Fusion Engineering and Design 85 (2010) 865–873

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Lithium coatings on NSTX plasma facing components and its effects on boundary control, core plasma performance, and operation

H.W. Kugel[a,*], M.G. Bell[a], H. Schneider[a], J.P. Allain[b], R.E. Bell[a], R. Kaita[a], J. Kallman[a], S. Kaye[a], B.P. LeBlanc[a], D. Mansfield[a], R.E. Nygren[c], R. Maingi[d], J. Menard[a], D. Mueller[a], M. Ono[a], S. Paul[a], S. Gerhardt[a], R. Raman[e], S. Sabbagh[f], C.H. Skinner[a], V. Soukhanovskii[g], J. Timberlake[a], L.E. Zakharov[a], the NSTX Research Team

[a] *Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543, USA*
[b] *Purdue University, School of Nuclear Engineering, West Lafayette, IN 47907, USA*
[c] *Sandia National Laboratories, Albuquerque, NM 87185, USA*
[d] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[e] *University of Washington, Seattle, WA 98195, USA*
[f] *Columbia University, New York, NY 10027, USA*
[g] *Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*

ARTICLE INFO

Keywords:
Lithium
Lithium wall fusion regime
Recycling
Plasma wall interactions
Divertors
Spherical torus

ABSTRACT

NSTX high power divertor plasma experiments have used in succession lithium pellet injection (LPI), evaporated lithium, and injected lithium powder to apply lithium coatings to graphite plasma facing components. In 2005, following the wall conditioning and LPI, discharges exhibited edge density reduction and performance improvements. Since 2006, first one, and now two lithium evaporators have been used routinely to evaporate lithium onto the lower divertor region at total rates of 10–70 mg/min for periods 5–10 min between discharges. Prior to each discharge, the evaporators are withdrawn behind shutters. Significant improvements in the performance of NBI heated divertor discharges resulting from these lithium depositions were observed. These evaporators are now used for more than 80% of NSTX discharges. Initial work with injecting fine lithium powder into the edge of NBI heated deuterium discharges yielded comparable changes in performance. Several operational issues encountered with lithium wall conditions, and the special procedures needed for vessel entry are discussed. The next step in this work is installation of a liquid lithium divertor surface on the outer part of the lower divertor.

1. Introduction

Density and impurity control, tritium and dust removal, and long-lifetime plasma facing components (PFCs) for diverted high power DT reactors are challenging technology problems. Replenishable liquid lithium PFCs show promise toward resolution of these challenges by providing a low-*Z*, pumping, self-healing plasma facing surface [1–3], and enabling a lithium wall fusion regime [4]. Preliminary work indicates that the use of liquid lithium as a PFC can help to integrate four important potential benefits for fusion: (a) divertor pumping over a large surface area compatible with high flux expansion solutions for power exhaust, together with high temperature low density plasma edge conditions, (b) improved confinement [5,6], (c) reduction or elimination of edge localized modes (ELMs) [7–9], and (d) high-heat flux handling [2,10,11].

1.1. National Spherical Torus Experiment lithium research

The National Spherical Torus Experiment (NSTX) [12,13] has been investigating solid lithium (Li) coatings for density and impurity control [5–7]. In NSTX, recycling of deuterium species from plasma contact with ATJ graphite surfaces contributes to a secular density rise observed in most H-mode, neutral beam injection (NBI) heated plasmas. Lithium has the potential for control of this density rise due to its ability to absorb the atomic and ionic deuterium efflux through the formation of lithium–deuteride and lithiated compounds [14], which sequesters deuterium, making it unavailable for recycling. Due to the range of deuterium in lithium, and the immobility of the lithium–deuteride formed in solid lithium, the absorption can saturate in the near surface layer [15], limiting the deuterium pumping capability of solid lithium. Subsequent recoating can replenish the surface with fresh lithium. Liquid lithium on

---

[*] Corresponding author. Tel.: +1 609 243 3146; fax: +1 609 243 3248.
E-mail address: hkugel@pppl.gov (H.W. Kugel).

0920-3796/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.fusengdes.2010.04.004

the other hand has a much higher capacity for sequestering deuterium [16] because lithium–deuteride is more mobile in liquid lithium. In addition, it has potential for reactor applications [1–4]. Motivated by the long range potential of lithium PFCs, NSTX has been investigating lithium pellet injection and lithium evaporation for density and impurity control as part of a phased, three-part approach to lithium PFCs: first (i) lithium pellet injection [5], then (ii) lithium evaporators [6–8] and recently lithium powder [8], and finally (iii) a liquid lithium divertor [17,18]. This staged approach is allowing NSTX control systems, diagnostics, and research to be adapted to the evolving lithium technology.

2. Solid lithium coatings on graphite

In NSTX, the range of the 500–2000 eV deuterium efflux incident on lithium is 100–250 nm [15]. In the case of lithium coatings thicker than the range of the incident deuterium, lithium pumping via the formation of lithium–deuteride is restricted to a relatively thin surface region that can be quickly saturated by incident ion and neutral deuterium flux. This depletes the uncombined lithium available for lithium–deuteride formation. Also, lithium interactions with the NSTX residual vacuum constituents (H_2O, CO, and CO_2) yield surface accumulations of LiOH, Li_2O, and Li_2CO_3 which further decrease the amount of lithium available for deuteride formation. In addition, lithium can diffuse into relatively pure graphite and become unavailable at the surface for lithium–deuteride formation [19]. In NSTX, the diffusion of lithium was measured for the mature ATJ graphite divertor tiles to be limited to a few microns [19]. In addition, in the case of lithium coating thicknesses, less than the range of the incident deuterium, the lithium pumping efficiency is reduced as some incident particles are able to pass through the coating. Lithium coatings, for example, resulting from the injection of lithium pellets of a few mg deposited over 2 m^2 results in coating thicknesses of less than 30 nm which is significantly less than the 250 nm range.

In NSTX, the above effects have necessitated the continual deposition of fresh lithium between discharges to maintain active lithium pumping wall conditions.

2.1. Solid lithium coatings less than the range of incident deuterium in limiter and divertor experiments

Initially, TFTR obtained reduced recycling and significantly enhanced fusion performance by transitioning to a “supershot” regime. This was done by thoroughly degassing the inner toroidal limiter via about 40 helium conditioning discharges to obtain pumping by the graphite limiter. This graphite pumping state yielded the initial noteworthy fusion power results; however, the additional application of lithium deposition on the limiter, further enhanced limiter pumping, and yielded the very highest TFTR fusion power discharges [20]. TFTR also demonstrated that lithium deposition would not yield a performance enhancement without thorough limiter degassing beforehand. This can be understood as due to reactions of the freshly deposited lithium with fuel gas absorbed in the graphite, thereby making the relatively small amount of lithium unavailable for the pumping of subsequent deuterium efflux. Since TFTR, lithium pellet injection (LPI) was applied directly into normally fueled, diverted C-MOD, DIII-D, TdeV, and NSTX plasmas involving a variety of heating methods, but without thorough wall degassing, and confirmed that no performance improvement occurred other than a small decrease in core impurities.

2.1.1. NSTX LPI with degassed PFCs

NSTX LPI experiments with thoroughly degassed graphite surfaces obtained a reduction in recycling, and made contact with the TFTR performance enhancement results following lithium deposition on thoroughly degassed plasma wetted surfaces. The NSTX Center Stack provides an inner toroidal limiter during plasma startup and for toroidally limited plasmas. Ohmic helium, Center Stack Limited (CSL) discharges, and lower single null (LSN) diverted conditioning discharges were used to degas the Center Stack and the lower divertor. Fig. 1a shows how the $D\alpha$ luminosity indicates that although most of the degassing had been completed in about 8 discharges, it continued to decrease at a much lower rate, possibly due, in part, to mild recycling from distant main chamber surfaces. Three NBI reference discharges were then applied to test the conditioning of the limiting surface which was found to be satisfactory for LPI to begin. Then, LPI was started using 12 helium ohmic discharges, 9 with injection of either 1.7, 3.4, or 5.0 mg pellets at velocities of about 80–120 m/s. A lower rate of decrease in residual $D\alpha$ luminosity continued during this LPI deposition sequence into helium discharges. Shown in Fig. 1b is how the Li I luminosity from the Center Stack increased as total lithium injection increased to 30.2 mg. After completion of this LPI sequence, which deposited lithium on the Center Stack, deuterium reference discharges were taken to test for a reduction in recycling. Fig. 2 shows a 2 mg lithium pellet injected at 120 m/s into a helium ohmic discharge. At dis-

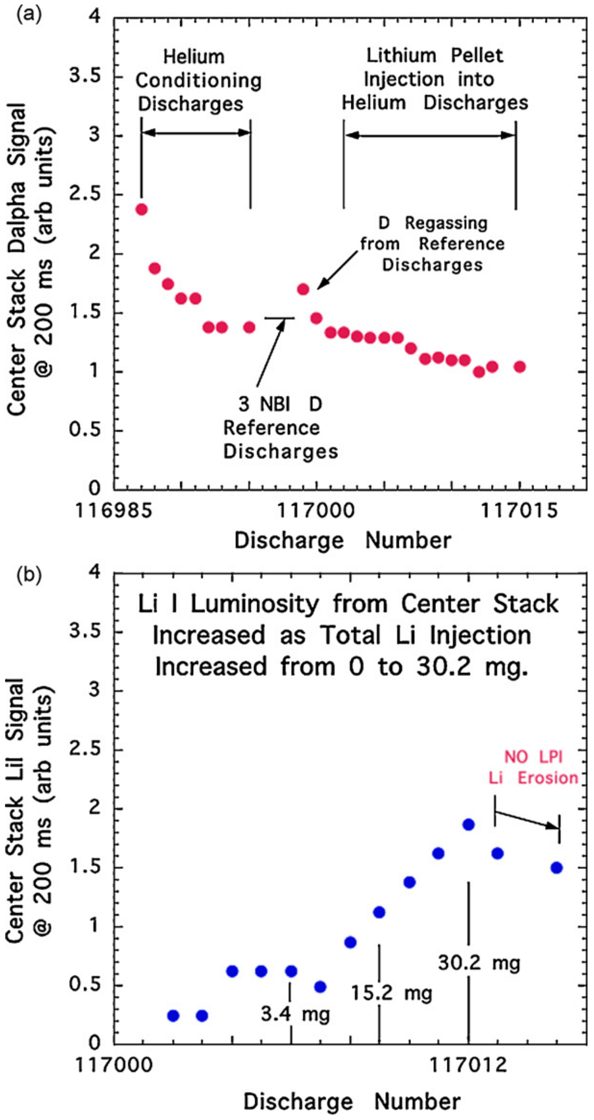

Fig. 1. (a) $D\alpha$ luminosity from the Center Stack region decreased during the helium conditioning as the discharge number increased and (b) the Li I luminosity increased.