Electron Temperature Measurement using Collisional Radiative Model in PFRC-II

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The PFRC-II experiment is a plasma containment device that aims to improve odd-parity rotating magnetic field (RMF) heating[1]. This method drives electrical current and is theoretically capable of heating a plasma to fusion temperatures. To achieve this goal, a myriad of different parameters must be assessed during a pulse that lasts only milliseconds long. The primary objective of my research was to study the electron temperature values as a function of time observed in each discharge of the PFRC-II experiment. A non-intrusive method of studying electron temperature is examining specific wavelengths of visible light that are emitted during an RMF pulse. These spectra are produced due to electron-impact and spontaneous excitation of neutral hydrogen followed by radiative de-excitation. The spectroscopic data central to studying electron temperature is the intensity of the three lowest energy spectra in the Hydrogen Balmer Series. To ensure a strong level of precision, an Ocean Optics Spectrometer was utilized to measure all three spectra and background radiation simultaneously. Using the empirically generated spectroscopic data and a collisional radiative model's approximations, electron temperature values were produced without impeding the heating process of the PFRC-II experiment.

Introduction

The Princeton Field Revered Configuration(PFRC) experiment is a plasma confinement device that is highly unique in design and purpose (Fig 1). It is currently on its second of four

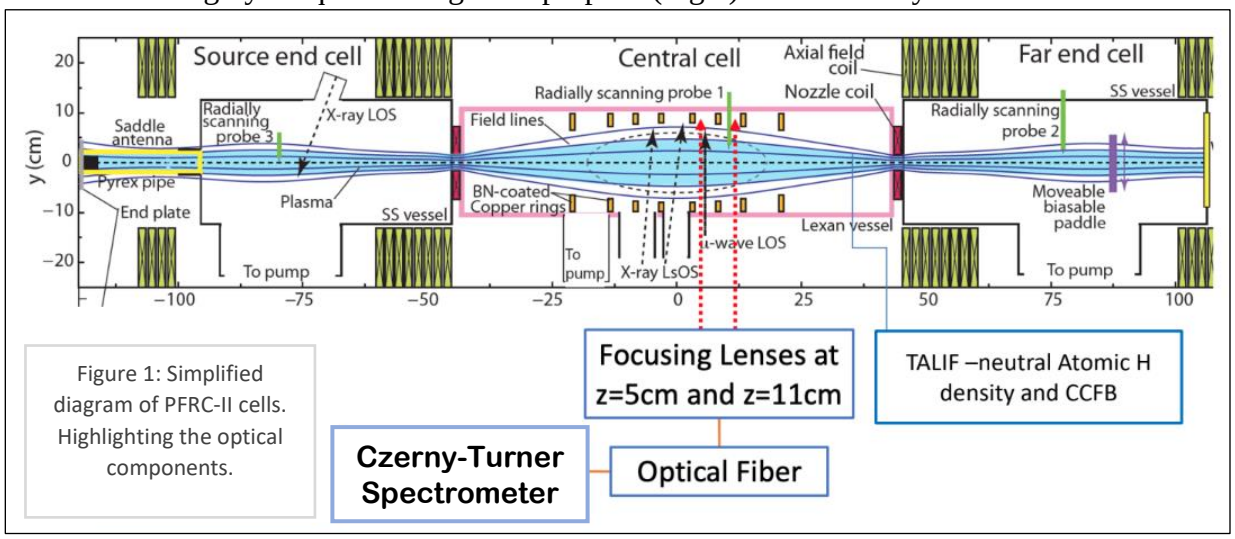

Figure 1: Simplified diagram of PFRC-II cells. Highlighting the optical components.

proposed iterations, progressing towards the goal of producing 10 MW of clean power. The PFRC-II is a high-β, fusion reactor with no toroidal magnetic field. Unlike conventional tokamaks that are striving to utilize the Deuterium-Tritium fuel cycle, the PFRC-II looks to explore aneutronic fusion in the form of the Dueterium-Helium-3 fuel cycle. It is a compact design, while some reactors need large warehouses to house the reactor and an equally massive place to house an intricate array of support systems, the PFRC-II can fit inside the back of a long-haul truck. This makes the reactor a prime candidate for specialized tasks like long range space exploration, providing emergency power rapidly in the wake of a natural disaster, or powering emerging energy markets in a simple and sustainable way. Its modular design is also invaluable for maintaining the device, while tokamaks may take years to update and repair, the turnaround for a future power producing PFRC iteration would take a fraction of this time.

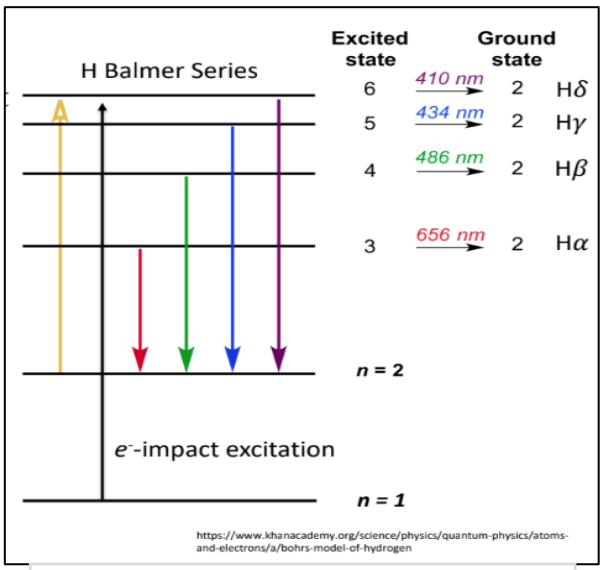

Figure 2: The ratio between H_α and H_β over the duration of an RMF pulse.

Method

During a pulse from the RMF, intense light from the visible spectrum is emitted from the reactor. Using non-intrusive methods of observation, including spectroscopy and interferometry, visible light can be collected, analyzed, and used to generate valuable information about the plasma in the central cell. For the purposes of this research, the intensities of the four spectra of the Balmer Series and the ratios between neighboring spectra were used to estimate electron

temperature values over the duration of an RMF pulse. The four spectra; H_α, H_β, H_γ, and H_δ, had wavelengths of 410 nm, 434 nm, 486 nm, and 656 nm, respectively (fig 2). Two different mediums of light capture were utilized: a monochromator and a visible light spectrometer. The monochromator can capture the intensity of a single narrow wavelength at a time. For the purposes of this research project, this device proved insufficient. The intensities of multiple wavelengths of light needed to be measured at each time step. To this end, a Czerny-Turner visible light spectrometer was utilized. Incoming photons are channeled through an optical fiber to the spectrometer and reflected through the device and onto a multichannel detector. The intensities of light between the 400 nm and 720 nm wavelength was collected and digitally displayed by the spectroscopic software.

Collisional Radiative Model

To get from spectral data to electron temperatures, a collisional radiative model[2] was utilized. To eventually reach fusion-ready temperatures, the PFRC-II uses a combination of molecular (H_2) and atomic (H) hydrogen in current experimental runs. The emission rate of specific spectra, Γ, is the product of the population density of the excited state and the Einstein coefficient ($A_{n1\rightarrow n2}$) for the $n_1 \rightarrow n_2$ where n_1 is the excited state and n_2 is the state of decay. It is also a product of the linear combination of the two species of hydrogen multiplied by the electron density (n_e) and a constant generated by the collisional radiative model that is a function of T_e and n_e. For H_α:

$$\Gamma_\alpha = n(3)A_{3\rightarrow 2} \tag{1}$$

$$\Gamma_\alpha = n_H n_e C_{H,\alpha}(T_e, n_e) + n_{H_2} n_e C_{H_2,\alpha}(T_e, n_e) \tag{2}$$

Generating the ratio between two emission rates, dividing Γ_β by Γ_α, the ratio between the two would end up being a function of T_e and n_e and the ratio between n_H and n_{H2}.

$$\frac{\Gamma_\beta}{\Gamma_\alpha} = f(T_e, n_e, \frac{n_{H_2}}{n_H}) \tag{3}$$

The collisional radiative model outputs a simulated rate of change in the population of an excited state over time based on a series of parameters listed below[2,3]:

- Collisional Radiative Model:

$$\frac{dn(i)}{dt} = \Big(n_e \sum_{k\neq i} n(k)\langle\sigma v\rangle_{k\rightarrow i} + \sum_{k>i} A_{k\rightarrow i} n(k)\Big) - \Big(n_e \sum_{i\neq k} n(i)\langle\sigma v\rangle_{i\rightarrow k} + \sum_{k<i} A_{i\rightarrow k} n(i)\Big) - n_e n(i)\langle\sigma v\rangle_{i\rightarrow \text{ion}} + n_H n_e \langle\sigma v\rangle_{H\rightarrow i} + n_{H_2} n_e \langle\sigma v\rangle_{H_2\rightarrow i} \tag{4}$$

Collisional excitation/deexcitation into state i; Radiative decay into state i; Collisional excitation/deexcitation out of state i; Radiative decay out of state i; Ionization of state i; Ground state H excitation to state i; Population via H_2 dissociation

Since the electron density, the ratio between atomic and molecular hydrogen, and (through spectroscopy) the ratio between the emissions of spectra are all known values, an electron temperature value can be generated using the collisional radiative model.

Monochromator Results:

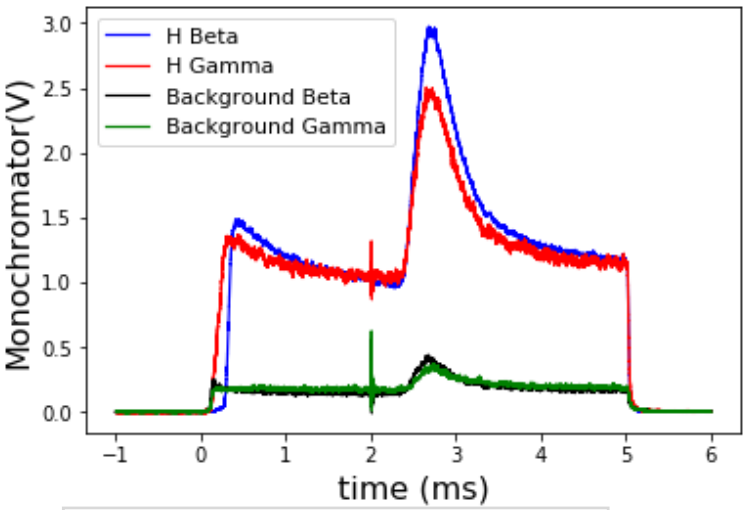

Figure 3: The strength of the voltage produced by each spectra over the course of an RMF pulse.

Since a monochromator can measure only one wavelength at any given time, the device must sweep over a large interval of wavelengths over time to generate information about all four visible spectra in the Balmer Series. Issues arose with the monochromator when trying to generate accurate ratio between the intensities of H_β and H_γ. As shown in Figure 2, H_γ peaks before H_β does during the period of rapid densification when the RMF pulse begins. H_γ is emitted due to electron de-excitation of the atomic decay, 5→2, while H_β is for 4→2. It would be expected that the population density of the n=4 state would be strictly larger than the population density of the n=3 state. While this issue is most apparent at t = 0.1 ms, H_β is below H_γ again at about t = 2.3 ms. These anomalies occur during periods of rapid change in the population of excited states. This severely undermines the legitimacy of potential electron temperature measurements. In figure 3, it is apparent that once the data is applied to the collisional radiative model, the model generates unrealistic values for the temperatures reached within the PFRC-II[1]. Whether this is a possible physical phenomenon for a mixture of atomic and molecular hydrogen goes beyond the scope of this paper, however, the reaction to this anomaly can be discussed further. Assuming this issue was a measurement delay, it was decided that the monochromator had to be replaced with a spectrometer that can easily take simultaneous measurements.

Spectrometer Results:

The Czerny-Turner spectrometer was connected to an optical fiber looking into lenses facing the central cell the PFRC-II. Twenty spectra were saved for a series of 100 RMF pulses that lasted 4 ms each. For this set of runs, the RMFs ran at 4.3 MHz and went up to 69 kW of utilized power. Intensities of photons within the visible light spectrum were recorded at each time step which lasted about 200 µs. Frames denoting the same time point during a RMF pulse were averaged together. Viewing an individual spectrum from this run (Appendix 1-4), it is apparent that H_γ and H_δ

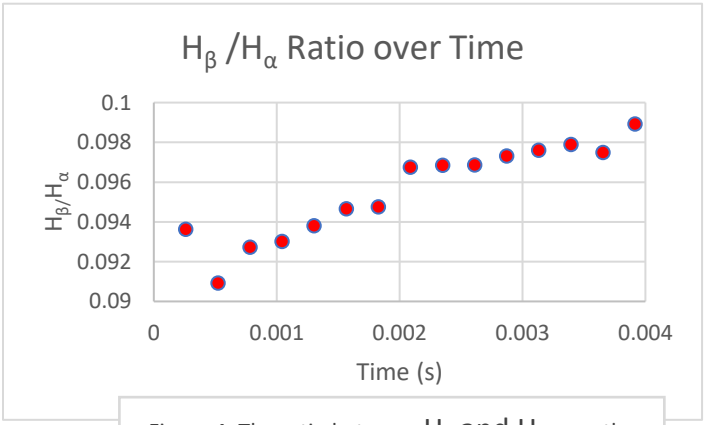

Figure 4: The ratio between H_α and H_β over the duration of an RMF pulse.

were too faint to generate meaningful data that is differentiable from background noise. H_α and H_β were both clearly differentiable from the background, though the shape of the H_α peak should be studied further due to its asymmetric nature. The peaks of H_α and H_β with local backgrounds subtracted from each spectra individually. Figure 4 shows the average ratio between these peaks over the course of a RMF pulse. From the plot it appears that the ratio between H_α and H_β gets larger with time. This indicates an increase in species entering and leaving higher excited states at greater rates the longer the pulse lasts.

Future Work

There are a variety of issues that need to address to verify the legitimacy of the Balmer Ratios generated from recent runs of the PFRC-II with the new spectrometer installed. Some error is unavoidable due to the nature of the gratings within the instrument. It is apparent that over the range of the spectrometer (figure 5), there are different grating efficiencies at different wavelengths of light. The PFRC-II uses a spectrometer using the grating denoted by "Grating #9", which has a rather constant efficiency between 400 nm and 560 nm. The device loses declines in efficiency above 560 nm, which may prove problematic for H_α measurement. The instrument response function of a spectrometer also limits the accuracy of spectral data by broadening spectral lines. To minimize this broadening a technique an absolute irradiance measurement can be taken from a lamp of known spectral power output.

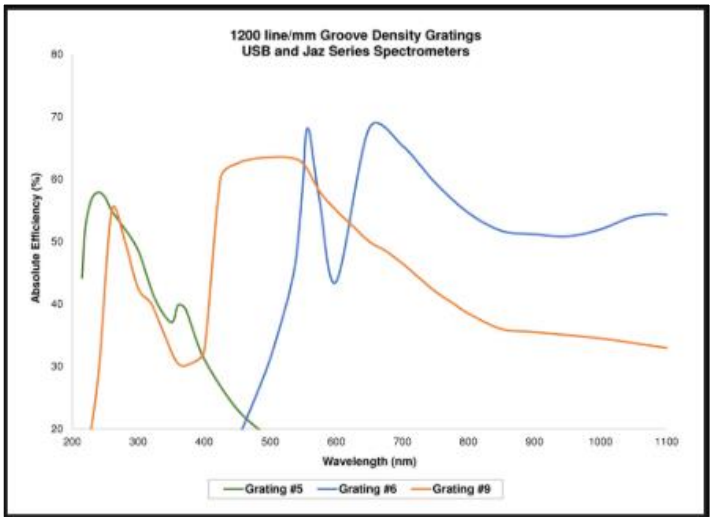

Figure 5: The grating efficiency of selected spectrometers.

While there are consistent measurements of the H_α H_β ratio with the expected values from the collisional radiative model, it is important that these results are reproduceable for other ratios as well. Getting a clear H_γ value that is clearly separated from any background noise and testing the H_γ H_β ratio is paramount to verifying the legitimacy of the H_α H_β ratio.

Acknowledgments

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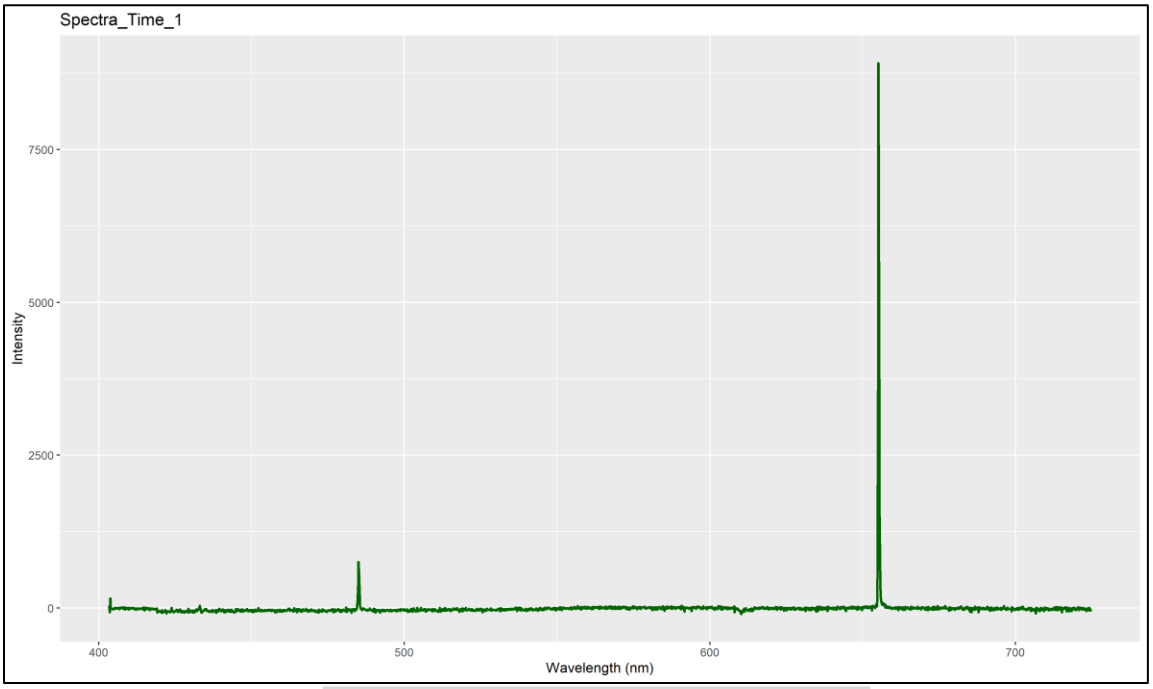
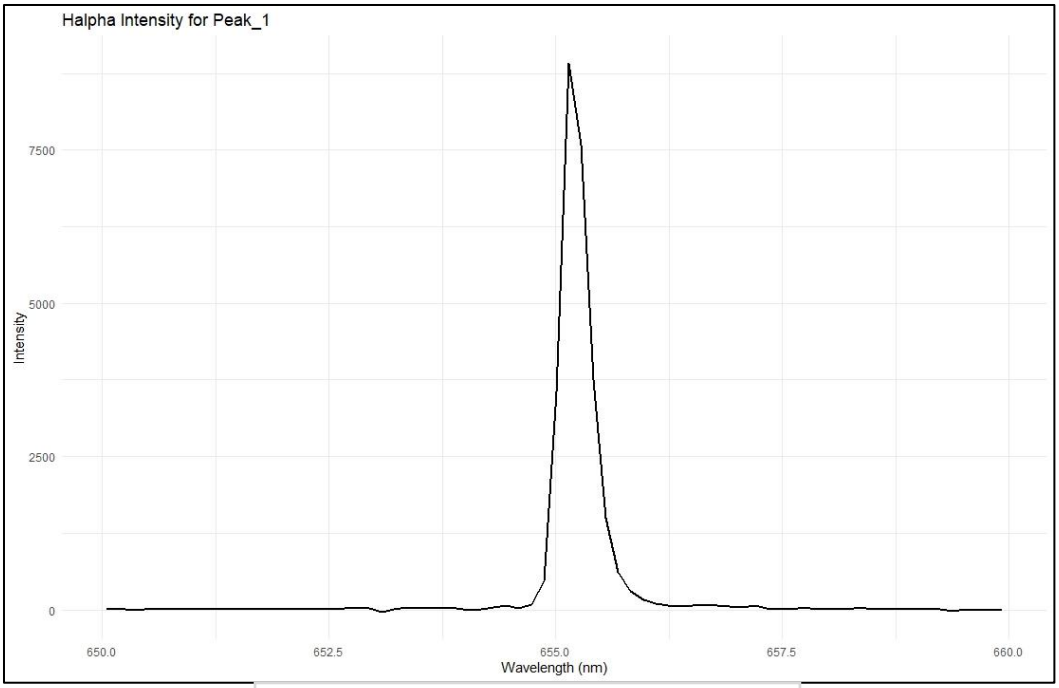
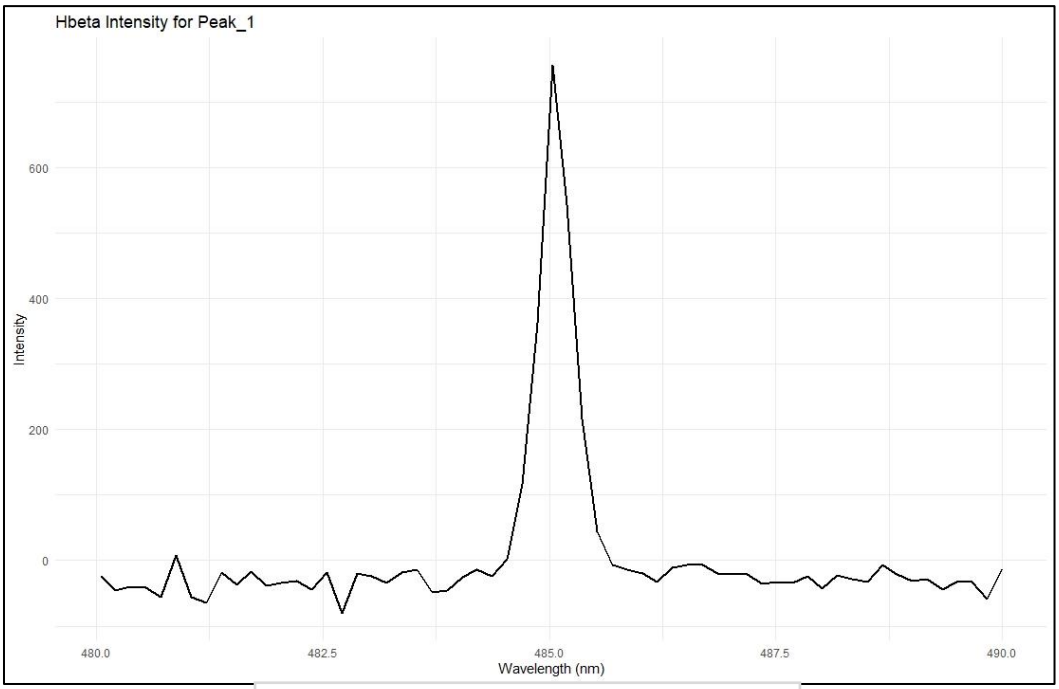
Appendix



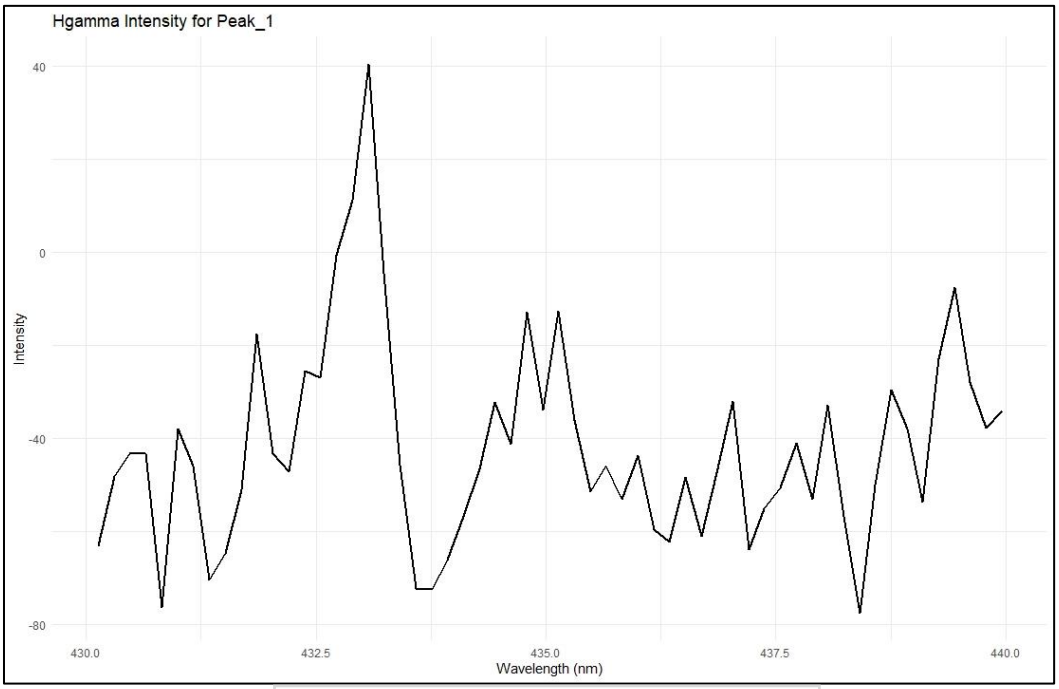
Appendix 1: Full visible spectrum.



Appendix 2: Isolated H_α peak



Appendix 3: Isolated H_β peak



Appendix 4: Isolated H_γ peak