Spectroscopic Analysis of Erosion Rate from Electrode Surfaces on the ZaP-HD Device

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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.

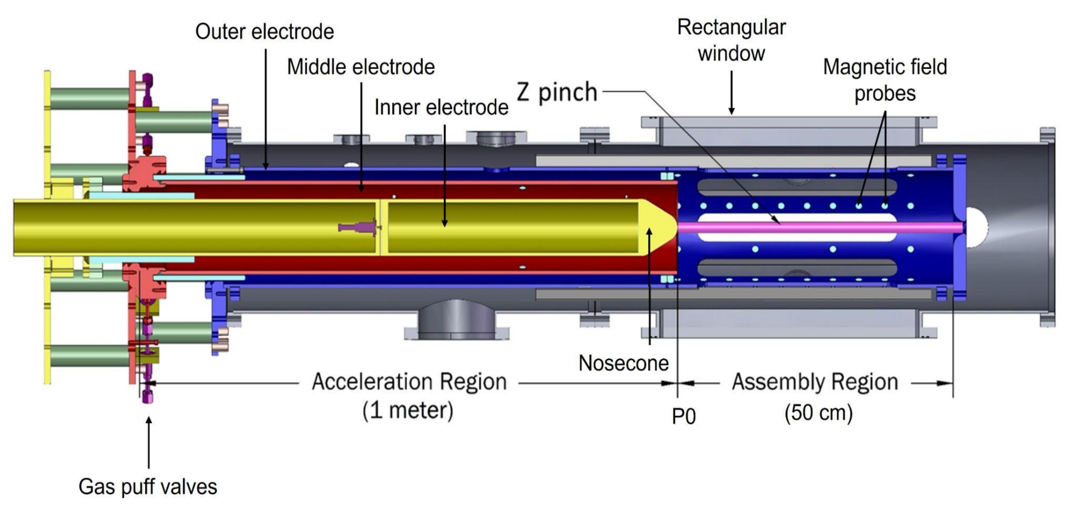

Figure 1. Cross-Sectional Diagram of ZaP-HD. ZaP-HD has three coaxial electrodes that form the pinch. he nosecone, an area of focus for erosion analysis, is the tip of the inner electrode.

MOTIVATION

Material erosion is a fundamental challenge to the lifetime and performance of plasma devices.

> Plasma-material interactions lead to sputtering, where atoms are ejected from surfaces due to energetic ion bombardment.

> In fusion systems, electrode erosion introduces impurities that degrade performance, while in electric propulsion, it lowers efficiency and can cause thruster failure.

> Diagnostic methods are needed to monitor and quantitatively evaluate erosion mitigation techniques.

> 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.

S/XB METHOD

> Various radiative processes occur in plasmas, contributing to energy loss but allowing the transmission of information through emitted photons.

> Energy is released as electrons in bounded ions transition from upper to lower energy levels.

> Line-of-sight integrated intensity of a particular line radiation is directly proportional to flux by the ionization per photon (S/XB) coefficients, given by:

$$\Gamma_A = \frac{4\pi}{1 - F_c} \frac{S}{XB} I_{\sigma,i \to j}$$

where S is the ionization rate, X is the excitation rate, B is the branching ratio, F_c is the reposition fraction that accounts for atoms that never ionize to this state.

> Coefficients obtained from OpenADAS[4] .

EXPERIMENTAL SETUP

> Erosion rate data is collected by the radial telescope that has a direct line-of-sight on the graphite nosecone. The 229.7nm UV C III line is viewed in this study.

> Collection fibers are 20 individual fused silica core fibers that are 400 μm in diameter and equally spaced apart. Fibers span a width of 23.6 mm, centered on the machine axis.

> Future work on this diagnostic expand data collection to the photomultiplier tube (PMT), which allows for time resolved measurements.

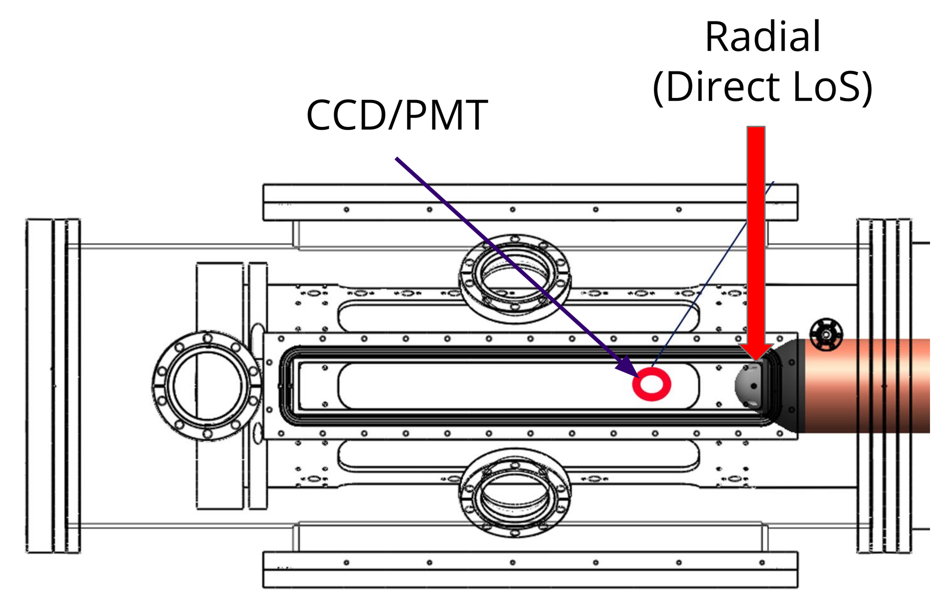

Figure 2. A schematic of the ICCD telescope placements on the ZaP-HD device. The radial telescope has a line of sight directly perpendicular to the machine central axis. The PMT is mounted on a rectangular window on the side of the machine as opposed to the top rectangular window.

ABSOLUTE CALIBRATION

> To convert the observed emission intensity level on the ICCD spectrometer to a flux measurement, an absolute calibration with a calibrated light source is required.

> Experimental hardware is implemented to replicate the attenuation on the optical path. The calibration setup is shown in Figure 3.

> The equation for the conversion factor is given below, it takes into account the difference in exposure and dark pixels:

$$Irradiance = C_{lamp} * \frac{I_{sample} - I_{dark,sample}}{I_{cal} - I_{dark,cal}} * \frac{t_{sample}}{t_{cal}}$$

where C_lamp is light source calibration data, I is the intensity in counts, and t is the respective exposure.

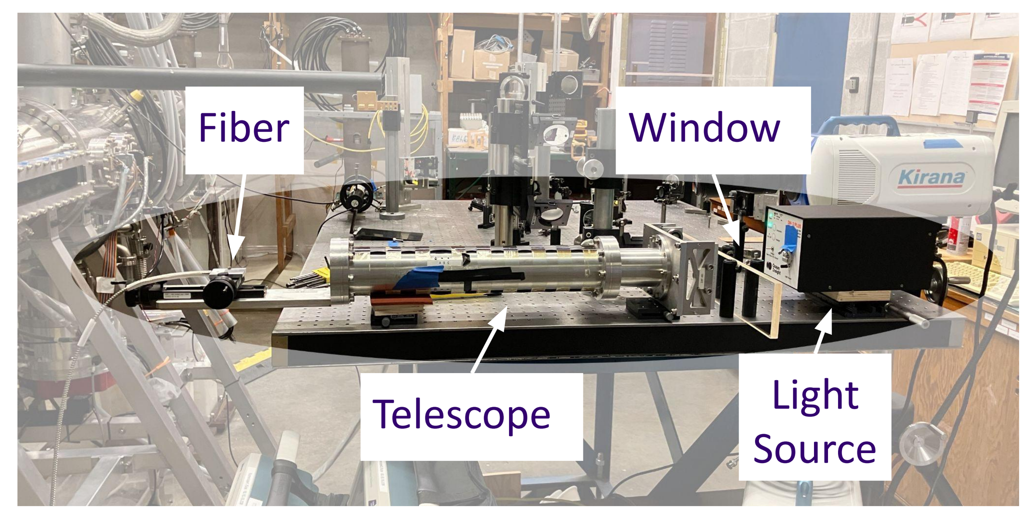

Figure 3. Absolute calibration setup consisting of fiber bundle, telescope, window and the light source.

RESULTS AND DISCUSSION

In preliminary data analysis, S/XB values were calculated using a radial distribution of electron density and temperature presented previously [1].

> Pixel space was mapped to the physical imaging location on the nosecone tip, as shown in Figure 4. Using what is known as a sharp pinch assumption, erosion rates are calculated up to a radius of 0.3 cm.

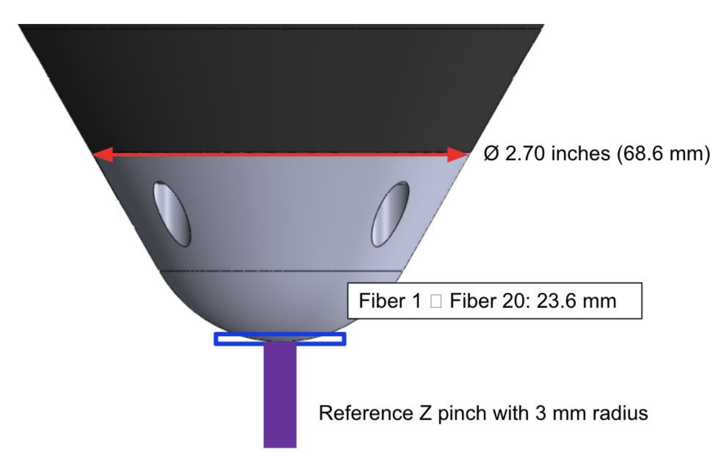

Figure 4. Blue box denotes the width of the fiber viewing location. They span a width of 23.8mm at the tip of the nosecone. Purple denotes the ideal sharp Z-pinch that is 3mm in radius.

> A plot of erosion rate with respective to radius is shown in Figure 5. The fiber viewing the center of the pinch peaks at around $4.5 \cdot 10^{30}$ atoms / m^2 / s and drops off to around $2.5 \cdot 10^{30}$ atoms / m^2 / s at the edge of the pinch.

> The peak sputtering flux is 2 magnitudes larger compared to the measured $2.8 \cdot 10^{28}$ atoms / m^2 / s on the graphite nosecone in the Fusion Z-pinch Experiment (FuZE) [5].

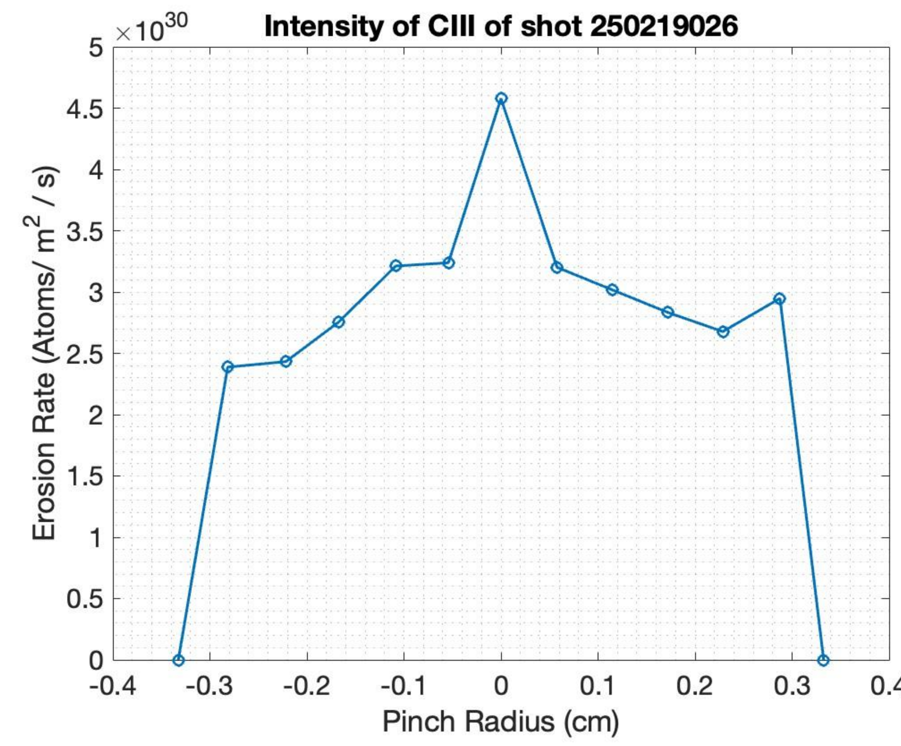

Figure 5. Preliminary data analysis if erosion rate with respect to pinch radius. Erosion rate peaks at center, at roughly 4.5 ·10^30 atoms / m^2 / s

> Taking the peak erosion rate to be a constant throughout the 50μs duration of plasma exposure, the erosion rate is 22.6 mg/C.

> Future work involves further data collection to characterize changes in erosion rate at different times and voltages, more rigorous data analysis technique to possibly account for the overestimation that line-of-sight integration gives.

CONCLUSION

> High-density and high-temperature plasma interacts with the graphite cathode on the ZaP-HD device, causing erosion on the surface through processes such as sputtering.

> A spectroscopic diagnostic system using an ICCD spectrometer and PMT is developed to quantitatively monitor erosion rates of the graphite electrode.

> A peak erosion flux of $4.5 \cdot 10^{30}$ atoms / m^2 / s is measured in the initial data analysis phase, which corresponds to a 22.5 mg/C erosion rate.

References:
[1] U. Shumlak, et al. Phys. Plasmas 24. 055702 (2017); https://doi.org/10.1063/1.4977468
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[3] Khairi, A. (2021). Graphite Electrode Characterization on the ZaP-HD Sheared-Flow-Stabilized Z-Pinch Device (thesis).
[4] OPEN-ADAS Team, "Atomic Data and Analysis Structure (ADAS)," , 2025.
[5] Thompson, M. C., et al, Phys of Plasmas 30, No. 10, 2023