EGAM Induced by Energetic-electrons and Nonlinear Interactions among EGAM, BAEs and Tearing Modes in a Toroidal Plasma

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In this letter, it is reported that the first experimental results are associated with the GAM induced by energetic electrons (eEGAM) in HL-2A Ohmic plasma. The energetic-electrons are generated by parallel electric fields during magnetic reconnection associated with tearing mode (TM). The eEGAM 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 eEGAM is provided with the magnetic components, whose intensities depend on the poloidal angles, and its mode number are \( m/n=2/0 \). Further, there exist intense nonlinear interactions among eEGAM, 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.

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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 \cite{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 \cite{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 \cite{1}

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 \cite{2}, and also driven by fast ions \cite{3,4,5}. The GAM was investigated both using gyro-kinetic simulations and analytical methods in toroidal and slab geometry, and observed extensively in torus plasma \cite{2,3}. Meanwhile, the BAE with \( n \neq 0 \) is also a low frequency mode with parallel wave number \( k_{||} = (n - m/q)/R_0 = 0 \), 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 \cite{4}.

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) \cite{5} \cite{6}, which is useful for helping reciprocally identify the instabilities in the experiments. The most simple dispersion relations of BAE/GAM are given by

\[
\omega_{\text{BAE}} = \omega_{\text{GAM}} \approx (2T_i/m_i)^{1/2}(7/4 + T_e/T_i)^{1/2}/qR_0
\]

Where \( q \) is safety factor, \( R_0 \) 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 \cite{11} \cite{8}. In this letter, it is reported that the first experimental results are associated with the GAM induced by energetic-electrons (eEGAM), and also present that there exists the intense nonlinear interactions among eEGAM, BAEs and strong TMs.

Experimental conditions and mode characteristics—HL-2A is a medium-size tokamak with major/minor radius \( R/a = 1.65m/0.4m \). The experiments discussed here were performed in deuterium plasmas with plasma current \( I_p \approx 150 - 170kA \), toroidal field \( B_t \approx 1.32 - 1.38T \), and safety factor \( q_n \approx 4.2 - 4.6 \) 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_γ = 10 – 200 keV divided into many energy bins by the PHA-software setting.

The eEGAM 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., \( \vec{B}_\theta \propto \sin(2\theta) \). The similar experimental results (\( \vec{B}_\theta \propto \sin(\theta) \)), 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 (\( \sim 3.4 cm \)) for the BAE excitation on HL-2A [8]. Note that the BAEs can not 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 \( \gamma_i \) 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.

**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.

**FIG. 2**: Enhancement of energetic electrons during magnetic reconnection at different CdTe channels on HL-2A for shot #17455. Magnetic probe signal (a) and corresponding spectrogram (e). Hard X-ray counts in arbitrary unit, (b)-(d) and (f)-(h). Left column, \( r_d = 5 cm \); Right column, \( r_d = 30 cm \). (b) and (f), \( E_γ = 30 - 40 keV \); (c) and (g); \( E_γ = 40 - 60 keV \); (d) and (h), \( E_γ = 50 - 60 keV \). Other energy bins do not been shown here.

**Relationship between energetic-electrons and EGAM**—The existence of energetic-electrons during magnetic reconnection results in the excitation of GAM. Generation of energetic-electrons during magnetic reconnection has been the subject of a number of theoretical and experimental investigations [18] [19] [20] [21]. The production rate depend critically on the amplitude of the electric field generated during reconnection. The electric field is \( E_{||} = (sB_\parallel/16r_s)w_mdw_m/dt \) [18], where \( w_m \) is the width of the magnetic island, \( w_m = 4(B_\parallel r_s R_0/n s B_\parallel)^{1/2} \), 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, \( \Delta m \) is the stability parameter, \( \eta \) is the plasma resistivity, \( r_s \) is the radius of the magnetic surface, \( B_\parallel \) 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 \( E_{||} \sim 5 V/m \) 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 eEGAM 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 eEGAM.

**Nonlinear interactions among BAEs, eEGAM 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 eEGAM, has been observed on HL-2A for shot #17455. Black, blue and red lines are corresponding to t=1100-1110 ms, 1300-1310 ms and 1480-1490 ms, respectively.

**Excitation Mechanism of eEGAM**—The excitation mechanisms of eEGAM can be discussed, briefly. As we known, the energy transfer from energetic particle to the wave can be expressed by $G \propto \omega \partial f/\partial W + n \partial f/\partial P_\varphi$
Here, $\partial f/\partial W$ and $\partial f/\partial P_\phi$ are, respectively, the particle energy derivative of the distribution function of energetic particle and the derivative for the toroidal momentum. For the GAM, the driving free energy may directly come from the positive gradient of the distribution function $\partial f/\partial W$ and indirectly (because of $n=0$) from the radial derivative of distribution function by nonlinear interactions. The magnetic island induces BAEs, then the eEGAM is excited via the nonlinear interactions among BAEs and strong TM which is a pump wave. While the matching conditions are satisfied, i.e. $\omega_1 + \omega_2 = \omega_3$ and $k_1 + k_2 = k_3$, the nonlinear interactions can occur between three waves in the plasma, and the coupled equations are bilinear and similar, and the coupling coefficients of the wave field amplitude determine the growth or damping of the waves [24]. According to Chen’s theory, while the purely Alfvénic state described by the Wålén relation $(\delta u/v_A = \pm \vec{B}/B_0)$ is broken [25], i.e. $\delta E_{||} \neq 0$ or $\omega^2 \neq k_r^2 v_A^2$, it will lead to significant perpendicular ponderomotive force and zonal flows. In our experiments, $\delta E_{||} \neq 0$ is satisfied obviously owing to the magnetic reconnection of strong TMs. The slow-sound-wave density and potential perturbation, which are induced by parallel ponderomotive, will have radially varying $(n = 0, m = \pm 1)$ poloidal structures. The parallel ponderomotive force can couple with the compressible dynamics of slow-sound-waves, and the two high-frequency Alfvénic modes can generate a low-frequency acoustic mode by nonlinearity. If the perpendicular incompressibility of shear Alfvén wave is broken by the magnetic curvature, i.e. $\delta u_\parallel \neq 0$, the AEs can nonlinearly generate $(n = 0, m = \pm 1)$ radially local magnetic perturbations. Recently, the theory investigation suggests that the plasma compressibility has a significant effect on nonlinear mode coupling of AEs, and the coupling of AEs is a more effective energy transfer at a lower amplitude level due to the enhanced compressional perturbations in the poloidal sidebands [28]. The GAM is toroidally symmetric mode unique to toroidal plasmas with mode structure that is nearly poloidally symmetric. The spatial overlap of the mode structures should be essential for the nonlinear mode coupling. Our experimental results indicates the TM, BAEs and eEGAM all localize at the q=2 surface, i.e., there exists an overlap between the mode radial structures of eEGAM and BAEs. It means that the AEs can propagate poloidally into the region of the zonal flows (ZF) due to the zonal mode structure of GAM and the mode structure overlap, and can interacts with the GAM/ZF, and the wave energy can transfer between the GAM and AEs, and the intensity of the AEs can influence on the growth, saturation and damping of the GAM.

**Summary**—The eEGAM has been recently observed for the first time on HL-2A. The magnetic fluctuation spectrogram indicates that the eEGAM is always accompanied by strong TM and BAEs. The analysis reveals that the eEGAM is provided with the magnetic components, whose intensities depend on the poloidal angles, and its mode numbers are $|m/n| = 2/0$. Further, a novel result, which is that there exist the cross-scale couplings among TM, BAEs and eEGAM, has been observed on HL-2A. The eEGAM is directly driven by energetic-electrons via the gradient of the velocity space or indirectly produced via the nonlinear mode coupling among BAEs and strong TM, but more theoretical works are needed because this phenomenon is a typical example with respect to multi-scale interactions. The eEGAM should have a significant effect on plasma transport in the vicinity of the magnetic island, and also have a profound regulatory effect on the turbulence around magnetic island. The experimental results indicate that the couplings possibly induce the energy transfer among TM, BAEs and eEGAM, and it is possible to be one of mechanisms of the energy cascade in Alfvén turbulences, and the BAE/GAM may be an energy channeling between different scales, such as macro-, meso- and micro-scale. The new findings give a deep insight into the underlying physics mechanism for the excitation of the LF Alfvén/acoustic fluctuation and ZFs.

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