Title:	**Development of a Direct Neutral Density Diagnostic for Fusion Edge Plasmas**
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Executive Summary

As magnetically confined plasmas progress towards ignition and long pulse experiments, measurement and control of the neutral density in the plasma edge has become a critical issue for stability, formation of transport barriers, and fueling. Recent experiments by our research group demonstrated that is possible to use two-photon absorption laser induced fluorescence (TALIF) to directly measure the density of neutral hydrogen in helicon sources and in the HIT-SI3 spheromak. While those experiments validated key elements of a diagnostic system that would enable similar measurements in tokamak plasmas, they did not fully address the issue of performance optimization in the presence of intense background light at the fluorescence wavelength and they also identified other issues that must be resolved before successful TALIF neutral density measurements in a tokamak are likely to be achieved. Additional specific concerns raised during design reviews with the leadership of the DIII-D tokamak facility included: the minimum detection threshold for this TALIF diagnostic (currently ~ 5 x 10^{15} m^{-3}) and the rate at which neutral density measurements could be obtained. Improving system performance to reduce the minimum detection threshold and demonstrating a faster rate of density determination are required to advance this diagnostic to the level where it could be considered for implementation on a major tokamak facility.

The key issues addressed through additional technological development during this project were: **validation of a new, chromatic aberration-free, xenon calibration scheme; increasing the output power of the laser; and suppression of background emission at the fluorescence wavelength through optimization of the collection optics and gating of the photomultiplier detector.** We completed these technological advancements through installation and testing of our prototype TALIF system on the proto-MPEX experiment at Oak Ridge National Laboratory (ORNL). The proto-MPEX facility provides plasma conditions similar to the edge plasma of a major tokamak experiment but with pulse lengths and pulse repetition rates ideally suited for extensive development of a TALIF neutral density diagnostic.

Measurement of the absolute neutral density in the edge of a magnetically confined plasma is necessary for plasma density control; calculation of charge-exchange power losses; control of plasma-wall interactions; determination of the braking of plasma flow; determination of the fuel mixture in deuterium-tritium plasma; and understanding the dynamics of the divertor region in the plasma edge. In terms of potential impact on the worldwide fusion program, we note that in burning plasma experiments, such as ITER, a 100 mJ/pulse Doppler-free TALIF diagnostic should be capable of directly measuring the deuterium/tritium (D/T) isotope ratio in the outer 0.5 to 1.0 m of the plasma radius. The D/T ratio is a critically important parameter for the control and optimization of burning plasmas. Therefore, development of the diagnostic system developed through this project is also relevant to long-term US participation in diagnostic development for large tokamaks.

DESCRIPTION OF ACCOMPLISHMENTS AND SUMMARY OF PROJECT ACTIVITIES

The original goals of this project were to

1. Upgrade the prototype hydrogen TALIF system developed at WVU through the DoE EPSCoR Laboratory Partnership Program and install it on the proto-MPEX facility at ORNL.
2. Using the proto-MPEX fusion-like plasma conditions, complete the following upgrades and validation experiments:
   - A. Design, installation, and validation of new collection optics specifically optimized for the new xenon, chromatic aberration-free, calibration scheme.
   - B. Upgrade of the Nd:YAG pump laser and optimization of the dye laser tripling system to achieve the full 8 mJ output power at the design target laser bandwidth to increase the signal-to-noise of measurements under tokamak like conditions.
   - C. Demonstration of a long-path length injection beamline.
   - D. Upgrade of detector electronics to implement real-time, active background light subtraction and achieve a detection threshold of 5×10^{14} m^{-3} (a ten-fold improvement).
   - E. Upgrade of laser control electronics to enable rapid scanning of laser wavelength.
   - F. Demonstration of Doppler-free TALIF in hydrogenic tokamak-like plasmas.

Through this project, the WVU TALIF system was moved to Oak Ridge National Laboratory (ORNL) in 2018 and successfully installed on proto-MPEX. Researchers from WVU went through an extensive period of training and safety reviews at ORNL and then the TALIF system was allowed to operate at ORNL. Initially there were some issues acquiring cooling water and power access, but these issues were resolved by our ORNL hosts and laser operation commenced in the fall of 2018.

As planned, the laser was installed in the Thomson scattering diagnostic room at the proto-MPEX facility, approximately 20 m away from the proto-MPEX vacuum chamber. The PI and graduate student upgraded the dye laser optics and repaired the Nd:YAG pump laser in the fall of 2018. While the original laser system never met its design specification of 8 mJ of energy per output pulse, we were able to raise its output energy from 4 mJ per pulse to 6-7 mJ per pulse.

The 20 m long beamline was installed in the proto-MPEX experimental hall and fully enclosed the UV beam. We had originally planned to fill the beamline with a dry nitrogen purge, but this was vetoed by the safety officials at ORNL so the beamline operated in room air. This reduced the available energy per pulse delivered to the target location to less than 1 mJ per pulse. An alternate option using an optical fiber to convey the injection light to the target location was considered, but no fibers capable of operating at 1 MW in the deep ultraviolet are commercially available. The experimental configuration is shown in the Figure below.

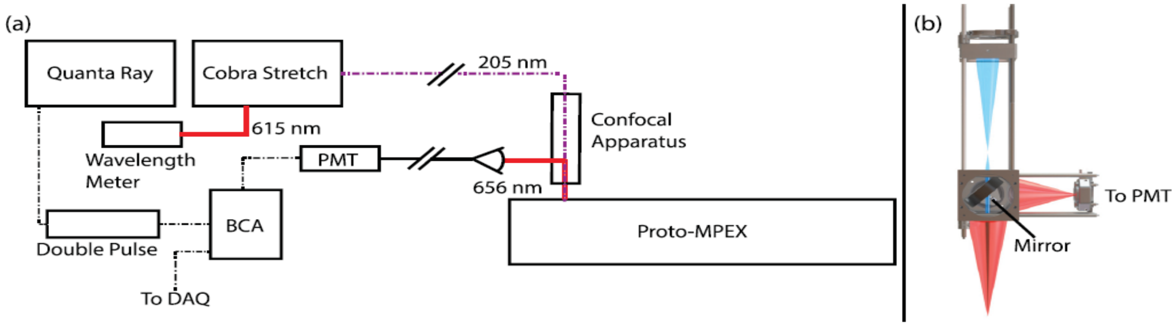

FIG. 1. (a) Cartoon of experimental layout. Photomultiplier tube is abbreviated as PMT, double pulse is a double pulse generator, and the boxcar averager is abbreviated as BCA. (b) Rendered image of the confocal apparatus. Injected light is compressed and collimated before passing through the mirror mounted at 45º. Laser light is injected and signal is collected along the same axis. Signal is reflected off the oblique mirror and is focused into a fiber that is coupled to the detecting electronics.

The detector electronics, including the real-time box car background subtraction scheme, were successfully upgraded. The TALIF system operated at a cadence of 20 Hz, which enabled 20 measurements per 1 s long proto-MPEX pulse. A series of experiments in deuterium plasmas that successfully demonstrated measurements of neutral density with both xenon and krypton calibration. The previously measured xenon to krypton cross section ratio provided identical measurements of the absolute hydrogenic neutral density. The TALIF schemes used for deuterium, krypton, and xenon are shown below.

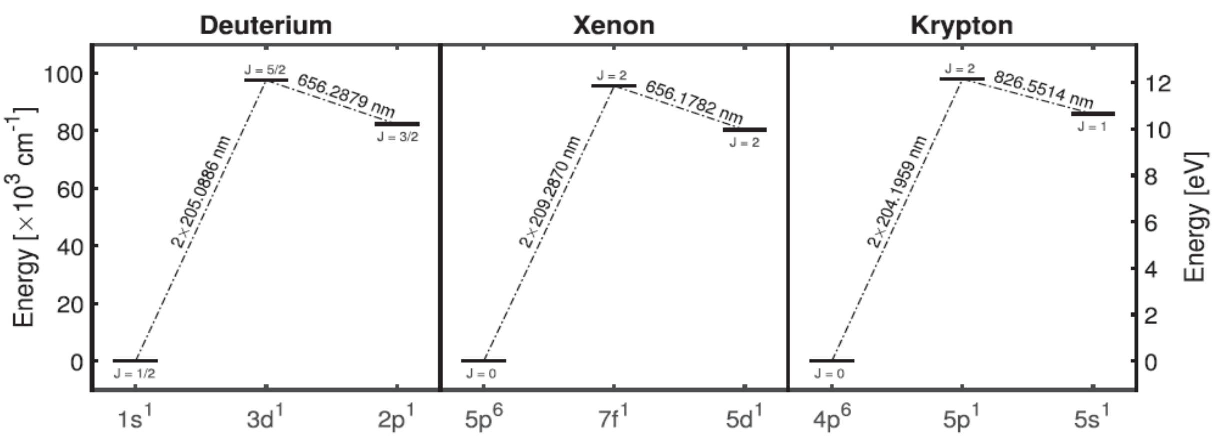

FIG. 2. Partial Grotrian diagram for atomic deuterium, xenon, and krypton schemes used in this work. Atomic deuterium is the target species. Xenon and krypton are used as calibration gases.

Using the TALIF system, the time evolution of the deuterium neutral deuterium velocity distribution function in proto-MPEX was measured for a series of high fill pressure proto-MPEX discharges (see Figure 3). The measurements were made near the helicon source antenna, not in the materials testing area as those ports were dedicated to Thomson scattering for the duration of the TALIF campaign at ORNL. These measurements provided both neutral temperature and absolute neutral density values. Shown in Figure 4 is the time evolution of the neutral density as measured by the TALIF system and the neutral pressure at the edge of proto-MPEX. The neutral temperature evolution is shown in Fig. 5 and the neutral flow evolution is shown in Fig. 6.

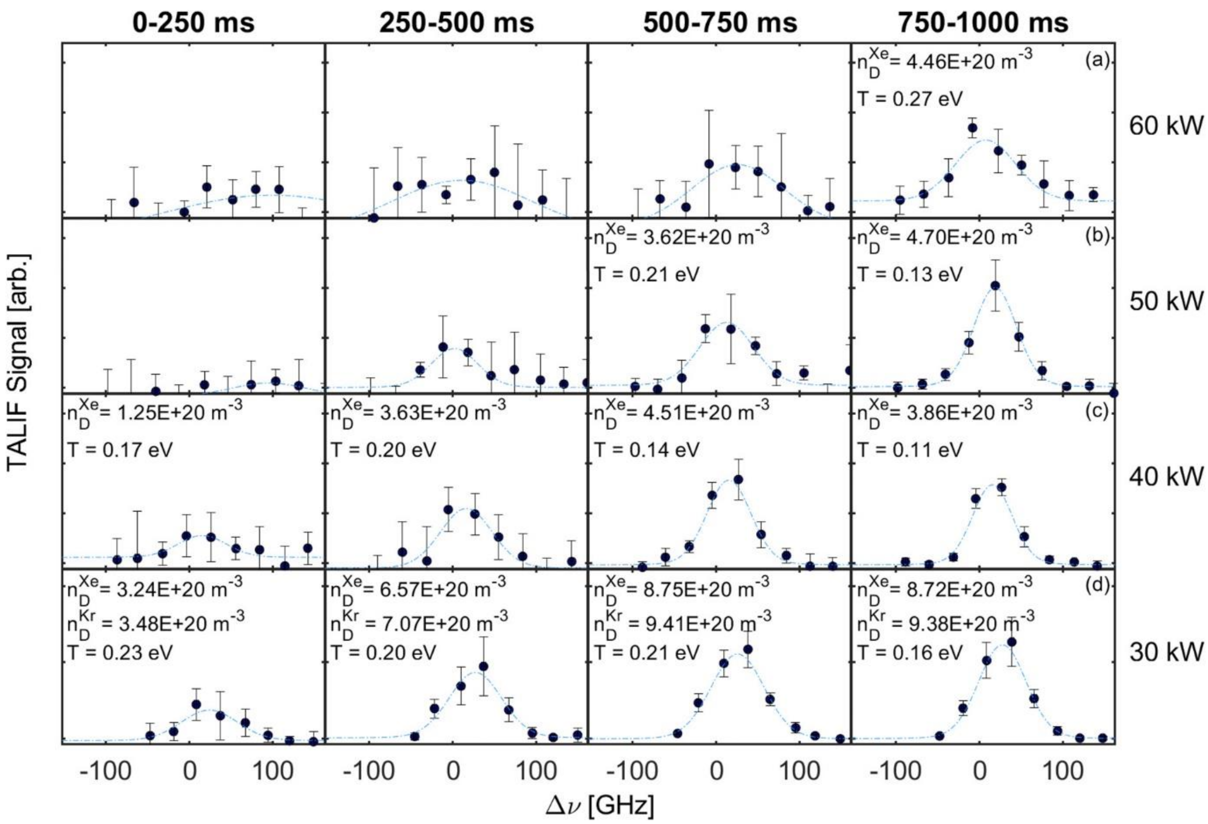

FIG. 3. Deuterium NVDF evolution over the plasma pulse for (a) P_{rf} = 60 kW, (b) P_{rf} = 50 kW, (c) P_{rf} = 40 kW, and (d) P_{rf} = 30 kW. Absolute atomic density and temperature are shown for every acceptable fit to the data. Lower powers produce sufficient signal for all times during the plasma pulse, whereas only later times exhibit discernible signal for higher powers. Comparison between xenon and krypton calibrated shots is shown where available

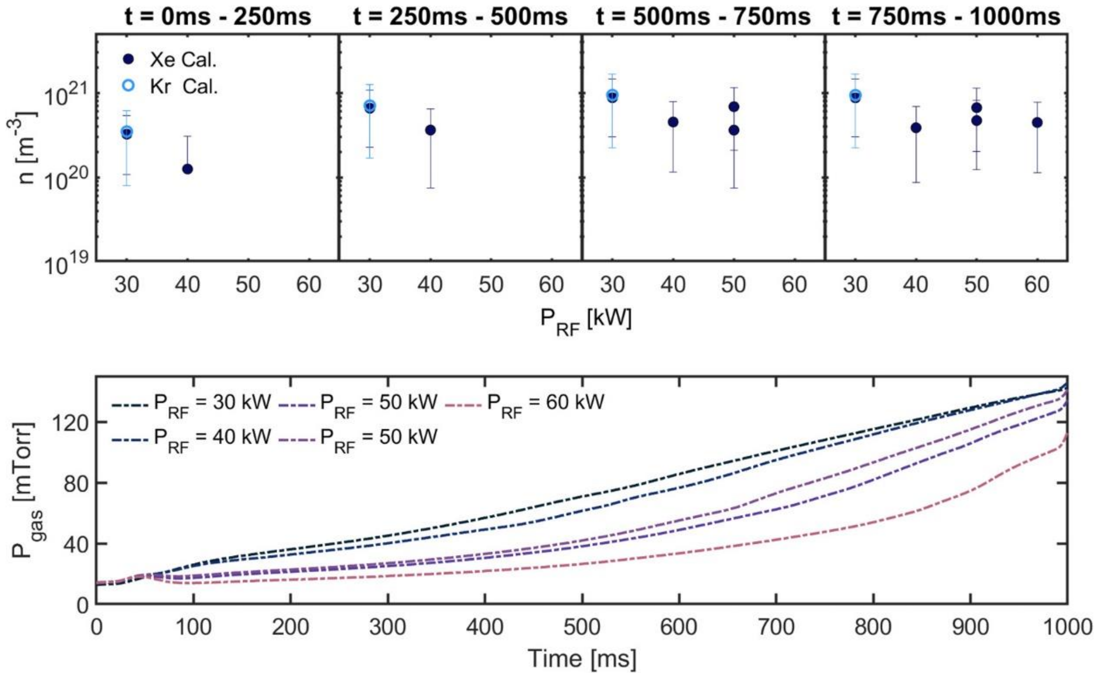

FIG. 4. (Upper plot) Evolution of neutral atomic density throughout the plasma pulse as a function of P_{rf} . Density was calibrated with both xenon and krypton for $P_{rf} =$ 30 kW. Atomic density values derived from krypton are shown in light blue open circles, and atomic density values derived from xenon are shown with dark blue solid circles. (Lower plot) Total neutral pressure evolution over the duration of the plasma pulse.

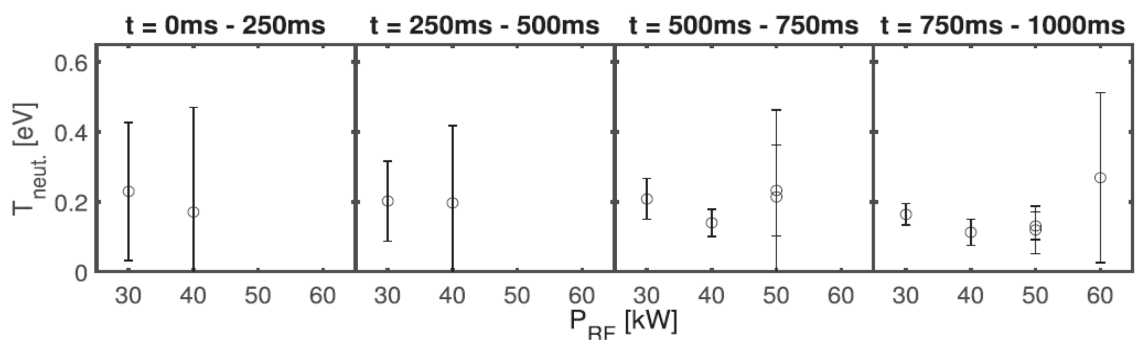

FIG. 5. Neutral deuterium temperature as a function of operating power. Temperatures derived from fits with sufficient signal are shown. A general decrease in temperature for later times throughout the pulse is observed due to the lack of the persistence of the plasma for higher pressures and later times.

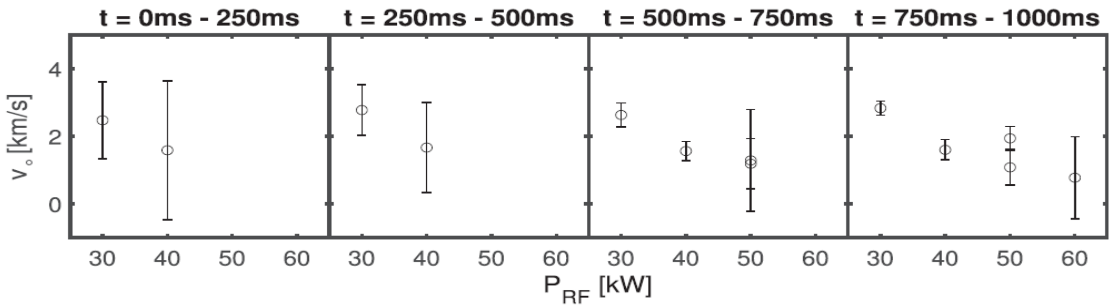

FIG. 6. Temporal evolution of neutral deuterium velocity as a function of power. Local bulk flow is observed to be radially inward and decreases monotonically as rf power increases. Neutral velocity is measured to be constant in time for a given rf power.

Because the confocal apparatus was moveable in the radial direction. We also demonstrated radial profile measurements of the neutral density in proto-MPEX. Shown in Figure 7 is the neutral velocity distribution as a function of time and radial location in proto-MPEX. The resultant neutral densities from the vdf measurements are shown in Figure 8.

These measurements demonstrated completion of nearly all the experimental objectives of this project. Neutral densities were measured in a tokamak-like environment using a TALIF diagnostic. The diagnostic was located a considerable distance away from the experiment and active background subtraction was demonstrated.

Because operational time on proto-MPEX was limited, we were unable to complete the last two elements of the planned experiments. We did not develop electronics to rapidly scan the laser wavelength, nor did we demonstrate Doppler-free TALIF on proto-MPEX. The combination of the Covid-19 pandemic, the decommissioning of proto-MPEX, and inability of proto-MPEX leadership to provide significant amounts of dedicated run time for these experiments limited us to focusing on the core experimental objectives.

SIGNIFICANCE TO THE FIELD:

The density sensitivity achieved with TALIF in proto-MPEX is sufficient, based on comparisons with measurements and simulations of expected background light levels in large tokamaks, to expect that the diagnostic will work in a tokamak environment if more energy per pulse can be delivered to the target plasma. The new xenon-based calibration scheme for hydrogenic TALIF works in an operational environment, which allows for improved optical alignment.

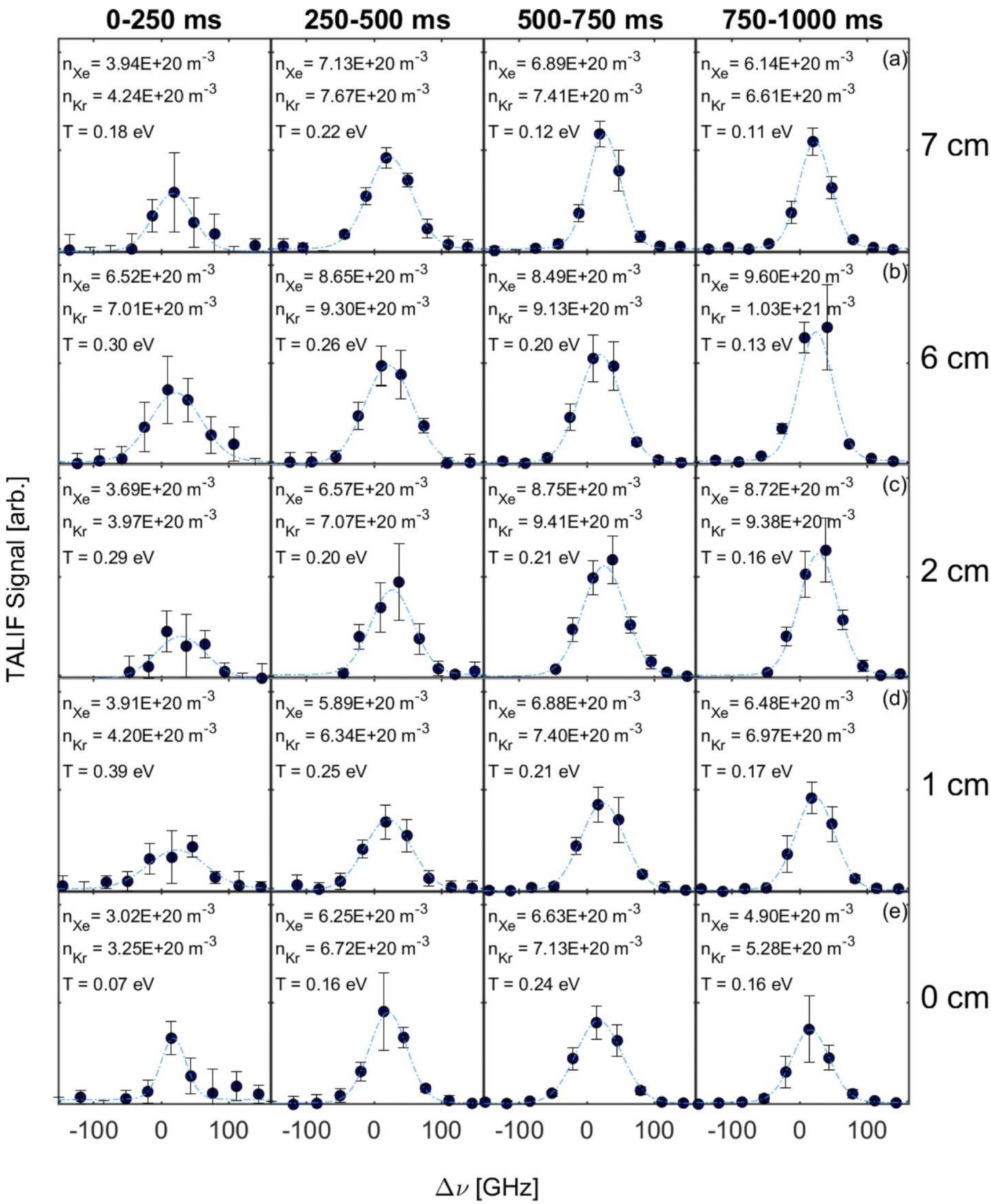

FIG. 7. Time evolution of deuterium NVDFs for r = 7; 6; 2; 1; and 0 cm in (a)–(e), respectively, for P_{rf} = 30 kW. Earliest times in the plasma pulse produce discernible signal, but with low SNR which yields a large spread in signal as compared to later times.

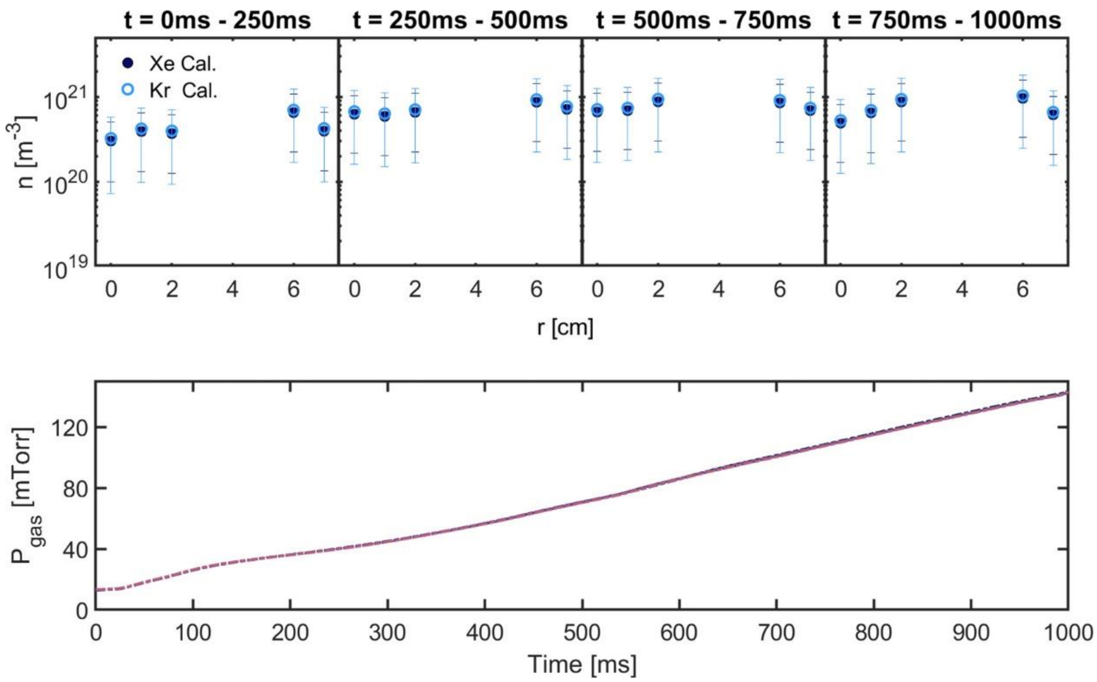

FIG. 8. (Upper) Evolution of atomic density vs r calibrated with both xenon (dark blue solid circles) and krypton (light blue open circles). Within the uncertainty of the measurement, the radial profile is essentially flat. Data for r = 3; 4; and 5 cm were inaccessible due to a magnetic support rod that physically obstructed the collection apparatus. (Lower) Evolution of total neutral pressure throughout the plasma pulse. All pressure traces for each radial location are plotted.

Research Products*

Publications Associate with this Project

1. Steinberger, T.E., J.W. McLaughlin, T.M. Biewer, E.E. Scime, and the Proto-MPEX Team, “Two-photon Absorption Laser Induced Fluorescence Measurements of Absolute Neutral Deuterium Density, Temperature, and Bulk Flow in Proto-MPEX,” Phys. Plasmas **28**, 082501 (2021); DOI: 10.1063/5.0054734

2. McKee J. S., E. E. Scime, I.A. Arnold, S. Loch "Radially localized electron heating in helicon plasmas by X-mode microwave injection," **28**, 022108 Phys. Plasmas (2021); DOI: 10.1063/5.0039641

3. Henriquez, M., D. S. Thompson, Andrew J. Jemiolo, and E. Scime, “Demonstration of confocal laser induced fluorescence at long focal lengths,” Rev. Sci. Instrum. **89**, 10D127 (2018); https://doi.org/10.1063/1.5039369.

4. Thompson, D., M. Henriquez, E. Scime, T. Good, “Confocal laser induced fluorescence with comparable longitudinal spatial resolution to the conventional method,” Rev. of Sci. Instrum. **88**, 103506 (2017).

Conference Presentations

1. T. Steinberger, “Two-photon Laser Induced Fluorescence Measurements of Neutral Density in the Prototype Materials Plasma Exposure eXperiment,” High Temperature Plasma Diagnostics Conference (remote) (2020).

2. T. Steinberger, “Two-photon Laser Induced Fluorescence Measurements of Neutral Density in the Prototype Material Plasma Exposure eXperiment,” American Physical Society Division of Plasma Physics Meeting (remote), JP19.00003 (2020).

3. T. Steinberger, Two-photon Absorption Laser Induced Fluorescence Diagnostic on Proto-MPEX,” American Physical Society Division of Plasma Physics Meeting, Ft. Lauderdale, FL (2019).

4. T. Steinberger, Two-photon Absorption Laser Induced Fluorescence Diagnostic on Proto-MPEX,” Laser Aided Plasma Diagnostics Meeting, Whitefish, MT (2019).

5. T. Steinberger, Development of a Two-photon Absorption Laser Induced Fluorescence Diagnostic for Proto-MPEX,” American Physical Society Division of Plasma Physics Meeting, Portland, OR (2018).