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EGAM induced by energetic electrons and nonlinear interactions among EGAM, BAEs and tearing modes in a toroidal plasma

W. Chen [a,*], X.T. Ding [a], L.M. Yu [a], X.Q. Ji [a], J.Q. Dong [a], Q.W. Yang [a], Yi. Liu [a], L.W. Yan [a], Y. Zhou [a], W. Li [a], X.M. Song [a], S.Y. Chen [b], Z.B. Shi [a], X.R. Duan [a], and HL-2A Team

[a] *Southwestern Institute of Physics, P.O. Box 432, Chengdu 610041, China*
[b] *College of Physical Science and Technology, Sichuan University, Chengdu 610065, China*

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ABSTRACT

In this Letter, it is reported that the first experimental results are associated with the GAM induced by energetic electrons (EGAM) in HL-2A Ohmic plasma. The energetic electrons are jointly generated by Ohmic electric fields and parallel electric fields during magnetic reconnection associated with tearing mode (TM). The EGAM localizes in the core plasma, i.e. in the vicinity of $q = 2$ surface, and is very different from one excited by the drift-wave turbulence in the edge plasma. The analysis indicated that the EGAM is provided with the magnetic components, whose intensities depend on the poloidal angles, and its mode numbers are $|m/n| = 2/0$. Further, there exist intense nonlinear interactions among EGAM, BAEs and strong tearing modes (TMs). These new findings shed light on the underlying physics mechanism for the excitation of the low frequency (LF) Alfvénic and acoustic fluctuations.

1. Introduction

The very low-frequency (LF) Alfvénic and acoustic fluctuations, such as beta-induced Alfvén eigenmode (BAE), and geodesic acoustic mode (GAM), are presently of considerable interest in the present-day fusion and future burning plasmas [1], e.g. ITER. The low-frequency waves can significantly affect the plasma performance, and induce the particle losses and reduce the plasma self-heating. These LF instabilities can play an important role in turbulence and anomalous transport regulation, especially, while there is significant fraction of high energy particles in plasma [2,3]. They can be used as energy channels to transfer the fusion-born alpha-particle energy to the thermonuclear plasma, i.e. GAM/BAE channeling [4].

The GAM with toroidal mode number $n = 0$ is an eigenmode sustained by the coupling of radial electrostatic field and the poloidal variational density perturbations, and is usually taken to be electrostatic oscillation. The GAM is excited via modulation instability and pumped by the nonlinear interaction of drift-wave turbulence [2], and also driven by fast ions [5–7]. The GAM was investigated both using gyro-kinetic simulations and analytical methods in toroidal and slab geometry, and observed extensively in torus plasma [2,3]. Meanwhile, the BAE with $n \neq 0$ is also a low frequency mode with parallel wave number $k_\parallel = (n - m/q)/R_0 = 0$, which is due to the plasma finite beta effect under the geodesic curvature, and usually believed to be electromagnetic oscillation, and created by the coupling between the shear Alfvén continuum with the poloidal mode number m and the sound continuum with the mode numbers $m - 1$ and $m + 1$, and driven by fast particles or large magnetic island. The BAEs were observed and investigated under different conditions in tokamak plasma [8].

It is worthwhile noting that the BAE and GAM have similar dispersion relations in the case of the long wavelength limit, i.e., the kinetic expression of the GAM dispersion relation can degenerate with that of the LF shear Alfvén accumulation point (BAE) [9,10], which is useful for helping reciprocally identify the instabilities in the experiments. The most simple dispersion relations of BAE/GAM are given by

$$\omega_{BAE} = \omega_{GAM} \approx (2T_i/m_i)^{1/2}(7/4 + T_e/T_i)^{1/2}/R_0$$

where R_0 is major radius, m_i is ion mass, and T_i, T_e are ion and electron temperatures, respectively. The energetic electrons and magnetic-island induced BAEs had been observed and investigated on HL-2A in the previous works [11,8]. In this Letter, it is reported that the first experimental results are associated with the GAM induced by energetic electrons (EGAM), and also present that there exists the intense nonlinear interactions among EGAM, BAEs and strong TMs.

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* Corresponding author. Fax: +86 28 82850300.
E-mail address: chenw@swip.ac.cn (W. Chen).

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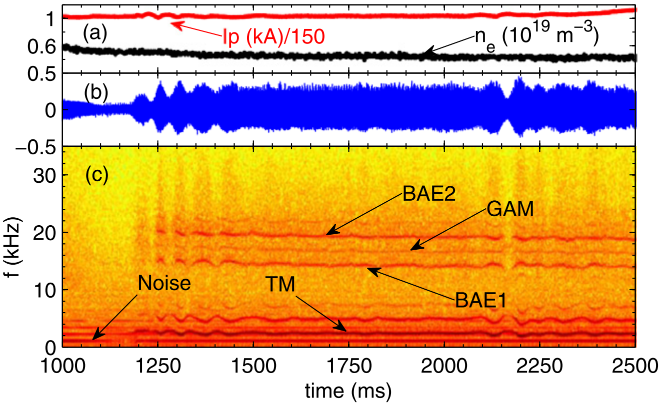

Fig. 1. Experimental parameters of the typical discharge with strong TM on HL-2A. Plasma current, I_p and density, n_e (a), magnetic probe signal (b), and corresponding spectrogram (c), respectively.

2. Experimental conditions and mode characteristics

HL-2A is a medium-size tokamak with major/minor radius $R/a = 1.65$ m/0.4 m. The experiments discussed here were performed in deuterium plasmas with plasma current $I_p \simeq 150$–170 kA, toroidal field $B_t \simeq 1.32$–1.38 T, and safety factor $q_a \simeq 4.2$–4.6 at the plasma edge. The line averaged density was detected by a hydrogen cyanide interferometer. The poloidal number m is measured using a set of seven Mirnov probes localized in the high field side (HFS) and eleven ones localized in the low field side (LFS). But the toroidal number n is measured using a set of ten Mirnov probes localized in the LFS of the vessel [12]. Four CdTe scintillator detectors are placed outside the vacuum vessel in order to obtain information of the hard X-ray emission, and chordal distances of sight lines are $r_d = 5, 9, 15$ and 30 cm, respectively. The range of the hard X-ray spectrum is $E_\gamma = 10$–200 keV divided into many energy bins by the PHA-software setting.

The EGAM has been observed in the HL-2A Ohmic plasma for the first time, recently. This phenomenon is perfectly reproducible, and a typical discharge parameters are shown in Fig. 1. A coherent MHD fluctuation is visible around 17.5 kHz from 1250 ms to 2500 ms. The toroidal mode number analysis indicates that this fluctuation does correspond to GAM due to $n = 0$. In general terms, the magnetic component of GAM is two-order than the electric one, therefore it is very difficult that it is observed in Ohmic plasma. However, the magnetic components of GAM had been observed in the same discharge. The analysis indicated that the poloidal number of GAM is $m = 2$, and the fluctuation intensity depends on the poloidal angles. The phenomena can be interpreted by Zhou's theory [13] which suggests that the GAM has a magnetic component with $m = 2$, which is created by the $m = 2$ parallel return current, and the fluctuation intensity depends on the poloidal angles, i.e., $\tilde{B}_\theta \propto \sin(2\theta)$. The similar experimental results ($\tilde{B}_\theta \propto \sin(\theta)$), which are associated with the density fluctuation induced by GAM, can be found in the previous document [14]. The BAEs are also visible during strong TM activity with $m/n = -2/-1$ in the same discharge. The characteristics of the BAEs were investigated in previous works [8]. The mode numbers of the BAEs are $m/n = 2/1$ and $-2/-1$. There exists an island width threshold (~ 3.4 cm) for the BAE excitation on HL-2A [8]. Note that the BAEs cannot be completely explained by the present theory [15]. The magnetic fluctuation spectrogram indicates that the GAM is always accompanied by strong TM and BAEs, and their frequencies comply with $f_{GAM} = f_{BAE2} - f_{TM}$, $f_{GAM} = f_{BAE1} + f_{TM}$ as well as $f_{GAM} = (f_{BAE2} + f_{BAE1})/2$. The GAM localizes in the core plasma, i.e., in the vicinity of $q = 2$ surface where the ion Landau damping γ_i is larger than the edge due to $\gamma_i \propto \exp(-q^2)$, and it is very different from one excited by the drift-wave turbulence in the edge plasma on HL-2A [16,17]. Such GAM is not observed in the absence of strong TM or BAEs.

3. Relationship between energetic electrons and EGAM

The existence of energetic electrons during magnetic reconnection results in the excitation of EGAM. Generation of energetic electrons during magnetic reconnection has been the subject of a number of theoretical and experimental investigations [18–21]. The production rate depend critically on the amplitude of the electric field generated during reconnection. The electric field is $E_\parallel = (sB_t/16r_s)w_m\,dw_m/dt$ [18], where w_m is the width of the magnetic island, $w_m = 4(B_r r_s R_0/nsB_t)^{1/2}$, and dw_m/dt is the growth rate of magnetic island described by the tearing mode equation $dw_m/dt = 1.2(\eta/\mu_0)\Delta'_m$ in the case of low beta. Here, Δ'_m is the stability parameter, η is the plasma resistivity, r_s is the radius of the magnetic surface, B_r is the radial magnetic field perturbations, and $s = (r/q)\,dq/dr$ is the magnetic shear. On the basis of experimental parameters, we can evaluate that electric fields are of the order of $E_\parallel \sim 0.1$–0.2 V/m during the process of magnetic reconnection on HL-2A. Analysis of HXR energy distribution has indicated that the energy of the energetic electrons in flight is of the order of 20–200 keV. The time resolution of the PHA analysis did allow one to determine temporal modifications of the spectrum. More details will be introduced in a separate paper. Fig. 2 shows that the HXR fluxes with different energy bins increase with TM growing at $t = 1270$ ms, and the GAM is also driven. Further, during strong TM, the energy distributions of energetic electrons are all enhanced at different CdTe channels, shown in Fig. 3, and the non-Maxwell distribution beams exist in the core plasma, as a result, these energetic electrons induce the excitation of BAEs and EGAM.

4. Nonlinear interactions among BAEs, EGAM and TMs

The nonlinear mode coupling can produce coherent mode structures which can provide overlap of wave–particle resonances in the minor radius, and transfer wave energy across different spatial scale. The role of nonlinear mode coupling is generally important in determining the mode excitation, saturation or damping. The nonlinear interaction also affects energetic particle redistribution/transport or plasma confinement. A novel result, which is nonlinear mode couplings among TM, BAEs and EGAM, has been observed on HL-2A. For studying the nonlinear mode coupling, the squared bicoherence [22] is given by $\hat{b}^2(f_1, f_2) = |\hat{B}_{XYZ}(f_1, f_2)|/\langle|X(f_1)Y(f_2)|^2\rangle\langle|Z(f_3)|^2\rangle$ with the Fourier bispectral $\hat{B}_{XYZ}(f_1, f_2) = \langle X(f_1)Y(f_2)Z^*(f_3)\rangle$, $f_3 = f_1 \pm f_2$ and $0 < \hat{b}^2(f_1, f_2) < 1$, where $X(f)$, $y(f)$ and $Z(f)$ are the Fourier transform of the time traces of $x(t)$, $y(t)$ and $z(t)$, respectively. The symbol $\langle\rangle$ denotes the ensemble average over many realizations. It is convenient to represent the contribution of the nonlinear coupling from multiple modes to one mode with the summed squared bicoherence, which is defined as $\sum b^2_{XYZ} = \sum_{f=f_1\pm f_2} \hat{b}^2(f_1, f_2)/N(f)$, where $N(f)$ is the numbers of realizations. To investigate the nonlinear mode coupling more precisely, the summed squared bicoherence must be higher than the noise level, which has the value of $(1 - b^2_{XYZ}/N)$. Fig. 4 shows the squared bicoherence and summed squared bicoherence of a poloidal Mirnov signal. It is found that the nonlinear interaction between the fundamental $n_{BAE} = 1$ (or $n_{BAE} = 1$) BAE with f_{BAE} and $n = 1$ TM with f_{TM} at each different moment. The following matching conditions are satisfied among these modes, i.e. $n_{TM} + n_{BAE} = n'_{BAE/GAM}$ and $f_{TM} + f_{BAE} = f'_{BAE/GAM}$ for TM and BAEs. Moreover, the $n = \pm 1$ BAEs interact with TM further and create