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Abstract

The Lithium Tokamak eXperiment (LTX) is a spherical tokamak with $R_0 = 0.4$m, a = 0.26m, $B_{TF} \sim 3.4$kG, $I_P \sim 400$kA, and pulse length ~ 0.25s. The focus of LTX is to investigate the novel, low-recycling Lithium Wall operating regime for magnetically confined plasmas. This regime is reached by placing an in-vessel shell conformal to the plasma last closed flux surface. The shell is heated and then coated with liquid lithium. An extensive array of magnetic diagnostics is available to characterize the experiment, including 80 Mirnov coils (single and double-axis, internal and external to the shell), 34 flux loops, 3 Rogowskii coils, and a diamagnetic loop. Diagnostics are specifically located to account for the presence of a secondary conducting surface and engineered to withstand both high temperatures and incidental contact with liquid lithium. The diagnostic set is therefore fabricated from robust materials with heat and lithium resistance and is designed for electrical isolation from the shell and to provide the data required for highly constrained equilibrium reconstructions.

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	LTX
Major radius (R_0)	40 cm
Minor radius (a)	26 cm
Elongation (κ)	1.55
Toroidal field (B_t)	3.5 kG
Ohmic current (I_p)	>250 kA
Peak density (n_e)	$5\text{x}10^{19}\text{m}^{-3}$
Peak electron temperature (T_e)	>500 eV (predicted by ASTRA modeling)
Peak ion temperature (T_i)	>150 eV (predicted by ASTRA modeling)
Current flattop	>100 ms

TABLE I: LTX experimental and theoretical parameters.[6]

Introduction

A major challenge facing magnetic fusion as a viable, alternative energy source is finding an acceptable reactor first wall material. One solution may come in the form of lithium as a liquid metal. Liquid metal could act as a self-replenishing first wall, and so reduce the concern of vessel neutron damage and activation. The usage of lithium in particular could further simplify reactor design through integration of the requisite tritium breeding blanket into the vacuum vessel itself, as lithium is a key component in the breeding cycle. Furthermore, lithium has been shown to retain deuterium in a 1:1 ratio,[1] thus leading to pumping of hydrogenic species, significantly reducing recycling at the edge, and flattening electron and ion temperature gradients. These effects together vastly improve plasma performance, and this enhancement with the introduction of liquid lithium has been demonstrated in a number of experiments.[2–5]

Building upon these past results, the Lithium Tokamak eXperiment (LTX) is the first experiment to study the effects of having a fully liquid lithium first wall. Experimental parameters are summarized in Table I. Entering this Lithium Wall (LiWall) operating regime is accomplished through the introduction of a heated, in-vessel shell conformal to the plasma last closed flux surface (Fig. 1). The experimental setup will permit $\sim 90\%$ of plasma facing surfaces to be coated with liquid lithium.

This novel regime requires detailed magnetic characterization, but the harsh environment inside LTX poses difficulties for traditional magnetic diagnostics. LTX addresses this

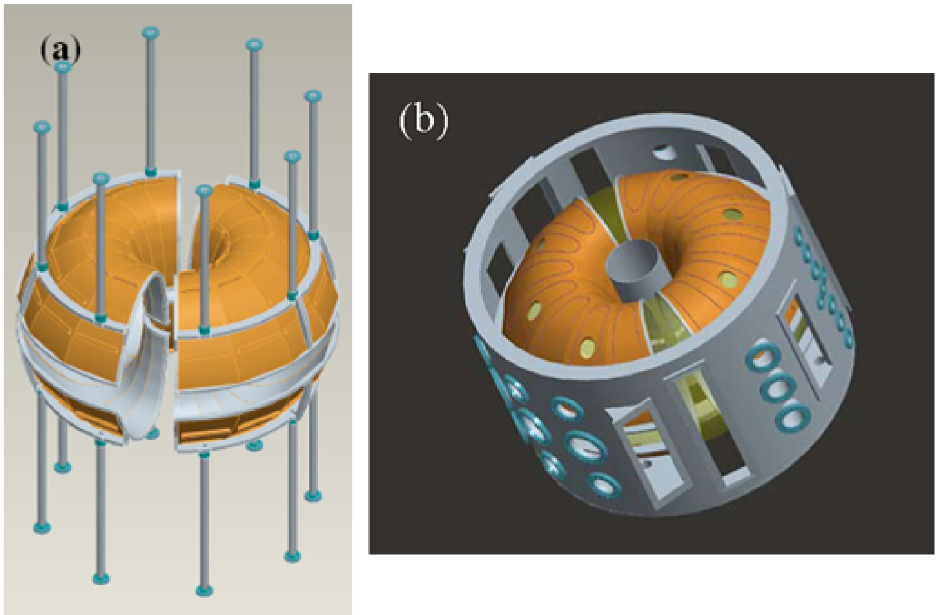

FIG. 1: LTX heated, conformal shell (a) View of shell with support legs (note toroidal and poloidal breaks) (b) View of shell within vacuum vessel.

issue through an extensive set of magnetic diagnostics carefully designed to survive heat and incidental lithium contact and to yield comprehensive data suited for equilibrium reconstructions.

Results

An approximate layout of the magnetic diagnostics may be seen in Fig. 2. The magnetic diagnostics set includes an array of small-scale Mirnov coils placed, with respect to the shell, at three internal locations (Fig. 2(c)). These coils are one hundred turns of 0.01" diameter wire wound on 1" sections of alumina and fed into stainless steel hypodermic tubing. This tubing is safely installed internal to the shell despite the presence of energetic plasma particles because of the shell's construction. Each of the four shell segments is comprised of seven flat plates that were rolled to conform to the plasma last closed flux surface. These plates then form 'crooks' where joined, forming a small space, several mm, between the plasma last closed flux surface and the shell surface. It is in this area that the interior probes are placed. A set of five coils is located inside each shell half (upper and lower) at a single toroidal location, yielding a total of ten poloidal field measurements. To remove n=1 contributions to the signals, another internal coil set of ten is placed 180°

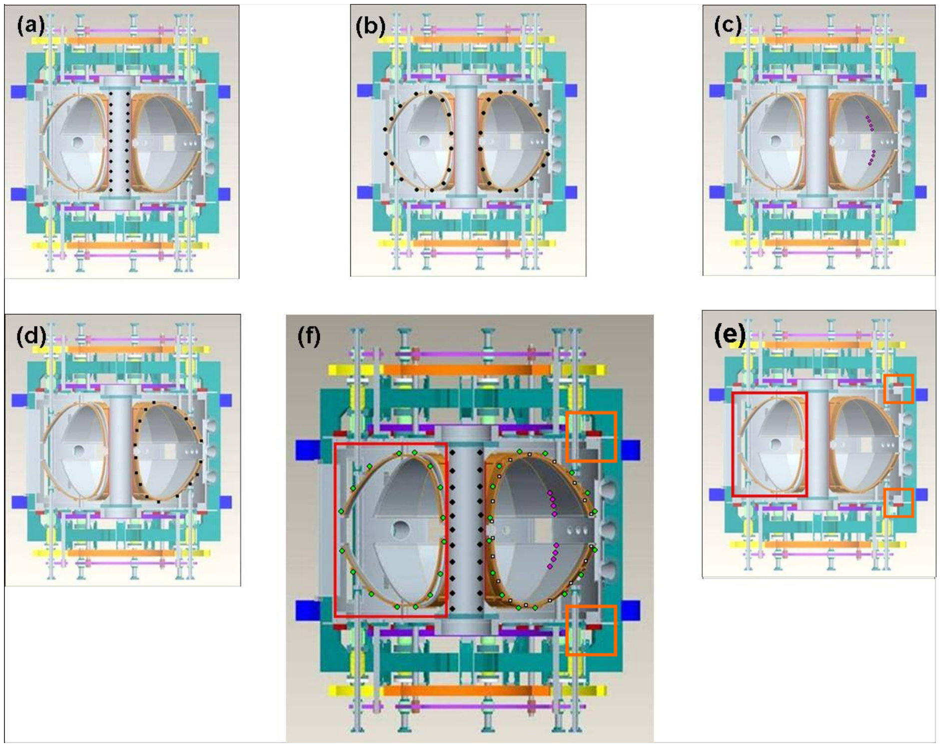

FIG. 2: LTX layout, highlighting each set of magnetic diagnostics - (a) Centerstack flux loops, (b) Flux loops on conformal shell, (c) Mirnov coils interior to the shell, (d) Mirnov coils along shell edge, and (e) Approximate path of Rogowskii, diamagnetic loop, and corner Rogowskii coils. Larger, central figure (f) shows cross-sectional view with these diagnostics superimposed.

toroidally from the first set. An auxiliary set of four coils is also placed 22.5° from the main set, in the main set's neighboring 'crook'. These internal coils permit field measurements within the plasma with minimal influence from the shell.

Although the shell has both toroidal and poloidal breaks (Fig. 1), the possibility of high-order induced currents in the shell cannot be neglected. Therefore, coils are placed external to the shell at similar toroidal and poloidal positions as the internal sets. These external coils permit a comparison of field measurements with and without the shell's influence, thus allowing fields due to any shell currents to be quantified.

To further diagnose plasma field, a total of eighteen two-axis Mirnov coils are placed in one toroidal shell gap (nine probes in the upper shell gap and nine probes in the lower shell gap) (Fig. 2(d)). These are wound on cores of 1" x 1" x 1/2" yttria stabilized magnesium oxide, a unique material less brittle than boron nitride and, unlike standard alumina, able to maintain structural integrity while subject to heat and incidental lithium contact. In order to provide signals with minimal contributions from eddy currents in the shell edge, these gap coils are mounted in, approximately, the toroidal center of the gap on 316-stainless steel tabs attached to the shell edge. These gap Mirnov coils are able to provide data on both the toroidal and poloidal plasma field with minimal shell contributions.

There are an additional twenty-six Mirnov coils external to the shell, placed poloidally at several toroidal locations, and used to constrain the poloidal magnetic field in equilibrium reconstructions. These Mirnov coil sets consist of nine coils located veritcally along the center stack, seven located vertically outboard of the shell, five placed radially above the shell, and five placed radially below the shell. As these coil sets are located external to and away from the shell, standard fabrication techniques and materials were used.

The magnetic diagnostics set includes eleven flux loops spaced evenly within the air-side of the center-stack (Fig. 2(a)). These include one at the mid-plane used to measure loop voltage - an important rough indicator of plasma performance. Sixteen flux loops are located on the conformal shell (Fig. 2(b)) as well. These are two-turn, center-tapped loops to decrease the likelihood of ground loop formation. Each of the wires in the two-wire conductor is wrapped in fiberglass, with a fiberglass sleeve over both as well. This is then threaded through a 316-stainless steel tube bent to fit into the proper shell position. Although the loops are mounted directly on the shell, they have been carefully fabricated to provide electrical isolation from the shell. Steatite fish-spine is beaded on top of the 316-stainless steel tube, except in the shell gaps where the 316-stainless steel tube is left bare while the tube on the shell gap edges have magnesium oxide sections which are clamped to the shell. The shell loops are located such that flux measurements with full coverage of the poloidal plasma cross-section are possible and so permit highly-constrained equilibrium reconstructions.

A total of seven saddle flux loops are placed in the same upper and lower shell gaps as the gap Mirnov coils. These are fabricated from the same two-wire conductor as the shell flux loops and threaded through a 316-stainless steel tube bent into a rectangle fit to the appropriate shell gap position. The saddle loops are placed such that three cover the upper outboard shell gap and three cover the lower outboard shell gap, while one spans the poloidal break between the upper and lower shells. The purpose of these saddle loops is to monitor eddy fields near the shell edge formed by currents in the shell, thus further quantifying any magnetic effects introduced by the shell.

One Rogowskii coil encircling the plasma cross-section is used to measure plasma current, and two re-entrant Rogowskii 'elbows' at an upper and lower vacuum vessel corner monitor currents in the vessel. The plasma Rogowskii coil was fabricated from heat resistant wire on a teflon core to avoid damage due to proximity to the shell. There is also one internal diamagnetic loop with a corresponding compensation coil to measure the plasma diamagnetic effect and constrain reconstructions (Fig. 2(e)). As the diamagnetic coil and corner Rogowskii coils are located outside and away from the shell, standard fabrication techniques were used.

Conclusions

As the first experiment with the capability to reach a true LiWall operating regime, LTX is unique with its internal, heated, conformal shell. The introduction of the shell and lithium presents a number of challenges to conventional magnetic diagnostics. Therefore, the magnetic diagnostics set for LTX has been carefully designed to overcome the inherent difficulties, which include a secondary conducting surface, heat, and incidental lithium contact. This design will permit diagnostic survival during operation as well as compensation for any field produced by currents in the shell. Signals from these specialized magnetic sensors will then be used to calculate equilibrium reconstructions of the plasma magnetic field. This detailed characterization is expected to lead to a greater understanding of the LiWall operating regime and its enhancments to plasma performance, potentially influencing future decisions regarding first walls for magnetic fusion reactor design.

Acknowledgments

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