Scenario for α-driven Alfvén modes in deuterium-tritium JET plasmas

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Introduction Alfvén Eigenmodes (AEs) driven by fusion-born α-particles are one of the most important ITER relevant issues [1]. Continued investigation of AEs are motivated by the potential of such waves to redistribute α-particles in the core of the machine affecting the plasma heating profile, the magnitude of α-particle losses and the distribution of the helium ash. Furthermore, AE studies are also important due to their potential of providing valuable information on α-particles (slowing-down time and radial profile) and on plasma characteristics (q-profile evolution and D:T concentration) [2-4]. A possible future deuterium-tritium (DT) campaign on JET would present an opportunity to experimental study of α-particle driven AEs. However, α-particle driven AEs were not seen in JET DT H-mode discharges with record-high fusion yield and $\beta_\alpha(0) \cong 0.7\%$ [5], and α-particle driven AEs could not be identified in JET discharges with Internal Transport Barriers (ITBs) because of the AE driven by ICRH. For exciting AEs with α-particles on JET, a dedicated scenario has to be developed. This presentation investigates the possibility of such scenario.

JET reference discharge

The α-particle drive for AE scales as $\gamma_\alpha / \omega \propto q^2 d\beta_\alpha / dr$ so one has to maximise the value $q^2 \beta'_\alpha$ in the scenario of interest. The best scenario that yields high fusion yield in plasmas with elevated q is an ITB-type discharge. On JET, the ITB scenario typically uses ICRH. However, ICRH-driven AEs easily obscure effects from fusion born α-particles, so for demonstrating pure α-particle driven AEs we should consider plasmas without ICRH, i.e. NBI-only (or NBI+LHCD) ITB discharges. JET reference discharges with high performance, elevated q, and NBI only are rare. The required NBI-only ITB plasmas were briefly studied on JET in the 90s, with the best D discharge #40214 (B=3.46 T, I=3 MA, Figs. 1, 2).

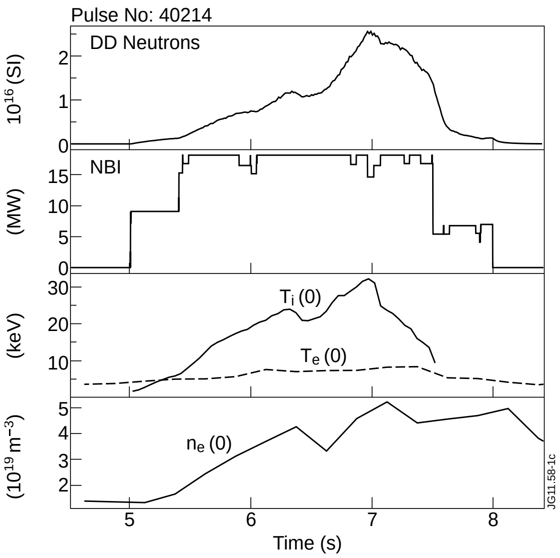

Figure 1. JET NBI-only ITB discharge #40214: DD neutron rate, NBI power waveform, ion and electron on-axis temperatures, and on-axis electron density.

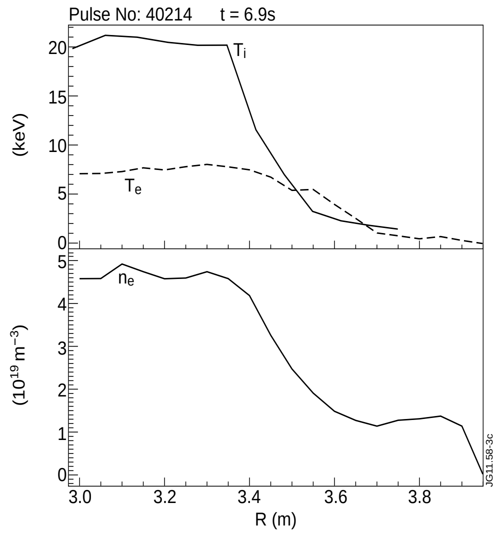

Figure 2. Top: Radial profiles of electron and ion temperatures, and bottom: radial profile of electron density at the time of peak fusion performance in ITB discharge #40214.

It was found in [5] that the strongest TAE damping for typical JET DT plasmas comes from $V_{\parallel} = V_A / 3$ resonant interaction between TAE and the beam and thermal D ions. By stepping down (or switching off) power of the beam one can decrease these two main damping effects and excite AEs in the time interval after the slowing-down of 100 keV beam ions / cooling down of the thermal ions, but before the longer slowing-down of 3.5 MeV alpha-particles: $t_{SD}^{NBI} \cong (100 \div 150)\ ms \approx \tau \cong 200\ ms < t < t_{SD}^{\alpha} \cong (0.6 \div 1)\ s$. This "beam afterglow" [6] scenario was successfully used on TFTR [7, 8] allowing AE excitation at $\beta_\alpha(0)$ as low as 0.02%.

TRANSP simulation of the reference discharge with D-T plasma

We now consider what fusion power and β_α the reference discharge #40214 could deliver in the case of D-T. For that, TRANSP analysis is done first with a D only plasma (as the reference discharge had), and, second, TRANSP simulation is done with D:T mixture provided by 50:50 gas puff and NBI. In this analysis, the sources for T beams were selected ad hoc. T fuelling chosen results in a D-T mixture very close to the optimal (D:T=55:45), and the predicted DT neutron rate was found to be similar to that of a highest power ITB discharge on JET (#42746), i.e. ~ $2.8\text{x}10^{18}\ \text{sec}^{-1}$ corresponding to ~ 8 MW of fusion power with a maximum $\beta_\alpha(0) \cong 0.33$ (Fig.3). The highest value of β_α is achieved ~250 msec after the peak neutron rate at ~7 sec. This time delay is in agreement with [5, 9] and further enhances beam afterglow scenario. In discharge #40214, $q(0)$ decreases in time down to 1.2 (Fig.4), and during the decrease, the value $q^2\beta'_\alpha$ achieves maximum at 6.4 sec and remains nearly constant then.

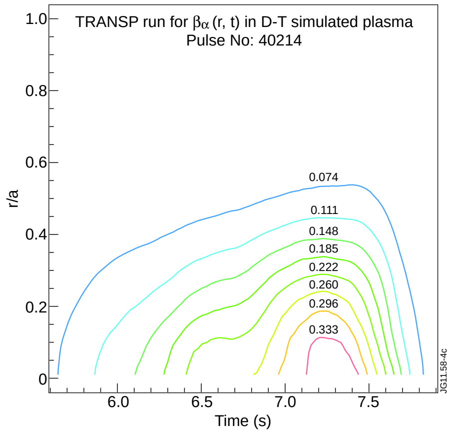

Figure 3. TRANSP simulation for discharge #40214 with D-T mixture shows $\beta_\alpha(r/a,\ t)$ achieving maximum value of ~0.33 % at 7.2 sec.

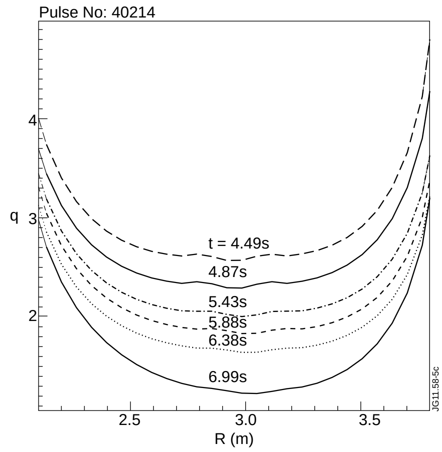

Figure 4. Temporal evolution of q-profile in the reference discharge #40214

TAE spectrum, α-particle drive, and thermal plasma damping

We reconstruct plasma equilibrium with EFIT and HELENA codes in discharge #40214 at time slice 6.4 s, compute Alfvén continuum with the CSCAS code, and compute the AE discrete spectrum for $n = 4 \div 7$ with the spectral MHD code MISHKA-1. Taking into account that α-particles are localised within $r/a \leq 0.5$ as Figures 3, 5 suggest, we select only those AEs which have main part of the mode within $r/a \leq 0.5$ too.

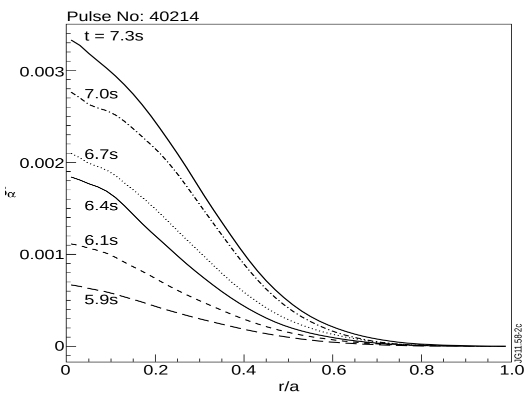

Figure 5. Radial profiles β_α computed with the TRANSP code for several time slices.

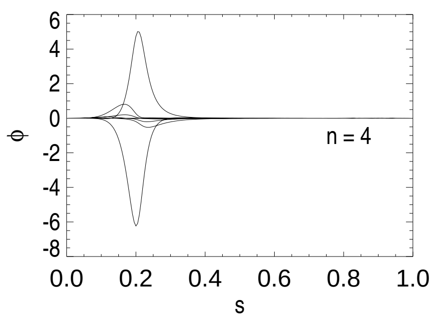

Figure 6. MISHKA-1: Core-localised n=4 TAE in #40214 (perturbed electrostatic potential as function of $s = \sqrt{\psi_{POL}/\psi_{POL}(a)} \approx r/a$)

A core-localised anti-symmetric $n = 4$ TAE (Fig.6) with negligibly small radiative damping [10] is investigated then in detail as it is the least damped AE of all. For the highly-localised TAE shown in Fig.6, a local stability analysis is accurate enough. By using the local drive [11] and damping [12] expressions for slowing-down isotropic α-particle distribution function and Maxwellian thermal species, one obtains

$$\frac{\gamma_\alpha}{\omega} \cong 0.56\%\,;\ \frac{\gamma_D}{\omega} \cong -1.38\%\,;\ \frac{\gamma_T}{\omega} \cong -0.134\%\,;\ \frac{\gamma_e}{\omega} \cong -0.2\%\,.$$

Analytical estimate of the beam damping effect varies significantly (~ 1 - 2 %) depending on the assumptions used (is beam T or D, and what the beam anisotropy is). The estimates above show that AEs should be very stable for the plasma parameters similar to those in #40214 (with DT plasma). However, AEs could be excited in the beam afterglow phase when the condition $\left|\gamma_{beam} e^{-t/t_{SD}^{NBI}} + (\gamma_D + \gamma_T) e^{-t/\tau} + \gamma_e\right| < \gamma_\alpha e^{-t/t_{SD}^{\alpha}}$ is satisfied. The excitation time and net growth rate of AE strongly depend on the beam damping, with a typical scenario ($|\gamma_{beam}/\omega| \approx 1\%$, $t_{SD}^{NBI} \approx 100\ ms$) exhibiting a positive net drive for AE from 0.45 s to 0.95 s after NBI switch-off with net drive $|\gamma_\Sigma/\omega| \approx 0.032\%$. The problem of minimising the beam damping by, e.g. changing T sources from normal to tangential, is the key to a more extended period of more unstable AE. The HAGIS code and CASTOR-K code are being used for more accurate computing of the α-particle drive and the beam and thermal ion damping effects.

Conclusions

NBI-only ITB plasma on JET is investigated for the possibility of studying α-particle driven AE in DT plasma. It is shown that AE could be excited in the beam afterglow phase. Further increase in AE instability could be achieved by minimising damping from D and T beams and raising $q(0)$ with LHCD.

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References. [1] ITER Phys. Basis, Ch.5, Nucl. Fusion 39 (1999) 2471; [2] J.P. Goedbloed et al., PPCF 35 (1993) B277; [3] S.E. Sharapov et al., Phys. Lett. A289 (2001) 127; [4] A. Fasoli et al., PPCF 44 (2002) B159; [5] S.E. Sharapov et al., Nucl. Fusion 39 (1999) 373; [6] R.V.Budny, Nucl. Fusion 32 (1992) 429; [7] R. Nazikian et al., Phys. Rev. Lett. 78 (1997) 2976; [8] R. Nazikian et al., Phys. Rev. Lett. 91 (2003) 125003; [9] V.Yavorskij et al., Nucl. Fusion 50 (2010) 025002; [10] R.Nyqvist et al., 37th EPS, Dublin (2010); [11] B.N.Breizman and S.E. Sharapov, PPCF 35 (1995) 1057; [12] J.W.Connor et al., 21st EPS, Montpellier (1994).