

## **Extending the low-recycling regime to higher performance discharges and liquid lithium walls in the Lithium Tokamak Experiment- $\beta$**

D.P. Boyle<sup>1</sup>, R. Bell<sup>1</sup>, D. Elliott<sup>2</sup>, C. Hansen<sup>3</sup>, P. Hughes<sup>1</sup>, S. Kubota<sup>4</sup>, A. Maan<sup>1</sup>, R. Majeski<sup>1</sup>

<sup>1</sup>*Princeton Plasma Physics Laboratory, Princeton, NJ USA*

<sup>2</sup>*Oak Ridge National Laboratory, Oak Ridge, TN USA*

<sup>3</sup>*University of Washington, Seattle, WA USA*

<sup>4</sup>*University of California at Los Angeles, Los Angeles, CA USA*

[dboyle@pppl.gov](mailto:dboyle@pppl.gov)

In order to extend the low-recycling regime first observed in the Lithium Tokamak Experiment [1] to higher performance, steadier discharges with solid and liquid lithium wall coatings, and to study unique physics in more detail, LTX was upgraded to LTX- $\beta$ . The upgrade improves the Li evaporation system, roughly doubles the toroidal field and ohmic heating power supplies, adds neutral beam injection for heating and core fueling, and adds or improves numerous diagnostics [2]. Recent experiments have extended the duration and performance of the low-recycling regime in ohmic discharges with solid and liquid Li walls .

### **Introduction: Lithium, low-recycling, LTX and the LTX- $\beta$ upgrade**

Lithium wall coatings have been predicted and shown to improve performance in many fusion devices [3]. In addition to its advantages for impurities and liquid metal walls, Li chemically binds H and reduces neutral recycling. Without cold recycled gas, the plasma can have a hot edge and a flat temperature profile with no gradient to drive transport or instabilities, allowing higher confinement. This low-recycling regime has been long predicted and was first demonstrated in LTX using solid Li coatings [1].

In LTX and LTX- $\beta$ , lithium is evaporated onto four heatable shell quadrants that almost fully surround the plasma, conformal to a toroid with  $R_0=40\text{cm}$ ,  $a=26\text{cm}$ ,  $\kappa=1.6$ ,  $\delta=0.4$ . Initially in LTX, helium-dispersed Li evaporation suffered from impurities when heating the shell to liquify the Li [4]. An electron-beam enabled liquid Li coatings in LTX but required waiting hours for the shell to cool for solid Li [1,5]. In LTX- $\beta$ , mesh baskets holding Li are inserted at the midplane and heated to evaporate within minutes onto a hot or cold shell. [2,6]

In order to drive more plasma current ( $I_p$ ) and heating power in LTX- $\beta$ , the ohmic heating capacitor bank (OH) was doubled, with the net OH solenoid current swing increased from 48 kA to 62 kA, presently limited by forces on coil leads. The toroidal field (TF) was

increased from 0.17 T to 0.3 T by adding two supplies in series, while the poloidal field (PF) coil power supplies were also rearranged and optimized for a faster  $I_p$  ramp and higher  $I_p$ .

The addition of neutral beam injection (NBI) will provide auxiliary heating, core fueling, and torque. In initial experiments, fast ions were almost completely lost, and thus NBI is not used for the discharges in this paper. Performance improvements to increase  $I_p$  and density (like those shown in this work) are predicted to enable good beam coupling [2,7,8].

The diagnostic suite is greatly enhanced, with new and improved magnetics, Langmuir probes, a sample exposure probe, fast cameras, visible, UV, and EUV spectroscopy [2,6-8]. The addition of NBI enables CHERS and the Thomson Scattering (TS) camera, spectrometer, and electronic trigger have been improved to reduce background and stray TS laser light.

### Analysis of LTX- $\beta$ discharges: High current, Thomson scattering, PSI-Tri, and TRANSP

Initial LTX- $\beta$  experiments in 2020 using the increased TF and NBI but before the OH supply upgrade were modestly higher performing than LTX plasmas, with  $I_p < 100$  kA. After the 2021 OH upgrade,  $I_p = 135$  kA was achieved. Peak  $I_p$  with the shell heated to  $\sim 200^\circ\text{C}$  for liquid Li is often lower, likely because the higher shell electrical resistivity changes the eddy currents at breakdown, and unoptimized coil timings slow the  $I_p$  ramp up. LTX- $\beta$  discharges typically start at low density ( $n_e$ ) with minimal fueling to maximize the current ramp and then a large  $\text{H}_2$  gas puff increases  $n_e$  and pressure. While the puff cools the edge in a similar way to recycling, once fueling ceases and the Li retains H, the edge recovers while  $n_e$  decays. About half of the total injected  $\text{H}_2$  inventory is retained 0.5 s after the discharge ends.

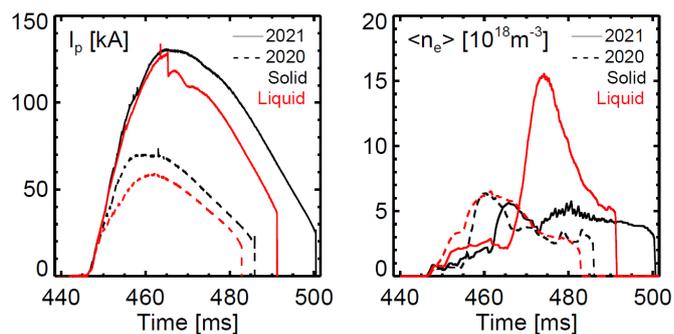


Fig. 1: Plasma current  $I_p$  (left) and density  $n_e$  (right) for solid Li (black) and liquid Li (red) discharges in 2020 (dashed) and 2021 after the OH upgrade (solid). The 2021 high- $I_p$  discharges with liquid Li used large 7 ms puffs (solid Li discharges used 3 ms), reaching higher  $n_e$  with liquid Li but dropping  $I_p$  significantly.

The Thomson scattering (TS) laser fires one pulse per discharge, so repeated shots are used for time resolution, and to improve photon statistics at low density. In the low- $I_p$  liquid Li discharges and both low- and high- $I_p$  solid Li discharges, flat  $T_e$  profiles were observed for multiple confinement times in LTX- $\beta$ , while they had only been measured transiently in LTX [1]. The gas puff in the high  $I_p$  liquid experiments was so large (achieving record pressure  $p_e$ ) that the edge  $T_e$  had not recovered at the end of the TS time scan, so flattening was not seen.

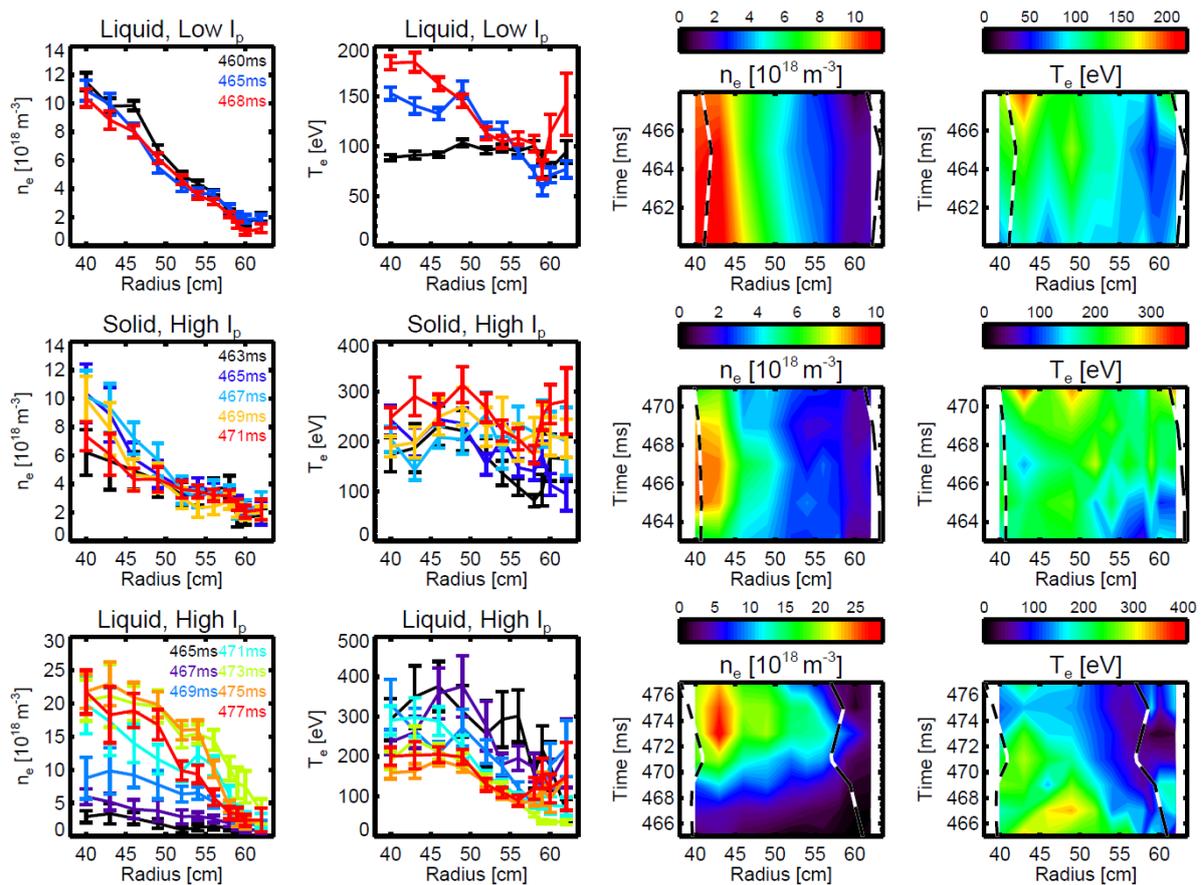


Fig. 2: TS profiles for 2020 low- $I_p$  liquid Li (top) and 2021 high- $I_p$  solid (middle) and liquid (bottom) Li. Electron density  $n_e$  and temperature  $T_e$  at different times and as contour plots. Dashed lines in contour plots show magnetic axis and last closed flux surface from PSI-Tri equilibrium reconstructions.

Kinetic magnetic equilibrium reconstructions are performed with PSI-Tri [9], supplementing the magnetics with TS data to constrain the pressure profile (assuming  $p_i = 0.3p_e$ ), as well as the interferometer line-integrated density  $\langle n_e L \rangle$  to rescale the TS  $n_e$  profile. TRANSP uses the reconstructions, TS profiles, and magnetic and interferometer waveforms to calculate ohmic heating power  $P_{OH}$ , stored energy  $W_{tot}$ , and energy confinement time  $\tau_E$ . Ion power balance is calculated assuming neoclassical ion confinement, and is seen to match core  $T_i \sim 150$  eV measured with C VI 529 nm emission. Despite lower  $I_p$  in the liquid Li discharges the faster  $dI_p/dt$  transfers poloidal field energy into additional  $P_{OH}$ . In both cases, stored energy follows  $\langle n_e \rangle$  closely, and confinement follows and then exceeds the Linear Ohmic Confinement (LOC) scaling  $\tau_{LOC} \sim 7 \times 10^{-22} \langle n_e \rangle a_{eff} R^2 q^{0.5}$  [10]. In LTX- $\beta$ ,  $\tau_E$  increases along with  $\langle n_e \rangle$ , but does not decrease after the large puff ends and  $\langle n_e \rangle$  decays. While typically  $\tau_E$  in the LOC regime eventually stops improving above a critical density  $n_{SOC}$  and enters the L-mode Saturated Ohmic Confinement regime, in the high current liquid Li discharges  $n_e$  exceeds  $n_{SOC}$  without any clear evidence of saturated confinement.

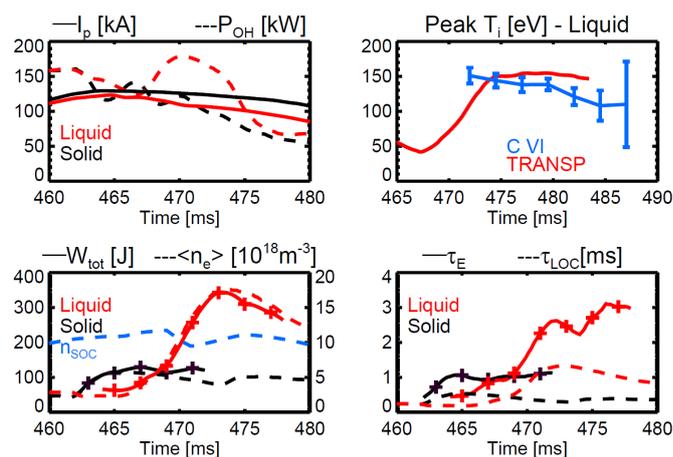


Fig. 3: Results of TRANSP analysis of 2021 high- $I_p$  solid Li (black) and liquid Li (red) discharges. Plasma current  $I_p$  (solid) and ohmic heating power  $P_{OH}$  (dashed). Peak  $T_i$  in liquid Li discharges from C VI emission (blue) and TRANSP neoclassical model (red). Stored energy  $W_{tot}$  (solid), average density  $\langle n_e \rangle$  (dashed), and SOC critical density  $n_{SOC}$  (blue). Energy confinement time  $\tau_E$  (solid) and LOC scaling  $\tau_{LOC} \sim 7 \times 10^{-22} \langle n_e \rangle a_{eff} R^2 q^{0.5}$  (dashed)

### Future Work: Upgrades, Operations, and Diagnostics

Future work will focus on further extending the low-recycling regime with steadier, more stable, denser high-performance discharges that are better optimized for beam fast ion confinement and recycling studies. Improvements to reinforce OH leads and correction coils have begun to allow larger peak OH current to drive  $I_p$  faster and/or steadier. Improvements to the PSI-Tri code [9] and the addition of 5 kW 11 GHz ECRH heating should aid in improving breakdown and ramp up to most efficiently use the OH swing. Recent improvements in NBI operation and modeling of NBI coupling should allow both plasma and beam parameters to be optimized to achieve core heating, fueling, torque, and/or CHERS measurements [7,8]. The TS system will add high-sensitivity polychromators with new views in the core on the high field side to better constrain the magnetic axis, and in the low field side edge to measure the hot, low density boundary and scrape off layer. Understanding the unique physics of the low collisionality SOL is important generally and for investigation of recycling using DEGAS2 modeling constrained by Lyman- $\alpha$  profiles. Fluctuations and instabilities with and without temperature gradients will also be a key area of study.

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