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Energetic Particle Physics and MHD Stability in JET and START

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Abstract

Data from sawtoothing JET discharges with Ion Cyclotron Resonance Heating (ICRH) has revealed a correlation between the heated ion contribution to the $m = 1$ kink energy and the Shafranov shift gradient at $q = 1$, consistent with theory. A correlation has also been found between the total energetic particle kink energy and sawtooth period in a sequence of JET pulses with different beam tritium concentrations. Neutral particle analyser (NPA) measurements of alpha particles in JET, which reveal MeV deuterons resulting from nuclear elastic scattering, can in principle yield information on alpha particle anisotropy. The spherical tokamak geometry in START has provided a rigorous test of toroidal Alfvén eigenmode (TAE) theory: independent codes give consistent results for TAE mode frequencies and structure. A mechanism capable of explaining the excitation of chirping fishbones by circulating beam ions in START has also been identified.

1. Introduction

Magnetohydrodynamic (MHD) stability of plasmas in the presence of energetic particles is a crucial issue for large tokamak experiments. For example, the period of sawtooth oscillations in the International Thermonuclear Experimental Reactor (ITER) may be determined largely by fusion alpha particle parameters [1]. It is therefore important to compare predictions of energetic particle effects on sawtooth stability with data from experiments in existing large tokamaks, such as those carried out in the 1997 deuterium-tritium campaign on JET (DTE1). We report here recent progress in such studies. We also present the first measurements, using a Neutral Particle Analyser (NPA), of nuclear elastic scattering of fuel ions by fusion alpha particles. The use of low magnetic fields in Spherical Tokamaks (STs) implies a low particle energy threshold for Alfvénic instabilities. In START, Toroidal Alfvén Eigenmodes (TAEs) were excited by beam injected ions with energies of less than 30 keV. Since TAEs and other high frequency instabilities are expected to be driven by alpha particles in tokamak power plants, the use of Neutral Beam Injection (NBI) in STs such as START and MAST provides an important opportunity to examine issues likely to be relevant for ignited plasmas. We describe recent modelling of fast particle instabilities observed during NBI in START.

2. Fast Particle Effects on Sawtooth Stability in JET

The period between sawtooth crashes τ_s in JET discharges with minority Ion Cyclotron Resonance Heating (ICRH) often varies (within a single discharge) with ICRH power P_{RF} . The left plot of Figure 1 shows P_{RF} and central electron temperature in a DT pulse. For multiple times in this pulse, and for several pure D pulses, we have calculated the heated ion contribution to the $m = 1$ internal kink energy $\delta\hat{W}_h$ and the Shafranov shift gradient at the $q = 1$ surface Δ' [2]. The right plot of Figure 1 shows $\delta\hat{W}_h$ and Δ' versus τ_s , for times corresponding to the vertical lines in the left plot. The kink energy is normalised to $6\pi^2\xi^2\varepsilon_1^4R_0B_0^2/\mu_0$, where ξ is the kink displacement, R_0 is major radius, B_0 is toroidal field, and $\varepsilon_1 = r_1/R_0$, r_1 being the minor radius of the $q = 1$ surface. Ideal MHD/kinetic theory implies that as pressure and hence Δ' increase, continued stabilisation should occur if $\delta\hat{W}_h$ rises sufficiently. The correlation in the right plot is consistent with this picture: a separate, empirical finding is that $\delta\hat{W}_h$ and Δ' both increase with τ_s . In a sequence of JET discharges with identical NBI power but different DT mixtures [3], it was found that τ_s increased with tritium concentration [4]. For these discharges the MHD/kinetic code NOVA-K [5] has been used to compute contributions to the $m = 1$ internal kink energy from beam ions ($\delta\tilde{W}_{NB}$) and fusion alpha particles ($\delta\tilde{W}_\alpha$). In this case the kink energy is normalised to $2\pi\xi^2\varepsilon_1^2R_0$

$s_l B_0^2 / \mu_0$, where s_l is magnetic shear at $q = 1$. The effects of sheared plasma rotation inside $q = 1$ were taken into account [6]. A positive correlation was found between $\delta\tilde{W}_{\text{NBI}} + \delta\tilde{W}_\alpha$ and τ_s (Figure 2), bearing out earlier semi-analytical studies [4]. The beam ion energies were comparable to or less than the energy at which ion-electron and ion-ion collisions are equally important: as a result, the beam ions were subject to significant pitch angle scattering, and trapped beam ions were present in sufficient numbers to give sawtooth stabilisation. In Figure 2 there is a strong variation of $\delta\hat{W}_{\text{NBI}}$, despite identical levels of NBI power: this can be attributed in part to the dependence of beam ion slowing-down on the masses of beam and bulk ions.

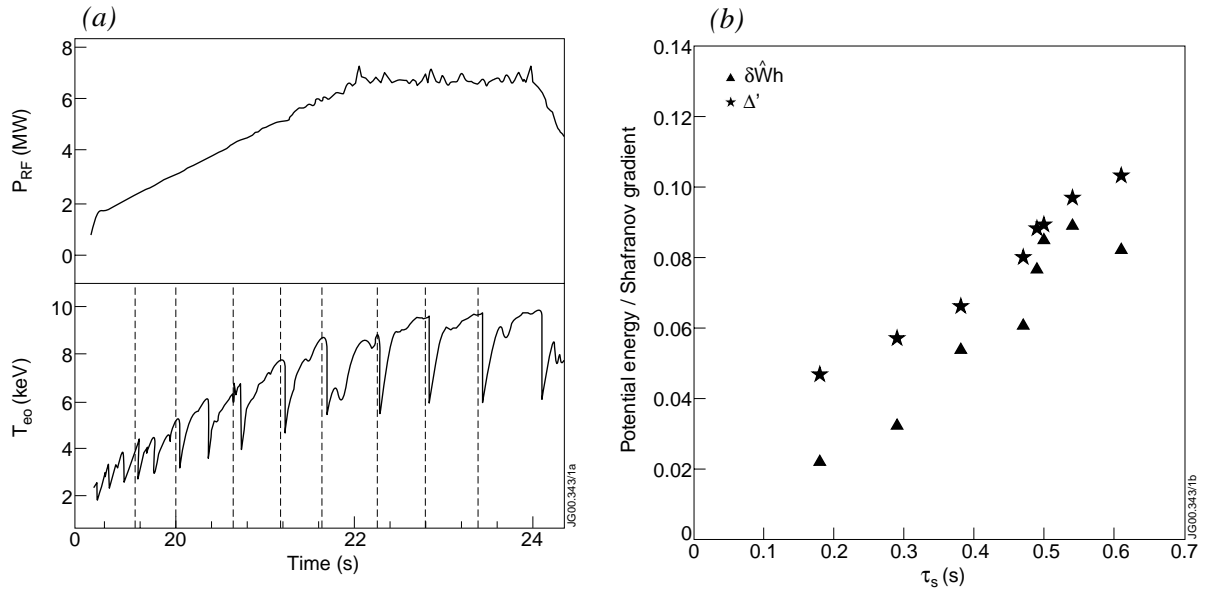


Figure 1: (a) profiles of P_{RF} and T_{e0} in a JET DT discharge (b) computed values of $\delta\hat{W}_h$, Δ' and measured values of τ_s in seconds at times indicated by vertical lines in left plot [2].

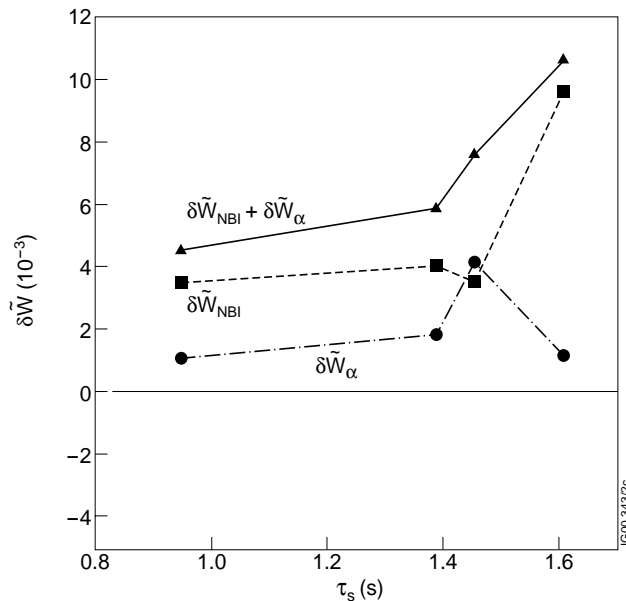


Figure 2: Normalised beam ion ($\delta\tilde{W}_{\text{NBI}}$) and alpha particle ($\delta\tilde{W}_\alpha$) contributions to the $m = 1$ internal kink energy versus sawtooth period in a sequence of DTE1 JET discharges [3], computed using NOVA-K.

3. Neutral Particle Analyser Measurements in JET

In the course of alpha particle measurements in JET using an NPA, a population of MeV energy deuterons was uncovered [7]. This is the first observation of energetic knock-on ions produced by nuclear elastic scattering (NES) collisions between DT fusion alpha particles and plasma fuel ions. Figure 3 shows comparisons, for two pulses, between measured and calculated deuteron energy distributions. The calculated distributions were obtained using isotropic (dashed curves) and anisotropic (solid curves) alpha particle distributions $F_\alpha(E)$. In the anisotropic case, $F_\alpha(E)$ was calculated using the FPP-3D Fokker-Planck code [8]. The quantity δ in Figure 3, defined in Ref [7], measures the anisotropy of the alpha particle distribution [$\delta = 1$ for isotropic $F_\alpha(E)$].

Subsequently, NES has been incorporated into FPP-3D [9], and the observed anomalies in the knock-on deuteron distribution apparent in Figure 3 have been reproduced in the calculations. By comparing deduced and calculated knock-on fuel ion distributions, the anisotropy of the alpha particle distribution could be determined experimentally [7]. The close correspondence between measured and calculated knock-on deuteron distributions, in both magnitude and spectral shape, provides an experimental demonstration of classical confinement and slowing-down of DT fusion alpha particles in JET. The JET NPA has also been used to measure internal radial redistribution of confined ICRF-accelerated MeV ions, arising from chirping fishbone modes [10].

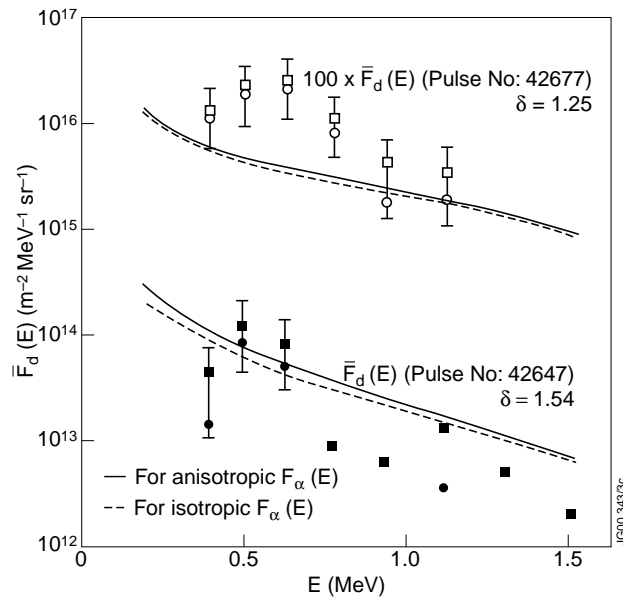


Figure 3: Deuteron distributions $F_d(E)$ in two JET DT discharges, deduced from NPA measurements (circles and squares), and calculated assuming isotropic (dashed curves) and anisotropic (solid curves) alpha particles [7].

4. Fast Particle Instabilities in START

Oscillations in the Alfvén frequency range, identified as TAEs, were observed at volume-averaged $\beta < 10\%$ during beam-heated discharges in START [11,12]. In one case, such fluctuations were excited immediately after the end of beam injection [12]. Continuous shear Alfvén spectra corresponding to START equilibria contain wide toroidicity-induced gaps, within which multiple TAEs can be driven unstable by beam ions [11,12]. Independent codes have yielded good

agreement for the frequency eigenvalues and mode structure of TAEs observed in START #35305 (Figure 4). Damping of TAEs in START, modelled using NOVA-K and the MHD/kinetic code CASTOR-K [13], appears to have been predominately ion Landau damping [11,12]: it appears likely that the absence of TAEs from higher performance START discharges was due to this particular damping mechanism. The net TAE growth rate, calculated for #35305 using NOVA-K with the aid of Monte Carlo simulations of the beam distribution [11], was found to be positive, with the drive coming mainly from beam ion pressure gradients, as in conventional tokamaks. TAE effects on fast particle confinement in STs remain to be investigated.

In START shots with relatively high β ($\geq 3 - 5\%$) chirping fishbone modes were observed [11]. These appear to have been driven by circulating beam ions: because of the use of tangential beam injection and charge exchange losses, few of the beam ions were trapped. In Ref [14] a dispersion relation is derived for the $m = 1$ internal kink mode in the presence of passing energetic ions. When the kink mode is close to ideal marginal stability, the dispersion relation yields a mode frequency [11]

$$\omega \cong \frac{2r_1\Delta_b c_A \beta_{b\theta}}{3R_0^2 r_{pb} s_1} \quad (1)$$

where c_A is Alfvén speed, $\beta_{b\theta}$ is beam ion poloidal beta, r_{pb} is beam ion pressure scale length, Δ_b is the drift orbit width of beam ions at the injection energy, and all quantities are evaluated at $q = 1$. Eq. (1) gives $\nu \sim 50$ kHz, as observed [11]. In ASDEX Upgrade, fishbones excited during tangential NBI had the effect of maintaining plasma current profiles which were conducive to good plasma confinement. There is no evidence of such effects occurring on START, but the results from ASDEX Upgrade provide strong incentives for further studies of fishbones on the new spherical tokamak MAST [16].

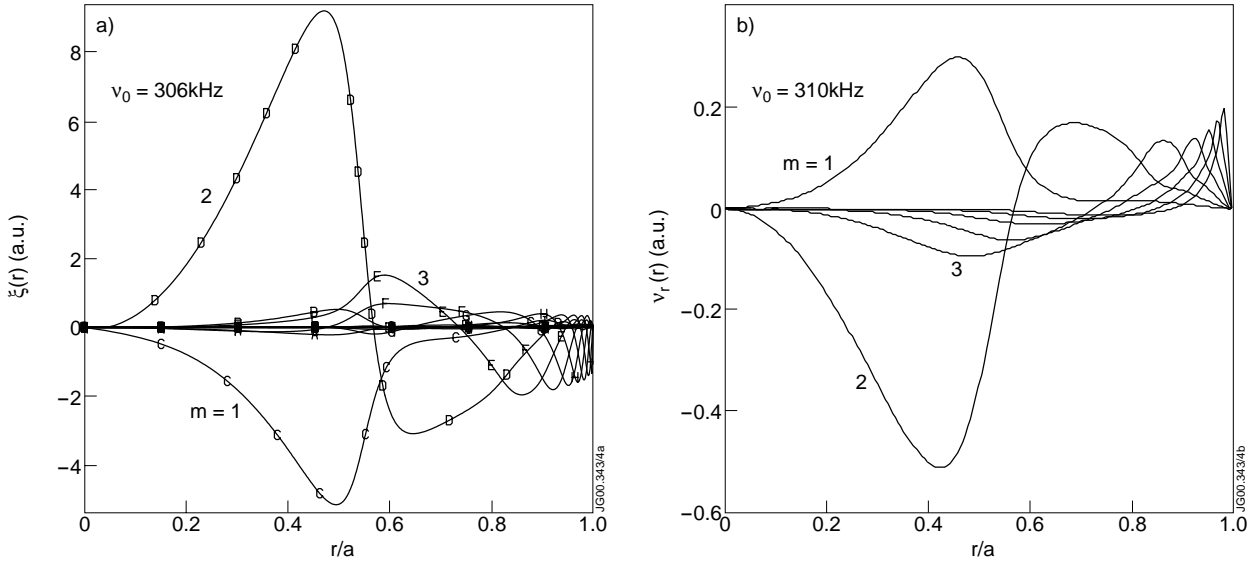


Figure 4(a): $n = 1$ TAE displacement eigenfunction $\xi(r)$ obtained from the NOVA code [5] using parameters of START #35305 ($r/a \propto \sqrt{\psi}$, where ψ is poloidal flux)

Figure 4(b): radial velocity eigenfunction $v_r(r) \equiv \xi(r) \propto -\dot{\xi}(r)$ obtained from the MISHKA-1 code [17].

5. Summary and Conclusions

Recent JET campaigns have included sawtooth ICRH pulses in which both sawtooth characteristics and the energetic minority ion population evolved substantially. Modelling of these pulses indicates a correlation between minority ion stabilisation of the $m = 1$ internal kink mode and destabilising toroidal effects, as expected: this enhances confidence in the applicability of the kinetic-fluid energy principle to sawtooth phenomenology in future tokamak experiments involving fast particles. Results from the DTE1 campaign on JET also contain clear evidence of sawtooth stabilisation by beam ions. Modelling of NPA measurements of knock-on deuteron energy distribution functions in JET DT plasmas indicates that such ions, arising from nuclear elastic scattering collisions between DT fusion alpha particles and plasma fuel ions, convey detailed information about confined alpha particle dynamics, such as alpha particle anisotropy.

This suggests that NPA measurements of knock-on ions could in the future be a powerful diagnostic of confined fusion alpha particles [7]. Benign instabilities observed during NBI in START included modes which have been identified as TAEs and chirping fishbones. Frequency eigenvalues computed using two different codes are consistent with frequencies of modes excited in START at low β : the computed eigenmodes, moreover, are consistent with each other.

The damping of these modes appears to have been dominated by ion Landau damping, with instability being driven mainly by beam pressure gradients. In shots with relatively high β ($\geq 3 - 5\%$), fishbones were observed at frequencies below 50 kHz: these can be attributed to $m = 1$ kink mode excitation by passing beam ions.

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