Energetic particle physics and MHD stability in JET and START

K. G. McClements 1), R. Akers 1), L. C. Appel 1), R. O. Dendy 1), A. Gondhalekar 1), A. A. Korotkov 1), M. R. O'Brien 1), S. E. Sharapov 1), R. J. Hastie 2), J. P. Graves 3), K. I. Hopcraft 3), D. N. Borba 4), M. F. F. Nave 4), M. Mantsinen 5), N. N. Gorelenkov 6), M. V. Gorelenkova 7), F. S. Zaitsev 8)

1) EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK
2) MIT, Plasma Science and Fusion Center, Cambridge, Massachusetts, USA
3) School of Mathematical Sciences, Nottingham University, Nottingham, UK
4) Associaçao EURATOM/IST, Centro de Fusão Nuclear, Lisbon, Portugal
5) Association EURATOM–TEKES, Helsinki University of Technology, Espoo, Finland
6) Princeton Plasma Physics Laboratory, Princeton University, Princeton, USA
7) TRINITI, Troitsk, Moscow Region, Russia
8) Moscow State University, Moscow, Russia

e-mail contact of main author: k.g.mcclements@ukaea.org.uk

Abstract. Data from sawtoothing JET discharges with 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 analyzer (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 $\tau_{\rm s}$ 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 FIG. 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 FIG. 1 shows $\delta\hat{W}_h$ and Δ' versus $\tau_{\rm s}$, for times corresponding to the vertical lines in the left plot. The kink energy is normalized to $6\pi^2\xi^2\epsilon_1^4 R_0 B_0^2/\mu_0$, where ξ is the kink displacement, R_0 is major radius, B_0 is toroidal field, and $\epsilon_1 = r_1/R_0$, 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 $\tau_{\rm s}$.

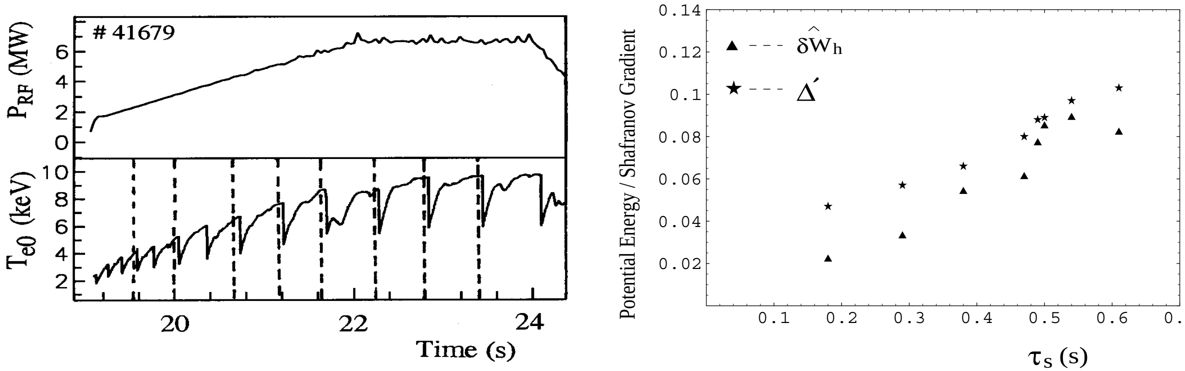

FIG. 1. Left: profiles of $P_{\rm RF}$ *and* $T_{\rm e0}$ *in a JET DT discharge. Right: Computed values of* $\delta\hat{W}_h$, Δ' *and measured values of* $\tau_{\rm s}$ *in seconds at times indicated by vertical lines in left plot [2].*

In a sequence of JET discharges with identical NBI power but different DT mixtures [3], it was found that $\tau_{\rm s}$ 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 ($\delta\tilde{W}_{\rm NBI}$) and fusion alpha particles ($\delta\tilde{W}_\alpha$). In this case the kink energy is normalized to $2\pi\xi^2\epsilon_1^2 R_0 s_1 B_0^2/\mu_0$, where s_1 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 $\delta\tilde{W}_{\rm NBI} + \delta\tilde{W}_\alpha$ and $\tau_{\rm s}$ (FIG. 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 FIG. 2 there is a strong variation of $\delta\tilde{W}_{\rm NBI}$, 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.

3. Neutral Particle Analyzer 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. FIG. 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 FIG. 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 FIG. 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].

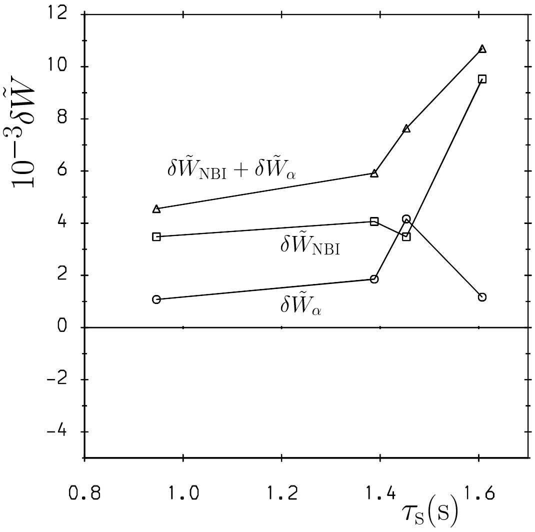

FIG. 2. Normalized beam ion ($\delta\hat{W}_{\rm NBI}$) and alpha particle ($\delta\hat{W}_\alpha$) contributions to the $m = 1$ internal kink energy versus sawtooth period in a sequence of DTE1 JET discharges [3], computed using NOVA–K.

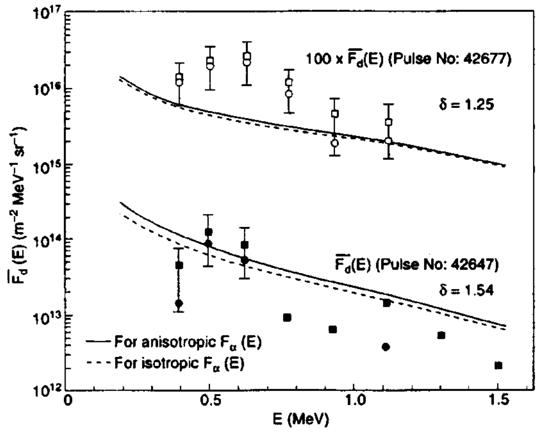

FIG. 3. Deuteron distributions $\bar{F}_d(E)$ in two JET DT discharges, deduced from NPA measurements (circles and squares), and calculated assuming isotropic (dashed curves) and anisotropic (solid curves) alpha particles [7].

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 shot #35305 (FIG. 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 shot #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]

$$\omega \simeq \frac{2r_1 \Delta_b c_A \beta_{b\theta}}{3R_0^2 r_{pb} s_1^2}, \tag{1}$$

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 $\nu \sim 50\,\mathrm{kHz}$, 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].

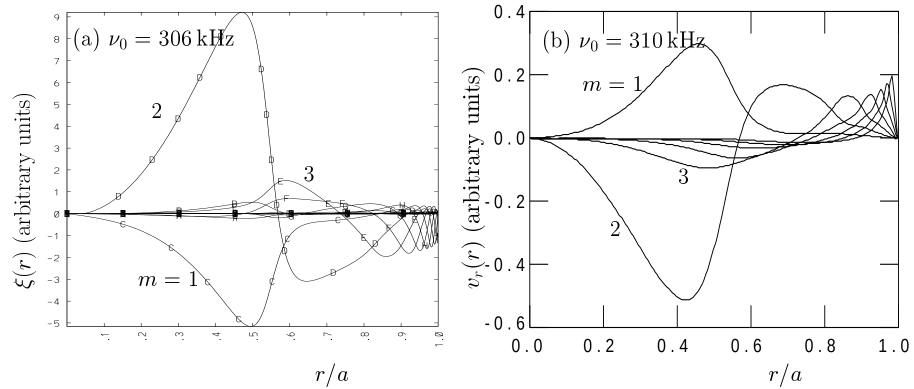

FIG. 4. (a) $n=1$ TAE displacement eigenfunction $\xi(r)$ obtained from the NOVA code [5] using parameters of START shot #35305 ($r/a \propto \sqrt{\psi}$, where ψ is poloidal flux). (b) radial velocity eigenfunction $v_r(r) \equiv \dot{\xi}(r) \propto -\xi(r)$ obtained from the MISHKA–1 code [17].

5. Summary and Conclusions

Recent JET campaigns have included sawtoothing 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.

This work was funded by EURATOM and the UK Dept. of Trade & Industry. It was partly carried out in the framework of the JET Joint Undertaking and under the European Fusion Development Agreement.

References

[1] PORCELLI, F., et al., "Model for the sawtooth period and amplitude", Plasma Phys. Control. Fusion **38** (1996) 2163.

[2] GRAVES, J.P., et al., "Sawtooth evolution during JET ion–cyclotron–resonance–heated pulses", Phys. Rev. Lett. **84** (2000) 1204.

[3] THOMAS, P.R., et al., "Observation of alpha heating in JET DT plasmas", Phys. Rev. Lett. **80** (1998) 5548.

[4] NAVE, M.F.F., et al., "Sawtooth stability in JET deuterium–tritium discharges", 25th EPS Conf. on Contr. Fusion and Plasma Physics, ECA **22C** (Prague, 1998) 365 (CD–ROM file B158pr.pdf).

[5] CHENG, C.Z., "Kinetic extensions of magnetohydrodynamics for axisymmetric toroidal plasmas", Phys. Reports **211** (1992) 1.

[6] GORELENKOV, N.N., et al., "Effect of plasma rotation on sawtooth stabilization by beam ions", 27th EPS Conf. on Contr. Fusion and Plasma Physics (Budapest), to be published (CD–ROM).

[7] KOROTKOV, A.A., et al., "Observation of MeV energy deuterons produced by knock–on collisions between deuterium–tritium fusion α–particles and plasma fuel ions", Phys. Plasmas **7** (2000) 957.

[8] ZAITSEV, F.S., et al., "Three–dimensional neoclassical nonlinear kinetic equation for low collisionality axisymmetric tokamak plasmas", Phys. Fluids B **5** (1993) 509.

[9] ZAITSEV, F.S., et al., "Perturbations to deuterium and tritium distributions caused by close collisions with high–energy alpha–particles", Nucl. Fusion (submitted).

[10] GONDHALEKAR, A., et al., "Measurement and analysis of radial displacement of high energy ICRF driven ions due to MHD modes in JET plasmas", JAERI–Conf 2000–004 (Naka, 2000), 22.

[11] McCLEMENTS, K.G., et al., "Physics of energetic particle–driven instabilities in the START spherical tokamak", Plasma Phys. Control. Fusion **41** (1999) 661.

[12] MCCLEMENTS, K.G., et al., "Alfvén eigenmodes in a beam–assisted ohmic START discharge", 27th EPS Conf. on Contr. Fusion and Plasma Physics (Budapest), to be published (CD–ROM).

[13] KERNER, W., et al., "Theory of Alfvén eigenmode instabilities and related alpha particle transport in JET deuterium–tritium plasmas", Nucl. Fusion **38** (1998) 1315.

[14] BETTI, R., FREIDBERG, J.P., "Destabilization of the internal kink by energetic circulating beam ions", Phys. Rev. Lett. **70** (1993) 3428.

[15] GÜNTER, S., et al., "The influence of fishbones on the background plasma", Nucl. Fusion **39** (1999) 1535.

[16] AKERS, R., et al., "On the Neutral Beam Heating of MAST", these proceedings.

[17] MIKHAILOVSKII, A.B., et al., "Optimization of computational MHD normal-mode analysis for tokamaks", Plasma Phys. Rep. **23** (1997) 844.