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Stability of Alpha Particle Driven Alfvén Eigenmodes in High Performance JET D-T Plasmas

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INTRODUCTION

The transport of fusion-born alpha particles (α's) is a key issue for deuterium-tritium (DT) plasma in a tokamak reactor, as it influences the plasma heating profile, the magnitude of alpha losses and the distribution of the helium ash. Over the α-particle slowing down time the fast ion radial transport can be significantly enhanced over the neoclassical level by the presence of Alfvén Eigenmodes (AEs) which resonate with fast ions. These modes, which are associated with the frequency gaps of the shear Alfvén spectrum in toroidal plasmas, were extensively studied in JET deuterium plasmas using various excitation methods [1]. High fusion power DT experiments on JET (Table I) have made feasible direct experimental investigations of AE stability in the presence of α-population with $P_\alpha \leq 3.2\,\mathrm{MW}$.

Discharge	P_{fusion} MW	$\frac{n_\alpha(0)}{n_e(0)}[\%]$	$\beta_\alpha(0)[\%]$	$\langle\beta_\alpha\rangle[\%]$	$\lvert R\,\beta_\alpha\rvert$	$\frac{V_\alpha}{V_A(0)}$
#42676 H-mode	12.9	0.4	0.6	0.1	0.034	1.56
#42677 H-mode	11.5	0.3	0.4	0.08	0.02	1.56
#42974 H-mode	15.9	0.37	0.58	0.11	0.037	1.6
#42746 Shear-optimised	8	0.34	0.44	0.07	0.033	1.4
#42940 Shear-optimised	7.3	0.17*	0.3	0.04	0.022	1.4
#42976 H-mode	16.1	0.44	0.7	0.12	0.035	1.6
ITER with current 21 MA	1.5GW	0.3	0.7	0.2	0.06	1.9

TABLE I Alpha-particle characteristics in JET high fusion power DT experiments (from the TRANSP code) and their target values in ITER [2]. The low density of α-particles is caused by the disruption ~1 sec after the start of the NBI heating; this time interval is shorter than the α-particle slowing-down time, $\tau_{SD} \approx 1.5$ sec.*

An important result from the high fusion power Hot-ion H-mode DT experiments on JET is that AEs are stable even at the highest fusion power with α-particle beta $\beta_\alpha(0) \cup 0.7\%$. The aim of this paper is to analyse whether the stability of α-driven AEs in DT plasmas is consistent with observations of AE instabilities driven by ICRH-generated fast protons in similar deuterium discharges [1], and with modelling of AE instabilities.

ICRF-DRIVEN AES IN HOT ION H-MODE DEUTERIUM PLASMA

We select one of the deuterium discharges (pulse #40308) with an ICRH power of $P_{ICRH} = 4.5$MW, which is sufficient [1] for exciting AEs by the ICRH-generated fast protons. This discharge has a high DD fusion performance, $R_{DD} = 2S_n \approx 9.5 \cdot 10^{16}$ sec^{-1} (S_n is the neutron rate) and plasma parameters, B = 3.4 T, I = 3.6 MA, $n_e(0) \approx 3.8\ 10^{19}$ m^{-3}, $T_i(0) \approx$ 20 keV, $T_e(0) \approx 13$ keV, which are very similar to the high performance DT discharges. AEs with toroidal mode numbers ranging from n = 5 to n = 11, are observed on the magnetic fluctuation spectra in this discharge (Fig.1). The peak magnetic fluctuation level is $\delta B / B_0 \approx 10^{-7}$ at the plasma edge. The analysis by the MISHKA code [3] shows the existence of the following normal modes in the TAE frequency range at t =12.5 sec: edge-localised TAE, core-localised TAE [4] and Kinetic TAE (KTAE) [5]. Core-localised TAEs agree best with the measured eigenfrequencies, i.e. the MISHKA results in normalised units, $\omega R_0 / V_A(0)$, are: 0.457(n =5); 0.444(n = 6); 0.447(n = 7); 0.442(n = 8); 0.440(n = 9); 0.438(n = 10); 0.446(n = 11), and the experimental measurements are: 0.39(n = 5); 0.4(n = 6); 0.4(n = 7); 0.4(n = 8); 0.396(n = 9); 0.396(n = 10); 0.394 (n = 11). The computed core-localised TAEs have ballooning structure of the eigenfunction and can interact effectively with ICRF-generated ions, *trapped* at the outer side of the torus. The computed modes are localised in the region of the maximum fast ion pressure, $r/a \approx 0.2 - 0.4$. In conclusion, the observed AEs are identified as core-localised TAEs.

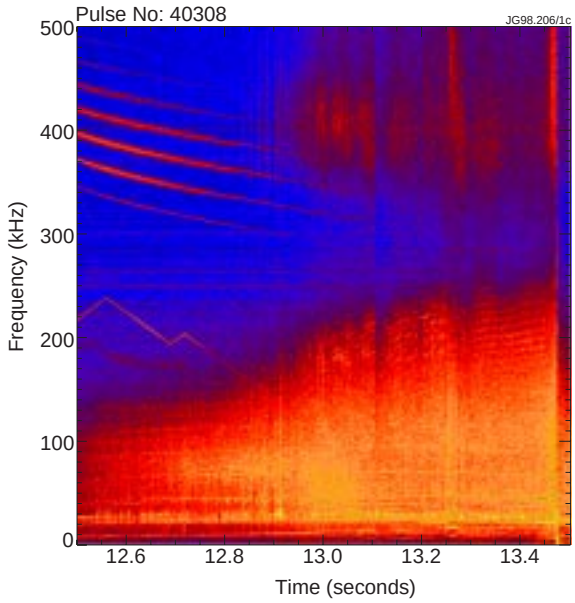

Fig. 1 Spectrogram of magnetic perturbations, $\delta\dot{B}_p$, measured by the external Mirnov coils in the discharge #40308 during an ELM-free period. Multiple AEs with different toroidal mode numbers ranging from n = 5 to n = 11 are observed at frequencies $f_n^{LAB} = 350 \div 500$ kHz at t < 13.1 sec.

It is seen in Fig.1 that the amplitudes of the TAEs gradually decrease in time. Finally, the TAEs disappear completely at the time of the peak DD fusion performance (Fig.2), which corresponds to the time of the highest α-particle pressure in similar DT discharges. The distribution of ICRH-generated fast protons computed by the PION code [6] shows that neither the fast ion energy content nor the fast ion pressure gradient decrease during the time of the observed TAE activity. Consequently one cannot explain the observed decline and disappearance of TAEs by a decrease in the fast ion drive.

In order to understand the temporal evolution of the core-localised TAEs, the JET plasma equilibria and normal modes are computed for the pulse #40308 at time slices ranging from

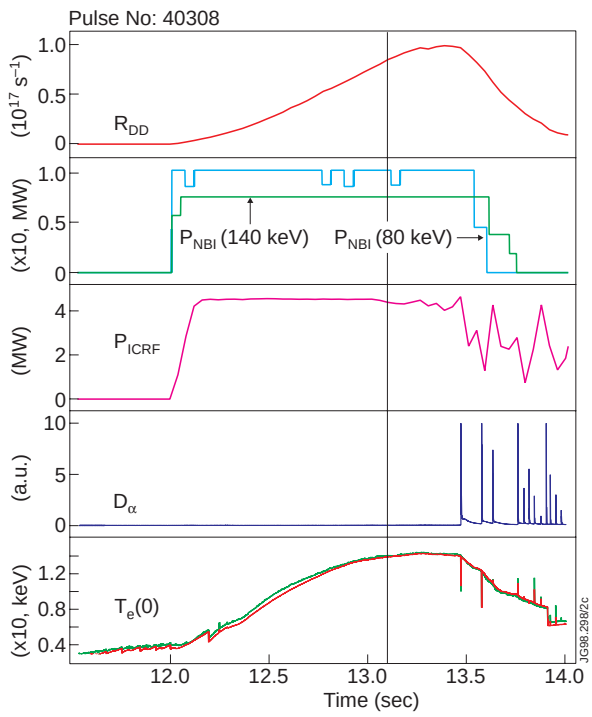

Fig.2 Time evolution of the DD fusion rate, NBI and ICRF powers, D_α and T_e in discharge #40308.

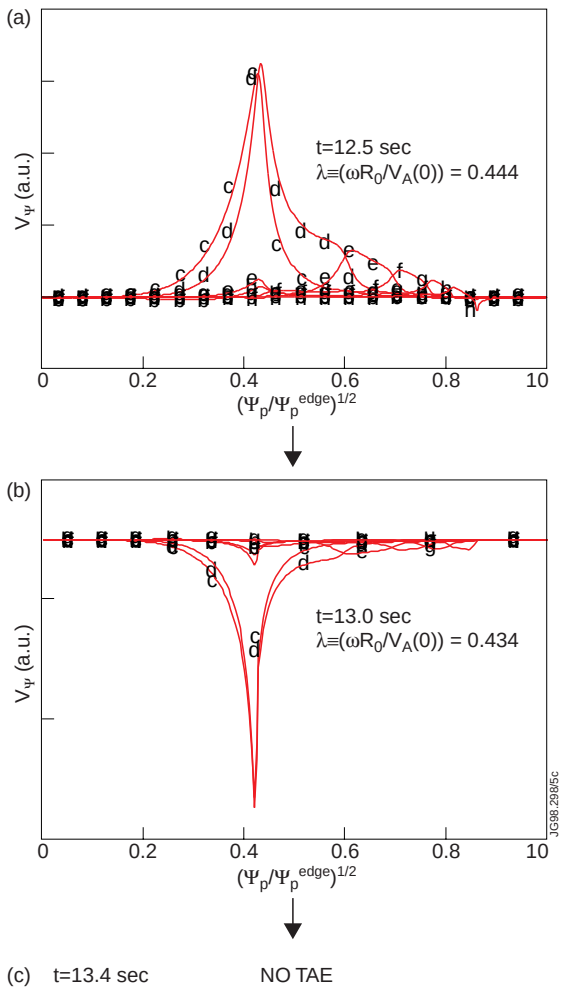

Fig.3 Radial structure of the computed core-localised TAEs (n = 6) in deuterium discharge #40308 with increasing plasma pressure. The equilibrium parameters at the different time slices are: (a) $q(0) = 0.788$, $\alpha(s \approx 0.44) = 0.22$, $S(s \approx 0.44) = 0.3$;(b) $q(0) = 0.796$, $\alpha(s \approx 0.42) = 0.34$, $S(s \approx 0.42) = 0.3$;(c) $q(0) = 0.85$, $\alpha(s \approx 0.32) = 0.39$, $S(s \approx 0.32) = 0.167$.

Here $s \equiv \sqrt{\psi_p / \psi_p^{edge}}$ is the radial variable; V_ψ is the normal component of the plasma velocity.

t = 12.5 sec to 13.4 sec (Fig.3). It is found that the radial width of the computed core-localised TAE reduced with increasing plasma pressure gradient and no core-localised TAEs exist at t > 13.0 sec when the plasma pressure gradient exceeds a critical value [4]: $\alpha > \alpha_{crit} = \varepsilon + 2\Delta' \pm S^2 \approx 3\varepsilon \pm 2S^2$, where $\alpha = -R_0 q^2 d\beta/dr$, $S = (r/q)dq/dr$, β is the plasma toroidal beta, Δ' is the Shafranov shift, and $\varepsilon = r/R$. The MISHKA modelling shows that the only AEs, which persist at t > 13.0 sec, are the KTAEs [5]. However, KTAEs have antiballooning structure and cannot interact effectively with ICRF-generated trapped ions. Therefore KTAEs can only be excited by *passing* fast ions, such as α-particles.

STABILITY OF ALPHA-PARTICLE DRIVEN KTAES

Hot-ion H-mode discharges similar to #40308 were repeated with a DT mixture to maximize fusion performance. For the modelling of α-driven AEs we select a NBI only DT discharge (pulse #42677) with fusion power P_{fusion}=11.5 MW. Core-localised TAEs are found by the

MISHKA code for #42677 for early times only. The only AEs which can be computed by the code at the later times of peak performance are the KTAEs, which are radially-extended and are therefore subject to stronger damping than the core-localised TAEs. Linear stability analysis of KTAEs driven by the alpha-particles is performed by the CASTOR-K code [7] and the MISHKA code. It is found that the α-particle drive yields a normalised growth rate $\gamma_\alpha/\omega = 0.27\%$, while the deuterium, tritium and beam ion Landau damping effects are $\gamma_D/\omega = -0.45\%, \gamma_T/\omega = -0.2\%$ and $\gamma_b/\omega = -0.53\%$. The radiative and collisional electron damping effects computed by the MISHKA code are $(\gamma_R + \gamma_e)/\omega = -0.23\%$. The computed KTAEs are therefore found to be stable, in agreement with observations.

CONCLUSIONS

AE instabilities are not observed in high fusion power DT hot-ion H-mode discharges on JET. This result is in agreement with both the observed AE evolution in deuterium comparison discharges and the modelling of AEs.

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