Alfvénic ion temperature gradient activities in a weak magnetic shear plasma

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Abstract – We report the first experimental evidence of Alfvénic ion temperature gradient (AITG) modes in HL-2A Ohmic plasmas. A group of oscillations with $f = 15$–$40$ kHz and $n = 3$–$6$ is detected by various diagnostics in high-density Ohmic regimes. They appear in the plasmas with peaked density profiles and weak magnetic shear, which indicates that corresponding instabilities are excited by pressure gradients. The time trace of the fluctuation spectrogram can be either a frequency staircase, with different modes excited at different times or multiple modes may simultaneously coexist. Theoretical analyses by the extended generalized fishbone-like dispersion relation (GFLDR-E) reveal that mode frequencies scale with ion diamagnetic drift frequency and $\eta_i$, and they lie in KBM-AITG-BAE frequency ranges. AITG modes are most unstable when the magnetic shear is small in low pressure gradient regions. Numerical solutions of the AITG/KBM equation also shed light on why AITG modes can be unstable for weak shear and low pressure gradients. It is worth emphasizing that these instabilities may be linked to the internal transport barrier (ITB) and H-mode pedestal physics for weak magnetic shear.

Kinetic Alfvén and pressure-gradient-driven instabilities are very common in magnetized plasmas both in space and in laboratory [1–3]. In present-day fusion and future burning plasmas, they are easily excited by energetic particles (EPs) and/or pressure gradients. They can not only cause the loss and redistribution of EPs but also affect plasma confinement and transport [4,5]. The physics associated with them is an intriguing but complex area of research. For weak magnetic shear ($s = (r/q)(dq/dr) \sim 0$) and low pressure gradients ($\alpha \sim -Rq^2d\beta/dr < 1$; with $\beta$ the ratio of kinetic to magnetic pressures), their stability and effect, such as the Alfvénic ion temperature gradient (AITG) mode [6,7], kinetic ballooning mode (KBM) [8], have not been hitherto unrecognized. At weak magnetic shear, the first pressure gradient threshold becomes very small or vanishes and the AITG/KBM spectrum is unstable in the very-low-pressure-gradient region [9,10]. For equilibria with reverse shear where $q_{min}$ is off axis and $\alpha_{max}$ near $q_{min}$, there exists an unstable low-$\alpha$ global branch of AITG and trapped electron dynamics can further destabilize it [11]. The AITG/KBM modes, on the one hand, can cause cross-field plasma transport that sets an upper limit on the plasma beta; on the other hand, this electromagnetic turbulence could be a paradigm which can bridge electron and ion transport channels via finite $\beta$-effects. For the case of weak magnetic shears and low pressure gradients, so far, no clear experimental evidences supported this theoretical understanding, based on analytical and numerical simulation results. This paper presents a direct experimental evidence of the AITG existence and corresponding physics mechanisms of mode excitation in tokamak plasmas.
The experiments discussed here are performed in deuterium plasmas with plasma current \( I_p \approx 150-170 \text{kA} \), toroidal field \( B_t \approx 1.32-1.40 \text{T} \), and an edge safety factor \( q_0 \approx 4.2-4.8 \) on HL-2A, which has the major/minor radius \( R_0/a = 1.65 \text{m}/0.4 \text{m} \). The HL-2A plasma is almost a circular cross-section equilibrium although it corresponds to a divertor configuration in all during the discharges. The electron density was detected using a multi-channel HCOOH laser interferometer [12]. The poloidal mode number \( m \) is measured using the electron cyclotron emission imaging (ECEI) signals by the spatial two-point correlation method [13]. The safety factor profile is obtained by the current filament code combined with far-infrared (FIR) polarimetry data. This electromagnetic instability is observed only in high-density Ohmic plasmas, especially with peaked density profiles in the limiter or divertor configuration. The phenomenon is perfectly reproducible. Mode features, including its frequency, mode number and propagation direction, can be observed by ECEI, soft X-ray and microwave interference signals, respectively [14]. Figure 1 shows two typical experimental results during the plasma density ramp-up. Many coherent MHD fluctuations are visible around \( t = 320-360 \text{ms} \) for shot I and \( t = 1000-1150 \text{ms} \) for shot II. These fluctuations do not appear on Mirnov signals. The poloidal mode number is obtained by the relation \( m = L k_\theta/2\pi \), where \( k_\theta \) is the poloidal wave vector and \( L \) is the distance between two poloidal ECEI signals. These coherent modes have typical poloidal mode number \( m = 3-6 \) and wave vector \( k_\theta = 0.2-0.6 \text{cm}^{-1} \), and propagate poloidally in the ion diamagnetic drift direction, \( e.g., m > 0 \). Occasionally, the nonlinear behavior of modes, which is shown in fig. 2, can be observed during the frequency staircase. It is found that the mode frequency has a characteristic with the chirping-up. It suggests that the mode is an Alfvénic instability, \( e.g., \) the mode is electromagnetic but electrostatic. To identify instabilities causing these fluctuations, we need to determine local plasma parameters. In the high-density Ohmic regime, we assume \( T_i = T_e \) and \( n_i = n_e \). Figure 3 gives electron temperature, density and safety factor profiles during the coherent modes at two different times (t1 and t2). Figure 3 shows that magnetic shear is weak during MHD activities and \( q_{\text{min}} \approx 1 \). Further, the soft X-ray array measurements also indicate that there are \( q = 1 \) rational surfaces. According to the \( q \)-profile, radial mode localization and poloidal mode number, we determine the toroidal mode number \( n = m/q \sim m \). At the \( q = 1 \) surface, \( T_i \sim 0.6 \text{keV}, \rho_q = 1 \approx 0.22, -R_0 \nabla \ln n_i \equiv 1/\varepsilon_n \approx 6.0, \eta_i \equiv \nabla \ln T_i/\nabla \ln n_i \approx 1.5, \beta_i \approx 0.3\% \), \( \alpha \sim 0.1 \) and \( |s| \ll 1 \). As anticipated earlier, the observed electromagnetic instabilities are unstable in regions of weak shear and low pressure gradients.

The coherent modes occur in Ohmic plasmas with peaked density profiles and without any EPs, and they sometime have the behaviors of the frequency staircase. These observations suggest that they are possibly driven by pressure gradients and there is a threshold for mode excitation. To verify and understand them, we adopt the extended general fishbone-like dispersion relation (GFLDR-E) and AITG/KBM equation in the absence of EPs, respectively. Both these analytical theories assume the local s-\( \alpha \) model equilibrium for shifted circular magnetic surfaces [15].

The GFLDR-E, which is derived by Zonca and Chen and includes various kinetic effects [16,17], such as finite Larmor radii (FLR) and finite orbit widths (FOW), etc., can be written as follows:

\[
-2\sqrt{Q}\frac{\Gamma\left(\frac{3}{2} - \frac{\Lambda^2}{4}\right)}{\Gamma\left(\frac{3}{2} - \frac{\Lambda^2}{4}\right)} = \delta W_f, \tag{1}
\]
where $A^2 = \frac{\omega^2}{\omega_A^2}(1 - \frac{\omega}{\omega_A}) + q^2 \frac{\omega}{\omega_A} \left[ \left( 1 - \frac{\omega}{\omega_A} \right) F - \frac{\omega}{\omega_A} G - \frac{\omega}{\omega_A} \right]$, $Q^2(\omega) = \frac{3^2}{2^2} k^2 (\frac{\omega}{\omega_A})^2 \left( 1 - \frac{\omega}{\omega_A} \right) - \frac{\omega}{\omega_A} + q^2 \frac{\omega}{\omega_A} S(\omega) + \left( \frac{\omega}{\omega_A} \right)^4 \left( \frac{\omega}{\omega_A} \right)^2 \left[ \left( 1 - \frac{\omega}{\omega_A} \right) \right]$. All symbols are standard. By trial and error, a trial Alfvén-acoustic continuum structure can be modified by \( \omega \) and \( \eta \), showing excellent agreement. All properties of the observed coherent modes are consistent with their interpretation as AITG modes. To show the Alfvénic ion temperature gradient activities in a weak magnetic shear plasma.

Fig. 4: (Colour online) Solutions of the GFLDR-E according to parameters at the $q = 1$ surface, $s = -0.05$, $k_B \rho_i = 0.1$ and $\theta_h = 0$. Real frequency (a) and growth rate (b) vs. $T_i$; real frequency (c) and growth rate (d) of the $m/n = 4/4$ mode vs. $\eta_i$. $A^2 = 0$ denotes the marginal stability, and all other situations $\delta W_f$ are from the approximate expression given in ref. [18].

Fig. 5: (Colour online) Diamagnetic effect ($\Omega_{ni} \equiv \omega_{ni}/\omega_A$) from the density gradient on the stability of coherent modes. Parameters from the $q = 1$ surface, $s = -0.05$, $k_B \rho_i = 0.1$ and $\theta_h = 0$. Solid line: $A^2 = 0$; dashed line: GFLDR-E, $\delta W_f \neq 0$. Observed value: $\Omega_{ni} \sim 0.54$.

Table 1: Comparison between measured frequency and real frequency from the GFLDR-E. Note: $f_{v B}$ is the toroidal rotation frequency at the $q = 1$ surface. Parameters from the $q = 1$ surface, $s = -0.05$, $k_B \rho_i = 0.1$ and $\theta_h = 0$. Solid line: $A^2 = 0$; dashed line: GFLDR-E, $\delta W_f \neq 0$. Observed value: $\Omega_{ni} \sim 0.54$.
and Larmor radius effects. Obviously, for the mode excitation with weak magnetic shear $\eta_i$ and $-R_0\nabla \ln n_i$, both have thresholds which are responsible for the onset of turbulence and the profile stiffness, and the modes are more unstable in the case of large $\eta_i$ and $-R_0\nabla \ln n_i$. For weak magnetic shears, the $\alpha$ threshold for mode excitation is very low. Meanwhile, larger $k_\theta r_i$ values have a stabilizing effect. Figure 7 presents the mode frequency and growth rate at different magnetic shears, and it is found that $s$ has a very narrow window for the unstable modes at $\alpha = 0.1$. This window becomes wider for increasing $\alpha$ and the magnetic shear corresponding to the maximum of growth rate shifts towards the positive shear region. Figure 7(b) gives the eigenfunctions of the unstable modes at weak magnetic shear and low pressure gradient. The parallel mode structure is very extended along the magnetic field, which is different with respect to the electrostatic ITG ballooning structure. These analysis results shed light on why we observed coherent modes only in plasmas with peaked density profiles and with $|s| \ll 1$.

The AITG modes can become unstable for $\eta_i$ larger than a critical value $\eta_{ic}$ which is given by $\eta_{ic} \approx 2/\sqrt{7+4\eta q^\prime} \Omega_{\text{eni}}$ [16]. For our experiments, $\Omega_{\text{eni}} < \sqrt{7}/4 + \eta q$ is satisfied. With the density peaking and $T_i$ decreasing at the $q = 1$ surfaces, $\eta_{ic}$ drops. Therefore, the threshold condition weakens and the modes become unstable more easily. For the modes with different mode numbers, $\eta_{ic}$ may be different so that the frequency staircase occurs during the density ramp-up corresponding to $\eta_{ic}$ sequential decreasing at the marginal stability. With a milder density ramp-up and/or constant density, multiple branches of modes may simultaneously appear.

The AITG modes may have important implications on plasma transport and effectively limit the maximum achievable density and pressure in tokamaks. Figure 1 shows that the low-frequency kink-tearing mode with $m/n = -2/-1$ or $-1/-1$ grows rapidly after the AITG modes are driven unstable by density peaking. Subsequently, the bulk plasma produces a minor disruption. This suggests that the disruption is potentially linked with the nonlinear evolution of these instabilities. Another important experimental result which is shown in fig. 8 is that these instabilities can be observed in the core plasma on LOC-SOC (linear and saturated Ohmic confinement regime) and density limit experiments. And it is difficult that they are observed in the LOC regime. Generally, it is believed that the trapped electron modes (TEMs) are dominant in the LOC regime but the ITG modes are dominant in the SOC regime. However, this experimental result suggests that the AITG modes can also exist in the SOC regime. The AITG modes may destroy the plasma confinement so that the plasma store energy is not enhanced further with increasing density in the SOC regime. The effects of AITG modes on plasma confinement/transport are unclear at present, and it is necessary to further investigate them.

In summary, we report the experimental observation of AITG instabilities in HL-2A Ohmic plasmas. A group of coherent modes with $f = 15-40$ kHz and $n = 3-6$ is consistently measured by multiple diagnostics in high-density Ohmic regimes. They arise in plasmas with peaked density and weak magnetic shear. The instabilities are excited by pressure gradients. Different unstable modes can be excited at different times during density ramp-up, when
plasma conditions pass through marginal stability, yielding the characteristic signature of a frequency staircase. Meanwhile, at nearly constant plasma density and radial profiles, multiple modes coexist and are simultaneously observed. Theoretical analyses by the GFLDR-E reveal that mode frequencies scale with ion diamagnetic drift frequency and $\eta_i$, and they lie in the KBM-AITG-BAE frequency range. These AITG modes are more unstable when the magnetic shear is small in low-pressure-gradient regions. AITG/KBM equation also sheds light on why AITG modes can be unstable for weak shear and low pressure gradients. The low-$\alpha$ AITG modes consist in the thermal plasma ion wave-particle interaction mediated by geodesic curvature coupling and, thus, they are observed in experiments due to weak magnetic shear and low pressure gradient. With increasing $s$ and $\alpha$, the toroidal mode number of the most unstable mode also increases, and coherent modes gradually evolve into Alfvenic turbulence. The AITG is an electrostatic ITG counterpart, and, within an unstable window, its growth rate is larger than that of the ITG mode which is clearly stabilized by finite-$\beta$ effects. The threshold for AITG destabilization is typically lower than that of ideal marginal stability ($\alpha_{\text{AITG}}/\alpha_c \simeq 0.5$) [19]. The stability of AITG modes has a strong and complex dependence on values of $s$ and $\alpha$, and various effects including trapped electron, finite $B_\parallel$, plasma shape, Shafranov shift and parallel ion current [10,20–22]. Thus, a full and thorough assessment of the mode stability requires a kinetic global simulation using the realistic configuration and profiles. The synergetic effect of $s$ and $\alpha$ is a dominant factor for the mode stability, and it maybe plays an important role in the formation and evolution of internal/external transport barriers (ITB/ETB, corresponding to large $\eta_i$ and strong $-R_0\nabla \ln n_e$, respectively) with weak and negative magnetic shears. Similar AITG/KBM phenomena have been observed in DIII-D QH-mode plasmas [23] and HL-2A ITB plasmas with weak magnetic shear. However, observations reported in the present work are the first clear experimental identification of this phenomenon, fully consistent with the theoretical interpretation and numerical stability analyses. In addition, it needs to be stressed that these instabilities can exist in the SOC regime and density limit plasmas. The interaction between AITG/KBM activities and EPs should also be investigated with greater attention in fusion plasmas, such as ITER, since weak magnetic shear amplifies the role of and possible excitation by EP of these fluctuations, as predicted by the GFLDR-E. This work is the first clear experimental evidence of AITG/KBM and complex plasma behaviors which are fully consistent with the theoretical framework of the GFLDR-E. It also paves the road to more in-depth analyses of similar phenomena in fusion plasmas with nonperturbative EP populations, with the suggestive possibility of controlling the plasma performance by a careful choice of plasma profiles in the weak shear core region typical of burning fusion plasmas.

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