

# 6 THEORY

## 6.1 INTRODUCTION

The Theory and Modelling Programme aims to provide theoretical models and calculations that expedite the rapid development of fusion power, the “fast track” approach (Chapter 2). The programme’s approach is to provide the theoretical interpretation needed to enhance understanding of the existing experimental programmes on JET and MAST, and predict the performance of future devices: the spherical tokamak; MAST-Upgrade; and burning plasma devices, such as ITER (Chapter 8), DEMO or a spherical tokamak component test facility (CTF) or power plant (Chapter 7).

The programme’s activities cover many of the key plasma physics issues that need to be resolved for the successful development of fusion power, applicable to both ITER-like and spherical tokamak devices: (i) confinement and transport, with an emphasis on understanding the conditions for establishing improved confinement regimes; (ii) the avoidance or mitigation of instabilities that can limit plasma pressure, heating and current, and hence plasma performance, or damage the device – this includes those instabilities driven by energetic particle populations arising in a burning plasma, e.g. alpha particles; (iii) the heat loads on divertor target plates due to plasma exhaust, particularly the transient events associated with edge localised modes (ELMs); and (iv) the integrated plasma modelling required for developing steady state operational scenarios.

These topics are addressed by exploiting UKAEA Culham’s traditional strengths in analytic theory, but also by building up its capability in computational modelling. The latter benefits from resources provided through EPSRC, such as the high performance computer, HPCx at Daresbury, as well as investment in UKAEA’s own parallel computing facilities, such as Columbus. The programme also works in close contact with Culham’s experimental programmes on JET (Chapter 3) and MAST (Chapter 5), which both stimulate the development of models and provide the opportunity to validate them, a crucial element in providing a reliable predictive capability. There are strong collaborative links with fusion institutes in the rest of Europe, Russia and the US, and participation in the International Tokamak Physics Activity (ITPA), in particular hosting and managing the ITPA Profile Database. Strong support for the European Integrated Modelling Task Force is given, supplying a Deputy Leader and a number of the Project Deputy Leaders. The programme plays a leading part in Culham’s “outreach” to UK universities and the broader plasma physics community; this includes both collaborative projects with university staff and supervision of a substantial number of PhD students with CASE awards on projects related to fusion.

Section 6.2, describing progress since the last Annual Report, is organised under the headings listed above. Thus Section 6.2.1 describes work on plasma confinement. This involves: (i) large scale

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computing of the micro-instabilities responsible for turbulent transport with the flux tube gyro-kinetic code GS2, focused on simulating, with physical interpretations, high pressure plasmas in MAST; (ii) the further development of the global, two-fluid, electromagnetic code CENTORI, valid for general tokamak plasma shapes; (iii) the results of a successful proposal to run our nonlinear turbulence codes, GS2 and CENTORI, on the supercomputer HPCx; (iv) analytic studies of the collisionality dependence of trapped electron mode transport; relevant to internal transport barriers (ITBs); (v) studies of the effect of magnetic islands on the micro-instabilities causing turbulent transport in a torus; (vi) the effect of neutral beam injection on neoclassical confinement of ion energy and toroidal momentum; (vii) improved self-consistent Monte Carlo simulations of collisional ion energy transport; (viii) a fluctuation-induced transport model to describe fast transient transport events; (ix) testing the canonical profiles transport model on MAST data; and (x) a model for the effect of magnetic islands on fast particle losses in MAST.

In Section 6.2.2 equilibrium and stability problems are addressed: (i) two fluid plasma model calculations of the effect of toroidal flows on spherical tokamak equilibria; (ii) numerical studies of the effects of a fast particle population on sawteeth; (iii) calculations of the fast particle redistribution and loss due to so-called tornado modes in JET (iv) development of the “fluid-like” equations describing tearing modes in the banana regime of collisionalities, but including neoclassical effects; (v) gyro-kinetic studies of neoclassical tearing mode (NTM) island dynamics; and (vi) an effect of rotation shear in destabilising ideal MHD pressure-driven ballooning modes.

The work in Section 6.2.3 on the plasma edge region and scrape-off layer (SOL) focuses on: (i) further development of the peeling mode relaxation model for edge localised modes (ELMs) involving instabilities driven by the edge plasma current; (ii) numerical studies of the MHD stability of the edge plasma for highly shaped equilibria tending towards having an “X-point”; (iii) edge current and rotation drive by asymmetric plasma fuelling; and (iv) characterisation of the turbulent fluctuations in the edge plasma of MAST using advanced statistical techniques.

Section 6.2.4 on integrated modelling summarises our activities in support of the EU Integrated Modelling Task Force and includes our contributions to managing the ITPA International Profile Database.

There are also sections on collaborations with UK universities (6.2.5) and the facilities that support the Theory and Modelling Programme: the parallel computer; Columbus; and the Culham Library (6.2.6). Finally, Section 6.3 summarises the future programme.

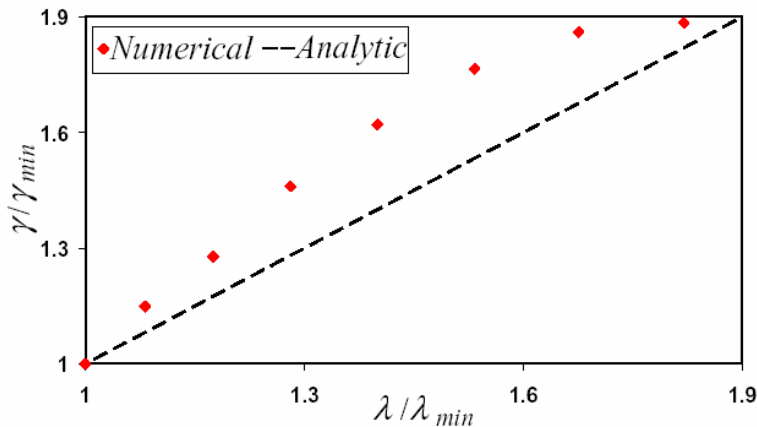
## 6.2 PROGRESS DURING 2006/07

### 6.2.1 CONFINEMENT

#### A Gyro-kinetic Micro-stability and Micro-turbulence Calculations

Gyro-kinetic theory is used to study the short length-scale plasma instabilities (with perpendicular wave-lengths of the order of the Larmor radius) which are thought to be responsible for anomalous transport in tokamaks. UKAEA, in collaboration with Imperial College and University of York, has been exploiting the state-of-the-art flux-tube geometry code GS2 for gyro-kinetic studies of MAST plasmas, and here we report on the progress which has been made over the last year. This effort has largely been focused on trying to make contact between code results and analytic theory, with a view to improving our understanding and confidence in the simulations.

Detailed studies of short wavelength (i.e.  $k_y \rho_e \sim O(1)$  where  $k_y$  is the perpendicular wave-number and  $\rho_e$  is the electron Larmor radius) electron temperature gradient (ETG) driven modes for MAST have revealed that ETG mode growth rates are rather sensitive to the presence of impurity ions. ETG growth rates are found to reduce significantly if impurity ions are included. On the face of it this seems surprising, as it is electrons which provide the instability drive, and at such short wavelengths the ions have a simple adiabatic response (i.e. the ion density perturbation  $\delta n_i$  due to the perturbed electrostatic

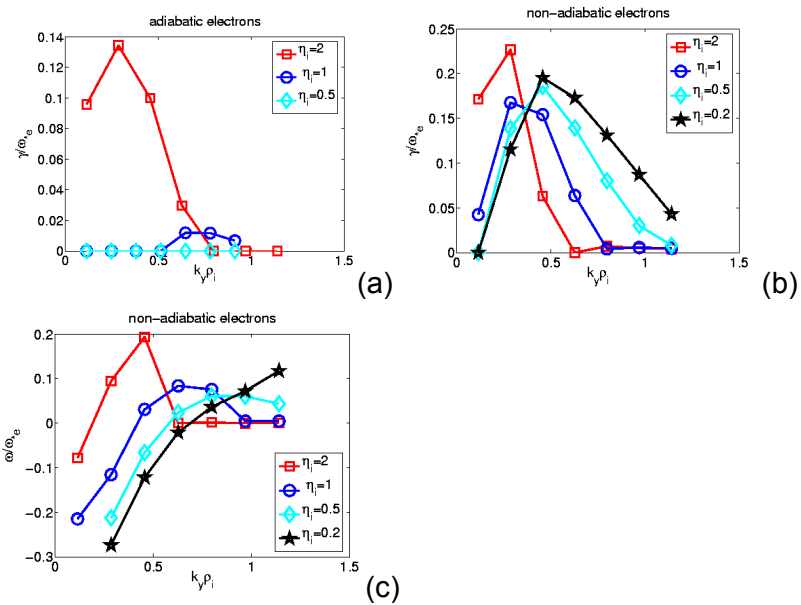


**Figure 6.1:** Normalised growth rate  $\gamma/\gamma_{min}$  as a function of the parameter  $\lambda/\lambda_{min}$  where  $\lambda=1/\sqrt{\sum_j Z_j^2 n_j/T_j}$ , and where the sum is over all ion species.  $\lambda_{min}$  denotes the minimum value of  $\lambda$  in the scan, and  $\gamma_{min}$  is the corresponding growth rate. The dashed line shows the linear dependence predicted by the analytic theory. The left-hand side of this plot corresponds to the situation where the impurities have a stronger influence in reducing the mode growth rate

potential  $\Phi$  is given by  $\delta n_i/n_i = Z_i e \Phi / T_i$ ). A relatively straightforward analytic calculation demonstrates the sensitivity of the ETG growth rate to including ion impurities, and this analytic theory has been found to give results that correspond qualitatively very well to those

from GS2 simulations (see Figure 6.1). It has been common practice in ETG calculations to neglect impurity ions and to consider only a single adiabatic ion species. This work demonstrates that in quantitative predictions with experiments it might often be important to include ion impurities, even when they have a simple adiabatic response.

Simplified electrostatic micro-stability calculations have also been performed for MAST at longer perpendicular wavelengths, much greater than the ion Larmor radius, where we have studied mode sensitivity to the profile parameter  $\eta_i = d(\ln T_i)/d(\ln n_i)$  (the ratio of the gradient scale lengths of density and temperature). With an adiabatic electron response, instabilities resembling toroidal ITG modes are found when  $\eta_i \sim 2$ . These modes generally propagate in the ion diamagnetic drift direction, and are stabilised as  $\eta_i$  falls below 2 (Fig. 6.2(a)).



**Figure 6.2:** Electrostatic calculation showing  $\gamma/\omega_{*e}$  (where  $\omega_{*e}$  is the electron diamagnetic frequency and  $\gamma$  is the growth rate) versus  $k_y \rho_i$  for various choices of  $\eta_i$ , (a) with adiabatic electrons and (b) including the full electron response; (c) shows the real frequency spectrum corresponding to the calculations shown in (b)

On including the full electron response however (see Figures 6.2 (b) and (c)), an instability, propagating in the electron diamagnetic drift direction, survives as  $\eta_i$  is reduced below 2. This mode is influenced both by trapped electron physics and by ion temperature gradients ( $\eta_i > 0$ ). For sufficiently positive values of  $\eta_i$  ( $\eta_i \geq 0.5$ ) the real frequency,  $\omega$ , of the mode (Fig. 6.2 (c)) rises with  $k_y \rho_i$ , and passes through zero close to the peak in  $\gamma/\omega_{*e}$ . The transition from an electron drift mode to a mode propagating in the ion diamagnetic direction was noted previously by B. Coppi, where the ion mode was termed the “ubiquitous” mode. In the low frequency transition region the mode is a fluid instability driven by ion and electron magnetic drifts in the

adverse curvature region. The mode is closely related to the toroidal ion pressure gradient driven mode, but no longer requires ion temperature gradients to destabilise it, though positive  $\eta_i$  still contributes to instability.

Work is also ongoing in trying to further understand the basic drive mechanisms of the micro-tearing mode, which is frequently found to be unstable in MAST. Recent progress has confirmed that passing electron magnetic drifts and the perturbed electrostatic potential are important for this instability.

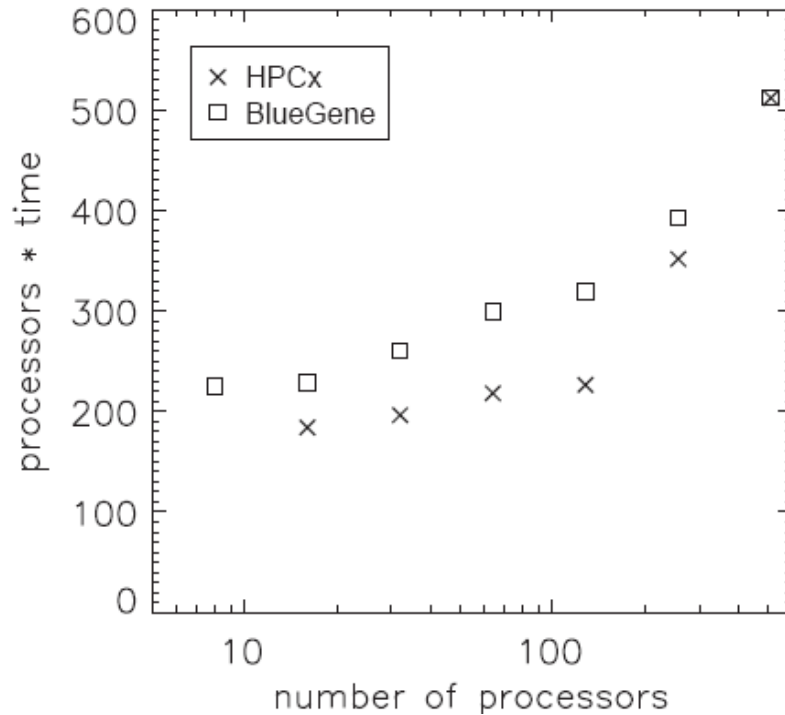
A new collaboration with the University of Warwick aims to complement local flux-tube geometry, gyro-kinetic simulations using GS2 with global calculations exploiting the particle in cell code ORB5, which was originally developed at CRPP in Lausanne. The objective of this project is to perform the first nonlinear ITG simulations for MAST in realistic geometry, and such simulations will require access to massively parallel supercomputers.

## **B CENTORI Development**

The CENTORI turbulence code solves a complete system of two-fluid, electromagnetic, quasi-neutral plasma equations of motion in realistic tokamak geometries. During the period under review, through the collaboration between UKAEA and the Edinburgh Parallel Computing Centre (EPCC) at the University of Edinburgh, the domain decomposition within the code has been upgraded from being a one-dimensional division of labour to a fully three-dimensional method. This change has relaxed restrictions on the number of parallel processes that the code can use for physically sensible calculations, thus providing the possibility for the full utilisation of national supercomputing facilities for the first time, and enabling a potentially dramatic increase in the physics capabilities of the program. The solution procedure has also been modified to remove the need for continual switching between position space and Fourier space, a computationally expensive operation.

Figure 6.3 shows the run-time scaling of the upgraded code, for a typical medium resolution physics calculation, on two supercomputing platforms. Perfect scaling would result in the plot having a flat curve, since the time taken should change in inverse proportion to the number of processors used; however, a factor of only a roughly two change in (number of processors X time for run) between eight and 512 processors is still a very promising result.

A new PhD studentship was initiated in September 2006 with EPCC to facilitate the continuation of the collaboration. The work performed this year has provided the means to launch CENTORI into full production mode by Summer 2007, when the incorporation of the final physics equations should be completed.



**Figure 6.3:** The run-time scaling of the upgraded CENTORI code, for a typical medium resolution physics calculation, on two supercomputing platforms. Perfect scaling would result in the plot being horizontal

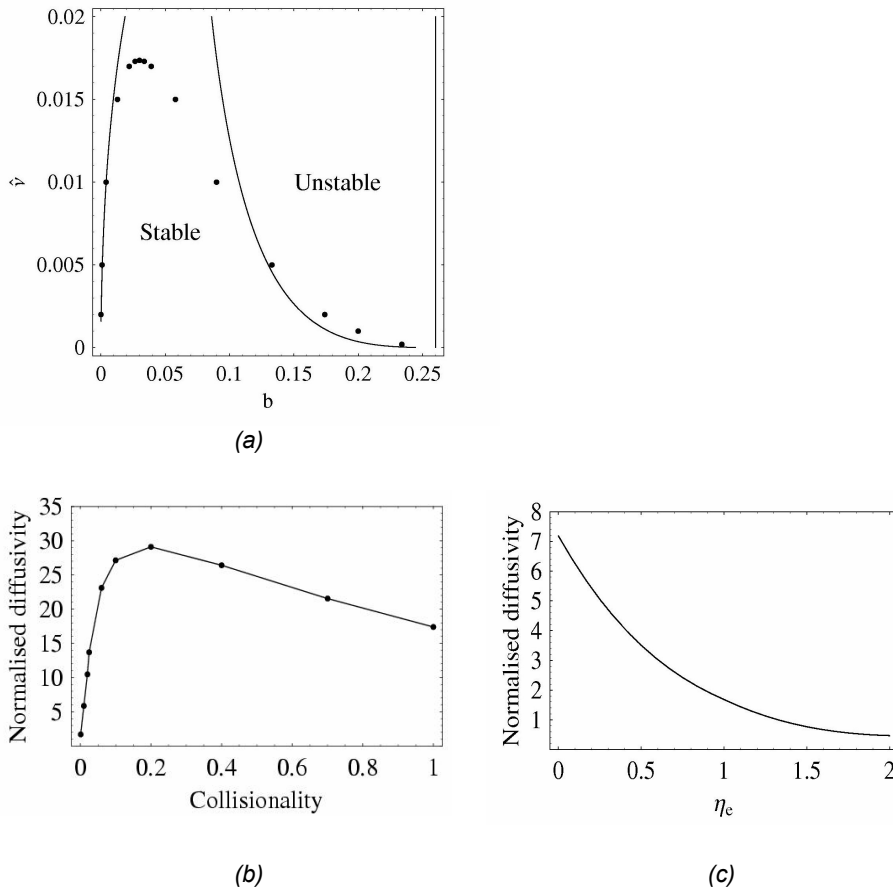
### C Supercomputing for Plasma Turbulence Simulations

A grant of time on the UK national supercomputer HPCx terminated in mid-2006. In their final assessment of that grant the EPSRC referees judged that the project overall was “tending to outstanding” and that it also provided “outstanding cost-effectiveness”. We used this grant for nonlinear gyro-kinetic micro-turbulence simulations with GS2, and two-fluid MHD turbulence simulations with CENTORI (see Section 6.2.1 B). Highlights arising from this grant included:

- Nonlinear GS2 simulations on HPCx suggest that ETG turbulence could generate significant electron heat transport in MAST;
- In collaboration with EPCC, CENTORI's domain decomposition has been substantially improved so that the code can now exploit much higher numbers of CPUs. More details on recent work with CENTORI are given in Section 6.2.1 B.

It is proposed to build on progress made under that grant by exploiting EPSRC's imminent HECToR facility. We intend also to use the global gyro-kinetic code ORB5 to significantly extend the range of calculations that can be performed. HECToR will come online at EPCC in late summer 2007 and will be capable of very high calculation rates up to 60TFlop/s for applications that can exploit all 10,000 of its processors.

## D Transport due to Trapped Electron Modes in Steep Plasma Profiles



**Figure 6.4:** (a) The stabilisation of long wavelength trapped electron modes at low collisionality (points) shown in the  $\hat{\nu}$ - $b$  plane, the lines are analytic asymptotic expression capturing the numerical results in their respective limits; (b) The collisionality,  $\hat{\nu}$ , dependence of the diffusion coefficient, normalised to a Bohm-like value showing a sharp reduction as the long wavelength modes are stabilised; and (c) The dependence of the diffusion coefficient on  $\eta_e$  indicating a particle pinch

The trapped electron mode (TEM) is a candidate micro-instability to explain anomalous electron transport in tokamaks. The TEM can be destabilised by collisions or precessional drift resonances, but the latter effect will be exponentially small in steep density gradients, such as at an internal transport barrier (ITB). In the collisional regime there is an unstable dissipative trapped electron mode (DTEM) for all  $\eta_e = d(\ln T_e)/d(\ln n_e)$ , but at low collisionalities, using a simple Krook collision operator, one finds stability at long wavelengths for positive  $\eta_e$ . In the previous Annual Report we described a model to explore the transition between stability and instability. The main outcome of that work is that below a critical collisionality, defined by the parameter  $\hat{\nu} = \nu_{\text{the}} L_n / V_{\text{thi}}$  (where  $\nu_{\text{the}}$  is the thermal electron collision frequency,  $L_n$  the density scale length, and  $V_{\text{thi}}$  the ion

thermal speed), there is strong stabilisation of long wavelength modes ( $b \ll 1$ , where  $b = k_{\perp}^2 \rho_i^2$  with  $\rho_i$  the ion Larmor radius), so the unstable spectrum may be restricted to shorter wavelengths as the collisionality falls and the density profile steepens (Figure 6.4 a).

We have now calculated the quasi-linear particle flux associated with this instability. Because of the stabilisation of long wavelength modes one finds the collisionality dependence shown in Figure 6.4(b) (the diffusion coefficient  $D$  is normalised to a Bohm-like value). Interestingly the stabilising effect of  $\eta_e$  leads to the dependence of  $D$  shown in Figure 6.4(c), implying a particle pinch.

### **E Influence of Tearing Modes on Micro-stability**

The loss of heat and particles from tokamak plasmas is largely a consequence of plasma turbulence driven by small-scale micro-instabilities. Plasma flows can suppress the transport and lead to insulating regions of the plasma called transport barriers. Such transport barriers may be linked to so-called rational surfaces in the tokamak. Magnetic islands, driven by tearing modes, can form at the rational surfaces, and these are predicted to have strongly sheared plasma flows in their vicinity. This raises the intriguing question of whether tearing modes can actually suppress turbulent transport, perhaps triggering the formation of transport barriers.

In collaboration with the University of York, we have addressed this question by constructing a gyro-kinetic theory for the interaction between small scale magnetic islands and ion temperature gradient (ITG) modes. We consider magnetic islands with a width comparable to the ion Larmor radius, studying a model sheared slab magnetic geometry. We employ a nonlinear gyro-kinetic description for the ion response to both the electromagnetic perturbation of the island and the electrostatic field perturbations of the island and ITG mode. Working in a frame of reference where the island is at rest (in which case there is in general an equilibrium radial electric field to take into account), we decompose the electron and ion responses into a time-independent piece resulting from the island and a time-dependent piece from the ITG instability. We retain the full nonlinear response to the island, but linearise with respect to the time-dependent fluctuations associated with the ITG instability. Applying quasi-neutrality to the time-independent terms determines the steady electrostatic potential and therefore the flow profile about the island. A second equation, arising from imposing quasi-neutrality in the time-dependent terms, yields our new dispersion relation for ITG modes in the presence of the island. Having derived the system of equations, future work will be to develop the code required for their solution. This will enable us to assess whether or not tearing modes can suppress the ITG instability. As mentioned above, this could be an important ingredient in understanding transport barrier formation. In addition, it is likely also to be relevant for the study of neoclassical tearing modes close to threshold (see Section 6.2.2 E).

## F Collisional Bulk Ion Transport and Poloidal Rotation driven by Neutral Beam Injection

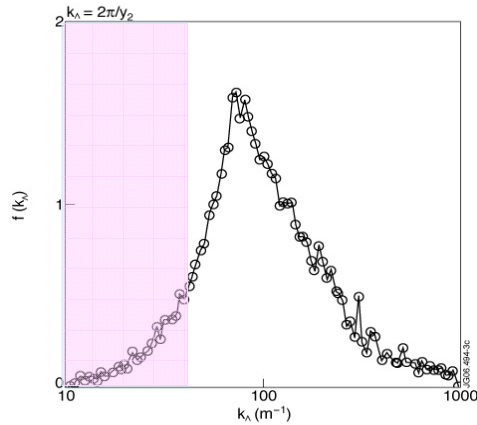
Neutral beam injection (NBI) is known to significantly affect the radial transport in a tokamak plasma. The radial transport of toroidal angular momentum in low collisionality plasma predicted by standard neoclassical theory, is much smaller than that observed experimentally, in regions of near neoclassical bulk ion thermal transport. Furthermore, recent observations have shown poloidal velocities, in the presence of NBI, significantly in excess of the standard neoclassical value. Motivated by this, explicit analytical expressions for the additional collisional radial bulk ion fluxes of particles, heat and toroidal angular momentum, as well as the bulk ion poloidal velocity, driven by fast ions resulting from NBI, have been determined. The expressions have been derived for the case of a low collisionality, pure ( $Z_{\text{eff}} \sim 1-1.2$ ) plasma, with strong toroidal rotation (which may be comparable to the bulk ion thermal speed) and arbitrary aspect ratio. Strong heating and toroidal acceleration of the bulk plasma by the NBI are accounted for, whilst turbulent transport is also included formally. Higher order velocity space structure of the fast ion distribution function has been retained compared to previous work and can be significant at tight aspect ratio. The time evolution of the bulk ion parameters due to the beam deposition may be dominant, in the case of strong neutral beam injection, or may be taken to be formally comparable to that arising due to standard neoclassical transport processes. In both cases, the additional normalised beam-driven heat and angular momentum fluxes were comparable. In the former case, the effects of toroidal acceleration caused by the beam dominate the radial fluxes at large aspect ratio. In the latter case, the additional beam driven heat flux is comparable to the usual neoclassical heat flux. The additional beam driven angular momentum flux will therefore be larger than the usual neoclassical momentum flux by a factor of approximately  $5.6 \varepsilon^{-3/2}$ , where  $\varepsilon$  is the inverse aspect ratio. Finally, the driven poloidal velocity is seen to depend strongly on system parameters, becoming larger at higher beam density and lower beam energy.

## G Monte Carlo Model for Collisional Transport

The computer program QORBIT is based upon a Monte Carlo test particle using the guiding centre drift kinetic equation (see earlier Annual Reports, 2003-06, describing the previous computer program XORBIT). The program was previously extended with a model for recycling of lost particles. Calculations have now been made with various ad hoc schemes for the recycling of lost momentum and energy to test particles. The loss probability varies strongly with the test particle initial conditions which are obtained from a scan of a compact phase space. The calculations made have experimented with changing the algorithm for scanning real space as particles starting near the edge are more likely to be lost quickly than particles starting in the core. The new scanning algorithm alternatively selects particles at the edge and the core. This ensures that the lost

momentum and energy can rapidly be communicated to core particles. Calculations have demonstrated a complete self consistent modelling of the ion population of a thermal plasma by a finite number of test particles. Accumulated plasma profiles of density and temperature agree with assumed plasma profiles (see Annual Report 2005/06). The recycled power profile, i.e. rate of lost test particle energy, agrees with the divergence of the accumulated heat flux. This agreement has been established for peaked L-mode profiles and for hollow H-mode profiles.

### H Heat and Cold Pulse Propagation



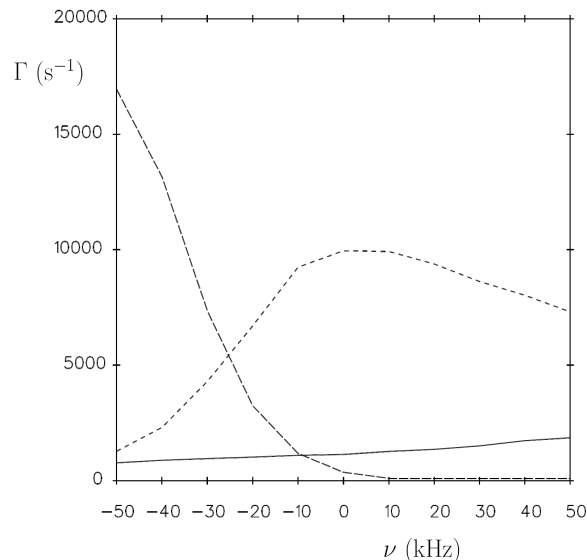
**Figure 6.5:** The predicted spectrum for turbulent fluctuations in a plasma agrees with that observed on TFTR. The shaded area for small wave vectors  $k_{\perp}$  is not observed

A theoretical model for the rapid propagation of changes to tokamak confinement has been developed. Such changes occur when a heat pulse is produced after a sawtooth collapse or when a cold pulse is produced by laser ablation; the L to H mode confinement transition also produces a rapid change. The propagation velocity for these phenomena is some 100-200m/s in JET and TFTR. The model is developed from turbulent guiding centre drift motion and incorporates some standard ingredients of turbulence theory. The model predicts a turbulence-fluctuation spectrum as shown in Figure 6.5. This spectrum is in qualitative and quantitative agreement with fluctuation measurements on the US tokamak TFTR, except for the smaller values of the wave vector not detectable by the experimental diagnostic, shown as the shaded area in the figure. The model also predicts that the changes to confinement will propagate with the guiding centre drift velocity scaled by the ratio between fluctuation and thermal energy; this prediction matches the experimental observation when the fluctuation level ranges from 1% (core) to 10% (edge) as observed on TFTR.

## I Transport Modelling for MAST

A transport model for the electron and ion temperatures and plasma density, based on the conservation of the temperature and pressure profiles (the so called “canonical profiles transport model”), has been developed at the Kurchatov Institute, Russia and in a collaboration with UKAEA has been applied to simulate both Ohmic and NBI discharges in MAST. This model has been assessed by analysing the plasma pressure profiles in MAST, where it has been found that these profiles tend to be preserved and close to the canonical profiles in the gradient zone during the discharge evolution and under variations of the plasma density and deposited power. Comparisons of results of calculations using the canonical profiles transport model with experimental data from MAST demonstrate reasonable agreement.

## J Fast Particle Confinement in Spherical Tokamak Plasmas with Magnetic Islands



**Figure 6.6:** Loss rates,  $\Gamma$ , of 40keV beam ions in MAST-like plasmas with large amplitude magnetic islands, plotted versus island rotation frequency,  $\nu$ . Positive values of  $\nu$  indicate rotation in the plasma current direction. The three curves correspond to the following scenarios: counter-current beam injection with the deposition profile peaking at the beam injection tangency radius (solid curve); co-injection peaking at the tangency radius (dashed curve); and counter-injection peaking outboard of the magnetic axis (dotted curve). In the case of the dotted curve most of the beam ions are lost promptly; the curve indicates the rate of delayed losses caused specifically by the island chain

A full orbit test-particle code CUEBIT has been used to study the collisionless transport of energetic ions in spherical tokamak plasmas with rotating magnetic island chains. Such islands are associated with neoclassical tearing modes (NTMs, see Section 6.2.2 E), which occur in the vicinity of rational surfaces in many tokamaks, and, in the case of the conventional tokamaks DIII-D in the US and Asdex Upgrade in Germany, have been observed to enhance fast particle transport. High loss rates of fast ions from tokamak plasmas are generally

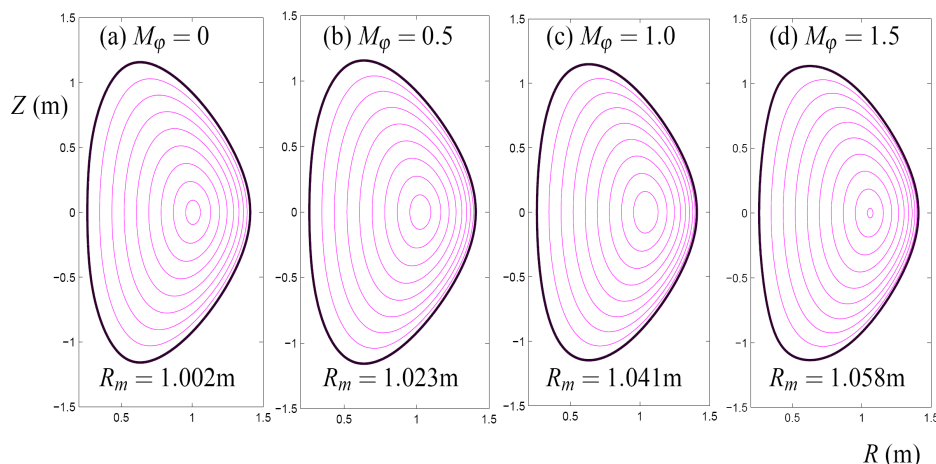
regarded as undesirable, because of the consequent loss of heating (and, in some cases, current drive) that the ions would otherwise have provided, and also because of the potentially damaging effect of these particles on plasma-facing components. It is therefore important to be able to predict and understand the effect of particular field perturbations on fast particle confinement.

Magnetic island chains were represented in the code simulations as single-helicity perturbations to the poloidal magnetic flux. Loss rates of neutral beam-injected fast ions were computed for a range of perturbation amplitudes and rotation frequencies in plasma equilibria representative of those in MAST. As in previous studies of island-induced fast particle losses in the US tokamak DIII-D and the German tokamak ASDEX Upgrade, most of the losses were found to be of ions born into passing rather than trapped orbits. For some injection scenarios the loss rate depends sensitively on mode frequency, and the rate is generally lower for island chains rotating in the direction of beam injection than it is for islands that are either static or rotating counter to the beam direction (Figure 6.6). This result, which can be understood by recognising that the temporal evolution of particle energy in the presence of a single-helicity magnetic field perturbation is linked in a specific way to that of toroidal momentum, indicates that island rotation is likely to be beneficial to beam ion confinement in tokamak plasmas with such islands.

## 6.2.2 STABILITY

### A Two-Fluid Equilibria of Rotating Spherical Tokamak Plasmas

The use of neutral beam injection in MAST has produced plasmas with toroidal rotation velocities approaching and, in some cases, exceeding the local sound speed. The presence of such flows can benefit both stability and confinement. It is important to consider the effects of steady flows on plasma equilibria before assessing their effect on stability. In collaboration with Uppsala University, Sweden, we have applied a two-fluid model of tokamak equilibria with flows to rapidly-rotating MAST-like plasmas. The model allows for a wide class of toroidal rotation profiles, ranging from rigid-body rotation of flux surfaces (required by MHD in the absence of poloidal flows) to “Keplerian” rotation, in which the ion fluid on a given flux surface rotates with constant angular momentum. We have solved generalised Grad-Shafranov equations describing two-fluid equilibria in the rigid-body and Keplerian limits. Figure 6.7 shows results obtained numerically for Keplerian rotation, a fixed plasma boundary, and a range of experimentally-relevant sonic Mach numbers  $M_\phi$ . It can be seen that the magnetic axis moves outboard as  $M_\phi$  is increased; the shift observed in the case of rigid body rotation is of similar magnitude, indicating that this parameter is insensitive to the type of rotation. On the other hand the predicted variation of electron density on a flux surface changes significantly when a rigid body rotation profile is replaced with a Keplerian one.



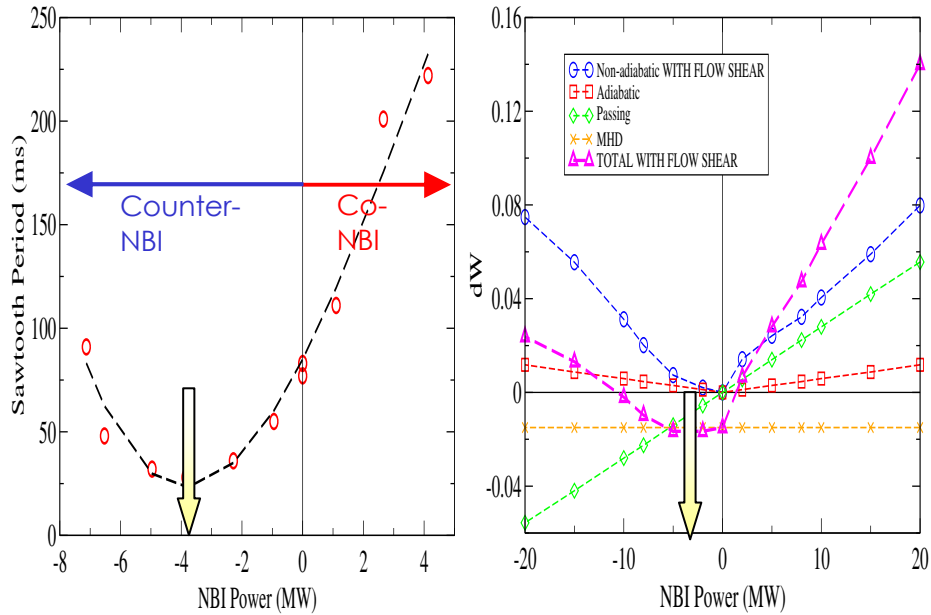
**Figure 6.7:** Flux surfaces in MAST-like plasmas with Keplerian rotation. The sonic Mach number  $M_\phi$  is evaluated at  $R = 0.85\text{m}$ . The major radius of the magnetic axis (the centre of the contours) is denoted by  $R_m$

## B Fast Particle Effects on Sawtooth Oscillations

The magneto-hydrodynamic (MHD) stability of burning plasmas is a key issue for operation of ITER. The reaction  $\text{D} + \text{T} \rightarrow {}^4\text{He}(3.5\text{MeV}) + \text{n}(14\text{MeV})$  produces fusion-born  $\alpha$  particles that can affect the stability of the plasma. One key MHD instability which will be affected by these  $\alpha$  particles is the sawtooth oscillation (a periodic relaxation of the core plasma density and temperature). Based on experimental evidence, it is thought that the  $\alpha$  particles will lead to large amplitude sawteeth which have been shown to result in the triggering of other instabilities called neoclassical tearing modes (NTMs), which can have deleterious ramifications for plasma confinement. As such, recent experiments have identified various methods for the control of sawteeth in order to confine the perturbation to the plasma core whilst retaining the benefits of small, frequent sawtooth crashes, such as the prevention of core impurity accumulation. One experimental technique is to apply neutral beam injection (NBI) heating in the opposite direction to the plasma current. This has been shown to result in shorter sawtooth periods than those in Ohmically heated plasmas in JET, MAST and the German tokamak TEXTOR. Furthermore, each experiment exhibits an asymmetry of sawtooth period with respect to NBI direction. Recent advances in modelling both the effects of anisotropic fast particle distributions (using the particle-in-cell HAGIS code) and MHD stability including toroidal flow (using the MISHKA-F stability code) have enabled the development of a coherent physics explanation of sawtooth stabilisation on both conventional and spherical tokamaks. Sawtooth stabilisation is explained by different mechanisms depending upon the fast particle distribution functions and plasma rotation profiles.

In JET, there are relatively low toroidal flows, so sawtooth stability is governed by the energetic particle population. It is found that whilst the trapped particles are always stabilising, passing particles can be destabilising. The small flows do not affect the stability but the flow

shear does change the stabilising effect of the trapped particles and, together with the passing particle destabilisation, explains the experimental asymmetry. Figure 6.8 (a) shows the sawtooth period as a function of injected NBI power on JET. The sawtooth period exhibits a clear minimum when ~3.5MW of counter-current NBI power is injected. The HAGIS modelling shown in Figure 6.8 (b) gives excellent agreement as the change in the potential energy of the  $n/m=1/1$  kink mode – which is generally accepted to be related to sawtooth oscillations – is minimised at approximately the same NBI power as that which results in the minimum sawtooth period. On MAST, the toroidal rotation profile is broad and relatively flat, and therefore does not significantly affect the stabilisation of the predominantly trapped population. However, the high beam power per unit volume and low moment of inertia results in the plasma rotating at velocities approaching the deuterium sound speed. Such strong rotation can stabilise the kink mode with the asymmetry being explained by the direction of the beam-induced flow relative to the ion diamagnetic drift as described in last year’s Annual Report.



**Figure 6.8:** (a) shows the sawtooth period in JET as a function of NBI power, exhibiting a clear minimum in the counter-NBI regime; (b) shows the modelling using the HAGIS code, which shows that the  $n=m=1$  internal kink mode is most unstable (see red curve) at approximately the same counter-NBI power

**C Fast Ion Redistribution and Losses due to “Tornado” Modes**

In JET discharges with high current (axial safety factor  $q(0) < 1$ ) and high power ion cyclotron radio-frequency heating (ICRH), monster sawteeth with long periods (~1sec) and fast crash times (~50µsec) are typically observed. These degrade plasma confinement and sometimes trigger NTMs. Significant improvements made in the detection of Alfvén instabilities allow one to identify high-frequency precursors to monster sawtooth crashes, the so-called “tornado”

modes. These multiple modes have frequencies in the Toroidal Alfvén Eigenmode (TAE) frequency range, but in contrast to the usual TAEs, they exhibit a significant sweep in frequency and are observed with mode numbers decreasing one-by-one before the sawtooth crash. The effect of the tornado modes on fast ions in JET discharges is investigated with Far Infra Red (FIR) interferometry and improved X-mode reflectometry, while energetic ions are measured with the new lost ion scintillator and gamma-ray and neutral particle analyser (NPA) diagnostics. Modelling with the HAGIS code shows the possibility of resonant redistribution and losses of fast trapped ions with energy as high as  $>5\text{MeV}$ , and the frequency sweep of tornado modes is found to play an important role in depleting the fast ion density inside the  $q = 1$  radius.

#### **D Tearing Mode Stability in the Banana Regime of Collisionality**

Tearing mode stability is believed to play a role in important tokamak phenomena such as sawteeth and disruptions. This mode involves magnetic field reconnection, which takes place at so-called resonant layers where the parallel wave-number of the mode vanishes. It is normally analysed using resistive MHD or two-fluid Braginskii plasma models. However for large hot tokamaks like JET or ITER the collisionality is such as to place them in the banana regime where kinetic effects intervene. We have developed a theory of the resonant layer physics appropriate to such a regime. The outcome is a set of “fluid-like” equations whose coefficients encapsulate all neoclassical physics: the neoclassical Ohm’s law, enhanced ion inertia, neoclassical cross field transport of particles, heat and momentum all play a role. While earlier treatments have also addressed this type of neoclassical physics, we differ in incorporating the more physically relevant “semi-collisional fluid” regime, when parallel collisional electron transport competes with the mode’s oscillation frequency. Furthermore we also include thermal physics, which may modify the results. (Interestingly there is experimental evidence, for example, that the sawtooth instability is triggered when the electron temperature gradient,  $dT_e/dr$ , exceeds a critical value.) While our electron description is of wide relevance, the fluid treatment of the ions used requires the ion banana orbit width to be less than the semi-collisional electron layer. This limits the application of the present theory to low magnetic shear – however this is highly relevant to the sawtooth instability. (For finite shear one needs to consider large ion banana width effects which will provide a strong stabilising effect, analogous to the role of finite ion Larmor radius (FLR) in slab geometry). The outcome of our calculation is a set of one-dimensional radial differential equations of rather high order. These equations describe the perturbed electron and ion temperatures, the perturbed density, Ohm’s law, vorticity and Maxwell’s equations. The equations can, of course, be equally applied to the twisting parity neoclassical ballooning modes. While this system of equations in general will require numerical solution, various simplifications that reduce the computational task of solving them can be proposed. Furthermore we

can make some particular observations: for example, we note the role of neoclassical ion inertia in reducing tearing mode growth rates and that the bootstrap drive from the resonant layer overcomes “Glasser” stabilisation at tight aspect ratio.

### **E Neoclassical Tearing Mode Stability**

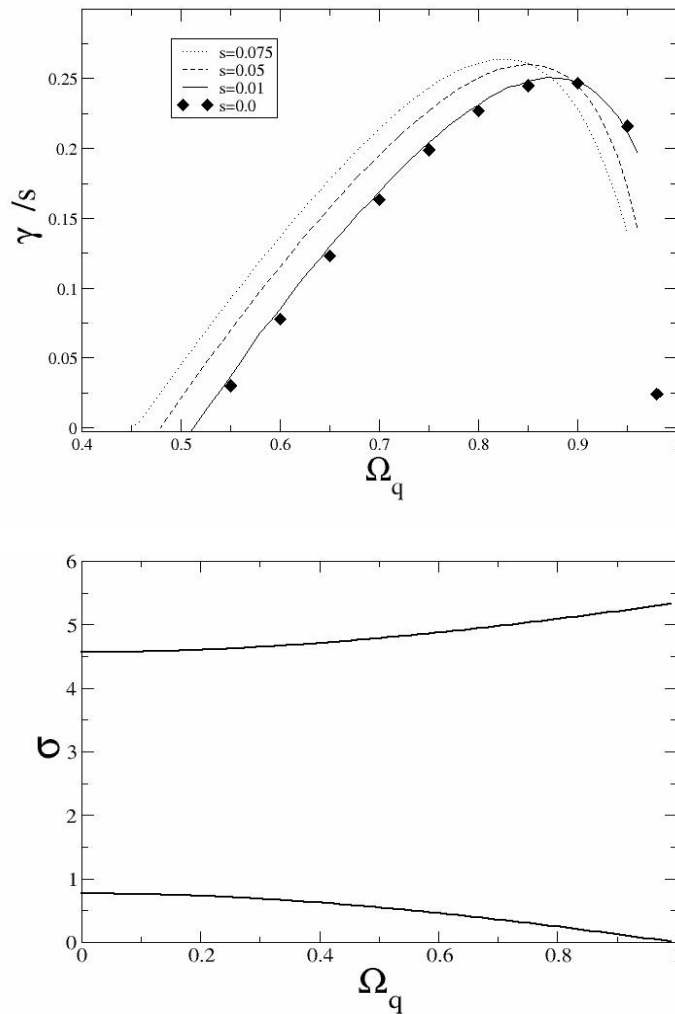
The neoclassical tearing mode instability facilitates the formation of magnetic islands and thereby inhibits the performance of fusion plasmas by increasing the energy fluxes from the plasma core. The growth of magnetic islands is influenced by currents running parallel to the magnetic field and, for long narrow islands (with the width comparable to the ion Larmor radius), it is the contribution of the polarisation current that is the most significant. A numerical solution of the gyro-kinetic equations confirms and extends previous studies of the contribution of the polarisation current to the island stability, as reported in the 2005/06 Annual Report. In that work, unphysical steep gradients arose near the island separatrix; in reality these would be smoothed by the neglected cross field transport which can compete with the dominant parallel transport in these circumstances. In more recent work the effect of cross field diffusion on the electron density near the island separatrix has been modelled by the inclusion of a smoothing function. The results indicate that, for physically observed rates of diffusion, the cross field diffusion will have a small, but noticeable, effect on the parameter  $\Delta_{\text{pol}}$  which measures the contribution of the polarisation current to the free energy available to the island for growth.

### **F A Destabilising Effect of Rotation Shear on Magneto-hydrodynamic Ballooning Modes**

The stability of plasma to ideal magneto-hydrodynamic (MHD) ballooning modes provides a limit to the maximum pressure that can be maintained. For the most dangerous, high- $n$  modes (where  $n$  is the toroidal mode number in an axisymmetric plasma), this limit can be calculated for a stationary plasma using the ballooning transformation; this reduces the problem to a one-dimensional ordinary differential equation for the plasma perturbation. However the introduction of a sheared plasma flow destroys the translational symmetry required for the application of the ballooning transform, and leads to a two-dimensional eigenvalue problem. We parameterise the toroidal rotation shear as  $\Omega_q = d\Omega/dq$ , where  $\Omega = \Omega_T/\omega_A$  is the toroidal plasma rotation frequency,  $\Omega_T$ , normalised to the Alfvén frequency,  $\omega_A = RB_T/(m_i n_i)^{1/2}$ , with  $m_i$  and  $n_i$  the plasma ion mass and density, respectively,  $R$  the plasma major radius and  $B_T$  the toroidal magnetic field;  $\Omega_q$  is a flux surface function and thus can be considered as a function of the safety factor,  $q$ . As  $\Omega_q$  approaches zero, it can be shown analytically that the ballooning mode growth rate is reduced from its value in stationary plasma (which is determined by choosing the most unstable value of the so-called

ballooning angle parameter  $\theta_0$ ), essentially averaging its value over all  $\theta_0$  - or time in the time-dependent formulation (see the 2004/05 Annual Report).

This has been confirmed by considering the low rotation shear limit of the solutions of the two-dimensional problem appropriate to finite shear, specifically for the model  $s - \alpha$  equilibrium ( $s = (r/q) dq/dr$  is the magnetic shear and  $\alpha = -(2Rq^2 / B_T^2) dp/dr$  is the normalised pressure gradient parameter). With increasing rotation shear the growth rate continues to decrease (indeed the mode can become stable) but, surprisingly, above a critical value, the growth rate begins to increase, before finally stabilising as  $\Omega_q \rightarrow 1$  (these numerical solutions of the two-dimensional problem were reported in the 2003/04 Annual Report). To understand this numerical result we have considered the limit of low  $s$  and  $\alpha$  to obtain a much simpler problem (involving the solution of a simple second-order differential eigenvalue equation in which the parameters  $s$  and  $\alpha$  collapse into a single parameter:  $\sigma = \alpha^2/s$ ) which displays these very same features. In the limit of very low  $s$ , with  $s \propto \alpha^2$ , we demonstrate in Fig. 6.9 (a) that the two-dimensional results converge to those from the simpler treatment. These results imply that the unstable region of the  $s - \alpha$  diagram (indicated by the two marginal stability values of  $\sigma$  in Fig. 6.9 (b)) grows as  $\Omega_q$  increases beyond this critical value, eating into both first and second stability regions; indeed the first stability region entirely disappears as  $\Omega_q \rightarrow 1$ .



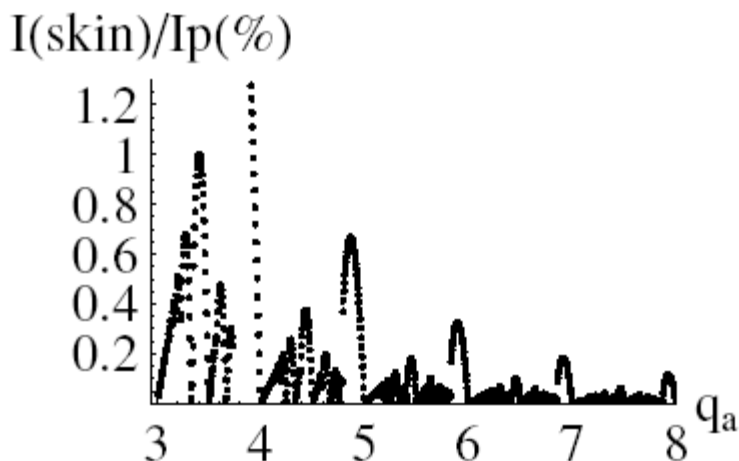
**Figure 6.9:** (a) The convergence of the numerical results from a 2D solution of the MHD equations to the solution of the simpler eigenvalue problem, shown by full diamonds, as magnetic shear  $s \rightarrow 0$  at fixed  $\sigma=0.53$ . There is a critical value of  $\Omega_q = 5.2$  above which there is instability; (b) The effect of rotation shear,  $\Omega_q$ , on the first and second stability boundaries as characterised by the parameter  $\sigma$  at low  $s$ . The lower (upper) curve corresponds to the first (second) stability boundaries of the  $s - \alpha$  diagram

### 6.2.3 PLASMA EDGE PHENOMENA

#### A Modelling of ELM Instabilities

In previous Annual Reports we have presented a model for (Type III) edge localised modes (ELMs) based on ideas derived from peeling mode and relaxation theory. With no fitted parameters, it was shown that the balance that is struck between a destabilising increase in edge current and the stabilising formation of a negative edge current sheet produces ELM widths (and hence plasma ELM losses) that are in good general agreement with experimental observations. Results from the model for the predicted ELM widths, for example, exhibit sensitivity to the precise position of the edge plasma with respect to

low order rational surfaces, leading to a seeming “scatter” in these. Arguing from the toroidal peeling stability criterion, losses become larger with decreasing collisionality, as observed in experiments such as MAST.



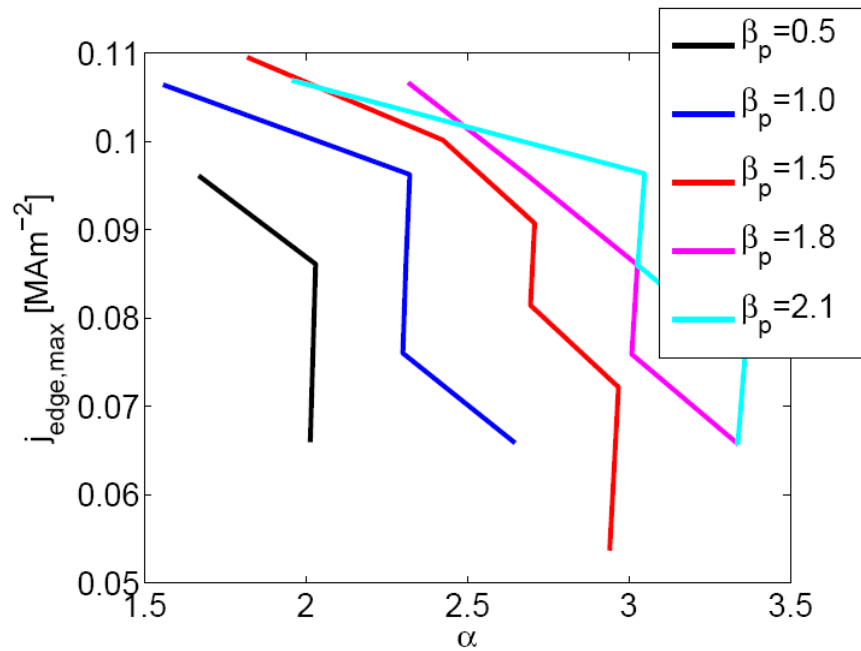
**Figure 6.10:** The values of the total skin current,  $I(\text{skin})$  predicted by the peeling mode relaxation theory as a percentage of the total plasma current,  $I_p$ , plotted against  $q_a$ , the edge value of the safety factor

It has subsequently been shown that the surface negative current sheet produced by the relaxation process in this model will itself be ideal MHD stable, but inevitably resistively unstable. We may speculate that the explosive filamentary structures observed on MAST to accompany an ELM (Section 5.2.3A) are a concomitant of the break up of this current sheet. Let us take for example MAST 750kA discharges operating between  $4 < q_a < 5$ , where  $q_a$  is the value of the safety factor at the plasma edge. Typically  $\sim 10$  post-ELM filaments are observed, each measured to be carrying 200A, giving a total of 2kA which is  $\sim 0.26\%$  of the total plasma current. In Figure 6.10 we show the model predictions for the total skin current as a percentage of the total plasma current, and we see that there is good quantitative agreement between the calculated model skin current and the total observed ELM filament current.

## B MHD Stability Analysis of ELMs

Previous MAST modelling of edge localised modes using MHD stability analysis has been expanded to investigate the effect of an “X-point” (corresponding to a null in the poloidal magnetic field) on edge instabilities. It was found that modifying the plasma boundary shape from a “round” ellipse towards one with a “sharp” X-point has a stabilising effect on the current driven peeling modes that are localised close to the edge. The stabilising effect on the peeling-ballooning modes that have a wider radial extent is more modest. Only the peeling component of the mode is stabilised while the ballooning component that peaks inside the plasma is not affected.

In many experiments, such as the Japanese tokamak JT-60U, JET and the German tokamak ASDEX Upgrade, it has been found that increasing poloidal beta,  $\beta_p$ , has led to a change of ELMs from large Type I ELMs to smaller 'grassy' ELMs. The effect of  $\beta_p$  on the edge stability was analysed by keeping the edge parameters fixed and varying the core pressure. As can be seen in Figure 6.11, increasing core pressure (and therefore  $\beta_p$ ) significantly improves the edge stability against pressure driven ballooning modes. The stabilising effect on the current driven modes is small.



**Figure 6.11:** Stability diagram of a poloidal beta,  $\beta_p$  scan. The abscissa  $\gamma$  is the normalised edge pressure gradient and the ordinate is the edge current density. The lines represent the stability boundaries for each value of  $\beta_p$ , where  $\beta_p$  is a global measure of poloidal beta, i.e. plasma is unstable above and to the right of the line and stable below and to the left of it

This study fails to treat an actual X-point where the magnetic geometry undergoes a topological change. To examine this, a model X-point equilibrium has been constructed that separates the effects of shaping from this topology change by confining the effect of the X-point to a small region of an otherwise circular cross section (see the 2005/06 Annual Report). This is being used to examine peeling mode stability.

### C Fuelling-Driven Tokamak Current and Rotation

The cross-field transport that takes place in a tokamak, and the refuelling or heating that balances it, is in general not poloidally symmetric. Turbulent transport is usually believed to be in-out asymmetric due to the ballooning nature of the underlying instabilities, and is probably also up-down asymmetric in the edge region if the separatrix has an X-point. Similarly, the incoming particle flux that balances this transport is poloidally asymmetric, too, since much of

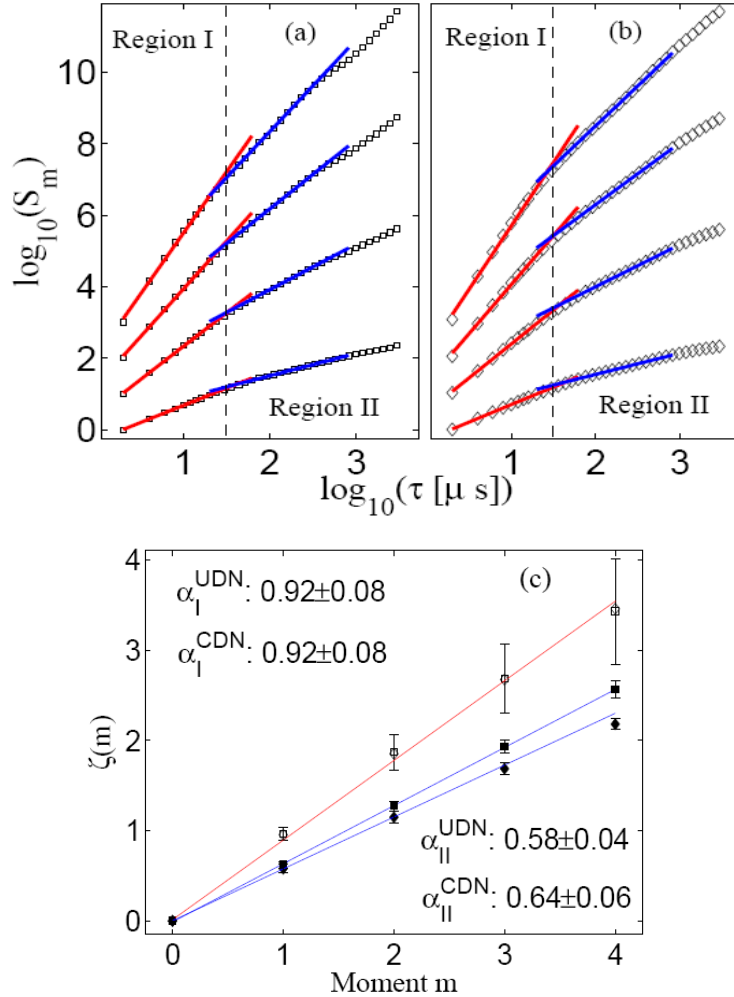
the recycling takes place in the divertor region close to the X-point. External means of refuelling, such as injection of neutral beams or pellets, is also poloidally asymmetric in general. We have found that a poloidally asymmetric particle source (or sink from transport), such as that naturally occurring at the edge, produces a plasma current parallel to the magnetic field. This current arises essentially because the electrons and ions from the source, although equal in number, spread out over the flux surface in different ways. It is estimated to be of the order of a few kA in the edge plasma of JET, and is thus typically smaller than the bootstrap current produced by the H-mode pressure pedestal. It could however have a radial structure enabling it to influence the stability of the tokamak to edge-localised “peeling” modes.

A similar calculation also shows that edge plasma rotation can arise in response to up-down asymmetric fuelling. It has been observed in the US tokamak Alcator C-Mod that the rotation depends strongly on the location of the X-point and has intriguing links to the L-H transition. The mechanism attributed to the cause of the rotation is that the transport mostly occurs in the outer mid-plane, from where plasma flows to the divertor along open lines in the scrape-off layer. Depending on whether the X-point is at the top or at the bottom, most of this flow is either in the co-current or in the counter-current direction. It is believed that these scrape-off layer flows cause the plasma inside the separatrix to rotate accordingly, presumably through cross-field viscosity. However, our results show that up-down asymmetric fuelling also creates plasma rotation directly. This rotation is comparable to that caused by parallel plasma flows in the scrape-off layer, and it thus seems likely that the two mechanisms should operate in parallel.

## **D Fusion Plasma Turbulence Studies**

Understanding the role of turbulent processes in magnetically confined plasmas is central to understanding their transport and confinement properties. One route is provided by systematic quantitative characterisation of measurements of the strongly nonlinear phenomena that are observed, for example by probes investigating tokamak edge plasma turbulence. This process requires the application of state-of-art statistical physics techniques. A second route is provided by direct numerical simulation using computational implementations of mathematical models of turbulence in plasmas. This approach is limited by resource constraints; even using simplified models such as MHD, which reduces the number of degrees of freedom compared to a kinetic treatment, boundary effects and dissipation limit the range of spatio-temporal scales over which pure turbulence can be simulated. This raises the theoretical physics challenge of extracting the maximum reliable information, subject to these limitations. For both observations and simulations of turbulence, an important question is to distinguish features that are generic or even “universal”: for example, features that may be shared by turbulence in all toroidal magnetically confined plasmas, as distinct

from features that are signatures of particular magnetic geometries or plasma operating regimes. Collaborative projects in both these aspects have been carried out in conjunction with the Centre for Fusion, Space and Astrophysics at Warwick University.



**Figure 6.12:** Comparison of statistical properties of edge turbulence measurements for MAST plasmas with different magnetic field geometries: upper double null (UDN) and connected double null (CDN). Structure functions of orders  $1 \leq m \leq 4$  for (a) signal UDN-14219 and (b) CDN-14222. (c) Scaling exponents  $\zeta(m)$  derived from the structure functions of  $I_{sat}$ : open squares-UDN in Region I, open diamonds-CDN in Region I, filled squares-UDN in Region II and filled diamonds-CDN in Region II

Work on quantitative statistical characterisation of the strongly nonlinear signals obtained from probe measurements of the ion saturation current  $I_{sat}$  in tokamak edge plasmas in MAST has focused on a series of L-mode plasmas with plasma current  $I_p \approx 700kA$ . These differ in their outer magnetic field configurations – unbalanced upper null, unbalanced lower null, and connected double null – but are otherwise similar. The corresponding  $I_{sat}$  datasets were obtained with a reciprocating Langmuir probe, sampling at rates of 500kHz or 1MHz, during episodes when the distance from the probe to the

plasma edge was approximately constant and the same in all cases. Significant quantitative results arise both from investigation of the probability density functions (PDFs) of the  $I_{\text{sat}}$  fluctuations, and from analysis of the  $m$ th moments  $S_m$  (structure functions) of the summed  $I_{\text{sat}}$  fluctuations. The PDF of the fluctuations from all the MAST plasma considered, sampled on a timescale  $\tau = 2\mu\text{s}$ , is well fitted by an extremal Fréchet distribution with index  $a = 1.25$ . For individual MAST plasmas, Fréchet distributions give the best fit for  $\tau \leq 40\mu\text{s}$ , and Gumbel for  $\tau \geq 40\mu\text{s}$ . This transition at  $40\mu\text{s}$ , which may correspond to filamentary structures observed in optical imaging, is confirmed by the structure function scaling properties  $S_m \sim \tau^{\zeta(m)}$  that we identify, see Figure 6.12.

In addition to a well defined discontinuity at  $40\mu\text{s}$ , plots of  $\log(S_m)$  versus  $\log(\tau)$  demonstrate self-similar scaling  $\zeta(m) = \alpha m$ . The value of  $\alpha$  is the same for all the L-mode plasmas considered on timescales up to  $40\mu\text{s}$ , suggesting universality in the character of these fluctuations. On longer timescales,  $40\mu\text{s}$  to  $400\mu\text{s}$ , two distinct groups of scaling exponents are found, that exhibit weak dependence on poloidal magnetic field structure.

## 6.2.4 INTEGRATED MODELLING

### A Contribution to the Integrated Tokamak Modelling Task Force

During the last year Culham provided contributions to the EFDA Task Force on Integrated Tokamak Modelling (ITM) in various areas. Task Force leadership was also provided by Culham (Dr Michele Romanelli) and three integration projects were coordinated at the level of deputy project leaders. A machine independent version of the equilibrium code EFIT has been finalised (EFIT2006) and it is now available for benchmarking and testing. First tests of the code have been carried out on machine data from MAST, JET and the Italian tokamak FTU in collaboration with the Italian Association ENEA. The functions FLUSH needed to interface EFIT2006 and any equilibrium code complying with the ITM Task Force data structure to the JETTO transport code and JAMS (JET Analysis and Modelling System) codes have been developed. The sawtooth and ELM models developed by the Task Force have been included and tested in JETTO. The contribution of Culham also covered the comparative study of turbulence codes: a series of runs of the two-fluid, electromagnetic, global turbulence and transport code CUTIE has been launched to study the threshold value of the normalized ion temperature gradient for turbulent driven transport based on CYCLONE parameters and initial profiles (CYCLONE is a benchmark case proposed by US modellers). The results of runs with CUTIE will be compared with that of other global fluid and gyro-kinetic codes.

## B International Profile Database

Culham has continued to host and manage the ITPA International Profile Database for testing transport models. Work is progressing towards a new public release, with an accompanying publication, to update that released in 2000.

### 6.2.5 SYNERGIES WITH BASIC SCIENCE

#### A Fast Alfvén Wave Heating and Acceleration of Ions

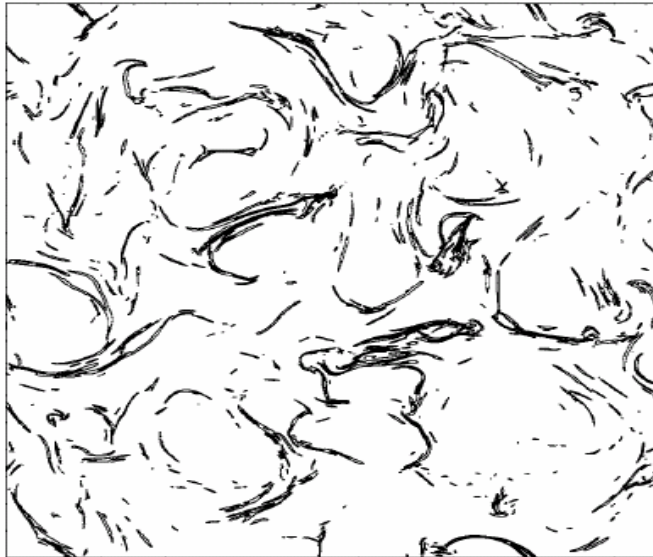
In collaboration with the University of Glasgow, test-particle simulations have been used to study the collisionless response of ions to fast Alfvén waves propagating in plasma with a non-uniform magnetic field configuration. This is a problem of common relevance to fusion and space plasmas. The field perturbations associated with the waves were taken to be exact solutions of the MHD equations for a two-dimensional X-point field. In the simulations ions were observed to be effectively heated in the direction parallel to the magnetic field, although the parallel velocity distribution was generally non-Maxwellian and some protons were accelerated to highly supra-thermal energies. This heating and acceleration can be attributed to the fact that protons undergoing  $\mathbf{E} \times \mathbf{B}$  drifts due to the presence of the wave are subject to an effective force in the instantaneous direction of  $\mathbf{B}$ . The process is effective for all ion species, but has a negligible direct effect on electrons.

#### B MHD Turbulence

In many astrophysical and laboratory plasmas, including fusion plasmas, the kinetic and magnetic Reynolds numbers are large and the dynamics are turbulent. Where magnetic fields are present, which is often the case, the study of magnetohydrodynamic (MHD) turbulence becomes necessary. The plasmas are three dimensional objects, however if the magnetic field is strong, there will be a corresponding anisotropy in the plasma dynamics and, by extension, in the properties of the MHD turbulence. Tokamak plasmas are in essence three-dimensional, although for some purposes a two-dimensional approximation (suppressing the toroidal direction) may be helpful. The ways in which turbulent properties vary between two and three spatial dimensions are thus of interest and, even for the relatively simple case of MHD turbulence, this remains a largely open question. An important factor is the nature of the self-similar turbulent cascade by which energy is transferred down the hierarchy of lengthscales. To what extent is it governed by classical fluid-type phenomenology (“Kolmogorov 1941”) or Alfvénic phenomenology (“Iroshnikov-Kraichnan”)? Figure 6.13 shows a numerical simulation of driven two-dimensional MHD turbulence incorporating resistive and viscous dissipation.

We have applied the statistical techniques of contemporary fluid dynamics to the spatially distributed set of velocity vectors  $\mathbf{v}$  and

magnetic field vectors  $\mathbf{B}$  that comprise the evolving simulation. These techniques are designed to overcome, so far as possible, the limitations that factors such as dissipation and finite simulation domain impose on our ability to identify the self-similar cascade. These techniques are also designed to capture the essentially nonlinear consequences of intermittency – the fact that a few sporadic major dissipation events carry equal weight to the smooth distribution of smaller dissipation events. We find that there are two key determinants of the simulated turbulence: the geometry of the dissipating structures, which is “thread-like” in two dimensions (see Figure 6.13), implying “sheet-like” in three dimensions; and the value of the parameter which governs how the rate of dissipation scales with eddy size which, likewise, can be extracted from analysis of the numerical simulation. In contrast, it is unnecessary to specify whether the cascade is Kolmogorov or Iroshnikov-Kraichnan in character; both are subsumed within a single statistical description of the simulation results. This represents a useful step towards a unified description of MHD turbulence in two and three dimensions.



**Figure 6.13:** A numerical simulation of driven two-dimensional MHD turbulence incorporating resistive and viscous dissipation. The geometry of the dissipating structures, which is “thread-like” in two dimensions, implies it is “sheet-like” in three dimensions

### **C Exact Two-body Bound States with Coulomb Repulsion in a Periodic Potential**

In collaboration with the Institute of Fusion Studies, Texas, US, an elementary quantum mechanical calculation is used to show that two particles interacting via a short range repulsive force in an external periodic potential can form a bound state. In the centre of mass system the spatial wave function in the relative distance between the particles is square integrable and corresponds to a discrete energy. For instance, a combination of short-range (i.e. screened) binary

Coulomb interactions and the periodic potential provided by the stationary ions can create a two-electron bound state in a crystalline solid. The phenomenon delineated here is universal in the sense that, under appropriate conditions, bound states are possible, independent of the nature of the particles and/or the mechanism by which the external periodic potential is engineered (e.g. such as those created by suitable laser fields in cold-ion traps). This generic wave mechanical result may explain recent experimental results presenting evidence of such bound pair states in solids and photonic lattices. It has many other potentially interesting consequences even for classical interacting wave systems (e.g. solitons) propagating in a periodic background. This result of wave mechanics and interference is remarkable in that two repulsively interacting particles cannot form a bound state when moving in vacuum. Two non-interacting particles moving in a periodic external potential can only ever form uncorrelated two-particle Bloch states and yet when both physical conditions are present they can move as a "bound pair".

This result, a characteristic of the wave nature of matter, does not apply to classical particles. Classical waves, on the other hand, do indeed duplicate this remarkable behaviour of quantum particles; well-defined bound states (called "Gap modes") of the Alfvén waves emerge in an effective repulsive potential embedded in a periodic potential created by the toroidal magnetic field geometry in tokamak plasmas. Nonlinearly interacting wave motions in a periodic external background (due to magnetic geometries or rotation) are also of great interest in plasmas (drift waves) and fluids (Rossby waves).

## **6.2.6 FACILITIES**

### **A Computing Facilities**

The parallel computing facilities continue to be improved. It is proposed to approximately double the capacity of the Myrinet based machine, Columbus. Culham's original cluster, Aethelwulf, is also being updated by replacing a third of its oldest processors by 64-bit X2-Athlon nodes and upgrading the networking to Gigabit Ethernet. This will enable a wider range of jobs, covering both plasma and materials (Chapter 7) simulations, to be run that require greater memory and/or faster communication between processes.

### **B Library**

The Culham Library is the main repository of plasma physics and fusion literature in the UK. This collection exists to provide a site wide resource for UKAEA fusion scientists and EFDA JET secondees. This unique assembly of monographs, text-books, serials, conference proceedings, technical reports, computer data files (subscription-based online databases), software and videotapes, covers a wide area. Astrophysics, condensed matter physics, theoretical nonlinear physics and relativity, atomic, molecular and optical physics, and fluid and plasma physics are just a few of the subject fields. The collection

is developed in response to the research programmes of Culham – for example in recent years, there has been a greater emphasis on materials research, and library purchases reflect this growth.

A wide range of electronic information services, including electronic journals and online databases such as the Web of Science, British Standards Institute (BSI) and HIS (formerly Technical Indexes), for construction/engineering material, can be accessed from the Library web pages.

### 6.3 FUTURE PROGRAMME

In the coming year we plan to contribute broadly to theoretical modelling of ITER-like and spherical tokamaks, involving collaborations within the EU, US and Russia, while continuing to strengthen links with UK Universities. The range of topics and activities envisaged is listed below:

- Support the Integrated Tokamak Modelling (ITM) Task Force, including providing a Deputy Leader and Project Leaders, and contribute to projects such as equilibrium reconstruction, fast particle physics and turbulence code benchmarking;
- Develop and implement the fully parallelised version of the CENTORI global two-fluid turbulence simulation code with demonstration applications to MAST and other tokamaks;
- Use the local gyro-kinetic code GS2 for modelling micro-instabilities in MAST, including the effect of rotation shear, seeking physics-based interpretations of the results;
- Enhance gyro-kinetic modelling capability for modelling, possibly based on the ORB5 code from CRPP Lausanne, to allow for the large orbit widths and strong profile effects in MAST;
- Develop the toroidal linear layer theory of tearing modes at ITER-like collisionalities, including large ion Larmor orbits, and apply to sawteeth and neoclassical tearing modes (NTMs);
- Refine theories of NTMs to understand the conditions for island growth and of Resistive Wall Modes (RWMs) to understand the damping phenomena associated with plasma rotation;
- Continue the modelling of the effect of tearing mode islands on fast particle confinement in spherical tokamak geometry with application to MAST;
- Model fast particle effects on sawteeth and fishbones in MAST and JET and other tokamaks;
- Model Toroidal Alfvén Eigenmodes (TAEs) and energetic particle modes (EPMs) and their nonlinear evolution and impact on fast particle confinement;

- Further develop Alfvén spectroscopy of tokamak plasma for diagnostic purposes using energetic particle driven Alfvén Eigenmodes;
- Establish peeling mode criteria for shaped cross sections, including X-points, comparing with numerical simulation results;
- Investigate the effect of equilibrium bootstrap current on the predictions of the peeling relaxation model for ELMs;
- Characterise quantitatively edge plasma turbulence from probe measurements under different confining magnetic field configurations in MAST using advanced statistical methods;
- Support studies of the proposed MAST Upgrade and the potential for a Component Test Facility based on the spherical tokamak concept;
- Host and manage the ITPA Profile Database, aiming to have a new public release;
- Contribute to ITPA multi-machine studies of energy confinement in Hybrid plasmas;
- Implement the upgrade to the Columbus parallel cluster in order to double its processing capability.