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REVIEW PAPER

Summary of magnetic fusion plasma physics in 1st AAPPS-DPP meeting

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Abstract This article consists of summary of the presentations in magnetic fusion plasma section of the 1st Asia–Pacific conference on plasma physics. Recent significant progresses achieved in steady state capable of superconducting toroidal devices as well as conventional fusion devices in Asia are highlighted in this article. Contributions from no Asian fusion devices are also included. Selected significant progresses from the presentations are then summarized and future major challenges in fusion plasmas are discussed.

Keywords Magnetic fusion · Plasma physics · Tokamak

1 Introduction

The 1st Asia–Pacific conference on plasma physics, organized by AAPPS-DPP, was held in Chengdu, China during September 18–23 hosted by Southwestern Institute of Physics. This conference is the general conference covered wide research field on plasma physics in Asia–Pacific region, similar to the APS-DPP and EPS-DPP conferences on plasma physics, and it is physics oriented and provides interdisciplinary and in-depth discussions among various sub-disciplines of plasma physics and application. At the Conference, over 500 hundreds of scholars from about 30 countries and regions participated, research topics were categorized into seven research sections: fundamental plasma, basic plasma, applied plasma, laser plasma, space plasma, solar/Astro plasma and magnetic fusion (MF) plasma. MF plasma

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was the largest section in this meeting. There were nearly 200 participants in MF section and covered 9 plenary, 20 overview, 69 invite, 31 oral and 63 poster presentations (http://aappsdpp.org/DPPProgramlatest/wholeitem/Plenarysessions.html; http://aappsdpp.org/DPPProgramlatest/topical_session.html).

At this conference, plasma scientists not only from Asia–Pacific area, but also from Europe and USA participated and exchanged the recent progress on various topics and had in-depth discussions among various sub-disciplines of the MF plasma physics. Fusion energy is one of the few options to satisfy the requirement of large-scale sustainable energy generation and global warming suppression. Fusion energy is regarded as a potential source of secure, inexhaustible and environment friendly energy; therefore, it must be developed as quickly as possible. There are still tremendous challenges to reach the final goal in developing the fusion energy. Precise understanding of the physics of fusion plasma is the key for the fusion energy dream. Steady but significant progresses have been made during the past decade and efforts have been focusing on physics understanding. Exchanges and cooperation between national and international institutes have been carried out for the past decade in Asia–Pacific region and the activities are supported by each government, scientific foundations and among institutes. This was the first such large-scale meeting in Asia–Pacific region, which was very successful through heroic joint efforts by organizer and participants. This summary is prepared to highlight the new progresses presented at this conference and is focused mainly on physics understanding. Future challenges are discussed in the last section.

2 Highlight

Important progresses have been made during past few years with major contributions by four Asia leading devices (HL-2A, EAST, KSTAR, LHD) which provide nearly 100 contributions for this conference. *Wan [P11]* reported the progress in steady-state tokamak operation in EAST, *Park [P18]* stressed the role of KSTAR in Korean fusion energy development, *Osakabe [P25]* presented the initial deuterium experimental results in LHD, and *Duan [P29]* stressed the contribution of HL-2A to ITER and CFETR. HL-2A (*Liu, MF-OV1)* shows efforts focusing on plasma instability control and H-mode physics, especially to explore a new edge localized mode (ELM) control method by supersonic molecular beam injection (SMBI), and passive–active multi-junction (PAM) lower hybrid current drive (LHCD) launcher. KSTAR (*Oh, MF-OV2*) makes continuous efforts establishing new physics through advanced diagnostics and has achieved long pulse high beta H-mode plasma up to 34 s without edge localized mode (ELM)-crash. LHD already started its deuterium (D) operation with well-calibrated neutron diagnostics and other special diagnostics. The ion temperature of 10 keV was achieved in D experiments. Triton burn-up rate over 0.4% was achieved which is comparable to tokomak. Some indications of isotope effects, electron energy transport and impurity behavior were observed. EAST (*Liang, MF-OV6*) is still leading its efforts focused for advanced steady-state operation. 100 s H-mode (up to 80 s truly steady-state condition with plasma loop voltage $v_{\mathrm{p}} = 0$) was achieved with radio-frequency (RF) heating only under actively cooled tungsten (*W*) monoblock divertor.

While small machines in universities and research institutes continue to make unique contributions for basic plasma science, physics understanding and training next-generation plasma scientist. Energetic particle physics study remains as a hot topic (over 20 presentations) and related nonlinear processes have been presented. Theory and simulation (nearly 40% of the total contribution) play a key role for understanding physics and future scenario developments.

3 Major progresses

3.1 Unique contribution from different machines

In this conference, more than 25 machines provide unique contributions to the MF plasma section. In HL-2A, majority of research results was focused on plasma instability control and H-mode physics. For plasma instability control, robust ELM control methods have been explored. Massive gas injection (MGI) and SMBI were used to mitigate runaway current. Real-time active control of neoclassical tearing mode (NTM) and suppression of ion fishbone by electron cyclotron resonance heating (ECRH) have been investigated (Duan et al. 2017). For H-mode physics, observation of double critical gradients of electromagnetic turbulence in H-mode has been reported (Zhong et al. 2016). Mechanism of L–H transition has been extensively studied (Cheng et al. 2016). Various pedestal instabilities have been observed (Zhong et al. 2017). For the first time, high coupling efficiency of LHCD with the PAM antenna was successfully demonstrated in H-mode on the HL-2A tokamak (Ekedahl et al. 2016). In LHD, after the completion of the facilities and long legal procedure for the safety issues, the deuterium experiment has started since March 7th, 2017. The first deuterium experiment campaign was successfully completed (Takeiri et al. 2017; Osakabe et al. 2017). In the following experiment, two positive-ion-based neutral beams (NB) were injected to the deuterium plasma and the plasma parameters rapidly increased, then the ion temperature $T_{\rm i}$ of $\sim$ 9.1 keV was obtained only 1 week after the first deuterium experiment. Improved energy confinement obtained in the EC heated deuterium plasma could be an indication of the isotope effect based on the trapped electron mode, which is predicted by a gyrokinetic simulation (Nakata et al. 2017). Here, the trapped electron mode is suppressed more in deuterium plasma in the higher collisional regime. KSTAR made good progress in fundamental science and steady-state H-mode with high beta. KSTAR emphasized the unique capabilities including tokamak plasma symmetry, in-vessel control coils (IVCC), 2D/3D microwave imaging diagnostics, and long pulse neutral beam (Jeon et al. 2012; Park et al. 2013a; Won-Ha et al. 2015; In et al. 2015; Lee et al. 2016). Various operation regimes have been expanded, such as high beta long pulse H-mode operation up to $\sim$ 72 s, as well as other operation modes such as ITER baseline scenario (IBS), internal transport barrier (ITB), hybrid (normalized fusion performance $G > 0.4$), high poloidal beta ($\beta_{\rm P} \sim 3$), and low edge safety factor q. In particular, plasma current of 1MA and higher elongation ($\kappa > 2$) plasmas exceeding design specification has been achieved. For ELM suppression experiment, KSTAR obtained a long ($\sim$ 34 s) ELM-crash suppressed discharge with $n = 1$ resonant magnetic perturbation (RMP) and achieved ELM-crash suppression at low edge q ($\sim$ 3.4) with $n = 2$ RMP which is compatible to ITER operation. KSTAR also reported important physics results in ELM study such as NTV-related rotation physics and role of turbulence induced by RMP, and systematic control of ELM suppression with the phase and amplitude of RMP. In EAST, strong efforts have been emphasized on advanced steady-state operation (Wan 2017; Garofalo et al. 2015b; Hu 2015) and the record 100 s steady-state H-mode operation with zero loop voltage has been achieved in the W-Wall environment. In this long pulse operation, 3 MW RF heating including LHW, ICRF and ECH was injected. The current driven by the LHCD is about 76% of plasma current. The H-factor of $H_{98y2} \sim 1.1$ has been maintained throughout the pulse. It should be noted that W-Divertor temperature was saturated after $t = 20$ s.

In addition, there are contributions from other fusion devices. The progress was reported in expanding the H-mode operating space and physics basis from DIII-D (Garofalo et al. 2015b; Chen et al. 2016). *Chen* (MF-O29) showed that the radial wave number of turbulence increases with E $\times$ B shearing rate. Isotope experiments and scenario development towards the DT phase was contributed from JET (*Jofflin, MF-OV3*). DD fusion yields have been extended to 2.9×10^{16} neutrons/s for 5 s (Litaudon et al. 2017; Nunes et al. 2016). 20 MW of NBI, 7 MW of ICRF and 6 MW of ECRH were equipped in ASDEX-U (*Stober, MF-OV7*) and integrated scenarios for ITER and DEMO have been developed (Bobkov et al. 2016; Schweinzer et al. 2016; Suttrop et al. 2017). European medium tokamaks (AUG, MAST-U, TCV) coordinated research was reported by *Meyer* (MF-OV13). Fully non-inductive plasma start-up has been successfully attempted in QUEST (*Hasegawa, MF-OV10*) and operation of the plasma up to 1 h 55 min discharge was successfully achieved in this device (Hanada et al. 2015, 2016, 2017). RMP system on J-TEXT (*Yang, MF-OV18*) has a unique fast rotating capability (up to 6 kHz) and applied to control of tearing mode and disruption mitigation (Hu et al. 2013; Zhuang et al. 2015, 2017). Heliotron-J (*Okada,MF-OV14*) has used controllable five sets of coil systems to realize a wide range of configurations by changing the coil-current ratios (Sano et al. 2000; Obiki et al. 2001). Top-launching capacitively coupled combine (CCC) antenna of the lower hybrid wave alone demonstrated the formation of a spherical tokamak (ST) plasma in TST-2 device (*Takase, MF-OV4*) (Shinya et al. 2015, 2017). Toroidal Alfven Eigen modes during minor disruptions have been found in SUNIST (*Gao, MF-OV19*) (Liu et al. 2016a). Direct mode conversion of the X-mode to Electron Bernstein Wave from the low field side was successfully utilized to enhance the ECH pre-ionization in VEST (*Na, MF-OV5*) (Chung et al. 2013; An et al. 2015, 2017). A significant improvement of the energy confinement time was observed in negative triangularity discharges in TCV (*Porte, MF-I53*) and DIII-D (*Marinoni, MF-I54*) (Pochelon et al. 2012; Marinoni et al. 2009; Merlo 2015). KTX (*Liu, MF-OV17*) realized low q tokamak discharges up to 200 kA with advanced diagnostics (Liu et al. 2014; Xie et al. 2014). Spontaneous helical equilibrium formation associated with hot electron thermal structures was observed in RFX-mod (*Zuin, MF-OV9*) as well as RELAX (*Masamune, MF-OV15*) (Lorenzini et al. 2016; Zuin et al. 2017). Low loop voltage start-up and current ramp-up experiments have been carried out using ECRH and ICRH in ADITYA/U (*Ghosh, MF-OV8*) (Tanna et al. 2017). A medium-sized washer gun is developed in KMAX (*Sun, MF-OV20*) (Sun 2013). EU has made coordinated research on medium sized tokamaks to addresses critical ITER issues, such as alternative divertor configuration, RMP ELM suppression and modeling of runaway electron beam dissipation (Suttrop et al. 2017; Willensdorfer et al. 2016; Dunne et al. 2017; Havlickova et al. 2015; Pautasso et al. 2017).

3.2 H-mode physics

Study of H-mode physics is widened for understanding of the plasma confinement and stability, and attaining high performance plasmas. While taming of the standard ELMy H-mode with various techniques, performances of the quiescent H-mode (QH), small ELM H-mode were suggested as an attractive alternative for ITER and future devices. *Garofalo* (MF-OV12) reported the simulation study of high performance (ITER discharge of $Q = 10$ in ITER) at high plasma density (80% of the Greenwald limit) based on a type of QH-mode obtained on EAST using tungsten divertor (Garofalo et al. 2015a, b). Xu (MF-I6) presented a stationary small-ELM H-mode regime operation in EAST (Xu et al. 2016). This regime was obtained at high edge safety factor ($q_{95} > 6$),high poloidal beta ($\beta_p > 1.6$),high triangularity ($\delta > 0.55$), and optimized high internal inductance ($l_i \sim 1.1$), similar to the plasma parameter space of the grassy ELM H-mode regime obtained previously in JT-60U (Kamada et al. 2000). *Ekedahl* (MF-I21) introduced the progress of LHCD PAM for small ELM in HL-2A (2016). *Shao* (MF-O11) found the regime of small amplitude oscillations at EAST, which are consistent with the physical mode of zonal-flows and turbulence interaction (Kim and Diamond 2003). Study on L–H transition mechanism has been extensively carried out in many devices, recently. *Ko* (MF-I30) studied the L–H transition under the non-axisymmetric magnetic fields in KSTAR and found the sensitive dependence on resonant components and no dependence of non-resonant fields on the L–H power threshold. The result strongly suggests that intrinsic non-axisymmetric fields (error fields) should be minimized to economically secure the access to H-mode in ITER and future reactors (Ko et al. 2015; In et al. 2015). *Chung* (MF-I55) demonstrated a 7 s internal transport barrier (ITB) discharge in a weakly reversed q-profile in KSTAR. Time trace of the plasma parameters demonstrated that the plasma performance such as temperatures, the stored energy and the β_N is comparable to that of the H-mode in the same discharge (Chung et al. 2017). *Guttenfelder* (MF-I11) used gyrokinetic prediction to understand the confinement scaling ($\tau_E \sim 1/\nu$) at low collisionality which is critical for the future spherical tokamak and pointed out that the global multi-scale simulations that would be required to simulate the turbulence and transport (Guttenfelder et al. 2011, 2012, 2013) is necessary and possible in a near future. *Weiland* (MF-I7) predicted zonal flows play a key role in L–H transition and the kinetic ballooning modes and peeling modes dominate on the H-mode barrier (Weiland and Zagorodny 2016; Weiland 2014, 2015, 2016, 2018).

3.3 Physics and control of the ELMs

ELM control with variety of control tools such as SMBI, pellet, LHCD, laser-blow off (LBO), Li granule, RMP made great progress in recent years, especially on study of physical mechanisms. As the modeling has been improved, excellent agreement between theory and experiments on ELM physics has been reported by several presenters. These outstanding progresses reported in this conference help to improve our physics understanding on this subject. *Zou* (MF-I17) claimed a new shear flow oscillation in the pedestal region during the ELM mitigation phase with SMBI in EAST. It has strong nonlinear interaction between shear flow oscillations and background turbulence. Both experiments in EAST and HL-2A have revealed the underlying physics mechanism for ELM mitigation, showing that how shear flow oscillations regulate the pedestal turbulence and control ELMs (Zou 2012; Xiao et al. 2012). *Zhong* (MF-I29) reported double critical impurity gradients of electromagnetic turbulence in HL-2A, which was well reproduced by theoretical predictions. The turbulence can also be excited by externally seeded impurity. The finding suggests that the quasi-stationary edge localized impurity profile offers a possibility of active control of the pedestal dynamics and ELMs via pedestal turbulence (Zhong et al. 2016, 2017). New micro-electromagnetic instabilities are found in magnetically confined toroidal plasmas with two ion species (main and impurity ions) from gyrokinetic simulations by *Dong* (MF-I8). The instabilities are induced by impurity ion density gradient and finite β effect (Du et al. 2016; Shen et al. 2016). *Zhang* (MF-P6) used LBO-seeded impurity to control ELMs in HL-2A. Micro-instabilities were observed during the ELM suppression phase. *Zhu* (MF-I49) presented the results using MHD modeling for the study of ELM. It showed that increasing pedestal resistivity due to lithium conditioning can fully stabilize low-n ELMs (Banerjee et al. 2017a, b). For ELM control by RMP, significant progresses have been made both on experiments and modeling. *In* (MF-I16) presented results on the expanded operation boundary and capability of the RMP-driven ELM-crash-suppression in KSTAR. It suggests that global plasma response against applied RMP should be simultaneously factored, while tailoring edge resonant components of magnetic perturbations for the ELM-crash suppression (In et al. 2015). More modeling results for understanding of ELM mitigation by RMP were presented by *Li* (MF-I20) and *Kim* (MF-I18) (Kim et al. 2014; Li et al. 2016). The plasma response to the applied 3D RMP fields was considered in the models. *Yan* (MF-O12) proposed that RMP helicity could be used as a new scheme for controlling neoclassic toroidal viscosity (NTV) peak location (Yan et al. 2017). *Liang* (MF-P7) presented the result of ELM mitigation by the $n = 1$ RMP in HL-2A (Duan et al. 2017). A significant progress has been made in ELM control using RMP on EAST in recent years. The observations in EAST reveal both linear and nonlinear plasma response effects on ELM suppression, as presented by *Sun* (MF-I48). It indicates that a critical level of magnetic topological change taking into account nonlinear plasma response plays a key role in accessing the final ELM suppression (Sun et al. 2016, 2017). *Xiao* (MF-I46) showed the results on the propagation dynamics with resonant magnetic perturbations field in H-mode plasmas. It has been studied using an innovative experimental approach based on the application of small edge perturbations induced by SMBI (Xiao et al. 2012, 2016). Optimization of resonant and non-resonant magnetic perturbations in KSTAR has been done by *Park* (MF-I45). It implies the possibility of advanced and systematic optimization of coils and configurations in tokamaks, without demanding expansive search of 3D field spectrum in experiments (Park and Logan 2017; Park et al. 2013b). *Cheng* (MF-I19) observed an electromagnetic mode prior to the ELM crash. It was identified as a trigger of the ELM.

3.4 Energetic particles

Study on energetic particles (EPs) remains the hot topic. Behaviors of energetic particles and EP-driven instabilities play an important role in plasma confinement especially for burning plasmas. *Gorelenkov* (MF-I1) presented frontiers in energetic particle research in fusion and proposed potential directions for EP studies (Gorelenkov et al. 2014; Gorelenkov 2016; Belova et al. 2015). For the transport of fast ion, nonlinear regimes should be the focus in both theoretical and experimental work to be performed. For theoretical modeling, initial value codes and reduced models will be pursued. Deleterious effects on EP and thermal plasma confinement should be emphasized. Geodesic acoustic mode (GAM) is a branch of zonal flow in toroidal plasmas and driven by not only turbulence but also energetic particles. *Ido* (MF-I4) reported a subcritical instability of the GAM driven by the EGAM and the EPs in LHD. One of the important features of subcritical instabilities is that these instabilities are driven when the initial perturbation exceeds a threshold (Ido et al. 2015, 2016; Lesur et al. 2016). *Yu* (MF-I3) gave an overview of recent MHD instabilities excited by energetic electrons in the HL-2A. TAE with frequency in the range of 160–380 kHz was observed in the plasma with high-power ECRH (Ding et al. 2013; Chen et al. 2013; Yu et al. 2017). *Chen* (MF-I56) claimed the observation of Alfvenic ion temperature gradient (AITG) mode $f = 80$–200 kHz ($f_{\mathrm{BAE}} < f < f_{\mathrm{TAE}}$) mode which appears in the ITB plasmas with weak magnetic shear and high gradients of T_{i} in HL-2A (Chen et al. 2013). *Dong* (MF-I36) observed a toroidal Alfven eignemode (TAE) mode during the plasma disruption. It was found that the mode can limit the strength of runaway beam (Duan et al. 2017). *Tan* (MF-O8) also observed TAEs in ramp down phase during the minor disruption (Liu et al. 2016a). In HL-2A, it was observed that there are energy transport between double fishbones (Jiang et al. 2017). For the modeling, *Zhu* (MF-I66) showed that strong tearing mode behavior can make frequency chirping weak due to overlapping of TAE and TM resonances in phase space. Nonlinear processes and saturated spectrum of Alfvén eigenmodes have been studied by *Qiu* (MF-I2). The associated nonlinear processes exhibit meso-scale, resulting in qualitative and quantitative modifications in the nonlinear processes of AEs (Chen and Zonca 2016; Qiu et al. 2017). Influence of energetic ions on neoclassical tearing modes has been studied by *Cai* (MF-I40). It is predicted to use EP to suppress NTM for the steady state and hybrid scenarios with weak magnetic shear (Cai et al. 2011; Cai and Fu 2012; Cai et al. 2016). *Zhang* (MF-I5) showed nonlinear phase space structure of e-BAE.

3.5 MHD instabilities

The topic of MHD instabilities also made great progress within recent years, especially on new findings of MHD, multi-scale interaction between MHD and small-scale turbulence, and NTM-related issues. *Ida* (MF-I9) observed a tongue of the magnetic field in the low density plasma with significant energetic ions injected by neutral beam in LHD. As a phase space response of ions, the distortion from Maxwell–Boltzmann distribution of epithermal ions was observed for the first time (Ida et al. 2016). The trigger mechanism of MHD burst was believed to be different from the conventional picture where the instability of the MHD mode grows. Full toroidal computation of resistive MHD instabilities based on asymptotic matching approach was presented by *Wang* (MF-I41). The method developed in the PEST3 code (Pletzer and Dewar 1991). *Nornberg* (MF-I62) showed the progress in application of the integrated data analysis to optimize measurements critical to the validation of MHD simulations (Galante et al. 2015). Multi-scale nonlinear interaction between a large-scale MHD instability and small-scale turbulence has been presented by Choi (MF-I51) and Jiang (MF-O20) in KSTAR (Choi et al. 2017) and HL-2A (Jiang et al. 2018), respectively. It was noted that the interaction between the large-scale MHD and small-scale turbulence is important for the electron thermal transport. Radial profiles of poloidal flow and density fluctuation around the magnetic island were firstly observed in HL-2A. *Sabbagh* (MF-I47) reported direct measurement of the generalized Neoclassical Toroidal Viscosity (NTV) offset rotation profile V_0^{NTV} in KSTAR (Sabbagh et al. 2017). This measurement has direct relevancy in ITER operation. *Wang* (MF-I38) presented simulation results on nonlinear interaction of the NTM, which predicted that ECCD can effectively reduce 2/1 NTM island width. Deposition of ECCD at 2/1 surface can further stabilize 3/2 NTMs (Wang et al. 2015; Wei et al. 2016; Wang et al. 2017). *Qu* (MF-I39) presented results on the neoclassical polarization current contribution to the NTM evolution by solving the drift-kinetic equation in a so-called ion-banana-center coordinate system without assumption of the large island width (Qu et al. 2016). Simulations that include self-consistent NTM width and frequency and plasma profiles can help designing more robust control schemes for ITER, as reported by *Poli* (MF-I37) (Poli et al. 2016).

3.6 Turbulence and transport

With regard to the topic of turbulence and transport physics, more attention has been on the theory and simulation study as shown in presentations in this conference. There are many different types of macroscopic instabilities in fusion plasmas. *Liu* (MF-I33) reported study on physics and control of macroscopic instabilities in magnetically confined fusion plasmas. MARS-Q modeling of DIII-D ELM suppression experiment reproduced large density pump out (Liu et al. 2016b, 2008; Liu and Bondeson 2000). *Li* (MF-O18) presented the result on the influence of strong magnetic field (Larmor radius less than the Debye length) on plasma transport (Dong et al. 2016). Based on first-principle model, gradient-driven gyrokinetic simulations have often been used to explain the turbulence-driven transport in present fusion devices; generalized tokamak simulator (GTS) simulations demonstrated a decent agreement in ion thermal transport, as reported by *Ren* (MF-I15) (Wang et al. 2010; Ren et al. 2015). Multi-scale phenomena and cross-scale interactions often found in fusion, space, and astrophysical plasmas represent complexity of plasma behaviors. *Watanabe* (P5) presented study on a more general class of multi-scale interactions in the drift wave turbulence and zonal flows. Specifically, micro-tearing mode (MTM) turbulence can be suppressed by electron temperature gradient (ETG) turbulence through destruction of the current sheet structures (Maeyama et al. 2017; Watanabe et al. 2015). First principle-based gyrokinetic simulation of the turbulent transport under strong gradient was performed by the GTC code with the HL-2A experiment parameters and found that the turbulent transport coefficient decreased with the applied gradient, which is contradictory to the conventional wisdom of the trend of the transport coefficient under weak gradient (Xie and Xiao 2015; Xie et al. 2017), as reported by *Xiao* (MF-I50). Recently, the global gyrokinetic code NLT in terms of the magnetic coordinates has been developed. This code is based on a special numerical Lie-transform perturbation method, called the I-transform perturbation method, as introduced by *Wang* (MF-I12) (Ye et al. 2016; Wang 2012, 2013). *Satake* (MF-I14) presented recent progress in formulations of the global and local drift-kinetic simulation models and the consideration on the neoclassical viscosities which play the key role in the evaluation of the neoclassical radial particle and energy fluxes, bootstrap current, toroidal and poloidal torque. (Honda et al. 2015; Satake et al. 2011). *Yi* (MF-I10) proposed a new physical picture of non-local transport by the turbulent spreading (Yi et al. 2014).

3.7 DSOL physics and plasma wall interaction

For successful operation of the ITER *W* divertor, divertor and scrap-off layer (DSOL) physics and plasma wall interaction (PWI) are still crucial topics. It is imperative that more modeling work is needed for better understanding. *Pitts* (MF-OV11) discussed key areas of the physics basis for the ITER W divertor which have driven the design, focusing separately on steady state and transient power fluxes. It was shown that the baseline is partially detached operation on full-W divertor using low *Z* seeding assist for dissipation of 50–70% heat power in the SOL region (Pitts et al. 2013). Tungsten is among the main candidate of the plasma-facing materials (PFM) for fusion reactor and will be exclusively used in the ITER divertor. Melting is one of the major risks associated with the use of a metal as PFM. *Coenen* (MF-I42) introduced the study on tungsten components in fusion, including the issues of power loading and melting (Litaudon et al. 2017). Modeling of PWI and impurity transport in magnetic fusion devices was reported by *Kirschne* (MF-I57) (Brezinsek et al. 2015). The result showed that the lifetime issues of the Be wall are much less critical with respect to the machine availability than the *W* erosion in the divertor. *Xia* (MF-O24) presented simulation results of the SOL width with helical current filaments (Wan 2017). SOLPS modeling results presented by *Sang* (MF-I65) concluded that the closure of divertor also has a great impact on the upstream plasma condition (Sang et al. 2017). Coupling of the SOL density profiles with edge plasma parameters was studied by *Wu* (MF-O23). *Corr* (MF-O19) reported that high power steady-state MAGPIE II linear plasma device is under construction. *Hu* (MF-I63) reported that the Li coating provided an excellent wall conditioning in W divertor and effectively suppressed W impurity (Hu et al. 2015b, 2016) in EAST. *Zakharov* (MF-I64) showed that Li wall fusion is important for confinement and particle control (Zakharov et al. 2007). *Francisquez* (MF-I31) presented global 3D two-fluid simulations of turbulent transport in the tokamak edge region (Zhu et al. 2017). Progress on active handling of the heat flux and impurity accumulation in EAST long pulse operation with tungsten divertor was given by *Wang* (MF-I43). The utilization of in–out divertor asymmetry and optimization of configuration & strike point play a key role (Wang et al. 2013; Liu et al. 2016c; Wang et al. 2017). Modeling of heat load and impurity for snowflake, tripod configurations in HL-2M was presented by *Zheng* (MF-I44) (Zheng et al. 2016). *Wu* (MF-O16) showed the results about active feedback control of radiation for power exhaust in EAST long pulse operations (Wan 2017).

3.8 Steady-state operation

Recent experimental advances towards the steady-state operation have been reported by several devices. On EAST, several methods, including (i) change of the edge magnetic topology by application of either LHWs or RMPs, (ii) radiating divertor with impurity seeding, and (iii) a quasi-snowflake divertor configuration, have been applied successfully for active control of heat and particle fluxes deposited on the divertor targets in steady-state operation (Wan 2017), as reported by *Liang* (MF-OV6). KSTAR has made significant advances in developing long pulse and high performance plasma scenarios utilizing the advantage of fully superconducting tokamak as presented by *Oh* (MF-OV2). According to the effort in plasma control, H-mode plasma discharge in KSTAR has extended up to 1 MA in plasma current and up to 70 s in flat top duration at 0.45 MA with highly non-inductive current drive fraction over 0.9. For the improved plasma performance in steady-state, KSTAR device will be upgraded in heating systems and in-vessel structures (In et al. 2015). On ASDEX-U, it will be equipped with 20 MW of NBI, 7 MW of ICRF and 6 MW of ECRH and two new ECRH units with 2×1 MW, 10 s, at 140 GHz/105 GHz are taken into operation in 2017. Full ELM suppression and non-inductive operation up to a plasma current of $I\mathrm{p} = 0.8$ MA could be obtained at low plasma density, as reported by *Stober* (MF-OV7) (Bobkov et al. 2016; Suttrop et al. 2017). Efforts toward steady-state operation in long duration discharges with the control of hot wall temperature on QUEST were reported by *Hasegawa* (MF-OV10). Fully non-inductive plasma start-up and its maintenance up to 1 h 55 min were successfully achieved on QUEST with a microwave of 8.2 GHz, 40 kW and well-controlled gas fueling and plasma-facing wall (PFW) temperature of 373 K. The gas fueling is feedback controlled to keep constant $H\alpha$ signal, which is a good indicator of the in-coming H flux to the plasma facing materials (PFMs) (Hanada et al. 2015, 2016; 2017).

3.9 Negative triangularity

Power and particle control in fusion reactor is quite challenging tasks. Recently, discharges with negative triangularity provided an alternative way of power handling in tokamak configuration. There were four presentations in this topic, covering simulations and experiments. *Kikuchi* (MF-O13) studied the negative triangularity tokamak (NTT) as an innovative concept to reduce the transient ELM heat load and the quasi steady-state heat load in both double- and single-null configurations (Kikuchi et al. 2014; Medvedev et al. 2015, 2016). Negative triangularity experiments in TCV were presented by *Porte* (MF-I53). It was shown that the pedestal in negative δ H-mode is smaller than that in positive δ (Marinoni et al. 2009; Merlo 2015). For better understanding of the vertical displacement events (VDEs) characteristic of the negative triangularity plasma, the VDEs of the double-null negative triangularity configurations are compared to that of the corresponding positive triangularity configuration in HL-2M, by the DINA code, as presented by *Xue* (MF-O14) (Zheng et al. 2014). *Marinoni* (MF-I54) observed H-mode-like confinement with L-mode edge in negative triangularity plasmas on DIII-D. High core confinement, low impurity content and ELM-free characteristics have been obtained (Marinoni et al. 2009).

3.10 Plasma diagnostics

Development of diagnostic system is the basis for the fusion plasma research. Relentless efforts have been dedicated to developing more reliable, higher spatiotemporal resolution and advanced imaging diagnostics. The ITER Project is now rapidly advancing in several fronts. This includes the buildings, the major components and the independent systems including diagnostic systems. Currently, the diagnostic systems for ITER are being developed on by teams all around the world. *Walsh* (MF-I60) presented the current status of the ITER diagnostic development and outstanding challenges of the diagnostic systems including assessment of the different risks, commissioning, installation and operation planning of these systems. Advances in diagnostic developments for steady-state tokamak operation on EAST in support of future applications on CFETR were given by *Liu* (MF-I61) (Hu et al. 2011). A new gas-puff imaging (GPI) diagnostic system developed to study two-dimensional (2-D) plasma turbulence, Z_{eff} measurement by visible bremsstrahlung diagnostic and seven-channel Motional Stark effect (MSE) diagnostics based on dual photo-elastic modulators (PEMs) in HL-2A were reported by *Yuan* (MF-O10), *Liu* (MF-O26) and *Chen* (MF-O28), respectively. *Sanpei* (MF-O7) introduced the high-speed tangential soft X-ray (SXR) imaging diagnostics which were developed to identify the emission structures in RELAX (Ohdachi et al. 2007; Nishino et al. 2006; Onchi et al. 2010).

3.11 Plasma control and scenario development

Plasma control and scenario development are critically important for well-confined burning plasma physics in the forth coming fusion reactor experiments including

ITER and CFETR. The requirement of robust and disruption-free discharges in these devices demands highly elevated levels of reliability and performance only possible with control algorithms based on sufficiently accurate models, as reported by *Humphreys* (MF-I35) (Humphreys et al. 2007). DIII-D, EAST, KSTAR and other machines are also advancing their integrated plasma control plans toward disruption-free operation. With the high level of attention to both areas, experimental programs in present day and next-generation devices will be benefit from exploiting this powerful synergy. Systematic experimental and theoretical investigation on DIII-D and EAST showed attractive transport properties of fully non-inductive high β_p plasmas. Shafranov shift can increase the local rational shear and be essential for the threshold of β_p for wider ITB formation in the high β_p scenario, as simulated by *Ding* (MF-I28) (Li 2016). Plasma scenario development for the HL-2M tokamak was given by *Ji* (MF-I34) with METIS code (Artaud et al. 2010) and the results claimed that it can partially address the physics issues in operation conditions expected on ITER, CFETR with high b_N, $T_i \sim T_e$, and vanishing loop voltage simultaneously. High beta operation has been the focus on advanced scenario study in KSTAR (Park et al. 2013b). The development of stable low q_{95} operation and hybrid scenario with sawteeth tailoring for addressing applicability to high beta steady-state discharges was presented by *Yoo* (MF-I27). *Stober* (MF-OV07) reported the development of integrated scenarios for ITER and DEMO on ASDEX Upgrade (Bobkov et al. 2016; Suttrop et al. 2017; Kikuchi et al. 2014). Experiments with low collisionality, which comprise current drive, ELM mitigation/suppression and fast ion physics, are mainly done with freshly boronized walls to reduce the tungsten influx at these high edge temperature conditions. Full ELM suppression and non-inductive operation up to a plasma current of $I\text{p} = 0.8$ MA could be obtained at low plasma density. Plasma exhaust is studied under conditions of high neutral divertor pressure and separatrix electron density, where a fresh boronization is not required. Integrated modeling for high beta scenarios on JT-60SA was presented by *Romanelli* (MF-I26) (Romanelli et al. 2014). The goal of the reference high beta non-inductive scenario of JT-60SA is achieving steady-state discharge with the normalized beta values above 4 and bootstrap-current fractions of 80% at densities well below the Greenwald density-limit for controlled operations.

4 Future challenges

Construction of ITER (Campbell, P4) is successfully progressing and operation plan has to meet the scientific mission of ITER which should be the first priority for fusion plasma community during next decade. ITER will continue the current phase of construction without obstruction but risk may be in its scientific research phase unless there is now significant efforts on resolving issues such as off normal events (e.g., plasma disruption), confinement and transport physics of the burning plasma, high performance long pulse and steady-state operation, and high power exhaust. These are urgent issues to be resolved within the fusion plasma community.

Off normal events exit since the advent of tokamak device and have not been fully solved yet such as disruption with various reasons. An elevated efforts in theory, modeling and technology for advanced integrated control are needed to achieve a robust, disruption-free operation scenarios. Confinement and transport for the alpha particle heating dominated plasma in the presence of AE driven by super thermal fast ions may have to be investigated by simulation. It is clear that a significant loss of Alpha/fast ions may degrade the plasma H&CD efficiency and may lead to quenching of the DT burning discharge. Robust and reliable burning plasma diagnostics may be needed to explore with simpler technical solution in preparation of the ITER burning plasma physics.

High-performance steady-state H operation over 400 s is the goal of ITER operation which needs interactive dynamics for many physical quantities from both the core and edge. For the core plasma performance, efficient non-inductive CD in H-mode, high bootstrap current fraction and low impurity concentration are required simultaneously. In the edge and SOL region, it is essential to have a controllable plasma surface interaction for sustainment of low impurity generation and particle recycling in *W* divertor, low peak heat load for a tolerable transient heat shock (small/no ELMs) and allowable erosion. The current steady-state tokamak devices such as KSTAR and EAST may have to conscious on these problems and researches on these devices should be oriented toward a long pulse operation of the high-performance plasmas.

In ITER, peak heat fluxes near the technological limit ($> 20\ \mathrm{MW/m^2}$) are foreseen and the present ITER solution may be marginal for DEMO. Integration of DEMO working condition is very challenging which needs both new physical (advanced divertor and impurity seeding) and technical (new robust DEMO $20\ \mathrm{MW/m^2}$ target) solutions and integrated experiments validation on long pulse tokamak is also needed in next decade. Solid experimental database is required before ITER operation.

5 Summary

This conference covers the recent progresses that have been made in the area of fusion plasma, not only from Asia–Pacific, but also from Europe and USA. This summary paper is made by summarizing almost most important issues which address future ITER-related experiments. Major efforts have been made which focus on physics understanding and new findings. By good comparison between theory simulation and experiments, transport and turbulence are reproduced well which give confidence for future ITER. Understanding of H-mode and ELMs, and effective control scenarios have been progressed. Using different combination of ELM control, a robust ELM control method will be soon established based on the understanding and technology development which will establish a solid base for future ITER ELM control. Energetic particles and advanced steady-state operation remain two urgent issues for preparing successful operation of ITER in near future and efforts should be made.

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