Study of Alfvén Eigenmodes in the TJ-II Stellarator*

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(Received 6 December 2009 / Accepted 13 April 2010)

Energetic ion driven Alfvén Eigenmodes (AEs) in the NBI-heated plasma at the TJ-II heliac were studied by Heavy Ion Beam Probing (HIBP) in the core, and by Langmuir and Mirnov probes (LP and MP) at the edge. HIBP observed the locally (~ 1 cm) resolved AE at radii $-0.5 < \rho < 0.9$. The set of AE branches with low poloidal numbers ($m < 8$) was detected by MP. The most plausible candidates are global, helical and toroidal AEs. AEs on the density, electric potential and poloidal magnetic field oscillations were detected by HIBP at frequencies $50\,\mathrm{kHz} < f_{\mathrm{AE}} < 300\,\mathrm{kHz}$ with a high resolution (< 5 kHz). The amplitude of the AE potential oscillations $\delta\varphi^{\mathrm{AE}} \sim 10\,\mathrm{V}$ was estimated. The MP and HIBP data have a high coherency at f_{AE}. When the density rises, AE frequency is decreasing, $f_{\mathrm{AE}} \sim n_{\mathrm{e}}^{-1/2}$, but the cross-phase between the density and potential remains permanent. Poloidally resolved potential measurements by HIBP and LP shows high coherency and finite cross-phase at f_{AE}, resulting in finite electric field δE_{pol}. Depending on the cross-phase between δn_{e} and δE_{pol}, AEs may bring small or significant contribution to the turbulent particle flux $\Gamma_{\mathrm{E\times B}}$ for the observed $k_\theta < 3\,\mathrm{cm}^{-1}$.

Keywords: Alfvén eigenmode, turbulent flux, HIBP, TJ-II, NBI

DOI: 10.1585/pfr.5.S2019

1. Inroduction

Interactions between energetic ions and MHD perturbations are the hot topic under study in major tokamaks and stellarators due to the excitation of the Alfvén Eigenmodes (AEs) and their possible disturbing effect on the transport. Energetic ion driven AEs are routinely observed both in tokamaks [1] and stellarators like W7-AS [2], CHS [3], LHD [4]. Recently, AEs were observed in the TJ-II flexible heliac [5, 6]. In these helical plasmas, where the magnetic shear is low, almost zero or negative over the whole plasma, various types of AE were observed, similar to tokamaks.

AEs are conventionally studied by Mirnov probes (MP), which provide the poloidal m and toroidal n mode numbers and their spectral characteristics. However, MPs are located outside plasma, and cannot always detect AEs deep in the plasma core. Moreover, they do not provide information about the mode localization and the structure, which is crucial for calculating both fast particle drive (which has maximum at highest gradient of hot ion pressure) and continuum damping. Other diagnostics, like reflectometry [7], soft X-rays and EC emission [8] produce data about the density or temperature oscillations originated due to the interaction of AEs with the bulk plasma, i.e., indirect information about AE as an electromagnetic wave. AEs are directly characterizing by the oscillating electric δE and magnetic δB fields. The development of the new techniques to measure these quantities presents a challenge for modern diagnostics [9]. Such diagnostics would contribute to ITER research needs as tools to understand and control burning plasma, which is affected by alpha particles.

The paper discusses the contribution of HIBP [10] as

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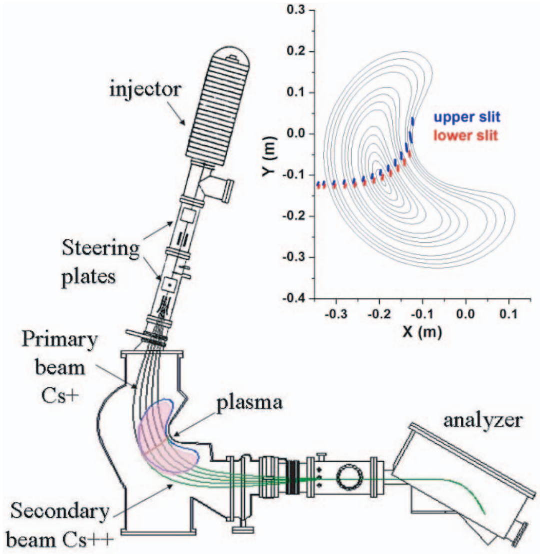

Fig. 1 HIBP experimental set-up at TJ-II. Top: detector lines for the poloidally resolved potential and density measurements.

a new tool to study AEs by example of the NBI heating regimes in TJ-II. Originally designed and used in many tokamaks and stellarators to study of the mean electrostatic potential [11], HIBP may be applied to study of B_{pol} [12]. Recently HIBP expands its frequency bandwidth up to several hundred of kHz, and it was applied to study the potential oscillations, the broadband turbulence and quasi-coherent modes like Geodesic Acoustic Modes [13].

2. Experimental Set-Up

TJ-II is a four-field-period low-magnetic shear stellarator with helical axis and the following parameters: $B_{tor} = 1$ T, $<R> = 1.5$ m, $<a> = 0.22$ m, $\bar{n}_e = (0.3\text{-}6) \times 10^{19}$ m^{-3}, two gyrotrons with the total power up to P_{ECRH} = 300 kW each, combined with two co- and counter- neutral beam injectors (NBI) of 30 kV H^0 beam with the total power up to P_{NBI} = 400-450 kW each. HIBP in TJ-II operates with Cs^+ ions, E_b = 125 keV [6, 14].

The crucial element in the HIBP upgrade is the two-slits energy analyzer of secondary ions, which allows us to observe two detector lines simultaneously, Fig. 1. Two sample volumes are optimized to find the poloidal component of the electric field E_{pol} by the difference in local potentials, $E_{pol} = (\varphi_1 - \varphi_2)/x$, $x \sim 1$ cm. Finally, the radial turbulent particle flux $\Gamma_r = <\tilde{n}_e \tilde{v}_r> = \Gamma_{E\times B}$, was extracted for the first time in stellarators [6].

3. Experimental Evidence of the AEs

A low-density, $\bar{n}_e = (0.3\text{-}0.6) \times 10^{19}$ m^{-3}, ECR heated target plasma was additionally heated by NBI. When NBI was applied, the high-frequency AEs were observed by various diagnostics: reflectometry, Mirnov probes (MP), SXR, Langmuir probe (LP) and HIBP. The time trace of

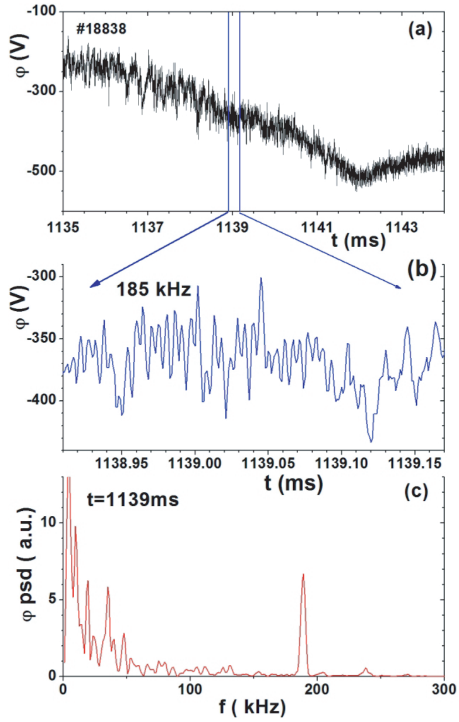

Fig. 2 AEs are pronounced in the plasma potential: a) time trace of the plasma potential at ρ = 0.5; b) expanded view of the potential time trace. AE with 185 kHz are visible; c) potential power spectral density (PSD).

the plasma potential observed at ρ = 0.5 is presented in Fig. 2 (a). It demonstrates a large variety of the plasma oscillations. Figure 2 (b) shows the AE as a quasi-monochromatic oscillation dominating the broadband turbulence. The corresponding Fourier power spectral density (PSD) is shown in Fig. 2 (c). Oscillation amplitude of the AE, averaged over 1 ms is $A_{185\,kHz}$ = 10 V. The temporal evolution of the PSD (Fourier spectrograms) of the plasma potential, density and the beam toroidal shift, representing the poloidal magnetic field δB_{pol} are presented in Fig. 3. The HIBP time sampling is 1 μs, the time interval for the elementary spectrum reconstruction is 1 ms. When NBI starts (P_{NBI} = 900 kW), AEs appear as a set of the pronounced multiple quasi-monochromatic peaks with a high contrast to the broadband noise. In many shots, the density n_e starts to rise with some delay (in a range of a few dozens ms) after NBI starts, Fig. 3 (c). The frequencies of the quasi-monochromatic modes are changing as $f_{AE} \propto n_e^{-1/2}$, indicating the Alfvénic nature of the modes.

Preliminary assessment with the ideal MHD code CONTI [15] has shown that several gaps in Alfven continuum may reside, where AEs driven by fast particles may be unstable. Example of one Alfvén mode family is shown in Fig. 4. Global Alfvén Eigenmodes (GAE), Helicity induced Alfvén Eigenmodes (HAE) and Toroidicity induced Alfvén Eigenmodes (TAE) are plausible candidates for the observed AEs in TJ-II.

The spectrogram of the coherence between the bulk

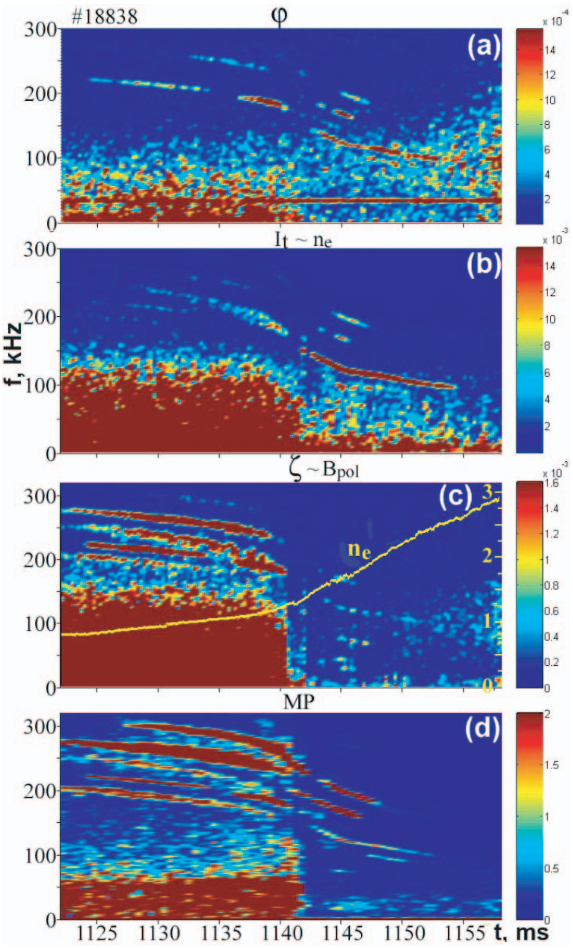

Fig. 3 PSD for HIBP and Mirnov signals. AEs are pronounced: a) on the potential; b) on the total secondary beam current I_t (plasma density); c) on the toroidal shift of secondary beam ζ (poloidal magnetic field), d) on Mirnov probe signal. Growth of line-averaged density n_e and suppression of broadband turbulence interpreted as better confinement NBI sustained plasma state.

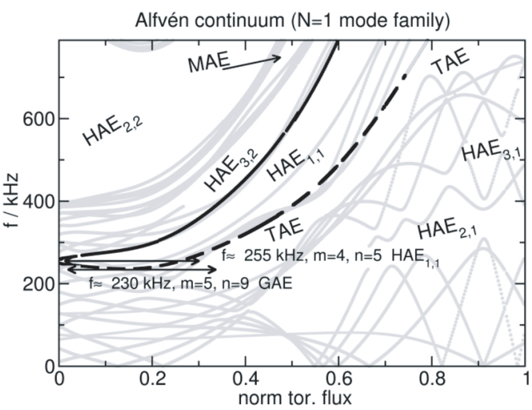

Fig. 4 Calculated Alfvén continuum for the shot, presented in Fig. 3, at $t = 1140$ ms.

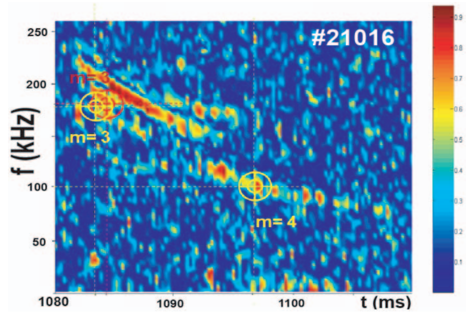

Fig. 5 Spectrogram of the coherence between n_e oscillations (HIBP) at $\rho = 0.16$ and Mirnov probes signal. Circles indicate the AE branches with poloidal mode numbers m detected by Mirnov probes.

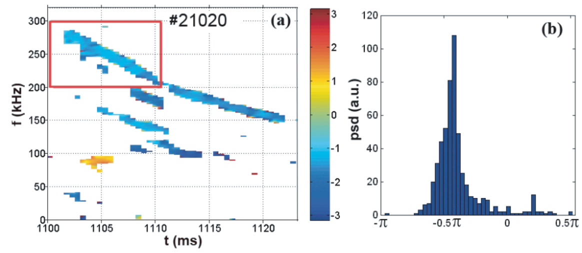

Fig. 6 (a) Spectrogram of the cross-phase between n_e and δB_{pol} in the same sample volume; (b) histogram of the cross-phase, computed over the area marked by red rectangle.

plasma density oscillations, measured by HIBP at $\rho = 0.16$, and the Mirnov probes signal is presented in Fig. 5. The high coherency ($c > 0.8$) between Mirnov signal, which is mainly peripheral, and HIBP, which is localized close to the plasma centre, indicates a global character of the observed branches of AEs. AEs visible on the density, potential and B_{pol} also show the high coherency between different characteristics. Figure 6 shows that cross-phase between n_e and B_{pol} is finite and remains permanent, while the frequency is varied due to the density rise, cross-phase value is not sensitive to the observation time. Figure 7 shows the example of the temporal evolution of the family of AEs in the shot with a sequence of spontaneous L-H and H-L transitions. During the direct L-H transition, which happens in the pure NBI sustained plasma, the edge and core fluctuations of the local plasma density, potential and poloidal electric field E_{pol} show some reduction [6]. We see the strong broadband turbulence suppression in the H-mode (Fig. 7 (a)) and reduction in $\Gamma_{E\times B}(f)$ obtained by spectral analysis technique [16] (Fig. 7 (c)). At the back H-L transition, $\Gamma_{E\times B}$ and δn_e show a full recovery to the initial L-mode features. The AE branches are suppressed in the H-mode, and they recover after the back L-H transition, that is seen in both HIBP and Mirnov signals. Note that some AEs, which are pronounced in the density, potential and B_{pol} oscillations as high contrast quasi-monochromatic peaks, are not visible in the spectrogram of $\Gamma_{E\times B}$, measured either in the plasma core by HIBP, Fig. 7 (c), or at the edge by the Langmuir probe, Fig. 7 (d). There is a significant coherence found (~ 0.7) between δE_{pol} and δn_e for some AE

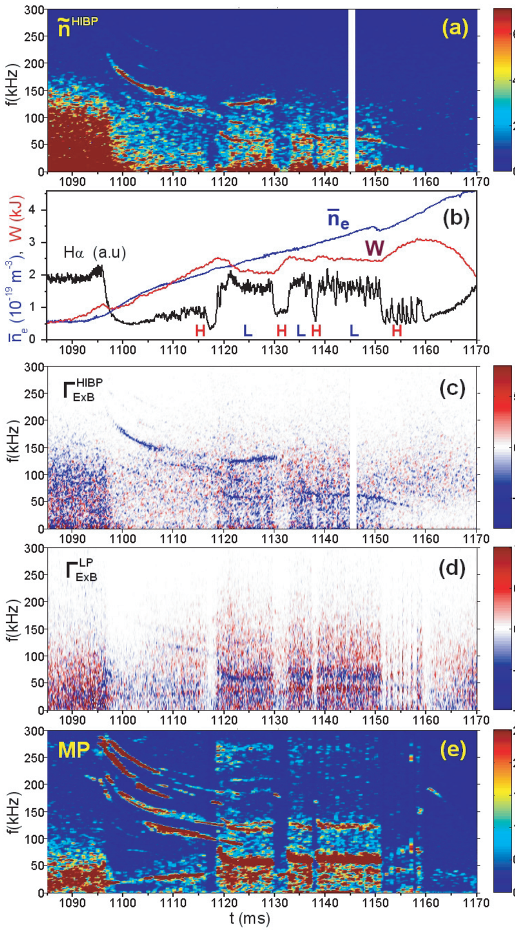

Fig. 7 Temporal evolutions of plasma parameters during spontaneous L-H and H-L transitions, shot #18954: (a) PSD of plasma density at ρ = 0.5; (b) stored plasma energy W, density $\bar{n}_e$ and H_α emission; PSD of the $\Gamma_{E\times B}$ (arb. un.) measured by HIBP at $\rho = 0.5$, $k_\theta < 3\,\mathrm{cm}^{-1}$ (c) and by Langmuir probe at $\rho = 0.9$, $k_\theta < 10\,\mathrm{cm}^{-1}$ (d); PSD of the Mirnov probe signal (e). Idle period of HIBP is shown by white ribbons.

branches, as shown in Fig. 8 (a). The branch with the cross-phase close to $\pi/2$, shown in Fig. 8 (c) does not contribute to the $\Gamma_{E\times B}$, while the one with the cross-phase close to $3\pi/4$, shown in Fig. 8 (d) does contribute, see Fig. 7 (c).

4. Conclusions

NBI induced AEs in TJ-II are pronounced in all three parameters observed by HIBP: potential/density/B_{pol} due to their intrinsic electric and magnetic fields and pressure (density) oscillations; all three quantities presents high coherency and finite cross-phase between each other, while the AE frequency varies strongly due to the density variation.

NBI induced AEs are characterized by electric potential oscillations ~ 10 V. This is the first direct observation of

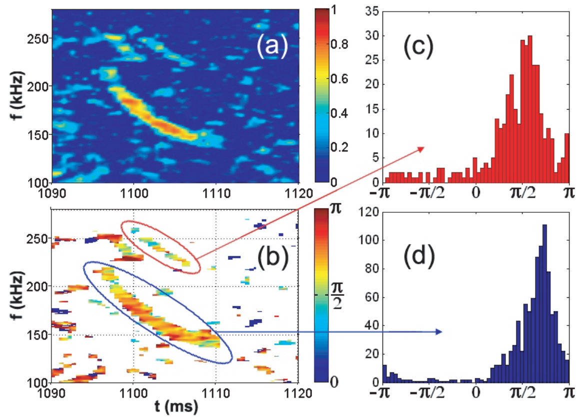

Fig. 8 Coherence (a) and cross-phase (b) between δE_{pol} and δn_e for the same shot as in fig. 7, (c) and (d) are histograms of the cross- phase, computed over the marked areas.

the potential oscillation of AEs in toroidal plasmas. GAE, HAE and TAE are plausible candidates for the observed AEs in TJ-II.

AEs may bring small or significant contribution to the $\Gamma_{E\times B}$ depending on the cross-phase between δn_e and δE_{pol}.

Acknowledgments

We are grateful to Dr. Z. Guimaraes-Filho and Prof. S. Benkadda for valuable comments. This work was supported by FASI RF contract 02.740.11.5062, RFBR grants 08-02-01326 and 10-02-01385.

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