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EU-US transport task force workshop on transport in fusion plasmas: transport near operational limits

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Abstract
This conference report summarizes the contributions to, and discussions at, the 9th EU-US transport task force workshop on 'transport in fusion plasmas: transport near operational limits', held in Córdoba, Spain, during 9–12 September 2002. The workshop was organized under three main headings: edge localized mode physics and confinement, profile dynamics and confinement and confinement near operational limits: density and beta limits; this report follows the same structure.

1. Introduction

The workshop on 'transport in fusion plasmas: transport near operational limits', was held in Córdoba, Spain, a city of long cultural tradition, during 9–12 September 2002, with EURATOM-CIEMAT as hosts and Hidalgo acting as scientific secretary. This was the ninth in a series of joint EU-US transport task force (TTF) workshops; the previous one in the EU was held in Varenna, Italy in 2000, while the last one in the US was in Fairbanks, Alaska in 2001. The current chairs of the EU and US TTFs are Connor and P Terry, respectively.

The scientific programme of this workshop was organized under three headings: edge localized mode (ELM) physics and confinement, organized by Loarte (experiments) and Connor (theory); profile dynamics and confinement, organized jointly by Garbet and Mantica; and confinement near operational limits: density and beta limits, led by Greenwald and

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Giannone. The organizers above were responsible for arranging overview talks and selecting a balanced programme of oral contributions for their sessions; other contributions were presented in a common poster session. They also chaired their respective sessions and led lengthy discussion periods on their topics before presenting action plans at the closing session of the workshop. In total, there were six invited talks, 33 oral presentations and 29 posters; 67 participants attended.

In order to promote new ideas and a free discussion, it was agreed not to publish full proceedings of the workshop (although there is information on the abstracts and some of the presentations on the workshop web-site http://www-fusion.ciemat.es/ttf2002/), but rather to prepare a conference report for publication in a plasma physics journal. Thus, this report summarizes the contributions and draws some conclusions from the workshop, the following sections being aligned with the three topic headings listed above.

2. ELM physics and confinement

In H-mode plasmas an edge transport barrier forms, leading to steep edge gradients of plasma pressure. The plasma parameters at the interior boundary of this barrier are known as the pedestal values; high values of the temperature pedestal are crucial for good core confinement, at least for ‘stiff’ profiles controlled by critical gradients. However, these steep, edge pressure gradients lead to repetitive relaxations of the plasma edge, known as ELMs, believed to be associated with MHD instability. ELMs play a beneficial role in controlling particle and impurity content to enable steady state operation, but have adverse effects on other aspects of tokamak performance. On the one hand they degrade confinement, on the other, they lead to transient heat loads on the divertor target plates that may cause unacceptable damage in a burning plasma scale tokamak. Understanding and controlling ELMs is thus a key issue for such devices. The sessions on ELMs and the related edge pedestals contained experimental and theoretical contributions on these topics and these are reported separately below.

2.1. Experimental studies of ELMs and edge pedestals

The experimental characteristics of pedestal plasmas and the plasma energy and particle losses due to Type I ELMs in tokamaks were reviewed by G Saibene. Type I ELMs cause a fast ($\sim$200 μs) decrease of the plasma density and temperature in the outermost part ($r/a = 10$–25%) of the main plasma, which leads to the expulsion of $\Delta W_{\mathrm{ELM}} = 3$–10% of the plasma energy onto the divertor and main chamber walls. Increasing the pedestal plasma density, n_{ped}, not only decreases ΔW_{ELM} but also changes the transport mechanisms that determine this loss. At low n_{ped}, about two thirds of ΔW_{ELM} is due to the decrease of the edge plasma temperature at the ELM (i.e. by conduction), while at high n_{ped} the plasma temperature decrease at the ELM becomes very small and ΔW_{ELM} is dominated by the particle losses (i.e. by convection).

Purely convective Type I ELMs (i.e. no change in T_{e} at the ELM) have been observed both in JET and DIII-D. Examination of the density and temperature profiles before and after the ELM in JET and DIII-D, reveals that the decrease of ΔW_{ELM} with increasing n_{ped} is not driven by the reduction of the plasma volume affected by the ELMs, but is due to a decrease of the size of (mostly) the temperature perturbation in this volume. The ELM-affected volume is influenced by the shape of the plasma, namely smaller volumes are involved for more shaped (i.e. more triangular) plasmas, in qualitative agreement with predictions of the peeling–ballooning model of the ELM trigger [1].

Analysis of ELM energy losses in various plasma conditions from ASDEX Upgrade, DIII-D, JET and JT-60U has shown that the ELM energy losses normalized to the pedestal energy ($3n_{\mathrm{ped}}T_{\mathrm{ped}}V$, where V is the plasma volume) are well correlated with the pedestal plasma collisionality. Two physical processes are thought to be responsible for this dependence: (a) changes in the edge bootstrap current with collisionality affecting the ELM trigger and (b) the transport of energy during the ELM crash being affected by the pedestal plasma collisionality. Research is ongoing to determine which is the dominant physical mechanism behind this empirical correlation.

Contrary to the case of ELM energy losses, ELM power losses (i.e. $f_{\mathrm{ELM}} \times \Delta W_{\mathrm{ELM}}$, where f_{ELM} is the ELM frequency) depend weakly on pedestal plasma parameters and are typically ~40% of the plasma input power. Deviations from this value are observed in regimes with additional energy losses between ELMs, such as mixed Type I-Type II ELMs in JET and ASDEX Upgrade.

An important issue for next step devices is not only the relative ELM size with respect to the pedestal energy but also the absolute ELM size, which is influenced by the relation between the total plasma energy and the pedestal energy. Measurements from JET, DIII-D and ASDEX Upgrade show that the pedestal energy accounts typically for 20–50% of the total plasma energy. With increasing triangularity the contribution of the pedestal to the total energy increases. Although this is a very complex issue that involves MHD stability, plasma profile stiffness, power deposition profiles etc, present experiments indicate that at typical ITER triangularities (~0.5), more than 40% of the plasma energy will come from the pedestal contribution, which is somewhat higher than previous estimates (~30%) and has obvious implications for the ΔW_{ELM} expected in ITER.

Two other poster presentations dealt with detailed measurements of the pedestal plasma and the ELM particle losses in tokamaks. In the first, M Beurskens presented an analysis of temperature and density pedestal gradients and widths in JET. The typical pedestal widths in JET 2MA Type I ELMy H-modes are 2–4 cm and increase with plasma density. For a similar density (normalized to the Greenwald density limit, $n_{\mathrm{G}} \propto I_{\mathrm{p}}/a^2$, where I_{p} is the plasma current and a the minor radius) the density pedestal width decreases with plasma current as $\sim I_{\mathrm{p}}^{-1.5}$, which is in agreement with both the larger pressure gradient from MHD stability at larger currents and the larger neutral ionization mean free path at the plasma edge of lower current discharges. In the second, I Nunes presented an analysis of reflectometry measurements at the inner and outer mid-plane during the ELM-induced plasma density collapse in ASDEX Upgrade. Two new major results concerning ELM physics were shown in this presentation: (a) the ELM plasma density collapse starts at the outer mid-plane and follows ~50–70 μs later at the inner mid-plane; and (b) the collapse of the density profiles caused by the ELM is not symmetric; the ELM-affected radius at the outer mid-plane is typically 20–30% of the plasma minor radius, while it is only 10–15% at the inner mid-plane. These observations provide the clearest experimental confirmation so far of the ballooning nature of the ELM trigger and are in good agreement with expectations from the peeling–ballooning physics picture for the ELM instability.

The experimental characterization of the transport of energy and particles lost from the main plasma towards the plasma facing components (PFCs) during ELMs was reviewed by M Fenstermacher. DIII-D experiments in near double-null plasmas indicate that ELM particle and energy fluxes originate in the outer region of the plasma (in agreement with the ballooning nature of the ELM trigger) from whence ions and electrons travel along and across the field to the divertor target and main chamber PFCs. Measurements of ELM divertor particle and power fluxes are consistent with the formation of a high temperature sheath at the target during the ELM. Hence, the duration of the divertor ELM energy flux pulse is correlated with the ion parallel transport time from the pedestal to the divertor and not with the duration of the ELM MHD instability. The power deposition width at the outer divertor during ELMs is not significantly broader than between ELMs (at most a factor of 2), which indicates that anomalous transport at the ELM increases in similar proportion to the parallel transport. Observations at the inner divertor show more scatter between experiments. This is probably due to the inner divertor being in various states of plasma recycling (high recycling or detached) in different experiments. In DIII-D, where the inner divertor is usually detached, transient re-attachment is observed at the ELMs from fast measurements of the D_α and CIII emission. This detachment between ELMs and attachment at the ELM is consistent with the decrease of divertor power flux width at the ELM seen at the inner divertor in DIII-D.

An unresolved issue concerning the ELM energy fluxes is the in/out ELM asymmetry. Some experiments (ASDEX Upgrade and DIII-D) show a larger energy flux to the inner divertor during ELMs, while in others, such as JET, the ELM energy flux is more in/out balanced. A possible explanation for this is that the asymmetry of the divertor between ELMs causes this imbalance through the influence of the sheath on the ELM power flow. Besides the large power and particle fluxes to the divertor, ELMs also cause significant radial particle fluxes, which reach the main chamber walls. At present, it is not clear how much energy flows during ELMs to the main chamber walls together with these particle fluxes. Divertor ELM energy measurements indicate that it may be in the region (30–50%) ΔW_{ELM}.

The issue of main chamber particle fluxes and anomalous scrape-off layer (SOL) transport during ELMs at JET was discussed in detail in a presentation by B Gonçalves. Measurements of the SOL density profile with Langmuir probes during JET ELMs show a large increase (a factor of 2–4) of the plasma density very far out in the SOL ($\sim$7 cm from the separatrix at the probe position). The enhanced particle transport during ELMs is characterized by large density perturbations that propagate at radial velocities of $\sim$1 km s^{-1}. Thus, the characteristic time for ion radial transport to the wall during ELMs ($\sim$100 μs) is similar or shorter than along the field from the pedestal to the divertor target ($\sim$300 μs) and ions may reach the main chamber wall before the divertor target. This radial propagation velocity of the ELM-expelled particles is in reasonable agreement with that deduced from $\boldsymbol{E} \times \boldsymbol{B}$ SOL turbulence measurements. Furthermore, the radial velocity of these particles is well correlated with the 'ELM size' as determined by the ELM-induced radial density gradients in the SOL, with larger radial velocities for 'larger' ELMs. These observations are similar to those of 'bursty' SOL turbulent transport but with the ELM events being of a larger size and propagating at larger velocities. This indicates that similar mechanisms operate in the radial propagation of density 'blobs' [2] (see section 4) in the SOL independently of the origin of the blobs (turbulence or ELMs).

The important issues of ELM control and the study of alternative H-mode regimes without ELMs were dealt with in presentations by Y Martin and W Suttrop, respectively. Experiments in TCV Type III ELMy H-modes have shown that the 'natural' ELM frequency can be modified by cyclic up/down displacement of the plasma vertical position by $\sim$5 mm. ELMs are triggered in the up-movement phase, consistent with the increase of edge current density caused by the plasma movement. This method is effective in de-synchronizing the ELM from other perturbations such as sawteeth.

Suttrop reported on ASDEX Upgrade experiments to reproduce stationary ELM-free H-modes, such as the enhanced D_α (EDA) mode observed on Alcator C-Mod and the quiescent H-mode (QH-mode) observed on DIII-D. The strategy followed to reproduce the EDA mode is based on the achievement of discharges with pedestal plasmas similar to C-Mod in dimensionless parameters (normalized gyro-radius, ρ^*, collisionality, ν^* and plasma beta, β), but has proven unsuccessful due to the impossibility of achieving C-Mod collisionalities in

ELM-free regimes in ASDEX Upgrade. In contrast, the attempts to reproduce the DIII-D QH-mode have been very successful. Here, the DIII-D scheme has been reproduced in ASDEX Upgrade (a reversed I_p, NBI counter-injection, reversed toroidal field, B_t, high clearance configuration with strong pumping) and QH-mode phases of up to 2 s have been obtained. Similar to DIII-D, an edge harmonic oscillation (EHO) with a ~10 kHz frequency has also been observed. Studies in ASDEX Upgrade have revealed that the EHO is the envelope of a bursty high frequency activity (~350 and 490 Hz) believed to be caused by the destabilization of modes with toroidal mode number $n = 12$ by fast ions. The main problems to be resolved in this regime remain the low plasma density and the large impurity content of these discharges (effective charge, $Z_\mathrm{eff} \sim 5$).

ELMs are not only observed in tokamaks but also in stellarators, with a decrease of the plasma density and temperature and power/particle fluxes to plasma facing components, qualitatively similar to those in tokamaks. Understanding the physics behind such ‘current-free’ stellarator ELMs remains an outstanding theoretical challenge. H Thomsen presented measurements of ELM particle fluxes to the island divertor in W7-AS. Apart from specific geometric issues, the ELM particle fluxes have very similar characteristics to tokamak ELMs (rise time of the H_α emission ~1 ms and enhancement of ELM particle fluxes ~2.5, typical of small tokamak ELMs). The similarities of ELMs in tokamaks and stellarators extend also to the radial propagation of particle fluxes during ELM-like events, as shown for the TJ-II stellarator in a poster presentation by M Pedrosa. For discharges with reduced magnetic well (0.2%) ELM-like events are observed, which lead to large radial particle fluxes with propagation velocities ~1 km s^{-1}, similar to those reported for JET ELMs.

2.2. *Theories of ELMs and edge pedestals*

This sub-session was introduced by an invited paper from P Diamond (presented by Connor, in his absence). This presentation first discussed generic issues for theoretical modelling of the edge plasma pedestal and ELMs: what physical scale sets the pedestal width, what transport processes and relaxations occur in the pedestal, what causes the fast ELM crash in the context of the peeling–ballooning MHD stability model? It then proceeded to describe a bi-stable sand-pile model for these phenomena. This model contains three critical gradients: one for the onset of L-mode transport, one for flow shear stabilization of this transport and one hard limit for the onset of MHD instability, i.e. ballooning modes.

Above a critical fuelling rate, this sand-pile model leads to the spontaneous development of an edge pedestal, whose width increases with the rate without obvious limit; this width bears no relation to any physical scale. In the core, transport involves large avalanche events (corresponding to L-mode), but these stop at the pedestal shoulder. In the pedestal, transport is non-local, determined by the requirement of marginality to ideal MHD ballooning modes. However, small intermittent bursts, or avalanches (edge relaxation phenomena, termed ERPs), occur there. Large ERPs leading to a pedestal collapse can only occur after a long period of quiescence and are rare: ERPs are not an explanation of ELMs. Thus, the ‘large-event’ portion of the avalanche spectrum is dominated by the core: in the pedestal this portion is depleted and the high frequency, f, part, the ERPs, is increased. In short, the pedestal shields the edge from the core avalanches and removes the $1/f$ range, characteristic of self-organized criticality (SOC), in the avalanche spectrum. Inclusion of diffusion in the model can reduce the ERPs and more ELM-like events can occur.

Following this description of the sand-pile study, Diamond raised a number of more general questions: Is an ELM a ‘mode’ (e.g. as in the peeling–ballooning model) or an avalanche, or are there aspects of both? How does the bifurcation to a strongly unstable state leading to a fast ELM crash occur? He also proposed a more complete ELM model, building on an earlier zero-dimensional one [3] that followed the self-consistent evolution of pressure gradient, drift wave and ballooning mode turbulence levels and the radial electric field that suppresses the turbulence. This improved model would be one-dimensional and incorporate peeling mode dynamics, including the effects of a turbulent hyper-resistivity. More speculatively, he suggested developing a non-linear MHD peeling model capable of bifurcation in order to describe fast ELM crashes.

R Sánchez presented ideas related to those of Diamond, modelling L-mode, H-mode pedestal and ELMs by introducing diffusion into a sand-pile model—a 'diffusive, running sand-pile'. The behaviour of the model is characterized by the parameter D/Γ, the ratio of diffusion coefficient to fuelling rate Γ. For low values of this parameter an 'L-mode' solution with a SOC edge and a diffusive core emerges, the width of the edge region increasing with Γ. However, increasing Γ also leads to a supercritical edge. The model mimics an L–H transition by associating this steep edge with shear suppression of transport. As a result, a diffusive pedestal, whose width increases with Γ, develops. Finally, Type I ELMs can be modelled by introducing a further critical gradient for the triggering of MHD relaxations.

A poster by L Garcia did generalize to some extent the work of Lebedev *et al* mentioned by Diamond, by introducing the effects of particle and energy transport; it also included the effect of flow shear on the ballooning stability criterion. This model leads to a variety of dynamical behaviours, some of which correspond to experimental observations, and has the capacity to explore the radial structure and propagation of ELMs, as well as the associated losses of particles and energy. In another poster, B Van Milligen discussed the use of 'quiet-time' statistics, rather than 'waiting-time' statistics, as a potentially better indicator of SOC dynamics, but concluded it only provided a consistency test. Applications of this approach to edge fluxes in W7-AS and JET showed that these are indeed consistent with SOC.

An outline of the peeling–ballooning model and some detailed comparisons of the predictions of the model with DIII-D data, by P Snyder, were presented by Connor. Thus, the radial extent of the ELM-affected region and the onset time of ELM activity are consistent with linear stability and eigen-mode calculations with the ELITE code [4] when diamagnetic effects are included.

If the MHD stability is monitored as edge profiles are evolved by a transport code, it is possible to model the complete ELM cycle, a crash being triggered when a stability boundary is crossed. J Lönnroth described a study of the impact of gas-puffing on JET ELM activity using this approach. Experimentally, increasing the gas-puff produces a transition from Type I to the more frequent Type III ELMs, with an associated degradation in confinement. With increasing gas-puff, the edge collisionality increases and the bootstrap current decreases accordingly, leading to higher magnetic shear: this impacts on the MHD stability. The stability calculations show that at low gas-puff, the edge plasma is in the second ballooning stability region but strongly kink (or peeling) unstable; this situation corresponds to Type I ELMs. With increasing gas-puff the edge stability is controlled by the first stability boundary that corresponds to lower values of the ideal MHD ballooning stability parameter α, where $\alpha = -2(R\mu_0 q^2/B_t^2)(\mathrm{d}p/\mathrm{d}r)$ with R the tokamak major radius, q the safety factor and $\mathrm{d}p/\mathrm{d}r$ the pressure gradient. Following an ELM crash, the edge plasma recovers this lower value of α more rapidly, so that the ELM frequency increases in this case. This picture of a back transition from Type I to Type III ELMs with increasing gas-puff, is borne out by fully integrated transport-stability code modelling.

The heat load appearing transiently on the divertor plates due to an ELM event depends on the plasma energy deposited in the SOL by the ELM and its subsequent transport along the field lines to the plates. D Tskhakaya described kinetic simulations of the propagation of energetic particles produced by Type I ELMs in the JET SOL using a particle-in-cell (PIC) code. The code incorporates binary Coulomb collisions and collisions with neutrals, secondary electron emission due to ions and electron impact and sheath effects; at present the neutral and plasma temperature profiles are taken from the EDGE2D-NIMBUS fluid code [5]. The ELM-produced energetic particles provide a source and the divertor plates a sink of energetic particles. The simulations indicate that secondary electrons have little effect, but sheath effects are important in two ways: (i) the parallel heat flux exceeds the Spitzer-Härm value even in the collisional region; (ii) the potential drop in the sheath affects the timescale of heat loads on the divertor in the presence of the ELM. During the ELM there is a first, small heat load peak on the electron timescale due to high-energy electrons, followed by a main peak due to the arrival of energetic ions.

The description of supra-thermal electrons in the divertor plasma was addressed in a poster by O Bakunin. Because of the ballistic nature of their motion, their distribution function satisfies a non-local functional equation. Using an analytic closure for this equation based on a theory of correlations, he obtained an approximate solution for the electron velocity distribution as a Levy function: $F(v) \propto \nu^{-\gamma} F(1/\nu)$ where γ is a parameter.

The transient heat load on divertor target plates resulting from an ELM event (and indeed the continuous heat load during steady state exhaust) is partly controlled by cross-field transport in the SOL. There is experimental evidence that fast, convective radial transport due to coherent structures occurs, particularly in the far SOL region. These structures are associated with density blobs (see section 4). A theoretical model for such blobs was presented by S Benkadda, based on an interchange instability model for SOL turbulence; the model consists of the continuity and vorticity equations in the presence of shear flows. The focus was on the self-consistent evolution of a density perturbation; the situation modelled was a large amplitude density perturbation, of symmetric shape around the field direction. Numerical solutions showed this to evolve as a propagating pulse with the formation of a shock front and a tail as it convected radially. The role of parallel current loss due to sheath resistivity at the target plates was then investigated. Radial propagation and steepening still occur, but there is a reduction in the propagation velocity. The predicted signals for the particle flux as measured by a probe agree well with experimental measurements in the SOL.

The poster of S Yoon, which analysed transport of deuterium and carbon in ASDEX Upgrade, provided evidence for large transport in the far SOL. While deuterium transport is characterized by a diffusion coefficient of $\sim 0.1\,\mathrm{m^2\,s^{-1}}$ in the H-mode pedestal region and $\sim 0.5\,\mathrm{m^2\,s^{-1}}$ in L-mode, this rises to $\sim 10\,\mathrm{m^2\,s^{-1}}$ in the far SOL (for carbon an additional strong pinch velocity, $\sim 15\,\mathrm{m\,s^{-1}}$, is needed).

The simulation of transport due to resistive ballooning mode turbulence at the tokamak edge was described in a poster by P Beyer, who identified two types of structure: large scale radial transport events (or bursts) and zonal flows (poloidally and toroidally symmetric radially sheared plasma flows) which regulate transport levels. Adding a layer of stochastic magnetic field lines leads to a reduction of the zonal flows with the appearance of long lived eddies: i.e. the field perturbations do not quench the convective flux.

In the discussion session a number of issues and actions were identified. On the theoretical side these included experimental tests for validating the peeling–ballooning model for ELMs and further development of the model to a one-dimensional (i.e. radial) and time-dependent description to predict ΔW_{ELM} and ΔN_{ELM}, the total number of particles lost during an ELM (in particular explaining observations on the relative sizes of Δn_{ELM} and ΔT_{ELM}), and the theoretically challenging fast timescale of the ELM event. Experimental actions included further characterization and understanding of ΔW_{ELM} and ΔN_{ELM} and how these scale with ν^*_{ped} or n_{ped}/n_G; the relative fractions of ΔW_{ELM} and ΔN_{ELM} that are deposited on the main chamber as opposed to the divertor, which involves understanding perpendicular transport and the role of the sheath in parallel transport; the impact of ELMs on the energy confinement time, τ_E, and their possible links to the density limit; and developing and characterizing other ELM regimes, such as Type II ELMs, the EDA or QH-mode which could be suitable for ITER needs.

3. Profile dynamics and confinement

The session on profile dynamics and confinement was divided into sub-sessions: core heat transport, turbulence, internal transport barriers (ITBs) and improved core confinement and particle transport. This section will follow the same scheme.

3.1. Core heat transport

This sub-session was introduced with an overview by M Ottaviani on recent progress in transport theory and scaling laws for the dependence of transport coefficients on ρ^*, β, ν^* and q. The question of scaling laws is of prime importance in view of the need to extrapolate results towards a next step device. Analysis of the international experimental database suggests L-mode confinement has a Bohm-like scaling while H-mode core confinement appears to be gyro-Bohm (although the issue is still under discussion). However, electrons are always found to exhibit gyro-Bohm scaling and turbulence measurements show a gyro-Bohm character, while there is now agreement that theory predicts gyro-Bohm scaling in the limit of small ρ^*. It is crucial to clarify the uncertainties related to the Bohm scaling in L-mode and the suggestion was made to try enforcing the theoretically predicted gyro-Bohm scaling on the L-mode database to verify that there is indeed an incompatibility. The plasma current scaling may not be a true scaling, as it could come mainly from a dependence of an instability threshold on q.

The issue of stiffness was discussed extensively. It was remarked that steady state evidence for a temperature scale-length, L_T, independent of power in experiments where only the absolute value of power is varied, does not imply the existence of a threshold. More decisive tests are from experimental results with a variation of the heat deposition profiles, either in steady state or with perturbative techniques. Mantica presented results from JET modulation experiments in L-mode which provided evidence in favour of the onset of stiff transport in the electron channel above a critical value $R/L_T \sim 5.4$, in agreement with results previously obtained on ASDEX Upgrade, FTU and Tore Supra. The degree of stiffness has been quantified through the use of a semi-empirical model that has been proposed for use on different machines in order to facilitate inter-machine comparisons. Cold pulse experiments show that edge perturbations propagate to the plasma centre faster than predicted, even on the basis of a stiff model that explains the modulation data.

A Jacchia described results on steady state and modulation experiments from FTU where the heat deposition profile was varied using the flexibility of ECH. These results are all consistent with critical gradient-length driven transport where a correlation has been established between the value of the threshold and the parameter s/q (where s is the magnetic shear). This is in agreement with electron temperature gradient (ETG) theory predictions and findings on Tore Supra, although evidence more in favour of trapped electron modes (TEM) was found on ASDEX Upgrade, so the issue of TEM versus ETG is still open. Also, evidence for the presence of a heat pinch term is found in some cases with off-axis ECH on FTU.

T Luce, on the other hand, described modulation experiments on DIII-D in which no evidence for stiffness could be found. He stressed the role of damping and convective terms in the linearized heat transport equation, and the need to analyse a wide range of frequencies in order to identify the real value of the perturbative diffusivity, χ_e^{pert}. Analysis of DIII-D NBI heated discharges with ECH modulation in the outer half of the plasma yields $\chi_e^{\mathrm{pert}} \sim \chi_e^{\mathrm{PB}}$, the power balance diffusivity, consistent with a simple diffusive model featuring a constant χ.

V Andreev presented modelling of T-10 ECH switch-on and -off experiments based on a non-local assumption for the heat transport coefficients. The data are modelled satisfactorily assuming that at power switch-on or -off, the heat pinch velocity changes more rapidly than the characteristic time of the transient process, while the heat diffusivity remains unchanged. A poster by Mantica also provided evidence for the existence of heat convection. This presented modelling using the Weiland model [6], of earlier RTP data that provides evidence for a heat pinch, together with new experimental results from ASDEX Upgrade off-axis ECH experiments, suggesting the existence of a heat pinch velocity on the order of $2\,\mathrm{m\,s^{-1}}$ in the region inside the ECH deposition radius.

Successful modelling of experiments on RTP, both steady state and transient, using turbulence simulations by the CUTIE code [7] was shown in a poster by E Min. A poster by C Sozzi presented an alternative approach to the question of stiffness through the application of a profile-consistency model, based on stationary magnetic entropy [8], to both FTU and JET data. This model obtained a good fit for shots where there is evidence for the existence of a critical gradient threshold. F Imbeaux presented a poster on analytical solutions for the propagation of heat pulses with a temperature gradient-length dependent diffusion coefficient.

During the final discussion session some indications for future work emerged. These included: further investigation of stiffness, especially through inter-machine comparisons of experiments varying the power deposition profile, both in steady state and transient conditions, including H-mode plasmas; more work on the issue of coupled electron and ion transport; further improvement of transport models and their validation on existing data, including transients; further work on global scaling laws and their match to theoretical predictions; addressing the issue of modelling ‘odd features’ of electron transport (e.g. non-locality and a heat pinch) as a test for the physical mechanisms at work; and further investigation of the connection between transport and MHD phenomena.

3.2. *Turbulence*

The scaling of transport with, for example, ρ^*, β, and ν^* depends on the fluctuations responsible. Although turbulent simulations predict gyro-Bohm scaling at low ρ^*, as discussed by Ottaviani in section 3.1, there are significant departures from this at moderate values of ρ^*; these can be due to the diamagnetic part of the velocity shear (as pointed out by R Waltz), boundary conditions (e.g. edge physics) and possible non-local effects. The value of ρ^* below which the confinement is gyro-Bohm is still under investigation. Furthermore, it is not yet clear whether experimental results are all compatible with theory.

The dependence on β is an open issue and was extensively discussed throughout the meeting. Increasing β destabilizes kinetic ballooning modes (KBM), but also stabilizes ion temperature gradient (ITG) and TEM branches. In addition Shafranov shift effects are stabilizing (through the same physics as for the second stability regime). The latter effect is found to be dominant in NSTX as shown in the poster by C Bourdelle. On the other hand, some experimental results suggest that a destabilizing effect of β may be responsible for the density limit observed in tokamaks, as reviewed by Greenwald (see section 4). Similarly, the possible destabilization of the KBM raises the interesting question of the nature of the β limit in a fusion device: is it degraded transport or a ‘hard’ MHD limit?

The role of collisions is also subject to debate. Ion collisions may damp zonal flows and hence increase turbulent transport. On the other hand, electron collisions enforce electron adiabaticity, and therefore favour large amplitude zonal flows. It seems that electron collisions play a dominant effect in Alcator C-Mod as described by D Mikkelsen.

Determining the origin and nature of electron heat transport is still an open issue in spite of many recent experimental results. In particular, the respective role of TEM and small-scale ETG-driven modes is unclear. A simple mixing-length estimate of the electron heat diffusivity due to ETG modes yields a value that is much lower than the experimental one. Thus, the amplification of ETG transport by radially extended ‘streamers’ is crucial. Unfortunately turbulence simulations generate contradictory information. Recent gyro-fluid simulations show little amplification of ETG transport compared to a mixing-length estimate, in spite of the presence of streamers, as noted by Ottaviani. This contradicts previous results obtained with gyro-kinetic simulations [9]. In the domain of large scales, many simulations emphasize the role of TEM modes. It is found in particular that in DIII-D, ITG modes alone would be stabilized by $\boldsymbol{E}\times\boldsymbol{B}$ velocity shear. Fair agreement is found with experiment when TEM modes (with the right degree of collisionality) are included, as described by Waltz in his talk on the new global, gyro-kinetic simulation code GYRO. Simulations with a global, gyro-kinetic PIC code including electron dynamics were described in the poster submitted by J Lewandowski.

Structures play an important role in turbulent transport. It is widely believed that they are responsible for intermittency. Zonal flows and streamers are the structures that are quoted the most frequently. Zonal flows have a stabilizing effect on turbulence via a shearing effect while streamers enhance the turbulent transport. A poster by V Pavlenko demonstrated that turbulence can also generate fluctuations of the poloidal magnetic field (zonal fields) via a mechanism similar to the generation of zonal flows; these zonal fields are also stabilizing. Also avalanches have been found to be important since they allow fast relaxations of the profiles toward a marginal (possibly self-organized) state. Most turbulence simulations find one of several types of such structures.

On the experimental side, a wealth of information is found in studies of edge plasmas. In particular, a poster by M Hron (presented by Hidalgo) showed that the damping of poloidal velocity in the edge is due to a turbulent viscosity rather than to collisional friction. Conversely, the existence of structures in core plasmas is not yet fully proven. P Politzer presented evidence for avalanches in DIII-D. Small devices that are well equipped with fluctuation measurements provide useful information in this field. For instance, it was pointed out in both the poster by M Ramisch and the talk by U Stroth, that geodesic acoustic modes (GAM) have been observed in the stellarator TJ-K. These modes damp zonal flows, in agreement with turbulence simulations from a drift-Alfvèn code. It was also shown in the poster by C Lechte and the talk by Stroth, that in the same device the turbulence exhibits mainly drift wave characteristics with, nevertheless, some features of MHD interchange modes at low wave numbers. A poster by S Baeumel on two-dimensional electron cyclotron emission measurements on the stellarator W7-AS with ECH, described how these showed electron drift wave structures, in agreement with numerical simulations. Kelvin–Helmholtz and Rayleigh–Taylor instabilities have been studied in the linear device Mistral, as reported in the poster by J-V Paulsen.

For future work, the actions proposed deal essentially with clarifying the dimensionless scaling laws (in particular the dependence on β and ν^*), electron transport (the role of streamers and the respective contributions of TEM versus ETG modes), and a better understanding of the role of structures in the turbulence dynamics. The latter question raises the issue of a statistical description of turbulence.

3.3. ITBs

The physics of ITBs was reviewed by A (G) Sips. The question of triggering is still unclear. A common belief is that an inter-play occurs between stabilizing effects due to magnetic shear, Shafranov shift (and possibly impurities) and $\boldsymbol{E} \times \boldsymbol{B}$ velocity shear. It was reported that the magnetic shear seems to be the main ingredient in a number of devices: FTU (by E Barbato), TCV (by M Henderson) and Tore Supra and JET (by F Imbeaux). Interestingly, a similar conclusion was drawn for the TJ-II stellarator by F Castejón.

The role of low-order rational surfaces was emphasized in a poster on JET by Yu Baranov and another on TJ-II by B Zurro. A poster by A Chmyga (presented by Hidalgo) reported that a heavy ion beam probe has been used on TJ-II to measure the plasma potential. It was found that MHD modes generate bursts of potential. These perturbations may in turn affect the turbulence close to the resonant surfaces where these MHD modes are located. However, the work of C Fourment showed Shafranov shift effects do not seem to be important in triggering barriers in JET and Tore Supra, but do play a role in sustaining the barrier once it is formed.

The work of G Conway, reviewed by Sips, shows that low frequency turbulence decreases when an electron barrier appears in JET. This observation is consistent with stabilization of TEM modes. Finally, cold pulse propagation provides useful information on the nature of the transition. The amplification of the pulse amplitude observed in the outer part of the barrier is consistent with a ‘second-order’, rather than a ‘first-order’, phase transition, as pointed out by Mantica.

Once a barrier is triggered, rotational shear, bootstrap current and Shafranov shift increase and a self-amplifying process takes place. This process has been demonstrated in several calculations of predictive modelling of ITBs, as reported in talks by Barbato, Imbeaux and D Newmann and the poster by A Pankin. Imbeaux and Barbato also stressed that the non-inductively driven current must be accurately calculated since the magnetic shear plays a central role in ITB formation. Most of these models use simplified expressions to represent the stabilizing effects of the magnetic and velocity shears. Many ITB features can be reproduced this way. However, transport models are still far from providing a reliable prediction for the confinement in a next step device.

An important step in the direction of steady state hollow current profiles was achieved in TCV where it proved possible to produce plasmas with more than 100% bootstrap current (with counter ECCD).

Sips noted that two difficulties, at least, have been identified in terms of the relevance of ITBs for a reactor. First it seems difficult to reach high density ITBs, i.e. densities that approach the Greenwald limit. At the moment this remains an experimental fact: no theoretical explanation has been proposed. Another limitation comes from the impurity accumulation that often occurs when the density profile is peaked. Regarding this issue, it may be that a flat magnetic shear is more favourable than strongly reversed magnetic shear (as it produces less-peaked density profiles). Also such accumulation results from an unfavourable alignment of the density and temperature gradients in so far as their individual contributions to the direction of the impurity flux are concerned. Better control of the impurity influx in the edge may improve the situation.

The main question to be addressed in the future is the nature of the transition and the identification of the triggering parameters. This is a key issue for predicting a power threshold for ITBs in a next step device. Among several unresolved issues, the role of rational values of the minimum in q certainly deserves special attention. The questions of high density ITBs and impurity accumulation must also be addressed.

3.4. Particle transport

The topic of particle transport has begun to receive more consideration from both theoretical and experimental sides. L Garzotti summarized work carried out at JET in L- and H-mode plasmas, in the presence of mixed NBI + ICRH and pure ICRH heating (i.e. no core particle source). Modelling of both steady state and transient data provided by deep and shallow pellet injection shows the existence of an anomalous pinch in L-mode. The data can be reproduced using the Weiland model with off-diagonal and convective terms or using a mixed Bohm/gyro-Bohm model with an anomalous pinch velocity, v, that is $\sim$10 times larger than the neo-classical Ware pinch. It is not possible at the moment to identify whether such a pinch is mainly due to thermo-diffusion ($v \propto \nabla T/T$) or turbulent equi-partition ($v \propto \nabla q/q$) [10]. The results in H-mode are not as clear, possibly due to the lower values of the turbulence-driven particle diffusivity and pinch and to the higher value of the Ware pinch term.

Garbet presented a theoretical investigation of the anomalous particle pinch based on ITG/TEM turbulence. The pinch is generated by the dynamics of trapped electrons and is clearly evident in turbulence simulations with the three-dimensional fluid code TRB, yielding peaked density profiles in the absence of the Ware pinch and core particle sources. It is found that the dominant contribution to such a pinch term is due to turbulent equi-partition.

Terry presented a theoretical investigation of the issue of particle flux reversal in conditions of strongly sheared flow, as observed in DIII-D probe-induced shear layers. He showed that in conditions of magnetic shear and strong $\boldsymbol{E} \times \boldsymbol{B}$ flow shear, the interplay between the two can lead to a particle flux that reverses its sign at certain locations along the direction of the shear.

Particle transport studies in TCV were summarized in a poster by A Zabolotsky containing a detailed analysis of density profiles in TCV Ohmic L- and H-mode and ECH L-mode plasmas. The data suggest that both turbulent equi-partition and turbulent thermo-diffusion may contribute to building up the observed anomalous pinch velocity.

B Zurro presented a poster on experimental studies on TJ-II of impurity confinement, using laser ablation and a powerful x-ray camera to investigate the presence of topological structures and their possible influence on impurity transport.

Recommended actions include: experimental investigations of light impurity transport (Ne, N, and ^{4}He modulated gas-puff), and comparison with theoretical predictions for light impurity and main ion transport; comparing transport of non-recycled and recycled impurities; more perturbative particle transport studies; addressing the theoretical issue of the relation between transport of tracers and transport of main ions; more first-principle based modelling of impurity and particle transport experimental results; further investigation of the roles of the Ware and anomalous pinches, especially in H-mode; and addressing the issue of impurity accumulation and main ion transport in ITBs.

4. Confinement near operational limits: density and beta limits

This session began with an overview by Greenwald on the role of transport in causing the tokamak density limit. The basic phenomenology of the density limit was briefly reviewed along with a description of empirical scaling results. The main theme of the presentation was the search for the physical mechanisms that underlie the limit. While there is general agreement on the proximate cause for the disruptive limit; i.e. edge cooling followed by contraction of the current profile to a MHD-unstable state, the relative importance of the processes that lead to this cooling is still not clear. To date, most work on this subject has focused on radiation and power balance models that attempt to calculate the density threshold for various high-density phenomena like poloidal detachment, MARFEs or divertor detachment.

While these models have had some success, they have two principal drawbacks. First, the phenomena named do not necessarily occur at the density limit (for example divertor detachment is observed anywhere from 0.3 to 1 times the empirical limit). Second, they require assumptions about cross-field energy and particle transport that are often not supported by measurements. Results from experiments over a number of years have led some researchers to a hypothesis that attributes the density limit to changes in turbulence and transport.

Recent measurements of the SOL on Alcator C-Mod have focused on the dominance of cross-field transport in a wide range of edge and divertor phenomena. Two SOL regimes have been identified: the near-SOL with steep gradients, low transport and moderate fluctuation amplitudes, and the far-SOL with very flat gradients, high levels of transport and large, well-organized fluctuations (sometimes called blobs, see section 2). These structures can be imaged and are seen to have large outward radial velocities, in the range 0.4–1 km s^{-1}. As the density is raised, this region moves inward, crossing the separatrix and intruding into the main plasma at high density. In this picture, the density limit is associated with the degradation of edge transport and the destruction of the edge velocity shear layer that leads to strong edge cooling.

Some theoretical support has been offered by simulations appearing in [11] that find a regime of dramatically increased turbulence under conditions of high density and low temperature. Some quantitative confirmation for the simulations comes from ASDEX Upgrade where edge conditions near the density limit are reasonably close to the calculated boundary of the high transport region.

A theoretical model of the EDA mode of Alcator C-Mod was presented in a talk by A Rogister. It was shown that the parallel velocity gradient predicted by neo-classical theory for the $q_{95} \cong 3.4$ discharge is also close to the threshold value for the parallel velocity shear Kelvin–Helmholtz (PVS K–H) instability. The frequency and poloidal mode number of the threshold PVS K–H instability correspond to those of the coherent oscillation observed in the EDA mode. A non-linear model based on the assumption that anomalous transport keeps the plasma near marginal stability leads to the ratio of particle and energy confinement times, τ_p/τ_E, that is observed in the EDA mode.

The TEXTOR RI-mode (radiatively induced mode) uses impurity seeding to produce an improved confinement mode. The influence of gas-puff intensity on confinement was examined in a talk by D Kalupin. Usually, the transition to the RI-mode is attributed to a significant reduction of the ITG instability [12]. Alternatively, a large particle flux could influence drift wave instability-driven edge transport and result in impurity screening and a reduction of Z_{eff}. Calculations show that edge transport must be increased by a factor of 3 above that predicted by drift wave and dissipative TEM instabilities. This enhancement is attributed to the inclusion of ion-neutral friction that could be a further driving force for the drift wave instability.

Experimental results concerning impurity transport in high-density plasmas on FTU and JET were presented by M Valisa. The flattening of the density profile as the result of central deposition of 3 MW ICRH in addition to the original 10 MW NBI heating, suppresses the impurity accumulation of puffed Argon. In FTU, a 40% improvement in confinement time was achieved by Neon puffing. In this case, the avoidance of impurity accumulation is attributed to the reduction of impurity influx at the plasma boundary as a consequence of a reduced conducted power through the plasma edge that lowers the associated sputtering.

D Frigione presented a transport analysis of FTU high-density, pellet-fuelled discharges. Enhanced particle and energy confinement in sawtooth-stabilized discharges fuelled with multiple pellet injection has been achieved. In the post-pellet phase, the electron thermal diffusivity is significantly reduced and the ion channel, with thermal diffusivity values close to those expected from neo-classical theory, is dominant.

The mechanism of confinement degradation in DIII-D ELMy H-mode experiments when the density is raised was addressed by D Baker. The tearing mode free cases at lower densities are calculated to be just at the stability limit for the ITG drift wave. The simultaneous appearance of two or more neo-classical tearing modes (NTMs) causes the largest confinement degradation when raising the density. The analysis that shows the ion thermal diffusivity is now higher than the tearing mode free case suggests that the combination of ELMs, sawteeth and NTMs, rather than drift waves, is responsible for the degradation in confinement.

Aspects of transport in high normalized beta, β_N, discharges on ASDEX Upgrade was the subject of the talk by Y-S Na. An advanced H-mode scenario with β_N up to 3.5 under stationary conditions has been achieved. Transport simulations using the Weiland model are able to reproduce the q and T_i profiles well, but tend to overestimate the measured T_e profile. The presence of a strong $m = 3, n = 2$ NTM (m and n are the poloidal and toroidal mode numbers, respectively) was given as the limiting factor for confinement and β_N.

Density limit experiments in LHD were discussed by B Peterson. It was shown that the density limit is determined by the radiative collapse of the plasma and that the input power scaling is similar to the Sudo limit [13]. The formation of a poloidally asymmetric radiation structure similar to a MARFE, preceded by a thermal instability with shrinking temperature profiles, was described.

A theoretical model for the high-density H-mode (HDH) of operation in the W7-AS stellarator was presented by Y Igitkhanov. The formation of a density gradient at a sufficiently large gas-fuelling rate is proposed as the mechanism for generation of a radial electric field. This can then suppress plasma edge turbulence; the observed impurity shielding is explained in terms of plasma rotation.

On the basis of a simple radiation model for a one-dimensional plasma [14], a heuristic model for the density limit in stellarators was presented by Giannone. It is proposed that the high-beta discharges on W7-AS can be explained in terms of a model that combines the density limit and energy confinement scalings to derive a beta limit scaling. Steady state density limit discharges with 2 MW NBI heating for up to 1.4 s and hollow radiation profiles can be sustained in the HDH-mode.

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