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Flowing liquid Lithium PFCs studies at the EAST tokamak

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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, three 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, with a goal to create a continuously flowing 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 design uses a circulating Li layer with a thickness of <0.1 mm and a flow rate ~2 cm^3s^{-1} to get a smooth Li flow, as well as a pumping layer for particle control. In this case, a few basic issues for the control of droplet ejection, particle pumping and heat removal were considered together. A thin Li film flow is expected to reduce the plasma-induced current in the Li. Then, surface tension competes against the J×B force induced by the plasma for the suppression of Li droplet ejection from the limiter surface. A Li flow rate of about 2cm^3/s, or ~10^{23} Li atom would capture D particles from the plasma (a 10% likelihood of Li atom to D particles).

The FLiLi limiter uses a thin guide plate substrate with the thickness of < 0.5mm, 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 < 450ºC, this system can be viewed as a flowing PFC, due to low evaporation rates.

To design a continually FLiLi limiter system with a closed recirculation loop, a substrate plate with/without 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 limiter surface is 350 mm × 300 mm. In practice, the liquid Li flow is gravity-driven along the plasma-facing guide plate down to the collector. A special distributor at the top of the limiter, which is an array of 200 horizontal channels perpendicular to the toroidal magnetic field to provide a uniform supply of liquid Li onto the guide plate. Wire heaters and cooling channels embedded in the backside of the plate use for temperature control. A 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 dedicated inner EM pump was designed and applied. The current comes from an external DC power supply, and the magnetic field from the steady-state toroidal magnetic field of EAST. 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 though the surface of the substrate plate.

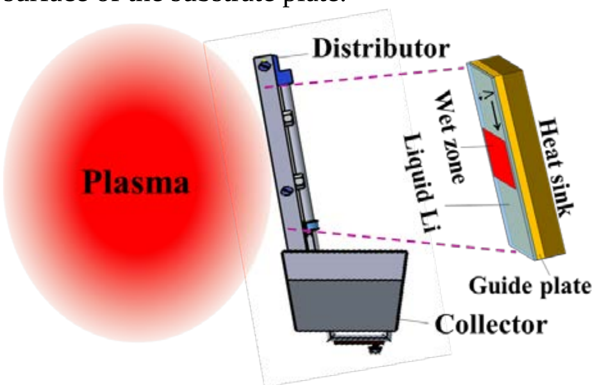


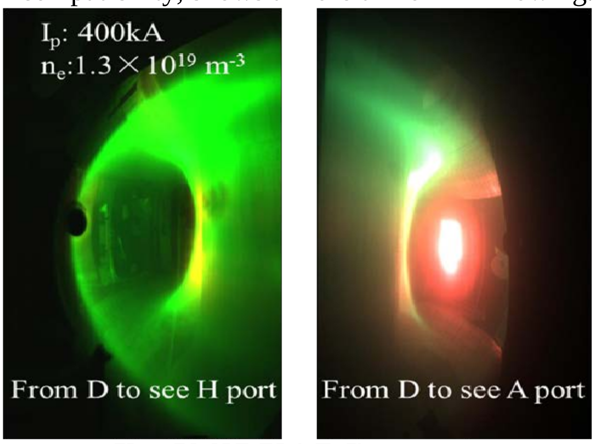
Fig. 1, Sketch of the FLiLi limiter in EAST

The science and technology of flowing liquid lithium limiters has been advanced via US-PRC PMI collaboration on EAST. Three generations of liquid lithium limiters tested in EAST, as listed in table 1. The main difference is material and thickness of SS substrate, heat sink using copper alloy or Mo body. The variety of position espoused to plasma leads different heat flux from plasma. The movable system, upgraded from an existing material and plasma evaluation system (MAPES), was designed to insert the limiter as far as 2.5m to contact with the separatrix nominally at R~2.28 m, i.e. 6.7 cm inside of the fixed Mo limiter in the machine. Gen. 1 tested in HT-7 in 2012 and then EAST in 2014. Gen. 2 tested in EAST in 2016. Gen. 3 tested in 2018.

Generation	Heat Sink	SS thickness (mm)	JxB pumps	Max. P_{aux} (MW)	Max. q_{exh} (MW/m^2)	Max. W_{MHD} (kJ)
1	Cu + SS	0.1	1	1.9	3.5	120
2	Cu + SS	0.5	2	4.5	4	170
3	Mo (TZM)	NA	2	8.3	TBD	280

Table 1. Three generations of FLiLi tested in EAST

During experiments, continuous closed-loop flow of FLiLi was achieved. It was found the FLiLi are effective to reduce impurities and recycling, and to improve plasma confinement. It is well compatible with H-mode discharges with vary heating mode, i.e. LHCD, NBI. The upgraded FLiLi, Gen 2, overcome some damage found from Gen 1 due to some new techniques used, i.e. a thicker stainless steel protective layer, an additional jxB magnetic pump, surface texturing and an improved method for manufacturing the top Li distributor. It was found those methods is effective for the limiter protection and increase of Li wetted erea from 30% to 80%. The 3rd generation FLiLi, made of Mo for Li compatibility, shows a more uniform Li flowing.



Shot52687 50A DC current

Fig.2, FLiLi exposed to plasma and Li emission during the experiment in 2014

Typical FLiLi and Li emission exposed to plasma during experiment shown in Fig.2. FLiLi limiter was demonstrated to be compatible with 8 MW 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 dievrtor 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 WMHD and H98 were observed for the first time in 2016 with the FLiLi limiter.

The experiments showed that 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. Except of heat removal via convection, heat load on the FLiLi limiter can be partly removed via Li evaporation from the surface. And power radiation by Li particles, evaporated from the limiter and ionized in the SOL plasma, can reduce the plasma heat flux to FLiLi. The passive Li injection also would mitigate transient heat fluxes from ELMs. Moreover, 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.

Those positive results make FLiLi to be a competitive choice PFCs in future fusion reactors.

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