# Development of a Fiber-Coupled Dispersion Interferometer for Low Electron Density Measurements

N. R. Hines[1], Sonal Patel[2], Daniel J Scoglietti[2], Mark A Gilmore[1], S. L. Billingsley[1], R. H. Dwyer[1], Thomas Awe[2], Darrell Armstrong[2], David Bliss[2], George Laity[2], Michael E Cuneo[2]

1) The University of New Mexico, Albuquerque, NM 2) Sandia National Laboratories, Albuquerque, NM

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## Objective

- Development of a fiber-based Dispersion Interferometer (DI) will enable the first direct measurements of electron sheath flow on Z, between $10^{14} - 10^{18}\ elec/cm^2$.
  - Reduce the present lower limit of the available electrode plasma density measurements by a factor of 100.
  - Perform studies on reliable delivery of current to magnetically driven loads, which can influence electrode plasmas and reduce coupling efficiency.
    - Plasma is spawned via ohmic heating of the electrode; a sheath is formed due to the surface charge generated as ions and electrons diffuse from the plasma at different rates.
- This DI design operates with a Fundamental (F) wavelength at 1550 nm, CW 0.65 Watts, with frequency-doubling to a Second-Harmonic (SH) wavelength at 775 nm.
  - The design is fiber-coupled due to spatial limitations inside Magnetically Insulated Transmission Lines (MITLs).

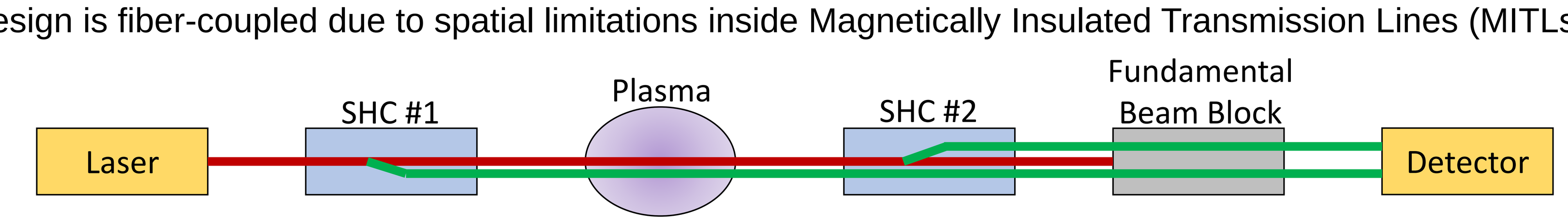



**FIG 1:** Diagram of basic DI design composed of the laser source, the first second-harmonic crystal (SHC), the plasma itself, the second second-harmonic crystal, a fundamental beam block, and a detector.

- First, the diagnostic has been installed on the UNM Helicon-Cathode (HelCat) plasma device[1].
  - Comparisons against line-average electron density measurements made via a 94 GHz mm-wave interferometer verify the DI's lower bound accuracy.
- Second, it will be deployed at Sandia's Mykonos 1-MA driver.
- Third, it will be fielded on Sandia's Z machine.
  - Measurements will be made of electron sheath flow on MITLs.

## UNM HelCat Experimental Setup

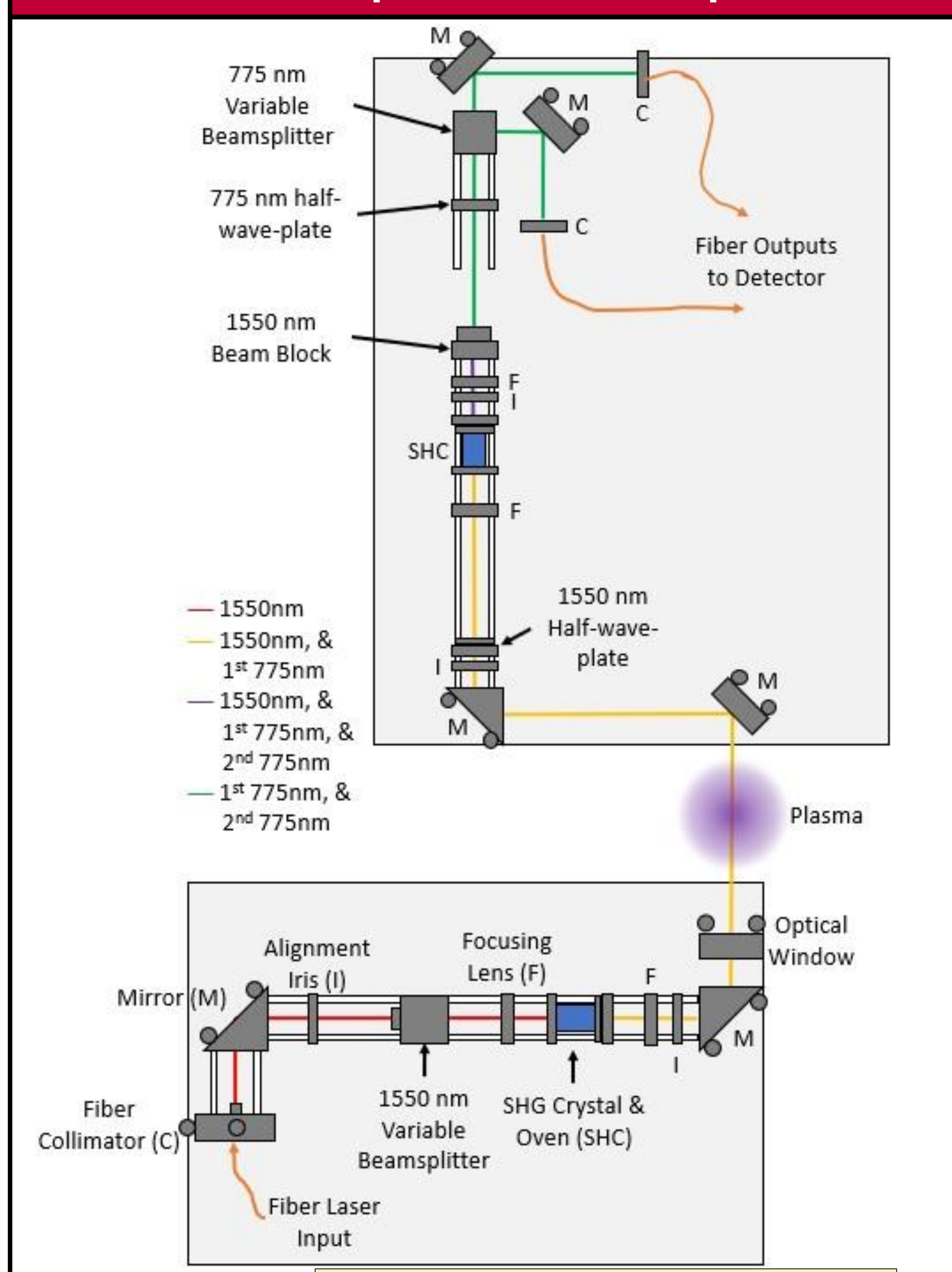



**FIG 2.1:** A 2-D horizontal-plane diagram of the DI optical setup on UNM's HelCat device.

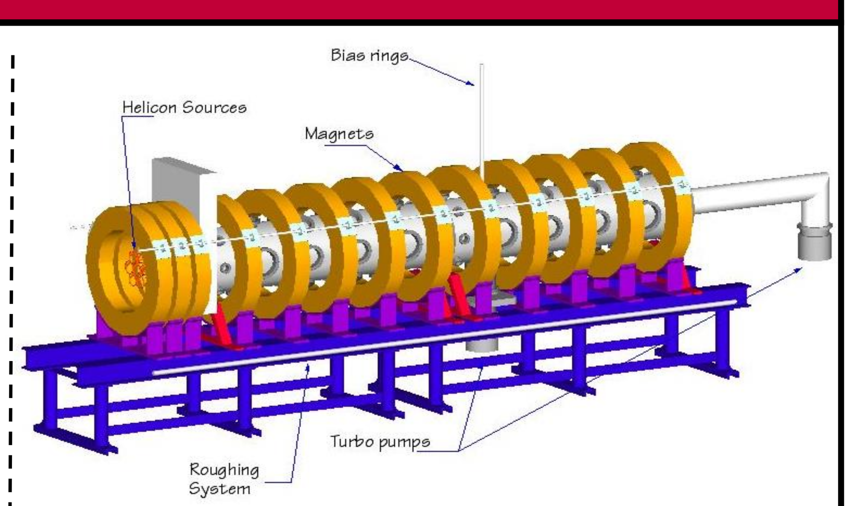
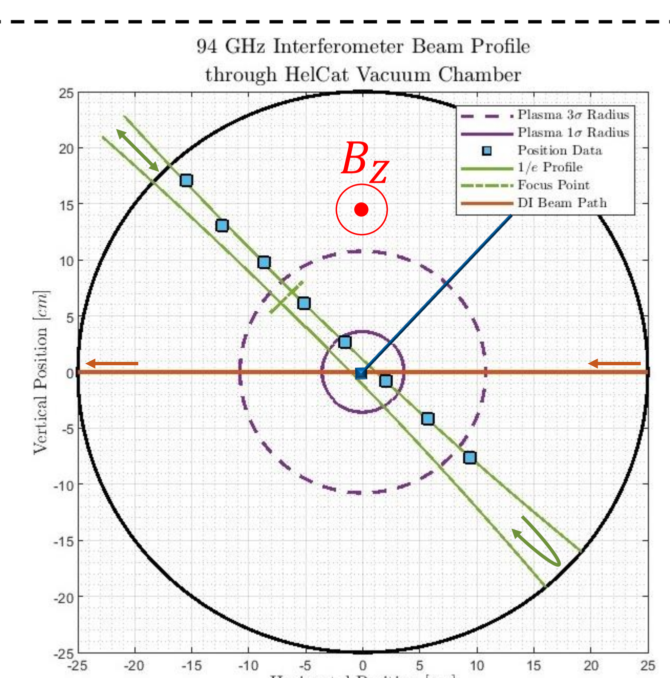



**FIG 2.2:** A 3-D render of UNM's HelCat device.




- (red) The DI path, traveling through plasma once.
- (blue) Radially scanning double Langmuir probe.
- (green) The 94 GHz 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 Data

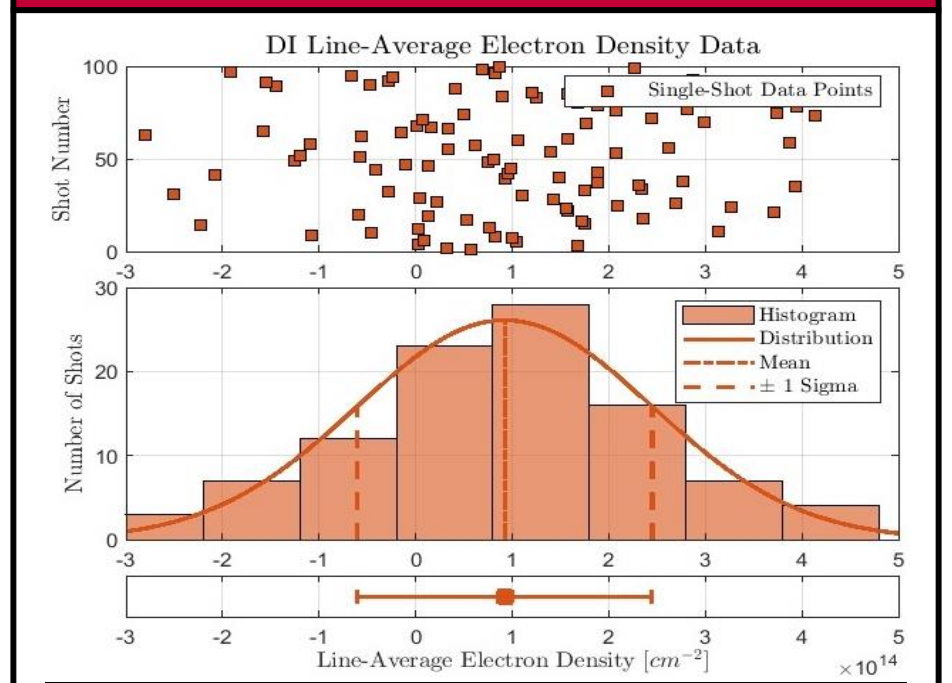



**FIG 3.1:** DI 100 shot line-averaged electron density measurements made on the UNM HelCat device, and a normalized representation.

- The DI is measuring a median line-averaged electron density of $9.23x10^{13}\ elec/cm^2 \pm 15.27x10^{13}\ elec/cm^2$.
  - The spread is mostly caused by the large system drift (170 $mV \pm 29\ mV$, over 20 seconds) and system noise ($\pm$ 20 $mV$). Expected signals from the HelCat plasma are $\sim 5\ mV$.

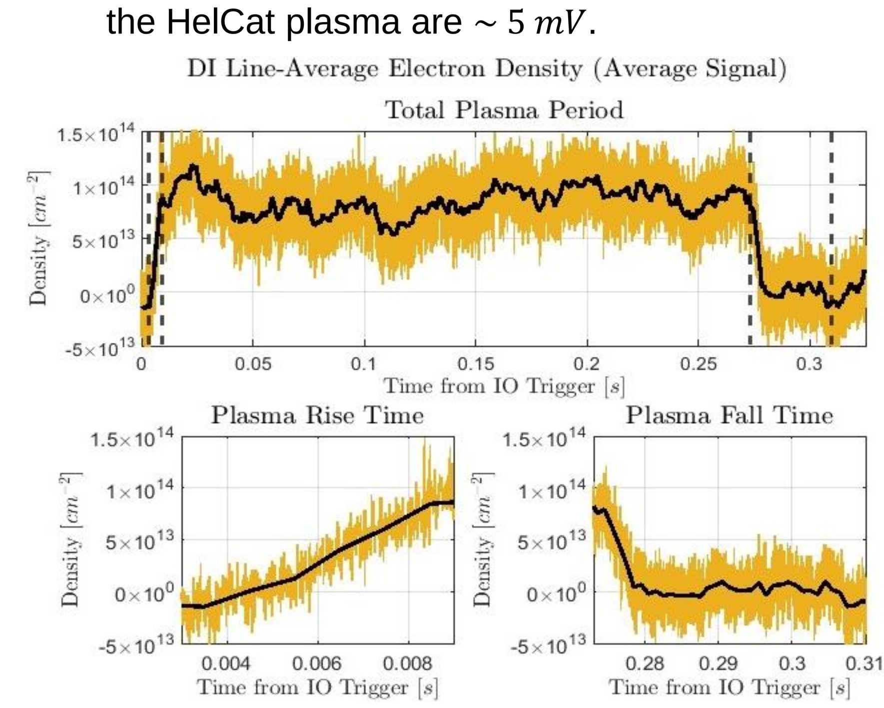



**FIG 3.2:** DI 100 shots' averaged signal (reduced noise and drift) density data taken on the UNM HelCat device (yellow) and noise filtered (black).

## 94 GHz Interferometer Data

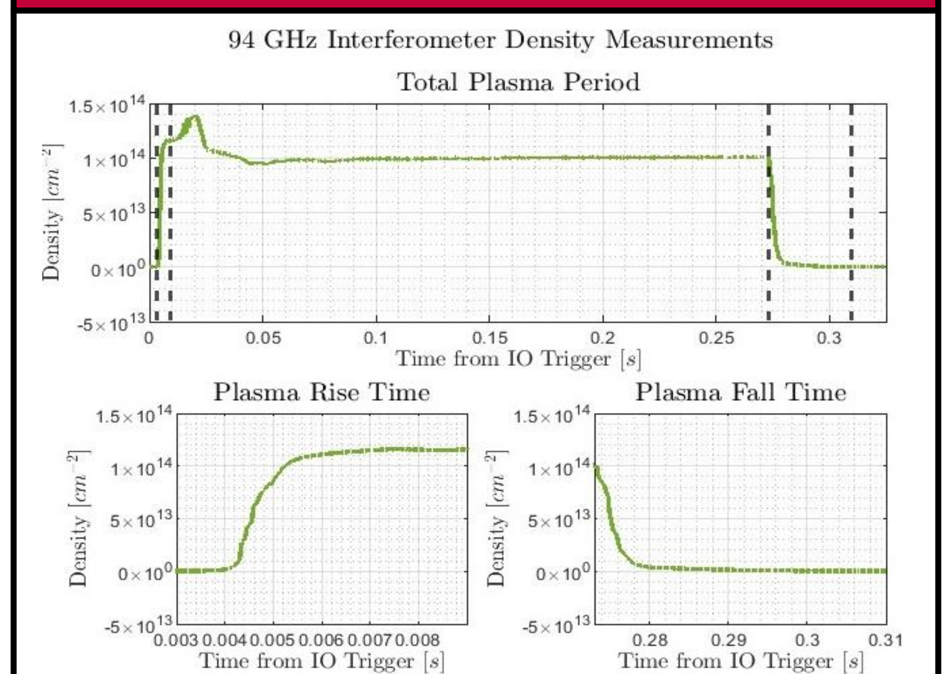



**FIG 4.1:** 94 GHz interferometer average density data from 10 shots on the UNM HelCat device.

- This measured a line-averaged electron density of $10.13x10^{13}\ elec/cm^2 \pm 4.79x10^{11}\ elec/cm^2$.

## Double Langmuir Probe Data

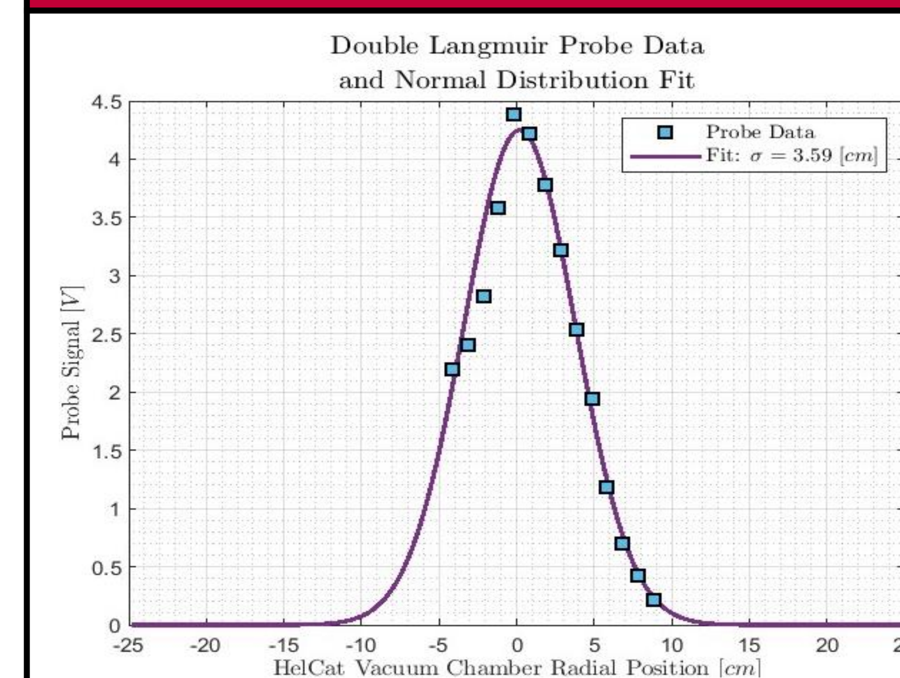



**FIG 5.1:** Double Langmuir probe radial sweep data and normalized distribution curve fit.

- The double Langmuir probe matches closely with a normalized distribution with $\sigma = 3.59\ cm$.

## HelCat Electron Density Results

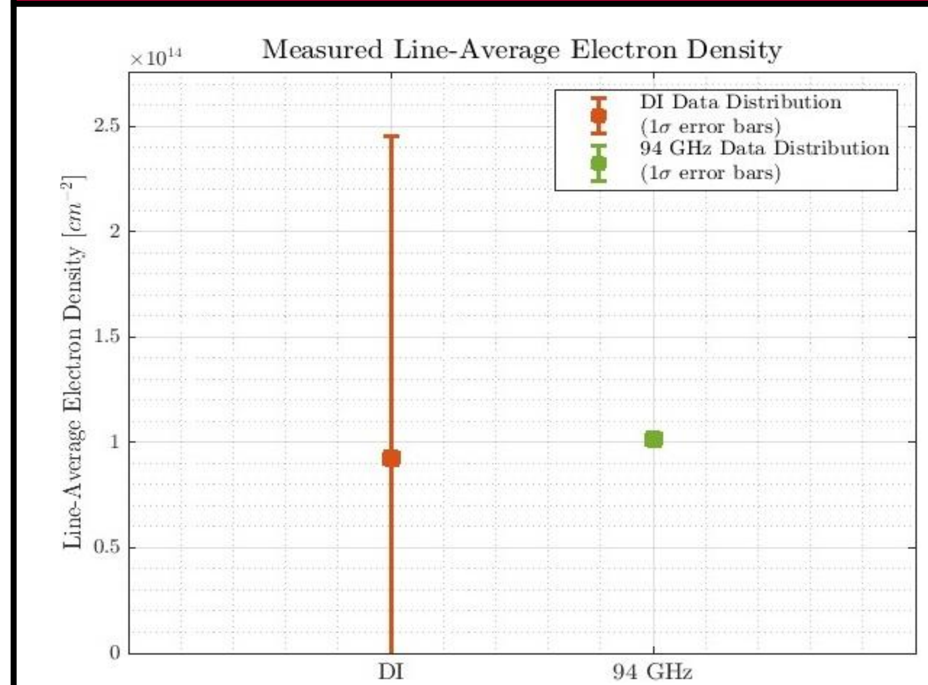



**FIG 6.1:** The measured line-averaged electron density from the laser DI data distribution, and the 94 GHz interferometer data distribution.

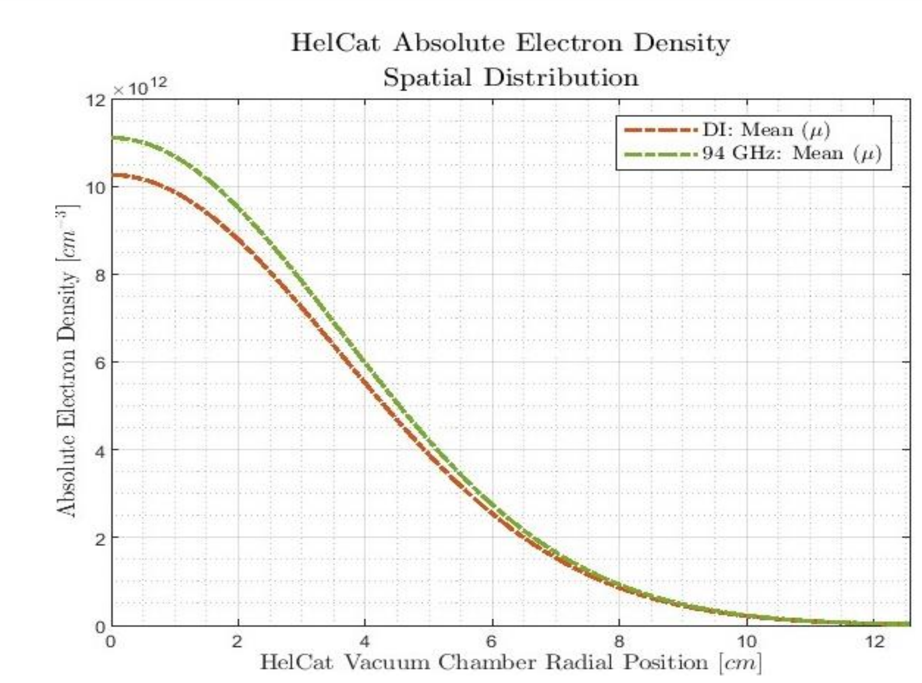



**FIG 6.2:** Absolute electron density distribution in the UNM HelCat chamber plot corresponding to the line-averaged electron density data collected in FIG. 6.1 and the spatial distribution data collected in FIG. 5.1.

## Principles of Operation

- The DI system is effectively measuring the relative phase changes that two wavelengths undergo whilst passing through a magnetized plasma in x-mode (the electric field of the laser beam is perpendicular to the background magnetic field), via a wavelength dependent index of refraction, $N_\lambda$:

$$N_\lambda = \sqrt{1-\left(\frac{n_e e^2 \lambda^2}{\epsilon_0 m_e 4\pi^2 c^2}\right)\left(\frac{\frac{4\pi^2 c^2}{\lambda^2}-\frac{n_e e^2}{\epsilon_0 m_e}}{\frac{4\pi^2 c^2}{\lambda^2}-\frac{n_e e^2}{\epsilon_0 m_e}+\frac{eB}{m_e}}\right)} \quad (1)$$

- The total phase change undergone from vacuum to plasma is related to the two wavelengths, $\lambda_F$ and $\lambda_{SH}$, along the plasma path length, $l$, background magnetic field, $B$, and electron density, $n_e$, as:

$$\Delta\phi_{total} = \left(2 * \frac{2\pi}{\lambda_F}\int_0^l \left(1-\sqrt{1-\left(\frac{n_e e^2 \lambda_F^2}{\epsilon_0 m_e 4\pi^2 c^2}\right)\left(\frac{\frac{4\pi^2 c^2}{\lambda_F^2}-\frac{n_e e^2}{\epsilon_0 m_e}}{\frac{4\pi^2 c^2}{\lambda_F^2}-\frac{n_e e^2}{\epsilon_0 m_e}+\frac{eB}{m_e}}\right)}\right)\right) - \left(\frac{2\pi}{\lambda_{SH}}\int_0^l \left(1-\sqrt{1-\left(\frac{n_e e^2 \lambda_{SH}^2}{\epsilon_0 m_e 4\pi^2 c^2}\right)\left(\frac{\frac{4\pi^2 c^2}{\lambda_{SH}^2}-\frac{n_e e^2}{\epsilon_0 m_e}}{\frac{4\pi^2 c^2}{\lambda_{SH}^2}-\frac{n_e e^2}{\epsilon_0 m_e}+\frac{eB}{m_e}}\right)}\right)\right) \quad (2)$$

- Use the measured voltage signals to calculate the effective total change in radians, $\Delta\phi_{total}$.
- Use a numerical solver to iteratively calculate the average electron density, $n_e$, from equation (2).
- Multiply by the total plasma path length, $l$, to calculate the line-average electron density, $\bar{n}_e$.
  - For the HelCat system: $\bar{n}_e \approx \mathbf{10e13}\ [\mathbf{electrons\ per\ cm^2}]$
- For absolute electron density calculations, use independent probe data to find the normalized electron density profile as a function of position, $p_e(x)$.
- Replace the average electron density factor, $n_e$, with the absolute density profile, $p_e(x)n_{e,max}$.
  - For the HelCat system: $n_{e,max} \approx \mathbf{1e13}\ [\mathbf{electrons\ per\ cm^3}]$

## Future Work

- Reduce Noise and Drift
  - Better SHC insulation and temp. control, DAQ, and shorter plasma periods of pulsed devices).
- Move the diagnostic to Sandia National Labs' Mykonos and Z pulsed power machines.
- Develop a multi-channel DI design for spatial resolution capabilities.

## References

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2. Fernando Brandi and Francesco Giammanco, "Harmonic interferometry in the visible and UV, based on second- and third-harmonic generation of a 25 ps mode-locked Nd:YAG laser," Opt. Lett. 33, 2071-2073, 2008.
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