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Conference Report

Conference Report on the 8th International Symposium on Liquid Metals Applications for Fusion (ISLA-8)

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Abstract

The International Symposium on Liquid Metals Applications for Fusion (ISLA) aims to assemble scientists and engineers engaged in research on lithium and liquid metal applications for fusion devices, facilitating discussions on recent advancements and challenges in an open forum to support the development of viable fusion reactors. The 8th International Symposium on Liquid Metals Applications for Fusion (ISLA-8) was organized by the Institute of Plasma Physics, Chinese Academy of Sciences, from 8 to 12 September 2024, in Hefei, China. The symposium was attended by over 70 participants, marking one of the highest attendance figures in the series. A total of 68 presentations were delivered, including 59 presented on-site, while

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the remainder were conducted online. The participants represented 10 countries, namely China, Japan, the Netherlands, Russia, the USA, the Czech Republic, Italy, Thailand, Spain, and Germany. The symposium covered 10 topics, structured into 13 sessions. Additionally, an opening session provided an overview of the current symposium, while a closing session summarized reports from each session chair.

Keywords: liquid metal applications, liquid metal plasma-facing components, nuclear fusion reactor, plasma–surface interactions, CFETR, DEMO reactor

(Some figures may appear in colour only in the online journal)

1. Introduction

In future nuclear fusion power reactors, achieving long-pulse or steady-state operation necessitates precise control over plasma boundary behavior [1–4], which is essential for maintaining core plasma confinement performance and ensuring the durability of plasma-facing components (PFCs). High-Z metal divertor materials, such as tungsten (W) and its alloys, possess inherent limitations in steady-state heat and particle handling capacities. Exceeding these thresholds may result in component failure, necessitating extensive maintenance or replacement and imposing stringent constraints on machine size and power dissipation in the scrape-off layer (SOL) [2, 5]. Disruptive events, including vertical displacement events, plasma disruptions, and unmitigated edge localized modes (ELMs), can produce energy fluxes reaching 10 MJ m^{-2} on divertor targets in ITER, causing wall erosion and reducing the operational lifespan of fusion reactors [6]. Additionally, prolonged exposure to 14.1 MeV neutron irradiation further deteriorates PFC performance and thermal conductivity [7]. These limitations restrict the power and particle handling capabilities of conventional solid metal materials under steady-state conditions. However, liquid metals (LMs) offer a significant advantage due to their capacity to endure and recover from transient events without sustaining permanent damage.

A promising approach for managing heat and particle fluxes involve utilizing LM as an alternative material for PFCs [8–10]. LM is considered a durable PFC material due to its low susceptibility or resistance to neutron-induced damage, efficient heat flux dissipation, high tolerance to transient events, and capability to absorb and remove impurities during flow. The self-healing nature of LM enables the restoration of damaged surface materials through its inherent fluidity. Furthermore, flowing LM not only facilitates the removal of excessive heat [11] and particle fluxes but also provides shielding for the solid substrate against heat and particle deposition [12]. By continuously circulating LM across the PFC surface, both surface heat loads and accumulated impurities can be effectively transported out of the vacuum chamber, contributing to improved reactor performance and longevity.

Liquid metals offer significant potential for fusion applications; however, several critical challenges must be addressed for their successful implementation. One major issue is the interaction between liquid metals and plasma [13], which can lead to sputtering, evaporation, or droplet ejection, potentially contaminating the plasma and destabilizing fusion reactions. To mitigate these effects, capillary structures [14] have been developed to stabilize liquid metal surfaces and reduce droplet formation. Another challenge involves the compatibility of liquid metals with structural materials [15], as corrosion and the formation of brittle phases at high temperatures pose significant concerns. The development of corrosion-resistant materials or protective coatings represents a key approach to addressing this issue. Additionally, MHD effects [16], which occur when liquid metals flow in strong magnetic fields, can increase flow resistance and induce instabilities. Tritium (T) retention and permeation in liquid metals [17], particularly lithium, may also affect fuel cycle efficiency and pose safety risks. Furthermore, thermal management issues [18], such as thermal fatigue and mismatched thermal expansion coefficients, necessitate innovative solutions. ISLA-8 provides a platform for researchers to present potential solutions to these challenges, fostering advancements in liquid metal applications for fusion technology.

The historical developments in magnetic fusion research have driven the global scientific community to establish a dedicated forum for discussions and exchanges on liquid metal PFCs (LM-PFCs). This initiative led to the inception of the International Symposia on Liquid Metals Applications for Fusion (ISLA) series. Since its establishment, the ISLA series has been held seven times since 2010. The first symposium was hosted by Y. Hirooka at NIFS, Japan, in 2009 [19], followed by the second, organized by M. Ono at PPPL, USA, in 2011 [20]. The third was conducted by G. Mazzitelli at ENEA, Italy, in 2013 [21], while the fourth took place at CIEMAT, Spain, in 2015, hosted by F.L. Tabares [22]. The fifth symposium was led by S. Mirnov at TRINITI, Russia, in 2017, and the sixth by D.N. Ruzic at the University of Illinois, USA, in 2019 [23]. The seventh symposium returned to Japan in 2022, organized by Y. Hirooka at Chubu University [24]. The current edition, ISLA-8, is hosted by the Institute of Plasma Physics, Chinese Academy of Sciences. The symposium continues to focus on all liquid metals that are potential candidates for PFCs in DEMO, breeding blankets, and liquid metal loop systems.

2. Symposium summary for the technical sessions

Session 1 on overviews and LM experiments, chaired by J.S. Hu of ASIPP, China

In Session 1, two overview papers were presented.

The first overview paper, titled ‘A summary of the laboratory experiments on heat and particles transport in GaInSn and liq. Li’, was presented by Y. Hirooka from Chubu University, who served as the General Chair of ISLA-7 in 2022. This paper reviewed proof-of-principle experiments conducted from 1998 to 2024 in the steady-state plasma facility VEHICLE-1**, investigating several LM-PFC concepts utilizing $J \times B$-forced convection for power and particle control in a steady-state magnetic fusion DEMO reactor. The findings indicate that both natural and forced liquid convection significantly enhance the transport of heat and particles reaching the surfaces of GaInSn and liquid Li. Furthermore, these effects on heat transport have been independently reproduced in an infrared heating facility. **Vertical and Horizontal positions Interchangeable test stand for Components and Liquids for fusion Experiments. (This paper contributors include: Hailin Bi).

The second overview paper was presented by T.W. Morgan from the Dutch Institute for Fundamental Energy Research (DIFFER), who is the chairman of the upcoming ISLA-9 conference. DIFFER is currently developing a new laboratory for the research and testing of LM PFCs. The presentation provided an update on the progress of various components within this project, which comprises four primary aspects: (1) the completion and installation of an Additive Manufacturing (AM) device, (2) the development of a Tin (Sn) injector along with a specialized heating system for a wetting device, (3) solutions for Liquid Metal (LM) handling and diagnostic protection in Linear Plasma Devices, and (4) the conceptual design of a dedicated Thermal Desorption Spectroscopy (TDS) device. (This paper contributors include: R.S. Al, S. Alonso van der Westen, H. Beens, S. Brons, J.A.W. van Dommelen, H.J.N. van Eck, M.G.D. Geers, H.J. van der Meiden, M. Morbey, C. Orrico, M.J. van de Pol, F. Romano J.G.A. Scholte, J. Scholten, V.F.B. Tanke, R.H.M. Timmer, J.W.M. Vernimmen and E.G.P. Vos).

Session 2 on overviews and LM experiments, chaired by Y. Hirooka of Chubu Univ., Japan

In Session 2, two overview papers and three invited papers were presented.

The session began with an overview paper by R. Maingi from the Princeton Plasma Physics Laboratory (PPPL), USA, titled ‘Integration of attractive core operation with high heat flux exhaust via LM-PFCs in NSTX-U’. As the lead author was unavailable, the paper was presented online by co-author M. Ono from PPPL. This paper provided an overview of activities related to the Liquid Metal Core-Edge (LMCE) facility, which is being developed to support the creation of durable LM-PFCs capable of handling high power and particle fluxes in the National Spherical Tokamak eXperiment-Upgrade (NSTX-U), scheduled to begin operation in early 2026. The LMCE is designed to accommodate multiple LM-PFC concepts, including: (1) Vapor Box, (2) Capillary Porous System with Flow (CPSF), (3) Divertorlets, and (4) Li-Metal Infused Trench (LiMIT). (This paper contributors include: and the NSTX-U Team).

The second overview paper, presented by J.S. Hu from the Academy of Science, Institute for Plasma Physics (ASIPP), China, was titled ‘Overview of Lithium Applications in EAST for Improved Plasma Performance and Materials Compatibility’. This paper reviewed the development of LM-PFCs, primarily utilizing molten lithium, alongside the progress of plasma performance in the Experimental Advanced Superconducting Tokamak (EAST). The evolution of EAST was examined from the first H-mode observed in 2008 to the most recent achievement of long-pulse H-mode in 2023 through the application of lithium coating and the Flowing Liquid Lithium Limiter (FLiLi). Experimental results highlighted several advantages associated with liquid lithium, including reduced hydrogenic particle recycling, decreased impurity levels from the first wall, and mitigation of interactions between the core plasma and the FLiLi plasma-facing surface due to the formation of lithium vapor clouds. These effects contributed to the successful realization of long-pulse H-mode in EAST. Additionally, through the experience gained in LM-PFC development, the chemical compatibility of materials with liquid lithium has been determined in the following order: W $>$ ODS-RAFM $>$ Mo $>$ CLF-1 $>$ TZM $>$ 316L SS $>$ 304 SS $>$ Cu, with copper being particularly prone to forming intermetallic compounds such as CuLi. (This paper contributors include: G.Z. Zuo, Z. Sun, X.C. Meng, W. Xu, D.H. Zhang, R. Maingi, D.D. Andruczyk).

An invited paper by Z. Sun from PPPL, USA, titled ‘The beneficial role of solid lithium injection in the achievement of record-long duration high-performance plasma in EAST’ was presented, detailing the effects of real-time lithium powder injection. These effects include improved plasma density control, attributed to reduced wall recycling, and enhanced impurity regulation, both of which have contributed to the achievement of the 1000 s H-mode plasma. (This paper contributors include: Z. Wang, L. Peng, Y.W. Yu, R. Maingi, G.Z. Zuo, W. Xu, L. Zhang, J.P.).

A contributed paper was then presented by A. Prishvitsyn from the Troitsk Institute for Innovation and Fusion Research (TRINITI), Russia, titled ‘Lithium radiation in the T-11M tokamak SOL during the closed-loop components test’. This paper discussed the use of a lithium evaporation–condensation loop limiter in the T-11M tokamak. Notable findings indicate that intense edge turbulence occurs when there is a strong interaction between the limiter and the core plasma, leading to increased lithium evaporation, whereas a weaker interaction results in reduced turbulence. Plasma density was also observed to exhibit asymmetric radial profiles, peaking near the edge of the limiter. (This paper contributors include: A. Djurik, V. Lazarev, Ya.Vasina, A. Shcherbak).

The final contributed paper of Session 2 was presented by F. Gou from Sichuan University, China, titled 'Study of the superficial vapor behavior of liquid lithium target under steady-state and pulsed plasma irradiation'. This study examined the effects of both pulsed and steady-state plasma bombardment on liquid lithium. Under pulsed plasma exposure with high heat loads reaching 10 GW m^{-2} and an axial magnetic field, liquid lithium splashing was observed, resulting in droplet formation. Some of these droplets were ionized within the plasma column, while others were deposited on the chamber wall. In contrast, during steady-state plasma bombardment, lithium vapor exhibited a symmetric distribution with lower losses when an axial magnetic field was applied. (This paper contributors include: R.F. Tang, Z.B.Ye).

Session 3 on overviews and LM experiments, chaired by T.W. Morgan of DIFFER, Netherlands

In Session 3, one overview paper and three invited papers were presented.

The fifth overview paper, titled 'The Usage of Lithium Kapillary Pours Structures in Ohmic Discharges of T-10 Tokamak', was delivered online by V. Vershkov from the National Research Center Kurchatov Institute, Moscow, Russia. The presentation provided a comprehensive review of results obtained from employing lithium-filled CPS structures in ohmic discharges of the T-10 limiter tokamak. Three key experimental phases were highlighted: (i) investigations on lithium gettering with graphite main limiters (2006–2011); (ii) studies involving a movable lithium capillary porous limiter in the tokamak SOL with tungsten main limiters (2016); and (iii) findings from the implementation of a lithium capillary porous limiter in the region of closed magnetic surfaces (2017). The incorporation of the Li limiter in the SOL enhanced plasma purity by reducing both light and heavy impurities. However, plasma purification was attributed to the sorption properties of lithium accumulated in the chamber rather than the impurity sorption by the limiter itself. A low Li concentration in the core plasma was observed, resulting from strong screening by the main limiters. The reduction of tungsten in the plasma was linked to decreased sputtering and a reduction in neoclassical W accumulation rather than the suppression of its sputtering through Li surface coating. The application of the Li limiter on closed magnetic surfaces, under conditions of low D_2 gas influx and intense sputtering of superheated lithium by high-temperature plasma, resulted in an all-lithium plasma. To mitigate tungsten influx, complete Li impregnation of the capillary structure must be ensured; otherwise, discharges exhibiting high tungsten content and the formation of a hollow temperature profile were observed. In certain cases, the Ampere force, driven by the current flowing from the plasma to the limiter in the toroidal magnetic field, extruded lithium from the capillary structure. To counteract this, the limiter requires cooling and segmentation in alignment with the force direction. A thermal Li limiter stabilization effect was noted due to strong lithium evaporation at about 450 °C. Lastly, it was demonstrated that even in a fully lithium plasma, radiation losses remain negligible in the overall power balance. (This paper contributors include: D. Sarychev, D. Shelukhin, A. Nemetz, S. Mirnov, I. Lublinsky, A. Vertkov, M. Zharkov).

The next invited presentation, titled 'Comparison of Basic Plasma Performance Between Li Coating and B Coating in EAST', was delivered in person by G.Z. Zuo from the Institute of Plasma Physics, CAS (ASIPP), Hefei, China. This presentation detailed recent experimental campaigns in which either Li or B coatings were applied in the EAST tokamak to facilitate a systematic comparison. Findings indicated that both Li and B coatings effectively controlled impurities, with Zeff reduced to about 2 following either coating procedure. Compared to the B coating, the Li coating demonstrated a greater capacity to reduce fuel particle recycling. In contrast, controlling hydrogen release was more challenging with the B coating due to hydrogen co-deposition in the B-coated film, leading to increased fuel recycling during the initial plasma phases. Consequently, the L-H transition threshold appeared lower with the Li-coated wall, though further systematic research is required to confirm this observation. Furthermore, plasma confinement performance, as indicated by H98, was about 15% higher with the Li coating than with the B coating. However, the Li coating exhibited a shorter lifespan than the B coating, suggesting that for long-pulse and high-performance plasma operations, Li powder injection is necessary to sustain real-time wall coating. (This paper contributors include: W. Xu, Z. Wang, Y.H. Guan, Z. Sun, R. Maingi, R. Ding, L. Wang, X.Z. Gong, and J.S. Hu).

The next invited presentation, titled 'Results from the Helium Retention Mechanism Experiment in a Stellarator (HeRMES) Campaign', was delivered in person by N. Mihajlov from the Center for Plasma Material Interactions, University of Illinois, Urbana, USA. This presentation covered recent investigations utilizing the HIDRA stellarator to assess lithium's capability to pump helium. Observations of helium retention by lithium were reported across multiple experimental campaigns in HIDRA, as well as in other devices such as Magnum-PSI and EAST. The HeRMES campaign involved conducting baseline plasma shots, followed by lithium evaporations into a helium plasma. Results indicated a strong correlation between the introduction of lithium ions and helium retention in HIDRA. Experimental evidence demonstrated that helium was retained by lithium films on HIDRA's wall, as confirmed by implementing a wall heating element. Helium desorption was observed when lithium reached its melting temperature of 180 °C. A retention mechanism has been proposed, suggesting that helium and lithium co-deposit in high-flux regions, potentially leading to helium bubble formation. However, additional research is required to validate this hypothesis. If confirmed, this mechanism could provide a direct method for helium pumping in fusion reactors using lithium. However, its applicability to molten, flowing lithium, which would be necessary for continuous pumping, remains uncertain and requires further investigation. (This paper contributors include: A. Shone, G.M. Le, M. Bradleya, S. Gula, R. Maingi, D. Andruczyk).

The following invited presentation, titled 'Hydrogen Isotope Retention in Lithium Co-Deposits', was delivered in person by Y. Gasparyan from the National Research Nuclear University MEPhI, Moscow, Russia. This presentation focused on the trapping of hydrogen isotopes during lithium transport and co-deposition, a critical issue for reactor fuel self-sufficiency. Laboratory experiments conducted at MEPhI on deuterium co-deposition with lithium were discussed, primarily utilizing the MD-2 device under magnetron discharge conditions with D_2 gas and a lithium CPS cathode. The findings indicated that the substrate temperature and lithium evaporation flux were key factors determining the feasibility of Li co-deposit film growth. Favorable conditions for lithium deposition were achieved by maintaining $T > 300$ °C–350 °C at low deposition rates. It was observed that lithium films with minimal hydrogen content could be grown within the temperature range of 250 °C–350 °C. However, the removal of tritium from thick lithium layers posed significant challenges. The decomposition of lithium hydride phases was found to initiate at 400 °C–450 °C. Additionally, the presence of an H_2 or H_2O gas atmosphere enabled the removal of heavy hydrogen isotopes at lower temperatures while maintaining the overall hydrogen content in the film. (This paper contributors include: S. Krat, A. Popkov, A. Prishvitsyn, R. Selivanov, I. Sorokin, A. Pisarev).

The next invited presentation, titled 'The Design of 3D-Printing Solid Tungsten-Liquid Lithium Combined Target Plate and Its Interaction with High-Density Plasma', was delivered in person by Z.B. Ye from Sichuan University, Chengdu, China. This presentation introduced a newly designed finger-type 3D-printed W plate impregnated with lithium, which was tested under both steady and pulsed plasma irradiation. The capillary structure effectively confined the liquid metal, and optimal pore size was identified as a balance between maintaining good wetting properties and withstanding plasma loading. The design exhibited excellent wicking capability, as demonstrated in both simulations and experiments. Additionally, vapor shielding was observed, and the plate remained intact under high-parameter plasma conditions. (This paper contributors include: Fujun Gou).

The following invited presentation, titled 'Testing an Ultrasonic Injector of Lithium Microdroplets on T-11M Tokamak', was delivered in person by V. Lazarev from JSC SRC RF TRINITI, Moscow, Russia. This presentation described efforts to develop a high-speed injection device for delivering lithium into the T-11M tokamak. The ultrasonic injector successfully generated lithium fluxes in the tokamak chamber at rates ranging from 12 to 125 mg s^{-1}. The injection of lithium suppressed the formation of runaway electron beams and reduced hard x-ray radiation levels. To enable the use of the ultrasonic injector in larger tokamaks with prolonged discharges, a system allowing lithium refilling without depressurization is required. Such an injector has been developed for the T-15MD tokamak and is currently undergoing testing. (This paper contributors include: Vertkov A.V., Zharkov M.Yu., Kuryachi A.V., Vasina Ya.A., Dzhurik A.S., Mirnov S.V., Shcherbak A.N).

The final invited presentation of the session, titled 'Lifetime Testing of a Vertical Lithium Limiter with External Lithium Supply on T-11M Tokamak', was delivered in person by I. Vasina from JSC SRC RF TRINITI, Moscow, Russia. This presentation provided an overview of the performance of a lithium limiter designed for extended operation without the need for refilling. The current version of the limiter, developed for the T-11M tokamak by JSC NIKIET, is a vertical limiter that enables lithium replenishment without requiring vacuum chamber depressurization. Long-term operation in the tokamak over 2 years allowed for the determination of lithium consumption in various operating modes. Additionally, physical and chemical processes occurring on the limiter surface were analyzed. The results demonstrated that the vertical lithium limiter with an external lithium supply could function without refilling for at least 500 discharges (90 s). The refilling mechanism effectively restored the lithium quantity in the limiter to its initial level without requiring chamber depressurization. XRD analysis identified the presence of Li_2O, Li_2C_2, Li_2CO_3, LiOH, and LiH on the limiter surface, with lithium predominantly existing as Li_2O (85%). It was observed that lithium consumption mainly occurred during the preparation of the tokamak vacuum chamber for operational conditions, particularly during induction heating of the walls and glow discharges, rather than during plasma discharges. (This paper contributors include: V.B. Lazarev, S.V. Mirnov, A.N. Shcherbak, N.T. Djigailo, P.A. Antonov, A.V. Zorin, A.S. Prishvitcyn).

Session 4 on the latest results of laboratory experiments with LM, chaired by Y. Gasparyan of National Research Nuclear University MEPhI, Russia

In Session 4, six invited papers and two oral papers were presented, showing the latest laboratory experiments involving LM.

The session commenced with the invited paper titled 'Magnetically-Guided Liquid Metal Divertor Revisited', presented by M. Shimada (QST, Japan). The study revisited the concept of utilizing strong convection of liquid metal as a means to enhance heat removal in fusion reactors (MAGLIMD). Various schemes of $J \times B$ forces, induced by currents in the liquid metal, were analyzed to facilitate poloidal flow and enable efficient convective heat dissipation.

The second invited paper, 'Experimental Measurements of Thermally Enhanced Sputtering Yields at Nano-PSI', was presented by J. Cecrdle (IPP, Czech Republic). The study focused on thermally enhanced sputtering as a critical mechanism contributing to liquid metal erosion. Based on current data, estimations suggest that this process may dominate under specific tokamak operating conditions. Experimental results on the sputtering of liquid tin by argon plasma at the Nano-PSI device were discussed. The sputtering yield, deduced from spectroscopy data, exhibited a clear dependence on temperature and ion energy, which varied from 20 to 80 eV. Technical challenges encountered during the experiments, such as the metallization of diagnostic windows, were also addressed. (This paper contributors include: J. Scholte, T.W. Morgand, J. Horacek).

The next invited paper, titled 'Study of Lithium-Boron Composite Physical Properties', was delivered by S. Krat (MEPhI, Russia). The presentation explored lithium-boron composite materials (LBCM), which are utilized in high-temperature batteries. These materials exhibit properties similar to conventional lithium-filled capillary-porous structures (CPS), providing protection to the solid matrix under high-flux plasma exposure and making them a potential candidate for PFCs in fusion devices. In this case, the matrix material consists of lithium borides. Measurements of LBCM electrical conductivity revealed values comparable to those of pure lithium. During the initial heating cycle in a vacuum, significant expansion of LBCM was observed; however, after preliminary heat treatment, the material demonstrated predictable behavior. (This paper contributors include: Ivan Sorokin, Rostislav Selivanov, O. Volkova, V. Zaharov).

The next invited paper, titled 'Liquid Metal Droplet Ejection Under Hydrogen Plasma Exposure', was presented by J.G.A. Scholte (TU/e, Netherlands). The droplet ejection process was analyzed as a potential limitation for liquid metal applications. It was demonstrated that the low solubility of hydrogen in tin and similar materials could lead to bubble formation. Under plasma irradiation, the hydrogen concentration in plasma-facing materials may rapidly exceed the solubility limit due to direct ion implantation and the presence of chemically reactive free radicals. This mechanism is not expected to occur in lithium, which exhibits high hydrogen solubility. (This paper contributors include: R.S. Al, D. Horsely, M. Iafrati, A. Manhard, J.W.M. Vernimmen, T.W. Morgan).

The invited paper, titled 'Insight into the Re-Deposition Equilibrium of Sn Contaminant on First Mirrors Surface During Hydrogen Plasma Cleaning', was presented by S.S. Wang (SCU, China). The study investigated the efficiency of RF plasma cleaning for Sn films on Ru optical elements. The removal rate of surface tin in hydrogen plasma was observed to be relatively high, reaching up to 6 nm h^{-1}; however, as the Sn film thickness decreased, the cleaning rate gradually declined. Based on density functional theory calculations, re-deposition was identified as a potential cause of this effect. A combined approach involving gas purging and an increased concentration of active particles was considered a possible solution to this issue. (This paper contributors include: Zongbiao Ye, Fujun Gou).

The invited paper, titled 'Development and Testing of Between-Shot Lithium Evaporators for LTX-Beta and NSTX-U', was presented by A. Maan (PPPL, USA). Lithium evaporators were identified as a crucial tool for achieving full lithium wall coverage in LTX-beta, thereby enhancing plasma performance and reducing recycling levels to about 0.5. Three generations of evaporators were developed, each improving impurity reduction, coverage uniformity, and homogeneity. The most recent version features remote actuation and automated lithium loading. These evaporators are planned for later deployment in NSTX-U and ST-40. Additionally, the importance of maintaining good vacuum conditions for lithium utilization in fusion devices was emphasized. (This paper contributors include: R. Majeski, R. Lunsford, R. Maingi, B. Stratton, C. López Pérez, M.N. Perez).

The oral paper, titled 'Overview of the Liquid Metal Research for Fusion Applications of the Plasma Control Group at the Princeton Plasma Physics Laboratory', was presented by F.J.S. Castro (Princeton University, USA). This presentation explored the influence of strong magnetic fields on liquid metal behavior. It was observed that a magnetic field perpendicular to the liquid metal flow resulted in an increased flow height. Numerical simulations were compared with experimental results from the Liquid Metal Experiment-Upgrade (LMX-U) using Galinstan at PPPL, with strong agreement between the two. To mitigate this effect, PFCs were proposed to be aligned predominantly along magnetic field lines. MHD numerical simulations for the 'divertorlets' concept were also presented, predicting that the liquid lithium surface temperature could remain below 450 °C under a heat load of 10 MW m^{-2}. (This paper contributors include: Brian Wynne, Yufan Xu, Jabir Al-Salami, Zhen Sun, Egemen Kolemen).

The final oral paper of the session, titled 'The Use of Optical Diagnostics During Liquid Metal Vapor Deposition in High Heat Flux Linear Plasma Generators', was presented by V.F.B. Tanke (DIFFER, Netherlands). Intensive lithium evaporation posed challenges for optical plasma diagnostics, as thick deposits formed on optical windows during operation in the Magnum-PSI device. To address this issue, the use of mirrors was proposed. Experimental results indicated that pure tantalum and TZM-based mirrors could be reused effectively for optical diagnostics in linear plasma devices during lithium deposition. (This paper contributors include: S. Brons, F. Romano, J. Scholten, R.H.M. Timmer, J.W.M. Vernimmen, and T.W. Morgan).

Session 5 on the topic of liquid metal corrosion issue with structural materials employed in nuclear reactor, and hydrogen permeation behavior as well as its interaction with laser, chaired by Z.B. Ye of Sichuan University, China

In Session 5, five invited papers and two oral papers were presented, focusing on liquid metal Y. Hirooka from Chubu University, who served as the General Chair of ISLA-7 held in 2022, presented a contributed paper titled 'Observations of Liquid Metal Responses to Short-Pulsed High Energy Impact'. This study summarized recent observations from high-power laser irradiation of liquid metals. A pulsed YAG laser with a wavelength of 532 nm, a pulse duration of 8 ns at 10 Hz, and a beam power of 2 W was used to irradiate GaInSn, a liquid metal, to investigate the behavior of LM-PFCs under short-pulsed high-energy impacts similar to ELMs occurring during H-mode discharges. It is well established that high-power laser impact induces the emission of plasma plumes from target materials. In this study, plasma plume behavior emitted from GaInSn was analyzed using a beam intensity profiler and optical spectroscopy under vacuum conditions of about

10–6 Torr, as well as in ambient gases composed of $N_2 + O_2$ with pressures ranging from 0.01 Torr to 76 Torr. The results indicated that plume plasma brightness varied significantly with ambient gas pressure, while the composition of excitation lines also changed. Notably, at pressures near 1.5 Torr, Sn-II ($Sn+$) excitation lines were detected alongside Ga-I, In-I, and Sn-I, suggesting plasma heating effects. This observation supports the hypothesis that adiabatic compression heating occurred in the emitted plasma plumes interacting with ambient gases.

The second invited presentation, titled 'Investigation of Hydrogen Permeation Through Niobium Membranes in Contact with Liquid Lithium', was delivered by H.L. Bi from the School of Mechanical Engineering, Hefei University of Technology. A model describing hydrogen adsorption, diffusion, and permeation through niobium membranes in contact with liquid lithium was introduced to enhance the effective utilization of liquid lithium. Hydrogen transport simulations were conducted using a COMSOL-based module, with results showing reasonable agreement with experimental data. The findings highlight that maintaining the high permeation performance of niobium membranes, comparable to their oxidation-free state, is critical for the efficiency of hydrogen isotope measurement and recovery devices in lithium liquids. A recommended approach to prevent oxidation involves coating the vacuum-side surface of the niobium membrane with a layer of palladium or a palladium-silver alloy. (This paper contributors include: Chunpeng cheng, Guizhong Zuo, Zongbiao Ye, Xudi Wang).

The third presentation was delivered by X.C. Meng from the Institute of Energy, Hefei Comprehensive National Science Center, titled 'Corrosion of fusion materials in static liquid lithium and lithium-lead'. STATIC-1 and S&D (STATIC and DYNAMICS) were developed with parameters $T \approx 1000$ K, $P \leqslant 5 \times 10^{-4}$ Pa, $t \geqslant 1000$ h, $V \sim 0\text{–}2$ m s^{-1} to examine the corrosion behavior of liquid lithium (Li) and lithium-lead (LiPb) on molybdenum-based alloy, tungsten, reduced activation ferritic martensitic (RAFM) steel, 304 and 316L stainless steel (SS), and copper (Cu). The findings indicate that, except for Cu, most materials experienced slight mass loss due to the selective dissolution of C or depletion of Cr/Ni elements after exposure to liquid Li and LiPb. The protection grades of most tested materials, as determined from weight loss, were observed to decline with increasing liquid metal temperature. Based on the results, W, Mo, TZM, and certain RAFM steels were recommended for use in liquid Li loops and PFC substrates. (This paper contributors include: D.H. Zhang, G.Z. Zuo, D. Andruczyk, J.S. Hu).

The fourth invited presentation was given by Veronika Kirillova from the National Research Nuclear University, Moscow Engineering Physics Institute, titled 'Corrosion of tungsten/RAFM brazed joints in liquid lithium'. ITER-grade tungsten and self-passivating tungsten alloys were brazed to RAFM steels using a Ti–48Zr–4Be amorphous brazing alloy, with a Ta interlayer incorporated to mitigate thermal stress to evaluate corrosion behavior in liquid lithium. Microstructure, mechanical properties, thermal stability, and corrosion resistance of three types of brazed joints (W/Ta/Rusfer, WCrZr/Ta/CLAM, WCrY/Ta/Eurofer) were analyzed. It was demonstrated that multi-phased seam structures are resistant to selective corrosion, and WCrY, WCrZr alloys, along with W/Ta/Rusfer, WCrY/Ta/Eurofer, and WCrZr/Ta/CLAM brazed joints, exhibit corrosion resistance in liquid lithium at 600 °C after 100 h of exposure. However, RAFM steel within the joint was the most vulnerable to dissolution in Li. (This paper contributors include: Alexey Suchkov, Diana Bachurina, Nikita Popov, Xiaoyue Tan, Julia Gurova).

The fifth invited presentation was delivered by Y.C. Xu from the Institute of Solid State Physics, Chinese Academy of Sciences, titled 'The simulation study on the corrosion of Fe-based alloys in liquid lead-lithium under nuclear-fusion devices'. The dissolution corrosion of steels in liquid Li and Pb was examined through energetics evaluation of the adsorption of Li and Pb atoms and the escape of Fe atoms on Fe surfaces (001), (110), and (111) using first-principles calculations to assess the degradation of Fe-based structural materials. The results indicate that both Li and Pb atoms preferentially adsorb on Fe surfaces, subsequently facilitating the escape of surface Fe atoms. The dissolution corrosion associated with adsorption and escape processes was found to strongly depend on surface structures, the coverage of adsorbed Li or Pb atoms, alloying elements, and operating temperatures. Both metallic (Fe, Cr) and non-metallic (C, N) elements alter the structure of liquid Pb-Li due to variations in atomic electronegativity, with non-metallic elements significantly affecting Li diffusivity.

M. Bugatti from the Politecnico di Milano, Department of Energy, contributed to the sixth oral presentation, titled 'Corrosion resistance of HiPIMS W-based films for a Liquid Sn Divertor'. The study focused on developing effective corrosion barriers by evaluating barrier materials, substrate preparation, deposition techniques, and the influence of microstructure on corrosion resistance. The tests confirmed that W coatings function as excellent corrosion barriers, as the film structure remained unaffected by interaction with liquid Sn. Corrosion resistance was enhanced by modifying the single-phase W columnar structure. The introduction of a secondary element during film deposition facilitated the formation of an improved amorphous structure, which subsequently reduced cross-film diffusion of Sn. (This paper contributors include: L. Bana, D. Vavassori, M. Iafrati, D. Dellasega, M. Passoni).

The final oral presentation was given by D.H. Zhang from the Institute of Plasma Physics, Chinese Academy of Sciences, titled 'Corrosion characteristics of 3D-printing W and WZrC in static liquid Li'. The 3D-printed W and WZrC exhibited mild grain boundary corrosion and pitting corrosion after exposure to static liquid Li at 550 °C for 500 h. No new corrosion products or phase transitions were observed following Li treatment. Compared to WZrC, W exhibited significant changes in thermal diffusivity. The addition of ZrC to W was suggested as a potential strategy to improve the corrosion resistance of W. (This paper contributors include: X.C. Meng, G.Z. Zuo, J.S. Hu).

Session 6 on liquid metal experiments and modeling II, chaired by M.J. Ni, of University of Chinese Academy of Sciences China

In Session 6, one overview paper, four invited papers, and one oral paper were presented, all focusing on liquid metals PFC. Five studies were conducted in China, while one was based in Thailand.

The session commenced with J.C. Yang from Xi'an Jiaotong University, China, who presented in person an overview paper titled 'Overview of experimental studies on liquid metals related to nuclear fusion components at the MFM Lab'. The paper provides a comprehensive summary of experimental research carried out in the MFM laboratory over the past two decades. Methods for measuring liquid metal velocity were developed based on Ohm's law and Doppler effects, designated as TVVP and MPUDV. Subsequently, various liquid metal flows were examined. Regarding liquid metal free surface flow in PFCs, a scaling law was established to describe the increase in film thickness with the Stuart number (N), which was further validated through theoretical analysis. Studies on liquid metal blankets demonstrated that heat transfer efficiency is significantly influenced by flow structures. The flow undergoes a series of transitions induced by the magnetic field, evolving from 3D to Q2D and ultimately to 2D flow. (This paper contributors include: YanWu Cao, DingYi Pan, XinYuan Chen, YiFei Huang YiJun Wang, Ze Lyu, JianDong Zhou, NianMei Zhang, ZhaoHui Yao, MingJiu Ni, MFM Lab members).

Z.D. Li from Sichuan University, China, presented an invited paper titled 'The investigation of gas and plasma-driven hydrogen permeation behavior in a molten liquid metal lithium-iron membrane bilayer structure'. This study focuses on the hydrogen permeation characteristics in liquid lithium/iron bilayer films subjected to hydrogen gas and hydrogen plasma. In the gas-driven permeation mode, steady-state permeation flux exhibits a positive correlation with both temperature and pressure in the upper chamber, whereas it shows a negative correlation with material thickness. Based on the obtained data, the primary permeation mechanism of hydrogen atoms in this system is identified as bulk diffusion. Subsequently, permeation parameters such as diffusion coefficient, permeation rate, and solubility were determined. In the plasma-driven mode, key plasma parameters influencing the permeation process, including electron temperature and electron density, were first identified, along with the classification of particle types in this environment. (This paper contributors include: Zongbiao Ye, Fujun Gou).

L.L. Li of Xi'an Jiaotong University, China, presented an invited paper titled 'Evolution of liquid metal surface waves under the influence of a gas jet'. The impact of a gas jet on the free surface flow of liquid metal was examined. The results demonstrated that the cavity depth induced by gas jet impingement can be theoretically predicted. Based on energy transfer analysis, a linear correlation was observed between the dimensionless wave amplitude and the Reynolds number of the gas flow. Additionally, wave velocity was found to correspond with the velocity of shallow water waves. The surface wave generated by gas jet pulsations was identified as a gravity-capillary wave. Power spectral density distribution analysis revealed a two-scale behavior, with gravity wave turbulence occurring at low frequencies and capillary wave turbulence at high frequencies. Furthermore, experimental findings indicated that the spectral exponents remained unaffected by variations in the pulsation frequency and amplitude of the gas flow. (This paper contributors include: YiYang Zhang, JuanCheng Yang, MingJiu Ni).

J.H. Pan of the University of Chinese Academy of Sciences, China, presented an invited paper titled 'MHD effects on the film flow in a divertor'. A laminar, gravity-driven, conducting liquid metal film flow in an inclined open channel subjected to a magnetic field was analytically investigated. The study primarily focused on the influence of the magnetic field and film thickness. Using the MHD-Multiphase HPC platform at UCAS, it was determined that MHD can also exert destabilizing effects on film flows, leading to the formation of wavy patterns. Additionally, scaling laws for film thickness were derived and validated, considering factors such as magnetic field orientation and strength, volume flow rate, channel inclination, and wall conductivity. The established scaling laws enhance understanding of the MHD damping effect on film thickness, contributing to the optimization of liquid metal divertor (LMD) design. (This paper contributors include: Ming-Jiu Ni).

Y.J. Wang of the University of Chinese Academy of Sciences, China, presented an invited paper titled 'Liquid metal film flow on a prefilled substrate in a strong magnetic field'. This study involved the design of a micropillar array and the application of a vacuum filling method to create a solid–liquid composite surface that reduces the contact angle of liquid metal from 140° to 40°, improving wettability and enhancing the spreading effect of film flow. Experimental evaluations of film stability in a strong transverse magnetic field demonstrated that the film remains stable even at a low flow rate. Observations also revealed the 2D effect of flow waves and an increase in flow velocity due to kinetic energy conversion, counteracting the influence of MHD drag. This study presents an innovative approach for surface plate design in flowing lithium divertors, emphasizing advantages such as low flow rate, stability, and fluidity in magnetic field conditions. (This paper contributors include: Li Kailun, Chen Ruizhi, Ni Mingjiu, Yao Zhaohui).

N. Somboonkittichai of Kasetsart University, Thailand, presented an oral paper titled 'MHD Stability Associated with Vaporization of Liquid Metal Plasma Facing Surface'. The study developed an MHD solver for partially ionized plasma to analyze vapor clouds above LM PFCs, with a particular focus on the effect of vapor spreading on MHD stability. The findings indicate that: (1) Evaporation of the liquid Li surface at high temperatures significantly increases the influx into the plasma, with several orders of magnitude increase in Li population, while temperature variation remains within one order of magnitude. (2) Plasma pressure rises due to net ionization and Li release, leading to a steep pressure gradient near the plasma edge, which gradually becomes less pronounced further from the edge. (3) Even in the absence of curvature and external current drive, plasma stability is reduced as a result of decreasing pressure gradient. (This paper contributors include: Guizhong Zuo, and C. Albert).

Session 7 on simulation of liquid metals, chaired by M. Shimada, of National Institutes for Quantum and Radiological Science and Technology, Japan

In Session 7, six invited papers were presented, all focusing on the simulation of liquid metals.

J. Horacek from the Institute of Plasma Physics of the CAS delivered the first invited talk, titled 'Predictive simulation HeatLMD of Liquid Metal Divertor for Tokamak COMPASS Upgrade'. One of the major challenges in fusion research is ensuring the protection of the divertor's heat shield from plasma heat loads under both steady-state and shock conditions. Conventional approaches, such as impurity-seeded detachment and ELM buffering, exhibit limitations when applied to reactors like SPARC and DEMO. LMD targets utilizing tin and lithium have demonstrated resistance to surface impacts of 3 MJ m^{-2} at QSPA and sustained heat loads of 12–16 MW m^{-2} (including 12 kJ m^{-2} ELMs) on the COMPASS tokamak. Simulations indicate that while eroded lithium or tin can cool and dilute plasma under DEMO-level heat loads, damage can be mitigated through backside cooling. The scaling behavior of Li and Sn atoms released from the liquid divertor under varying plasma conditions was analyzed and reported in this study [25]. The findings highlight the necessity for water cooling beyond the engineering limit of the ITER divertor. (This paper contributors include: S. Lukes, F. Jaulmes, D. Tskhakaya, J. Cecrdle, M. Komm).

The second invited talk, presented by Wen *et al* from DUT China, was titled 'Integrated Modelling of Edge and Core Impurity Transport under a Liquid Metal Divertor on EAST'. The study utilized the EMC3-EIRENE and OMFIT frameworks to examine edge transport and core accumulation of lithium impurities under a liquid lithium divertor on EAST. A consistent density distribution of Li^{2+} ions was obtained in both STRAHL and EMC3-EIRENE modeling. Based on these findings, lithium core density and radiation distributions were further analyzed using STRAHL modeling, revealing that lithium core radiation has a negligible effect on the H-L back transition under the current H-mode plasma parameters on EAST. (This paper contributors include: Z.H. Gao, B. Liu, Z. Zhou, P.S. Smith, Y. Feng and S.Y. Dai).

The third invited talk, delivered by Y.D. He from DUT China, was titled 'Simulation of the Suppression of Tungsten Wall Erosion during Real-time Lithium Powder Injection Discharges in EAST'. An integrated model for impurity migration and wall component evolution was developed and applied to simulate real-time lithium powder injection experiments on EAST. The study investigated the effects of lithium powder injection on tungsten erosion flux. The incident Li particle flux increased with lithium powder injection, leading to an increase in tungsten erosion flux. However, lithium powder deposition on the target plate surface resulted in a reduction in the surface density of tungsten, consequently decreasing tungsten erosion flux. The combined influence of these effects led to an overall reduction in tungsten target erosion. (This paper contributors include: ChaoFeng Sanga, GuiZhong Zuo, Wei Xu, YiHan Wu, YiLin Wang, YanJie Zhang, DeZhen Wang).

The fourth invited talk, delivered by Zhang *et al* from DUT China, was titled 'Experimental and Numerical Simulation Study on the Distribution of Visible Light in the Lithium and Boronization Wall of EAST'. Various wall treatment experiments were simulated, and the results exhibited both qualitative and quantitative agreement with experimental data, confirming the accuracy of visible light distribution simulations. The simulations provided explanations for the variations in visible light distribution within the 545–550 nm range under different wall treatment conditions: (i) During lithium injection discharges, visible light primarily originates from the excitation reaction of Li^{1+}, with intense light emission observed near the injection port. (ii) In lithium coating discharges, Li^{1+} accumulates in the divertor region, generating strong visible light emissions. (iii) In boron coating discharges, visible light is predominantly produced by tungsten impurities, with W^{8+} and W^{11+} exhibiting high densities on the high-field side, playing a dominant role in visible light generation. (This paper contributors include: E. Bray, C. Marchetto, F. Subba, R. Zanino).

The fifth invited talk, presented by Y.L. Liu from DUT China, was titled 'Global Simulation of Lithium Impurity Transport under a Liquid Lithium Divertor with ITCD Code'. The ITCD code, a three-dimensional Monte Carlo simulation tool, has undergone significant enhancements, particularly in the expansion of its simulation domain. A hybrid particle push scheme combining full-orbit and guiding-center approaches was implemented to manage the gyration scrape-off effect while simultaneously improving computational efficiency. The code was applied to analyze lithium impurity density and deposition distributions across different charge states in detail. (This paper contributors include: Chaofeng Sang, Yu Bian, Ming Chen, Yao Huang, Yilin Wang, Dezhen Wang).

F. Romano from DIFFER Netherlands delivered the sixth and final invited talk, titled 'Toward a Real Liquid Metal Divertor: Recent Advances in the Lithium Vapour Box Module for the Linear Plasma Generator Magnum-PSI'. The lithium vapor box divertor concept aims to regulate extreme heat fluxes in tokamak divertor regions by utilizing liquid metals to enhance the longevity of PFCs. Experiments with a modular vapor box module on the Magnum-PSI device were conducted in two configurations. In the first configuration, pre-existing lithium vapor was employed, resulting in a 50% reduction in plasma power. The second configuration involved lithium vaporization induced by plasma exposure to simulate realistic conditions. Both methods effectively confined lithium and mitigated heat loads, with diagnostics providing valuable insights into lithium behavior, advancing the feasibility of liquid metals for fusion reactor applications. (This paper contributors include: V.F.B. Tanke, J.A. Schwartz, R.J. Goldston, T.W. Morgan).

Session 8 on liquid metal experiments, chaired by J. Horacek, of Institute of Plasma Physics of the CAS, Czech Republic

In Session 8, seven invited papers and one oral paper were presented.

E. Oyarzábal from the Centre for Energy, Environment, and Technology, Spain, delivered the first invited paper of the session, titled 'Exposure of Sn-wetted W CPS Targets to NBI and High-power Laser Pulses at the OLMAT Facility'. The study investigated tin-wetted tungsten capillary porous systems (CPS) subjected to combined neutral beam injection (NBI) and high-power laser pulses (hundreds of MW m^{-2} for 2 ms, simulating ELMs). The results indicate that tin droplet ejection occurs with each laser pulse or when exceeding 13 MW m^{-2} for more than 150 ms. Tin does not provide sufficient protection to the underlying tungsten substrate against laser-induced damage, posing a challenge due to excessive radiative cooling in tokamak plasmas. However, this issue appears to be significantly reduced or absent when lithium is used. Among the five CPS technologies tested, the best performance was observed with 3D-printed tungsten. (This paper contributors include: A. De Castro, D. Alegre, D. Tafallaa, K.J. McCarthy, P. Fernandez-Mayo, M. Iafrati, J.G.A. Scholte, T.W. Morgan, T. Estrada and the OLMAT Team).

The second invited paper was presented by E. Marenkov from the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Russia, titled 'Liquid Metal Erosion Module for SOLPS Code and its Application to T-15MD Lithium Divertor Simulations'. A newly developed liquid metal erosion module for the SOLPS 4.3 simulation was introduced, specifically designed to model lithium divertor configurations. The module incorporates key processes such as physical and thermal sputtering, evaporation, and prompt redeposition (similar to the HeatLMD model by J. Horacek), along with a unique kinetic transport model for eroded neutrals [26]. Simulation results indicate that in the T-15MD tokamak, lithium divertors effectively reduce target power loads due to lithium vapor shielding while maintaining acceptable levels of core plasma contamination. Additionally, target surface temperatures and erosion rates remain within acceptable limits for current target designs. The improvements in the module and the simulations provide valuable insights into lithium flow and erosion behavior under various operational regimes. (This paper contributors include: A.A. Pshenov).

The next invited paper was delivered by R. Rulev from NIIEFA, Russia, titled 'Advanced Divertor Target for Future Tokamaks'. The study focused on the development of an advanced divertor target suitable for high-power tokamaks, including ITER, TRT, and EU-DEMO. Various solid metal divertor PFC concepts capable of withstanding steady-state heat fluxes beyond 20 MW m^{-2} were compared, including a 1 Hz strike point sweeping technique. Experimental results revealed that solid tungsten armor endures extreme heat loads of 30 MW m^{-2} over 100 000 thermal cycles, with only minor crack formation. (This paper contributors include: P. Piskarev, V. Kuznetsov, R. Rulev, V. Tanchuk).

The following invited paper was presented by Vicente Manuel Queral Mas from the Centre for Energy, Environment, and Technology, Spain, titled 'Li Divertor Targets and Walls for the ASTER Liquid Stellarator Reactor Concept'. The study compared the storage requirements of LiPb breeding blankets following neutron irradiation in fusion reactors. While the ITER-like LiPb breeding blanket requires extensive hot-cell storage post-irradiation, liquid lithium storage is significantly less demanding. A 0.5 m thick molten lithium wall, stabilized using centrifugal force, was simulated and experimentally tested on a small scale. Additionally, a patented concept of a distributed divertor was introduced. (This paper contributors include: A. de Castro, J. Varela, S. Cabrera, I. Fernández, D. Spong, E. Rincon).

The next invited paper was presented by Z. Sun from the Institute of Plasma Physics, Chinese Academy of Sciences, titled 'Dynamics of Passive Filling of Liquid Metals in a Microchannel-Based Capillary Porous System'. A theoretical model, supported by CFD simulations of wetting behavior, was developed to quantify the heat flux limit of the CPS. The analysis indicated that lithium boiling and capillary-driven flow impose a heat flux limit ranging from 16 to 50 MW m^{-2} for a realistic CPS geometry, excluding potential effects on tokamak plasma. (This paper contributors include: Xinyuan Qian, Xuebing Peng).

The fifth invited paper was presented by G. D'Ovidio from the Centre for Energy, Environment, and Technology, Spain, titled 'The LiFIRE Experimental Facility: Commissioning and Recent Experimental Evidence on Lithium Ignition'. The presence of large quantities of liquid lithium in future fusion devices presents physical, chemical-toxicological, and radiological risks, which must be minimized in accident scenarios involving lithium spills and combustion. The Lithium Fire (LiFIRE) facility has been developed to support safety analyses regarding lithium fire protection requirements and licensing processes. The assembly and commissioning of the LiFIRE experimental setup were recently completed at the CIEMAT Liquid Metal Lab. Preliminary tests confirmed lithium's high chemical reactivity, even in its solid state, as well as its ignition and combustion under conditions relevant to IFMIF-DONES. Future applications of the LiFIRE facility include serving as a multipurpose experimental platform, with planned upgrades to enhance its flexibility in replicating a wide range of safety-related experiments for the use of liquid metals in fusion facilities. (This paper contributors include: Víctor Gutiérrez, Daniel Alegre, Francisco Martín-Fuertes, Joaquín Mollá).

The sixth invited paper was presented by B.T. Moore from the University of Illinois Urbana-Champaign, USA, titled 'Recent Results from the Actively Pumped Open-Surface

Lithium Loop (APOLLO)'. The study reviewed the benefits of a slowly flowing lithium wall, limiter, and its associated subsystems. The primary goals of APOLLO include measuring and purifying liquid lithium from hydrogen, which is used as a proxy for radioactive tritium. Experimental validation of lithium loop technologies, including flow meters, pumps, and load lock systems, was conducted. Continuous operation for over 24 h, along with flow stoppage and restart, was successfully demonstrated. The ECR plasma source was analyzed using an array of 18 Langmuir probes, a radical probe, and a retarding field energy analyzer. Additionally, the Hydrogen Distillation facility has been machined. Future work will focus on validating thermoelectric magnetohydrodynamic effects and steady-state hydrogen inventory tracking. (This paper contributors include: D. O'Dea, P.F. Buxton, K. Moshkunov, D.N. Ruzic).

The final oral paper was presented by W.Y. Zhou from the Institute of Plasma Physics, Chinese Academy of Sciences, titled 'Design of a Flowing Liquid Lithium Loop in a High-Flux Linear Plasma Device'. The study highlighted key components of the CRAFT facilities, including the world-unique, divertor-like 24 h plasma devices SWORD and SPARROW, which incorporate a liquid lithium loop. Experimental optimizations of liquid lithium spreading over FLiLi were demonstrated, with significant improvements achieved using simple water tests. Additionally, thermal simulations were conducted, analyzing performance at heat fluxes of up to 10 MW m^{-2} and temperatures reaching 835 K. (This paper contributors include: Lin Han, HaiShan Zhou, Xin Yang, JuanCheng Yang, Yu Li, GuiZhong Zuo, MingJiu Ni, GuangNan Luo and JianSheng Hu).

Session 9 on simulation of liquid metals, chaired by Z. Sun of Princeton Plasma Physics Laboratory (PPPL), USA

In Session 9, two overview papers and three invited papers were presented.

The session began with an overview paper by M. Ono from PPPL, titled 'Active Divertor Heat Flux Control using the Impurity Powder Dropper'. This study explored the application of the Impurity Powder Dropper (IPD) for managing divertor heat flux in fusion reactors. The proposed Active Radiative Liquid Lithium Divertor (ARLLD) is designed to reduce transient heat fluxes, providing protection for liquid lithium divertors (LLD). The IPD serves as an effective near-term testbed for developing the physics basis of ARLLD. This approach has been tested across multiple fusion facilities, demonstrating improvements in plasma performance. A computational model for IPD has been developed to account for spatial and temporal variations in particle and energy fluxes, allowing integration with plasma transport modeling codes. The model is currently undergoing validation through IPD experiments, with the objective of enhancing predictive capabilities for future applications, including ITER. (This paper contributors include: the IPD team).

The second overview paper was presented by D. Andruczyk from the University of Illinois Urbana-Champaign (UIUC), USA, titled 'Lithium Vapor Shielding in PFCs'. This research focused on lithium vapor shielding mechanisms in PFCs. Experiments conducted at both the Magnum-PSI and HIDRA facilities demonstrated that a locking temperature of about 790 °C can sustain steady-state heat fluxes of up to 20 MW m^{-2}. The findings suggest that mass loss alone does not fully account for the total dissipated power unless the global recycling coefficient is significantly low ($R \sim 0.1$). The analysis identified excitation losses as the primary dissipation pathway, with power dissipation efficiency showing a strong dependence on electron temperature (T_e). The Zapdos-CRANE model further supported the conclusion that lithium's power screening potential increases with flux but declines sharply at higher T_e values. (This paper contributors include: Rabel Rizkallah, Davide Curreli, Andrew Shone, Rajesh Maingi, Fabio Romano and Thomas Morgan).

An invited paper was presented by D. Boyle from PPPL, USA, titled 'Demonstration of Low Recycling and NBI Fueling with Liquid Lithium Walls in the Lithium Tokamak Experiment-β'. The study focused on recent advancements in the Lithium Tokamak Experiment-β (LTX-β), emphasizing the achievement of a low-recycling regime ($R \sim 0.6$) using liquid lithium walls. This configuration has demonstrated compatibility with effective tokamak operations without introducing significant operational challenges. Key findings include the formation of a hot plasma edge and a relatively uniform electron temperature profile, both crucial for maintaining optimal plasma performance. The integration of NBI fueling with liquid lithium has further extended the low-recycling regime, enhancing overall performance levels. Ongoing system upgrades aim to provide deeper insights into the unique physics of low-recycling regimes and assess the viability of liquid lithium technology for future fusion applications. (This paper contributors include: S Abe, S Banerjee, W Capecchi, D Elliott, M Francisquez, C Hansen, E Jung, S Kubota, M Lampert, B LeBlanc, A Maan, R Maingi, D Majeski, A McLean, J Menard, V Soukhanovskii, G Wilkie, L Zakharov).

The second invited paper was presented by E. Emdee from PPPL, titled 'Update on Lithium Vapor Cave Design Studies Using SOLPS'. This study provided updates on design investigations for a lithium vapor cave utilizing the SOLPS code. The concept simplifies the lithium vapor box to a private flux region lithium vapor cave while incorporating drift effects into the simulations. Drift-enabled simulations predict that both the inner and outer targets can sustain heat fluxes below 10 MW m^{-2} while maintaining a low lithium concentration (2.5%) relative to electron density at the last closed flux surface. Additional design modifications, such as the introduction of gas puffing at the inner target, are being explored to improve model flexibility and optimize implementation strategies. (This paper contributors include: M.S. Parsons, M. Porcelli, R.J. Goldston).

The final invited paper of Session 9 was presented by M.S. Parsons from PPPL, titled 'Preliminary Design of a Lithium Vapor Divertor Module for Operation in a Pulsed Tokamak'. This study introduced initial design efforts for a lithium vapor divertor (LVD) module specifically intended for pulsed tokamak operations. The design addresses challenges posed by the cyclical nature of tokamak discharges, including the regulation of lithium evaporation rates by positioning the lithium CPS outside the direct line of sight of plasma radiation. This approach has guided the development of operational characteristics for the LVD system. Additionally, prototyping efforts using 3D-printed molybdenum components have commenced, allowing key design concepts to be tested in laboratory conditions. (This paper contributors include: E.D. Emdee, M. Porcelli, R.J. Goldston).

Session 10 on the liquid metal blanket of CFETR, chaired by X.J. Zhang of Southwestern Institute of Physics, China

In Session 10, one overview paper and five invited papers were presented.

The first overview paper, titled 'Status of the Design and R&D Activities for Breeding Blanket in ASIPP', was presented by S.L. Liu from the Institute of Plasma Physics, CAS (ASIPP), Hefei, China. This presentation provided a comprehensive overview of the design and research & development (R&D) activities for breeding blankets at ASIPP, with a particular focus on the Water-Cooled Ceramic Breeder (WCCB) and the Coolant-Cooled Lithium Lead (COOL) blankets for the China Fusion Engineering Test Reactor (CFETR). The WCCB and COOL TBMs are scheduled for testing on the BEST machine, with system design updates and test plans set to commence in 2027. The R&D efforts aim to address challenges related to neutronics, thermal hydraulics, and structural mechanics to ensure the feasibility of breeding blanket concepts for CFETR. (This paper contributors include: Lei Chen, Kecheng Jiang, Xuebin Ma, Xiaoman Cheng, Qingjun Zhu, Qinzhu Liang, Qiuran Wu, Wenjia Wang, Qiankun Shao, Shuailing Lu, Pengdi Zhai, Long Chen, Juancheng Yang, Nianmei Zhang, MingJiu Ni).

The next invited presentation, titled 'Progress in the Conceptual Design of the Supercritical CO_2 Cooled Lithium-Lead Blanket for CFETR', was delivered in person by L. Chen from the Institute of Plasma Physics, CAS (ASIPP), Hefei, China. This study detailed advancements in the conceptual design of the Supercritical CO_2 Cooled Lithium-Lead (COOL) blanket for CFETR, developed by ASIPP-UCAS. The COOL blanket design offers high thermal efficiency, reasonable construction costs, and simplified online tritium extraction. Key topics discussed included design features, the Tritium Breeding Ratio (TBR), neutronics and nuclear heating analysis, MHD effects, thermo-mechanical performance, and the BEST test blanket system. The presentation emphasized the COOL blanket's potential as an advanced solution for fusion applications, with a focus on safety and efficiency. (This paper contributors include: Wenjia Wang, Kecheng Jiang, Lei Chen, Songlin Liu).

The following invited presentation, titled 'Progress in the PbLi and S-CO_2 Loop for CFETR COOL Blanket', was delivered in person by K.C. Jiang from the Institute of Plasma Physics, CAS (ASIPP), Hefei, China. This study provided updates on the development of PbLi and S-CO_2 loops for CFETR's COOL blanket, with a focus on achieving economic and efficiency goals while avoiding the use of beryllium. The design addresses key scientific challenges, including turbulent heat transfer and MHD effects, with the objective of achieving a minimum thermoelectric conversion efficiency of 42%. The PbLi loop is expected to be completed by November 2024, and the S-CO_2 loop by May 2025, both of which are essential for addressing critical scientific issues before reactor installation. (This paper contributors include: Xuebin Ma, Songlin Liu).

The next invited presentation, titled 'Numerical Simulations with Modified RELAP5/MOD3.3 on the High-Temperature PbLi Experimental Facility', was delivered in person by Y. Yu from the Institute of Plasma Physics, CAS (ASIPP), Hefei, China. This study focused on numerical simulations of a high-temperature PbLi experimental facility using the modified RELAP5/MOD3.3 code, with an emphasis on MHD effects and mixed convection phenomena. The key findings included validation of the simulation's predictive capabilities, necessary adjustments to energy loss coefficients, and confirmation that the facility meets design specifications with optimized valve and power adjustments. (This paper contributors include: Lei Chen, Songlin Liu).

The subsequent invited paper, titled 'Numerical Simulations of MHD Coupling Effect Relevant to COOL Blanket', was presented in person by P.D. Zhai from the Institute of Plasma Physics, CAS (ASIPP), Hefei, China. The study examined the MHD coupling effect in the COOL blanket at ISLA-8, utilizing simulations to evaluate the influence of varying flow velocities on channel electromotive forces and current distribution. Key results identified the presence of reverse jet zones in low-speed channels and significant reductions in pressure drops with the application of FCI. These insights contribute to optimizing the design and operational performance of the COOL blanket in fusion reactors. (This paper contributors include: Songlin Liu, Xuebin Ma, Kecheng Jiang, Long Chen, Xiaoman Cheng, Qingjun Zhu, Qiuran Wu, Wenjia Wang, Qiankun Shao, Shuailing Lu, Pengdi Zhai, Juancheng Yang, Nianmei Zhang, Ming-Jiu Ni).

The final invited paper of the session, titled 'Electromagnetic Analysis of the COOL Blanket for CFETR', was presented in person by S.L. Lu from the Institute of Plasma Physics, CAS (ASIPP), Hefei, China. This study focused on the electromagnetic analysis of the COOL blanket for CFETR, particularly the effects of strong magnetic fields on electromagnetic loads. The findings demonstrated that the FCI effectively reduces Lorentz forces by 20%, while the highest eddy current densities are concentrated in the tungsten armor. (This paper contributors include: Kecheng Jiang, Lei Chen, Songlin Liu).

Session 11 on liquid metal MHD effects, RAFM steel corrosion in liquid LiPb, and neutronic experiment for fusion LiPb blanket, as well as Li target for BNCT, chaired by S.L. Liu of Institute of Plasma Physics Chinese Academy of Sciences, China

In Session 11, four invited papers and three oral papers were presented.

The session commenced with the invited paper titled 'Investigations of Liquid Metal MHD Effects for Fusion Blankets in SWIP' by X.J. Zhang (SWIP, China). This study systematically investigated the ferromagnetic MHD effect through experimental and numerical simulations under conditions relevant to fusion reactors. Results indicate that for ferromagnetic rectangular ducts, magnetic field lines predominantly concentrate along the side walls, leading to an overall magnetic shielding effect. (This paper contributors include: Yao Zhao, Zhenchao Sun, Lei Wang, Xinting Lv).

The second invited paper, 'Scheme of Neutronic Experiment on Supercritical CO_2 Cooled Lithium-Lead Blanket Mock-up', was presented by Q.K. Shao (ASIPP, China). This study outlined the mock-up design, fabrication of components, preparation and testing of detectors, and experimental plans for the COOL blanket. (This paper contributors include: Qingjun Zhua, Songlin Liu).

The following invited paper, 'Numerical Investigations of 3D Magnetohydrodynamic Flows in a Mock-up of the ITER WCLL Test Blanket Module', was presented by B. Lyu (KIT, Germany). The study concluded that the manifolds in the WCLL TBM contribute to the majority of the pressure drop and that the liquid metal flow is not evenly distributed across all BUs. An optimization analysis was conducted, recommending a design modification to ensure equal flow rates among BUs. (This paper contributors include: L. Buhler, C. Courtessole, C. Koehly, C. Mistrangelo).

The next oral paper, 'MHD Pressure Drops of Liquid Metal Flows Through Multiple Electrically Coupling Ducts with U-Turn Bends in Fusion Blankets', was presented by X.T. Lyu (SWIP, China). This study demonstrated the significant influence of duct numbers on the MHD flow state and explored structural modifications as a potential solution to mitigate these effects. (This paper contributors include: Xiujie Zhang, Zhenchao Sun, Lei Wang, Yao Zhao).

The following oral paper, titled 'The Laminar-Turbulence Transition in Wall-Bounded Incompressible Magnetohydrodynamic Flows', was presented by L. Wang (SWIP, China). The study analyzed turbulence transition phenomena in wall-bounded incompressible MHD flows using the energy gradient analysis method. It was mathematically proven that the initial turbulence transition position in the Hartmann layer remains at 69.31% of the Hartmann layer thickness from the Hartmann wall, regardless of the Hartmann number or the wall conductance ratio. (This paper contributors include: Xiujie ZHANG, Xinting LV and Zhenchao SUN).

T The oral paper titled 'The Ductility Loss of RAFM Steel After Stress Corrosion in Flowing Pb-17Li' was presented by Z.C. Sun (SWIP, China). Long-term stress corrosion in flowing Pb-17Li was examined through tensile tests within the temperature range of 300 °C–400 °C. The fracture mechanisms were analyzed based on the supply of liquid metal and the formation of micro-cracks due to coarse laths. The reduction in ductility observed in RAFM steel following exposure to liquid Pb-17Li was attributed to the combined effects of applied stress and liquid metal interaction. (This paper contributors include: Xiujie Zhang, Yao Zhao, Lei Wang, Xintin Lv).

The final invited paper of the session, 'Progress of an Active Water-Cooled Lithium Target for Boron Neutron Capture Therapy', was presented by W. Xu (IEHCNSC, China). A specialized solid lithium target with a finned cooling structure was designed. The maximum temperature of the target was determined to be about 138 °C (based on simulations and tests), remaining below the required 180 °C threshold. Additionally, a uniform lithium film of about 107 μm thickness was successfully produced using the PVD process. (This paper contributors include: X.L. Wang, J.C. Wang, X.C. Meng, P. Lu, B. Hong, Y.Z. Qian, K.Y. Ou, Q. Li, L.Z. Liang, C.D. Hu).

3. Conclusion

During the closing session, summaries of the sessions were presented by the respective session chairs. Additionally, T.W. Morgan provided an overview of the current status of DIFFER. It was announced that ISLA-9 is scheduled to take place in the fall of 2026 in the Netherlands. Concluding remarks included expressions of gratitude to all members of the international organizing committee, the local committee, and the volunteers for their contributions to the event.

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