

The LTX- β Research Program and First Results

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Abstract

The research program for LTX- β , the upgrade to the Lithium Tokamak Experiment, combines lithium walls to produce gradient-free temperature profiles and stabilize ion and electron temperature gradient-driven modes, with approaches to stabilization of ∇n -driven modes, such as the trapped electron mode (TEM). Candidate stabilization mechanisms for the TEM include sheared flow stabilization, which will be tested on LTX- β using neutral beam induced rotation. The goal is to reduce anomalous transport in a low aspect ratio tokamak. The upgrade will approximately double the toroidal field of LTX- β (to 3.4 kG) and plasma current (to 150 – 175 kA), compared to LTX. Upgrades to the diagnostic set are in the areas of equilibrium, core transport, scrape-off layer (SOL) physics, and plasma-material interactions. Neutral beam injection at 20 kV, 35 A will be added, using a neutral beam system provided by Tri-Alpha Energy Technologies. A 9.3 GHz, 25-50 kW, short-pulse (5-10 msec) magnetron will be available for electron heat pulse propagation experiments. New lithium evaporation sources allow between-shots recoating of the walls. LTX- β is a collaborative effort, with major participation from Oak Ridge and Lawrence Livermore National Laboratories (ORNL and LLNL), and the Universities of Wisconsin, Washington, and California at Los Angeles (UCLA). ORNL and the University of Tennessee will focus on spectroscopic improvements, and edge plasma/plasma-material interaction (PMI) analysis. LLNL plans research in the areas of SOL transport and plasma-surface interactions with lithium and tin. UCLA is upgrading the LTX profile reflectometer for high k_r backscattering. The 1 mm UCLA interferometer system will also be upgraded to probe low k_\perp density fluctuations. The LTX- β research program will be discussed, and initial operation of the upgraded device will be described.

1. INTRODUCTION

The research program for LTX- β , the upgrade to the Lithium Tokamak Experiment, combines low recycling walls and the resultant gradient-free temperature profiles [1], which are expected to stabilize ion and electron temperature gradient-driven modes, with approaches to stabilizing ∇n -driven modes, such as the

trapped electron mode (TEM). Candidate stabilization mechanisms for the TEM include flow shear, which can be tested on LTX- β using neutral beam-induced rotation. The goal is to significantly reduce anomalous transport in tokamaks, leading to the possibility of developing a very compact, tokamak-based fusion core.

At the same time, modifications to the scrape-off layer (SOL) should greatly reduce peak power deposition at the divertor target plates, especially for low aspect ratio tokamaks, without the need for radiating any significant fraction of the fusion power.[2] Power spreading at the divertor, and the diversion of some SOL power to the walls (with broad deposition), combined with the use of liquid lithium divertor and walls provide an avenue for dealing with the increased fusion power produced by a compact core.

2. THE UPGRADE TO LTX, LTX- β

LTX- β will approximately double the toroidal field of LTX from ~ 1.7 kG to ~ 3.4 kG. The maximum plasma current achieved by LTX was somewhat less than 100kA. In LTX- β , an expanded Ohmic power supply, higher power longer pulse ECH startup, and improved lithium coating techniques will nearly double the plasma current to 150 – 175 kA. LTX- β retains the basic geometry of LTX - major radius $R_0 = 40$ cm, minor radius $a=26$ cm (for an aspect ratio $A = 1.6$), elongation $\kappa = 1.6$, and very modest triangularity $\delta = 1.2$. The shell or liner is also unchanged, and is constructed of 1.5 mm stainless steel explosively bonded to 1 cm thick copper in four segments, equipped with 37 kW of electric cable heaters installed in channels on the back (nickel-plated copper) side of the shells. The shell is designed to accept interior, plasma-facing coatings of lithium over the high-Z stainless steel substrate. No low-Z materials (e.g. carbon) are employed in the construction. The LTX- β plasma is not magnetically diverted, but limited on the high-field side, lithium-coated surface, of the shell. Primary access for diagnostics is through the outer toroidal gap between shells. Full poloidal access is provided at the two toroidal gaps in the shell structure. An engineering view of LTX- β is shown in Fig. 1.

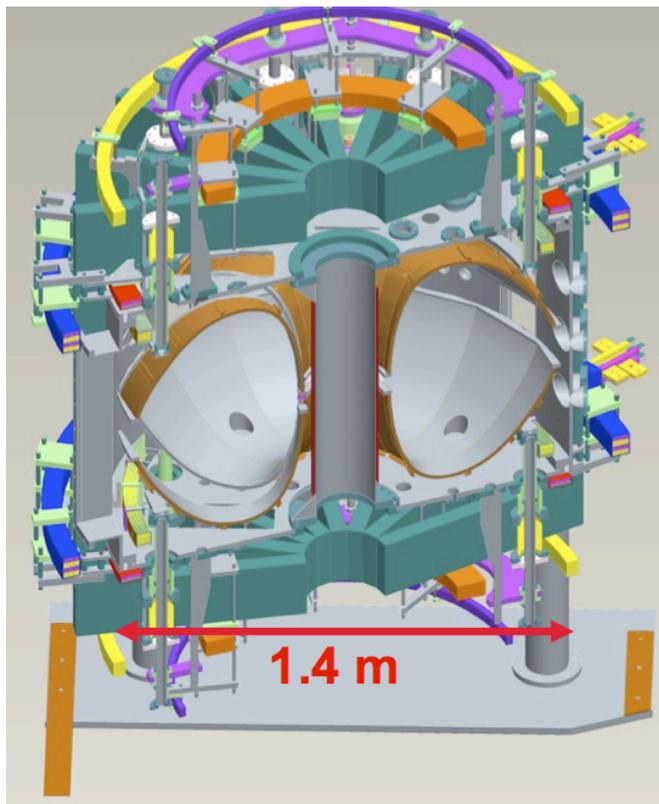


FIG. 1. Elevation of LTX- β . The shell or heated liner is visible, with the inner and outer toroidal gaps indicated, as well as one of the two poloidal cuts (the two poloidal cuts are separated by 180° C).

In addition to the increase in toroidal field, a new pair of poloidal field coils has been installed (the coils color-coded orange in Fig. 1), which will improve plasma shaping.

The tokamak has very recently resumed operation after completion of the upgrade to LTX- β .

3. NEUTRAL BEAM INJECTION

Neutral beam injection at 20 kV, 35 A is a major part of the LTX- β upgrade. A neutral beam system was provided by Tri-Alpha Energy Technologies for this purpose. A layout of the tokamak and neutral beam injector

is shown in Fig. 2. The initial beam pulse duration will be 5-8 msec, with an upgrade to 10 – 15 msec in 2019 - 2020. A further upgrade to the beam power supply to provide a 30 – 50 msec pulse is in the planning stage, with ~50 msec being the limiting pulse length due to heating of the edge cooled grids. LTX- β will have a modest in-vessel lithium inventory (limited to 200g), but for safety reasons, water cooling is excluded from the vacuum envelope. Between-shots gas cooling will be used for the beam calorimeter and plasma source – as well as for the internal fast poloidal field coils just visible in the corners of the vessel in Fig. 1.

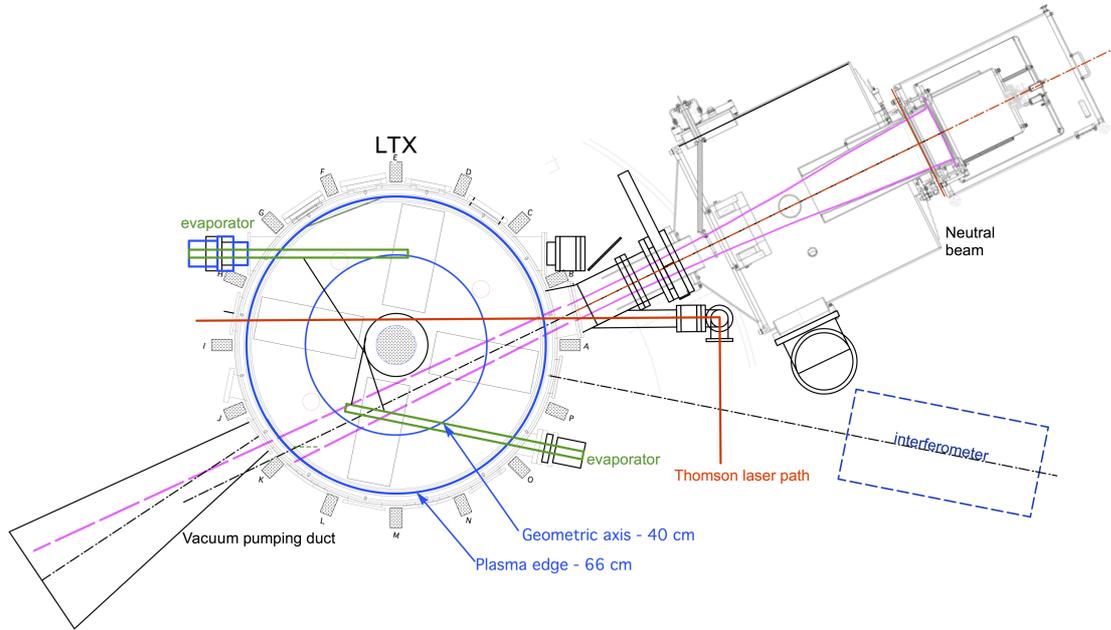


FIG. 2. LTX- β , showing the neutral beam and locations of the new lithium evaporators.

Neutral beam injection will test the resilience of flat temperature profiles produced with very low recycling walls to a more highly peaked power deposition profile. The production of flat ion temperature profiles with an ion heating source will be explored for the first time. A comparison of the modeled electron power deposition profile with Ohmic heating, using the PSI-Tri equilibrium code [3], and the modeled neutral beam power deposition profile with NUBEAM [4] is shown in Fig. 3.

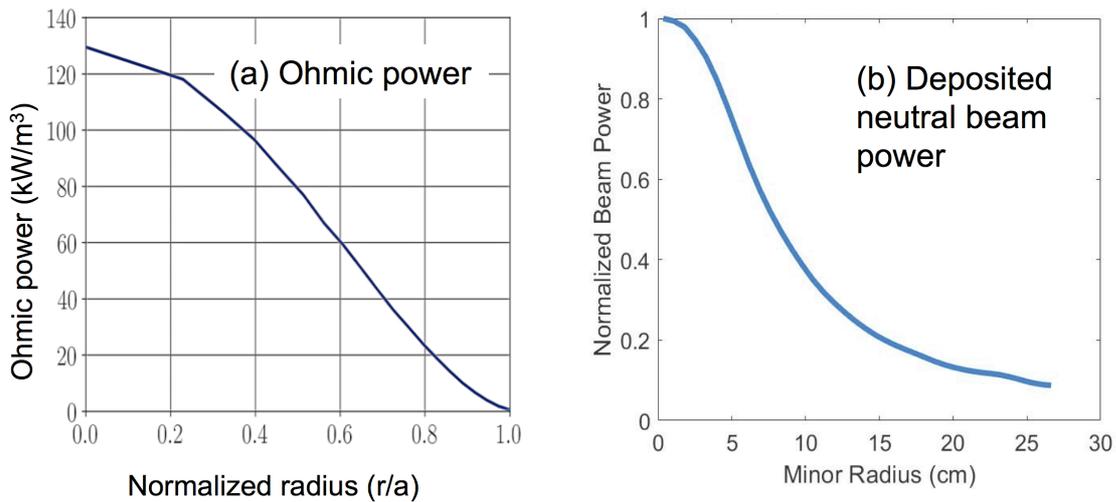


FIG. 3. Computed Ohmic power deposition in LTX (a), and modeled neutral beam power deposition in LTX- β (b).

Flat temperature profiles could only be achieved transiently in LTX through cessation of gas-puff fueling [1], after which the discharge density decayed as the temperature flattened. In LTX- β , 35A of neutral beam fueling will provide up to half of the particle fueling needed to sustain the discharge, without the introduction of edge gas, which can negate the effect of low recycling walls. Additional modest pulsed fueling sources including an

upgraded high field side gas nozzle, and a top-mounted supersonic gas injector [5], should allow sustainment of the plasma density with only a modest degradation of the effective recycling coefficient, by strongly limiting neutral gas injected at the plasma edge.

4. ECH/EBW, VACUUM SYSTEM, AND LITHIUM DEPOSITION

A 9.3 GHz, 25 - 50 kW, short-pulse (5-10 msec) magnetron source will be available in 2019 - 2020 for electron Bernstein wave heating, startup, and electron heat pulse propagation experiments. In the nearer term, a 2.5 kW 10.36 GHz CW klystron source will provide ECH startup. Based on results from a predecessor to LTX- β , the Current Drive Experiment - Upgrade (CDX-U) [6], ECH at this power level should lead to a very modest seed tokamak equilibrium, to reduce the loop voltage requirements for startup from the (already low) level of 2V required to start up LTX. Other options for ECH startup are under consideration, in collaboration with Columbia University.

Very good base vacuum conditions are necessary to maintain metallic lithium plasma-facing surfaces [7]. The pumping speed of the LTX- β vacuum system has been doubled in comparison to LTX, to 8,000 L/sec on a vacuum vessel with only 1.4 m³ internal volume. The bakeout system for LTX- β has also been modestly upgraded.

New lithium evaporation sources, at the positions shown in Fig. 2, will allow rapid recoating of the shell system with a lithium film, typically a few 10s to 100 nanometers thick. These sources will also function as prototypes, for use on NSTX-U, or other confinement experiments. The design employs a porous metal cylinder filled with lithium, surrounding an axial tube, which is heated by electron bombardment from an internal emitter. The total heated mass of the evaporative system which is *not* lithium is minimized through the use of a low density foamed metal to retain the lithium evaporant via surface tension. The evaporative lithium source is designed to be easily replaced when necessary. A remotely actuated motion stage will allow recoating to occur between discharges in order to ensure that a highly metallic lithium plasma-facing surface fronts the plasma. Coating thickness will be monitored by a set of two quartz crystal deposition monitors.

The first experiment in lithium wall conditioning, however, will not involve the new evaporation sources, but a lithium granule dropper developed for NSTX-U. [8] The granules injected by the dropper will be 500 microns in diameter. Initial injection into Ohmic plasmas will utilize a single granule per discharge, but the dropper is capable of injecting multiple granules into neutral beam heated discharges, at 4 msec intervals.

5. DIAGNOSTICS

Upgrades to the diagnostic set will strengthen the research program in the critical areas of equilibrium, core transport, scrape-off layer (SOL) physics, and plasma-material interactions

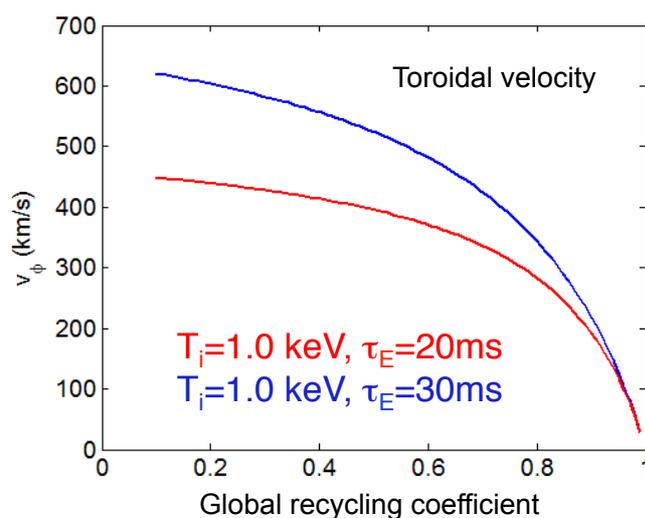


FIG 4. Toroidal velocity predicted in LTX- β during neutral beam injection, as a function of the global recycling coefficient. Recycling coefficients of 10-20% are accessible with lithium walls.

LTX- β is a collaborative effort, with major participation from Oak Ridge and Lawrence Livermore National Laboratories (ORNL and LLNL), the University of Wisconsin, the University of Washington, Princeton University, and a private company (LiWall Fusion), as well as the University of California – Los Angeles (UCLA). ORNL in conjunction with the University of Tennessee has two major research foci on LTX,

spectroscopic improvements, and edge plasma/plasma-material interaction (PMI) analysis. ORNL has installed a new CHERS system. The CHERS system will monitor core ion temperatures, impurity concentration, and plasma rotation and shear during neutral beam injection. Shear is an important parameter, since a low collisionality, low aspect ratio tokamak like LTX- β has a large trapped particle population, and should be unstable to trapped electron modes (TEM). CHERs will provide a capability for diagnosing the sheared flow. Upgraded camera and triggering systems will increase the sensitivity of the core Thomson scattering system. Modeling (performed by ORNL) of the plasma rotation in LTX- β expected during neutral beam injection is shown in Fig. 4.

ORNL has developed and deployed many “Filterscope” systems on plasma devices around the world, including LTX and LTX- β . A Filterscope essentially consists of an array of photomultiplier tubes (PMT), which observe light collected from plasma lines of sight through a narrow band transmission optical filter, effectively allowing the emission intensity of a single spectral line to be monitored at high-gain and at high-speed. Filterscopes can be used both as impurity monitoring, and as fluctuation, diagnostics. Finally, ORNL has tentative plans to install a modest multichannel resistive bolometer array on LTX- β .

The neutral beam injected ions (protons; LTX- β will not operate in deuterium) are marginally super-Alfvenic over most of the plasma volume, so that fast ion instabilities are of interest. The University of Wisconsin group will study Alfvenic instabilities using the available magnetic diagnostics, and a neutral particle analyzer to be installed on LTX- β . Modifications to the equilibrium caused by the fast ion population will be modeled by a private company, LiWall Fusion.

Both LiWall Fusion and the University of Washington group will explore reconstructions of the LTX- β equilibria, including the effects of eddy currents in the surrounding copper shells.

The plasma-material interaction and edge physics efforts involve probe upgrades, a new polychromator-based edge Thomson scattering system, and material analysis. The increased sensitivity of the polychromator system will reduce uncertainty in temperature profiles for the low density SOL. High field side swept Langmuir probes have been installed, and a movable swept probe will monitor the low field-side SOL. A gridded energy analyzer will provide ion energy measurements in the outer midplane SOL. A new sample exposure probe employing a “vacuum suitcase” approach to transfer samples exposed to the SOL plasma in LTX- β has been constructed. Samples will be transferred to a nearby surface science laboratory operated by Princeton University for analysis by advanced material characterization techniques, such as high resolution Rutherford back-scattering, low energy ion scattering spectroscopy (LEISS), and x-ray photoelectron spectroscopy (XPS); a more complete suite of analysis than was formerly available on LTX. [7]

LLNL plans research in the areas of SOL transport and plasma-surface interactions with both lithium and tin. Fast camera imaging and Langmuir probes will be used to study SOL filament size, radial velocities, fluctuation levels, and statistical properties at low collisionality, with significantly reduced neutral damping due to lithium wall pumping, for comparison with filament propagation theories. Studies of solid and liquid lithium erosion and evaporation are planned, using fast spectrally-filtered cameras and spectrometers, with emphasis on the role of oxygen and compound molecules in lithium sputtering and hydrogen ion recycling processes. The SOL transport and PMI studies will be supported by continuum gyrokinetic code (COGENT) simulations. These first studies of liquid tin erosion and core transport in a small spherical tokamak will employ a sample exposure system to expose liquid tin-filled porous metal structures to the LTX- β SOL plasma. LLNL has also installed an upgraded flat-field grazing-incidence grating spectrometer. This diagnostic, the Long-Wavelength Extreme Ultraviolet Spectrometer (LoWEUS), employs a variable space grating with an average spacing of 1200 lines/mm and covers 90–270 Å wavelength band. With a line width (FWHM) of ~ 0.3 Å, the spectrometer is able to resolve Lyman- α lithium lines, L-shell lines of oxygen, and K-shell lines of carbon.

UCLA is significantly upgrading the LTX reflectometer density profile and interferometer capabilities as well as adding coherent and turbulent density fluctuation measurements. The repetition rate of the density profile reflectometer will be doubled to 250 kHz, and the same hardware will be used as a high- k_r \tilde{n} backscattering diagnostic allowing access to higher- k \tilde{n} in the TEM range. A new dual-channel tunable-frequency reflectometer will simultaneously monitor density fluctuations at two locations in the plasma core and will probe lower- k \tilde{n} . Finally, a new detector will increase the sensitivity of the 1 mm interferometer for chord-averaged line density as well as far-forward scattering \tilde{n} measurements ($k_r \lesssim 2$ cm $^{-1}$).

Other plasma diagnostics which are new or have been upgraded in LTX- β include a new multichannel tangential Lyman- α array, which will enable better characterization of global recycling across the entire plasma cross section with improved capability to analyze the evolution of the eddy currents induced in the shells during

poloidal field ramps. The array employs a filtered avalanche photodiode (APD) array. A second APD array images the same set of tangential chords, and can either be filtered to provide a companion H- α profile, or operated without a filter, to yield an approximate profile for the total radiated power.

The magnetic diagnostics for equilibrium reconstruction have been expanded, and a new toroidal array of magnetic fluctuation diagnostics has been installed. Additional Mirnov coils have been installed on the back side of the shells (away from the plasma) to allow more accurate characterization of the eddy currents induced in the shells during the poloidal field coil ramp. These coils can also provide information on currents induced in the shells as a result of MHD activity.

A second, edge-localized view of the 20 J ruby Thomson scattering laser will provide edge Thomson at 5 spatial locations. The edge Thomson system employs a more efficient polychromator-based system with APD detectors, rather than the TVTS system employed in the plasma core. Installation of an additional multipulse core Thomson scattering system with 1 msec time resolution is under consideration.

A high-throughput accurate-wavelength lens-based (HAL) visible spectrometer [9, 10] which had been in use on LTX will be retained on LTX- β . As the passive optics produce 15 toroidal and 12 poloidal views, only 11 of which can be simultaneously imaged by the current spectrometer, the HAL spectrometer is instrumented with a patch panel to select the viewed fibers. This spectrometer provides ion profile measurements from visible lines corresponding to impurity charge states

6. NEAR-TERM RESEARCH PLANS

LTX- β resumed plasma operations a few weeks prior to the 2018 IAEA FEC, so few results are available at this writing. Near term research will focus on characterizing plasma performance with the NSTX-U lithium granule dropper, and comparing the effect of wall conditioning with the dropper to wall conditioning with the lithium evaporators. This comparison will begin with Ohmic plasma operation at 1.7 kG, and be extended to higher toroidal field (> 3 kG) operation. The comparison will be extended to neutral beam heated discharges in early 2019.

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