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Analysis and interpretation of observations of Alfvénic activity in Wendelstein 7-AS

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1. Introduction. This work continues a series of our works aimed to explain various manifestations of Alfvénic activity in NBI heated plasmas of the W7-AS stellarator [Alfvén Instabilities (AI) observed before 2001 are described in an overview [1]]. Earlier we have shown that the observed successive changes of the frequencies of the destabilized modes correlate with an "estafette" of wave-particle resonances during temporal evolution of the plasma density (see Ref.[2] and an overview [3]). Later a comparison of the observed wide frequency spectrum with the location of gaps in Alfvén continuum and eigenfrequencies enabled us to identify various AIs [3-5]. Recently it was predicted that a monochromatic wave can enhance the electron thermal conductivity [6], which suggested a possible mechanism of strong drops of the plasma energy content during instability bursts reported in Ref. [1]. In this work, we make an attempt to understand why Alfvénic activity in different W7-AS shots had various forms and sometimes disappeared. In addition, we model oscillations of the plasma energy in W7-AS in the presence of periodic bursts of AIs.

2. Comparative study of W7-AS observations. Alfvén waves are destabilized by fast ions when the destabilising influence of these ions exceeds the wave damping. Resonant wave-particle interaction is responsible for AIs. Although the lack of axial symmetry leads to additional resonances in stellarators in comparison with tokamaks [7] and, moreover, there exists a variety of resonances associated with the finite orbit width of fast ions [8], the destabilizing mechanism in principle is simple and robust; it is actually the same for the gap modes and the continuum modes. In contrast to this, there are various mechanisms of the wave damping and, moreover, some of the damping mechanisms are very sensitive to plasma parameters. Therefore, it is reasonable to make a comparative analysis of various shots, restricting ourselves to a consideration of the instability drive only. If such an approach turns out successful, it seems reasonable to apply it to predictions of Alfvénic activity in future machines, such as W7-X and a Helias reactor. Note that, in general, because of the mentioned sensitivity of the wave damping to various factors, predictive calculations based on analysis of the driving part of the growth rate are more reliable than those involving a calculation of the wave damping. On the other hand, to know the dominant mechanisms of the wave damping can be of importance for the explanation of particular experiments.

Aiming to analyse shots with very different parameters (where the electron density and injected power varied by a factor of 5), we make assumptions that ignore relatively small differences of parameters in various shots. First, we assume that injected ions had the same birth profile and pitch angles in all the considered shots. Second, we neglect the differences in the magnetic configurations (main Fourier harmonics of the magnetic field vary less then by 25%). Third, we assume that the dominant longitudinal resonant velocity, $v_{\parallel}^{res}$, is proportional to v_A, where v_A is the Alfvén velocity. Fourth, we assume that the main effect of Coulomb collisions on the injected ions is slowing down by electrons. As a result, using a general expression for the instability growth rate of Ref. [7] and neglecting the damping, we obtain:

$$\gamma_{LF} \propto \frac{P_{abs} T_e^{3/2}}{n_e} \frac{B}{\iota^3 \left(\sum_i M_i n_i\right)^2}, \qquad \gamma_{HF} \propto \frac{P_{abs} T_e^{3/2}}{n_e} \frac{B}{\iota \left(\sum_i M_i n_i\right)^2}, \tag{1}$$

where γ_{LF} are γ_{HF} are the growth rates relevant to the modes with $\omega \propto \iota v_A$ [low-frequency modes, e.g., toroidicity-induced modes (TAE)] and the modes with $\omega \propto v_A$ [high-frequency modes, e.g., mirror-induced modes (MAE) and continuum modes], respectively, ι the rotational transform, P_{abs} the absorbed NBI power, B the magnetic field, T the temperature, n the density, M the particle mass, subscripts e, i label electrons and ions, respectively. In addition to the growth rates, we calculate a collisionality parameter ν_{col} (defined under Table 1) [6]. The results of the calculations are shown in Table 1, their analysis below Table 1.

Note that the ions with $\varepsilon_1 = 48$ keV, $\varepsilon_2 = 24$ keV, and $\varepsilon_3 = 16$ keV are injected simultaneously in W7-AS. Because of this, the fast ions energy distribution has sharp negative gradients at $\varepsilon = \varepsilon_j$, $j = 2, 3$, which leads to some wave damping when $v_{\parallel}^{res} = v_j \chi_j$, where $v_j = \sqrt{2\varepsilon_j / M}$, χ_j is the pitch angle of injected ions. This damping may be of importance when plasma is close to the margin of stability, in which case it can lead to stabilization of instabilities during evolution of the plasma parameters. In particular, the moments of the disappearance of Alfvénic activity in the shots #54929 ($t \approx 0.23$ s) and #56936 ($t \approx 0.3$ s) correlate with the moments when $v_{\parallel}^{res} \approx v_3 \chi_3$, with $\chi_3 = 0.9$.

3. Modelling oscillations of the plasma energy in the shot #34723. According to Ref. [6], the plasma energy confinement time, τ_E, was strongly deteriorated at the end of AI bursts in the W7-AS shot #34723 because a kinetic Alfvén wave with a rather large amplitude was generated and the plasma was in the collisional regime in the sense that $\delta_{col} >> 1$. Let us see whether the periodic deterioration of τ_E leads to the observed oscillations of the plasma energy. With this purpose we solve the following equation of the plasma energy balance: $\frac{dW_p}{dt} = -\frac{W_p}{\tau_E(t)} + P_{abs}$, where W_p is the plasma energy content. We assume that a crash lasts for $\tau_{crash} = 1.5$ ms, the oscillation period $\tau_{osc} = 8$ ms, (see the left graph in Fig. 1) and $P_{abs} = 740$ kW. Then we obtain 25% drops of the plasma energy with $\tau_E^{crash} = 3.4$ ms when $W_{p,\max} = 5.9$ kJ, $\bar{\tau}_E = 7.9$ ms, where the bar means averaging over the oscillation period, ($t \sim 0.2$ ms in Fig. 1) and $W_{p,\max} = 8.5$ kJ, $\bar{\tau}_E = 11.4$ ms ($t \sim 0.27$ ms in Fig. 1), in agreement with the experiment.

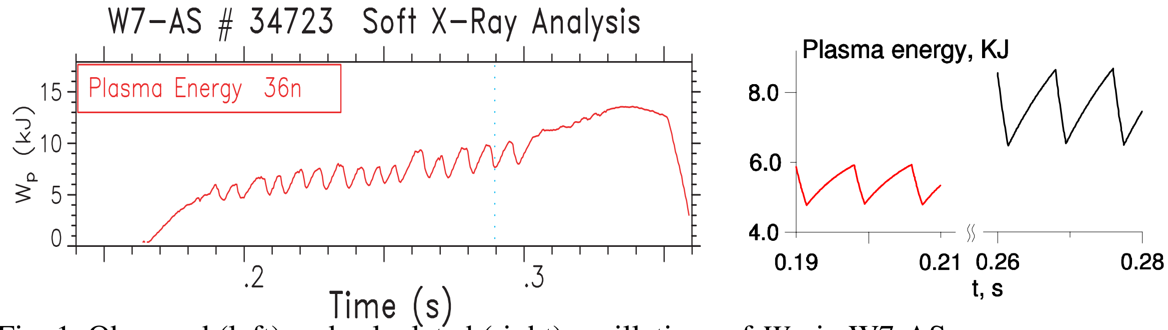

Fig. 1. Observed (left) and calculated (right) oscillations of W_p in W7-AS.

4. Summary. We have shown that (i) calculation of γ given by Eq. (1) and the collisionality parameter δ_{col} (which determines the regime of the wave-induced electron transport [6]) is a useful tool for understanding different forms of Alfvénic activity and its effects on the bulk plasma confinement in W7-AS; (ii) the wave damping caused by multi-energy structure of the NBI source can explain the disappearance of AIs in the shots where plasma is close to the margin of stability; (iii) oscillations of the plasma energy content in the shot #34723 are reproduced by modelling periodic degradations of τ_E during AI bursts.

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	#34723	#43348	#51348	#54022	#54929/#54930	#56358	#56936
t, ms	290	190 → 270	249	350	320	185 → 235	279
P_{abs}, MW	0.74	1.8 → 1.55	3.1	2.9	3.1/2.7	1.26 → 1.26	3.2
T_e, eV	215	282 → 361	327	197	190	203 → 239	291
ι	0.423	0.356 → 0.371	0.434	0.489	0.641	0.520 → 0.527	0.462
$n_e \times 10^{-14}$, cm^{-3}	0.99	0.495 → 1.06	1.68	2.32	2.636	1.049 → 1.479	2.48
B, T	1.21	1.15	-1.19	-0.85	-1.18	-1.20	-1.19
beam / plasma	H / D	H / D	H / H	H / H	H / H	H / H	H / H
Z_{eff}	2	1.1 → 1.2	1.6	1.2	1.3	1.3 → 3	1.3
Effects of AI on the bulk plasma	thermal crashes	decrease of dW_p/dt at t=0.19-0.20 s				decrease of W_p at t=0.17-0.19 s	
$\gamma_{LF}/\gamma_{LF}^{\#54929}$	8.6	245 → 28	26	2.4	1.00/0.86	13 → 3.8	6.4
$\gamma_{HF}/\gamma_{HF}^{\#54929}$	3.7	75 → 9.2	23	1.4	1.00/0.875	18 → 5.3	3.3
δ_{col}	3.7	0.73 → 1.0	2.2	5.2	5.2	2.3 → 5.4	3.0

Table 1. Beam drive (γ_{LF} and γ_{HF}) and collisionality parameter (δ_{col}) at a middle of the plasma radius, $r = a/2$, (where the instability drive in W7-AS is maximum) in various W7-AS shots. Here $\delta_{col} = \nu_{ei}^{col}/\omega_t$, ν_{ei}^{col} is the electron-ion collision frequency, $\omega_t = k_\parallel (T_e / M_e)^{1/2}$, with $k_\parallel = \iota/(2R_0)$, is the electron transit frequency in the wave field [6], W_p is the plasma energy content.

We conclude from Table 1 that (i) the drives in different shots are different, which justifies the used rough approach; (ii) the growth rate is minimum in high-density shots #54022, #54929, #54930, where plasma was close to the margin of stability; (iii) the drive decreases with time, in agreement with observed weakening Alfvénic activity; (iv) the drive is strongest in the shot #43348, which together with the observed continuous frequency spectrum at $40kHz < \omega < 250kHz$ indicate the destabilization of energetic particle modes (EPM) at $0.18 < t < 0.21$ s; (v) both the collisionality parameter and the drive were rather large in the shot #34723, where strong thermal crashes were observed – in agreement with the predicted wave-induced enhancement of the electron thermal diffusivity in the collisional regime [6].