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A new developed in-between shots lithium evaporation coating system for improving plasma performance in EAST

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ABSTRACT

A new in-between shots evaporative lithium coating system has been successfully developed and implemented on the Experimental Advanced Superconducting Tokamak (EAST) for the 2017 campaign. This paper describes a novel technique for the introduction of lithium into the EAST vessel allowing evaporative coatings to be applied between discharges without requiring a significant amount of time to insert and retract the lithium source. This newly designed system utilizes a rotating axis driven by a vacuum dynamic sealing feedthough under remote control to open and close a shutter. A compression bellows, which drives the delivery tube, guarantees accurate position of the oven thus avoiding possible direct contact with the plasma. This allows the new evaporation system to be operated in two distinct modes. One mode is operated in-between shots to refresh pre-coated lithium film, the other is a real-time lithium vapor injection during plasma operations to provide active wall conditioning during long pulse plasma discharges. In this paper, operation of this new lithium deposition system in the in-between shots replenishment mode is described. Initial experiments show that this system worked well during the interval of discharges in EAST, and the in-between shots lithium coating effectively reduced the wall recycling and impurity concentrations. Moreover, the application of fresh lithium coating lead to sustain the plasma stored energy and confinement, as well as a reduction of impurity radiation.

1. Introduction

The appropriate choice of plasma facing materials (PFMs) and the application of wall conditioning techniques play important roles for the achievement of high plasma performance and steady-state operation in tokamak devices [1]. Impurity influx and wall recycling are serious problems which must be considered when accounting for plasma-material interactions (PMI) [2]. High impurity concentration in the plasma can also lead to high power radiation loss and a subsequent deterioration of plasma performance [3]. In addition, high wall recycling, especially for deuterium fuel, may leads to termination of the discharge due to uncontrolled density ramping [4]. Finally, control of the H content within the plasma, as indicated by the H/(H + D) ratio, must be limited to less than 10% in order to provide high ICRF minority heating efficiency [5]. Therefore, an advanced wall conditioning technique, applicable on existing plasma facing components (PFCs) which will both reduce impurity concentration as well as suppress wall recycling is quite important for high performance and long pulse plasma operation. As a low Z material with low evaporation temperature, lithium (Li) is an attractive wall conditioning material for controlling impurity, wall recycling and H content in tokamak devices [6]. Various Li introduction techniques have already been successfully applied on a range of fusion research devices, such as TFTR [7], TJ-II [8], NSTX [9] and EAST [10]. These experiments have shown that Li wall conditioning can significantly reduce impurity concentration and wall recycling in the plasmas [11]. In TFTR, Li was first introduced through the pneumatic injection of Li pellets which resulted in a substantial increase in D-T fusion power [7] leading to the “Super-Shot” regime. In TJ-II, a strong decrease in recycling, enhanced density control and discharge reproducibility were obtained with uniform Li wall coatings by utilizing four Li ovens installed symmetrically around the midplane [8]. In NSTX, evaporative Li wall coating was shown to be beneficial for reducing particle recycling, aiding in the control of plasma density and transiently eliminating Edge Localized Modes (ELMs) [12].

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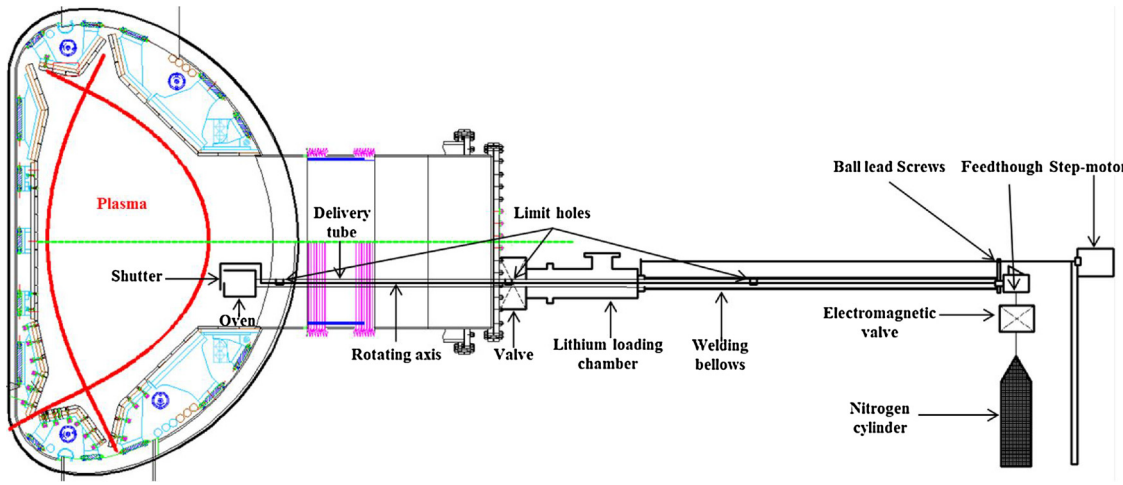

Fig. 1. The sketch of in-between shots Li evaporation coating system on EAST.

For the reasons described above, EAST has chosen pre-shot Li evaporation as its primary wall conditioning technique in order to actively modify plasma-wall interactions and improve plasma performance. This technique has provided routine wall conditioning on EAST during standard operations since 2009. Li evaporative coatings associated with He-ICRF were first carried out in 2009 [13]. Despite only 2 g of Li being introduced, substantial reductions of both residual impurities and deuterium were obtained after Li coating. Inspired by the previous results of Li application, two stable Li evaporation systems were developed in 2010. In order to improve the Li film coverage, the two systems were located on the J and F mid-plane port with a separation of approximately 180°degrees. With the help of Li coating, EAST's first H-modes, 100 s long pulses, and 1 MA discharges were all separately achieved [14]. Encouraged by the improvement of discharge conditions as a result of Li coating, three almost evenly distributed Li ovens, each of which could be inserted to the poloidal center of the plasma vessel, were installed to provide nearly full toroidal evaporative coverage during the 2012 experimental campaign. The toroidal location of these three systems increased the surface area Li film coverage from 35% to 85%. As a result of the improved coverage, stationary H-modes exceeding 30 s and long pulse discharges over 400 s were now achieved [15]. To further improve uniformity of the Li coating on the divertors, a dedicated oven with two evaporation nozzles was installed on EAST. Recently, a new milestone of H-mode operation in excess of 100 s was successfully obtained under a modified operational scenario with Li coated walls.

Even though the previous Li evaporation coating system could be used for the improved plasma operation on EAST, it still required a substantial amount of time to operate. Standard operating procedure was to utilize the evaporators prior to plasma operation in the early morning of typical run day due to the amount of time required for oven insertion and heating [15]. As such, it was not possible to utilize Li evaporation during the interval between discharges to maintain maximum effective coverage. Operational experience has shown that the coated Li film would begin to lose its effectiveness in suppressing impurities and reducing wall recycling after approximately 40–50 plasma discharges [16]. To maintain enhanced performance during extended periods of operation, and especially as EAST moves to longer pulse discharges, it became necessary to develop an advanced in-between shots Li evaporative coating system to refresh the pre-coated Li film. With the expectation of long pulse operation, this system needed to have both the capability to be easily operated during plasma discharges as an active means of refreshing the coating in real-time as well as operation within the interval between discharges to refresh the pre-coated Li film.

A new Li evaporation and coating system meeting these requirements has been successfully developed on EAST. In this paper, the evaporator system design and results from first experiments on EAST will be presented. The structure of the remaining paper is as follows. Key system components for the coating system and newly designed oven are described in Section 2, with preliminary experimental results presented in Section 3, and further discussion and summary found in Section 4.

2. New developed in-between shots Li evaporation coating system

2.1. In-between shots Li evaporation coating system design

In order to rapidly replenish the pre-existing Li coating, a system needed to be developed to quickly insert the evaporation oven and deliver evaporated Li within the interval between standard discharges. To refresh Li coatings during long pulse operation, the system also needed highly accurate positioning. As such, the evaporator is equipped with a delivery system which guarantees that the oven can be accurately stopped 10 mm from last closed flux surface (LCFS) of an active discharge, thus avoiding direct contact with the edge plasma. The key components of this delivery system include: the delivery tube, welded compression bellows, ball lead screws and step-motor. Fig. 1 shows the sketch of evaporator and delivery arm as installed on EAST. A step motor drives the ball lead screws thus compressing the bellows. The bellows is 4 m in length with a 50 mm diameter and 3 m compression stroke. This bellows contains the delivery tube, made from 316 stainless steel, which is 4.1 m in length and 30 mm in diameter, with a 1 mm thickness and joined with the compression bellows thus allowing the delivery tube to be pushed into the vacuum vessel. Mounted to the front of the delivery tube is the dedicated Li oven which is positioned to be delivered to a position 10 mm away from the LCFS. In addition, there is also an exchange chamber which allows loading of Li and external vacuum pumping for the system. Finally the Li reservoir heater wire and attendant thermocouple wire were placed in the inner delivery tube and connected to a vacuum static seal feedthrough.

In order to fully control the introduction of Li vapors, an oven with flexible shutter was designed and employed. The control system manages the shutter, rotating axis, limit hole, feedthrough, electromagnetic valve, and nitrogen gas cylinder. As shown in Fig. 2, and described more fully in the subsequent section, the shutter can fully cover the evaporation nozzle. The shutter is mounted on a central rod which runs down the length of the delivery tube. The rod extends around the oven and allows the shutter to be rotated over the delivery opening to block the flow of Li vapors. In order to maintain the axis of rotation, three limit holes are symmetrically placed along the delivery tube. Finally the rotating axis was jointed with a vacuum dynamic sealing feedthrough

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