IAEA nuclear fusion

CONFERENCE REPORT

Conference Report on the 4rd International Symposium on Lithium Applications

IOP Publishing | International Atomic Energy Agency Nuclear Fusion

Nucl. Fusion 56 (2016) 127002 (8pp) doi:10.1088/0029-5515/56/12/127002

Conference Report

Conference Report on the 4rd International Symposium on Lithium Applications

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Received 20 April 2016, revised 14 August 2016
Accepted for publication 15 August 2016
Published 8 September 2016

Abstract

The fourth International Symposium on Liquid Metal Application for Fusion Devices (ISLA-2015) was held on 28–30 September 2015 at Granada, Spain, with growing participation and interest from the community working on general aspects of liquid metal research for fusion energy development. The ISLA symposia remain the largest, and arguably, the most important meetings dedicated to liquid metal application for the magnetic fusion research. Overall, 43 presentations plus 7 posters were given, representing 28 institutions from 12 countries. The latest experimental results from 9 magnetic fusion devices were given in 17 presentations from NSTX and LTX (PPPL, USA), FTU (ENEA, Italy), T-11M (Trinity, RF), T-10 (Kurchatov Institute, RF), TJ-II (CIEMAT, Spain), EAST (ASIPP, China), HT-7 (ASIPP, China), DIII-D (GA, USA), ISTTOK (IPFN, Portugal) and KTM (NNC RK, Kazakhstan).

Sessions were devoted to the following: (I) liquid metals (LM) in magnetic confinement experiments (facility overviews), (II) LM in magnetic confinement experiments (topical issues), (III) laboratory experiments, (IV) LM tests in linear plasma devices, (V) LM theory/modeling (VI) LM technology and (VII) a special session on lithium-safety and lithium handling. There were contributions from fusion technology communities including IFMIF and TBM, which provided productive exchanges with physics-oriented magnetic confinement liquid metal research groups. This international workshop will continue on a biennial basis (alternating with the Plasma–Surface Interactions (PSI) Conference), with the next workshop scheduled for Moscow, Russian Federation, in 2017.

Keywords: Conference Proceedings, liquid metals, target materials, fusion reactor

1. Introduction

The fourth International Symposium on Lithium Application for Fusion Devices (ISLA-2015) was held on 28–30 September, Granada, Spain. The first one was organized in Japan by NIFS in 2010 [1], the second one was hosted in Princeton, USA by PPPL in 2011 [2] and the third one in Frascati, Italy by ENEA [3]. The interest in liquid metal applications continues to grow, e.g. expanding from the use of liquid metals as plasma-facing components (PFCs) for a future fusion reactor to use as an injected species for ELM control.

Although several recent to enhance the properties of tungsten as a plasma facing material (PFM) for a reactor divertor target show promise, experimental validation has not yet been achieved. Therefore its use is foreseen with stringent requirement on the power load i.e. radiative power from core and divertor greater than 90%, and electron temperature in front of the plate $\leqslant$5 eV. The combination of all of these conditions has never tested in operating fusion devices to date.

Alternate configurations, such as as snowflake divertors, super-x divertors and liquid metal PFC, have been proposed as possible mitigation techniques. Following the 2013 ISLA meeting, the Scientific Committee decided to open the symposium to liquid metals other than Li: tin, tin–lithium (Li/Sn), and gallinstan (GaInSn) experiments are also included in the present report. These liquid metals have melting temperatures higher than lithium, less hydrogenic retention, and a wider operational window. Baseline reactor heat loads of 20–25 MW m^{-2} should be tolerated by the LM target without excessive net evaporation.

ISLA remains as the largest and the most important meeting dedicated to liquid metal application for the magnetic fusion research. Overall, 43 presentations plus 7 posters were given, representing 28 institutions from 12 countries. Sessions were devoted to the following: (I) liquid metals (LM) in magnetic confinement experiments (facility overviews), (II) LM in magnetic confinement experiments (topical issues), (III) laboratory experiments, (IV) LM tests in linear plasma devices, (V) LM theory/modeling (VI) LM technology and (VII) a special session on lithium-safety and lithium handling. The latest experimental results from nine magnetic fusion devices were presented in 17 presentations from NSTX and LTX (PPPL, USA), FTU (ENEA, Italy), T-11M (Trinity, Russion Federation), T-10 (Kurchatov Institute, RF), TJ-II (CIEMAT, Spain), EAST (ASIPP, China), HT-7 (ASIPP, China), DIII-D (GA, USA), ISTTOK (IPFN, Portugal) and KTM (NNC RK, Kazakhstan). The results from these devices indicate a growing interest on the application of liquid metals PFCs as alternatives to solid materials, i.e. tungsten.

All of the presentations are available online (www-fusion.ciemat.es/quixplorer/). In this conference report, the symposium papers are summarized in presentation order. It must be noted that many of the papers summarized here are currently under peer review for a special issue of *Fusion Engineering and Design*. The international program committee members are Drs Y. Hirooka, G. Mazzitelli, S.V. Mirnov, M. Ono, Prof J.M. Perlado (co-Chair) and F.L. Tabares (Chair). The local organizing committee members were Prof J.L. de Segovia, Drs D. Tafalla, E. Oyarzabal and A.B. Martin-Rojo and Mr Alfonso de Castro.

2. Symposium summary of presentation on lithium applications for fusion devices

2.1. Session I: liquid metals in magnetic confinement experiments overview talks

The first session of the 4th ISLA was dedicated to magnetic confinement experiments. The kickoff talk was given by F.L. Tabares, who reported on the experiments performed on TJ-II, the only stellarator operating with a full lithium scenario, complemented with laboratory experiments. Motivated by the discovery of an anomalously high secondary electron emission (SEE) coefficient of lithium surfaces exposed to a plasma, the program has grown to include experiments of positive or negative biasing of the liquid lithium limiter (LLL), and dedicated small capillary porous system (CPS) probes versus a carbon limiter on the vessel. For example, the exposure of twin limiters, one made of carbon, the other a lithium CPS system in TJ-II under full lithiated walls, confirmed generation of inter-limiter currents at the SOL due to the development of different floating potentials on the limiters, otherwise exposed to the same local plasma parameters. This effect vanished when the same component (Li) was used on both limiters.

While it is not exactly known how a SEE yield >1 of a PFM would affect the plasma performance, enhanced plasma particle confinement was observed at positive bias voltages of the LLL at values above the nominal floating potential of ~$3kT_e$, but was absent during biasing of the carbon limiter. Although extrapolation of these observations to a reactor divertor is difficult, exploring the unique properties of LM surfaces may lead to new discoveries that would ease the implementation of the associated LM concepts in a reactor.

The development of a vapor shield on top of the liquid elements in the presence of the plasma was also investigated. Although no direct surface temperature measurements were made during the plasma exposure, an estimate of the expected increase by the plasma thermal load was made under the assumptions of a semi-infinite solid slab model. For a full 600 kW ECRH launched power, and taking into account the absorption efficiency and the radiated losses, a local increase of ~50 °C, at the contact point, and an average of 30 °C over the full LLL surface were computed from the change in the Li evaporation rate during the shot. Power balance analysis points to a strong shielding effect by the evaporated Li, such that the power reaching the Li surface of the limiter is reduced to ~1/3 of its nominal value. The installation of pyrometers and IR cameras looking at the plasma-exposed elements are planned for the next campaign for verification. Also, a Li/Sn alloy (20/80 at. ratio) will be tested under the CPS arrangement in TJ-II.

Starting from the good performance obtained on NSTX with the use of lithium, M. Ono discussed on the possibility to use liquid lithium in a future reactor. Four main 'concerns' were presented: high lithium evaporation above 500 °C, high tritium retention, incompatibility with other materials, i.e. corrosion, and lithium volatility and safety. The last point was the subject of a later session, while corrosion is a long-term technological problem pursued by IFMIF. The remainder of the talk concentrated on the first two issues.

Lithium radiation, evaporation and ionization could be the physical mechanism to handle high steady-state divertor heat flux up to 10 MW m^{-2} at 700 °C. A radiative liquid lithium divertor was discussed in detail, but more experimental data are needed to assess the effectiveness of lithium radiation. Considering that lithium would be present in liquid form in a future reactor, tritium could be removed in real time with a set of cold traps. The conclusion from preliminary calculations is that T inventory should be quite manageable [4].

When more than 2 MW of ECRH are coupled in T-10 discharges, a strong influx of carbon was observed, due to high heat load on a relatively small surface area. A. Verkov presented a new limiter setup proposed to prevent plasma contamination. The new setup will consist of three elements: one main poloidal circular limiter of W, one rail moveable limiter of W and one moveable rail Li limiter. The Li limiter will be inserted in T-10 from an upper port and will operate in the shadow of the main W limiter. The plasma-facing surface of the limiter is made of a capillary-porous system (CPS) filled with lithium. The Li limiter will be mainly used as a source of lithium to mitigate the heat load on W limiter to avoid strong W influx into the discharge.

G. Mazzitelli gave a summary of LM limiter research in FTU. In past years a prototype of a CPS with liquid Li has been tested successfully on FTU. In 2013 an actively cooled version, the cooled lithium limiter (CLL), was installed and the first tests were carried out on its performance. In 2014, long pulses up to 2.5 s were attempted for the first time in FTU, although several technical problems limited this investigation. In the near future (2016) a cooled liquid Sn limiter will be tested under quasi-steady state conditions, i.e. up to 3.5 s of plasma duration, and thermal loads as high as 10 MW m^{-2}. The CLL dedicated discharges were both ohmic and heated with auxiliary power ($P_{ECRH} = 500$ kW). Circular and elongated shapes (κ ~ 1.2) were tested, as well as different CLL positions under the TZM toroidal limiter shadow, up to 1.8 cm inside the last closed magnetic surface in elongated plasmas.

For almost all the conditions, the Li surface temperatures monitored by a fast infrared camera was maintained below the onset of strong Li evaporation (~500 °C). Heat loads up to 2.3 MW m^{-2} were withstood by the limiter surface for the 1.5 s duration of the plasma discharge. However for the maximum insertion, a few localized hot spots were observed on the joint points of the strips of the CPS structure, which has a maximum design heat load ~2 MW m^{-2}. Non-negligible Li evaporation (500–570 °C) was consistently detected by monitoring the Li visible line intensity at 670.7 nm. Nevertheless plasma disruption due to Li evaporation was not observed, and visual inspection of the CLL surface by an *in situ* optical window view of CLL volume did not reveal any damage. Recognizing the misalignment of the W strips of the CPS structure to be the cause of the observed hot spots, the misalignment has been corrected by manufacturing a new active CLL refrigeration head in Red Star Labs. Moreover, two important upgrades of the system have been implemented in ENEA following the indications coming from the first experiments. They are: (1) more rapid monitoring of the water CLL temperatures, with up to 0.1 s of time resolution for calorimetric measurements of the thermal loads, and (2) improvement of the control system of the cooling water circulation. The second upgrade has been successfully implemented on a laboratory mock-up to be ready to be applied on the real CLL.

The future plans of research in NSTX-U were described by M. Jaworski. The previous results provide impetus to a focused effort to determine the temperature limits of liquid lithium PFCs in a tokamak divertor and the corresponding consequences on core operation. To accomplish the scientific program, an all-metal NSTX-U is envisioned. By executing the all-metal upgrades incrementally, scientific productivity will be maintained while enabling physics and engineering-science studies to further develop the solid and LM components.

The first of these upgrades is the NSTX-U High-*Z* Divertor Upgrade 1 (DU1) which will implement a continuous row of high-*Z* tiles in the outboard divertor. The goals of the DU1 experiments are to provide experience of operating a high-power tokamak with the divertor strike-points directly impinging high-*Z* metal components with and without lithium coatings. Plasma shape studies and a 0D analysis indicate the potential to operate with 9 MW heating power producing heat fluxes roughly 66% of those expected in full-power (15 MW), high-performance, high-triangularity discharges in NSTX-U. Preliminary experiments examining the incident heat-flux were carried out during the 2015 experimental campaign.

Pre-filled liquid metal targets have been examined as a possible intermediate step between high-Z PFCs with evaporated lithium coatings and fully flowing liquid-lithium modules in the NSTX-U. These components utilize a pre-filled reservoir in contact with a wick component and capillary surface similar to the CPS. These components feature a flat surface suitable for usage in a divertor configuration without the use of linear actuation. Wire electro-discharge machining (EDM) processes have been tested for manufacturing capillary structures as well as bulk fabrication of the PFCs and prototype testing with surrogate liquids were reported.

The lithium tokamak experiment (LTX) is an ohmically heated moderate-sized low aspect ratio tokamak with a heated liner or shell, which covers 80% of the plasma surface area (4 m^2). Its progress was described by R. Majeski. In 2014, a new approach to lithium wall coatings was developed. The shells are now preheated to 300 °C, and previously applied lithium coatings are allowed to oxidize in base vacuum. An electron beam system is then used to evaporate lithium from a pool of liquid at the bottom of the lower shell. The e-beam system produces a 50–100 nm coating of liquefied lithium in $<$5 min. Compared to previous results with helium-dispersed coatings, discharges using the new approach have strongly reduced impurities, especially oxygen.

Magnetic analysis indicates that confinement in LTX Ohmic discharges is now improved by up to 10×, compared to results with helium-dispersed coatings. Confinement times now exceed ITER ELMy H-mode scaling by 2–4×. This is the first experimental evidence that high performance tokamak discharges are compatible with large-area liquid lithium walls. Core impurity concentrations of lithium have been measured to be $<$0.5%, with full liquid lithium walls at 240 °C. The only other detectable impurities are oxygen and carbon, but at low enough levels so that the total measured core Z_{eff} is $<$1.2. Surface analysis of the e-beam evaporated films has been performed. Recent experiments in which the discharge density is fueled by high field side gas puffing to ~3 × 10^{19} m^{-3}, and then allowed to decay with no further fueling, show the development of broad, flat electron temperature profiles after gas puffing is terminated, with temperature peaking factors

($T_{e,\ central}/T_{e,\ average}$) in the range of 1.2–1.3. Broad, flat electron temperature profiles have long been predicted as a consequence of very low recycling walls.

In the last two years, a number of activities of lithium applications and researches in EAST were carried out accompanying the EAST facility enhancements, as described by J.S. Hu. First, good progress has been made in understanding the physical mechanism of the steady-state quiescent high confinement plasma with 18 s ELM-free in EAST obtained in 2012. It was shown that the steady-state ELM-free H-mode is accompanied by a strong edge coherent MHD mode (ECM) at a frequency of 35–40 kHz with a poloidal wavelength of 10.2 cm, providing continuous heat and particle exhaust, thus preventing the transient heat deposition on PFCs and impurity accumulation in the confined plasma. The Li injection appears to promote the growth of ECM, owing to the increase in Li concentration and hence collisionality at the edge, as predicted by GYRO simulations. Second, lithium coating was carried out on mixed walls of C, Mo and W in the campaign of 2014. Its effects on recycling, impurities and plasma performances were studied, which would be useful for exploring the lithium coating on metal walls. Active lithium coating via real-time injection of lithium granules was carried out in plasmas with NBI heating. It was found that the Li coating is effective to suppress impurities, to reduce recycling and to improve plasma performance with high stored energy and mitigated ELMs. Third, the flowing liquid lithium (FLiLi) concept with developed techniques was tested on EAST in 2014. A few key components, such as an inner electromagnetic (EM) pump directly using toroidal magnetic field, and a temperature controlled Li valve with short response time replacing mechanical metal valves in vacuum, were successfully designed and tested. It was found that the lithium flowing speed depends on the inner EM current. The limiter is compatible with various plasmas such as LHW or NBI heated H-mode plasmas. Those new results showed that use of lithium as PFCs or coating materials has much promise. In addition, Li is not only used for the PFM, but also for ELM mitigation to achieve steady-state H mode plasmas with low divertor heat flux, a critical R&D area for future fusion devices.

D. Ruzic reported on the progress achieved in the liquid–metal infused trenches (LiMIT) concept, presently under development at the Center for Plasma Material Interactions and intended to be a flowing liquid lithium PFC. The system can tolerate the intense particle and heat fluxes of a diverted fusion plasma by providing a clean and continuously replenishing lithium surface. A liquid surface mitigates the damage and erosion problems of typical solid PFCs, and lithium has also been shown to provide several additional benefits, namely reducing edge recycling, aiding in ELM suppression, and enhancing plasma performance. LiMIT uses thermoelectric magnetohydrodynamic (TEMHD) flow to self-propel lithium down a series of trenches, employing lithium as both a plasma facing surface and a coolant. LiMIT in a horizontal divertor configuration has been tested in several devices, namely HT-7, the UIUC SLiDE and TELS facilities, and Magnum-PSI, at heat fluxes of up to 3 MW m^{-2}. Ongoing testing of LiMIT at UIUC has demonstrated the system's potential for use as a limiter or general first wall material by showing TEMHD-driven flow in trenches inclined at an arbitrary angle from horizontal. In all cases, the velocity of the liquid lithium in the LiMIT device has been shown to agree well with theoretical predictions for the experiments performed. Performance of the LiMIT concept under multiple angles of inclination from the horizontal was shown and the scalability of LiMIT to typical ITER heat fluxes and preliminary designs for a LiMIT test as a limiter on the EAST tokamak were also discussed.

2.2. Session II: lithium in magnetic confinement topical experiments

Dr Loureiro of the University of Lisbon, presented recent data taken from the ISTTOK tokamak. A temperature-controlled probe, containing liquid metals, has been exposed to tokamak discharges. These include Sn and Sn–Li, proposed as alternatives to Li, the evaporation rate of which may be too high for future reactor operation. The deuterium retention after plasma exposure has been measured by means of nuclear reaction analysis (NRA), employing a 1.2 MeV He ion beam. The deuterium concentration in Sn has been measured to be 0.068 atomic %, but that in Sn–Li has turned out to be below the detection limit of NRA. Also found is the surface precipitation of LiSn, $LiSn_2$, Sn which are conjectured from the phase diagram of the Sn–Li system.

Dr Iafrati of ENEA, Frascati, presented the latest data concerning a new temperature control system implemented in the CLL. At first, the significant fluctuation of measured temperature was observed during the operation of CLL, which has turned out to be due to the slow data-sampling rate of thermocouples. To mitigate the temperature fluctuations, resistance temperature detectors have successfully been employed for the PID feedback control. For further improvement, a new diagnostic tool such as a ball-pen probe will be employed in the future when tin is used for the CLL in FTU.

Lazarev of Kurchatov Institute demonstrated the capabilities of a high-speed video camera used for the observation of plasma interactions with lithium on the CPS limiter in the T-11 tokamak. The videos documented the temporally evolving behavior during the discharges, including the initial ramp-up stage, the steady phase of the plasma discharge, and then the evolution of the emission during a period of run-away electrons, leading to a disruption. The location of lithium was indicated by Li-II emission localized in the edge area, and splashing of the lithium bubbles was observed, along with possible hydrogen particle loss.

Dr Maingi of PPPL presented data from NSTX, related to the effects of progressively increasing lithium conditioning sequences on the edge transport and stability in high triangularity, high performance H-mode plasmas. The core and edge plasma performance improves as the amount of pre-discharge lithium evaporation increases. In addition the occurrence of ELMs is eliminated during H-mode operation with sufficiently high lithium dose. Significant changes in the edge temperature and density profiles are observed, indicating a strengthening of the edge transport barrier with increasing

Li dose. Data-constrained 2D SOLPS modeling was used to quantify the changes in recycling and edge transport.

Two types of lithium injection at DIII-D were described by Dr Lunsford and Dr Osborne respectively. First, four sets of lithium granules ranging in size from 300 to 900 microns in diameter were injected into various discharges with low natural ELM frequencies to test the ability to trigger ELMs at faster than the natural frequency. A vibrating piezoelectric disk gravitationally fed a rotating impeller drove granules into the edge plasma at velocities ranging from 50–150 m s^{-1}. This resulted in a 2–4× increase of the ELM frequency from its natural 20–25 Hz–50–100 Hz, with a corresponding reduction of the peak heat flux measured by IR thermography. The increased ELM frequency and the corresponding particle out flux were also observed to clamp the rise of the Ni impurity buildup within the core. Utilizing high speed imaging along the granule insertion trajectory, the dynamic expansion of the ablation cloud was captured, with measured ablation times of the order of several hundred microseconds. The inferred granule penetration depths range from 2 to 5 cm, dependent upon the size of the injected granules. These data allow an accurate estimation of the perturbation to the density profile in the steep gradient region, which corresponds to the ability of the injected granule to trigger an ELM. The lithium granule ablation data is being compared to present neutral gas shielding models. In addition, future experiments with the lithium granule injector on DIII-D and NSTX-U were discussed, including using the granule injector to benchmark the energy dissipated by injected lithium for radiative liquid lithium divertor scenarios.

Secondly, the injection of an aerosol of 45 μm diameter lithium particles at rates ~20 mg s^{-1} produced periods of ELM-free H-mode with increased pedestal pressure on the DIII-D tokamak. Lithium was introduced via a gravity feed using a PPPL designed and built injector. Lithium induced ELM free periods persisted for up to 350 ms and reached pedestal pressures up to 50% higher than comparable duration ELM free periods without lithium. Lithium injection at a level sufficient for triggering the extended enhanced phases resulted in significant lithium in the plasma core, but carbon and other higher Z impurities, as well as radiated power levels, were reduced. Recycling of the working deuterium gas appeared unaffected by this level of lithium injection. The enhanced pedestal periods were associated with large amplitude, $\tilde{n}/n$ ~ 0.1 density fluctuations localized to the region near the separatrix. Although the fluctuations were observed in some inter-ELM periods without lithium, their duration and probability of occurrence greatly increased with lithium. These fluctuations occurred in bursts every ~1 ms with frequency varying within each burst near f ~ 80 kHz. The poloidal wavelength of this mode, $k\theta\rho s$ ~ 0.1–0.2, and its observed propagation in the electron direction in the plasma frame are characteristics consistent with both trapped electron and micro-tearing instabilities. Analysis of the radial structure of the fluctuations indicated outward radial propagation, and the mode's presence was correlated with flattening of the electron density and temperature profiles near the separatrix and an increase in divertor $D\alpha$ emission, indicating an association with the plasma parameters in this region. The resulting localized reduction in pressure gradient allowed higher overall pedestal pressure at the peeling-ballooning stability limit, as the steep pressure gradient region moved radially inward. The pedestal pressure was also larger than expected under the EPED model due to reduction of the pressure gradient below the 'ballooning critical profile' in the region near the separatrix. Reduction of the ion pressure by lithium dilution may have contributed to the long ELM-free periods.

By examining the observations presented in the talks by Dr Hu, Dr Maingi and Dr Osborne, it is clear that there are some similarities and differences in the DIII-D, EAST, and NSTX observations with lithium injection. With the lithium aerosol injector (used both in EAST and DIII-D), edge fluctuations appear to be enhanced, and there are similarities between the edge coherent mode (EAST) and bursty chirping mode (DIII-D). Both are ion-scale fluctuations that propagate in the electron drift direction, and provide enough continuous particle exhaust to prevent impurity buildup in the absence of ELMs. Lithium applied as a coating to surfaces in NSTX and EAST prior to discharges, however, does not enhance edge fluctuations, but it does reduce recycling. In the case of NSTX, the recycling is reduced to the point of density and pressure profile modification, which eliminates ELMs. In the absence of a continuous edge mode, however, impurities accumulate in NSTX. Thus experiments in NSTX-U should compare both lithium evaporation and lithium aerosol injection, with the goal of obtaining steady ELM-free, confinement enhanced discharges with a continuous mode. On a similar note, edge stability analysis of the EAST discharges should be initiated, once reliable edge profiles become available.

2.3. Session III: laboratory experiments

There were five presentations in the lithium laboratory experiments session. The first talk entitled 'A laboratory study on the $J \times B$-force convected liquid metal plasma-facing component concept for boundary-controlled magnetic fusion experiment' by Y. Hirooka described an innovative concept, employing the $J \times B$ force to drive a GaInSn liquid metal flow. GaInSn based proof-of-principle experiments have been conducted successfully. GaInSn has also demonstrated particle pumping capabilities for both under hydrogen and helium plasma bombardment, and is therefore worth investigating as a PFM. Technical issues, however, need to be resolved include electro-chemical corrosion, particularly for lithium and Joule heating effects.

The rest of the session reports on significant progress on hydrogenic retention on lithiated surfaces. 'In-vacuo analysis of LTX wall samples exposed to lithium and implications for high-Z plasma-facing components in NSTX-U' was presented by R. Kaita. Experiments on LTX and NSTX with liquid lithium divertor and laboratory measurements show the ability of surfaces containing lithium and oxygen to bind hydrogenic species and that hydrogen retention does not necessarily depend on lithium hydride formation. This may also help reduce tritium inventory in PFCs but lithium surface temperature must be controlled.

'Comparative studies of H absorption/desorption kinetics and evaporation of liquid lithium in different porous systems and in free surfaces' was presented by E. Oyarzabal. A significant reduction of the evaporation rate was observed when Li was trapped in a microstructure of sintered stainless steel with a characteristic porous size of 5–10 microns. On the other hand, a negligible rate of H_2 uptake was found at temperatures above 500 °C in all cases. Interestingly, most of the hydrogen can be desorbed before Li is completely evaporated.

'Deuterium retention studies on lithiated–tugsten (Li–W) exposed to glow discharge plasmas under varying lithiation environment using LIBS and NRA' was presented by A. De Castro. In this work the deuterium retention on Li–W has been studied for the first time. Preliminary results indicate a comparable D uptake for W surfaces exposed to Li evaporation under He flow (only evaporation) and under He plasma conditions (evaporation and implantation), thus suggesting low retention by the implanted Li itself.

'Deuterium release from Li–D films deposited in magnetron discharge' was presented by Yu.M. Gasparyan. The major part of D was observed to desorb from Li–D films with a very sharp peak at 670–710 K. Air exposure leads to D release from the Li film without any additional heating. And finally, interaction (chemical reaction) with water vapor plays the main role in D removal from Li films.

2.4. Session IV: liquid metal tests in linear plasma devices

There were seven excellent talks in the session on liquid metals in linear plasma devices. A short summary of each is given below.

'Empirical phenomenon of lithium vapor cloud under argon plasma dumping with applied electric field' was given by W. Ou from the Institute of Nuclear Science and Technology at Sichuan University in Chengdu, China. He described a new liquid lithium loop. The liquid lithium biased target can be acted on by a single cathode cascaded arc plasma source. The maximum field is 0.45 T, and a 150 A, 10^{20} m^{-3} plasma with a T_e of 1 eV is produced. A mesh holds the lithium, and mesh dry out was observed when exposed to the plasma. Before the lithium is completely sputtered and evaporated away, evidence of vapor shielding is observed.

'Exposure of liquid lithium confined in a capillary structure to high plasma fluxes in PILOT-PSI' was given by A.B. Martin-Rojo from Euratom-Ciemat, Madrid, Spain. The influence of temperature on D retention was investigated. They studied hydrogen retention in liquid lithium and showed that at high temperature, little is retained.

'Free surface stability of liquid metal plasma facing components' was given by D. Ruzic from the University of Illinois at Urbana-Champaign, USA. Droplet formation was studied and experiments with differently sized trenches in a LiMIT device were compared to theoretical analysis. The key is to know the current induced in the lithium from the plasma. An experiment was set up to measure these currents. Using the measured currents, stability against droplet emission was predicted, and confirmed by the experiment.

'Results of reactor irradiation of liquid lithium saturated with deuterium' was given by Y. Tazhibayeva from Kazakhstan. Lithium samples which had been pre-loaded with 1.5% D by atomic percentage at different temperatures were irradiated with neutrons using a nuclear reactor. Thermal desorption spectroscopy was performed from 50 to 450 °C, with monitoring of the tritium and helium release. Above 400 °C T_2 was observed, and below that temperature, the main species was DT. Helium desorbed in small bursts from the liquid metal. Desorption rate coefficients as a function for temperature were determined.

'Interactions of tin with high flux plasma in SCU-PSI linear device' was given by X. Cao from the Institute of Nuclear Science and Technology Sichuan University, China. A tungsten mesh CPS system was wetted with Sn, and exposed to a linear plasma device similar to Pilot-PSI. A strong Sn signature in the spectra was not seen until 990 °C. At 887 °C the Sn began dripping off of the surface, and was not confined to the vertical mesh. Some alteration of the W mesh was seen, but this could be explained by ion beam effects or corrosion.

'Self-regulated plasma heat flux mitigation due to liquid Sn vapor shielding' was given by Thomas Morgan from DIFFER. Vapor shielding from Sn in a W CPS system was monitored. The temperature of the Sn goes to 1800 °C, and then stays independent of the heat flux. The target heat flux is reduced to 1/3 of its original value, due to vapor shielding. An oscillatory behavior was observed in the Sn temperature evolution.

'Lithium Granule Injection for High Frequency ELM Pacing on DIII-D' was given by A. Bortolon, and presented by R. Maingi. In ITER ELMs need to be triggered ~30 times faster than they would normally occur, to keep the heat fluxes to a manageable level. ELM triggering on DIII-D with the lithium granules was successfully demonstrated, with an enhancement over the natural ELM frequency by 2–4.

2.5. Session V: lithium metal theory/modeling

This session focused on the modeling of liquid metal concepts, including constraints on the models presently used. In the first talk on 'Lithium vapor box divertor' by R. Goldston, presented by M. Jaworski, a concept to use multiple physical boxes to differentially pump a high pressure and temperature lithium vapor was presented. The high pressure in the end box dissipates incoming plasma flux, while the differential pumping reduces the lithium reflux back to the plasma. Simple fluid modeling along with a 2D Navier–Stokes calculation supported the feasibility of the concept.

The talk 'Flow arrangement and heat transfer capabilities of a PFC in the form of a CPS' was given by L. Benos. This study analyzes the different concepts underpinning operation of a CPS for liquid metal PFCs. In particular, heat transfer considerations were addressed, and the static configuration was investigated numerically by calculating the shape of a liquid metal drop that rests on top of the CPS in contact with plasma, considering the capillary force, an external electric field, and the dielectric constants of the two media. Furthermore, the pore radius effects were investigated numerically. Upon decreasing the pore radius, the capillary rise velocity was seen to decrease linearly to the radius, owing to the emergence of radially-directed viscous effects. As the pore radius increased, the effect of liquid inertia becomes evident by reducing the seepage velocity.

Two talks titled 'Poiseuille flow of liquid Li in Fe and Mo microchannel' and 'Interatomic potentials and their applications to the interface properties of Li and materials used in fusion' were given by H. Deng. A computational method termed 'modified analytical embedded-atom method' was used to compute interatomic potentials for liquid lithium, as well as lithium alloys with Fe, W, Cu and Pb. The computed lithium properties for lattice constants, formation and migration energies agreed quite well with data. These computed potentials were then used to simulate the structural properties at the liquid lithium/solid iron interface at various interface temperatures. Predictions of resulting properties, e.g. diffusion of lithium atoms near this interface region, were made. It was shown that as the interface temperature increases, the layering in the liquid and the lateral ordering became weak. Finally, a talk titled 'Liquid lithium divertor for DEMO—boundary conditions at the divertor plate' was given by G. Pelka. A 2D edge transport code, TECXY, was used to simulate lithium performance in a CPS design for DEMO. The main conclusion was that CPS design appeared to be valid for DEMO, from an edge transport point of view. The heat removal was conduction limited, and detachment was not always observed. Both snowflake and standard divertors were simulated with the lithium CPS, but both configurations had advantages and disadvantages with respect to each other.

2.6. Session VI: LM technology

Seven reports were presented in this session, one of which was devoted to experimental studies. The goal of this experimental work, which was presented by S. Krat (National Research Nuclear University MEPhI, Moscow, Russian Federation), was to study wetting of solid lithium compounds formed through interaction of liquid lithium with atmospheric gases. This issue may be relevant for the using of lithium CPS in real tokamak experiments. In the course of these experiments the wetting of lithium compounds by liquid lithium was studied, and the surface tensions of Li_3N, Li_2O, Li_2CO_3 by liquid lithium were measured. It was discovered that the wetting points of Li_3N and Li_2O are in the range 250–260 °C and Li_2CO_3 has the highest wetting point among all lithium compounds at 323 °C, but which is below the wetting points for W, Ta and Mo (~350 °C).

The review of Dr A. Ibarra (CIEMAT, Spain) was devoted to the problem of the IFMIF-DONES Project: the neutron source for DEMO, the main aims of which are the early selection of DEMO technologies and the immediate specific needs for fusion materials database. The notable achievement was the successful demonstration of the validation of IFMIF lithium Target Facility with liquid Li (250 °C) flow speed at 15 m s^{-1} and the high long-term operation stability with $\pm$1 mm amplitude.

Dr B. Garcinuno (EUROfusion) presented the design of a permeation membrane against vacuum for tritium extraction from eutectic lithium–lead, which can be used in a future commercial fusion reactor. Currently, the conceptual design of the experimental device is carried out; the next step will be the implementation of its detailed design.

Dr R.G. Arrabal *et al* (Instituto de fusión nuclear, IFN, Spain) presented the paper 'Development of high corrosion-resistant coated for the inside of pipes'. The report contained a description of the equipment for pipe coating by sputtering of different materials available at IFN Institute. In particular, a coaxial magnetron was set up to cover the inner surface of pipes or tubes. For example, high purity W coatings with thickness in the μm range were deposited on the inner surface of steels pipes. Deposit of SiC is in the future plans.

Professor I. Tazhibayeva (National Nuclear Center, Kazakhstan) presented the 'Project—development of technology for fabrication of lithium CPS on the basis of carboxylic fabric coated with carbon nanotubes'. The project goal is the use of carbon nanotubes for a matrix of lithium CPS. The main advantages of this new material are: the high level of capillary forces provided by very-low effective radius (R_{eff}) of pores (nano-level), the thermal and mechanical stability.

Dr A. Vertkov *et al* ('Red Star' RF and EUROATOM-ENEA, Italy) presented the joint project of RF and Italy: 'Liquid tin limiter of FTU tokamak on basis of CPS (TLL Project)'. Liquid Sn has a high capability for withstanding of heat loads, up to tens of MW m^{-2}. The main task of this project is the experimental test of liquid Sn behavior in tokamak conditions. The activity of this project is on the stage of detailed design, with implementation scheduled in 2016.

Dr K. Kravalis (Latvia) gave a short review 'Lithium and lithium alloys research activities at Institute of Physics University of Latvia'. Their main focus is on the behavior of lithium and lithium alloys in strong magnetic fields, including (a) lithium film flow on a stainless steel matrix, (b) the behavior of liquid metal jets (Li, Ga) in magnetic fields up to 5 T, (c) blanket module tests in 5 T magnetic fields, (d) investigations of thermoelectromagnetic forces in CPS, (e) production of the PbLi eutectics, and (f) as the next step the characterization of PbLi corrosion process in EUROFER and permeation barriers under the effect of a magnetic field.

2.7. Session VII: lithium-safety and lithium handling

This session offered a forum for discussion after two initial presentations. The first, by Richard Nygren noted some areas of concern in ongoing work: simultaneous use of water and lithium planned in FTU, experience at Sandia with liquid metal embrittlement of a ferritic steel by lithium, and a fractograph in the presentation by researchers from Sichuan University that (Nygren observed) seemed to show liquid metal embrittlement of tungsten by tin. He also noted that safe handling of Li and awareness of Li safety are important for our research and in communicating with scientists, funders and the public about our work and noted his poster, 'Concerns about lithium safety and some implications for fusion components', at TOFE2014 in Anaheim, CA, USA.

At ISLA-3 Nygren agreed to form a working for the exchanging information on Li handling and safety, and he reported the progress. Also, Bob Kaita (PPPL, USA) summarized the Peer Review of Lithium Safety at the Princeton Plasma Physics Laboratory held in 2015.

The following points were suggested to launch open discussion that then continued into the general meeting discussion in Session 8: high volume Li systems (grams of Li $>$ explosive limit for vessel); protocols for safe experimental systems, for example possible new requirements being considered for NSTX-U of (a) no water and (b) inert argon purge system for the vessel; technology for safety such as catch basins and a circuit-closure method for detecting leaks in Li piping and PLC logic that requires 'all systems go' to enable use of equipment; and how much the program should focus on long term goals such as the integration of systems that involve the recovery of tritium versus more near term activities in research with lab systems.

3. Conclusions

New exciting results on the use of liquid metals as potential PFCs for a fusion reactor were reported in the fourth edition of the ISLA meeting in Granada, Spain. Furthermore, interesting and promising results on the use of lithium injection for ELM pacing and mitigation were presented. Noteworthy, extension of the studies to other liquid metals than lithium was significant. As a realistic solution for the choice of PFCs beyond ITER is direly needed, liquid metal research is becoming a key element in the research programs of all ITER partners. Such a research endeavor has been systematically addressed in the ISLA events according to the following sequence:

1. 1st workshop was held at NIFS Toki, Japan in 2010;
2. 2nd workshop was held at PPPL Princeton, USA in 2011;
3. 3rd workshop was held at ENEA Frascati, Italy in 2013;
4. 4th workshop was held by NIF at Granada, Spain in 2015;
5. 5th workshop to be held at TRINITI Moscow, Russian Federation in 2017.

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