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An overview of lithium experiments on HT-7 and EAST during 2012

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ABSTRACT

In 2012, lithium coating with an upgraded system on EAST, the first application of lithium granules injection for ELMs pacing on EAST, and the first flowing lithium limiter experiments on HT-7 have successfully been carried out and several new results were obtained. On EAST, it was found that both the Mo first walls and the C divertors were well coated by lithium and the lithium film coverage was increased up to 85%, which greatly contributed to the new achievements of EAST, especially stationary H-mode plasma over 30 s and long pulse plasma over 400 s. And at the same time, ELMs suppression by active lithium conditioning and ELMs pacing using lithium granules injection were demonstrated and reported for the first time on EAST. On HT-7, flowing liquid lithium limiters using the TEMHD concept and using a thin flowing film concept were also initially tested and some references were obtained for the future development. Those experiments show that lithium should be an important material for fusion devices. It could be used for wall conditioning, ELMs mitigation and also provide a self-recovery plasma facing components in future fusion devices.

1. Introduction

Wall conditionings on plasma facing materials can play a key role for high plasma performance and steady-state operation, and therefore, be beneficial for the economic and effective operation of fusion devices. Lithium (Li) serving as coating material for plasma facing components (PFCs) has been employed in several fusion devices, such as NSTX, FTU, T-11 M, TJ-II [1–7]. It has a low melting point (180 °C), and is easily vaporized. It is compatible with fusion plasmas due to its low atomic number ($Z=3$). In addition, compared to boron and silicon, it has demonstrated stronger wall gettering capability for hydrogen (H) isotopes and impurities, such as carbon (C) and oxygen (O) [8].

As superconducting tokamaks, both EAST and HT-7 in Hefei, China are capable of high performance long-pulse plasmas. As an ITER-like machine with divertor configurations, the main missions of EAST are to achieve steady-state high performance plasma and to study related advanced physics and technologies. At the same time, HT-7 with a limiter configuration has recently been used to support the EAST project both scientifically and technically. In the recent years, H-mode plasmas on EAST and long-pulse plasmas up to 400 s both on HT-7 and EAST were successfully obtained [9].

To improve plasma performance, over the last several run campaigns, wall conditioning techniques have been explored, such as active cleaning including baking, glow discharge cleaning (GDC), ion cyclotron resonant frequency (ICRF) cleanings [10,11]. Wall coatings, including boronization [12], siliconization [13] were also employed. However, before the application of Li coatings, EAST plasma performance could not be improved significantly owing to a high edge recycling. In addition as the main plasma auxiliary heating method, the ICRF heating efficiency in the minority heating mode was low and difficult to be improved due to a high ratio of H/(H+D) [14].

To resolve long-term problems of EAST operation, such as high edge recycling and high H content during plasma discharges, Li coating have been applied on EAST since 2009. It was found that Li coating could be used not only to reduce impurities, but also to control recycling and H content. Li was used to reduce the ratio of H/(H+D) so as to improve ICRF heating efficiency in the H minority heating mode. A Li coating campaign was also undertaken to obtain experience in high parameters plasmas operation, especially, steady-state H-mode plasmas with a low recycling. Moreover, Li active conditioning (lithium powder is directly dropped to plasma during plasma discharge for active

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coating, using a lithium powder dropper system) was expected to suppress edge localized modes (ELMs) during H-mode plasmas, such as in NSTX [15].

Flowing liquid plasma facing walls as compared to solid PFCs, offer a self-recovering surface and good heat removal. Liquid Li PFCs have been broadly investigated in CDX-U, FTU, T-11M [16–18]. It was expected that discharges using Li as PFCs would have low edge recycling compared to using carbon (C) PFCs, and would have a low radiated power compared to using tungsten (W) PFCs. Moreover, flowing liquid Li PFCs would supply a renewable surface, which would have continued effectiveness in the suppression of impurities and lowering of particle recycling. And then, it would be beneficial for high performance steady-state plasma operation.

Further, type-I ELMs with high heat loading on PFCs have been observed during H-mode plasmas on several tokamaks, such as JET [19] as well as EAST. For ITER, to avoid damage to divertor plates, the peak power load is limited to 10 MW/m^2 in steady-state conditions and 20 MW/m^2 in transient conditions during type-I ELMs [20]. Thus, developing ELMs mitigation techniques is important for H-mode plasma operation in future fusion devices, such as ITER. Similar to D_2 pellet injection for triggering higher frequency smaller ELMs in order to avoid large low-frequency type-I ELMs with high heat load on divertors, Li granule/pellet injection is a potential method for ELMs pacing and could be beneficial for the mitigation of type-I ELMs.

For the 2012 run campaign, the EAST first wall plasma facing material for was changed from doped graphite to Mo while graphite was still used for both the top and bottom divertors. Similarly on HT-7, all graphite limiters were changed to Mo. Firstly, the retention of hydrogen isotopes on Mo walls is much lower than that on graphite walls. Secondly, high lithium reactivity with carbon atoms and the intercalation of lithium in graphite would weak the effectiveness of lithium. These modifications were expected to reduce edge recycling during plasma discharges and to enhance the effectiveness of Li coatings. Using these new PFCs, multiple Li experiments on both HT-7 and EAST were carried out during the 2012 campaign. Among these were Li coating experiments using upgraded Li systems, the first application of Li granule injection for ELMs pacing on EAST, and the first flowing Li limiter experiments on HT-7. In this paper, the results of those experiments on HT-7 and EAST will be introduced and discussed.

2. Li coating experiments on EAST in 2012

2.1. Motivations for Li coating experiments

Li coatings have been explored on EAST since 2009 [21]. In the first test on EAST with full carbon walls, a single effusion oven with a Li capacity of 2 g was used for Li evaporation. It was observed that the resulting Li film tended to be localized near the oven and, therefore, most PFC surfaces had not been covered by Li. Nevertheless, these limited Li coating positively, but not dramatically, influenced the suppression of impurities, the reduction of particle recycling and the reduction of attainable H/(H+D) ratios – all of which led to measurable improvements of plasma performance. Subsequently, before the 2010 campaign, the initial coating system was upgraded. Two deeply inserted ovens with larger volumes for Li (15 g/oven) were used to deposit pre-discharge coatings and a new Li dropper from NSTX was used for active (i.e. real-time) conditioning [22]. As a result of these changes, it was observed that the coverage of Li coating was increased to more than 35%. As a result not only were impurities effectively suppressed, but also recycling and the attainable ratio of H/(H+D) were significantly reduced. In fact, with accumulation of deposited Li, the ratio of H/(H+D) was reduced to lower than 10%, which allowed increased ICRF heating efficiency to be obtained using H minority heating. Using these improved Li coatings, MHD activity was significantly reduced, the plasma electron temperature increased and became broader, and the H-mode threshold power gradually decreased. Real-time Li coating using the dropper extended the lifetime of Li films and proved to be extremely helpful for long-pulse and H-mode plasmas. Accordingly in 2010, H-mode plasmas were routinely obtained on EAST with Li coatings either using the Li ovens or real-time Li powder injection [23]. Li coatings became the easiest and most effective method for recycling control and H content reduction in EAST. Li coatings thus resolved the long-term problems of EAST operation, and therefore improved plasma performance – especially for H-mode and long-pulse plasmas.

Against this background, the main goal of the EAST campaign in 2012 was to obtain long duration H-mode plasmas on low recycling walls. It was anticipated that, for good impurity suppression and reduced recycling, Li coatings should be applied as uniformly as possible on all PFCs and the effectiveness of Li coatings on the new molybdenum (Mo) first walls should be studied. In addition, coating Li on the graphite divertors was considered extremely important. Therefore, the main motivations of the Li coatings effort on EAST in 2012 included: (1) to improve Li coating uniformity; (2) to develop a dedicated Li system for coating the graphite divertors; (3) to investigate Li coating on Mo walls; (4) to optimize the active real-time Li conditioning during plasma discharges; (5) to improve H-mode and long-pulse plasmas parameters; (6) to obtain experience with plasma operation on walls with low recycling to provide a database for future devices, such as ITER; (7) to obtain experience with Li coating in the event of serious leaks and other off-normal vacuum events.

2.2. Upgrading of EAST Li coating systems in 2012

In 2012, the existing oven evaporation systems were upgraded in four important ways. These changes were undertaken mainly to expand coverage to all PFCs, improve coating uniformity and especially to increase the coverage on the C divertor surfaces. First, the oven evaporation systems were redesigned so as to allow them to be inserted to center of the EAST vessel with major radius R = 1.9 m and minor radius a = 0.5 m, as shown in Fig. 1. By increasing the length of their insertion bellows, the newly designed ovens could be inserted deeper in the vessel than previously (R = ∼1.85 m in 2012 versus R = ∼2.3 m in 2010). This change increased the line-of-sight coating area on the vacuum chamber walls with ITER-like D-shaped section when previously the ovens had to be positioned near the horizontal ports. Second, the oven volumes were enlarged in order to increase the maximum deposition possible with one evaporative coating. Compared to 15 g/oven in 2010, the capacity of each upgraded oven was increased to about 25 g. Third, the three existing oven insertion points were repositioned toroidally to achieve more complete Li coverage. As shown in Fig. 4, oven insertion points were repositioned to horizontal ports (bays M, J and D) with interval angles of 135°, 68° and 157°, respectively. The fourth upgrade was a dedicated bidirectional Li oven designed to allow both upward and downward evaporation so as to direct Li vapor onto both the upper and lower C divertors simultaneously as shown in Fig. 2.

Real-time Li coatings were also carried out on EAST using a dropper apparatus developed by the Princeton Plasma Physics Laboratory. Using a resonating piezoelectric disk with a central aperture, the dropper injects an evaporating Li aerosol into the plasma SOL by simply dropping spherical Li powder in a controllable manner [22]. Li injection rates as low as ∼1 mg/s (4.3×10^4 spheres/s) and as high as ∼120 mg/s (5.1×10^6 spheres/s) can be attained reproducibly using this device. On EAST, during plasma, 40 μm spherical Li powder was injected through the upper divertor gap with an adjustable flow rate of 30∼60 mg/s. The

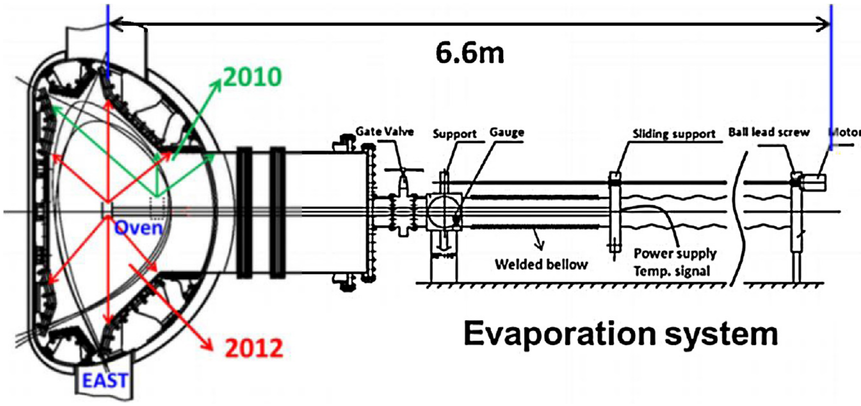

Fig. 1. Oven evaporation system on EAST in 2012.

velocity of the powder was about 10 m/s when contacting the SOL plasma. The use of this simple device provided flexibility in the amount and timing of Li deposition. In 2012, real-time Li powder injection was routinely accomplished for periods up to 30 s. The dropper location is shown in Fig. 3.

2.3. New results of the Li coating experiments on EAST in 2012

In the 2012 EAST campaign, about 10–50 g Li were used for each coating employing additional oven evaporators whereas only about 10–30 g Li used for the 2010 campaign. During the 2012 campaign, a total of 2.3 kg Li was used whereas only 982 g were used in the 2010 campaign. Most coatings were normally carried out before beginning plasma operation each day. Besides using the evaporators at the start of most run days, coatings were occasionally carried out in between individual discharges. In addition to Li coatings using evaporators, 10 g of Li powder was also used for active real-time conditioning during plasma discharges.

Using the upgraded evaporation system, new results were obtained during the 2012 campaign. As shown in Fig. 4, based on post-run inspection with naked eyes, it was observed that the Mo first walls were well coated with Li. Not only due to the coating, but also the effect of material migration happening during plasma discharges is one possible contribution. This was main reason of the effective suppression of Mo impurities [24] and beneficial for plasma operation in general. With the help of the dedicated bidirectional evaporator, which delivers Li vapor simultaneously both upward and downward to the top and bottom divertors, the surfaces of the C divertors were also effectively coated, which was helpful for the suppression of C and O impurities [24]. Both of impurity influxes from PFCs and core impurity content were reduced gradually with the increase of Li accumulation on walls. Normalized

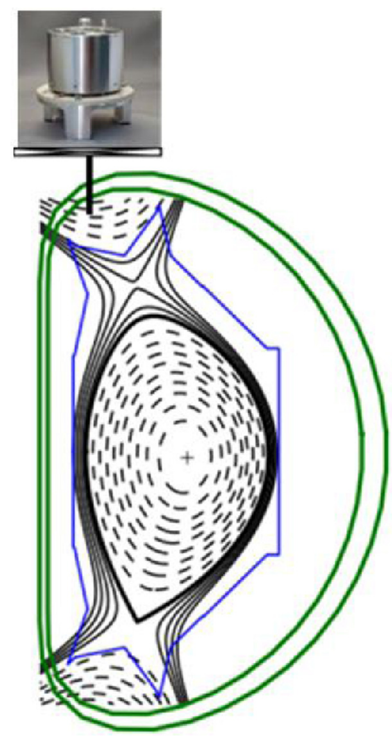

Fig. 3. Real-time and in situ Li powder dropper on EAST.

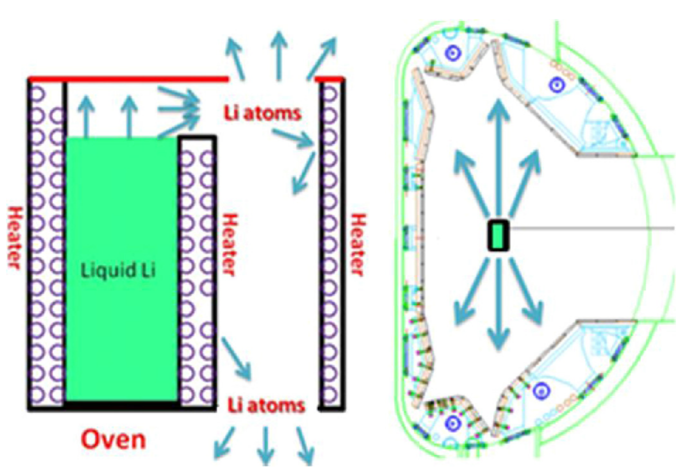

Fig. 2. Dedicated bidirectional Li oven evaporation system for coating both C divertors on EAST.

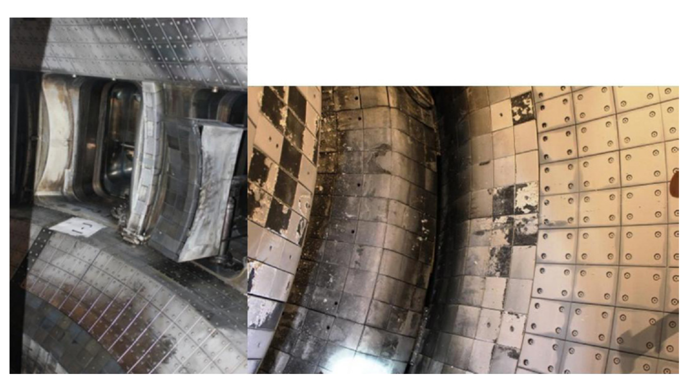

Fig. 4. Li coatings on Mo first walls and C divertors in 2012 campaign on EAST.

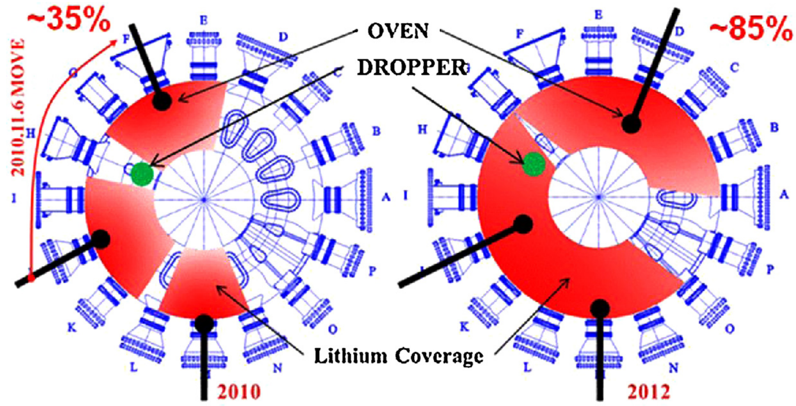

Fig. 5. Comparison of the coverage of Li coat in 2010 and 2012 campaigns on EAST.

to plasma density, the emissions of CIII, OII and MoI were reduced by a factor of 6, 8 and 3, respectively, after the forth Li coating, which is better than that in 2010. In was further observed that, by using three well placed evaporators in the 2012 campaign, the Li coatings were more uniform than those in 2010 campaign using only two evaporators. As shown in Fig. 5 and based on observation by the naked eye, the coverage of thick Li coatings in the 2012 campaign increased to ~85% of full internal area coverage, compared to ~35% in 2010. Film thicknesses near the ovens were about 3 mm, measured with ruler. However, far from the ovens, possibly due to uniformity of the coating or due to material mitigation during plasma discharges, the films were less uniform and thicknesses of most films were only a few hundreds of nanometers, observed by SEM. These observations suggest that with more evaporators, more film uniformity could be achieved. Hence it appears that ideally at least one more oven should be used to cover the remaining ~15% of the EAST surface area.

As compared to 2010, during the 2012 EAST campaign C impurities were greatly suppressed and recycling was effectively reduced [24]. These improvements are attributable to both the newly installed Mo first walls and the expanded coverage of Li coatings. It was observed that the recycling coefficient decreased step-by-step and that this trend could be maintained for many discharges after one Li coating. With the attainment of low recycling conditions, the plasma density was easily controlled by feedback, which was important for long-pulse plasma operation. Subsequently, long-pulse plasmas of over 400 s were obtained routinely [25]. At the same time, the H concentration in plasmas was significantly decreased due to Li conditioning. Remarkably low ratios of H/(H+D)—as low as 2.5%—were obtained easily with Li conditioning whereas the lowest ratio in 2010 was about 10%. These low H/(H+D) ratios, in turn, greatly increased the heating efficiency of ICRF. Drawing on the dual advantages of reduced recycling and increased heating efficiency, stationary H-mode plasmas lasting over 30 s were routinely and reproducibly obtained during the 2012 campaign [26].

Real-time Li powder injection potentially offers an extremely attractive tool for active wall conditioning in future high power steady-state operation. Real-time Li powder injection was accomplished not only for active wall conditioning and real-time replenishment of the previously deposited Li films, but also for the effective suppression of MHD activity ($m/n = 2/1$ tearing mode) in L-mode discharges [23]. On EAST, Li powder injection was typically applied to enhance the coating effects brought on by use of evaporators. During these active Li wall conditioning using the dropper, Li powder particles ablate and ionize quickly in the plasma edge as shown in Fig. 6.

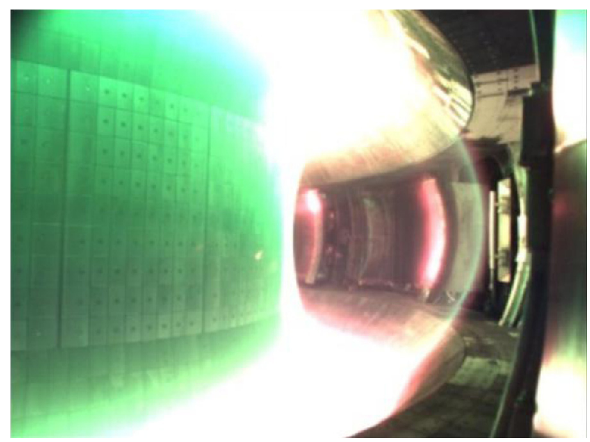

Fig. 6. Li powder particles ablation and ionization during Li powder injection.

In addition, a new observation indicated that active Li injection could be used for ELMs suppression, which has also been demonstrated using Li coating only on NSTX [15,27]. As shown in Fig. 7, compared with a plasma (shot 41081) without the active Li injection with a flow rate of about 50 mg/s, ELMs and its induced MHD

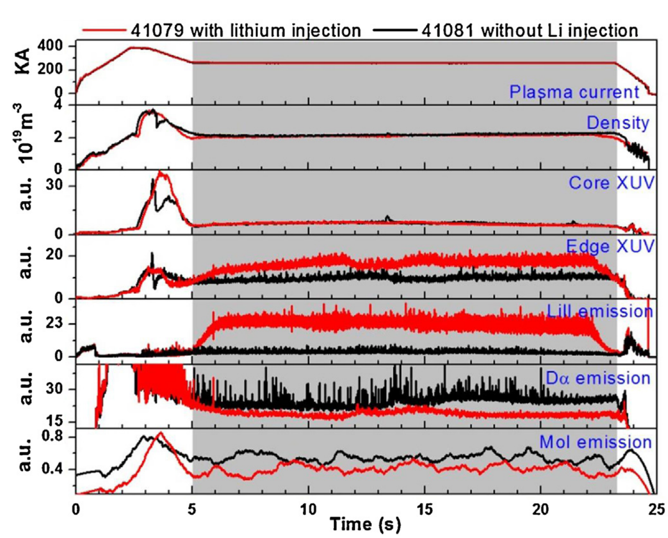

Fig. 7. Comparison of two long pulse H-mode discharges between with and without real-time Li injection (double null divertor configuration, LHW ~ 1.4 WM and ICRF ~ 0.7 WM).

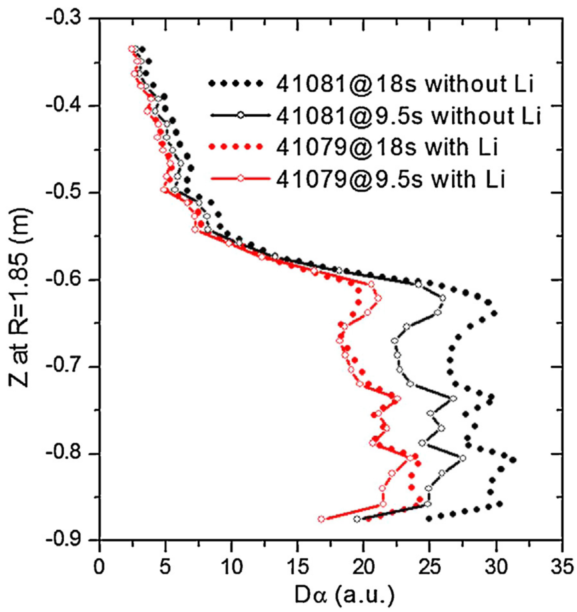

Fig. 8. Emission of Dα between ELMs at different chords between with and without real-time Li injection.

activity in an H-mode plasma (shot 41079) were effectively suppressed by the real-time injection of Li powder during active Li coating, represented in the gray area. As shown in Figs. 7 and 8, with real-time lithium injection, the recycling at divertor was reduced and Mo impurity (in Fig. 7, the signal of MoI is smoothed curve) was suppressed, which maybe the main reason for the ELMs suppression. And edge radiation near divertor was high due to Li powder injection. This result may be useful for the operation of long H-mode plasma without ELMs and could reduce the heat flux onto the first wall. Hence it could be possible mitigate the challenge of PFC design in future fusion reactors.

During the 2012 campaign, several lessons were learned about plasma recovery with the help of Li coatings after serious vacuum events. One such particularly serious event occurred during which ~2500 kg of water and half a liter of oil entered the EAST vacuum vessel. Remarkably, plasma operating conditions were recovered after only two Li coatings requiring 90 g of Li following 1 week of standard baking and cleaning (with GDC & ICRF) procedures.

In a similar event the EAST vessel was exposed to air thus contaminating the 800 g of accumulated Li coatings present at the time of the incident. Upon exposure to air the Li film was transformed into a film of Li carbonate (Li_2CO_3). The remaining film was then removed manually using wet cloths. After this particular event, plasma operations were also recovered with the help of only two Li coatings.

In yet another event the vacuum vessel was filled with N_2 to allow the calibration of the EAST Thomson scattering system. This particular event caused three days of disruptive discharges. Subsequently, two Li coating were carried out and reliable plasma operation was immediately recovered.

The vacuum episodes described above indicated that with the help of Li coatings, reliable plasma operation could be quickly recovered. They also indicated that water leaks, air exposure or nitrogen contamination should be not be viewed as obstacles for the application of Li coating in tokamak devices. However, it could actually be a problem in a reactor due to need of larger inventories of lithium and the presence of tritium. This required technology development and should be studied in the future.

2.4. Discussion of Li coating on EAST

The experiments on EAST have demonstrated that Li coating is an effective method to suppress impurities and to reduce recycling and hydrogen concentrations. Further, as a practical matter, Li coating can be used for routine wall conditioning. Li can be effectively coated onto both C and Mo walls for the improvement of plasma performance. It appears that the change from C to Mo walls enhanced the effectiveness of the Li coating, which allowed the attainment of improved plasma parameters with low recycling and low impurities level. In the near future, the EAST divertors will be changed to W from C and Li coating will be performed on fully metal PFCs. It is expected that recycling could be further reduced and plasma performance could be further improved with the help of Li coating.

The new conditioning methods applied in 2012, such as the increase in the number of Li evaporators, using more Li with deeply inserted ovens and a dedicated bidirectional evaporator to coat the divertors, appear to have improved the Li coverage. Because most hydrogen influx and recycling are expected to have come from C divertors, to have suppressed such divertor recycling was extremely important to the success of the EAST 2012 campaign. The dedicated bidirectional Li evaporator likely enhanced the effectiveness of the Li coating effort. Improved uniformity of Li coating was also important. In the experiments in 2012, Li coverage increased to ~85%. It is anticipated that if one more evaporator can be installed in the future, the coverage could be increased to more than ~95% and plasma performance could be further improved.

The history of Li coating on EAST also indicated that the methods applied in 2012 were well chosen. In 2009, Li coating with a single small oven only caused a small improvement of plasma performance. In 2010, while using two ovens with a larger Li capacity of 30 g for each coating, plasma performance was significantly improved and culminated in the first EAST H-mode plasma as well as a 100 s-long plasma. In 2012, with the help improved coating methods, EAST performance was further improved eventually attaining a stationary H-mode plasma of over 30 s and a 400 s-long discharge.

Based on pre-coating using evaporation, active Li wall conditioning using the Li powder dropper appeared to be a good method to both suppress impurities and reduce recycling in real-time during plasma discharges. This method supplied “fresh” Li and protected the previously deposited Li films. Active Li injection was observed to suppress both MHD activity and ELMs during long H-mode plasmas. This technique was quite useful for the attainment of long-pulse and high performance plasma operation.

3. Flowing liquid Li limiter experiments on HT-7

3.1. Motivations of flowing liquid Li limiter experiments on HT-7

Before the 2012 flowing liquid Li limiter experiments, liquid Li limiters had been investigated on HT-7 since 2009 [28–30]. Both movable liquid Li limiters with a free-surface and a large-area capillary porous structures (CPS) had been successfully tested during ohmic plasmas without additional heating. In addition, an external Li supply was also successfully tested.

It was observed that the influence of the liquid Li limiters on the improvement of plasma performance was generally similar to that of Li coatings. The use of liquid Li increased plasma confinement, suppressed impurities and reduced recycling. Compared with a free surface limiter, the Li limiter with a CPS confined surface was beneficial for reduction of Li droplet ejection, for an increase in the compatibility between the Li and the plasma and for a reduction in the percentage of disruptive plasmas. A re-filling experiment

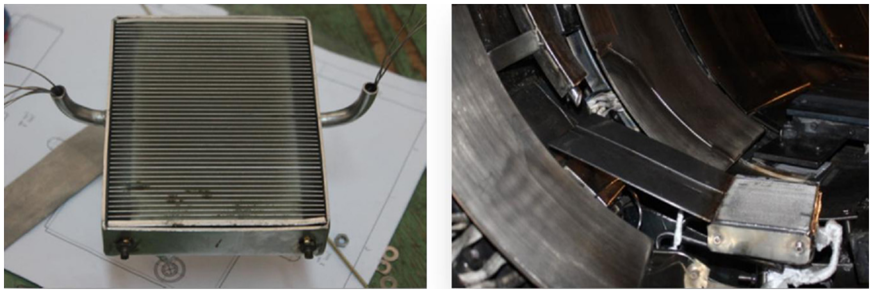

Fig. 9. Design and setup for LIMIT using TEMHD effect in HT-7.

showed that liquid Li could be readily driven by pressured Ar, which is important in the effort to increase the lifetime of the Li limiter. In addition, a test bench for the flowing liquid Li limiter concept has been developed. Initial tests have resolved several of the technology issues associates with a liquid Li loop, such as filling and driving the Li, heating, the use of valves and Li collection techniques.

Based on those experiments, a flowing liquid Li limiter experiment has been proposed and the present focus is on designing an advanced and reliable flowing liquid Li surface for EAST. This limiter will be used to resolve technical questions that arose during previous experiments and to prepare to serve a tokamak with long-pulse H-mode plasmas on low recycling walls. The main motivations for the flows liquid Li limiter experiments in 2012 on HT-7 were as following: (1) to apply the results of previous experiments for new design of a reliable flowing Li limiter; (2) to master key technologies involved in flowing Li operation; (3) to test components of a liquid Li loop – such as heating/cooling, valves, and the drive system; (4) to test multiple design concepts of flowing Li PFCs; (5) to investigate the interactions between flowing liquid Li and the plasma; (6) to develop technology for future flowing Li limiter/divertor for EAST with a large area and uniform flow.

3.2. Design of the flowing liquid Li limiters on HT-7

In 2012 two kinds of flowing liquid Li limiter systems were employed in the final run campaign of the HT-7 tokamak with major radius $R = 1.22$ m and minor radius $a = 0.27$ m. Both flowing liquid Li limiters provided renewable plasma facing surfaces for removing retained particles in lithium and heat flux from the plasma edge.

The first system is referred to as the Li-metal infused trenches (LiMIT). This system exploited the thermoelectric magnetohydrodynamic (TEMHD) effect to drive the liquid Li flow [31]. The thermoelectric effect produced a current between the liquid Li and the trench walls when a temperature gradient caused by strong plasma heat flux, >100 kW/m^2, which depends on the limiter position, was created at liquid/plasma interface during HT-7 discharges. This current which has a component perpendicular to the limiter surface would drive the liquid Li flow along the trench by electromagnetic force. The limiter was located at the bottom of the vessel at $r = 270$ mm. The trenched material was Mo. The width of Li plate in the poloidal direction was 100 mm and the toroidal extent was 120 mm, as shown in Fig. 9. The trenches were 5 mm in depth and 2 mm in width. The gap between trenches was 2 mm. The limiter used resistance heaters and was cooled using nitrogen gas. Heating and cooling were accomplished separately, so as to establish temperature gradients used to drive Li flowing. However, only after one try, the resistance heater was broken. Then, the limiter without cooling was only heated by hot nitrogen gas.

The other liquid limiter system used a thin flowing film concept [32], as shown in Fig. 10. The so-called flowing liquid Li limiter (FLiLi) had a manifold distributor with multiple channels on the top of a stainless steel guide surface protected from the plasma on its edges by two Mo plates. The design of the distributors utilized the magnetohydrodynamic (MHD) effect of the pressure drop when the liquid Li was moving across the channels in a magnetic field. In order to insure a uniform Li supply from the channels to the guide surface, the system was designed for a velocity of less than 1 cm/s and with a flow thickness of 0.1 mm. These parameters result in small MHD Reynolds and Hartmann numbers so as to guarantee a negligible interaction of the free surface flow with a magnetic field. Also, the small thickness of the flow and viscous drag led to reduced $J \times B$ force on the flow. The limiter was located at the mid-plane on the high field side at $r = 270$ mm. The stainless steel plate had a poloidal width of 150 mm and a toroidal extent of 500 mm. All parts of the limiter could be heated to 400 °C using resistance heaters while either pressured Ar or an EM pump was designed to drive the Li flow. However, EM pump have not used in this experiment due to a failure of the pump.

3.3. Main results of flowing liquid Li limiter experiments in 2012

Using the LiMIT limiter, liquid Li was successfully injected into the limiter at an increased temperature about 390 °C. However, the wetting of Li on Mo substrate seemed not good and most Li flowed out from the sides of the limiter, as shown in Fig. 11. Only several trenches of the limiter were filled with liquid Li. This result

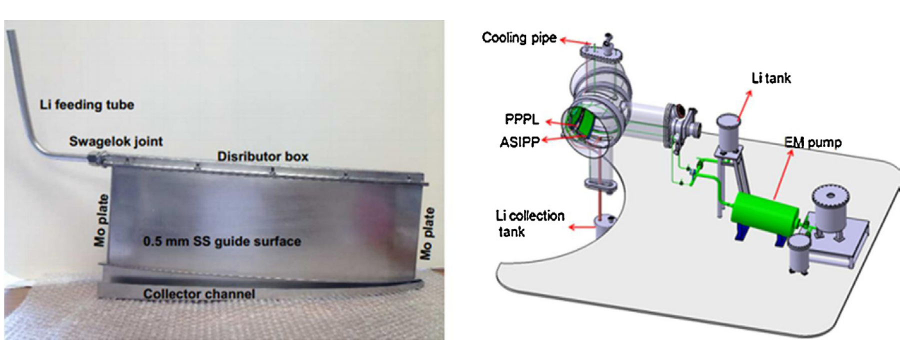

Fig. 10. Flowing liquid Li limiter system using a thin flow film concept on HT-7.

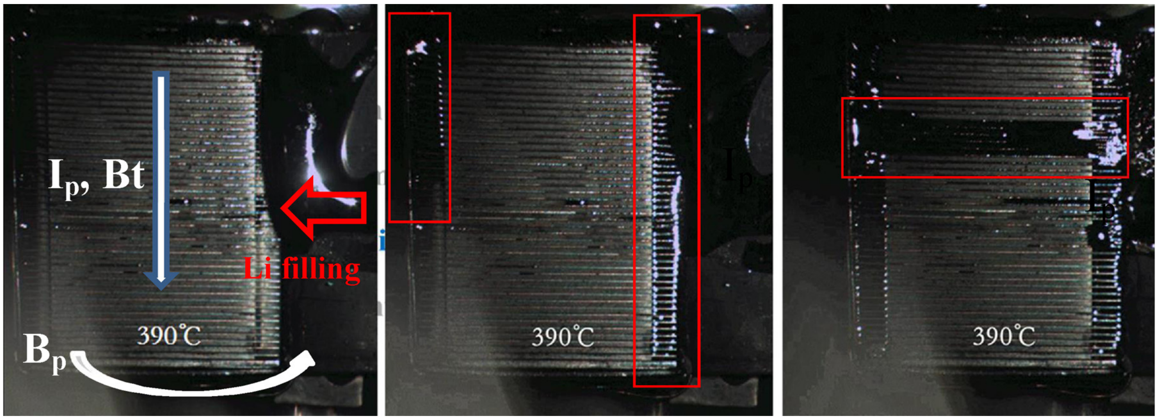

Fig. 11. Li filling and wetting on the LIMIT limiter in HT-7.

indicated that the wetting of the Li on limiter surface needs to be improved by effective measures, such as increasing temperature, keeping a fresh surface and using a Li coating. From the Fig. 12, even though the temperature control by heating and cooling was failed, it was still observed that liquid Li near plasma touched area could flow with a velocity about 3.7 ± 0.5 cm/s along the trenches driven by $J \times B$ force during the plasma discharges [33]. However, the liquid lithium at the edge of limiter with a far distance to plasma touched area has not moved. This indicated Li could be driven by TEMHD due to gradient of temperature caused by heating of plasma itself with a heat flux about 130 kW/m^2 measured by Langmuir probe The velocity of liquid lithium in the trench could be calculated through: $\bar{u} = \frac{P}{B} \times \frac{dT}{dz} \times \frac{H\alpha - tanh(H\alpha)}{H\alpha + Ctanh(H\alpha)}$, where $\bar{u}$ is the average velocity of lithium, P is the difference of the Seebeck coefficients between SS and Li and $H\alpha$ is the Hartmann number. Gradient of temperature $\frac{dT}{dz}$ could be calculated from the heat flux by $q = -k\,\frac{dT}{dz}$, where k is the thermal conductivity of Li. Applying to HT-7, the average velocity is about 4.2 cm/s which is approximately accordant to the experimental results. And this concept could possibly be used for flowing Li PFCs in future fusion devices. In the future, for a better operation, the problems of the shortage of Li and precise control of temperature should be resolved, and the stability of the heating and cooling system should be improved.

For the FLiLi limiter, the application of the limiter without Li coating resulted in a non-uniform flow film on the guide surface of stainless steel plate. After about 1 h of coating with 5 g of Li, it was observed that the liquid film crept along the guide surface of the limiter, and that the velocity of the flow depended on the Ar driving pressure. Moreover, the Li flow crept through the whole guide plate with a thin uniform film when Ar driving pressure reached 40,000 Pa, as shown in Fig. 13. When the driving pressure reached 40,000 Pa, the Li average flowing speed on limiter reached 2.1 mm/min, which calculated by the wetted positions at two times. The typical particle flux to the wall in HT-7 Tokamak can be assessed as 4.4×10^{21}/m^2 s. Assuming Li absorbing capacity as 10% (atomic), removal the particle flux from limiter would require replenishment of 3.3×10^{21}/s atoms of Li or less than 0.1 cm^3/s. The reference minimal velocity is based on thickness of the Li layer and the width of the contact zone with plasma. Applying to HT-7, the designed velocity can remove enough particle flux while using limiters. The velocity measured by CCD camera is lower than the design. Main reason may be no enough pressure or larger MHD pressure drop than that designed. However, this observation demonstrated that the possibility to refresh the Li surface and remove the particle flux by using a FLiLi limiter by means of an improved velocity in the next step experiment. The heat flux is possible to be effectively removed via heat sink by using an appropriate cooling way due to thin lithium film, and it can be calculated through: $\Delta T = qh/k$. In this formula, q is heat flux, k is thermal conductivity and h is the height of the lithium flow. The temperature drop across the 0.1 mm lithium layer can be

Fig. 12. Li flowing along trenches of the LiMIT limiter in HT-7 during ohmic plasma discharge (plasma current $Ip = 125$ kA and plasma density about $Ne = 1 \times 10^{19}$ m^{-3}).

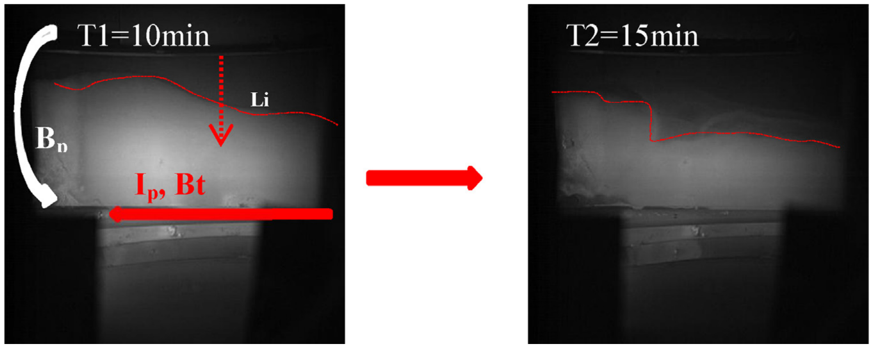

Fig. 13. Slowly flowing Li film on stainless steel plate of the FLiLi limiter with 40,000 Pa Ar driving.

assessed as 4 °C per 1 MW/m^2 heat flux, indicating that the flow is essentially transparent to the heat flux, which has to be removed by the copper heat sink.

During the experiments, it was also observed that strong interactions between plasma and liquid Li, could cause strong Li influx and lead to disruptive plasmas [34]. Using a free surface limiter, significant amounts of Li would be ejected from the surface during plasma discharge mainly due to the $J \times B$ force. It was seen that plasma instabilities and non-uniform flow of Li could make the interaction stronger. Possibly due to the wide trenches of the LiMIT limiter causing inadequate Li confinement, Li droplet ejection seemed still strong and would lead to plasma disruptions. After extensive testing, it was observed that Li droplet ejection from the FLiLi limiter with a thin film on stainless steel plate was much less than in other cases if the plasma was well controlled. These results provide technical references for the design of a flowing liquid Li limiter/divertor in tokamaks to avoid strong droplet ejection and hence to decrease disruptive plasmas.

By application of the two types of flowing Li limiters in HT-7, reduction of particle recycling and improvement of the confinement were achieved similar to Li coating. It was especially encouraging to see that, even though the Li coating had already improved the plasma performance, a flowing liquid limiter would be also very useful to further enhance the plasma confinement. Two ohmic HT-7 shots with the same current of 100 kA and density of 2×10^{19}/m^3 were carried out with and without the FLiLi limiter, respectively. It was noted that Hα emission intensity significantly reduced while using the FLiLi limiter. This result proved the effect of the FLiLi limiter on reducing H recycling. It was also observed that by using the FLiLi limiters, electron temperature slightly increased and soft x-ray emission decreased. These indicated the FLiLi limiters were effective for decreasing the impurities level and improving the plasma confinement. Furthermore, one can see how the energy confinement time is expressed by $\tau_E = W_{in}/P_{in}$, where $W_{in} = 3/2 \times \int n_e \times (T_e + T_i)\,dv$ is the stored energy and $P_{in} = I_p \times V_{loop}$ is the input power. Compared with the shot without FLiLi limiter after Li coating, the shot with FLiLi limiter had a slightly increased T_e and identical n_e, the W_{in} of two discharges were similar. The plasma with and without the FLiLi limiter had loop voltage 2.04 V and 2.56 V, respectively. So the $P_{in} = I_p \times V_{loop}$ was reduced ~20% while using the FLiLi limiter. Calculated from $\tau_E = W_{in}/P_{in}$, the plasma confinement using the FLiLi limiter after Li coating improved about 25%, due to the decrease of radiation. Similar results were obtained with the LiMIT limiter. Even with incomplete wetting of Li on Mo trenches, the confinement also increased ~10% with the help of the LiMIT limiter.

3.4. Discussion and further plans for flowing Li limiter/divertor

Flowing liquid Li as a PFC can continuously pump particles and remove heat flux from the plasma. Two kinds of the mentioned flowing liquid Li limiter are beneficial for the improvement of plasma performance. From the experiments on HT-7, it was determined that keeping a uniform Li flow and optimizing plasma control are keys to increasing the compatibility between the plasmas and the flowing Li so as to reduce plasma disruptions.

For the future application of flowing Li limiter/divertors with a large plasma facing surface, several technologies need to be improved. The experiments on HT-7 demonstrated that Li wetting should be improved and disruptive discharges due to too much Li influx should be suppressed. The Li influx could possibly be reduced by employing a CPS structure or by forming uniform Li film flow. How to remove high heat flux on liquid limiter/divertor surfaces should also be considered to limit the increase in the PFC surface temperature due to the incident heat flux. Using active water or high pressured gas cooling may be good choices, but these technologies need to be developed and tested. Wetting of Li on the limiter surface is the determinant of a reliable and improved performance for a Li PFC. Hence the wetting of Li on various metal substrates should be improved. With the help of pre-coating using Li, the wetting of Li on stainless steel should be much improved so that uniform Li flow can be obtained. Increasing the substrate temperature should also be a benefit for attaining a uniformly flowing Li film.

Also, the limiter components used in the experiments on HT-7 should be improved. In particular, the heating and cooling systems should be engineered for more reliability. The resistance heaters used for both limiters were both fragile and readily contaminated by Li. Thus protection for the heaters needs to be improved. In addition, development of measurement technologies for Li inflow and outflow rates is needed to estimate Li consumption during plasma discharges.

To help resolve the problems mentioned above, multiple bench test experiments have been carried out with flowing liquid Li. New heaters and diagnostics for Li flow have been developed. Wetting experiments of liquid Li onto various substrates have also been carried out [35]. From this work it has been observed that high substrate temperature, pre-coating with Li and cleaning with GDC can greatly improve Li wetting. It was also found that liquid Li wets better to Mo than to stainless steel. The details of this work will be submitted for publication shortly. In addition to those experiments, tests of various limiter head configurations will be carried out soon. This work should provide useful design guidance for a flowing Li limiter/divertor to be installed on EAST.

At present, based on the HT-7 experiments and the bench testing described above, a movable limiter which is aimed at achieving continuously flowing liquid Li operation is being designed for EAST. During the next campaign on EAST, the flowing Li limiter will be installed on the end of the present Materials and Plasma Evaluation System (MAPES) located on the mid-plane and inserted from the low field side, as shown in Fig. 14. Both limiter concepts – using a flowing Li film and the TEMHD effect – are under consideration as

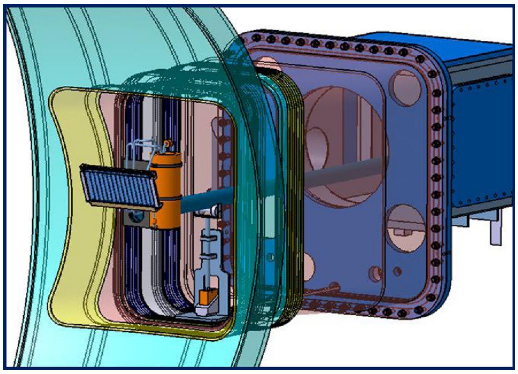

Fig. 14. Scheme of the planned flowing Li limiter on EAST.

candidate limiter surfaces. The limiter will have a length of 300 mm and a width of 150 mm. Liquid Li will flow from the top to the bottom of the limiter driven by Ar pressure, the TEMHD effect, or electromagnetic (EM) forces. Liquid Li will be confined by strong surface tension such as in a CPS system, narrow channels in the TEMHD design or by thin Li flow to prevent uncontrolled Li influx. In order to remove the heat flux from plasmas with high power and long-pulse duration, a high pressure He cooling system is planned. It is further anticipated that the interactions between the flowing liquid Li and high performance plasmas with long pulse durations will be investigated during the next run campaign.

4. ELMs pacing using Li granule injection

4.1. Motivation for using Li granule injection in 2012

Heat loads accompanying type-I edge localized modes (ELMs) can pose a threat to the tokamak divertor target plates [36]. Thus controlling the ELM frequency is an important task for the development of high performance plasma scenarios. One proven method for ELM triggering involves periodic injection of high-speed cryogenic deuterium pellets [37]. However, the method of injecting fuel pellets to pace ELMs introduces the prospect of increased plasma density, therefore the flexibility to use pellet materials other than D_2 fuel is desirable. On EAST, H-mode plasmas with type-I ELMs were observed in the 2010 campaign [38]. This required developing ELMs mitigation techniques. Besides supersonic molecular beam injection (SMBI), D_2 pellet injection, resonance magnetic perturbations (RMP) and lower hybrid wave modulation, Li granules injection proved to be one new choice for ELMs control, for EAST. During the 2012 campaign, a new system of applying Li called the Li granule injector was introduced in order to trigger ELMs.

4.2. Li granule injector

As shown in Fig. 15, the Li granule injector was designed as an extension of the Li dropper. Li granules are dropped by the resonant vibration of a piezoelectric disk and fall down a narrow guide tube where they encounter a high-speed rotating impeller [39]. The impeller strikes the falling granules and injects them into the plasma edge in the horizontal direction, thus influencing plasma performance. Using the injector, the speed and pacing frequency of the granules can be controlled between 0–100 m/s and 0–500 Hz, respectively. Further, the dropper allows the user to select among four different size granules. The design of the system thus allows a wide range of parameters to achieve optimal granule injection on EAST.

4.3. Main results ELMs pacing using Li granule injection

EAST has demonstrated, for the first time, ELM pacing using the innovative solid Li-pellet injection technique. Small Li granules, ~0.7 mm, were injected from the outer mid-plane into the plasma using a rotating impeller with a tunable velocity to actively control the depth of penetration. Each injected granule was seen to trigger an ELM during an otherwise ELM-free phase. The amplitude of the induced ELMs as measured by Dα was clearly reduced compared to natural ELMs, which have been reported in detail elsewhere [37]. Fig. 16 shows the time evolution of an H-mode discharge with the injection of Li granules. The Li granules are injected into the plasma at a speed of ~50 m/s with a repetition rate of ~25 Hz. During the initial experiment, it appeared that Li granule injection was essentially 100% efficient at triggering ELMs and the amplitude of the induced ELMs has been clearly reduced, compared to that before

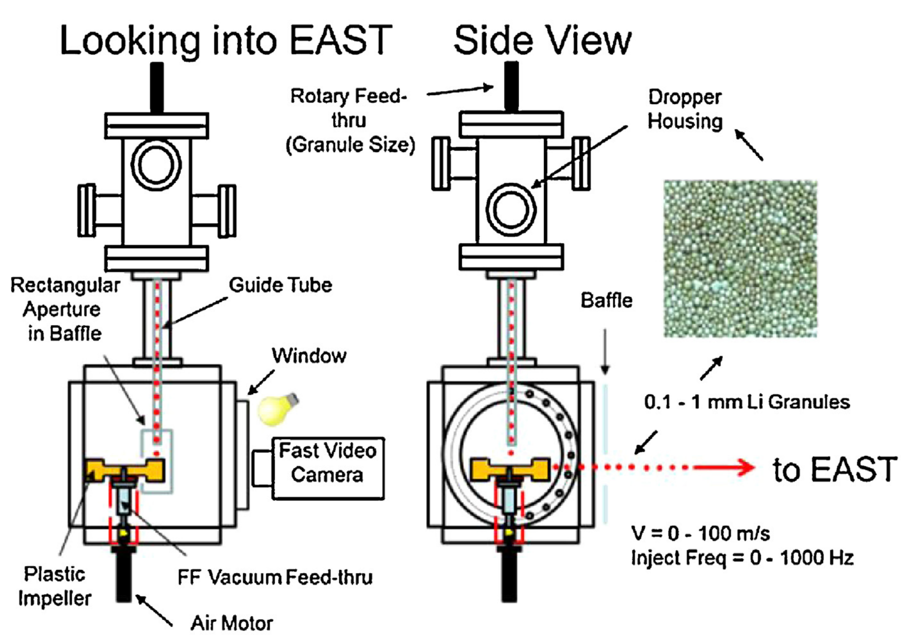

Fig. 15. Scheme of Li granule injector.

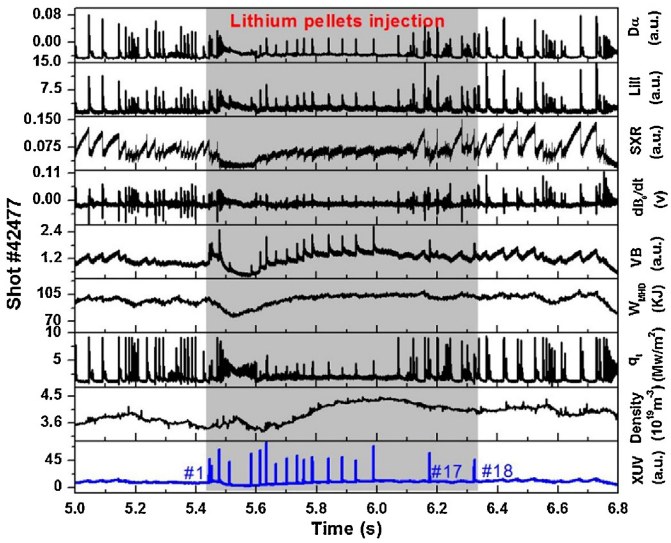

Fig. 16. ELM pacing using Li granule injection with spherical granule size 0.7 mm at a velocity of 50 m/s (shot 42477, with low single null, plasma current ~400 kA, P_{LHW} ~1.4 WM and P_{ICRF} ~1.2 WM).

injection. Each Li pellet triggered one small ELM (no spikes observed during L-mode after lithium granules injection). The particle flux caused by pellet triggered high frequency ELMs on divertor is lower than that caused by naturally-occurring ELMs before pellet injection by a factor of 2 or 3. The stored energy in plasma decreases less than 10% and strong XUV radiation at plasma edge was observed during the ELM crash. Magnetic perturbations resembling those during natural ELMs were also detected by Mirnov coils. However, occasional H–L–H transitions were caused by granule injection, which could be avoided by using optimized injection parameters in the future.

4.4. Discussion of ELMs pacing using Li granules injection

The initial experiments on EAST showed that Li granule injection is an effective method to pace ELMs, which is an important first step. More experiments should be performed to investigate and understand the pacing mechanism. To avoid the occasional H–L–H transitions caused by granule injection is important. Moreover, profiles of the density and temperature of the edge plasmas during granule injection should be carefully measured in future experiments. In addition, plasma performance and heat flux mitigation on divertor surfaces during Li granule injection should be studied. In the next campaign, the size and the injection speed of Li granules will be tested to optimize ELMs pacing.

5. Summary

In 2012, many Li experiments on HT-7 and EAST were carried out, such as Li coating experiments with upgraded system, the first application of Li granule injection for ELMs pacing on EAST, and the first flowing Li limiter experiments on HT-7. As discussed above, multiple new results were obtained.

On EAST, with new Mo first walls and C divertors, three deeply inserted and newly designed ovens and a real-time dropper of fine Li powder were used for Li coating. It is observed that both the Mo first walls and the C divertors were well coated by Li. More than 2 kg Li was used in this campaign and the coverage area was increased up to 85%, especially on the divertors, which was larger than 35% in 2010. With the help of Li coatings on reducing recycling and hydrogen content in deuterium plasmas (≤3%), new achievements of EAST were obtained, such as stationary 30 s H-mode plasmas and 400 s long-pulse plasmas. It is also discovered that even if large leaks happened after Li coating, enhanced plasma could be recovered quickly. Also during 2012, active wall conditioning using a dropper has been tested as a better way to regenerate Li films. Exciting observations of the ELMs suppression using active wall conditioning was demonstrated for the first time on EAST, which can possibly be useful for long-pulse H-mode plasmas. For the improvement of plasma performances, Li coating will be carried out on EAST with a W divertor in 2014 and new heating systems, such as NBI.

On EAST, ELMs pacing using small Li spheres injected mechanically into H-mode discharges was also successfully performed. Triggering of ELMs was accomplished using a simple rotating impeller to inject sub-millimeter size granules at speeds of a few tens of meters per second into the outer mid-plane of EAST. The observation that ELMs can be triggered using the injection of Li other than frozen hydrogen pellets allows for the contemplation of Li ELMs pace-making on future fusion devices.

On HT-7, flowing liquid Li limiters using the TEMHD concept and using a thin flowing film concept were also initially tested and some references were obtained for the future development. Flowing Li limiters were beneficial for the improvement of plasma performance. The experiments on HT-7 showed that Li wetting should be improved and disruptive discharges due to Li ejection should be suppressed. The Li droplet ejection could possibly be resolved by employing a CPS structure or by forming a uniform Li film flow. How to remove high heat flux on liquid limiter/divertor should be considered in the future to limit the increase in the PFC surface temperature due to the incident heat flux. Using active water or high pressured gas cooling may be good choices, but both need to be tested. After the experiment on HT-7, multiple experiments have been carried out on the test bench for flowing Li. Based on the experiments on HT-7 and the test bench, a movable flowing Li limiter is under design for EAST, which is aimed to achieve continuously flowing liquid Li operation.

These experiments show that Li should be an important material for fusion devices. It could be used for wall conditioning, ELMs mitigation and would also possibly provide self-recovering PFCs in future fusion devices.

Acknowledgements

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