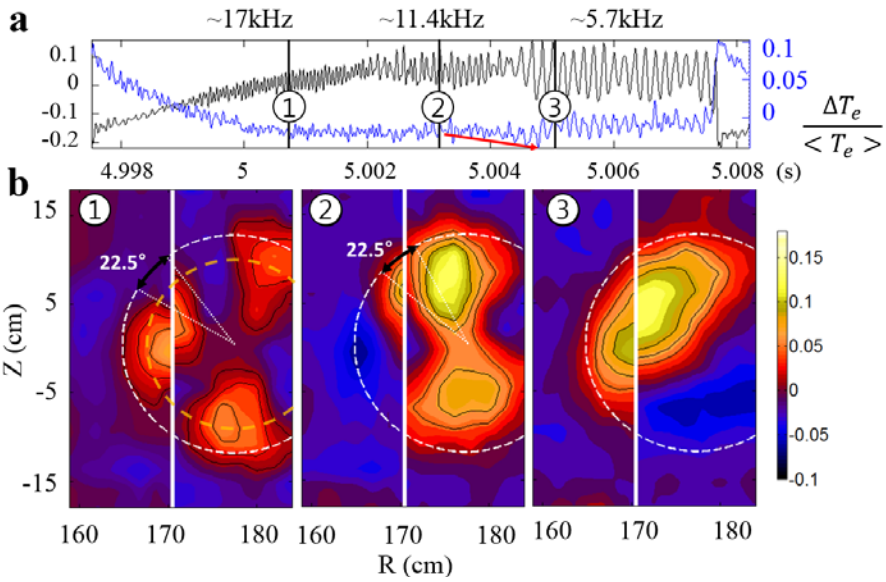

Figure 1. Temporal evolution of the m/n=3/3 mode structure. **a)** ECE time traces at the core (black) and outside of the inversion radius (blue). **b)** ECE images of m/n=3/3, 2/2, 1/1 modes corresponding to ~17kHz, ~11.4kHz, and ~5.7kHz oscillation phases. [1]

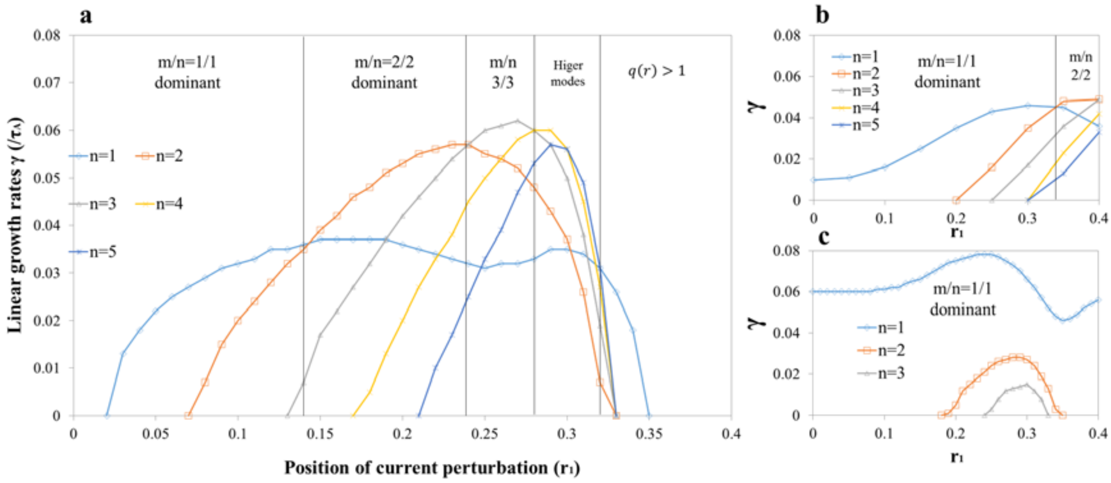

Figure 2. Linear growth rate spectra of m≤5 modes with various current perturbation position ($0<r_1<0.4$) and three different q_0 values: **a)** q_0=1.04 **b)** q_0=0.98 **c)** q_0=0.80. Higher order modes dominate as r_1 move toward the q~1 radius when q_0>1.

decay. The corresponding images for each mode are provided in Fig. 1b. Since it is rather difficult to perform a non-linear simulation for whole period, linear simulation with the M3D-C1code [7] has been performed at a fixed time with the equilibrium q profile that supports the highest growth rate for each mode. The result is illustrated in Fig.2. The q profiles with three different central values (0.8, 0.98 and 1.04) within the q~1 surface and various current perturbation positions (r_1) with the positive current blip (negative blip in q profile) are used for this simulation. For the m/n=1/1 mode, the growth rate is highest for q_0=0.8 and gradually reduced with the increase of the q_0 value as shown in this figure. As shown in this figure, the growth of higher order modes (m/n=2/2, 3/3 and higher mode) dominates as the current blip position is moved toward the ~q=1 surface while the q_0 is maintained above ~1. The observed time evolution of the m/n=3/3 mode to m/n=2/2, m/n=1/1 and crash, can be interpreted as follows; the observed m/n=3/3 mode right after the crash in Fig.1 supports that the q_0 has to be above ~1 and the position of the current blip is between 0.23 and 0.27 to have the growth of the m/n=3/3 mode. This is quite consistent with the experimental condition. As time evolves, the m/n=3/3 mode transforms into the m/n=2/2 mode. This observation may suggest that the current build up due to the local heating and diffusion of the current blip at the same position forms a negative blip slightly toward the center while the q_0 is still maintained above ~1. During the period when the dominant mode is the m/n=1/1 mode, the central q value is dropped well below ~1 in a fast time scale due to accumulation of the core current density and current diffusion from the current blip toward the core. In summary, the q_0 value has to be above ~1 after the sawtooth crash and initial build-up of the core current is slow (i.e., q_0 is above ~1) and a rapid rising phase of the current is followed. In addition, excitation of the higher order mode (m/n=6/6) and sustainment for a long period of time in a discharge with no sawtooth oscillations (presumably q_0>1) is further supports the hypothesis of q_0 evolution in sawtoothing discharge.

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