Doppler-Free Saturation Spectroscopy (DFSS) for Magnetic and Electric Field Measurements in an FRC plasma

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A SUMMARY REPORT SUBMITTED TO THE US DEPARTMENT OF ENERGY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS OUTLINED IN THE CRADA
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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 a feasibility study of Doppler-free saturation spectroscopy (DFSS) as a diagnostic strategy to measure the internal magnetic and electric fields of TAE's C-2W field-reversed configuration (FRC) fusion device. Non-perturbative measurements of magnetic and electric 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 linewidths and reveal Zeeman/Stark split hyperfine structures of target emission lines. The collaboration involved the use of ORNL's suite of experimentally validated quantum mechanical modelling codes to simulate theoretical atomic spectra for a variety of machine parameters and laser beam configurations. TAE's expertise was heavily used to provide measurements/models of the required machine parameters needed as inputs to the simulations. Results of an all-encompassing error analysis demonstrate the favourable capabilities of the diagnostic and provided invaluable insights as to how DFSS can be best used to accurately measure internal B/E-fields 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. A direct measurement of electric fields would greatly improve the understanding of underlying physics associated with edge biasing in C-2W.

Measurements of low magnetic field and electric 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 and Stark 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 electric and magnetic fields in FRC plasma devices.

2. Statement of Objectives

The following are the technical objectives set out in the CRADA No. NFE-20-0843- for collaboration between ORNL and TAE regarding DFSS:

Objective 1 - Electric and Magnetic Field Error Analysis

An error analysis will be conducted to determine the minimum magnetic and electric field that can be determined by DFSS and the measurement uncertainty as a function of magnetic/electric field magnitude and direction. The error analysis will be conducted using a Monte Carlo approach while incorporating possible sources of systematic error such as a non-Maxwellian distribution of H atoms. Potential sources of systematic error will be identified using C-2W plasma parameters. Specifically, the theoretical analysis will address the following points:

• An estimate of the range of Bz & Er at the center of the field reversed plasma (x=0, y=0, z=0) in C-2W that can be measured using DFSS.
• Presentation of simulated expected spectra with varying magnetic and electric field and plasma parameters to highlight the Bz & Er sensitivity of the DFSS diagnostic.
• Detailed uncertainty analysis and estimate of the signal-to-noise ratio of Bz & Er over the C-2W plasma parameters.
• Estimate of magnitudes of the broadening mechanisms used to simulate the line profiles (e.g., instrument, natural, power, Stark, and Doppler) over the plasma parameter range.
• The limiting time resolution of a DFSS diagnostic implementing the Toptica DL pro diode laser and potential solutions to increase the time response to ≤1ms.
• The criteria used for the line-selection (e.g. Ha, Hb, Hg) from the plasma spectrum.
• Calculation of the required laser beam power needed to implement DFSS on C-2W.

Objective 2 - Preliminary Design of a DFSS System for C-2W FRC plasma

Recommend preliminary design for the DFSS system based on C-2W machine parameters, accessibility, and the desired spatial and temporal resolution. The design will include an itemized list of optical components and laser hardware with estimated costs and expected lead times for any custom made or hard to obtain parts. A schematic of the optical layout and recommended machine interface will be supplied.

3. Technical work performed

3.1. Modelling of DFSS spectra: ORNL's EZSSS and sFIT codes

For the feasibility study outlined in this CRADA collaboration between ORNL and TAE, several plasma parameters from TAE's C-2W FRC device were used as inputs to a quantum mechanical modelling code developed by ORNL, the Explicit Zeeman Stark Spectral Simulator (EZSSS). For a given set of magnetic and electric field vectors, pump/probe beam configuration, and plasma parameters, a synthetic spectrum is simulated using EZSSS in a three-step process [7]:

1. The solution to the Schrödinger equation containing both the static magnetic and time periodic electric field vector operators is found.
2. The transition probabilities are calculated using the electric dipole connection operator and time-dependent first order perturbation theory.
3. The continuous spectrum is calculated by convoluting the discrete spectra with the DFSS relevant broadening mechanisms: uncertainty principle, power broadening, Stark broadening, and residual Doppler broadening.

Noise is then added to the simulated DFSS absorption lineshape that reflects an expected signal-to-noise ratio (SNR) based on the overall population in the lower metastable state population, spatial resolution, laser power, number of channels, etc. The synthetic spectrum is then fitted using a second code developed by ORNL called sFIT. The code determines the electric and magnetic field vector from the synthetic spectra using a statistical minimization routine until convergence. The neutral propeties and fields for C-2W that are used in the simulations are described in the Appendix.

3.2. Spatial/Spectral resolution analysis

3.2.1. Beam shaping and ray tracing

Spatial resolution characterization drives the probe-pump beam angle for a DFSS diagnostic. The larger the angle between both beams, the higher the spatial resolution of the measurement yet the smaller the reduction in Doppler broadening. For high temperature plasmas, residual Doppler broadening basically determines the resolution of magnetic/electric field measurements since it is the dominant broadening mechanism and fundamentally limits the ability to resolve split fine-structures of target transitions.

A parametric study was conducted to determine the spatial resolution that can be achieved based on geometric properties of the pump/probe laser beams. (i.e., beam shape, optics size, focal length, angle, etc.). For a fiber-coupled DFSS system, laser light is routed to the measurement location using single-mode polarization maintaining (PM) fibers, which produces high quality Gaussian beams. Diffraction limited optics can then be utilized to shape the beams accordingly (e.g., circular, elliptical and/or rectangular profile) and focus them to a small spot size for a spatially-resolved measurement. The resulting intersection volume between both beams dictates the resolution along the optical axis as well as the DFSS signal level.

A code was developed at ORNL to run ray tracing simulations for different starting pump/probe laser beam sizes and angles. Figure 1.a shows the spatial variation in the beams cross-section for 10.5 mm FWHM collimated beams (starting point) focused at 1.5 m and aligned at 1° with respect to each other (probe aligned with the optical axis). Figure 1.b shows the volumetric resolution that can be achieved with this configuration, defined by the fraction of area under Doppler-free signal intensity curve (70% of the area corresponds to a width of 92.1 mm). Figure 2 shows several spatial resolution curves as a function of pump/probe angle for different starting beam sizes and focal lengths. Smaller initial beam size leads to a bigger focused spot size and thus a larger overlapping volume and worse spatial resolution. Increasing probe/pump beam angle leads to better spatial resolution yet larger residual Doppler broadening.

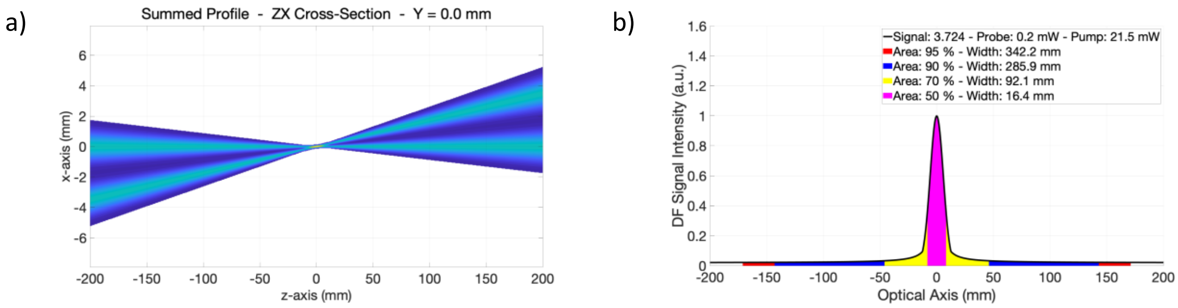

Figure 1. (a) Spatial variation of Gaussian-shaped probe/pump laser beam cross-sections (b) Doppler free signal intensity highlighting the spatial resolution achievable with this beam layout.

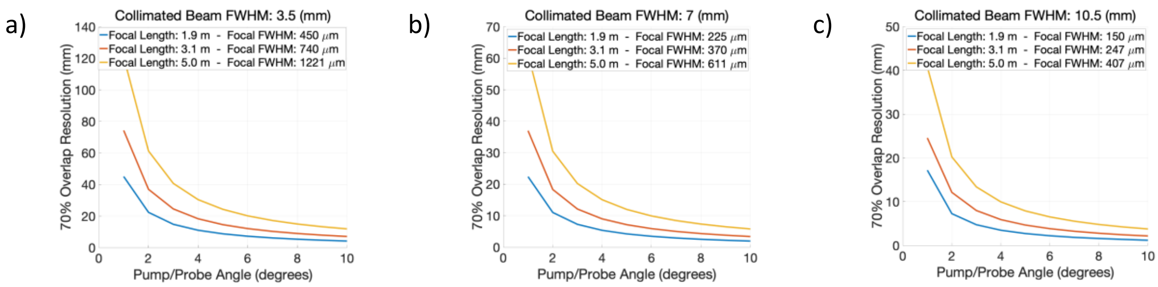

Figure 2. Spatial resolution characterized by 70% area overlap of Doppler free signal as a function of pump/probe beam angle for different starting beam FWHM sizes (a) 3.5 mm, (b) 7 mm, (c) 10.5 mm.

3.2.2. Residual Doppler broadening

Given the high temperatures of charge-exchange neutrals in the FRC core, residual Doppler broadening limits the resolution of a DFSS diagnostic in C-2W due to smearing of fine-structure spectra. The residual full-width at half-maximum (FWHM) for different neutral deuterium temperatures and pump/probe beam angles was calculated (see Fig 3.). Higher temperatures imply flatter absorption lines with less peak intensity and, consequently, higher values of residual broadening ($\Delta\nu_{D,\text{res}} \propto \sqrt{T_D}$). It was found that for good measurement resolution (<20 Gauss) at expected neutral temperatures, pump/probe beam angles should be kept below ~1°.

a) b)

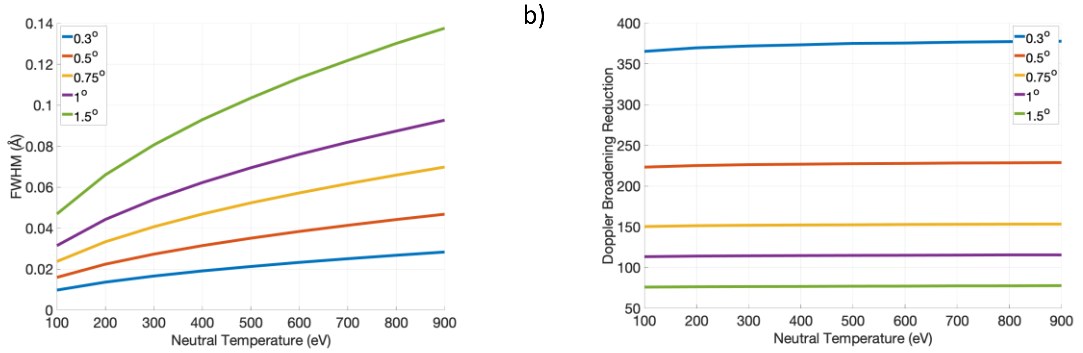

Figure 3. (a) Residual Doppler broadening FWHM as a function of expected neutral temperatures in the FRC core of C-2W for various pump/probe beam angles and (b) the respective FWHM Doppler broadening reduction.

3.3. Initial error analysis

3.3.1. Magnetic field

Simulation of fine-structure splitting of D_α transitions were performed for expected internal magnetic field in C-2W (Figure 4). Different set of simulations were conducted for field profiles parallel (‖) and perpendicular (⊥) to beam propagation. In addition, both linear and circular laser light polarizations were incorporated in the models. For modelling the D_α spectrum, Einstein A-coefficients from NIST were integrated over all solid angles (4π steradians) and crossover resonances were included. Initial simulations included Stark broadening assuming 10^{13} cm^{-3} electron density and added random noise for a signal-to-noise ratio (SNR) of ~20 (considered 5% white noise, 3% Poisson noise). Estimated error (Figure 5) was determined by fitting 100 spectra per each input condition (sum of χ^2); the code solves Schrodinger's equation considering laser line-of-sight with respect to magnetic field orientation and beam polarization.

- Linear polarization (LP): both σ and π polarizations were evaluated. For $B_\perp$ (magnetic field perpendicular to laser LOS), key differences between σ and π components were due to crossover resonances (important to avoid residual FWHM higher than 0.14 Å). For $B_\parallel$ (magnetic field parallel to laser LOS) no clear differentiation between σ and π spectrum was observed.
- Circular polarization (CP): both σ^+ and σ^- polarizations were evaluated. No clear differences for the $B_\perp$ case, similar to $B_\parallel$ for LP. However, for $B_\parallel$ simulations with CP, σ^+ and σ^- polarizations produced shifted spectra that could be easily resolved (i.e., very sensitive to magnetic field). Also, as previously expected, circular dichroism enables directionality of the field to be extracted.

a) b)

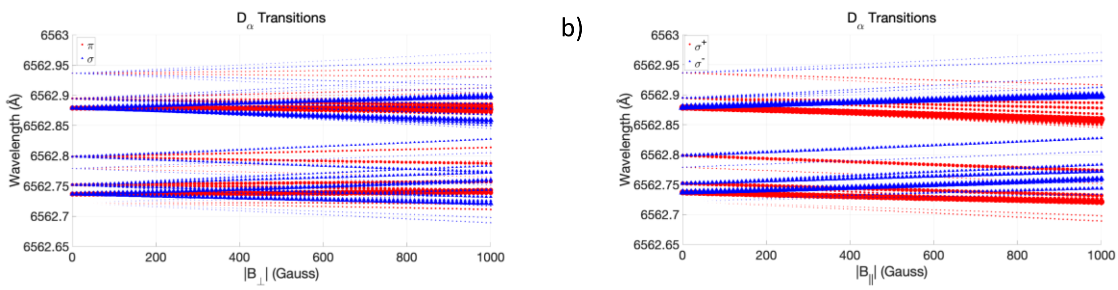

Figure 4. Example fine-structure splitting of D_α energy levels for polarized laser light as a function of magnetic field orientation: (a) Linearly polarized beam perpendicular to B-field and (b) circularly polarized beam parallel to B-field

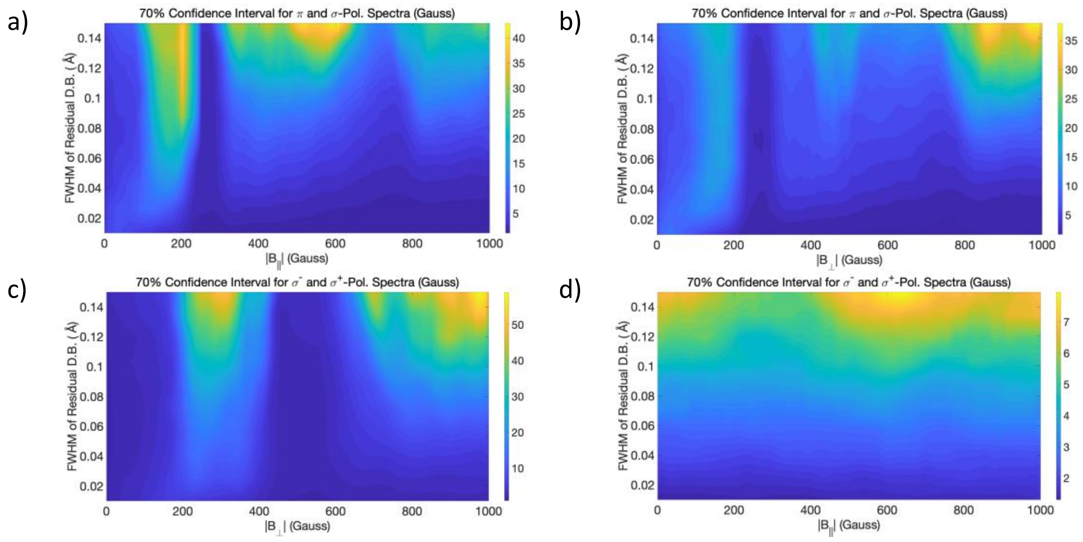

Figure 5. Error analysis output for (a) LP with $B_{\parallel}$, (b) LP with $B_{\perp}$, (c) CP with $B_{\perp}$, and (d) CP with $B_{\parallel}$.

3.3.2. Electric field

Error analysis was performed to evaluate the sensitivity of the DFSS technique to expected electric fields in C-2W. Analysis was done for E_r from 0-60 V/cm (E_r pointing perpendicular to B_z). For $B_{\perp}$ with linear polarization (beam parallel to E_r) spectra is somewhat sensitive, but completely dependent on crossover resonances. Crossover resonance model needs to be further validated (experimentally). Results showed that the Stark effect for the D_{α} transition had approximately a 1-to-1 V/cm to Gauss sensitivity (compared to splitting due to Zeeman effect). Considering that the expected electric fields (5-20 V/cm) are relatively small compared to magnetic fields (500-1000 Gauss), they cannot be extracted with sufficient accuracy using DFSS in C-2W. Electric fields, however, must be considered as a fitting parameter in a full error analysis for magnetic fields.

3.4. Full error analysis

One of the primary goals of this collaboration between ORNL and TAE Technologies was to determine whether or not it would be possible to implement DFSS in C-2W to measure the internal magnetic field vector in the center of the device with sufficient accuracy and spatial resolution. To this end, a full error analysis was performed using C-2W plasma parameters as well as all relevant fitting parameters (neutral temperature, polarization vector, offset of Gaussian distribution, radial electric field, instrumental broadening, power broadening, etc.). It was determined that the best chance to make a successful magnetic field measurement with minimum error was to explore the longitudinal Zeeman effect with circular polarization.

Figure 6 presents the simulated error in the axial magnetic field as a function of magnitude/polarity and the angle between the pump and probe laser beams. Using circular polarized laser beams provides a nearly uniform response with respect to the magnetic field magnitude and the highest accuracy. The spatial and signal-to-noise ratio (SNR) are functions of the angle between the pump and probe laser beams. For increasing angle, the spatial resolution decreases and the SNR increases. Multiple pump/probe angles were simulated to help determine the optimal setpoint when considering accuracy, spatial resolution, and SNR. The spatial resolution is expected to be within 20 and 60 mm for the angle range of 0.5 to 1.0 degree. The exact spatial resolution is a function of the focal length and thus the setup on C-2W.

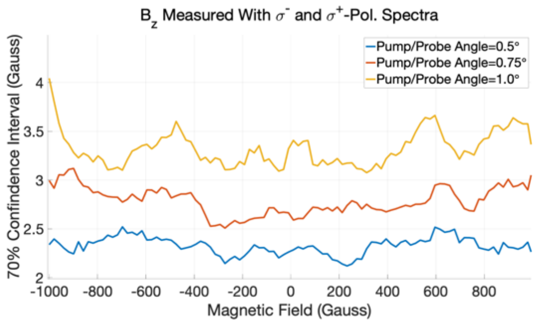

Figure 6. Simulated error associated with an axial magnetic field measurement in the C-2W machine. Left and right-hand circular polarized laser beams provide the highest accuracy (< 5 Gauss).

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.

List of presentations, diagnostic development, publications:

1. INFUSE Workshop (Virtual) December 1st, 2020. Deepak Gupta (TAE): "Doppler-Free Saturation Spectroscopy (DFSS) for Magnetic & Electric Field Measurements in a FRC plasma"
2. ARPA-E: FUSION Diagnostics Program Review (Virtual) March 5, 2021. Elijah H. Martin (ORNL): "Magnetic Field Vector Measurements Using Doppler-Free Saturation Spectroscopy."
3. Design and deployment of a proof-of-principle system at TAE for first measurements of internal magnetic field vector in an FRC (currently underway). Deepak Gupta and Marcel Nations (TAE), Elijah Martin (ORNL)
4. Publication(s) are expected for this work

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: Estimations of neutral properties and fields in C-2W

In order to estimate the signal-to-noise achievable with DFSS at the desired E/B-field measurement location in C-2W, information of some key machine parameters is needed to use as inputs to the code. Key parameters used in this feasibility study are listed below:

5.1. Estimate of the 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.

5.2. 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

5.3. Magnetic and electric filed profiles in the CV

Multiple interpretative models at TAE would benefit tremendously from internal B/E-field measurements to constrain solutions. It would enable TAE to better understand, control and enhance FRC plasmas in its devices and accelerate progress toward the company's goal of developing a commercial fusion reactor. At present, several methods are utilized at TAE to reconstruct FRC magnetic field topologies. Below is a list of the main strategies:

- Flux mapping w/ Bayesian inference based on a current tomography model
- 2D interpretative equilibrium solver: pressure balance including kinetic fast ions.
- Grushenka: reconstructs fully 2D equilibrium using routine magnetics data by solving a modified Grad-Shafranov equation which accounts for rapidly rotating fast-ions.
- Lamy-Ridge 2D multi-fluid equilibrium code with Monte Carlo beam transport: investigation of FRC equilibrium with fast ions from NBI (predictive code).

In addition, electric filed profiles can be reconstructed using radial momemntum balace and the direct measurements of impurity ion rotation, density, and temperature profiles in the CV.

5.4. Survey emission spectra

A set of intensity-calibrated survey spectrometers installed on the CV routinely measure volumetrically averaged emission in C-2W. The spectrum gives an overall picture of the plasma content with several impurity lines in addition to the Balmer lines for hydrogen/deuterium. This study will focus on the feasibility of targeting the D_α transition (~3–4x brighter than D_β) emitted from the hot neutral population in the FRC core sustained by neutral beam injection.

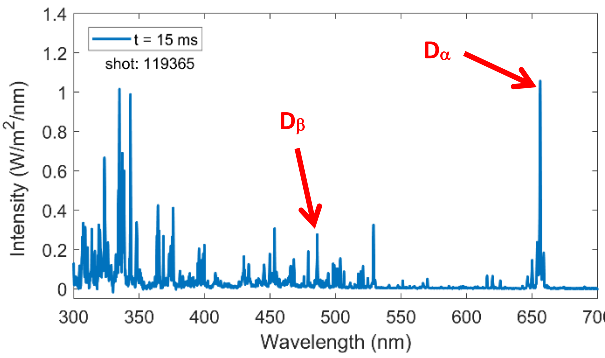

Figure D. Four survey spectrometers installed in the CV cover the UV-VIS-NIR spectral range: 250–1100 nm. Line-integrated data obtained from uncollimated views (NA ~ 0.22).

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