PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Alpha-particle physics in tokamaks

W. Heidbrink, G. Martin, F. Porcelli, F. Romanelli, G. Sadler, K. Tobita, J. W. Van Dam and S. Zweben

Phil. Trans. R. Soc. Lond. A 1999 **357**, 493-513
doi: 10.1098/rsta.1999.0338

THE ROYAL SOCIETY

Alpha-particle physics in tokamaks

By S. Putvinski[1], W. Heidbrink[2], G. Martin[3], F. Porcelli[4], F. Romanelli[5], G. Sadler[6], K. Tobita[7], J. W. Van Dam[8] and S. Zweben[9]

[1] *Physics Design Integration Group, San Diego ITER Co-Center, 11025 North Torrey Pines Road, La Jolla, CA 92037, USA*
[2] *University of California, Irvine, CA 92717, USA*
[3] *Association Euratom-CEA, Cadarache, R-13108, Saint-Paul-les-Durance Cedex, France*
[4] *Dipartimento di Energetica, Politecnico Di Torino, Torino, Coeso Duca degli Abruzzi 24, I-10129, Italy*
[5] *Associazione Euratom-ENEA, Frascati, Casaccia Research Centre, PO Box 2400, I-00100, Rome, Italy*
[6] *JET Joint Undertaking, Abingdon, Oxfordshire OX14 3AE, UK*
[7] *Japan Atomic Energy Research Institute, Naka-machi, Naka-gun, Ibaraki-ken 311-01, Japan*
[8] *Institute for Fusion Studies, The University of Texas at Austin, RLM 11.222, Austin, TX 78712, USA*
[9] *Princeton Plasma Physics Laboratory, Princeton University, PO Box 451, Princeton, NJ 08543, USA*

Efficient plasma heating by energetic fusion α-particles is a key element of achieving ignition or high fusion gain regimes ($Q \gg 1$) in a tokamak reactor. The paper summarizes issues and reviews the latest theoretical and experimental results in the area of energetic particle physics in tokamaks.

The discussion includes the classical physics of α-particle heating, effects of perturbations on a single-particle confinement, collective instabilities driven by energetic α-particles, description of the potential α-particle loss channels and their impact on a design of the plasma-facing components in a tokamak reactor.

Most of the extrapolations to tokamak reactors are done with the use of ITER parameters and operational scenarios as an example.

Keywords: fusion; tokamak; energetic α-particles; confinement; heating; instabilities

1. Introduction

Self-sustained ignition of a thermonuclear plasma in a tokamak reactor depends on heating by highly energetic α-particles (i.e. ^{4}He ions) produced from fusion reactions. The α-particles are born at 3.5 MeV in a reacting deuterium–tritium (D–T) plasma and transfer their energy to thermal ions and electrons. Present-day experimental tokamaks are too small to reach ignition and have to use various auxiliary heating methods to achieve high plasma parameters. Therefore, most present-day experimental observations of plasma heating by energetic particles refer to the high-energy ions that are either externally introduced by neutral-beam (NB) injection or internally generated by minority ion-cyclotron wave resonant heating. Only recently has fusion α-particle heating been demonstrated in experiments with D–T plasmas carried out on TFTR (Taylor *et al.* 1996) and JET (Thomas *et al.* 1998). Various diagnostic techniques developed for experimental study of energetic particles in the plasma core (Conroy *et al.* 1988; Medley 1996) and particle loss on the wall (Hermann *et al.* 1997) have produced valuable experimental information on high-energy particle confinement in tokamaks.

Many years of tokamak research have shown that the fast ions used to heat tokamaks normally do so with high efficiency and without causing problems. Sometimes, however, the fast-ion heating efficiency has been reduced due to non-axisymmetries such as toroidal-field (TF) ripple, or due to energetic-ion-driven collective instabilities such as various Alfvén eigenmodes. Such losses can not only reduce the α-particle heating efficiency, but also lead to excessive heat loading and damage to plasma-facing components (e.g. vessel walls and divertor-plate structure) of a tokamak reactor. A detailed study of α-particle loss in the proposed experimental tokamak reactor (the International Thermonuclear Experimental Reactor (ITER 1997)) has shown that the latter effect could be much more restrictive in reactor-grade machines. Indeed, taking into account the observed degradation of plasma-energy-confinement time with the total heating power, $\tau_E \propto P^{-\alpha}$ (Post *et al.* 1999), one can simply derive from the plasma power-balance equation that the α-particle loss will be equivalent to a degradation of the energy-confinement time by the factor $(1 - L)^{1-\alpha}$, where L is the α-particle power-loss fraction. If one assumes $\alpha = 0.67$ as in the ITERH-93P scaling (Post *et al.* 1999), then a tokamak with an ignition margin of *ca.* 10% would be allowed to have an α-particle loss of up to 25% without losing the ignition. This is clearly not a severe limitation. On the other hand, it was shown (ITER 1997) that even 5% α-particle loss could be damaging for the first wall in ITER. The reason for this is that the lost particles have small grazing angles and, hence, the α-particle heat loads on the first wall have a high degree of localization. Therefore, not only the total loss but also the distribution of the lost α-particles should be a subject of theoretical and experimental studies, and numerical codes should be able to predict these losses for the next-step device.

Just as for other plasma processes, the α-particle behaviour in a tokamak can be characterized by means of essential dimensionless parameters, which in the case of α-particles are

(i) normalized Larmor radius of α-particles, ρ_α/a;

(ii) α-particle beta, β_α;

(iii) ratio of fast-particle velocity to Alfvén velocity, V_α/V_A;

(iv) plasma aspect ratio, A;

(v) safety factor, q; and

(vi) fast-particle collisionality, $v^* = 2\pi R/\tau_s V_\alpha$, where τ_s is the collisional slowing-down time for energetic α-particles.

Each of these parameters is achievable in the present experiments but not simultaneously. Indeed, to have the same ρ_α/a and V_α/V_A as in a tokamak reactor, an experimental device should have the same $n_e a^2$ as the reactor, which is clearly not possible, and, therefore, the full demonstration of efficient α-particle heating in tokamaks should wait for ignition experiments. In the meantime, it is important to study experimentally and theoretically the physics phenomena that can affect α-particle confinement, and to develop and validate codes that can predict α-particle behaviour in the next-step machine.

Some of these problems have been studied in existing experiments and analysed theoretically. Reviews have previously been given of the detailed behaviour of α-particles (Kolesnichenko 1980; Furth *et al.* 1990) and of various energetic particle issues (Heidbrink & Sadler 1994; Cheng *et al.* 1997; Putvinski *et al.* 1995). In this paper we summarize current knowledge about major issues that have been identified: namely α-particle production and heating (§ 2); single-particle confinement and ripple loss (§ 3); and collective instabilities and anomalous transport (§ 4). Most of the extrapolations to tokamak reactors in the text will be done with the use of ITER parameters and operational scenarios as an example (ITER 1997).

Due to size limitations, we have not included within the scope of this paper the physics of confinement and removal of slowed-down α-particles, i.e. He ash. Recent experimental studies of He transport in tokamaks have shown that the He-confinement time in the plasma core is comparable with the D–T particle confinement time (see, for example, Synakowski *et al.* 1995; Shirai 1998) and, therefore, it is likely that He concentration in the core of the burning plasma will be defined by the plasma-edge physics rather than the He-core transport. A discussion of the physics processes and a review of experimental results on He-ash confinement in tokamaks can be found in Post *et al.* (1999).

2. Classical physics of energetic-particle confinement and plasma heating

The simplest approximation for α-particle behaviour in a tokamak can be based on the following assumptions: (1) the high-energy α-particles interact only with ions and electrons of the main plasma but not with each other, which is justified by their low density, $n_\alpha/n_\mathrm{e} \ll 1$; and (2) the tokamak magnetic field is perfectly axisymmetrical. In this case the fusion α-particles are well confined ($\rho_\alpha/a \ll 1$) and slow down in energy as a result of classical Coulomb collisions with ions and electrons (Sivukhin 1966),

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{2E}{\tau_\mathrm{s}}\left[1 + \left(\frac{E_\mathrm{crit}}{E}\right)\right]^{3/2}, \tag{2.1}$$

where τ_s is the characteristic Spitzer slowing-down time of field electrons, and E_crit is the so-called critical energy. These are given by

$$\tau_\mathrm{s} = \frac{3\sqrt{2\pi}T_\mathrm{e}^{3/2}}{\sqrt{m_\mathrm{e}}m_\mathrm{b}A_\mathrm{D}}, \qquad A_\mathrm{D} = \frac{n_\mathrm{e}e^4\ln\Lambda}{2\pi\varepsilon_0^2 m_\mathrm{b}^2}, \qquad E_\mathrm{crit} = (\tfrac{3}{4}\sqrt{\pi})^{2/3}\left(\frac{m_\mathrm{i}}{m_\mathrm{e}}\right)^{1/3}\frac{m_\mathrm{b}}{m_\mathrm{i}}T_\mathrm{e}. \tag{2.2}$$

Because the slowing down time τ_s is inversely proportional to the plasma density, $\tau_\mathrm{s} \sim n_\mathrm{e}^{-1}$, the local values of n_α/n_e and β_α/β, where n_α and β_α are the fast-α-particle density and beta values, respectively, with

$$\beta = \beta_\mathrm{e} + \beta_\mathrm{i} + \beta_\alpha$$

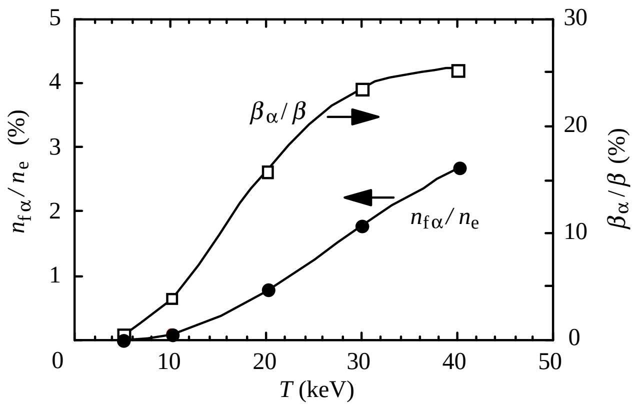

Figure 1. Local values of n_α/n_e and β_α/β, for the case of $T_i \sim T_e \sim T$ and $Z_{eff} = 1.5$ (from Uckan *et al.* 1988).

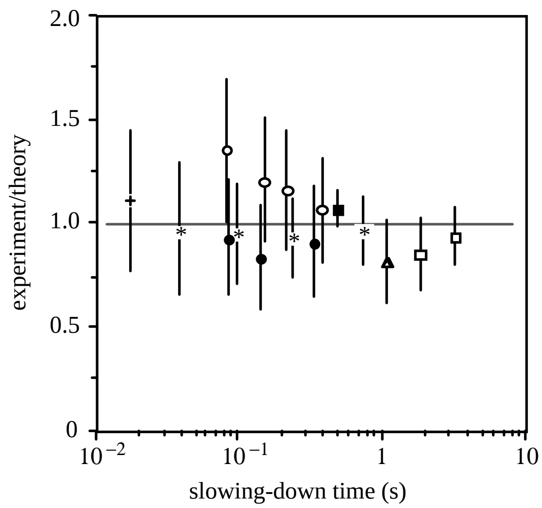

Figure 2. Ratio of the measured slowing-down time to that predicted by classical theory (modified from fig. 20 in Hermann *et al.* 1997). The data points denote 38–75 keV D-beam ions (□) and D–T alphas (■) in TFTR (from Strachan *et al.* 1997), D-beam ions in DIII-D (○), 75 keV D-beam ions in DIII-D (●), 1 MeV triton fusion products in JET (△), 250–400 keV D-beam ions in JT-60U (*) (from Ushigusa *et al.* 1997), and 30 keV D-beam ions in ISX-B (+).

the total plasma beta value, depend only on the temperature (Uckan *et al.* 1988). Both n_α/n_e and β_α/β increase with the temperature (as shown in figure 1). For a representative temperature of $\langle T\rangle = 10$ keV, we have $n_\alpha/n_e \approx 0.1\%$ and $\beta_\alpha/\beta \approx 5\%$. In the core region where temperatures are expected to exceed 20 keV, the values of n_α/n_e and β_α/β can be as high as *ca.* 0.8% and *ca.* 15%, respectively.

Abundant experiments on plasma heating in tokamaks by energetic particles indicate that, in the absence of MHD activity in the plasma, their deceleration obeys classical theory. Figure 2 shows the measured slowing-down time compared with the theoretical prediction over the range $0.5 \leqslant E_b/E_{crit} \leqslant 35$, extending from where electron friction is dominant to where bulk ion friction is dominant. The slowing-down time of energetic ions agrees well with classical theory over a wide range of fast-ion energies, plasma temperatures, and densities (Heidbrink & Sadler 1994; Strachan *et al.* 1997; Ushigusa *et al.* 1997).

In present-day experimental tokamaks, the width of the α-particle orbits (banana width) is comparable with the plasma minor radius and the first orbit loss might be essential. In a reactor-scale plasma with plasma current of 10–20 MA, the banana width is much smaller than the minor radius and this loss is negligible. Alpha-particles experience collisional neoclassical diffusion while slowing down, but their diffusion rate in an axisymmetrical field is very small (Catto & Tessaroto 1988)

$$D^{\alpha}_{\mathrm{scatt}} \cong 0.24\varepsilon^{1/2}(\rho^2_{\mathrm{p},\alpha}/\tau_{\mathrm{s}}), \tag{2.3}$$

where $\rho_{\mathrm{p},\alpha}$ is the α-particle poloidal Larmor radius at the birth energy, $\varepsilon = r/R$, the inverse aspect ratio. One can see that the total radial displacement during the slowing-down history is less than a poloidal gyroradius, and, hence, α-particles deposit their energy near their birth location.

Based on theoretical modelling and experimental observations, one can expect that in the axisymmetrical magnetic field of a tokamak reactor, α-particles are well confined and provide efficient plasma heating. However, as will be shown below, even small perturbations of the magnetic field produced externally, as by plasma instabilities, can cause a significant loss of energetic α-particles. These regimes should be avoided in a tokamak reactor.

3. TF ripple loss and other single-particle effects

Potentially significant losses of α-particles can occur in reactor-size machines due to TF ripple, i.e. toroidally asymmetric perturbations of the toroidal magnetic field due to the discreteness of the TF coils. The TF ripple amplitude is defined as

$$\delta = \frac{B_{\max} - B_{\min}}{B_{\max} + B_{\min}}, \tag{3.1}$$

where $B_{\max}$ and $B_{\min}$ are the magnitudes of the toroidal magnetic field calculated at two points having the same radial and vertical coordinates in the meridian cross-section but different toroidal coordinates: one under a TF coil and another midway between two neighbouring coils. Here we describe the ripple loss using parameters of the ITER TF coil as a typical example for tokamaks with moderate aspect ratio ($A = 2.5$–3.5) and a large number ($N > 16$) of TF coils. The TF magnetic system in ITER has 20 coils, with a maximum ripple amplitude at the plasma edge of 0.6%. The ripple profile for the ITER plasma cross-section is shown in figure 3. Due to the poloidal variation of the magnetic field on a magnetic surface, the magnetic ripple wells exist only near the equatorial plane, and mostly at the outer part of the plasma cross-section where the ripple is relatively large.

The effect of TF ripple on the confinement of energetic particles in tokamaks has been well studied both theoretically (Yushmanov 1990) and experimentally (Scott *et al.* 1985; Ikeda *et al.* 1996; Tobita *et al.* 1992; Tobita *et al.* 1997; Sadler *et al.* 1992; Tubbing *et al.* 1995; Putvinski *et al.* 1994; Basiuk *et al.* 1994; Duong *et al.* 1997; Zweben *et al.* 1998). Efficient numerical codes have been developed (White & Boozer 1995; Konovalov *et al.* 1995; Tobita *et al.* 1995) and validated by comparison with experimental results. This is an area in the physics of the fusion plasmas where models based on first principles are able to produce quite accurate quantitative results.

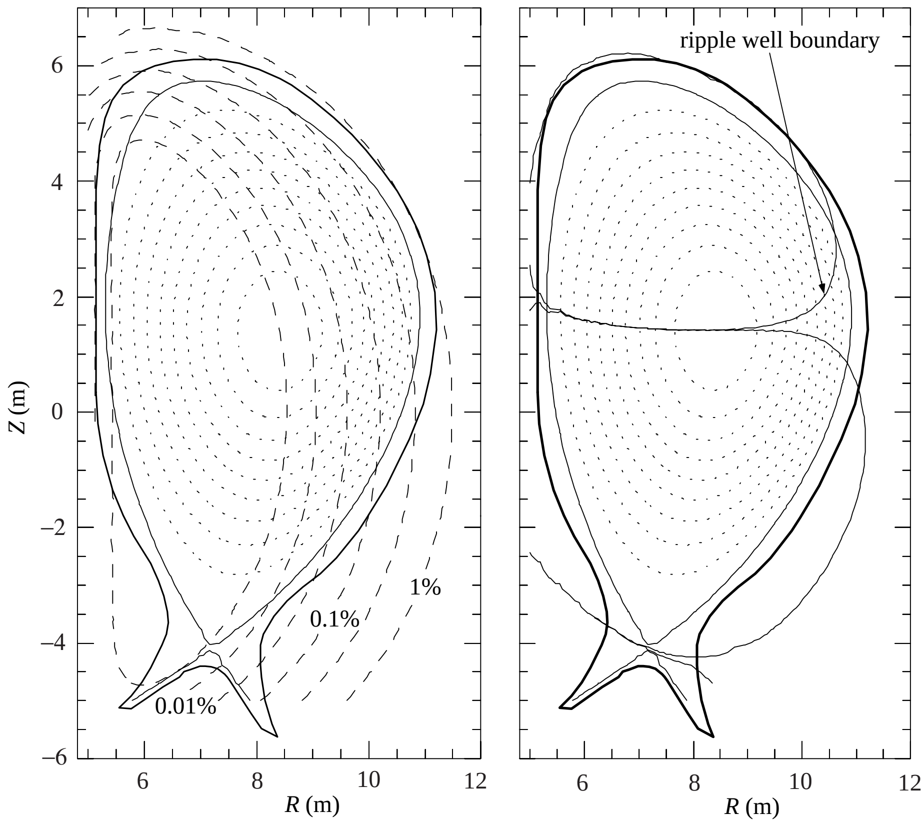

Figure 3. TF ripple contours on the plasma cross-section (left) and ripple well boundary (right), for the reference ITER plasma configuration with $I_p = 21$ MA (ITER 1997).

There are several channels for energetic-particle loss that are important for an ITER-type ripple profile as follows.

1. *Convective loss of ripple-trapped particles*: particles born in the ripple-well region with a very small parallel velocity, $(v_{\|}/v) < \delta^{1/2}$, can be trapped in the magnetic well. These particles experience vertical magnetic drift and will be lost (Yushmanov 1990).

2. *Collisionless ripple-well trapping of banana particles*: particles following banana orbits have a very small velocity near the turning points and can be trapped in a well if one of the turning points is located in the ripple-well region (Yushmanov 1990; Goldston & Towner 1981).

3. *Residual drift of banana particles*: when the ripple profile is up–down asymmetric (as in ITER), a banana particle that has at least one banana turning point in the ripple-well region experiences a residual radial drift (Goldston & Jassby 1976; Yushmanov *et al.* 1993) $v_b = v_{\text{drift}}\sqrt{\delta A}$, which is also rapid on the collisional timescale.

4. *Collisional scattering* of transit and banana particles in the loss cone significantly increases the particle ripple-loss fraction and contributes significantly to the energy-loss fraction.

5. *Stochastic ripple diffusion* (Goldston *et al.* 1981) is a very fast and powerful loss channel if it exists. However, in the ITER-type ripple profile, the ripple magnitude decreases rapidly away from the ripple-well boundary, and the stochastic region in ITER-type geometry is very narrow.

The major numerical tools for the analysis of ripple loss in tokamaks are orbit-following Monte Carlo codes (White & Boozer 1995; Konovalov *et al.* 1995; Tobita *et al.* 1995). The codes automatically take into account all ripple-loss mechanisms but their drawback is the need for extensive computational run time, which limits the statistics for the lost particles. An approach based on a combination of full orbit-following and mapping techniques allows the calculations to be speeded up significantly (Konovalov *et al.* 1995).

A comprehensive set of fast-ion ripple-loss experiments has recently been performed on JT-60U, JET, Tore-Supra and TFTR for the purpose of code validation (Ikeda *et al.* 1996; Tobita *et al.* 1992; Tobita *et al.* 1997; Sadler *et al.* 1992; Tubbing *et al.* 1995; Putvinski *et al.* 1994; Basiuk *et al.* 1994; Duong *et al.* 1997; Zweben *et al.* 1998). In JT-60U (Ikeda *et al.* 1996; Tobita *et al.* 1992; Tobita *et al.* 1997), special attention was paid to measuring hot spots on the first wall due to fast-ion ripple loss. OFMC code predictions agreed well with both the measured positions and the heat flux of the ripple-loss channels on the wall. Two dedicated TF ripple experiments were performed on JET (Sadler *et al.* 1992; Tubbing *et al.* 1995) in which the TF ripple at the outboard midplane was varied in a controlled manner from 1% to 12%. The fast-ion loss was consistent with Monte Carlo calculations of the expected TF ripple loss (Putvinski *et al.* 1994). The loss of ripple-trapped ion-cyclotron-heated minority tail ions in the energy range 100–300 keV has been investigated in Tore-Supra with the use of a set of graphite probes mounted in ports between the TF coils (Basiuk *et al.* 1994). Most of the ions are lost on trajectories originating from the boundary of the TF ripple-trapping region, as expected. The effect of TF ripple on deuterium–tritium α-particles in TFTR was measured with the pellet-charge-exchange diagnostic and escaping-α-particle scintillator detectors. The radial profile of the confined trapped alphas measured by pellet-charge exchange shows an empty region near the outboard plasma edge (Duong *et al.* 1997; Zweben *et al.* 1998), which is consistent with modelling of the expected stochastic TF ripple diffusion boundary.

The codes, validated and tested on experimental data, have been applied to ITER conditions in order to evaluate the ripple loss of energetic ions and the peak heat loads on the plasma-facing components (ITER 1997). Because of the high peaking factors (typical for the loss of energetic particles), the local heat loads in ITER will be more limiting than the total deterioration of the plasma heating efficiency. The magnitude of the ripple in ITER has been adjusted so that the α-particle ripple loss is low, less than 0.5% in ignited regimes with high plasma current, and the heat loads acceptable. One should note that the exact pattern of the local heat loads is very sensitive to small misalignments of the elements of the first wall, such as blanket modules, antennas, limiters, etc., and, hence, predictions of the local heat load pattern are less certain than estimates of the total loss (ITER 1997). The

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

misalignments cannot be avoided in a real machine and, therefore, the individual elements of the first wall should be designed in a such a way as to minimize the local heat loads due to their possible misalignment.

We can conclude that the ripple loss of energetic particles is well understood and that available codes allow derivation of reliable estimates of the ripple loss. The losses are controllable through the design of the TF coil and the ripple can be reduced so as to provide an acceptable level for the α-particle loss.

4. Collective α-particle and energetic-ion instabilities

A variety of collective instabilities, ranging in frequency from 10 Hz to 10^9 Hz, may be driven by α-particles (Kolesnichenko 1980; Furth *et al.* 1990). Results from present-day experiments have shown that two classes of instabilities are especially effective in causing anomalous transport of energetic ions: low-frequency MHD-type instabilities, such as the fishbone, internal kink and ballooning modes, associated with the resonance between the mode frequency and the toroidal precession frequency of the fast particles; and higher-frequency instabilities, such as the shear Alfvén gap modes, associated with the resonance at the fast-particle poloidal transit/bounce frequency.

(*a*) *Low-frequency MHD modes*

Low-frequency MHD oscillations, such as sawteeth, ELMs and other repetitive perturbations, almost always exist in tokamak plasmas and play an important role in the plasma performance. It is well known that energetic particles can affect these oscillations as well as be affected by the perturbations. The main physical mechanism is related to the non-MHD behaviour of fast ions with magnetically trapped orbits. The banana orbits of trapped particles precess toroidally at a rate determined by the precessional drift frequency, ω_{D}, which is proportional to the particle energy. For fast ions with energies in the MeV range, ω_{Df} can become larger than the typical frequency, ω, of a low-frequency MHD perturbation. In this case, the energetic-ion banana orbits can complete many toroidal revolutions during the timescale of variation for a low-frequency MHD fluctuation, so that the magnetic flux through the toroidal trajectory of the banana centre is adiabatically conserved (third adiabatic invariant). This non-MHD constraint can prevent the growth of low-frequency MHD modes.

The relevant dimensionless parameters that describe α-particle interaction with the low-frequency MHD modes, namely ρ_α/a and β_α, are well reproduced in the present experiments. Therefore, one can expect, in the next step, device phenomena similar to those observed in present-day tokamaks.

(i) *Sawteeth oscillations*

It is believed that the presence of energetic particles is responsible for the enhanced stability of internal kink modes (Porcelli 1991; Hastie *et al.* 1987) and the occurrence of long sawtooth suppression (often referred to as 'monster sawteeth' (Campbell *et al.* 1988)) in ion-cyclotron wave-heated tokamak discharges. In JET, sawtooth-free periods of between 1 and 5 s have been obtained in discharges with intense ion-cyclotron wave heating, where minority ions reach energies in the MeV range.

Similar results have been obtained in TFTR (Hosea *et al.* 1991) and other tokamaks (Heidbrink & Sadler 1994).

For a long time it was not clear whether sawteeth redistribute energetic particles during a sawtooth crash as they do with the thermal particles. Recent direct measurements of the evolution of α-particle profiles have shown that α-particles can be affected by sawteeth. Radial redistribution of deuterium–tritium α-particles due to sawteeth has been observed on TFTR with the pellet-charge-exchange diagnostic (Petrov *et al.* 1995), although the loss of alphas during sawtooth crashes appears to be very small. Neutral-beam ions and deuterium–deuterium tritons both seem to be redistributed by sawteeth in JET (Jarvis *et al.* 1994; Marcus *et al.* 1994). Present-day thinking is that the higher the energy of the particles, the less likely they are to be disturbed by sawteeth, and that different types of sawteeth have different effects on the fast particles. Theoretical explanations of the redistribution of fast particles during a sawtooth crash has been offered (Odblom *et al.* 1995; Kolesnichenko & Yakovenko 1995).

Just as for internal kink modes, fast ions can either suppress ballooning modes or excite them resonantly. The corresponding instability is known in the literature as kinetic ballooning modes (Tsai & Chen 1993; Chang 1996). An increase of α-particle loss induced by this instability has been observed in the D–T experiments on TFTR (Chang 1996).

In the ignited regime of a next-step device, the fusion α-particles may be expected to suppress sawteeth transiently (Romanelli *et al.* 1991), for periods that are long on the energy-confinement timescale. An extrapolation from the JET results indicates that long-duration monster sawteeth with periods of the order of 100 s are possible in ignited ITER discharges. This conclusion is corroborated by simulations (Porcelli *et al.* 1996). Although such transient sawtooth suppression may be beneficial in allowing for peaked profiles and an increased ignition margin, the large crashes associated with the long-duration periods are a concern. Large-scale redistribution of the α-particles due to sawteeth might result in an increase of the local heat loads on the first wall of the reactor.

(ii) *Fishbone oscillations*

Fast α-particles with somewhat lower energies can interact resonantly with low-frequency MHD modes, the relevant resonance condition being $\omega_{\mathrm{Df}} = \omega$. With ω estimated as the thermal ion diamagnetic frequency, $\omega_{*\mathrm{i}}$, the condition $\omega_{\mathrm{Df}} = \omega_{*\mathrm{i}}$ is satisfied by particles with energy $E_{\mathrm{f}}/T_{\mathrm{i}} \sim 2R/r_{\mathrm{p}}$, where r_{p} is the thermal ion pressure gradient length. The typical fast-ion energy of this regime in present-day tokamak experiments is in the 100 keV range. Obviously, in this regime, the third adiabatic invariant is no longer a relevant constraint. In fact, the resonant fast ions can destabilize internal kink modes, and this resonant destabilization is thought to be the physical mechanism for the so-called fishbone instability, named after the characteristic experimental trace of the associated magnetic fluctuation bursts (McGuire *et al.* 1983).

Fishbone oscillations were first observed in PDX experiments with nearly perpendicular NB injection (McGuire *et al.* 1983). The structure of the unstable mode was identified as the $m = 1$, $n = 1$ internal kink mode. Fishbone oscillations were later observed in DIII-D experiments with nearly tangential NB injection, and in many

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

other tokamaks worldwide (Heidbrink & Sadler 1994). Fishbones were observed to cause severe losses of beam ions in PDX, but only minor fast-particle redistribution in large tokamaks such as JET, TFTR and JT-60U. The first theoretical interpretation (Chen *et al.* 1984) of the fishbone instability correctly identified the resonant wave–particle interaction at the magnetic precession frequency of the trapped fast ions as an essential part of the instability mechanism. Eventually, a more complete theory emerged that accounts for both collisionless and collisional regimes, the trapped- as well as the transit-ion response of the fast ions, and finite-orbit width corrections (Fogaccia & Romanelli 1995; Wu *et al.* 1994).

The fusion α-particles can excite fishbone oscillation if their pressure exceed a certain threshold value. Simulation codes and analytic study (Wu *et al.* 1994) for ITER parameters that included the effects of shaping, finite aspect ratio and finite beta have found fishbone instability when the α-particle beta exceeds 1% on axis, which is only slightly higher than the nominal value expected in ITER. The effect of the fishbone oscillation on the α-particle heating profile is similar to the effect of sawteeth: namely, the fishbones might redistribute the α-particle pressure profile within the central region, near the $q = 1$ magnetic surface. Numerical simulations have indeed shown a redistribution of α-particles in ITER, but no additional loss was observed (Candy 1997).

There are a few other types of low-frequency modes that can be affected by energetic particles in a next-step device but which received much less attention. One example is 'edge-localized modes' (ELMs). It is well known that ELMs can affect the global plasma confinement, divertor performance and impurity content in a plasma. There is an indication from present-day experiments that the ELM amplitude and frequency might be affected by the presence of energetic particles near the plasma edge. The other example is neoclassical tearing modes. It is believed that neoclassical tearing modes are responsible for the so-called soft beta limit: the phenomena observed at several tokamaks in quasi-steady-state discharges (Post *et al.* 1999). Energetic particles could possibly affect the threshold and magnitude of the neoclassical islands in the same way they stabilize sawteeth oscillations. Theoretical studies as well as analysis of experimental results are needed in order to understand the possible effect of energetic particles on both types of oscillations.

In conclusion, one can expect fusion α-particles to significantly affect the low-frequency plasma oscillations in a reacting plasma. However, it is unlikely that these modes can incur severe loss of the α-particles and, hence, jeopardize achievement of ignition and sustained burn in a next-step device.

(*b*) *Alfvén frequency modes*

An intensive study of Alfvén eigenmodes in tokamaks started about ten years ago, when it was realized that these modes could be a serious threat to the good confinement of energetic α-particles and, hence, to achievement of ignition in a next-step device (Cheng *et al.* 1985; Candy 1997; Fu & Van Dam 1989). Since that time, there has been significant progress in the development of theory and in dedicated experimental study of Alfvén modes in present-day machines. The various eigenmodes were observed and identified in experiments and simulated numerically with an impressive degree of detail.

Toroidicity causes the continuous frequency spectrum of shear Alfvén waves in a tokamak plasma to exhibit a radial 'gap' (analogous to a Brillouin band gap for valence electrons in a periodic crystal lattice). Within this gap discrete-frequency modes can exist, called toroidal Alfvén eigenmodes (TAEs) (Cheng *et al.* 1985; Cheng & Chance 1986). The frequency gap is centred at $\omega_{\mathrm{TAE}}(r) = v_{\mathrm{A}}/2qR$, with v_{A} the Alfvén speed, q the safety factor and R the major radius. The gap width is of the order of the inverse aspect ratio, $\Delta\omega/\omega_{\mathrm{TAE}} \sim O(r/R)$. Since α-particles in a thermonuclear plasma have velocities that are typically superAlfvénic, they can resonantly interact with and destabilize the weakly damped TAEs (Fu & Van Dam 1989).

In high-temperature plasmas, non-ideal effects such as finite ion Larmor radius and electron collisions can become important in the gap region and cause the Alfvén continuum to split into a series of *kinetic toroidal Alfvén eigenmodes* at closely spaced frequencies above the ideal TAE frequency (Mett & Mahajan 1992). In the central region of the plasma, a low-shear version of the TAE can arise, called the *core-localized mode* (Fu 1995; Berk *et al.* 1995). Non-circular shaping of the plasma poloidal cross-section creates other gaps in the Alfvén continuum, at higher frequencies. Ellipticity creates a gap, at about twice the TAE frequency, within which exist *ellipticity-induced Alfvén eigenmodes*, and, similarly, for the *triangularity-induced Alfvén eigenmodes* at three times the TAE frequency (Betti & Freidberg 1991). The ideal and kinetic TAE, as well as the ellipticity and triangularity Alfvén eigenmodes, are 'cavity' modes, whose frequencies are determined by the bulk plasma. In addition, a 'beam' mode can arise that is not a natural eigenmode of the plasma, but is supported by the presence of a population of energetic particles, and also destabilized by them. This so-called *energetic-particle mode* (Chen 1994), which can also exist outside the TAE gap, has a frequency related to the toroidal precessional frequency and poloidal transit/bounce frequency of the fast ions.

The schematic in figure 4 illustrates these various modes. Shown are radial plots of shear Alfvén continuum curves, with a toroidicity-induced gap that extends radially across the plasma, as well as ellipticity and triangularity gaps at higher frequencies. Straight horizontal lines are heuristically drawn to indicate the typical frequency, mode location and mode width for the various kinds of mode.

The stability of the various Alfvén modes depends on the competition between the α-particle pressure-gradient drive and dissipative mechanisms such as continuum (Berk *et al.* 1992) and radiative damping (Mett & Mahajan 1992), ion Landau damping (for both thermal and fast ions), electron Landau damping and trapped-electron collisional damping (Gorelenkov & Sharapov 1992). For modes with low to moderate toroidal mode numbers, typically, ion Landau damping is dominant, whereas for high-n modes, the trapped-electron collisional damping and radiative damping are strong stabilizing mechanisms.

(i) *Review of Alfvén eigenmode experimental results*

Much recent experimental work has been performed on Alfvén-frequency collective instabilities excited by energetic ions (Heidbrink & Sadler 1994). Each of the instabilities of interest has been observed to be excited by NB fast ions or ion-cyclotron wave-heated tail ions, and some have also been seen with α-particles. The most serious instability seems to be the toroidicity-induced Alfvén eigenmode, which has caused up to *ca.* 70% loss of injected fast beam ions in the TFTR (Wong *et al.* 1991) and DIII-D tokamaks (Strait *et al.* 1994), albeit only when the toroidal field was lowered to make the NB ions nearly superAlfvénic. TAEs are also commonly observed

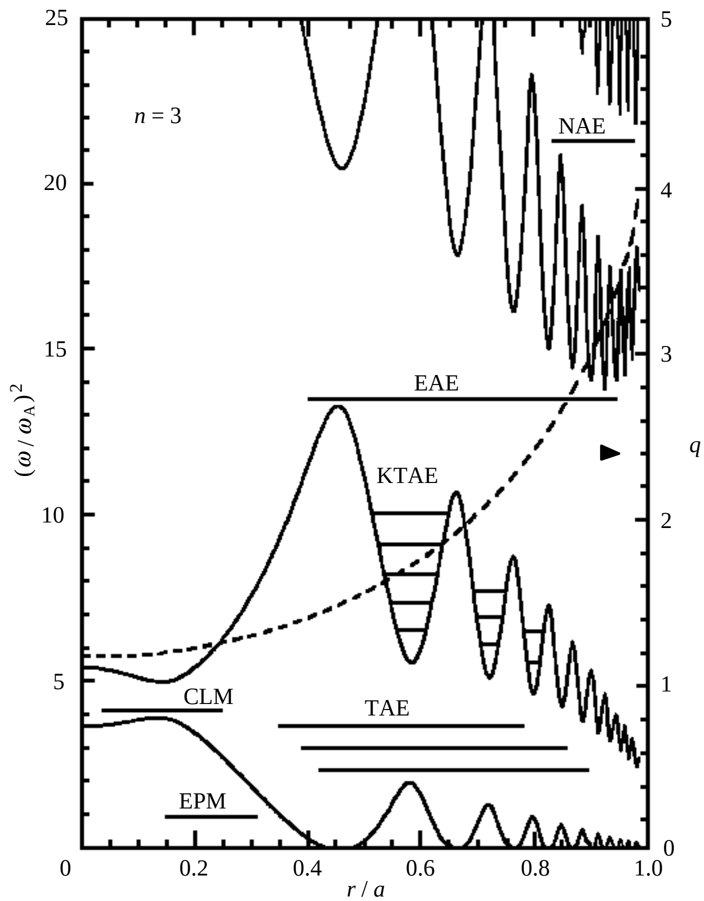

Figure 4. Schematic showing representative shear Alfvén frequency continuum curves as functions of minor radius r, for $n = 3$, with horizontal lines indicating the approximate frequency, radial location and mode width for the TAE, kinetic TAE (KTAE), core-localized TAE (CLM), ellipticity Alfvén eigenmode (EAE), triangularity Alfvén eigenmode (NAE) and energetic-particle continuum mode (EPM) (Adapted from Kramer *et al.* 1998).

with hydrogen-minority energetic tail ions due to ion-cyclotron resonant heating in TFTR (Fredrickson *et al.* 1995), JT-60U (Kimura *et al.* 1995) and JET (Ali-Arshad & Campbell 1995). Instabilities driven by energetic ions are also observed with frequencies below the TAE frequency (Heidbrink *et al.* 1993).

The first observation of TAEs purely driven by α-particles was made in TFTR deuterium–tritium experiments, but only in discharges with high $q(0)$ and weak magnetic shear, and only (*ca.* 100 ms) after the NB heating was turned off (Nazikian *et al.* 1997). These conditions were consistent with predictions for the transient excitation of core-localized TAEs. In this special regime, the α-particle beta threshold for these modes was as low as $\beta_\alpha(0) \sim 1\text{–}2 \times 10^{-4}$, i.e. about 50 times lower than the expected value for ITER. The mode amplitudes were very low (as illustrated in figure 5), and no TAE-induced α-particle loss was observed, although the α-particles were apparently redistributed radially outward.

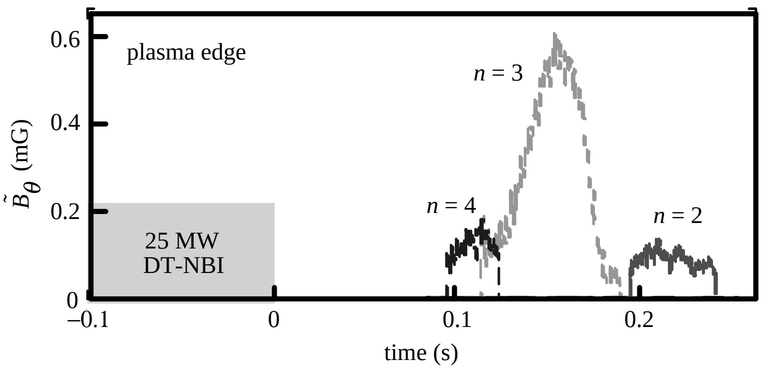

Figure 5. Observation of α-driven TAEs in TFTR (from Heidbrink *et al.* 1993).

Both ideal and kinetic TAEs have been actively excited in JET in an ohmic plasma (without any energetic ions) by using external antennas, and their frequency and damping rate directly measured with passive antennas (Fasoli *et al.* 1997). Excellent agreement between the observed and predicted TAE frequencies was obtained for these externally launched TAEs. In these antenna experiments, it was also noticed that the formation of an X-point stabilizes low-n TAEs, probably due to increased shear.

Various numerical codes were developed (Huysmans *et al.* 1993; Jaun *et al.* 1995; Spong *et al.* 1995) to interpret the Alfvén eigenmodes observed in fast-ion experiments on present-day tokamaks. Many more instances of theory, code and experimental interplay could be cited. In general, the theoretical frequencies and mode structure have been found to match the experimental measurements quite well, while the stability thresholds, more difficult to calculate, are in reasonable agreement.

(ii) *Linear stability thresholds in ITER*

The major difference between present-day tokamaks and a next-step device is the much smaller value for the normalized Larmor radius, ρ_α/a, of the superAlfvénic energetic particles ($V_\alpha/V_A \geqslant 1$). As a result, the toroidal diamagnetic drift of the energetic particles is much slower in a next-step machine and, hence, the necessary instability condition (Mett & Mahajan 1992) $n\omega_{Df} > \omega_A$ can be fulfilled only for higher mode numbers, n, than in present-day machines. If Alfvén modes are unstable in a tokamak reactor-type plasma, then they will be high-n modes.

Numerical simulations have confirmed this conclusion. In particular, the stability of ITER with respect to TAEs has been examined. A large-aspect-ratio stability code found that the reference equilibrium profiles in ITER (1997) would be unstable for toroidal mode numbers in the range $6 < n < 60$; these results were useful in focusing attention on the issue of high-mode-number stability (Candy & Rosenbluth 1995). Calculations done with the NOVA-K code have indicated (Cheng *et al.* 1996) that ITER plasmas are in fact stable for $n \leqslant 10$ (and possibly higher), but that more peaked profiles are unstable for $n \geqslant 12$. Plasma cross-section shaping, i.e. varying the ellipticity and triangularity while fixing the aspect ratio, minor radius and pressure and safety factor profiles, tends to reduce TAE instability (Fu 1997). Simulations with the TAE/FL code also found that the ITER-type profiles are stable, up to $n = 20$. With the CASTOR-K code, it was found that for a peaked α-particle pressure

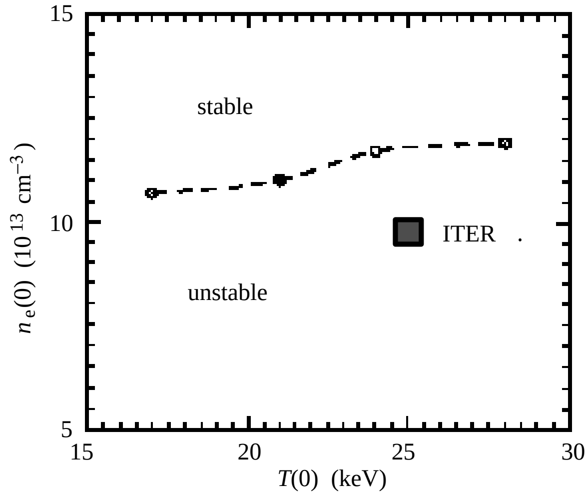

Figure 6. Stability boundary in the $n_e(0) - T(0)$ POPCON diagram for an $n = 15$ core-localized TAE in an ITER-type plasma (from Cheng *et al.* 1996). ITER reference operational point is shown.

profile, kinetic TAEs in the upper continuum with $n > 10$ can be unstable (Borba *et al.* 1996; Berk *et al.* 1997*a*).

The most unstable type of TAE in ITER is probably the core-localized version, whose growth rate tends to be stronger that of the usual TAEs. This mode can occur in the low-shear central region of the plasma, which is where destabilizing α-particles are plentiful. Numerical simulations (Cheng *et al.* 1997; Cheng *et al.* 1996), including ion Landau damping, found that the $n = 15$ core-localized TAE in ITER can be unstable, nearly independent of temperature, when the peak plasma density is less than 10^{20} m^{-3} (see figure 6).

Thus, although the stability predictions are sensitive to details of the equilibrium profiles, in general, the code results, as well as theoretical estimates, all indicate that the stability of high-n TAEs ($n > 10$) is the critical issue for large-size devices like ITER. Accordingly, special high-n global codes have been developed that can analyse the full two-dimensional eigenmode structure for equilibria specific to the ITER configuration. The HINT high-n code (Cheng *et al.* 1995) and the 2DWKB code (Vlad *et al.* 1995) are based on a WKB (i.e. ballooning type) formalism. For a typical ITER-like scenario, it was found (Gorelenkov *et al.* 1997) that the mode structure is a mixture of ideal and kinetic TAEs. The mode frequency is shifted toward the lower Alfvén continuum (Romanelli & Zonca 1994) by finite-beta effects (Santoro & Chen 1996; Fu & Cheng 1990), so that radiative damping is enhanced, and the TAEs tend to be stable. More details on these studies can be found in the review by Post *et al*. (1999).

Therefore, linear stability analysis has shown that the ignited plasmas in the next-step tokamak could be unstable to high-n TAEs with mode numbers $n > 10$. The ITER-type profiles seem to be close to the instability thresholds for most of the modes. To be unstable, ITER plasmas require either somewhat higher β_α or more peaked pressure profiles than are predicted. The exception are the core-localized TAEs that are predicted in ITER.

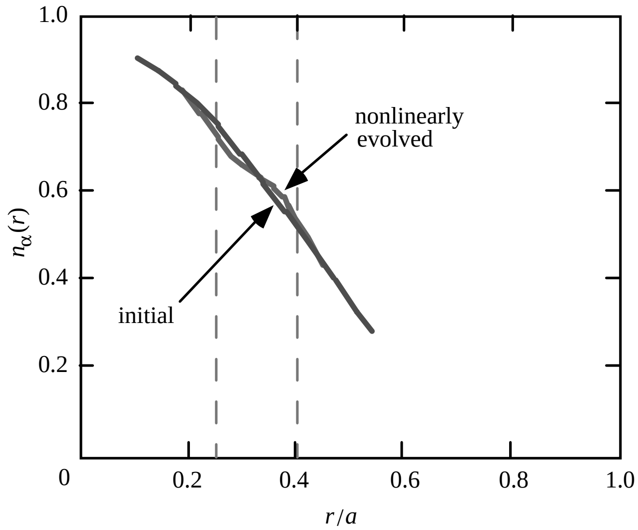

Figure 7. Anomalous diffusion of the α-particle distribution caused by ten strongly unstable core-localized TAEs in ITER (from Candy *et al.* 1997).

(iii) *Nonlinear behaviour and anomalous transport*

While the linear theory of the Alfvén modes is well developed by now, the nonlinear theory and models for qualitative description of particle loss caused by Alfvén modes are far from completion. We should note that a direct extrapolation of the TAE-induced loss observed in present-day experiments to an assessment of the loss in a next-step tokamak is not possible. Present-day machines are unstable to a few low-n modes, while a next-step tokamak can simultaneously have many high-n modes unstable. One can expect that the loss pattern will be also quite different. Therefore, it is very important to identify possible mechanisms of loss and validate the models in present-day experiments.

This work is in progress (Candy 1997; Berk *et al.* 1993; Wong *et al.* 1997; Berk *et al.* 1997*b*; Breizman *et al.* 1997; Candy *et al.* 1997). Two main physical mechanisms that have been studied for the nonlinear TAE behaviour are kinetic wave–particle trapping and fluid mode–mode coupling. The emerging models predict either 'bursting' in the α-particle loss (as is sometimes observed in NB experiments in DIII-D and TFTR), or redistribution of α-particles and saturation of the modes at the low level. As long as the particle resonances do not overlap, the nonlinear oscillations are benign in the sense of not causing appreciable particle loss or change of the α-particle heating profile. However, if mode overlap occurs because the saturation level is high enough or because multiple modes become unstable, then the α-particle distribution can change significantly, with a substantial amount of the free energy of the energetic particles being rapidly converted to wave energy (Breizman *et al.* 1997).

As was mentioned above, the ITER profiles might be unstable to the core-localized modes. Transport of α-particles resonantly interacting with a realistic set of ten strongly unstable core-localized TAEs was studied with the FAC code specifically for ITER parameters (Candy *et al.* 1997). The α-particles were found to be moved outwards, with their time-evolved distribution locally flattening, but the density-profile modification is minimal and no α-particles are lost (see figure 7). This result suggests that redistribution of alpha or other energetic particles may, possibly, be much smaller in ITER than in current tokamaks.

(*c*) *Collective effects at the ion-cyclotron frequency range*

This frequency range has been studied both theoretically and experimentally and several important phenomena that might affect α-particle heating have been observed and identified (Sauter & Vaclavik 1992; Herrmann & Fish 1997; Johnson *et al.* 1995; Darrow *et al.* 1996; Cottrell *et al.* 1993; Cauffman & Majeski 1995; Dendy *et al.* 1994; Gorelenkov & Cheng 1995; Hellsten *et al.* 1985; Fish 1995).

One is the interaction of energetic α-particles with ion cyclotron resonance heating (ICRH), which is one of the main candidates for plasma auxiliary heating in a tokamak reactor. The concern is that the fusion α-particles have the same cyclotron frequency as deuterium ions of the main plasma but much higher energy and Larmor radius and, hence, in the heating scheme based on the second harmonic, when the absorption increases with $k\rho_{\mathrm{L}}$, the alphas can significantly affect the ICRH power deposition profile (Sauter & Vaclavik 1992; Hellsten *et al.* 1985). Obviously, since the main parameter is the α-particle density, n_α/n_{e}, the theoretical studies were aimed at the evaluation of the critical α-particle density. It was shown (Sauter & Vaclavik 1992) that the effect could be significant at high α-particle density $n_\alpha/n_{\mathrm{e}} > 1\%$ $(\beta_\alpha/\beta > 1)$. At the α-particle densities typical for ITER plasmas, namely, $n_\alpha/n_{\mathrm{e}} \sim 0.1\%$, the effect of α-particles on ICRH is expected to be negligible (Sauter & Vaclavik 1992).

The possibility of using RF waves to increase ion heating by α-particles and also to transform part of their kinetic energy in the plasma current drive (α-particle channelling) have been discussed in the literature (Herrmann & Fish 1997; Fish 1995). The experimental studies of these effects are in a very early stage and further analysis and experimental confirmation are required to understand if this is feasible in a tokamak reactor. However, clear evidence of the expected impact of the RF waves on energetic particle confinement from TFTR experiments has been reported (Darrow *et al.* 1996).

Strong and highly reproducible ion cyclotron emission (ICE) has been observed in the presence of high-energy fusion products on many tokamaks (see Johnson *et al.* 1995; Cottrell *et al.* 1993; Cauffman & Majeski 1995; and references therein). The typical ICE spectrum consists of several narrow spikes at the cyclotron harmonics superimposed on a broad continuum. The frequencies of the spikes and their spacing in the spectrum correspond to local cyclotron frequencies at the plasma edge near the outer midplane. At least in JET experiments, the intensity of the ICE lines is linearly proportional to the total neutral source rate for intensities ranging over three orders of magnitude (Cottrell *et al.* 1993). This is a clear indication that the fusion energetic particles are a source of free energy for the emission. The total emitted energy is usually a negligible fraction of the α-particle heating power, with no noticeable effect on α-particle confinement. This phenomenon has received significant theoretical attention, and several candidate instabilities have been proposed for interpretation of ICE (Cauffman & Majeski 1995; Dendy *et al.* 1994; Gorelenkov & Cheng 1995). It is not expected that this phenomenon can be an issue for α-particle confinement and heating in a tokamak reactor. However, it might be useful as an α-particle diagnostic in a next-step machine (Cottrell *et al.* 1993).

5. Concluding remarks

The understanding of the special physical behaviour of α-particles has significantly advanced in recent years, due to new theoretical models, simulation codes and numerous fast-particle experiments, all of which have benefited from extensive interaction. ITER has actually helped stimulate this advance in understanding by focusing attention on issues, many previously unexplored, that are of concern for a large-scale burning plasma.

Powerful numerical tools have been developed for analysis of the TF ripple loss of energetic particles in tokamaks. The codes were validated in present-day experiments, which allows us to evaluate, with high confidence, the ripple loss in a next-step tokamak. This loss channel can be controlled by the design of the TF coils and minimization of the ripple.

Alpha-particle induced instabilities, and especially the Alfvén modes, have received intensive theoretical and experimental study during the last decade. The linear theory of these modes has been well understood, and the modes have been observed and identified in experiments. It has become clear that a next-step device might be different from present-day machines in terms of the mode spectrum and the number of unstable modes. At the same time, it has also been found that these instabilities can be avoided. Even if parameters fall in the unstable region, the numerical simulations indicate that the loss might be more benign than was previously expected and might result in a redistribution of the α-particles rather than in their appreciable loss.

Most of the theoretical and experimental studies of the confinement of energetic particles and their effects on plasma performance have been carried out for the standard L- and H-mode regimes. Much less is known about α-particle confinement and collective effects in the new reversed-shear configurations that are now considered to be an attractive candidate for steady-state operation of a tokamak reactor. Analysis of TF ripple loss of energetic particles has shown that these advanced configurations are more susceptible to ripple loss and impose more stringent limits on the magnitude of the TF ripple. Clearly, much more work is needed to assess collective effects and to obtain an experimental database on energetic-particle confinement and plasma heating in these types of advanced regimes.

The experimental exploration of energetic-particle physics in present-day tokamaks has natural limits imposed by their scale. To a large extent, what can be done here has already been accomplished, and further significant advances in the study of α-particle physics in tokamaks can be achieved only in a next-step device predicated on ignition and high-Q operation.

Valuable information has been obtained from the TFTR and JET deuterium–tritium experiments, and more understanding can be derived from their analysis (Taylor *et al.* 1996; Thomas *et al.* 1998). A next-step device, such as ITER, however, will fully enter the new regime in which high-energy α-particles are copiously produced and the plasma heats itself. Studying the properties of instabilities such as Alfvén eigenmodes and fishbones and their associated anomalous transport, inventing operating techniques to control or mitigate their consequences, exploring how to reduce ripple loss (especially when the plasma operates in shear-optimized advanced modes), designing observational diagnostics appropriate for the harsh environment of a burning plasma; these are all important science issues that can be properly addressed in a burning-plasma experiment.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

References

Ali-Arshad, S. & Campbell, D. J. 1995 *Plasma Phys. Control. Fusion* **37**, 715.

Basiuk, V. *et al*. 1994 *Fusion Technol.* **26**, 222.

Berk, H. L., Van Dam, J. W., Guo, Z. & Lindberg, D. M. 1992 *Phys. Fluids* B **4**, 1806.

Berk, H. L., Breizman, B. N. & Ye, H. 1993 *Phys. Fluids* B **5**, 3217.

Berk, H. L. *et al*. 1995 *Phys. Plasmas* **2**, 3401.

Berk, H. L. *et al*. 1997*a* In *Fusion energy 1996* (*Proc. 16th Int. Conf. Montreal, 1996*), vol. 2, p. 439. Vienna: IAEA.

Berk, H. L., Breizman, B. N. & Petviashvili, N. V. 1997*b* *Phys. Lett.* A **234**, 213.

Betti, R. & Freidberg, J. P. 1991 *Phys. Fluids* B **3**, 1865.

Borba, D., Candy, J., Kerner, W. & Sharapov, S. 1996 In *Theory of fusion plasmas* (*Proc. Int. School of Plasma Physics, Varenna, Italy, 1996*), p. 267. Bologna: Editrice Compositori Societa Italiana di Fisica.

Breizman, B. N. *et al*. 1997 *Phys. Plasmas* **4**, 1559.

Campbell, D. J. *et al*. 1988 *Phys. Rev. Lett.* **60**, 2148.

Candy, J. 1997 In *Proc. Sherwood Meeting*, 2D03.

Candy, J. & Rosenbluth, M. N. 1995 *Nucl. Fusion* **35**, 1069.

Candy, J., Borba, D. N., Berk, H. L., Huysmans, G. T. A. & Kerner, W. 1997 *Phys. Plasmas* **4**, 2597.

Catto, P. J. & Tessaroto, M. 1988 *Phys. Fluids* **31**, 2292.

Cauffman, S. & Majeski, R. 1995 *Nucl. Fusion* **35**, 1597.

Chang, Z. 1996 *Phys. Rev. Lett.* **76**, 1071.

Chen, L. 1994 *Phys. Plasmas* **1**, 1519.

Chen, L., White, R. B. & Rosenbluth, M. N. 1984 *Phys. Rev. Lett.* **52**, 1122.

Cheng, C. Z. & Chance, M. S. 1986 *Phys. Fluids* **29**, 3695.

Cheng, C. Z., Chen, L. & Chance, M. S. 1985 *Ann. Phys. (NY)* **161**, 21.

Cheng, C. Z., Gorelenkov, N. N. & Hsu, C. T. 1995 *Nucl. Fusion* **35**, 1639.

Cheng, C. Z. *et al*. 1996 In *Plasma physics and controlled nuclear fusion research 1994* (*Proc. 15th Int. Conf. Seville, 1994*), vol. 3, p. 373. Vienna: IAEA.

Cheng, C. Z. *et al*. 1997 In *Fusion energy 1996* (*Proc. 16th Int. Conf. Montreal, 1996*), vol. 2, p. 953. Vienna: IAEA.

Conroy, S., Jarvis, O. N., Sadler, G. & Huxtable, G. B. 1988 *Nucl. Fusion* **28**, 2127.

Cottrell, G. A. *et al*. 1993 *Nucl. Fusion* **33**, 1365.

Darrow, D. S. *et al*. 1996 *Phys. Plasmas* **3**, 1875.

Dendy, R. O., Lashmore-Davies, C. N., McClements, K. G. & Cottrell, G. A. 1994 *Phys. Plasmas* **1**, 1918.

Duong, H. H. *et al*. 1997 *Nucl. Fusion* **37**, 271.

Fasoli, A. *et al*. 1997 *Plasma Phys. Control. Fusion* **39**, B287.

Fish, N. J. 1995 *Phys. Plasmas* **2**, 2375.

Fogaccia, G. & Romanelli, F. 1995 *Phys. Plasmas* **2**, 227.

Fredrickson, E. D. *et al*. 1995 In *Plasma physics and controlled nuclear fusion research 1994* (*Proc. 15th Int. Conf. Seville, 1994*), vol. 1, p. 275. Vienna: IAEA.

Fu, G. Y. 1995 *Phys. Plasmas* **2**, 1029.

Fu, G. Y. 1997 In *TAE modes and energetic particle physics* (*Proc. IEA Tripartite Workshop W36, Naka, Japan, 1997*), p. 69. Japan Atomic Energy Research Institute, Naka, Japan.

Fu, G. Y. & Cheng, C. Z. 1990 *Phys. Fluids* B **2**, 985.

Fu, G. Y. & Van Dam, J. W. 1989 *Phys. Fluids* B **1**, 1949.

Furth, H. P., Goldston, R. J., Zweben, S. J. & Sigmar, D. J. 1990 *Nucl. Fusion* **30**, 1799.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Goldston, R. J. & Jassby, D. 1976 Phenomena accompanying gradient-B drift injection of energetic ions into tokamak plasmas. Report MATT-1244, Princeton Plasma Physics Laboratory.

Goldston, R. J. & Towner, H. H. J. 1981 *J. Plasma Phys.* **26**, 283.

Goldston, R. J., White, R. B. & Boozer, A. H. 1981 *Phys. Rev. Lett.* **47**, 647.

Gorelenkov, N. N. & Cheng, C. Z. 1995 *Phys. Plasmas* **2**, 1961.

Gorelenkov, N. N. & Sharapov, S. E. 1992 *Physica Scr.* **45**, 163.

Gorelenkov, N. N., Cheng, C. Z. & Fu, G. Y. 1997 In *TAE modes and energetic particle physics* (*Proc. IEA Tripartite Workshop W36, Naka, Japan, 1997*), p. 103. Japan Atomic Energy Research Institute, Naka, Japan.

Hastie, R. J., Chen, Y.-P., Ke, F.-J., Tsai, S. T. & Chen, L. 1987 *Chinese Phys. Lett.* **4**, 561.

Heidbrink, W. W. & Sadler, G. J. 1994 *Nucl. Fusion* **34**, 535.

Heidbrink, W. W. *et al.* 1993 *Phys. Rev. Lett.* **71**, 855.

Hellsten, T., Appert, K., Vaclavik, J. & Villard, L. 1985 *Nucl. Fusion* **25**, 99.

Hermann, H. W. *et al.* 1997 *Nucl. Fusion* **37**, 293.

Herrmann, M. C. & Fish, N. J. 1997 *Phys Rev. Lett.* **79**, 1495.

Hosea, J. C. *et al.* 1991 In *Plasma physics and controlled nuclear fusion 1990* (*Proc. 13th Int. Conf. Washington, DC, 1990*), vol. 1, p. 669. Vienna: IAEA.

Huysmans, G. T. A., Goedbloed, J. P. & Kerner, W. 1993 *Phys. Fluids* B **5**, 1545.

ITER 1997 ITER Technical Basis for the ITER Detailed Design Report, Cost Review and Safety Analysis (DDR). ITER EDA Documentation Series, no. 13, IAEA, Vienna.

Ikeda, Y. *et al.* 1996 *Nucl. Fusion* **36**, 759.

Jarvis, O. N., Conroy, S. W., Hone, M., Sadler, G. J. & Van Belle, P. 1994 In *Controlled fusion and plasma physics* (*Proc. 21st Eur. Conf. Montpellier, France, 1994*), vol. 18B, part 1, p. 270. Geneva: European Physical Society.

Jaun, A., Appert, K., Vaclavik, J. & Villard, L. 1995 *Comput. Phys. Commun.* **92**, 153.

Johnson, D. W. *et al.* 1995 *Plasma Phys. Control. Fusion* **37**, A69.

Kimura, H. *et al.* 1995 *J. Plasma Fusion Res.* **71**, 1147.

Kolesnichenko, Y. I. 1980 *Nucl. Fusion* **20**, 727.

Kolesnichenko, Y. I. & Yakovenko, Y. V. 1995 *Nucl. Fusion* **35**, 1579.

Konovalov, S. V., Takizuka, T., Tani, K., Hamamatsu, K. & Azumi, M. 1995 Analysis of high energy ion ripple loss in the up–down asymmetric configuration by OFMC plus mapping hybrid code. Report 94-033, Japan Atomic Energy Research Institute.

Kramer, G. J. *et al.* 1998 *Phys. Rev. Lett.* **80**, 2594.

McGuire, K. *et al.* 1983 *Phys. Rev. Lett.* **50**, 891.

Marcus, F. B. *et al.* 1994 *Nucl. Fusion* **34**, 687.

Medley, S. S. 1996 *Plasma Phys. Control. Fusion* **38**, 1779.

Mett, R. R. & Mahajan, S. M. 1992 *Phys. Fluids* B **4**, 2885.

Nazikian, R. *et al.* 1997 *Phys. Rev. Lett.* **78**, 2976.

Odblom, A., Anderson, D., Eriksson, L.-G. & Lisak, M. 1995 *Nucl. Fusion* **35**, 1571.

Petrov, M. P. *et al.* 1995 *Nucl. Fusion* **35**, 1437.

Porcelli, F. 1991 *Plasma Phys. Control. Fusion* **33**, 1601.

Porcelli, F., Boucher, D. & Rosenbluth, M. N. 1996 *Plasma Phys. Control. Fusion* **38**, 2163.

Post, D., Uchan, N. & Perkins, F. (eds) 1999 ITER physics basis. *Nucl. Fusion.* (In the press.)

Putvinski, S., Tubbing, B. J. D., Eriksson, L.-G. & Konovalov, S. V. 1994 *Nucl. Fusion* **34**, 495.

Putvinski, S. *et al.* 1995 In *Plasma physics and controlled nuclear fusion research 1994* (*Proc. 15th Int. Conf. Seville, 1994*), vol. 2, p. 535. Vienna: IAEA.

Romanelli, F. & Zonca, F. 1994 In *Tokamak concept improvement* (*Proc. Workshop Varenna, 1994*), p. 191. Bologna: Editrice Compositori Societa Italiana di Fisica.

Romanelli, F., Chen, L. & White, R. B. 1991 *Nucl. Fusion* **31**, 631.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

Sadler, G. *et al*. 1992 *Plasma Phys. Control. Fusion* **34**, 1971.
Santoro, R. A. & Chen, L. 1996 *Phys. Plasmas* **3**, 2349.
Sauter, O. & Vaclavik, J. 1992 *Nucl. Fusion* **32**, 1455.
Scott, S. D. *et al*. 1985 *Nucl. Fusion* **25**, 359.
Shirai, H. 1998 *Phys. Plasmas* **5**, 1712.
Sivukhin, D. V. 1966 *Review of plasma physics* (ed. M. A. Leontovich), vol. 4, p. 93. New York: Consultants Bureau.
Spong, D. A., Hedrick, C. L. & Carreras, B. A. 1995 *Nucl. Fusion* **35**, 1687.
Strachan, J. D. *et al*. 1997 *Plasma Phys. Control. Fusion* **39**, B103.
Strait, E. J., Heidbrink, W. W. & Turnbull, A. D. 1994 *Plasma Phys. Cont. Fusion* **36**, 1211.
Synakowski, E. J. *et al*. 1995 *Phys. Rev. Lett.* **75**, 3689.
Taylor, G. *et al*. 1996 *Phys. Rev. Lett.* **76**, 2722.
Thomas, P. R. *et al*. 1998 *Phys. Rev. Lett.* **80**, 5548.
Tobita, K. *et al*. 1992 *Phys. Rev. Lett.* **69**, 3060.
Tobita, K. *et al*. 1995 *Nucl. Fusion* **35**, 1585.
Tobita, K. *et al*. 1997 In *Fusion energy 1996* (*Proc. 16th Int. Conf. Montreal, 1996*), vol. 1, p. 497. Vienna: IAEA.
Tsai, S. T. & Chen, L. 1993 *Phys. Fluids* B **5**, 3284.
Tubbing, B. J. D. *et al*. 1995 In *Controlled fusion and plasma physics* (*Proc. 22nd Eur. Conf. Bournemouth*), vol. 19C, part IV, p. 1. Geneva: European Physical Society.
Uckan, N. A., Tolliver, J. S., Houlberg, W. A. & Attenberger, S. E. 1988 *Fusion Technol.* **13**, 411.
Ushigusa, K. *et al*. 1997 In *Fusion energy 1996* (*Proc. 16th Int. Conf. Montreal, 1996*), vol. 1, p. 37. Vienna: IAEA.
Vlad, G., Zonca, F. & Romanelli, F. 1995 *Nucl. Fusion* **35**, 1651.
White, R. B. & Boozer, A. H. 1995 *Phys. Plasmas* **2**, 2915.
Wong, K. L. *et al*. 1991 *Phys. Rev. Lett.* **66**, 1874.
Wong, K. L. *et al*. 1997 *Phys. Plasmas* **4**, 393.
Wu, Y., Cheng, C. Z. & White, R. B. 1994 *Phys. Plasmas* **1**, 3369.
Yushmanov, P. N. 1990 In *Reviews of plasma physics*, vol. 16, p. 117. New York: Consultants Bureau.
Yushmanov, P. N., Cary, J. R. & Shasharina, S. G. 1993 *Nucl. Fusion* **33**, 1293.
Zweben, S. *et al*. 1998 *Nucl. Fusion* **38**, 739.

Discussion

C. Gormezano (*JET Joint Undertaking, UK*). I would like to comment on the production of toroidal Alfvén eigenmodes (TAEs) in advanced tokamak regimes. In JET, we can compare optimized shear discharges and hot-ion H-modes with similar fusion reactivity and power levels but with significant differences in the current profile. In contrast with hot-ion H-modes, in optimized-shear discharges with central $q > 1$ there was a large spectrum of TAEs at various n numbers. But there were no associated observable losses with these TAEs.

S. Zweben. This result from JET seems to be consistent with the TFTR observations, in which α-driven TAEs were seen only in the 'advanced' $q(0) > 1$ regime. In TFTR there was also no observable alpha loss during these TAEs, but perhaps there was some internal redistribution of alpha. If this result held for the ignition experiment, the TAE would be a benign phenomenon; however, I do not believe we

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

understand the nonlinear saturation and transport processes well enough yet to be sure about this.

J. Jacquinot (*JET Joint Undertaking, UK*). It was mentioned that the ITER reference regime is somewhat inside the TAE instability domain. How large a relaxation of the profile of the α-particle pressure would be necessary to be marginally stable?

S. Zweben. This question was discussed at the last ITER Expert Group Meeting on alpha physics, and work has begun on it; however, I do not know if, or how, it was resolved.

M. G. Haines (*Imperial College, London, UK*). On the subject of TAEs, JET has operated below the critical number density of energetic α-particles for instability. Should ITER-relevant experiments be undertaken with a higher α-particle density, even if this is carried out artificially, in order to assess the importance of this instability?

S. Zweben. Yes, if JET could obtain the conditions needed to study α-driven TAEs, these experiments would be very valuable for both their plasma physics interest, and also for any future tokamak reactor. Of particular relevance is a TAE instability in weak-shear $q(r)$ profiles without RF tail ions, which most closely corresponds to an advances tokamak reactor. A special challenge will be to measure any spatial redistribution and/or loss of the α-particles during such activity.