Plasma Science and Technology

Summary of the 11th Conference on Magnetic Confined Fusion Theory and Simulation (CMCFTS 2023)

Summary of the 11th Conference on Magnetic Confined Fusion Theory and Simulation (CMCFTS)

Guangzhou HAO (郝广周)[1,*], Jianqiang XU (许健强)[1,*], Youwen SUN (孙有文)[2], Zhibin GUO (郭志彬)[3] and Organizing Committee of CMCFTS (磁约束聚变理论与模拟会议组委会)

[1] Southwestern Institute of Physics, Chengdu 610041, People's Republic of China

[2] Institute of Plasma Physics, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei 230031, People's Republic of China

[3] State Key Laboratory of Nuclear Physics and Technology, Fusion Simulation Center, School of Physics, Peking University, Beijing 100871, People's Republic of China

[*]E-mail of corresponding authors: haogz@swip.ac.cnhaogz@swip.a.cn and xujq@swip.ac.cn

Abstract

This conference report summarizes recent progress in plasma theory and simulation that was presented in contributed papers and discussions at the 11th Conference on Magnetic Confined Fusion Theory and Simulation (CMCFTS) held in Chengdu, China, 27–30 October, 2023. Progress in various fields has been achieved. For example, results on the zonal flow generation by mode coupling, simulations of the key physics of divertor detachment, energetic particle effects on magnetohydrodynamic modes in addition to ion and electron scale turbulence, physics of edge coherent modes and edge localized modes, and the optimization of ion heating schemes as well as confinement scenarios using advanced integrated modeling are presented at the conference. In this conference, the scientific research groups were organized under six categories: (A) edge and divertor physics, (B) impurity, heating, and current drive, (C) energetic particle physics, (D) turbulent transport, (E) magnetohydrodynamic (MHD) instability and (F) integrated modeling and code development. A summary of highlighted progress in the above working groups is presented.

Keywords: magnetic confined fusion (MCF), theory and simulation, modeling, tokamak.

1. Introduction

The 11th Conference on Magnetic Confined Fusion Theory and Simulation (CMCFTS) was held in Chengdu, 27–30 October, 2023. The conference has been successfully held ten times from 2013 to 2022. As the scale and influence of the conference gradually expanded, it has become an important event and academic exchange platform in the field of magnetic confined fusion (MCF).

The goal of the CMCFTS is to report the latest progress in theories and numerical simulations on magnetic confinement fusion as well as other plasma physics. It also discusses the latest developments in domestic and foreign magnetic confinement fusion investigations which are needed for the future fusion reactors. The conference topics include: equilibrium and magnetohydrodynamic (MHD) instability, micro-instabilities and turbulent transport, heating and current drive, fast particle and alpha particle physics, boundary physics, impurity transport, plasma-wall interactions, fusion reactor physics and integrated modeling, deuterium-tritium plasma physics, new conceptual design, large-scale numerical simulation and high-performance computing, and applications of artificial intelligence technology.

This year, the categories were similar to those of previous meetings. The presentations are divided into six topics as follows: (A) edge and divertor physics, (B) impurity, heating and current drive, (C) energetic particle (EP) physics, (D) turbulent transport, (E) magnetohydrodynamic instability and (F) integrated modeling and code development. The reports focus on the above six topics including 5 plenary talks, 10 invited oral talks, 74 oral talks, and 96 posters. More than 300 people actually attended the conference. In the following sections, the main results and significant progress presented by these presentations are summarized.

2. Summary of plenary and invited talks

2.1. Summary of plenary reports

Zhong reported an overview of recent research activities on the newly built large-scale research facility: HL-3 tokamak. On the HL-3, a milestone was achieved: high-confinement mode (H-mode) with the plasma current exceeding 1 MA. High-performance discharges with advanced (e.g. snowflake) divertor configurations have been realized [1]. These breakthroughs represent the recently significant improvements of operational level of China's MCF device. Hu reported the significant progress in various topics including core confinement improvement and turbulence suppression, turbulence current drive, MHD and turbulence interaction, error field penetration, edge localized mode (ELM) suppression and ELM free regime investigation, transport barriers control and improvement, plasma wall interaction, RF dominant heating noninductive plasmas on the EAST [2–4]. The key achievements on the HL-3 and EAST provide the important platforms and the solid physics basis for solving key issues in MCF as well as supporting to ITER research plan.

Wang reported the new results on the nonlinear gyro-kinetic simulations [5]. The long-time nonlinear global simulations, performed by NLT code, successfully revealed the formation dynamics of internal transport barrier (ITB) for the first time. It was found that the ITB is a kind of self-organized marginal structure. The initial formation of ITB near the magnetic axis is due to inward propagated avalanche. The outward expansion of ITB is the catastrophe induced by the outward propagated avalanche. Ma presented the progress on the mechanism and active control of plasma disruption [6]. The impurity injection is a useful control technique to mitigate heat deposition and halo current on the wall, and to reduce the amplitude of runaway current. In addition, combined with MHD instability control, CLT simulations have indicated that the external fueling is an effective way to improve operational density limit without disruption [7]. Chen reported the recent progress in the energetic particle (EP) physics [8]. Zonal flow (ZF) can be generated by the non-linear interaction between Alfvén eigenmodes. EPs can affect the performance of edge plasma. For example, instabilities driven by EP play a role in triggering ELM, pedestal collapse and nonlocal transport. It is suggested that the multi-scale nonlinear interactions among different instabilities are essential for understanding of complex plasma behaviors [9−12].

2.2 Summary of invited talks

There are 10 invited talks that give several important results in the theories and simulations of turbulent transport, ZF, three-dimensional physics in stellarator, nonlinear MHD simulations, interactions between internal kink modes and EPs, neoclassical impurity transport, and edge-localized mode (ELM) simulations. Here, we summarize the key results of each talk.

Xiao reported the global gyrokinetic GTC simulations of ion temperature gradient (ITG) turbulence transport and ZF physics [13] in reversed magnetic shear configuration based on the designed equilibrium for CFETR [14]. A comparison revealed that magnetic shear can suppress ITG instability by controlling the distribution of density on the rational surface. This suppression effect persists in the absence of ZFs in nonlinear ITG turbulence, and in the case of negative magnetic shear. Wang simulated the MHD instabilities in the CFQS stellarator, which indicates that bootstrap current will lead to the generation of low-order rational surfaces and magnetic islands, causing the breaking of some magnetic surfaces. When the plasma resistivity is high, the resistive ballooning modes exist in the regions where the pressure gradient is large. However, the fast ions have a stabilizing effect on resistive ballooning mode [15].

Jian presented numerical results related to the recent DIII-D high β_p experiment. It was found that the plasma achieved a high-performance regime due to the existence of internal transport barrier (ITB). However, the unstable kinetic ballooning mode (KBM) instabilities inside ITB [16] limit the further increase of plasma performance.

Wang reported the results obtained by employing the global gyro-kinetic code GKNET, which includes a heating source term. It was shown that the stability of the ***E***×***B*** staircase was weakened with increasing the heating power. Meanwhile, the outward propagation of avalanche structures is enhanced and more intermittent turbulent bursts occur [17].

Zhou has simulated the sawtooth collapse phenomenon observed on the W7-X stellarator using M3D-C1. A small amount of near-axis electron cyclotron current drive leads to two $\iota = 1$ resonance positions on the rotational transform profile, which result in appearance of two $(n, m) = (1, 1)$ (n and m are toroidal and poloidal mode numbers, respectively) internal kink modes. A small collapse occurring near the inner resonance position might be responsible for the sawtooth precursor. While the large collapse occurring near the outer resonance one qualitatively matches the experimental indicators such as the temperature reversal minor radius [18]. Dong reported that the drift kinetic resonance of EPs has a stabilizing effect on the internal kink mode. Here, the precession drift resonance of trapped particles plays a dominant role [19].

Guo showed that the dilution effect of EPs reduces the real frequency of the density gradient driven long-wavelength collisionless trapped electron mode (CTEM), thereby increasing the growth rate of CTEM. This is mainly because the smaller phase velocity of CTEM leads to more electron cyclotron resonance, which enhances the driving force of the CTEM instability [20, 21]. Su reported the newly developed Parametric Perturbation Instability Calculation (PPIC) code, which was used to systematically simulate characteristics of parametric instability of low hybrid waves. Starting from the "double-well structure" in the parametric instability equation, the decay channel for parametric instability has been clearly defined, which greatly improves the reliability of growth rate calculations [22].

Pan developed a theoretical model which was able to investigate the features of asymmetrical distribution of impurity ion density in flux coordinates for various plasma shapes. The asymmetry of the poloidal magnetic field in the single-null divertor configuration can lead to an asymmetrical distribution of impurity ion density, which provides a new mechanism for neoclassical impurity transport [23]. Li presented a detailed analysis of the ELM suppression in the quasi-snowflake divertor discharges on the EAST. It was reported that the local magnetic shear plays an important role in controlling ELM dynamics. The change of local magnetic shear alters the amplitude of the Reynolds stress, which in turn determines the redistribution of energy to the low-*n* mode and affects the ELM size [24−26].

3. Edge and divertor physics

Xu reported the experimental results of detached divertor scenarios on the EAST. Under the conditions of low q_{95}, high density, and high-power heating, pure neon injection results in small ELMs on the pedestal and divertor detachment. The density can approach the Greenwald density limit. At the same time, the ratio of radiation power to total heating power reaches up to 50% [27, 28]. Du reported the numerical results on the quantitative dependence of divertor detachment on particle recycling [29]. Mao developed a numerical suite to carry self-consistent simulation of transport and turbulence in tokamak edge plasma [30, 31]. The modeling results (e.g. ELM cycles) agree with the EAST experiments.

Ou presented a fluid model to investigate the effect of the super-thermal electrons on the heat flux through a magnetized sheath. It is revealed that the variation of the plasma density and sheath potential drop at the Debye sheath entrance with the super-thermal electrons and magnetic field modifies the particle and heat fluxes across the Debye sheath to the material surface, and the sheath heat transmission coefficient can increase significantly even for a very small super-thermal electron population [32]. Zhou numerically studied the effect of mixed impurity injection (40%D_2+60%N_2) on divertor detachment. It was found that the radiation of nitrogen impurity plays the dominant role on the realization of detachment for discharge HL-2A #38008 [33]. Zhang studied the influence of strike point position on the decay length of particle and heat fluxes on the divertor device using SOLPS-ITER code. Results showed that when the strike point was located on the horizontal target plate, the decay length is longer than that for the case of locating on the vertical target plate. Here, the input parameters for simulations are adopted based on the EAST discharge #98332 [34].

Ji applied a reduced fluid model to study the influence of multi-field coupling effects on the plasma stability in scrape-off layer (SOL). Results indicated that multi-field coupling may introduce new mechanisms of driving instabilities, which is beneficial for exciting turbulence and reducing the divertor heat load on the divertor target. Niu investigated the temporal evolution of ELM induced heat flux on the monoblock (MB) surface and in the gap between MBs. The heat flux in the gap is even higher than that on the MB surface, which is beneficial for the design of advanced divertor [35]. Wu studied the evolution of plasma and impurity radiation, profile redistribution, and turbulent transport before and after disruption. It revealed that the increase in density and core ion temperature, and the decrease in edge turbulent transport, are the main reasons for the enhanced core confinement after detachment [36].

Zou reported the experimental results on the interaction between turbulence and zonal flows on HL-2A during tungsten impurity injection. It demonstrated that tungsten impurity can significantly enhance the ZF and almost does not affect the frequency of ZF. Here, the non-linear coupling between turbulences determines the variation of ZF amplitude [37]. Deng developed a machine learning regression model to quickly select the appropriate RMP coil phasing for controlling ELMs on the EAST. The effective rate of this model reaches 88% [38, 39]. He developed a new method to reconstruct plasma shape through multiple spectral imaging system equipped on the HL-3 tokamak. The visible spectral image is used to identify the mid-plane plasma boundary with a temporal resolution of milliseconds, which is important for real-time control of plasma shape.

4. Impurity, heating and current drive

Du applied the Circuit/3DLHDAP code to optimize the conjugate-T circuit for ion cyclotron resonance heating (ICRH) antenna system. Results show that the antenna system with conjugate-T circuit maintains a lower reflection coefficient (< 0.4) without adjusting the impedance matching, when the plasma parameters vary in a wide range. Xu extended the DIVIMP impurity transport code to include the $\boldsymbol{E}\times\boldsymbol{B}$ drift effect. Combined with the SOLPS-ITER code, simulations showed that $\boldsymbol{E}\times\boldsymbol{B}$ drift plays an important role on affecting the tungsten impurity transport from divertor region to core plasma. Yin reported the numerical results on increasing the efficiency of heating ions by optimizing parameters of ICRH system (e.g. wave frequency, parallel wave number) and plasma density in SOL for the ITER device [40].

Lu introduced the progress of a newly developed code for studying the ICRH power coupling in the plasma boundary. This code includes the non-linear effects related to the radio-frequency sheath and can be applied to design ICRH antenna system and to study impurity sputtering issues [41]. Wu calculated several ICRH schemes for the EHL-2 device using TORIC. It was found that the ratio of ion temperature to electron temperature strongly affects the efficiency of heating ions [42]. Zhou reported the simulations of tungsten impurity transport for the HL-3 tokamak with considering different divertor configurations. It was found that the tungsten impurity concentration in the core of the snow-flake divertor is higher than that of the conventional divertor. Shi showed the progress of a solenoid-free current drive via ECRH on the EXL-50 device. The maximum of ECRH driven current reaches up to 180 kA [43].

Wang presented the modeling results on the divertor detachment with neon impurity seeding on the EAST. It was found that the inner divertor target is easier to be detached than the outer one for the case with a favorable toroidal magnetic field. Tao developed a numerical code for solving 1D gyro-kinetic equation, which was applied to study the effect of impurity on ITG mode. The decay length of impurity plays an important role on stabilizing ITG [44]. Li analyzed the sheath structure and energy flux to the divertor target in the presence of hot electrons under EAST parameters with the particle-in-cell simulations, elaborated effect of the hot electrons on the temperature of the divertor target with ANSYS fluent calculation, and compared with the case of heat flux calculated with the classical sheath heat transmission coefficient [32, 44]. Liu applied the gyro-fluid code ExFC to study the effect of carbon impurity on ITG turbulence. It was shown that ITG induced turbulent transport strongly depends on the impurity density gradient. Yang developed a 3D Monte Carlo code SURO-FUZZ to study the formation and growing process of tungsten fuzz (e.g. porous nanostructure). The simulation results agree well with the experiments on the devices (PISCES-A, NAGDIS-II) [46].

5. Energy particle physics

Xu discussed how the fast ions affect turbulent transport in ITB, based on the HL-2A experiments. Results indicated that the enhancement of nonlinear electromagnetic stabilization effects caused by fast ions can significantly reduce heat transport level [47]. Xie reported that the non-thermal distribution can increase the fusion reaction rate by about 0.5–1 times for deuterium-tritium nuclei and by 1–3 times for hydrogen-boron fusion [48]. Liu reported the polarization characteristics of ion cyclotron instability (ICI) observed on the HL-2A device with the newly developed diagnostics for the first time. ICI can be used to infer the information of alpha particle distribution in fusion reactors [49]. Gao found a new resonant condition for the interaction between passing EPs and tearing mode (TM) through M3D-K simulation. It was found that the passing EPs can excite a 2/1 fishbone which can interact strongly with TM, thus enhancing EP losses. Cao reported that a kind of helical Alfvén eigenmode (AE) can be induced in magnetic islands in tokamak plasmas.

Zheng reported a new form of Hamiltonian in the wave-particle resonance coordinate. This theory simplifies the treatment of multi-scales problems. Bao presented a brief overview of the MAS code. This code has been extended to include multi-components of energetic particles and applied to study various AEs for tokamak devices [50]. Zhang carried out a linear simulation study of the $m/n = 1/1$ mode using hybrid code CLT-K. They pointed out that the parallel inertia and δB response terms significantly affect the eigenvalues of kink instabilities. These two terms should be carefully treated in the MHD-kinetic simulation. Chen investigated the influence of elongation on the dispersion relation of the EP-induced geodesic acoustic mode (EGAM) through gyro-kinetic theory. It revealed that the elongation has a weak effect on the frequency of EGAM, but significantly reduces its growth rate. The theoretical results agree well with GENE simulations [51]. Kong reported that the hydrogen-boron fusion reaction rate is enhanced for the slowing-down distribution of ions, compared with the Maxwellian case [52].

Wei developed an eigenvalue code to calculate the frequency and parallel mode structure of AEs in general geometry, which was applied to predict continuous spectrum and toroidal Alfvén eigenmode (TAE) structure for divertor tokamak test (DTT) facility. DTT is being built at the ENEA Research Center in Frascati, Italy [53, 55]. You studied the formation of ambipolar radial electric fields in random magnetic fields by gyro-kinetic code NLT. Zheng showed that the 3D perturbations (e.g. ripple fields, TM) have a synergetic influence on fast ion losses. When the amplitude of TM exceeds a threshold, the fast ion transport and losses are determined by TM [56].

6. Turbulent transport

Shen presented the gyrokinetic simulations of the KBM. It was shown that impurity plays a stabilizing role on KBMs when the impurity density profile peaks in the same direction as those of the electron and main ion density profiles. There are obvious thresholds for the first and second KBM stable regions in the electron density gradient. Hu developed a new gyro-kinetic PIC code TEK, which was benchmarked with GENE code for the case of ITG mode. Tan numerically investigated the turbulence on the spherical tokamak EHL-2. In the high beta region, KBM is the dominant electro-magnetic micro-instability. Zhao carried out nonlinear simulation of KBM turbulence using global gyrokinetic code NLT [57]. Results showed that as β increases, the turbulence transport level first decreases and then increases, corresponding to the suppression of ITG by finite β and the enhanced turbulence transport caused by KBM excitation.

Xie simulated the edge coherent mode (ECM) on EAST with the global gyrokinetic code GEM, which showed that ECM is an electrostatic electron mode with dominant toroidal mode number of n = 18 and drives significant outward particle and heat fluxes, thus greatly promoting the maintenance of the long pulse H-mode [58]. Li presented a one-dimensional simplified model of dynamic critical gradient (DCG) for studying the dynamics of transport barriers. The self-consistently evolving critical gradient weakens the profile stiffness and promotes the generation of transport barriers such as ITBs. Li studied the influence of magnetic island width on the interaction between islands and ITG turbulence. Results indicated that the increase of island width enhances the helical flow at the island boundary which is consistent with the earlier experimental observations on the HL-2A [59]. Kong used the gyrokinetic electron and fully kinetic ion (GeFi) model to study the parametric decay instability (PDI) in uniform, magnetized plasmas. It was found that PDIs heat electrons and ions in the parallel and perpendicular directions, respectively [60]. Yu used the particle orbit tracing code (PTC) [61] to study the dynamics of runaway electrons (REs). The process of avalanche induced by large-angle collisions between runway electrons and background electrons was presented [62, 63].

Wang studied the nonlinear excitation of ZFs in toroidal plasmas using the NLT code [64]. In the quasi-linear stage, the ZFs are initially excited by the self-interaction of the eigenmodes [65]. However, in the nonlinear saturation stage, both the self-interaction and the modulated instabilities are important. Zhang carried out the self-consistent simulations on coherent vortex flows in the magnetic island using a five-field gyrofluid model. The coherent vortex flows exhibit different parity along the radial direction, which can be explained by a theoretical model of nonlinear parity instability [66]. Xie presented the non-local thermal transport phenomenon triggered by multiple SMBI on the J-TEXT device. As the density gradually increases, the non-local transport weakens. After SMBI, the temperature rises in the core region and a heat pulse propagates outward. Sun pointed out the importance of injection time of pellets for increasing plasma density, based on the CLT simulations [67]. When a pellet is injected after the growing of double tearing mode (DTM), the radial flow generated by the reconnection brings the injected particles to the core region. As a result, the plasma density significantly increases and exceeds the Greewald limit without disruption in simulation.

7. MHD instability

Porcelli showed that vertical displacement oscillatory modes, with a characteristic frequency close to the poloidal Alfvén frequency, can interact resonantly with energetic ions, giving rise to a new type of fast ion instability with mode number $n = 0$. Li reported that the neoclassical toroidal viscosity (NTV) torque dominates in the total net torque for the ITER baseline scenario. The resonant and non-resonant parts dominate at low and high toroidal rotations, respectively [68]. Lu discussed the complex dependence of explosively growing reconnection rate of 3/1 DTM on the plasma resistivity in different parameter regions. The distance between two 3/1 rational surfaces seem to be the key parameter [69].

Ma studied the dynamics of resistive internal kink modes in the runaway plasma of HL-2A using the extended 3D MHD code M3D-C1 [70, 71]. The study revealed that REs can linearly affect the growth rate scaling of resistive internal kink modes on resistivity. In addition, the presence of runaway current leads to a significant suppression of sawtooth oscillations, resulting in the loss of REs outside the q = 1 surface, with minimal impact on the majority of REs well-confined within it. Zu reported that impurity radiation can cause the decrease of plasma temperature in the edge, which leads to the shrinking of the temperature and current profiles. Finally, TM related to density limit is destabilized at the q = 2 rational surface. Chen studied the ELM collapse process through both simulations and experiments. CLT simulation results indicated that the peeling-ballooning instability in the pedestal region can generate magnetic islands, which may lead to the formation of stochastic field region in the edge and in turn trigger the ELM collapse [72]. Huang simulated the nonlinear dynamic of Type-III ELM in EAST experiment using BOUT++ [73]. When the parallel current and electric field are included, the time for achieving nonlinear stage of ELM is delayed and the stored energy loss is significantly enhanced. Huang studied the nonlinear evolution and saturation of NTM by CLT. The poloidal asymmetry of the bootstrap current reduces the saturation level of NTM. The effects of magnetic curvature and Hall term on NTM were also discussed in the presentation.

Wang reported that the relation between linear growth rate and toroidal mode number can be used to roughly distinguish ballooning mode, peeling mode, and the coupled peeling-ballooning mode. When the pressure gradient is fixed, mode transits from ballooning to peeling-ballooning and then to peeling-dominated mode as the edge current and magnetic shear vary. Zhang numerically studied the effect of RMP on neoclassical transport of impurity using NTVTOK code. When the diamagnetic drift exceeds the $\boldsymbol{E}\times\boldsymbol{B}$ drift frequency, the impurity particle flux induced by NTV is pointed inward, and vice versa [74]. Li reported that the Kelvin-Helmholtz instability coexists with the DTM through nonlinear mode coupling in the weak reverse magnetic shear configuration. Meng showed that in Kelvin-Helmholtz instabilities, the dynamical system is pseudo-Hermitian and undergoes a PT-symmetry-breaking bifurcation, which can be interpreted as the spatial coupling and phase locking of vorticity waves. The transient growth near marginal stability is explained as non-Hermitian critical dynamics near exceptional points, where the eigenvectors are nonorthogonal and lead to nonmodal phase-slip dynamics of vorticity waves [75].

8. Integrated modeling and code development

Sang reported the progress of the developed numerical framework which provides an effective platform for the systematic study of boundary physics and the plasma-wall interactions [76]. Wang developed a neural network code which realizes the fast integration modeling for studying the compatibility between the heat flux control and the plasma confinement. Feng developed a module for calculating the damage cross-section related to the irradiations induced by fusion neutrons and by the deuterium nucleus, which allows the prediction of material's displacement per atom under the irradiations. Chen developed a zero-dimensional D-^{3}He fusion analysis code HED to investigate the D-T fusion assisted ignition process of D-^{3}He fusion in tokamak through PID feedback control of the D:T:^{3}He density ratio. METIS simulations show that, under the same plasma current, the volts-seconds provided by the solenoid were able to trigger the ignition of D-T fusion.

Zhang developed the INTFLUK code based on a non-local model. The code can mimic the mode conversion process from fast wave to ion Bernstein wave during ICRH [77]. Liu presented the progress of the development of MHD-kinetic hybrid code GMEC. The first version of this code has been completed and benchmarked. GMEC has been used to simulate the Alfvén eigenmode driven by alpha particles for CFETR. Li introduced a flexible workflow on super-computing system. Yu discussed the possibility of improving core plasma confinement by optimizing the electron cyclotron heating power scheme for the HL-3 hybrid scenario, based on the METIS integrated modeling.

Guo introduced an MHD-accurate-particle hybrid code MAP. Here, the structure-preserving algorithm is used to describe the dynamics of particles. Chen merged PTC code into the OMFIT framework, which allows the modeling of neutral beam injection. Results from the integrated simulations are in good agreement with the workflow calculations using NUBEAM under the core plasma conditions for CFETR. Lu constructed and trained a deep neural network (NN) for the predictions of equilibriums on the EAST. The NN's predictions showed good agreement with the results provided by EFIT [78]. Shi analyzed two different high-β_N discharges on the HL-2A using METIS code. The key quantity profiles (e.g. temperature, density) obtained from modeling agree with the experiment measurements [79].

9. Poster section

In this section, 96 posters were presented to report the achievements in many topics in MCF. Several highlights are reported below. Hu developed a code ATEC to investigate the equilibrium with reversal current for the advanced tokamak discharge. ATEC is a useful tool for the optimization of the equilibrium control coil current, the design of divertor plates, MHD stability analysis and transport study [80]. Chen extended the CLT-EQ code to study the self-consistent equilibrium including plasma toroidal rotation. It was shown that the Shafranov shift is increased by ~$0.1a_0$ when the Mach number at the magnetic axis reaches 0.2. Here, a_0 labels the minor radius of plasma [81]. Lan designed and constructed a novel electromagnetic probe array (EMPA). Compared with the regular magnetic probe, EMPA strongly improves the measurement ability of toroidal mode number n (up to $|n| \leq 112$) for the magnetic fluctuation [82]. Yang investigated the effect of internal kink on beam fast ion transport and loss for the 15 MA scenario of ITER. The internal kink mainly induces the redistribution of fast ions in the core region, while almost does not lead to the fast ion loss (loss rate < 0.1%) [83].

10. Conclusion

Significant progress has been made in several areas since the 10th CFMTS. Nonlinear gyrokinetic simulations have revealed the important role of zonal flows in the formation of transport barriers as well as the impact of electromagnetic turbulence on confinement performance. The scheme of impurity injection and fueling with controlling disruption was proposed. Many hybrid simulations have shown that the interactions between EPs and MHD instabilities might be important for fast ion loss in future fusion devices. A considerable advance has been made in the simulations of core-edge coupling, especially for the divertor detachment. Various fluid simulations lead to a deeper understanding of the physics of ELM control. Several advanced simulation codes have been developed and extended, such as NLT, ExFC, CLT/CLT-K, TEK, PTC, MAS, ATEC. These codes provide the useful tools for exploring the frontier of plasma physics with the goal of speeding the realization of fusion energy. More presentations related to burning plasmas are expected in the next CMCFTS conference.

The 12th CMCFTS was held in Beijing in 24-27 May, 2024, and the organizer was the School of Physics of Peking University.

Acknowledgments

The co-executive chairmen of the 11th CMCFTS (Guangzhou Hao, Youwen Sun, and Zhibin Guo) express their gratitude to the helpful supports from CMCFTS committee members, the local organizers (Prof. Xuru Duan, Prof. Wulyu Zhong and the conference volunteers), who made significant efforts that led to the success of the 11th CMCFTS.

The sponsors of the conference were the Plasma Physics Branch of the Chinese Physical Society, the Nuclear Fusion and Plasma Physics Branch of the Chinese Nuclear Society, and the Theory and Simulation Project Group of the National Magnetic Confinement Fusion Energy Research and Development Program of China. The organizer sponsor of the conference was the Southwestern Institute of Physics

(SWIP), China National Nuclear Corporation (CNNC).

Data availability

The Chinese abstracts summarized in this conference report are available from the corresponding authors upon reasonable request.

Appendix. Organizing committee of CMCFTS

Co-executive chairmen

Guangzhou Hao, Youwen Sun, and Zhibin Guo

Organizing committee of CMCFTS

Baonian Wan, Zhiwei Ma, Xiaogang Wang, Shaojie Wang, Zhengxiong Wang, Zhiyong Qiu, Lu Wang, Ge Zhuang, Youwen Sun, Qilong Ren, Ping Zhu, Ding Li, Jiquan Li, Jiangfeng Song, Wei Chen, Wenlu Zhang, Chijie Xiao, Yong Xiao, Zhihong Lin, Xuru Duan, Xiwei Hu, Nong Xiang, Guangzhou Hao, Xueqiao Xu, Zhe Gao, Tianyang Xia, Jiaqi Dong, Guoyong Fu.

Local committee

Xuru Duan, Wulyu Zhong, Shuo Wang, Linzi Liu, Ji He, Fan Wu

References

[1] ITER NEWSLINE: MIESTONE FOR CHINA'S HL-3 DEVICE, 2023, Sep.11. https://www.iter.org/newsline/-/3921

[2] Song Y T *et al* 2023 *Sci. Adv.* **9** eabq5273

[3] Zhang Y *et al* 2024 *Nucl. Fusion* **64** 076016

[4] Ding B J *et al* 2024 *Nucl. Fusion* **64** 074003

[5] Wang S J, Wang Z H and Wu T N et al 2024 *Phys. Rev. Lett.* **132** 065106

[6] Wang X *et al* 2023 *Nucl. Fusion* **63** 096023

[7] Zhang W *et al* 2019 *Plasma Phys. Control. Fusion* **61** 075002

[8] Chen W *et al* 2022 *Fundam. Res.* **2** 667

[9] Shi P W *et al* 2021 *Chinese Phys. Lett.* **38** 035202

[10] Yu L M *et al* 2022 *EPL* **138** 54002

[11] Chen W *et al* 2019 *Nucl. Fusion* **59** 096037

[12] Zhu X L *et al* 2023 *Nucl. Fusion* **63** 036014

[13] Lin Z *et al* 1998 *Science* 281: 1835

[14] Dimits A M *et al* 2000 *Phys. Plasmas* **7** 969

[15] Wang X Q *et al* 2021 *Nucl. Fusion* **61** 036021

[16] Jian X *et al* 2023 *Phys. Rev. Lett.* **131** 145101

[17] Wang W *et al* 2020 *Nucl. Fusion* **60** 066010

[18] Zhou Y *et al* 2023 *Phys. Plasmas* **30** 032503

[19] Dong G Q *et al* 2023 *Phys. Plasmas* **30** 072104

[20] Hussain M S *et al* 2021 *Plasma Phys. Control. Fusion* **63** 075010

[21] Hussain M S *et al* 2022 *Nucl. Fusion* **62** 056013

[22] Li M H *et al* 2022 *Nucl. Fusion* **62** 126055

[23] Pan C K 2023 *Nucl. Fusion* **63** 046021

[24] Piras F *et al* 2010 *Phys. Rev. Lett.* 1**05** 155003

[25] Ma J F *et al* 2014 *Nucl. Fusion* **54** 033011

[26] Ishizawa A *et al* 2007 *Nucl. Fusion* **47** 1540-1551

[27] Meng L Y *et al* 2022 *Nucl. Fusion* **62** 086027

[28] Li K *et al* 2023 *Nucl. Fusion* **63** 026025

[29] Ma H C *et al* 2023 *Phys. Scr.* **98** 115608

[30] Zhang D R *et al* 2019 Computer Physics Communications **239** 126-133

[31] Zhang D R *et al* 2020 *Nucl. Fusion* **60** 106015

[32] Ou J *et al* 2024 *Phys. Plasmas* **31** 043506

[33] Zhou Y L *et al* 2022 *Plasma Phys. Control. Fusion* **64** 065006

[34] Zhang C *et al* 2022 *Nucl. Fusion* **62** 076012

[35] Niu G J *et al* 2023 *Nucl. Fusion* **63** 066036

[36] Wu T *et al* 2023 *Plasma Sci. Technol.* **25** 015102

[37] Zou Q *et al* 2023 *Nucl. Fusion* **63** 126029

[38] Sun Y *et al* 2016 *Phys. Rev. Lett.* **117** 115001

[39] Xie P *et al* 2023 *Nucl. Fusion* **63** 096025

[40] Zhang J H *et al* 2022 *Nucl. Fusion* **62** 076032

[41] Myra J R *et al* 2021 *J. Plasma Phys.* **87** 905870504

[42] Wu X S *et al* 2023 *Nucl. Fusion* **63** 106015

[43] Shi Y J *et al* 2022 *Nucl. Fusion* **62** 086047

[44] Tao Y Q *et al* 2023 *Nucl. Fusion* **63** 076008

[45] Li D H *et al* 2016 *Phys. Plasmas* **23** 072120

[46] Yang K R *et al* 2022 *Nucl. Fusion* **62** 096019

[47] Xu J Q *et al* 2023 *Nucl. Fusion* **63** 126026

[48] Xie H S *et al* 2023 *Plasma Phys. Control. Fusion* **65** 055019

[49] Liu L Z *et al* 2023 *Nucl. Fusion* **63** 104004

[50] Bao J *et al* 2023 *Nucl. Fusion* **63** 076021

[51] Chen Z *et al* 2024 *Nucl. Fusion* **64** 036009

[52] Kong H Z *et al* 2024 *Plasma Phys. Control. Fusion* **66** 015009

[53] Albanese R *et al* 2017 *Fusion Eng. Des.* **122** 274

[54] Zonca F *et al* 2015 *New J. Phys.* **17** 013052

[55] Falessi M V *et al* 2019 *Phys. Plasmas* **26** 022305

[56] Zheng Y F *et al* 2023 *Nucl. Fusion* **63** 046016

[57] Ye L *et al* 2016 *Journal of Computational Physics* **316** 180-192

[58] Xie B Y *et al* 2023 *Nucl. Fusion* **63** 026017

[59] Li J C *et al* 2023 *Nucl. Fusion* **63** 096005

[60] Kong W *et al* 2023 *Phys. Plasmas* **30** 052108

[61] Wang F *et al* 2021 *Chinese Physics Letters* **38** 55201

[62] Hoelzl M *et al* 2021 *Nucl. Fusion* **61** 065001

[63] Hu D *et al* 2023 *Nucl. Fusion* **63** 066008

[64] Ye L *et al* 2016 *J. Comput. Phys* **316** 180-192

[65] Chen L *et al* 2000 *Phys. Plasmas* **7** 3129-3132

[66] Zhang Y *et al* 2023 *Phys. Plasmas* **30** 092103

[67] Strauss H R *et al* 1999 *Nucl. Fusion* **39** 2069

[68] Li L *et al* 2020 *Nucl. Fusion* **60** 016013

[69] Lu X Q *et al* 2024 *Nucl. Fusion* **64** 016020

[70] Jardin S *et al* 2012 *Comput. Sci Discovery* **6** 014002

[71] Zhao C *et al* 2020 *Nucl. Fusion* **60** 126017

[72] Wan L W *et al* 2022 *Chinese Phys. Lett.* **39** 115202

[73] Xia T Y *et al* 2013 *Nucl. Fusion* **53** 073009

[74] Zhang W M *et al* 2022 *Phys. Scr.* **97** 045604

[75] Meng C and Guo Z B 2023 *Phys. Rev. E* **108** 065109

[76] Sang C F *et al* Modelling of the effects of drifts on the tungsten impurity transport and core accumulation on east by developing a kinetic impurity transport code In: *29th IAEA Fusion Energy Conference* London: IAEA 2023 https://www.iaea.org/sites/default/files/23/10/cn-316_fec_preliminary_program.pdf

[77] Zhang J H *et al* 2022 *Nucl. Fusion* **62** 076032

[78] Lao L L *et al* 1985 *Nucl. Fusion* **25** 1611

[79] Artaud J F *et al* 2018 *Nucl. Fusion* **58** 105001

[80] Hu Y M *et al* 2024 *Plasma Sci. Technol.* **26** 025102

[81] Chen W J *et al* 2022 *Plasma Sci. Technol.* **24** 03510

[82] Lan H *et al* 2023 *Plasma Sci. Technol.* **25** 075105

[83] Yang G M *et al* 2023 *Plasma Sci. Technol.* **25** 055102

[84] Wang Z B *et al* 2023 *Plasma Sci. Technol.* **25** 081001