Observation of an Isothermal Electron Temperature Profile with Low Recycling Lithium Walls in LTX

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Abstract Discharges with high edge electron temperatures and flat radial electron temperature profiles, extending to the last closed flux surface, and into the low field side scrape-off layer, have now been achieved in the Lithium Tokamak eXperiment (LTX), with lithium-coated walls. Flat temperature profiles are a long-predicted consequence of low recycling boundary conditions. Temperature profiles are measured in repeated discharges with Thomson scattering; data from several discharges is averaged at each time point to improve accuracy at low density. Modeling indicates that the ion temperature profiles are also flat, which should eliminate temperature gradient–driven instabilities. The confined plasma therefore appears to be (separately) isothermal in the electron and ion populations. The edge density is very low, with a density profile which decreases approximately linearly with the poloidal flux. So far experiments are transient. Gas puffing is used to increase the plasma density. After gas injection stops, the discharge density is allowed to drop, and the edge is pumped by the low recycling lithium wall. The core impurity content, even in low density plasmas without fueling, and edge electron temperatures of 200 eV, remains low. $Z_{effective}$ is approximately 1.2, with most of the increase from oxygen, followed by carbon. The smallest fraction of the $Ze_{ffective}$ increase, especially in the core, is from lithium. An upgrade to LTX, which includes a 35A, 20 kV neutral beam injector to provide core fueling and auxiliary heating, is underway. Two beam systems have been loaned to LTX by Tri Alpha Energy. With core fueling provided by the neutral beam, an equilibrium similar to the "Isomak" – a tokamak discharge in thermodynamic equilibrium, may be accessible in LTX, for the first time. A widened operational window, in both toroidal field and plasma current, is also planned, as well as eventual operation in diverted geometry. Results from the most recent experimental campaign will be described, as well as the upgraded configuration of LTX.

1. Introduction

The Lithium Tokamak eXperiment (LTX) is a low aspect ratio tokamak with R=0.4 m, a=0.26 m, and κ=1.5. Typical parameters are $B_{toroidal} \sim 1.7$ kG, $I_P < 100$ kA, and a discharge duration < 50 msec. LTX features a conformal 1 cm thick copper shell or liner. The plasma-facing surface of the shell is clad with stainless steel, and prior to a day's operations, the shell is coated with lithium to form the plasma-facing surface. The shell conforms to the last closed flux surface (LCFS), and covers 85% of the plasma surface area, and can be electrically heated to 320 °C. LTX was designed to investigate modifications to tokamak equilibrium caused by low recycling walls.

2. Results with lithium walls in the absence of gas puffing

Discharges with high edge electron temperatures and flat radial electron temperature profiles – an isothermal confined electron population - have now been achieved in LTX,[1] using a coating system which employs electron beam heating of two lithium pools in the lower shell structure. The lithium pools are heated to ~ 500 °C for 10 – 20 minutes, to produce 10 – 100 nm thick lithium coatings, over the entire plasma-facing surface. Very low levels of residual water in the device (partial pressures in the mid to upper 10^{-10} Torr range) assist in maintaining lithium surface conditions. The surface composition of lithium coatings in LTX has been analyzed with post-discharge X-ray photoelectron spectroscopy, which indicates that the principal surface contaminant is oxygen. Initially the lithium-oxygen ratio in the surface is ~8:1; over a period of ~10 hours (longer than a run-day) the oxygen content of the surface increases until the lithium-oxygen ratio approaches 2:1, which is indicative of the formation of lithium oxide.[2]

Flat temperature profiles extending to the bounding wall have been predicted to be a consequence of low recycling boundary conditions,[3] but have not been previously observed in any magnetic confinement device. Temperature profiles in LTX are measured in discharges with multipoint, single-pulse Thomson scattering. The evolution of the electron temperature profile was determined by stepping the measurement time through the discharge, and averaging the data over several discharges for each time point (especially for the low density edge), using a set of 60 identical discharges. The evolution of the electron temperature, density, and the electron pressure is shown in Figure 1. These experiments are transient. The plasma density is initially increased with gas puffing. Gas injection is then terminated at t = 465 msec, and the discharge density is allowed to drop, while the remaining edge neutral population fuels the discharge, and is in turn pumped by the lithium wall over

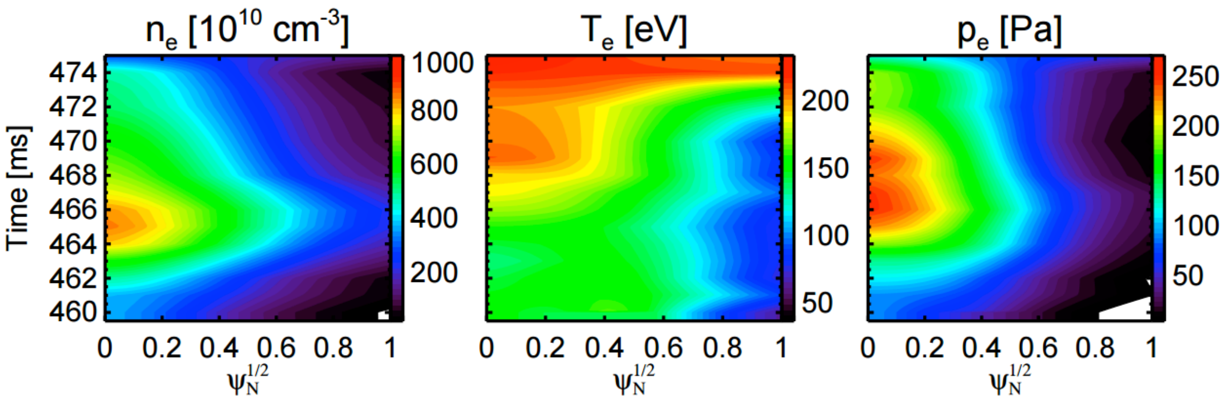

FIGURE 1. Contour plots of the evolution of the electron density, temperature, and pressure profiles in LTX. Gas puffing is terminated at 465 msec. 3-5 msec are required to clear hydrogen gas from the feedlines, at which point there is neither puffed gas nor a significant recycled gas component in the plasma edge. Low recycling and the lack of cold gas leads to nearly complete flattening of the electron temperature profile by 474 msec in the discharge. At the same time, the edge plasma density in the scrape-off layer drops to 2-3 × 10^{17} m^{-3}. The pressure profile broadens, despite peaking in the density profile. Note that the plasma is initiated at 445 msec.

the following 3-5 msec. As the neutral gas in the edge is pumped, the electron temperature profile evolves from broad, but still peaked on axis, with an edge temperature of ~30 eV at the LCFS (typical of earlier discharges in LTX, which exhibited relatively flat core electron temperature profiles out to r/a ~0.7-0.8, dropping to 20 – 30 eV at the LCFS[4]), to a very flat profile with an edge temperature > 200 eV (see Fig. 1).

Although the density profile remains peaked during the period when the electron temperature profile flattens (see Figure 1), the combined effect of density and temperature profile evolution is to broaden the electron pressure profile, as can also be seen in Figure 1.

Analysis with the TRANSP code,[5] supported by spectroscopic measurements of impurity ion temperatures, indicates that the ion temperature profiles are also flat, which should eliminate temperature gradient–driven instabilities. The edge density is very low, with a density profile which decreases approximately linearly with the poloidal flux. Collisionality is also low, with $\boldsymbol{\nu}^*_{i,e} < 0.1$ over the entire plasma volume, and approaching 0.01 in the SOL. The core impurity content, even in low density plasmas without hydrogen fueling, and edge electron temperatures of 200 eV, is low. Z_{eff} is approximately 1.2, with most of the increase from oxygen, followed by carbon. The smallest fraction of the Z_{eff} increase, especially in the core, is from lithium. The contribution to $Z_{effective}$ for lithium, carbon, and oxygen is shown in Figure 2. Low lithium content in the core plasma has also been observed with lithium coatings in NSTX[6] and in TFTR,[7] but partial lithium coverage of the graphite walls in those devices led to an accumulation of carbon in the core plasma. In NSTX, this was especially true during the inter-ELM period in the discharge. In LTX, the substrate for the lithium coating is metallic, and the carbon and oxygen content originates only from residual background gas in the vacuum chamber. The contribution of carbon to $Z_{effective}$ remains ≤ 0.1. Other results from LTX include successful operation with full liquid lithium walls, 4 m^2 in area, covering >80% of the plasma surface area, and forming all of the plasma-facing components (PFCs), with wall temperatures up to 270 °C. Similar impurity levels are seen in these discharges, with $Z_{effective}$ remaining below 1.5, which demonstrates for the first time that tokamak operation is compatible with liquid lithium PFCs.

It is important to note that with an edge electron temperature in the range of 200 – 300 eV, the wall sheath potential for a conventional Debye sheath, and hence the ion impact energy on the wall, will approach 1 kV. This is somewhat in excess of the peak sputtering energy for

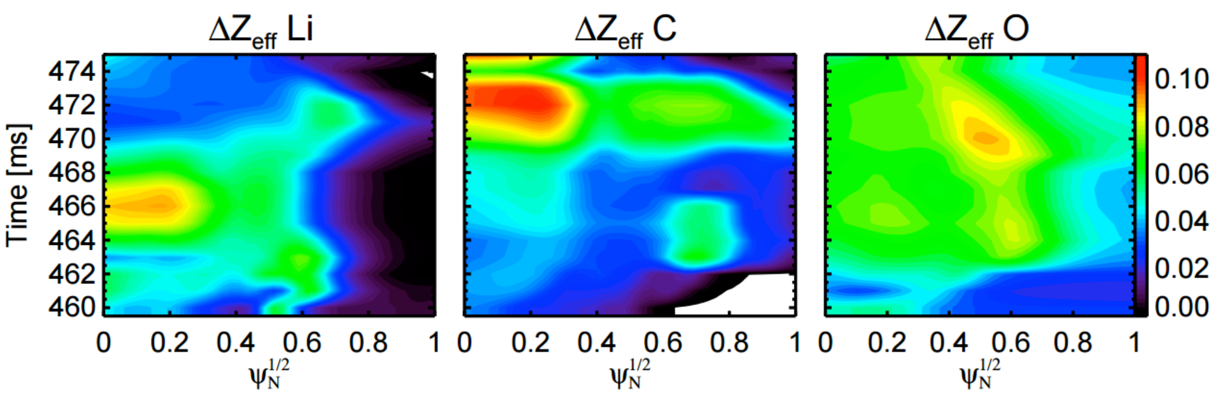

FIGURE 2. Contour plots of the evolution of the contribution of lithium, carbon, and oxygen to the discharge $Z_{effective}$ in LTX. Carbon and oxygen are the primary impurities in the discharge.

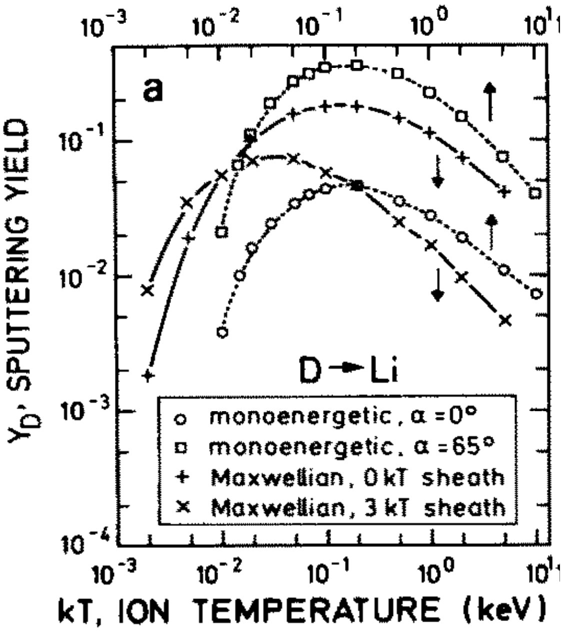

FIGURE 3. TRIM-SP calculations of the sputtering yield for deuteron impact on lithium, from Laszlo and Eckstein, 1991. The various curves are calculated for different sheath conditions and ion energy distributions. All the sputtering yields peak below 1 keV.

hydrogen impact on lithium, shown in Figure 3 (taken from a TRIM-SP calculation by J. Laszlo and W. Eckstein[8]). Note that proton impact (LTX uses hydrogen as a working gas) will result in a shift in the sputtering peak to slightly higher energies.
Discharges in LTX are limited on the high field side wall, and collisionality in the outer, low field side SOL is very low.

The gap between the outboard last closed flux surface and the outer lithium-coated shell surface is indicated in Figure 4. These discharges were operated at moderately low plasma current (~60 kA in the flattop). The edge neutral pressure is in the high 10^{-6} Torr range; the mean free path for ion charge exchange is ~ 1 km. Most ions near the outboard LCFS are trapped, and the relatively long pitch angle scattering time (τ_{ii} > 1 msec, ~ 10 ion bounces in LTX) mitigates SOL losses. The development of a broad low field side SOL is attributed in part to large ion orbit widths in the low collisionality discharge. The ion poloidal gyroradius

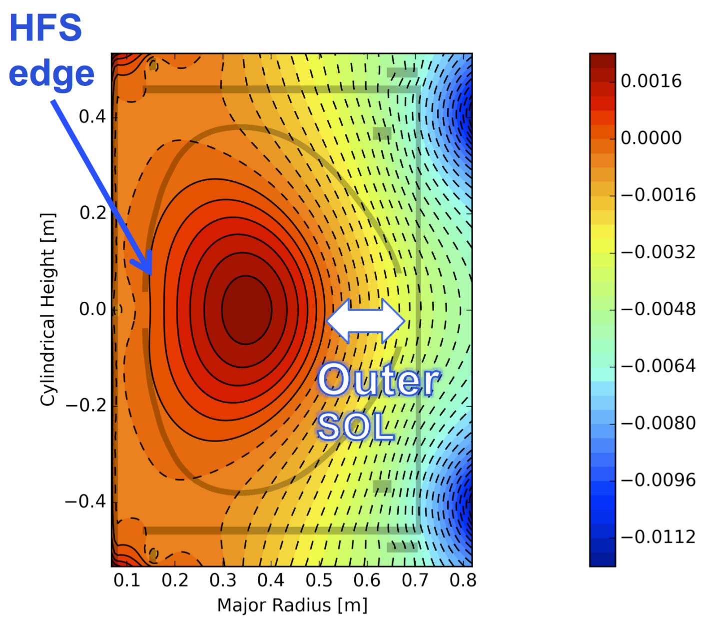

FIGURE 4. Equilibrium reconstruction of the LTX plasma with the PSI0TRI code (U. Washington). The distance between the outer LCFS and the shell-defined wall is 10 - 12 cm at times when the electron temperature profile is fully flat.

(the ion banana width) for 40 – 80 eV hydrogen is approximately 10 cm, for the so-called “fattest banana” orbit. This is similar in magnitude to the observed gap between the last closed flux surface (LCFS) from equilibrium reconstructions, and the outer boundary of the lithium-coated shells. High ion temperatures at the edge of a low recycling lithium tokamak have strong implications for edge power flow in a tokamak reactor. Since the temperature is flat to the wall, the implied temperature decay length in the SOL is infinite. Since the ion temperature at the edge is high, the density scrape-off length, which must exceed the ion poloidal gyroradius by at least a modest factor, must be long (as is experimentally observed in LTX). This implies that the divertor power footprint in a low recycling tokamak will be much broader than for a high recycling machine, possibly eliminating the need for advanced divertor configurations such as the snowflake or super-X divertors. Of course, maintenance of a very low recycling edge is incompatible with puffing a radiating gas such as neon or nitrogen.

There are as yet no scalings for the power deposition profile in a low recycling tokamak; future experiments in LTX-***β*** will investigate this for the first time.

3. The upgrade to LTX - LTX-*β*

In late 2015 LTX was vented in preparation for an upgrade to LTX-β. LTX-β will feature neutral beam injection, using one of two neutral beams loaned to the LTX group by Tri-Alpha Energy, a private company investigating FRC-based fusion concepts in Foothills Ranch, CA. The neutral beam will be operated at 20 kV, with up to 35 A in injected current, in hydrogen. The initial operating pulse will be power supply limited to 8 msec, with a subsequent doubling of the pulse length, through the use of both available neutral beam power supplies. Another doubling of the pulse length is planned, with an expansion of the existing ppower supplies, to a total of 30 msec. The beam will provide both heating and

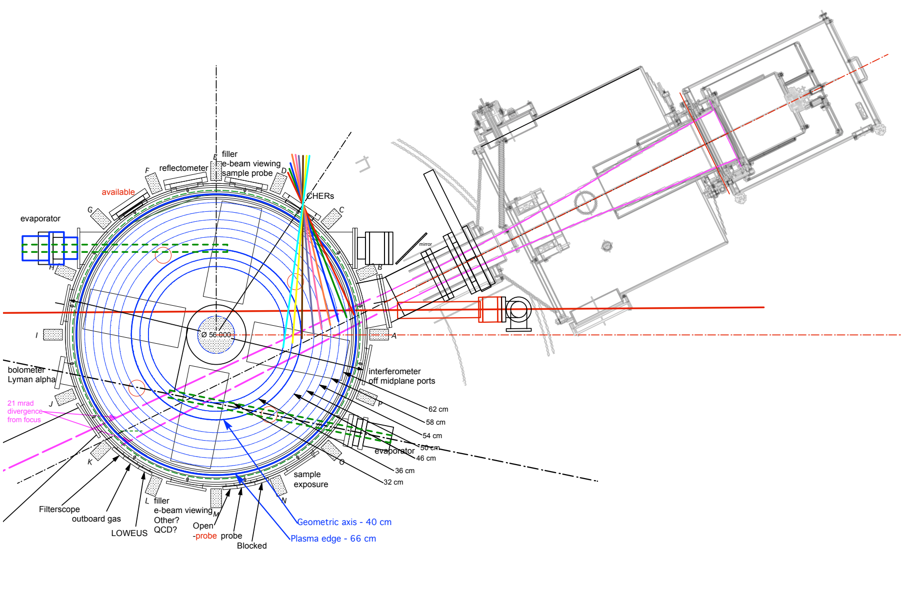

FIGURE 5. Layout of the neutral beam installation on LTX.

partial fueling of the core plasma, which will reduce the need for gas-puff fueling. A collaboration with Oak Ridge National Laboratory will provide beam-based core plasm diagnostics (CHERs). A collaboration with the University of California at Los Angeles will upgrade the existing microwave profile reflectometer diagnostic to record core electrostatic fluctuations. A new edge detector array for the Thomson scattering system will be completed, and SOL diagnostics will be expanded. Additionally, the toroidal field is being doubled to 3.5 kG, and the plasma current will be increased to 150 – 200 kA.

4. Summary

Experiments in LTX have demonstrated several key features of the lithium tokamak.

1. The production of flat temperature profiles – an “Isothermal Tokamak” or “Isomak” discharge.[9] The absence of recycled gas (and significan radiative losses) in the edge removes the mechanisms by which a confined plasma is cooled in the SOL and edge. Confined particles which exit the plasma are only slowed in the lithium wall itself. The thermal gradient, which drives conduction losses, should be robustly eliminated, so long as another cooling mechanism is not introduced into the edge.

2. Core impurity control with low-Z walls. The use of lithium coatings which entirely overlay a high-Z substrate results in modest core impurity content, despite very high ion impact energies, produced by a hot SOL. High ion impact energies are unacceptable with solid high-Z PFCs, such as tungsten, since significant surface damage to the PFC would result, as well as sputtering of high-Z impurities into the plasma. The surface of a liquid cannot be damaged by ion impact. With lithium walls, a transition to higher ion energies would result in decreased transfer of energy to surface atoms, and decreased sputtering, as shown in simulations.

3. Broadening of the scrape-off layer. The absence of a SOL temperature gradient, and the broadened ion poloidal gyroradius, contribute to a significant broadening of the SOL scale length for power deposition. The low edge density, the lack of charge exchange losses due to recycled gas, and the high mirror ratio in a low aspect ratio tokamak imply that ion trapping in the SOL is dominant. The time scale for pitch angle scattering of the ions from trapped to passing orbits is long compared to the flow time ($C_{sound}/L_{connection}$) to the wall, which will significantly modify the SOL in a lithium tokamak.

5. Acknowledgments

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6. References

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