Studies on Neutral Beam Ion Confinement and MHD Induced Fast-Ion Loss on HL-2A Tokamak

LIU Yi[1], ISOBE Mitsutaka[2], PENG Xiao-Dong[1], Wang Hao[3], JI Xiao-Quan[1], CHEN Wei[1], ZHANG Yi-Po[1], Dong Yun-Bo[1], MORITA Shigeru[2] and TOI Kazuo[2], DUAN Xu-Ru[1]

[1]Southwestern Institute of Physics, P.O. Box 432, Chengdu 610041, China
[2]National Institute for Fusion Science, 322-6 Oroshi-cho, Toki-shi 509-5292 Japan
[3]The Graduate University for Advanced Studies, Toki 509-5292, Japan
e-mail contact:yiliu@swip.ac.cn

Abstract

Experiments with a high-energy deuterium neutral beam (NB) injection (30 keV, about 0.6MW) were performed on the HL-2A tokamak. To obtain information on NB deposition and the slowing down of beam ions in HL-2A plasmas, a very short-pulse deuterium NB injection, or the so-called “blip” injection, was applied into MHD-quiescent Ohmic deuterium plasmas. Analysis of neutron decay following the NB “blip” injection indicates that tangentially injected beam ions are well confined, slowing down classically in the HL-2A. In contrast to the MHD-quiescent plasma, anomalous losses of beam ions were observed when a core localized mode with a frequency up-chirping from 15 to 40 kHz was present in the plasma. The core localized mode was identified as a beta-induced Alfvén acoustic (BAAE) mode by its frequency up-chirping behavior and numerical calculation. Such a high energetic particle driven mode led to fast-ion loss, showing a strong influence of the core localized fast-ion driven BAAE mode on the fast-ion transport. Furthermore, a clear frequency splitting was firstly observed on the Alfvén-acoustic type mode, and is found to be strongly linked to the effect of the resonant wave particle interaction, providing further insights into how frequency splitting structures are generated in plasma.

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1. Introduction

In recent years, significant progress has been made in the fusion energy development. Plasma parameters of tokamak and helical devices are steadily approaching the reactor-relevant condition. It is well known that energetic alpha particles born from d-t reactions in a future burning plasma play an essential role to sustain the self-ignition condition. Once substantial loss of energetic alphas occurs due to some reason, a self-ignited state will be terminated. Moreover, the localized heat load on the first wall due to impact of escaping alphas may seriously damage the device. Because of these reasons, great attention is now being paid to physics issues related to energetic ions such as magnetic field ripple transport of energetic ions [1], anomalous transport and/or loss of energetic ions caused by fast particle driven modes [2].

Neutron diagnostics have played an important role to study energetic-ion physics in deuterium neutral beam (NB) heated deuterium plasmas, providing information of confinement property of energetic beam ion in toroidal fusion plasmas [3]. One of effective methods to check whether beam ions slow down classically or not is to measure the decay rate of neutron emission following deuterium NB injection and to compare experimental decay rate with decay rate predicted by classical slowing down theory. Experimental study based on an approach of short pulse NB injection, or so called NB "blip" injection, which duration is much shorter than τ_S, has been carried out in DIII-D [4], CHS [5], and other devices. One of the advantages of NB "blip" injection is that the "blip" injection does not give a significant effect on plasma parameters. Another is that beam ions can be recognized as test particles having a narrow distribution in the velocity space.

A number of electromagnetic collective processes may affect, through wave-particle interaction mechanisms, the dynamics of the alpha particle population generated by deuterium-tritium fusion reactions in magnetically confined thermonuclear plasmas. Amongst these, weakly damped Alfvén eigenmodes (AE), global discrete modes existing within the shear Alfvén spectrum in toroidal devices [6], can interact resonantly with the fusion produced alpha particles during their slowing down, being driven unstable and in turn affecting their orbits. Over the last few years much attention has been given to a new type of low frequency electromagnetic modes dubbed beta-induced Alfvén-acoustic eigenmodes BAAEs within the framework of ideal magnetohydrodynamics (MHD) [7]. These modes can be detrimental for the magnetic fusion arising from the induced fast ion loss, and therefore potentially play an important role in fusion plasmas. Recently, inclusion of kinetic effects into the description of BAAE or TAE in warm plasmas has produced several new results: for BAAE the kinetic theory frequency is surprising close to the observations; for TAE the kinetic theory predict a mode frequency splitting. A further study of BAAE is needed to understand the role of the kinetic effects such as resonances with thermal ions.

High-energy deuterium neutral beam (NB) injection has recently begun in HL-2A tokamak experiments. Currently, a ^{235}U fission chamber is employed in HL-2A to measure total neutron yield. To obtain information of NB deposition and slowing down of beam ions in HL-2A, a very short pulse of deuterium NB, was injected into MHD-quiescent Ohmic deuterium plasmas to analyze whether beam ions in HL-2A plasma slow down classically or not. Also, anomalous transport and/or loss of fast ion caused by fast ion driven instabilities are also of our great concern.

This paper describes results on confinement property of beam ions from the viewpoint of d-d neutron emission, and MHD induced fast-ion loss on HL-2A Tokamak. In Sec. II we propose an analysis of confinement property of beam ions from the viewpoint of d-d neutron emission in HL-2A. In Sec. III fast-ion loss induced by MHD activities on HL-2A Tokamak was described, where a strong influence of a core-localized fast-ion driven BAAE mode on the fast-ion transport was observed. In Sec. IV we investigate the feature of the observed core-localized mode with comparison with ideal MHD predictions; then, we discuss the nonlinear splitting of BAAE in HL-2A plasma. Finally, we summarize the results in Sec. V.

2. Analysis of Beam Ion Transport from Neutron Emissivity Measurement in Deuterium Neutral Beam-Heated Deuterium Plasmas

On the HL-2A [8], which is a tokamak with double null divertors (R_{ax}=1.65 m, a=0.4 m, B_t up to 3 T, I_p up to 0.5 MA), an NB injector equipped with four positive-ion-sources is installed. NB is tangentially co-injected with the tangency radius of 1.35 m. The acceleration voltage E_b and port-through power P_{nb} of NB were typically ~30 keV and ~0.6 MW, respectively, in the recent experimental campaign. In HL-2A, total neutron yield is being measured with a ^{235}U fission chamber (uranium oxide of 3 g) [9]. The ^{235}U fission chamber is surrounded by the polyethylene-moderator of ~5 cm thick to decelerate d-d neutrons (2.45 MeV) to thermal energy range in order to enhance neutron counts.

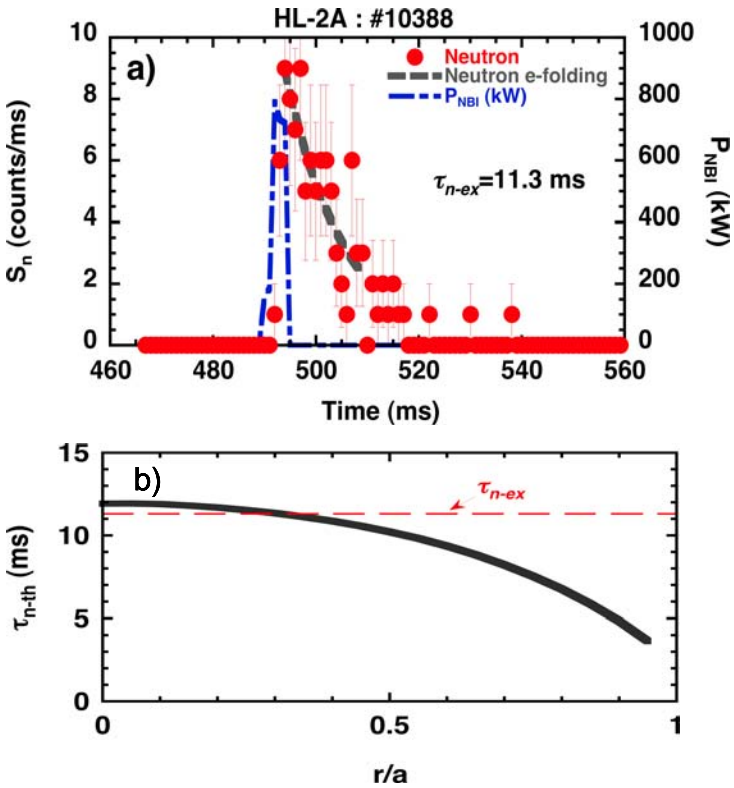


Figure 1. a) Typical time evolution of d-d neutron emission rate when "blip" NB is injected. b) The radial profile of d-d neutron decay time predicted by the classical slowing-down theory with the measured neutron decay time.

Figure 1(a) shows time traces of d-d neutron emission rate S_n and P_{nb} in HL-2A. In this shot, deuterium NB 'blip' of which pulse width is ~ 5 ms was injected into an MHD-quiescent deuterium Ohmic plasma. In HL-2A, most neutrons generated in deuterium NB-heated plasmas are produced in beam-plasma reaction. This is because E_b (~30 keV) of beam ions is much higher than ion (deuteron) temperature T_i (typically ~1 keV) in the current HL-2A condition. Fusion reactivity rapidly rises as the relative velocities between the two colliding ions increase. It can be seen that neutrons suddenly appear right after NB turn-on and S_n starts to decay exponentially after NB turn-off. The neutron emission rate from the beam-plasma reaction can be scaled as $S_n \propto n_i n_b \langle\sigma v\rangle_b$. Here, n_i and n_b are background deuteron density and beam deuteron density, respectively. Assuming that $\langle\sigma v\rangle_b$ decreases exponentially as injected beam ions slow down classically without loss and n_i is constant after NB turn-off, S_n is predicted as $S_n(t)$ $\langle\sigma(v(t))v(t)\rangle_b \approx \exp(-t/\tau_{n-th})$. Here, τ_{n-th} is theoretically predicted e-folding decay time of neutron rate. According to the classical slowing down theory [10], τ_{n-th} can be expressed as

$$\tau_{n-th} = -\int_{E_n}^{E_b} \frac{dE}{\{dE/dt\}_{th}} \cong \frac{\tau_{se}}{3} \ln \frac{E_b^{3/2} + E_c^{3/2}}{E_n^{3/2} + E_c^{3/2}}$$

where E_n is the energy at which $\langle\sigma v\rangle_b$ is reduced by $1/e$ from the value at E_b, E_c is the critical energy of beam ions at which the electrons Coulomb friction equals to the bulk ion Coulomb friction, τ_{se} is the Spitzer's slowing-down time on electrons. In the NB "blip" shot shown in Fig. 1(a), the experimental neutron decay rate $\tau_{n\text{-}ex}$ is evaluated to be ~11.3 ms. Consequently, we obtain the profile of predicted $\tau_{n\text{-}th}$, assuming that $T_i(r/a)$ is equal to $T_e(r/a)$. The line of $\tau_{n\text{-}ex}$ is drawn as well in Fig. 1(b). As seen in Fig. 1(b), $\tau_{n\text{-}th}$ becomes shorter toward the peripheral region since τ_{se} which is a key parameter in determining $\tau_{n\text{-}th}$ becomes shorter toward the peripheral region. It is noted that E_c becomes smaller as T_e becomes smaller and E_n becomes slightly larger toward the edge. E_n is a function of $<\sigma v>_b$ through the value of T_i. What has to be noticed is that $\tau_{n\text{-}ex}$ is in agreement with $\tau_{n\text{-}th}$ within ±5 % in the core region (r/a<0.4). It means that tangentially injected beam ions have a peaked profile, decelerating classically in HL-2A.

3. Fast-Ion Loss Induced by MHD activities

Anomalous transport of energetic ion due to MHD activities is also of our great concern. Growing interest has emerged regarding modes of Alfvénic type in the lowest part of the spectrum during neutral beam injection which causes losses of the fast particles in the experiments [11].

In HL-2A, significant depletion of total neutron yield (S_n) was observed in NB-heated HL-2A plasmas. Figure 2 shows temporal evolutions of plasma current and neutron yield in discharge 10391 with a NB injection from 480ms to 780ms. Although the NB power P_{nb} kept constant and the plasma parameters were almost the same as that before instability onset, neutron yield gently decreased according to growth of a core localized instability in the frequency region of about 15~40 kHz as shown in figure 3.

It reveals that there is a very low frequency mode below the characteristic TAE frequency and the geodesic acoustic mode frequency (f_{TAE}=240 kHz, f_{GAM}=45 kHz), and this core localized instability has cause a lose of neutron yield as much as 5%, which is apparent different from the

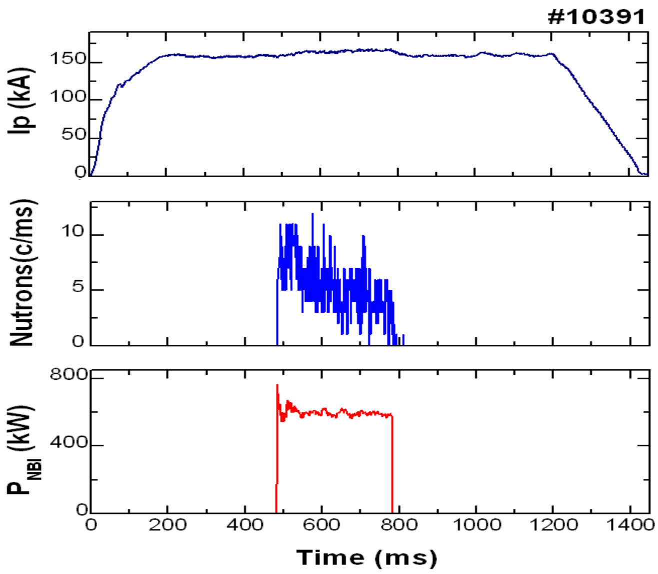


Figure 2. Temporal evolution of plasma parameters of a discharge with relatively low magnetic fields (B_0=1.37T) during NBI of 30keV.

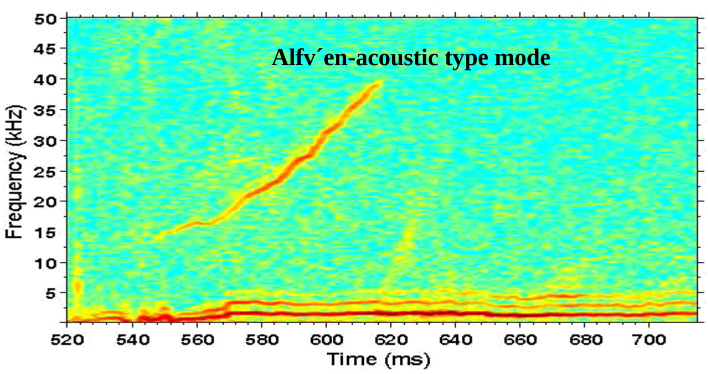


Figure 3. Spectrogram of central SXR at r/a=0.05, showing the low and high frequency modes.

central region and the mode frequency up-chirps form 15 to 40 kHz in about 70ms. Though, the plasma is characterized by relatively low beta β_p < 0.6%, we proved that the beta-induced Alfvén acoustic (BAAE) can be responsible for observation in HL-2A plasma in the central region, by analysis of its frequency up-chirping behavior, mode structure and its dynamics, which will be discussed in detail in next section.

4. Fast Particle Driven BAAE Waves and its Frequency Splitting

4.1 Fast Particle Driven BAAE Waves

The low-frequency plasma oscillations observed on HL-2A have a typical feature of frequencies corresponding to BAAE frequency of $v_A k_{\|} / \sqrt{1+2q_{\min}^2}$. The plasma equilibrium was computed with the CRONOS code, figure 4(a) shows the q profile at t=560ms with $q_0 \cong 0.95$. Usually, BAAE exists in the low magnetic safety factor region near the extrema of the Alfvén-acoustic continuum. As the safety factor decreases in time due to plasma current diffusion, Alfvén-acoustic continuum evolves and so do the frequencies of BAAE, which is the typical feature of the low-frequency up-chirping mode observed on HL-2A as shown in figure 4(b). In order to further identify observed instabilities, we utilize the reduced model developed in Ref. [11] to investigate the fast ion driven unstable mode observed at *f*=15-40 kHz in the HL-2A plasma during NBI heating.

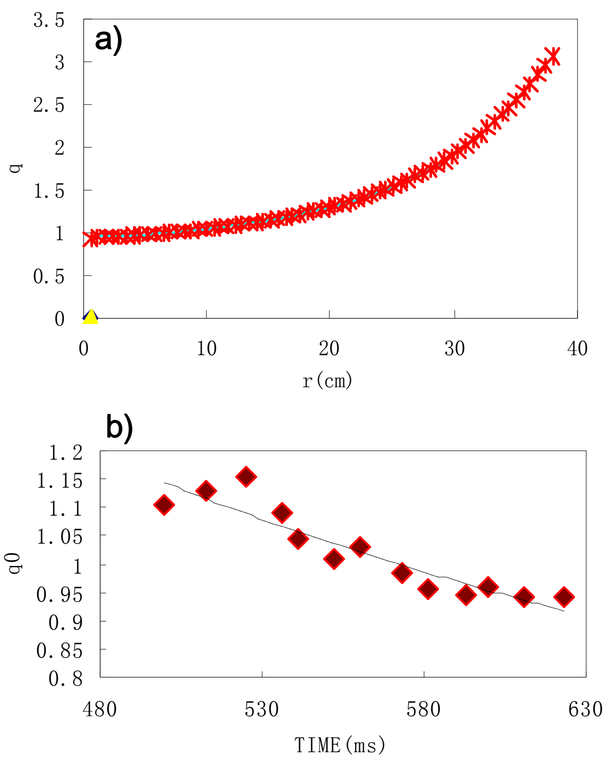


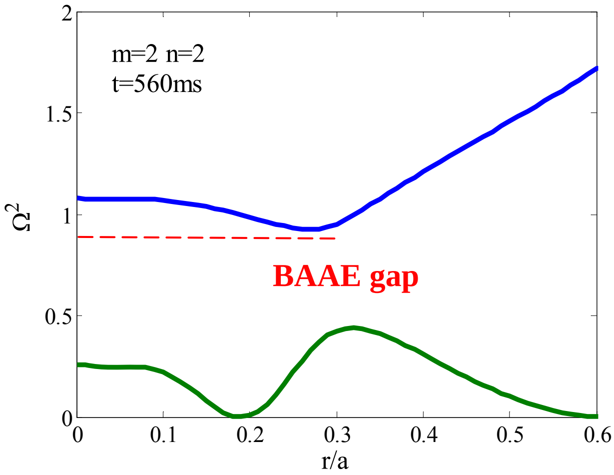
Figure 4. (a) q profile computed with the CRONOS code. (b) evolution of the central value of the factor.

A search was performed for eigenmodes from the dispersion relation deduced from ideal MHD equations for the continuum, which incorporates both the shear Alfvén and the acoustic branches:

$$(\Omega^2 - k_0^2/\delta)(\Omega^2 - k_{+1}^2)(\Omega^2 - k_{-1}^2) = \Omega^2(2\Omega^2 - k_{+1}^2 - k_{-1}^2) \tag{1}$$

Where, $\Omega^2 = k_0^2/\delta$ is the shear Alfvén wave, $\Omega^2 = k_{\pm1}^2$ are the two acoustic modes in the coupling, and $\Omega^2 \equiv (\omega R_0/v_A)^2/\delta$, $k_j^2 = (j/q + k_0)^2$, $\delta \equiv \gamma\beta/2$, and γ is the specific heat ratio.

The analytical solution of Eq. (1) for n=2 in HL-2A plasma equilibrium are shown in Fig.5_a ($\delta = \gamma\beta/2 = 0.002$, $\beta \simeq 0.2\%$). BAAEs in HL-2A typically are in the Alfvén-acoustic gap but stay near the acoustic continuum frequency $f = \frac{V_A}{2\pi R}\sqrt{\delta\Omega_+^{\ 2}}$, which is about 40 kHz in the plasma frame. In Fig.5_b, we show results of CASTER simulation for n=2 and the particular plasma equilibrium, for which several component with different poloidal number have been found. It can be seen that the dominant component in BAAE would be the m=2, which has a spatial structure roughly consistent to the gap in Fig.5_a.



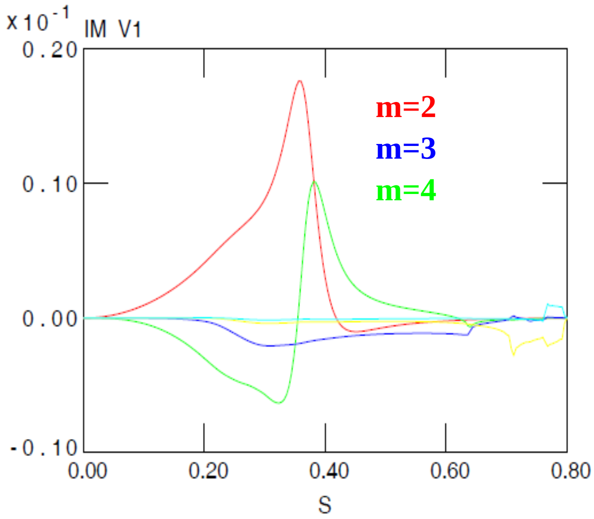


Figure 5. (a)Alfven-acoustic continuum and Alfvén-acoustic gap calculated with HL-2A parameter. The radial extent of global BAAE and its frequencies is shown as a dashed line. (b) The radial BAAE mode structure of the dominant poloidal harmonic of the normal component of the plasma displacement vector in arbitrary units.

Thus, in the frame work of ideal MHD theory, we can identified the core localized mode as the beta-induced Alfvén acoustic (BAAE) by its frequency up-chirping behavior, mode structure and its dynamics. It should be noted that the $m \pm 1$ sidebands perturbation component are also present from the kinetic MHD theory [11] but degenerate in frequency. Such degeneracy will be lost due to the effect of resonant wave particle interaction and collision-like relaxation of the resonant particles, which will be discussed in next section.

4.2 Frequency Splitting of BAAE Waves

A clear splitting was firstly observed for such an Alfvén-acoustic type mode，the mode frequency splits into two sidebands along with the original mode, highlighted in Figure 6. As these modes are externally driven with a dominant n=2 component and the plasma toroidal rotation is negligible in HL-2A Ohmic plasmas, they cannot correspond to Doppler

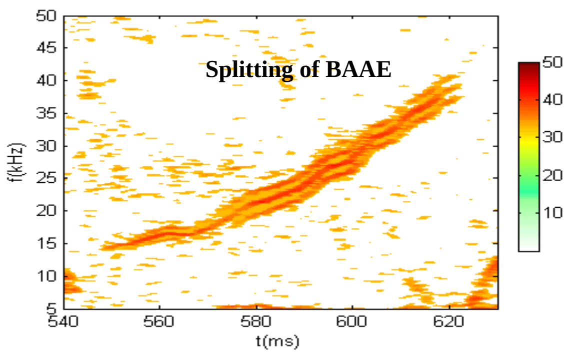


Figure 6. Spectrogram of central SXR r/a=0.15, showing the frequency splitting of BAAE.

shifted peaks of different *n*. Furthermore, such splitting is only found near the q=1 rational surface near r/a=0.15, while there is no splitting found on both side away form this rational surface (see figure 3 and 6).

An explanation of these new observations can be proposed by applying a nonlinear theory for kinetic instabilities near threshold [12], which can be applied to many types of resonant particle driven instabilities. Up to now, the splitting of TAE observed on JET [13] has been explained with the general nonlinear phenomena due to the combination of resonant wave particle interaction and collision-like relaxation of the resonant particles on the basis of the nonlinear model of near-threshold kinetic instabilities. Since the BAAE contains an electromagnetic component due to the Alfvén coupling, the particle trapping in the wave undergo nonlinear oscillations at a characteristic frequency $\omega_B = (ek\hat{E}/m)^{1/2}$, where $\hat{E}\cos(\omega t - kx)$ is the perturbing longitudinal electric field, similar to the case of resonant TAE wave-particle interaction.

In the nonlinear model of near-threshold kinetic instabilities, the competition between the resonant wave-particle interaction with drive term of γ_L and collisionlike relaxation of the resonant particles characterized by a damping rate of ν_{eff}, leads to a nonlinear evolution of the mode amplitude A as follow[12]:

$$\exp(-i\phi)\frac{dA}{dt} = \frac{\gamma}{\cos\phi}A - \frac{\gamma_L}{2}\int_0^{t/2}\tau^2 d\tau \int_0^{t-2\tau} d\tau_1 \exp[-\nu_{eff}^3\tau^2(2\tau/3+\tau_1)] \times A(t-\tau)A(t-\tau-\tau_1)A^*(t-2\tau-\tau_1)$$

It is found that the saturated state for sufficiently small mode linear growth rate γ could become unstable and bifurcates when γ exceeds a critical value γ_{cr}, e.g. the equation admits a solution as: $A = A_0[1+\alpha_1\exp(i\Delta\omega t)+\beta_1\exp(-i\exp(-i\Delta\omega t)+\alpha_2\exp(2i\Delta\omega t)+\beta_2\exp(-2i\Delta\omega t)$ Where A_0 is the amplitude of the main spectral component, and $\Delta\omega$ is the sideband frequency split, α_i and β_i are the amplitudes of the sidebands. For the situation of the positive energy BAAE with negative dissipation from resonant ions on HL-2A, the value of ϕ should be set to be 0 and the mode frequency split into two sidebands as predicted in [13]. This is exactly consistent with the observed feature of the frequency splitting of BAAE on HL-2A NB injection experiment. Furthermore, the experimentally measured sideband frequency split form the spectrum shown in Figure 7 is about $\Delta\omega_{EX} = 1.65\times10^3\times2\pi s^{-1}$, roughly

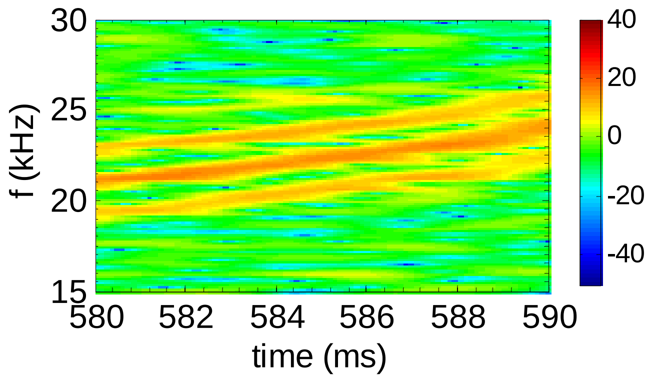


Figure 7. Zoomed view of the splitting of BAAE, showing a frequency split of about 1.65kHz.

consistents with the value estimated form the theory, which is about $\Delta\omega_{th} = 0.575\nu_{eff} \approx 1.5\times10^3\times 2\pi s^{-1}$, where the ν_{eff} is estimated from the bounce frequency ω_b , $\omega_b \approx (\gamma_{cr}/\gamma_L)^{1/4}\nu_{eff} \le \nu_{eff}$, and ω_b can be calculated as $\omega_b = \frac{v_\perp}{qR_0}(\frac{r}{2R_0})^{1/2} \approx 3.1\times10^3\times 2\pi s^{-1}$. We note another interesting observation that though the BAAE can extend up to 0.3r/a in the HL-2A plasma the splitting of BAAE was only observed near q=1 surface, which requires further experimental and theoretical studies.

5. Conclusions

In this paper we presented an experimental study of slowing down process of beam ions from high-energy deuterium neutral beam injection in HL-2A plasmas with a very short-pulse deuterium NB injection. Analysis of neutron decay following the NB “blip” injection indicates that tangentially injected beam ions are well confined, slowing down classically in the HL-2A.We also presented experimental observations of beta-induced Alfvén acoustic (BAAE) modes, which qualitatively support the theoretical predictions. Numerically we have found a eigenmode of BAAE in the gap of Alfven-acoustic continuum, which is formed near the extremum points of the continuum in low beta plasmas of HL-2A. It was found that ideal MHD simulated BAAE frequency evolution qualitatively agrees with HL-2A observations. Furthermore, a clear frequency splitting was firstly observed on the Alfvén-acoustic type mode in HL-2A plasma, and is found to be strongly linked to the effect of the resonant wave particle interaction, providing further insights into how frequency splitting structures are generated in a plasma.

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