Results from LTX with Lithium-Coated Walls

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Abstract. The Lithium Tokamak eXperiment (LTX) is a low aspect ratio tokamak with R=0.4 m, a=0.26 m, and kappa=1.5. Typical discharge parameters are now: Toroidal field of 2.1 kG, plasma current less than 100 kA, and discharge duration less than 25 msec. LTX is fitted with a conformal 1 cm thick heated copper liner or shell. The plasma-facing surface of the shell is clad with stainless steel, and is conformal to the last closed flux surface (a close-fitting wall). The shell can be heated to 300 - 400 C, and coated with lithium. LTX was designed to investigate the modifications to tokamak equilibrium with low recycling walls of liquid or solid lithium. 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 plasma currents of 15 kA, and discharge durations of order 5 msec. With lithium coatings discharge currents exceed 70 kA, and discharge durations exceed 20 msec, a factor of 4-5 increase in both peak current and duration. Peak electron temperatures, from preliminary Thomson scattering measurements, range from 100 – 200 eV; electron temperature profiles for lithium-wall discharges are broad and relatively constant in the plasma core. Lyman-alpha arrays are used to estimate the recycling coefficient. Other spectroscopic diagnostics include edge measurements of impurity lines, and a scanning VUV spectrometer. Discharge fueling employs gas injection. We have studied the fueling efficiency of a number of different gas injection techniques, including supersonic gas injection, and molecular cluster injection. The use of highly directed gas jets results in the highest fueling efficiencies, up to 0.35. A system to fill each of the two the lower shell segments with up to 50 g of liquid lithium has been constructed and is now undergoing testing. Experiments with liquid lithium are imminent. Spectroscopic measurements of the Doppler shifted emission of Li ions have been made to estimate the ion temperature and rotation profiles of LTX discharges. Preliminary results indicate $T_i \sim T_e/2$, which is unexpectedly high for a low density Ohmic discharge.

1. Introduction

The Lithium Tokamak eXperiment (LTX) was designed to investigate modifications to tokamak confinement and equilibrium with low recycling coatings of liquid or solid lithium

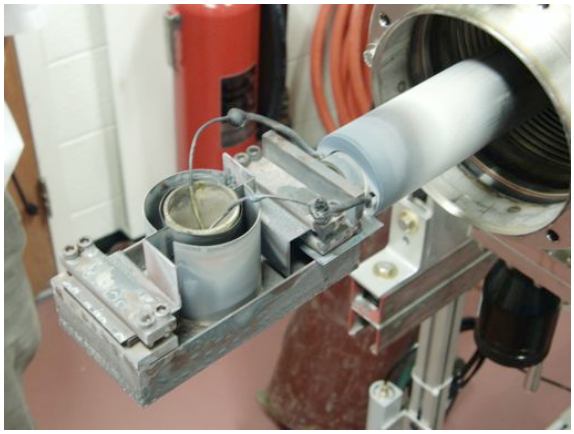

Figure1. One of the LTX evaporator crucibles after initial use. 2 evaporators, 180° apart toroidally, are installed. Each crucible is typically filled with 8 grams of lithium. Typically a total of 4 grams of lithium is used per evaporation. The crucibles are ceramic yttria, and are not attacked by liquid lithium at temperatures up to 600 °C.

on a conductive, close fitting wall consisting of a thin (1.5 mm) stainless steel barrier on a thick (1.0 cm) heated copper shell. The heated shell system is designed to permit liquefaction of the lithium inventory. LTX is a low aspect ratio (A=1.6) tokamak, with major radius R=0.4 m, minor radius a=0.26 m, maximum elongation κ=1.5, and modest triangularity δ < 0.2. Discharges are limited on the conformal wall; there is no provision for diverted operation. Design targets for the device are $B_{toroidal}$ = 3.4 kG, I_P < 400 kA, and $\tau_{discharge}$ ~ 100 msec, although at present the device will be limited to $B_{toroidal}$ < 2.1 kG, I_P < 100 kA, and $\tau_{discharge}$ ~ 30-35 msec.

2. The effect of lithium wall coatings on LTX discharges

Most of the results obtained to date involve solid coatings of lithium on the plasma-facing surfaces of the shells. Shell coatings are applied with a simple system of evaporators, which operate with a helium gas fill of the vacuum vessel to 1-5 mTorr, to disperse the evaporated lithium. A photograph of one of the evaporator systems, after an evaporation cycle and prior to cleaning, is shown in Figure 1.

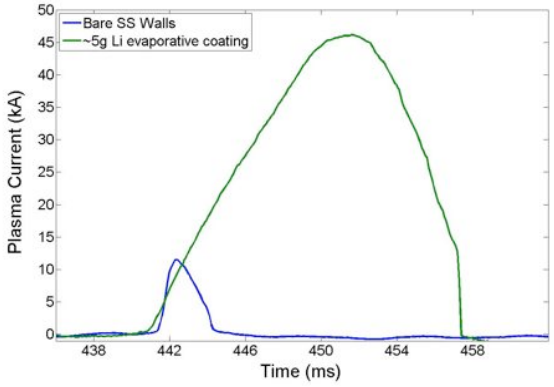

Figure 2. Discharge current pre- (blue trace) and post- (green trace) 5 g of lithium wall coatings in LTX. The prefill was increased for the post-lithium discharge (see Fig. 3), but all other field programming was identical for the two discharges.

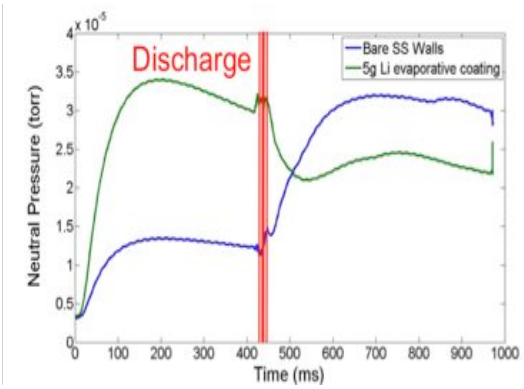

Figure 3. Time history of the neutral pressure before and after two discharges in LTX. The discharge duration is denoted by the red band. Note that the pressure gauge is connected to the main vessel by a duct, which significantly slows the time response of the system.

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 were limited to plasma currents ~ 10 kA, and discharge durations ~ 5 msec. With lithium coatings, discharge currents exceed 70 kA, and discharge durations exceed 30 msec, a factor of 4-5 increase in both peak current and duration; a comparison of the plasma current in a pre-lithium and a post-lithium discharge is shown in Figure 2. The reduction of recycling is a major factor affecting peak plasma current, although lithium coatings also reduce high-Z impurities. The time history of the vessel pressure both before and after pre- and post- lithium discharges is shown in Fig. 3.

Peak plasma current was found to depend on the total localized hydrogen flux (from fueling) in the edge. Localized saturation of the lithium coatings with hydrogen resulted in a drop in

peak plasma current by 30 – 40%. High plasma current operation could be restored by changing fueling locations, until the lithium coatings local to the new fueling location were again saturated. Since LTX has three toroidally-separated high efficiency fueling locations, this process could be repeated once again, until the coatings local to the last fueling system are finally saturated. This highlights the need for high efficiency fueling, since low efficiency fueling results in faster saturation of the wall coatings. Note that saturation of the wall with hydrogen does not produce an impurity source, but rather additional fueling, with a high recycling wall. The result therefore supports the conclusion that good plasma performance in LTX, with a close fitting metallic wall, is highly dependent on the level of wall recycling, rather than simply requiring the reduction in impurities afforded by low-Z wall coatings.

Repetitive application of lithium to the stainless steel inner shell liner in LTX produced efficient overall wall pumping. In Figure 4 the overall fraction of the fueled gas which was pumped by the wall is shown, as a function of the overall number of injected particles. This fraction is calculated from the measured vessel pressure immediately before, and within 100 – 150 msec after, a discharge (before the torus vacuum system can affect the pressure). A pumping wall requires that the discharge be fueled actively, rather than by recycling. LTX lacks pellet fueling, and, until 2013, neutral beam injection.

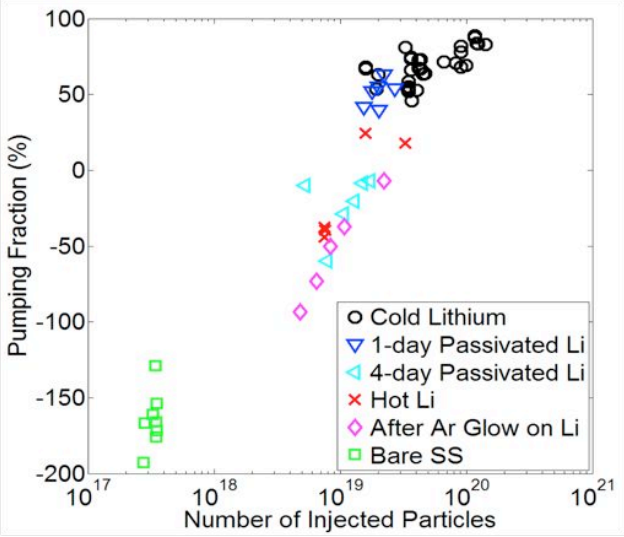

Figure 4. The fraction of the total number of injected hydrogen atoms which are pumped by the LTX wall, under various conditions. A negative fraction implies that the wall is a source of particles, rather than a sink.

3. Lithium coatings on hot walls

A test of lithium evaporation onto hot (300 °C) walls was also performed. Operationally, a 4 gram evaporation onto cold walls was performed, followed immediately by plasma operations. 48 hours later, 4 g of lithium was evaporated onto the heated, 300 °C shell, followed again by immediate plasma operations. Comparisons shown below are for discharges from these two adjacent periods of plasma operations. It was found that lithium coatings on a hot shell did not produce similar gains in discharge performance compared to coatings on a room-temerature wall. It should be noted that discharges run against hot lithium coated walls had variable performances. In Figure 4, hot-wall discharges are indicated by a red “x”; the wall is seen to either modestly pump or modestly recycle.

During evaporation onto a hot shell, rapid passivation of the wall coatings was observed. This was evidenced by the dark coloration of the wall coatings deposited during hot wall operation, which indicates the rapid formation of hydroxide coatings, although the coatings probably consisted of a mixture of compounds. A photograph of the hot shell surface immediately after lithium evaporation is shown in Figure 5.

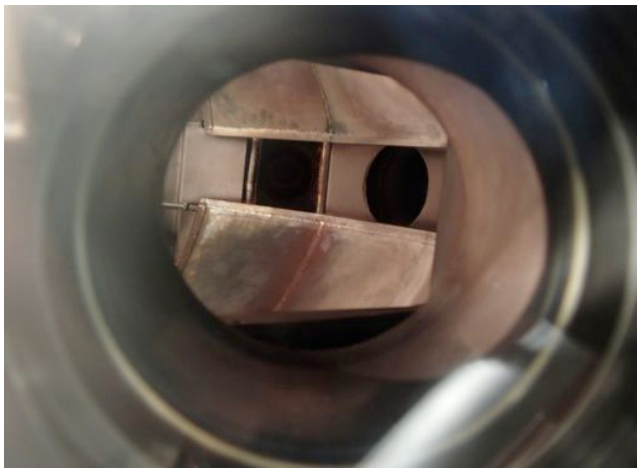

Figure 5. Inner shell surface after coating with lithium, with the shell at 300 ℃. Note the dark coloration of the coated shell surface. The photograph is taken through a glass viewport, which is protected by a closed gate valve during evaporation.

The resultant discharge current and duration is compared to a shot with clean, cold (room temperature) lithium wall coatings in Figure 6.

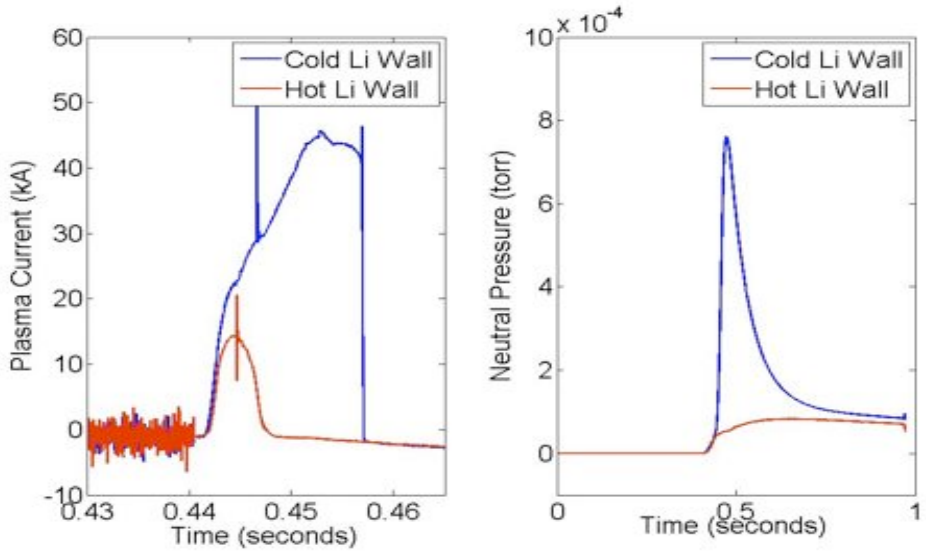

Figure 6. Comparison of the plasma current and evolution of the chamber gas pressure for cold (blue) and hot (red) walls. Discharge current and plasma pumpout of the fuel gas for hot walls is similar to the case with uncoated walls.

Several factors contribute to the immediate passivation of lithium coatings on the hot LTX shells. A total of ~40 g of lithium, which would produce a 4 micron coating if evenly distributed over the 5 m^2 shell area, had been previously deposited on the shell face, and exposed to background gasses until passivated (converted to lithium hydroxide, or other oxides and carbonates). The oxygen inventory in the lithium prior to the hot wall experiment is not known, but the shell coating could have chemically bound nearly 100 g of oxygen. Once the shells are heated above the melting point of lithium, the mobility of impurities in

the lithium is greatly increased. It is therefore possible that the hot lithium coating was infused with oxygen from previous coatings, and effectively passivated immediately upon deposition. This effect would likely occur to some degree even if the shells had not been previously coated with lithium, since stainless steel surfaces typically have high oxygen content as well. Molybdenum has a similar oxide coating.

The situation is complicated by the fact that the partial pressure of water in the LTX vacuum vessel is elevated during hot shell operations, since the 5 m^2 shell surface, radiating at 300 °C, heats areas of the vacuum vessel which are not otherwise effectively baked. Water is then desorbed from the heated vessel interior. Therefore the lithium surface would also be passivated more rapidly due to the higher partial pressure of water in the chamber, and it is difficult to determine which effect – passivation from residual chamber water, or passivation due to oxygen migration from underlying layers, dominates. Based on the rapidity of passivation of the hot lithium surface, however, it is suspected that migration of oxygen from the passivated substrate dominates. Even with the observed factor of ten increase in the partial pressure of water during the hot shell experiment, the lithium surface should have remained active for 2-5 hours, if the sole source of passivation was background gasses.

4. Gas fueling experiments in LTX

LTX discharge fueling employs gas injection. We have now studied the fueling efficiency of a number of different gas injection techniques, including supersonic gas injection (SGI), and molecular cluster injection (MCI).[1] The use of either of these highly directed gas jets results in high fueling efficiencies, up to 30-35% (see Fig. 7). 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. Note that all fueling systems are installed on the low-field side. A summary plot of fueling efficiency vs. particle flux is shown in Figure 7.

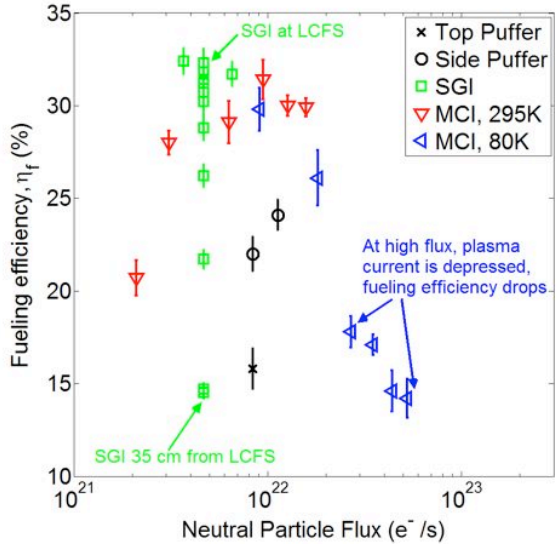

Figure 7. Summary plot of fueling efficiency vs. fueling rate for the systems tested in LTX. The highest fueling efficiencies are obtained for the SGI and the MCI. The "top puffer" is a conventional wall-mounted piezoelectric gas valve. The "side puffer" is also a piezoelectric valve system, but it is 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.

5. Electron and ion temperature measurements, and plasma rotation

Results from the LTX multipoint Thomson scattering system indicate that electron temperatures are in the 100 – 200 eV range, for lithium-coated PFCs. Recently obtained electron temperature profiles are broad and flat, out to the last available Thomson data point

at r=60 cm (see Fig. 8). Note that the shell is located at R=66 cm, and the axis is at R=40 cm. Flat electron temperatures are of course consistent with the expected effect of low recycling walls, but more data, edge Thomson data, and finally data with a liquid lithium fill in the lower shells are all still needed.

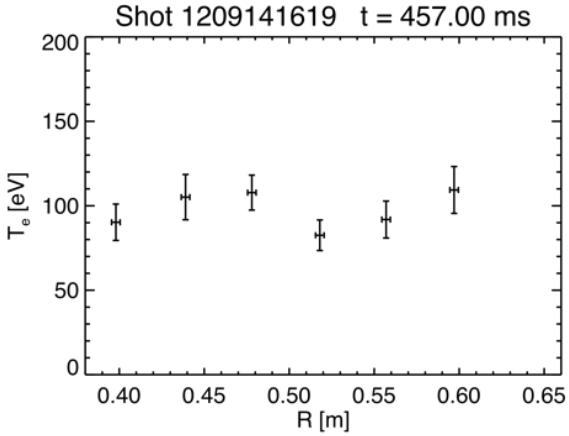

Figure 8. Example Thomson scattering data indicating a constant, ~100 eV electron temperature out to r/a ~0.8.

In March 2012 the LTX OH system was reconfigured to produce longer discharges (30-35 msec, twice the discharge duration on CDX-U), [2] with reduced loop voltage, in preparation for liquid lithium operation. The data shown in Figure 6 was taken with modest plasma current (50 kA), during a 30 msec discharge.

Passive CHERs data has also been obtained, [3,4] in a collaboration with the Oak Ridge National Laboratory, and indicates relatively high ion temperatures (up to ~70 eV) for a low (few × 10^{19} m^{-3}) density, Ohmic discharge. Ion temperature profiles from the ORNL CHERs system are shown in Figure 9(a), along with toroidal velocity profiles in Figure 9(b).

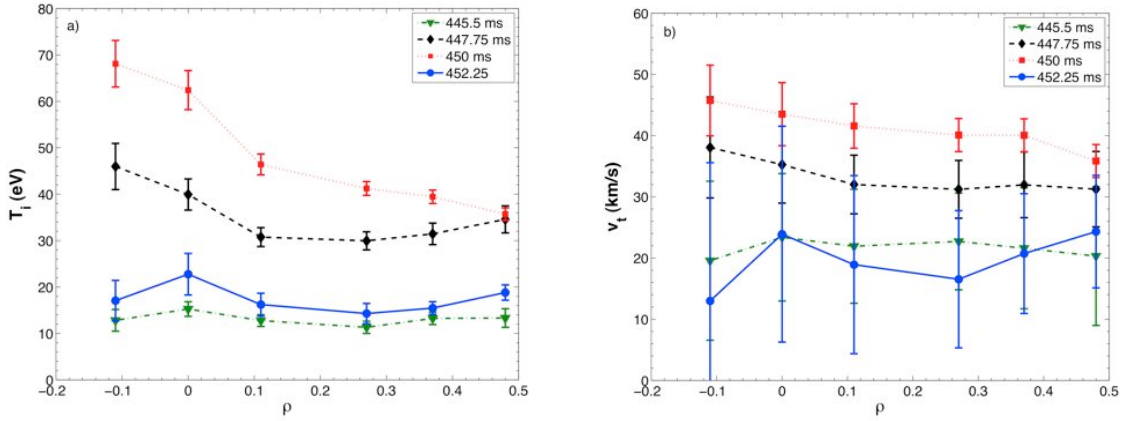

Figure 9(a) Ion temperature profiles in LTX during operation with lithium-coated walls, and (b) toroidal velocity profiles, measured with the ORNL CHERs system (passive operation).

A flat-field grazing-incidence grating spectrometer was installed on LTX in collaboration with Lawrence Livermore National Laboratory. This diagnostic, the Long-Wavelength Extreme Ultraviolet Spectrometer (LoWEUS), [5] has the same characteristics as the instrument used on NSTX. LoWEUS employs a variable space grating with an average spacing of 1200 lines/mm and covers 90–270 Å wavelength band. With a line width (FWHM) of ~0.3 Å, the spectrometer is able to resolve Lyman-a lithium lines, L-shell lines of oxygen, and K-shell lines of carbon.

Initial spectra from LoWEUS in LTX plasmas indicate the presence of OIV, OIV, and OIV lines, which are consistent with a core electron temperature of approximately 100 eV. Among the goals of the LoWEUS measurements is to determine the feasibility of ion temperature measurements with a higher resolution LLNL spectrometer.

Finally, the LTX equilibrium has been reconstructed for a number of discharges, [6] although accurate magnetic reconstruction in the presence of the highly conducting shells is a work in progress.

7. Acknowledgments

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

8. References

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