6 Theory

6.1 OVERVIEW

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), DEMO or a spherical tokamak Component Test Facility 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, in both ITER-like and spherical tokamak devices:

- confinement and transport, with an emphasis on modelling the turbulence mechanisms that underlie the loss of energy in the tokamak;
- 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;
- the integrated plasma modelling required for developing steady state operational scenarios. This is a priority for future development.

These topics are addressed by exploiting UKAEA Culham's traditional strengths in analytic theory, but also by its rapidly increasing capability in computational modelling. The latter benefits from EPSRC's high performance computers, such as HECTOR at Edinburgh (and also European supercomputer facilities), as well as investment in UKAEA's own parallel computing facilities, such as Columbus. The programme also works in close contact with UKAEA'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 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 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 are also sections on collaborations with UK universities (Section 6.2.4) and the facilities that support the Theory and Modelling Programme: the parallel computer; Columbus; and the Culham Library (Section 6.2.5). Finally, Section 6.3 summarises the future programme.

6.2 PROGRESS DURING 2008/09

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 code) or may treat more general distributions of ions/electrons using the *gyro-kinetic* approximation. Also these gyro-kinetic turbulence codes may treat local regions of the plasma (such as in the GS2 code, see below) or the whole plasma (such as in the ORB5 code). In the UK not only does Culham have significant capability in the area of turbulence modelling, but also UK universities (notably Oxford, Sheffield, Warwick and York) have a very strong capability in turbulence modelling and theory. Combined with the availability of MAST data as a stringent test of the turbulence models, this places the UK in a leading position in this area.

A Global turbulence simulations with ORB5 for MAST

ORB5 is a global gyrokinetic particle in cell code for simulating micro-turbulence in axisymmetric toroidal plasmas that was developed jointly in Germany at IPP-Garching and in Switzerland at EPFL (Lausanne). Global gyrokinetic simulations with ORB5 include the physics of radial variation in the plasma equilibrium, which may be significant in devices like MAST where the ion gyro-radius is relatively large. UKAEA is collaborating with the University of Warwick, IPP-Garching (Germany) and EPFL (Switzerland) to exploit ORB5 for the study of microturbulence in MAST. Studies of Ion Temperature Gradient (ITG) driven turbulence, with ORB5, show the ITG instability to be unstable in MAST, though plasma rotation effects (not yet included in these ORB5 simulations) may alter this picture (see next sub-section).

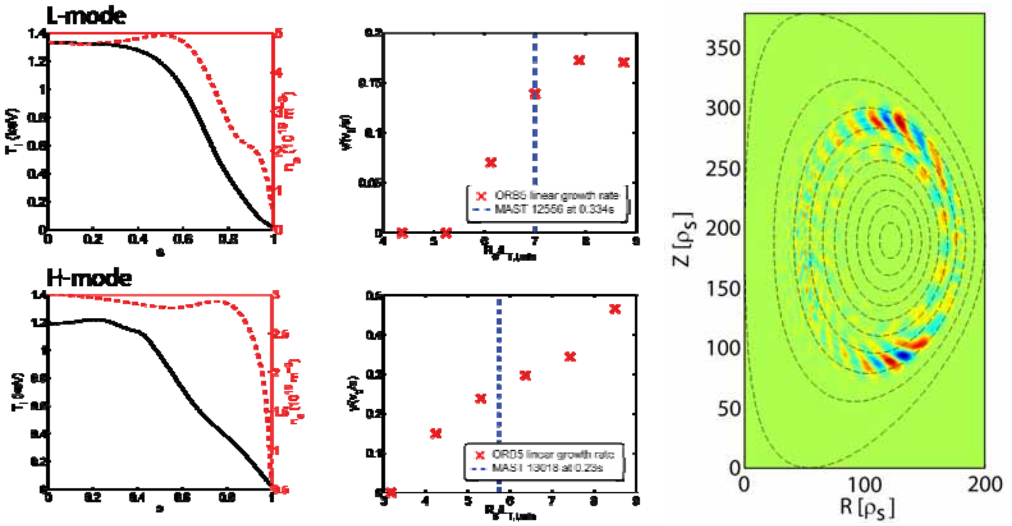

Figure 6.1: *Calculation with the ORB5 turbulence code for MAST cases. Calculations have been made for both low confinement (L-mode) and high confinement (H-mode) plasmas. The left hand plots show the plasma temperature (black) and density (red) profiles in these two confinement modes. The middle plots show how the ITG growth rate (*γ*) varies with the temperature gradient scale length (*L_T*) – in these plots the blue dashed line indicates the MAST value and it can be seen that the ITG is unstable (i.e.* $\gamma > 0$*). The right hand plot shows the electrostatic potential variation for an ITG mode in MAST*

B Effect of shear in plasma flow on plasma turbulence

Plasma flows are important in many present day tokamaks including MAST, and can be greatly enhanced by neutral beam injection. When the flow varies across the radius of the plasma, it is said to be sheared and when there is significant shearing of the flow on the scale length of the turbulent instabilities, it can inhibit the growth of the turbulence. This turbulence can either be ion or electron driven. Since the scale lengths for ion driven turbulence are much larger it is more likely to be suppressed by sheared flow, leaving the electron turbulence as dominant – this is thought to be frequently the case in MAST.

As reported in last year's Annual Report, GS2, a local flux-tube gyrokinetic solver, has been modified to include sheared equilibrium flows. Calculations for a model test case (CYCLONE) show that the flow shear to stabilise the ion turbulence decreases as the relative rate of magnetic twist of the field lines (*magnetic shear*) decreases (Figure 6.2). The fact that the magnetic shear tends to be relatively low in MAST, combined with the high flow shear that occurs, shows that the ion turbulence is likely to be suppressed. Computer time on an IBM BG/P machine in Paris (obtained through the DEISA computer consortium) has been used to perform nonlinear GS2 simulations including flow shear. These simulations have been carried out both for the CYCLONE benchmark equilibrium and for typical MAST conditions. Including the physics of equilibrium flow shear is very important for MAST, and these calculations are shedding light on how sheared equilibrium flows suppress turbulence.

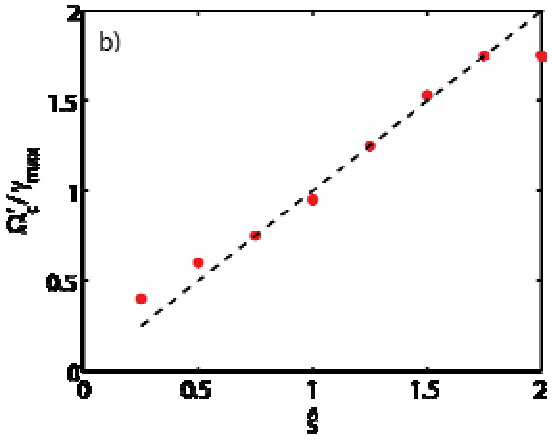

Figure 6.2: *Calculation with the GS2 turbulence code showing the flow shear(Ω'_c) to stabilise ion-scale turbulence decreases as the magnetic twist rate ($\hat{s}$) decreases. Here the flow shear is normalised to the maximum turbulence growth rate (γ_{max})*

C CENTORI code

Development work on the CENTORI plasma turbulence code has continued on several fronts as discussed here. CENTORI evolves the average plasma quantities and the fluctuating quantities separately. The average equilibrium quantities are recalculated on a much slower timescale (10s of microseconds) than the evolution time-step for the fluctuations (nanoseconds). This is physically reasonable since the equilibrium quantities will evolve much more slowly. It is also numerically more optimal because the equilibrium evolution is a relatively slow computational operation and not easy to optimise. The new code is ready for deployment on MAST and some initial physics runs have commenced (Figure 6.3).

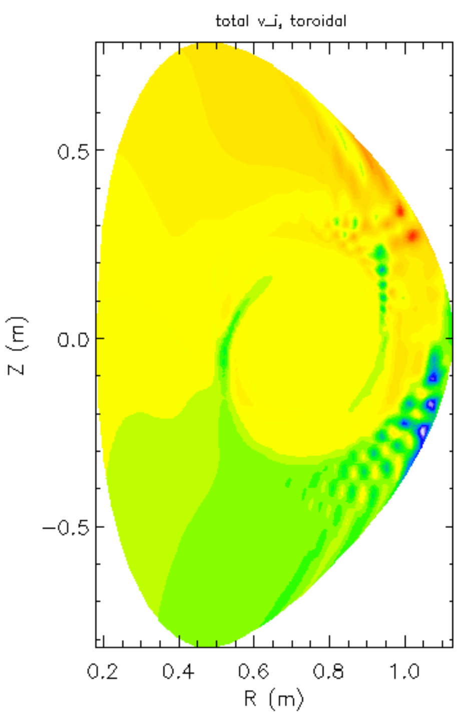

Figure 6.3: *Colour contour plot of toroidal flow showing an initial turbulence simulation for MAST with the CENTORI code (the red and blue regions are the areas of strongest flow)*

Optimisation of the CENTORI plasma turbulence code is an ongoing project with EPCC at the University of Edinburgh. In previous years the effort has been to efficiently spread the CENTORI calculations across many processors (*parallelisation*). This has led to CENTORI being able to be run on up to about 1,000 processors before the necessary communications between processors reduce the efficiency. In the past year the optimisation of CENTORI has concentrated on improving the efficiency of the computation on each processor. The amount of data held in memory has been reduced and some quantities are now recalculated as needed. Also a method known as vectorisation which reduces the number of CPU cycles per mathematical operation (such as addition) has been implemented. The vectorisation is dependent on the computer architecture and so to minimise changes when CENTORI is moved from one computer to another, the machine dependent vectorisation routines have been restricted to a small number of low level routines by rewriting the code. These developments are now in their final phase and a speed-up of the code by a factor of between three and ten is expected.

D Fast ion stabilization of ion-scale turbulence

A significant fraction of the ions can have energies well above that of the main fuel gas in tokamak-plasmas, when auxiliary heating is used. For example neutral beam injection in MAST produces ions with energies an order of magnitude above the background, while radio frequency heating of ions in JET leads to energies which are two orders of magnitude above the background. In future burning plasmas the generation of α-particles will bring about a large population of energetic ions. Fast ions have several well known beneficial effects: they heat the plasma and can cause sheared rotation in the system, but it remains to be determined if fast ions adversely affect the turbulence and thus the confinement properties of the working gas. This issue has been examined for JET hybrid scenario plasmas. Calculations with the GS2 code, including the magnetic response terms, show that instabilities with a short wavelength (of order the ion gyroradius) have a magnetic island forming parity and are stabilised for fast ion temperatures above about 150 keV. However instabilities with a wavelength of many gyro-radii become destabilised for ion energies above approximately 50 keV. The change in character of the turbulence brought about by the fast ions suggests that a corresponding change in the local transport properties of the plasma can be expected. In conclusion it cannot be ruled out that fast ions will affect the transport properties of future burning plasmas. This work is continuing in order to provide quantitative predictions of the confinement in the presence of fast ions in MAST, JET and ITER.

E Test-particle simulations of turbulent impurity transport

Impurity (non-hydrogenic) ions, including thermalised fusion alpha-particles (‘helium ash’), are generally undesirable in tokamaks because they dilute the fuel required for fusion reactions and, via the radiation that they produce, can also degrade plasma energy confinement. The theoretical description of the turbulent and collisional transport of such ions is simplified by the fact that they are generally present in only trace quantities, with the result that the effects of their transport on the bulk plasma can often be neglected.

With the assistance of an undergraduate from the University of Oxford, the two-fluid global electromagnetic turbulence code CUTIE has been combined with a full-orbit test-particle code (CUEBIT) to simulate directly the transport of trace impurity ions in tokamak plasmas. To test the scheme, the orbits of nickel ions were computed using static fields obtained from a CUTIE simulation of an H-mode plasma with parameters approximating those in MAST (Figure 6.4). For ions launched close to the plasma centre, the particle confinement time estimated from the loss rate is of the same order as the energy confinement time in the CUTIE simulation, as observed experimentally in JET and other tokamaks.

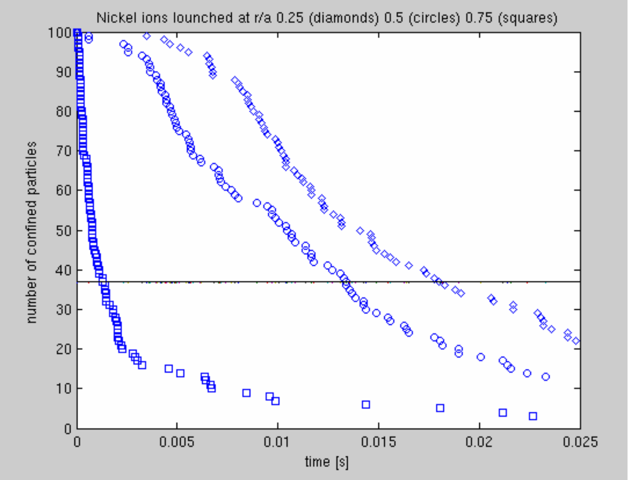

Figure 6.4: *Computed number of fully-ionised nickel ions remaining in the plasma versus time for three different launch positions. In each case the particle confinement time is indicated by the time at which the number of remaining particles drops below the black line*

F TGLF code

While direct first principles turbulence simulations are undoubtedly the way to achieve a fundamental understanding of energy confinement in tokamaks, they are very intensive in terms of computer time and presently impractical for the types of scans involved in designing new devices. As a consequence empirical descriptions of plasma energy losses are frequently used in exploring new operating scenarios. A significant improvement on this empirical approach can be achieved through a gyro-Landau-fluid model formulation, based on fitting to direct turbulence simulations (without any empirical adjustments), which greatly speeds up use of the first principles approach. Such an approach is feasible, in terms of computer time, for designing new scenarios. With US collaborators (from General Atomics and Princeton Plasma Physics Laboratory) UKAEA scientists are involved in validating the TGLF (Trapped Gyro Landau Fluid) code, which is based on the approach of fitting a reduced quasilinear model to direct first principles non-linear gyrokinetic turbulence results.

The TGLF formulation is still under development and has been tested against various experimental results including MAST (Figure 6.5).

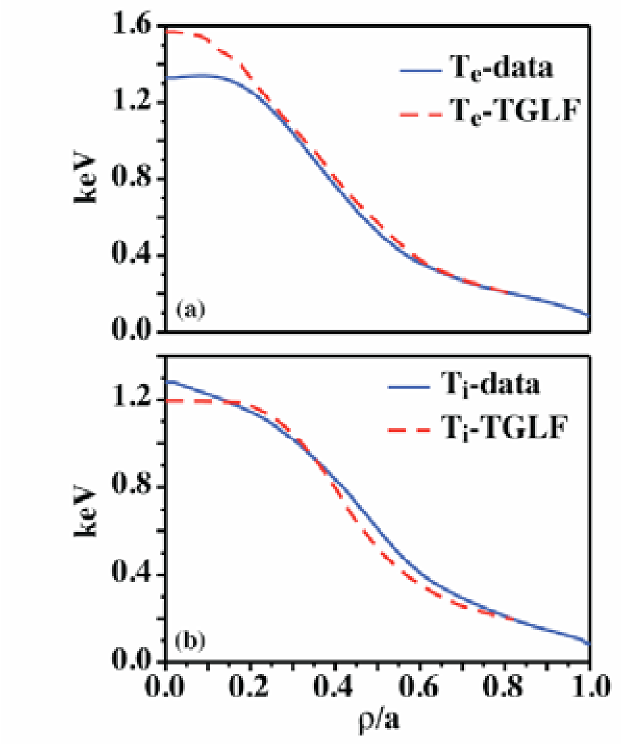

Figure 6.5: *Electron (T_e) and ion (T_i) temperature versus normalised radius from the centre to the edge of the plasma (ρ/a). The TGLF predicted profiles are comparable to the data from MAST measurements*

6.2.2 PLASMA STABILITY

A Resistive wall mode

In optimised plasma operating regimes instabilities driven by the plasma pressure can occur. These instabilities are often stabilised by the conducting metal wall surrounding the plasma, which constrains the instability by stopping the magnetic field growing at the wall. In practice the metal walls have a resistance (they are not super-conductors) and so the magnetic field from the plasma can slowly grow at the wall. This class of pressure driven instabilities, whose growth rates are governed by the wall time constant, are known as Resistive Wall Modes (RWMs) and are expected to set performance limits in regimes suited to steady-state power plant operation.

Experimental evidence suggests the RWM is stabilised by relative rotation between the plasma and the instability which is locked to the wall, and so almost static. This relative rotation allows resonances to occur between the instability and certain classes of the plasma ions which on average rotate with the plasma (see Figure 6.6).

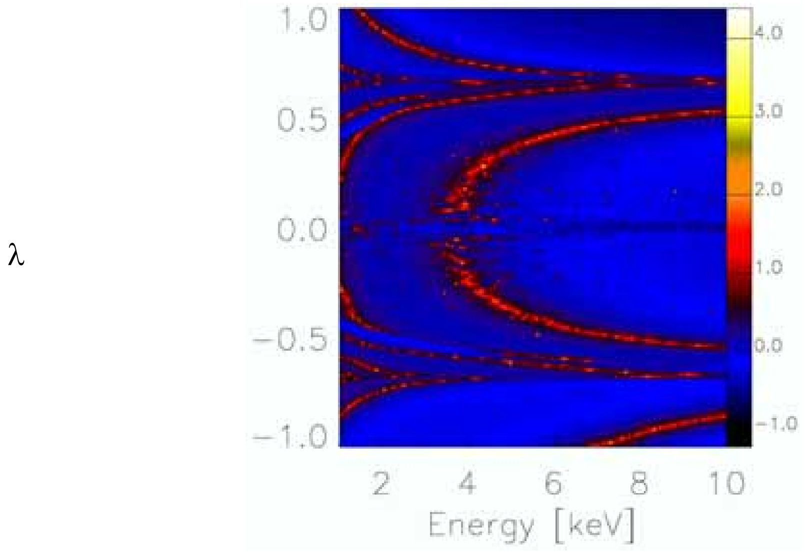

Figure 6.6: *Contour plot showing strength of resonant particle interaction as a function of ion energy and pitch angle (λ=ratio of ion speed parallel to magnetic field to its total speed) for JET parameters. In this case the plasma rotates at 8,000Hz. The different resonances (red regions) correspond to classes of particles that are trapped in the magnetic field and passing in the field*

Two approaches have been followed for studying the damping of the RWM due to resonances between the instabilities and ions. One approach, termed the *perturbative approach,* includes the effect of the ion resonances exactly by following ion trajectories in the instability magnetic field (obtained from a numerical calculation not including the resonances). This perturbative approach treats the resonant interaction precisely, but does not include the back-effect of the kinetic terms on the structure of the instability. In the alternate self consistent approach the particle interaction terms are included into the instability calculation directly. This self consistent approach includes the main resonances, but is subject to certain approximations.

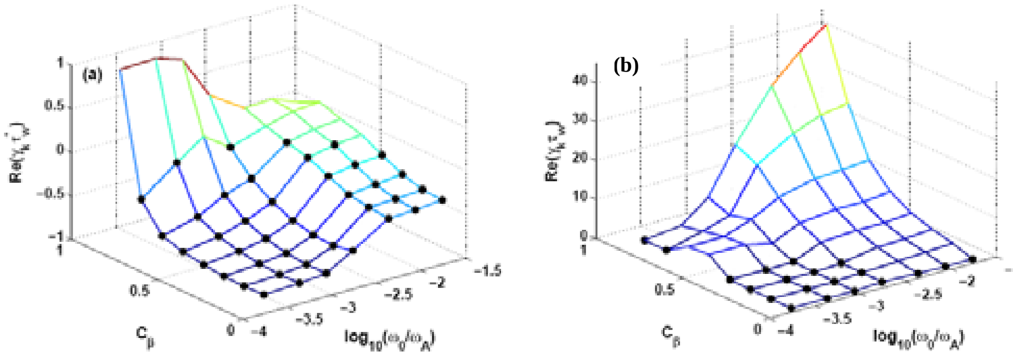

Figure 6.7: *RWM growth rate ($\gamma_k\tau_w$) as a function of normalised pressure (C_β) and normalised plasma rotation rate (ω_0/ω_A). The stable regions [Re($\gamma_k\tau_w$)<0] are indicated by black dots. In plot (a) the results are from the perturbative approach, whereas the self consistent results in (b) show a diminished domain of stability*

B The influence of the separatrix on edge-plasma stability

Most present tokamaks, including JET and MAST, and ITER in the future, have a diverted magnetic configuration. The outer boundary of the plasma (the *separatrix*) resembles a tear-drop shape, and beyond that boundary the magnetic field lines terminate on the divertor in the bottom of the tokamak. This arrangement is used not only to handle the high power exiting the plasma in the divertor region at the bottom of the device, but also because the tear-drop plasma boundary shape is associated with access to the higher energy confinement H-mode (the baseline ITER operating mode). In the H-mode periodic energy releases occur from ELMs, which are a major concern for ITER-scale devices because of the high transient power loads.

ELMs are thought to be associated with plasma stability in the separatrix region. Numerical studies have looked at this issue but the strong plasma shaping makes them challenging and likewise it also causes difficulties for analytic approaches to the problem. To overcome this difficulty the technique of conformal mappings (widely used for example in studying aerofoils) has been adapted to allow its application to plasma stability problems. This is accomplished in two steps, firstly mapping an equilibrium with a tear drop plasma boundary onto a circular shape (Figure 6.8). Secondly the conformal mapping technique is generalised beyond textbook presentations, by showing how the boundary conditions map under a transformation – something that greatly enhances the range of problems to which the technique may be applied. This subsequently allows the stability properties near the boundary to be determined with an analytic model. The results show a strong stabilising effect on peeling instabilities which are thought to be associated with ELMs. Further studies are now in progress to look at the effects of terms such as plasma resistivity on peeling stability in the separatrix region.

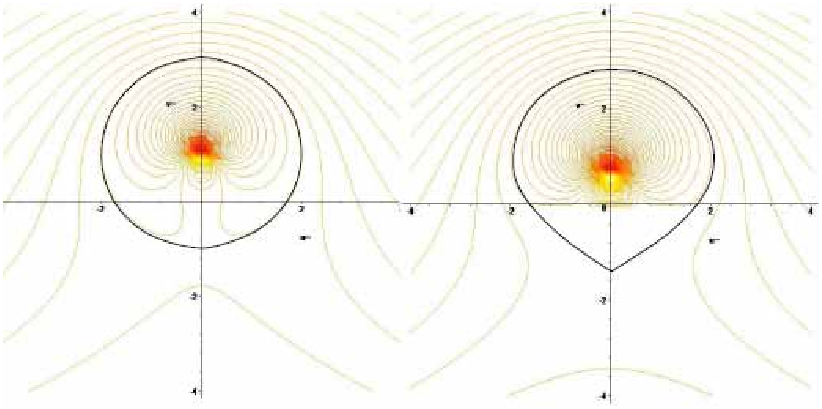

Figure 6.8: *Conformal mapping (a Karman-Trefftz transformation) maps the tear-drop shaped separatrix boundary (right hand plot) onto a circular boundary (left hand plot)*

C Magnetic reconnection

Internal instabilities, known as *sawteeth*, can lead to periodic collapses of the core temperature and density in tokamaks. Sawteeth have long been understood to be associated with large scale *kink* instabilities in the centre of the tokamak but such a model does not explain the rate at which the sawtooth instability develops. The flow associated with the kink instability is known to lead to the development of very localised current sheets in the plasma core. Recent computational studies with collaborators from Princeton University (U.S.), the University of Oxford and Imperial College have shown that these current sheets can be unstable to much smaller scale instabilities, forming what are termed *Plasmoid Chains* (Figure 6.9). These Plasmoid Chains can then be responsible for the faster development of the sawtooth event. This type of model also applies to astrophysical events such as solar flares.

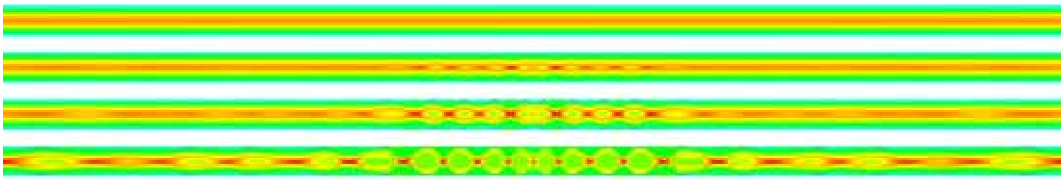

Figure 6.9: *Contour plots at four sequential times showing the high current density sheet and how it is unstable and develops Plasmoid Chains. The times from top to bottom are 0.63*τ_A*, 0.96* τ_A*, 1.03* τ_A*, 1.27* τ_A *where* τ_A *is the Alfvén time*

D Diamagnetic effects on error fields

Magnetic error fields arise from a range of sources including coil construction and alignment errors, current connections to the coils, magnetic material (iron) etc. It has long been known that these field errors can drive instabilities in the plasma. This places limits on the tolerable size of field errors and has led to ITER having a dedicated magnetic field error correction system. The theory of how magnetic error fields interact with rotating plasmas was developed over two decades ago at Culham and has been refined in several ways since then. Recent studies at Culham in collaboration with the Institute for Fusion Studies (University of Texas at Austin) have examined the effects of flows generated by plasma pressure gradients (so-called *diamagnetic flows*). Normally error fields drive localised reconnecting structures at particular radii in the plasma where the magnetic field lines are resonant. However in the presence of diamagnetic flows, for certain ranges of parameters, drift waves radiate energy away from the resonant surfaces leading to highly non-localised structures (Figure 6.10). It is likely that further refinements to the theory are needed to examine wave particle interaction effects that could damp the drift waves. However, this work shows an important direction for future studies; that diamagnetic effects must be taken into account in studying error field effects.

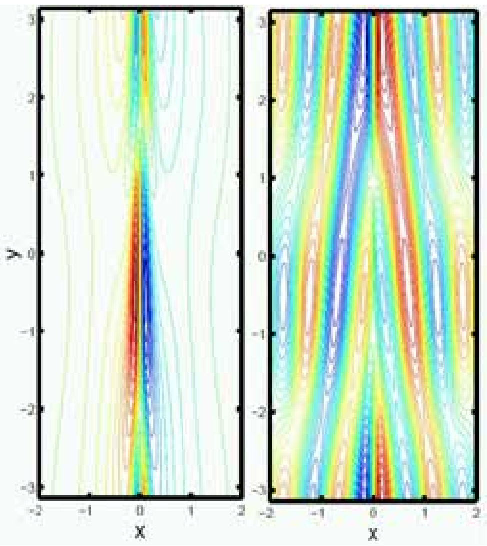

Figure 6.10: *Contour plots of vorticity. In the left hand figure the error field drives structures that are localised to the resonant surface (at x=0), whereas in the right hand plot the diamagnetic terms lead to highly non-local structures*

E Sawtooth control using off-axis neutral beam injection

Sawtooth oscillations occur in most modern-day plasmas and are expected in baseline operating scenarios in ITER. These instabilities result in a periodic collapse in the core density and temperature. Control of sawteeth remains a crucial issue for present and future devices. Since long period sawteeth are more likely to trigger deleterious neo-classical tearing modes, techniques have been developed to deliberately destabilise them, including off-axis neutral beam injection (NBI). Collaborative experiments to study fast ion effects on sawteeth have been conducted with the ASDEX Upgrade tokamak (at IPP-Garching, Germany). This tokamak is equipped with two tangential NBI sources, which inject fast ions towards the plasma mid-radius. The angle of injection has been varied in order to scan the fast ion deposition location. As the NBI was injected further off-axis the sawtooth period dropped, in good accordance with analytic theory. Drift kinetic modelling of these discharges qualitatively shows that the passing fast ions born outside the q=1 rational surface can destabilise the n=1 internal kink mode, thought to be related to the sawtooth instability. This effect can be enhanced by optimising the deposition of the off-axis beam energetic particle population with respect to the mode location. This has been successfully compared with similar experiments on MAST reported in Section 5.2.5.

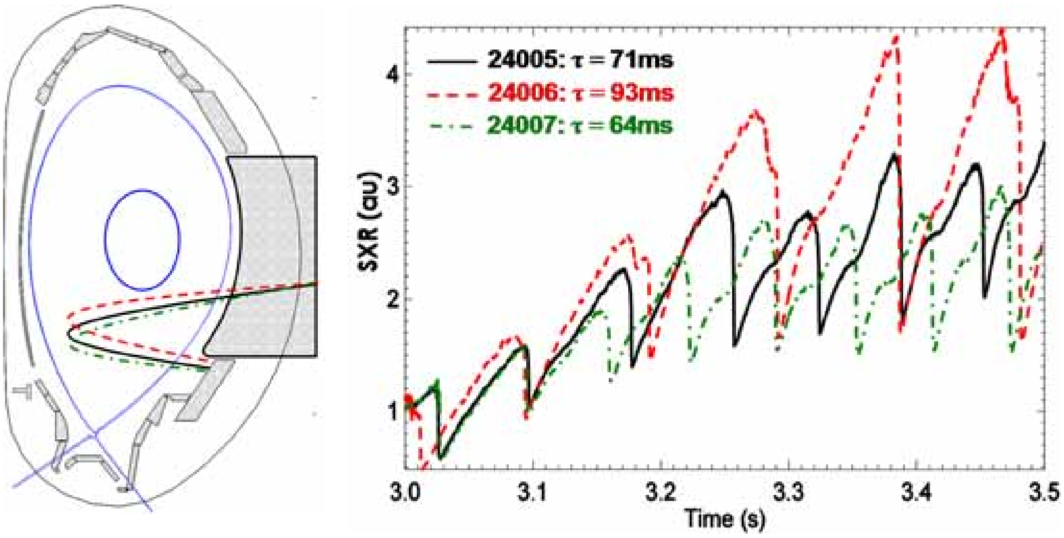

Figure 6.11: *Depositing neutral beam energetic ions further off-axis in ASDEX Upgrade plasmas can shorten the sawtooth period, making the sawteeth less likely to trigger neo-classical tearing modes*

6.2.3 INTEGRATED MODELLING

A Integrated Tokamak Modelling Task Force

During 2008 UKAEA Culham continued its effort in supporting and contributing to the work of the EFDA Task Force on Integrated Tokamak Modelling (ITM). At the last call for participation issued in December 2008 UKAEA has increased its commitment to the task force by bringing its contribution to over three man years for the year 2009. Contributions will continue in the various areas of plasma equilibrium, linear and nonlinear MHD, transport, turbulence and fast particle physics, while new manpower has been brought in the task force in the area of atomic, molecular and nuclear data (by Strathclyde University). The renewed commitment augments last year's effort when Culham contributions included:

- the release of the equilibrium reconstruction code EFIT++ with full user and programmer's documentation in a publicly accessible code repository hosted at Culham. EFIT++ has been successfully installed on the ITM Gateway (a computer system at Portici, Italy) – a task carried out in collaboration with the Italian fusion Association (ENEA). The Gateway version of EFIT++ has been tested to reconstruct various tokamak equilibria, amongst which are FTU (Italy), MAST and FAST (proposed Italian machine);

- the task of providing the ITM with the equilibrium toolbox ITM_FLUSH has been completed. The ITM_FLUSH routines are now available and can be installed on the Gateway;
- UKAEA has contributed to the modelling of resistive wall modes, neoclassical tearing modes (NTM) and the modelling of plasma disruptions through participation at various ITM meetings. The data structure for NTM modules has been contributed and the formalism for a new code to predict NTM threshold physics has been prepared in collaboration with the University of York;
- both edge physics codes ‘Edge2d/Nimbus/Eirene’ and ‘SOLPS’ have started to be installed on the Gateway platform. Further work on this task is contingent on data definitions resulting from the structures used in the transport codes. The first task will be to implement the numerical grid used to model the edge plasma geometry, which will require interfacing to grid generators as well as Edge2d/Nimbus/Eirene and SOLPSl;
- the two fluid global electromagnetic turbulence code CUTIE has been benchmarked against other turbulence codes gathered by the ITM and the results have been published (G. Falchetto (ENEA, Italy) et al, in the journal Plasma Physics and Controlled Fusion, 2008). Further comparative studies targeting electromagnetic turbulence issues will be agreed in due course;
- on the task force management side the task of providing EFDA with one ITM Deputy Task Force Leader was completed in July 2008. The management of nonlinear MHD modules has been carried out by UKAEA providing the Deputy Project Leader and an ITM Workshop on modelling of neoclassical tearing modes was organised at Culham Science Centre in Spring 2008.

In addition, under the ITM Task Force UKAEA has led and significantly contributed to the modelling of ITER scenarios – this is discussed in the next section.

B Predictive modelling of ITER plasma fuelling by pellets

UKAEA leads the ITER scenario modelling effort which involves input from many European Fusion Associations. A range of issues have been studied and many of these were reported at the IAEA Fusion Energy Conference in 2008.

One issue studied concerns the fuelling of the plasma with frozen fuel gas pellets – the primary proposed method for fuelling ITER plasmas. Fully predictive simulations of the plasma temperature and density behaviour for ITER Scenario 2, in the high confinement H-mode phase, have been carried out with the JETTO computer code. Frozen pellets composed of 50% Deuterium and 50% Tritium, and a volume of 125 mm^3, are assumed to be injected from the inner side of the plasma (so-called *high field side* (HFS) injection). HFS injection is known to aid penetration of the injected gas into the plasma core because of an outward drift of the ionised gas (which for pellet injection from the inner side is towards the plasma core).

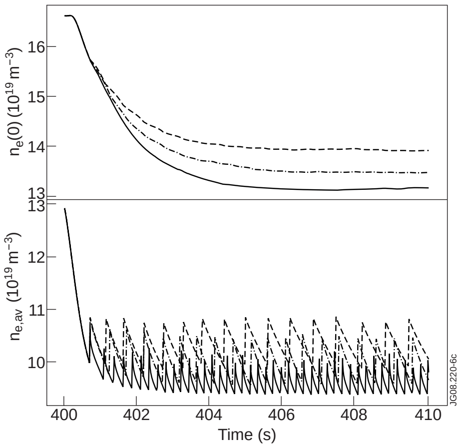

Figure 6.12: *Electron density in the plasma core (top) and average electron density (bottom); the different curves represent different assumptions on the pellet drift solid - 0% drift, chain - 50% drift, dash - 100% drift*

These simulations address the following issues: (i) what will be the main ion density profile in ITER with a shallow localised particle source; (ii) how much plasma performance, in general (and main ion confinement in particular), depends on how deep pellets drift into the plasma core; and (iii) how much particle throughput depends on pellet penetration (a large amount of gas exiting the plasma places heavy demands on gas pumping systems).

To examine the effect of the pellet drift, simulations applying 0%, 50% and 100% of the calculated pellet drift displacement have been made (Figure 6.12). The pellet injection rate is adjusted so in all cases the average plasma density stabilises at a constant level of 10^{20} m^{-3} ± 5%. Also the average temperature remains roughly constant once the discharge settles down, although the electron temperature and energy content are reduced by 15% in the case of 100% drift mainly because of core cooling by deeply penetrating pellets. The required pellet injection frequency stabilises at 5 Hz for 0%, 2 Hz for 50% and 1.5 Hz for 100% pellet drift and the average particle confinement time increases from 4 s for 0%, to 6 s for 50% and to 8 s for 100% pellet drift.

Due to the high ablation rate already at the very edge of the ITER plasma, the pellet simulations indicate that at the available injection speeds sufficient pellet particle penetration into the plasma and high particle confinement times can only be reached by HFS injection.

C International profile database

UKAEA led preparation and publication of the 2008 public release of the ITPA international multi-tokamak confinement profile database. The 2008 public release updates the first profile database released in 2000, and contains a wide variety of interesting discharges from many of the world's leading tokamak experiments along with a number of simulations of ITER reference scenarios. The database is described in a paper (led by UKAEA) which has appeared in the journal Nuclear Fusion. UKAEA continues to host and manage this database for the testing of transport models.

6.2.4 SYNERGIES WITH BASIC SCIENCE

A Alfvén wave acceleration of electrons

Due to two-fluid or kinetic effects the electric field associated with shear Alfvén waves can have a component E_z that is aligned with the ambient magnetic field; the acceleration of charged particles, in particular electrons, is then possible. Alfvén waves with finite E_z are described as inertial (rather than kinetic) when the ratio of plasma pressure to magnetic field pressure is less than the electron to ion mass ratio. Beta values as low as this can occur in the edge regions of tokamak plasmas and during the latter stages of tokamak disruptions, when the plasma temperature has dropped to a few electron volts. Energetic 'runaway' electrons, which are known to be produced in disruptions, can damage plasma-facing components on impact. The presence of Alfvén waves could contribute to the production of these runaway electrons. In collaboration with the University of Glasgow, the acceleration process has been studied in detail for a simple model case. The fraction of electrons accelerated has been calculated for the case of an initially Maxwellian electron population, and shown to depend critically on the perturbation amplitude, the initial electron temperature and the transverse length scale of the pulse. The velocity distribution of accelerated electrons is strongly peaked at a velocity somewhat greater than the Alfvén speed. In addition to having tokamak applications, processes of this type could contribute significantly to the production of energetic electrons in astrophysical plasmas.

B Statistical properties of edge turbulence

Within the European fusion programme, three toroidal magnetic confinement concepts are being pursued with modern facilities: 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 in Germany. 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 conventional aspect ratio tokamak. A collaboration in this field between Warwick University, UKAEA Culham, 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-UKAEA CASE grant, and shorter visits by both his UKAEA Culham and Warwick joint supervisors.

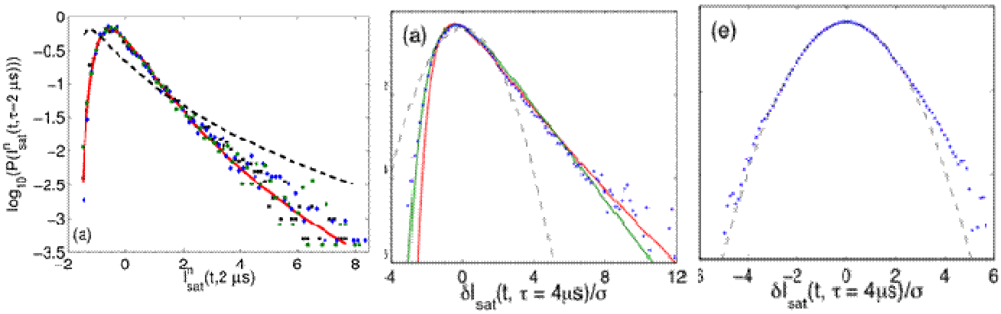

Figure 6.13: *(left) shows the probability density function for turbulent fluctuations sampled on two-microsecond timescales in the MAST edge plasma, and (centre figure) shows those sampled at a particular edge location in LHD on four-microsecond timescales. These are both well fitted by ‘extreme value’ distributions, whereas a simple Gaussian provides a good fit to the distribution in (right figure), which was obtained in LHD simultaneously with the central panel, at a location only a few millimetres away*

C Relaxation-based models of ELMs

In collaboration with the University of Manchester (Jodrell Bank Centre for Astrophysics), work has continued developing a model of Edge Localised Modes (ELMs) in tokamaks, based on relaxation theory. The underlying premise of the modelling is that the plasma is initially unstable to edge peeling mode instabilities and this unstable plasma then relaxes to a lower energy state (*Taylor relaxes*) radially inwards from the edge, until a stable point is reached. By examining the radial distance of relaxation for a given equilibrium profile, it is possible to calculate the predicted ELM width.

In order to explain ELM mitigation by the application of external magnetic field perturbations on tokamaks such as JET and MAST, we propose that the effect of a resonant perturbation from an external coil is to evolve the magnetic field into a non-axisymmetric equilibrium which is stable to perturbations of the corresponding mode number. For example, if a perturbation with a toroidal mode number, n = 1, is applied, the effect is to remove ELMs for which n = 1 modes were the marginally stable modes, resulting in larger ELMs disappearing for ranges of values of the edge q. Figure 6.14 shows that surviving ELMs in these ranges have much smaller width and higher toroidal wave number.

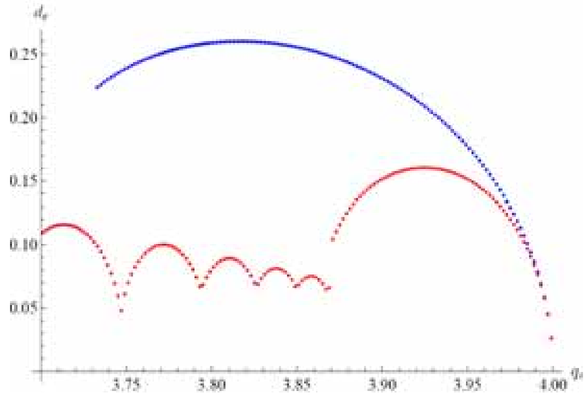

Figure 6.14: *Plot of ELM width against edge q. The blue curve represents ELM width predictions when the n=1 mode is present, and the red curves are the predictions when the n=1 is removed. The red curves give smaller ELM widths, with ‘resonances’ corresponding to a sequence of higher n numbers*

D The influence of magnetic islands on ITG mode

Heat and particle transport in tokamaks is widely believed to be a consequence of plasma turbulence. In many situations this is driven by the so-called ion temperature gradient (ITG) mode. The nature of this instability and its non-linear consequences has been studied extensively. However, these studies have generally assumed that the magnetic flux surfaces in a tokamak are a set of nested tori. There are situations when this is known to be a poor approximation, and magnetic islands form. Known examples include neoclassical tearing modes (NTMs), locked modes due to error fields and islands driven by forced magnetic reconnection, e.g. due to resonant magnetic perturbations applied to control ELMs. In addition to these examples, there is a range of physical mechanisms that can provide chains of very small magnetic islands, with a width comparable to the ion Larmor radius, at many rational surfaces. Such small islands would not be detectable with existing tokamak plasma diagnostics.

In a collaborative project with the University of York we have explored the consequences of very small magnetic islands for the linear stability of the ITG mode. The island has two effects: (1) a reduction of the plasma density and temperature gradients; and (2) a strong sheared flow in its vicinity. These are derived in a consistent model employing a sheared slab equilibrium, and the implications for ITG mode stability and structure assessed.

Figure 6.15 shows the 2-D ITG mode structure in the x-y plane. Plasma gradients are in the x-direction, and the magnetic island is oriented along the y-direction. The magnetic field points in the z-direction at the rational surface (x=0), but has an increasing y-component as x varies (i.e. shear). We find that the island has a stabilising effect on the ITG mode, primarily due to the suppression of the temperature gradient drive caused by the island. It is interesting to note that the island has the effect of localising the ITG mode in the y-direction, but that this localisation is not at the X-point of the island (where the gradient is strongest). To explore this, we have developed a simpler model equation; Figure 6.16 shows a comparison of the ITG eigenfunction in the y-direction along the rational surface (x=0). The simpler theory model indicates that it is the diamagnetic effects that break the symmetry and cause this shift of maximum amplitude away from y=0.

Islands are generally believed to be detrimental to plasma confinement. While this is certainly true for large islands, this work indicates that very small islands can suppress the ITG mode, and also limit the region of a flux surface that is affected by them. Thus the level of transport due to ITG mode turbulence is expected to be reduced in the presence of a magnetic island, with potential implications for triggering transport barriers, models for the NTM threshold and ELM suppression techniques based on resonant magnetic perturbations.

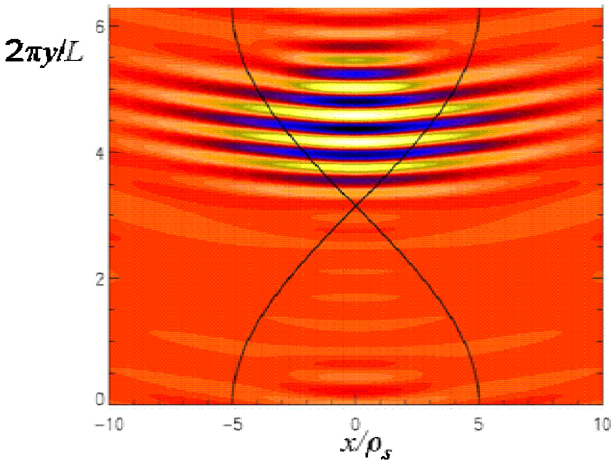

Figure 6.15: *Colour contour plot of the potential, φ for a linear ITG mode in the presence of a magnetic island (as indicated with the black curve). In the absence of a magnetic island, one predicts plane waves, evenly distributed in the y direction. The density and temperature gradients peak at the X-point and are close to zero at the island O-point*

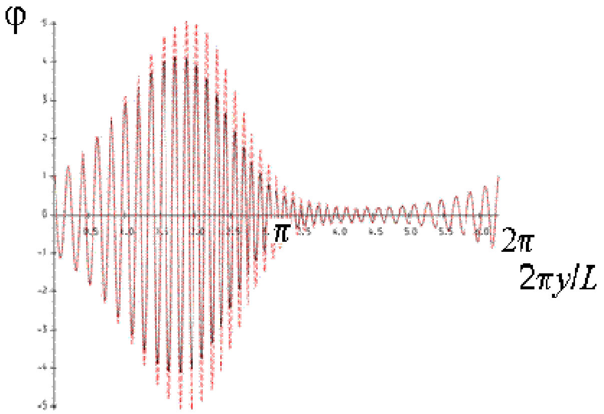

Figure 6.16*: Eigenmode structure for the potential φ along the y-direction. The red, dashed curve is the simpler (WKB) solution, the black, full curve is the full 2-D solution. This shows good agreement and gives insight into the localisation (in y) seen in Figure 6.15*

6.2.5 FACILITIES

A Computing

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

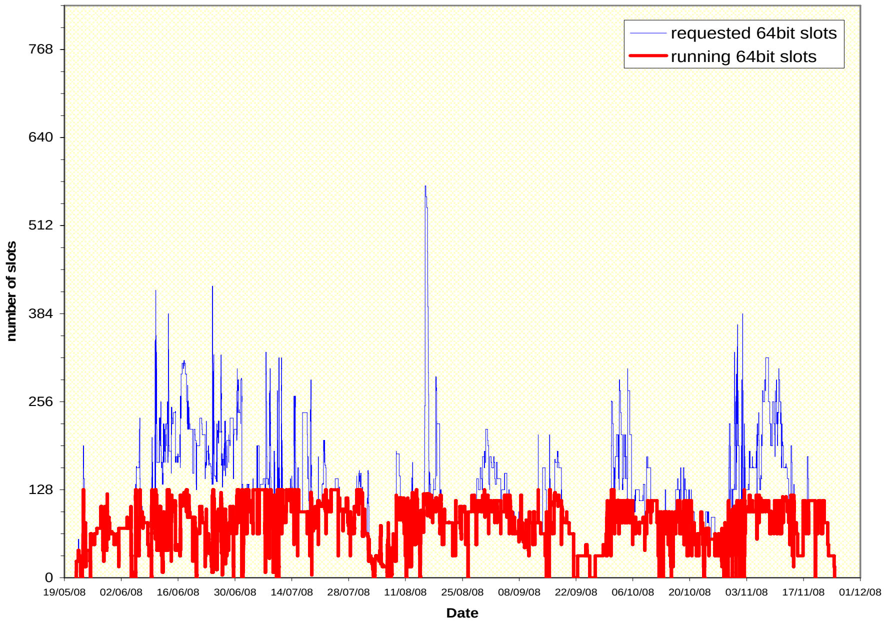

Figure 6.17: *Showing usage of the available 128 nodes with 64 bits (red curve) on Columbus and requests to use these nodes (blue curve) during the period May-November 2008. Requests above 128 nodes represent computer runs that are queued and waiting to execute*

Statistics show (Figure 6.18) the dominant usage of Columbus is on materials calculations (see Chapter 7), with second biggest usage being on turbulence simulations with the codes including ORB5 and GS2 (see Section 6.2.1 above).

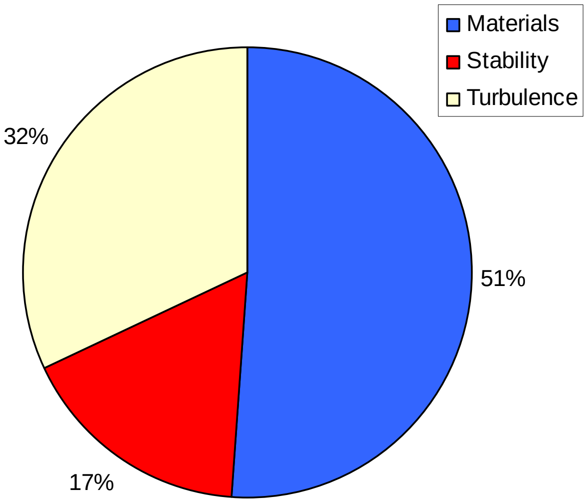

Figure 6.18: *Usage of Columbus by topic in the period May-November 2008*

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 visitors.

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 covered by the library stock. 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 range of electronic information services, including electronic journals and online databases such as ISI Web of Science, can be accessed via the Library web pages.

6.3 FUTURE PROGRAMME

We will continue strong support for EU and international activities, through active collaborative studies under the EU Integrated Tokamak Modelling Task Force (in particular in the area of ITER scenario modelling) and by continuing to host the ITPA Profile Database for testing transport models. The main physics issues the theory and modelling programme will address in the next year include:

- *turbulence-driven losses:* The work on energy confinement, which controls the size of fusion devices, will involve both computational and analytic theory; the effects of plasma flow on confinement will be a major theme. 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. These turbulence studies are done in close collaboration with UK universities (Warwick, York, Oxford and Imperial). The TGLF transport formulation will be developed with US collaborators, to give a robust model for use at low aspect ratio. The CENTORI code will also be used for studies of global electromagnetic turbulence in MAST and JET, particularly with regard to studying momentum transport and fast ion transport in the presence of turbulence. Optimisation of CENTORI will continue with the University of Edinburgh (EPCC).
- *Instabilities:* Studies will concentrate on modes that limit plasma pressure and current. In particular the so-called resistive wall mode that limits performance in advanced power plant relevant scenarios will be studied, to understand the implications for control requirements in ITER. These studies will be complemented by development of analytic theories for plasma stability in ITER relevant regimes.
- *ELMs:* These edge-localised instabilities can cause high transient heat loads on the divertor target plates and are a key question for ITER and STs. Stability in the region of the pressure pedestal near the plasma edge (separatrix) is key to understanding ELMs and studies in this area will be extended to include non-ideal effects. Also filament structures associated with ELMs, and material power loads, will be modelled in JET and MAST. Work in this area will be done in collaboration with the Universities of York and Manchester.
- *fast particle instabilities:* These 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 include developing a theory understanding of Alfvén antenna results on MAST, and be performed in close collaboration with UK universities (Imperial, York, Warwick and Oxford).