Alfvénic instabilities can be driven by the energetic particle in future burning plasma devices, such as ITER and DEMO, where energetic particles will be abundantly produced by high power heating and fusion reaction. These instabilities can lead to significant loss of fast particles, which are very harmful for plasma heating and reactor’s first wall. So it is very important to study them theoretically and experimentally in present-day tokamak plasmas. The instabilities driven by fast ions, such as toroidalicity-induced Alfvén eigenmodes (TAEs), have been observed and investigated widely in many fusion devices [1]. In contrast, the modes related to energetic electrons are much less explored. Understanding of energetic-electron behaviors can provide a strong contribution to clarify physics of burning plasma behaviors because their effect on low-frequency MHD modes can be used to simulate and analyze the analogous effect of α particles characterized by small dimensionless orbits similar to energetic electrons in present-day tokamak plasmas [2].

The β-induced Alfvén eigenmode (BAE) excited by energetic electrons has been identified for the first time both in the Ohmic and electron cyclotron resonance heating plasma in HL-2A. The features of the instability, including its frequency, mode number, and propagation direction, can be observed by magnetic pickup probes. The mode frequency is comparable to that of the continuum accumulation point of the lowest frequency gap induced by the shear Alfvén continuous spectrum due to finite β effect, and it is proportional to Alfvén velocity at thermal ion β held constant. The experimental results show that the BAE is related not only with the population of the energetic electrons, but also their energy and pitch angles. The results indicate that the barely circulating and deeply trapped electrons play an important role in the mode excitation.

Alfvénic instabilities can be driven by the energetic particle in future burning plasma devices, such as ITER and DEMO, where energetic particles will be abundantly produced by high power heating and fusion reaction. These instabilities can lead to significant loss of fast particles, which are very harmful for plasma heating and reactor’s first wall. So it is very important to study them theoretically and experimentally in present-day tokamak plasmas. The instabilities driven by fast ions, such as toroidalicity-induced Alfvén eigenmodes (TAEs), have been observed and investigated widely in many fusion devices [1]. In contrast, the modes related to energetic electrons are much less explored. Understanding of energetic-electron behaviors can provide a strong contribution to clarify physics of burning plasma behaviors because their effect on low-frequency MHD modes can be used to simulate and analyze the analogous effect of α particles characterized by small dimensionless orbits similar to energetic electrons in present-day tokamak plasmas [2].

The β-induced Alfvén eigenmodes (BAEs) were first observed in DIII-D and then TFTR plasmas with fast ions [3–5]. Subsequently, the BAEs (termed as m-BAEs; here the ‘‘m’’ denotes that the BAEs are excited by magnetic islands) have also been observed during a strong tearing mode (TM) activity in FTU and TEXTOR Ohmic plasmas without fast ions [6–8]. Recently, the BAEs have also been reported during a sawtooth cycle in ASDEX-U and TORE-SUPRA plasmas with fast ions [9,10]. The detailed excitation mechanism of the BAEs is still not fully assessed due to many effects, such as ion diamagnetic drift, thermal ion compression, finite Larmor radius or finite orbit width, and energetic-particle effects. In this work, we discuss for the first time experimental observations of BAEs (termed as e-BAEs) destabilized by energetic electrons in the Huan-Liuqi-2A (HL-2A) tokamak, and a comparative analysis of e-BAEs and m-BAEs is also presented in this Letter.

HL-2A is a medium-size tokamak with major radius \( R = 1.65 \) m and minor radius \( a = 0.4 \) m. The experiments discussed here were performed in deuterium plasmas with toroidal plasma current \( I_p = 160/300 \) kA, toroidal field \( B_t = 1.3/2.4 \) T, safety factor at the edge \( q_a = 4.0 \), and electron cyclotron resonance heating (ECRH) as the main heating. The line averaged density was detected by a hydrogen cyanide interferometer. The electron and ion temperature were measured by the Tomson laser scattering and neutral particle analyzer, respectively. The hard-x-ray spectrum detected by cadmium-telluride (CdTe) and the nonthermal radiation measured by the electron cyclotron emission (ECE) were used to analyze the behaviors of the energetic electrons.

Mode characteristics.—The e-BAE has been observed in the HL-2A ECRH plasma. This phenomenon is perfectly reproducible. The mode features, including its frequency, mode number, and propagation direction, can be observed by magnetic pickup probes. The observed mode activity exhibits no amplitude bursting or frequency chirping, different from electron fishbone characteristics in HL-2A [11,12]. The mode frequency is comparable to that of the continuum accumulation point (CAP) of the lowest frequency gap induced by the shear Alfvén continuous spectrum due to finite β effect [13]. Figure 1 shows a typical experimental result with low plasma density during ECRH. Electron cyclotron wave (1 MW, 68 GHz, second harmonic heating) was launched into the plasma with 1.3 T toroidal magnetic field. Here, the plasma density, ECRH pulse, neutral-beam injection (NBI) pulse, magnetic fluctuation signal from Mirnov probes, and its frequency spectrum are shown from the top to the bottom. A coherent MHD fluctuation is visible around 20 kHz between 420 and 800 ms. The density slightly increases after NBI at \( t = 550 \) ms, but the mode remains almost unchanged. The mode becomes very weak after ECRH switched off at \( t = 800 \) ms.