SAND2022-7691C

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Design and Development of Laser Optical Imaging Diagnostics for Investigation of Low-Density Plasmas for MagLIF Experiments

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ICOPS 2022

Abstract #300

Motivation

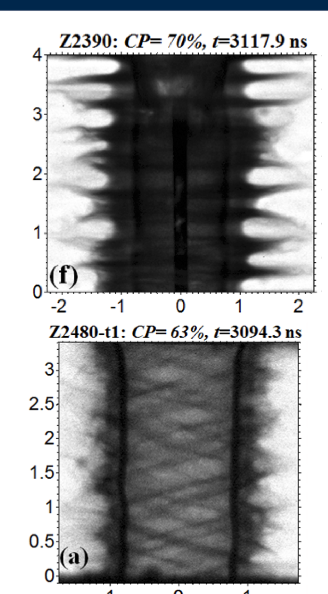
Goal: To construct a suitable experiment to field and develop a laser imaging suite to diagnose plasma density profile and flow. These diagnostics will aid the efforts of studying magneto Rayleigh-Taylor (MRT) instabilities relevant to magnetized liner inertial fusion (MagLIF) experiments on the Z machine at Sandia.

Why: Experiment would help understand the relevance of low-density plasma surrounding a thin metallic liner and its effect on the development of instabilities.

How: Experiments will be designed and performed on MAIZE, a 1-MA class pulsed power driver with 200ns rise time, so that it can be applied to Z. Using self-emission imaging and refractive angle measurements, plasma densities as well as instability wavelengths can be inferred.

Background

In MagLIF on the Z Machine [1], a major concern is whether the MRT instability that forms in the liner can be sufficiently controlled to enable the assembly and confinement of a thermonuclear fusion fuel. MRT is observed to create helical plasma striations when an axial magnetic field is pre-embedded in the liner. One of the proposed origins of this so-called helical instability is from magnetic flux compression of a low-density plasma surrounding the liner that is hypothesized to originate from the high current densities on the transmission lines. This motivated the development of a laser schlieren refractometer [2] and a laser interferometer system that will provide density measurement capabilities to study these low-density plasmas and better understand their effects on the imploding liner.



Angular Filter Refractometer

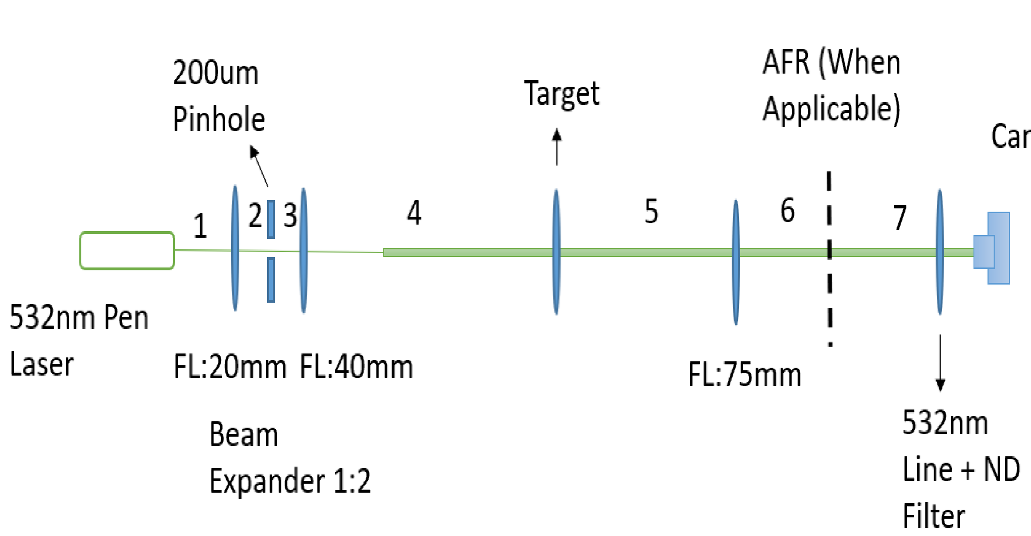
-Angular filter refractometer utilizes a bullseye pattern to discretize the refraction angle measurement due to the transverse density gradients of plasma creating a contour map.

The total refraction of a laser probing through a plasma medium can be described by $\theta_{total} = \int_0^L \frac{1}{n}(\nabla_\perp n)dx$

Minimum deflection cutoff

$\theta_{min} = {}^{y_s}/_{f}$ = 10mRad = 1.15deg
y_s = 0.75mm
f = 75mm
*On actual experiment, the collection lens will adjust appropriately to the minimum deflection angle

Test Set-up



Lengths:
1-74mm
2-20mm
3-41mm
4-100mm
5-90mm
6-75mm
7-375mm

Targets:
1. USAF Resolution
2. Concave Lens FL=-25mm small angle approx.: ~θ = 120mRad = 6.88 deg

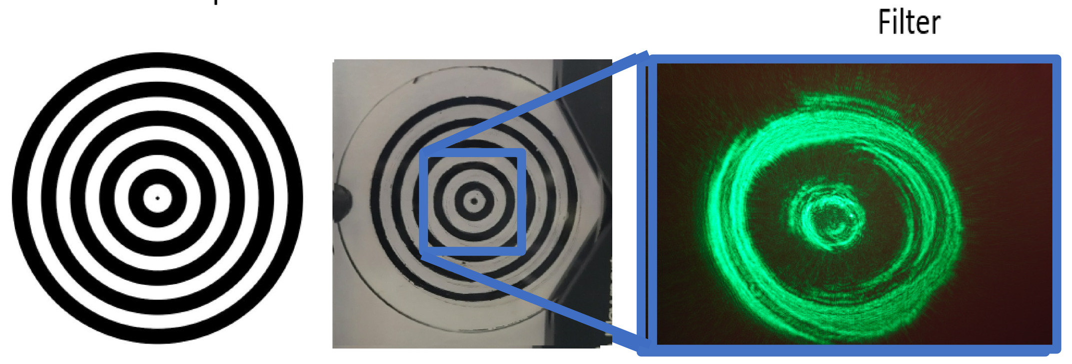
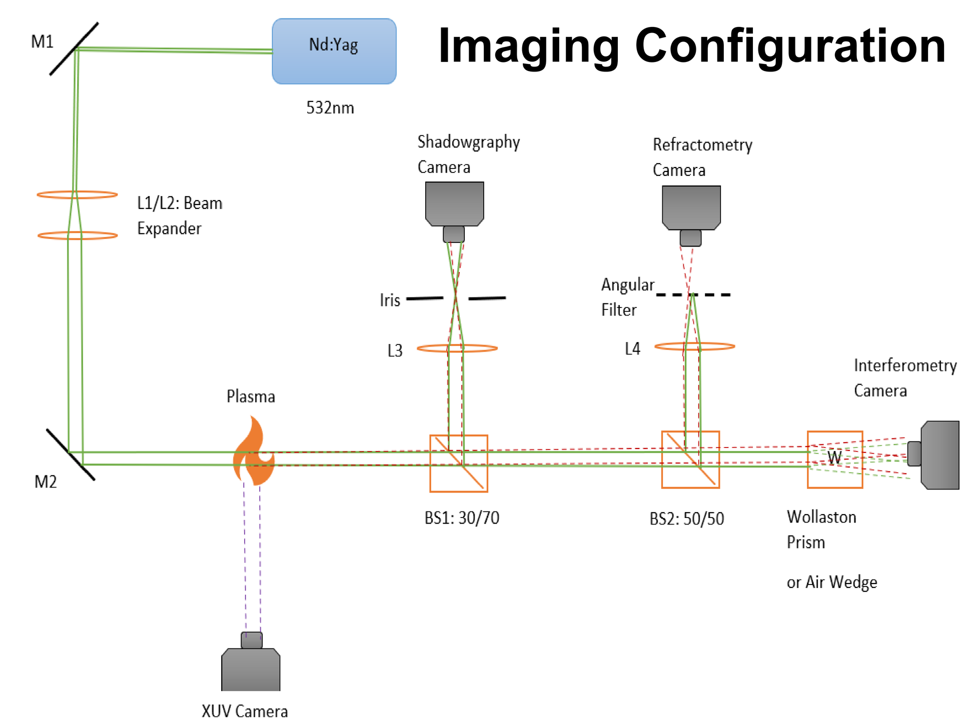


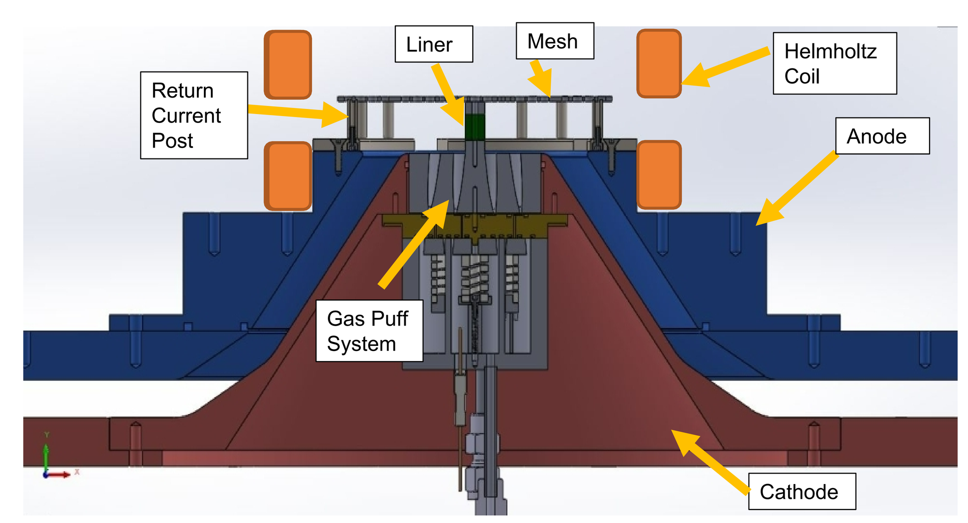
Illustration pattern for filter **Fabricated angular filter** **Refracted light through filter**

-The fabricated filter was calibrated with a concave lens to confirm the passband angles through the transparent bands. A plasma source will be tested to measure refraction angles

Experimental Set-up



-Four optical diagnostics will be used to characterize plasma:
1. Shadowgraphy
2. Refractometry
3. Wollaston Interferometer
4. XUV imaging



Load Hardware

-Main load hardware utilizes the gas puff system with a foil liner load place center of the gas puff.

-The gas puff is used as a source of low-density plasma to surround the liner.

-Helmholtz coil is in development to pre-embed axial magnetic field onto the low-density liner for flux compression

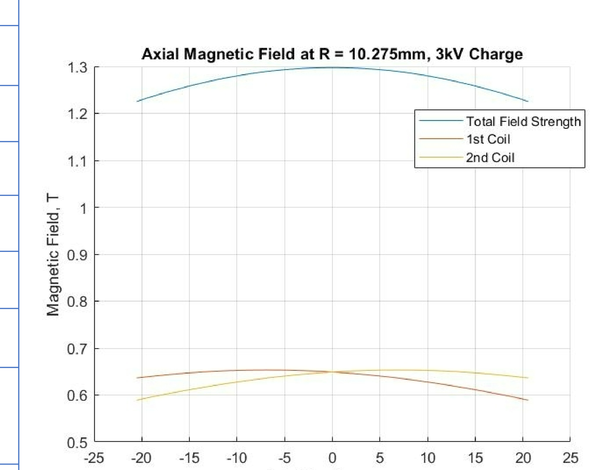
Helmholtz Coil Design

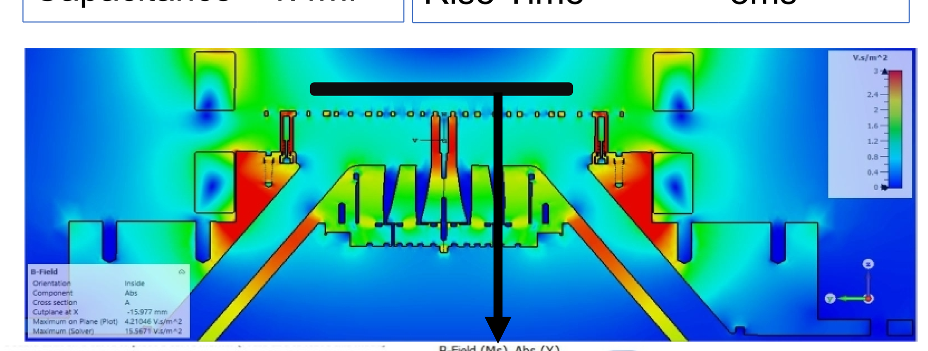
- A slow uniform axial magnetic field is needed to enable the study of flux compression as well a helical instabilities. To do so a Helmholtz coil was designed.

Helmholtz Coil Parameter	
# of Turns	100, each
Radius	77mm
Height	20.55mm
Thickness	24mm
Total Resistance	0.2Ω
Total Inductance	19.4mH
Current	270-804A
Magnetic Field Strength	0.4-1.3T
Rise Time	8ms

Drive Bank Parameter	
Voltage	1-3kV
Capacitance	1.4mF

$$B(z) = \frac{1}{2}(\mu_0 NI * \frac{r^2}{(r^2+z^2)^{\frac{3}{2}}})$$



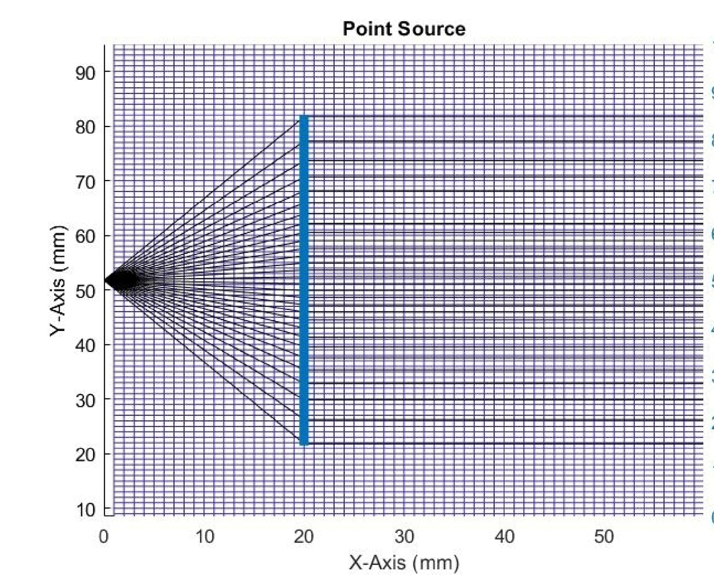


-The current and risetime through the coil load were calculated analytically and used as inputs for CST magnetostatic calculation

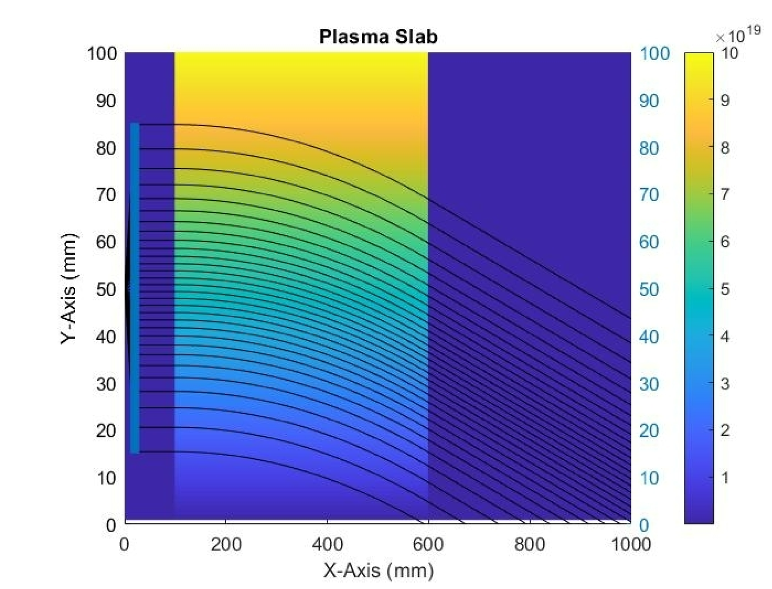
-The magnetic field had slight variation between the inner nozzle and the outer nozzle of ~0.9T and 1T, respectively

Ray Tracing Code

A simple 2-D ray trace code is in development to predict the refractive angle measurements due to low density plasma for a 532nm laser. A plasma slab was used to validate the code. Future calculations will utilize plasma density profiles of liner from MHD codes like PERSUES to predict refractive angles.



A single point source emitting rays of 60deg fan angle onto a collimating lens



A large plasma slab with a density gradient of $10^{19} - 10^{20} cm^{-3}$ was used to simulate refraction of rays

Conclusion and Future Work

Conclusion

-We present a suitable experimental platform and optical diagnostics on MAIZE, a MA class pulsed power machine, to study low density plasma effects on liner experiments.

-Development of an angular refractometer to measure plasma density profiles along with a ray trace to predict the refractive angles.

-Helmholtz coil calculations show uniform magnetic field of ~1T above the gas puff nozzle.

Future Work

-Have a more refined method to construct angular filter through material sputtering or masking.

-Test ray trace with PERSUES simulation of gas puff plasma. Continue to develop ray trace code with 3D capabilities along with phase information in the rays.

References and Acknowledgement

[1] D. Yager-Elorriaga et al., "An overview of magneto-inertial fusion on the Z Machine at Sandia National Laboratories," Nuclear Fusion, 2021
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***Work supported by SNL LDRD Project No. 22-0671. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525**

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