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Overview of lithium injection and flowing liquid lithium results from the US–China collaboration on EAST

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Abstract

A multi-institutional team consisting of national labs and universities has been conducting research to understand and control the plasma-material interface (PMI) to improve long pulse discharge control and performance in the EAST device in Hefei, China. One particular focus of the group has been to evaluate the performance of different plasma-facing component (PFC) technologies and materials, particularly lithium. Flowing liquid lithium PFC technologies are currently into their third generation of development and deployment in EAST, demonstrating recycling control and mitigation of edge-localized modes (ELMs). A lithium powder dropper has also been used to control ELMs while a lithium granule injector has demonstrated ELM triggering and pacing. To support this work, the facilities at the Center for Plasma Material Interactions such as HIDRA are being commissioned and utilized to develop/test the technologies before deployment on EAST. This paper will present a summary of the collaborative lithium PMI program on EAST.

Keywords: EAST, plasma material interactions, fusion, plasma facing components, liquid lithium, flowing liquid lithium limiters

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

Introduction

One of the outstanding issues in fusion today is the fact that the current solid material used for the first wall and divertor have not provided a sufficient solution to survive the harsh environments in a reactor. As an example, tungsten's thermal and structural properties degrade under neutron flux [1] and also develop nano structures such as 'fuzz', bubbles and dust under helium and hydrogen bombardment [2, 3]. With this in mind, liquid metals and in particular liquid lithium potentially offer a solution by providing a self-healing, low-Z and low-recycling surface [4–7]. Thus, being able to do a proper study of lithium's effects in a high-powered device is important.

With this in mind, a multi-institutional team led by the Princeton Plasma Physics Laboratory (PPPL) has led a study in plasma-materials interactions (PMI) in a cooperative collaboration with the Institute of Plasma Physics, Chinese Academy of Science (ASIPP) based in Hefei China, based on their superconducting tokamak, the Experimental Advanced Superconducting Tokamak (EAST). The team consists of

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members from PPPL, Oak Ridge National Laboratory, Los Alamos National Laboratory, Johns Hopkins University, the University of Illinois Urbana-Champaign (UIUC), the University of Tennessee Knoxville, and the Massachusetts Institute of Technology, and was funded through the US Department of Energy.

The EAST device [8] is located in Hefei, China and was built to demonstrate high-power, long pulse operations under fusion relevant conditions. It has an ITER-like 'D-shaped' cross section with two symmetric divertors at the top and bottom, accommodating both single null and double null divertor configurations. EAST has a major radius or $R_0 = 1.85$ m and minor radius $a = 0.45$ m and an on axis toroidal field up to $B_0 = 3.5$ T. The auxiliary heating systems have up to $P_{heat} < 20$ MW ($P_{ICRH} < 4$ MW, $P_{LHCD} < 4$ MW, $P_{ECRH} < 2$ MW, $P_{NBI} < 10$ MW) and plasma current of $I_P = 1$ MA. The lower hybrid wave/current drive (LHW/LHCD) heating is enabled at 2 frequencies: 4.6 GHz and 2.45 GHz with 3 MW and 1 MW heating capabilities respectively. EAST is designed to have pulse length up to 1000 s in duration [8].

Overall, there are three objectives of the US-PRC collaboration:

1. To evaluate the performance of the different PFC materials which include tungsten, molybdenum, and graphite and the role that Li wall conditioning plays in the performance of the plasma.
2. Analyze the roles of the lithium and the divertor cryopump in long pulse recycling and density control [9].
3. Measure net erosion and material migration with the use of marker tiles, and enhanced impurity diagnostics [10, 11].

This paper, due to the size of the collaboration, will focus only the results from the first point.

Powder dropper and granule injection

A device for controlled injection of a variety of powdered materials has been developed and installed on EAST. The powder dropper is described in detail by Nagy *et al* [12]. In essence uses a vibrating diaphragm with a small hole in the center to shake in different material in powder form. A variety of materials are intended to be used with this including lithium, boron and tungsten. However, for these studies a powdered form of lithium is used for injection into EAST to study recycling control.

The powder dropper is used to shake lithium powder into the EAST plasma in two locations: above the upper X-point and into the scrape-off layer of upper-single discharges. Typical Li injection rates are between 10 and 100 mg s^{-1} (9e20 to 9.e21 Li atoms s^{-1}). The dust ablates as it interacts with the plasma and the lithium is distributed throughout the vacuum vessel. This provides an alternate method to coat the inside of a vacuum vessel as opposed to the lithium evaporator systems (LITER) [5] and to have the lithium interact with the edge plasma. As has been shown in the past, lithium has the ability to remove impurities and reduce recycling and suppress instabilities like edge localized modes (ELMs) in EAST [13] and NSTX [14].

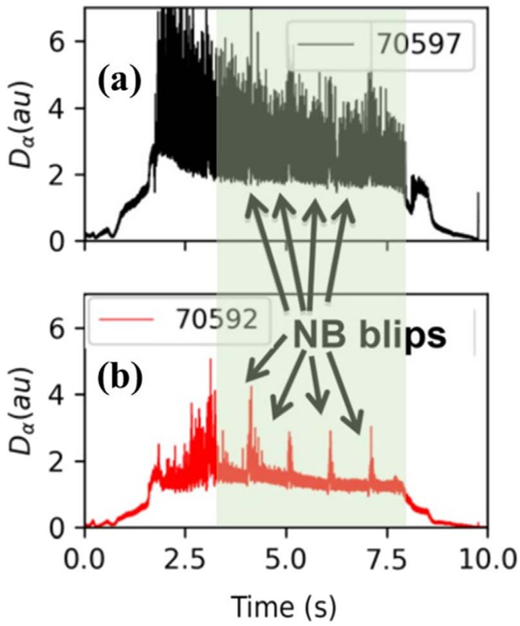

Figure 1. Time traces comparing two discharges. Shot #70 957 (black) is a reference shot and shot #70 592 (red) is with the lithium powder dropper [12]. Here the plots (a) and (b) are the most significant showing the progressive elimination of the ELMs as the powder dropper is used and also the overall D_α level is lower due to the lower recycling. The powder dropper is operational from 3.5 to 8 s in the discharge. The blips at 4, 5, 6 and 7 s are the neutral beams.

ELMs in particular have been successfully eliminated using the powder dropper with tungsten operation in the divertor. Here, the lithium powder was injected into the scrape-off-layer of the upper tungsten divertor for 3–5 s and saw that ELMs disappeared for the duration of the powder dropper operation in the discharge, shown in figure 1(b) [13].

It has also been shown that with the use of the lithium powder injector, having a constant supply of fresh lithium into the vessel allows for impurities and cold hydrogen to be absorbed by the lithium, thus bringing down the recycling rate during plasma operation [15]. It is important to have the lithium continually injected, since a single application of lithium has previously experienced passivation. Long term, single use of lithium becomes neutralized, essentially the plasma sees a regular wall and none of the benefits of lithium. The recycling reduction can be a factor of two, as shown between figures 1(a) and (b). The blips in the signal at 4, 5, 6, and 7 s are the operation of the neutral beams. The powder dropper is in operation from 3.5 to 8 s in the discharge. With power loss during ELMs decreasing, we speculate that power loss between ELMs increases, as the stored energy stayed roughly constant. Most likely this power flows to the wall, as the power between ELMs at the target does not change appreciably between ELMs. Previous SOLPS analysis of the recycling drop concluded that the recycling reduction corresponded to a net reduction of the divertor recycling coefficient by 0.2 (Canik IEEE TPS 46 (2018) 1081).

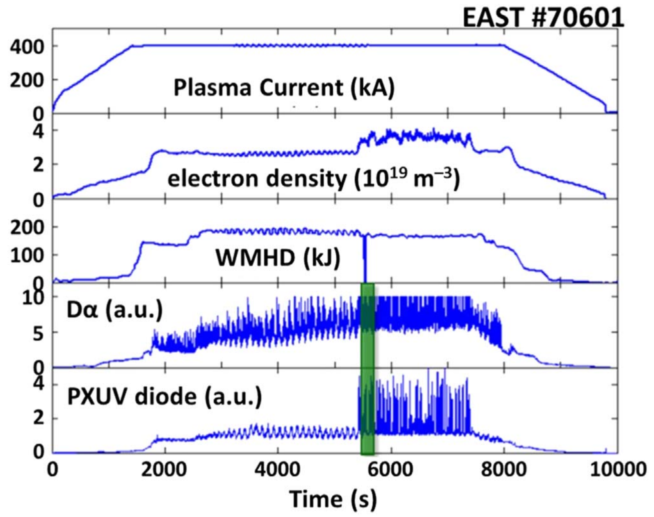

Figure 2. Discharge parameters for the LGI in EAST [25]. The green bar shows the expanded region shown in figure 3. Reproduced from [25].

With the suppression of ELMs and reduction of the recycling in EAST, eventual accumulation of core impurities that cannot be flushed out is a possibility if the inter-ELM turbulence is too low. This impurity build-up can lead to a return to large ELM events or to a collapse in the plasma. In the past it has been shown that pellet injection of cryogenic fuel [16, 17] or impurities [18–22] can mitigate and control the ELM heat flux incident to a surface. With this in mind, the next step up from the powder dropper is a lithium granule injector (LGI) based on a rotating impeller design. The LGI is simple, i.e. with no complex cryogenic systems, and does not inject potentially detrimental plasma impurities.

The LGI is described extensively by Sun *et al,* Nagy *et al* and Lunsford *et al* [23–26]. The main chamber has 4 housing volumes where 4 different sized of granules can be stored and rotated through. The granules typically are between 0.1 and 2 mm in diameter. A piezo-plate vibrates at the desired frequency to drop the granules. A rotating impeller then matched at the plate frequency then 'slaps' the granules into the plasma at the outer midplane into upper-single null discharges, with a near 100% strike rate. These granules then interact with the plasma and trigger a small ELM-like event.

The idea of using the LGI is similar to the way cannons are used to trigger small avalanched in mountainous regions to avoid a large catastrophic avalanche. The smaller ELMs are triggered, where the heat flux is much smaller and can be handles easily by the plasma facing surfaces, in order to keep the core flushed out of the impurities and thus avoiding a large disastrous ELM event. Figure 2 shows shot #70 601 in EAST where 0.9 mm diameter spherical granules are injected at ~70 Hz (Li injection rate of 13 mg s^{-1} or 1.2e21 atoms s^{-1}) to pace ELMs, resulting in increasing electron density during the pacing while the overall stored energy level within the plasma remains the same [25]. A clear change in the D_α ELM signal is seen. Note that the increase in electron density in figure 2 is likely due to increased edge Li concentration and the associated electrons.

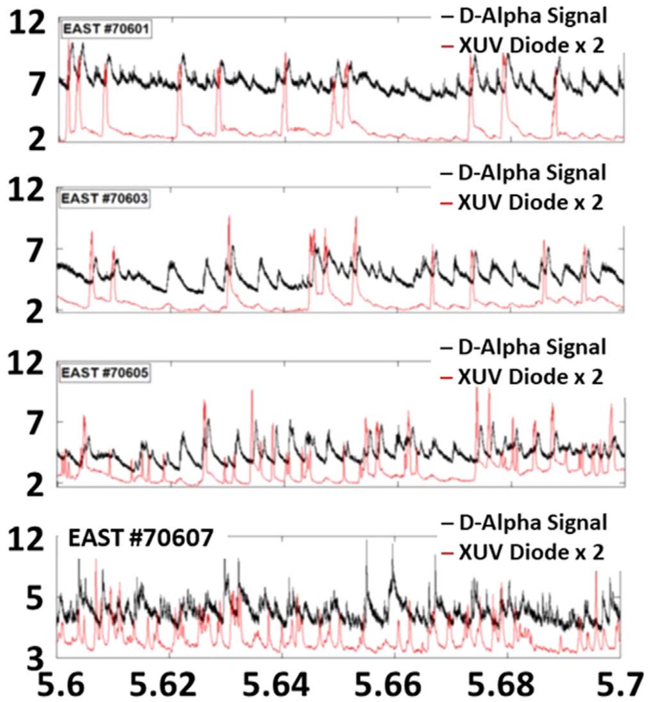

Figure 3. The D_α and XUV traces for several EAST discharges with the LGI. The top traces represent shot #70 601. Reproduced from [25].

Figure 3 has an expansion of the D_α and PXUV diode signal shown in the green bar in figure 2. The panels show granule injection and ELM triggering from average granule sizes of 0.9 mm, 0.8 mm, 0.6 mm, and 0.3 mm respectively. The top two graphs show a clear 1:1 correlation between injected granules (0.9 and 0.8 mm diameter) and triggered ELMs as reflected by spiked on the D-alpha signal. The third panel shows a strong correlation of injected granules and triggered ELMs, but not quite 1:1, while the bottom trace show there is no 1:1 correlation for the smallest granules. These data were used to identify a granule size threshold near 0.6 mm for efficient ELM triggering [25].

Flowing liquid lithium limiters

The development of a working flowing liquid lithium systems has been in development for several years. The first flowing lithium limiter (FLiLi) was tested on HT-7 [27] and subsequently has been adapted for use in EAST. In the same series a LiMIT plate was also tested [27, 28]. The FLiLi plate works on a slow gravity flow down the front surface of a plate that is 0.32 m by 0.3 m in size. The first generation (GEN-1) front plate was made from stainless steel that is explosively bonded to a copper heat sink to help with heat transfer [29, 30]. The objective of FLiLi is to both handle heat flux and provide a continuously replenishing low recycling and low-*Z* surface and to remove any capture impurities and hydrogenic species. The liquid lithium is fed and collected via a distribution-collection system and a MHD pump mounted on the underside of the collector circulates the lithium (figure 4). The

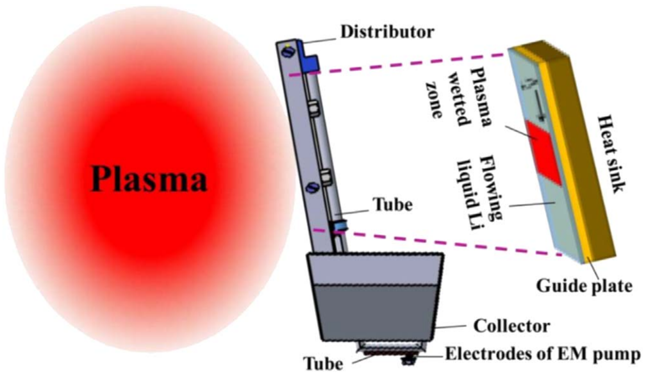

Figure 4. A schematic of the FLiLi plate used in EAST, showing the set up for the distributor, collector and MHD pump for circulation. The vertical and horizontal extent of the limiter plate is ~35 cm.

Figure 5. The FLiLi plate before installation into EAST. This is a Gen 1 plate showing clearly the reservoir, front plate distributor and EM pump.

LiMIT plate, uses trenches do drive a TEMHD flow [27, 31] and the trenches, through surface tension forces also can eliminate droplet ejection [31, 32].

Figure 5 shows the actual FLiLi system before installation in EAST. The left-hand side panel shows a head on view of the plasma-facing surface, with plate dimensions 35 cm long, 30 mm wide, and 1.9 cm thick. The right hand side panel shows a side view, showing the one of the four threaded rods used to attach the plate to the W-shaped support structure.

Several generations of FLiLi [29] have now operated in EAST, each with the aim of improving the flow characteristics of the thin lithium film down the surface. The generation 1 plate (GEN-1) [33] had a 0.1 mm plate explosively bonded to copper. It was used successfully however the front surface did not wet completely and there was some damage due to plasma interaction [34]. This led to the development of the GEN-2 plate [35, 36] which had a thicker stainless-steel plate, 0.5 mm in thickness, explosively bonded to stainless steel. This, along with an improved heating system had an increased wetted area which allowed the limiter to survive for longer. Ultimately, the heaters failed due to eventual exposure to liquid lithium through evaporation and creep around due to wetting.

The GEN-3 plate was a direct result to try and develop from the start a FLiLi system that will not only be more durable to plasma exposure anywhere there is no lithium wetting, but at the same rate also be resistant to lithium corrosion [37]. Molybdenum was the material of choice since it allowed the whole plate to be machines out of one block and

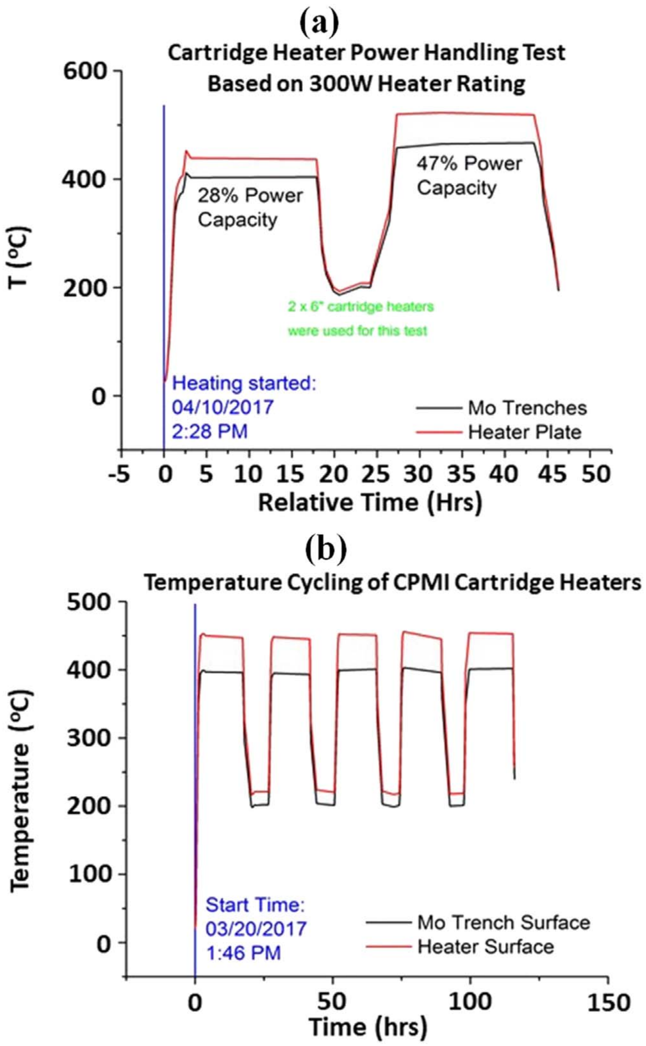

Figure 6. Operational test of new armored heaters for FLiLi. (a) Full cycle over a 5 d period showed no loss in performance and (b) only 47% of power capacity needed to heat the plates.

not needing to be bonded to a copper base. Though the heat transfer of molybdenum is not as good as copper being made from one uniform block gives it good thermal advantage being able to bring the cooling channels closer to the surface. Molybdenum also has much better wetting properties to stainless steel, which its wetting temperature much lower, $T_{wet,Mo} \sim 280$ °C rather than $T_{wet,SS} = 320$ °C–350 °C [36].

Development and pre-testing of new armored cartridge heaters was performed at UIUC at the Center for Plasma Material Interactions (CPMI) where the heaters were put through a rigorous testing of being cycled through a full 5 d work week in EAST, shown in figure 6. The heaters were cycled between 200 °C and 400 °C and held on average for 14 h. The armoring consists of a stainless-steel jacket over the leads which is welded to the main heater body and protects the leads from lithium attach, which was the previous failing point.

The heaters were also submerged in lithium for several cycles. The cladded heater had evaporated lithium on it which did not penetrate to the leads while a second braided heater

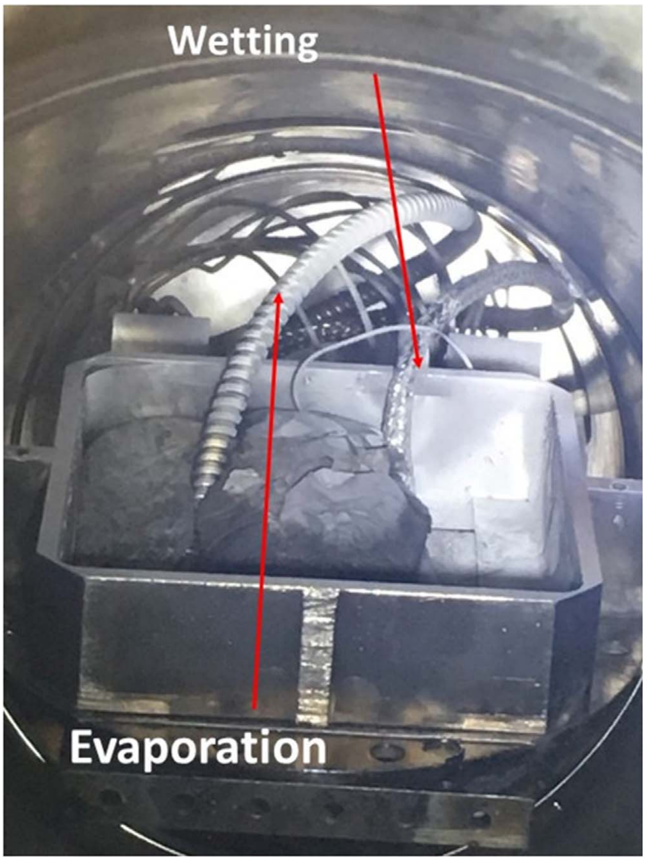

Figure 7. Lithium dunk test for the armored cartridge heaters. This shows 2 types, one that had a full stainless-steel protection and survived another had a braid which the lithium still wet through and damaged the leads.

which was also tested still had lithium wet through and damage the leads at 350 °C, shown in figure 7. These improved armored heaters were more than up to the task and indeed the tested heaters were then re-used in EAST experiments. The heaters had more than enough heating capacity to heat the molybdenum plate, which was also tested with a test plate at UIUC.

With the successful testing of the heaters these were installed into the GEN-3 FLiLi plate. Shown in figure 8 are results from the 2018 summer campaign in EAST with the GEN-3 plate. Operation with the GEN-3 plate was successful the main take-aways being that there was a significant reduction in the ELM size as well a substantial reduction of the recycling rate seen by the lower D_α level, figure 8(b). Also, it shows an improvement in the plasma performance with about a 5%–10% increase in the overall stored plasma energy, figure 8(c), with no overall decrease in the plasma density figure 8(d), with heating power of $P_{\text{heat}} = 8.3$ MW.

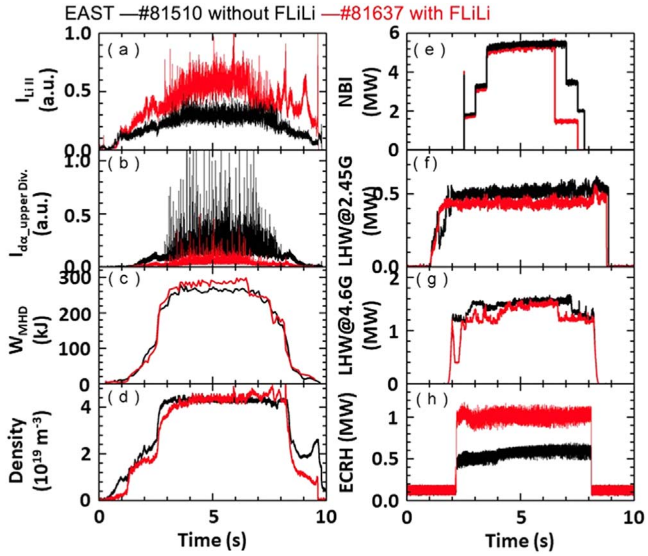

Figure 8. GEN-3 FLiLi operations in EAST over the summer of 2018. (b) shows the reduction in ELM size and (c) a 5%–10% increase in stored energy while (d) the overall density stays the same [35–37]. Auxiliary heating is shown in the right-hand side panels.

Figure 9. First plasma inside HIDRA. Parameters were $B_0 = 0.1$ T, $P_{\text{ECRH}} = 2$ kW, $t = 60$ s, gas = He. HIDRA will be brought in to test the future technology needed to successfully operate FLiLi and LiMIT.

Using HIDRA for future liquid metal studies

The Hybrid Illinois Device for Research and Applications (HIDRA) is a long pulse toroidal plasma device based on a classical stellarator design at UIUC. This is the former WEGA device that was operational in Greifswald before W7-X and has the potential to also operate as a tokamak. HIDRA is a classical stellarator with a $l = 2$, $m = 5$ configuration, with 40 toroidal field coils and 4 helical coils. It can operate steady state with a transformer-rectifier system to provide current to the coils. The coils are water cooled and the plasma heating is through ECRH done via two 2.45 GHz magnetrons, a 6 kW and 20 kW system respectively. Additional information on the machine parameters and control systems are described fully by Andruczyk *et al* [39–41] and Johnson *et al* [42]. HIDRA is being brought into the collaboration as a technology test stand for PFC concepts such as FLiLi and LiMIT. HIDRA arrived from Greifswald in the winter of 2014 and by April 2016 the first plasma was struck, shown in figure 9, this was a $B_0 = 0.1$ T and $P_{\text{ECRH}} = 2$ kW, $t = 60$ s and working gas

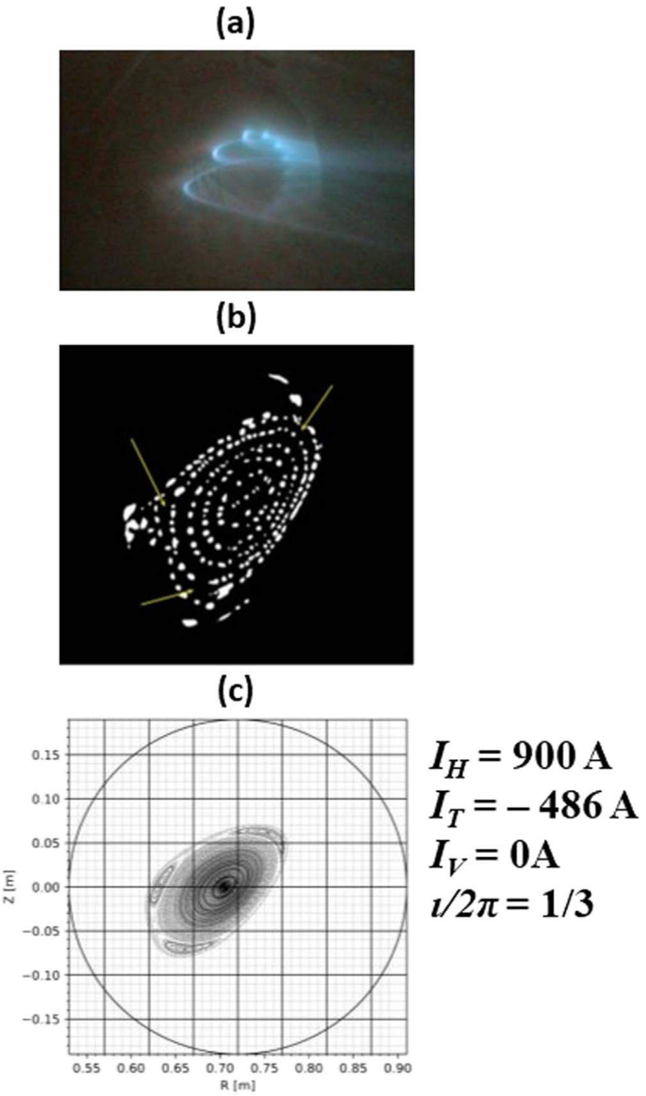

Figure 10. Flux surface measurements in HIDRA [44]. The profiles show that the line tracing code can be used to predict the plasma profiles. Reproduced from [38], with the permission of AIP Publishing.

was helium. Parameters such as the magnetic field have been calibrated and measured. HIDRA can reach on axis toroidal magnetic fields up to $B_o = 0.5$ T with up to $I_T = 3.5$ kA running through the toroidal coils and $I_H = 7$ kA in the helical coils [43].

Operationally, two things need to be completed on HIDRA before experiments with any limiter can be performed: first the surface flux measurements need to be measured for different ι configuration and to know where a limiter plate can be placed, second the long pulse operational abilities need to be proven.

In figure 10 the surface flux measurements are shown and have been used to verify a line tracing code developed to predict the iota profiles for HIDRA. This has allowed a position to be identified and due to the five-fold symmetry of HIDRA both FLiLi and LiMIT can be tested simultaneously [44].

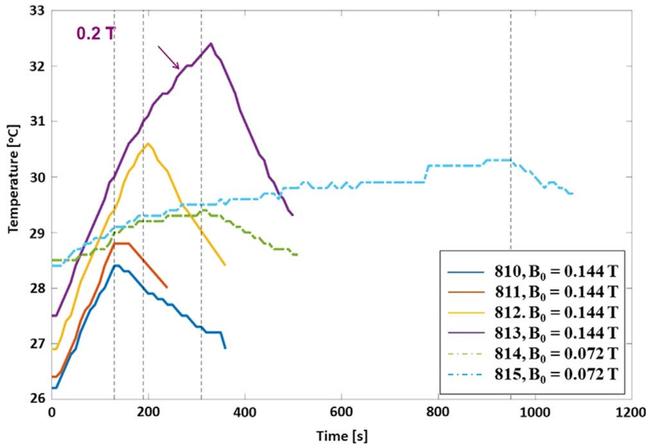

Figure 11. Long pulse discharges in the HIDRA coils showing that long pulse operations are possible.

Long Pulse operation in HIDRA has been shown successfully with operational test with the magnetic coils and cooling system up to $B_T = 0.2$ T with minimal temperature rise in the coil temperatures. The temperature limit in the coils is set to 60 °C before operations need to cease. With low field operation set for the 2.45 GHz magnetron heating resonance a pulse length has been up to 18 min and extrapolation from that shows that operating for 60 min is possible. This shows the long pulse operation of HIDRA, figure 11.

Summary and future experiments

The US–China collaboration on EAST has successfully shown that recycling and ELMs can be controlled with lithium powder and granule injection respectively. Three generations of flowing lithium limiters have been operated and show that a constant flowing lithium surface can mitigate instabilities and control the recycling rate. Operation in HIDRA is ramping up and the device will be brought to do technology testing with FLiLi and LiMIT in the future while EAST is undergoing upgrades.

Acknowledgments

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