Journal of Nuclear Materials xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Journal of Nuclear Materials

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

Results and future plans of the Lithium Tokamak eXperiment (LTX)

J.C. Schmitt [a,*], T. Abrams [a], L.R. Baylor [b], L. Berzak Hopkins [a], T. Biewer [b], D. Bohler [a], D. Boyle [a], E. Granstedt [a], T. Gray [b], J. Hare [a], C.M. Jacobson [a], M. Jaworski [a], R. Kaita [a], T. Kozub [a], B. LeBlanc [a], D.P. Lundberg [a], M. Lucia [a], R. Maingi [b], R. Majeski [a], E. Merino [a], A. Ryou [c], E. Shi [a], J. Squire [a], D. Stotler [a], C.E. Thomas [d], K. Tritz [e], L. Zakharov [a]

[a] Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[b] Oak Ridge National Laboratory, Oak Ridge, TN, USA
[c] University of Pennsylvania, Philadelphia, PA, USA
[d] Third Dimension Technologies, Oak Ridge, TN, USA
[e] Johns Hopkins University, Baltimore, MD, USA

ARTICLE INFO

Article history:
Available online xxxx

ABSTRACT

The Lithium Tokamak eXperiment (LTX) is a spherical tokamak with the unique capability of studying the low-recycling regime by coating nearly 90% of the first wall with lithium in either solid or liquid form. Several grams of lithium are evaporated onto the plasma-facing side of the first wall. Without lithium coatings, the plasma discharge is limited to less than 5 ms and only 10 kA of plasma current, and the first wall acts as a particle source. With cold lithium coatings, plasma discharges last up to 20 ms with plasma currents up to 70 kA. The lithium coating provides a low-recycling first wall condition for the plasma and higher fueling rates are required to realize plasma densities similar to that of pre-lithium walls. Traditional puff fueling, supersonic gas injection, and molecular cluster injection (MCI) are used. Liquid lithium experiments will begin in 2012.

1. Introduction

The Lithium Tokamak eXperiment (LTX) is a spherical tokamak with major radius $R = 0.4$ m, minor radius $a = 0.26$ m, and elongation $\kappa = 1.5$ [1–3]. Typical discharge parameters are now $B_{\text{toroidal}} < 2.1$ kG, $I_P < 100$ kA, and a discharge duration <25 ms. LTX is fitted with a conformal 1 cm thick heated copper shell, suspended within the vacuum vessel on a system of legs that permit thermal expansion relative to the vacuum vessel and provide electrical isolation from the vessel. The plasma-facing surface of the shell is clad with an explosively bonded 1.5 mm thick layer of stainless steel. The shell, consisting of two upper and two lower sections with toroidal and poloidal breaks, is conformal to the last closed flux surface (a close-fitting wall), and covers 85% of the plasma surface area. The shell is heated by a system of electrical cable heaters with routine operation in the 300 °C range, well above the melting point of lithium (180.5 °C). LTX was designed to investigate the modifications to tokamak equilibrium with low recycling walls of hot or cold lithium.

The heated shell system is designed to permit liquefaction of the lithium inventory. Most of the results obtained to date, however, involve thin coatings of lithium on the plasma-facing surfaces of the shells. Shell coatings are applied with a simple system of two evaporators toroidally separated by 180°. Each evaporator consists of a yttria crucible, filled with (typically) 8 g of room temperature (solid) lithium. The evaporators are inserted into the plasma volume and then heated to ~580 °C with a commercial tantalum heater. An evaporation cycle typically lasts for 2–3 h. To disperse the evaporated lithium uniformly over the inner surfaces of the shell, the vacuum vessel is filled with helium to 5 mTorr prior to and during the evaporation cycle. Modeling of the coating system has been performed with DEGAS2. In Fig. 1, we show the calculated atomic flux of lithium during evaporation as a function of poloidal distance around the shells for a range of helium gas fill pressures. The figure shows that with a He fill pressure of 5 mTorr, the lithium flux is relatively uniform across the top and bottom shells, more so than with the other fill pressures. A visual inspection of the lithium coating during evaporation confirms that the coating is being distributed uniformly across the shell when the fill pressure is 5 mTorr. More rigorous verification of the uniformity of the layer thickness has not been performed.

Following an evaporation cycle, the helium is pumped from the vacuum chamber and the crucibles are allowed to cool below the

* Corresponding author. Address: Princeton Plasma Physics Laboratory, 100 Stellarator Road, Princeton, NJ 08540, USA.
E-mail address: jschmitt@pppl.gov (J.C. Schmitt).

0022-3115/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jnucmat.2013.01.241

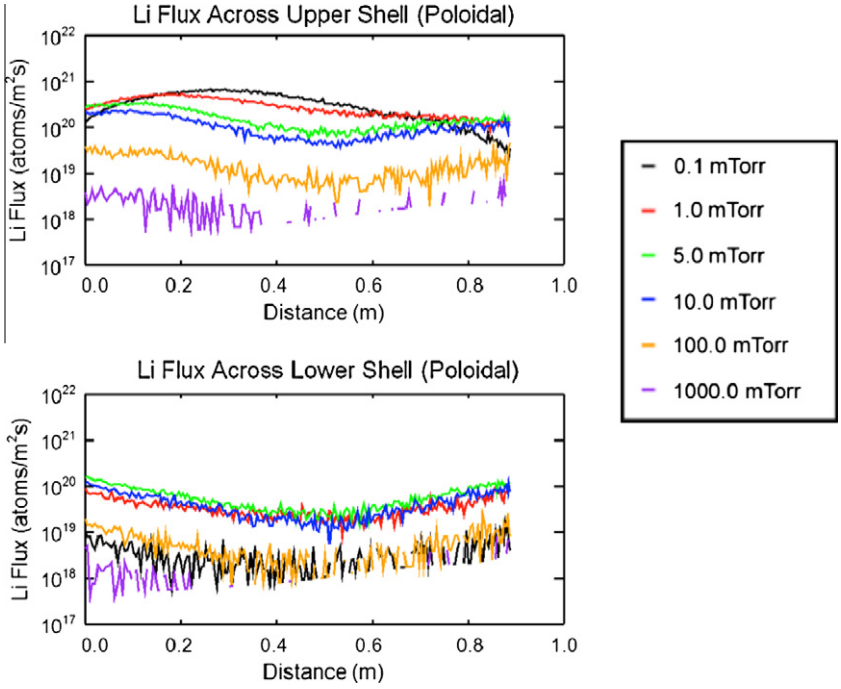

Fig. 1. DEGAS2 calculation of the lithium flux to the lower and upper shells as a function of poloidal distance from the inboard midplane. A typical lithium evaporation cycle is approximately 3 h long.

melting point of lithium before being withdrawn beyond the plasma boundary. Plasma discharges are initiated within 1–2 h of an evaporation cycle.

In the case of the hot wall experiment, where the lithium coating is kept above its melting temperature, the evaporation cycle was performed after the shell system was preheated to 300 °C. The shell temperature was kept constant while the crucibles were cooled and helium backfill pumped from the vessel. Plasma discharges were initiated within 1 h after the termination of the coating cycle.

2. Effect of lithium wall coatings on the discharge

With a close-fitting high-Z wall, discharges are strongly affected by wall conditioning. In LTX, the only wall conditioning technique used is lithium coating. Discharges without lithium wall coatings are limited to a maximum plasma current of about 10 kA and discharge durations of 5 ms. With lithium coatings, the plasma current exceeds 70 kA and the duration exceeds 20 ms, a factor of 7 increase in peak current and a factor of 4 increase in discharge length; a comparison of a pre-lithium and a post-lithium discharges are shown in Fig. 2. The lithium coating reduces high-Z impurities and hydrogen recycling, and the net effect is an increase in peak plasma current. The time history of the vessel pressure, both before and after pre- and post-lithium discharges, is shown in Fig. 3. With bare stainless steel walls, the neutral pressure after the discharge is larger than before the discharge, which indicates that the wall acts as a net particle source. In contrast, fresh lithium coatings provide significant pumping of the hydrogen fuel, and the prefill pressure needs to be increased to avoid runaway electrons and allow normal plasma discharges. As the lithium layer passivates with time, its pumping ability decreases. After 4 days, the lithium coating no longer acts as a significant particle pump [4].

Peak electron temperatures based on preliminary Thomson scattering measurements are in the range from 100 to 200 eV with relatively flat to hollow profiles. The Thomson scattering system is still under improvement with additional edge channels being added. Density profiles are also hollow, suggesting that the present plasma current ramp rate is too high to allow current diffusion into the core. We are modifying the ohmic power system to permit lower loop voltage operation to reduce the plasma current ramp rate and to facilitate longer pulse lengths.

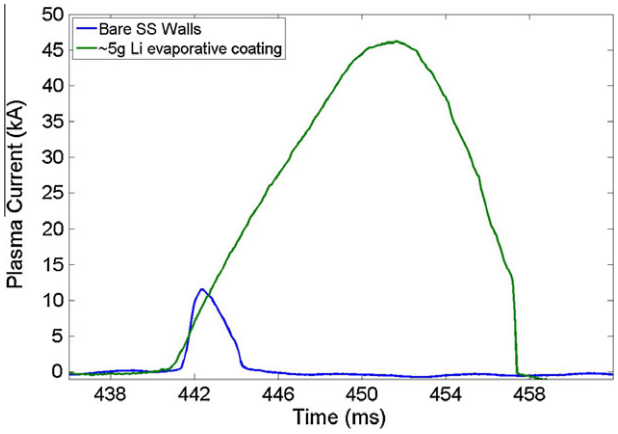

Fig. 2. Discharge current pre- (blue trace) and post- (green trace) 5 g of lithium wall coatings in LTX. The fuel prefill was increased for the post-lithium discharge (see Fig. 3), but all other field programming was identical for the two discharges. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Fueling and pumping

LTX lacks pellet fueling, and neutral beam injection is not scheduled until 2013. Discharge fueling is accomplished by gas

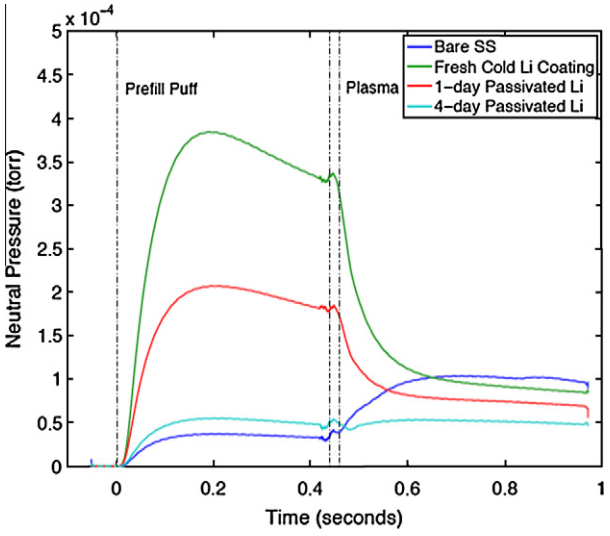

Fig. 3. Time history of the neutral pressure before and after discharges in LTX for various wall conditions: bare stainless steel walls (blue), fresh, cold Li evaporative coatings (green), 1-day passivated Li coating (red) and 4-day passivated Li coating (cyan). The plasma discharge time is between the dashed black lines. Fresh Li coatings required an increase in the prefill pressure to prevent runaway electrons. The pressure drop after the discharge indicates pumping of hydrogen. Fresh Li coatings provide substantial pumping, while passivated Li coatings provide less pumping. Bare stainless steel walls act as a particle source. Note that the pressure gauge is connected to the main vessel by a duct, which significantly slows the time response of the system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

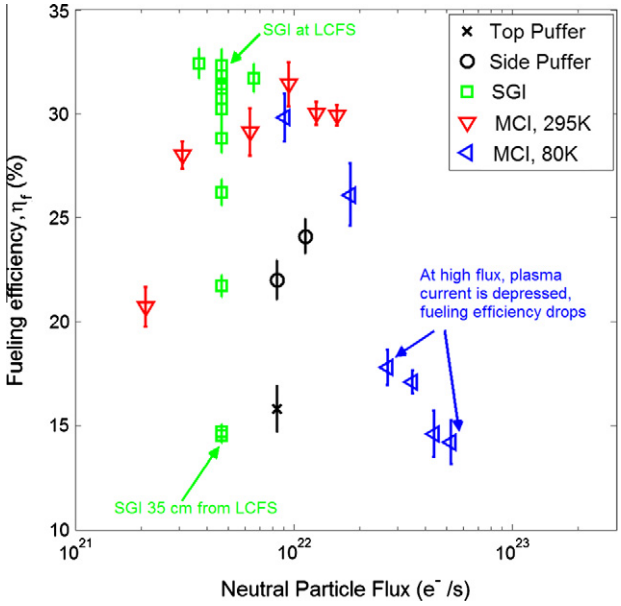

Fig. 4. Summary plot of fueling efficiency versus fueling rate for the systems tested in LTX. The highest fueling efficiencies are obtained for the SGI and the MCI. The "top puffer" is a conventional wall-mounted piezoelectric gas valve. The "side puffer" is also a piezoelectric valve system, but it is more closely coupled to the vacuum chamber, and gas is ducted from the valve to the plasma edge through a short 2 cm diameter tube.

injection. We have studied the fueling efficiency of a number of different gas injection techniques, including traditional gas puffing, supersonic gas injection (SGI), and molecular cluster injection (MCI) [5]. The use of either highly directed gas jet system (SGI or MCI) results in high fueling efficiencies, up to about 35%, which is about 2–3 times more efficient than the wall-mounted gas puffing systems. The highest fueling rates are obtained with a cryogenic MCI system designed to fuel at least partly with condensed clusters of hydrogen molecules. However, we have not observed an enhancement of fueling efficiency or a change in particle deposition profile using cluster injection. This may be due in part to the fact that in regimes where the exhaust of the MCI is dominated by molecular clusters, the discharge is overfueled and plasma current begins to collapse. Future development of higher density discharges may allow a good evaluation of the effect of cluster injection on the fueling profile. Note that all fueling systems are installed on the low-field side. A summary plot of fueling efficiency versus particle flux is shown in Fig. 4.

Using these fueling systems, we have characterized wall pumping by lithium coatings in LTX. The fraction of the total injected gas is determined by measuring the vessel pressure immediately before and immediately after the plasma discharge, before the gas load can be appreciably removed by the pumping system. The results are shown in Fig. 5. Fresh cold lithium films pump nearly 100% of the injected gas. Hot lithium films show evidence of short-term pumping but lose their pumping ability as the coating passivates much more rapidly compared to the cold lithium coating. Tokamak operations with the shells at 300 °C did result in an elevated level of water in the vacuum vessel (from heating and outgassing of the inner wall of the vacuum vessel), but the partial pressure of water during hot wall operation ($\sim 2 \times 10^{-8}$ Torr) was only a factor of four higher than the partial pressure of water during cold wall operation ($\sim 5 \times 10^{-9}$ Torr). Since the deposition rate for impurities in a vacuum is proportional to the partial pressure,

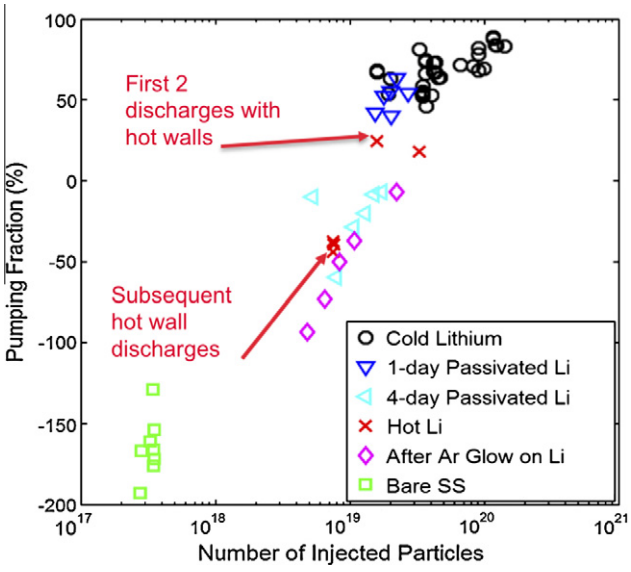

Fig. 5. Fraction of the total injected gas inventory which is pumped by the lithium-coated wall in LTX. "Cold Lithium" indicates pumping results with a fresh, cold film of lithium deposited a few hours prior to the discharge. Nearly 100% of the injected gas is pumped by the lithium film under these conditions. Note that a negative pumping fraction indicates that additional gas is devolved from the wall during the discharge. The hot lithium film acts as a particle pump for only two discharges, after which the film acted as a particle source.

the expectation would be that lithium deposited on the hot shell should have taken 10–12 h to passivate. Instead, it passivated at least 10× faster. We have tentatively explained this rapid passivation of the lithium surface at high temperatures as due to oxygen segregation to the surface of the liquid, which has been previously observed in laboratory experiments [6].

We are now in the process of determining the detailed wall recycling coefficient as a function of time during the discharge using the Lyman-α detector system.

4. Summary and future work

LTX is the first tokamak to operate entirely with lithium coated high-Z walls. Lithium wall coatings are found to be necessary in order to obtain satisfactory discharge current levels and discharge durations. First results indicate that wall coatings are effective at pumping during the discharge, although a detailed estimate of the wall recycling coefficient has not yet been obtained.

Although liquid lithium systems were expected to provide a further reduction in recycling, as was observed on CDX-U [7], the thin hot films employed so far in LTX are passivated rapidly. This highlights the need for careful control over the surface impurities in experiments with liquid lithium PFCs.

A system to fill each of the two lower shell segments with up to 100 cm^3 of liquid lithium has been constructed and is now undergoing testing. Experiments will begin in early spring 2012. This system will include provision for stirring the lithium pools with a steerable electron beam to avoid surface impurity accumulation.

Acknowledgment

This work supported by USDoE contracts DE-AC02-09CH11466 and DE-AC05-00OR22725.

References

[1] R. Majeski, L. Berzak, S. Gershman, et al., First operation of the Lithium Tokamak eXperiment (LTX) with lithium wall coatings, in: Proceedings of the 23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea, October 11–16, 2010 (Paper ICC/P3-01).
[2] L. Berzak Hopkins, J. Menard, R. Majeski, et al., Nucl. Fusion 52 (2012) 063025.
[3] R. Kaita, L. Berzak, D. Boyle, et al., Fusion Eng. Des. 85 (2010) 874.
[4] D.P. Lundberg, Fueling Studies on the Lithium Tokamak Experiment, Ph.D. Dissertation, Princeton University, 2012.
[5] D.P. Lundberg, R. Kaita, R. Majeski, Nucl. Fusion 52 (2012) 013016.
[6] R. Bastasz, J.A. Whaley, Fusion Eng. Des. 72 (2004) 111.
[7] R. Majeski, R. Doerner, T. Gray, et al., Phys. Rev. Lett. 97 (2006) 075002.