Joint meeting of 9th Asia Pacific-Transport Working Group (APTWG) & EU-US Transport Task Force (TTF) workshop

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This conference report summarizes the contributions to, and discussions at the joint meeting of the 9th Asia Pacific-Transport Working Group (APTWG) & EU-US Transport Task Force (TTF) workshop held online, hosted by Kyushu University, Japan, during 6-9 July 2021. The topics of the meeting were organized under five main topics: 1)Isotope effect on transport and physics on isotope mixture plasma, 2)Turbulence spreading and coupling in core-edge-SOL, 3)Interplay between MHD topology/instability and turbulent transport, 4)Interaction between energetic particle driven instability and transport, 5)Model reduction and experiments for validation.

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I. INTRODUCTION

The joint meeting of the 9th Asia Pacific-Transport Working Group (APTWG) & 2021 EU-US Transport Task Force (TTF) workshop was held online during 6-9 July 2021, Japan. The Research Center for Plasma Turbulence and Research Institute for Applied Mechanics in Kyushu University hosted this meeting. This is the first joint APTWG & EU-US TTF meeting organized by the APTWG conference organizers & chair and co-chair of the EU-US TTF. This joint meeting was originally planned for 2020. The joint meeting was postponed due to the pandemic of COVID-19 and was held online as a virtual conference in 2021. This meeting is a series of APTWG meetings, which started at NIFS Japan in 2011[1] and has been held every year 2011 - 2018 and every two years afterward in China, Korea, or Japan [2–8]. The topics varied at every meeting, to focus on the urgent and essential issues regarding the underline physics of turbulence and transport in toroidal plasmas.

This joint meeting aims to understand the basic mechanisms of turbulence and MHD responsible for particle, momentum, and energy transport in magnetically confined toroidal plasmas through the discussions of experts from Asia, the EU, and the US. The joint meeting of the APTWG & EU-US TTF workshop consisted of (a) special plenary sessions, (b) working group sessions, (c) summary sessions. This series of the meeting have a session solely devoted for discussion, led by one working group leader to clarify urgent and essential issues. Participation in this joint meeting is 80, and 74 talks were presented in five days. The morning session is devoted to EU participation, while the evening session is dedicated to US participation, to accomodate the different time zones.

Special plenary sessions

These sessions aim to focus on the emerging issue of turbulence and transport in tokamaks. The following four talks were presented;
1) Turbulent and neoclassical transport of impurities: from W accumulation to light impurity peaking modeling in tokamaks by P.Manas.
2) Strong reversal of simple isotope scaling laws in tokamak edge turbulence by E.Belli.
3) Experimental study on the interaction between magnetic islands and turbulence in HL-2A plasmas by M.Jiang.
4) Gyrokinetic simulations of zonal flow staircase in tokamak plasmas by L.Qi.

Working group sessions

This year, the topics of the working group were decided by the Program Committee members consisting of APTWG conference organizers and chair of the EU-US TTF. The following five topical foci have been identified for the working groups.

A. Isotope effect on transport and physics on isotope mixture plasma (Session leaders: T. Kobayashi and J. Citrin)

This working group discusses a long-standing mystery in magnetically confined fusion plasma. The gyro-Bohm scaling predicts better confinement with smaller diffusivity for the isotope with a smaller mass. Better confinement in deuterium plasma than hydrogen plasma observed in the experiment, contradicts the theoretical prediction. Therefore, the understanding of the underline physics causing this discrepancy is an urgent issue of transport physics. Although the isotope effect on heat transport has been studied intensively, there have not been many studies on other transport channels, such as particle, momentum and impurity transport. The particle and heat transport are strongly coupled because the turbulence level is also sensitive to density gradient (e.g., TEM). Because of the nonlinear interaction of turbulences between different scales (e.g., TEM and ETG), the bifurcation between other turbulence states can occur. Interaction between different transport channels (e.g., particle and heat transport) causes a strong impact of particle transport on heat transport. Recently the impact of impurity gradient on heat transport has been pointed out, and the coupling between impurity and heat transport has been recognized to be crucial. The interaction between different transport channels is one of the candidates to explain the discrepancy between the experimental results and theoretical prediction.

B. Turbulence spreading and coupling in core-edge-SOL (Session leaders: R. McDermott and J.M. Kwon)

Turbulence spreading is a radial propagation of turbulence intensity from the unstable region to the linearly stable region in the plasma. The turbulence spreading becomes crucial near the boundary layer, such as the last closed flux surface, the separatrix of the magnetic island, and the footpoint of the internal transport barrier. The significant turbulence intensity observed in the linearly stable region of the scrape-off-layer (SOL), the O-point of the magnetic island, and the ITB region is evidence of turbulence spreading. Turbulence spreading plays an important role, especially on the boundary between an unstable region and a stable or more weakly unstable region. A typical example is between the pedestal and scrape-off-layer (SOL) at the plasma boundary. The turbulence in the SOL is mainly determined by the turbulence spreading from the pedestal. This working group discusses the turbulence spreading and coupling in the core-edge-SOL

C. Interplay between MHD topology/instability and turbulent transport (Session leaders: M.J. Choi and T. Zhang)

There are three magnetic topologies in a toroidal magnetic field configuration. They are nested magnetic flux surface, the magnetic island and the stochastic magnetic field. The resonant magnetic perturbation (RMP) field has been commonly used to mitigate the edge localized mode (ELM), which would cause severe damage to divertors in nuclear fusion devices. On the other hand, the RMP was found to affect the turbulence and transport and hence the power threshold for L-mode to H-mode. The RMP field changes the magnetic topology near the plasma edge by producing the magnetic island and the stochastic magnetic field. Therefore, the understanding of the interaction between MHD topology and turbulence and transport is essential. Recently, characteristics of turbulence inside the magnetic island and the stochastic region have been investigated in the experiment. This working group discusses the Interplay between MHD topology/instability and turbulent transport for a deeper understanding of the impact of magnetic topology on turbulence and transport.

D. Interaction between energetic particle driven instability and transport (Session leaders: L.M. Yu and E. Bass)

The MHD activity driven by energetic particles (EP) significantly impacts transport because of the coupling between the EP-driven MHD instability and zonal flow, which reduces the transport. The main topics in this working group are EP-driven MHD instabilities and their effect on Alfvén eigenmodes and zonal flow. The mitigation and control of Alfvén eigenmodes and nonlinear EP Physics are also discussed. This working group discusses the interaction between energetic particle driven instability and transport.

E. Model reduction and experiments for validation (Session leaders: C. Holland and M. Honda)

Recently, the reduced model became more demanding for the validation of simulation code using experimental results [9]. This working group addresses both the formulation of new models of plasma transport and the validation of model predictions against experimental measurements and covers impurity transport, nonlocal transport due to the coupling between the core and pedestal. The physics relating to the density limit is also discussed in this working group. Prediction of transport and profiles from data analysis, such as machine learning, is increasingly becoming popular nowadays. This topic is also covered here.

Summary sessions

In the summary session, the summary talks for each working group were given by one of the working group leaders. The poster session and young research forum that had been organized in the previous meeting were canceled.

II. ISOTOPE EFFECT ON TRANSPORT AND PHYSICS ON ISOTOPE MIXTURE PLASMA

In this working group, a long-standing mystery in magnetically confined fusion plasma study, the isotope effect, was discussed from different aspects. The isotope effect is a phenomenon where better plasma confinement is achieved in plasmas fueled with heavier hydrogen isotopes. The isotope effect is important for plasma performance prediction in future reactor relevant devices that are operated with a tritium and deuterium mixture fuel. Since the isotope effect feature is contrary to what the simple scaling theory and general turbulence simulation predict, intensive study on the background physics is ongoing. There were four subtopics in this working group: the isotope effect in thermal transport, the isotope effect in particle transport, roles of multiscale physics, and the impurity effect. Here, we summarize the key results of each talk.

A. Isotope effects in thermal transport

Belli presented the role of the nonadiabatic response of electrons on the strong reversal of simple isotope scaling laws in tokamak edge turbulence [10] in her plenary talk in the first slot of the conference. They took into account the nonadiabatic response of electrons that arose from fast electron parallel motion. The ion thermal flux was formulated by terms associated with the nonadiabatic electron response having reversed gyro-Bohm ion mass dependence, in addition to the conventional gyro-Bohm term. It was found that the finite electron mass correction was weak in the ITG core, but dominated the mass scaling in the L-mode edge in DIII-D simulation.

Kobayashi focused on the thermal transport in the self-organized structure formation in the Large Helical Device (LHD). They found transition thresholds between the L-mode plasmas and the internal transport barrier (ITB) plasmas, which were sensitive to the plasma ion mass. In deuterium plasmas, the transition occurred with lower input power, normalized by plasma density, compared to the hydrogen plasmas [11]. They measured the radial electric field response in the ITB formation using a heavy ion beam probe to investigate the background physics. What they found was that the radial electric field structure emerged when the ITB was formed in both cases. The radial electric field structure was excited with less heating power, normalized by electron density in deuterium plasmas, which was considered to play a role in the isotope effect on the ITB threshold condition [12].

Kinoshita presented isotope effects in the ECRH heated LHD L-mode plasmas with plenty of turbulence data [13]. They scanned the plasma density in deuterium and hydrogen plasmas. The central electron and ion temperatures became higher in deuterium plasmas above a critical density of $\bar{n}_{\rm e} > 1.7 \times 10^{19}$ m^{-3}. In the density range where the isotope effects appeared, the ion-scale turbulence amplitude was reduced in deuterium plasmas. This turbulence amplitude behavior was similar to the electron density peaking behavior. Therefore, the density profile shape may have an impact on the thermal transport through turbulence activity.

B. Isotope effects in particle transport

The isotope effect on particle transport is crucial because the turbulence level, especially of the trapped electron mode (TEM), is sensitive to density gradient. Two talks were dedicated to the particle transport study. As was discussed above, how the density profile settles is crucially important for thermal transport. Tanaka dealt with modulational obtained particle transport coefficients in the TCV density scan experiment in the energy confinement transition. As was reproduced in many tokamak plasmas, the linear Ohmic confinement to the saturated Ohmic confinement transition was found. The transition threshold density was lower in hydrogen plasmas than deuterium plasmas. Only in the saturated Ohmic confinement regime, particle diffusivity showed a clear isotope effect. As a result, diffusivity in deuterium plasmas was reduced compared to hydrogen plasmas. This observation implied the coupling of different transport channels, which may play a role in isotopic plasma confinement dependence.

The isotope mixing is a phenomenon in which different isotopes (hydrogen and deuterium) are mixed quickly due to the large ion diffusivity (not electron diffusivity) in isotope mixture plasma[14, 15]. Marin investigated the fast isotope mixing observed in JET, where the central neutron rate was found to quickly increase just after the injection of a deuterium pellet in a pure hydrogen plasma [16]. To model this phenomenon, they performed integrated modeling using JINTRAC with QuaLiKiz and HPI2 as physics-based turbulent transport and pellet models, respectively [17]. They successfully reproduced the fast penetration of deuterium to the core. The key prediction of continued ITG turbulence in a positive density gradient regime was validated by the QuaLiKiz [18, 19] comparison with linear GENE [20] simulation.

C. Roles of multiscale physics on isotope effect

Belli's comprehensively dealt with realistic electron dynamics and coupling between electrons and ions are key to understanding the isotope effect. Watanabe and Maeyama's group contributed to deepening the multiscale physics that potentially affected the isotope effect using a local gyrokinetic simulation code, GKV. Particularly, Watanabe's talk emphasized the nonlinear interaction between TEM turbulence and ETG turbulence. They showed that the TEM growth rate was reduced in the presence of the ETG turbulence. This reduction of the TEM growth rate can be understood as turbulent diffusion by the ETG turbulence. Maeyama applied this logic to a burning plasma simulation where the electron temperature was higher than the ion temperature, and multiple plasma species including electrons, deuterium ions, tritium ions, and helium ions coexisted. TEM was found to be stabilized by the ETG through disturbed precession drift resonance, which affected the isotope effect on the burning plasma relevant condition.

D. Impurity effect

The isotope effect on impurity transport is also important because heat transport was found to be sensitive to impurity density gradient in simulation[21, 22] and in experiment [23]. Four talks concerned the impurity effect. Xu presented the anomalous tungsten transport driven by ion temperature gradient turbulence. Tungsten particle flux was found to be a linear function of tungsten density gradient in the trace particle limit in the GKV simulation. The critical gradient in which the particle flux flipped its sign was demonstrated to be lowered in the nonlinear simulation. The poloidal structure of the particle flux was examined. In a low tungsten density gradient where the particle flux was directed outward, the transport was localized at the outer mid-plane. In the higher tungsten density gradient case where the inward tungsten flux was observed, different poloidal structures were observed in linear and nonlinear simulations. The localization was maintained in the linear case, while a structure broadening appeared in the nonlinear case.

Zhang discussed the impurity effects on the trapped electron mode with an inverted electron density profile [24]. The inverted electron density was found to have an effective stabilizing effect on TEM. In addition, the impurity had a stabilizing effect on TEM when its density gradient was less than a critical value, which increased with the temperature gradient. Heat transport induced by TEM and the ITG in the presence of impurity was studied using a quasilinear model by Li [25]. The injection of impurities induced a reduction of ion heat transport at the edge, while the electron heat fluxes remained almost unchanged. Han reported the turbulent impurity transport and its temperature screening effect using numerical simulations [26].

It was demonstrated that the impurity transport was dominated by an impurity mode. This framework was then applied to understand the impurity transport observation in the HL-2A tokamak. The impurity mode turbulence was demonstrated to be a plausible mechanism for the transport of impurity ions with an edge peaking impurity density profile, and even the temperature fluctuation was small.

III. TURBULENCE SPREADING AND COUPLING IN THE CORE-EDGE-SOL

This session included eighteen oral contributions and one plenary. Five presentations focused on the plasma edge and scrape off layer with an emphasis on turbulence spreading in this region. In a second category, seven contributions focused on simulations or experimental measurements of zonal flows or $\mathbf{E} \times \mathbf{B}$ staircase structures. Finally, an additional seven contributions considered various aspects of heat, particle, and momentum transport in the core of fusion plasmas. An overview of the key results from all nineteen contributions is presented below.

A. Turbulence spreading and SOL transport

Turbulence spreading is the movement of turbulence from an unstable region into a stable or more weakly unstable region. Via this mechanism it is possible to increase the local turbulence in a stable (or weakly unstable) region above the level one would expect from a local stability limit [27]. As such, turbulence spreading is an inherently non-local phenomenon and is not included in most of the commonly used turbulence codes. The work of Q. Yan expanded the standard turbulence picture of drift waves plus zonal flows to include both turbulence spreading and avalanching. The main result of this work is that the time derivative of the average fluctuating electro-static potential is explicitly non-local as it is impacted by other radial positions within several banana orbits. Q. Yan also found that non-local effects increase the propagation speed and penetration depth of turbulence spreading. Ideally, this expanded model could eventually be incorporated into the more commonly used gyrokinetic simulation tools.

X. Chu discussed the possibility that turbulence spreading could help to increase the size of the scrape-off-layer (SOL) power fall off length, λ_q, to ease the power handing requirements of divertor targets in future generation devices. While in principle, by its natural inclination to move particles and energy across magnetic field lines, turbulence could potentially be of assistance in this matter, first sufficient turbulence must be generated at the desired location. X. Chu examined the SOL stability and found it to be generally stable due to $\mathbf{E} \times \mathbf{B}$ shear and sheath resistivity. However, the pedestal is not. If sufficient turbulence can be generated there and transported radially outward, it can impact λ_q. The power fall-off-length was found to be dependent on the turbulent intensity flux across the separatrix, which in turn is set by pedestal parameters. The intensity flux is balanced by linear and nonlinear damping mechanisms in the SOL such that there exists a minimal intensity flux across the LCFS that is necessary for λ_q to increase above the heuristic drift model introduced by Goldston et al. [28]. The contribution emphasises the need to include turbulence spreading in models for λ_q and identifies the key question to be answered as, can pedestal turbulence broaden λ_q sufficiently, while maintaining adequate confinement? The results point to turbulent pedestal states, such as the Grassy ELM regime, as candidates for this purpose.

In related experimental work, T. Wu presented experimental measurements at the boundary of HL-2A, comparing two ohmic L-mode plasma scenarios with different plasma currents [29]. The higher current scenario features a larger radial electric field, E_r, and $\mathbf{E} \times \mathbf{B}$ shear at the plasma edge, which has a direct impact on the turbulence and transport. The higher current scenario results in smaller electron density turbulence fluctuations and also smaller overall particle flux and a smaller λ_q, compared to the lower current scenario. Turbulence spreading is quantified by so-called turbulent intensity flux, given by the average of the product of the square of the density fluctuation amplitude and the fluctuating radial velocity, $\langle \tilde{n_e}^2 \tilde{V_r} \rangle$. T. Wu shows that the turbulence intensity flux is higher in the low current scenario not only at the plasma edge, where a clear increase in turbulence is visible, but also in the SOL, where the density fluctuations are larger for the lower current scenario. This data is consistent with the idea of turbulence spreading from the more strongly unstable region at the plasma edge into the SOL.

T. Tokuzawa also showed experimental evidence for the existence of turbulence spreading. In this contribution, electron cyclotron resonance heating, ECRH, was deposited in the pedestal in an attempt to excite turbulence in this region. During the pulses of ECRH the electron temperature at the pedestal top showed a clear increase, as did the turbulent intensity measured in the SOL. In addition, the pedestal generated turbulence was observed to propagate outward, consistent with a spreading phenomenon. Modulation and conditional averaging techniques were employed to determine the phase and speed of the propagation. These results also suggest that turbulence can and does spread from the pedestal into the SOL.

J. Cheng reported on a gyrokinetic simulation study of blob dynamics in the SOL using a global full-f PIC code XGC1 [30]. Initially, as seeds for blobs, coherent density perturbations were imposed along equilibrium magnetic fields. It was shown that the blobs exhibit markedly different dynamics, depending on the perturbation amplitude. For blobs with a moderate level of perturbations (e.g. $\delta n_e/n_e \sim 0.1$), it was found that their motions are strongly affected by ambient $\mathbf{E}\times\mathbf{B}$ flow shear. When they enter into the SOL, their structures are strongly deformed by the $\mathbf{E}\times\mathbf{B}$ shear. On the other hand, for blobs with large initial perturbations (e.g. $\delta n_e/n_e \sim 0.5$), the blobs maintain their initial structures, which are dominated by blob spin. At a later time in their evolution, blobs were found to be no longer aligned with the equilibrium magnetic field lines for both moderate and large initial perturbations. It was also found that the radial motion of a blob, v_b, is dominated by $\mathbf{E}\times\mathbf{B}$ motion and consistent with the simple theory $v_b\sqrt{\delta n_e/\left(\delta n_e + n_{e0}\right)}$ [31].

B. Zonal flow and $\mathbf{E}\times\mathbf{B}$ staircases

L. Qi gave a plenary talk on zonal flow staircases in tokamak plasmas [32]. He introduced various experimental observations and simulation studies of zonal flow staircases in geophysical fluids and tokamak plasmas. Particular emphasis was given to their roles in regulating global transport avalanches. He also reported recent progress in identifying and analyzing the staircase structure in a KSTAR L-mode plasma [33]. By performing global, gyrokinetic simulations using a delta-f PIC code gKPSP [34], it was shown that TEM turbulence can generate zonal flows with a staircase structure. The step size of the staircase was $\Delta \sim 40\ \rho_i$, which is consistent with the measured step size of the ∇T_e corrugations in the KSTAR plasma. As an underlying physical mechanism of the zonal flow staircase, the traffic-jam mode [35, 36] was suggested and investigated. It was found that jam instability can occur by a finite time delay between mean particle flux and local density fluctuation, which is further strengthened by a feedback loop via the generated zonal flow.

W. Liu reported an experimental investigation of $\mathbf{E}\times\mathbf{B}$ staircases in HL-2A L-mode plasmas [37]. Multiple diagnostics were employed for the study, the reflectometry for n_e, ECE for T_e, and 2D BES for fluctuations covering a wide radial domain. An amount of independent evidence for $\mathbf{E}\times\mathbf{B}$ staircases was found: 1) corrugated ∇n_e and ∇T_e profiles, 2) the correlation of the staircase step size with the radial extent of turbulence, and 3) the low permeability of turbulence through the shear layers. The structural changes of the turbulence across the shear layers were thoroughly investigated by examining the conditional spectrum of the turbulence $S\left(k_\theta, f\right)$. It was found that the poloidal propagation velocity of the density fluctuations is reversed or changies rapidly across the shear layers. This is consistent with the expected role of the shear layers, which regulate the radial extent of turbulence such that it does not exceed the step size of the staircase.

In the JT60-U inclusion of NBI power in the ramp-up leads to the formation of reversed shear q-profiles. When q-min crosses 5, a bifurcation in the ion temperature gradient is observed, leading to the formation of an internal transport barrier (ITB). F. Kin showed reflectometry measurements during an NBI power scan conducted across several discharges using this scenario. At lower NBI power (8-11 MW) the transport barrier is not sustained, but at 12 MW it persists for multiple energy confinement times. Before the formation of the ITB, bursty fluctuations are observed by the reflectometry leading to avalanche behavior that is observed in both density and temperature diagnostics and are well correlated. These measurements show the turbulent bursts lead to outward transport and a relaxation of the core profiles, maintaining the stiff L-mode gradients. These bursts are suppressed at the formation of the ITB, and in the 12 MW case remain suppressed. This suggests that the formation of the ITB is a direct result of the suppression of the bursty fluctuations, which exist at low frequency and exhibit an inverse frequency behavior, reflective of size-invariance and characteristic of avalanche behavior.

Y. J. Kim reported a global gyrokinetic simulation study of nonlocal transport events in tokamak plasmas. Employing a global full-f code GKNET [38], flux-driven ITG turbulence simulations were performed with varying levels of input power. Two types of global transport events were identified: 1) quasi-periodic ones with spatial extents of the size of $\mathbf{E}\times\mathbf{B}$ staircases and 2) intermittent ones carrying much higher heat fluxes over longer distances. It was shown that the intermittent phase-matching of turbulent eddies can lead to the latter type of global transport events [39]. The resulting extreme avalanches carry heat fluxes across the staircases. For detailed statistical analyses of turbulent heat flux, the probability distribution function (PDF) of the heat flux was calculated according to the size of the global transport events. It was found that the size of the PDF in log-scale exhibits three piece-wise power laws with different combinations of slopes and ranges for the quasi-periodic and bursty transport events.

M. Leconte proposed a new physical mechanism to generate profile corrugations in drift-wave turbulence. He presented a 1D reduced model, namely an extended wave-kinetic model [40], derived from the 2D modified Hasegawa-Wakatani model. Focusing on the role of the cross-phase between density and potential fluctuation in suppressing turbulent transport, a novel route for the formation of zonal structures was investigated. By performing BOUT++ simulations of the 2D modified Hasegawa-Wakatani model, it was shown that drift-wave turbulence can drive zonal density corrugations. The reduced model exhibits a predator-prey like dynamic of zonal density and turbulence amplitude while the total energy is conserved. Interestingly, it was found that the zonal density can suppress turbulent transport via the radial modulation of the transport cross-phase. Then, this modulation leads to the formation of a zonal flow staircase. Experimental ideas were discussed to measure the transport cross-phase and identify the distinctive signatures of the staircases formed by the novel route.

P. Ivanov presented an analytical and numerical study of the physics of the Dimits shift in ITG turbulence using a fluid model described in [41]. He performed 2D and 3D fluid simulations of ITG turbulence in slab geometry with constant magnetic curvature. In the 2D simulations, it was found that ITG turbulence is saturated by quasi-static zonal staircases in flow and temperature, and the system is evolved toward a Dimits state dominated by strong zonal flow. The evolution of the zonal flow is governed by a competition between the Reynolds stress and diamagnetic stress. In the 3D simulations, small scale parasitic slab-ITG modes, which are excited by the gradients of the large-scale ITGs, contribute to the nonlinear saturation. It was noted that the box size and resolution in a parallel direction are important to accurately capture the physics of the parasitic modes. With a proper choice of the size and resolution, it was shown that the system is pushed toward a Dimits state by the parasitic modes.

Y. Kawachi reported a recent experimental study of the dynamic interactions of different modes in the linear device, PANTA. Employing a movable azimuthal probe array, detailed measurements were carried out for a plasma in which different types of fluctuations are excited [42]. Two different modes were identified by measuring the poloidal and toroidal mode number (m,n) of the fluctuations: 1) an axially symmetric (AS) flute like mode with (m,n)=(1,0) and 2) a resistive drift wave (DW) with (m,n)=(4,1 2). To investigate the nonlinear interactions of the two modes, bi-coherence and Ritz analyses were performed with conditional averages to improve the signal to noise ratio of the measured data. It was found that the AS mode can gain energy from DW via the nonlinear interactions, which leads to the intermittent bursts of the AS mode. It was also found that the bursts of the AS mode are synchronized with an increase of the zonal component of the electrostatic potential.

C. Turbulent transport in the plasma core

J. Seo presented the impact of light impurities on ITG non-linear simulations. For this purpose, the global, PIC, delta-f, gyrokinetic code gKPSP [34] was used. The simulations were run with adiabatic electrons and the linear growth-rates of pure and impure cases were matched by adjusting the impurity density profile to isolate nonlinear effects. Therefore, the direct effect of the dilution on linear stability is excluded from the simulations. The simulations with and without impurities were compared for two different values of the safety factor, q. At low q the ion heat flux is reduced in the presence of impurities, compared to simulations only considering deuterium. However, at high-q similar heat transport was obtained in the simulations with and without impurities. At low-q, there are stronger $\mathbf{E}\times\mathbf{B}$ staircase structures in the simulations with impurities than without, while at high q $\mathbf{E}\times\mathbf{B}$ staircase structures are weaker both with and without impurities. However, at high-q GAM activities are larger. In conclusion, light impurities are observed to have a stabilizing effect on ITG in low-q plasmas by enhancing the staircase-like $\mathbf{E}\times\mathbf{B}$ shearing.

G. Z. Ren presented a global fluid simulation study of finite β effects on ion heat transport. Based on a global Landau fluid model, ITG-KBM turbulence simulations were performed with a range of β values from 0.1% to 1.0%. It was shown that zonal flows and their effects on the transport become weak as β increases beyond the threshold for kinetic ballooning modes (KBM). For high β values, zonal magnetic fields become more pronounced, though their contributions to the saturation of turbulence and heat transport are relatively small. The non-linear saturation occurs in two stages, and the excitation of magnetic fluctuations with low toroidal mode numbers (n=1 3) in the second stage are important. They are nonlinearly generated during the downshift of the fluctuation energy spectra in the second stage. It was also found that the zonal currents associated with the zonal fields cause corrugations in the q-profile around low order rational surfaces, which can result in the enhancement of local perturbations and transport.

J. Liu presented work on quasi-linear particle transport induced by the coupling of TEM and ITG modes in the presence of tungsten impurities. In this contribution, a gyrokinetic integral eigenvalue equation was used and a systematic analysis of the impact of tungsten and carbon impurities on the mode characteristics and particle flux was performed. The considered parameters include: the density gradient, charge concentration, charge number of the impurity ions, and the poloidal wave number spectrum. It is found that compared with carbon, the weakly ionized tungsten ions with an inwardly peaked density profile and a relatively a high charge concentration have stronger stabilizing effects on the modes. Furthermore, the increasing Z tends to decouple the hybrid mode into coexisting modes or a dominating TEM/ITG mode in different parameter regions. All simulations considered only realistic values of Z_{eff}, with $Z_{\mathrm{eff}} < 2$.

W. Wang reported a global gyrokinetic simulation study of TEM instability in reversed magnetic shear plasmas. The GKNET code was extended to incorporate: 1) numerical equilibrium from the TASK/EQ code and 2) non-adiabatic electrons from hybrid and full kinetic models. From linear benchmark tests, it was demonstrated that full kinetic electron responses increase TEM growth rates significantly through the destabilization of non-adiabatic passing electrons. It is noteworthy that this mechanism was also emphasized in the plenary talk by E.A. Belli as a key underlying physics element of the isotope scaling in the global energy confinement. The stabilizing effects of the plasma elongation on TEM were also well reproduced. It was found that TEM can be stabilized by the precession reversal of toroidal drift in reversed magnetic shear configuration. Also, in the reversed shear configuration, negative triangularity shows destabilizing effects on TEM, due to the Shafranov shift and the resulting enhancement of local pressure gradients in the bad curvature region.

On the experimental side, G. Xiao presented improvements to supersonic molecular beam injection (SMBI) systems. SMBI is a fueling technique that has been utilized on multiple fusion devices. In addition to plasma fueling, SMBI can be used for particle transport studies by providing a time dependent source of neutral atoms. However, to extract reliable information from such an experiment, the spatial and energetic distribution of the neutral particles must be known. This work presents a new schlierer system for detecting the initial spatial distribution of the particles before interaction with the plasma [43], which is a necessary ingredient for modeling of the neutral particle interaction with the plasma. Measurements have been made with the new system for different gas species and comparisons to simulation results agree well for low background gas pressure.

Y. Y. Xie presented experiments performed in the J-TEXT on non-local heat transport (NLT) induced by successive SMBI pulses, which cool the edge plasma as well as increase the plasma density. The time interval between SMBI pulses is 30 ms. In low density plasmas NLT behavior is observed, while the signatures of NLT become weaker as the density increases. The NLT transport is observed to correlate with the turbulence intensity; during NLT, the relative turbulence intensity increases outside of r/a=0.8 and decreases inside of this location with a stronger decrease observed for the region $0.5 < r/a < 0.8$. The electron density profile is also observed to steepen in this region. An array of Langmuir probes also enable an analysis of the edge turbulence behavior. The edge turbulence-driven particle flux and radial electric field decrease during the NLT. The former is due to the suppression of the radial velocity fluctuations while the latter is caused by a reduction in the turbulence driven poloidal flows. In addition, the GAM is significantly suppressed after each SMBI pulse as a result of collisional damping.

Finally, Y. Ohtani presented a new method to evaluate the temporal evolution of momentum transport based on the Hilbert transform and analytical mode decomposition [44]. This method enables both temporal and radial dependence of the transport coefficients to be maintained in the analysis. The method was applied to a JT-60U H-mode plasma that had previously been analyzed with more traditional, time invariant transport coefficients [45] and found to be in good agreement. However, the new method was able to isolate changes to the transport coefficients in the plasma that occurred part way through the experiment. At r/a=0.3 the momentum diffusivity was found to increase, while the ion heat conductivity remained constant, leading to an increase in the Prandtl number from 1 up to 2.5 at this location. The normalized electron density gradient was also not constant during the experiment and increases in both the diffusion and the inward convection were observed to correlate with increases in R/L_{ne}. The latter is qualitatively consistent with a Coriolis momentum pinch. Outward residual stress was identified in the core region, consistent with expectations for TEM turbulence. It was not observed to modulate with the NBI or to impact the calculation of the diffusion and convection.

IV. INTERPLAY BETWEEN MHD TOPOLOGY/INSTABILITY AND TURBULENT TRANSPORT

A. Turbulence and transport with stochastic magnetic fields

The external field penetration, which can form the region of stochastic magnetic fields in plasmas through the overlapping of neighboring magnetic islands, would degrade the plasma confinement, but sometimes it is intentionally introduced. For example, the intentional narrow stochastic layer at the pedestal top by the resonant magnetic perturbation (RMP) field has been utilized successfully to suppress the edge localized mode growth by limiting the pedestal height. The RMP field is often applied in a proactive manner during the L-mode phase to achieve the completely ELM suppressed H-mode. However, this caused the increase of the power threshold of the LH transition by modifying the edge $E \times B$ flow profile significantly [46]. More research is required to keep the balance in using the RMP field.

Recently, several theoretical research have been conducted and were presented in the meeting. They attempted to improve general understanding of the stochastic field effects on the ion heat and momentum transport

(P.H.Diamond), to suggest a specific mechanism for the increased power threshold of the LH transition with the magnetic field perturbation (W.X. Guo and C.C. Chen), and to understand the behavior of multiscale turbulence over the stochastic fields (M.Cao).

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P.H. Diamond presented that the dominant mechanism of the ion transport with the stochastic fields can be different, depending on the size of two terms ($k_\parallel C_s$ and $k_\perp^2 D_T$) where D_T indicates the turbulence scattering effect related to the stochastic field diffusivity [47]). When the former is larger, the ion heat transport is dominated by the sound wave propagation along with the stochastic fields, as shown in the previous work [48]. The previous study predicted the kinetic stress was, in fact, residual stress. When the latter is larger, the kinetic stress takes the form of a viscous stress $\langle b_r \delta P \rangle \approx -D_{ST} \partial \langle V_\parallel \rangle / \partial r$, with an effective viscosity $D_{ST} = C_s^2 \Sigma_k |b_{r,k}|^2 / k_\perp^2 D_T$, determined by stochastic field scattering and the ambient turbulence correlation time. In this case, the structure of the kinetic stress differs fundamentally from that in the quasilinear limit. Its infrared behavior implies the importance of large-scale perturbation fields.

W.X. Guo and C.C. Chen presented a different, but complementary idea to explain the increased LH transition power threshold in view of the reduction of flow shear. They both used a quasilinear theory, and its validity was discussed in reference [49]. Guo presented that the cross phase between stochastic fields can be aligned to have non-zero Maxwell stress ($\langle \tilde{b}_r \tilde{b}_\theta \rangle \neq 0$) by the $E \times B$ shear flow and its contribution to the flow will oppose the electrostatic turbulence driven Reynolds stress $\langle \tilde{V}_r \tilde{V}_\theta \rangle$ contribution. Here, the importance of the novel scale of stochastic layer width was realized [50]. It would provide not only an explanation of the increased LH transition power threshold (since it impedes the Reynolds stress involved positive feedback loop of the edge $E \times B$ shear flow generation), but also implies various contributions of the Maxwell force driven radial current on plasma density, flow, and temperature. On the other hand, Chen presented that stochastic magnetic fields can cause decoherence of Reynolds stress, thus reducing the flow generation. This effect becomes noticeable when the stochastic field broadening of drift waves is large enough. This stochastic fields dephasing of the Reynolds stress would restrain the eddy-tilting feedback loop and increase the required power for the LH transition. This effect was parameterized by $\alpha \equiv (b^2/\sqrt{\beta}\rho_*^2)(q/\epsilon)$ where $b^2 = \langle \tilde{B} \rangle / B_0^2$ and $\rho_* = \rho_s / a$. This indicates the stronger the stochasticity is ($\alpha > 1$), the higher the power threshold will increase [51]. The simulation result shows a linear-like increment of the LH transition threshold with increasing α and the $\alpha \propto 1/\rho^2$ dependence implies that it can be more serious in large devices such as the ITER.

M. Cao presented that turbulence over the stochastic fields would be a multiscale problem. With a given large scale mode over the high-k stochastic fields, small scale modes (convective cells) should be driven to hold $\nabla \cdot J = 0$ at all scales. This indicates that the correlation $\langle \tilde{b}_r \tilde{\varphi} \rangle$ is non-trivial and a turbulent viscosity ν is driven. On the other hand, the evolution of a large-scale mode can also be affected by the stochastic fields and the small-scale convective cells, e.g., the increase of effective inertia by stochastic fields can contribute to the stabilization of the large-scale mode. This intrinsically multiscale interaction would complicate the stability of modes, but it should be considered for the proper understanding of the turbulence with the stochastic fields.

B. Turbulence spreading into a stochastic region or magnetic island

Turbulence spreading is a nonlocal and nonlinear process where turbulence excited in a linearly unstable region propagates into a stable region [52] (propagation via a toroidicity induced linear mode coupling is also possible [53]). According to theoretical argument [52], turbulence spreading is expected to be strong when both stable and unstable regions are close to each other, to make a large fluctuation intensity gradient difference. The stationary stochastic layer in stellarators or a large magnetic island in tokamak plasmas can correspond to such a configuration.

M. Kobayashi presented that the broadband density fluctuation in 10 - 500 kHz and $k_\perp \rho_s < 1$ spreads into the stochastic layer in LHD plasmas with the appearance of low-frequency magnetic fluctuation. The magnetic fluctuation seems to reduce the $E \times B$ flow shearing rate at the boundary of the stochastic layer, and turbulence spreading could occur with the reduced interference of the flow shear. Note that the density turbulence level in the stochastic region increases with the magnetic fluctuation level, although there is no direct coherence between them. This analysis is consistent with the previous numerical simulation [54] and experiment [55] where turbulence spreading is controlled by the flow shear at the boundary. There is one beneficial consequence of turbulence spreading, such that the divertor heat load profile broadens with the increased density fluctuation over the stochastic edge layer. This would be potentially important for the control of divertor heat loads in future devices.

In the literature, more observations of turbulence spreading were reported with a large stationary magnetic island in tokamak plasmas. The interior and exterior of the large island would be linearly stable and unstable for gradient-driven micro instabilities, respectively. In the DIII-D, modulation of the electron cyclotron resonance heating was applied to study a hysteresis relation between fluctuation and flux for identification of turbulence spreading [56]. The opposite time delay between density fluctuation and heat flux propagations could be understood by the opposite contribution of nonlocal turbulence spreading on turbulence measurement in the X- and O-point regions. In the KSTAR, another important characteristic of turbulence spreading, that it can carry the heat or particle flux, was observed [57]. Correlated transport of the heat flux from the exterior to the interior of the magnetic island is observed with turbulence spreading.

In the meeting, T.S. Hahm presented a theoretical analysis on how turbulence spreading into a magnetic island can occur [58], which provides an explanation for the more active turbulence spreading through the X-point rather than the O-point. Specifically, the two-point decorrelation theory was applied to study distortion of turbulence eddy structure by the vortex $E \times B$ shear flow within a magnetic island geometry. It was found that the effective shearing rate of turbulent eddies by the vortex flow is much weaker near the X-point, due to the elongated geometry of the magnetic island and the flow incompressibility, which can result in more active turbulence spreading through the X-point.

C. Review of interaction between a magnetic island and turbulence in HL-2A

Theories and simulations have shown that various interactions between a magnetic island and turbulence can occur. Recently, many experimental observations on their interaction have been reported from different devices [59] with the advance in plasma diagnostics, and important contributions were made from the HL-2A. In the meeting, M. Jiang presented a review of key results of the HL-2A experiments. They include the enhanced flow shear at the island boundary [60], modulation of both temperature and density fluctuations between the island O- and X-points, the island threshold width for the profile and fluctuation modulation, turbulence spreading across a large and flat island [61], nonlinear mode coupling [62], and excitation of the quasi-coherent mode outside the island by the steepened temperature gradient [63]. In particular, the finite fluctuation level above the noise level was measured inside the flat and large magnetic island where the linear drive would be negligible. The relaxed fluctuation intensity profile across the island boundary can result from turbulence spreading. In addition, the effect of core magnetic islands on the divertor heat load was also reported, such that it can broaden the heat load profile.

V. INTERACTION BETWEEN ENERGETIC PARTICLE DRIVEN INSTABILITY AND TRANSPORT

This working group dealt with topics related to the energetic particle (EP) driven magnetohydrodynamic (MHD) Instabilities, Alfvén eigenmodes (AEs) mitigation and control, nonlinear EP physics, EP transport and losses, effects of EPs on AEs and Zonal flow, and so on. There are 11 oral presentations, consisting of three experiments and eight simulations or theory works. The main points in these presentations are summarized below.

A. EP driven MHD instabilities

M.L. Yu and X. Zhu presented experimental works on the energetic ion-induced energetic particle mode (EPM) and electron-driven toroidal Alfvén eigenmode (e-TAE) observed in the HL-2A and EAST tokamaks. The EPMs are found in HL-2A neutral beam injection (NBI) plasmas [64]. The frequency of the EPM chirps down rapidly from 65 to 35 kHz within the time interval of 1 ms. The EPM is located on the Alfvén continuum, between the BAE- (beta induced Alfvén eigenmode) and TAE-gap. Owing to the injection angle of the NBI system, the EPM is driven by the transit resonance of the predominantly circulating energetic ion population. The edge localized e-TAE, with a frequency in the range of 100-300 kHz, is observed both in deuterium plasmas and the helium plasmas in EAST low-density Ohmic discharges. The frequency of e-TAE is proportional to Alfvén speed (v_A). The energy of the runaway energetic electrons, which may excite the e-TAEs, is estimated in the range of 150-240 keV.

G.J. Choi and J. Yang reported the simulation results of MHD instabilities in the DIII-D and NSTX by the GTC and 1-D eigenvalue model of the perturbed magnetic field, respectively. Recent studies of interactions of EPs with AEs and MHD modes in DIII-D plasma via GTC are summarized. It is identified that a low-frequency mode [65] observed in the beta-induced Alfvén-acoustic eigenmode (BAAE) frequency gap is a thermal pressure-driven interchange-like mode [66]. The 1-D eigenvalue model of the perturbed magnetic field is used to evaluate the effect of EPs on kink and tearing mode (TM) stability in the NSTX [67]. The results show that the island growth can be well simulated by adjusting the coefficients in the modified Rutherford equation, which is in good agreement with the measurement. In the future, the results will be compared to the M3D-C1 (K) calculations.

Besides, H. Wang showed a prediction of AEs which may appear in the CFQS using MEGA. An m/n=3/1 (where m and n are the poloidal and toroidal mode numbers) global Alfven eigenmode (GAE) is excited under the presence of magnetic islands. Some other components (n=3 and n=-1) are also strong because of strong mode coupling. Similarly, an $m/n = 5/2$ TAE is excited without magnetic islands. The mode growth rates of GAE and TAE increase with EP pressure, but the mode frequencies do not depend on EP.

B. AE mitigation and control

J. Kang reported recent high β_N experiments in the KSTAR and the role of energetic particle transport for the high β_N scenario achievement. EP-driven Alfvénic activities used to be observed in high-NBI-power injected KSTAR H-mode experiments. The mitigation of TAEs has not only been achieved by fine tuning of electron cyclotron wave heating (ECH) resonance, but has been reproduced in a wide range of q_{95} regimes. Numerical investigation with a TRANSP/NOVA/Kick-model was performed in addition to the experimental observation. Especially, the impact of the mode tailoring q profile was intensively analyzed. The confinement of thermal plasma and fast ions was dominantly changed according to TAEs amplitude in a recent KSTAR high β_N baseline scenario [68] and showed a strong potential to accomplish the high β_N milestone.

G.J. Choi presented the role of dissipation on nonlinear saturation of multiple-n BAEs by the simulation of GTC. From simulations of reversed shear AEs (RSAEs) with micro-turbulence, it is found that the micro-turbulence provides an effective dissipation for RSAE saturation and dominates over collisional dissipation in our target DIII-D plasma.

C. Nonlinear EP Physics

X. Zhu reported that a low-frequency mode ($\sim$ 20 kHz) driven by multiple e-TAEs with the same frequency difference was identified as a GAM in the EAST tokamak. Further analysis shows that the GAM is strongly driven by multiple edge localized TAEs, due to the synergy effects of multiple TAE pairs, with their frequency difference comparable to GAM frequency, and a mode number matching condition for nonlinear mode coupling is satisfied, i.e., $f = f_{GAM} + f', n = n_{GAM} + n'$.

Y.M. Hou used the Berk-Breizman model, the BOT (Bump-on-tail) code to analyse the effects of diffusion and drag on nonlinear behaviors of the chirping mode in the HL-2A experiments [69]. The generation and motion of phase-space hole-clump pairs in a kinetically driven, dissipative system can result in frequency chirping [70]. Asymmetric frequency chirpings are produced with drag effect, which is essential to enhance holes, and suppress clumps. Although both diffusion and drag effects suppress the clumps, downward sweepings are observed, caused by a complicated interaction of diffusion and drag. In addition, mode splitting is also produced via the BOT code for a marginal case with large diffusion.

H. Wang showed the MEGA simulation results that the GAE frequency chirps down in the saturated phase of GAE in the CFQS. The frequency of resonant particles moves from the high-frequency region to the low-frequency region in EP phase space. A hole-clump structure is formed, and the frequency of particles in the hole-clump also chirps down. In the saturated phase of TAE, the frequency of the dominant branch chirps down, and the frequency of the sub-dominant branch chirps up. The orbit frequency of particles in the hole-clump also chirps down (and up) simultaneously. Nonlinear features of the interactions between the internal kink mode and neoclassical tearing mode [71] in the phase space in the DIII-D were presented by G.J. Choi.

D. EP transport and losses

L.M. Yu reported experimental evidence of nonlinear avalanche dynamics of the EPM for the first time in the HL-2A. In the strong EPM burst, the EPMs move from the plasma core (q=m/n=2, where q is the safety factor) to the plasma edge (q=3 and 4). The EPM mode structure and their evolution in poloidal cross-section are obtained by tomography of SXR arrays. The process can be completed within $\Delta t = 0.06$ ms. The ratio of typical growth time of the EPM to Alfvén time is $\tau/\tau_A \sim 200$, which is in the expected range where convective EP redistributions can take place. The relationship between the EMP chirping rate ($\dot{\omega}$) and mode amplitude (A) in the experiment satisfies the scaling $A \propto q\dot{\omega}$ from the relay runner model (RRM). The observed mode radial propagation velocity is comparable to that of EPs, as predicted by RRM model.

L. Wang presented the drift loss of fast ions, induced by the combination of a perturbed non-axisymmetric magnetic field and a strong radial electric field in the tokamak pedestal [72]. The strong radial electric field in the pedestal significantly reduces the toroidal precession frequency of trapped fast ions, which plays an important role in the loss of trapped fast ions. Taking typical plasma parameters in the pedestal of the DIII-D [73], the parametric effects on the drift loss are analyzed. The fast passing ions can be well confined and will not escape from the plasma, while the deeply trapped fast ions can be lost from it, but the loss range of parameters is narrow. There is a strong relationship between the drift loss time of trapped fast ions and parameters. The finding of this work implies that the RMP makes the confinement of fast ions generated by perpendicular NBI weaker than that of fast ions generated by tangential NBI. Moreover, the drift loss time is shorter than the slowdown time by three orders of magnitude. Therefore, the drift loss of trapped fast ions induced by the RMP is an important loss mechanism in the DIII-D pedestal.

P.J. Bonofiglo reported on the development of an integrated transport model which tracks energetic particle losses. The TRANSP/NUBEAM code provides a time-dependent model for the equilibrium and fast ion distribution for use in the ORBIT-kick model, which calculates the fast ion transport associated with a supplied energetic particle instability. Furthermore, the geometry for a series of thin-foil Faraday cup fast ion loss detectors, capable of spatial and energy-resolved loss measurements [74] was installed in the code to produce synthetic loss signals for comparison to the experiment. Perturbatively induced losses can then be tracked to the detector geometry to produce synthetic loss signals. Overall, the model can provide a full transport analysis of the loss of energetic particles, such as wave-particle resonances and phase-space topology, and loss information that can be quantitatively validated by measurement. In addition to validation studies on previous experimentation, the model can be used in predictive studies for future scenario development.

E. Effects of EP on AEs and Zonal flow

Y.W. Cho studied the analytic derivation of residual zonal flow level in the long wavelength, high aspect ratio limit collisionless toroidal plasma with a bi-Maxwellian distribution, using the modern bounce-kinetic theory. The result, which generalizes the well-known formula for the Maxwellian distribution function, shows a strong dependence on the temperature ratio. For $v_\perp/v_\parallel < 1$, the residual zonal flow level is higher and turbulence and transport are expected to get lower. This residual level scaling can be understood from the scalings of a barely trapped/passing particle population fraction and their radial orbit width as well as those of the second adiabatic invariant and the bounce/transit frequency.

E.M. Bass discussed the transport-limited profile of NBI ions in DIII-D discharges with different hydrogen isotopes by the TGLF-EP+Alpha model of EP transport. The predictions apply to a recent hydrogen isotope campaign designed to explore a regime at or near super-Alfvénic EPs (Alfvén Mach number $v_{EP}/v_A > 1$, where v_{EP} is the EP thermal velocity), closer to that expected in the ITER. NBI collisional slowing-down time τ_s also decreases with reduced NBI-ion mass, with correspondingly lower classical beam densities (at a fixed source rate) for less massive NBI ions. When NBI mass is reduced by switching from deuterium to hydrogen, increased v_{EP}/v_A is destabilizing to AEs, but decreased τ_s is stabilizing, since the driving EP density is lower. The TGLF-EP+Alpha critical gradient model, based on "stiff" transport and local stability calculations with the TGLF gyro-Landau fluid model, accounts for these competing effects self-consistently. Increased instability due to higher v_{EP}/v_A is reflected in a lower critical gradient, while decreased τ_s results in a stronger slowing-down particle sink that lowers mode drive. The central EP density deficit from the classical prediction, driven by AE transport, increases with beam power. Competing effects in the H-into-D case are found to cancel roughly, with central EP density varying little from the baseline D-into-D case at all powers. The decreased slowing-down time dominates in the H-into-H case, with a central reduction across tested beam powers about 15% greater than in the other isotope scenarios.

VI. MODEL REDUCTION AND EXPERIMENTS FOR VALIDATION

This working group addressed both the formulation of new models of plasma transport, and the validation of model predictions against experimental measurements, and new experimental results that require modeling to understand and interpret. The use of neural nets, machine learning, and other data science techniques in formulating new models as complements to traditional analytic theory approaches is rapidly expanding, and was evident in a number of the presentations. There were a total of sixteen presentations in this group, which are summarized below.

A. Impurity transport

P. Manas presented a plenary talk providing an overview of progress modeling turbulent and neoclassical transport processes for both light and heavy impurity ions in the ASDEX Upgrade plasmas. Previous modeling of boron transport exhibited systematic errors relative to experimental values for cases of high normalized ion temperature gradient scale R/L_{Ti} and toroidal rotation gradient dV_{tor}/dr, typical of plasmas with strong neutral beam injection heating. When combining neoclassical transport predictions made with the drift-kinetic code NEO [75] with turbulent transport calculations made with the gyrokinetic code GKW [76], it was found that including fast beam ions in the calculations increased the turbulent boron outflow via both thermo- and roto-diffusion effects, as well as stabilizing the ITG mode and reducing the ratio of turbulent impurity diffusion to thermal ion transport. This reduction of turbulent diffusion in turn leads to an enhanced neoclassical contribution. When these effects were combined with a self-consistent calculation of the thermal ion density profiles to account for the fast ion density profile, the net result was a prediction of hollow boron profiles in much closer agreement to measurement[77]. The interplay of neoclassical and turbulent transport mechanisms in controlling tungsten accumulation was also addressed using the ASTRA integrated modeling framework [78]. In cases with strong central electron density peaking and low ECRH, the combination of low T_e/T_i and weak turbulent particle diffusion allowed the neoclassical pinch effect to generate central tungsten accumulation. At the other extreme, plasmas with low central electron density peaking, large T_e/T_i and strong turbulent diffusion could prevent the accumulation of central tungsten. A key conclusion from both studies was the closely intertwined nature of the impurity and bulk plasma transport, such that accurate predictions of impurity transport require the turbulent thermal and particle transport to be correctly described.

R. McDermott provided additional information on the validation of low-Z impurity transport predictions in ASDEX Upgrade. A database of boron impurity density transport coefficients was constructed, which demonstrated that R/L_{Ti} is the organizing parameter for both diffusion and convection[79]. In particular, values of $R/L_{Ti} > 6$ were required to obtain hollow boron profiles. Application of ECRH generated larger responses of the transport than equivalent changes in NBI heating, with even small amounts of ECRH yielding significantly increased turbulent diffusion and convection leading to increased impurity peaking. Predictions of boron transport made by a combination of quasilinear gyrokinetic [76] and neoclassical [75] models yielded quantitative agreement with the measured density gradient scale length R/L_{nB} as well as the diffusivity and convection velocity in plasmas with low amounts of NBI and ECRH. Conversely, neither convection nor diffusion was well-predicted by the models for purely NBI heated, ITG-dominant plasmas.

M.K. Han discussed the results of a gyrokinetic investigation of impurity modes (IMs) in plasmas with hollow impurity density profiles [26], performed with the HD7 eigenvalue code [80]. The IMs were predicted to be driven by impurity density gradients of the opposite sign as the electron density gradient, and found to be able to drive impurity fluxes an order of magnitude greater than TEM turbulence when both modes coexist. Coexistence of IMs with main ion ITG and ETG modes was found to reduce the impurity transport through a temperature screening-like effect. Modeling of argon injection experiments in the HL-2A, using a quasilinear description of transport from IMs, main ion ITG, and ETG yielded impurity peaking factors consistent with the measurements.

B. Nonlocal transport and its impacts

T. Tsujimura detailed new observations of nonlocal, non-diffusive electron thermal transport in the LHD. In these plasmas, application of off-axis ECRH leads to the formation of hollow T_e profiles, while additional on-axis ECRH leads to central peaking of T_e. Through modulation of the on-axis ECRH, the local electron heat flux q_e flux-gradient relationships were mapped at different radii in the plasma. Although a monotonic relationship was observed at radii beyond the off-axis ECRH location, a hysteresis-like effect was found at smaller radii, indicating that the nonlocal effects impact the diffusive contributions to q_e.

B.J. Kang presented gyrokinetic modeling of transport in LOC and SOC KSTAR plasmas using the global gKPSP code [34]. Consistent with experimental measurements and previous studies, TEMs were found to be the dominant instability in LOC plasmas, with the ITG dominant in the SOC regime. Although the simulations were gradient rather than flux-driven, a staircase-like structures in fluctuation intensity and particle flux were observed in the SOC case but not the LOC case. For both cases the simulations exhibited avalanches and bursty transport dynamics, although their quantitative properties differed.

C. Transport in pedestal and edge-like conditions

J. Yang discussed observations from the KSTAR of a limit cycle oscillation before the L-H transition, and its suppression via application of RMP fields. Similar to the DIII-D LCO results detailed by Schmitz et al.[81], increases in edge density and electron temperature were correlated with the appearance of a low frequency Dα emission oscillation. Bispectral analysis of beam emission spectroscopy (BES) data during this time indicated a clear coupling between the zonal mode and background turbulence in this phase. However, application of RMP fields both increased the turbulence levels and decreased their coupling to the zonal mode, and consequently delayed the L-H transition. The appearance and frequency of the LCO were found to depend on both heating power and RMP amplitude.

W. Lee presented observations and analysis of quasi-coherent modes (QCMs) in high-density KSTAR H-mode plasmas. Measurements obtained via a collective scattering system[82] showed that the QCMs occured during inter-ELM crashes, but disappeared during ELMs, indicating that they are localized to the pedestal region. Furthermore, the intensity of the QCMs increases strongly with the pedestal density gradient, obtained in the experiment through application of additional NBI heating. Gyrokinetic stability analysis performed with the CGYRO [83] code indicated that the QCMs are likely dissipative trapped electron modes (DTEMs) driven by the pedestal density gradient.

J.F. Parisi addressed characteristics of ETG turbulence in the pedestal region. Linear gyrokinetic stability analysis of JET-ILW pedestal conditions using the GS2 code [84] predict that toroidal modes with ion-scale binormal wave numbers $k_y\rho_i < 1$ have very short electron-scale perpendicular wave numbers $k_\perp\rho_e \sim 1$ and peak far away from the outboard midplane[85]. Slab modes with $k_y\rho_i \sim k_\perp\rho_e \sim 1$ are also found to be unstable, but subdominant. Nonlinear gyrokinetic simulations performed with the STELLA code [86] predicted that the combination of steep pedestal temperature gradients and strong shaping can drive fluctuations and corresponding turbulent fluxes which peak at the top and bottom of the flux surfaces, rather than at the outboard midplane, as expected for traditional ballooning modes. The off-axis localization was shown to be controlled via a combination of finite Larmor radius effects and the ratio of diamagnetic drift to magnetic drift frequencies.

N. Kasuya described simulations examining the ion mass dependence of resistive drift wave turbulence in the PANTA linear plasma column experiment. At larger mass numbers of 30 - 40, only a few modes with low axial mode numbers n $\sim$ 1-3 are unstable. However, as mass number is reduced, the number and range of unstable axial modes increases (e.g. n $\sim$ 4-16 unstable at mass number $\sim$ 4-5). Changes in growth rates are driven by both changes in the ratio of ion gyro-radius to density gradient scale length as well as the ion-neutral collision rate. For cases with a sufficiently broad range of unstable mode numbers (e.g. He plasmas), the nonlinear simulations predict they can efficiently couple to drive a zonal flow[87].

D. Physics of the density limit

Two talks addressed advances in theoretical and experimental understanding of density limit physics [88]. R. Singh presented a theoretical model which links the density limit to a collapse of the edge shear flow layer [89]. The collapse in the shear flow leads to an increase in transport, which in turn leads to radiative cooling and eventually plasma disruption. The model predicts that this collapse should occur when the ratio of $\rho_s/\sqrt{(\rho_{SC} L_n)}$ falls below a critical value, with ρ_{SC} being the zonal flow screening length. The B_θ dependence of ρ_{SC} leads to smaller values of ρ_{SC} at larger plasma current I_p, corresponding to stronger zonal flow persistence at a large current and in turn a larger density limit. Additionally, the model predicts a linear scaling of Greenwald density with current ($n_G \sim I_p$) in viscosity-dominated regimes, but stronger $n_G \sim I_p^2$ regimes where charge exchange friction dominates.

Complementing this theoretical work, Long detailed an experimental study of edge shear flow dynamics near the density limit in the J-TEXT tokamak. Consistent with the Singh et al. model predictions, a collapse in edge shear flow and increase in particle transport was observed as density was raised to the Greenwald limit. This collapse was understood in terms of a measured reduced nonlinear coupling between the turbulence and edge shear flow. In addition, edge density fluctuation measurements show showed an increase in low-frequency avalanche-like behavior as mean density is increased, leading to further transport and edge cooling.

E. Development, coupling, and application of reduced core turbulent transport models

Six talks were delivered which addressed different elements of reduced models of core turbulent transport. G. Staebler discussed the development of the new "SAT2" saturation rule for the quasilinear gyrofluid TGLF turbulent transport model [90]. Relative to previous saturation models, the SAT2 model for fluctuation intensity includes a number of new improvements. First, an improved treatment of geometric shaping effects and parallel mode structure provided better fidelity to gyrokinetic results. Second, an improved treatment of electron collisions and trapped particle bounce averaging increased agreement with gyrokinetic calculations. Finally, SAT2 was calibrated against a new dataset of nonlinear gyrokinetic CGYRO simulations that were performed with improved gyroaveraging resolution relative to the older GYRO simulation database previously used for saturation rule calibration. These improvements enable enabled significantly improved agreement in energy fluxes predicted by TGLF relative to CGYRO predictions. Moreover, preliminary results from transport modeling of L-mode plasmas using SAT2 indicate significantly improved agreement with experimental measurements at large radii, which is important for more accurate predictions of the current ramp up/down phases at the beginning and end of plasma discharges.

S. Toda presented advances in predictions of temperature profiles in the LHD stellarator using gyrokinetic transport models. Both heat diffusivity coefficient and thermal fluxes models have been constructed to reproduce nonlinear gyrokinetic simulations of LHD turbulent transport [91]. The diffusivity-based models enabled predictions of temperature profiles, but could not reproduce the flat or hollow density profiles often observed in the LHD. Therefore a new quasilinear gyrokinetic model was developed, which uses linear gyrokinetic calculations to determine growth rates and cross-phase relationships self-consistently at each timestep of a transport solver. These results are were then combined with a model of saturated fluctuation intensity that includes the zonal flow shearing effects to predict particle and energy fluxes directly.

E. Narita described new developments of the neural network (NN) based quasilinear DeKANIS transport model [92]. A key feature of DeKANIS is that it explicitly distinguishes between diffusive and non-diffusive transport processes in its formulation of electron particle and energy fluxes. The coefficients determining the relative magnitude of each component of the fluxes were provided by an NN which was trained on linear gyrokinetic simulations of JT-60U H-mode plasmas. Absolute transport levels were determined by a saturation rule, which was updated to better incorporate zonal flow physics. The new saturation rule provides the potential for improved accuracy across multiple machines, relative to the previous semi-empirical model, calibrated to specific experimental results.

H. Li provided details of a new machine learning-based model of turbulent transport. Simulation data from the ExFC (extended fluid code) which include both ITG and TEM turbulence was used to train a neural network model, ExFC-NN [93]. It was demonstrated that ExFC-NN could successfully reproduce the dominant turbulence instability, turbulence flux magnitudes, and radial profiles of fluctuations and fluxes. The model was used to interpret observations of QCMs in the HL-2A tokamak, which were connected to a transition between ITG and TEM turbulence.

M. Honda detailed the development of the new steady-state GOTRESS transport solver, which uses global optimization techniques such as genetic algorithms to efficiently find solutions. Furthermore, GOTRESS has been parallelized to improve computational efficiency when using models such as TGLF (which is also parallelized), such that it can effectively utilize thousands of cores on supercomputing platforms. Further speed-ups in solution time were obtained through use of a neural-network based surrogate model for TGLF [94], which enabled application across a variety of plasma conditions and for future scenario development.

C. Holland presented the first results from an integrated modeling study examining transport physics in compact fusion reactors. Using the OMFIT STEP workflow [95], self-consistent equilibrium and core transport solutions were found for both inductive and steady state scenarios capable of producing 200 MW or more net electric power in a $B_0 = 8$ T, $R = 4$ m device. Although almost all heating (both auxiliary and fusion) was to the electrons, and T_e/T_i was slightly larger than unity across the entire core plasma, strong collisional coupling and radiation leads to the ions being the dominant thermal transport channel in both scenarios. Correspondingly, in both scenarios ITG and other long-wavelength modes were predicted by TGLF to be the dominant instabilities, with both neoclassical transport and short-wavelength turbulence providing, at best, modest contributions. The strongest uncertainty in the predictions was found to come from the amount of density peaking predicted by TGLF, which was significantly more pronounced in electrostatic simulations than when magnetic fluctuations were included.

VII. SUMMARY AND PROSPECT

The critical issues were to explore the topics that have not been discussed and provide a new viewpoint on turbulence transport and MHD instability. The topics explored in each working group are summarized.

Isotope effect

The isotope effects on thermal, particle, and impurity transport were discussed for understanding the isotope effect on each transport channel and the interaction between different transport channels. The role of the nonadiabatic response of electrons on the strong reversal of simple isotope scaling laws in tokamak edge turbulence was discussed. The positive gradient of electron density with hollow profiles was found to have an effective stabilizing effect on TEM. The impurity had a stabilizing effect on TEM when its density gradient was less than a critical value. In contrast, fast isotope mixing occurs in a positive density gradient regime where ITG turbulence is unstable, and TEM is stabilized. The isotope effect on transport with multiscale turbulence was also discussed. TEM was found to be stabilized by ETG through disturbed precession drift resonance, which affected the isotope effect on the burning plasma relevant condition. Studying the isotope effect on the interaction between different transport channels and different turbulence scales may be crucial in the future.

Turbulence spreading

The role of turbulence spreading on the coupling between the edge and SOL was discussed. The SOL region is generally stable due to $\mathbf{E}\times\mathbf{B}$ shear and sheath resistivity, but the pedestal is unstable. Therefore, turbulence generated at the pedestal is transported radially outward and strongly impacts the power fall off length λ_q. The turbulence spreading also plays an essential role in the structure formation in the core region, where the locally driven turbulence is considered to be dominant. The typical example of structure formation is $E \times B$ zonal flow staircases. Many simulations or experimental results of $E \times B$ zonal flow staircase structures were presented in this meeting. It was found that the jam instability can occur by the finite time delay between mean particle flux and local density fluctuation, which is further strengthened by a feedback loop via the generated zonal flow. The turbulence spreading was found to be an emerging issue for understanding the physics mechanism of nonlocal transport and structure formation. A global gyrokinetic simulation study of nonlocal transport events in tokamak plasmas and a new physical mechanism to generate profile corrugations in drift-wave turbulence were discussed. The impact of light impurities on the ITG, a global fluid simulation study of finite β. effects on ion heat transport, and quasi-linear particle transport induced by the coupling of TEM and ITG modes was discussed.

MHD topology and turbulent transport interaction

The stochastic field effects on the ion heat and momentum transport and turbulence spreading into a stochastic region or magnetic island are discussed. The magnetic fluctuation was found to reduce the $E \times B$ flow shearing rate at the boundary of the stochastic layer, and turbulence spreading could occur with reduced interference of the flow shear in the LHD. This experimental result of turbulence spreading to the stochastic layer demonstrates that flow shear is key to suppressing the turbulence spreading, consistent with the previous numerical simulation. In addition, a general understanding of the stochastic field effects on the ion heat and momentum transport has been progressed. This model suggests a specific mechanism for the increased power threshold of the LH transition with the magnetic field perturbation. The turbulence measurements inside the magnetic island in the KSTAR and DIII-D clearly show the evidence for the turbulence spreading and resulting heat or particle flux. The theoretical model explains the turbulence spreading from X-point and O-point observed in the experiment, which includes the anisotropy of flow shear at the boundary of the magnetic island.

EP-driven instability and transport interaction

EP-driven MHD instabilities, Alfvén eigenmode mitigation and control, nonlinear energetic particle physics, energetic particle transport and losses, and effects of the energetic particle on the Alfvén eigenmode and zonal flow were discussed. The energetic ion-induced energetic particle mode (EPM) and the electron-driven toroidal Alfvén eigenmode (e-TAE) are studied in the HL-2A and EAST tokamaks. The EP-driven Alfvénic activities were observed in high-NBI-power injected KSTAR H-mode experiments, and the mitigation of TAEs has been observed in a wide range of q_{95} regimes. Nonlinear features of the interactions between the internal kink mode and neoclassical tearing mode in phase space in the DIII-D were studied by GTC simulation. The evidence of nonlinear avalanche dynamics of energetic particle modes was found for the first time in the HL-2A. The analytic derivation of residual zonal flow level in the long wavelength, high aspect ratio limit collisionless toroidal plasma with a bi-Maxwellian distribution using the modern bounce-kinetic theory was studied.

Model reduction and validation

New models have been proposed by using neural networks, machine learning and other data science techniques for impurity transport (ASTRA [78]), nonlocal transport (gKPSP [34]), pedestal transport (GS2 [84] and STELLA [86]), density limit (Singh model [89]), and transport coupling (SAT2 [90]). High-Z impurity is expected to be accumulated to the plasma center due to neoclassical transport for the plasma with peaked electron density and large T_e/T_i, while the impurity accumulation is mitigated by turbulent transport for the plasma with flat electron density and high T_e/T_i. The nonlocal, non-diffusive electron heat transport is observed in the experiment. The gyrokinetic simulation shows that TEMs are the dominant instability in LOC plasmas and that ITG is dominant in the SOC regime. It is an interesting finding that the quasi-coherent modes (QCMs) occur during inter-ELM crashes but disappear during ELMs, suggesting they are localized to the pedestal region. Stability analysis indicates that the QCMs are likely dissipative trapped electron modes (DTEMs) driven by the pedestal density gradient. A new theoretical model which links the density limit to a collapse of the edge shear flow is proposed. Significant progress of the reduced model was presented in this meeting.

Conclusion and future plans

In total, there were 74 oral presentations from Asia, the EU and the US. In order to promote new ideas and a free discussion, there are no published proceedings. This conference report gives the essence of each presentation and the emerging issue discussed in this meeting. The joint meeting of the 9th Asia Pacific-Transport Working Group (APTWG) & 2021 EU-US Transport Task Force (TTF) workshop provided a place for fruitful discussion on the new topics of (1) interaction of isotope effect between different transport channels (2) turbulence spreading to SOL, magnetic island, and stochastic region (3) structure formation by turbulence spreading, (4) interaction between EP-driven MHD instability and zonal flow, and (5) nonlocal transport model. The new experimental results offer new insights. Several speakers demonstrated this new trend of the research, especially on turbulence spreading and interaction between MHD and turbulence. The next meeting will be held in Korea in 2023.

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