Diagnostics for Plasma-Material Interactions on the ZaP-HD Sheared-Flow-Stabilized Z Pinch

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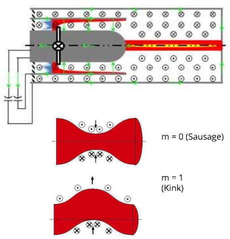
Abstract

Applying sheared velocity flow to the Z pinch successfully mitigates MHD instabilities, enabling the concept to scale to high energy densities on the ZaP-HD device. This provides a unique platform for studying the plasma-material interactions (PMI) of a Z pinch at fusion-relevant conditions. High particle and energy flux to the electrodes leads to erosion of the plasma-facing surface, especially at the location of current attachment at the nose cone. Initial PMI experiments will study the behavior of a graphite nose cone using new diagnostics currently under development. During the discharge, impurity flux measurements will be made with spectroscopy by converting line-of-sight emission intensities using the number of ionization events per photon, known as the S/XB value. An infrared imaging system will be implemented to attain surface temperature measurements and heat flux. In addition, the study will include conventional ex-situ diagnostics such as scanning electron microscopy, profilometry, and mass-loss techniques that measure net changes resolved over an experimental campaign. A redesigned nose cone will enable quick and frequent removal of a portion of material for this analysis. The planned implementation of these techniques is described here.

The Z-pinch concept

- A Z pinch is a column of plasma with axial current and self-generated magnetic field.
- Avoids the cost and complexity of external magnets, resulting in a compact design.
- Inherently unstable to pressure-driven instability modes. However, the m = 1 mode may be stabilized by application of radial shear to the axial flow velocity[1].



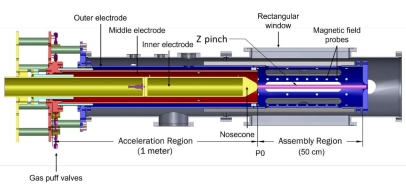
[1] Shumlak 1995, *Physical Review Letters*

SFS Z pinches at UW scale to high plasma parameters

- Demonstrated quiescent plasma for thousands of instability growth times.[3]
- By increasing the current, pinch is more confined and plasma density and temperature can be increased.
- ZaP-HD produces a plasma with high particle and heat flux.
- The electrodes supply the pinch current and are plasma-facing components.

Parameter	ZaP[2]	ZaP-HD[3]	FuZE[2],[4]
Pinch current (kA)	50 - 100	150	150 - 300
Pinch radius (cm)	0.5 - 1	0.2 – 0.5	0.1 - 0.3
Electron density (cm^{-3})	10^{16}	10^{17}	> 10^{17}
Plasma temperature (eV)	100	1000	1000-2000

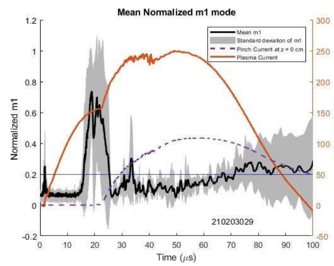
[2] Forbes 2019, *Fusion Science and Technology*
[3] Shumlak 2017, *Physics of Plasmas*
[4] Zhang 2019, *Physical Review Letters*

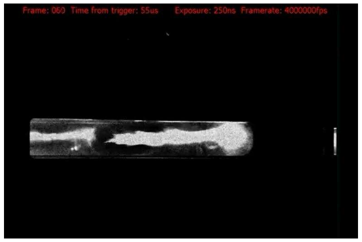


Plasma characterization with existing diagnostics

Pinch current peaks at 100 kA with a 33 μs quiescent period, however up to 60 μs durations were observed. The mean m_1 mode uses axially averaged magnetic field data to quantify stability. The 0.2 threshold indicates the current centroid is within a cm of the electrode axis.

At 55 μs, the pinch is well collimated with a large attachment area on the nose cone. This coincides with peak pinch current. Image is from a Kirana 05M high speed imaging camera.

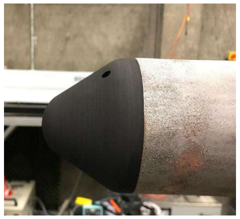




Electrode erosion lacks sufficient investigation

- Significant erosion was observed on metallic (tungsten-sprayed copper) electrode nose cones. The 0.02" tungsten spray was completely removed from nose cone tip.
- FuZE and ZaP-HD now use graphite electrodes. ZaP-HD nose cone shows negligible erosion after a year of operation.
- High energy fluxes from the plasma can limit material lifetime and reliability, while impurity species removed from solid components detrimentally cool and contaminate the bulk plasma.
- Important questions to answer are:

- How do we quantify material response to plasma exposure?
- What are the effects of the electrode material on the plasma parameters and pinch performance?



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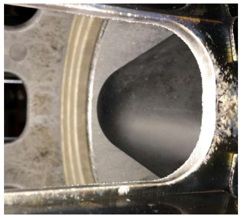


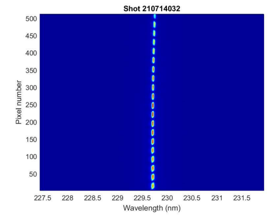
Imaged May 2022

PMI-specific diagnostics

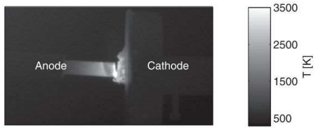
The PMI study focuses on the processes that occur at the interface of the electrode and the plasma. In order to characterize PMI processes on ZaP-HD, a combination of in-situ and ex-situ diagnostics will be implemented:

1. Visible/UV spectroscopy to measure the influx of carbon from the nose cone. This addresses a major source of impurities.

$$\Gamma_{in} = 4\pi \frac{S}{XB} I \quad [m^{-2}\ s^{-1}]$$

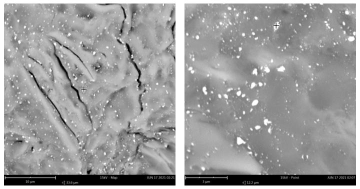


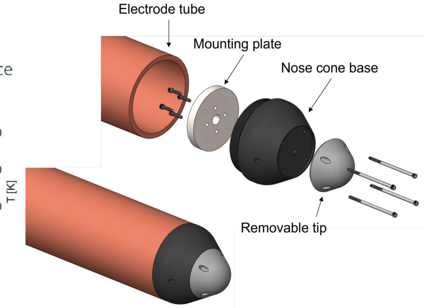
2. Remote temperature sensing (IR/pyrometry) to measure surface temperature and heat flux.



[5] Ng, 2015, Journal of Applied Physics

3. SEM, AFM, and profilometry to measure changes to surface topography. This is enabled by a redesign of the nose cone to include a removable insert.





Future work and acknowledgments

- Manufacturing of PMI nose cone
- Absolute calibration of spectroscopy
- Spectral survey and burn-through characteristics of ions

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