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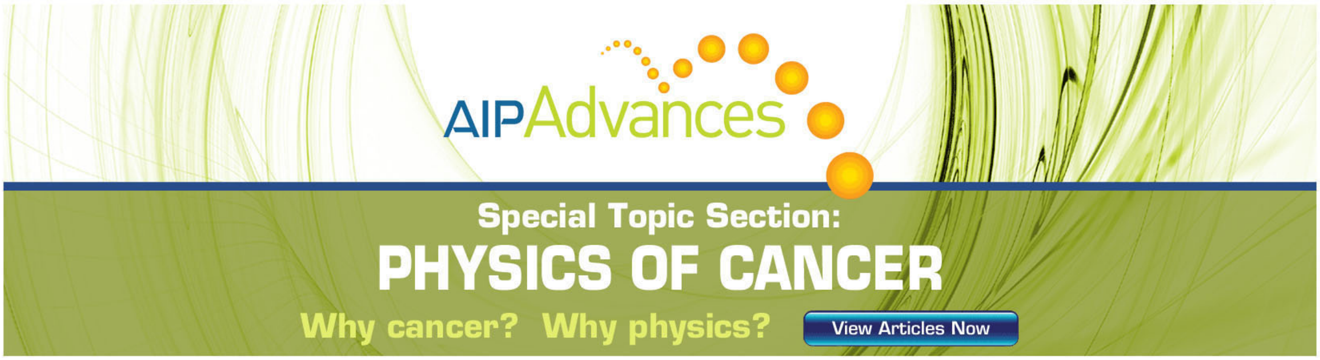

REVIEW OF SCIENTIFIC INSTRUMENTS **83**, 10D537 (2012)

# Spectral emission measurements of lithium on the lithium tokamak experiment[a]

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There has been a long-standing collaboration between ORNL and PPPL on edge and boundary layer physics. As part of this collaboration, ORNL has a large role in the instrumentation and interpretation of edge physics in the lithium tokamak experiment (LTX). In particular, a charge exchange recombination spectroscopy (CHERS) diagnostic is being designed and undergoing staged testing on LTX. Here we present results of passively measured lithium emission at 5166.89 Å in LTX in anticipation of active spectroscopy measurements, which will be enabled by the installation of a neutral beam in 2013. Preliminary measurements are made in transient LTX plasmas with plasma current, $I_p < 70$ kA, ohmic heating power, $P_{oh} \sim 0.3$ MW and discharge lifetimes of 10–15 ms. Measurements are made with a short focal length spectrometer and optics similar to the CHERS diagnostics on NSTX [R. E. Bell, Rev. Sci. Instrum. **68**(2), 1273–1280 (1997)]. These preliminary measurements suggest that even without the neutral beam for active spectroscopy, there is sufficient passive lithium emission to allow for line-of-sight profile measurements of ion temperature, $T_i$; toroidal velocity and $v_t$. Results show peak $T_i = 70$ eV and peak $v_t = 45$ km/s were reached 10 ms into the discharge. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4746812]

## I. INTRODUCTION

Recent results from tokamaks[1–4] and stellarators[5] around the world have demonstrated the positive benefits of lithium wall conditioning techniques. Results from National Spherical Torus Experiment (NSTX) (Ref. 6) and the current drive experiment-upgrade (CDX-U) (Ref. 7) have shown increases in their energy confinement times, $\tau_E$. The best results on CDX-U were accomplished with a toroidal liquid lithium limiter and lithium evaporation inside the vacuum chamber. As a follow on to CDX-U, the lithium tokamak experiment (LTX) was designed and built[9] to increase the pulse length and magnetic field of CDX-U as well as provide an experiment where ~90% of plasma facing components are liquid lithium.

The LTX will potentially explore plasma regimes where the majority of the plasma facing components exhibit very low recycling. To determine not only how this will change the edge plasma in the scrape-off layer but also edge transport and core confinement, comprehensive modeling of LTX discharges with the Scrape-off Layer Plasma Simulation (SOLPS) suite of codes will be utilized in a manner similar to what has already been carried out on NSTX.[8] To constrain this modeling, radial profiles of electron density, $n_e$; electron temperature, $T_e$; ion temperature, $T_i$; and the toroidal plasma velocity, $v_t$ are needed along with edge diagnostics such as $H_\alpha$ emission and heat flux measurements. The LTX measures radial profiles of $n_e$ and $T_e$ using a single pulse, Thomson scattering system, and has an array of hydrogen Lyman $\alpha$ filtered photodiodes to measure edge hydrogen emission. To measure $T_i$ and $v_t$, a preliminary set of toroidal sight lines have been installed on LTX. This preliminary diagnostic was designed with 6 sight lines to measure the passive emission from lithium interactions with thermal ions in LTX. In the next 1–2 years, a neutral hydrogen beam is planned for LTX. Active charge exchange measurements will commence once the neutral beam is installed but will likely be able to utilize the same spectroscopic hardware and more extensive sight lines. Section II will further describe LTX and the spectroscopic hardware that has been installed. Section III will present preliminary line-of-sight measurements and then finally, Sec. IV will present a summary and conclusions.

## II. OVERVIEW OF THE LITHIUM TOKAMAK EXPERIMENT

The LTX has a major radius, $R_M = 0.4$ m with a minor radius, $a_m = 0.26$ m. It has been designed to have approximately 90% of its plasma facing surfaces below recycling. This is accomplished via the application of lithium onto copper shells in LTX. The copper shells consist of 4 quadrants with toroidal and poloidal breaks and have a thin stainless steel layer on their plasma facing surface. Present experiments apply lithium with 2 midplane evaporators which are toroidally displaced by 180°; future experiments will inject liquid lithium into the lower shells, which can be heated to 300–500 °C. Current LTX plasmas have plasma currents, $I_p < 70$ kA and durations of 10–15 ms with line-averaged density of order $0.5\text{–}1\times(10)^{19}$ $m^{-3}$ with peak electron

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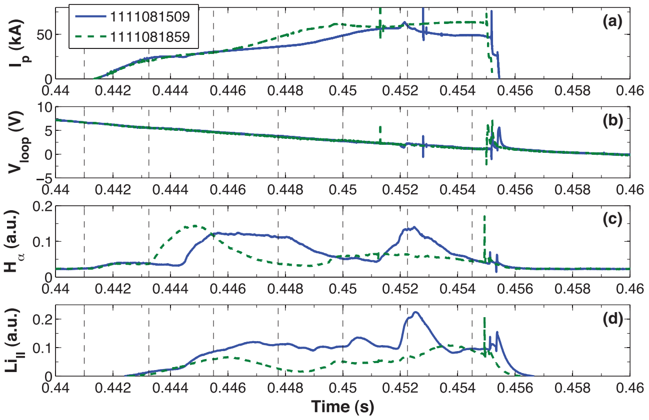

FIG. 1. (a) Plasma current, $I_p$; (b) Loop voltage, $V_{loop}$; (c) $H_\alpha$; and (d) Li II 5485 Å filterscopes viewing the high field side of the shells in typical LTX plasmas for discharges shortly after lithium evaporation (–) and after 20 discharges of similar $I_p$ and gas fueling (- -). The vertical dashed lines represent the center of the time integration window.

temperatures of 100–200 eV. Typical LTX discharges are shown in Fig. 1; one soon after a lithium evaporation of ~3 g and one after approximately 20 discharges and 4 h of lithium passivation. When no lithium evaporation is performed prior to plasma operations for several days, $I_p$ is typically limited to < 10 kA and discharge lifetimes of 4–5 ms due to poor wall conditioning.

The LTX plans to install a neutral beam on the experiment once plasma operations can support it. Since there is currently no neutral beam on LTX, the measurements are of passive emission of excited Li ions. This Li III emission arises from excited $Li^{2+}$ ions which could be due to thermal CX reactions, electron-impact ionization or recombination of fully stripped $Li^{3+}$ ions. However, the diagnostic hardware and software should be similar when the neutral beam is installed and these preliminary measurements allow an estimation of the active CX emission in LTX. The preliminary diagnostic consists of 6 toroidal sight lines connected to a Kaiser Optical Holospec spectrometer via a fiber optic patch cable. The spectrometer has a fixed high density grating similar to the design used on NSTX.[10] The spectrometer has a curved 75 $\mu$m entrance slit and matched f/1.8 imaging optics. The instrument broadening of each sightline was measured to have a full-width half-maximum (FWHM) of between 0.88 and 0.92 Å during neon glows in LTX. The instrument broadening is accounted for when determining $T_i$. A ProEM CCD camera from Princeton Instruments is used to measure the individual spectra from 5090–5190 Å. Frame rates of 2.25 ms are typical with this configuration; although frame rates of 1.5 ms have been achieved with electron multiplied readout.

An example spectra is shown in Fig. 2. The inset of Fig. 2 is zoomed into the region of interest in the spectra around the Li III line at a rest wavelength in air of 5166.89 Å (n = 7→5 transition). This line can be problematic as it can overlap with a molecular carbon line, the $C_2$ Swan band, that ranges from ≈5150 Å up to 5165.25 Å, an impurity line at 5168.89 Å believed to be Fe I,[11] and there is a possibility of a C VI line (n = 14→10 transition) at 5166.67 Å.[12] Given the current electron temperatures in LTX of 100–200 eV, emission from the C VI line is neglected. However, it may be necessary to account for carbon CX emission once the neutral beam is installed. Because of the impurity emissions potentially polluting the Li III measurements, a nonlinear least square fit of the spectra using Gaussian functions to describe the head of the $C_2$ Swan band, the suspected Fe I emission and the Li III emission are required.

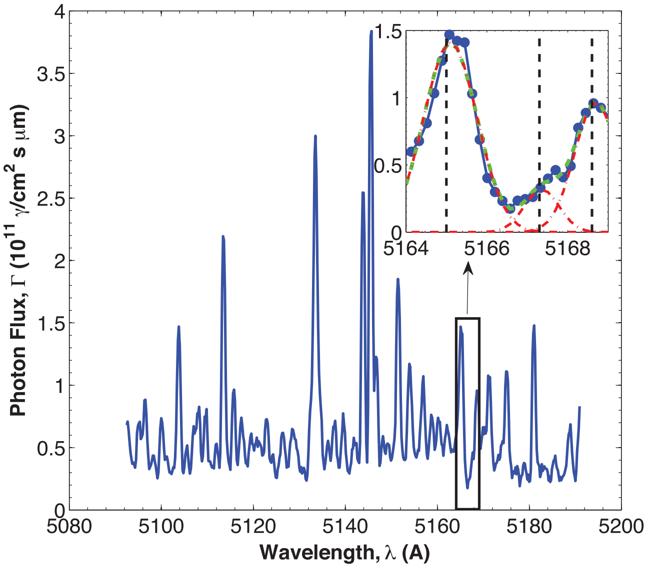

FIG. 2. Example spectra measured during a LTX discharge. Inset: Zoom in of the region of interest around λ = 5166.89 Å.

## III. RESULTS

Given that LTX discharges, in their present state, are limited to ≈15 ms, fast time resolution is necessary to understand the plasma dynamics. Figure 3 shows the time evolution of the lithium III spectra in LTX for a discharge taken after lithium evaporation. The features of the spectra are similar to the inset of Fig. 2 with the $C_2$ Swan band and suspected iron impurity lines present throughout much of the discharge. However, from Fig. 3, by 445.5 ms (5.5 ms after the discharge is initi-

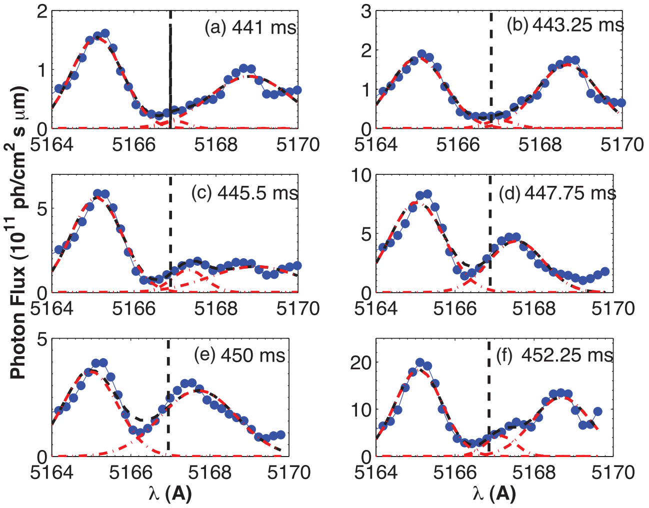

FIG. 3. Time evolution of spectra for a typical LTX discharge. –●– is the measured spectra, - - fit of measured spectra, and -.-. individual Gaussian fits.

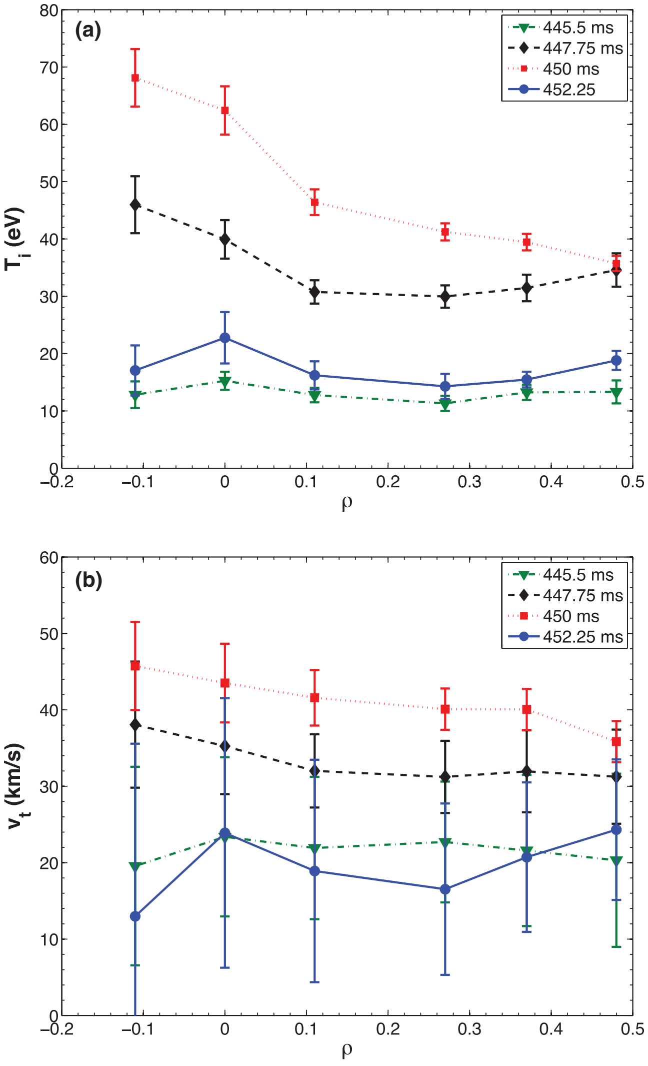

FIG. 4. Line-of-sight measurements of (a) lithium ion temperature, $T_i$ determined from Doppler broadening measurements of the lithium 5166.89 Å emission and (b) toroidal velocity, $v_t$ determined from the Doppler shift of the lithium 5166.89 Å emission line based on line-of-sight measurements as a function of normalized radius, $\rho = r/a_m$.

ated) the Li III emission is comparable to the iron emission and by 447.75 ms the Li III emission clearly dominates the iron impurity emission. This trend is reversed at the end of a discharge when the iron impurity emission is again comparable to the Li III emission. This is likely a consequence of LTX discharges commonly ending with disruptions against the stainless steel clad copper shells.

Based on these measurements, an ion temperature ($T_i$) and toroidal velocity ($v_t$) can be inferred based on the Doppler broadening and shift of the Li III emission. Figure 4 shows the line-of-sight measurements of $T_i$ and $v_t$ versus the normalized radius, $\rho = r/a_m$. Peak ion temperatures of 60–70 eV are reached approximately 10 ms into the discharge. The line-of-sight $T_i$ profiles are mostly flat except when the peak $T_i$ is reached when the radial profile is slightly peaked. The discharge ends shortly after the peak $T_i$ is reached. So further evolution of the $T_i$ profile is not possible. Similarly, a peak $v_t$ of 45 km/s is reached simultaneously with the peak $T_i$ at 10 ms into the discharge as shown in Fig. 4(b). However, the $v_t$ radial profiles remain spatially flat but increasing through the discharge. The source of the toroidal velocity is unclear and is currently under investigation.

## IV. CONCLUSIONS

Preliminary passive Li III measurements have been performed on LTX plasmas with a set of 6 toroidal sight lines. Even without a neutral beam on LTX, passive lithium III emission is sufficient to be easily measured on LTX. Measurements of $T_i$ and $v_t$ have been made and show peak $T_i = 70$ eV and $v_t = 45$ km/s which is reached approximately 10 ms into the discharge. Due to the limited number of sight lines and no edge sight lines, no attempt at inverting the measured profiles has been made. Given the measured Li III emission, design and installation of a more extensive toroidal fiber optic array is underway. This will provide more complete radial coverage of the LTX plasma and provide the needed experimental constraints for transport modeling with SOLPS. When the neutral beam is installed on LTX in the next few years, active charge exchange measurements should be feasible with the existing spectroscopic hardware.

## ACKNOWLEDGMENTS

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