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CONFERENCE REPORT

11th EU-US Transport Task Force workshop on transport in fusion plasmas

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Abstract
This report summarizes the contributions presented at the 11th EU–US Transport Task Force workshop on transport in fusion plasmas, held in Marseilles, France, 4–7 September, 2006[8]. There were sessions on momentum transport, multi-scale physics, electron transport, particle transport and transport in the scrape-off layer.

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1. Introduction

This workshop on transport in fusion plasmas is the eleventh in a series organized jointly under the auspices of the EU and US Transport Task Forces with Connor as the EU chair. The previous workshop in Europe was in Varenna, Italy, in 2004 [1]. The present workshop took place during 4–7 September, 2006, in Marseilles, France, hosted and organized by the Département de Recherches sur la Fusion Contrôlée, Association Euratom-CEA, in cooperation with the European Physical Society, Plasma Physics Division. C. Bourdelle, assisted by G.T. Hoang, chaired the local organizing committee. There were sessions on momentum transport, multi-scale physics, electron transport, particle transport and transport in the scrape-off layer (SOL). The session on momentum transport was organized by Hidalgo, while that on multi-scale physics was done by Diamond. Organization of the session on electron transport was shared by Mantica (experiment) and Hammett (theory). The session on particle and impurity transport was under the auspices of Angioni and that on transport in the SOL was organized by Loarte. These organizers solicited invited overviews, selected oral presentations and posters from the submitted abstracts and chaired discussion periods for their respective sessions. The reports below are organized under the same headings as the above-mentioned sessions.

[8] The present workshop: http://www-fusion-magnetique.cea.fr/ttf2006/.

2. Momentum transport (C. Hidalgo)

Momentum transport is an important issue in magnetically confined plasmas. Plasma rotation controlled by momentum transport plays a key role in both confinement (e.g. development of transport barriers) and MHD stability (e.g. enhancing the stabilizing effect on resistive wall modes). Rotation can be driven by external forces such as momentum from neutral beam injection (NBI). However, in large-scale devices such as ITER (where the available NBI power is limited and the energy of injected neutrals must be high to reach the core plasma region) the NBI driven rotation will be limited. From this perspective, it is important to study the possible roles of other mechanisms which can drive plasma rotation.

Reviews of momentum transport from the experimental and theoretical (including neoclassical and turbulent mechanisms) perspectives were presented by K. Ida and A.G. Peeters, respectively. The physics mechanisms underlying the non-diffusive terms for momentum transport (off-diagonal terms of the transport matrix) and spontaneous rotation were discussed by Ida in relation to the radial electric field and the symmetry of the plasma, based on experiments in plasma devices with both toroidal symmetry (tokamak) and helical symmetry (stellarators). Amongst the physics mechanisms determining spontaneous rotation, the radial electric field, E_r, and symmetry of the plasma are important elements, as well as momentum viscosity, because the $\boldsymbol{E} \times \boldsymbol{B}$ drift is a driving term and the parallel and perpendicular viscosities are drag terms, and the direction of the spontaneous rotation is sensitive to the viscosity tensor.

In parallel, the improvement in plasma modelling tools allows a better study of the complex coupling between profiles, plasma flows and turbulence. The possible role of the Reynolds stress components ($\langle \tilde{v}_r \tilde{v}_\theta \rangle$ and $\langle \tilde{v}_r \tilde{v}_\parallel \rangle$) generated by the turbulence in the self-organization of plasma toroidal/poloidal rotation profiles was discussed. The importance of symmetry breaking mechanisms (via sheared electric fields) on parallel momentum driven by turbulence was emphasized by Peeters, T.S. Hahm and Diamond. The quasi-linear theory of turbulent generation of spontaneous toroidal rotation was presented by Ö.D. Gurcan.

An inter-machine comparison of intrinsic toroidal rotation was presented by J.E. Rice. The intrinsic rotation velocity has been found to increase with plasma stored energy or ion pressure in JET, Alcator C-Mod, Tore Supra, DIII-D, JT-60U and TCV and to decrease with plasma current in some of these cases. Utilizing dimensionless parameters has led to a somewhat unifying scaling: $M_A \propto \beta_N$, where M_A is the Alfvénic Mach Number and β_N the normalized plasma β. Other scalings of the intrinsic rotation velocity show no correlation with collisionality or normalized gyroradius. For an ITER discharge with $\beta_N = 2.6$, an intrinsic rotation $M_A = 0.02$ may be expected from the above scaling, possibly high enough to stabilize resistive wall modes without external momentum input.

An overview of intrinsic toroidal rotation measurements in Tore Supra, performed in various heating regimes (ohmic, OH, lower hybrid, LH, ion cyclotron resonance, ICRH, heated plasmas), without any external torque was presented by C. Fenzi-Bonizec. In particular, ICRH plasmas (co-rotation) exhibit good correlation between plasma toroidal rotation and energy confinement, as already observed in other devices. However, changes in toroidal velocity do not always scale like $W_{\rm dia}/I_{\rm p}$, the ratio of stored energy to plasma current, showing better correlation with the evolution of ion temperature, $T_{\rm i}$. ICRH (counter-rotation) results are consistent with fast ion losses. Correlations between toroidal momentum and heat transport in ASDEX Upgrade (AUG) were reported by Angioni. Experimental findings show a strong link between the ion heat and momentum diffusivities. Such a link can lead to a feedback loop on confinement degradation via the reduction of $\boldsymbol{E} \times \boldsymbol{B}$ sheared flows.

Mantica reported toroidal and poloidal momentum transport studies in JET. Charge exchange (CX) measurements of impurity ion poloidal rotation velocity in JET plasmas with an internal transport barrier (ITB) show strong local spin-up at radial positions with the steep gradients in ion temperature and toroidal rotation velocity (v_ϕ) associated with an ITB. Poloidal rotation measurements an order of magnitude higher than the neoclassical predictions for thermal particles across internal transport barriers have been reported in the JET tokamak. In addition, poloidal rotation measurements have been recently compared with neoclassical theory predictions in the DIII-D tokamak, showing significant discrepancy. Poloidal rotation driven by turbulence (via Reynolds stress) is a candidate for explaining the JET and DIII-D experimental findings. These findings support the idea of a non-neoclassical origin for the poloidal flow, although a critical test of neoclassical theory is still needed. The toroidal momentum confinement time scales with the ion energy replacement time in JET. However, the local momentum diffusivity is always lower than the ion heat diffusivity and in addition toroidal rotation profiles are broader than ion temperature profiles in H-mode regimes.

The use of probe arrays and, more recently, 2D beam emission spectroscopy and fast visible cameras has permitted a transition from mostly single point measurements to 2D visualizations. This improvement in plasma diagnostics is providing a route to a better understanding of edge turbulence and momentum transport. Fast visible imaging of plasma edge has recently been used to investigate 2D electrostatic plasma turbulence in the NSTX spherical tokamak (C.E. Bush) and the TJ-II stellarator (A.J. Alonso). This method is used to characterize the turbulent structure's geometry and polarity in different poloidal velocity shear regimes. As the shear is increased in TJ-II, structures became stretched. An ordering effect of the shear is also observed, the structures becoming oriented in roughly the poloidal direction of the magnetic surfaces. NSTX L- and H-mode recordings were analysed. Fewer structures are detected in H-mode recordings than in the L-mode ones. Their elongation and ordering is noticeably higher than those of the structures found in L-mode plasmas, in analogy with TJ-II regimes with and without sheared flow in the edge region. A 1D transport model has been used to study hysteresis effects in edge spontaneous poloidal flow generation in the TJ-II stellarator (A. Ware *et al*) during gas puffing experiments.

Experimental evidence of parallel flows dynamically coupled to radial turbulent transport was reported in a linear plasma machine (SLPM) (E. Anabitarte). The degree of coupling also shows variations at different plasma radii and with plasma heating conditions. These findings suggest that the intermittent transport cannot be understood without considering the coupling to plasma flows.

Transport of parallel momentum during reconnection events has been investigated in the Madison symmetric torus (MST) reversed field pinch (RFP) (G. Fiksel and V.V. Mirnov). The events are characterized by a sudden increase in resistive tearing magnetic fluctuations leading to magnetic field reconnection and generation of magnetic flux. The plasma toroidal rotation abruptly decreases. Local measurements of fluctuation-induced mean Maxwell stress reveal that it cannot account for the change in the plasma momentum. Other terms in the momentum balance must be important, in particular, the fluctuation-induced Reynolds stress. The contribution of the viscous and the pressure terms is also under investigation. Measurements of the two-point correlation function of the ion velocity distribution function in a weakly collisional gas discharge were reported by F. Skiff.

Some actions were proposed in the general discussion, including (i) an investigation of the impact of sheared electric fields on $\langle \tilde{v}_r \tilde{v}_\parallel \rangle$, to clarify the role of the electric field as a symmetry breaking mechanism, (ii) a systematic investigation of the relaxation of electric fields and flows in tokamaks, stellarators and non-fusion devices for the better understanding of damping physics and (iii) studies of momentum re-distribution during transients (e.g. the transition to improved confinement regimes).

3. Multi-scale physics (P.H. Diamond)

'Multi-scale physics' is a label which encompasses a broad range of topics, and this session indeed lived up to that characterization of its title. The session began with a comprehensive review by Y. Sarazin, and so it seems only appropriate to summarize the session within the framework set forth in that overview. Put trivially, multi-scale phenomena are those which involve the interaction of several scales. In the context of magnetic confinement transport problems, multi-scale phenomena may be somewhat more substantively sub-divided into four categories, all of which were discussed at the workshop. These categories, and the papers which fell within each of them, are

(i) continuous multi-scale interaction in k-space—cascades and spectra: P. Hennequin, N. Mahdizadeh, I. Sandberg and S. Kubota,
(ii) continuous multi-scale interaction in real space-avalanches and transport: G. Darmet, V. Grandgirard and L. Vermare,
(iii) disparate scale interaction with secondary structures—in particular zonal flow and transport barriers: D. Mikkelsen, G.R. Tynan, M. Leconte, G. Falchetto, P. Guzdar, R. Sabot, Diamond, H. Punzmann, K.H. Burrell and Y. Hamada and
(iv) disparate scale interaction involving turbulence and MHD phenomena: no papers on this sub-topic were presented, though it was discussed by Sarazin in his overview.

Cascades and spectra are surely the most familiar topics in multi-scale phenomena. A major question motivated by theories of electron temperature gradient (ETG) turbulence is that of determining the spectral density at high-k ($k_\perp \rho_i \gg 1$, where ρ_i is the ion Larmor radius and $k_\perp$ is a perpendicular wave-number), since ETG is thought to be most virulent there. Relevant to this, Hennequin presented results from scattering experiments on Tore Supra which indicated a $k_\perp^{-3}$ spectral power law for $k_\perp \rho_i < 1$, followed by an *extremely* sharp spectral fall-off for $k_\perp > k_{\rm crit}$, where $1 < (k_\perp \rho_{\rm i})_{\rm crit} < 2$. At the break, the spectra decayed faster than $k_\perp^{-6}$ and could even be fit by an exponential! These results constitute a significant challenge to ETG-based transport theories and thus were a notable result of the workshop. Other papers dealing with spectra and cascades were presented by Mahdizadeh, Sandberg and Kubota.

Just as cascade models seek to explore and exploit self-similarity of the fluctuation spectra, models of avalanches and self-organized criticality (SOC) seek to explore the self-similarity of *transport events*, which may be thought of as a physical manifestation of fluctuations in the transport flux. Such fluctuations are usually ignored by quasi-linear models (i.e. of the mean field genre). A key point here is that the flux fluctuations, which take the form of overlapping structures called avalanches, can conspire to form short-lived but radially extended structures which cause significant enhancement of transport beyond levels predicted on the basis of *averaged* fluctuation correlation lengths and times. Avalanche and SOC theories were reviewed by Sarazin, who noted both their relevance to the question of breaking gyro-Bohm scaling *and* the many instances of such departures from conventional scalings which have been observed in confinement experiments. Successful simulations of avalanches require fixed-flux boundary conditions, which allow the local gradient drive to self-consistently adjust and evolve in the regions of interest. In the past, fixed-flux boundary conditions have been implemented in fluid codes only. Thus, it was notable that Darmet presented the first results with fixed-flux boundary conditions in a *kinetic* simulation code at this workshop. Analysis of these interesting findings is ongoing. It should also be noted that the associated computational advances which enabled this progress were reported by Grandgirard, who discussed a novel semi-Lagrangian gyro-kinetic code which appears to constitute a significant step forward in the simulation genre. Finally, Vermare presented studies of the β-scaling of transport on AUG and argued that micro-tearing turbulence may be at work in driving the degradation with increasing β.

By far the most popular sub-topic in the multi-scale session was that of disparate scale interaction and secondary structure formation. These phenomena were thoroughly reviewed by Sarazin, who discussed zonal flows, geodesic acoustic modes (GAMs), their impact on the underlying drift wave turbulence via shearing, their generation by modulational and parametric instabilities and the various global conceptual pictures of the interplay of these processes, most notably the 'predator–prey' paradigm. Other papers in this group fell into three sub-categories, namely, basic shearing and zonal flow physics, GAM physics and transport barrier formation.

In the topics of basic shearing and zonal flow physics, Guzdar reported on work seeking to relate shear driven instabilities of the zonal flow, termed tertiary instabilities, to the onset of large transport, in particular that which occurs at the density limit. Such instabilities have been proposed as an alternative to collisions as a zonal flow damping mechanism. This scenario is somewhat controversial, on account of the sensitivity of flow shear driven instabilities to magnetic shear. Guzdar sought to address this issue by the proposal that the tertiary instability is initiated at low-q resonant surfaces at or near the plasma edge in regimes of high current. Some qualitative agreement with experimental trends was demonstrated. The effects of mean electric field shear and collisional damping of the zonal flow were not addressed. Leconte presented a basic study of the effects of velocity shear on the cross-phase in the transport of a passive scalar in a driven, turbulent flow. This study was motivated by a controversy in the literature between Kim and Diamond [2], who predicted a relatively weak scaling of cross-phase with shear, and an earlier paper by Terry *et al* [3] which predicted a strong dependence. Leconte's results were in good agreement with the predictions of Kim and Diamond. Future results on the self-consistent cross-phase evolution are eagerly anticipated. Computational studies of the limitations of the 'Dimits shift' regime of zonal flow excitation were presented by Mikkelsen.

Experimental results on zonal flow physics were reported by Tynan, Hamada and Punzmann. Tynan presented a comprehensive study of zonal flows in the edge of the DIII-D tokamak, together with supporting simulations. Tynan's results indicated that the dominant secondary structure in the edge plasma is the GAM and that GAMs quite clearly modulate the edge turbulence. Simulations suggest that further inside—in the plasma core—zero mean frequency zonal flows dominate. Interestingly, Tynan reported that bi-coherence studies indicated that a *forward* coupling (i.e. towards smaller scales) of internal energy (i.e. $\left\langle(\tilde{n}/n)^2\right\rangle$) was mediated by the GAMs. It should be noted that this result is *not* at odds with the conventional wisdom concerning quasi-2D turbulence, since it is the *kinetic energy* (i.e. $\sim\langle\tilde{v}^2\rangle$) which tends to inverse the cascade in that case. Hamada presented results from studies in the JIPPT-IIU tokamak. He reported observations of both GAMs and streamers and claimed that (high frequency) GAMs were the dominant secondary structure. The streamers were observed to have narrow poloidal and broad radial extents, in accord with theoretically motivated expectations. Hamada also reported that wavelet analysis indicated that the density fluctuations associated with background drift wave turbulence were 'more chaotic' than those of the GAMs. Results of studies of the role of zonal flows in the formation of the density pedestal in the H-1 heliac were presented by Punzmann. Taken together, the experimental papers on zonal flows showed significant progress in understanding and elucidating basic physics mechanisms in zonal flow dynamics and the effect of zonal flows on turbulence and transport.

Theoretical and experimental work on GAM dynamics was discussed by Falchetto and Sabot, respectively. Falchetto presented results of gyro-fluid simulations of GAM dynamics. The simulation results were in good agreement with theoretical predictions of the linear GAM frequency (for the quasi-marginal, high frequency root) and of the neoclassical transport (for the damped low frequency root). In the presence of turbulence, a down-shift in the GAM frequency was observed. The mechanism of GAM excitation was not addressed. Sabot reported on observations of modes in the 'ion acoustic' frequency range in Tore Supra. The possible taxonomic classification of these 'animals' as GAMs and/or BAEs (beta Alfvén eigenmodes) was discussed in detail.

Burrell and Diamond presented papers dealing with transport barrier formation. Burrell discussed a novel scenario to explain the ITB formation at low order resonant values of q, based on extensive studies of DIII-D data and on GYRO simulations. Experimental results indicate the appearance of corrugations (i.e. peaks and nearby flat spots in $\nabla T/T$, which may be associated with the related structure in the E_r shear) just prior to the drop in fluctuations and the observed increase in plasma flow associated with the formation of an ITB in off-axis, minimum-q plasmas (which are frequently termed 'reversed shear' plasmas). In contrast to previously proposed scenarios, no magnetic activity is observed at the ITB transition in DIII-D, so models of corrugations based on magnetic islands, double tearing modes, etc are *not* applicable. Instead, Burrell and collaborators hypothesize that corrugations are accompanied by enhanced zonal flow activity, which then triggers ITB formation. This hypothesis is claimed to be supported by GYRO simulations. The authors also speculated that the enhanced level of zonal flows was due to a change in the density of mode rational surfaces due to weak magnetic shear. It should be noted that the GYRO simulations did not self-consistently evolve the *mean* E_r shear. This interesting paper provoked extensive discussion at the workshop and is of considerable value as a stimulus for further research on this fascinating and important topic. Diamond presented an exact analytical solution of the two-field (density and temperature) Hinton model of the L–H bifurcation. While the exact results determined the pedestal width as a scale obtained from a Maxwell construction, a simplified perspective links the pedestal width to the edge fuelling depth, which is usually the neutral penetration depth. This result, which is a simple consequence of the fact that in the Hinton model E_r is driven by ∇P, is pessimistic for ITER, on account of its high neutral opacity. Extension of the Hinton model to include pressure curvature effects eliminated certain degeneracies and ambiguities in the theory but did not alter the basic result.

Disparate scale interaction involving MHD phenomena was discussed briefly by Sarazin in his overview, but not otherwise mentioned at the workshop. In this class of problem there are three 'players in the game', namely, micro-turbulence, secondary structures (i.e. zonal flows) *and* MHD fluctuations (i.e. islands, tearing modes, etc). As is apparent, this class of problem is considerably more challenging than the 'two-player' drift wave-zonal flow problem and so is still in its early stages of development. Several physical processes may be at work simultaneously, such as effects of turbulent dissipation (or anti-dissipation!) on the MHD, interaction of zonal shears with MHD and the effect of MHD-induced profile modifications on the turbulence. No doubt participants in future TTF workshops will see far more activity in this interesting and important area, which is particularly important to ITB formation and is also potentially quite important to edge localized mode (ELM) dynamics.

4. Electron transport (P. Mantica and G.W. Hammett)

The experimental work on electron transport was reviewed by F. Imbeaux. Collaborative work involving AUG, JET, DIII-D, TCV, Tore Supra and FTU and focusing on plasmas with dominant electron heating ($T_e \gg T_i$) has provided a body of experimental evidence for the existence of a threshold in R/L_{Te} for the onset of turbulent electron transport (here, R is the tokamak major radius and L_{Te} the electron temperature gradient scale-length). T_e modulation experiments allow the observation of an incremental electron thermal diffusivity, χ_e, discontinuity across the threshold. Using a semi-empirical critical gradient model, threshold and stiffness factors can be derived from experimental data and compared across various devices. They are found to agree with theoretical predictions of trapped electron mode (TEM) turbulence using the linear version of the GS2 gyro-kinetic code. Recent work comparing the threshold from AUG experiments and the TEM threshold from GS2 was presented by F. Ryter. R/L_n (L_n is a density scale-length) and collisionality are found to affect the TEM threshold in accordance with GS2 predictions, whilst the role of magnetic shear is unclear due to difficulty in scanning a large experimental range. T_e modulation results are always consistent with a gyro-Bohm dependence of electron transport, which implies that effective stiffness scales with temperature and therefore that hot machines will be even closer to the threshold. A point to be clarified is whether the heat flux or the heat diffusivity is linear with R/L_{Te} above the threshold. Also the role of plasma shape on electron transport as observed in TCV is not understood. A clear transition of electron transport from TEM driven to ion temperature gradient (ITG) driven turbulence with increasing collisionality was observed in AUG. However, no clear experimental evidence so far exists for a role for ETG turbulence in determining electron transport, although under experimental conditions with $T_{\mathrm{e}} \sim T_{\mathrm{i}}$ the ETG threshold is low enough for ETG modes to be excited. In discussion it was suggested that one should investigate ITB layers, where ITG/TEM are stable but electron transport is still non-neoclassical, or other regimes or plasma regions where the ITG/TEM threshold might be higher than the ETG threshold, such as the inner plasma core or in the presence of high ion temperatures. Probing these regions with perturbations and performing turbulence measurements up to high wave numbers may provide some evidence for ETG transport (see the work of Hennequin reported in section 3).

Experimental work on electron transport barriers has shown the importance of negative magnetic shear and the existence of a link between transport reduction and the degree of reversal of the q profile. An investigation of the interplay between the current profile and an electron ITB was reported in F. Turco's presentation of giant T_{e} oscillations in Tore Supra. Perturbative studies of electron ITBs in JET have characterized ITBs as narrow layers below threshold. A similar conclusion was reached in DIII-D for ion ITBs by probing them with electron heat pulses. This work, presented by J.C. DeBoo, has underlined the strong link between electron and ion transport beyond collisional coupling and therefore the need to consider such coupling when interpreting electron heat transport experiments under conditions where the ion channel also carries a significant heat flux ($T_{\mathrm{e}} \sim T_{\mathrm{i}}$). It is important to study electron heat transport in more detail under these conditions, which are in fact the most relevant to ITER. Some evidence exists from JET T_{e} modulation that electron stiffness increases in plasmas with mixed ITG/TEM with respect to dominant TEM conditions. This has been confirmed by the work presented by Yu. Baranov showing rather large values of the intrinsic electron stiffness factors (as defined in [4]) derived from the propagation of heat pulses generated by ELM collapses. It was noted that a very fruitful area for near term work would be to test electron transport models in the $T_{\mathrm{e}} \gg T_{\mathrm{i}}$ regime, which has been well characterized by experiments and may be a simpler regime to understand when only TEM modes dominate, instead of combined ITG/TEM turbulence. The greater challenge for future work will be in understanding electron transport in a wider range of ITER relevant conditions, $T_{\mathrm{e}} \sim T_{\mathrm{i}}$, including low or negative magnetic shear regimes where the confinement is improved. In this regard, J.E. Kinsey presented a new 1D model (TGLF) based on a database of non-linear GYRO simulations, which should improve the previous GLF23 model, providing a better description, in particular, of electron transport and also taking into account the effect of shaped geometry and negative magnetic shear regimes. The authors plan for this model to be available for public use in about a year. The comparison of non-linear 3D turbulence simulations of electron transport with experiments has still a long way to go. X. Garbet presented first simulations of a JET T_{e} modulation experiment using the 3D non-linear fluid turbulence code TRB. It is found that the electron stiffness level in TRB is significantly higher than that measured experimentally. Finally, the issue of turbulence spreading was tackled in a presentation by Mantica showing very fast cold pulse propagation in JET plasmas whilst the T_{e} modulation in the same shot behaves according to a local, although non-linear, critical gradient model. The fast propagation requires non-local transport features and a 1D model featuring transport of turbulence into linearly stable regions can at least in part account for the asymmetry of behaviour between an edge cold pulse and a T_{e} modulation. This idea deserves further investigation as it potentially could explain a number of experimental situations where transport is evidently anomalous in regions predicted to be linearly stable, as for example in the core of hybrid plasmas. A poster on predictive modelling of hybrid plasmas by G.M.D. Hogeweij using the CRONOS transport code with the semi-empirical Bohm/gyro-Bohm model and the theory-based GLF23 model shows that in the cases where theory-based models fail in reproducing the data, the semi-empirical models still have a value for scenario development, allowing assessments for example of the impact of various heating and current drive schemes.

Theoretical work on electron transport was reviewed by D.R. Ernst. He began with a survey of simulations of ITG driven turbulence including trapped electrons. While this may be an important cause of electron energy transport in many cases, ITG turbulence with trapped electrons usually has $\chi_{\mathrm{e}} < \chi_{\mathrm{i}}$ and so cannot explain regimes where electrons are the dominant loss channel. Most of Ernst's review focused on the TEM, which can give stronger electron transport. Present analytic theory does not appear to accurately describe the TEM instability thresholds in R/L_n and R/L_{Te} in all the regimes. There has been some recent work on better TEM formulae based on analytic theory in some parameter regimes or based on fits to gyro-kinetic stability calculations. Comparisons of linear quasi-linear and/or non-linear gyro-kinetic TEM calculations are being made with the Alcator C-Mod and AUG experiments. Interestingly, Ernst's GS2 simulations of C-mod have found that zonal flows cause a non-linear up-shift in the critical *density* gradient needed to drive significant TEM turbulence, similarly to the non-linear Dimits shift in ITG turbulence, but there does not appear to be a non-linear up-shift in the critical *temperature* gradient for TEM. The non-linear up-shift in the critical density gradient is found to increase strongly with collisionality. Recent work on C-Mod has developed a synthetic diagnostic for direct comparison between non-linear TEM simulations and density fluctuation measurements. The measured wavelength spectrum of density fluctuations, in a case where the TEM is strongly unstable, has been reproduced by the simulations. AUG experiments with ECH heating indicate a critical electron temperature gradient in the transport consistent with linear/quasi-linear gyro-kinetic simulations of TEM. F. Jenko presented several parameter scans studying the physics of non-linear saturation in his gyro-kinetic TEM simulations and presented improved formulae for the resulting thresholds and transport. Among other topics, Hammett summarized results from E. Belli's recent PhD thesis finding that the Dimits non-linear up-shift is enhanced by stronger shaping. This can be understood from the fact that the Rosenbluth–Hinton residual flows are enhanced by smaller banana widths of particles at high elongation and triangularity (and/or high values of radial gradients of these quantities) at fixed q. G. Sonnino presented a novel, non-linear, thermodynamic field theory approach to collisional transport processes in tokamak plasma; while ion classical and Pfirsch–Schlüter heat fluxes are found to be unaffected, the electron heat and particle fluxes are enhanced.

Recent work on ETG was summarized in Ernst's review and presented in more detail in other talks and posters. Several presentations showed evidence supporting their view that previous differences between particle-in-cell (PIC) and continuum simulations of ETG turbulence have been resolved by understanding the role of particle noise in PIC simulations. (Some of these are presented more fully in [5].) The elongated nature of ETG eddies relative to ITG eddies can make them more sensitive to noise in some cases. This of course does not mean that all PIC simulations of ETG turbulence in all parameter regimes are affected by noise [6] and W.M. Nevins showed results from a forthcoming paper [7] demonstrating cases of good benchmarking between four different gyro-kinetic codes, using both continuum and PIC algorithms. Global PIC simulations presented by A. Bottino *et al* supported the conclusions in [5], and extrapolated to relatively strong ETG turbulence. Bottino's poster also discussed methods of reducing noise. ETG simulations in some regimes (such as at high magnetic shear including trapped electrons) can run away, with 'jets' that extend all the way across the simulation domain, making convergence studies and cross-code comparisons difficult. The ETG benchmarking cases presented by Nevins focused on lower magnetic shear (which provides an easier benchmark point when trapped electrons are included). J. Candy presented ETG simulations with non-adiabatic ions, which is computationally very challenging because of the extreme range of space and time scales that must be resolved. Results were presented from simulation domains as large as $1920\rho_e \times 1920\rho_e$ $(64\rho_i \times 64\rho_i) \times 2\pi q R$ that resolved up to $k_\perp \rho_e \sim 0.5$ (ρ_j is the Larmor radius of species j). Non-adiabatic ions are found to lead to a more robust saturation of ETG turbulence, avoiding the runaway sometimes observed with adiabatic ions. While it is hard to generalize from a small number of non-linear simulations, and further convergence studies would be useful, it may be that ETG is usually small compared with the ITG/TEM turbulence, except for the cases where the thresholds for ITG and TEM are higher than that for ETG, such as in the hot ion regimes or in transport barriers or other cases with strong sheared flows that reduce the ITG/TEM transport. Nevins showed examples from a number of experiments where the observed electron transport has $\chi_e \sim 5$–15 electron gyro-Bohm units, in the range where ETG turbulence could be significant.

5. Particle and impurity transport (C. Angioni)

The transport of particles, namely, electrons and main ions, and impurities is an essential ingredient in the understanding of the transport processes in magnetically confined plasma. There is an increasing amount of evidence confirming that the same micro-instabilities are responsible for the transport in both the heat and particle (as well as momentum) channels. Moreover, particle transport determines the density profiles of electrons, main ions and impurities, with important implications for the assessment of our ability to extrapolate to ITER from the presently developed tokamak scenarios. This involves issues connected with the need and amount of external fuelling, with density or MHD limits, and with the requirement of external means, such as localized central auxiliary heating, to avoid serious impurity accumulation. The issue of the existence, magnitude and properties of an anomalous, turbulence driven particle pinch is, of course, central in this framework.

The session on particle and impurity transport was opened by P. Helander with a comprehensive review talk on theoretical issues concerning particle and impurity transport. Both classical collisional and turbulent mechanisms producing a particle pinch were discussed. In particular, it was recalled that a pinch mechanism also arises from NBI due to friction between electrons and beam ions, and this effectively shifts the fuelling profile inwards (outwards) for counter- (co-) injection by about a banana width. A pinch mechanism similar in nature to the Ware pinch also stems from a radio-frequency wave current drive, but it is usually very small under conditions of present experiments, such as those performed in Tore Supra with lower hybrid. Considerable emphasis was laid on turbulence driven mechanisms producing a particle pinch. Simple kinetic and fluid descriptions of curvature and thermo-diffusion mechanisms of particle pinch were presented. Both trapped and passing electrons can carry a pinch, depending on the kind of turbulence. Finally, transport of fast particles was reviewed. In particular, it was mentioned that non-linear, gyro-kinetic simulations (GYRO) show that high temperature Maxwellian trace particles undergo larger transport per particle than the thermal ones, which is expected to produce some broadening of the alpha particle density profile.

The second review talk was presented by M.E. Puiatti, who gave a comprehensive account of the different experimental aspects of impurity transport in the various operational regimes in tokamaks. Experimental observations from different devices of impurity accumulation were discussed, in particular, in advanced scenarios of C-Mod, AUG and DIII-D. Results from different devices, such as C-Mod, AUG, FTU and DIII-D, show that impurity accumulation can be reduced by central radio-frequency heating. This tool is also effective for high Z impurities and is mainly related to an increase in the central anomalous diffusivity which is not accompanied by a proportional increase in the inward pinch. Electron heating is found to be more efficient than ion heating and anomalous pinches directed in opposite directions have been measured under two heating conditions in JET. The application of central heating for increasing anomalous diffusion and suppressing impurity accumulation is predicted to be also effective in ITER. This is supported by the experimental evidence that impurity diffusivity and main ion heat conductivity are often observed to be coupled in present experiments. Finally, an example of chaos-dominated impurity behaviour in RFP experiments was reported.

During the contributed papers session, interesting new results for different topics were presented. D.L. Brower showed measurements of particle transport induced by magnetic fluctuations in the high temperature plasmas of the RFP MST. A fast polarimeter measured the core mean and fluctuating fields and currents, ingredients of the magnetic fluctuation-induced transport. The particle transport is driven by resistive tearing modes and originates from non-linear mode–mode interactions. Since this kind of transport is not intrinsically ambipolar, it involves charge separation which generates a locally strong electric field and a related spontaneous $\boldsymbol{E} \times \boldsymbol{B}$ driven zonal flow. These are measured and found to change sign across the tearing mode resonant surface and achieve peak values of $5\,\mathrm{kV\,m^{-1}}$ and $50\,\mathrm{km\,s^{-1}}$, respectively. T. Parisot presented experimental results of impurity transport in Tore Supra ohmic plasmas. Measurements of laser ablated impurities are performed with bolometers, V-UV and soft X-ray spectrometers, and the diffusion and pinch of impurities are determined with the ITC code. By injection of impurities from $Z = 13$ to $Z = 32$, it is found that the confinement time of the impurities does not depend on Z. A scan over density shows that the confinement time of impurities increases with increasing density. The investigation of the size of diffusivity and pinch for Ni in these plasmas shows that impurity transport in Tore Supra ohmic plasmas is largely anomalous. A. Sirinelli reported experimental evidence for the effect of the neoclassical Ware pinch in Tore Supra ohmic density profiles. Measurements are performed by reflectometry and show the existence of an additional peaking of the density profile in the very central region of the plasma. This peaking disappears in the absence of loop voltage or at high levels of measured central density fluctuations, which indicates an increase in the central diffusivity.

On the theoretical side, F. Spineanu proposed the idea that common ground can exist between the density pinch and the transition to high confinement regimes in tokamaks. The contribution of the process of self-organization of vorticity to the formation of a density pinch in tokamak plasmas was discussed. Different solutions of the Charney–Hasegawa–Mima equation in 2D were presented and interpreted as a description of the L and the H confinement modes. Corresponding to the high confinement state, a class of density profiles which can be strongly peaked close to the axis has been found. P.W. Terry showed that in a fluid model for trapped electron mode turbulence a contribution to the particle flux which is not included in quasi-linear models can be identified analytically and quantified by projection onto an eigenmode basis set. This non-linear contribution has the form of an inward pinch, whose scaling with density and temperature gradients is different from that of the quasi-linear flux, and is connected with the non-linear excitation of a damped eigenmode. This non-linear inward pinch is found to provide a significant reduction in the quasi-linear outward particle flux in the proximity of the threshold. M. Vlad presented a new model for the anomalous particle pinch, the 'ratchet pinch'. This pinch has been shown to originate from the gradient of the magnetic field and to have a complex dependence on the characteristics of the turbulence. It is small compared with the related diffusion, but can produce density peaking in the experimental range in the presence of a poloidal rotation, since the latter significantly reduces the diffusivity. Moreover, it is found that the ratchet pinch decreases with increasing collisionality, in qualitative agreement with the scaling of JET H-mode data. The ratchet pinch has been proposed as a candidate for explaining the density peaking in H-mode plasmas. N. Dubuit presented results of global fluid simulations of turbulent impurity transport. The effects of different pinch mechanisms, namely, curvature pinch, thermo-diffusion and parallel compression, are quantified by specific non-linear simulations, by switching off and on appropriate terms in the code. It is found that the curvature dominates over the thermo-diffusion and that thermo-diffusion implies an increasing peaking of the impurity profile with an increasing ratio of ion to electron heat flux. Finally, the effects of parallel compressibility are shown to reduce the inward thermo-diffusion contribution, but not to produce a total particle pinch directed outwards as measured in some experiments. Specific simulations of Tore Supra plasmas show no (or at least only a very small) Z dependence of transport, in agreement with the experimental measurements reported by Parisot.

R.V. Budny presented results of a set of global non-linear gyro-kinetic simulations of JET plasma in the H-mode in both the standard and the hybrid scenarios performed with the GYRO code. Comparisons with the experimental fluxes as reconstructed by TRANSP are performed over all the transport channels, namely, ion and electron heat, momentum and particle transport. Particularly good agreement is found in the H-mode at small ρ_* (normalized ion Larmor radius), low density and low β_{N}. In contrast, energy flows are found to be a factor of 2–3 higher in the JET hybrid plasmas. Simulations with both one and two kinetic ion species have been performed. Cases with inward and outward deuterium, impurity or electron flows are found, but experimental particle fluxes are not normally found to be better reproduced by the two ion species simulations. Effects of flow shear and collisionality have been studied in dedicated scans. A reduction by a factor of 10 in the gradient of E_r provides an increase in the energy transport by a factor of 2. Inward particle flows are found to increase as the collisionality is reduced.

In the poster session Angioni presented a statistical study of density peaking in H-mode plasmas based on a combined database of AUG and JET observations, which identifies collisionality as the statistically most relevant parameter. M. Gilmore presented a feedback method for the control of turbulent transport in the new linear device HELCAT. Biased concentric rings generate sheared $\boldsymbol{E} \times \boldsymbol{B}$ flows which are used to modify the transport level, whose related turbulent state is monitored with probe arrays. Finally, H. Isliker presented the extension of the continuous time random walk method to both position space and momentum (or energy) phase space. The basic equations have been derived and numerical solutions obtained by expansion in Chebyshev polynomials, presented in the particular case of the simulation of cold pulses, which are found to be super-diffusive.

6. Transport in the SOL (A. Loarte)

This session reviewed the progress in the experimental characterization of transport at the plasma edge in fusion devices and dedicated experimental facilities for low temperature plasma studies, its modification by ergodic magnetic fields and in modelling of edge turbulence and transport. The experimental evidence for the mechanisms driving radial transport in the open field lines of fusion devices was reviewed by G. Counsell. Most fusion devices find that SOL particle transport is dominated by large 'intermittent' events, which start at the last closed flux surface, on a higher frequency (Gaussian) background. This is the mechanism that is presently understood to dominate the anomalous transport of particles to the main chamber wall in divertor tokamak discharges and, thus, is of high relevance for determining the erosion of plasma facing components in the next generation of fusion devices, such as ITER. The relative size of these events increases with the distance to the separatrix leading to strongly non-Gaussian probability distribution functions (PDFs) for the measurements of density fluctuations in the far SOL (TCV, DIII-D, MAST, JET, TEXTOR, W-7AS). These large 'intermittent' events are associated with spatially localized density (mono-polar) structures in the radial and poloidal directions aligned with the magnetic field (DIII-D, NSTX, MAST) linked to a dipolar perturbation of the electric potential (C-Mod, CASTOR), which is responsible for their radial movement by the $\boldsymbol{E} \times \boldsymbol{B}$ drift. Despite this, measurements of the radial velocity of propagation of density blobs and potential dipoles in CASTOR presented by P. Devynck show that density blobs can propagate substantially faster than the associated electric potential dipoles ($1300\,\mathrm{m\,s^{-1}}$ versus $580\,\mathrm{m\,s^{-1}}$), which is indicative of the existence of short connection lengths in the CASTOR SOL and of the role of viscosity (by neutral–plasma interactions) in generating turbulent radial flows. The origin of these turbulent intermittent events is localized in a region of $\pm 30^{\circ}$ around the outer mid-plane, as demonstrated by experiments in Tore Supra in which the poloidal location of the contact point between the plasma and the limiter has been changed, demonstrating the role of the magnetic field curvature in turbulent particle transport generation in fusion devices. A major problem in all these studies is the experimental identification and characterization of coherent bursts in a turbulent background, for which advanced signal processing techniques are required. A new promising recursive method based on wavelet analysis, with advantages over other conventional methods such as conditional averaging, was presented by M. Farge and applied to Langmuir probe measurements in the Tore Supra SOL.

Despite the obvious differences in plasma conditions and magnetic field configurations between plasmas in fusion devices and those in low temperature plasma experimental facilities, many of the characteristics of turbulent transport in SOL plasmas are very similar to those in these facilities. Experiments in TORPEX reported by A. Fasoli and F.M. Poli clearly demonstrate the influence of curvature on the density fluctuation levels and associated transport, in good qualitative agreement with the findings in Tore Supra. Similarly, the correlation between events in open field lines and closed field lines seen in fusion experiments and the de-correlation between density and potential fluctuations as the events propagate across the SOL is in good qualitative agreement with findings in experiments in the toroidal facility TJ-K and in TORPEX presented by U. Stroth and I. Furno, respectively. In fact, the relatively simple accessibility to the plasma in these and other facilities (such as linear plasmas in LAPD presented by T.A. Carter or a Helimak configuration similar to that of TORPEX presented by D. Miracle) for quantitative measurements of the turbulence characteristics makes them very useful for (a) experimental studies aimed at understanding the physics mechanisms behind SOL turbulence in fusion devices and its modification by external means and (b) the detailed validation of turbulence modelling codes that are used for simulations of anomalous transport at the plasma edge in fusion devices.

The influence of the magnetic field structure on plasma transport was discussed in two papers: one reporting the results from the dynamic ergodic divertor experiments in TEXTOR by M. Lehnen and one describing the use of externally imposed magnetic fields for ELM control by E. Nardon. Measurements in TEXTOR show a clear correlation between the magnetic field structure and the measured plasma temperature and plasma potential at the plasma edge, similarly to previous results from Tore Supra, which is in good agreement with the existence of a laminar and ergodic flow region as modelled with the EMC3 code. As a consequence of this, the electric field shear layer can move away, up to 8 cm from the ergodic divertor target plates, leading to the formation of a transport barrier between the ergodic and confined plasma regions. The stepwise increase in this distance by increasing the magnitude of the current in the divertor coils is accompanied by an increase in plasma density, which is not presently understood in detail. The effect of ergodic fields in affecting the edge transport has been proposed as a mechanism to control ELMs in fusion devices and demonstrated in experiments in DIII-D. MHD self-consistent modelling of the application of these fields by the JOREK code was presented by Nardon. This study shows that plasma effects can significantly modify the edge magnetic field structure with respect to that estimated by the 'vacuum' fields, in which the plasma response to the external field is neglected. These new self-consistent simulations show that the magnetic field perturbation can be amplified at the edge by the presence of a large bootstrap current, as expected in ITER, but can also be reduced by plasma rotation, as the externally applied fields are screened by the plasma. The calculations show, in addition, that the resonant magnetic fields applied to suppress the ELMs cause a static $n = 3$ perturbation of the plasma potential at the edge that can lead to substantial enhancement of radial particle transport by $\boldsymbol{E} \times \boldsymbol{B}$ effects, in agreement with the loss of plasma density reported in the DIII-D experiments. While the comparison between modelling and experiment is still at a qualitative stage, the effects identified in this work have major implications with respect to the applicability of this method to control Type I ELMs in ITER and research along these lines seems very promising and will be pursued further.

Edge plasma transport and turbulence modelling was the subject of three oral presentations and four posters. The importance of understanding energy transport in the SOL for anomalous particle transport modelling was demonstrated by V. Naulin. The model for plasma turbulence contained in the ESEL code (which has been compared with experimental measurements from TCV, C-Mod and JET) has been upgraded to include ions with finite temperature. The main results of the modelling carried out is that accounting for hot ions in the SOL leads to more localized blobs, which move across the SOL at higher speeds and, thus, have a higher probability of reaching the main chamber wall in divertor tokamaks. The influence of turbulent transport in determining the pedestal properties in H-mode plasmas was assessed by P. Ghendrih. Modelling of turbulence spreading into a system analogous to the pedestal and SOL region in fusion devices shows that, although turbulence is suppressed in the transport barrier itself, the ongoing fluctuations on both sides of the barrier can have sufficient amplitude so as to affect the effective barrier width. This indicates that the pedestal properties in H-mode plasmas are strongly linked to those of core and SOL transport, in qualitative agreement with experimental data presented at the workshop (from DIII-D by R.J. Groebner). The control of turbulent particle transport by the application of temporally and spatially varying electric potentials was studied in a poster presentation by G. Ciraolo, which showed that well-adapted and relatively small modifications to the background fluctuation potential can lead to a significant reduction in the turbulent transport-driven diffusion coefficient. The need to model in a self-consistent way turbulent plasma transport in the outer plasma region (including closed and open field lines) with their real 3D geometry was discussed in a poster presentation by P. Tamain, in which the first results of a new 3D two fluid code for the modelling of transport and turbulence in the edge plasma were presented. Finally, the first results from gyro-kinetic simulations of the SOL and pedestal plasmas by the XGC-1 code were presented by C.S. Chang. This study reveals that the inapplicability of neoclassical transport at the plasma edge (the banana width becomes larger than the radial plasma scale-length) invalidates the usual assumption of superposition of neoclassical and turbulence drivers for plasma transport, which must be modelled together self-consistently in this region. The self-consistent kinetic simulations of the pedestal and SOL plasma in H-modes presented reproduce many of the experimental features of this regime, such as the strong electric field well in the vicinity of the pedestal region and associated sheared $\boldsymbol{E} \times \boldsymbol{B}$ flows and the anisotropy of the ion temperature distribution in the SOL. This indicates that the basic physics mechanisms are properly included in the model, which will thus be applied to determine the precise physics mechanisms that drive anomalous transport at the plasma edge in these regimes.

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