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Abstract*—The lithium tokamak experiment (LTX) is a small spherical tokamak currently operating to investigate the low recycling regime for magnetically confined plasmas through the utilization of liquid lithium coated plasma facing surfaces. The LTX machine is unique in that it incorporates inside the vacuum vessel a heated conducting shell that encloses about 80% of the last closed flux surface of the plasma. The conforming shell operates at temperatures up to 500^{o}C and is coated with a thin liquid lithium film. Two retractable crucible evaporators are used to deposit the lithium film on the shell inner surfaces. Various methods and procedures for lithium deposition onto the shell surfaces have been tested by varying the component temperatures and vessel pressure, and utilizing concurrent glow discharge. Operating procedures and safety systems have been developed and implemented to ensure the safe operation with lithium at elevated temperatures. The machine has successfully operated with lithium coated shells demonstrating improved plasma performance as a result. Maintaining an active lithium surface between lithium evaporations was an issue and new features are currently being installed to address this. The machine has also been vented and the internal surfaces cleaned without any difficulty. Operating results, current status, ongoing upgrades and future plans will be presented.

Keywords-component; Lithium, Liquid lithium, Plasma facing surface

I. THE LTX EXPIERIMENTAL DEVICE

The lithium tokamak experiment (LTX) is a small spherical tokamak currently operating to investigating the low recycling regime for magnetically confined plasmas through the utilization of liquid lithium coated plasma facing surfaces. The LTX machine is unique in that it incorporates inside the vacuum vessel a heated conducting shell that encloses about 90% of the last closed flux surface of the plasma. The construction of LTX utilized the core components including the vessel, OH and TF coils from the former current drive experiment. The LTX, as configured for the initial period of lithium operation, is shown in figure 1. The primary design parameters of LTX are listed in table 1.

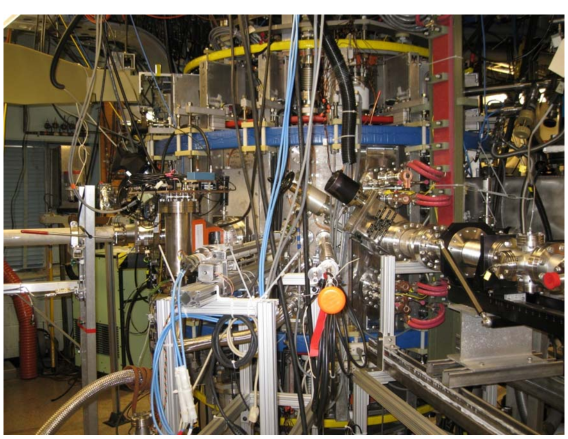

Figure 1. The Operational LTX Device

Table 1. LTX Design Specifications

LTX Design Specifications	
Major Radius	**0.4 m**
Minor Radius	**0.26 m**
Toroidal Field	**0.34 T**
Plasma Current	**400 kA**
Current Flattop	**>100 ms**
Ohmic Flux	**225 mV-s**
Wall Temp.	**400^{o}C to ~500^{o}C**

II. PLASMA FACING SURFACE

The plasma facing surface consists of a shell like structure conforming to the outer most closed flux surface of the plasma with about a 1cm gap between its internal surface and the plasma's outer surface. This shell is constructed in four symmetrical segments with a gap in the horizontal mid-plane and a gap vertically along a plane through the center of the machine's center stack. The shell was fabricated in house from explosively bonded stainless steel 1.6mm thick on copper 9.5mm thick and shaped to conform to the plasma surface. The stainless steel side faces the plasma and is actively coated prior to machine operation. The copper outer side provides good thermal conduction for a uniform surface temperature and is nickel plated for protection and to reduce emissivity. Each of the four shell sections is equipped with eight single ended cable heaters tightly clamped to the copper surface with a total heating capacity of 7630 Watts per shell. Each cable heater consists of a sealed single ended stainless steel outer jacket with a heating element imbedded inside with magnesium oxide. The heating portion of each heater extends only along the section attached to the shell. At the point where the sealed tube leaves the shell, there is an internal transition to cold power leads. The cold portions of the heater tube extend from the shell surface through a vacuum seal to the outside of the vessel. In this manner all electrical connections and feedthroughs are external. The temperature of each shell section is measure with eight thermocouples distributed over the surface. Each shell section is independently supported external to the vacuum vessel with four stainless steel legs which provide thermal, electrical and mechanical isolation. Figure 2 is a section view showing the shells installed inside the LTX machine and figure 3 shows the configuration of the four shells alone.

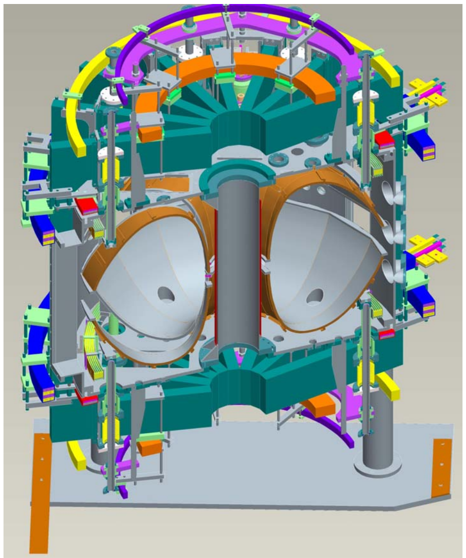

Figure 3. Section of the LTX machine showing the installed shell sections

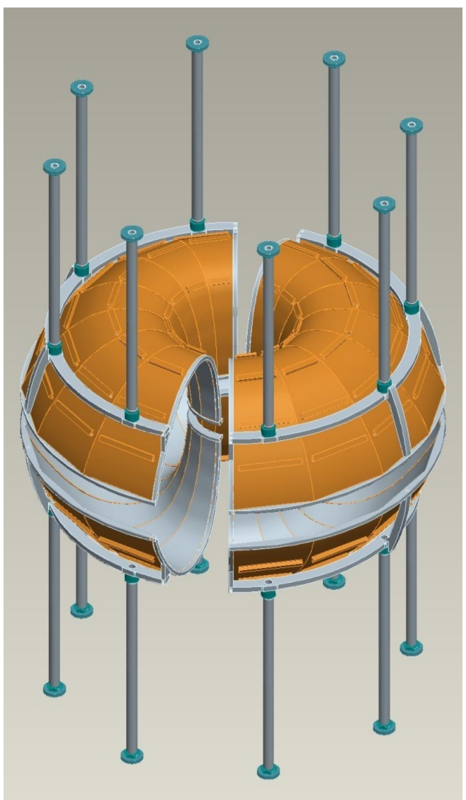

Figure 4. Shows the configuration of the four shells independent of the other machine elements

III. Lithium Injection

Various methods of both liquid and vapor lithium deposition on the shell surfaces were planned and new ones are under consideration. Vapor deposition using two retractable evaporators were used for the initial lithium campaign. Each evaporator consisted of an Y_2O_3 crucible surrounded with a tantalum resistive heater and mounted on the end of a linear motion drive. The evaporators were placed in the horizontal mid-plane of the machine opposite each other and centered between a pair of upper and lower shell segments. Two thermocouples were placed in each crucible for monitoring the temperature of the molten lithium and determining evaporation rates. Dual isolation valves were used to connect the evaporator drives to the machine vessel in order to enable their removal to a remote location for filling and cleaning. The evaporator assembles were tested to 700^{o}C prior to installation on the LTX machine. Figure 5 shows a new evaporator unit and figure 6 shows a unit after about 20g of lithium deposition onto the shells.

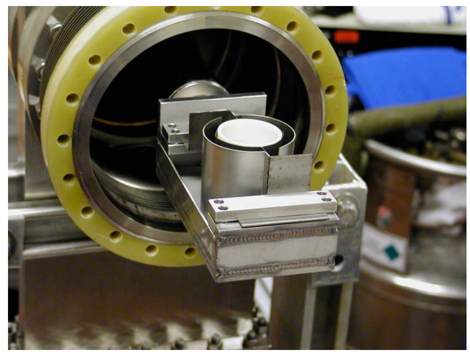

Figure 5. A new evaporator unit

Figure 6. Used evaporator prior to cleaning

IV. Initial Lithium Expierments

Prior to the first deposition of lithium onto the plasma facing shells, the internal surfaces were cleaned to remove trapped material. The shells were baked to over 300°C for several hours followed by a helium glow discharge for several more hours until no further improvement was observed on the residual gas analyzer. Initial evaporations were performed into a helium glow discharge with the color of the emitted light changing from a blue for the helium alone to a deep red for the lithium vapor. The evaporation rates were approximately 0.75grams per hour. Table 2 lists the initial lithium evaporation sequence.

Table 2. Initial Evaporation Sequence

Operation	Evaporator #1	Evaporator #2	Total Li	Wall Temp.
Fill Crucible	5g	5g	10g	
Evaporate	0.7g	0.48g	1.18g	25°C
Evaporate	0.34g	0.33g	0.67g	25°C
Evaporate	4.0g	4.2g	8.2g	25°C
Fill Crucible	8.3g	8.4g	16.7g	
Evaporate	2.4g	1.6g	4.0g	25°C
Evaporate	1.7g	2.4g	4.1g	280°C

V. Plasma Performance

Lithium deposition was performed on both a cold (~25°C) and hot (~300°C) shell wall with significantly different results. The initial evaporation was performed onto a cold shell surface. The plasma current and duration significantly increased after a few hours of evaporation. Figure 7 illustrates the improvement in plasma current with about 5g of lithium deposited on the cold shell wall. Figure 8 illustrates the change of the wall from a source of material without the lithium to a pump of material with the lithium and clearly shows the reduction in recycling.

Lithium deposition performed on a hot shell wall of about 300°C did not exhibit a significant reduction in recycling. Approximately 4 grams of lithium were deposited on the hot shell resulting in an average surface thickness of less than 5×10^{-6} meter. It is thought that this hot thin coating is rapidly contaminated with impurities transported to the surface. The surface of this coating is observed to have a dull grey appearance unlike that of clean metal.

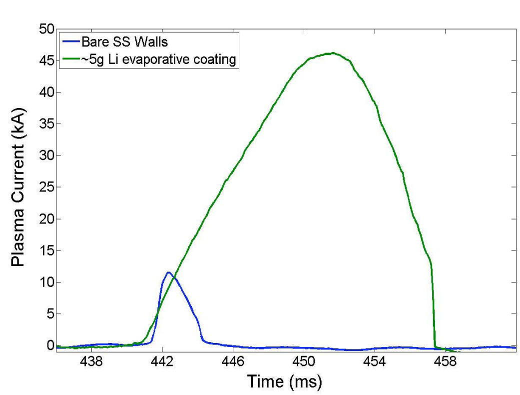

Figure 7. Plasma Current with and without lithium

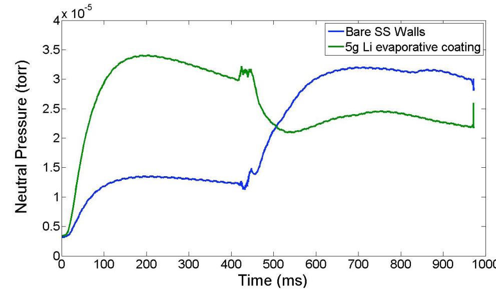

Figure 8. Comparison of machine pressure with and without lithium

VI. Machine Performance

The shell heaters performed well and without any problems, delivering sufficient heat with little more than half power. The shell copper backing provided excellent thermal uniformity over the entire surface of the shell section. The external shell mounting provided good thermal isolation and mechanical strength, but the long legs enabled the shell sections to move horizontally 1 to 2 centimeters as a result of induced eddy currents in the shells. During these experiments the machine base pressure was marginal at only about 2×10^{-7}Torr. Lithium clean up after vessel venting and purging proved to be simple and efficient.

VII. Future Plans

In preparation for the next phase of lithium operation, several improvements and modifications are underway. The vessel vacuum seals have been improved in order to reduce the machine base pressure and two lithium evaporation getter pumps will be installed on the outside of the vessel for pumping water. To reduce the motion of the shell sections, restraining clamps have been installed internally between the vessel walls and the shell supports. Initial testing indicated that these clamps only partially restrained the shell motion since the ends of the long mounting legs were to some extent still free to pivot external to the machine. Additional external shell leg restraints are currently in the design phase.

For the next sequence of experiments, the use of a larger quantity of liquid lithium is planned. Pools of lithium will be established in the bottom section of the two lower shell sections. Small dams at each end of the bottom shells were installed when they were fabricated in anticipation of this mode of operation. With this mode of lithium operation, a large shell motion during the pulse could splash the lithium out of the shell while a slight motion may help stir the lithium pool.

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