6 Theory

6.1 INTRODUCTION

The Theory and Modelling Programme provides strong support to existing devices (e.g. MAST and JET) and to future burning plasma devices such as ITER (Chapter 8), a spherical tokamak component test facility (CTF) or DEMO (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, in both ITER-like and spherical tokamak devices:

a) Confinement and transport, with an emphasis on modelling the turbulence mechanisms that underlie the loss of energy in the tokamak;

b) The avoidance or mitigation of instabilities that can limit plasma pressure, heating and current, and hence plasma performance, or damage the device – this for examples includes studies of instabilities (Resistive Wall Modes) likely to limit performance in steady-state power plant scenarios;

c) The integrated plasma modelling required for developing steady state operational scenarios. This is a priority area for present and future development.

These topics are addressed by exploiting CCFE's traditional strengths in analytic theory, but also by its rapidly increasing capability in computational modelling. The latter benefits from resources provided through EPSRC, such as the high performance computer, HECTOR at Edinburgh, through a European computer (HPC-FF, Juelich, Germany), as well as investment in CCFE's own parallel computing facilities, such as Columbus. The programme also works in close contact with CCFE's experimental programmes on JET (Chapter 4) 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 Tokamak Modelling Task Force is given, particularly in the area of scenario modelling for ITER. The programme plays a leading part in Culham's 'outreach' to UK universities which includes both collaborative projects with university staff and supervision of a substantial number of PhD students on projects related to fusion.

Section 6.2 describes progress since the last Annual Report in the areas of plasma confinement (Section 6.2.1), plasma stability (Section 6.2.2) and integrated modelling (Section 6.2.3). There is also a section on the facilities that support the Theory and Modelling Programme: the parallel computer; Columbus; and the Culham Library (Section 6.2.4). Finally, Section 6.3 summarises the future programme.

6.2 PROGRESS DURING 2009/10

6.2.1 CONFINEMENT

In the tokamak the loss of energy from the discharge is known to be dominated by short scale length turbulent instabilities. This turbulence is generally studied using large computer simulation codes. These codes either treat the plasma like a fluid (such as in the CENTORI codes) or may treat more general distributions of ions/electrons using the *gyro-kinetic* approximation (such as in the GS2 or ORB5 codes).

A Global gyrokinetic modelling of MAST turbulence

Non-local turbulence effects are important especially in devices where the ratio of ion gyroradius to plasma size (ρ_i*) is large. Turbulence spreading arises beyond the region of direct instability, from the equilibrium profile variation. While the local gyrokinetic flux-tube approximation provides guidance on the linear microstability of ion temperature gradient (ITG) driven turbulence, in non-linear simulations of ITG turbulence at large ρ_i* only a global treatment of the plasma can give more insight into the transport mechanism.

Under a collaboration, including the University of Warwick, we have simulated a MAST discharge using the global gyrokinetic particle-in-cell (PIC) code ORB5. The linear growth rates of ITG modes match well with those obtained with the GYRO code. The non-linear simulations show how the radial heat flux due to ITG turbulence spreads from the linearly unstable region of *s*=0.7-0.8 (s≈normalised radius) to cover the plasma from *s*=0.5 to *s*=0.8 (Fig. 6.1). The stabilising effect of turbulence driven *zonal flows* after $t=1.5\text{x}10^4\Omega^{-1}$ is also obvious. The turbulence reaches steady state by $t=2.0\text{x}10^4\ \Omega^{-1}$.

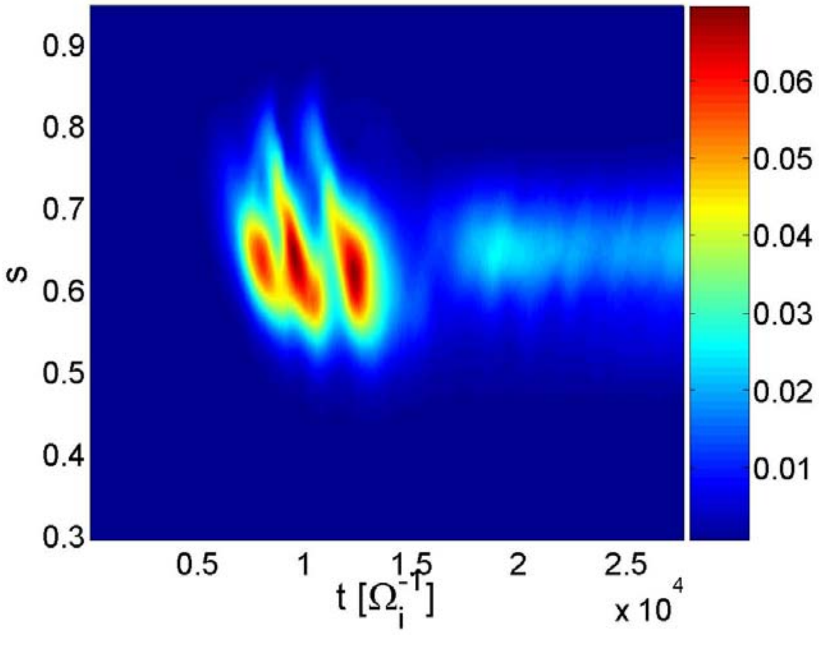


Figure 6.1: *Colour contours of the radial heat flux in MW/m^2 as a function of simulation time (normalised to ion gyroperiod Ω_i) and radius (s) in a non-linear ORB5 simulation of MAST discharge #22807 at 0.25s*

B Zonal flows

Inhomogeneous plasmas are naturally prone to turbulence and self-organization, which often lead to the formation of long lived, mesoscale structures. The complex interplay between these coherent structures and the turbulent fluctuations determines the primary mechanism causing transport of particles and energy in the plasma. A paradigm for this mechanism has been investigated - this is the formation of poloidally and toroidally symmetric band-like structures in the electric and poloidal magnetic field (usually referred to as 'zonal' perturbations) from a turbulent bath of drift waves. The study is based on an extensive numerical characterization of the problem (see Figure 6.2). The main result is the observation that low magnetic shear resonant surfaces play an important role in the creation of the zonal perturbations. In these locations, the magnitude of the zonal magnetic field can become significant and, at the same time, a pressure increase could trigger a feedback mechanism leading to transport barriers. These results may explain related observations on the triggering of internal regions of enhanced confinement in tokamaks such as JET.

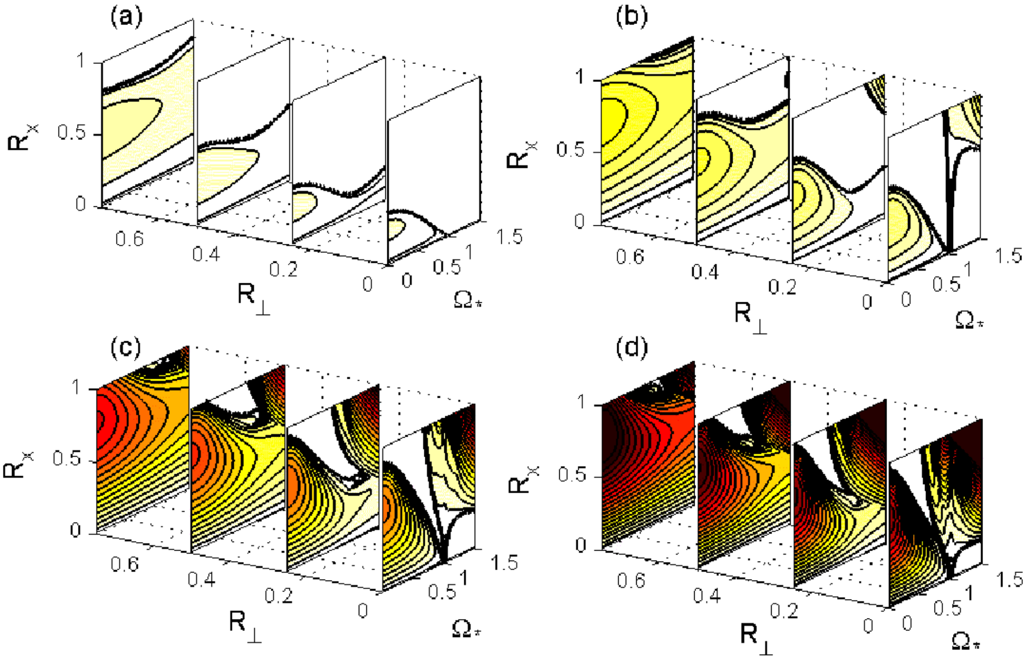


Figure 6.2: *Isocontours of the growth rate of the most unstable zonal flow/field for different plasma parameters and turbulence strength.* $R_\perp$ *and* R_x *are the typical perpendicular scale length of the turbulence and the radial scale of the zonal perturbation, respectively.* Ω^* *depends on plasma pressure multiplied by the ratio between the typical parallel and perpendicular scale of the turbulence. Going from figs (a) to (d) the strength of the turbulence increases and it can be seen that the region of strong zonal flows (dark contours) increases*

C CENTORI code

The CENTORI turbulence code treats the plasma as two fluids of electrons and ions, and evolves the electromagnetic fields together with the fluid flows and density and temperature characteristics of the plasma self-consistently, in a realistic tokamak geometry. During the past year, the code has taken advantage of time awarded to CCFE on EPSRC and European high performance computers to validate the physical model, and this has allowed the preliminary benchmarking of the code against a typical MAST discharge (Figure 6.3).

In addition, using CENTORI-generated electromagnetic fields and density and temperature distributions, the full-orbit particle code MCUEBIT has been used to track the distribution of test impurity particles, to provide both visual and quantitative descriptions of the rate at which these ions diffuse around the plasma. Figure 6.4 shows some typical test particle orbits.

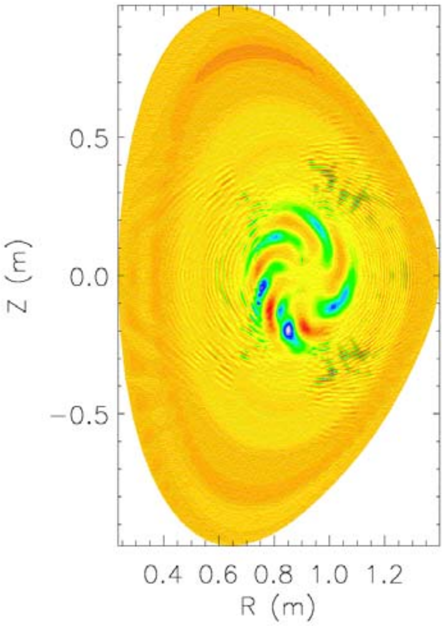


Figure 6.3: *Snapshot of the time-varying component of the electron density for MAST as calculated by CENTORI, with vortices and other features of turbulence clearly visible. Green / blue features in the plot are positive fluctuations, while red / orange features are negative*

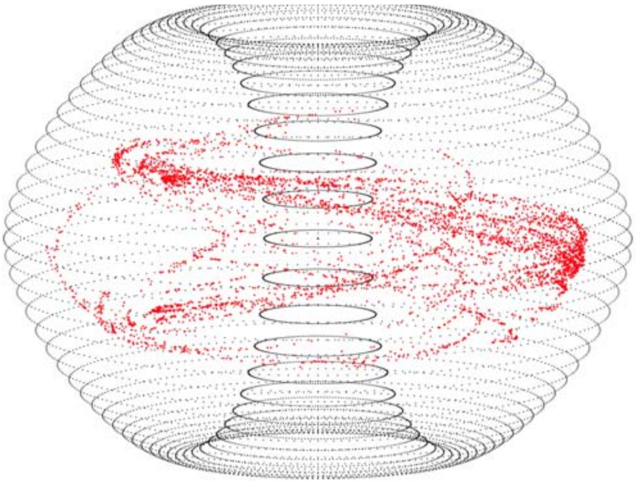


Figure 6.4: *Particle orbit trajectory (red) in the plasma. The grey lines show the plasma outer boundary*

D Plasma transport theory in non-inertial frames

Equations describing the nonrelativistic motion of a charged particle in an arbitrary non-inertial reference frame have been derived from first principles. It has been found that the equations of motion can be written in the same form in inertial and non-inertial frames, with the effective electric and magnetic fields in the latter modified by inertial effects associated with centrifugal and Coriolis accelerations. These modifications depend on the particle charge-to-mass ratio, and the vorticity, specific kinetic energy, and compressibility of the frame flow.

The Newton–Lorentz, Vlasov, and Fokker–Planck equations in such a frame have been derived. Reduced models, such as those embodied in the gyro-kinetic, drift-kinetic, and fluid equations can be obtained from these equations in the appropriate limits, using standard averaging procedures. The use of general non-inertial frames enables one in principle to formulate gyro-kinetic theory under circumstances, such as toroidal rotation at the speed of sound in tokamak plasmas, in which the usual assumptions of this theory are not applicable in the laboratory frame. The general analysis could also be applied to radially-accelerating plasmas, such as those in inertially-confined fusion experiment, or rapidly-rotating astrophysical plasmas, such as pulsar magnetospheres.

E The orbital dynamics and collisional transport of massive impurity ions in rotating plasmas

Impurity ions in tokamak plasmas are generally undesirable because they dilute the fusion fuel and, via radiative losses, reduce plasma energy confinement. Very massive impurity ions in rotating tokamak plasmas have mean toroidal velocities that can greatly exceed the thermal speed of those ions. In a joint project with a PhD student at the University of Glasgow, the effects of this ‘hypersonic’ rotation on particle orbits and collisional transport have been studied analytically and using test-particle simulations. Impurity ions of sufficiently high mass are deeply trapped by the centrifugal force in the outer region of the plasma, with a bounce period that is shorter than both the bounce period of magnetically-trapped ions and the collision time. The collisional random walk of the ions in this regime has been found to be higher than that of a non-rotating plasma. Irrespective of the collisionality regime, it has been found that the interaction of massive impurity ions with bulk ions leads to an outward advection that is proportional to the impurity ion mass (Figure 6.5). Due to modifications to the effective magnetic field arising from the Coriolis force, the increase in transport is greatest for relatively low charge states of massive impurity ions in plasmas rotating in the same direction as the plasma current. These results have potentially important implications for the retention of very massive, fusion-relevant impurities such as tungsten in rotating tokamak plasmas.

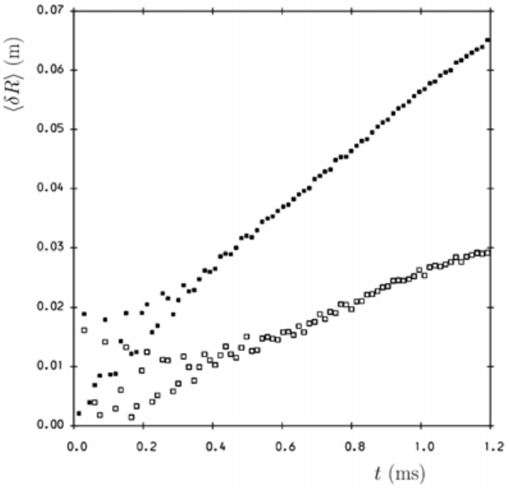


Figure 6.5: *Mean radial excursion versus time of tungsten ions (W^{20+}: solid squares, upper curve) and molybdenum ions (Mo^{10+}: open squares, lower curve), computed for a MAST-like plasma equilibrium using a test-particle orbit-following code. The slopes of ‹δR› versus t indicate outward advection velocities of approximately 50kms^{-1} for tungsten and 25 kms^{-1} for molybdenum*

F The TRINITY code

To model the transport of energy and particles in fusion devices, one must include the effect of rapid, small-scale plasma turbulence on the more slowly evolving large-scale temperature and density profiles. Resolved first-principles simulations are very challenging because of the range of time and length scales involved, and because the turbulence evolves in a five-dimensional phase space. We (in collaboration with the University of Oxford and US collaborators) are developing a new approach using the open-source codes TRINITY and GS2 in which turbulence calculations from multiple nonlinear gyrokinetic flux tubes are coupled together via transport equations to obtain self-consistent large-scale plasma profiles for comparison with experiment. Results have been obtained for conventional tokamaks including JET, and simulations of MAST are also under way. A single such simulation requires around 10^6 core hours on a high-performance computer such as HECToR (EPSRC) or HPC-FF (European); this should be compared with (an impratical) 10^{14} core hours for an imagined simulation not taking advantage of the scale separations involved or the anisotropy of the turbulence.

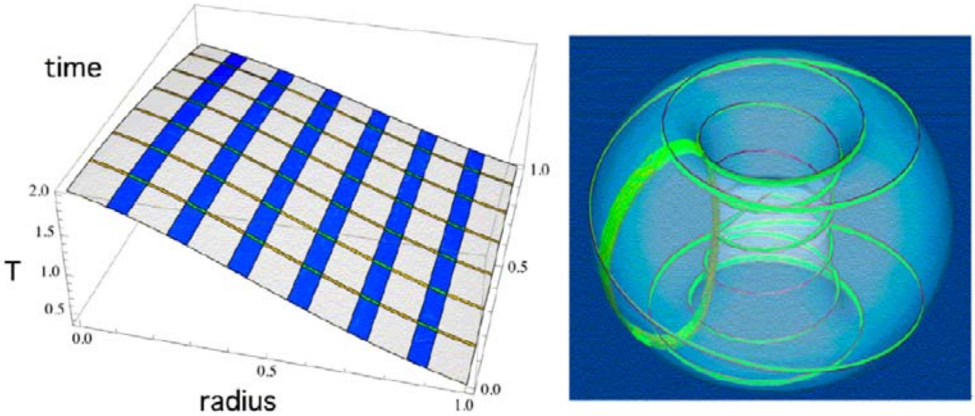


Figure 6.6: *Schematic (left) of multi-scale space-time grid used in TRINITY. Blue (vertical) and yellow (horizontal) regions represent radial and time domains respectively. Green (overlap) regions correspond to the reduced space-time domain used in TRINITY. Each of these is a GS2 flux tube (right) over which a fine mesh is used to calculate turbulent fluxes, and is also a grid point in the coarse mesh used to solve the transport equations*

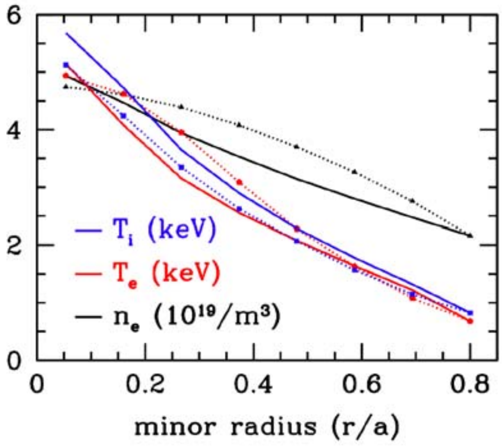


Figure 6.7 *Comparison of steady-state density and temperature profiles for JET shot 19649 inferred from experimental data by the TRANSP code (points and dotted lines) with those calculated by TRINITY and GS2 (solid lines). This shows reasonably good agreement between experiment and theory modelling with TRINITY*

G GS2 optimisation

It is important that the GS2 code run quickly with minimal use of computing resources, not only because the problem of simulating a five-dimensional, time dependent plasma even in the flux-tube approximation is very demanding, but also because of the increasing use of GS2 as a module forming part of the TRINITY global transport code (see sub-section F above). In a certain physical limit, which is of increasing interest, namely that of low magnetic shear, the algorithm used by GS2 becomes very inefficient. Work is therefore in hand to replace the present implicit algorithm used in GS2 with a different, explicit algorithm. As numerical analysis has developed considerably since GS2 was first written, the opportunity has been taken to consider new algorithms for the primary task of modelling advection, specifically Discontinuous Galerkin methods. Work carried out in collaboration with the High Level Support Team of HPC-FF, based at IPP Garching, has demonstrated the value of the new schemes in test cases, see Figure 6.8.

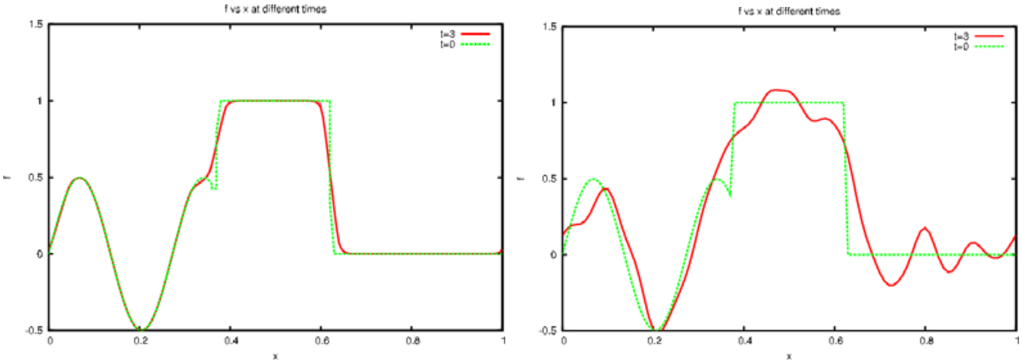


Figure 6.8: *Test case comparison of existing GS2 algorithm and candidate, replacement algorithm. The idea is that a perfect advection scheme will preserve the shape of the density distribution as it is translated through a length which is an exact multiple of the period shown. Hence the accuracy of a scheme may be inferred from the difference between the initial profile, drawn in green, and the profile produced by the algorithm indicated after advection through three periods, drawn in red. The left-hand figure shows results from one of the more optimal algorithms being investigated*

H Fast ion stabilization of ITG turbulence in JET hybrid scenario ITBs

A significant fraction of the ions can have energies well above that of the background plasma in tokamaks where auxiliary heating is employed. Neutral beam injection in MAST produces ions at a nominal energy above 60 keV while ICRH heating in JET can generate ions with energies up to 1 MeV. In future burning plasmas the generation of α-particles will bring about a large population of fast ions which will then interact with the thermal deuterium and tritium. Fast ions have several well known beneficial effects: they heat the plasma and inject sheared momentum in the system, but the question of how the fast ions affect the confinement properties of the plasma remains open. In other words it is important to understand how the presence of a population of fast ions can change locally the character of the plasma turbulence responsible for energy and particle losses. The idea that fast ions can provide a stabilizing mechanism for the micro turbulence and improve the energy confinement comes from the analysis of internal transport barrier formation in plasmas with monotonic safety factor (q) profiles. The JET hybrid scenario, sometimes called an ‘Improved H-mode’, is often characterized by a good confinement region at the plasma edge, as in a standard H-mode. Core confinement improvement is observed in the JET hybrid scenario and sometimes an internal transport barrier (ITB) appears.

The ITG stability in the region at the foot of the ITB in JET pulse #59137 has been investigated with the flux-tube gyrokinetic code GS2. By increasing the temperature of the fast ions the normalised plasma pressure gradient (α) increases and the growth rate of the electrostatic turbulence mode (Figure 6.9a) decreases. However a long wavelength electromagnetic mode is found to be unstable for fast ion temperatures, T_{fast}>50keV (Figure 6.9b). The impact of this long wavelength mode on the transport and the stability is still under investigation nevertheless the results of this analysis show that a population of fast ions such as that found in NBI + ICRH heated JET plasmas is sufficient to increase locally the plasma beta and its gradient around the critical value for stabilization of the electrostatic ITGs. The change in character of the turbulence brought about by the fast ions (from ITG to electromagnetic micro tearing modes) suggests that a corresponding change in the local transport properties of the plasma can be expected. This work will continue in order to provide quantitative predictions of the confinement in the presence of fast ions in MAST, JET and ITER.

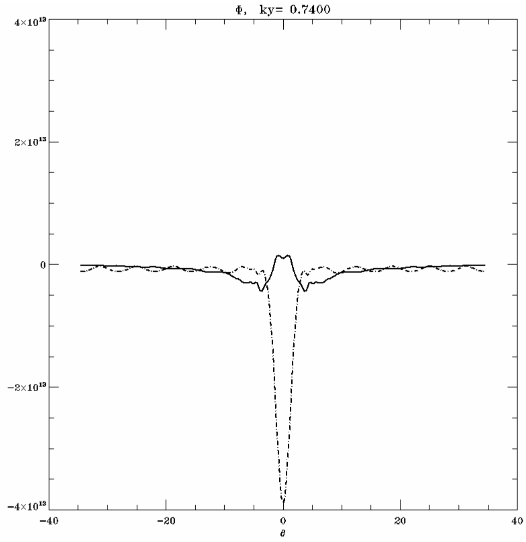


Figure 6.9 (a): *Amplitude of the electrostatic potential vs ballooning angle (along the flux tube, □) for JET 59137 plasma parameter in the electrostatic limit*

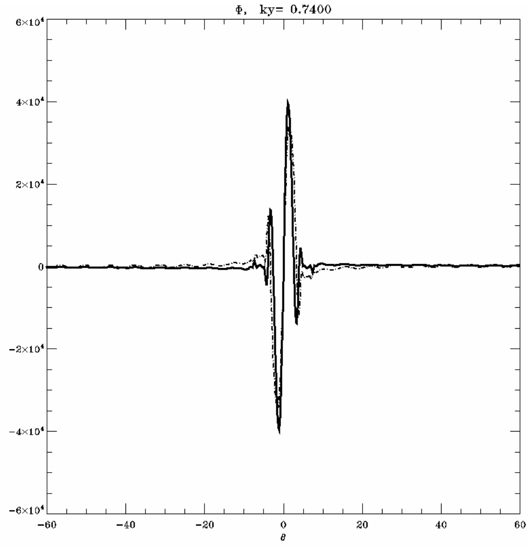


Figure 6.9 (b): *Amplitude of the electrostatic potential vs ballooning angle□ for JET 59137 when electromagnetic fluctuations are taken into account*

I Gyrokinetic Simulations with Equilibrium Flow Shear

Variations of equilibrium flow with radius in the plasma (*flow shear*) strongly influence the amplitude of turbulence and the corresponding level of anomalous plasma transport. Turbulence suppression ensues when the perpendicular flow shear parameter $\gamma_E = dV_\perp/dr$ approaches the maximum linear growth rate γ_{max}. Equilibrium flows that approach the sound speed in tokamaks are toroidal, and sheared toroidal flows have components that are both perpendicular and parallel to the magnetic field. Sheared perpendicular flows act to suppress turbulence, while parallel flow shear generates further turbulence. With toroidal flows the parallel flow shear is given by $U_{\|}' \sim qR/r\ \gamma_E$. Figure 6.10 gives results from the gyrokinetic codes GS2 and GKW, that show the influence of flow shear for large aspect ratio model equilibria with $qR/r \sim B_\phi/B_\theta$ = 7.7 and 12. The suppression of turbulence is seen to be favoured at low values of the geometry factor $qR/r \sim B_\phi/B_\theta$, which arise naturally in spherical tokamaks.

Equilibrium flow shear at mid-radius in MAST is often sufficient to suppress ion temperature gradient (ITG) driven turbulence, but not shorter wavelength electron temperature gradient (ETG) driven modes. Linear suppression of ITG instabilities in MAST, allows nonlinear gyrokinetic simulations of ETG turbulence to use the local flux-tube domain used in the GS2 code. Contours of the electrostatic potential are shown in Figure 6.11 at the intersection between the flux-tube and the outboard mid-plane, for an artificially enhanced level of flow shear $\gamma_E = 0.5\ \gamma_{max}$. Without flow shear the ETG turbulent eddies would be radial in this plane, but the eddies become tilted at this high level of flow shear. This level of flow shear only modestly reduces the electron heat flux from a value that is comparable with experiment.

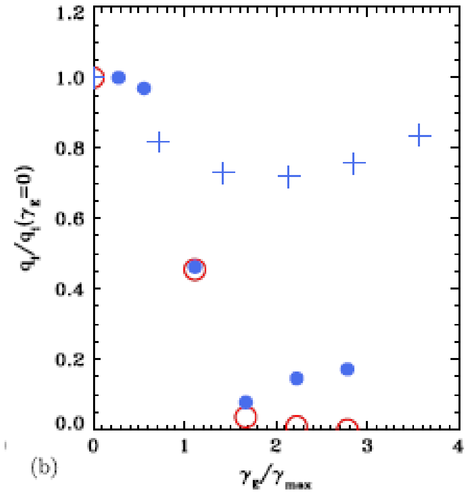


Figure 6.10: *Ratio of saturated ion heat flux, q_i to that with $\gamma_E = 0$ is plotted versus γ_E/γ_{max}. Red open and blue filled circles respectively show GS2 results for the large aspect ratio CYCLONE equilibrium (qR/r= 7.7) with and without the parallel component of flow shear. GKW results with both perpendicular and parallel flow shear are shown as blue crosses for a similar equilibrium with lower poloidal field and higher q (qR/r= 12)*

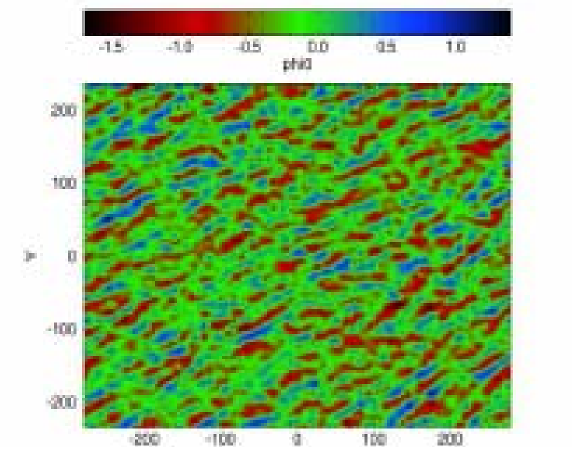


Figure 6.11: *Contour plot of the electrostatic potential at the intersection of the flux-tube with the outboard midplane, from a simulation of ETG turbulence with artificially enhanced flow shear with $\gamma_E = 0.5\ \gamma_{max}$.*

J Statistical properties of edge turbulence

Within the European fusion programme, a range of toroidal magnetic confinement concepts are being pursued with modern facilities including: the large conventional aspect ratio tokamak, represented by JET and ASDEX-U, and in the future ITER; the spherical tokamak, represented by MAST; and the stellarator, such as the Wendelstein 7-X facility under construction. Physical understanding of key plasma processes is greatly assisted by identifying and studying features that are generic to toroidal magnetic confinement. Such features would arise in all three confinement systems, and would display universal characteristics; for example, their statistical properties, when rescaled with respect to the size of the device and other key bulk parameters, would be the same. Comparison between data from spherical tokamaks and from stellarators is potentially of high value because it enables one to 'triangulate' with respect to the large conventional aspect ratio tokamak. A collaboration in this field between Warwick University, CCFE, and Japan's National Institute for Fusion Science – home of the world's leading operational stellarator, the Large Helical Device (LHD) – has recently borne fruit. The scaling properties of edge fluctuations in LHD, have been studied using state-of-art nonlinear time-series analysis techniques previously applied to MAST (see last year's Annual Report). This sheds light on shared, and different, physical behaviour at two levels. There is a broad question: to what extent are the measured statistical properties similar? And there is a more technical question: given that the stellarator edge magnetic structure encompasses both regular and stochastic field line regions, do these affect local turbulence measurements and do they relate to spherical tokamak scenarios where the edge magnetic field is deliberately stochasticised? Importantly, experiments involving the latter process are under way in MAST. This project has involved an extended working visit to LHD by a Warwick PhD student supported by an EPRSC-CCFE CASE grant, and shorter visits by both his Culham and Warwick joint supervisors.

6.2.2 PLASMA STABILITY

A MHD stability in rotating tokamak plasmas

Modern-day plasmas heated by neutral beam injection (NBI) can rotate at a significant fraction of the Alfvén speed. It has been shown that such strong rotation can ameliorate or suppress many magnetohydrodynamic (MHD) instabilities, resulting in significantly improved plasma performance. Consequently it is important to be able to model this stabilisation in order to optimise plasma operational scenarios and make predictions for ITER and other next-step devices. The effect of toroidal rotation on one such MHD instability – the internal kink mode – has been studied by including the centrifugal effects of toroidal plasma rotation upon the equilibrium, and also inconsistently when the equilibrium is treated as static. The sensitivity of the stability of the ideal n=1 internal kink mode to variations in the plasma profiles has been analysed both analytically and numerically for rotating tokamak plasmas. The change in plasma stability due to rotation is partially (consistent equilibrium) or wholly (inconsistent treatment) determined by the radial profiles of the plasma density and rotation velocity. It has been found that the stability of the internal kink mode is highly sensitive to variations in the plasma density and rotation profiles, as seen in Figure 6.12, and that the treatment of the equilibrium flow can significantly alter the results.

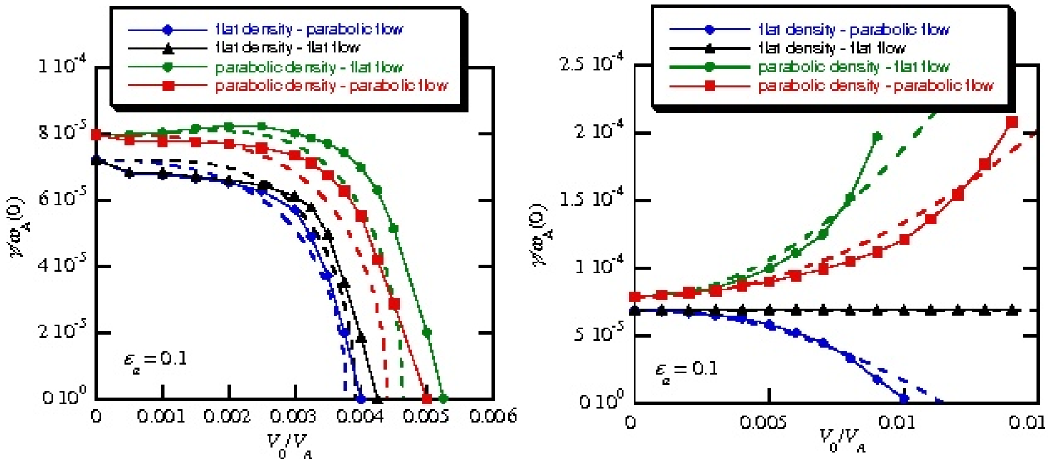


***Figure 6.12:** The growth rate of the kink mode with respect to rotation speed for different combinations of plasma profiles for an equilibrium including flow (left) and a static equilibrium (right) calculated analytically (dashed) and numerically (solid). It is evident that the mode stability is highly sensitive to these profiles and assumptions*

B Resistive wall modes (RWMs)

The fusion power available from a potential tokamak power plant scales approximately with the plasma pressure squared. However, increasing the plasma pressure is difficult because many instabilities are driven by it. If a resistive wall is fitted around the plasma and the plasma is rotated above a critical frequency (of order 1% of the Alfvénic rotation frequency) the maximum pressure can be increased by around 40%, thus doubling the fusion power available. The mechanism for this stabilization, which is observed experimentally, is not fully understood and so it is difficult to predict the rotation required in machines such as ITER and DEMO. A cylindrical fluid model of the resistive wall mode (RWM) has been developed with a single rational surface in the plasma. The plasma couples together the response at the rational surface to the resistive wall. In this model the RWM is stabilized by dissipation mechanisms at this rational surface, including resistivity and viscosity. It was found that this cylindrical model was not sufficient to explain the experimental results. An analytic model with toroidal effects included has now been developed. This model can reproduce features of a pressure-driven instability and has had some success in describing the RWM.

C Fast ion effects on RWMs

The stability of the resistive wall mode can also be significantly influenced by the kinetic effects resulting from the mode resonating with the precession motion of the plasma thermal particles or the fast ions. The fast ions in a fusion device come either from the fusion reaction (Helium-4 with 3.52MeV birth energy), or from the auxiliary heating (typically Hydrogen or Deuterium ions of a few hundreds keV). Numerical modelling for an ITER target plasma, in a full toroidal geometry, predicts that the RWM can be fully suppressed by the thermal+fast ion kinetic effects, in certain areas of parameter space. The fast ions, which are normally destabilising to other MHD modes, seem to be stabilising to the RWM in ITER plasmas. An example shows the computed stability boundary in the space of two key parameters – the toroidal plasma rotation frequency along the x-axis, and the plasma pressure factor along the y-axis as shown in Figure 6.13. The stable domain is accessed due to the kinetic stabilisation by both thermal and fast particles.

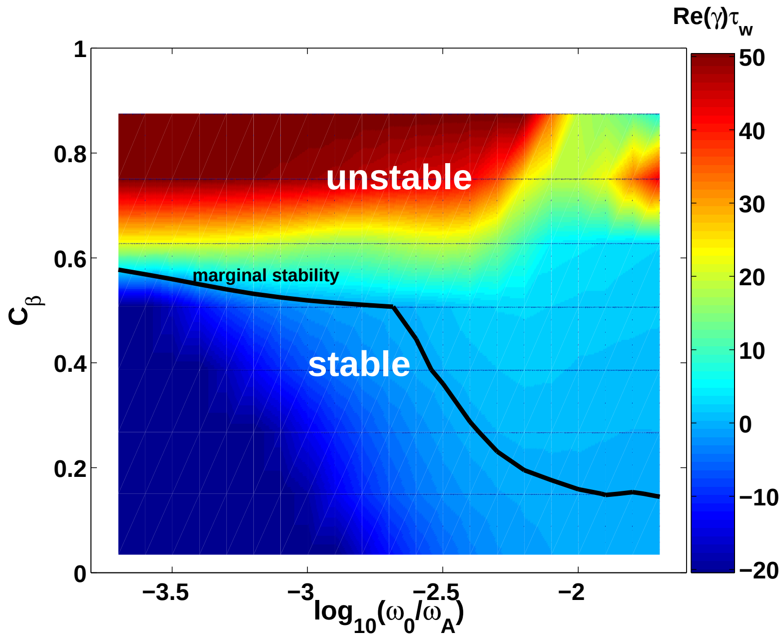
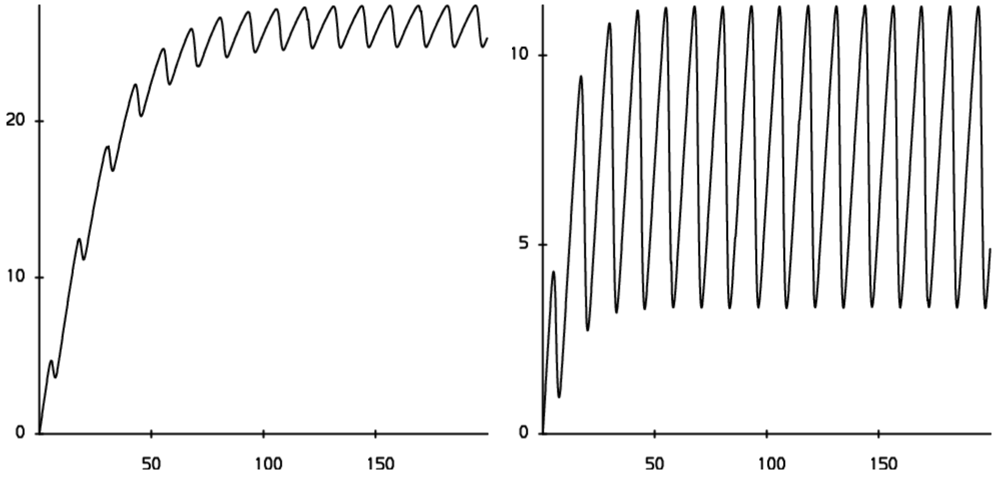


Figure 6.13: *Contours of RWM growth rate γ (normalised to the wall time constant, τ_W), these are plotted versus the degree of drive for the RWM (C_β) and the toroidal rotation (ω_0) normalised to the Alfven frequency (ω_A)*

D Nonlinear tokamak modelling using symmetry

The use of symmetry to constrain and simplify models of physical processes has been extensive and successful in areas such as elementary particle physics and atomic physics. Over the past two decades, it has proved its utility in the analysis of simple laboratory fluid dynamical models, such as the Taylor-Couette problem involving the rotation of a hollow cylinder of fluid (usually water). This and other recent successes have led to the further development of a branch of mathematics known as equivariant bifurcation theory (EBiT). Making plausible assumptions about experimental signals, in particular that they are produced by a system close to the instability of a small number of modes, EBiT rigorously describes the allowed qualitative behaviour subject to the constraints of symmetry. It also opens up the possibility of constructing more quantitative models, which could be important for prediction and control.

Work has concentrated on determining the symmetry group of the tokamak, in the case of magnetohydrodynamic (MHD) modes in a device of circular cross-section. This has enabled the construction of a very simple model, consisting of three coupled nonlinear ordinary differential equations, for the evolution of the sawtooth instability and its interaction with the main plasma column, see Figure 6.14. Possible application to other gross instabilities such as tearing modes, resistive wall modes and edge-localised modes has also been considered.



[Simple symmetric model.]

[More complicated model.]

Figure 6.14: *Output from simple models of sawtooth oscillations. The more complicated model (right figure) includes an extra feedback term*

E Layer theories for tearing modes

Key tokamak phenomena such as the ubiquitous sawteeth, plasma disruptions, neoclassical tearing mode islands and the penetration of external resonant magnetic perturbations are controlled by the physics of a resonant reconnecting layer at a rational *q*-surface. For a cool, resistive plasma one can consider addressing these problems using a global calculation. However, for high temperature plasma it is unrealistic to calculate the linear or non-linear stability of toroidal confinement systems using such a global method because of the vastly different scales of the reconnecting layer and the system size. A more natural approach is to match the solution of the eigenvalue equations in the 'external', ideal MHD region, characterised by the stability parameter, Δ' to a fully kinetic solution in the 'inner' tearing layer.

For plasma typical of JET or ITER the relevant physics must incorporate semi-collisional electron effects (i.e. allow collisional transport along the field line to compete with the mode frequency), trapped particle effects and finite ion orbits. An analytic formulation has been developed for the case when the ion Larmor radius is small compared to the semi-collisional layer width, but this is only appropriate at low magnetic shear, a situation that can perhaps be justified for the sawtooth instability. For the alternative case of large ion orbits we have derived a method, in the case of a cylindrical geometry, which captures the known stabilising effect on tearing modes of large ion orbits at low plasma pressure but can also be applied to more realistic higher pressures. In particular, at high pressure one finds that the use of a previously introduced Padé approximation to the complicated ion Larmor radius response can be fully justified. This approach has been used to obtain analytic dispersion relations governing the stability of both the tearing mode and internal kink mode resonant at *q*=1 that could play a part in the sawtooth instability.

F A comparison of ELM modelling with JET results on ELM mitigation

ELMs (Edge Localised Modes) are periodic instabilities of the plasma edge that transiently increase power loads to the material surfaces of the divertor. As such ELMs can cause erosion of the divertor target, and this is a significant issue for ITER. An ELM model initiated at CCFE (and further developed in collaboration with the University of Manchester, Jodrell Bank Centre for Astrophysics), assumes that an unstable ‘peeling’ mode (driven by the edge plasma current density) triggers a constrained energy minimising relaxation of the edge plasma, leading to a flattened current density and an associated negative edge skin current. This model predicts, with no fitted parameters, the radial extent of the post-ELM equilibrium that is produced by the relaxation. The model predictions are very sensitive to both the value of the edge current density and to a measure of the ‘distance’ of how far potential resonant surfaces are from the plasma/vacuum interface. Recent JET results concerning the effect of an externally applied external field (EFCC) on ELM amplitudes and frequencies have also revealed finely detailed structural dependence of the ELM frequency arising when the EFCC is applied, with respect to the edge safety factor q_a.

It is hypothesised that the EFCC eliminates the triggering effect of any peeling modes (instabilities thought to initiate ELMs) with the same toroidal mode number. Hence, the (m,n) peeling mode with n ≠ 1 having the next smallest predicted ELM width becomes the appropriate trigger (when an n=1 EFCC is applied). Thus, if the original ELM width were determined by a mode with toroidal mode number n=1, the width is then reduced. Taking the ELM repetition time to be the time taken for the post-ELM relaxed state to diffuse in a classical manner back to the initial state, a simple qualitative measure of the ELM frequency is given by $f \alpha 1/(\text{ELM width})^2$, allowing a prediction of the dependence of the ELM frequency with q_a (Fig 6.15). This simple model reproduces many qualitative aspects of the ‘multi-resonance’ effect observed recently on JET.

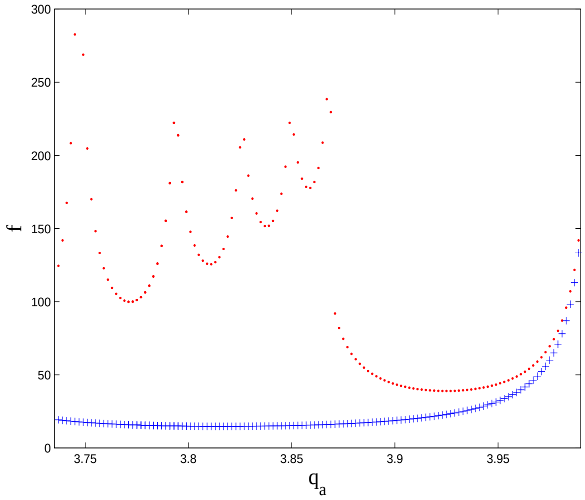


Figure 6.15: *Model predictions for ELM frequency (f) with (red) and without (blue) an n=1 applied EFCC field present, plotted against edge q value q_a. The EFCC produces higher ELM frequencies with ‘resonances’ qualitatively similar to those observed experimentally on JET*

6.2.3 INTEGRATED MODELLING

In Europe, ITER Scenario modelling is coordinated through the ITER Scenario Modelling (ISM) Group, which involves input from 11 European Fusion Associations. CCFE plays a key role in the ISM: having provided the ISM Leader until the end of 2009. A range of issues have been studied, including modelling of the current ramp phase and impurity penetration in ITER. The development of models for ITER is assisted by the database of profiles from existing tokamaks hosted by CCFE. A systematic development of a code suite for ITER is being undertaken by the European Integrated Tokamak Modelling (ITM) Task Force.

A Modelling of current ramp up phase in ITER

Predicting the current ramp up in ITER (the initial phase of all ITER operational scenarios immediately following the plasma breakdown) is important to ensure that the formation and maintenance of the current density profile is compatible with the vertical stability of the plasma column. A key issue is the avoidance of sawtooth crashes (large MHD events which increase the energy and particle losses) which can be triggered by strongly peaked current density profiles. The current profile diffusion is determined by electron temperature and therefore depends on thermal electron transport. Self-consistent simulations of temperature and current evolution have been performed for the baseline H-mode ITER scenario to estimate: the duration of the sawtooth-free period assuming different transport models. Two models, well validated against present experiments, have been used: a theoretical model, based on the quasi-linear approach to plasma turbulence; and an empirical transport model. The auxiliary heated current ramp up phase starting with the formation of the small circular plasma and finishing with the full-volume shaped plasma at 15MA of total plasma current, after 80s, was simulated.

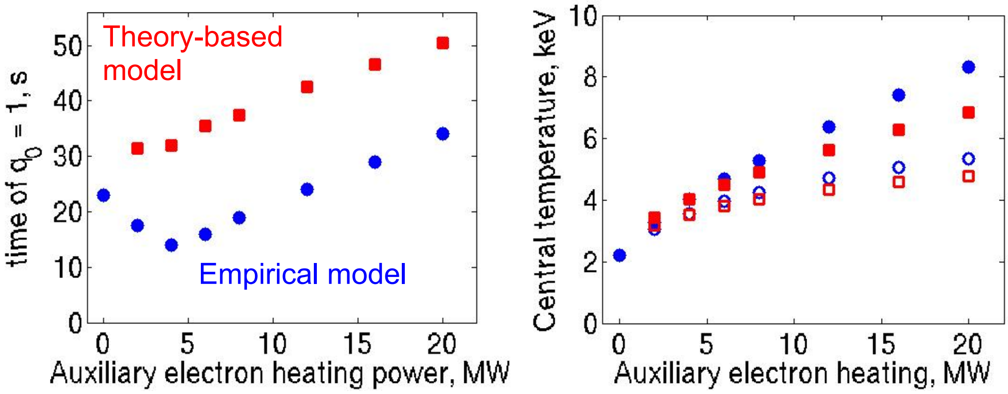


Figure 6.16: *Duration of the sawtooth-free phase (left) and electron (closed symbols) and ion (open symbols) temperature at the end of the current ramp up (right) obtained in simulations with an empirical (Bohm-gyroBohm, blue) and theory-based (Gyro-Landau Fluid 23, red) transport models*

The modelling predicts that the duration of the sawtooth-free phase is in the range 15-52s and strongly depends on the transport model and applied heating power (Figure 6.16). Although the central heating strongly delays the inward current diffusion maintaining a broad sawtooth-stable current density profile for a longer time, a non-monotonic dependence of the sawtooth-free period on heating power has been found with the empirical transport model. A reduction of the sawtooth-free phase with heating power has been obtained in low power plasmas with nearly flat voltage profile (close to steady-state), where a peaked electron temperature enhances the current density peaking due to the temperature-dependent current conductivity. As for the modelling results of the existing and past tokamaks JET, DIIID and TFTR, both models predict similar temperatures at moderate heating power in ITER, with somewhat larger differences at higher power. The other factors that increase the sawtooth-free phase are impurity peaking and the formation of the edge pedestal. The beneficial effects of these factors along with plasma heating should be taken into consideration when optimising the current ramp up phase in ITER.

B Modelling of impurity penetration in ITER

A series of predictive simulations were also carried out to investigate impurity penetration into the plasma core of ITER. For these simulations, the plasma boundary conditions were modelled using the plasma edge transport code

EDGE2D for a range of gas-puffing conditions and different fluxes of hydrogenic species through the plasma edge, to assess the effects of incomplete pellet penetration. Future steady-state fusion power plants will probably be fuelled by injection of frozen pellets of deuterium and tritium, and it is important to know how the plasma will react to this process. The simulations show that variations in the edge temperature of around 100eV, for a given pressure profile, can result in a reduction, or under some conditions reversal, of the outward neoclassical convective velocity of the impurities, allowing heavier impurities to be drawn through the edge transport barrier.

C International Profile Database

To facilitate the development and validation of transport models for ITER, a database of profile data from existing tokamaks has been developed over a number of years. This database has been hosted by CCFE for over a decade, though it is planned eventually to move it to the control of the ITER organisation.

D ITM work

A suite of integrated codes for modelling ITER is being developed by the European Integrated Tokamak Modelling (ITM) Task Force. During 2009 CCFE continued its effort in supporting and contributing to the work of the ITM Task Force. In response to the call for participation issued by EFDA in December 2009 the above commitment has been confirmed by CCFE and the contribution to the task force for 2010 has been increased to 4.15 professional person years. Contributions to the task force continued in the various areas of infrastructure support, linear and nonlinear MHD, disruptions, turbulence and fast particle physics and in the area of atomic, molecular and nuclear data. In 2009 CCFE contributed to the task force ITM two deputy project leaders (one in the area of linear and nonlinear MHD and one on the task of modelling ITER scenarios).

Key contributions by CCFE include:-

- In the area of infrastructure support (ISIP) where a detailed study on the issues of handling large data flows in complex KEPLER workflows has been completed. The study highlights several issues which will have to be evaluated by the TF in order to prepare the ground for future demanding simulations. The final report has been sent to the ITM task force leaders and has been circulated between the project leaders.
- A RWM (Resistive Wall Modes) module has been delivered and installed on the ITM Gateway computers. The module is now ready for inclusion in the European Transport Solver (ETS).
- An EF (error field model) analytic model has been developed for the inclusion of error field effects in the ETS transport code. The model has been coded in a Fortran module which has been delivered on the ITM gateway computer.
- Within the nonlinear MHD activities CCFE led the project of delivering a two fluid MHD code for the evaluation of the width and rotation of NTM islands. Existing codes solving numerically the selected analytical model (amongst which the CCFE code CUTIE) have been evaluated and tested. The results of this ongoing task have been presented to the ITM general meeting in Juelich, September 2009.
- The machine description and data mapping for MAST have been delivered, which will allow MAST data to be used in validating ITM codes.

- Another important contribution of CCFE (in collaboration with the University of Strathclyde) to the 2009 ITM activities has been the provision of AMNS (Atomic Molecular Nuclear Specialist) data to ITM code. CCFE has also provided the coordination of the data for each of the AMNS sub groups.

6.2.4 FACILITIES

A Computing

The in-house Culham parallel computing facility, Columbus, was upgraded in 2007 by adding 32 further nodes, each utilising two dual-core 64-bit Intel Xeon (Woodcrest) processors clocked at 3.0GHz and 8GB of memory Usage statistics show continued fairly heavy usage of these upgraded nodes (Figure 6.17).

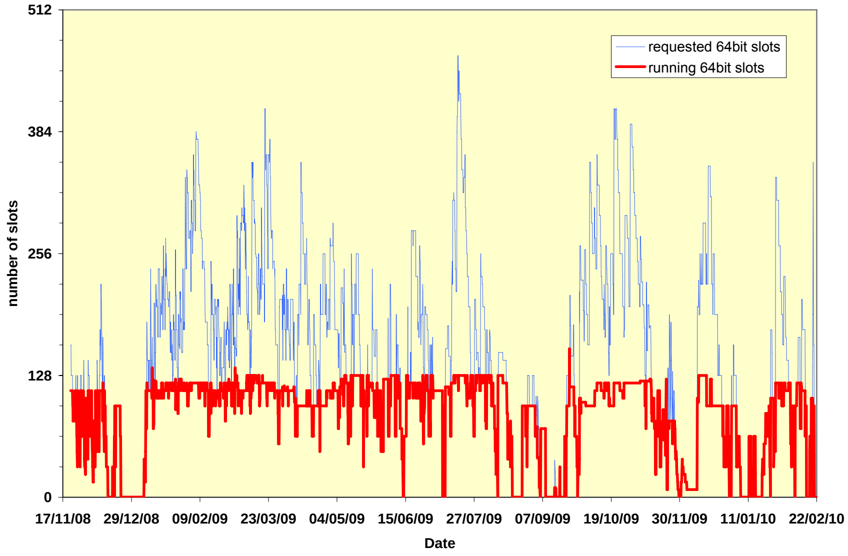


Figure 6.17: *Showing usage of the available 128 nodes with 64 bits (red curve) on Columbus and requests to use these nodes (blue curve) during the period November 2008 – February 2010. Requests above 128 nodes represent computer runs that are queued and waiting to execute*

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 CCFE staff and EFDA JET secondees. This unique assembly of monographs, text-books, serials, conference proceedings and technical reports, 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.

A range of electronic information services, including LIBRIS the library database, links to electronic journals and commercial databases such as ISI Web of Science, can be accessed via the Library web pages.

The library is also involved with the CCFE publications clearance procedure and is responsible for submission of scientific papers from CCFE authors to publishers worldwide, together with handling related copyright issues.

6.3 FUTURE PLANS

The main physics issues the theory and modelling programme will address in the next year include:

a) Turbulent driven losses. The work on energy confinement, which controls the size of fusion devices, will involve both computational and analytic theory. The computational work will use the 'leading edge' turbulence codes GS2 and ORB5, giving a comparison of local versus global effects for MAST, and involve the extensive use of large high performance computer systems. The TRINITY code formulation will continue to be developed and exploited. These turbulence studies are done in close collaboration with UK universities (Oxford, Warwick, and York);

b) We will continue to strongly develop our ITER scenario modelling capability. This will be achieved partly through active collaborative studies under the EU Integrated Tokamak Modelling Task Force. Also our hosting of the ITPA Profile Database for testing transport models will continue;

c) Consistent with the emphasis on edge physics in the JET and MAST-U programmes we will develop our capability to model edge processes and parameters. Also we will develop models of how edge instabilities, known as ELMs, can be ameliorated by applied non-axisymmetric fields. Work in this area will be done in collaboration with the Universities of York and Manchester;

d) Fast particle instabilities can be driven by energetic particle populations, created by either fusion reactions or plasma heating schemes, and lead to loss of these particles, which could degrade the heating power in ITER. MAST and JET provide excellent test-beds for modelling these phenomena and we will exploit this to model fast-particle instabilities that are observed to exhibit a range of non-linear behaviours. These studies will be performed in close collaboration with UK universities (York, Warwick and Oxford).