Fusion Engineering and Design 137 (2018) 202–208

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Real-time reduction of tungsten impurity influx using lithium powder injection in EAST

W. Xu[a,b,c], J.S. Hu[c,d], R. Maingi[e], Z. Sun[c,*], G.Z. Zuo[c], D.K. Mansfield[e], A. Diallo[e], K. Tritz[f], M. Huang[c], X.C. Meng[c,g], L. Wang[c], Y.Z. Qian[c], L. Zhang[c], F. Ding[c], R. Lunsford[e], T. Osborne[h], J.G. Li[c]

[a] Advanced Energy Research Center, Shenzhen University, Shenzhen, 518060, People's Republic of China
[b] Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Optoelectronic Engineering, Shenzhen University, Shenzhen, 518060, People's Republic of China
[c] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, 230031, China
[d] CAS key Laboratory of Photovoltaic and energy conservation materials, Hefei 230031, China
[e] Princeton University Plasma Physics Laboratory Princeton, NJ, 08543, USA
[f] Johns Hopkins University, Baltimore, MD, 21211, USA
[g] Department of Applied Physics, Hunan University, Changsha, 410082, China
[h] General Atomics, PO Box 85608, San Diego, CA, 92186-5608, USA

A R T I C L E I N F O

Keywords:
Tungsten
Lithium powder
Impurity
EAST

A B S T R A C T

We report the first successful use of solid material injection, in powder form, to reduce core tungsten impurities in EAST discharges with tungsten divertor plasma-facing components. Tungsten is the leading plasma-facing material for use in ITER as well as future fusion devices. However, tungsten sometimes accumulates in the plasma core of fusion devices, which is an impediment to the achievement of high-power, long-pulse H-modes. In this work, tungsten impurity influx from the tungsten divertor was reduced by real-time injection of lithium powder into EAST discharges. An increase in stored energy and confinement accompanied the sharp reduction of core tungsten with real-time lithium powder injection in L-mode discharges. In H-mode discharges, real-time lithium powder injection reduced the tungsten core impurity emission while also mitigating ELMs. During powder injection, the divertor electron temperature was reduced, which reduced the tungsten source. The tungsten impurity emission remained low in discharges even after active lithium injection was terminated, a signature of improved and lasting wall conditioning in the tungsten divertor.

1. Introduction

Adequate protection of in-vessel structures, sufficient heat exhaust handling, and compatibility with plasma purity will be increasingly significant concerns for future fusion research devices, such as ITER [1]. As such, ITER has committed to tungsten (W) as the divertor material to sustain the combination of long-pulse and high-power operation with severe restrictions on permitted core impurity concentrations and adequately low tritium retention. A pristine W divertor can withstand a heat flux of 10 MWm^{-2} in steady state, and exhibits much lower tritium retention as compared to carbon (C) as a plasma-facing material (PFM) [2]. However, the use of W could result in high-Z impurity accumulation in the plasma, which would cool the plasma and thus deteriorate fusion performance [1]. In order to examine plasma performance using W, some fusion devices have been upgraded with W as the primary PFM. For example, ASDEX-Upgrade has been operating as a device with 100% W plasma-facing components (PFCs) since 2007 [3]; JET was upgraded with an ITER-like wall in 2011 [4]; and EAST finished installation of a W mono-block upper divertor structure in 2014 [5]. Operation of these machines with W PFCs has led to a series of notable experimental observations. In ASDEX-U, it has been observed that the central accumulation of W in combination with density peaking restricts steady operation [6]. In JET, the decrease of W influx with strong hydrogenic fueling is likely due to a strong decrease of sputtering yield at the resulting lower divertor temperatures [7]. It is evident, therefore, that avoiding W impurity accumulation in the core plasma is important to the attainment of high power and steady-state long-pulse operation. Consequently the development of a real-time wall conditioning

* Corresponding authors at: Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, 230031, China.
E-mail addresses: hujs@ipp.ac.cn (J.S. Hu), sunzhen@ipp.ac.cn (Z. Sun).

https://doi.org/10.1016/j.fusengdes.2018.09.009
Received 1 February 2018; Received in revised form 8 August 2018; Accepted 13 September 2018

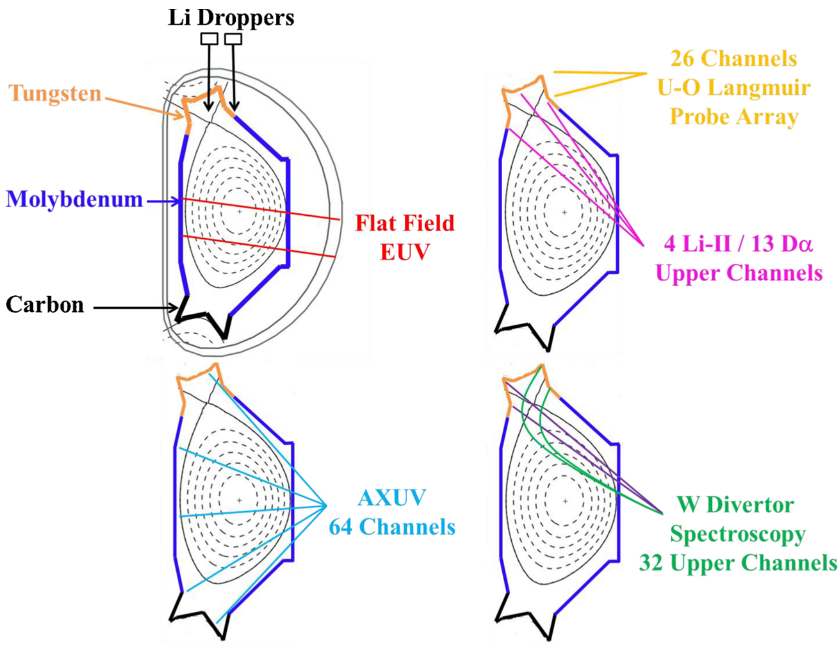

Fig. 1. A sketch of the Li dropper positions, plasma facing materials and central diagnostics in EAST. All inner and outer surfaces of the upper divertor are covered by W spectroscopy. A 26 channel array of poloidally distributed Langmuir probes covers the upper-outer section of the W divertor. The real-color video cameras used in this work are described in the text.

technique which could effectively suppress the influx of W from the divertor would be important for sustaining long-pulse plasma discharges in future fusion devices.

Lithium (Li), which has lowest atomic number of any metal, could be a good PFM candidate for future thermonuclear magnetic fusion devices [8]. It is easily ionized in the plasma edge due to its low ionization potentials (I-5.4 eV, II-75.6 eV, III-122.5 eV) [9]. Additionally, it has also been shown that Li can significantly reduce the concentration of other impurities in the plasma [10,11]. Any such high-Z core impurity reduction would reduce the plasma radiative power loss. To date, several techniques to introduce and exploit Li in fusion discharges have been used successfully in various fusion devices. These techniques include, but are not limited to: pneumatic injection of Li pellets into TFTR [12], evaporative pre-deposition via Li effusion ovens in TJ-II [13], the use of a capillary porous system as a liquid Li limiter on both T-11M [14] and FT-U [15] and the use of liquid-Li-coated walls Li on CDX-U and LTX [16,17]. In addition NSTX has exploited Li pellets, Li evaporators [18] and real-time injection of a Li aerosol using a simple piezoelectric device to drop fine powder into the plasma scrape-off layer (SOL) [19].

As part of a long-term effort to improve plasma performance by actively modifying the plasma-wall interaction, EAST has chosen to investigate Li as surface conditioning material. Experiments involving evaporative Li coatings [20,21], powder injection [22,23], granule injection [24,25] and a liquid Li limiter [26] have been performed successfully on EAST in the past. It has been observed that Li is a promising material for low-Z impurity suppression, recycling reduction and also ELM mitigation - all of which are beneficial for stationary long-pulse H-mode performance. Li coatings using He-ICRF discharge-assisted deposition and real-time Li powder injection (LPI) are effective methods to both suppress C and O impurity influx and to reduce particle recycling [21,27]. Recently, Li wall conditioning has also enabled the achievement of a stationary H-mode plasmas with over 100 s duration using a W divertor. This was preceded by the attainment of a 32 s H-mode using a carbon divertor [28]. In addition, a step forward was made by achieving a new steady-state ELM-free H-mode for durations exceeding hundreds of energy confinement times using real-time injection of Li powder. The resulting steady-state ELM-free H-mode was accompanied with an edge coherent mode that provided steady fuel and impurity exhaust to prevent accumulation [22]. Also, an advanced flowing liquid Li limiter was recently tested in EAST. Placing the liquid Li limiter near the plasma separatrix was shown as an effective method to both suppress impurities and to reduce the particle recycling as well as being beneficial for attaining H-mode plasmas [26].

After the ITER-like W mono-block structure was installed as an upper divertor, EAST started operation to study W divertor performance [29]. However, significant W impurity accumulation has been clearly observed in EAST discharges and represents a crucial impediment to achieving high-power, long-pulse H-modes [30]. Therefore, methods to improve wall conditions, such as real-time LPI, need be explored in order to suppress W influx from the divertor and reduce the resulting impurity accumulation in the plasma core.

2. Experiment setup

The Experimental Advanced Superconducting Tokamak (EAST) is a non-circular, fully superconducting, steady-state experimental device with an advanced ITER-like W upper divertor. The mission of EAST is to establish the scientific and technological foundation for next generation tokamaks. The major radius of EAST is R = 1.9 m, the minor radius is a = 0.5 m, and the plasma-facing surface area is ~58 m^2 [29]. During the 2008–2010 run campaigns, the main PFM was doped graphite (GBST1308: 1%B, 2.5%Si, 7.5%Ti) with a 100–200 μm SiC coating. To facilitate long-pulse operation, EAST upgraded the graphite in the main chamber to molybdenum (Mo) tiles in 2012, while both upper and lower graphite divertors remained unchanged. In 2014, the upper graphite divertor in EAST was replaced by an ITER-like W mono-block. Fig. 1 shows the configuration of PFCs in the EAST vessel and the main diagnostic systems used in this research.

Two piezoelectric-based dropper devices have been used on EAST to accomplish real-time LPI into the plasma scrape-off layer by simply dropping a fine spherical Li powder in a continuous and controlled manner. These devices were developed in collaboration with the Princeton Plasma Physics Laboratory [19]. The use of these droppers to accomplish real-time LPI during plasma operation was originally intended to restore and replenish preliminary Li coatings in the EAST vessel. The reservoir capacity of each Li dropper is ~150 cm^3 corresponding to ~50 g of Li powder. The Li powder used in this work was produced by FMC Corporation [19], and the average diameter of the spherical particles was ~44 μm. The key component in the dropper is a piezoelectric disk (PZD) with a 2.5 mm central aperture, through which the Li powder exits when the PZD is vibrated at resonance. Li powder