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Measurement of Magnetic Field using Doppler-Free Saturation Spectroscopy (DFSS) in C-2W FRC Plasma

CRADA Final Report

CRADA Number: NFE-21-08757

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Executive Summary of CRADA work:

The Cooperative Research and Development Agreement (CRADA) between Oak Ridge National Laboratory (ORNL) and TAE Technologies (TAE) focused on implementing an existing mobile Doppler-free saturation spectroscopy (DFSS) diagnostic to determine the direction of the equilibrium magnetic field within TAE's C-2W field-reversed configuration (FRC) fusion device. Non-perturbative measurements of magnetic fields in the core of FRCs can provide critical information needed to constrain equilibrium models and for the continued advancement of the fusion research program at TAE. DFSS is a well-established, laser-based absorption spectroscopy technique used to suppress inhomogeneous (Doppler) broadening and reveal the Zeeman fine structure of the target emission lines. The collaboration involved the use of ORNL's recently constructed mobile DFSS diagnostic. The DFSS diagnostic was shipped and installed on C-2W in February 2023. TAE's expertise was used to design and construct the mechanic support structures required to mount the optical hardware on C-2W. Additionally TAE provide critical input to minimize the noise imposed on the DFSS signal by vibrations of the mechanic support structure during operations. DFSS data was obtained for over 500 C-2W shots and will continue until the expiration of this CRADA on September 30th 2023. Over the course of this work, significant progress was made to maximize the signal to noise (SNR) ratio. Analysis of recently acquired data is on-going, however, initial indications are highly suggestive that a DFSS signal above background has been successfully acquired in C-2W.

1. Background

The advanced beam-driven FRC plasma, such as in the TAE Technologies C-2U/C-2W devices [1,2], is a simple compact toroid magnetic confinement system, without toroidal coils linking the plasma, and thus with predominantly poloidal fields. FRC plasmas have an unique magnetic field radial profile that goes to zero field at null-locations (called O-point) and reverses direction of the axial magnetic field [3]. Measurements of internal magnetic field profile are important to verify the presence of the FRC in the confinement chamber and anchor equilibrium models. Further, successful operation of C-2W requires application of edge biasing to generate radial electric fields that help stabilize, control and enhance the FRC plasma.

Measurements of low magnetic field in high temperature plasmas, like in TAE Technologies' high performance FRCs, needs special consideration. Probes (magnetic and electrostatic) or similar insertable diagnostics not only get easily damaged but also severely degrades plasma performance. Line-splitting signals from conventional optical emission spectroscopy (OES) techniques are difficult to resolve due to large Doppler broadening of spectral lines at high temperatures. Moreover, Zeeman signals are small in FRCs due to low fields. DFSS is a laser-based technique capable of reducing Doppler broadening and practically eliminating instrument broadening present in conventional OES measured spectra [4–6]. Coupling this technique's spectral sensitivity with the accuracy of current state of the art quantum mechanical modelling yields an extremely powerful diagnostic for non-intrusive measurements of magnetic fields in FRC plasma devices.

2. Statement of Objectives

The following are the technical objectives set out in the CRADA agreement (NFE-21-08757) for collaboration between ORNL and TAE regarding DFSS.

a. Install mobile DFSS diagnostic on C-2W.

b. Validate that adequate signal-to-noise ratio (SNR) as well as temporal and spatial resolution can be achieved with DFSS in C-2W plasma.

c. Demonstrate the capability of DFSS to non-intrusively measure low magnetic fields and its direction in the core of the FRC plasma.

d. Experimentally assess the presence of a reversed magnetic field configuration inside the C-2W plasma.

3. Technical Discussion of Work Performed

3.1. DFSS Diagnostic Installation on C-2W

The DFSS diagnostic used for this work was designed, fabricated, assembled, and tested at ORNL. This effort was carried out independently of the CRADA and was funded under an ARPA-E grant. Once the DFSS diagnostic testing phase was completed at ORNL, the system was disassembled and packaged for shipment to TAE. The DFSS diagnostic arrived at TAE Technologies on February 13th 2023 and was installed over the next seven days. The DFSS diagnostic was completely operational by February 21st 2023. Figure 1 presents images of the DFSS diagnostic laser and controller hardware installed in the diagnostic laboratory at TAE and the optical hardware installed on C-2W.

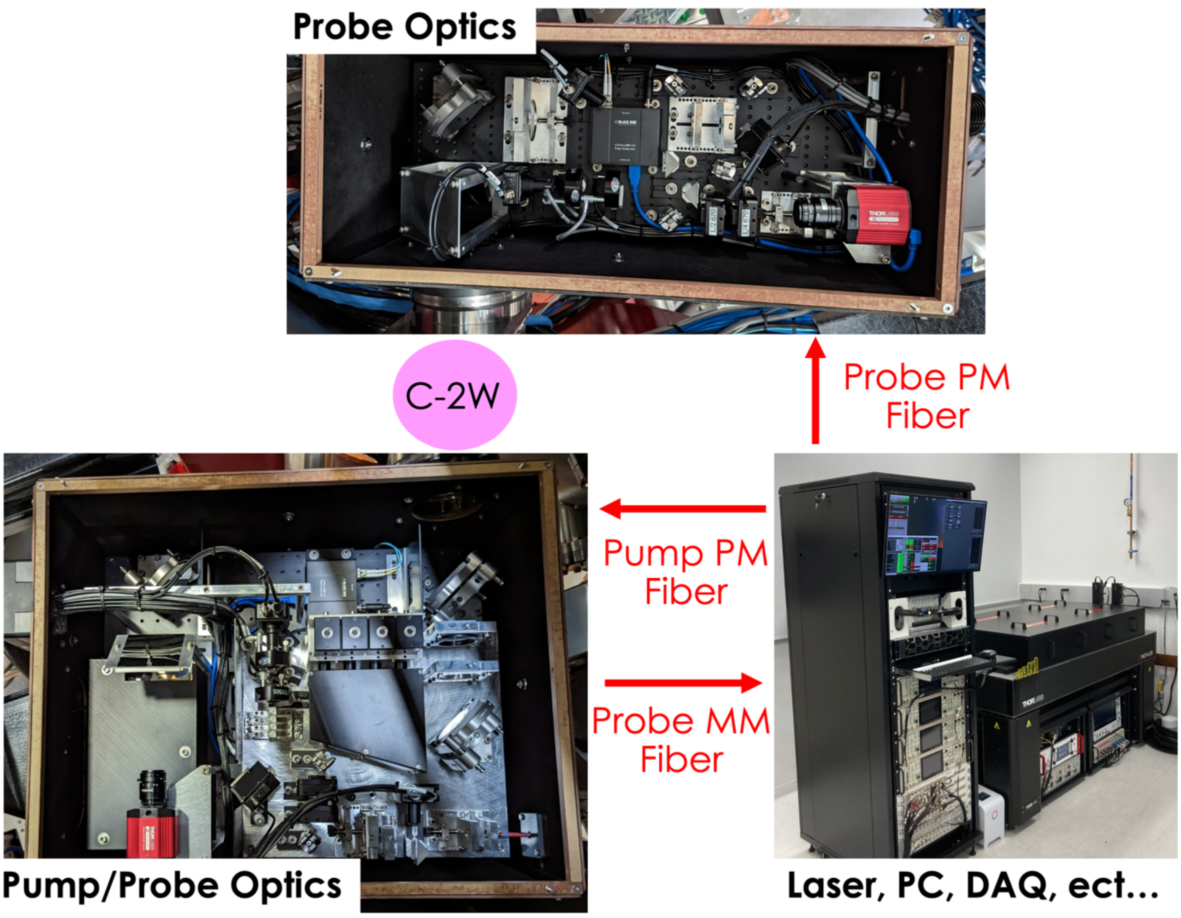


Figure 1. The DFSS diagnostic laser and control hardware in the diagnostic laboratory at TAE is coupled to the optical hardware installed on C-2W by fiber optic cable. Polarization maintaining (PM) fiber connects the laser source to the optical assemblies. Multimode (MM) fiber connects the probe beam transmitted through C-2W to the detects in the diagnostic laboratory.

The DFSS diagnostic was installed to yield a probe/pump angle of 0.9 degrees. The beam shaping was initially set to yield an intersection length of 25 mm. However, after DFSS data acquisition and analysis it became evident that a larger intersection length was needed to maximum the SNR. The intersection length was then set to 500 mm. The installed DFSS diagnostic geometry yields a residual Doppler broadening of 0.08 Å for the expected neutral temperature of 1 keV. To date, 500 shots with DFSS data have been obtained. Currently, the DFSS diagnostic is being operated by TAE under the remote assistance of ORNL. Work is underway to obtain enough data to increase the SNR above the noise floor by averaging. Data acquisition will continue until the expiration of the CRADA on September 30th 2023.

3.2. DFSS Diagnostic Data Acquisition on C-2W

During initial operation of the DFSS diagnostic it was determined experimentally that the signal level was substantially lower than the noise floor of the system. Three actions were identified to increase the signal level above the noise floor: 1) reduce the laser noise, 2) decrease the mechanical vibration experienced by the optical assemblies installed on C-2W, and 3) average over a large dataset. To reduce the laser noise, ORNL developed a numerical method in which the measured laser noise could be subtracted from the signal data. To measure the laser noise, one of the four signal data channels was dedicated as a background. The measured laser noise was digitally subtracted from the three remaining signal data channels by shifting/scaling the noise until the fluctuation amplitude was minimized during a time window after the shot. This method decreased our noise floor substantially, typically by a factor of 30. Figure 2 presents a 5 μS window of raw signal data (black) and noise subtracted signal data (red).

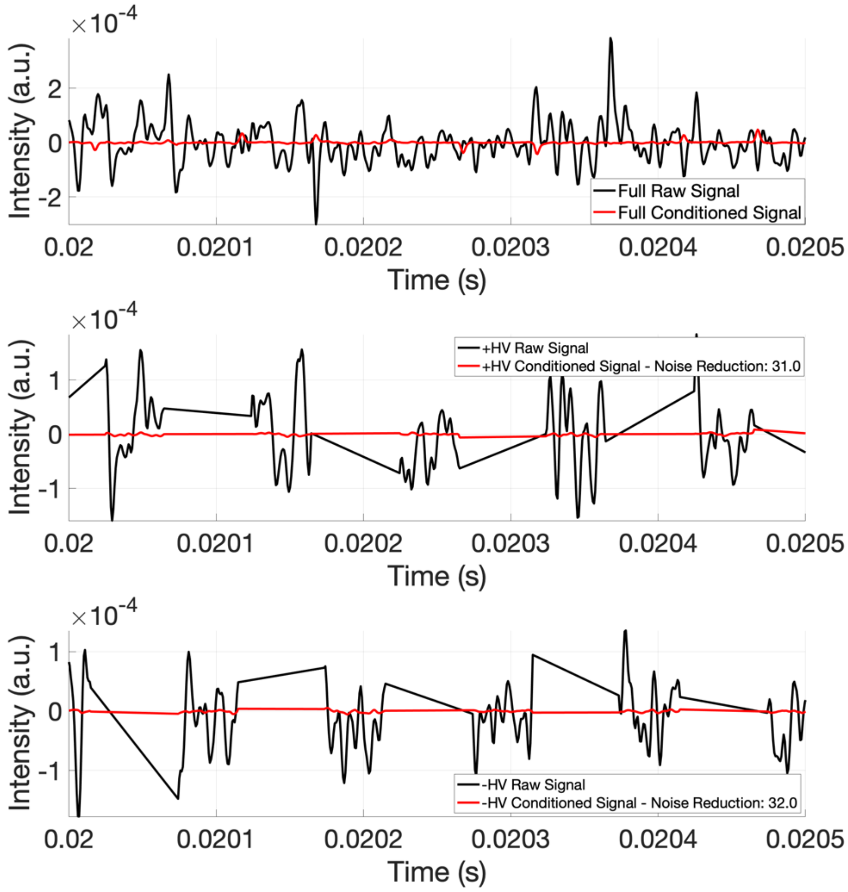
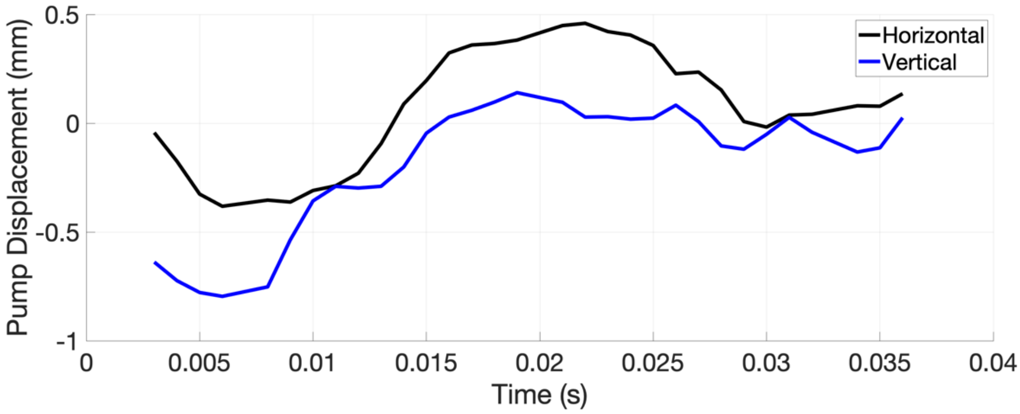


Figure 2. Snapshot of the raw (black) and noise subtracted (red) signal data. A noise reduction on the order of 30 is typically achieved.

The DFSS diagnostic implements a real-time alignment system for both pump and probe beams that is capable of correcting for mechanical vibrations having a frequency of ≤30 Hz. The natural vibration frequency spectrum for C-2W has strong 45 and 90 Hz components and is thus outside of the operational range for real-time alignment system. It was found that normal operation of C-2W generated a vibration amplitude of approximately 3 mm pk-pk for both the pump and probe beams after exiting the vessel, approximately 6 m from the beam source. The observed 3 mm pk-pk noise amplitude added substantial noise to the signal data. To decrease the vibration amplitude generated by C-2W operations, struts were added to the optical assembly support platforms and the current waveforms used to power the magnetic field coils were smoothed. It was found that the struts and current waveform smoothing increased and decreased, respectively, the vibration amplitude. The struts were removed and C-2W operations focused on DFSS data collection implemented current waveform smoothing. In this scenario the vibration amplitude was decreased to 0.5 to 1 mm pk-pk. The pump and probe displacement for a typical C-2W shot is presented in Fig. 3. After implementing the noise subtraction algorithm and current waveform smoothing the noise floor of the DFSS system was 1.0 μV.



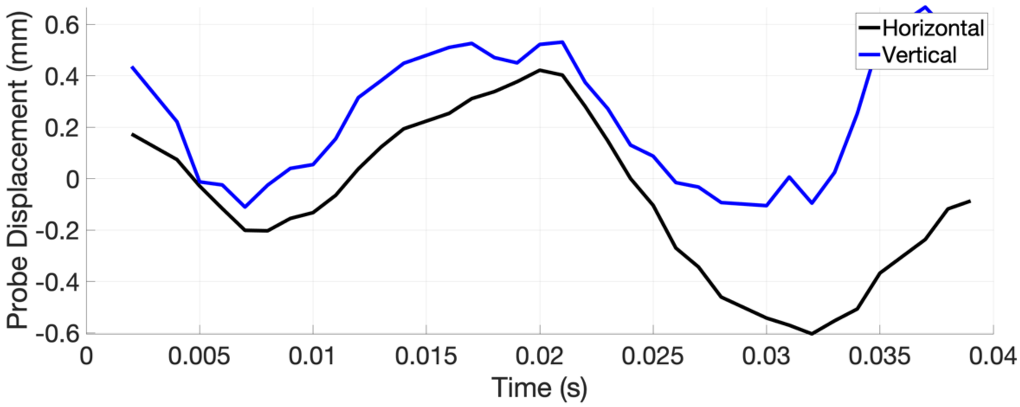


Figure 3. Pump and probe beam displacement during a typical C-2W shot with smoothing of the current waveform used to power the magnetic field coils. The displacement is measured after exiting C-2W, approximately 6 m from the beam source.

To estimate the signal level a series of 25 shots were averaged. Figure 4 presents the results of the 25 shot average. The time series and corresponding fast Fourier transform (FFT) of the data is presented in the left and right panes, respectively, of Fig. 4. The red curves of Fig. 4 represent the shot-averaged DFSS signal spectrum obtained during the 10 to 40 μS time window of the shots. The black curves of Fig. 4 represent the shot-averaged DFSS background spectrum obtained after the shot. A collection of 100 background spectrum were calculated at unique time windows. The ensemble of background spectrum is used to calculate the noise floor. The blue curves of Fig 4. represent the average of the ensemble of the shot-averaged DFSS background spectrum and are used to determine the offset.

Analyzing the shot-averaged spectrum of Fig. 4, It was found that the signal level was on the order of 0.25 μV. Using the measured 1.0 μV noise floor, the SNR for a single shot was determined to be 0.25. An SNR on the order of 4 is required to analyze the data with sufficient accuracy. To achieve a sixteen times increase in the SNR, approximately 250 shots must be averaged due to the square-root scaling of Poisson statistics. Work is underway to obtain a 250-shot dataset for both a mirror and FRC magnetic field equilibrium. Data acquisition will continue until the expiration of the CRADA on September 30th 2023.

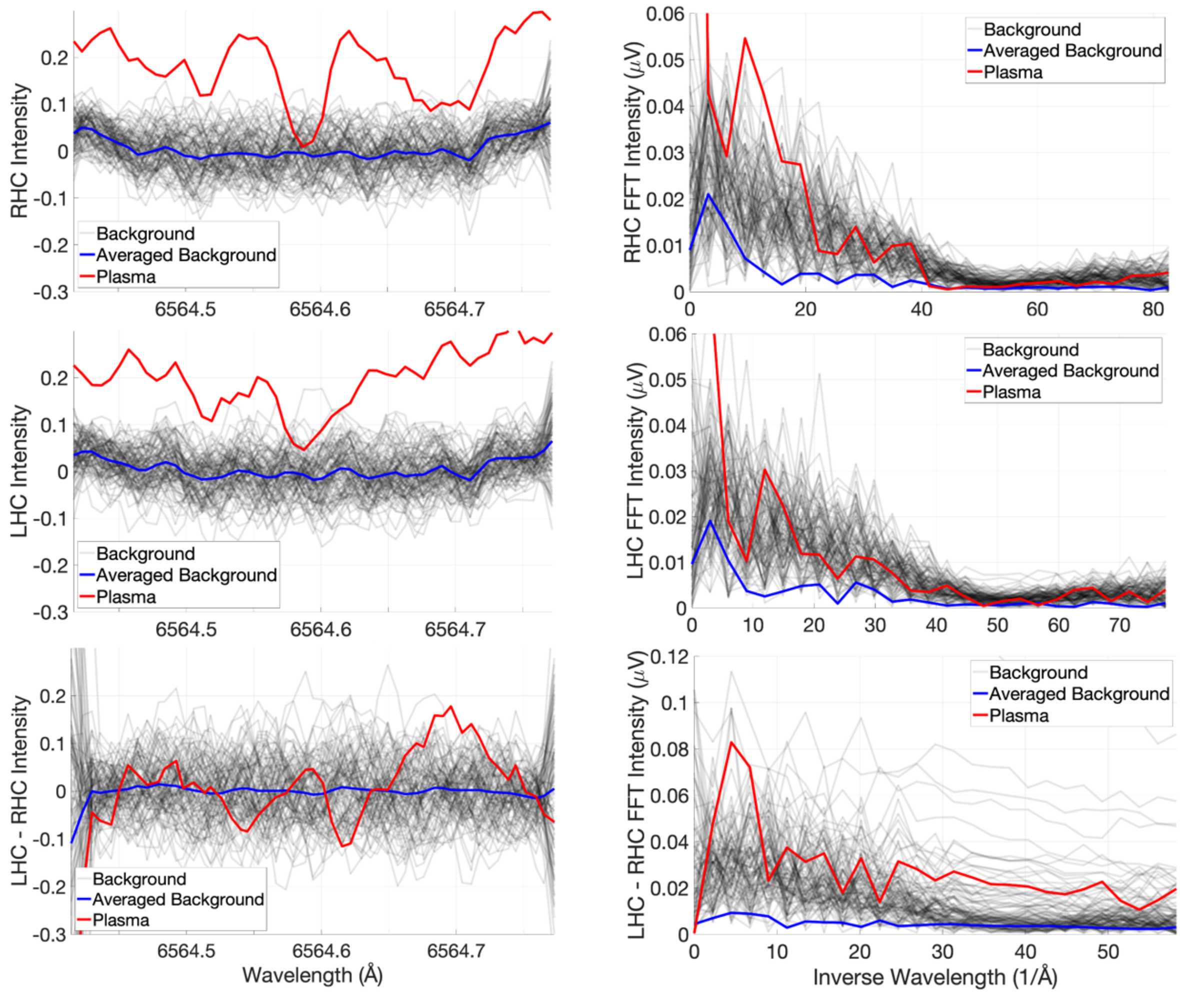


Figure 4. DFSS spectral results averaged over 25 shots. The time series and corresponding fast Fourier transform (FFT) of the data is presented in the left and right panes, respectively. The red curves represent the shot-averaged DFSS signal spectrum obtained during the 10 to 40 μS time window of the shots. The black curves represent the shot-averaged DFSS background spectrum obtained after the shot.

4. Potential Applications and Technology Transfer

The completed work has identified a suitable configuration for DFSS to be implemented in C-2W to measure local magnetic field vector in the core of the device. Analysis suggests that the diagnostic has the potential to serve as a tool to monitor the magnitude and direction of the magnetic field with a near axial probe/pump beam geometry using circular polarization. The results from this collaboration provides an exciting opportunity to experimentally validate theoretical predictions with a proof-of-concept system and, potentially, the design and construction of TAE's own DFSS system. This would bring a substantial mitigation of technical and financial risk for the company.

5. Benefits of the Collaboration to DOE's Mission

High-level motivation and capabilities of the DFSS diagnostic is to provide experimentally measured equilibrium B-field data needed to optimize and accelerate the fusion concept. The project also strengthens the collaboration between TAE and ORNL, benefiting both parties by cross-fertilization of ideas and opening the doors for further cooperation in fruitful public-private partnerships.

Appendix: C-2W Plasma Parameters

To accurate simulate the DFSS data obtained in C-2W, information of some key machine parameters is needed to use as inputs to the code. Key parameters are listed below:

A.1. Electron Density and Temperature

Electron density profiles are measured with Thomson scattering (local) and FIR (line-averaged) diagnostic systems at the A-plane (z = 0 m). Electron density profiles are typically hollow, peaking inside the FRC (at r ~ 0.75–0.85*R_s). Current range of electron density at the axis (r = 0 cm) varies from ~ 0.6–1.2e19 m^{-3}. Density peak in the range of ~ 1.2–2.4e19 m^{-3} and near the CV wall (r = 80 cm) triple Langmuir probe measurements of n_e is approximately 0.5–1.5e17 m^{-3}.

Electron temperature profiles are measured with Thomson scattering diagnostic at the A-plane. Temperature profiles are nearly flat inside the FRC and has a fairly sharp gradient at the scrape-off-layer. Current range of flat top T_e ~ 200–600 eV and values near the CV wall (r ~ 80 cm) measured by triple Langmuir probe is approximately 10–30 eV.

A.2. Total and Metastable Density of Neutrals in the CV

A neutral particle model analyser model (DEGAS2) was used to estimate the neutral distribution in the confinement vessel due to various sources of neutrals. Results are typically coupled with a Monte Carlo fast-ion model to calculate charge-exchange losses. Results are compared to images of Balmer-alpha emission from filtered, high-speed cameras and other diagnostics. Estimates of metastable (n=2) density are derived from Lyman-alpha emission profiles. The Lyman-alpha emissivity can be calculated using photo emission coefficients from Open-ADAS, together with estimates of neutral density from DEGAS2 and measured electron densities and temperatures. Overall profile shape in agreement with previously measured Balmer-alpha profiles; significant variability in the open field-line region relates to assumptions used in the DEGAS2 reconstruction. Using these Lyman-alpha profiles, estimated metastable density in the A-plane of C-2W are obtained. At the center of the machine, the population density of atomic neutrals in the metastable state (n =2) are expected to be of the order of 10^5–10^6 cm^{-3} in C-2W.

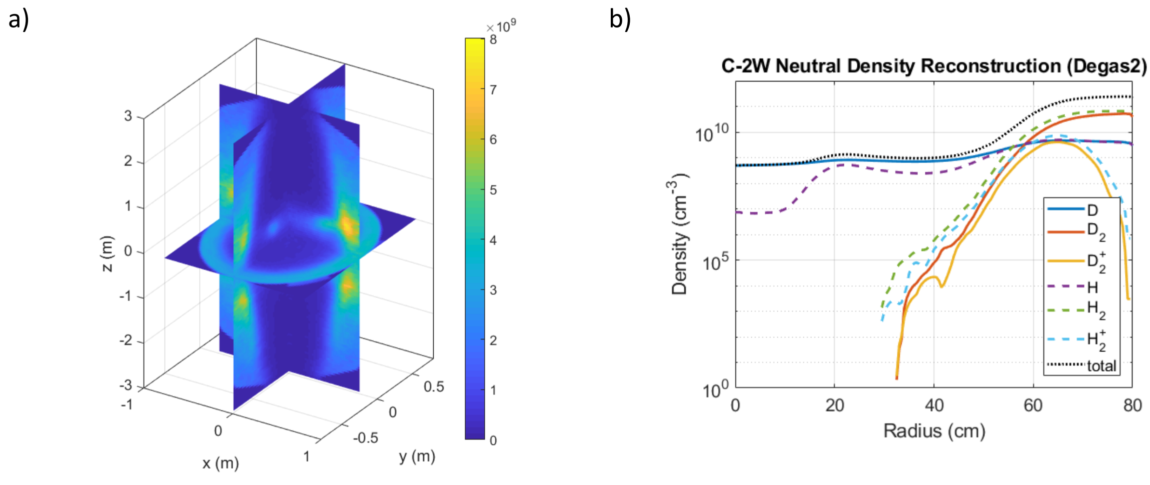


Figure 5. (a) 3D neutral density reconstruction with DEGAS2 and (b) 1D radial densities averaged over azimuthal angle and an axial region representing what is sampled by fast ions: +/- 1 m from A plane.

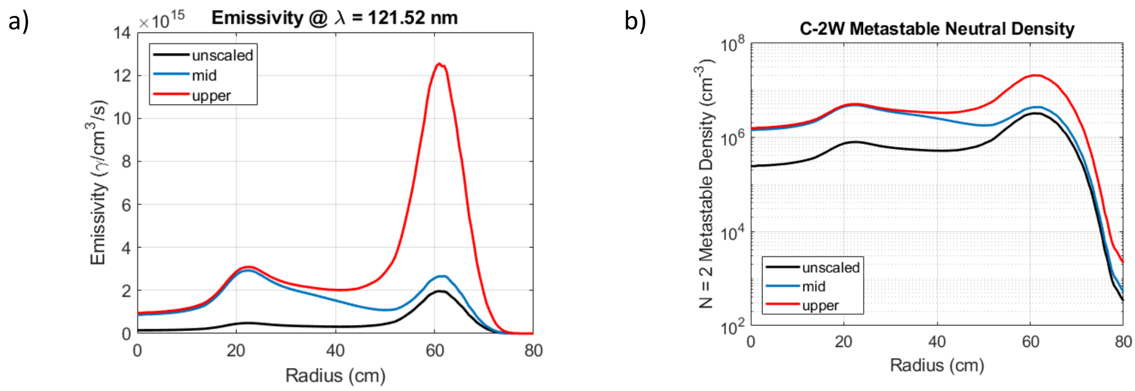


Figure 6. (a) Lyman alpha emissivity and (b) estimated metastable density profiles in the CV.

A.3. Neutral Temperature Estimates in the FRC Core

Hot neutrals in the FRC core are sustained by NBI injection through a cascade of charge-exchange processes between the beams and the bulk plasma ions. To first order, we will assume that hot neutrals in the core are thermalized with main-ions. A charge-exchange recombination spectroscopy diagnostic (ChERS) recently deployed to C-2W measured main-ion temperatures in the range of 0.1–0.8 keV for different bias schemes. Here, these values will be used as estimates of neutral temperature for the purpose of assessing DFSS signals.

Refences

1. Binderbauer, M. W., T. Tajima, L. C. Steinhauer, E. Garate, M. Tuszewski, L. Schmitz, H. Y. Guo, et al. “A High Performance Field-Reversed Configuration.” Physics of Plasmas 22, no. 5 (May 2015): 056110. https://doi.org/10.1063/1.4920950.

2. Gota, H., M. W. Binderbauer, T. Tajima, S. Putvinski, M. Tuszewski, B. H. Deng, S. A. Dettrick, et al. “Formation of Hot, Stable, Long-Lived Field-Reversed Configuration Plasmas on the C-2W Device.” Nuclear Fusion 59, no. 11 (June 2019): 112009. https://doi.org/10.1088/1741-4326/ab0be9.

3. Tuszewski, M. “Field Reversed Configurations.” Nuclear Fusion 28, no. 11 (November 1, 1988): 2033. https://doi.org/10.1088/0029-5515/28/11/008.

4. Martin, E. H., A. Zafar, J. B. O. Caughman, R. C. Isler, and G. L. Bell. “Applications of Doppler-Free Saturation Spectroscopy for Edge Physics Studies (Invited).” Review of Scientific Instruments 87, no. 11 (November 1, 2016): 11E402. https://doi.org/10.1063/1.4961287.

5. Zafar, Abdullah, Elijah Martin, and Steve Shannon. “High Resolution Magnetic Field Measurements in Hydrogen and Helium Plasmas Using Active Laser Spectroscopy.” Review of Scientific Instruments 89, no. 10 (October 1, 2018): 10D126. https://doi.org/10.1063/1.5039334.

6. Zafar, Abdullah, Elijah Martin, and Steve Shannon. “Doppler-Free, Stark Broadened Profiles at Low Plasma Densities in Helium.” Journal of Quantitative Spectroscopy and Radiative Transfer 230 (June 1, 2019): 48–55. https://doi.org/10.1016/j.jqsrt.2019.03.020.

7. Martin, Elijah H. “Electric Field Measurements of the Capacitively Coupled Magnetized RF Sheath Utilizing Passive Optical Emission Spectroscopy.” PhD Thesis, North Carolina State University, 2014