The initial operation of LTX-β

- **FES:** Conduct energy confinement studies of neutral beam-heated and fueled plasmas with very low recycling walls in the recently upgraded Lithium Tokamak eXperiment (LTX)-β. Generate plasmas that simultaneously achieve 0.3 T of toroidal magnetic field and 0.5 MW of injected neutral beam power, while all plasma-facing components are coated with lithium. Submit a report documenting the results of these experiments to DOE by March 31, 2019. (Objective 1.1)

LTX-β has now been operated with full lithium coating of the plasma-facing surfaces (the internal liner or shells), and at a magnetic field of >0.3 T. Currently, the lithium coating on the shell inner surfaces averages 1.4 microns in thickness, which is more than sufficient to ensure that plasma ions interact only with lithium. In addition, 40 A of ion current at 18.5 keV has been extracted from the neutral beam source, which at the specified neutralization efficiency of 83 – 86% produces > 600 kW of injected neutral beam power. These three operating conditions have been simultaneously achieved in >50 discharges so far, to satisfy the requirements in the DOE notable outcome cited above. We are conducting energy confinement studies of both Ohmic and neutral-beam heated plasmas, in accordance with the above objective. However, it should be stressed that significant operational time will be required before a full assessment of plasma performance can be made. This report briefly summarizes the *preliminary* outcome of these recent LTX experiments.

A recent photograph of LTX-β from the north is shown in Figure 1, and from the south in Figure 2.

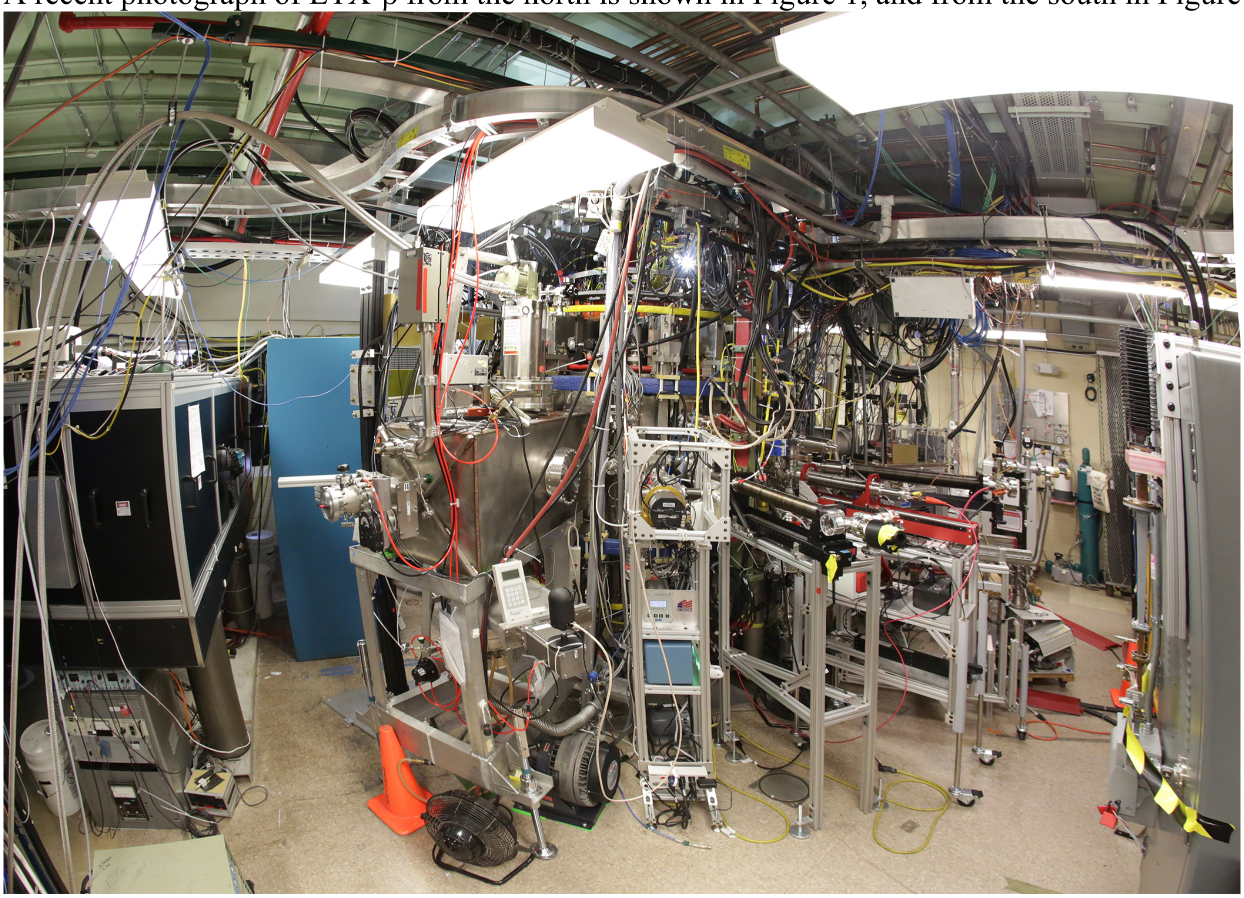

Figure 1. View of LTX-β from the north. The main pump duct and the Thomson scattering laser (black enclosure) are to the left, in this view.

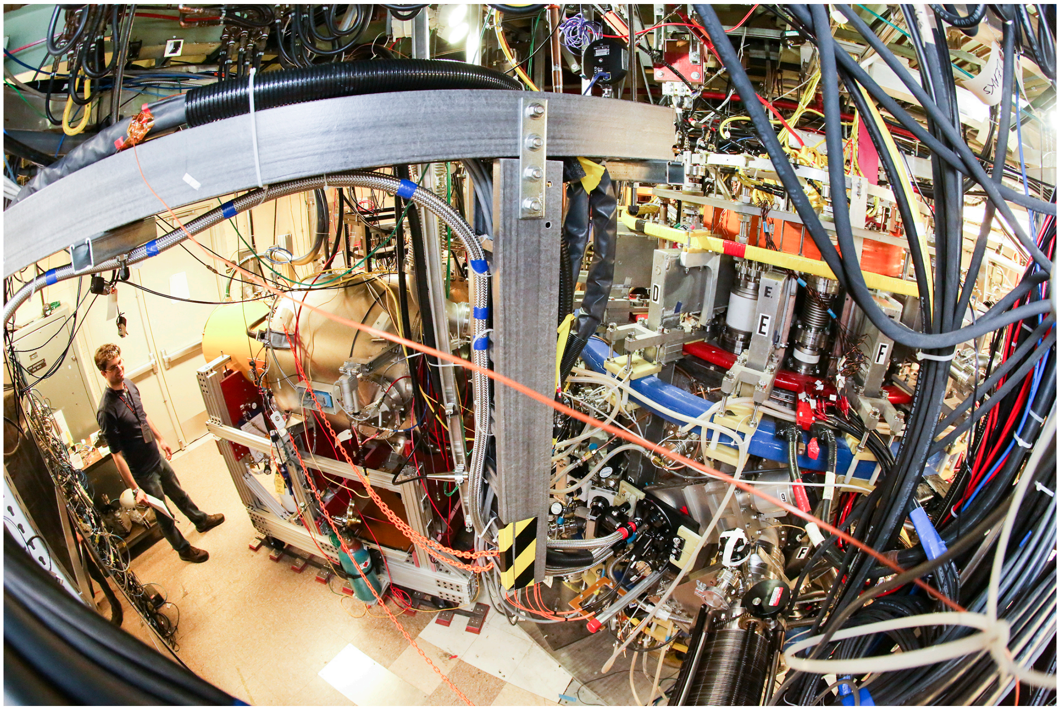

Figure 2. Wide angle photograph of LTX-β from the north. The neutral beam is to the left, in this view.

Neutral Beam Injection.
A neutral beam, on indefinite loan from Tri-Alpha Energy Technologies, with a nominal rating of 700 kW injected power has been installed. Assistance in the early commissioning of the beam, along with gas valves to replace the failed Russian original valves, were provided by the University of Wisconsin. At this time, beam power of up to 640 kW has been injected into the tokamak, for the full 5 msec capability of the beam power supply. Traces of the extracted beam power, and the injected neutral fraction (during plasma operation) are shown in Figure 3.

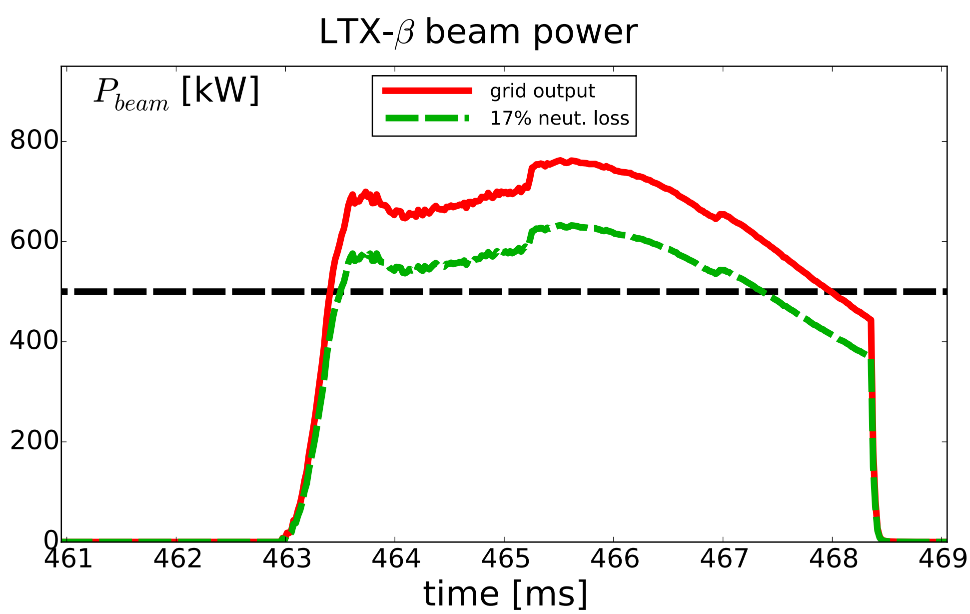

Figure 3. Ion (red) and neutral beam power (green) during a 3 kG LTX-β discharge.

In order to accurately assess confinement time in neutral-beam heated discharges, a measure of the beam deposited power (injected power less shine-through) is important. We have installed instrumented wall-mounted beam dumps, and compared the resultant measured beam deposition with NUBEAM modeling (performed by on-site ORNL personnel). The results of this comparison are shown in Figure 4. The plasma-deposited beam power is of course dependent on the plasma line density. Currently the beam target plasma is fueled with a centerstack-mounted gas puffer. We plan to augment the centerstack puffer with a supersonic gas injector (SGI), mounted at either the low field side midplane, or possibly at the top of the machine, at R=45 cm, to further increase the target density. As in LTX, gas puffing will be terminated during low recycling wall experiments, with the density partially maintained by neutral beam injection.

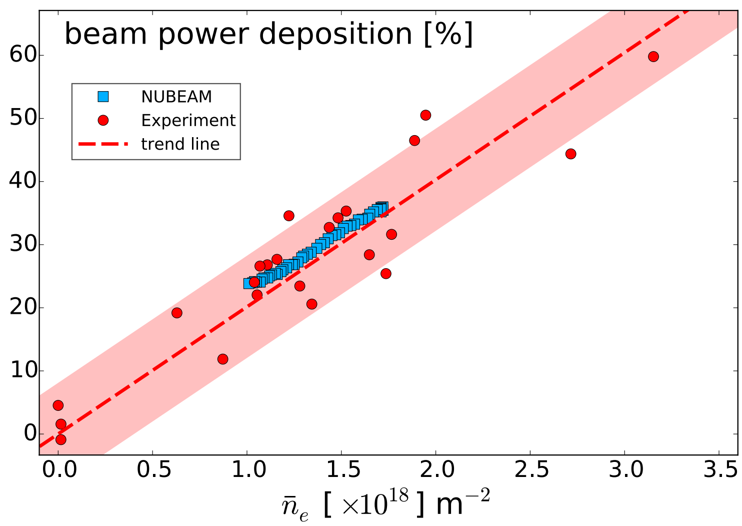

Figure 4. Measured and calculated (with NUBEAM) beam power deposition in the LTX-β discharge. The red dashed line is a fit to the experimental data.

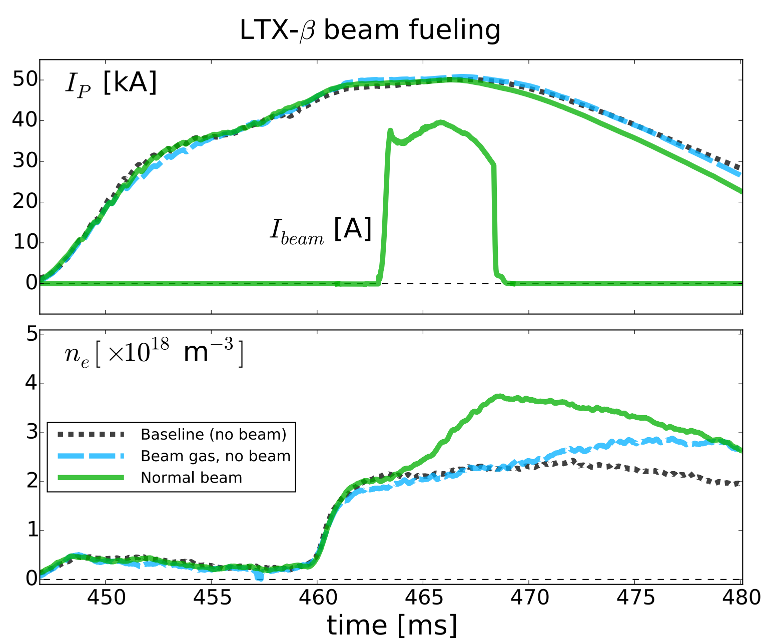

Figure 5. Comparison of the density rise in the discharge with beam injection (green line), and without beam (blue line). The neutral beam gas injectors were enabled for the "blue" discharge. Compared to a discharge without any beam gas, the blue "no beam" discharge shows evidence for modest gas fueling by the beam system, at late times. Beam injection provides a prompt, nearly linear rise in density.

One of the goals of neutral beam injection in LTX-β was to provide at least partial core fueling of the plasma, without gas puffing. Although results are not yet consistent, the line-averaged density of the discharge shows a strong increase under some conditions (Figure 5).

Toroidal field

During LTX-β operations, toroidal field was limited by the available voltage of the 500V, 20,000A power supply used to energize the field coils. Toroidal field current was thus limited to 2800A. The 20,000A Robicon power supply has now been moved to the main vertical field coils, and a pair of power supplies (one 300V, 5000A Robicon, and one 500V, 5000A PEI supply) are being operated in series to provide 5000A at 800V for the toroidal field coils. The circuit arrangement is center-ground, with one power supply above, and one below, building ground. This arrangement minimizes the voltage difference between the toroidal field coil windings and ground, so that the maximum conductor-ground voltage drop has not been increased relative to LTX pre-upgrade operation.

The PEI supply is a legacy supply from the operation of the PBX-M tokamak at PPPL in the late 1980s and very early 1990s. The supply was purchased by collaborators at UCLA (the group has since moved to UCSD) for biased limiter experiments, rather than for use as a field coil supply. In the end, it was necessary to completely rebuild the supply in order to bring it into operation. Only the power transformer, the SCRs, and the cabinet were retained; all other circuitry has been replaced, since repair of the original control circuitry proved infeasible. The two series power supplies are controlled with a single analog waveform generated by the LTX-β data acquisition and control system. The new series arrangement of power supplies provides, at present, up to 4200A of current, to achieve a toroidal field in excess of 3 kG.

Lithium coatings

Two new lithium evaporators have been installed on LTX-β. The evaporators feature a small quantity of lithium (~0.5 g) in a stainless steel screen "basket". The basket is surrounded by a tungsten filament, which is heated by a low voltage, high current DC power supply. The evaporator is inserted to a major radius of 45 cm; insertion depth is limited by the range of the mechanical bellows drive used to carry the evaporators. Two evaporators are inserted at toroidal locations 180° apart to provide full lithium coverage of the plasma-facing surface of the shells. A photo of one of the evaporators is shown in Figure 6.

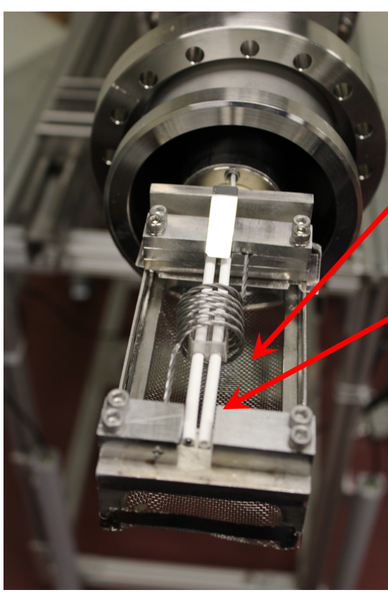

Figure 6. Photo of one of the LTX-β basket evaporators. The basket is suspended from a pair of ceramic yttria tubes within a cylindrical tungsten filament. Lithium coupons are inserted into the basket, after installation on LTX-β.

A full evaporation cycle requires approximately 15 minutes at present. Refilling both evaporators requires a vent-to-argon and pumpdown cycle of several hours. Lithium coating thickness is monitored by a pair of quartz deposition monitors which view the evaporator through the shell duct penetration. Monitors are installed at both toroidal locations of the evaporators. The monitors were installed by collaborators from the University of Tennessee. In addition, Princeton University and University of Tennessee researchers are employing a sample exposure probe to characterize the lithium coatings applied to the shell. During evaporation, the temperature of the lithium is monitored with a thermocouple protected from the lithium by one of the yttria tubes visible in Figure 6.

LLNL collaborators have installed a number of edge-viewing fast cameras on LTX-β. One of the cameras images in color. Figure 7 is a color frame of the low-field side shell, showing green emission characteristic of the lithium II line at 548.5 nm.

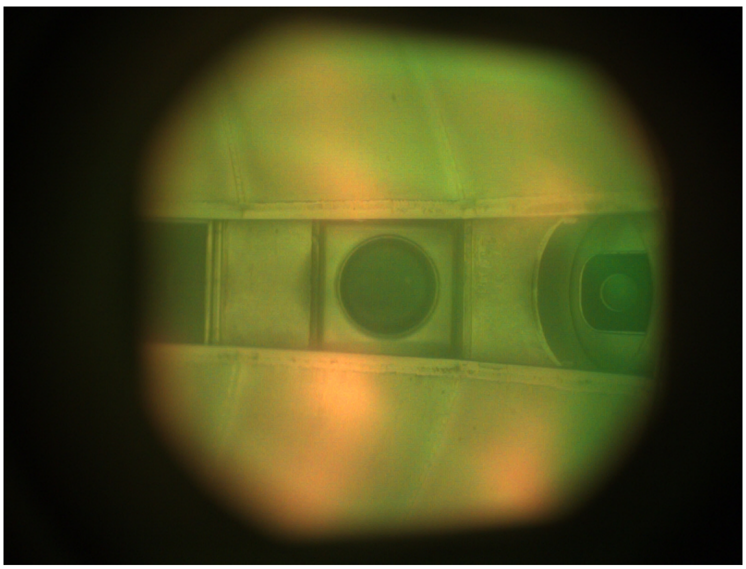

Figure 7. Fast camera image of the outer shell during a discharge. The green light is from the Lithium II line at 548.5 nm, while the yellow/orange light is from the Lithium I line at 610 nm.

Although the evaporators are performing well, a redesign is in process to significantly increase the available inventory, use lithium rod stock rather than foil to increase the available inventory, and modify the areal coverage to preferentially deposit on the high-field side shell area, where the plasma is limited.

Plasma performance

The increase in toroidal magnetic field has enabled an increase in plasma current, although the full expansion of the Ohmic power supply has not yet been implemented. Maximum plasma current in LTX-β is now 100 kA, and discharge development is still underway.

A full assessment of plasma confinement with lithium-coated walls has begun. Confinement estimates will focus on kinetic evaluation of the electron and ion temperatures, using Thomson scattering for the electron temperature and density profile, and CHERs (an ORNL task) for the ion temperature. At present, the 30+ year old ruby laser for the Thomson scattering diagnostic is undergoing repair, and should become available during April. Charge exchange light has been detected with the CHERs diagnostic, and the data obtained so far is in analysis. Equilibrium reconstruction using the analysis code developed by C. Hanson (University of Washington) has begun; one such equilibrium for a beam injected discharge is shown in Figure 8. Additional calibrations of the magnetic diagnostics are in process, and the alternative equilibrium reconstruction code developed by L. Zakharov is being implemented. The UCLA 1 mm microwave interferometer is functioning routinely, for line-averaged density measurements. Since lithium wall coatings have already been applied to the shells in order to meet the milestone discussed here, future confinement comparisons will be made between fresh, low recycling metallic lithium walls, and walls which have been saturated with hydrogen (low Z, but high recycling).

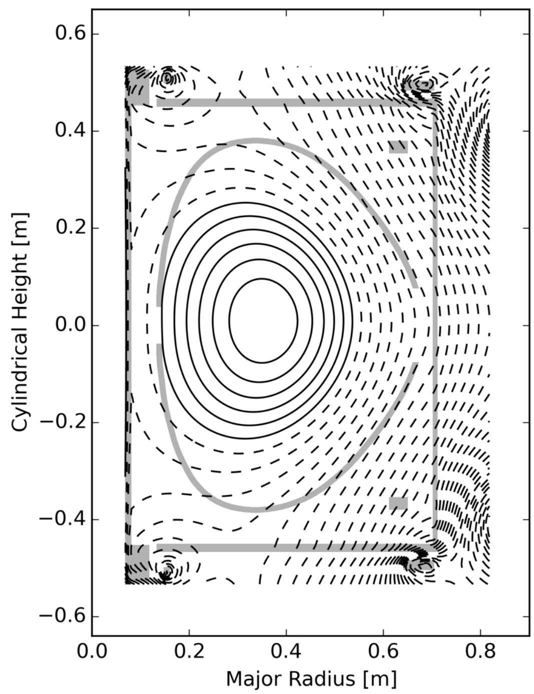

Figure 8. Equilibrium reconstruction of an LTX-β discharge during neutral beam injection, with full lithium coatings, at 3 kG toroidal field. The current centroid is at R=31 cm (B_{TF} = 3.5 kG), and the Shafranov-shifted magnetic axis is at R=35 cm (B_{TF} = 3.1 kG). Plasma elongation is low (κ = 1.3), but discharge development is ongoing.

Plasma impurity levels have decreased with successive lithium evaporations. In Figure 9 the evolution of the edge oxygen impurity is shown; absolute edge oxygen impurity levels are provided by the LLNL diagnostic set. Oxygen levels after the final lithium evaporation shown in Figure 9 are essentially at the noise floor of the diagnostic.

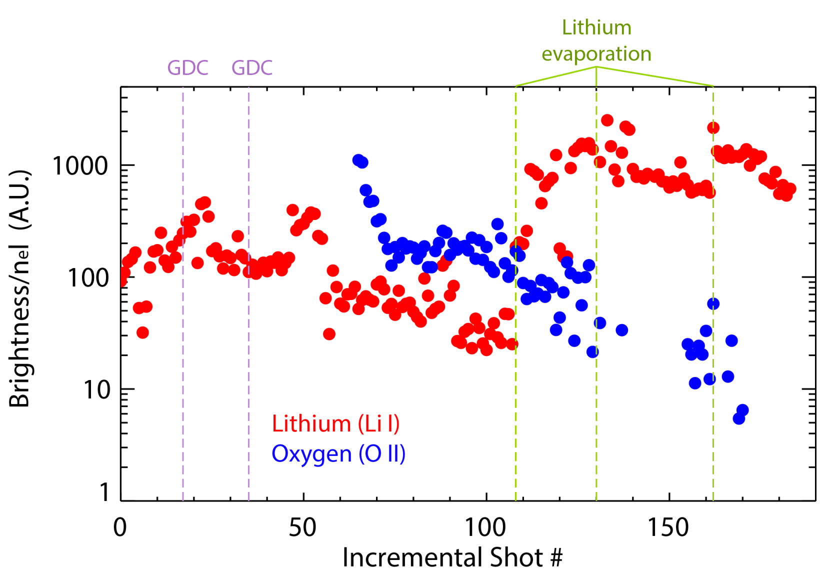

Figure 9. Lithium and oxygen levels, averaged over the early phase of the discharge (452 – 458 msec in Figure 5), for the recent dataset of discharges.

Finally, an initial estimate of the efficiency with which the lithium coating is retaining hydrogen is provided by comparing the evolution of the torus gas pressure with, and without, a discharge, after the wall is evaporatively coated with lithium. The results are shown in Figure 10.

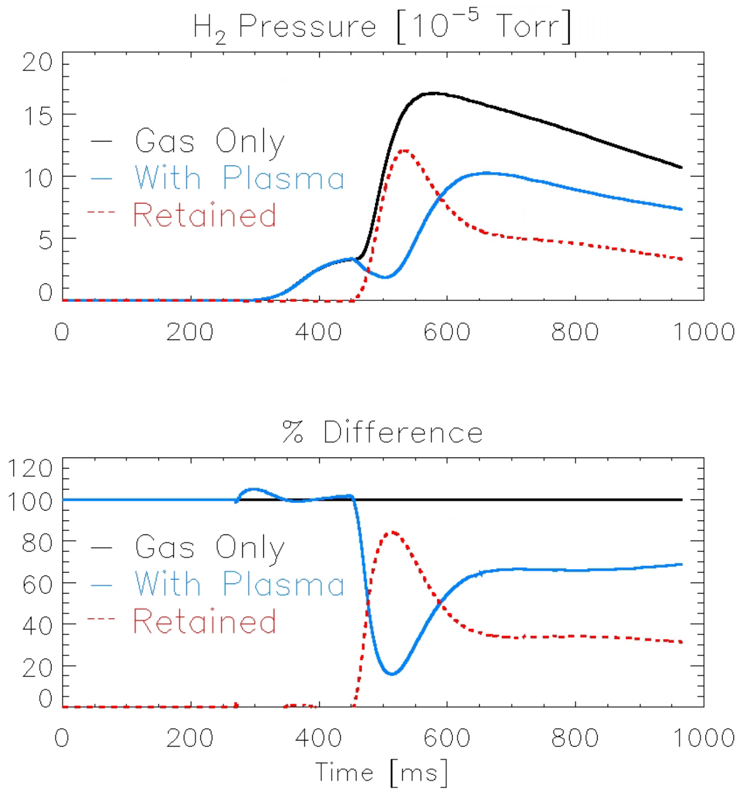

Figure 10. Torus gas pressure with and without a plasma discharge. About 1/3 of the total injected gas is retained long-term in the lithium wall. Although retention is significant, more analysis is require to derive a true recycling coefficient during the discharge.

Summary

LTX-β operations have reached, and surpassed, the goals delineated in the DOE notable outcome reproduced at the beginning of this report. A full assessment of confinement in a lithium walled tokamak, with auxiliary neutral beam heating, is now accessible. LTX-β remains the only tokamak in the world program which is capable of operation with full solid or liquid lithium walls, and now incorporates a neutral beam. Confinement studies will continue through FY20, at which point any need for a vent will be evaluated. It is important to take advantage of the considerable investment in the upgrade to LTX.