A 1D Lyman-alpha Profile Camera for Plasma Edge Neutral Studies on the DIII-D Tokamak

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ABSTRACT:

A one dimensional, absolutely calibrated pinhole camera system was installed on the DIII-D tokamak to measure edge Lyman-alpha (Ly-α) emission from hydrogen isotopes which can be used to infer neutral density and ionization rate profiles. The system is composed of two cameras, each providing a toroidal fan of twenty lines of sight, viewing the plasma edge on the inboard and outboard side of DIII-D. The cameras’ views lie in a horizontal plane 77 cm below the midplane. At its tangency radius, each channel provides a radial resolution of approximately 2 cm full width at half maximum (FWHM) with a total coverage of 22 cm. Each camera consists of a rectangular pinhole, Ly-α reflective mirror, narrow-band Ly-α transmission filter, and a 20 channel AXUV photodetector. The combined mirror and transmission filter have a FWHM of 5 nm, centered near the Ly-α wavelength of 121.6 nm and is capable of rejecting significant, parasitic carbon-III (C-III) emission from intrinsic plasma impurities. To provide a high spatial resolution measurement in a compact footprint, the camera utilizes advanced engineering and manufacturing techniques including 3D printing, high stability mirror mounts, and a novel alignment procedure. Absolutely calibrated, spatially resolved Ly-α brightness measurements utilize a bright, isolated line with low parasitic surface reflections and enable quantitative comparison to modeling to study divertor neutral leakage, main chamber fueling and radial particle transport.

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Keywords: Plasma, Tokamak, Diagnostic, Lyman-alpha, Pedestal, Neutral Density, Ionization Rate

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I. INTRODUCTION

At the boundary of magnetically confined plasmas, neutral particles ionize as they move towards the center of the plasma, acting as a source of ionized particles for the plasma density. The neutral source of ionized particles, typically neutral hydrogen or deuterium, is a key boundary condition for the core performance of current devices and extrapolation to future fusion energy devices.\textsuperscript{33} In particular for tokamaks, a high performance toroidal magnetic confinement fusion device, neutrals are expected to play a key role in a range of physical processes: setting global plasma pressure, height of the high confinement mode (H-mode) pedestal, divertor detachment, compatibility with advanced divertors and divertor closure.\textsuperscript{3,22,34,46}

Measurements of neutral hydrogen in fusion devices are generally made through either active spectroscopy, such as laser induced fluorescence (LIF), or passive measurement of hydrogen brightness. LIF-techniques allow a direct spatial localization of the measurement of neutral density using stimulated emission from laser systems.\textsuperscript{12,16,32,53} However, LIF require high power laser systems, and currently have limited applicability in fusion plasmas.\textsuperscript{16,32,53} In contrast to LIF, passive hydrogenic emission measurements, particularly in the visible range of wavelengths, rely solely on collection optics, and, therefore are more widely adopted. Passive spectroscopy measurements are line integrated and rely on the filtering of one or more lines of hydrogen emission. A measurement of the line brightness is required to calculate the local neutral density, the brightness must then be inverted to determine the local emissivity and combined with measurements of the local electron temperature and density to evaluate standard transition rate coefficients.\textsuperscript{25} In fusion plasmas, passive emission studies of neutral particles have utilized Balmer (\(n_{i>2} \rightarrow n = 2\)) and Lyman (\(n_{i>1} \rightarrow n = 1\)) series emissivity measurements in conjunction with density and temperature measurements, for instance from Thomson scattering.\textsuperscript{47} Since Balmer-alpha (\(B-\alpha\)) (\(\lambda = 656.3\) nm) is routinely measured in tokamaks, it has been adopted for neutral studies including on the DIII-D, Alcator C-Mod, NSTX-U, LHD and TEXT tokamaks.\textsuperscript{4,8,17,24,48,49} Lyman-alpha (Ly-\(\alpha\)) (\(\lambda = 121.6\) nm) diagnostics for neutral studies have been implemented on C-Mod and TCV\textsuperscript{10} and used for studies on the role of neutrals in the formation of the edge profiles, through particle and heat balance.\textsuperscript{5,13,26,27,50}

\(B-\alpha\) measurements are more frequently performed, but \(Ly-\alpha\) measurements offer key ad-
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Advantages for neutral studies. One challenge in using $B-\alpha$ measurements to measure hydrogen neutral density is the increased contribution to the line brightness of excited hydrogen neutrals from molecular reactions. Recent reports on NSTX-U have utilized $B-\alpha$ to estimate neutral density, however due to the large molecular interactions, advanced modeling is required to determine the relative molecular and atomic contributions to the line brightness which alters the inferred neutral densities. On DIII-D, molecules are suspected to be a significant fraction of main chamber recycling neutrals and can lead to an overestimation of ionization and density. In contrast, EDGE2D-EIRENE modeling on DIII-D suggests that molecular contributions to emission are negligible for measurements of the $Ly-\alpha$ line, suggesting that atomic neutral densities can be directly evaluated. Unlike $B-\alpha$, $Ly-\alpha$ does not readily reflect off of surfaces. Also, the intensity of $Ly-\alpha$ is at least an order of magnitude larger for typical plasma parameters found in the tokamak edge. These advantages come with additional engineering challenges. Optical filtering in the ultraviolet spectrum is more challenging than the visible spectrum due to a lack of high transmission narrow band filters. In particular, rejection of a nearby carbon-III ($C-\text{III}$) line ($\lambda = 117\text{ nm}$) becomes a concern. Since $Ly-\alpha$ is readily absorbed in air and most materials, optical components and detectors need to be placed in vacuum. Placing a diagnostic inside the primary vacuum of a tokamak further introduces engineering challenges in terms of limited space availability, limited access to the vessel, restrictions on materials and resilience to heat loads from plasma operation and cleaning procedures.

In this paper, we detail a new, compact, absolutely calibrated diagnostic, abbreviated LLAMA for **LLAMA is the Lyman Alpha Measurement Apparatus**, installed on the DIII-D tokamak to measure the $Ly-\alpha$ hydrogen neutral line brightness. The LLAMA diagnostic advances both the engineering and measurement solutions compared to previous $Ly-\alpha$ diagnostics. The new $Ly-\alpha$ camera on DIII-D introduces a second filtering component, a $Ly-\alpha$ notch reflective mirror, which narrows the band-pass and significantly reduces the neighboring $C-\text{III}$ line intensity. A pinhole which aligns with flux surfaces allows maximization of the resolution in magnetic flux space. The camera utilizes advanced engineering, including vacuum compatible 3-D printed Inconel parts, thermally and shock resistant adjustable mirror mounts, water-cooling and a compact footprint providing two views. The custom amplifier system mounts directly to the flange and provides a high gain adjustable amplification system in a small footprint with pseudo-differential outputs. Finally, a novel alignment pro-
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procedure relying on a coordinate measuring machine (CMM) allows alignment on the bench, minimizing the in-vessel time required for installation and alignment.

II. DIAGNOSTIC DESIGN AND OVERVIEW OF IN VACUUM COMPONENTS

LLAMA consists of two one-dimensional pinhole cameras placed in the primary vacuum of the DIII-D tokamak, viewing the high field side (HFS) and low field side (LFS) of the plasma. The optical components of each camera are highlighted in figure 1. Plasma emission enters the camera through a 2 mm by 8 mm rectangular pinhole cut by a waterjet and held in a rotatable mount for optimal alignment with plasma flux surface geometry. Next, the incoming spectrum is narrowed by a Ly-\(\alpha\) notch reflective filtering mirror\(^{35}\) mounted in a customized THORLABS mount\(^{36}\). The reflected light is then directed to a light tight box, the detector box, where it passes through a transmission filter towards\(^{37}\) an AXUV photo-diode detector. The detector consists of 20 channels providing twenty lines of sight\(^{38}\). Photocurrent is carried out of vacuum through Kapton insulated cable to a 25 D-sub connection. Cable lengths are minimized to reduce electrical pickup. The two cameras are separated by a 3D printed Inconel septum\(^{51}\) which can be seen in figure 1. The internal components are protected from tokamak bakes and glow discharges by a linearly actuated shutter. Enclosing the system, is a light tight tube which can be seen in figure 5b. Typical solid angles are \(5 \times 10^{-4}\) for the HFS and \(2 \times 10^{-3}\) for the LFS. The etendue for the LFS and HFS is approximately \(5 \times 10^{-9}\) m\(^2\) and \(1 \times 10^{-9}\) m\(^2\).

The filtering of the Ly-\(\alpha\) line is achieved through a combination of notch reflective and transmission thin-film filters both produced by Acton Optics. The reflective filtering mirror, thin-film transmission filter, and combined transmission curves can be seen in figure 2. Previous Ly-\(\alpha\) cameras isolated the Ly-\(\alpha\) line utilizing only the narrow-band transmission filter\(^{6,10}\). However, due to the carbon wall on DIII-D, there is significant intensity from a neighboring C-III line at 117.5 nm. The intensity of the C-III line, as measured by the divertor spectrometer, is comparable to that of Ly-\(\alpha\) on many shots. Addition of the reflective filter provides greater reduction of the C-III signal relative to Ly-\(\alpha\) by narrowing the band pass, as highlighted in figure 2c showing the normalized transmission curves. The combined mirror and transmission filter system is capable of reducing the carbon intensity relative to Ly-\(\alpha\).
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FIG. 1: (a) Cartoon schematic of the internal optical components of the Ly-α system. (b) Computer model of the LLAMA diagnostic showing the internal components with the outer tube removed. The HFS and LFS camera are separated by the 3D printed Inconel septum. (c) Rotating the camera ninety degrees and removing the detector box lid, highlights the LFS components. The HFS components and detector box are visible through the septum which has been rendered transparent. The transparency of the septum shows the embedded cooling loop path in blue. (d) The assembled diagnostic with the outer shield and detector box lid removed.
FIG. 2: Transmission curves of Ly-α light through the system by the two filtering components. (a) The reflectance curve for the Ly-α mirror at three angles. (b) The thin-film filter transmission curve is shown in black. The combined mirror and filter curve, assuming a 45° angle of incidence off the mirror, is shown in solid red. (c) Transmission curves normalized to their maximum. Normalized curves highlight the narrowing of the band-pass and relative reduction of C-III to Ly-α through the combined system.

by a factor of 10 with a full width half maximum of 5 nm centered around 123 nm. In addition, inclusion of the mirror facilitates a more compact optical design. The angle of incidence on the mirror varies from 35° to 45° for the HFS and 45° to 55° for the LFS. This introduces some dependence of the Ly-α transmission on the incident angle of light. However, the transmission dependence is accounted for in the absolute calibration procedure[29]. The bandpass of the system allows measurement of both the hydrogen and
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deuterium Ly-α line. DIII-D primarily operates with deuterium but has dedicated hydrogen campaigns; the LLAMA is capable of providing measurements for both hydrogen isotopes.

The reflective filter is held in a THORLABS mirror mount shown in figure 1d selected and customized to survive the challenging in-vessel environment of a tokamak while facilitating alignment on the optical bench. For the stability of the views, the mirror mount requires stability to 100 µrad through thermal and vibrational shock from the tokomak environment. A THORLABS Polaris K05 manual mirror mount was selected as the base design due to its microradian level stability over 15°C thermal and 2 times gravity shock cycling. The mount was further customized with non-magnetic parts to avoid displacement from the tokamak’s magnetic field and error fields. Components were selected to comply with material restrictions inside the primary vacuum of DIII-D, which included removing lubricants from all screws by using Nitronic-60 screws and replacing ball bearing contacts with ceramic pieces. This was all achieved in a compact footprint while still providing three-axes manual manipulation for easy alignment on the bench.

The primary engineering challenges constraining the mechanical design were the geometry of the port and thermal loads during the 350°C bakes performed on DIII-D before operation. The camera body is designed around a 3D printed Inconel septum, highlighted in figure 1b and 1c which provides support to the optical components, thermal stability with an embedded 6 mm diameter cooling loop, and a channel for the shutter actuation. Cooling tubes from the 3D printed Inconel septum pass through the stainless steel vacuum flange and are welded in place providing structural support and removing all water connections from inside the vessel. The 3D printed Inconel septum is deployed in-vessel and pressurized with water up to 850 kPa. Only during bakes thermal loads are large enough to require water cooling, with 15°C thermal excursion measured in the diagnostic by a thermocouple. However, the flow is left on during plasma to ensure thermal stability of the detector response. Embedding the cooling tubes in the mounting plate minimized the size of in-vessel components. The shutter, which protects the optics during bakes and plasma glow discharges, is also made of 3D printed Inconel to conform to the outer tube and has linear pneumatic actuation. The cameras are enclosed in an outer tube nearly matching the diameter of the port and mounted to the Inconel septum. The flange, which supports the entire diagnostic, is highlighted in figure 3. It consists of two 25 pin D-sub connectors, water cooling feedthroughs, and pass-through for the shutter actuator. The compact size and
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FIG. 3: Rendering of the LLAMA highlighting the air side components. Amplifiers are attached directly to the flange on a water cooled amplifier support.

flange-supported design allows the LLAMA to easily be exchanged with a duplicate from outside the vessel. This allows for regular calibration and maintenance to be performed away from the tokamak.

III. LLAMA AMPLIFIER SYSTEM

Due to previous experience with AXUV detectors on DIII-D, noise was a primary concern in design of the wiring and electronics for the LLAMA. The HFS and LFS detectors and signals are electrically isolated against the DIII-D tokamak (DIII-D) vacuum vessel potential and each other. The detectors are isolated from the machine by a custom made Macor mount and insulating film which can be seen in figure 1d. This setup provides a 5 kV standoff. Wire paths are kept short to minimize common mode pickup which was a concern since AXUV photodiode arrays consist of 20 photodiode detectors connected to one common ground. To further minimize pickup, the signals are immediately amplified by a variable gain $10^7$-$10^8$ V/A custom built amplification board mounted directly to the air side of the D-sub connectors on the flange as shown in figure 3. The custom amplifier boards shown in green
mount directly to the vacuum feedthroughs and cover the air side of the DB-25 connectors in figure 3. There are separate amplifier boards for the LFS and HFS system that are enclosed by a metal housing for shielding (shown for the HFS board). The amplifier boards have smaller, removable circuit boards, which contain the actual electronic elements of the amplifier and output circuits. The amplifier boards are mounted to a water cooled base plate whose cooling fluent copper leads exit to the right. Thermally conductive 5584 silicone interface pads enable good thermal exchange between the amplifier boards, boxes and base plate and fulfill the safety requirement of a 5 kV stand-off for DIII-D.

The AXUV photodiode detector arrays with 20 channels require a transimpedance amplifier system to measure the generated photocurrents. The photocurrents were modeled from the LLAMA responsivity and estimated Ly-α brightness in typical DIII-D scenarios to be on the order of 1 nA to 1000 nA. The expected wide range of photocurrents motivated variable gains of $10^7 \text{ V A}^{-1}$ and $10^8 \text{ V A}^{-1}$ to create measurable output voltages.

A schematic drawing of the implemented transimpedance amplifier is presented in figure 4a. Typically, a reversed bias voltage ($V_{\text{bias}}$) of 3 V is applied to the photodiode detector. The generated photocurrent is amplified and converted by an operational amplifier and a parallel resistor ($10^7 \Omega$ or $10^8 \Omega$), which determines the gain. The transimpedance amplifiers of the photodiode detector channels are grouped on amplifier stage boards. One amplifier stage board accommodates 4 photodiode detector channels, using a 4 channel operational amplifier in combination with the corresponding circuit resistors and capacitors. Each exchangeable amplifier stage board is equipped with one of the design gains, therefore changing the amplifier stage board alters the gains for 4 photodiode detector channels at a time. Each amplifier stage board can be easily replaced if a single component is damaged or fails due to exposure to high energy neutrons and ionizing radiation from the tokamak. Five amplifier stage boards are shown on the LFS amplifier board presented in figure 3 next to the DB-25 feedthrough.

The output of the amplifier boards is converted to a pseudo-differential signal that allows for a transmission less susceptible to noise. The generated differential signals are then passed through a DB-50 connector, which transfers them in pairs of twisted and shielded wires to the driver stage (2nd stage) located roughly 10 m of wire away from the LLAMA flange. The 2nd stage supports the signal transmission along 55 m of wire to the commercially available ACQ424ELF digitizer outside of the DIII-D machine hall.
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FIG. 4: (a) Schematic drawing of the circuit. The first circuit, outlined in black, amplifies the incoming photocurrent. The second circuit, outlined in grey, creates pseudo-differential outputs immediately after amplification to avoid common mode noise. (b) Nominal gain of the implemented transimpedance amplifiers: Two nominal direct current (DC) gains of $10^7$ V/A and $10^8$ V/A were chosen as the design target. The lower gain has a flat response up to roughly $10^4$ Hz, while the higher gain rolls off around $10^3$ Hz.

Data is digitized and stored at a rate of 500 kHz. Although bright transient events such as ELMs can be analyzed at higher frequencies, data analysis for steady state behavior of the Ly-α brightness is presently limited to about 1 kHz by noise from induced currents due to high frequency oscillations of the tokamak’s poloidal magnetic field coil’s power supplies. The signal amplitude to noise amplitude ratio at these frequencies ranges from 5 % to 20 %, depending on the configuration of power supplies and coils, plasma conditions and the amplifier gain. The inferred neutral density from the brightness measurements is also dependent on the frequency of electron temperature and density measurements performed. For example, for measurements of electron temperature and density by Thomson scattering, the neutral density is determined at the interleaved nominal laser pulse repetition rate of 250 Hz.\[11\]

To be able to resolve fast transient events in the plasma edge like edge localized modes (ELMs) that occur on a sub-ms timescale, a constant gain over a wide range of frequencies is desired. Figure 4b presents the modeled frequency and phase dependence of the
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FIG. 5: (a) HFS components during benchtop alignment. The outer tube, detector box lid and transmission filter are removed to allow significant transmission of the He-Ne laser used for alignment illustrated in red. The mount recreates the port geometry on the bench. (b) In-vessel image of the fully assembled diagnostic highlighting the three fiducials, the front plane, cutaway plane and inscribed circle used for the view registration. (c) The combined view geometry from the benchtop and in-vessel CMM measurements. The grey surfaces are from the laser tracking CMM measurements taken in-vessel on DIII-D.

circuits. As desired, both gains are constant up to almost $10^3$ Hz providing access to inter-ELM dynamics. The lower, $10^7$, gain exhibits a constant gain up to roughly $10^4$ Hz, allowing Ly-α brightness measurements of low frequency plasma fluctuations in the plasma edge like the fundamental frequency of the edge harmonic oscillation EHO.

IV. LLAMA VIEWS AND ALIGNMENT

Due to the geometry of the port, it was not possible to align the diagnostic in-vessel. Therefore, a novel alignment scheme was developed in which the majority of alignment can be performed on an optical bench. The alignment method relies on the use of a CMM fiducials placed on the front enclosure of the diagnostic, and an alignment mount recreating the port geometry on the optical bench. The views are determined on the bench with the diagnostic installed in the alignment mount. Then, the views are measured with the CMM along with the fiducials. After installation in DIII-D, the fiducials are measured with a CMM in the tokamak geometry. By overlaying the fiducial measurements from the bench onto the
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FIG. 6: A top down view, highlighting the toroidal geometry of the HFS and LFS views shown and red and blue, respectively. The tangency radii for each channel are shown in pink. The views terminate on the outer limiting surface of the DIII-D vacuum vessel.

tokamak fiducial measurements, the orientation of the views is determined in the tokamak coordinate system. This alignment procedure reduces the scarce time for in-vessel alignment available at DIII-D and allows the system to be operated immediately upon installation while still providing accurate positioning of the views.

An overview of the alignment procedure is shown in figure 5. The diagnostic is installed in the alignment mount which is designed to recreate the port geometry on DIII-D. Once installed in the alignment mount, from the perspective of the diagnostic, the plane of the bench is parallel to a horizontal plane inside DIII-D. A He-Ne laser is then used to create a fan of rays to which the internal components are aligned. The center channel is illuminated by aligning the laser parallel to the optical surface and perpendicular to the pinhole, as seen in figure 5a. The outer channels seen in figure 5a can then be determined by maximizing the signal on the corresponding detector channel. The He-Ne rays, detector and pinhole location are then measured using the CMM. All other views can then be interpolated from these quantities since the dimensions of the detector are known to 0.05 mm accuracy. The outer tube, detector box lid and transmission filter are removed during the He-Ne laser alignment,
FIG. 7: (a) A poloidal projection of LFS and HFS lines of sight in blue and red, respectively. The separatrices of three typical plasma scenarios on DIII-D are overlaid. The HFS view is vertically aligned while the LFS views are tilted by rotating the pinhole to 45°. (b) A magnified view of the LFS highlighting the tangency radii and spot size of a selection of channels projected onto the poloidal plane at their tangency radius. Due to the difference in distance to the tangency radii, the outboard channel is slightly smaller than the innermost channel. (c) A close up view of HFS the tangency radii and channel projection for a few channels. There is less variation in the size of detector projections than the LFS because the HFS lines of sight are a factor of two longer.

to allow significant light transmission to the detector.

The views determined on the benchtop are modeled in the tokamak coordinate system using a CMM and the fiducials marked on the front cap of the diagnostic. The three fiducials shown in figure 5b are measured on the bench along with the three He-Ne laser lines, and fit using an error reducing method. After the diagnostic is installed, the CMM is used in the tokamak to re-measure the fiducials. As seen in figure 5c, by overlaying the two fiducial measurements the views are reconstructed in the tokamak coordinate system.
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The resulting views in the toroidal and poloidal cross section can be seen in figure 6 and figure 7. The views are centered near the separatrix below the midplane for a variety of common plasma shapes on DIII-D. The central channel of each view has their tangency radius at 121.0 cm (HFS) and 192.9 cm (LFS) with an error of 1 mm in the radial direction resulting from the CMM measurement. The views are tilted from the horizontal by $1 \pm 1^\circ$ with HFS and LFS views pointing slightly downwards. Since there is no dependent coordinate of the 3D points measured by the CMM, uncertainty of the views from the alignment procedure was determined using a Monte Carlo simulation. The individual 3D coordinates measured by the CMM were varied by the experimentally determined uncertainty of a point, 0.5 mm. The fiducial alignment procedure was then performed with the varied coordinates. The resulting uncertainty in the position of the tangency radii and angles from the horizontal is reported to contain two standard deviations of the simulations.

The projection of individual channels onto their tangency radii plane can be seen in figure 7b and 7c. The projected image of each channel differs in size due to the varying distance to the tangency radii plane. Tangency radii for all channels are shown in magenta; the projected channels’ radii are highlighted with a white border. For the LFS, the full width half maximum for each channel measurement is 2.6 cm by 8.4 cm for the radial and vertical direction respectively. For the HFS, the full width half maximum is 2.1 cm by 9.2 cm. The finite size of the pinhole and detector result in a spot size which is much larger than the uncertainty in the positioning of the center of each channel determined from the CMM Monte-Carlo simulation. The spatial sensitivity distribution is emphasized by the higher density color near the center of the channel projection. Due to the finite size pinhole, there is overlap between channels, about half of the full width at half maximum (FWHM) overlaps with the neighboring channel.

The alignment and size of the pinhole was chosen to maximize signal while maintaining the lines of sight along a flux surface. The Ly-\(\alpha\) emissivity depends on electron temperature, electron density and neutral density. Electron temperature and density are flux functions; therefore, for small gradients in neutral density, the emissivity is expected to be a flux function. While modeling suggests poloidal asymmetries in neutral density, their scale is larger than a LLAMA channel view. Therefore, by aligning the detector projection with the flux surface, it is possible to minimize averaging of emissivity across flux surfaces improving the resolution with a relatively large detector projection. The effect of rotation of the
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A 1D Lyman-alpha Profile Camera for Plasma Edge Neutral Studies on the DIII-D Tokamak pinhole can be seen by comparing the HFS and LFS detector projections in figure 7b and figure 7c. On the LFS, the pinhole is rotated; the projection of the detector more closely matches the flux surface geometry reducing the averaging across flux surfaces. By rotating the LFS pinhole both the HFS and LFS can resolve features on a 50 mm radial scale. Initial estimate from the ionization cross section evaluated at the pedestal top, suggest neutral mean free paths of approximately 10 mm to 100 mm while previous models suggest neutral decay lengths comparable to the electron density pedestal width 20 mm to 50 mm. These scale lengths should be resolvable by the LLAMA system. Furthermore shifts smaller than 50 mm in the emissivity should be measurable due to the overlapping channel views.

The LLAMA diagnostic provides absolutely calibrated brightness measurements through a benchtop calibration which is regularly performed before and after campaigns to monitor stability of the diagnostics’s spectral response. The calibration procedure will be described briefly here and in detail in a dedicated article. Due to its compact size, the calibration is performed on a dedicated ex-vessel vacuum enclosure, which reaches pressure below $2 \times 10^{-5}$ Pa to avoid loss of Ly-$\alpha$ transmission. The procedure uses an absolutely calibrated Ly-$\alpha$ electrodeless gas discharge powered by a radio-frequency source, supplied by Resonance LTD, to illuminate the pinhole of the diagnostic with Ly-$\alpha$ light. The calibration source spectra are characterized by a vacuum ultraviolet (VUV) spectrometer and its intensity is measured by a NIST-absolutely calibrated photodiode to determine the intensity of Ly-$\alpha$ illuminating the diagnostic. Initial calibration of the LLAMA shows brightness measurements on the tokamak of $1 \times 10^{21}$ Ph sr$^{-1}$ m$^{-2}$ s$^{-1}$ and absolutely calibrated profiles can be seen in figure 9 and figure 10.

V. INITIAL LY-$\alpha$ BRIGHTNESS MEASUREMENTS IN DIII-D

The diagnostic regularly observes variations due to L-mode to H-mode transitions, ELMs, gas puffs, shape changes, and density changes. An example of observed brightness from channel four, highlighted in yellow in figure 7b on the LFS camera from a 2019 DIII-D experiment can be seen in figure 8. As observed on other tokamaks, when the plasma transitions from the low to high confinement mode, there is a drop in emissivity in the near scrape off layer. ELMs are also observed in the Ly-$\alpha$ emissivity due to the increase of particles outside of the core due to the collapse of the pressure pedestal. As a passive
FIG. 8: A single LFS channel time trace in black from channel four, highlighted in yellow in figure 7. The L to H-mode transition is seen at 0.8 s with a characteristic decrease in brightness. The D-alpha brightness is over plotted in red, showing the edge localized modes and pellet injections which are simultaneously observed in the LFS signal. The signal has been smoothed to remove pickup.

diagnostic, LLAMA can obtain brightness data on most shots, except for scenarios which could damage the system’s optics, such as counter neutral beam injection which populate the scrape off layer with suprathermal beam ions.

The diagnostic was recently commissioned which involved a rigid shift of the plasma boundary and increasing outboard gas puff. The commissioning discharges were performed in a lower single null configuration, which is shown in solid black in figure 7a, with a toroidal field of 2 T, 1.8 MA plasma current, 6 MW injected power and a line averaged density of $7 \times 10^{19} \text{m}^{-3}$. Brightness profiles from a rigid outward shift of the plasma boundary by 5 cm is shown in figure 9. The resulting movement of the separatrix in real space is indicated by the vertical line in figure 9a. LLAMA’s measured brightness profile tracks the overall movement across channels in absolute space, but maintains a similar profile when plotted in normalized flux space. The tracking with plasma movement demonstrates that the measured profiles are not due to diagnostic or geometric effects. The profiles in Fig. 9 are from ELM-synced analysis examining the last 65-98% of the ELM cycle. Figure 10 demonstrates the response of the brightness profiles to an increasing outboard gas puff across three shots: a base case with no additional gas (180910), 40 Torr-L/s gas puff (180914), and 80 Torr-L/s (180916). The displayed data examines time windows with steady state behavior and
FIG. 9: (a) Absolutely calibrated brightness profiles from the HFS and LFS arrays plotted in a) real space, $R$, and b) normalized flux space, $\psi_n$. Brightness is shown to track the movement of the separatrix via a rigid shift of 5 cm of the bulk plasma. The separatrix location is represented by the vertical line is ELM-synchronized including only the last 65-98% of the ELM cycle. As the gas puff rate increases, increasing the neutrals in the scrape of layer, the brightness profile increases as anticipated. The brightness gradient also increases as the gas puff rate increases. The resulting neutral density and ionization rate evaluated at the peak of the LFS brightness can be seen in table I.

Overall, the profile trends for both views agree with expectation and track with plasma shifts. The LFS profile show a brightness which peaks around the separatrix, similar to observations on C-Mod. The signal on the HFS is an order of magnitude larger than the LFS. Similar inboard-outboard asymmetries were observed for Ly-$\alpha$ measurements on C-Mod, $B_\alpha$ measurements on DIII-D and for neutral density temperature on Aditya-U. Poloidal asymmetries have also been suggested by modeling on DIII-D using the SOLPS code and several other machines. The HFS measurements also show significant brightness from well inside the separator, where the temperature would not suggest a significant neutral population for emitting Ly-$\alpha$ radiation. The source of this radiation is under investigation.
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<table>
<thead>
<tr>
<th>Shot</th>
<th>Additional Gas Rate [Torr L s(^{-1})]</th>
<th>Neutral Density ([10^{14} \text{ m}^{-3}])</th>
<th>Ionization Rate ([10^{21} \text{ m}^{-3} \text{s}^{-1}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>180910</td>
<td>0</td>
<td>3.3 ± 0.8</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>180914</td>
<td>40</td>
<td>6 ± 1</td>
<td>2.0 ± 0.4</td>
</tr>
<tr>
<td>180916</td>
<td>80</td>
<td>8 ± 1</td>
<td>2.6 ± 0.5</td>
</tr>
</tbody>
</table>

**TABLE I:** Neutral atomic density and ionization rate evaluated at the peak of the brightness from the LFS LLAMA array for the profiles shown in figure 10. Errors are calculated from mapping, calibration, background effects and variation within the window of data analyzed.

**FIG. 10:** Brightness profiles for a scan of increasing deuterium gas puff performed in DIII-D at 1.8 MA and target line average density of \(7 \times 10^{13} \text{ cm}^3\). The scan consists of a base case with no additional gas puff, labeled no gas (shot 180910), a 40 Torr-L/s gas puff (190914), and 80 Torr-L/s (180916).

The core radiation peak could be the result of neutrals penetrating deeper than expected through charge exchange interactions in a local colder region of the plasma. Another possibility is a source of radiation either from the core or where the HFS views terminate on the LFS wall which could result in signal miss-attributed to the tangency radius in the HFS brightness.
VI. CONCLUSION AND OUTLOOK

A one dimensional \textit{Ly-\alpha} camera providing radial profiles of the HFS and LFS \textit{Ly-\alpha} brightness profiles has been developed and implemented on DIII-D. A measurement of \textit{Ly-\alpha} is achieved with VUV reflective and transmission filters which can be utilized to determine the hydrogenic neutral density. The optical filtering is able to significantly reject the neighboring C-II line emission, isolating the \textit{Ly-\alpha} line. The optical system is successfully deployed in the primary vacuum of DIII-D by utilizing advanced manufacturing techniques such as embedding a cooling loop in 3D printed Inconel septum plate and non magnetic mirror mounts. Utilizing a custom amplifier system, a rotatable pinhole mount, and novel alignment scheme, the system is able to measure the \textit{Ly-\alpha} brightness on spatial and temporal scales relevant to pedestal physics. Results from a recent commissioning experiment demonstrate anticipated brightness magnitudes and trends with gas puffing showing the diagnostic is ready for physics studies of main chamber neutral behavior.

As a passive diagnostic, LLAMA provides brightness profiles on most plasma discharges and is well suited for quantitative studies on neutral transport with relevance to pedestal structure, divertor studies, and model validation. The two views provided by the system offer a unique opportunity for investigating in-out asymmetries of neutral particle behavior. Further improvements to the diagnostic are expected including improvement of the noise characteristics to fully exploit the time resolution for brightness measurements. A second system is also under consideration for installation above the mid-plane which would allow the investigation of up-down as well as inboard-outboard asymmetries.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in DATAVERSE at [DOI Pending], reference number PSFC/JA-20-17.

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A 1D Lyman-alpha Profile Camera for Plasma Edge Neutral Studies on the DIII-D Tokamak


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Note3. See https://www.actonoptics.com/products/filters-narrowband for further information on the deployed band-bass interference filter which is a custom sized version of part FN122-XN.


Note7. See https://mcphersoninc.com/detectors/vuv-si-diode.html for further information on the NIST-calibrated photodiode.
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