

## Merge and crash of dual hot core filaments visualized by 2-D ECE imaging

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### Introduction

A new type of internal instability distinct from the regular sawtooth instability has been observed via 2-D electron cyclotron emission imaging (ECEI) [1] in the KSTAR plasmas heated by electron cyclotron (EC) resonant waves. Unlike the internal  $m=1$  kink displacement of the entire core region ( $q < 1$ ) in the sawtooth oscillations, the new instability is characterized by dual filamentary hot flux tubes inside the  $q=1$  surface.

The control of sawtooth instability has been extensively investigated recently in part because large sawtooth crashes could trigger disruptions or other dangerous instabilities. In particular, the localized EC resonance heating [2] has been proved effective in controlling the sawtooth period. The experimental results were in good agreement with the simulation based on the sawtooth period model by Porcelli [3], which provides the crash trigger condition from the local plasma parameters at the  $q=1$  surface.

The observation of dual flux tubes in the plasma core suggests that the local EC heating could fundamentally change the core MHD dynamics rather than simply affecting the sawtooth crash trigger condition. In the following sections, the KSTAR ECEI system is briefly introduced and then the evolution of the observed dual flux tubes is described in detail.

### KSTAR ECEI

The ECEI is a 2-D imaging diagnostic technique based on the established radiometry for the local measurements of the electron temperature ( $T_e$ ) for optically thick plasmas [4]. Previous generation ECEI systems have made significant contributions to the understanding of the core MHD physics such as sawteeth [5], tearing modes [6], and Alfvén eigenmodes [7]. To extend the spatial coverage, the KSTAR ECEI system has implemented dual detector arrays capable

of simultaneous measurements of low-field side (LFS) and high-field side (HFS) in the same poloidal cross-section as schematically shown in Fig.1a. Each detector array provides 24 (vertical)  $\times$  8 (radial) = 192 local  $T_e$  measurements constituting a rectangular coverage  $\sim$ 50 cm  $\times$   $\sim$ 10 cm with the spatial resolution  $\sim$ 1–2 cm and the time resolution  $\sim$ 1  $\mu$ s.

Fig.1b is an ECEI snapshot of the core of a typical EC heated circular plasma (on-axis heating) showing a hot core structure. Time traces of several key plasma parameters are shown in Fig.1c. Note that the 1-D ECE signal from the core shows sawtooth-like oscillations during the EC heating. The sawtooth period is approximately 10 ms. One sawtooth period with the corresponding ECEI images is shown in Fig.2 for the highlighted time window.

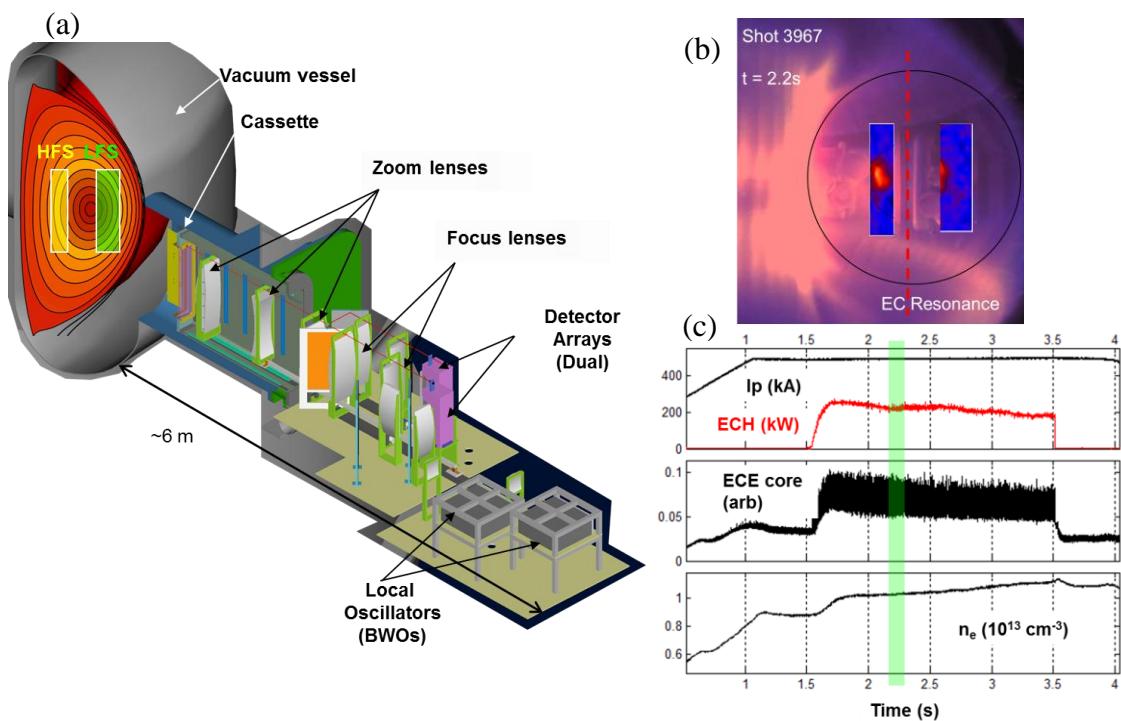


Fig.1. (a) KSTAR ECEI schematic. The two inset rectangles are the spatial overages corresponding to the dual detector arrays. (b) ECEI snapshot of the plasma core region for a typical EC heated plasma (shot 3967). The EC resonance position is on the magnetic axis as shown. (c) Corresponding time traces of plasma current ( $I_p$ ), heating power, ECE intensity, and line-averaged electron density.

### Dual flux tube in the core

The ECEI signal in Fig.2 shows a typical sawtooth-like time trace except the early appearance of the precursory oscillation and the sudden doubling in the oscillation frequency during the ramp-up phase. In the ECEI image, the frequency doubling corresponds to the emergence of a second hot core as indicated by an arrow. The two flux tubes presumably form along the local helical field line and they appear rotating counter-clockwise in the ECEI view due to the toroidal plasma rotation.

The evolution of this new core instability involves four distinct stages although the emergence of the second hot flux tube is random both in time and spatial location. Stage 1 is the growth of the first hot flux tube in the core. Stage 2 is a sudden emergence of the second hot flux tube. The two flux tubes rotate together at the same velocity inside the  $q=1$  surface (dashed circle). Stage 3 is the merging of the two flux tubes into a single large hot core resembling the internal  $m=1$  kink mode of the sawtooth instability. Stage 4 is the final crash. The heat transport during the crash is fast ( $< 100 \mu\text{s}$ ), collective, and localized, similar to the case of sawtooth crash [5].

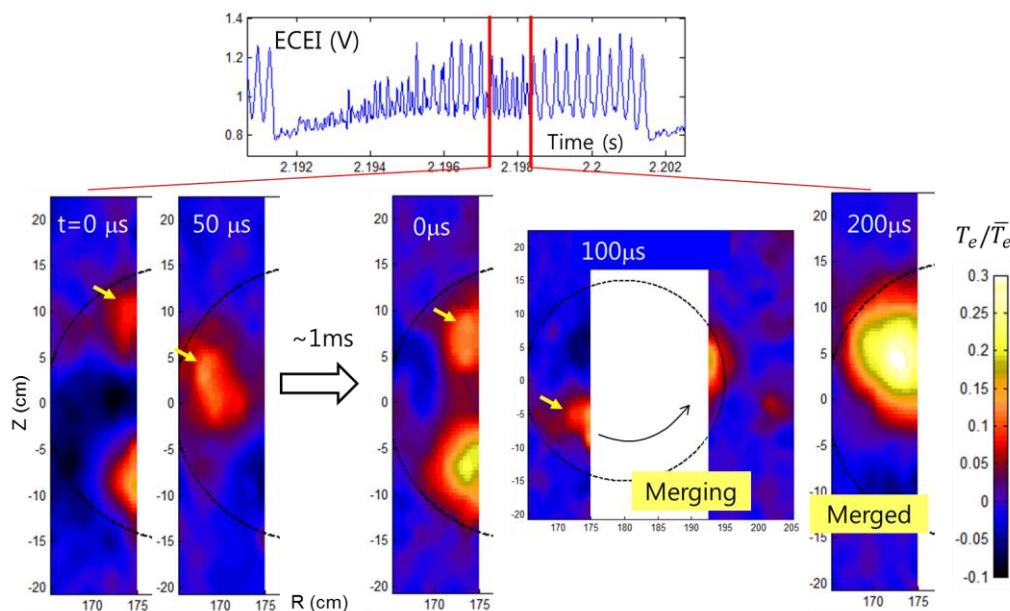


Fig.2. (top) ECEI signal time trace showing the frequency doubling in the middle of the ramp-up phase. (bottom) ECEI images of dual flux tubes. The arrow indicates the second flux tube. The dashed circle is the  $q=1$  surface inferred from the crash phase (see Fig.3).

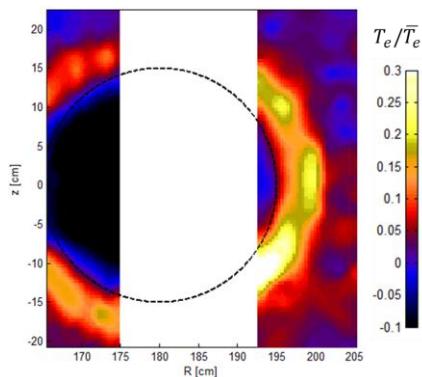


Fig. 3. Crash of the merged hot core. The crash occurred to the lower right side in this example. The crash pattern is identical to the sawtooth crash, i.e., fast, collective, and localized.

## Discussion and outlook

The fast oscillation pattern of the ECEI signal trace in Fig.2 resembles the  $T_e$  traces of

electron fishbone instabilities [8], which are  $m=1$  internal kink perturbations excited by barely trapped supra-thermal electrons via the toroidal precession of their banana orbits. However, the dual flux tube structure is clearly different from the  $m=1$  internal kink mode, excluding the relevance to the electron fishbone. Similar  $T_e$  traces characterized by multi-peak  $T_e$  profiles have been also observed in other tokamaks during EC heating [9, 10] and interpreted as a result of macroscopic magnetic island and localized heating along the island's outer flux surface [11]. Such interpretation would expect a large magnetic island and snake-like hot temperature band in the 2D ECEI data, none of which are observed.

The energetic electrons near the  $q=1$  surface generated by the EC resonance wave presumably play an important role in the dynamics of the hot flux tubes in the core. Future work will focus on measuring 2D structural evolution of the flux tubes at various EC heating conditions.

## Acknowledgement

This work was supported by the NRF Korea, the U.S. DoE, and the Association Euratom-FOM.

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