Amelioration of Plasma-Material Interactions and ELMs, and Improvement to Plasma Performance with Lithium Injection and Conditioning in EAST

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We present new results from a US-PRC boundary physics collaboration on lithium (Li) seeding of plasmas. The three principal sets of results are: 1) Li powder injected into upper-single null (USN) shape that used the ITER-like tungsten monoblock divertor succeeded in eliminating ELMs; 2) a 2nd generation flowing liquid Li limiter was inserted into the EAST midplane and used to mitigate plasma-materials interactions (PMI), paving the way for new experiments with a 3rd generation limiter made of Mo; and 3) Li granule injection was used for ELM triggering studies.

H-mode discharge duration continues to grow in EAST, from the recently published 60 second discharges[1] to ones exceeding 100 sec[2]. Wall conditioning plays a crucial role in enabling access to these long pulses. EAST relies on extensive wall conditioning via Li evaporation and real-time powder injection[3]. In previous experiments, Li powder injected into the lower-single shape with carbon PFCs eliminated ELMs in long pulse EAST H-modes[4]. However no strong pedestal modification was observed when Li pellets were injected into high-power H-modes in ASDEX-Upgrade, which uses all W PFCs[5], raising the question of whether Li seeding could work at all with high-Z PFCs. To assess this question, Li powder was injected into upper-single null H-modes in EAST that used the ITER-like W

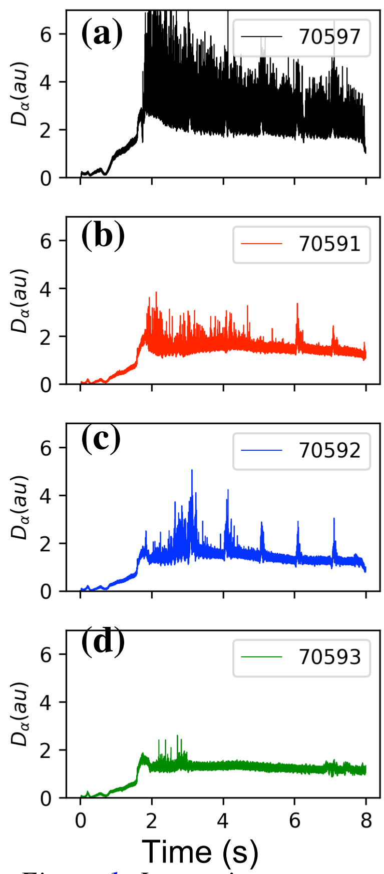

Figure 1: Increasing access to ELM elimination with Li powder injection at constant rate from 3.5-8 sec in EAST.

monoblock divertor, and ELMs were successfully eliminated[6]. At constant Li injection rates, the ELM elimination became progressively easier and of longer duration, e.g. in the second and third discharges with Li injection in figure 1. A few ELMs appeared to be triggered by the NBI short pulses for charge exchange recombination measurements (panels (1b, 1c)), with complete elimination in panel (1d). The baseline D_α emission was also reduced, indicating a cumulative wall conditioning effect of the Li injection, and cumulative reduction of the recycling coefficient by about 20%[7]. The edge n_e and T_e profiles were unchanged to within measurement accuracy, while global energy confinement was reduced by up to 10%. Nonetheless the H_{H98y2} was maintained at about 1.2, well above the previous ELM suppression with Li injection on the lower carbon divertor with $H_{H98y2} \sim 0.75$[4]. Furthermore these results provide an existence proof of ELM elimination with tungsten plasma-facing components, something that was not observed with Li pellet injection into the core of ASDEX-Upgrade[5]. Experiments in the coming year will focus on extending the ELM elimination to higher power, lower collisionality discharges.

For long pulse discharges, maintaining a clean Li surface requires continuous flow, which is one of the purposes of the flowing liquid Li limiter program[8, 9]. In this design, a Cu plate is used for the heat sink, with a thin stainless steel coating to shield the copper from direct Li interactions. A 2nd generation flowing liquid Li limiter was inserted into the EAST midplane and was found to be compatible with H-modes, even when placed within 1cm of the separatrix in RF heated discharges[10]. This limiter had several design improvements over the first generation limiter[11, 12]: 1) a thicker stainless steel protective layer, 0.5mm vs. 0.1 mm, to minimize Li-Cu interactions; 2) a second j×B magnetic pumps to augment the single pump in the 1st generation limiter; 3) surface texturing in the 2nd generation limiter for improved wetting; and 4) an improved method

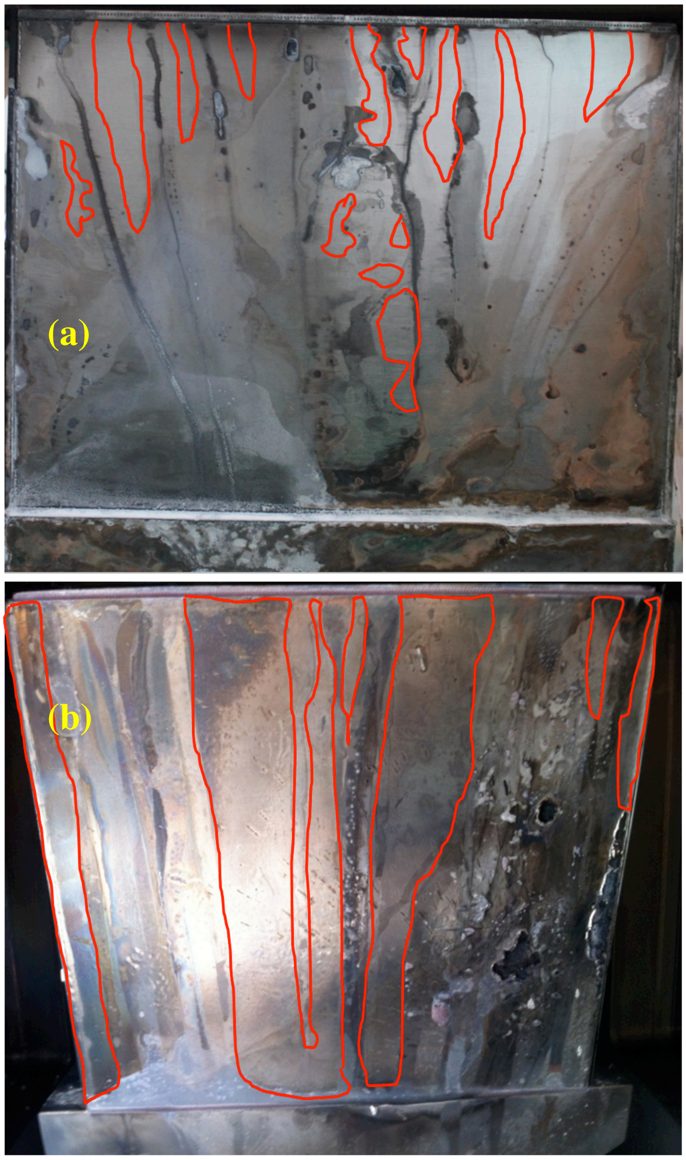

Figure 2: Comparison of (a) second (Dec. 2016) and (b) first (Oct. 2014) generation flowing liquid Li plate after plasma exposure. The red outlines indicate dry areas, i.e. where Li did not wet.

for manufacturing the top Li distributor, which cracked in the original deployment. Figure 2 compares the limiter plate condition after plasma exposure for 2nd generation (panel (a) - undamaged) vs. 1st generation (panel (b) – damage visible on the right hand side of the image). In addition the fractional surface area that was wetted (dry areas are shown by the red outlines) by the Li was > 80% in (a), vs. about 30% in (b). The heat flux exhausted by the 2nd generation limiter was up to 4 MW/m^2. In addition, for the first time in EAST, short-lived ELM-free phases with $H_{H98y2} \leq 2$ were observed when the 2nd generation limiter was used[13], similar to ELM-free scenarios with heavy pre-discharge Li evaporation in NSTX[14] and with Li powder in DIII-D[15].

Due to the progressive success with the flowing liquid lithium limiter program, a 3rd generation limiter constructed entirely of Mo was fabricated by conventional manufacturing techniques. Figure 3 shows the back side of the limiter, including grooves for insertion of Li-compatible cartridge heaters, and leak-tight inlet and outlet Mo tubes for steady state cooling by flowing He gas. The end connectors are Swagelok fittings, designed to accommodate stainless steel pipes to and from the He supply bottle. The front face of this limiter is smooth, with polishing for a mirror-like finish to facilitate easy wetting. Two copies of the plate were manufactured: one for insertion into EAST, and one for testing in the HIDRA device[16] at the Univ. of Illinois. In addition to the flat plate shown, a version also made out of Mo with trenches is being fabricated at UI-UC to augment the gravity-driven flow with thermoelectric MHD driven flow; this design is referred to as liquid metal infused trenches (LIMIT)[17]. Experiments to compare the performance of the flat and LIMIT plates are anticipated in HIDRA and EAST in the second half of 2018.

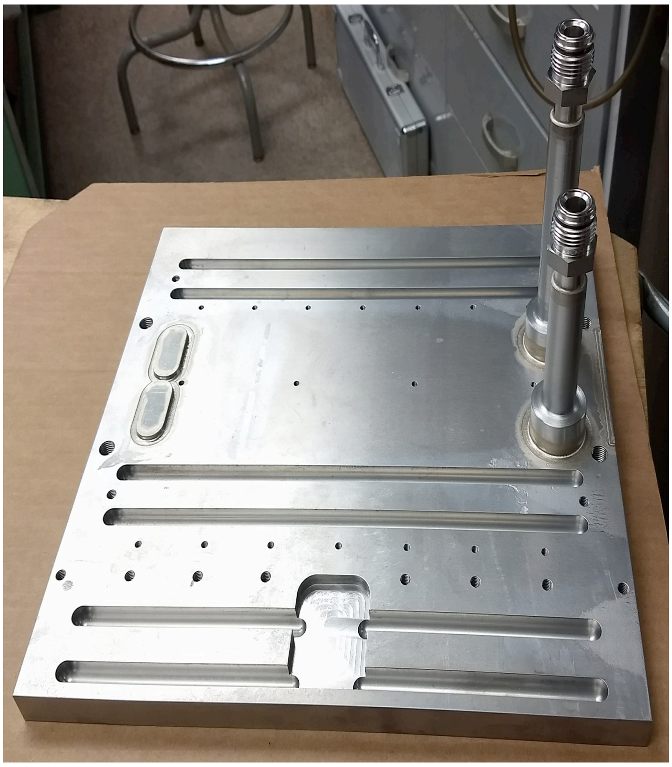

Figure 3: Back side of 3rd generation flowing liquid Li limiter plate, made entirely of Mo. The grooves are insets for heaters, and the tubes are the inlet and outlet for He gas cooling.

Finally ELM triggering studies with a four-chamber Li granule injector showed a clear size threshold of ~ 500 μm for a near-unity ELM triggering probability[18, 19]. This granule size threshold is remarkable similar to that observed in DIII-D[20]. The concept of a size threshold is predicted by theory[21], and also from the simple consideration of a sufficient-sized perturbation in the steep gradient region to destabilize a pressure-driven instability. In addition, ELM pacing was also observed, but in these cases the paced ELM frequency of ~ 60-80 Hz was below the natural ELM frequency between 100-200 Hz, which obviated ELM size mitigation experiments. Future experiments will focus on reproducing a robust low natural frequency ELMy H-mode for evaluation of the effects of ELM pacing and heat flux mitigation.

In addition to results from these Li delivery, the US-PRC collaboration includes work on thermography and the use of dual-band adapters for variable emissivity conditions, analysis of tiles removed from previous EAST campaigns[22], and modeling of surface response with Li coatings to plasma bombardment, all led by UT-K. Additional R&D includes implanted depth markers via the midplane insertable sample probe (MAPES) on EAST[23], led by MIT; analysis of cryopump design in comparison to Li pumping[24], led by ORNL; the future use of shell pellets and dual-filter imaging for impurity ionization dynamics[25, 26], led by LANL, and upgrading of the multi-energy soft X-ray system for core impurity studies, led by Johns Hopkins U.

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References

1. X. Gong *et al.*, 2017 *Plasma Science and Technology* **19** 032001
2. X. Gong *et al.*, 2017 *Bull. Am. Phys. Soc.* **62** BAPS.2017.DPP.TO4.1.
3. G. Z. Zuo *et al.*, 2012 *Plasma Phys. Control. Fusion* **54** 015014
4. J. S. Hu *et al.*, 2015 *Phys. Rev. Lett.* **114** 055001
5. P. T. Lang *et al.*, 2017 *Nucl. Fusion* **57** 016030
6. R. Maingi *et al.*, 2018 *Nucl. Fusion* **58** 024003
7. J. M. Canik *et al.*, 2018 *IEEE Trans. Plasma Sci.* **46** 1081
8. J. Ren *et al.*, 2014 *Physica Scripta* **T159** 014033
9. J. Ren *et al.*, 2015 *The Review of scientific instruments* **86** 023504
10. G. Z. Zuo *et al.*, 2017 *Rev. Sci. Instrum.* **88** 123506
11. J. S. Hu *et al.*, 2016 *Nucl. Fusion* **56** 046011
12. G. Z. Zuo *et al.*, 2017 *Nucl. Fusion* **57** 046017
13. G. Z. Zuo *et al.*, 2017 *Proc. 44th EPS Conf. on Plasma Physics, 26-30 June 2017, Belfast, No. Ireland, paper O5.133*
14. R. Maingi *et al.*, 2012 *Nucl. Fusion* **52** 083001
15. T. H. Osborne *et al.*, 2015 *Nucl. Fusion* **55** 063018
16. D. Andruczy *et al.*, 2017 *Fusion Science and Technology* **68** 497
17. D. N. Ruzic *et al.*, 2011 *Nucl. Fusion* **51** 102002
18. R. Lunsford *et al.*, 2018 *Nucl. Fusion* **58** 036007
19. Z. Sun *et al.*, 2018 *IEEE Trans. Plasma Sci.* **46** 1076
20. A. Bortolon *et al.*, 2016 *Nucl. Fusion* **56** 056008
21. G. T. A. Huijsmans *et al.*, 2015 *Phys. Plasmas* **22** 021805
22. T. Yang *et al.*, 20118 *Presented at the 23rd International Conference onf Plasma-Surface Interactions, Princeton, NJ, June 18-22, 2018.*
23. L. A. Kesler *et al.*, 2018 *Presented at the 23rd International Conference onf Plasma-Surface Interactions, Princeton, NJ, June 18-22, 2018.*
24. J. M. Canik *et al.*, 2018 *Presented at the 23rd International Conference onf Plasma-Surface Interactions, Princeton, NJ, June 18-22, 2018.*
25. Z. Wang *et al.*, 2017 *Proc. 2017 Euro. Conf. on Plasma Phys. and Contr. Fusion, Belfast, No. Ireland, June 26-30, 2017* paper P4_116
26. Z. Sun *et al.*, 2018 *Rev. Sci. Instrum.* submitted