

# Experiments of continuously and stably flowing lithium limiter in EAST towards a solution for the power exhaust of future fusion devices

Hu J.S.<sup>a,b,\*</sup>, Zuo G.Z.<sup>a</sup>, R. Maingi<sup>c</sup>, Sun Z.<sup>a</sup>, K. Tritz<sup>d</sup>, Xu W.<sup>a,e</sup>, Yang Q.X.<sup>a</sup>, D. Andruczyk<sup>f</sup>, Huang M.<sup>a</sup>, Meng X.C.<sup>a,e</sup>, Gong X.Z.<sup>a</sup>, D.N. Ruzic<sup>f</sup>, Ni M.J.<sup>g</sup>, Wan B.N.<sup>a</sup>, Li J.G.<sup>a</sup>, EAST team<sup>a</sup>

<sup>a</sup> Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

<sup>b</sup> CAS Key Laboratory of Photovoltaic and Energy Conservation Materials, Hefei 230031, China

<sup>c</sup> Princeton University, Plasma Physics Laboratory Princeton, Princeton, NJ 08543, USA

<sup>d</sup> Johns Hopkins University, Baltimore, MD 21211, USA

<sup>e</sup> Advanced Energy Research Center, Shenzhen University, Shenzhen 518060, China

<sup>f</sup> University of Illinois at Urbana-Champaign (UIUC), Urbana, IL 61801, USA

<sup>g</sup> University of Chinese Academy of Sciences, Beijing 100049, China

## ARTICLE INFO

### Keywords:

Limiter  
Lithium  
Plasma facing component  
EAST

## ABSTRACT

Liquid lithium (Li) can partly ameliorate lifetime and power-exhaust issues of plasma facing components (PFCs) by enabling a self-healing, self-replenishing surface with a reduced susceptibility to neutron damage in future fusion devices. To assess operational stability and heat-exhaust capability under tokamak exposure, two generations of continuously flowing liquid Li (FLiLi) limiters on the concept of a thin flowing Li film have been successfully designed and tested in high performance discharges in EAST. The design uses a circulating Li layer with a thickness of  $<0.1$  mm and a flow rate  $\sim 2$  cm<sup>3</sup>s<sup>-1</sup>. In addition, the limiter employs a novel electromagnetic pump to drive liquid Li flow from a collector at the bottom of the limiter into a distributor at its top. Free surface gravitational flow closes the loop for a continuously flowing liquid Li film on the wetted PFC. Here we summarize key FLiLi limiter development and experimental results in H-mode plasmas.

## 1. Introduction

In contrast to present experimental fusion devices and the next generation device, ITER, power producing fusion reactors, i.e. DEMO, should be operated in a steady-state regime with a burning plasma lasting for hours and lifetime neutron radiation doses from 30–150 dpa. DEMO needs motivate the development of long-life plasma facing components (PFCs) with low sputtering, low activation, high power handling, as well as good compatibility with high performance plasmas. For this reason, liquid metals have been suggested to partly ameliorate lifetime and power-exhaust issues by allowing for a self-healing, self-replenishing surface with no susceptibility to neutron damage in the liquid channel [1,2]. For stable operation in tokamaks and adequate heat-exhaust capabilities, a continuously flowing liquid metal PFCs is attractive for DEMO and beyond.

Candidate liquid metals and/or alloys include Li, Sn, Ga, and SnLi alloys [3–8]. Present-day experimental research focuses on liquid Li due to its low melting point and beneficial behavior on plasma performance [9–12]. Using Li as a plasma facing material, static liquid Li PFCs with

free surface structures have been tested in CDX-U [13], and with mesh-like or porous structure in the devices T-10 [14], FTU [15], and NSTX [16]. Those experimental results confirmed that the application of liquid Li PFCs enhanced plasma performance. Meanwhile, it was also observed that liquid Li surfaces can withstand heat flux over 10 MW/m<sup>2</sup> [17], partly due to heat load mitigation on the first wall via Li radiation.

The institute of plasma physics in China (ASIPP) has maintained a long-term program on the Li application for PFCs on two superconducting tokamaks over the past decade. In the HT-7 tokamak with a limiter configuration, we explored various designs using a static liquid Li limiter with either a free surface structure or with a CPS structure. It was confirmed that the limiter was beneficial for the improvement of plasma confinement. However, we also found that Li droplet ejection due to  $J \times B$  force on the limiters sometimes led to plasma disruption, if using Li films thicker than 1 mm. Further investigation showed that thin Li film with CPS would reduce Li droplet ejection. Therefore, based on these experiments, a flowing liquid Li (FLiLi) limiter on the concept of a thin flowing Li film on an actively-cooled heat sink was proposed and tested in HT-7 [18]. Initial experiments in HT-7 showed that the FLiLi

\* Correspondence author at: Tokamak Experimental Division, Institute of Plasma Physics, P.O. Box 1126, No. 350, Shushanghu Road, Hefei, Anhui 230031, China.  
E-mail address: [hujis@ipp.ac.cn](mailto:hujis@ipp.ac.cn) (J.S. Hu).

limiter would result in reduction of particle recycling, suppression of impurity emission and improvement of the confinement, which motivated the design of a more sophisticated Li limiter for use on H-mode plasmas in EAST diverted discharges.

EAST was built to demonstrate high-power, long-pulse operation under fusion-relevant conditions, with major radius  $R = 1.9$  m, minor radius  $a = 0.5$  m and design pulse length up to 1000 s [19]. The maximum plasma current and toroidal field currently achieved in EAST are  $I_p = 1$  MA and  $B_T = 3.5$  T. EAST has an ITER-like D-shaped cross section with two symmetric divertors at the top and bottom, accommodating both single null (SN) and double null (DN) divertor configurations. In order to facilitate long-pulse operations, EAST undertook an extensive upgrade to replace carbon tiles on the main chamber wall by molybdenum (Mo) tiles in 2012 and on the top divertor by tungsten (W) in 2014. Application of Li coating in EAST resulted in significant improvement of H-mode confinement, reduction of the L-H power threshold, and reduction in the divertor peak heat flux while maintaining low Li concentration in the core plasma, contributing to the record-long 101.2 s H-mode discharges [20]. In addition real-time Li powder injection resulted in a long ELM-free H mode plasma without transient heat flux or impurity accumulation [21].

Based on the concept of a thin flowing film that was initially tested in HT-7, two generations of FLiLi limiters have been developed and successfully tested in EAST, with a goal to create a continuously flowing (i.e. with no interruptions) liquid Li film in order to resolve the problem of contamination of Li surface monolayers by residual outgassing from the walls. The structure and design of the FLiLi limiters have been optimized step-by-step to achieve continuous and stable flow of the Li PFCs without droplet ejection. Meanwhile, the interactions between the plasma and flowing Li PFCs have been systemically investigated. This innovative effort aims to address the programmatic goals of the EAST, and to advance worldwide fusion energy and science development. The main results of design, development and experiment of the FLiLi limiters on EAST are summarized in this paper. Comparison of the design and results of two generation flowing Li limiter will be done, and the main results will be shown in a clear way.

## 2. Design upgrades of the FLiLi limiter

To get a smooth Li flow, as well as a pumping layer for particle control, i.e. deuterium recycling and impurity production, the thickness of the active pumping layer  $\sim 0.01$  mm is smaller than the thickness of the entire Li layer  $\sim 0.1$  mm, which is much smaller than the width and length of the limiter, as shown in Fig. 1. In this case, a few basic issues for the control of droplet ejection, particle pumping and heat removal were considered together. First, application of a thin Li film flow with a

thickness of less than 0.1 mm is expected to reduce the plasma-induced current in the Li. Then, surface tension competes against the  $J \times B$  force induced by the plasma, which is beneficial for the suppression of Li droplet ejection from the limiter surface. Second, the particle flux from plasma to the walls is less than  $10^{22}$  D/s, which means fast flow is not required to pump particles. We chose a Li flow rate of about  $2 \text{ cm}^3/\text{s}$ , or  $\sim 10^{23}$  Li atom flowing on the limiter surface per second. Assuming a 10% likelihood that a Li atom would capture D particles from the plasma, the particle flux from the plasma can be pumped. Third, the FLiLi limiter uses a thin guide plate substrate with the thickness of  $< 0.5$  mm, brazed on a copper heat sink with active cooling for power exhaust. The heat flux removal of this design is expected to be comparable with solid PFCs, neglecting the heat removed directly by the flowing Li. In addition, the FLiLi limiter is expected to improve heat flux control using vapor shielding effect to reduce heat flux with sufficient Li evaporation from FLiLi into the plasma, which is similar as that during Li injection. For Li temperature  $< 450^\circ\text{C}$ , this system can be viewed as a flowing PFC, due to low evaporation rates. At higher evaporation rates, the system can be used for active Li wall conditioning.

To design a continually FLiLi limiter system, a substrate plate with a copper heat sink to support Li flow, a Li distributor with well-separated flow channels, a liquid Li driving system, and a collector (also named as reservoir) are included, as shown in Fig. 1. The copper heat sink with dimensions  $350 \text{ mm} \times 300 \text{ mm} \times 19 \text{ mm}$  comprises the main body of the limiter. A thin SS foil brazed to the copper plate serves as a substrate plate to support Li flow and a protective layer between the liquid Li and the copper heat sink. In practice, the liquid Li flow is gravity-driven along the plasma-facing guide plate down to the collector. In this case, while as Li flows along the surface of the guide plate, plasma is expected to wet the flowing Li in the central area, as shown as the red zone in the Fig. 1. From this design, a thin film of liquid Li distributed uniformly on the SS plate is needed. For this purpose, the design contains a special distributor at the top of the limiter, which is an array of 200 horizontal channels ( $0.8 \text{ mm} \times 0.8 \text{ mm}$ ) perpendicular to the toroidal magnetic field to provide a uniform supply of liquid Li onto the guide plate. The temperature of the limiter was controlled using three FeCrAl wire heaters and cooling channels embedded in the backside of the copper plate. In order to accomplish the initial wetting, a bulk plate temperature approaching  $500^\circ\text{C}$  and to ensure rapid cooling of the copper plate after wetting to limit Li evaporation, an active cooling system employing 5 MPa of circulating He gas in the cooling channels was implemented. Thus, temperature could be controlled from  $300\text{--}400^\circ\text{C}$  during plasma discharges. The Li reservoir/collector is a storage vessel of liquid Li located at the bottom of the limiter. In order to drive stable liquid Li flow in fusion devices, a novel inner EM pump was designed and applied. Its basic components include positive electrode and

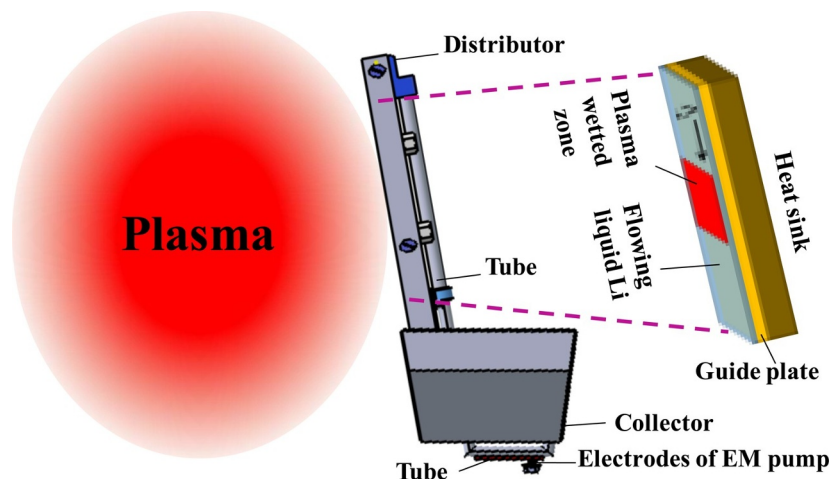


Fig. 1. Sketch of the FLiLi limiter in EAST tokamak.

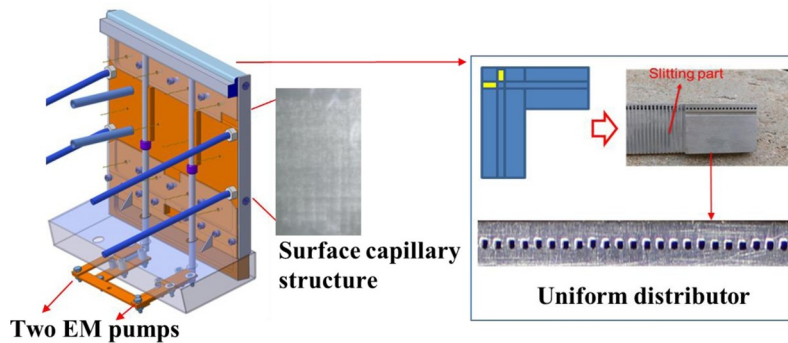


Fig. 2. Main upgrades for the second generation FLiLi limiter in EAST.

cathode, embedded in the liquid Li feed pipe. The liquid Li is driven by the  $J \times B$  force. The current comes from an external DC power supply, and the magnetic field from the steady-state toroidal magnetic field of EAST. The EM pump current is adjustable from 0 to 100 A. The maximum driven pressure from the EM pump is about 24 kPa, which is sufficient to drive Li upward on the plate at a rate of  $\sim 3 \text{ cm}^3 \text{ s}^{-1}$ . These components make the Li flow become a closed recirculation loop. Li is driven in the tube behind the plate from the collector to the distributor by the EM pump, and then it returns back to the collector through the surface of the substrate plate.

In addition, a liquid Li supply system is designed to fill Li to the collector and to wet the front surface of limiter, prior to positioning the limiter into the EAST plasma vessel by a movable system. The movable system, upgraded from an existing material and plasma evaluation system (MAPES), was designed to insert the limiter as far as 2.5 m to contact with the separatrix nominally at  $R \sim 2.28 \text{ m}$ , i.e. 6.7 cm inside of the fixed Mo limiter in the machine [22]. For safety reasons, the design involves a minimum inventory of Li and uses only low hydrostatic (and electromagnetic) pressure to move that inventory. Further, no mechanical part or joint comes in contact with liquid Li to minimize corrosion effects.

The 1st generation FLiLi limiter was tested in EAST in 2014. Continuous closed-loop flow of FLiLi was achieved for three hours through a sequence of plasma discharges [22]. The FLiLi was found to be effective to reduce impurities and recycling, and to improve plasma confinement. However, some issues including Li non-uniform distribution on the limiter surface and surface erosion were observed. Therefore, in order to resolve these problems, an upgraded 2nd generation FLiLi limiter for improved Li coverage uniformity and erosion resistance was successfully used in 2016 in the EAST device [23]. This 2nd generation limiter, as shown in Fig. 2, had several design improvements over the 1st generation limiter: 1) a thicker stainless steel protective layer (0.5 mm vs. 0.1 mm) to avoid macroscopic surface erosion; 2) an additional  $j \times B$  magnetic pump (two vs. one) for uniform flow; 3) surface texturing in the 2nd generation for improved wetting; and 4) an improved method for manufacturing the top Li distributor, which developed a crack in the original deployment.

### 3. Experimental results

During plasma experiments, the movable FLiLi limiter was located at the H port on EAST. At first, the FLiLi was pushed into the SOL within a few cm of the separatrix at  $Z \sim 0.122 \text{ m}$ , just above the outer mid-plane, beyond the main limiter at  $R = 2.35 \text{ m}$ . Then the FLiLi limiter was inserted step-by-step for contact with hot plasma with the separatrix at  $r = 2.283 \text{ m}$  during plasma experiments. In the first experiment in 2014, the plasma current ( $I_p$ ) was 0.4 MA, toroidal magnetic field ( $B_T$ ) was 1.9 T, in the lower-single null (LSN) configuration on the graphite divertor. In the second experiment in 2016, we used  $I_p = 0.45 \text{ MA}$ ,  $B_t = 2.6 \text{ T}$ , in the upper-single null (USN) configuration

on the tungsten divertor. The maximum auxiliary heating power was increased from 2 MW in 2014 to 4.5 MW in 2016 to increase the heat flux to the limiter.

#### 3.1. Li flow uniformity and erosion resistance

Both sets of FLiLi experiments confirmed that the liquid Li can be driven by built-in DC EM pumps to form a recirculating, closed-loop system. It was found that the flow rate of liquid Li could be controlled by adjusting the DC current. Observed by a visible CCD camera the time resolution of 8.2 ms, Fig. 3 shows the surface of SS foil plate with various driving DC current of the EM pump and at different phases of plasma exposure in the 2014 experiment. Comparing the panels 3(a) and (b) during the plasma ramp-up phase at 0.2 s, a few bright vertical lines representing individual Li streams on the plate were formed in 3(b), even at a low EM pump current of 20 A. In comparison panel 3(a) shows a simple horizontal stripe of plasma-wall interaction. After plasma ramp-up, it is difficult to see individual Li streams in 3(c), suggesting more uniform flow coverage.

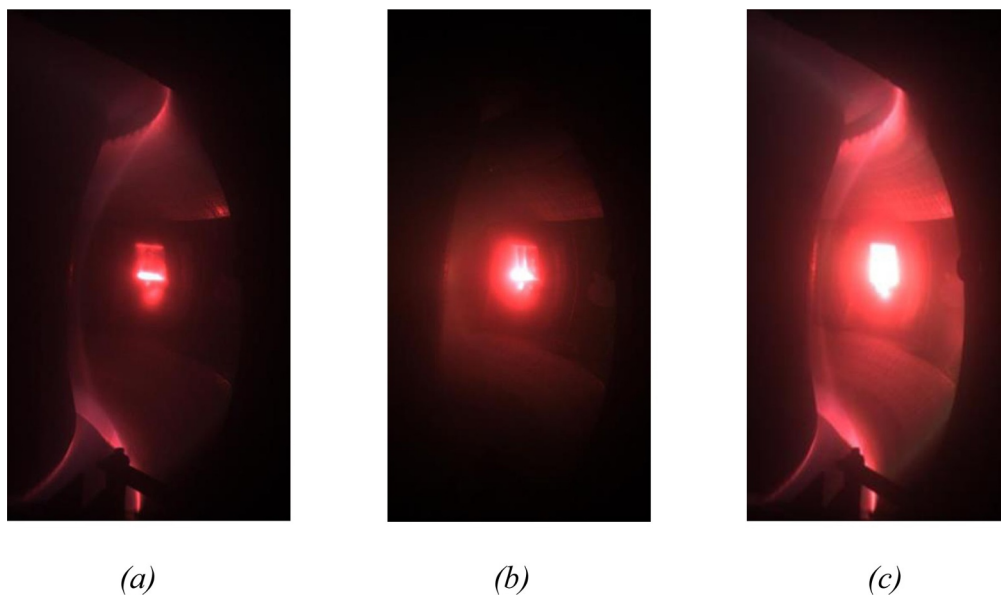
Unfortunately, comparable CCD camera images of the limiter were unavailable in the 2016 experiment. However, Li spectroscopic emission in 2016 was smoother than that in the 2014 experiment. In minor contrast to the 2014 experiment, there was no Li strong bursts in 2016 and very few plasma disruptions, even though the plasma heating power was increased from 2 MW in 2014 to 4.5 MW in 2016. Meanwhile, we compared the SS foil surface of the FLiLi limiters after plasma exposure after the two experiments, as shown in Fig. 4. It is shown that the fractional surface area that was wetted (outside red outlines) by the Li was  $\sim 30\%$  in the 2014 experiment and increase to  $>70\%$  in the 2016 experiment using the upgraded 2nd generation limiter. Meanwhile, after the 2014 experiment, visible damage was found on the surface of the SS foil plate, which was successfully avoided in the 2016 experiment using the 2nd limiter. The increase of the thickness of SS foil in the 2016 experiments appears to have improved resistance to surface erosion, even though the 2016 limiter was exposed to a higher power heating plasma. The other design changes, i.e. doubling the number of  $J \times B$  magnetic pumps, surface texturing, and a Li distributor with well-made channels, were beneficial for more uniform flow in 2016 compared with 2014.

#### 3.2. Heat flux control and removal

Liquid metal walls have a few advantages for heat flux control and removal over solid PFCs, which was confirmed by the FLiLi experiments on EAST. These are described sequentially below.

First, the heat absorbed directly from plasma can be removed via convection from thin Li film to the thin guide walls, and then to the heat sink. If the heat sink is well-designed with an active cooling system, the capacity of FLiLi limiter for heat removal should be comparable with solid PFCs. The heat flux exhausted by the 2nd generation limiter was



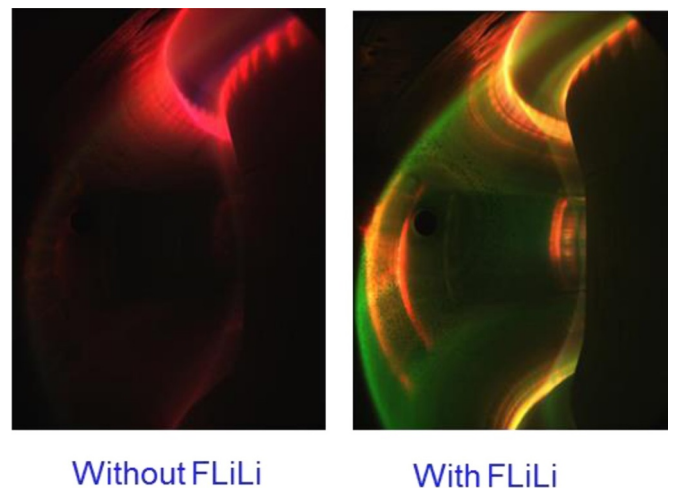


**Fig. 3.** Li Flow on the surface of SS guide plate: (a). without DC current, at the ramp up phase of plasma at 0.2 s; (b). with 20 A DC current, at the ramp up phase of plasmas at 0.2 s; (c). with 20 A DC current, at the flat-top phase at 2.75 s.

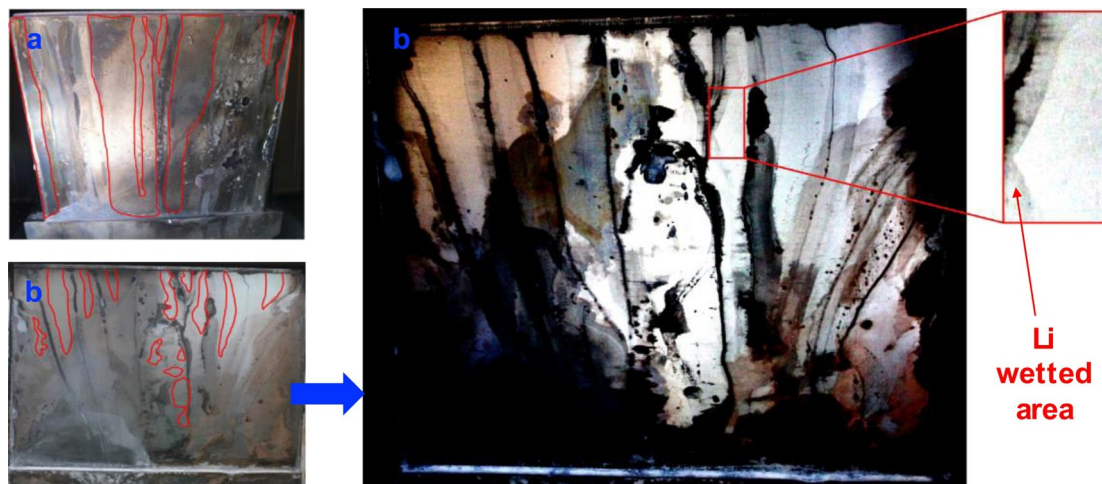
up to  $4 \text{ MW/m}^2$ , limited by the deployed auxiliary heating power and 2.5 MPa He gas cooling.

Second, heat load on the FLiLi limiter can be partly removed via Li evaporation from the surface. In the FLiLi experiments, a bright Li radiative mantle appeared at the plasma edge during FLiLi operation, as shown in Fig. 5 (with similar results in the 2014 experiment shown in reference [24]). Li passive particle efflux from FLiLi into the plasma was estimated at  $>5 \times 10^{20} \text{ atom s}^{-1}$ , mostly due to surface evaporation. With increasing heat flux on the limiter, i.e. with increased auxiliary heating power and/or proximity to the separatrix, the evaporation increases due to high surface temperature on FLiLi. Li bursts were observed in 2014 during brief temperature excursion and released Li atoms into the scrape-off layer (SOL), which was beneficial for cooling down of the Li surface [22]. Partly due to this evaporation, the Li surface temperature was well controlled to  $<450^\circ\text{C}$  during the EAST experiments.

Third, power radiation by Li particles, evaporated from the limiter and ionized in the SOL plasma, can reduce the plasma heat flux to FLiLi. Those evaporated Li particles transported toroidally to gradually form a bright Li radiative mantle with an obvious poloidally asymmetric



**Fig. 5.** Li ionized and transported at edge in plasma during the 2016 experiment of the 2nd flowing liquid Li limiter.



**Fig. 4.** Comparison of the SS foil surface of flowing liquid Li limiter after plasma exposure (a. after the 2014 experiment using 1st FLiLi limiter; b. after the 2016 experiment using the 2nd FLiLi limiter.).

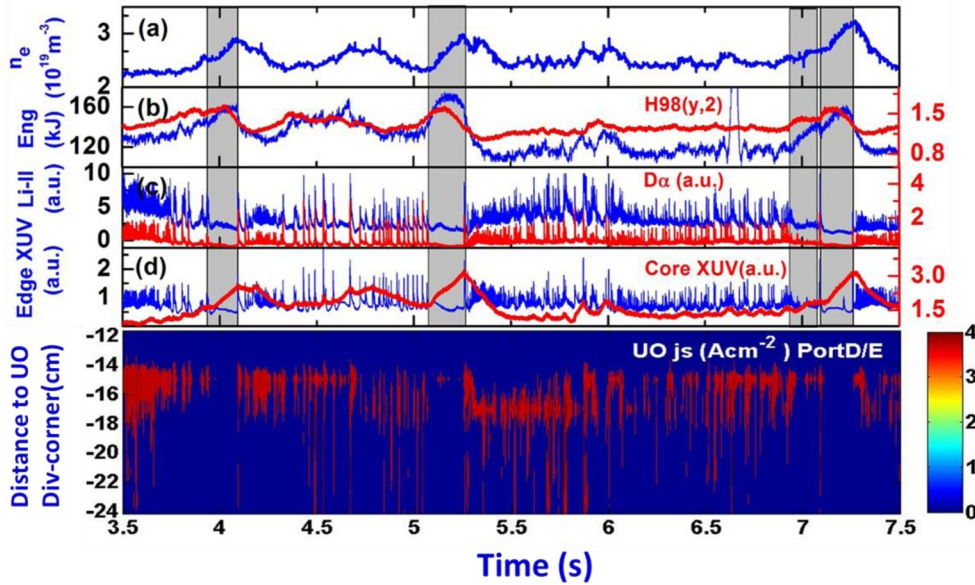


Fig. 6. Transient ELM-free H-modes achieved using the FLiLi limiter in EAST in 2016 (a, plasma density; b, stored energy and  $H_{98(y,2)}$ ; c, Li-II and  $D\alpha$  emission; d, Core and edge XUV radiation; and particle flux from Langmuir probes on outer target plate of upper W divertor.).

emission distribution. This strong Li radiation effectively reduced the divertor peak heat flux and a  $\sim 15\%$  reduction of the divertor strike point temperature [24]. This Li evaporation from FLiLi has similarities to the use of low-Z impurity injection for heat flux control in tokamaks.

Fourth, we found that passive Li injection successfully mitigated transient heat fluxes from ELMs. It is found that ELM frequency and amplitude gradually decreased discharge-by-discharge during the FLiLi experiment [23], which is similar to the gradual ELM mitigation by real-time Li aerosol injection in successive discharges in EAST [25].

Finally, the plasma wetted area was significantly enlarged by the FLiLi limiter, which may be the most important facet of heat flux control of liquid metal PFCs. As shown in Fig. 3, compared the solid surface (panel a), the plasma wetting area expanded to the surface with Li flowing Li (panel b) and then to all surface of the limiter (panel c). This significantly reduce the peak heat flux to the limiter, which will decrease the surface erosion and mitigate impurities production. This effect is also beneficial for power exhaust. The normal midplane heat flux width in EAST with  $I_p = 0.45$  in single-null configuration is about 1 cm [26]; for a normal area multiplication factor (divertor flux expansion and poloidal PFC tilt) of 3, outer strike point radius  $\sim 1.7$  m, and a 30% SOL heat flux width in the private flux as compared to the main SOL, a divertor wetted area  $\sim 0.4$  m<sup>2</sup> is computed. The finite size FLiLi limiter by itself has a 0.1 m<sup>2</sup> area; due to the use of a flowing liquid PFC, the entire surface area is used for power exhaust. A full toroidal belt limiter with flowing liquid metal would have nearly 50 times the surface area of FLiLi, i.e. 10 times the wetted area of the divertor in these EAST experiments.

### 3.3. Impact on the plasma performances

Both the 2014 and 2016 experiments showed that using FLiLi is beneficial for the impurity suppression and recycling reduction, which is similar to results from Li wall conditioning experiments. These elements help to improve plasma performance.

In ohmic plasmas [22], loop voltage ( $V_p$ ) slightly decreased and stored energy ( $W_{dia}$ ) slightly increased with FLiLi. In addition, actively flowing Li led to a measurable albeit modest reduction of over 10% in the divertor  $D\alpha$ , representing a reduction in target plate recycling. In addition, the influx of Li to plasma, calculated from Li-II emission, was 2.5 times higher with FLiLi than when without liquid Li flow. Also, the radiation in the core plasma is modestly lower with active Li flow than

without. Specifically, H-mode plasmas via neutral beam and lower hybrid wave (LHW) heating were fully compatible with insertion of the FLiLi limiter into the SOL. Finally, ELMs were partially mitigated using FLiLi limiter, with evidence of short ( $< 150$  ms) ELM-free phases.

In the 2016 experiments, FLiLi limiter was demonstrated to be compatible with 4.5MW auxiliary heating plasma with LHW heating, ion cyclotron resonance heating and electron cyclotron resonance heating. An enhanced and controllable Li emission layer at the plasma edge, due to the strong interaction between liquid lithium surface and plasma, modestly reduced divertor plate heat flux and slightly increased the plasma stored energy. Also, ELM frequency and amplitude are both lower with the FLiLi limiter than in discharges without the FLiLi limiter. Moreover, transient ELM-free H-modes with a strong 25% increase of  $W_{MHD}$  and  $H_{98}$  were observed for the first time in 2016 with the FLiLi limiter, as shown in Fig. 6.

## 4. Discussion and summary

Continuously flowing liquid Li limiters, based on the concept of thin film flow, have been successfully developed in the EAST device. Several key techniques and methods have been demonstrated. We confirmed that the liquid Li can be driven by built-in DC EM pumps to form a recirculating, closed loop system for fusion devices. The increase of the thickness of the SS foil in the 2016 FLiLi experiments was improved the resistance to surface erosion, even with higher auxiliary heating power. Also, increasing the number of the  $J \times B$  magnetic pumps, surface texturing, and improvements to distributor manufacturing, promoted more uniform Li flow in 2016 compared with 2014. The FLiLi limiter was found to be fully compatible with various plasma scenarios, including H-mode plasmas heated by lower hybrid waves or by neutral beam injection.

It was also found that the passive lithium emission from the limiter was beneficial for the reduction of recycling and impurities, for the reduction of divertor heat flux, and in certain cases, for the improvement of plasma stored energy, which is encouraging for the use of flowing liquid lithium PFCs in future fusion devices. Furthermore, heat flux control and exhaust using liquid metal PFCs is comparable to or possibly better than solid PFCs. Power exhaust with FLiLi also is augmented via vapor shielding, radiation, ELM mitigation, and Li evaporation. Most importantly, the FLiLi limiter would enlarge the plasma wetted area to reduce peak heat flux, which is one of main issues for

divertor design using solid material. Third generation FLiLi limiters using Mo instead of SS as the substrate material have been developed and will be tested soon in EAST.

## Acknowledgments

This research is funded by National Key Research and Development Program of China (2017YFA0402500), National Nature Science Foundation of China (11625524, 11775261, 11605246, 11075185 and 11021565) and as well as the US Department of Energy contract DE-AC02-09CH11466.

## Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.nme.2018.12.017](https://doi.org/10.1016/j.nme.2018.12.017).

## References

- [1] L.E. Zakharov, et al., Ignited spherical tokamaks and plasma regimes with LiWalls, *Fusion Eng. Des.* 72 (2004) 149 <https://doi.org/10.1016/j.fusengdes.2004.07.015>.
- [2] L.E. Zakharov, et al., Low recycling regime in ITER and the LiWall concept for its divertor, *J. Nucl. Mater.* 363–365 (2007) 453 <https://doi.org/10.1016/j.jnucmat.2007.01.230>.
- [3] J.W. Coenen, et al., Liquid metals as alternative solution for the power exhaust of future fusion devices: status and perspective, *Phys. Scr.* T159 (2014), <https://doi.org/10.1088/0031-8949/2014/t159/014037>.
- [4] J.P.S. Loureiro, et al., Behavior of liquid Li-Sn alloy as plasma facing material on ISTTOK, *Fusion Eng. Des.* 117 (2017) 208 <https://doi.org/10.1016/j.fusengdes.2016.12.031>.
- [5] Y. Hirooka, et al., Hydrogen and helium recycling from a JxB-force convected liquid metal Ga67In20.5Sn12.5 under steady state plasma bombardment, *Fusion Eng. Des.* 117 (2017) 140 <https://doi.org/10.1016/j.fusengdes.2016.06.028>.
- [6] M. Ono, et al., Liquid lithium applications for solving challenging fusion reactor issues and NSTX-U contributions, *Fusion Eng. Des.* 117 (2017) 124 <https://doi.org/10.1016/j.fusengdes.2016.06.060>.
- [7] F.L. Tabares, et al., Comparative studies of liquid metals for an alternative divertor target in a fusion reactor, *Phys. Scr.* T170 (2017) 014054 <https://doi.org/10.1088/1402-4896/aa9201>.
- [8] M.G. Hvesta, et al., Demonstrating electromagnetic control of free-surface, liquid-metal flows relevant to fusion reactors, *Nucl. Fusion*. 58 (2018), <https://doi.org/10.1088/1741-4326/aa9344>.
- [9] D.K. Mansfield, et al., Observations concerning the injection of a lithium aerosol into the edge of TFTR discharges, *Nucl. Fusion* 41 (2001) 1823 <https://doi.org/10.1088/0029-5515/41/12/310>.
- [10] J.S. Hu, et al., Investigation of lithium as plasma facing materials on HT-7, *Fusion Eng. Des.* 85 (2010) 930 <https://doi.org/10.1016/j.fusengdes.2010.08.034>.
- [11] G.Z. Zuo, et al., Lithium coating for H-mode and high performance plasmas on EAST in ASIPP, *J. Nucl. Mater.* 438 (2013) S90 <https://doi.org/10.1016/j.jnucmat.2013.01.014>.
- [12] M. Ono, et al., Conference report on the 2nd international symposium on lithium applications for fusion devices, *Nucl. Fusion* 52 (2012) 037001 <https://doi.org/10.1088/0029-5515/52/3/037001>.
- [13] R. Majeski, et al., Recent liquid lithium limiter experiments in CDX-U, *Nucl. Fusion* 45 (2005) 519 <https://doi.org/10.1088/0029-5515/45/6/014>.
- [14] S.V. Mirnov, et al., Li experiments on T-11M and T-10 in support of a steady-state tokamak concept with Li closed loop circulation, *Nucl. Fusion* 51 (2011) 073044 <https://doi.org/10.1088/0029-5515/51/7/073044>.
- [15] G. Mazzitelli, et al., Review of FTU results with the liquid lithium limiter, *Fusion Eng. Des.* 85 (2010) 896 <https://doi.org/10.1016/j.fusengdes.2010.08.038>.
- [16] M.A. Jaworski, et al., Liquid lithium divertor characteristics and plasma-material interactions in NSTX high-performance plasmas, *Nucl. Fusion* 53 (2013) 083032 <https://doi.org/10.1088/0029-5515/53/8/083032>.
- [17] S.V. Mirnov, et al., Experiments with lithium limiter on T-11M tokamak and applications of the lithium capillary-pore system in future fusion reactor devices, *Plasma Phys. Control. Fusion* 48 (2006) 821 <https://doi.org/10.1088/0741-3335/48/6/009>.
- [18] J. Ren, et al., First experiment results of flowing liquid lithium limiter in HT-7, *Phys. Scr.* T159 (2014) 014035 <https://doi.org/10.1088/0031-8949/2014/t159/014035>.
- [19] J. Li, et al., A long-pulse high-confinement plasma regime in the experimental advanced superconducting tokamak, *Nature Phys.* 9 (2013) 817 <https://doi.org/10.1038/nphys2795>.
- [20] X.Z. Gong, et al., 59th Annual Meeting of the APS Division of Plasma Physics, Milwaukee, Wisconsin, 2017.
- [21] J.S. Hu, et al., New steady-state quiescent high-confinement plasma in an experimental advanced superconducting tokamak, *Phys. Rev. Lett.* 114 (2015) 055001 <https://doi.org/10.1103/PhysRevLett.114.055001>.
- [22] J.S. Hu, et al., First results of the use of a continuously flowing lithium limiter in high performance discharges in the EAST device, *Nucl. Fusion* 56 (2016) 046011 <https://doi.org/10.1088/0029-5515/56/4/046011>.
- [23] G.Z. Zuo, et al., Upgraded flowing liquid lithium limiter for improving Li coverage uniformity and erosion resistance in EAST device, *Rev. Sci. Instrum.* 88 (2017) 123506 <https://doi.org/10.1063/1.4997806>.
- [24] G.Z. Zuo, et al., Mitigation of plasma-material interactions via passive Li efflux from the surface of a flowing liquid lithium limiter in EAST, *Nucl. Fusion* 57 (2017) 046017 <https://doi.org/10.1088/1741-4326/aa5ea0>.
- [25] R. Maingi, et al., ELM elimination with Li powder injection in EAST discharges using the tungsten upper divertor, *Nucl. Fusion* 58 (2018) 024003 <https://doi.org/10.1088/1741-4326/aa9e3f>.
- [26] L. Wang, et al., Particle and power deposition on divertor targets in EAST H-mode plasmas, *Nucl. Fusion* 52 (2012) 063024 <https://doi.org/10.1088/0029-5515/52/6/063024>.