Design of a Fiber Coupled Laser Interferometry System for FLARE

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GOALS

- **Develop a robust fiber coupled interferometry system capable of providing line averaged density data.**
- **Develop an easy to implement and inexpensive high resolution phase detection system.**

BACKGROUND: LASER INTERFEROMETRY

When an electromagnetic wave passes through a plasma it experiences as phase shift. This is due to the discrepancy in v_{ph} of the relative to the group velocity v_g of the wavefront. In ordinary mode dispersion (assumed for plasma interferometry applications) the dispersion relation governing the waves behavior in the plasma specifies the following index of refraction:

$$\eta = 1 - \frac{\omega_{pe}^2}{\omega^2}$$

Where ω_{pe}^2, the plasma frequency squared is:

$$\omega_{pe}^2 = \frac{n_e e^2}{\varepsilon_0 m_e}$$

This implies that the v_{ph} of the electromagnetic wave is greater than the speed of light. However, since due to information theory the wavefront cannot propagate faster than light speed (a simple calculation of group velocity using the dispersion relation confirms this) a phase advance occurs relative to a signal propagating through air or vacuum.

By using an interferometry this phase advance can be measured and a average electron plasma density across the laser path can be determined using the following formula:

$$\Delta\phi = \frac{n_e L e^2}{\varepsilon_0 m_e c \omega}$$

Where $\Delta\phi$ is the measured phase shift, L is the path distance through the plasma, ω is the laser frequency, and n_3 is the electron density. This equation also helps to roughly specify the measurement capabilities of a given interferometry system. Given the frequency of the laser or other EM radiation source being used and the path length through the plasma it is possible to determine the resolution and dynamic range of the system. The minimum measurable density change, or resolution, corresponds to a $\Delta\phi$ = 0.5 degrees in most measurement schemes, and the maximum measurable density before a fringe jump corresponds to a $\Delta\phi$ = 360 degrees phase shift (This limit can be overcome with proper measurement technology however).

As one can see the lower the frequency the higher the resolution of the system, however, frequency cannot be too low since if:

$$\omega^2 < \omega_{pe}^2$$

The wave is "cut off" and will no longer propagate in the plasma. Therefore in relatively high density plasmas such as those that will be present in FLARE microwave interferometers are not appropriate and lasers have to be used.

In order to effectively measure phase change using a laser system a laser heterodyne interferometer has to be used. This type of interferometer functions on the principle of the creation of a beat frequency. In order to do this one arm of the interferometer is frequency shifted by Δω, where:

$$\Delta\omega \ll \omega_{laser}$$

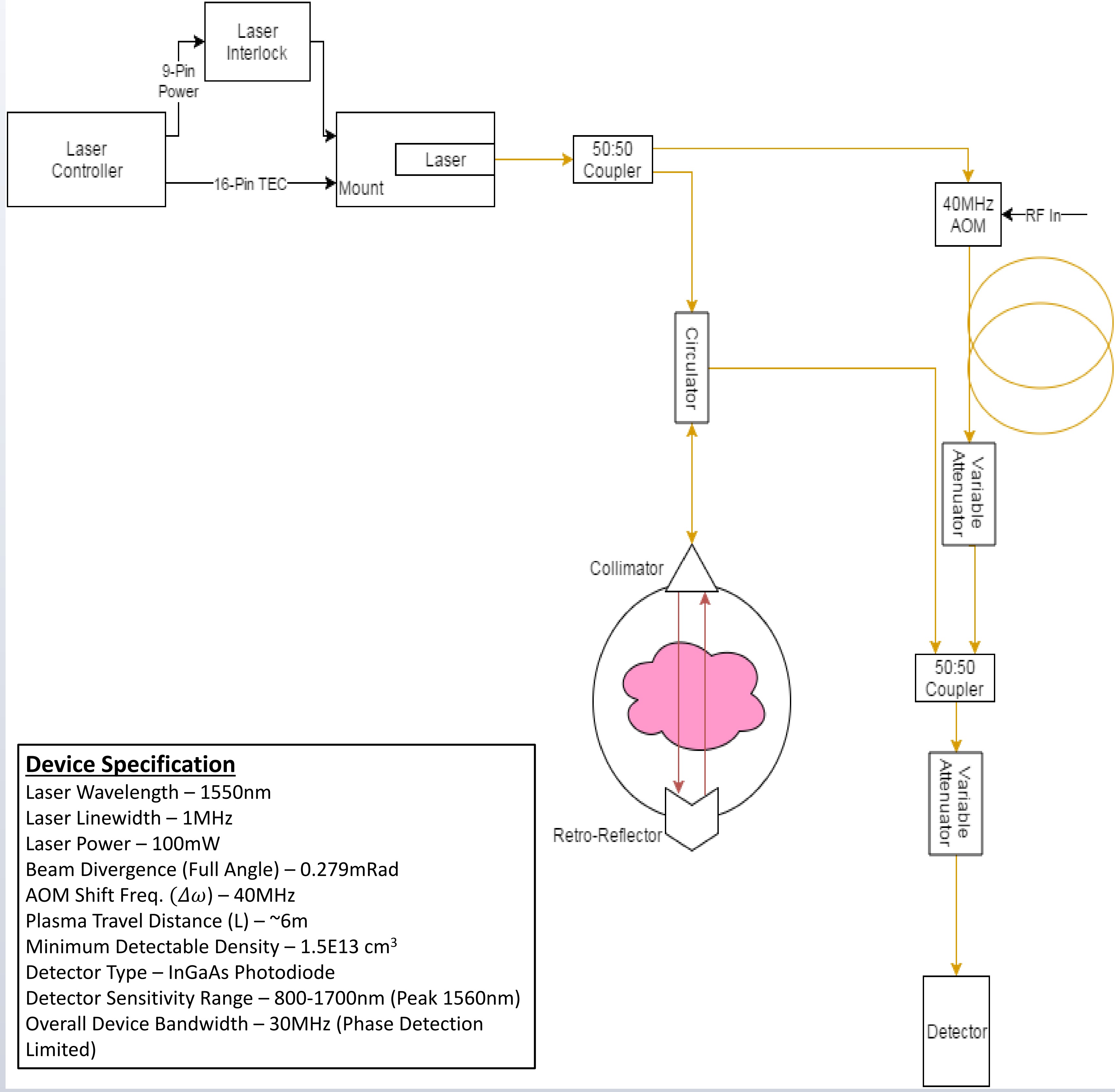
by an acousto-optic modulator (AOM). When the two arms of the interferometer are recombined a beat frequency is generated which has a phase shift equal to the phase shift acquired while the laser moved through the plasma relative to the reference frequency used by the AOM. With the form:

$$I(t) = \frac{1}{2}a^2 + \frac{1}{2}b^2 + ab\cos[\Delta\omega t + \Delta\phi]$$

An added benefit of heterodyne interferometry systems is their very fast response times and excellent time resolution since their bandwidth is equal to Δω which can be well over 100MHz.

Interferometer Design and Construction

- CO_2 interferometer used with the MRX required too much maintenance and alignment. Low maintenance, robust interferometry system was needed.
- Originally "off-the-shelf" fiber interferometry unit from Thorlabs was considered
  - Deemed inappropriate for our application.
  - Custom device needed to be designed and constructed.
- Long wavelength laser such as ~10.6µm CO_2 laser used in the MRX previously is not viable with current fiber optics technologies.
- A 1550nm Laser Heterodyne Fiber-Coupled Michelson Interferometer was the chosen topology for new FLARE interferometry system
  - Acceptable resolution ~1.5*10^{13}cm^{-3} assuming 6m beam path (expected number densities ~10^{14}cm^{-3} in FLARE)
  - Extensive selection of fiber optic components available thanks to use of the 1550nm band in telecommunications applications
  - High coherence, moderate power, OEM scientific grade 1550nm lasers available at relatively low costs.
- Major challenge in heterodyne interferometry, phase measurement, inexpensive phase detection circuit designed.
  - New phase detection chip, Analog Devices AD8302, designed for use in the telecommunications industry employed.
  - Fast response 30MHz bandwidth allows real-time data output and high time-resolution phase measurement.
    - Simple and direct phase measurement output (see figure 3). No complicated software needed to interpret phase detection output.
  - Using two chips in configuration in Figure 2 allows unambiguous phase detection
  - Similar phase detection systems have replaced older quadrature systems used with the laser interferometers at both ASDEX-U and COMPASS tokamaks.



Device Specification

Laser Wavelength – 1550nm
Laser Linewidth – 1MHz
Laser Power – 100mW
Beam Divergence (Full Angle) – 0.279mRad
AOM Shift Freq. ($\Delta\omega$) – 40MHz
Plasma Travel Distance (L) – ~6m
Minimum Detectable Density – 1.5E13 cm^3
Detector Type – InGaAs Photodiode
Detector Sensitivity Range – 800-1700nm (Peak 1560nm)
Overall Device Bandwidth – 30MHz (Phase Detection Limited)

Figure 1: Diagram of the interferometer system, and basic specifications. Yellow arrows represent fiber optic cabling red represents free space beam line.

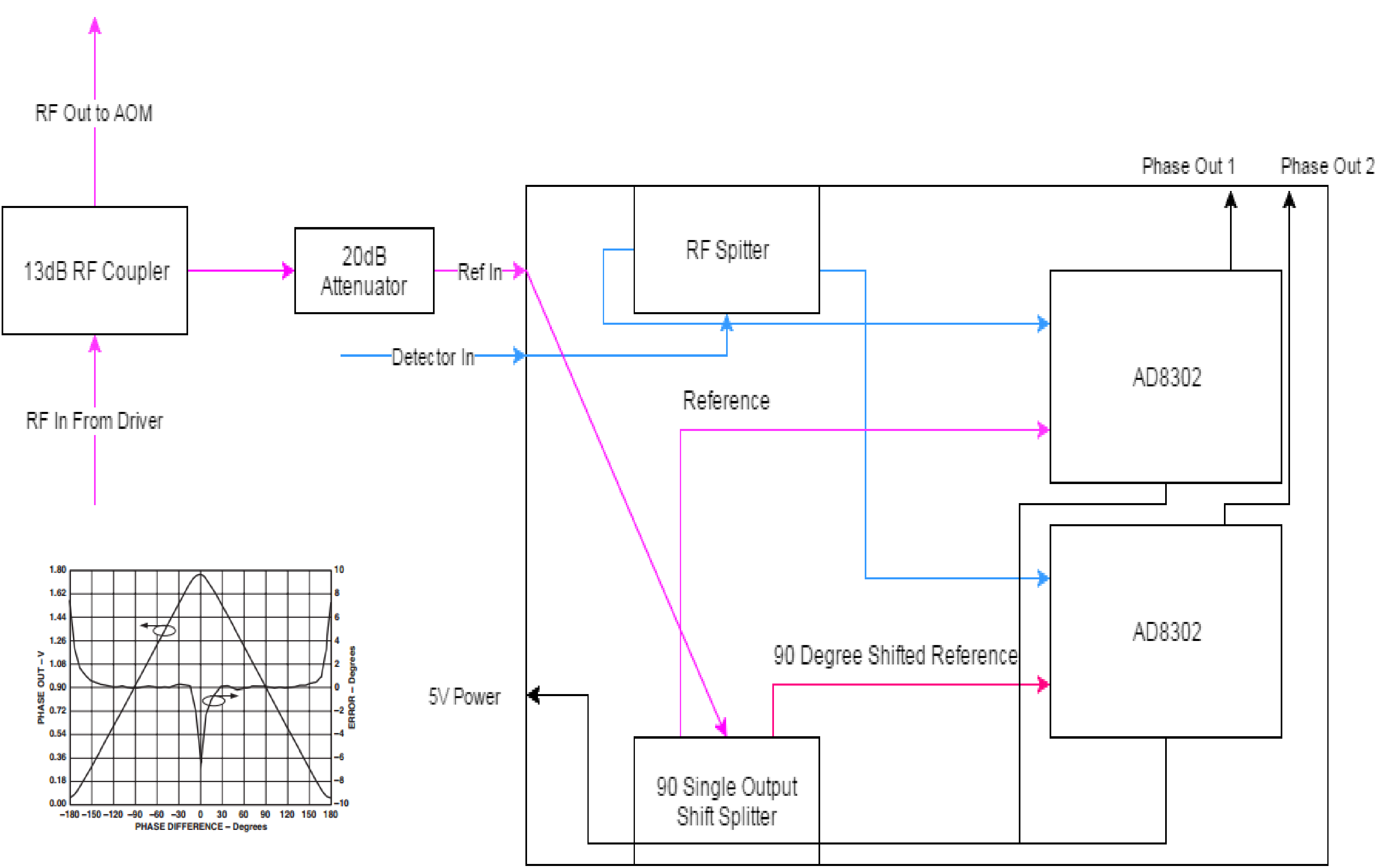


Figure 2: Diagram of the phase detection system and example of AD8302 output

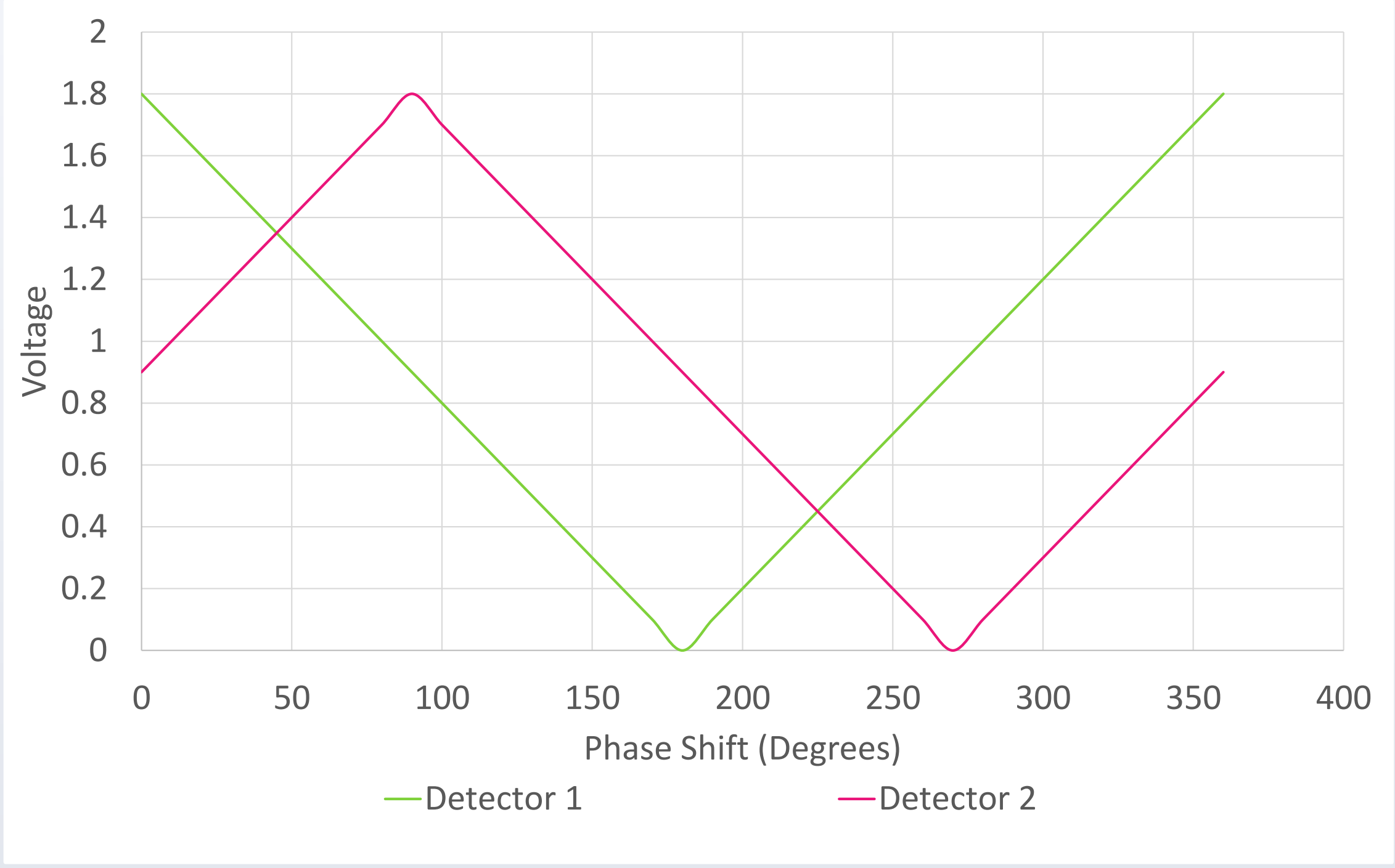


Figure 3: Ideal Phase Detection Output from Detection System

Future Plans & Conclusion

- Unfortunately ordering and manufacturing lead times have prevented completion of this project within the ten-week timeframe of SULI.
- Device Timeline
  - Initial laser testing and system verification beginning this week (8/8/16-8/12/16).
  - Density data collection and device calibration on MRX throughout September and October.
  - Fine-tuning including additions such as a phase shifter and filtering to phase detection circuit for optimal resolution, and fiber line-delay to laser interferometer lines for decreased phase noise.
  - Installation and use on FLARE
- Additional information and preliminary data will be presented at APS Plasma Physics Division 2016 Meeting when device construction is complete.

References

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Acknowledgements

This work was made possible by funding from the Department of Energy for the Summer Undergraduate Laboratory Internship (SULI) program. This work is supported by the US DOE Contract No. DE-AC02-09CH11466.