Calibrating Modified CCD Spectrometer For Impurity Monitoring In Z-Pinch Plasma

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INTRODUCTION

The Flow Z-Pinch is an innovative method to magnetically confine a high-temperature, high-density plasma.[1] The Z Pinch has a linear configuration, where magnetic field generated from the axial current in turn confines the plasma. The Flow Z-Pinch experiments investigate using sheared axial flow to provide stability, with applications for compact fusion energy and advanced space propulsion.[2] The Flow Z-Pinch lab operates the ZaP-HD device, shown in a cross-sectional view in Figure 1.

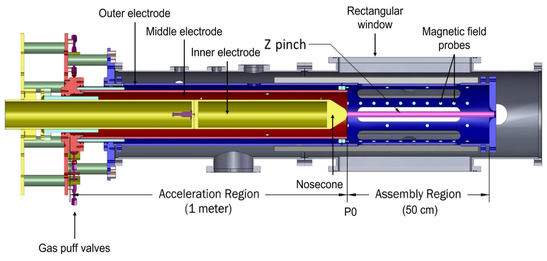

Figure 1. Cross-Sectional Diagram of ZaP-HD

MOTIVATION

In plasmas, impurities can often be produced by interactions between the high energy ions and material surfaces, which can provide useful information about plasma parameters.

> In plasma spectroscopy, measuring the width of emission profiles of impurities allows us to determine plasma parameters, such as ion velocity, which are often difficult to obtain from other diagnostics. A typical emission profile is shown in Figure 3.

> In particular, the nosecone on ZaP-HD is made up of graphite which introduces carbon impurities into the plasma.[3] Carbon has isolated spectral lines that allows accurate analysis.

> CCD spectrometer coupled with the Photomultiplier Tube (PMT) are diagnostic tools that provide wavelength and time resolved emission profiles of plasma impurities respectively.

MODIFIED SPECTROMETER

> The dial settings on the CCD spectrometer, which is a crank that controls the rotation of the diffraction grating, originally corresponded to units of angstroms.

> However, a beam splitter was installed to allow simultaneous use of the PMT, which offset the dial to wavelength conversion. A diagram of the modified spectrometer is shown in Figure 2.

> Wavelength calibration is required to find the dial setting that aligns a particular wavelength value to the middle of the spectrum.

> The PMT entrance slit spans an average of around 0.5nm of wavelength, which requires a precise calibration in order for effective use of the diagnostic.

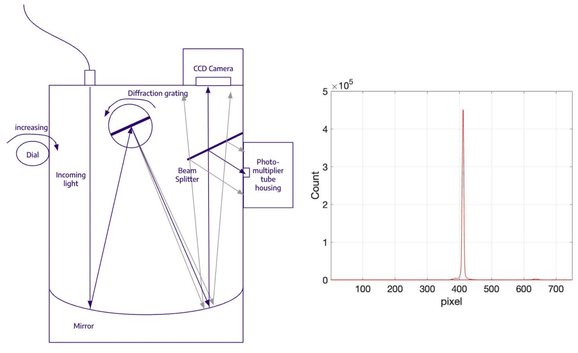

Figure 2-3. Schematic Diagram of the modified Fastie-Ebert Spectrometer (left) and a typical spectrum seen on the spectrometer (right)

WAVELENGTH CALIBRATION

> From the diffraction grating equation,

$$m\lambda = b\sin\theta \approx b\frac{y}{D}$$

$$\Delta y \approx \frac{Dm}{b}\Delta\lambda$$

we know that wavelength and distance between peaks projected to the camera pixels scales linearly. Thus, the range of wavelength contained in one spectrum scales linearly with dial setting.

> Therefore, wavelength is related to dial setting via a second degree fit.

> Wavelength calibration was then conducted with various calibration lamps. Spectra captured at different dial settings observing the same wavelength were superimposed to construct a pixel axis. Wavelength data was then fitted to dial setting using the pixel axis. The final calibration curve is presented in Figure 4.

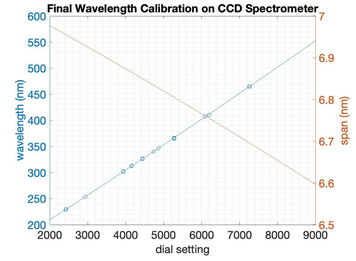

Figure 4. Final Calibration Curve of Fine Grating on the CCD Spectrometer

PHOTOMULTIPLIER TUBE (PMT) CALIBRATION

The purpose of PMT calibration is to determine the pixel location that maximizes PMT signal and improve PMT signal quality.

> PMT calibration was conducted using an electrometer, which is an instrument designed to measure voltage and current at very small scales. Figure 5 below shows the result of the calibration: middle pixel of the spectrum on the CCD spectrometer maximizes PMT signal.

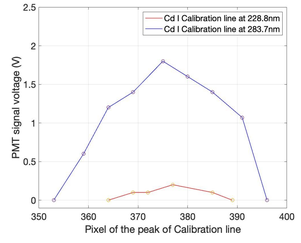

Figure 5. PMT Signal Voltage from Cadmium Calibration Lamp

> Additionally, PMT signal generated during operation usually exhibits noise due to electromagnetic interference from other diagnostics. The large frequency and magnitude of noise causes the analysis of true emission signal to be difficult. Therefore, a digital low pass filter is used on the PMT signals.

IMPURITY MONITORING

Using results from wavelength and PMT calibration, we obtained data from various impurity ions.

> Figure 6 below shows the line radiation of C-III at 229.7nm and C-V at 227.7nm respectively observed at the P10 axial location on ZaP-HD. Emission profiles of C-III and C-V confirms the progressive heating of plasma.

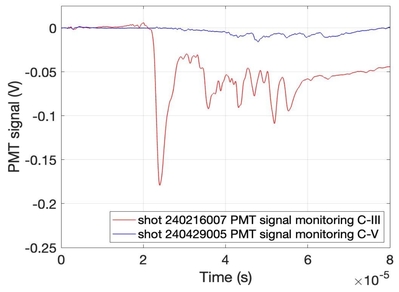

Figure 6. PMT Signal Voltage from C-III and C-V emission lines

> Early in the plasma pulse, C-III emission intensity peaks near 20us when plasma is formed.

> Later in the pulse, increase in plasma temperature causes electrons to be excited to higher energy levels, leading to measurable emission of C-V and matching a lower emission level of C-III.

CONCLUSION

> Impurities are introduced to the plasma produced in ZaP-HD due to interactions with its material surfaces.

> Two of the spectroscopy diagnostic tools, CCD spectrometer and PMT are calibrated in this research to allow for impurities to be monitored during each plasma pulse in ZaP-HD.

> In this research, comparison of emission levels of carbon allowed us to deduce qualitatively that plasma heating occurs in ZaP-HD. Plasma parameters can also be determined quantitatively using similar instruments in other research.

References:
[1]U. Shumlak, et al. Phys. Plasmas 24. 055702 (2017); https://doi.org/10.1063/1.4977468
[2]U. Shumlak. J. Appl. Phys. 127, 200901 (2020); https://doi.org/10.1063/5.0004228
[3]Khairi, A. (2021). Graphite Electrode Characterization on the ZaP-HD Sheared-Flow-Stabilized Z-Pinch Device (thesis).