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A Dispersion Interferometer Diagnostic used for Low Electron Density Measurements in Magnetically Insulated Transmission Lines on Sandia's Z-Machine*

ELECTRICAL & COMPUTER ENGINEERING

Sandia National Laboratories

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Objective

- Reliable delivery of current to magnetically driven loads.
  - Electron flow can generate electrode plasmas and reduce coupling efficiency.
  - Increased electron flow further reduces coupling efficiency.
- A fiber-based Dispersion Interferometer (DI) will enable the first direct measurements of electron sheath flow on Z.
  - This will reduce the current lower limit for electrode plasma density measurements available by a factor of 100.
- This DI design operates with a Fundamental (F) wavelength at 1550 nm CW, with frequency-doubling to a Second-Harmonic (SH) wavelength at 775 nm.
  - The design will be fiber-coupled because of spatial limitations.

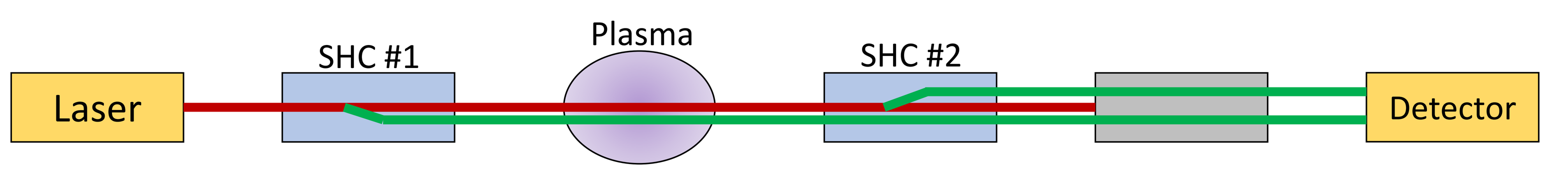


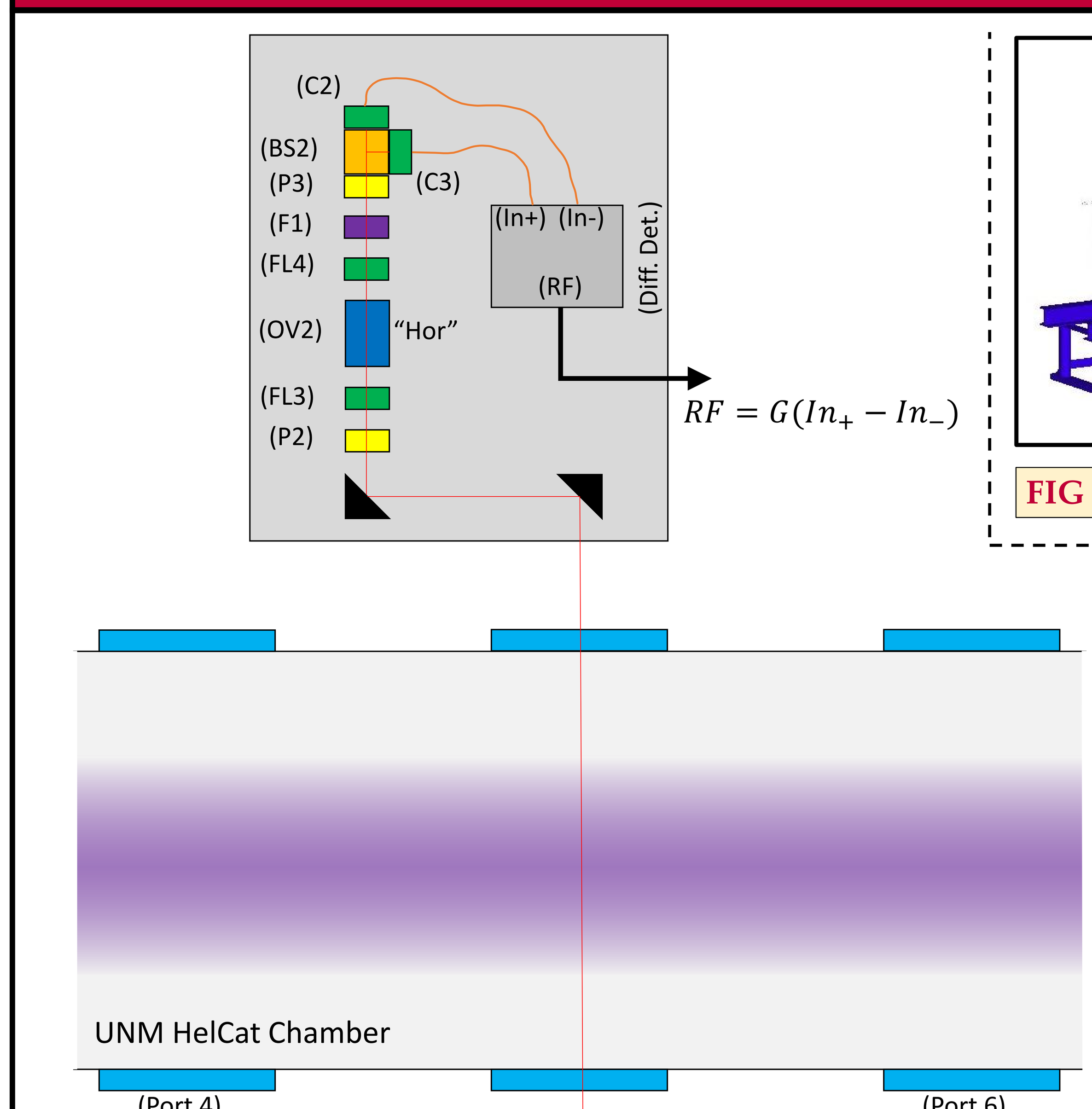
FIG 1: Diagram of basic DI design composed of the laser source, the first second-harmonic crystal (SHC), the plasma itself, the second second-harmonic crystal, a fundamental beam block, and a detector.

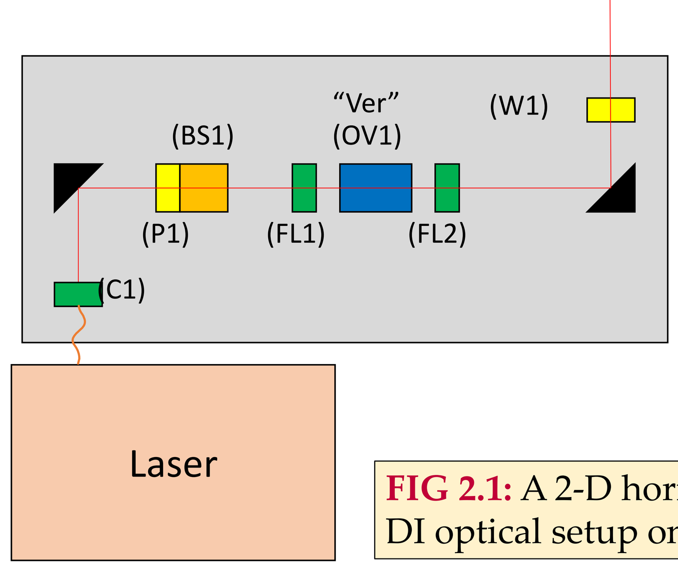
- The benefits of the DI over a conventional interferometer are key for its use on Z.
  - Due to the fundamental and second-harmonic waves traversing the same path along the plasma, mechanical vibrations from the firing of the machine impose the same relative path length shift on the two waves.
  - The design is operated in the optical regime and is to be mostly fiber-coupled, allowing for access to the tight spaces around Z's MITL structures, unlike a mm-wave interferometer.

Project Path

- First, the diagnostic will be set-up on the UNM Helicon-Cathode (HelCat) plasma device[1].
  - It will be compared against electron density profiles measured vie a mm-wave interferometer and scanning double Langmuir probe.
- Second, it will be deployed at Sandia's Mykonos 1-MA driver.
- Third, it will be fielded on Sandia's Z machine.
  - For measurements of electron sheath flow on MITL's.

UNM HelCat Experimental Setup





C	Fiber/Open-Beam Collimator
P	Polarization Shifting Plate
BS	Polarized Beam Splitter
FL	Focusing Lens
OV	Oven & Crystal
W	Optical Window
F	Optical Filter

FIG 2.1: A 2-D horizontal-plane diagram of the DI optical setup on UNM's HelCat device.

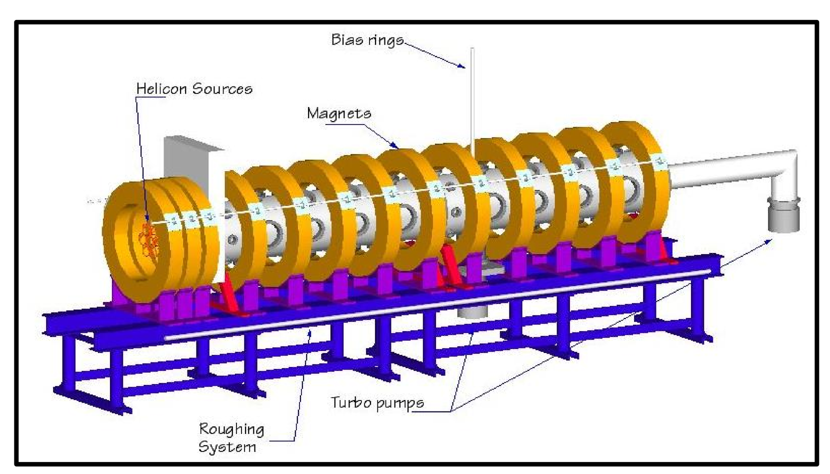
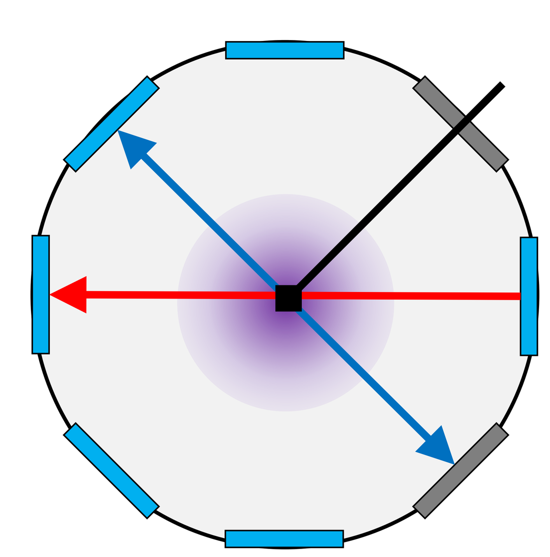


FIG 2.2: A 3-D render of UNM's HelCat device.



- (red) The DI path, traveling through plasma once.
- (black) Scanning double Langmuir probe.
- (blue) The mm-wave Interferometer path, traveling through plasma twice.

FIG 2.3: A 2-D axial cross section diagram of the three electron density diagnostics on UNM's HelCat device.

DI Principles

- The measured change in phase of a wave with frequency ω_λ will be related to the index of refraction of the plasma as:

$$\Delta\phi_\lambda = k_0 \int_0^l (N_\lambda - 1)\, dx \quad (1)$$

  - Where l is the plasma path length and…

$$N_\lambda = \sqrt{1 - \frac{p_e n_e e^2}{\epsilon_0 m_e \omega_\lambda^2}} \quad (2)$$

- For the DI, the total phase change is:

$$\Delta\phi_{total} = (2 * \Delta\phi_F) - \Delta\phi_{SH} \quad (3)$$

- Note: the first and second SH waves are perpendicularly polarized.
  - The reason for perpendicular polarizations of the 1st and 2nd SH waves is to split them into a differential detector while limiting the signal offset value.
- The information needed for an absolute electron density distribution is:
  - A pre-calibrated fringe sweep, defining the signal amplitude, A, and offset, DC.
  - A normalized electron density spatial profile of the plasma.
  - A measured phase change, from no plasma to plasma, between the two SH waves.
- With this, the total phase change is related to the measured signal as:

$$\Delta\phi_{total} = \sin^{-1}\left(\frac{V_0 + \Delta V - DC}{A}\right) - \sin^{-1}\left(\frac{V_0 - DC}{A}\right) \quad (4)$$

- This can be then compared to equation (3) to solve for the density.

UNM HelCat DI Data

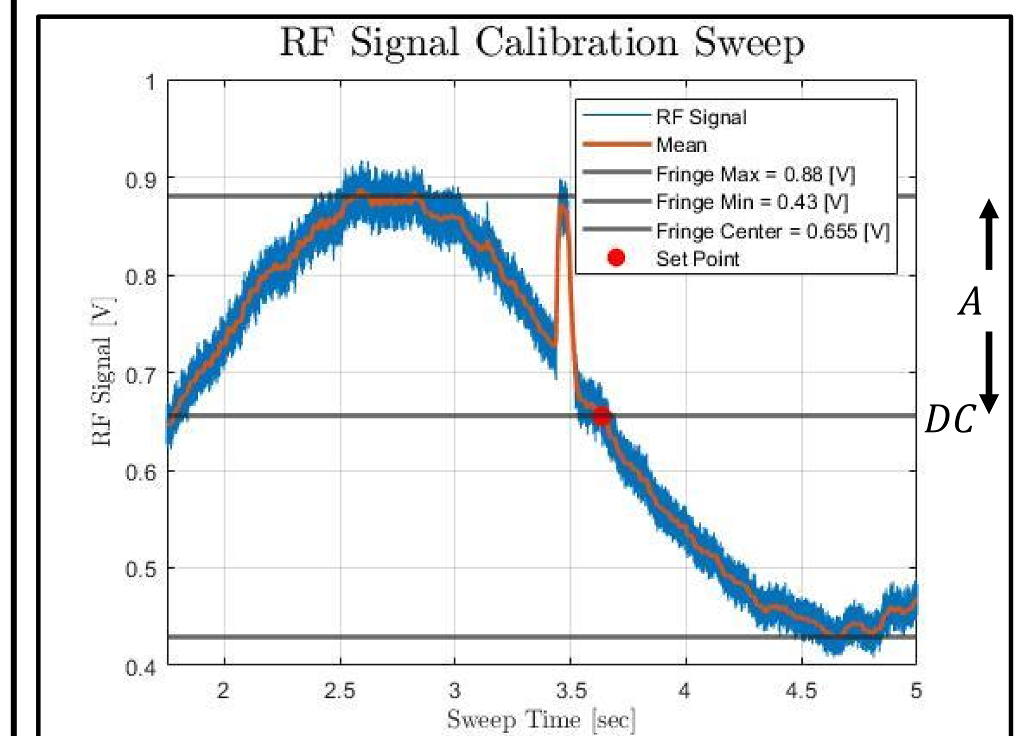


FIG 3.1: The "RF" signal sweep calibration data. Here we see the amplitude and DC-offset values we need.

- Variables: $A = 0.225\ V$ $DC = 0.655\ V$

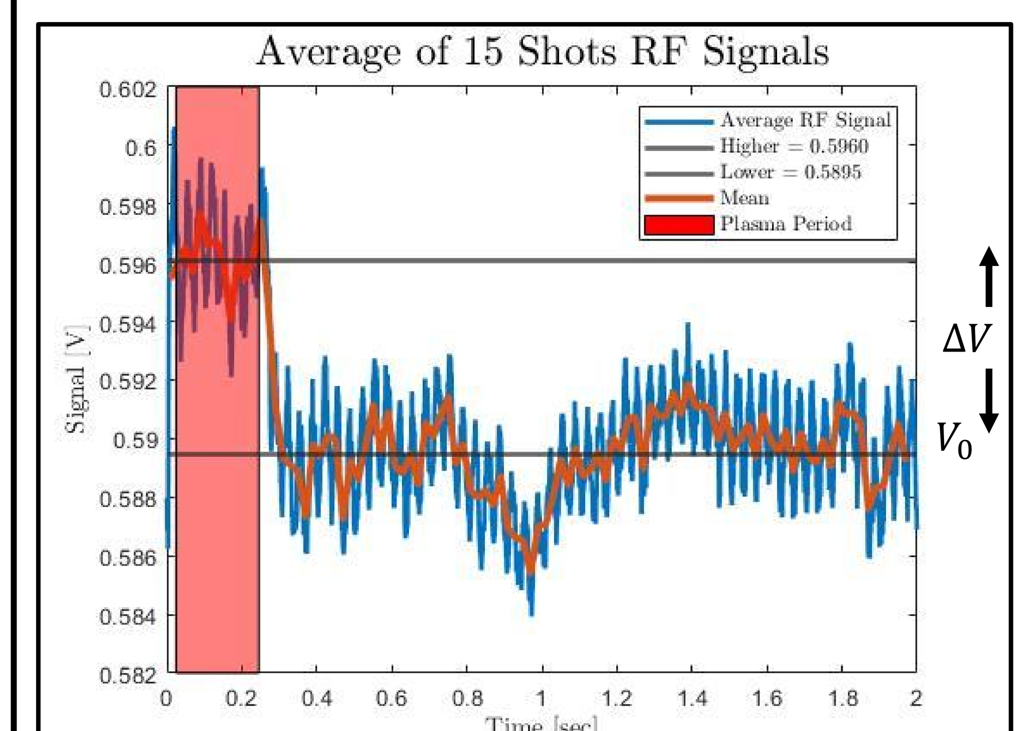


FIG 3.2: The 15 shot average "RF" signal, with a red highlighted section representing the plasma operation period (220ms), a "higher RF" value (596.0-mV), a "lower RF" value (589.5-mV), and an orange mean curve.

- Variables: $\Delta V = 6.5\ mV$ $V_0 = 0.59\ V$

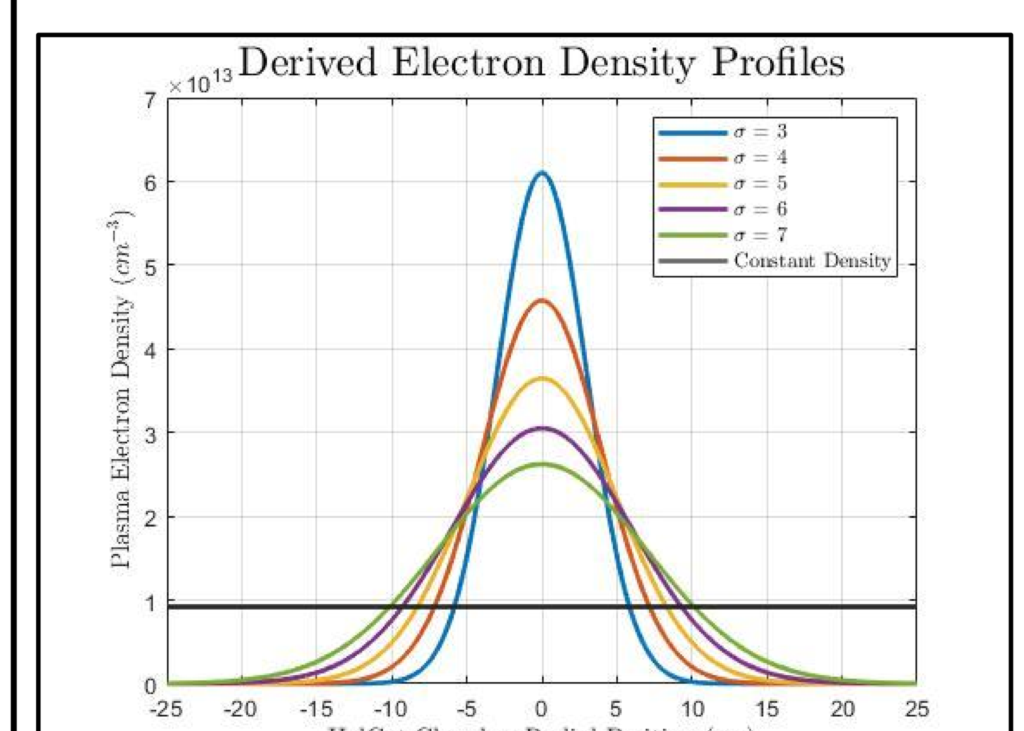
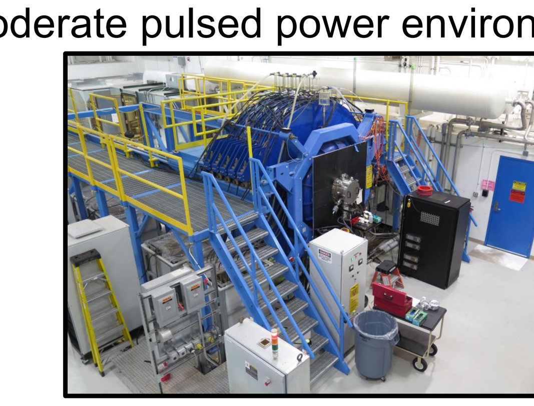


FIG 3.3: Derived absolute electron density of various radial profiles for the UNM HelCat machine, given the (above) signal data.

- These absolute densities match expected results.

Future Work

- Improve shot by shot variation and noise in the "RF" signal.
  - This is key for future experiments where shot count is limited.
- Collect HelCat profile density data with a scanning double Langmuir probe.
  - This will detail the normalized electron density radial profile shape inside the HelCat chamber.
  - Estimate the probe tip area to also get an absolute electron density distribution estimate, not just a normalized distribution shape.
- Collect HelCat mm-wave interferometer absolute line density data.
  - This will act as a verifying source against the DI diagnostic.
  - This will give an absolute electron density factor, with which to multiply into the scanning double Langmuir probe normalized distribution profile.
- Move the diagnostic to Sandia's Mykonos pulsed power machine and measure electron sheath flow in a moderate pulsed power environment.



  - Testing the device capabilities at fast time scales (with the hope for time resolution) and in noisy environments.
  - The device will shift to primarily fiber-coupled, from primarily open-beam on UNM's HelCat device.
- Employ the diagnostic at the Z machine.
  - Directly measure the electron densities in magnetically insulated flows.
- Develop a multi-channel DI design for spatial resolution capabilities.

References

1. Lynn AG, "The HelCat dual-source plasma device," Rev Sci Instrum. Vol. 80, pp. 103501, 2009
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