13th EU-US Transport Task Force workshop on transport in fusion plasmas

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Abstract. This report summarises the contributions presented at the 13th EU-US Transport Task Force workshop on transport in fusion plasmas, held in Copenhagen, Denmark, September 1 - 4, 2008. There were sessions on: core heat and particle transport; core and edge momentum transport; edge and scrape-off-layer transport; and MHD and fast particle interaction with transport.

1 Introduction

This workshop on transport in fusion plasmas is the thirteenth in a series. Previously they have been held under the auspices of the EU and US Transport Task Forces (TTFs), with J Connor as the EU TTF chair. However, the EU Transport Task Force has now been subsumed into the EFDA (European Fusion Development Agreement) Topical Group for Transport (TTG), chaired by C. Hidalgo with C. Angioni and C. Bourdelle as vice-chairs, so that it is also the 1st meeting of that group. The TTG will stimulate cross-European and international collaboration to maximize efficiency through the creation of specific task oriented research projects. The creation of such research projects will be a key element in the TTG activities when the need is felt to focus efforts for a limited time on a specific question.

The previous workshop in Europe was held in Marseilles, France in 2006 [1]. The present workshop took place during September 1 - 4, 2008, in Copenhagen, Denmark, hosted and organised by the Association EURATOM – Risø DTU, in the National Laboratory for Sustainable Energy of the Technical University of Denmark, in cooperation with the European Physical Society, Plasma Physics Division. The meeting took place in the convention rooms of the engineering society convention centre. V. Naulin, assisted by J. J. Rasmussen and C. Munch Westergaard, chaired the local organising committee and Connor the scientific programme committee. There were sessions on: core heat and particle transport; core and edge momentum transport; edge and scrape-off-layer transport; and MHD and fast particle interaction with transport. The session on core heat and particle transport was organised by A. Peeters, while that on core and edge momentum transport was organised by T. Tala. The session on edge and scrape-off-layer transport was organised by A. Kirk, while A. Fasoli organised that on MHD and fast particle interaction with transport. These organisers solicited invited overviews, selected oral presentations and posters from the submitted abstracts, and chaired discussion periods for their respective sessions. The reports below are organised under the same headings as the above mentioned sessions.

2 **Core heat and particle transport** (A. G. Peeters)

The core heat and particle session consisted of 2 invited and 10 contributed oral talks, as well as 22 poster presentations. It covered a range of topics including the effect of rotation on heat and particle transport, simulation of inhomogeneous (global) turbulence, validation of turbulence models, multi-scale properties of turbulence, and improved measurement techniques, a well as some other miscellaneous subjects. Below these topics are discussed in some detail.

A. Bottino gave an overview of the European effort in global gyro-kinetic code simulations. The numerical tools include ORB5 (CRPP / IPP Garching), GYSELA (CEA), ELMFIRE (VTT/HUT), GYGLES and EUTERPE (IPP Greifswald). An important step forward in this area is the benchmarking effort performed under the EU Integrated Tokamak Modelling (ITM) Task Force. One of the highlight is the recently developed method of noise control in particle-in-cell (PIC) codes. The noise control is obtained through a modified Krook collision operator which damps the weights of the markers used, but does not influence the zonal flows (axi-symmetric, m = n = 0 plasma flows, where m and n are poloidal and toroidal mode numbers, respectively) Stationary turbulence simulations with a saturated noise level are possible through this development. The simulation tools have also been extended to include the physics of neo-classical transport (GYSELA), magnetic islands (ORB5), and the toroidal Alfvén eigenmode (GYGLES). Results from the US code GTS were presented by W. Lee; results of this code suggest the somewhat different view that the turbulent heat flux becomes independent of the gradients in the non-linear state.

Multiple space scales appear even within the local approximation through the difference in ion and electron Larmor radius. Non-linear simulations, based on the GENE code, of the coupled ITG/TEM/ETG (ion temperature gradient, trapped electron mode, electron temperature gradient) system were presented by T. Görler. For some parameters a scale separation takes place with ion and electron scale turbulence co-existing. The turbulent electron heat flux generated by the electron scale turbulence can be significant.

Several presentations dealt with the effect of rotation on the turbulent heat and particle transport (the transport of the momentum itself was discussed in a separate section, see section 3). Y. Camenen investigated the influence of a toroidal rotation on the heat and particle fluxes. The gyro-kinetic equations are formulated in the co-moving system, with the rotation entering through the Coriolis drift. For general tokamak parameters the influence of rotation on the heat and particle fluxes is small, but rotation can become important for impurity transport or for rapidly rotating plasmas like those of the spherical tokamak. K. Gentle presented experimental results from the Helimak device on the important topic of $\mathbf{E}\times\mathbf{B}$ shear suppression of turbulence. In contrast with common wisdom the velocity shearing did not appear to influence the turbulent fluctuations or the radial correlation lengths. R. Sanchez presented a theoretical study on the transport across a sheared poloidal flow, and found it was sub-diffusive. Quasi-linear theory could therefore greatly overestimate the fluxes in this case. Finally P. Mantica presented experiments from the JET tokamak on ion 'stiffness' and instability threshold behaviour. It was found that the threshold for the ion heat transport at low rotation is close to the gyro-kinetic prediction, but is significantly increased at higher values of the rotation. The increase in the threshold is larger than can be explained on the basis of $\mathbf{E}\times\mathbf{B}$ shear stabilization.

The poster by E. Highcock obtained an integral equation for ion temperature gradient (ITG) stability in the presence of sheared flows in slab geometry and presented results from the GS2 code on the stabilising effect of these flows. D. Newman investigated the effect of sheared flows on transport dynamics as characterised by a range of tools for determining the fractional transport exponent, applying this to simulations of drift wave transport in slab geometry and exploring scalings with the strength of this sheared flow. Coherent structures cause intermittent 'bursty' transport events; J. Anderson used a novel, non-perturbative analytic method to show how sheared flows reduce the tails of the PDFs (probability distribution functions) of the momentum flux due to such coherent structures in ITG turbulence. The excitation of zonal flows as an element in a transport code was explored in a poster by J. Weiland, using a simple example in which only the transport of poloidal momentum is considered.

The important subject of code validation was discussed in an invited talk by C. Holland, and a contributed oral by A. Casati. Holland stressed the need for synthetic diagnostics that allow for a direct comparison of experimental measurements and code results. Local GYRO simulations of DIII-D L-mode experiments match energy flows and (measured) fluctuation characteristics quite well at half radius, but significantly under-predict magnitudes at $\rho = 0.75$, where ρ is the normalised minor radius. The spatial structure of turbulence is, however, reproduced at both locations. Casati presented the results of a validation effort based on Tore Supra experiments and GYRO simulations. In this case quantitative agreement between experimental turbulence measurements and non-linear simulations was obtained for the effective heat diffusion coefficient, the RMS value of the density fluctuations and the poloidal and radial spectra of the density fluctuations.

In a poster Casati also described new quasi-linear gyro-kinetic transport model, QuaLiKiz, based on the fast linear electrostatic gyro-kinetic code KINEZERO and which can account for all unstable modes. The code has been tested for coupled ITG and trapped electron mode (TEM) turbulence against both local and global non-linear gyro-kinetic simulations from GYRO and GYSELA, as well as comparing the turbulent spectra against data from Tore Supra. A scan with respect to the ion-to-electron temperature ratio, T_i/T_e, recovers the improved performance at high values of T_i/T_e seen in Tore Supra and DIII-D. In order to validate turbulence theories, experimental measurements of the radial correlation properties of turbulence using micro-wave reflectometry were reported by T. Estrada. To provide a comparative study, these were performed on the stellarator TJ-II and the JET tokamak, the former using a broadband, two-channel, fast frequency hopping system, the latter four two-channel narrowband reflectometers.

In his presentation, D. Hatch pointed out that the discussion of turbulent transport in terms of the most unstable mode is incomplete. Stable and marginally stable eigenmodes are found to play a critical role in the saturation of turbulence and the resulting transport flux. An experimental study on non-diffusive transport in the LHD stellarator was presented by N. Tamura. The core ion temperature is found to abruptly increase in response to an edge perturbation generated by a tiny plastic pellet. These results were discussed within the framework of non-local transport.

D. Brower reported on first measurements of stochastic magnetic field driven particle fluxes in the core of the MST reversed field pinch (RFP), particularly during the sawtooth crash when the stochastic field resulting from tearing reconnection is strongest. Direct measurements are made using a newly developed differential interferometer in combination with a fast Faraday rotation system. Measurements show that the convective electron particle flux from the stochastic magnetic field can account for the equilibrium density change at the magnetic axis during reconnection. The electron particle flux arises primarily from the correlation between the radial magnetic field fluctuations and the electron density fluctuations, while the ion flux results from the correlation between density fluctuations and ion velocity fluctuations.

Several posters also reported on the effect of magnetic fluctuations. P. Guzdar presented measurements of these on the Maryland Centrifugal eXperiment (MCX), showing these are dominated by the convection of a low azimuthal mode number (mainly m = 2), though with a broad frequency spectrum. MHD code simulations of the primary unstable interchange instability in the rotating mirror geometry are able to reproduce these features. R. Lorenzini examined the effect of magnetic topology changes in the RFX-mod RFP device when the transition to a Quasi Single Helicity (QSH) state with a single helical magnetic axis occurs (named the SHAx state); this transition is found to provide enhanced thermal content. The effects of magnetic shear and anisotropy of the magnetic fluctuation spectrum on stochastic magnetic field transport were explored by M. Negrea, using the 'decorrelation trajectory' method which handles the trapping effect of the turbulent field.

Non-linear gyro-kinetic simulations of density peaking in H-mode plasmas in Alcator C-Mod were presented by D. Mikkelsen, showing agreement with the experimental data. An important ingredient in achieving agreement with C-Mod data appears to be having an electron temperature gradient that is steeper than that of the ions, a situation which is related to plasma collisionality; however this regime is not relevant to ITER or neutral beam injection (NBI) heated plasmas in ASDEX Upgrade or JET. The influence of high plasma beta, near the kinetic ballooning mode (KBM) stability boundary, on ITG and TEM driven transport, as well as the contribution from micro-tearing modes, was investigated by F. Jenko, using linear and non-linear gyro-kinetic simulations with GENE and comparisons with quasi-linear theory. A semi-analytic calculation of the quasi-linear transport fluxes associated with ITG and TEM turbulence based on a solution of the gyro-kinetic equation with a model pitch-angle scattering operator which is in agreement with gyro-kinetic simulations, was presented by I. Pusztai. In the collisionless limit the particle transport due to ITG modes is inward, due to magnetic curvature and thermo-diffusion, but can be reversed as electron collisions are introduced, provided the plasma is far from marginal stability. However near to marginal stability collisions may even enhance the inward transport. On the other hand the TEM driven flux is expected to be outward far from marginal instability and inwards otherwise.

Several posters addressed impurity transport. Thus C. Giroud characterised impurity transport in JET in terms of the resulting peaking: for electron density peaking factors from 1 to 1.3, those for Carbon and Neon remained below this value, whereas that for Argon varied between 1.2 and 1.7. The impurity diffusion coefficient is reduced within the region $r/a \sim 0.3$ by an order of magnitude compared to its value at mid-radius, but is an order of magnitude above the neo-classical value. Control of impurity peaking has been investigated using ion cyclotron resonance heating (ICRH); these experiments show a change of impurity convection from inwards to outward, but this is limited to the region $r/a < 0.25$. Transport studies of impurity and core transport in the RFX-mod RFP by I. Predebon have developed codes to address the effect of stochastic magnetic fields for the RFP multiple helicity states and transport at the high density limit. K. McClements presented test particle studies of collisional impurity (specifically Carbon) in equilibria with and without toroidal flows, representative of the spherical tokamak MAST. Transonic flows, for both co- and counter current directions, are found to substantially reduce the impurity confinement time. The charge dependence of anomalous impurity transport predicted by the ITG/TEM model has been investigated by S. Moradi; the model has been extended to include collisions between impurities and main ions and these effects appear to provide a dependence of the anomalous convection and peaking factor in qualitative agreement with experiment.

A range of other miscellaneous topics on core transport were presented as posters. G. Sánchez discussed the use of test particles as 'tracers' in distinguishing convective and diffusive contributions to transport and for studying aspects of non-diffusive transport within the framework of the 'Continuous Time Random Walk' method. The method was illustrated by using data from the CUTIE turbulence code; this study also led to some support for the dependence of transport on safety factor predicted by the phenomenological 'q-comb' model. Tracers were also used by J. Mier to examine the changes occurring in numerical simulations of dissipative trapped electron mode (DTEM) turbulence as the strength of a sub-dominant diffusive channel is increased relative to the turbulent one. It is found that there is a 'soft transition' in behaviour from that characteristic of self-organised criticality (SOC) to the dominant turbulent transport becoming diffusive. A model for electron temperature gradient (ETG) turbulence that captures the critical electron temperature gradient and the shear, s, and safety factor, q, dependencies found in gyro-kinetic simulations has been compared with data from the MAST spherical tokamak, as reported by W. Guttenfelder; the model can explain the electron thermal transport near mid-radius, $r/a \sim 0.4 - 0.6$. M. Marinucci described peaked density profile discharges in FTU employing a lithized wall. These discharges have low recycling and low impurity content ($Z_{eff} \sim 1$) and a spontaneous increase in density with line-average values near, or beyond, the Greenwald limit (by up to a factor 1.6) can often occur. Furthermore, in conjunction with lower hybrid (LH) and electron cyclotron resonance heating (ECRH) power at relatively low density, access to internal transport barriers (ITBs) is facilitated. There could be a link between the high edge temperature and the low level of MHD activity observed in lithized discharges. L. Vermare presented results on the scaling with dimensionless parameters (β, the normalised plasma pressure, ρ^* the normalised ion Larmor radius and ν^*, the normalised collision frequency) of turbulence and transport in Tore Supra L-mode discharges. A weak dependence of global confinement time on β is found ($B\tau_E \sim \beta^{-0.25}$) which is mirrored in both local thermal diffusivity and turbulence levels. On the other hand a non-negligible ν^* dependence is found, with $B\tau_E \sim \nu^{*-0.3}$; there is also a weak dependence in the effective local heat diffusivity and the fluctuation level. Preliminary scans with respect to ρ^* show a Bohm-like, or worse, scaling, but these discharges were almost in the Ohmic regime which can explain this behaviour. Finally I. Voitsekhovitch described transport studies in non-inductive current drive advanced scenarios with high β_N (β_N is a normalised β appropriate to MHD stability) in JET (transiently $\beta_N \sim 3$ has been achieved in monotonic or flat safety factor profiles and without an ITB). Interpretative TRANSP simulations show that 50-70% of current is driven non-inductively, half of it being due to the bootstrap current. Predictive transport simulations with the GLF23 model show that **E**×**B** flow shear plays an important role in the ion thermal transport and produces a 40% increase in ion temperature.

3 Core and edge momentum transport (T. Tala).

Momentum transport has been one of the most studied transport topics in the last couple of years as it is well-known that rotation affects both the plasma confinement and stability. In the session on core heat and particle transport (section 2), the impact of rotation on stiffness and the critical temperature gradient was discussed. The rotation also plays a very important, although not fully understood, role in the physics of internal transport barriers (ITBs). Although evidence of the influence of rotation on H mode and pedestal physics exists, many issues in understanding the role of rotation remain open. The session contained 2 invited and 8 oral presentations, together with 3 posters.

A review of experimental momentum transport was given by W. Solomon. He emphasised the importance of MHD, such as Alfvén eigenmodes, in redistributing the NBI driven fast ions and therefore, the necessity to include anomalous fast ion diffusion in the calculation of torque density profiles. Also, a zero toroidal velocity profile had resulted in plasmas with two counter-beams and one co-beam on DIII-D, an indication of a significant intrinsic rotation flowing in the co-current direction. Finally, using NBI perturbations, a sizeable inward momentum pinch was reported on DIII-D plasmas.

The theory review of momentum transport was given by A. Peeters. The main emphasis was on the derivation and roles of different terms in the momentum flux. In particular, derivations of the Coriolis pinch term were made using both fluid and kinetic approaches. The Coriolis drift depends linearly on the velocity and leads to the generation of parallel velocity fluctuations and eventually to a pinch of parallel momentum. The strongest parametric dependencies of the inward pinch are due to R/L_n, q and s (R is the tokamak major radius, L_n, the density scale-length, q the safety factor and s the magnetic shear).

Non-linear gyro-kinetic simulations have confirmed the quasi-linear results obtained from a large number of linear gyro-kinetic simulations. The TEP (turbulent equilibrium partition) part of the inward momentum pinch was extensively discussed and illustrated by T. S. Hahm. In the TEP theory, the inward pinch in the observed quantity $nU_{||}R$ is a consequence of a tendency towards homogenization of the locally conserved quantity $nU_{||}R/B^2$ ($U_{||}$ is the parallel flow, n the density and B the magnetic field). The role of the so-called residual stress in explaining part of the intrinsic rotation, in particular that originating within the edge transport barrier region, was also reported. Therefore, a pedestal width dependence of the toroidal flow is expected as a signature of the suggested mechanism. In the paper of I. Holod, global gyro-kinetic particle simulations (with the GTC code) of toroidal momentum transport driven by ITG turbulence were reported, and an inward momentum pinch was found in these simulations. The Prandtl number, P_r (the ratio of momentum diffusivity to the ion heat conductivity) obtained from the simulations was found to be in the range from 0.2 to 0.7, which is in agreement with quasi-linear estimate of P_r~0.7.

In addition to that on DIII-D, experimental evidence of an inward momentum pinch was also reported on JET by G. Tardini and NSTX by S. Kaye. A NBI modulation technique with Fourier decomposition was used on JET to infer the momentum pinch and diffusivity. This NBI modulation created an amplitude modulation of about 5% in toroidal rotation, while it is much smaller, 1-2%, for ion and electron temperatures. Prandtl numbers around one were reported. Inward pinch velocities of a similar order to JET were also reported on NSTX by following the toroidal rotation recovery after n=3 mode magnetic plasma braking. The inward momentum pinch from NSTX was in good agreement with the theory of both Peeters and Hahm at large R/L_n~1. At lower values, R/L_n~0.1, the experimental results still agreed relatively well with the theory by Peeters. It was also stated that the inferred momentum diffusivity is much larger than the neo-classical momentum diffusivity, i.e. $\chi_\phi >> \chi_{\phi,neo}$ even if the ion energy transport is neo-classical.

A significant decrease in the magnitude of intrinsic rotation in plasmas with LHCD (lower hybrid current drive) on C-Mod was reported by J. Rice. A clear drop in rotation (counter-rotation) was correlated with the drop in internal inductance, l_i on the right timescale. This is in contrast with an increase in rotation due to ICRH generally observed on C-Mod. Even more significantly, an increase in rotation (by a factor of roughly two) was achieved with ICRH using a mode conversion scheme, with respect to the usual ICRH minority heating scheme. ICRH driven intrinsic rotation in the co-current direction was also reported on ASDEX Upgrade by S. Assas. Intrinsic rotation was found to be insensitive to ρ^* and υ^* and weakly dependant on β_N, in disagreement with results from other tokamaks. Ö. Gürcan presented a way in which poloidal rotation may be important in understanding the origin of intrinsic rotation. A possible route for intrinsic toroidal rotation could originate from a poloidal Reynolds stress causing the poloidal rotation, which would then lead to a radial electric field, E_r, shear and thus symmetry breaking in the parallel Reynolds stress.

Concerning the L-H transition on JET reported by Y. Andrew, no evidence of a spin-up in poloidal velocity, v_θ, is measured prior to the L-H transition, although a clear, localised increase in both v_θ and toroidal velocity, v_ϕ, is recorded during the following H-mode phase. The H-L transition is preceded by the disappearance of any significant shear in v_θ and v_ϕ and the development of a flat E_r profile. Direct measurements of E_r using the Doppler backscattering diagnostics on Tore Supra were shown by E. Trier. A good agreement is observed between the predicted ripple-induced E_r using the neo-classical ambipolarity condition and the experimental measurements near the mid-plane region.

P. Manz presented measurements of the zonal-averaged Reynolds stress in the torsatron TJ-K. The Reynolds stress is measured with a poloidal probe array consisting of 128 Langmuir probes on 4 neighbouring flux surfaces, also enabling the calculation of the radial gradient. In the paper by P. Diamond (presented by T. S. Hahm), the possibility that SOL (scrape-off-layer) flows exert a turbulent viscous stress on the plasma near the separatrix was explored. A simple calculation suggests that in the SOL, the profile of parallel flow speed increases with distance from the separatrix. This is primarily a consequence of particle balance, density profile structure, and the effect of flows on the cross-field diffusivity. B. Labit presented toroidal velocity measurements obtained on the TORPEX device in the presence of turbulence and related structures associated with electrostatic instabilities, relevant to SOL conditions in tokamaks. It was found out that there is clear evidence that plasma blobs carry momentum when they propagate radially outwards. The toroidal velocity measured inside the blobs is constant along the radial trajectory and is equal to the velocity measured at the location where the blobs are created.

Significant progress has been achieved over the last few years in the area of momentum transport. In particular, the existence of an inward momentum pinch of significant size has been observed on many tokamaks and the theory of this momentum pinch is well established. A more open question is to understand the source of toroidal rotation, in particular the intrinsic rotation, for example the differences observed in different heating schemes. Significant improvements in measuring rotation velocities and the radial electric field in the pedestal region were also reported. Notwithstanding the rapid progress reported in many papers, momentum transport remains a high priority transport topic for the future.

4 Edge and scrape-off-layer transport (A. Kirk)

The high confinement mode of operation, or H-mode, is the standard operating regime envisaged for ITER. The high confinement is achieved due to a narrow, insulating region, or transport barrier, that forms at the plasma edge as the heating power is increased above a threshold level. The pressure rises steeply from the plasma edge through the transport barrier, to create a “pedestal” on which the core pressure sits. The pedestal is located near the last closed magnetic flux surface and typically extends over a width of less than 5–10% of the plasma minor radius. This session reviewed some of the major outstanding plasma physics questions associated with the properties of this narrow region and its influences on edge transport. It contained 2 invited, 8 oral presentations and 18 posters.

Recent experimental efforts to characterize the edge pedestal in order to test pedestal models, were reviewed by A. Leonard. Pedestal transport is characterized by edge pedestal profiles and the energy and particle fluxes through both the electron and ion channels. However, the short scale-lengths in the pedestal make it difficult to determine the transfer of energy between electrons and ions. Additionally the neutral ionization source, which can be significant within the pedestal, is also difficult to measure.

Pedestal scaling measurements are useful for providing insight for pedestal model development. While the ion gyro-radius would be expected to play a role in determining the pedestal width from several theoretical considerations, no ion gyro-radius dependence for the pedestal width has been observed in experimental measurements. Recent experimental results across several tokamaks have found the pedestal width to scale with the square root of the pedestal poloidal beta ($\sqrt{\beta_{pol}}$). The combination of this scaling with the edge MHD stability has allowed a predictive model of the pedestal height to be constructed.

In order to make further progress the models need to be tested across various devices and a theoretical motivation for the observed width scaling needs to be developed. W. Stacey discussed how the pedestal structure can be affected by angular momentum, SOL flows and drifts. Several other parameters, though, cannot be accounted for by any of the models and these include neutral penetration, toroidal field ripple or non-axisymmetric fields, which have been used for ELM (edge localized mode) control.

E. Nardon reviewed the current understanding of ELM control using resonant magnetic perturbations (RMPs), which is one of the techniques likely to be implemented in ITER. DIII-D have managed to suppress ELMs completely using an $n = 3$ magnetic perturbation from two rows of six coils located inside the vacuum vessel (I-coils). Full suppression only occurs if the edge safety factor, q_{95}, is in a certain window ($3.5 < q_{95} < 3.7$ typically), which highlights the resonant nature of the magnetic perturbation. Experiments have been performed on JET, MAST and NSTX using sets of mid-plane coils. Although an increase of ELM frequency has been observed, complete ELM suppression has not been achieved, suggesting that the poloidal location of the coils is important. There is evidence that the RMPs modify the transport and/or recycling conditions and a very characteristic feature observed in all the experiments is a pump-out of the plasma density. The temperature profiles typically have a smaller response to the RMPs than the density profile. A possible explanation for this, presented by M. Tokar, is that there is a reduction of perpendicular neo-classical transport due to a heat flux limit phenomenon.

On TEXTOR the turbulence characteristics observed during the application of RMPs were discussed by A. Krämer-Flecken. The presentation discussed the interaction of

RMPs with geodesic acoustic modes (GAMs) where a clear reduction of the GAM activity in the ergodic layer was observed but an increase of the GAM activity was found close to the resonant surface of the RMP. This may suggest that the GAM can be driven by the RMP at the resonant magnetic surface and gains energy from the RMP. P. Guzdar discussed the source of excitation of GAMs, in particular, how the calculations have been extended to include finite beta effects. Preliminary studies seem to indicate that GAMs are suppressed before the plasma reaches the L-H transition threshold.

The H-mode power threshold and the validation of H-mode threshold scaling laws is a very important issue for next step fusion devices, such as ITER. P. Gohil discussed how on DIII-D, the H-mode power threshold varies strongly with the applied beam torque which also strongly affects the edge turbulence and flow characteristics. Other ways of affecting the H-mode transition were also discussed. D. Löchel showed how the effect of the localized injection of neutrals can affect anomalous transport driven by drift-Alfvén (DA) and drift resistive ballooning (DRB) instabilities, in particular how different puffing positions lead to significantly larger losses at the low field side, and suggested that this could offer an explanation for the dependence of the L-H transition power threshold on the puffing position observed on MAST and COMPASS-D. C. Silva and M. Pedrosa showed how the interplay between long-range correlations and local turbulent transport has an effect on the GAM amplitude on ISTTOK and lead to an improved confinement regime on TJ-II.

Coherent structures, often referred to as blobs or filaments, have been detected emerging from the edge of the plasma on all magnetic confinement devices. O. Garcia discussed how the motion of these structures is influenced by collisional friction with the neutral gas fluid. In the inertial regime the radial filament velocity scales as the square root of its size, whereas in the limit of strong friction the velocity scales as the inverse of the structure size. On the experimental side, the presentations focused on the diagnosis of these structures using visible imaging (an oral presentation by S. Muller) and Langmuir probes (in the posters by F. Mehlmann, C. Theiler and N. Vianello). The data collected from these and other devices have been subjected to in-depth statistical analyses (in the posters by B. Hnat, J. Horacek, K. Rypdal), which underline the universality of the dependence of the motion of these structures on plasma boundary conditions. In order to get a detailed understanding of the dependence of the motion of these structures on plasma boundary conditions, modelling has been performed with a variety of codes. The results from edge fluid turbulence models such as BOUT (lead author P. Popovich), ESEL (by J. Seidl), ATTEMPT (by A. Nielsen) and the gyro-fluid code G-ESEL (also by A. Nielsen) are able to explain many of the experimental observations. T. Ribeiro investigated the effect of the X-point in the modelling. This indicated the importance of the local magnetic shear, which is not accounted for in all the models. J. Peterson made a comparison of the different numerical methods used for simulating the edge plasma and J. Madsen discussed the difficulties in constructing gyro-kinetic and gyro-fluid models for the edge region of magnetized plasmas in the presence of strong radial electric fields. Most of the modelling presented was for L-mode turbulence, but A. Kendl presented preliminary gyro-fluid computations of an ELM event, which highlighted the necessity to resolve the ion gyro-radius scale. B. Scott reviewed the work going on to develop a delta-f gyro-kinetic formulation of edge turbulence, which highlights the essential non-linearity of edge turbulence. D. Tskhakaya presented results on a kinetic study of the parallel transport and heat loads to the ITER divertor targets during ELMs using a 1D plasma plus 2D neutral PIC (particle-in-cell) code, which shows that most of the power to the divertor is carried by the ions.

In summary, the edge region of the plasma is still an active area of research. Over the last few years much has been learnt about the turbulence structures observed in this boundary region, however, we still do not understand the mechanism for their suppression during the L-H transition. In H-mode there now seems to be an experimental consensus that the barrier width scales with the square root of beta poloidal; however, there is no theoretical explanation for this scaling. Controlling ELMs is a crucial issue for future devices and some success has been obtained using resonant magnetic perturbations but again the understanding of the underlying mechanisms is poor, which in part is due to our lack of understanding of the H-mode transport barrier. In order to make progress coordinated experimental and theoretical studies need to be focused on this region.

5 MHD and fast particle interaction with transport (A. Fasoli)

In the area of MHD and fast particle physics, a number of crucial issues for the understanding and control of burning plasmas can be identified, related to the dynamics of fast ions and its implications for the plasma self-heating process. These issues can be divided into three main categories:

-the interaction of fast ions with low frequency MHD, in particular during the ramp-up phase of the discharge, and its effect on core pressure, current and impurity (Helium ash) profiles, and on the triggering of macroscopic MHD modes;

-the interaction of fast ions with turbulence;

-the interaction of fast ions with collective modes in the Alfvén range of frequencies.

This last one is arguably the most developed topic, and includes in turn two kinds of questions: those related to linear stability, i.e. which modes are unstable, in which plasma scenarios, and which parameters can be acted upon to control them, and those related to alpha particle redistribution and losses, i.e. how to predict and limit the consequences of nonlinear wave-particle interaction in different scenarios. This session contained an invited overview paper and 3 oral presentations, together with 3 posters.

In the overview paper opening the session, W. Heidbrink showed that in recent experiments on a linear plasma device (LAPD), the profile of a beam of fast ions is broadened by resonance with a shear Alfvén wave, in good agreement with conventional theory. Theoretically, coherent interactions with Alfvén waves can cause convective, diffusive, or avalanche transport; experimental evidence for all of these was shown, based on a new fast ion density profile diagnostic on the NSTX spherical tokamak. In the DIII-D tokamak, many unstable Alfvén eigenmodes (AEs) cause rapid fast ion transport. These cases correspond probably to the best diagnosed experiment on the fast ion redistribution by Alfvén waves. The mode structure, amplitude, frequency and mode number spectrum are extremely well measured, as well as the details of the profiles of the plasma parameters influencing the wave-particle interaction process. Nevertheless, the calculations of the expected transport using the measured wave fields underestimate the transport by a significant factor. Highly non-linear phenomena related to the frequency sweeping of the instabilities, leading to resonant interaction with more of the fast ion population might lead to better agreement with experiment.

In a subsequent oral presentation, F. Nabais presented the first measurements of fast ion losses at JET in the presence of sawtooth crashes and of MHD activity driven by fast particles (‘fishbones’, TAEs, i.e. toroidal AEs, and ‘tornado’ modes). The data was collected using a recently installed scintillator probe, which can measure the number of lost ions as a function of gyro-radius and pitch angle. Fast ions are created on JET using on-axis hydrogen minority ion cyclotron radio frequency (ICRF) heating ($P_{ICRH} < 8MW$), applied on a low density plasma. As observed in other tokamaks (e.g. JT-60U), the so-called tornado modes (core localised TAEs whose frequency sweeps rapidly inside the TAE gap) are very effective at expelling the fast ions with “potato” orbits originally located in a central plasma region. Unfortunately, the very limited information presently available on the internal mode structure prevents a quantitative comparison of the fast ion loss level with theoretical predictions, critically dependent upon the eigenfunction shape.

During the discussion following these two presentations, it was pointed out that it would be very beneficial to identify methods and conditions to perform experiments in which a redistribution of fast ions can be induced in a controlled fashion (e.g. by externally driven perturbations). Such experiments would generate ideal test cases to compare theoretical predictions and direct measurements of fast ion transport, addressing the reasons for the present discrepancies.

As the damping rate determines both the mode stability and the non-linear development, of fundamental importance for the fast ion redistribution, a major effort is being made to measure this quantity for modes that can be subject to resonant excitation by fast ions in burning plasmas. This was the subject of D. Testa’s poster, in particular for AEs with toroidal mode numbers, n, in the range n ~ 5-15, as these are expected to interact most strongly with the alpha particles in burning plasmas such as ITER. The experiments are performed on JET using the recently installed in-vessel antennas comprising two sets of 4 coils each. A large database of damping rates of Alfvén modes with intermediate-n has already been constructed. In contrast with the low-n case, modes are driven and detected throughout both the limiter and diverted phases of the plasmas discharges, demonstrating that intermediate mode number AEs, for which the eigenfunctions are less radially extended, are less prone to strong edge continuum damping. A fully quantitative comparison with theory, even for the linear stability predictions, requires improving the experimental knowledge of the mode internal structure, as well as that of the details of the density and safety factor profiles. In addition, single mode tracking, a unique feature of the JET active MHD system, will provide experimental scalings of AE damping rates with the relevant plasma parameters, thus validating the theoretical models to be used for ITER predictions.

An important parameter determining the physics of the interaction between fast ions and waves in plasmas is the fast ion Larmor radius normalised to the machine size (minor radius), ρ^*_{fast}. In present experiments such a parameter is relatively large, i.e. only a small proportion of fast ion orbits are contained in the devices. The opposite will be true in ITER and DEMO. Such a difference in ρ^*_{fast} is expected to lead to different wave-particle interaction regimes, and represents one of the motivations to develop a new experiment, named FAST. The FAST device should produce large fast ion populations in the MeV range using ICRF heating, with a value of ρ^*_{fast} in between that of present devices and ITER. The poster by C. Di Troia discussed such a proposal in terms of the fast ion transport and confinement that present theories predict for the FAST conceptual design.

An important element of fast ion physics, both in present and future devices, is the determination of the fast ion distribution. Experimental measurements are at present scarce, in particular for the confined ions, and call for a strong diagnostic effort. One aspect of such effort is the development of the collective Thomson scattering method, which in principle allows spatially, temporally and directionally resolved measurements of the velocity distribution function of confined fast ions. A feasibility study for ITER was presented in a poster by S. Korsholm, which concluded that the optimal configuration for ITER should be based on a sub-harmonic system. The proposed configuration consists of two 60GHz, 1MW gyrotron beams viewed by two fixed receiver arrays located on the low and high field sides of the plasma. This enables measurements of the perpendicular and the parallel components of the ion velocity distribution over the full plasma cross-section, with spatio-temporal resolutions on the order of a/10 and 40 ms. Such a proposal for ITER is based on experience from TEXTOR and ASDEX Upgrade work, which was reviewed by F. Meo in a poster, in which he also showed studies of the confinement and redistribution of fast ions generated by NBI and of the interaction between fast ions and sawteeth.

Electromagnetic modes can also be driven by supra-thermal features in the electron population, and even for this case there exist concerns as to whether or not such resonant interaction can lead to significant redistribution and losses. In his poster, A. Macor showed instabilities driven by the fast electron population at frequencies consistent with bounce precession fishbone dispersion relation, in discharges heated by LH waves ($P_{LH} \sim$ 1.2MW). These instabilities, detected by measuring electron temperature and density fluctuations, using fast-ECE (electron cyclotron emission) and reflectometry, are driven by fast electrons produced by LH heating. Regular frequency jumps are associated with strong periodical losses and redistribution of fast electrons.

The area of MHD and fast particle physics, interest in which is growing as we are moving towards the realisation of burning plasma regimes, was discussed for the first time in the context of the European TTF Meeting. A relatively small sub-group of the fast particle physics community was present, so the presentations and discussions could not cover the entire field. Instead, emphasis was placed on the issues that have a large degree of overlap with the more traditional, core business of the TTF community, namely transport and turbulence. In particular, the time was devoted to discussing and possibly identifying the limits of the conventional paradigm, according to which small-scale turbulence influences only thermal particles, while fast ions are only affected by semi-coherent, Alfvén frequency modes.

It is commonly accepted that a consistent description of the interaction between fast particle orbits and the background (small scale) turbulence is lacking. Several mechanisms can lead to deviations of the particle motion from the **E**×**B** drift. C. Angioni gave an oral contribution in which he discussed gyro-kinetic calculations of the transport of energetic alpha particles in the presence of background turbulence with a slowing down equilibrium distribution function in the trace limit, using the two gyro-kinetic codes, GS2 and GKW. The results were compared with those obtained in the case of an equivalent Maxwellian distribution. The dependence of the diffusion coefficient on the energy variable in the velocity space could be reconstructed. For electron temperatures below 20keV, the energetic alpha particle diffusivity is at least 20 times smaller than that of Helium ash. The alpha particles are transported only in the very slow energy range of the distribution, below the slowing down critical energy.

A slightly different approach was proposed by F. Jenko, who presented an oral contribution on the mechanisms for fast particle transport in 3D tokamak micro-turbulence. Depending on the time scales of the different kinds of motion, the validity of the orbit-averaging process should be put into question. Orbit-averaging has a very strong impact on transport. Resonant mechanisms between perpendicular fast particle drifts and diamagnetic drifts of the bulk plasma can be responsible for significant transport levels for intermediate energies. The simulation data provided the dependence of the particle diffusion coefficient on energy for different pitch angles and magnetic shear values. These results suggest that transport can be significant up to energies corresponding to about 10 times the thermal energy, then falls inversely proportional to the energy, a slower dependence than orbit-averaging effects would suggest.

Both theoretical approaches indicated that no clear explanation of the anomalous diffusion invoked to account for the anomalies observed in the current drive processes by NBI on ASDEX Upgrade can be given theoretically. As these anomalies are inferred from a rather indirect analysis process, a strong motivation exists for designing experiments in which test ions can be produced and inserted into turbulent fields, and whose trajectories, possibly in both 0configuration and velocity space, can be reconstructed experimentally.

References

[1] J. W. Connor et al., Nucl. Fusion.**47** (2007) 361-369.