

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:

- (i) Confinement and transport, with an emphasis on modelling the turbulence mechanisms that underlie the loss of energy in the tokamak;
- (ii) 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;
- (iii) The integrated plasma modelling required for developing steady state operational scenarios.

These topics are addressed by exploiting CCFE's strengths in both analytic and 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 and Diego. The programme also works in close contact with CCFE's experimental programmes on JET (Chapter 3) and MAST (Chapter 5), which both stimulate the development of models and provide the opportunity to validate them, a crucial element in providing a reliable predictive capability. There are strong collaborative links with fusion institutes in the rest of Europe, Russia and the US, and participation in the International Tokamak Physics Activity (ITPA), in particular hosting and managing the ITPA Profile Database. Strong support for the European Integrated Tokamak Modelling Task Force is given, particularly in the area of scenario modelling for ITER (here CCFE now has a contract with F4E). 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 with CASE-type 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 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).

6 Theory

6.2 PROGRESS DURING 2010/11

6.2.1 CONFINEMENT

In the tokamak the loss of energy from the discharge is known to be often 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 (such as in the GS2 or ORB5 codes).

A Turbulent energy losses in MAST using the ORB5 Code

The gyrokinetic modelling of ion scale turbulence in a MAST L-mode plasma with shows clear non-local behaviour. While the linear unstable spectrum agrees well with the local flux tube analysis, the non-linear spreading of turbulence can only be observed in a global simulation (Fig 6.1). The flow shear has an asymmetric effect - flow in the direction of the plasma current is destabilising at low flow shear, but stabilising at high flow shear. Counter-flow is stabilising for all flow shearing rates. At the experimental level of flow shear, the MAST plasma is just marginally stable to ion scale length turbulence but a more complete treatment of the electron behaviour increases the growth rates and results in unstable modes even when experimental flow shear is taken into account, which also increases the non-linear heat flux significantly.

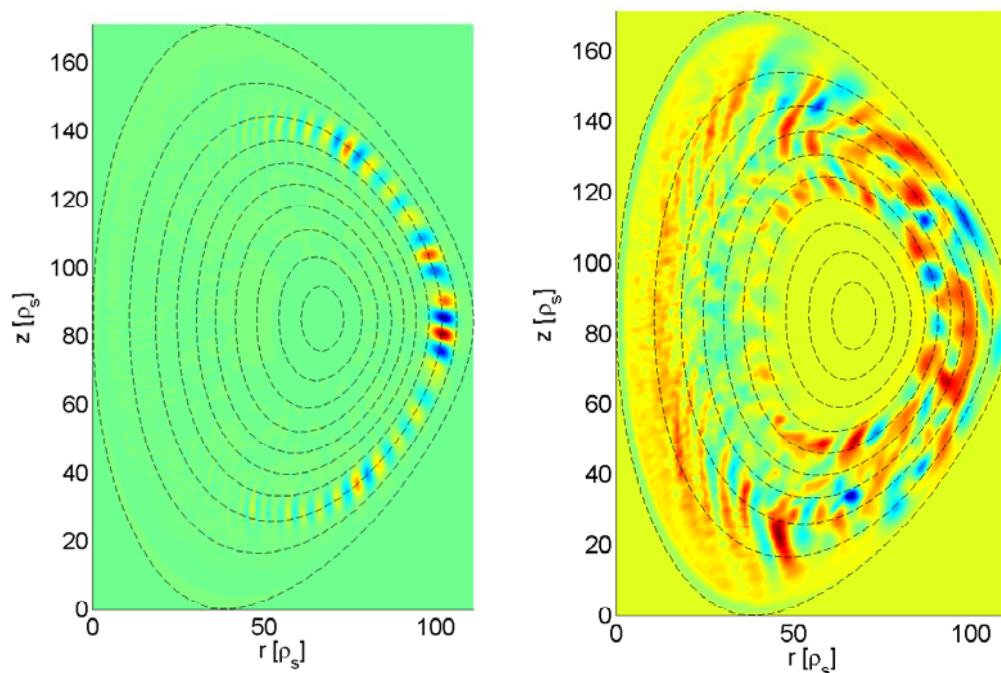


Figure 6.1: The left figure shows the convective cells during the linear phase and the right figure clearly shows the spreading of this turbulence in the nonlinear phase.

B Simulating energy transport in MAST using Trinity and GS2

Simulations of energy transport in MAST based on local turbulence simulations at multiple radii across the plasma, using the GS2 gyrokinetic code to model the turbulence within the Trinity transport solver have been performed. This multiscale framework averages turbulent energy fluxes over intermediate time and space scales, much smaller than the confinement time scale and background gradient length scale characteristic of the transport evolution. It therefore permits

much coarser resolution of the transport grid, in both time and space, than for global gyrokinetic simulations – resulting in significantly enhanced computational efficiency.

Experimental evidence indicates that anomalous ion thermal transport in MAST is often substantially suppressed. Our linear simulations support the paradigm that flow shear stabilizes turbulence at ion scales, and so only electron scales are modelled – further reducing the computational resource requirements.

When collisional transport is added to the ion channel the results show reasonable agreement with experiment in the outer part of the core plasma (Fig 6.2), but indicate the need for a more sophisticated model in the inner part, where electron scale instabilities are found to be linearly stable and the modelled electron energy flux is suppressed.

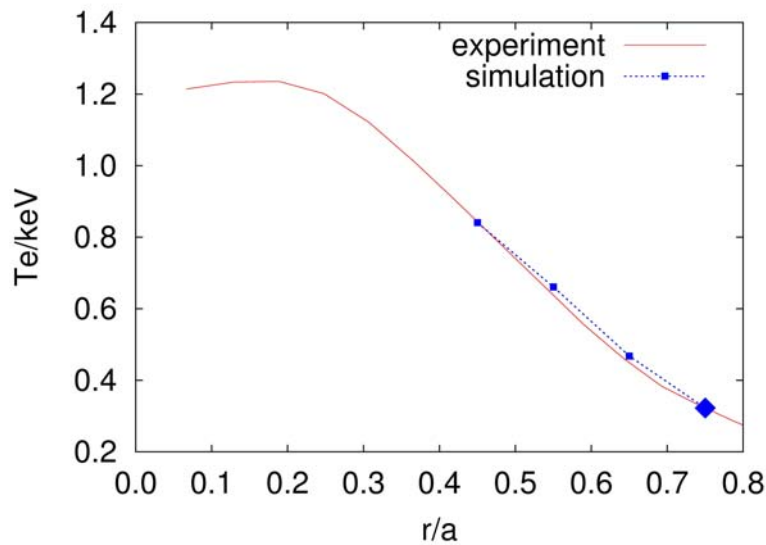


Figure 6.2: The experimental electron temperature (T_e) profile (red line), compared with the Trinity simulation result (blue line) – showing excellent agreement.

C CENTORI

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 period under review, the main code developments have concentrated on improving the versatility of the code's input/output routines, allowing the number of computing cores to be varied on successive runs. This work was carried out with support from the EUFORIA project in collaboration with EPCC, The University of Edinburgh and Barcelona Supercomputing Center, and enables CENTORI researchers to respond to different levels of computing availability on the supercomputers they use.

Benchmarking of the code against a typical MAST discharge has continued, together with work to compare the results from CENTORI against other European plasma turbulence codes, under the EFDA Integrated Tokamak Modelling Task Force.

Figure 6.3 shows a snapshot of the fluctuating component of the toroidal current density in 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.

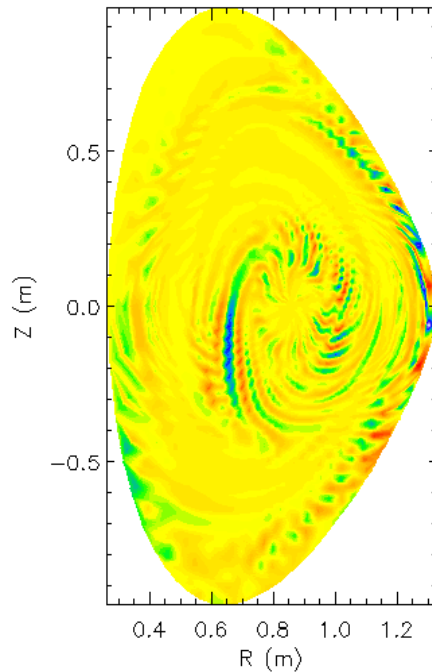


Figure 6.3: Fluctuations in the plasma current density computed by CENTORI for a MAST case.

D Linear microstability analysis of Low-Z impurity doped tokamak plasmas

Improved energy and particle confinement in the presence of low-Z impurities has been observed in many tokamaks under various experimental conditions. In particular peaked electron-density profiles have been obtained in Frascati Tokamak Upgrade (FTU) ohmic plasmas where high concentrations of lithium have been detected following the installation of a Liquid Lithium Limiter (LLL). Improved confinement has been also reported in NSTX when Lithium was introduced in the discharges. A gyrokinetic study on the effects of lithium and other low-Z impurities on the linear stability of deuterium and electron temperature gradient modes and their associated fluxes has been carried out for plasma parameters such as those found in the core of LLL-FTU plasmas. Simulations show that a lithium concentration in excess of $n_{Li}/n_e = 15\%$, as estimated in the initial phase of a reference FTU discharge, is found to have a strong stabilizing effect on electron scale turbulence (Fig 6.4). A significant stabilization of the electron driven modes can still be observed when the lithium concentration is reduced to 3%. In the presence of a significant impurity concentration ($n_{Li}/n_e = 3\% - 15\%$) the long wavelength ion modes drive an inward electron and deuterium flux, and an outward lithium flux (Fig 6.5).

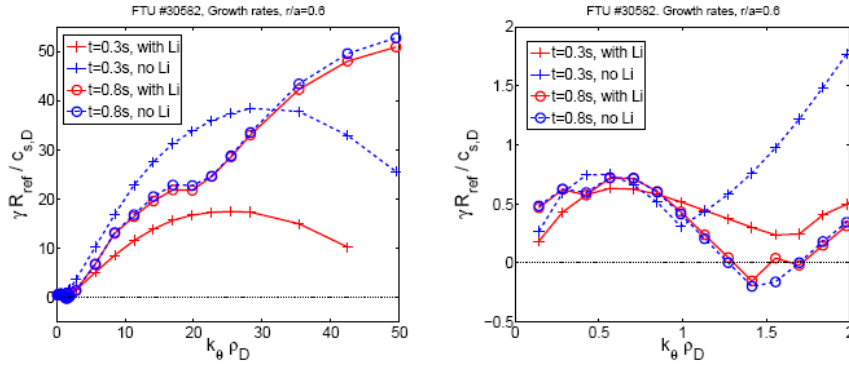


Figure 6.4: Growth rates of FTU #30582 at $t = 0.3$ s (crosses) and $t = 0.8$ s (circles). Left: short wavelength (ETG) modes, right: longer wavelength (ITG-TEM) modes up to $k_{\theta} \rho_D = 2.0$ (k_{θ} is the wavenumber and ρ_D is the deuterium gyro-radius). Results with the same parameters but without Li impurity are also shown (blue dashed). A concentration of $n_{Li}/n_e = 15\%$ is found to stabilize the ETG mode (left, crosses) and TEM modes (right, crosses).

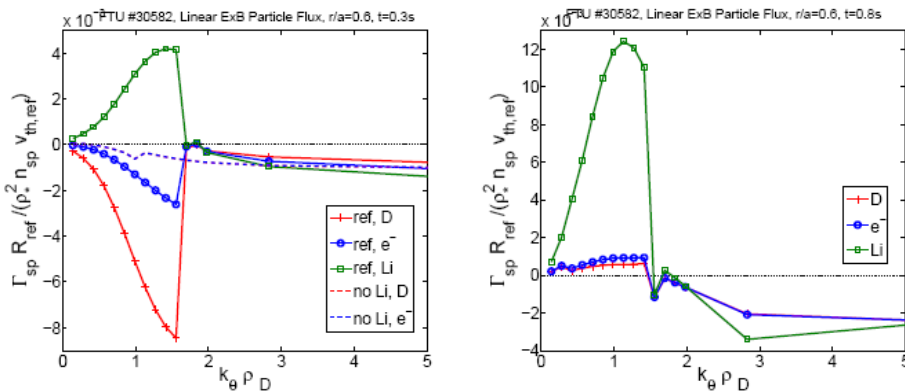


Figure 6.5: Linear $E \times B$ particle flux spectrum of the species (red: deuterium, blue: electron, green: lithium) at $t = 0.3$ s (left, $n_{Li}/n_e = 15\%$) and $t = 0.8$ s (right, $n_{Li}/n_e = 1\%$) at $r/a = 0.6$. Results with the same physical parameters but without the presence of lithium impurities are also shown (dashed).

The microstability analysis carried out indicates that for the considered plasma parameters the presence of a lithium concentration of $n_{Li}/n_e = 3\%$ - 15% in the initial phase of the discharge is enough to trigger an ITG-TEM driven inward flux of deuterium ions and electrons and an outward flux of the impurity ions. These dynamics eventually leads to the observed peaked electron density profile and low impurity content plasma.

E Full orbit simulations of impurity transport

In the strongly-varying equilibrium fields of MAST many of the simplifying assumptions that are often employed (e.g. small plasma inverse aspect ratio and low ratio of toroidal Larmor radius to poloidal Larmor radius) are not met by all particle species, and it is then appropriate to use a full orbit analysis to evaluate heat and particle fluxes. With the aid of a placement student from the University of Bath, the full orbit code CUEBIT has been used to study the collisional and turbulent transport of carbon and tungsten impurity ions. The equilibrium and fluctuating electromagnetic fields of MAST were modelled using the cylindrical and toroidal two-fluid codes CUTIE and CENTORI. It was found that the equilibrium radial electric field was sufficient to reduce the particle confinement time from its neoclassical value (around 400ms) to 25ms (Fig 6.6); the field fluctuations reduced this further to around 10ms. A detailed study of the scaling of particle diffusivity with collisionality revealed deviations from the standard

neoclassical theory, and difficulties in defining a local diffusivity at low collisionalities.

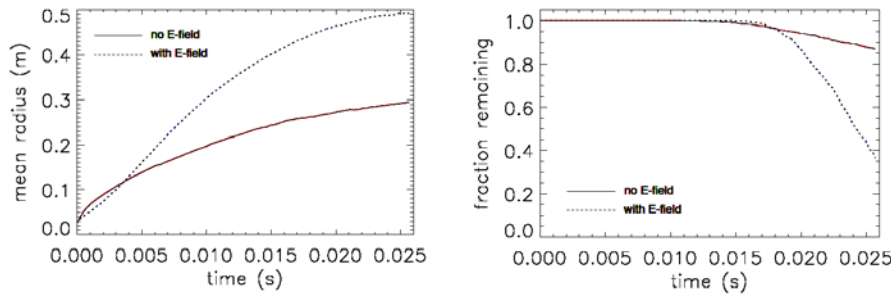


Figure 6.6: (a) Computed mean position of 10^4 tungsten ions in a simulated MAST H-mode plasma, plotted versus time following injection at the magnetic axis. The equilibrium magnetic and radial electric field were calculated using the two-fluid CENTORI code; field fluctuations were not taken into account. (b) Fraction of confined tungsten ions versus time.

In a collaborative project with a PhD student at the University of Warwick, CUEBIT has also been used to study the collisional dynamics of test impurity ions in spherical tokamak plasmas with strongly-sheared radial electric fields, whose scale lengths are comparable to the Larmor radii of the ions. The effect of such shear on neoclassical particle transport was quantified for a range of test particle mass and charge numbers. It was found that the change in confinement brought about by the sheared electric field can be explained in terms of a collisional drag force drift, which is proportional to particle charge number, but independent of particle mass. This drift acts inwards for negative radial electric fields and outwards for positive fields, implying strongly enhanced confinement of highly ionized impurity ions in the presence of transport barriers.

F GS2 optimisation

Under a project supported by the High Level Support Team (HLST) of the Juelich high performance computer the GS2 turbulence code is being optimised. Presently, GS2 uses an implicit algorithm for the evolution of linear terms, which while being a good numerically stable method can have a high computational cost in initialising the computation (which occurs each time the timestep is changed). The nonlinear terms are handled using an explicit second order time stepping scheme; which requires changing the time-step as the computation progresses and thus expensive re-initialisations of the large response matrix. For these reasons it was considered that a move to create a fully explicit solution method would be beneficial. As reported last year a Discontinuous Galerkin (DG) scheme is being installed into GS2 – this large project is progressing well. First the existing code has been run using an existing (sub-optimal) explicit scheme. A series of runs were performed to evaluate whether and to what extent this “explicit” scheme matches the results from the default implicit case. The results indicated that they do match well if a sufficiently small timestep is employed. As a next step a simple explicit solver was implemented in GS2, solving the same equation as the implicit solver. The work required a comprehensive study of the code before progress could be made, to determine the correct definition of the code variables and normalisations. Comparison of the simple explicit solver with the original implicit scheme over a range of time-steps confirmed that the implicit scheme was unconditionally stable for all time-steps, although at the highest timestep the accuracy started to reduce, as expected. The time-step had to be severely reduced in order to reach stability (and accuracy) for the same scheme when run in explicit mode, and for the new explicit scheme to converge a further reduction in time-step was needed. The code is now ready for installation of the

DG solver. It was decided to build a prototype explicit solver in a test program first, rather than attempt to incorporate it directly into GS2. This approach gave the opportunity to test the algorithm on a simple problem, and to evaluate the effectiveness of various adaptive solution methods to help with the choice of the most suitable method for GS2. The total number of time-steps remained close to (in fact marginally lower than) that necessary for the highest stable fixed time-step, indicating that this adaptive method is indeed close to optimal. The test code is presently being incorporated into GS2 ready for a first full test. The project has been extended until the end of 2011 with HLST support.

G Probing the linear structure of toroidal drift modes

High resolution computational studies of the nature of short wavelength, 2D linear toroidal drift modes are compared with predictions from a local ballooning theory, under a collaboration with the University of York – this is an important area of study to understand limitations of local approximations frequently employed in turbulence codes. The focus is on the ion scale instabilities. A 2D code has been benchmarked, and finds excellent agreement with results from a 1D ballooning code in the local limit. In the global limit with radial profile variation, the relative phases of the Fourier modes that couple to produce the 2D ballooning mode demonstrate a narrow spread of radial wavenumber (k) about $\pi/2$, as expected from higher order analytic ballooning theory. Measurements from the Alcator C-Mod tokamak are consistent with turbulence of this character.

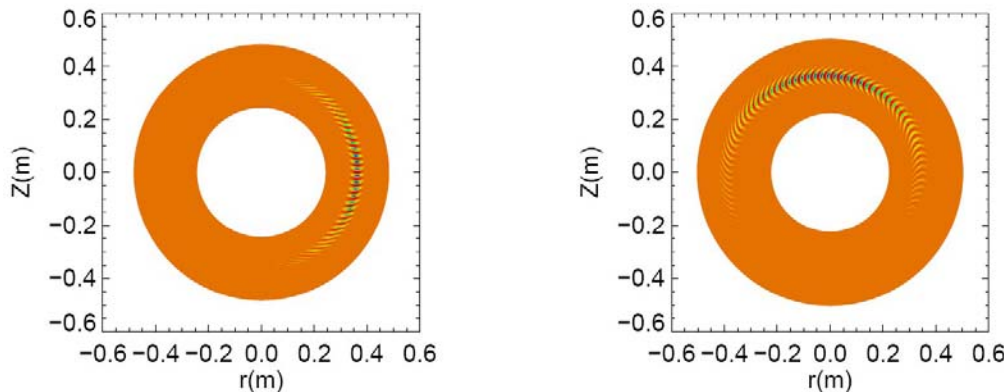


Figure 6.7: (a) Example isolated mode structure.

(b) Example general mode structure.

Contours in the poloidal plane of electrostatic potential for an isolated mode and a general mode as shown in Fig 6.7 – the key difference here being that the isolated mode is dominant when no radial variation of profiles are considered. A linear flow profile has been introduced into the 2D problem through a radially dependent Doppler shift to the mode frequency. At low levels of sheared flow the growth rates of isolated modes are reduced relative to the cases without flow, consistent with analytic theory. General modes are found to only be weakly affected by these low levels of flow shear. A key conclusion is that the proper choice of k is crucial in the use of local ballooning theory (or, equivalently, flux tube approaches) to study linear eigenmode stability. The importance for non-linear investigations remains an area of further work.

H Turbulence flow model

The competition between the drive and stabilization of plasma microinstabilities by sheared flow has been investigated, with the aim of clarifying aspects of the underlying physics. Focusing on the ion temperature gradient mode in sheared slab geometry, the characteristic equations for a dissipative fluid model were developed rigorously from the gyrokinetic equation, in a twisting-shearing representation. It can then be clearly seen that perpendicular flow shear convects perturbations along the field at a speed denoted by Mc_s (where c_s is the sound speed), whilst parallel flow shear appears as an instability driving term, analogous to the usual temperature and density gradient effects. The latter effect has been discussed previously in the literature. For sufficiently strong perpendicular flow shear, $M > 1$, the propagation of the system characteristics becomes unidirectional and no unstable eigenmodes may form. Perturbations are swept along the field, to be ultimately dissipated via collisions as they are sheared ever more strongly. Numerical studies of the equations also revealed the existence of stable regions when $M < 1$, where the driving terms conflict. However, in both cases transitory perturbations exist, which may attain substantial amplitudes before decaying. The case of $M \gg 1$ was studied analytically and it was shown that the perturbations exponentiate \sqrt{M} times. This may provide a subcritical route to turbulence in tokamaks.

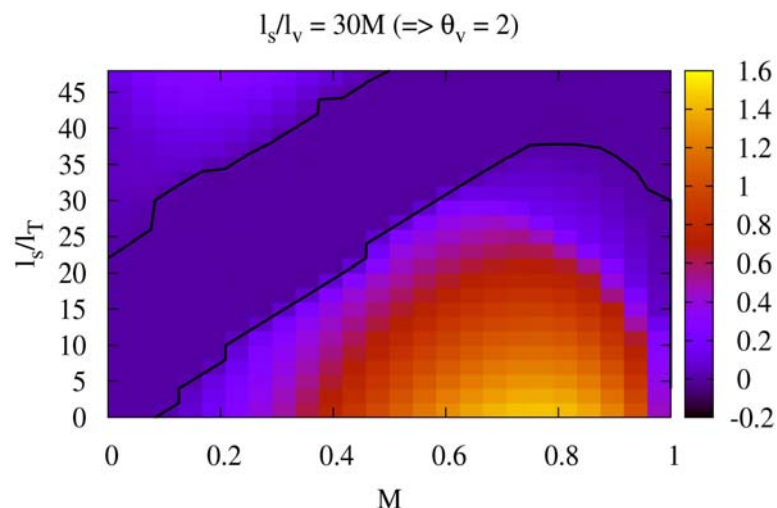


Figure 6.8: Variation of asymptotic growth rate with perpendicular flow shear M and temperature gradient I_s/I_T , at fixed parallel flow shear I_s/I_v with geometry ν typical of conventional aspect ratio.

I Multi-machine comparison of drift fluid dimensionless parameters

The behaviour of the turbulence in magnetic fusion plasmas has been examined in terms of three main dimensionless parameters which directly affect the adiabatic response of the plasma and hence control the electron response. Using experimental density and temperature profiles for existing divertor tokamaks (ALCATOR C-MOD, ASDEX Upgrade, JET and MAST), these dimensionless parameters are evaluated in different regions of the plasma, moving outwards from the core to the divertor. This analysis is repeated for future devices (ITER, DEMO and MAST-Upgrade), based on predicted density and temperature profiles. The chosen devices differ substantially in size, aspect ratio, magnetic field and heating power. However, clear multi-machine trends are evident (see Fig 6.9), suggesting a quasi-universal behaviour of the plasma. In particular, the trends show a clear separation of the plasma into four distinct regions: core, edge, Scrape-Off Layer and divertor, each of them characterized by a different set of parameters which, in turn, lead to significant variation of the

dominant physical mechanisms across the machine. The separatrix region emerges as the most complex, in which all three non-adiabatic effects are important. Also this analysis offers empirical extrapolations for future devices, such as for the Super-X divertor configuration in MAST-U.

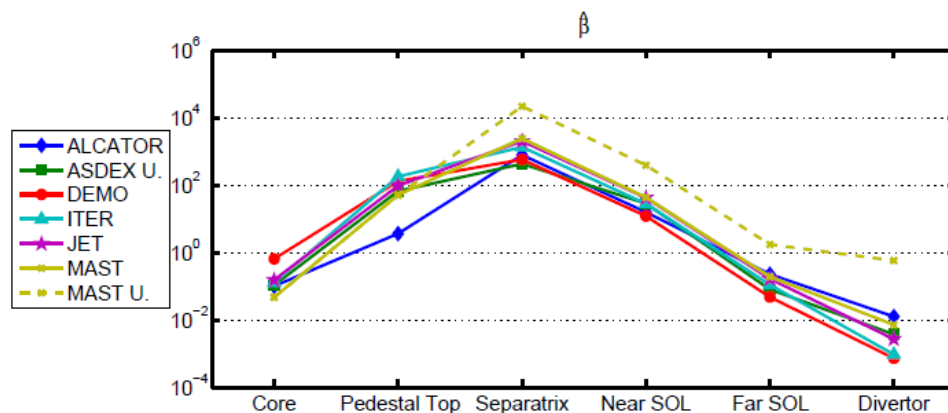


Figure 6.9: Variation of one of the 3 dimensionless parameters analysed from the centre to edge of the listed tokamaks.

6.2.2 PLASMA STABILITY

A Resistive wall modes (RWMs)

A resistive wall placed outside the plasma can significantly reduce the growth rate of instabilities which would be stabilized with a perfectly conducting wall. It has been demonstrated theoretically and experimentally that plasma flow can then stabilize the RWM completely. Stabilization of the RWM will allow higher plasma pressures to be attained and thus greater fusion power for a given input cost. This stability/stabilisation of the resistive wall mode (RWM) is critical to the expansion of the operational space of advanced tokamaks beyond the so-called no-wall pressure limit. The modelling tools have reached a certain level of maturity, in order to compute the mode stability in present devices under realistic experimental conditions, and to make reasonable predictions for the mode stability in ITER. In particular, the CarMa code, as a result of coupling the MHD stability code MARS-F/K, and the 3D electromagnetic code CARIDDI, has been developed to have the capability of computing the RWM growth rates in the presence of both 3D conducting structures (the walls with holes, the blanket modules, the RWM feedback coils, etc.) and the complicated damping physics inside the plasma (due to plasma rotation as well as the mode-particle resonance induced kinetic effects). The figure below (Fig 6.10) shows one example of the CarMa computation for an ITER plasma, where the eddy current flow pattern in the inner vacuum vessel, due to the onset of the RWM instability, is plotted. The 3D structures introduce coupling of modes with different toroidal periodicities.

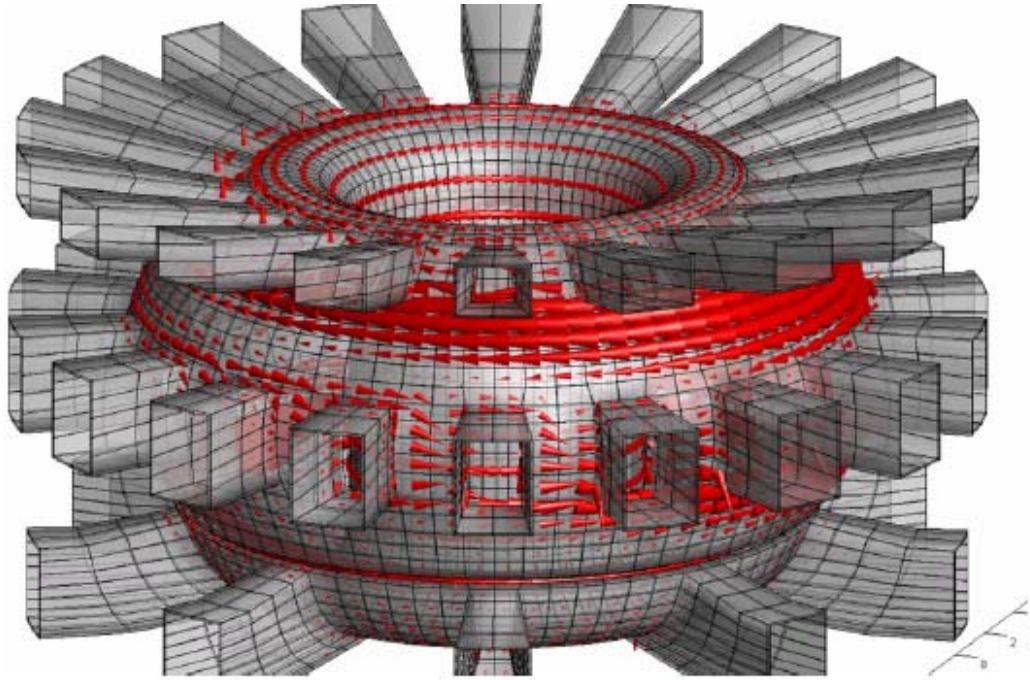


Figure 6.10: Computation with CARMA of the wall eddy currents for an ITER advanced scenario that is unstable to Resistive Wall Modes (work in collaboration with the Italian CREATE consortium).

In recent years there has been significant experimental evidence that the RWM can be stabilized with much lower levels of plasma flow than previous theoretical models suggested. The leading candidate mechanisms for this ‘slow rotation’ stabilization are either a resonance of the plasma with the precession of certain trapped particles or differential flow in the plasma. An analytical toroidal model has been developed which can reproduce the key aspects of the RWM and this has been used to demonstrate that differential rotation may be an explanation for the experimental results seen. Determining the cause of the stabilization at low rotation will have important consequences for the way RWMs are controlled on ITER and in potential tokamak power plants.

B Plasma stability at very high rotation speeds

Modern-day tokamaks heated by neutral beam injection (NBI) can rotate toroidally at a significant fraction of the Alfvén speed. Such strong toroidal rotation can ameliorate or suppress many magnetohydrodynamic (MHD) instabilities. However, the neutral beam driven rotation in ITER and future fusion reactors is likely to be much slower (though the intrinsic plasma rotation is extremely uncertain). Thus, it is important to assess whether the toroidal rotation in current devices plays a key role in MHD stability, which may then be absent in ITER. Furthermore, spherical tokamaks (STs) can have toroidal flows approaching the ion sound speed due to the small plasma volume per unit of NBI power and low moment of inertia of the plasma. At such large sheared rotation velocities, Kelvin-Helmholtz instabilities become a concern. Numerical studies of MHD stability in the presence of strong flows have shown that sheared toroidal rotation is found to increase the ideal external kink stability limit, with stronger shear resulting in enhanced stabilisation. Since the external kink is the ultimate performance limit in tokamaks, optimising the rotation profile to maximise the pressure is attractive for operating future high-performance fusion devices. However, for toroidal rotation approaching a significant fraction of the Alfvén

speed, the flow shear drives a Kelvin-Helmholtz global instability, setting an upper limit on the rotation speed for stable plasma operation.

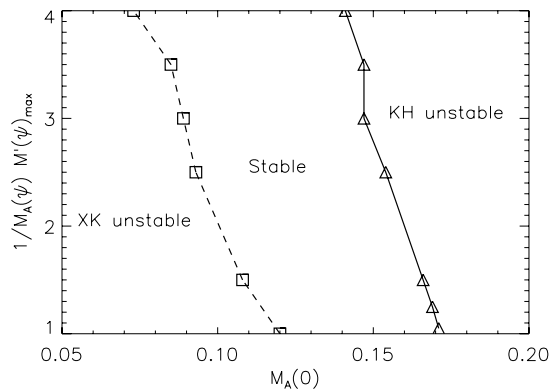


Figure 6.11: A stable operating space above the static pressure limits exists in an ITER-like plasma. The external kink (XK) is unstable at low rotation, whilst at very high rotation, Kelvin-Helmholtz (KH) instabilities occur, but there is a window of stable operation at intermediate sheared rotation.

C Alpha channelling

Optimal exploitation of the free energy of fusion products, notably the alpha-particles born at 3.5MeV in reactions between thermal deuterons and tritons at ~10-20keV, is central to the exploitation of fusion power through magnetic confinement. In the traditional framework, this energy is transferred through multiple collisions to the thermal electrons on a cumulative timescale ~0.1s; electron heating by fusion alpha-particles has been observed in the TFTR (former US tokamak) and JET tokamaks. The electrons in-turn sustain the temperature of the thermal ions to which they are collisionally coupled. It may be preferable, however, to use some of this free energy in “alpha channelling” scenarios. This term refers to mechanisms by which rapid collisionless collective instabilities (natural or induced) of the fusion product population could directly benefit the plasma equilibrium. A collaboration between Warwick University and CCFE, recently reported in Physical Review Letters, has simulated from first principles, for the first time, a key alpha channelling phenomenon for tokamak fusion plasmas. A key step has been to capture simultaneously the single-particle and collective dynamics of the energetic ion, thermal ion, and thermal electron populations, with realistic mass ratio, as they evolve self-consistently with the electromagnetic field. A “particle-in-cell” code, originally developed for astrophysical applications, evolves a parallel drifting ring-beam distribution of energetic ions in a thermal plasma. Collective instability gives rise to electromagnetic field activity in the lower hybrid range of frequencies. Obliquely propagating waves spontaneously excited by this lower hybrid drift instability undergo Landau damping on resonant electrons, drawing out an asymmetric tail in the distribution of electron parallel velocities (Fig 6.12 and 6.13), which constitutes a net current. These simulations demonstrate a key building block of some alpha channelling scenarios: the direct collisionless coupling of fusion product free energy into a form which can help sustain the basic equilibrium of the tokamak plasma.

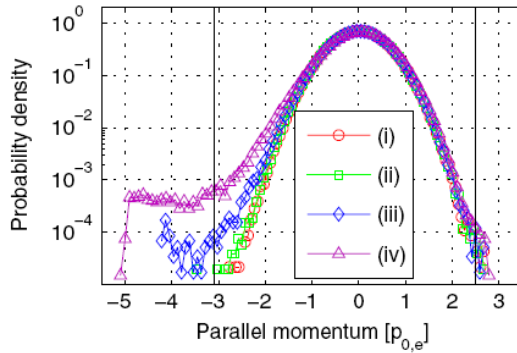


Figure 6.12: Drawing out a tail in the electron parallel velocity distribution. Four snapshots in time capture the development of a current-carrying tail in the distribution, arising from resonant Landau damping of lower hybrid waves excited by the energetic ions.

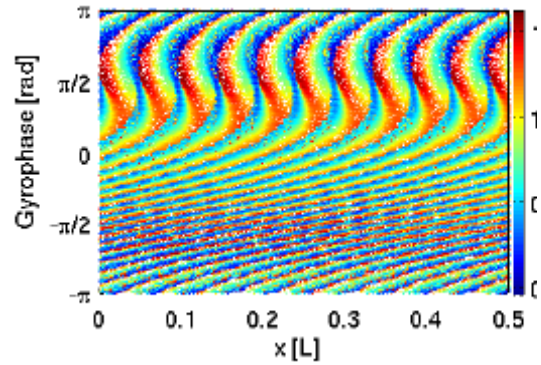


Figure 6.13: Gyrophase bunching – the mechanism underlying wave excitation by the energetic ions. The concentration of energetic ion energy versus gyroangle and position is plotted using a colour scale. The structure shown arises from resonant “kicks” at specific locations along the gyro-orbit, where the velocity of the ion transiently matches the phase velocity of the lower hybrid wave that is excited.

D Equilibria with poloidal flows and momentum sources

The equilibrium configurations, and hence stability, of tokamak plasmas can be affected by the presence of bulk plasma flows. “Transonic” poloidal flows, of the order of the sound speed multiplied by the ratio of poloidal magnetic field to total field, can cause the normally elliptic tokamak equilibrium equation to become hyperbolic in part of the solution domain, implying the presence of radial discontinuities in variables such as plasma density. The range of poloidal flows for which the equilibrium equation exhibits this behaviour increases with plasma beta (Figure 6.14), thereby complicating the problem of determining spherical tokamak plasma equilibria with transonic poloidal flows. A simple expression has been obtained for the variation of density on a constant temperature flux surface when poloidal and toroidal flows are simultaneously present. This expression could be used to infer information concerning flows on the high field side of a tokamak plasma, where direct measurements are not generally possible. It has also been found that there are four possible solutions for the plasma density when the flux surfaces are isothermal, corresponding to different poloidal flow regimes. However, there is no clear evidence for the occurrence of supersonic poloidal flows from either experiments or first principles-based theoretical modelling.

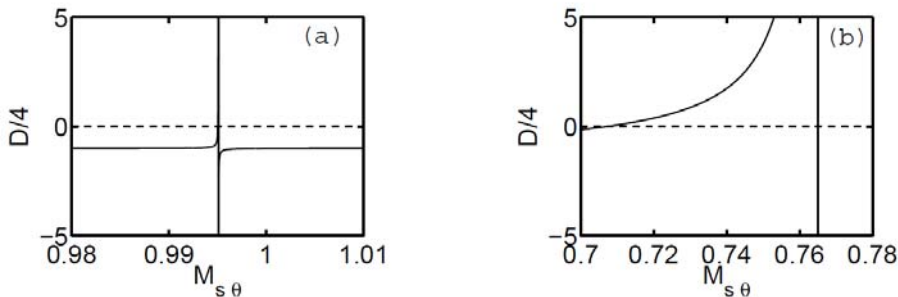


Figure 6.14: Discriminant D of the second order derivatives of the equilibrium equation versus poloidal sonic Mach number for (a) $\beta = 0.01$, magnetic field pitch $B_\theta/B_\phi = 0.1$, and (b) $\beta = B_\theta/B_\phi (= 1)$. Positive values of D indicate that the equilibrium equation is locally hyperbolic, and hence the possibility of radial discontinuities in plasma profiles.

In a separate study, equilibria with purely toroidal flow have been investigated using a two-fluid analysis, taking into account the presence of momentum and current drive, together with dissipative effects. The equilibria are described by a set of three equations describing the spatial variation of poloidal magnetic flux, plasma pressure and toroidal magnetic field. These equations indicate that magnetic flux surfaces do not in general rotate as rigid bodies, as required by ideal magnetohydrodynamics in the absence of momentum sources and poloidal flows. For specific momentum drive and damping scenarios, expressions have been obtained for the variation of density on flux surfaces and the dependence of toroidal rotation rate on temperature, that can in principle be tested experimentally. A relationship between the loop voltage and plasma current in an inductive tokamak plasma with toroidal flow has also been derived.

E Sawtooth control in ITER

Sawtooth oscillations result in a periodic collapse in the core density and temperature. Control of sawteeth remains a crucial issue for ITER, especially since long period sawteeth are more likely to trigger deleterious neo-classical tearing modes. Consequently there is an urgent need to assess the acceptable sawtooth period in ITER to avoid triggering secondary instabilities, and how much power is required from the actuators at our disposal in order to attain this acceptable period. As discussed in Section 4.6.1 CCFE has led an ITPA working group which established a database in order to infer an empirical scaling of the sawtooth period that will trigger NTMs in ITER. This suggested that the natural period predicted by transport modelling will be approximately at the threshold for NTM seeding. Whilst this means active control is essential, it gives confidence that sufficient control can be achieved by a relatively small reduction in period. Transport modelling coupled to ray-tracing predictions and using the linear stability thresholds for sawtooth onset suggests that 13MW of ECCD from the equatorial launcher could be sufficient to reduce the sawtooth period by 30%, and this being the case, dropping it below the NTM triggering threshold. As there are naturally uncertainties associated with this modelling, and it is prudent to plan to use more than one control actuator in order to reduce this risk, it is recommended that the capability of applying 10MW of ICRH (with real-time feedback) is also retained for sawtooth control in ITER. Figure 6.15 shows the effect of ICRH near $q=1$ in reducing the stabilising effect of the fusion-born alpha particles.

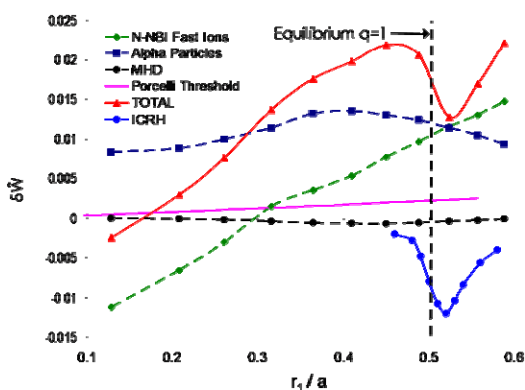


Figure 6.15: The effect of different energetic ion species on the internal kink mode responsible for sawtooth oscillations. In order to expect a crash the red line must cross below the pink line. By applying ICRH power, it is clear that one can achieve significant destabilisation to cancel the effect of the alpha particles.

6.23 INTEGRATED MODELLING

In Europe, ITER Scenario modelling is coordinated through the Integrated 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 and a deputy Leader starting in 2010. A range of issues

have been studied, including modelling of the pellet fuelling and current ramp phase 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 Pellet fuelling of ITER

A likely means of fuelling the ITER plasma is using pellets of frozen hydrogenic gas, injected at high speed into the plasma. Simulations of density behaviour and control in ITER using pellets, led by CCFE, have been performed in the framework of the ISM working group. Simplified simulations were performed with a theory based transport model (GLF23) with intermittent ELMs and pellet injection replaced by a continuous process. These showed the viability of fuelling the ITER baseline scenario by D-T pellets at an injection frequency of 4.6 Hz, and keeping at the same an acceptable burden on the gas pumping system to exhaust the injected gas. More complex simulations were performed with the JETTO transport code where a realistic description of the intermittent pellet particle source is implemented (Fig 6.16). It was shown that likely parameter variations result in a maximum variation of the pellet frequency required to maintain a certain density at the top of the Edge Transport Barrier (ETB) of at least a factor of two, whereas the variation of achieved average density and temperature is in the order of 10-15% and of Q (=Fusion Power Out/Power In) in the order of 40%. Also it was shown that if a feedback scheme is to be implemented to control the pellet fuelling system, a dedicated study will have to be performed to determine the parameter (or combination of parameters) one will have to control.

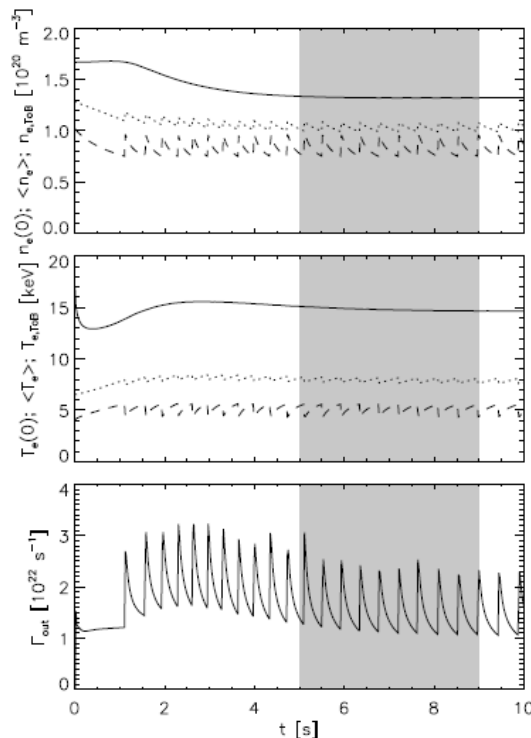


Figure 6.16: Evolution of plasma density (top) temperature (middle) and particle losses (bottom) for an ITER pellet fuelled baseline scenario. Each spike in particle losses represent a pellet being injected. In the top and middle frames solid lines correspond to on-axis values, dotted lines to volume averages and dashed lines to values at the top of the edge transport barrier. The grey shaded area highlights a time window where the quantities can be considered quasi stationary.

B Current ramp-up

Also within the ISM Group, and in collaboration with US colleagues, the phase near the start of the discharge in which the plasma current is increased (ramped-up) is being studied. The plasma current is largely increased by transformer action from a solenoid in the centre of the torus. As the current increases it has to diffuse into the plasma, and for ITER it is important to understand this, since the shape of the diffused current profile has implications for the vertical stability of the plasma. In order to benchmark this current diffusion data from a range of existing tokamaks is being modelled – one example is data from the US tokamak DIII-D that has been supplied to the ITPA data base (see item C below). Taking the measured temperature profiles it is found for the DIII-D cases examined that the current profile diffusion is well reproduced with the expected plasma resistivity (Fig 6.17). A further step is to study various transport models to see how well they reproduce the measured temperature profiles. This type of modelling results in increased confidence for the modelling of the current ramp phase in ITER.

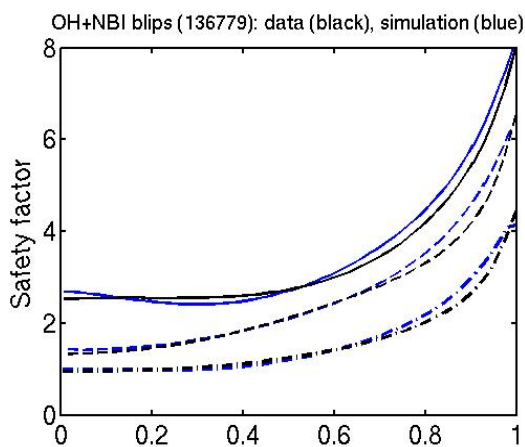


Figure 6.17: Safety factor profile measured (black) and calculated (blue) for DIII-D pulse 136779. From top to bottom the curves are at times $t=0.5$, 0.72 and 1.42 secs. The safety factor is the twist of the magnetic field and is directly related to the plasma current profile shape.

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 under the International Tokamak Physics Activity. This database has been hosted by CCFE for over a decade. Recent discharge submissions are being used to model plasma transport during the current ramp, to improve our understanding of how ITER will access its reference scenarios. It is planned eventually to move the profile database to the control of the ITER organisation.

D ITM work

The ISM work discussed above is within the auspices of the European Integrated Tokamak Modelling (ITM) Task Force; also within the ITM a suite of integrated codes for modelling ITER is being developed. During 2010 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 2010 the above commitment has been confirmed by CCFE and the contribution to the task force for 2011 is 2.57 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 during 2010.

Key contributions by CCFE include:-

- In collaboration with the University of Strathclyde provision of interfaces to the ADAS atomic database for use in modelling the radiating properties of ions and atoms in plasmas.
- A code to produce simulated data of a reflectometer (a diagnostic that very accurately measures plasma density versus radius) is being developed. This will allow the diagnostic signals to simulated for comparison with actual experimental data.
- Provision of the MARS-F plasma stability code into the ITM code framework.
- Development of a module, for the European Transport Solver code, that calculates the effect of error fields (due to small construction imperfections) on the magnetic structure

6.2.4 FACILITIES

A Parallel computing

The in-house Culham parallel computing facility, Columbus, has been complemented by a similar machine called Diego (the son of Christopher Columbus). It uses the same Myrinet based communication architecture as Columbus cluster. Myrinet is a packet-communication and switching technology that is widely used to provide a high performance, low latency interconnect between clusters of workstations, PCs and servers.

The Diego computer cluster is composed of 36 HP Proliant DL145 G2 servers with dual 2.6GHz Opteron 252 processors and 8GB RAM. A further 10 HP Proliant DL360 G5 nodes with quad-core 3GHz Xeon processors are due to be added shortly.

The Myrinet switch (top-right in Fig 6.18) is a fully populated 16-slot chassis unit capable of connecting up to 128 nodes. Each of the fibre connections provides full duplex 2Gbps communication link, with about 3 μ s latency. All the components were bought as second-user equipment at a very economical price. As there is still considerable room for expanding the number of nodes on the switch, the intention is to gradually add more servers as and when suitable PCs are sourced.



Figure 6.18: Photo of the Diego computer cluster.

B Simulating Fast Ions on graphics cards

One of the primary goals facing the MCF community is to understand, and be able to accurately model the behavior of high energy ions as they slow down and thermalize. In the case of MAST, the primary auxiliary heating scheme is via the injection of up to 5MW of 70keV Deuterium beams. Data routinely show that the fast ions in MAST drive instabilities and indicate that the fast ions are redistributed in velocity and real-space as a result. In order to gain insight into the perturbations to the 5D fast ion distribution function (2 real space, 3 velocity space dimensions) a number of new diagnostics are currently being commissioned, namely a FIDA imaging system and a multi-chord scanning neutron camera. Interpretation of these diagnostics requires a suite of numerical codes; in particular, model predictions for the fast ion distribution function are required for MHD modelling and for generating synthetic diagnostic data. Over the last year significant progress has been made in building a new fast ion code, capable of simulating the gyro-resolved fast ion distribution rapidly, on a very fine mesh, thereby allowing gradients in real and velocity space to be calculated accurately. The code, LOCUST-GPU exploits the latest generation of NVIDIA graphics cards to track millions of fast ions in a simulated plasma (with a speed up of typically x50 over a single Nehalem hyperthread (x200 for 4 GPUs)). The GPU is an example of a “disruptive technology”, over the last few years having found firm footing in the HPC market and top-500 list of supercomputers. This new technology enables cluster-level performance using desktop level hardware. CCFE have installed two dedicated high performance work-stations, each with 24GB of RAM and four high performance graphics cards, both of which are being used for algorithm development as well as production runs.

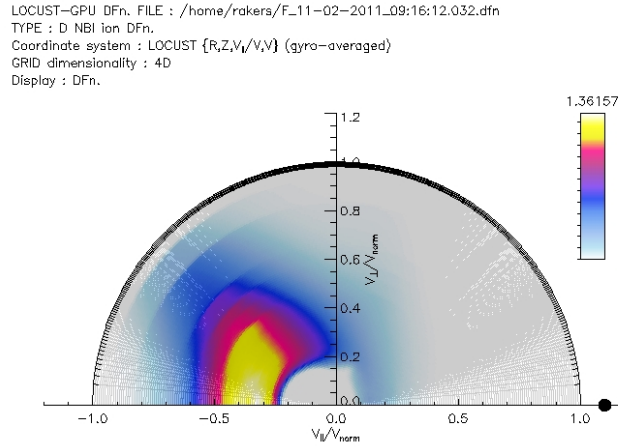


Figure 6.19: Fast ion distribution function (gyro-averaged) in velocity space for a spatial cell located in the core of a typical two PINI MAST discharge (23452, $t=200\text{ms}$ cell @ $R=0.929\text{m}$, $Z=0.081$).

C Library

The Culham Library is the main repository of plasma physics and fusion literature in the UK. Library facilities are available to all CCFE staff and EFDA JET secondees. Library users have access to an historic collection of books, reports, conference proceedings and printed journals. These cover not only plasma physics but a wide range of subject areas including physics, chemistry, mathematics, computing, engineering and management.

A range of electronic information services, including LIBRIS the library database, links to electronic journals, and commercial databases such as Thomson Web of Knowledge, can be accessed online through the Library intranet pages.

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