Extending the low-recycling regime to higher performance discharges and liquid lithium walls in the Lithium Tokamak Experiment-β

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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 its unique physics in more detail, LTX was upgraded to LTX-β. 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-β 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-β, lithium is evaporated onto four heatable shell quadrants that almost fully surround the plasma, conformal to a toroid with R_0=40cm, a=26cm, κ=1.6, δ=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-β, 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-β, 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-β discharges: High current, Thomson scattering, PSI-Tri, and TRANSP

Initial LTX-β 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 ~200℃ 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-β discharges typically start at low density (n_e) with minimal fueling to maximize the current ramp and then a large 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 H_2 inventory is retained 0.5 s after the discharge ends.

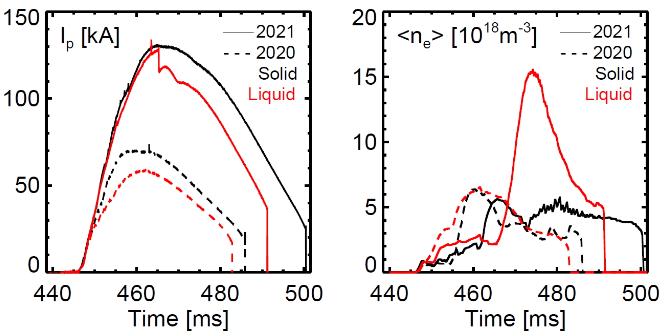

Fig. 1: Plasma current I_p (left) and density n_e (right) for solid Li (black) and liquid Li (red) discharges in 2020 (dashed) and 2021 after the OH upgrade (solid). The 2021 high-I_p discharges with liquid Li used large 7 ms puffs (solid Li discharges used 3 ms), reaching higher n_e with liquid Li but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

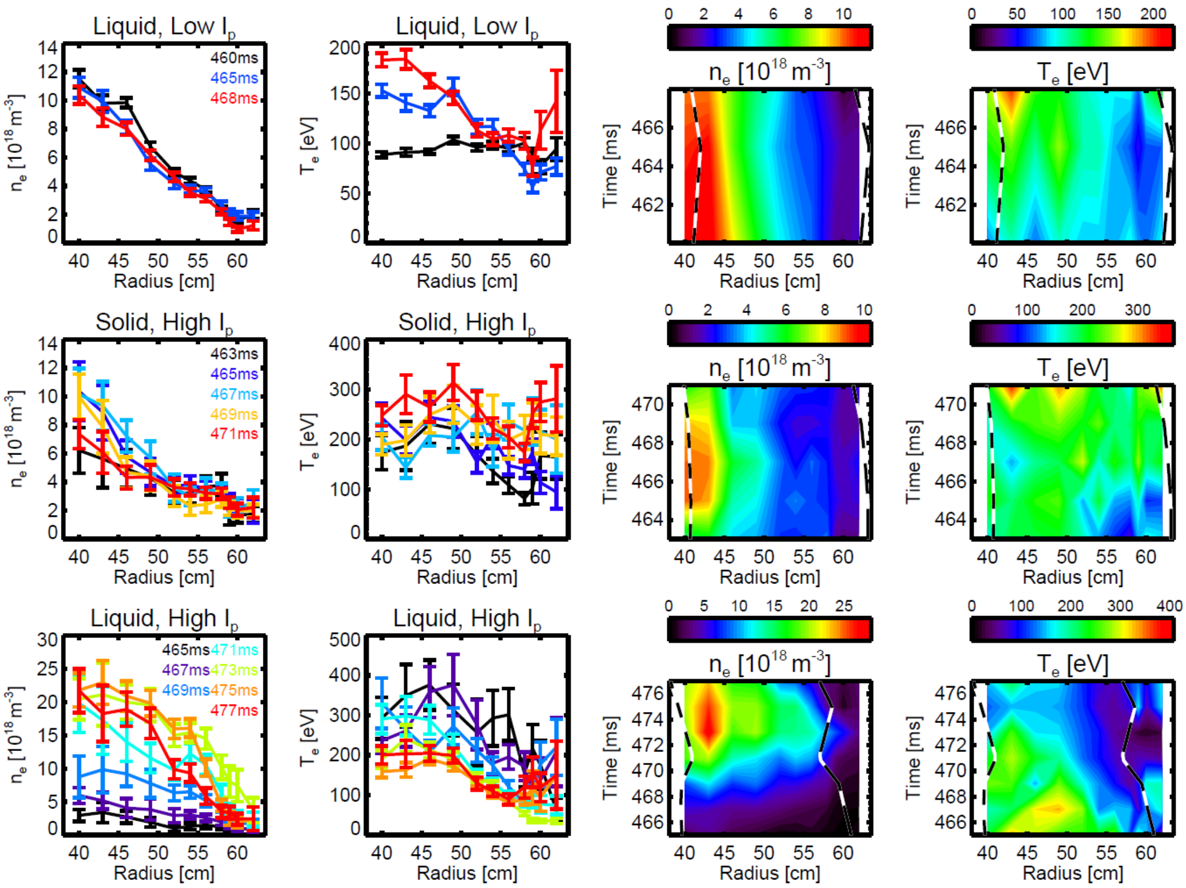

Fig. 2: TS profiles for 2020 low-I_p liquid Li (top) and 2021 high-I_p solid (middle) and liquid (bottom) Li. Electron density n_e and temperature T_e at different times and as contour plots. Dashed lines in contour plots show magnetic axis and last closed flux surface from PSI-Tri equilibrium reconstructions.

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 τ_E. Ion power balance is calculated assuming neoclassical ion confinement, and is seen to match core T_i ~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 τ_{LOC}~$7\times10^{-22}\langle n_e\rangle a_{eff}R^2q^{0.5}$ [10]. In LTX-β, τ_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 τ_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.

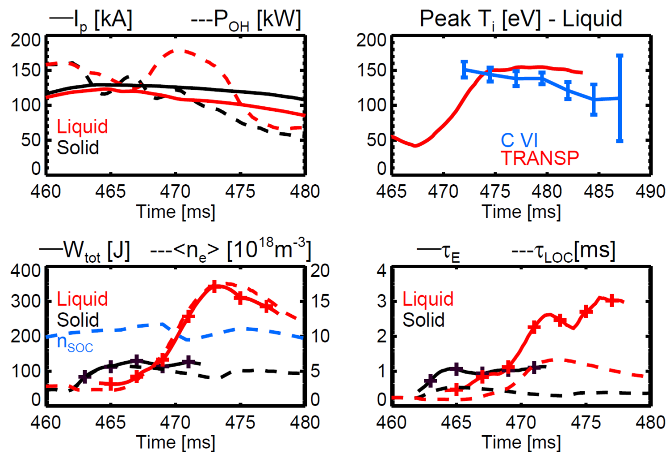

Fig. 3: Results of TRANSP analysis of 2021 high-I_p solid Li (black) and liquid Li (red) discharges. Plasma current I_p (solid) and ohmic heating power P_{OH} (dashed). Peak T_i in liquid Li discharges from C VI emission (blue) and TRANSP neoclassical model (red). Stored energy W_{tot} (solid), average density $\langle n_e \rangle$ (dashed), and SOC critical density n_{SOC} (blue). Energy confinement time τ_E (solid) and LOC scaling $\tau_{LOC} \sim 7\times10^{-22} \langle n_e \rangle a_{eff} R^2 q^{0.5}$ (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-α profiles. Fluctuations and instabilities with and without temperature gradients will also be a key area of study.

Acknowledgments

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