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Conference Report

Summary of the 19th Joint EU-US Transport Task Force Workshop

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Abstract
This conference report summarizes the contributions to, and discussions at, the 19th Joint EU-US Transport Task Force workshop, held in Culham, UK, during 8–11 September 2014. The workshop was organized under six topics: momentum transport, energetic particles, challenges in modelling transport in ITER and JT60-SA, L–H transition, impurity transport and SOL transport. This report follows the same structure.

Keywords: magnetic confinement, transport, turbulence

1. Introduction

The 19th Joint EU-US Transport Task Force workshop was held in Culham, UK, during 8–11 September 2014, with Culham Centre for Fusion Energy (CCFE) as host. The EU TTF Chair C. Angioni (IPP, D) and Deputy Chairs P. Mantica (CNR, IT) and V. Naulin (DTU, DK) took care of the workshop organization with the help of M. Romanelli (CCFE, UK, Chair of the LOC) and the collaboration of the US TTF Chairs, J. Rice (MIT, MA) and G. Staebler (GA, CA), and of the other members of the Programme Committee. The workshop was organized with six plenary sessions including review, invited, oral and poster contributions on six topics. Each topical session was coordinated by one or two session chairs. The session topics were: momentum transport (chairs C. Angioni, P. Mantica), energetic particles (chair S. Sharapov—CCFE, UK), challenges in modelling transport in ITER and JT60-SA (chair C. Bourdelle—CEA, FR), L–H transition (chair C.F. Maggi—CCFE, UK), impurity transport (chairs J. Rice, C. Hidalgo—CIEMAT, Spain), scrape-off layer (SOL) transport (chairs V. Naulin, G.S. Xu—ASIPP, CN) selecting oral contributions for their sessions; other contributions were presented in a common poster session. They also chaired their respective sessions, led the discussions and provided written input to the present report. The workshop was attended by 97 participants, of which 78 from EU, 11 from US, 4 from Japan, 4 from China. There were 20 invited talks, 21 contributed orals and 47 posters. This workshop was also the last meeting of the EFDA Transport Topical Group, which under the EFDA framework coincided with the EU TTF. Therefore the EU participants were covered by Euratom mobility support. Presently the EUROfusion General Assembly has approved the continuation of the EU TTF as partner of the US and Asian TTFs to maintain the regular organization of the joint workshops, which provide useful feedback into the EUROfusion work-programme. For the biennium 2015–2016 P. Mantica has taken up the role of EU TTF Chair and C. Bourdelle was voted during the Culham workshop as the new Deputy Chair. The wiki page of the EU TTF can be found at www2.euro-fusion.org/eu-ttf/.

In order to promote new ideas and a free discussion, it is traditional for TTF workshops not to publish full

* The list of all participants to the 19th Joint EU-US TTF workshop can be found at www.ttf2014.org.

proceedings. Subject to author consensus, a large subset of the presentations was made available under password protection on the workshop web-site www.ttf2014.org, where also all abstracts are publicly available. It was agreed at the workshop to prepare a short conference report for publication in a plasma physics journal, in order to provide a useful feedback to the whole fusion community and in line with previous TTF workshops (e.g. (J.W. Connor *et al* 2009 *Nucl. Fusion* **49** 047001)). The scope of the present report is therefore to provide a concise summary of the results and issues discussed at the workshop. The content will be organized in six sections corresponding to the session topics listed above, with a final section summarizing progress achieved, open issues and directions for future work. The affiliations of the authors are not reported to avoid making the text too heavy, but they can all be found on the workshop web-site under the Abstracts section.

2. Momentum transport

The momentum transport session focused on the role of neoclassical toroidal viscosity and on the interaction between neoclassical and turbulent transport effects.

The session was opened by an invited talk by W. Kernbichler on the neoclassical toroidal viscosity in quasi-linear regimes, which also had tutorial purposes. In this presentation the need was underlined for developing flexible tools which can compute the neoclassical toroidal viscosity in arbitrary geometry and collisional regimes, without any model assumption on the collision operator. General derivations for the calculation of the torque density associated with the presence of non-axisymmetric perturbations of the equilibrium as well as in the general case of 3D geometry were presented. These were based on the well-known force-flux relation, which directly links this torque to the non-ambipolar neoclassical particle fluxes arising due to the violation of the toroidal symmetry of the magnetic field. Then the specific features of the implementation of the NEO-2 code were outlined. For applications to tokamak non-axisymmetric magnetic field perturbations, the only limiting condition is that the non-axisymmetric perturbation field be small enough so that the effect of the perturbation field on particle motion within the flux surface is negligible, but no assumption is made on the equilibrium geometry or the collisionality regime. Finally, results of NEO-2 benchmarks highlighting properties in different collisionality regimes, and the application to the case of the ripple in ASDEX Upgrade were presented. A more extended set of benchmarks and applications was presented by A.F. Martitsch in a companion poster on the evaluation of the toroidal torque driven by external non-resonant non-axisymmetric magnetic field perturbations in a tokamak.

The other invited talk was presented by Y. Idomura, on the interactions between neoclassical effects and turbulence in toroidal momentum transport, and a comparison between flux driven and gradient driven simulations.

Comparisons between flux driven full-f gyrokinetic simulations and gradient driven delta-f gyrokinetic simulations were discussed. It is found that elements of the full-f physics have significant impacts on turbulent momentum transport and plasma size scaling. In the presence of non-axisymmetric turbulent fluctuations, turbulent momentum transport tends to be cancelled by its neoclassical counterpart, under the ambipolar condition including both turbulent and neoclassical fluxes. In the local limit regime $1/\rho^* > 300$, the plasma size scaling is significantly affected by the power degradation due to bursty nonlocal transport, which is induced by self-consistent interactions between temperature fluctuations and turbulent transport under a local power balance condition.

Oral presentations by M. Barnes and J.C. Hillesheim discussed recent results on the ongoing collaboration between the University of Oxford, CCFE, IST, and CIEMAT on intrinsic rotation. Additional recent progress from this collaboration was presented in posters by J. Ball, M.F.F. Nave and F.I. Parra. In this paragraph we provide a structured summary of all of these contributions. F.I. Parra presented a complete, self-consistent model for intrinsic rotation for conventional aspect ratio tokamaks. This model is being implemented in GS2 by M. Barnes. M. Barnes reported numerical results obtained with a reduced version of the model valid for turbulence with eddies much smaller than the ion poloidal gyroradius, a limit in which the effect of neoclassical flows on the turbulent momentum flux dominates over other intrinsic rotation drives. These results show clear intrinsic rotation reversals when the collisionality changes from the banana to the plateau regime. J. Hillesheim presented measurements from MAST demonstrating the first observation of intrinsic rotation reversals in a spherical tokamak. A comparison between the experimental measurements in MAST and a model based on the numerical results of M. Barnes showed the model reproduces the sign of the measured rotation across a range of plasma conditions. M.F.F. Nave compared detailed simulations with the new version of GS2 with a JET rotation profile in which the rotation changes from co-current in the edge to counter-current at the magnetic axis. The results of the simulation matched the profile in the region where the change of direction happens. Finally, J. Ball showed that tilted elliptical flux surfaces can generate sufficient intrinsic rotation to stabilize resistive wall modes.

E. Fable presented an oral contribution on the derivation of a toroidal momentum transport equation for transport codes and on its consistency with a gyrokinetic model.

Interpretation and prediction of toroidal momentum transport in present machines can be achieved via 1D transport codes such as ASTRA, JETTO, CRONOS, ETS, etc. The equation of transport of toroidal angular momentum is obtained by solving for the radial current with multiple ionized species. The components of the flow (parallel, poloidal, diamagnetic) can be detailed and included accordingly. Part of the stress tensor is expressed in the usual diffusion convection paradigm which can be adopted for the generalized form of the flow (parallel + poloidal + diamagnetic), provided it is made consistent with the gyro-kinetic equation. The next step is to test the proposed equation, as implemented in ASTRA, employing various pinch/residual stress models and compare predictions against experimental observations.

In the poster session, additional contributions were dedicated to momentum transport as well as to the impact of rotation on the plasma confinement properties.

G. Dif-Pradalier presented a comprehensive discussion of several aspects on which forcing and self-organization can play a prominent role in a wide variety of plasma behaviours from the core to the edge. The work has been performed with flux-driven simulations with the global gyrokinetic code GYSELA, where no scale-separation is assumed and the interplay of all scales is self-consistently accounted for. Various physical problems have been addressed. Turbulence spreading from the core has been investigated as the cause of transport in the near-edge region of L-mode plasmas. Reynolds stress generated local rotation in GYSELA is found to erode the micro-transport barriers connected with the self-consistently generated staircase pattern of shear flows. Finally, the impact of SOL flows has been examined in simulations where the no-slip boundary condition is replaced by poloidally asymmetric profiles of parallel velocity, which exhibit a broader avalanche behaviour in the core, leading to a reduction of confinement.

B.F. McMillan showed global gyrokinetic investigations on how momentum profiles in tokamaks can be driven via internal processes. Off-diagonal transport is known to yield weak flow generation through residual stresses. However, in this work it was also shown that for certain parameter regimes strong flow gradients can be driven by anti-diffusive momentum transport. These processes were distinguished via a ρ^* scaling exercise. In flux-driven simulations with the ORB5 code, large-scale modifications to temperature gradient profiles are generated when these toroidal flow structures grow and coalesce.

E. Narita analyzed properties of JT-60U plasmas with a moderate internal transport barrier (ITB) and a weak magnetic shear. It was found that the electron temperature ITB is steeper when toroidal rotation is in the co-direction than that when rotation is in the counter-direction. Examination of the dominant instabilities using the gyrokinetic code GS2 shows that the counter-case has trapped electron modes (TEMs) more unstable than the co-case. Due to this difference in the instability, the ratio of the electron to the ion heat diffusivity is higher for the counter-case. This tendency agrees with the experiment.

G. Verdoolaege presented a study dedicated to the scaling of core intrinsic rotation in tokamak plasmas using a robust regression technique. In particular, this work aims at clarifying the dependencies of intrinsic toroidal rotation on local plasma parameters in a rotation database obtained in ASDEX Upgrade L-mode plasmas. To this end a powerful new regression method is deployed, called geodesic least squares (GLS), which is robust in the presence of significant uncertainty in the regression model and in the measured response and predictor variables. Preliminary results for the scaling of the rotation gradient at mid-radius verify several dependencies obtained earlier using least squares regression and confirm the robustness of the method. The technique can be generalized in a straightforward manner to address uncertainties in other important scaling relations in the context of plasma confinement and transport.

The discussion session focused on different aspects related to the theoretical developments of models which can increase present prediction capability of toroidal rotation in future devices.

(a) Particular emphasis was given to the comparison between global and local (flux-tube) approaches to the description of turbulent transport of toroidal momentum, in relation to the possibility of including effects connected to profile variations in a local model, particularly motivated by the recent works by F. Parra et al. The limitations and differences of the global and local approaches, and the parameter domains in which different approaches should give comparable results were discussed.
(b) The study of combined neoclassical and turbulent transport simulations in full-f global models should also be more extensively considered, following the results of Y. Idomura, as well as the assessment of differences between fixed gradient and fixed flux approaches, as pointed out by G. Dif-Pradalier.
(c) It was agreed that the development of databases of experimental observations is a powerful experimental tool to investigate the main dependencies of the observed intrinsic rotation, against which the theoretical predictions of different models which describe different mechanisms producing an intrinsic torque can be compared. Therefore the experimental work dedicated to the completion and analysis of these databases should be continued, aiming at producing a large multi-device intrinsic rotation profile database.

Future activity will be devoted to the application of the different theoretical approaches, global and local, with emphasis on different physics ingredients, to the modelling of specific parametric dependencies, which are identified from the analysis of the datasets from multiple devices.

3. Energetic particles

As in the 13th EU-US TTF Workshop, and following the example of the structure of the US TTF working groups, an Energetic Particle (EP) Session was included in the Programme of this 19th EU-US TTF Workshop. This EP Session consisted of five talks (three invited and two oral) and one poster, and it also contained a discussion on the priority of EP issues within the framework of the EU-US TTF.

D.L. Keeling presented an experimental talk on the results of a scan in plasma density and neutral beam injection (NBI) heating power on the MAST device. Considering the flat-top phase of the plasma current, it was found that the global neutron emission rate in high density/low power shots matched well with the neutron emission rate modelled using the TRANSP code. As heating power was increased and/or density decreased, a systematic increase in the amplitude of fishbone magnetohydrodynamics (MHDs) was observed, together with a commensurately larger discrepancy between modelled and measured neutron emission rate. The discrepancy is attributed to fast-ion redistribution by the fishbone modes. Options for modification of the NBI injection geometry for MAST-Upgrade were shown with the intention of mitigating detrimental fishbone modes and avoiding fast ion redistribution.

O.M. Jones reported on bursting, frequency-chirping toroidal Alfvén eigenmodes (TAEs) routinely observed in beam-heated MAST plasmas during the current ramp-up phase (high values of the safety factor profile). Advanced fast-ion diagnostics were used to study the effects of these modes on fast ions. Transient drops in the neutron camera and fast-ion D-alpha signal typically accompany each of the bursts in Alfvénic mode activity, and observations of correlated spikes in edge D-alpha light and drops in the global neutron rate support the hypothesis that these modes cause losses of fast ions from the plasma. TRANSP modelling indicates a significant deterioration of global fast-ion confinement during periods of chirping mode activity.

D. Zarzoso presented a numerical study of the interaction between energetic particle-driven geodesic acoustic modes (EGAMs) and ion temperature gradient (ITG) turbulence. The model is based on the GYSELA code, which was developed and tested for ITG turbulence before, and on an analytically described source of deeply passing energetic ions driving EGAMs. Within the framework chosen, a convincingly accurate computation was performed for the long-time evolution of the coupled EGAM and ITG turbulence. A complex evolution of the coupled system energetic particle mode—zonal flow—turbulence was found, with EGAMs suppressing or pumping the ITG turbulence depending on the parameter space.

J.-B. Girardo considered the relation between geodesic acoustic modes (GAMs) non-linearly excited by turbulence and EGAMs. Through a linear, analytical model, in which the fast particles are represented by a Maxwellian bump-on-tail distribution function, it was found that the answer depends on several parameters. For low values of the safety factor q and for high values of the fast ion energy, the EGAM originates from the GAM: it can then be called 'an EGAM from GAM'. For high values of q and for low values of the fast ion energy, the GAM is not the mode which becomes unstable when fast particles are added: the EGAM then originates from a distinct mode, which is strongly damped in the absence of fast particles. The EGAM could then be called a 'Landau EGAM'. Some other parameters have an impact on the type of EGAM: the ratio of the ion temperature to the electron temperature, the width of the fast particle distribution, the mass and the charge of the fast ions. The ratio between the EGAM and the GAM frequencies was found in experiments (DIII-D) and in non-linear numerical simulations (code GYSELA) to be close to 1/2: the present analytical study allows one to recover this ratio.

B.N. Breizman presented an invited talk on global transport of energetic particles in fusion plasmas. A comparative discussion was given of the two transport scenarios: diffusive and convective. The first scenario implies soft non-linear saturation of the modes and involves stochastic diffusion of energetic particles over a set of overlapped resonances. In contrast, the convective transport is associated with phase space structures that form via hard nonlinear development of the instability. These structures can carry resonant particles over long distance in phase space. The convective transport produces a bursting pattern of losses with significant deviations from the instability threshold whereas the diffusive scenario keeps the system close to the threshold and is tractable within the marginal stability concept.

S.E. Sharapov had a poster presentation on TAE stability estimates for the baseline 15 MA ITER scenario. It was found that due to the low magnetic shear within the radius $r/a < 0.5$, the density of TAE gaps in the central region is very low, and highly localized TAEs consisting of two coupled poloidal harmonics could only exist for some toroidal mode numbers n. On the other hand, the very high density of TAE gaps found in the region $r/a > 0.5$, gives rise to numerous global TAEs consisting of many poloidal harmonics. Furthermore, the relatively low ion temperature of $T_i < 15$ keV in the outer region makes ion Landau damping of TAEs due to thermal D and T ions lower than the TAE drive due to fusion alpha-particles and NBI-produced super-Alfvénic ions, so TAE instability may develop in this region.

The EP session was closed by a discussion on the priorities of EP studies within the EU-US TTF framework. The following order of priorities was identified and discussed:

(a) Interplay between energetic particle modes and turbulence;
(b) Interplay between energetic particle modes and 'usual MHD' modes;
(c) Single mode transport versus multiple mode transport.

4. Challenges in modelling transport in ITER and JT60-SA

The topics of this session were very wide and with clear overlaps with other sessions. The aspects on which this session focused are

- improvement of first principle understanding of the confinement;
- improvement of non-linear codes and theory;
- improvement of the tools for integrated modelling.

With regard to first principle understanding, the role of fast ion pressure through non-linear electromagnetic stabilizing effects was shown to be key to explaining the improved confinement in hybrid H modes in the talk by J. Garcia. The turbulence at the L mode edge and the challenge it represents for gyrokinetic codes was discussed by D. Told. Benchmarking exercises in regions where turbulence measurements are of very high quality can shed light on the impact of numerical choices in gyrokinetic codes. Using GENE on ASDEX Upgrade and DIII-D edge parameters, no systematic heat flux under-prediction is found. Quasi-linear transport models should thus, in principle, remain applicable even for such parameters, provided that their non-linear saturation models are appropriately generalized. Validation of transport models is also required for the description of the transport produced by microtearing turbulence in the high beta conditions of spherical tokamaks. S.M. Kaye reported an application to NSTX, where the Rebut–Lallia–Watkins model is found to be a good predictor of the H-mode electron temperature when microtearing turbulence is dominant, but not as good when microtearing is stable or subdominant.

Progress in the comparison of turbulence measurements to non-linear gyrokinetic observations was reported. In particular, H. Arnichand has shown that plasma regions, where TEMs are expected linearly, exhibit quasi-coherent structures in the frequency spectra measured by reflectometry. In non-linear gyrokinetic modelling presented by J. Citrin, in the TEM case there is an observable separation between the zonal and drift-wave components of the frequency spectrum, qualitatively similar to the experimental observations. Experimental results on electron heat transport in JET carbon (C)-wall L-mode plasmas were presented by P. Mantica and compared to quasi-linear and non-linear gyrokinetic simulations. The foreseen stabilizing effects of the magnetic shear and collisionality are in evidence in the experiments. Linear threshold predictions have been found to be in good quantitative agreement with experimental thresholds, whilst the experimental stiffness levels seem higher than found in non-linear simulations. A comparison of JET ITER-like wall (ILW) (Be in the main chamber and W in the divertor) and C-wall high density H-mode plasmas was presented by H.-T. Kim. It is found that T_e peakedness is higher in the JET-ILW discharges. In MAST, gyrokinetic simulations with kinetic electrons, discussed by G. Colyer, show a saturated electron heat flux decreasing as the electron collisionality decreases, consistent with experiments. Flow shear, turbulence and zonal flows are investigated in MAST thanks to beam emission spectroscopy and Doppler reflectometry, as reported by M.F.J. Fox. T.A. Carter reported that in the linear large plasma device turbulence intermittency is observed to increase with increasing flow and flow shear, and in the high flow regime intermittent structures are entrained in the flow and do not propagate radially. Gas modulation experiments were performed in JET to study particle transport mechanisms at the edge of L and H mode, as shown by A. Salmi, who discussed the many complicating effects to be taken into account in interpreting such experiments. In ASDEX-Upgrade, Doppler reflectometry is used to investigate the ρ^* impact by changing the mass from D to H, and by scanning the magnetic field, as illustrated by P. Hennequin. A. Storelli measured GAM frequency profiles in Tore Supra that are below those predicted by a gyrokinetic simulation and by common theoretical models, with an increasing discrepancy when collisionality decreases.

With regard to improvement of non-linear codes and theory, P. Ghendrih showed that in full-f flux driven ITG gyrokinetic modelling by GYSELA, the departure from the gyroBohm scaling appears to be more strongly related to the scaling of the correlation time, the complex radial self-organized structure still scaling with Larmor radius. The gyrokinetic formalism has been re-analysed in presence of a strong-flow by A.Y. Sharma. The development of a tracer model to characterize radial turbulent transport in stellarator geometry was presented by J. Alcuson. In order to include short scale phenomena in the gyrokinetic code ORB5, the integral form of the polarization drift operator was modified, as discussed by J. Dominski. A full-f gyrofluid approach was compared to a delta-f gyrofluid code by M. Held. The importance of a fixed flux approach was pointed out in a 2D first principle model by C. Norscini. The connection between the density increase (via pellets or 'density puff') and the confinement was investigated through the impact of ionization on the ion orbits and the consequent torques by F. Spineanu. The statistics of ion trajectories was analytically investigated in relation with a transition from Bohm to gyroBohm transport by M. Vlad.

With regard to improvement of the tools for integrated modelling, the European Transport Solver developments were presented by P. Strand and the first use of it on various cases was shown. The implementation of TGLF in JETTO was presented by G. Szepesi. The TRINITY effort was presented by E. Highcock. It uses GS2 or any other gyrokinetic or fluid code and prescribes sources to predict temperature and density profiles. The need for an effort to compare various fixed-flux approaches was pointed out. The various fixed-flux approaches range from complete full-f non-linear gyrokinetic efforts (such as GT5D, GYSELA, ORB5) down to integrated modelling using quasi-linear codes such as TGLF or QuaLiKiz, and also include delta-f, fixed-gradient gyrokinetic codes implemented in transport solvers such as TRINITY or TGYRO. Using an identical source for a case with kinetic ions only, would allow us to compare the predicted ion temperature profiles and to understand whether quasi-linear codes in integrated platforms such as JETTO, CRONOS, ASTRA or ETS are reasonable approximations.

Finally, the use of integrated modelling transport tools was illustrated to analyze existing data and predict future machines. J.P.S. Bizarro showed JETTO+SANCO predictive simulations comparing core confinement in JET between C-wall and ILW discharges, yielding a lower pedestal pressure with ILW caused by an increase in time-averaged transport in the edge transport barrier (ETB), and also by a reduced heat flux from the core due to higher radiation there. The impact of W in the ramp up phases was also discussed. T. Suzuki showed that in predictions for JT60-SA, using the TOPICS and SONIC code suites, heating and current drive systems enable the control of current and rotation profiles to achieve high confinement and stability. Predictions are also based on ASTRA, JETTO and CRONOS codes equipped with the Bohm/gyro-Bohm, CDBM and GLF23 transport models, as presented by L. Garzotti. Predictions for ITER using GLF23 as transport model in ASTRA and SOL-divertor modelling by COREDIV including impact of impurities such as W were shown by I. Voitsekovitch. The coupling between divertor-SOL and core is very strong in the presence of W. Neon seeding is required to regulate the peak heat flux on the divertor. The gas fuelling was modelled by F. Koechl accounting for core and SOL using JINTRAC in stationary H-mode ITER baseline plasmas, showing that the density tends to saturate with increasing gas puff rate when the detachment limit is approached. The gas fuelling in ITER current ramp-up phase was investigated using the core/SOL JINTRAC code described by P. Belo. During the current ramp up both the input power and the gas fuelling rate have to increase concurrently. For a given input power, density increases with increasing gas inlet rate up to an optimum density. Further increase of the gas decreases the temperature in the divertor, but keeps unchanged the density at the separatrix. The input power increases the density for a given deuterium puff, as density in the SOL (and mainly in the divertor) increases. Predictions of plasma density depend on the assumptions of transport in both the core and the SOL.

The discussion was mostly focused on the first principles discovery of the stabilizing role of fast particles through non-linear electromagnetic effects. It was pointed out that TGLF reproduces part of this effect. An extension of quasi-linear transport models for integrated modelling accounting for such effects was pointed out as an essential improvement for present models. A second point that was discussed was the need to pursue the simultaneous modelling of the core and the SOL carried out for ITER prediction and accounting for W and for particle fuelling. The EU TTF aims to develop a shared transport culture from the core to the SOL by always having a SOL plenary session and no parallel sessions.

5. L–H transition

The focus of the L–H transition session was on recent results on limit-cycle-oscillations (LCOs) and related theoretical interpretation of observations and on the connection between local studies and global (power threshold) dependencies. The oral session included six long orals and two shorter orals, the poster session six posters.

T. Kobayashi presented an overview of the dynamical response of turbulence during LCO in the JFT-2M tokamak. The spatio-temporal structures of the LCO were clarified by heavy ion beam probe (HIBP) measurements. Poloidal flow modulation with amplitude of $500\,\mathrm{m\,s^{-1}}$ was observed at the edge, where zonal flows were not observed. Turbulence and density gradient modulation were observed. The Reynolds stress was evaluated to be insufficient to explain the observed flow modulation. Causal relation among the electric field, density gradient and turbulence were observed and the electric field bifurcation theory explained the observations. Rapid propagation of the turbulence front and density gradient was observed. These phenomena are explained by turbulence spreading theory.

L. Schmitz presented recent experimental progress in L–H transition physics on DIII-D. The L–H transition trigger is investigated with Doppler backscattering (DBS) near the power threshold in a regime characterized by LCO. It is shown for the first time that the initial (transient) turbulence collapse preceding the L–H transition is caused by turbulence-generated main ion flow and $E \times B$ flow opposing the equilibrium (L-mode) edge plasma $E \times B$ flow component related to the edge pressure gradient. As the LCO evolve, the resulting reduction of edge transport then enables a periodic increase of the edge pressure gradient and ion diamagnetic flow, eventually leading to a strong negative edge electric field and equilibrium $E \times B$ shear, on a $\sim$1–10 ms timescale. The observed transition sequence is consistent with energy transfer from the turbulence spectrum via the perpendicular Reynolds stress, however invokes main ion poloidal flow and $E \times B$ flow generation opposite to the pressure-gradient driven $E \times B$ flow. A two-predator one-prey model, retaining opposite polarity of the turbulence-driven and pressure-gradient-driven $E \times B$ flow, captures essential aspects of the transition dynamics.

A different interpretation, starting from similar DIII-D data, was presented by G.M. Staebler, who showed that L–H transitions and LCO can be derived from mean field transport equations. In particular, there exist LCO and single step L–H transition-type solutions to the mean field (low frequency) toroidal and parallel momentum transport equations. Using data from a DIII-D discharge to evaluate the momentum diffusion and collisional poloidal damping rates, the frequency of the LCO can be matched. The density dependencies of the L–H and LCO diamagnetic velocity thresholds are similar to that of the experimentally measured $P_{\mathrm{L-H}}$. Also the timescale of the L–H transition velocity 'trigger' agrees with experiment. This gives hope that the mean field transport equations, used successfully to predict core confinement, can predict H-mode dynamics with quasi-linear turbulence transport models. Solving the mean field momentum transport system is computationally much faster than flux driven turbulence simulations, which are required for a quantitative prediction of the turbulence-zonal flow-mean field system.

I. Cziegler presented the connection between microscopic turbulence and large scale dynamics in L–H and L–I transitions on Alcator C-Mod. The main diagnostic used is gas-puff imaging. For the L–H transition it is shown that the non-linear turbulent kinetic energy transfer rate into the shear flow reaches the estimated drift turbulence growth rate just as the turbulence is suppressed in the transition. The net energy transfer is quantitatively compared to the loss of turbulence power and is found sufficient to explain the observed change. A corresponding amount of growth is recorded in the shear flow kinetic energy. The edge pressure gradient is shown to build later and on a slower (1 ms) timescale as it locks in the H-mode. Thus the following time sequence is established for the L–H transition: first the normalized Reynolds power develops, then the turbulence collapses and finally the diamagnetic electric field shear forms. New analysis of the L–I and I–H transition is carried out in a time-resolved sense analogously to that of the L–H transition, clarifying the role of GAMs in changes to the broadband, low-frequency component of the edge turbulence.

L. Chôné presented on-going work on the dynamics of the onset of an edge transport barrier in non-linear plasma edge simulations with the code EMEDGE3D. Flux-driven resistive ballooning simulations of the plasma edge, accounting for neoclassical force balance governing the poloidal flow, show the spontaneous formation of a transport barrier above a certain threshold of input power. The three dimensional model describes the evolution of charge and energy balances in the confined plasma under the assumption of large aspect ratio and constant density. The radial and temporal variations of the neoclassical coefficients are taken as function of the pressure profile, allowing for qualitative features and characteristic dynamics of the L–H transition to be recovered. In particular, crossing the threshold with a slow power ramp exhibits rich interplay between turbulence, turbulence-generated flows and the mean flow due to neoclassical friction, resulting in a dithering radial electric field.

T. Pütterich showed that in ASDEX Upgrade a correlation is found between the L–H transition and the ion edge pressure gradients. The L–H transition occurs when the edge value of grad $p_{\mathrm{i}}/(en_{\mathrm{i}})$ approaches a minimum value of about $-15\,\mathrm{kV\,m^{-1}}$ at a magnetic field of 2.5 T, independently of electron density According to the radial force balance for the main ions, grad $p_{\mathrm{i}}/(en_{\mathrm{i}})$ corresponds to the radial electric field E_r for negligible poloidal and small toroidal rotation of the main ions and small effects of turbulence. The absolute value of E_r is thought to be a proxy of the shear of the $E \times B$ flow, as the width of the E_r well is measured to be approximately constant. In an independent analysis, the ion heat flux at the pedestal has been investigated for a database of L–H transitions, and found to consistently describe the dependencies of the L–H threshold on electron density, plasma current in the low density branch (this dependence on plasma current has been recently discovered in ASDEX Upgrade) and the electron/ion heating fractions, providing an explanation for the non-monotonic dependence of the threshold power on density. A scaling law for the minimum density for the transition is derived which consistently orders published data from several devices. While the scaling law is not perfectly matching all of the observations, it is able to close a large gap between Alcator C-Mod and other devices such as ASDEX Upgrade, DIII-D, JFT-2M and JET-ILW (at least for the configuration which exhibits a minimum). Consistently to this interpretation, the H–L transition occurs at the same value of the minimum of grad $p_\mathrm{i}/(en_\mathrm{i})$ and at the same ion heat flux at which the L–H transition takes place. A companion poster, presented by M. Cavedon, reported on fast (50–100 μs) edge charge exchange measurements of E_r. At the L–H transition the E_r minimum is found to be proportional to B_T, indicating a threshold on the $E \times B$ velocity shear for the H-mode onset.

L–H studies in JET with the new JET-ILW were presented by E. Delabie. They highlight considerable deviations from the ITPA scaling law for $P_\mathrm{L-H}$, as well as strong additional dependencies. In the high density branch $P_\mathrm{L-H}$ is reduced by 30% compared to JET C-wall, which is favourable for ITER. The JET C-wall H-mode threshold can be recovered with nitrogen injection, indicating that the changes in the plasma impurity composition from JET C-wall to JET-ILW are responsible for the changes in $P_\mathrm{L-H}$. Gyrokinetic simulations attribute this to the stabilizing effect of Z_eff on resistive ballooning modes (see contribution by C. Bourdelle below), which, in the simulations, are identified as the dominant turbulence mechanism in the high density branch. Strong dependencies of $P_\mathrm{L-H}$ on the magnetic configuration in the divertor are found, which could help to understand or influence the L–H power threshold. Using improved edge profile measurements, it is investigated whether the observed variations in $P_\mathrm{L-H}$ can be reconciled with the view that L–H transitions are sustained by $E_r \times B$ shear stabilization of turbulence. On JET-ILW the density dependence of $P_\mathrm{L-H}$ is in fair agreement with the existence of a critical diamagnetic E_r well. However, unlike on ASDEX Upgrade, the increase in $P_\mathrm{L-H}$ at low density cannot be explained by differences in electron and ion temperature nor by a monotonic decrease of the ion heat flux towards lower density. In addition, the effect of impurity composition and divertor configuration cannot be explained by the diamagnetic E_r contribution alone, as the discharges with higher $P_\mathrm{L-H}$ also exhibit higher edge temperatures and a concomitant deeper E_r well before the transition. The strong variation in $P_\mathrm{L-H}$ with divertor configuration hints at changes in the SOL directly affecting the transition. A possible mechanism is that SOL flows change Er in the SOL, which would affect the shear in the outer part of the E_r well.

J.J. Rasmussen presented numerical investigations of transitions to high confinement. The L–H mode transition dynamics is investigated by applying a first-principle, four-field fluid model, HESEL. The model is solved on a 2D domain at the out-board mid-plane of a tokamak, including both open and closed field lines. The parallel dynamics is parameterized in each region, accounting consistently for the parallel losses in the SOL. The results reveal different types of L–H-like transitions in response to ramping up the input power (ion temperature) and are found to be in agreement with recent experiments in EAST. This includes the dynamics of the oscillatory I-mode for the slow L–I–H transition and the power threshold. Additionally, a clear hysteresis is demonstrated for the L–H–L transition and the power threshold is found to increase with increasing density, as found in tokamak experiments in the high density branch of $P_\mathrm{L-H}$.

In the poster session, C. Bourdelle presented ongoing work on the derivation of parametric dependencies of the temperature threshold, since experimental evidence on various tokamaks points towards the existence of a critical temperature characterizing the L–H transition. Simple theoretical ideas are used to derive a temperature threshold. They are based on one hand on the underlying turbulence changing from resistive ballooning modes to ITG-TEM as the temperature increases and on the other hand on the $E \times B$ shear stabilization of the turbulence. The parametric dependencies of the derived temperature threshold obtained are consistent with experimentally observed trends for $P_\mathrm{L-H}$: an increase in temperature with magnetic field; a sharp increase in $P_\mathrm{L-H}$ in the low density branch below the minimum in density; a shift of the minimum in density towards lower density values with increasing Z_eff, as observed e.g. in JET-ILW.

T. Kiviniemi presented a gyrokinetic parameter scan of GAMs close to the L–H threshold for TEXTOR-like parameters using the full-f gyrokinetic code ELMFIRE. Good agreement was found with the analytic theory for the radial wavelength of GAMs. Onset of GAMs as a function of steepening density gradient was shown. Cross correlation analysis of electric field fluctuations showed both inwards and outwards propagating GAMs. The propagation velocity was shown to decrease for increasing ion mass.

A. Merle presented the results of the modelling with the ASTRA code of both L-mode and H-mode profiles, including the pedestal region, with a new approach which imposes a given value for the gradients of both the density and electron temperature in the edge region. This approach allows one to model both L-mode and H-mode in the same way, consistent with the observation at the edge of the TCV tokamak that standard L-mode plasmas exhibit an edge region where the profiles properties are similar to those of the H-mode pedestal.

G. Tynan reported that a net inward, up-gradient turbulent particle flux is found in cylindrical plasmas when collisional drift waves generate a sufficiently strong sheared azimuthal flow that non-linearly drives positive (negative) density fluctuations up (down) the background density gradient, resulting in a steepening of the mean density gradient. The results suggest the existence of a non-linear saturation mechanism for drift-turbulence driven sheared flows, which can cause up-gradient particle transport and density profile steepening.

X.L. Zou showed that mitigation of edge localized modes (ELMs) has been demonstrated in the EAST tokamak in quasi-steady state with multi-pulses of supersonic molecular beam injection (SMBI). Experiments on EAST have revealed the underlying physics mechanism for ELM mitigation, demonstrating how the SMBI induced pedestal small scale turbulence controls ELMs. The ELM mitigation is due to an enhancement of the particle transport in the pedestal, caused by small scale turbulence induced by SMBI or mitigated ELMs themselves.

The session was closed by an open discussion, in which recent progress and main open questions have been debated, in particular:

(a) Different conclusions are drawn from parallel studies on LCO dynamics in different devices, and different theoretical interpretations of the same observations are possible. Experiments should be devised in order to clarify potential inconsistencies and distinguish between the proposed models. In particular, it could be useful to extend the characterization with respect to variations of the main plasma parameters known to affect the L–H threshold, e.g. plasma density, magnetic field, isotope mass.
(b) The understanding of the connection between local and global dependencies of the L–H transition should be intensified and extended to multi-device comparisons, as it is a critical step to more reliably predict the H-mode power threshold in future devices.
(c) In parallel, parametric dependencies of the L–H temperature threshold derived from simple theoretical ideas and which capture the experimentally observed dependencies of $P_{\mathrm{L-H}}$ should also be pursued. They are a potential step forward in the input to transport codes used to predict the discharge evolution from L-mode to H-mode, e.g. for ITER, compared to the currently employed ITPA global $P_{\mathrm{L-H}}$ scaling law.

6. Impurity transport

The focus of the impurity transport session was dedicated to the role of inhomogeneities of the electrostatic potential in tokamaks and in stellarators (2D and 3D effects). In the presence of impurities with large mass and charge, these inhomogeneities produce field trapping and drifts and can significantly affect the flux-surface averaged radial impurity fluxes. The session was opened by two invited review presentations. The first was dedicated to theoretical aspects and was given by T. Fulop. The second was dedicated to experimental aspects and was given by M. L. Reinke.

T. Fulop showed that impurity poloidal asymmetries due to neoclassical effects can change on a very small radial scale. They can be strong enough to significantly affect impurity peaking in the vicinity of the pedestal. Applications to recent experiments in C-Mod show that neoclassical transport alone could explain positive impurity (Mo) peaking observed in the outer core of the C-Mod plasmas. However, within experimental uncertainties, turbulent transport is predicted to dominate over the neoclassical component, leaving a yet unresolved discrepancy for these C-Mod experiments.

M.L. Reinke openly discussed the impact of the high Z impurity asymmetries from an experimental perspective, addressing the question of whether these are important for radial transport or should be considered a diagnostic nuisance only. Partially-ionized, high-Z impurities have long been known for their ability to dramatically impact magnetically-confined plasma performance and stability through strong radiative losses. While on-axis accumulation of tungsten has been widely observed in tokamaks, and is generally accepted to be due to neoclassical transport, the physical mechanisms by which this effect is ameliorated, such as through application of on-axis auxiliary heating, are still under investigation. In comparison to low-Z ions, the large mass and high charge of heavy impurities can cause them to exhibit strong density variation within a flux surface. The current level of validation of parallel impurity transport physics was briefly described. Recently, experiments have begun to focus on the impact such asymmetries may have on the flux-surfaced averaged radial particle transport. Updates to on-going research in this area were summarized, and a detailed discussion of unique challenges faced was presented. Investigations must distinguish radial variations in impurity density from poloidal, stressing optimized diagnostic placement and the importance of accurate tomographic inversion of measurements such as soft x-ray (SXR) imaging. Established interpretative tools (i.e. STRAHL) solve the time-evolving 1D impurity transport equation in plasmas exhibiting 2D evolution, resulting in possible constraints on their use. The flux-surface variation of high-Z impurities is known to depend strongly on toroidal rotation and poloidal trapping of fast-ions, with no direct 'knob' to turn. Experiments designed to test asymmetry-induced radial transport must be carefully planned to avoid co-variances with other robust effects like ion temperature screening and MHD mode activity. Recent experimental results from Alcator C-Mod, JET and ASDEX Upgrade were used to illustrate these topics.

Following these invited talks, A. Alonso presented a contributed oral on the electrostatic potential variations along flux surfaces. These can significantly affect the radial flux of medium and high Z impurities. TJ-II probe measurements in low density electron cyclotron resonance heated plasmas, at two different sectors of the device, show tens of Volts differences on a same flux surface. These differences are shown to depend on electron temperature and/or radial electric field. Neoclassical Monte Carlo calculations with the EUTERPE code show similar overall dependencies with T_{e} and E_r, but no quantitative agreement was found at the precise locations of the measurements. This findings call for a verification of both measurements and simulations with other diagnostics and codes.

The contributed oral by Y. Camenen was dedicated to testing poloidal asymmetry models against impurity density, temperature and toroidal rotation measurements. Density, temperature and toroidal velocity of carbon impurities have been measured in TCV over the entire poloidal cross-section by scanning the plasma vertical position on a shot-to-shot basis. It was found that the carbon temperature is constant on flux surface whereas the density and toroidal velocity display a sizable in/out asymmetry. The in/out toroidal velocity asymmetry is consistent with the first order plasma flow structure expected from theory, provided the variation of the plasma density on a flux surface is taken into account. However, the measured in/out asymmetry of the carbon density is much larger than expected from centrifugal effects alone and is so far not understood. Some correlation of the asymmetry and the sawtooth activity was observed and the possibility that sawteeth drive a temperature anisotropy which induces the in/out asymmetry is under exploration.

F. Casson presented a contributed oral on the ongoing modelling of tungsten transport in the presence of ICRH and neoclassical tearing modes (NTMs) in JET. For heavy impurities, turbulent and neoclassical transport have been modelled using theory-based numerical tools (GKW and NEO respectively) with a comprehensive treatment of poloidal asymmetries, to predict 2D core W distributions in JET (as well as in ASDEX Upgrade, companion poster by C. Angioni). These predictions have been validated against SXR tomography. Neoclassical convection is found to be the generic cause of central W accumulation, but the inward convection can be mitigated by temperature screening or turbulent diffusion. Centrifugal effects increase neoclassical W transport by an order of magnitude, and their impact on W peaking also depends strongly on collisionality and profile gradients, such that models which exclude these asymmetries cannot accurately describe heavy impurity transport. In JET baseline H-modes, centrifugal effects increase W peaking, in contrast to the hybrid scenario in which their effect on W peaking is smaller. ICRH can have three beneficial effects in preventing W accumulation; (1) Flattening the core n_i profile, (2) Increasing turbulent W diffusion, (3) Adding temperature screening from the heated minority. When the appearance of a NTM is correlated with W accumulation, this may be due to a removal of both turbulent W diffusion and temperature screening inside the island. For W, both turbulent and neoclassical transport should be considered together, since the profile is often set by the ratio of neoclassical convection to turbulent diffusion. In standard H-mode conditions in ASDEX Upgrade, electron cyclotron resonance heating (ECRH) heating is still believed (not contradicted by the above) to prevent W accumulation by increasing turbulent W diffusion; this hypothesis has not yet been tested with the improved modelling capabilities.

The contributed oral by M. Chilenski was dedicated to the improvement of profile fitting and to the quantification of uncertainty in experimental measurements of impurity transport coefficients using Gaussian process regression (GPR). The need to fit smooth temperature and density profiles to discrete observations is ubiquitous in plasma physics, but the prevailing techniques for this have shortcomings that cast doubt on the statistical validity of the results. These shortcomings were outlined and a new methodology was presented based on GPR, a powerful nonparametric regression technique. Applications to L-mode impurity transport as well as to momentum transport were shown. These new techniques for profile fitting and uncertainty propagation are quite general, making them of interest for wider use in the transport community.

Finally, A. Kappatou presented an oral contribution dedicated to investigations on helium transport in ASDEX Upgrade. A Monte Carlo model for the helium plume emission has been developed at ASDEX Upgrade that reproduces the helium charge exchange spectra and allows for the derivation of accurate helium density profiles. An extensive database of helium and boron density profiles has been collected from dedicated discharges in which the plasma parameters theoretically relevant to impurity transport were varied. The helium density profiles were found to be as peaked as the electron density profiles at mid-radius. Detailed comparisons of the experimental data with the predictions of turbulent transport theory were presented. Qualitative agreement is observed, but the gyrokinetic modelling is found to underpredict the experimental profile gradients.

In the poster session, John Rice presented recent investigations of core impurity transport for a variety of confinement regimes in Alcator C-Mod plasmas from x-ray emission following injection of medium and high Z materials. In Ohmic L-mode discharges, impurity transport is anomalous ($D_{\rm eff} \gg D_{\rm nc}$) and changes very little across the LOC/SOC boundary. In ICRF heated L-mode plasmas, the core impurity confinement time decreases with increasing ICRF input power (and subsequent increasing electron temperature) and increases with plasma current. Nearly identical impurity confinement characteristics are observed in I-mode plasmas. In enhanced D-alpha (EDA) H-mode discharges the core impurity confinement time is much larger, but exhibits a similar scaling with plasma current, although there is a covariance with the density. There is a strong connection between core impurity confinement time and the edge density gradient. Central impurity density profiles in stationary regimes are generally flat, in spite of large amplitude sawtooth oscillations, and there is little evidence of impurity convection inside of $r/a = 0.3$.

C. Angioni presented a poster on the theoretical modelling of W Transport in ASDEX Upgrade, focusing on applications which can reveal aspects related to recent analytical developments of neoclassical transport theory to shed light on the impact of poloidal asymmetries on impurity transport. Combined neoclassical (NEO code) and turbulent (GKW code) transport calculations of W in ASDEX Upgrade experimental conditions reveal in general a good agreement for NBI only cases (confirming previous modelling results on JET). In the transient conditions of the ASDEX Upgrade improved H-mode with current overshoot, neoclassical temperature screening is sufficient to prevent accumulation. In the presence of ICRH, a more complete model is developed to describe the impact of temperature anisotropy on impurity density poloidal asymmetry. W transport, in particular from NEO, sensitively depends on the profiles of the perpendicular and parallel temperatures of the ICRH minority, computed by the TORIC/SSFPQL package. These can display locally very high gradients, which go beyond the applicability of drift kinetic theory.

P. Manas presented a study dedicated to the gyrokinetic modelling of carbon density profiles in JET. Consistent with recent findings on ASDEX Upgrade reported in the oral presentation by A. Kappatou, it is found that the modelling allows only a vague qualitative consistency with the observations, but does not reproduce quantitatively the data.

M. Romanelli presented a study dedicated to establishing the impact of the W concentration on the transport of main particle species and impurities in gyrokinetic modelling of typical JET plasma parameters. Concentrations above which a trace treatment becomes inappropriate are identified in different turbulence regimes.

D. Esteve presented ongoing studies of impurity transport with the GYSELA global gyrokinetic code, which allows the calculation of both neoclassical and turbulent transport within the same simulation, and by this allows the calculation of possible direct interplay between the two transport components, which are regularly computed independently.

In the discussion session it was concluded that, whenever possible, synergies should be promoted to complement capabilities in different areas to provide a bridge between experimental demonstration and basic understanding. The development of ITER / DEMO plasma scenarios requires an integrated treatment including:

(a) An engineering approach, i.e. use of empirical control parameters to avoid impurity accumulation in the core, like core heating or MHD.
(b) A physics research, i.e. basic understanding of underlying mechanism, like role of heating on gradients (neoclassical effects), role of heating on turbulent driven transport, flux surface plasma potential asymmetries and strong inertia and electrostatic forces resulting in poloidal asymmetries.

Thus, we need an integrated demonstration/understanding approach including both (a) Optimizing control parameters (engineering approach) and (b) Deepening physics understanding (physics/theory approach).

7. SOL transport

Managing the transport in the SOL, and thus the heat loads on divertor and wall components as well as the impact of the SOL on confinement, is important for present devices and will be essential for fusion devices like ITER and DEMO. The session on SOL transport started with overview talks on the turbulence modelling and the steady state classical modelling augmented by recent experimental results. J. Myra presented work performed with co-workers D.A. D'Ippolito and D.A. Russell on SOL turbulence with aspects of theory and modelling and the implications following from this. SOL turbulence is characterized by the blob-filament paradigm which provides a useful conceptual basis for understanding many transport-related phenomena in the SOL. Reduced interchange-type models, based on 2D fluid theory with parallel closures capture the essence of strongly non-linear $E \times B$ dynamics and order unity fluctuations necessary for a zero-order description of SOL turbulence. Collisionality affects SOL turbulence through increasing blob speeds and causing parallel gradients in, and disconnection of, the filamentary structures from divertor plate or limiter sheaths. Additionally X-point geometry and collisionality show synergistic behaviour with regard to disconnection. Ongoing and future studies aiming at predictive modelling of the SOL heat flux width, critical for power handling in ITER and future machines, will require attention to these turbulence features. Additionally, a better understanding of the role of neoclassical orbit effects in the SOL and their interaction with turbulence may be needed to address the scaling of the heat flux width in large major radius machines. G. Birkenmeier showed recent experimental results, with a focus on three points. Assessing the ion temperature in the SOL, it is observed that this exceeds the electron temperature. This is important to describe the blob dynamics correctly, which has to be done in a warm ion model, and has possibly serious consequences for sputtering and thus wall erosion in the main chamber, as these processes scale with ion temperature. For L-mode discharges going up the 'stepladder to ITER'-experiments from COMPASS, ASDEX Upgrade and to JET experiments show that the SOL transport increases significantly at higher densities. A clear correlation of flatter, at increased values, density profiles, larger blob transport (size and velocity) and degree-of-detachment is found. This change of regime is in line with resistive blob transport models. Finally in H-mode a similar phenomenology is found: the inter-ELM blobs behave like L-mode blobs, a flattening of the SOL profile is found at higher density and a considerable part of the input power is lost due to filament transport in the main chamber.

The view of steady state fluid SOL transport modelling was presented by L. Aho-Mantilla, who showed tests of various models for turbulent radial transport in 2D edge fluid code simulations (e.g. SOLPS, EDGE2D, UEDGE, SONIC) and comparisons to experiments. The typical approach is to apply a set of coefficients (χ, D) for heat conduction ($q_\perp = -\chi n \nabla T$) and particle transport ($\Gamma_\perp = -D\nabla n$) at the outer midplane and benchmark the resulting steady-state plasma profiles against experimental data. A practical choice is to use a diffusive model instead of a convective model, as only the resulting flux is used in the code calculations. The modelled target conditions can be sensitive to relatively small variations (~30%) in the transport coefficients in the SOL above the X-point, whereas similar variations in divertor transport lead to smaller effects at the targets, due to flux expansion. The benchmarking studies yield transport coefficients which increase with collisionality and have higher values in the SOL compared to the plasma edge (inside the separatrix). The often encountered difficulties in matching measured divertor parameters could point towards strong poloidal variation of SOL transport under certain plasma conditions, exceeding the level of ballooning usually assumed in the simulations. In these cases, however, other explanations like missing atomic and molecular physics or kinetic effects are possible.

F. Militello talked on intrinsic SOL instabilities, which were studied with Y. Liu using a flute approximation and incorporating the appropriate sheath boundary conditions at the target. The linear growth rate and the structure of the modes were obtained. The associated diffusion was estimated using the mixing-length approach for the fastest growing modes. The model used includes curvature and sheath drives, finite Larmor radius effects and partial line-tying at the target. The magnetic geometry was obtained using current carrying wires, representing the plasma current and the divertor coils, and naturally generates X-point geometry and magnetic shear effects. The calculation was performed for ITER relevant parameters and scans in SOL width and distance from the separatrix were presented. In addition to a standard lower single null, Super-X and Snowflake configurations were examined in order to assess the importance of the geometry on the stability of the boundary. Steep gradients were found to destabilize a divertor localized mode and increase the diffusion coefficient. This could have the beneficial effect of spreading the SOL width below the X-point, thus alleviating the divertor heat loads. The increased shearing of the mode in advanced configurations reduces the maximum growth rate of the instabilities. With respect to standard configurations, the upstream diffusion coefficient is doubled, although in the divertor region the much larger perpendicular wave number might significantly decrease the transport. This means that below the X-point upstream born intrinsic instabilities could play a reduced role in determining the SOL width. Experimental evidence shows filaments ejected from the separatrix in both L-mode and in the inter-ELM phase.

The transport due to these structures, which could account for 50–60% of the total, was not discussed in the presentation and might compensate the reduced diffusive coefficient due to the intrinsic instabilities in advanced configurations.

G. Conway presented efforts to understand the response of the plasma to externally applied magnetic perturbations (MPs), including application to ELM mitigation in H-mode. Studies of MP impact in simpler L-mode were performed, and in particular the radial and toroidal structures of the plasma response via the E_r and density turbulence using Doppler reflectometry on ASDEX Upgrade were investigated. For the structure of the MP he concentrated on the toroidal response to $n = 2$ MPs by rotating MP coil phase relative to the spatially fixed diagnostic. New data from 2014 shows distinct different response for SOL and edge regions, with general $n = 2$ sinusoidal E_r response, but unexpected toroidal shifts with radius, plus harmonic distortions, dependent on degree of the MP resonance etc. Modelling for these situations is in progress. Continuing on the topic of MPs D. Ryan argued that experiments indicate that differential phase between upper and lower coil sets could be a useful control parameter in resonant MP (RMP) experiments. A calculation of the plasma response shows that the applied RMP is strongly screened at rational surfaces, but may be amplified by coupling to kink modes and low-n peeling modes of the MHD spectrum. A scan of the differential phase shows that this resonant field amplification effect is sensitive to the differential phase, and that the differential phase which maximizes the pitch aligned field components is shifted significantly from its vacuum value. Finally L. Easy closed the loop back to filamentary blob structures. He showed simulations of isolated 3D SOL filaments in a slab geometry using a newly developed 3D reduced fluid code written using the BOUT++ framework. First, systematic scans were performed to investigate how the dynamics of a filament are affected by its amplitude, perpendicular size and parallel extent. The perpendicular size of the filament was found to have a strong influence on its motions, as it determined the relative importance of parallel currents to polarization and viscous currents, whilst drift-wave instabilities were observed if the initial amplitude of the blob was increased sufficiently. Next, the 3D simulations were compared to 2D simulations using different parallel closures; namely, the sheath dissipation closure, which neglects parallel gradients, and the vorticity advection closure, which neglects the influence of parallel currents. The vorticity advection closure was found not to replicate the 3D perpendicular dynamics and overestimated the initial radial acceleration of all the filaments studied. In contrast, a more satisfactory comparison with the sheath dissipation closure was obtained, even in the presence of significant parallel gradients, where the closure is no longer valid. Specifically it captured the contrasting dynamics of filaments with different perpendicular sizes that were observed in the 3D simulations which the vorticity advection closure failed to replicate. However, neither closure successfully replicated the Boltzmann spinning effects and associated poloidal drift of the blob that was observed in the 3D simulations. Although the sheath dissipation closure was concluded to be more successful in replicating the 3D dynamics, it is emphasized that the vorticity closure may still be relevant for situations where the parallel current is inhibited from closing through the sheath.

8. Conclusions

This section provides a summary of all of the sessions of the workshop, and outlines the main open issues and the priorities for future work, as these were identified during the respective discussion sessions.

In the session on momentum transport, a large spectrum of results was presented and different approaches (in particular global full-f flux-driven in comparison with local delta-f gradient driven simulations), as well as the respective advantages and limitations, were discussed. In the framework of global simulations, when turbulent and neoclassical transport are concurrently treated in a flux-driven full-f global gyrokinetic code, non-axisymmetric turbulent fluctuations lead to large neoclassical responses which tend to cancel the turbulent momentum transport component, under the condition of total ambipolarity. At sufficiently small ρ^*, the scaling with plasma size is affected by bursty nonlocal transport, which is induced by self-consistent interactions between temperature fluctuations and turbulent transport under a local power balance condition. In the same context, studies have been presented on different aspects where forcing and self-organization play a prominent role, as obtained in flux-driven simulations with a semi-Lagrangian global gyrokinetic code, in particular on the interaction between intrinsic rotation and micro-transport barriers produced by self-generated shear flows and on the impact of SOL flows. Other flux-driven simulations, this time with a particle-in-cell code, show that under certain conditions, anti-diffusive momentum transport can generate strong flows, which lead to large scale modifications of the temperature gradient profiles. In the framework of local simulations, a theoretical model for intrinsic rotation suited for implementation in flux tube codes has been developed and has been applied in the limit in which eddies are ordered much smaller than the ion poloidal gyroradius. In this limit, the impact of neoclassical flows is dominant, and implies a reversal of the predicted intrinsic rotation moving from banana to plateau collisional regime. This reversal is found to be consistent with the measured intrinsic rotation in MAST. Consistency is also found in the modelling of an intrinsic rotation profile in JET. Also the impact of tilted elliptical flux surfaces was considered and shown to generate sufficient intrinsic rotation to stabilize resistive wall modes. Applications in 1.5D transport codes require the adoption of a correct and complete transport equation for the toroidal angular momentum, which has been obtained by solving for the radial current density in a multi-species plasma. The different components of the flow can be properly included, with flexibility in the use of different theoretical models for diffusion, convection and residual stress. Among the transport components to be included in the modelling of toroidal rotation, an important role is played by the neoclassical toroidal viscosity. A flexible tool has been developed which allows the computations of the neoclassical toroidal viscosity in arbitrary geometry and collisional regime, without any model assumption on the collision operator. For applications to tokamaks, the only limiting condition is that the non-axisymmetric perturbation field be small enough that the effect of the perturbation field on particle motion within the flux surface is negligible. First applications to the case of the ripple in ASDEX Upgrade have been presented. Future research activities should be dedicated to further clarify the relationship between global flux-driven and local gradient–driven approaches and the conditions where these should be expected to give consistent results. Consistent approaches where neoclassical and turbulent momentum transport components are computed concurrently should also be more widely considered. The interesting and promising results obtained by the inclusion of neoclassical flows in the calculation of the residual stress should be extended to applications to other devices. In this context, the development of a multi-device profile database of intrinsic rotation remains an important goal. Improved statistical methods, based on GLS regressions, have been shown to be particularly well suited for these applications where large uncertainties are present in the measured response and predictor variables.

The session on energetic particles presented results on different mechanisms of transport. Experimental results on the transport of fast ions produced by MHD activity were presented as a consequence of fishbones modes and of bursting, frequency-chirping TAE modes in MAST, as supported by advanced fast-ion diagnostics and by results from TRANSP modelling. Several investigations were dedicated to the theoretical modelling of EGAM. Numerical studies with the GYSELA code dedicated to the interaction between EGAMs and microturbulence reveal EGAMs can suppress or pump the ITG turbulence depending on the parameter space. The relation between EGAMs and GAMs was also examined. For low values of the safety factor q and for high values of the fast ion energy, it is found that the EGAM originates from the GAM, whereas for high values of q and for low values of the fast ion energy, the EGAM originates from a distinct mode, which is strongly damped in the absence of fast particles. From a global perspective, transport of energetic particles can have both diffusive and convective character. Diffusive transport is produced by soft non-linear saturation of the modes and involves stochastic diffusion of energetic particles over a set of overlapped resonances. Convective transport is associated with phase space structures that form via hard non-linear development of the instability and carry resonant particles over long distance in phase space. Convective transport produces a bursting pattern of losses with significant deviations from the instability threshold whereas the diffusive scenario keeps the system at marginal stability close to the threshold. For the ITER baseline scenario, with low magnetic shear inside $r/a < 0.5$, the density of TAE gaps is very low, and highly localized TAEs consisting of two coupled poloidal harmonics could exist for some toroidal mode numbers n only. In contrast, for $r/a > 0.5$, the high magnetic shear gives rise to numerous global TAEs consisting of many poloidal harmonics. In this region, the TAE instability is expected to develop, since ion Landau damping due to thermal D and T ions is weak compared to the TAE drive due to fusion alpha-particles and NBI-produced super-Alfvénic ions. Future research activities within the TTF should give priority to the interaction between energetic particle driven modes and microturbulence, to the interplay between energetic particle modes and usual MHD activity, as well as to the modelling of transport due to multiple modes, beyond the single mode description.

The session on challenges in transport modelling for future devices addressed first principle understanding, work on non-linear codes and tools for integrated modelling. The non-linear electromagnetic stabilization of ITGs due to pressure gradient (including fast ion pressure) was shown to be a key player in the improvement of high β core confinement in hybrid scenarios. A fix to quasi-linear models to include such effects in scenario simulations is being worked out. L-mode edge heat flux shortfall was not found in GENE non-linear simulations, hinting that quasi-linear transport models should remain applicable in such region, provided that their non-linear saturation models are appropriately generalized. TEMs studies have validated theory predictions of linear thresholds, whilst the explanation for the experimental higher values of stiffness remains to be investigated. TEMs are found by reflectometry and in non-linear simulations as quasi-coherent structures in the frequency spectra. Comparison of JET ILW and C-wall plasmas indicated that anomalous electron heat transport is not degraded in ILW. In MAST, a beneficial effect of decreasing collisionality on electron temperature gradient (ETG) transport is observed in experiments and found in simulations. Ion-scale turbulence measurements have provided evidence for a correlation between tilting of eddies, shearing rate and reduced heat flux. Gas modulation experiments in JET with high quality reflectometry measurements have proved challenging to interpret, and further work is needed to assess whether they can provide evidence about the existence of a particle pinch in the pedestal. Experimental GAM frequency profiles in Tore Supra follow theoretical fluid prediction, while GAMs in simulations have higher frequencies close to the linear kinetic prediction. The ρ^* impact has been investigated experimentally in ASDEX Upgrade by Doppler reflectometry. Full-f flux-driven ITG gyrokinetic modelling by GYSELA has investigated the departure from the gyroBohm scaling and the role of the ion mass. The transition from Bohm to gyroBohm transport has been also investigated through the statistical properties of ion trajectories. Ion orbits directly after ionization, and related torque, have been also considered in relation to the dependence of energy confinement on plasma density. Improvements of the gyrokinetic formalism in the presence of a strong-flow or of short scale phenomena have been discussed. An electro-magnetic full-f two field gyrofluid model has been presented. The importance of a fixed-flux approach was pointed out in a 2D first principle model. ETS and some examples of its applications have been presented. An effort to implement TGLF in many EU transport codes has been made (JETTO, ASTRA, CRONOS, ETS) and benchmarking is ongoing. TRINITY has also been more extensively used. The need for an effort to compare various fixed-flux approaches was pointed out. Various examples of integrated modelling work have been presented, including JET ILW confinement reduction, JT-60SA scenarios and control of current and rotation. Integrated SOL/core ITER modelling with JINTRAC including impact of W, gas fuelling and Ne seeding has been presented. The need for more intensive work of this type on existing devices was pointed out.

The session on L–H transition presented recent progress on both experimental and theoretical studies dedicated to the confinement mode transition. A large part of the session was dedicated to the comparison of different observations of LCOs in different devices (in particular JFT-2M and DIII-D), as covered by different diagnostics, and their possible theoretical interpretation. Not only different devices provide different type of observations, potentially revealing the existence of different transition regimes, but it also appears that different models can be applied to explain the same observations, with different roles given to the turbulence driven zonal flow, the mean field and the plasma kinetic profiles. While in JFT-2M the LCO were observed in the absence of turbulence generated zonal flows, the role of turbulence-generated $E \times B$ flow was pointed out in the DIII-D experiments. This is shown to be responsible for the initial turbulence collapse preceding the L–H transition, and to be opposite to the equilibrium flow component due to the edge pressure gradient. Only in a later phase of the LCO, the periodic increase of the ion diamagnetic flow and consequent equilibrium $E \times B$ shear become significant. Experiments in Alcator C-Mod show an analogous time sequence, where first the normalized Reynolds power develops, then the turbulence collapses and finally the diamagnetic electric field shear forms. A predator-prey type of model is often called to interpret these experimental observations. However, from the observation that LCOs take place at frequencies which are in the range of those expected for the dynamics of the mean field, a different interpretation is possible, based on mean field transport equations, specifically applied to model the DIII-D results. Both LCO and single step L–H transition-type solutions are present in the mean field (low frequency) toroidal and parallel momentum transport equations and match the frequencies and time scales of the observed transitions. This opens a new paradigm within which these observations can be explained and, more in general, the physics of the L–H transition can be described, where the mean field transport equations, used successfully to predict core confinement, can also predict H-mode dynamics with quasi-linear turbulence transport models. On the side of theory-based turbulence simulations of the spontaneous formation of a transport barrier and the confinement transition, results from two different models and related codes were presented. A spontaneous formation of a transport barrier above a certain threshold of input power was reported in flux-driven resistive ballooning simulations of the plasma edge, accounting for neoclassical force balance governing the poloidal flow, with the code EMEDGE3D. Spontaneous transitions to high confinement were also presented with the 2D fluid model HESEL, showing simulation results which are found to be in agreement with recent experiments in EAST. Turbulence simulations have also been performed with the full-f gyrokinetic code ELMFIRE for TEXTOR like parameters, investigating the onset and properties of GAMs. Moving now to experimental results dedicated to investigations of local macroscopic plasma parameters at the L–H transition, in ASDEX Upgrade the L–H transition is always found to take place at the same minimum value of the radial electric field E_r for a given magnetic field, consistent with the main ion diamagnetic component. The minimum value of the radial electric field at the transition is measured and found to increase proportionally to the magnetic field, indicating a threshold on the $E \times B$ velocity shear for the H-mode onset, as the radial electric field exhibits a well of approximately constant width. An independent study has revealed the critical role of the ion heat flux at the pedestal to consistently describe the L–H threshold and to explain the non-monotonic dependence of the threshold power on density. This allows this dependence to be consistently ordered in a set of published data from multiple devices. Recent studies at JET with the ILW show considerable deviations from the ITPA scaling law for $P_{\mathrm{L-H}}$, as well as strong additional dependencies. In the high density branch $P_{\mathrm{L-H}}$ is reduced compared to JET C-wall, and the difference is found to be due to the reduced values Z_{eff}. This could be explained by the reduced drive of resistive ballooning modes, which, in the simulations, are identified as the dominant instabilities in the high density branch. This has also motivated the development of a quasi-linear model for the L–H transition, described in terms of a critical temperature, which is based on the competition between the instability drive, moving from resistive ballooning modes to ITG-TEM with increasing temperature, and the $E \times B$ shear stabilization, and which shows consistent dependences on various parameters with the experiment. Moreover, while the density dependence of $P_{\mathrm{L-H}}$ in JET is in fair agreement with the existence of a critical diamagnetic E_r well, as also reported in ASDEX Upgrade, other parametric dependences, as well as the impact of the divertor configuration, hint to additional effects playing a non-negligible role, also connected with the role of SOL flows, affecting the shear in the outer part of the E_r well. Future work is expected to give priority to further characterize the regimes with LCO, in order to unambiguously identify the correct physical mechanism behind these observations. The complex connection amongst the transition dynamics at the fluctuation level, the local edge plasma parameters and global parameters at the transition is being increasingly clarified, but still requires further investigations. Several hidden variables are still potentially at play, and should be identified before a reliable relation among all the relevant parameters and the required input power for the transition can be derived. Simple theoretical and partly heuristic ideas can be useful to address the research in this context, and highlight critical parameters which should be measured at the transition. These, however, should not be considered to have the reliability of first-principle models. From the theory standpoint, spontaneous formation of transport barriers and confinement transitions were reported in simulations with edge turbulence codes, with different type of models, including very different critical ingredients which lead to the predicted transition with increasing input power. In this framework, future work should be dedicated to increase the level of consistency of these models, testing the impact of the assumptions that these include and reducing the amount of heuristic ingredients in the equations.

The impurity transport session reported the important progress which was obtained in the theory-based modelling of the transport of heavy impurities over the last few years. Theoretical developments which describe the impact of poloidal asymmetries of heavy impurities on the radial transport are currently taken into account in the modelling. Neoclassical transport, which is greatly increased by centrifugal effects, is found to be the main player governing the behaviour of heavy impurities in most conditions. Modelling which combines neoclassical and turbulent transport, and includes the impact of poloidal asymmetries, is found to provide a quantitative description of the 2D W density distribution in a variety of conditions, as demonstrated by applications to JET and ASDEX Upgrade, and provides useful indications on possible means to control W accumulation, which is produced by the neoclassical pinch. Further investigations are required in the experimental assessment, and in the related comparisons with theoretical predictions, of the impact of these poloidal inhomogeneities on the radial transport. An interesting experimental result has been obtained in Alcator C-Mod through a thorough comparison of the confinement properties of impurities in different confinement regimes, which reveals that I-modes exhibit anomalously short values of impurity confinement time like the L-modes, whereas EDA H-modes have much larger values. Of course, several open questions still remain, particularly related to conditions where turbulent transport is found to dominate, and where often no quantitative agreement with the measurements is found, as in the case of the modelling of molybdenum in Alcator C-Mod plasmas. In addition, further modelling activity should be dedicated to the quantitative validation of the theoretical predictions in the presence of ion cyclotron and electron cyclotron heating. Further efforts should also be dedicated to the validation of neoclassical parallel transport, for both low and high Z impurities, since, although consistency between theory and observations is found at a qualitative level in several conditions, quantitative disagreement is documented in both TCV and TJ-II. These studies are critical in particular for applications to the plasma edge, as well as to stellarator geometry in general. There is clear evidence of interplay between both parallel and radial transport and MHD activity which requires further theoretical understanding. The development of numerical tools which allow the calculation of the impact of a MP like a magnetic island on the transport should be considered a priority. Furthermore, recent experiments in ASDEX Upgrade delivering high quality He density profiles shows that a reliable quantitative description of low Z transport, where regularly turbulent transport dominates, is still missing. The need for improved models for low Z impurity transport is also supported by the disagreement with experiment found in the modelling of carbon density profiles at JET. Among the effects to be explored there is the direct interplay between neoclassical and turbulent transport concurrently computed within the same simulation (similar studies have been also reported in the momentum transport session). Finally, and as a general remark, more systematic approaches dedicated to profile fitting and to the quantification of uncertainty in experimental measurements of impurity transport coefficients should be considered, like that allowed by the utilization of GPR, a powerful nonparametric regression technique.

Transport through the SOL does not only determine the power deposition profiles or the plasma fuelling, but has consequences for the SOL operating scenarios and thus feeds back on fusion plasma performance. The session gave a comprehensive overview on modelling approaches, where traditional modelling for analysis is done based on 2D codes and largely fitted transport coefficients, but with a high concentration on the plethora of atomic processes present at the interaction between plasma and non-ionized gases and solid surfaces. It became obvious that the analysis time for discharges has to be significantly reduced, and that these classical approaches have little predictive power, specifically not for new devices or advanced modes of SOL operation, such as detachment. Turbulence based SOL codes are just beginning to become more relevant for the experiments, but need development work by including geometry, boundary conditions and probably most of the atomic interactions. Here, for the future, a significant effort needs to be undertaken, focusing efforts on developing 3D turbulence simulations which allow for predictive statements on ITER and subsequent classes of fusion devices. This effort needs to be supplemented with advances in diagnostics, most urgently needed for ion temperature fluctuations and profiles, but also calling for data from the high field side region of tokamaks. These are areas where potentially smaller devices can also deliver useful results. Apart from these very fundamental issues, the interaction of the SOL with RMPs calls for attention if quantitative predictions on this ELM mitigation scheme are to be made. Also the role of the SOL in L–H transition is an important area of ongoing research. All in all, the SOL transport issues benefit greatly from being discussed in conjunction with the core transport efforts.

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