Magnetic Confinement Theory Summary S/1-3

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1 Introduction and Statistics

A total of 93 papers under the theory, TH, heading were presented at the conference, although a number of experimental papers also contained significant theory elements: only the former are reviewed here. A novel development was the inclusion of a Theory Overview paper [1], presented by P H Diamond, on the subject of zonal flows, currently a topic of great interest to the fusion community. The remainder of the theory papers were distributed amongst oral presentations (32, with 11 rapporteured and one a post-deadline submission) and 58 posters, one of which was post-deadline.

A number of **themes**, or **trends**, are evident, all springing from the growing use of numerical approaches to plasma theory. These are: (i) the use of direct numerical simulations to calculate and provide insights into turbulent transport (indeed there were ~ 30 papers with contributions on this topic), although analytic modelling plays a role in interpreting these 'numerical experiments'; (ii) increasing realism in modelling of geometry and physics in areas such as macroscopic MHD phenomena and radio-frequency heating and current drive, both of which involve modelling of fast-particle distributions; and (iii) a growing emphasis on integrated modelling, bringing together modules that describe interacting aspects of plasma behaviour.

In describing progress from the theory contributions since the previous conference in Lyon, 2002 [2], it is helpful to place them in the context of certain **'key questions'** that need to be answered on the road to the development of fusion power. These are:

- **Confinement**: confinement time scalings with plasma parameters and the conditions for improved confinement, e.g. transport barriers;
- **Stability**: the constraints on plasma current, density and pressure arising from macroscopic stability; the effects associated with fast particle populations such as alpha particles; and the consequences of loss of control of these instabilities;
- **Plasma exhaust**: acceptable heat loads associated with the steady flow of plasma to divertor target plates; seeking regimes with tolerable edge localised modes (ELMs), i.e. mitigating the transient heat loads without confinement degradation;
- **Steady operation**: integrating solutions to the above questions as well as developing efficient means of non-inductive current drive.

As well as specific items of progress on the above topics, say for ITER, one must not forget the growth in the **basic understanding** of these phenomena that is needed to give fusion energy research credibility in the broader scientific community. It is revealing to consider the proportions of the papers concerning these four topics. There are 45 on confinement (13 on transport barriers); 31 on stability (5 on neoclassical tearing modes (NTMs), 3 on resistive wall modes (RWMs), 3 on disruptions, 10 involving fast particles); 10 on exhaust of which 4 are on the key topic of ELMs; and 7 on heating and current drive and fuelling (2 on ion cyclotron (IC) and lower hybrid (LH) waves, 3 on electron cyclotron (EC) waves).

It is also interesting to break down the theory contributions according to **magnetic configuration**. Thus the vast majority (~ 80) deal with tokamaks, of which perhaps 10 have a specific ITER application and 7 relate to spherical tokamaks (STs). There were 8 on non-axisymmetric configurations and only 2 on alternative concepts.

2 Progress

A Confinement

(i) Basic Understanding

Although there were many papers presented on turbulence simulations, the complexity of the non-linear physics involved requires an analytic understanding of the basic processes. The Overview**,** on '*Zonal flows in plasma turbulence'*, by Diamond [1] was most timely. This described the role in drift wave turbulence of zonal flows, azimuthally symmetric plasma flows that vary radially on a micro-scale. They are ubiquitous and robustly generated in drift wave turbulence, being critical ingredients in regulating the non-linear dynamics of the system and leading to a saturated state: the so-called 'drift wave/zonal flow paradigm'. They have the effect of reducing the 'bare' gyro-Bohm estimate of transport by a factor R, proportional to the damping rate of the zonal flows, leading to a potential impact on the cost of a power plant: $C \propto R^{-0.8}$. Furthermore they are responsible for the non-linear increase in the critical gradient for turbulent transport (the 'Dimits up-shift'). Since there is a collisional damping of the zonal flows this introduces a dependence on collisionality, ν_*, and safety factor, q, as reported in [3], into an otherwise collisionless theory; furthermore these dependencies suggest means of turbulence control. However if collisional damping is weak there remain collisionless processes, eg via tertiary instabilities such as Kelvin-Helmholtz. Lest this all seems a purely theoretical construct, one should note the experimental identification of zonal flows in the CHS device [4]. There are many situations in turbulence where zonal flows play a role, but Diamond gave a unifying picture in terms of two generic parameters: a Kubo number, K, and a parameter S, representing the stochasticity of drift wave rays. Finally he provided a useful analysis of *'what we know, what we think we know and what we don't understand'*.

Two other basic mechanisms in turbulence are multi-scale interactions and the role of linearly damped modes. The first of these was investigated in the context of the interaction of ion temperature gradient (ITG) and electron temperature gradient (ETG) [5]; the straining of ETG scales by ITG motions are stabilising for ETG but the ITG-induced-scale temperature gradients are destabilising. The linearly damped modes are found to play key roles in the spectral flows and saturation mechanisms for trapped electron mode (TEM) and zonal flow dynamics [6]. With a view to investigating zonal flow effects in Hasegawa-Mima drift wave turbulence, a Lagrangian formulation for this system was developed [7]. A post-deadline poster, discussed control of test-particle transport in fusion relevant Hamiltonian systems [8].

(i) Core turbulence simulations

The main themes underlying the turbulence simulations were the use of global, as opposed to local flux-tube, codes; more complete plasma models (ion and electron physics, collisions, **E**×**B** shear, electromagnetic effects) and the effects of low magnetic shear associated with internal transport barriers (ITBs).

Results from the global code GYRO were reported [9]. Using a 'full physics' model it proves possible to simulate the trends in DIII-D L-mode scans in ρ_* (this failed if any physics element was missing). Indeed, because of uncertainties in experimental values of the temperature gradients, the actual numerical values of the thermal diffusivities could be modelled within experimental error. Using a feedback procedure on the profiles, there is the potential to simulate steady-state profiles in a burning plasma, such as ITER, with this code. The concept of 'turbulence spreading', whereby turbulence generated in strongly unstable regions (such as the edge plasma) can propagate and populate a more stable region in the plasma core, was demonstrated for ITG turbulence using the global GTC code [10] and analytic modelling [5, 10]; this effect can modify ρ_* scalings.

The electron thermal transport from ETG modes is of great topical interest, particularly for low magnetic shear, s, often associated with ITBs. Results from the global GTC code [11] show streamers but the associated thermal diffusivity, χ_e, is at the mixing length level, much smaller than that predicted by local codes [12] and suggests that trapped electron modes (TEMs) are needed to describe experiment. These simulations indicate that non-linear toroidal mode coupling plays an important role in the spectral cascade that determines the turbulent spectrum. The role of s in ETG transport was reported [13] who found low s leads to low χ_e, while high s produces streamers and high χ_e. The ETG transport in the presence of a minimum in q, q_{min}, where ITBs are often located, was explored with the global particle code GT3D [14]. For s < 0, zonal flows are found to suppress χ_e, while streamers develop in the region s > 0, leading to high χ_e; again toroidal mode coupling plays an important role.

The local 'flux-tube' code GS2 was used to model transport in IC heated discharges with ITBs in C-Mod [15]. It was found that there is a non-linear up-shift in the critical value of the density gradient for TEM instability. With off-axis heating there is equilibrium between the TEM induced particle flux and the Ware pinch; on-axis ICRH provides the possibility of control because of the temperature dependence of the anomalous flux. The fluctuations predicted in GS2 are in agreement with phase-contrast imaging (PCI) measurements on the experiment.

A number of contributions addressed specific aspects of ITG induced transport; again zonal flows were prominent. The competition between zonal flows, geodesic acoustic modes (GAMs) and toroidally induced parallel flows to extract energy from drift wave turbulence leads to a q-dependence of χ_i since zonal flows are suppressed at high q, while GAMs favour high q [16, 17]; this is broadly consistent with simple estimates [18]. Other studies indicate: an up-shift in the critical gradient within a fluid model [3]; a key role for a non-zero density gradient in the generation of shear flows [19]; the ability of reduced models to capture aspects of ITG dynamics such as relaxation oscillations (18 ordinary differential equations are needed to replace the full model) [20]; the role of entropy balances in the saturation of turbulence, taking account of the generation of fine-scale structures in velocity space [21]. Finally a careful benchmarking of the turbulence characteristics generated in different ITG simulation codes, GTC and GYRO was reported [22]. Fluctuation amplitudes are found to be in reasonable agreement and discrepancies between diffusivities could be associated with differences in cross-phases; a simple mixing length estimate fails.

(iii) Collisional Transport

When turbulence is suppressed, the irreducible collisional transport is revealed. A number of contributions extend the standard neo-classical theory to situations with large orbits, steep gradients and tight aspect ratio. Thus GTC-Neo describes situations with the ion banana width comparable with the pressure scale-length, $\rho_{ban} \sim L_p$; it finds significant differences in ion poloidal flow velocities and these depend on the toroidal rotation, ω [10]. A similar study using the δf Monte Carlo FORTEC code solves for the time-dependent radial electric field, exhibiting GAM oscillations; it is also applies to non-axisymmetric systems [23]. The expression 'omni-classical' was coined to describe collisional transport in spherical tokamaks [24]: the comparable effects from gyro- and drift-orbits approximately double the standard neo-classical value. Yet another term, 'paleoclassical', was added to the lexicon [25], associating a stochastic cross-field transport of electron energy with their transport along magnetic field lines as these undergo standard resistive diffusion. This idea captures a number of experimental features of electron thermal transport at modest temperatures.

(iv) General approaches

Turbulence simulations often indicate avalanche and non-diffusive behaviour. It is shown that such effects in pressure gradient turbulence can be compactly represented in transport codes by fractional derivatives [26]. In a similar vein, a transport model incorporating Levy flights and critical gradients has been developed [27]; it captures experimental phenomena such as a density pinch with off-axis fuelling, fast transients and power degradation. The principle of Stationary Magnetic Entropy has been tested against JET and FTU data: while it predicts q-profiles satisfactorily in a range of conditions, it achieves less success with temperature profiles [28].

(v) Edge transport, transport barrier and edge pedestal

The edge region provides the interface between the core and scrape-off layer (SOL). In H-mode the edge transport barrier and pedestal provide a boundary condition for core transport codes. A model for the pedestal based on a relaxation model incorporating 'Beltrami' flows and the MHD ballooning critical pressure gradient, was reported [29]. This leads to $T_{ped} \propto n^{-1}$ and a pedestal width $\Delta_{ped} \propto n^{-3/2}$, agreeing well with JT-60U data. Stability calculations with GS2 shows that drift waves, radially localised by the density profile rather than magnetic shear, are robustly unstable. (cf the old 'universal mode'!). Calculations with the code XGC incorporating neo-classical effects, neutral particles and X-point geometry [30] show a density pedestal developing in ~ 10ms, with a width $\Delta_{ped} \propto (T - T_c)^{1/2}/B_T$, where T_c is a threshold temperature and the width depends on the *toroidal* field B_T; the temperature pedestal is somewhat wider. The drift-Alfven model for the L-H transition has been extended [31], emphasising the role of the density gradient length L_n and finding $\Delta_{ped} \propto n^{-1}$. Since the transition and barrier formation is generally thought to be associated with plasma flows the time-dependent solutions of the coupled, non-linear system of equations for V_θ and V_ϕ in a neo-classical context with steep gradients have been investigated [32, 33]; chaotic oscillations can result.

A more basic approach to edge transport using a trans-collisional gyro-fluid code GEM was reported [34]. These simulations show a gradual transition from edge drift waves to core ETG/ITG modes, with the drift-wave/zonal flow system being stable against bifurcation so that some external source is needed for the L-H transition. A new gyro-kinetic code that captures all the competing scale-lengths associated with edge turbulence has beemn developed; results are similar to those from GEM but there is greater high $k_{\perp}$ activity in the turbulent spectrum. The ASCOT code that describes edge neo-classical effects and the associated radial electric field, E_r, has led to a new 'full f' code, ELMFIRE [35] that incorporates turbulence. An application of the code to the small tokamak FT-2 shows evidence of ITB formation. Transport in the edge region may involve impurity driven modes; an improved treatment of their stability is given [36].

(vi) Improved core confinement and internal transport barriers

Considerable attention was focused on the 'current hole' often associated with strong negative central magnetic shear. It was shown how a current-hole equilibrium can be generated and sustained by the development of a 'vortex pair' in the plasma core [37]. Using a transport code in which the current hole equilibrium was represented by a 'tri-magnetic island' model and the transport coefficients were sharply reduced in regions of reversed shear, It is possible to reproduce JT-60U results, as shown in [38]. The transport drops to neo-classical levels, resulting in the 'autonomous' formation of an ITB and a current hole through the large bootstrap current; the width of the ITB is narrow: Δ_{ITB} = 1.5 ρ_{poli}, the local ion poloidal Larmor radius. A study of the effect of the current hole on the redistribution of the alpha particle population in the poloidal plane during the trace tritium experiment on JET was reported [39]. Modelling the impact on the observed γ-decay, it is concluded that a 2MA experiment with a current hole is equivalent in this respect to 1 MA with normal shear.

The triggering of ITBs at q_{min} by the plasma flows associated with a double tearing mode was considered [40]. The stability of ITBs to ideal MHD ballooning modes and drift waves using a 'modelet' formulation to complement the ballooning theory that fails for the low s and significant velocity shear associated with ITBs, was presented [41]. It is found that narrow ITBs can sustain high stable pressure jumps at the ITB; although ITG mode structures differ across q_{min}, a gap in toroidal coupling can only exist for very long wavelength, a result consistent with findings in [9]. The impact on stability of low s, finite β and shears in both plasma flows and currents in a cylndrical plasma model, was studied by [42]. It is shown that the inclusion of poloidal impurity asymmetries can generate plasma flows that trigger the RI-mode bifurcation at lower impurity fractions than in the symmetric case [43].

Improvements in core confinement are often associated with sheared plasma flows, but the generation of the experimentally observed plasma rotation is not always well understood. Calculations of momentum loss due to quasi-linear drift wave mechanisms and through the effects of non-resonant magnetic islands were reported [44]. In addition, a further development of Coppi's 'accretion model' as a source for rotation (initiated at the plasma edge) is the identification of 'travelling' modes along **B** as a means to propagate rotation into the plasma core [44].

(vii) Transport Modelling

The emphasis in transport modelling is moving towards integrated modelling (such as the TASK initiative in Japan [32]), e.g. including an ECRH module [32] and edge-core modelling [29], see Section C. (The Multi-mode Model has now been extended to include low s and an ETG component [29].) A specific example of advanced, steady state ST scenarios was presented [45], reporting extrapolations with $\beta \leq 40\%$

based on experimental NSTX data. Testing the mixed Bohm/gyro Bohm model in the JETTO code for modelling ITBs on DIII-D, it is found that the addition of 'Shafranov-shift stabilisation' to the basic model is needed [46]. The code has also been used to simulate real time q control for JET. The calibration of the prescription for ITB formation in the Canonical Profile Transport Model (i.e. the 'second critical gradient') against data from MAST, DIII-D, JET and TFTR was described [47]. Similar fitting parameters emerge in each case and correspond quite closely to the ρ_{*T} criterion proposed for JET [48]. Other modelling contributions include ETG based modelling of Tore Supra and NSTX [49] and analysis of the ballistic responses associated with ECRH switch-on/off experiments on T-10 [50].

B Stability

(i) Tearing Modes including NTMs

Two issues concerning NTMs are: what is the trigger for the seed-island and what is the critical threshold size of this island? On the first question, the role of forced reconnection by non-linear coupling to other MHD modes present was examined [51], concluding that the initial frequency miss-match does not pose an obstacle to this mechanism. The time development of a trigger associated with resonant field amplification (RFA) has been explored [52]. The critical island width is often associated with the ion polarisation current, j_{pol}, assumed to be stabilising. Particle simulations of j_{pol} with the HAGIS code for island widths, w, comparable to or less than the ion banana width, ρ_{ban} have been performed [53], finding it decreases below the standard result: $j_{pol} \propto w/\rho_{ban}$ for $w/\rho_{ban} < 1$. Furthermore, this current can change sign near an island rotation frequency $\omega \approx \omega_{*e}$. Amongst other topics, the role of a turbulent viscosity was explored [54], concluding that it produces a dominant stabilising effect on the bootstrap current drive for islands rotating in the electron direction. This means it cannot explain a threshold for islands experimentally observed to be rotating in the ion direction. The impact of plasma rotation on NTMs was investigated [55], with the result that differential rotation stabilises whereas rotation with shear is destabilising.

On conventional tearing modes, it was shown that there could be a non-linear enhancement of their growth due to drift wave turbulence [56], while it was shown that there is an enhanced rate of reconnection within a collisional drift-tearing model, with parallel electron thermal conduction playing a key role [44]. A post-deadline oral presentation studied the non-linear stabilising effect of the island width, w, on the tearing parameter $\Delta'(w)$ [57], extending earlier work [58].

(ii) Resistive wall modes and disruptions

A key issue for steady state operation is stabilisation of resistive wall modes (RWMs). A validated model for rotation damping in the MARS code has been used to calculate the rotation, ω_ϕ, needed to stabilise the n = 1 RWM for a range of equilibria [59], finding $\omega_\phi \propto 1/q_{95}^2$. Applying the model to ITER, $\omega_\phi \approx (1.5 - 3)\%\omega_A$ is needed. Since this is close to the 2% predicted, control systems were investigated; it is found possible to approach 80% of the way between the 'no-wall' and the 'ideal-wall' limits. Using the M3D code, it was shown that the 'thick' walls in ITER slow the growth rate of RWMs [60]. A novel calculational method for RWMs was proposed [61], demonstrating that coupling of external modes to stable internal ones generates a 'peeling-like' structure.

The ability to perform non-linear MHD calculations in realistic geometry is exemplified by simulations of a disruption in a DIII-D reversed shear discharge with the NIMROD code [62]. This demonstrates that the asymmetric heat deposition on the divertor is associated with the n = 1 distortion. Likewise the M3D code was used to model the ITER halo current database [60]: for vertical displacement events (VDEs) it is found that the halo current fraction is ~ 0.35 and the toroidal peaking factor (TPF) ~ 2. Calculations of runaway currents, accounting for the avalanche mechanism and the self-consistent electric field response, were presented [63]. These simulations represent JET data well, showing a central peaking of current with ~ 1/2 of the total current converted to runaways; in the case of ITER this fraction is ~3/4. Calculations of eddy currents in the spherical tokamak ETE were reported [64].

(iii) Pressure limits

Many of the presentations on pressure limits concerned non-axisymmetric devices, reporting on studies of ideal ballooning and interchange modes [65, 66] as well as the implications for equilibrium and orbits [67], particularly for LHD and NCSX. Thus it was shown [65] that non-linear generation of toroidal flow reduces disruptivity, allowing β ~ 1.5% for LHD. A more 'realistic' treatment of the plasma boundary region, effectively reducing the 'bumpiness', improves stability and also the agreement with experiment in LHD; β ~ 3% is effectively stable, whereas β ~ 1% is less so [66]. A perturbative approach based on the work of Greene and Chance [68] was employed for locating second stability regimes [69]. Improved, two-fluid, non-linear modelling with M3D [70] is found to describe experimental results better: these effects stabilise ideal and resistive modes and suggest that there will be a 'soft' β - limit due to confinement degradation as magnetic islands grow larger.

An interpretation of rotation damping of ballooning modes due to sheared plasma rotation in terms of coupling to stable damped modes was given [71], this involves replacing the continuous spectrum by a model discrete one. This work complements [41], where the sharp transition from stationary plasma to a weakly rotating one is examined. The impact of sheared flows in suppressing MHD instability in a dense Z-pinch was investigated [72].

(iv) Fast-particle MHD

The main themes here were the use of more realistic fast-particle distributions, f_h, frequency sweeping, alpha particle losses and diagnostic opportunities. A number of presentations concerned the fishbone and internal kink modes, with an emphasis on non-perturbative treatments of f_h and new branches of the modes. The NOVA-KM code was used to explain low-frequency fishbones on JET [73], while there was work on hybrid fishbones and the coalescence of fishbones during JET monster sawteeth, employing an operating diagram in terms of γ_{MHD}, β_h and ω_{*i} [74]. Some non-conventional modes in spherical tokamaks (on account of low B) and 'doublet frequency' modes in ASDEX Upgrade due to passing particle contributions were described [75].

Turning to toroidal Alfven modes (TAEs) and energetic particle modes (EPMs), a hybrid MHD-gyrokinetic particle code was used to investigate the avalanching transport of alpha particles [76]. Analytic theory shows that the threshold for this process is near that for linear stability; their transport time-scale is ~ few $\times$ γ_{lin}^{-1}.

However this is largely a radial redistribution rather than a loss of alphas, although loss could occur in an ITER reversed shear discharge. A non-local EPM was also reported [77]; the radial width and location are both found to scale with the fast-ion orbit width. The M3D non-linear hybrid code was used to simulate a beam-driven n = 2 TAE in NSTX [78]; it exhibits a bursting behaviour as it propagates radially. For n = 10 TAEs in ITER it is found that the beam drive competes with that of the alpha particles; the loss fraction reaches 5% for T = 23keV [79]. The frequency sweeping of TAEs and EPMs can either be slow, related to equilibrium changes (e.g. as in [78] or Alfven Cascades, low frequency modes located near q_{min} as in JET [79], where it provides information on the q-profile), or fast sweeps, associated with the dynamics of phase-space holes [77, 79] (in this latter case it can be used as a diagnostic for related internal magnetic fields, $\delta\mathbf{B}$ [79]). New modes related to second stability situations in MAST and NSTX [79] and the possibility of Alfven Cascades in a cylinder, due to the radial density gradient [80] were proposed. A self-consistent treatment of the dynamics of f_h produced by the action of ICRH, collisions and a global Alfven eigenmode (GAE) using the SELFO code has been given [81]; this captures experimentally observed amplitude oscillations. Finally, a mechanism for a thermal quench of T_e from the χ_e attributed to the magnetic islands arising from the interaction of a GAE and KAW (kinetic Alfven wave) in W7AS, was proposed [82].

C Exhaust

The main themes here are turbulence, ELMs and integrated modelling

(i) SOL modelling

The structure and 3D dynamics (i.e. including variations along the field line associated with an X-point) of 'blobs' were investigated analytically [83]; these blobs are coherent structures appearing in the SOL. This work provides interpretations for aspects of turbulence simulations within a fluid plasma model of the edge region [84]. These turbulence calculations, performed with the BOUT code, include the edge of the core plasma and the SOL region, encompassing the divertor leg and X-point geometry. The code has been coupled to the UEDGE code to follow neutral particle transport effects on a transport time-scale. A significant result is the transition from so-called X-point modes to more virulent resistive ballooning modes as the density increases beyond the Greenwald limit. The increased transport from these modes could be associated with the density limit and also leads to X-point MARFEs. At these high densities the convective transport is enhanced by the presence of blobs; they dominate the tail of the particle flux, Γ_{wall}, reaching the wall.

The steady-state heat load on divertor target plates is related to the SOL width, Δ_{SOL}, which is determined in part by cross-field transport processes in the SOL. Two-dimensional turbulence simulations of the SOL, allowing for avalanching, or ballistic, density propagation, show $\Delta_{SOL} \propto L_{||}^{0.62}$, where $L_{||}$ is the length along the field lines to the divertor [85]. This result can be obtained by an analytic model and is nearer to the diffusive, rather than ballistic, estimate. This is an optimistic result, implying that Γ_{wall} is only 10% greater than the diffusive estimate for ITER. In a similar model [3] it was shown that zonal flows are suppressed in the SOL since field lines are connected to the sheath boundary condition on the electrostatic potential.

(ii) ELM modelling

The high transient heat loads associated with Type 1 ELMs pose a potential threat to H-mode operation, so the identification of tolerable ELM regimes is a high priority.

The 'peeling-ballooning' paradigm [86] is a useful basis for exploring these. An integrated approach, combining MHD stability calculations with an edge transport model is topical [29, 87]. Thus, a simulation of a DIII-D experiment using 'I-coils' [88] to suppress ELMs without causing serious degradation of confinement was performed [87]. This couples the MISHKA MHD stability code to a transport code incorporating an estimate of the contribution from ELMs and a stochastic element due to the I coils; it demonstrates that the edge pressure gradient drops below the instability limit without serious loss of confinement. Relaxation oscillations, reminiscent of ELMs, appear in simulations of resistive ballooning mode turbulence, being ascribed to transitory instability growth with a time-delay before the onset of shear-flow stabilisation [89].

A 'first-principles', analytic, treatment of the non-linear evolution of ballooning modes at the plasma edge shows an explosive growth of 'filamentary' structures, propagating radially into the SOL and aligned along the field [90]. Similar filaments have been seen in MAST and elsewhere, as well as in simulations with BOUT.

(iii) Carbon deposition

Carbon migration and deposition is another key issue for ITER. A detailed analysis and modelling of its erosion, migration and asymmetric deposition in JET was presented [91]; a successful simulation is achieved by introducing reflection of carbon at the walls above some critical temperature (~ 5 - 10eV).

D Heating, Current Drive and Fuelling

The key to steady-state operation is non-inductive current drive. Advances in the realism of the geometric and physics treatments, together with integration of various modules in a self-consistent manner, has been achieved - this is highly dependent on increased computational resources.

Full-wave treatments of ICRH and LH waves with self-consistent energetic particle distributions are now feasible. Thus 3D modelling for LHD accounting for the complex phase-space of the fast-particle distributions is possible [92]. These calculations show satisfactory agreement with the fast-particle energy spectrum detected by the NDD NPA diagnostic. In [93] it is shown, using the AORSA code, that parasitic absorption on alphas for ICRF at 56MGHz in ITER is low, < 5%. However, damping on fast neutral beam ions of high harmonic fast waves in NSTX is 59%. The full wave code TORIC for LH waves has been validated on C-Mod; it shows that diffraction suffices to fill the spectral gap, with damping at (2 - 3)v_{the} [93].

Relativistic treatments of EC and EBW (electron Bernstein waves) propagation and absorption in the presence of supra-thermal tails were reported [94, 95]. Current drive in NSTX by EBW was examined [95]: it is found that a current drive efficiency, η_{CD} = 3.2 at r/a = 0.5 is possible, based on the Ohkawa mechanism, whereas nearer the centre, r/a = 0.2, η_{CD} = 1.9, resulting from the Fisch-Boozer mechanism. The role of EC waves in energy transport was explored [96, 97]. Thus it is shown that it could be significant for ITER in reversed shear mode operating at ~35 keV [96]. Using a self-consistent treatment of the effects of supra-thermal tails and wave transport, the process is found not to be important for thermal plasma in ITER, but might be significant with ECCD [97]. The use of low frequency RF and NBI current drive on high β devices such as FRCs, RFPs and spheromaks was also addressed [98].

Finally, a new theory for pellet ablation was presented and with comparisons with experimental data from DIII-D [99]. For inside launch the efficiency, η_{mod}, is 100%, compared to the experimental value, η_{exp} = 92%, the small discrepancy being due to a small ELM; however, for outboard launch, η_{mod} was much less, at 66%, compared with η_{exp} = 46%, the larger discrepancy being the result of a strong ELM.

3 Conclusions and Outlook

Considerable progress has been made since the previous Fusion Energy Conference in 2002. Increases in computing power, allied to growing basic understanding of the underlying physics, are paving the way for the realistic and soundly based calculations of confinement, stability, exhaust and current drive needed for ITER and the successful optimisation and development of fusion power plants.

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