Microwave Interferometer Density Diagnostic for the Levitated Dipole Experiment

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Abstract

A plasma is collection of charged particles; knowing the number of particles present at any given location--which is to say the density--is vital, then, for even the most basic understanding of a plasma. The density, along with measurements of temperature and pressure and magnetic field, gives us sufficient information to model a plasma's behavior as an electrically conducting gas subject to the laws of thermodynamics and electromagnetism (MHD). In a plasma confined by a dipole magnetic field, MHD places strict requirements on the pressure profile but does not specify how the energy is apportioned between the density and temperature. Consequently, measuring the density profile will teach us interesting physics about a dipole-confined plasma, such as the stability of low-frequency drift modes.

To measure the density profile of the plasma in LDX, we are constructing a multi-channel microwave interferometer. Such a device makes use the relationship between a plasma's density and its index of refraction. The beams of an interferometer acquire a phase-shift when traversing the plasma and phase-shifts from multiple beams can be inverted to reconstruct a radially symmetric density profile. Concurrently with the initiation of experiments at LDX, we are perfecting a one-channel, heterodyne interferometer with a center frequency of 60 GHz and with phase-shifts measured in quadrature.

Basic Design

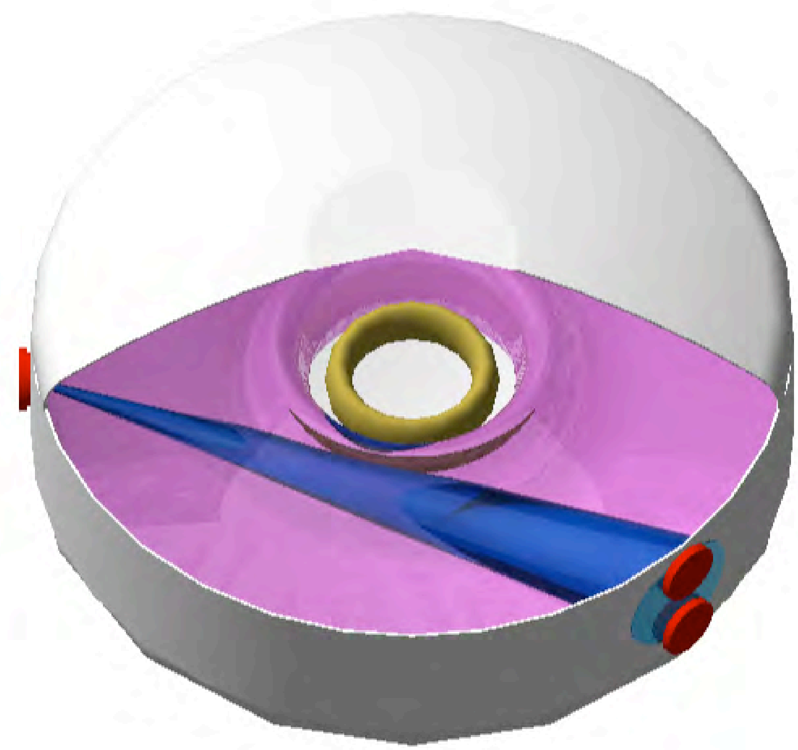
- An RF of 60 GHz puts our interferometer in the microwave spectrum.

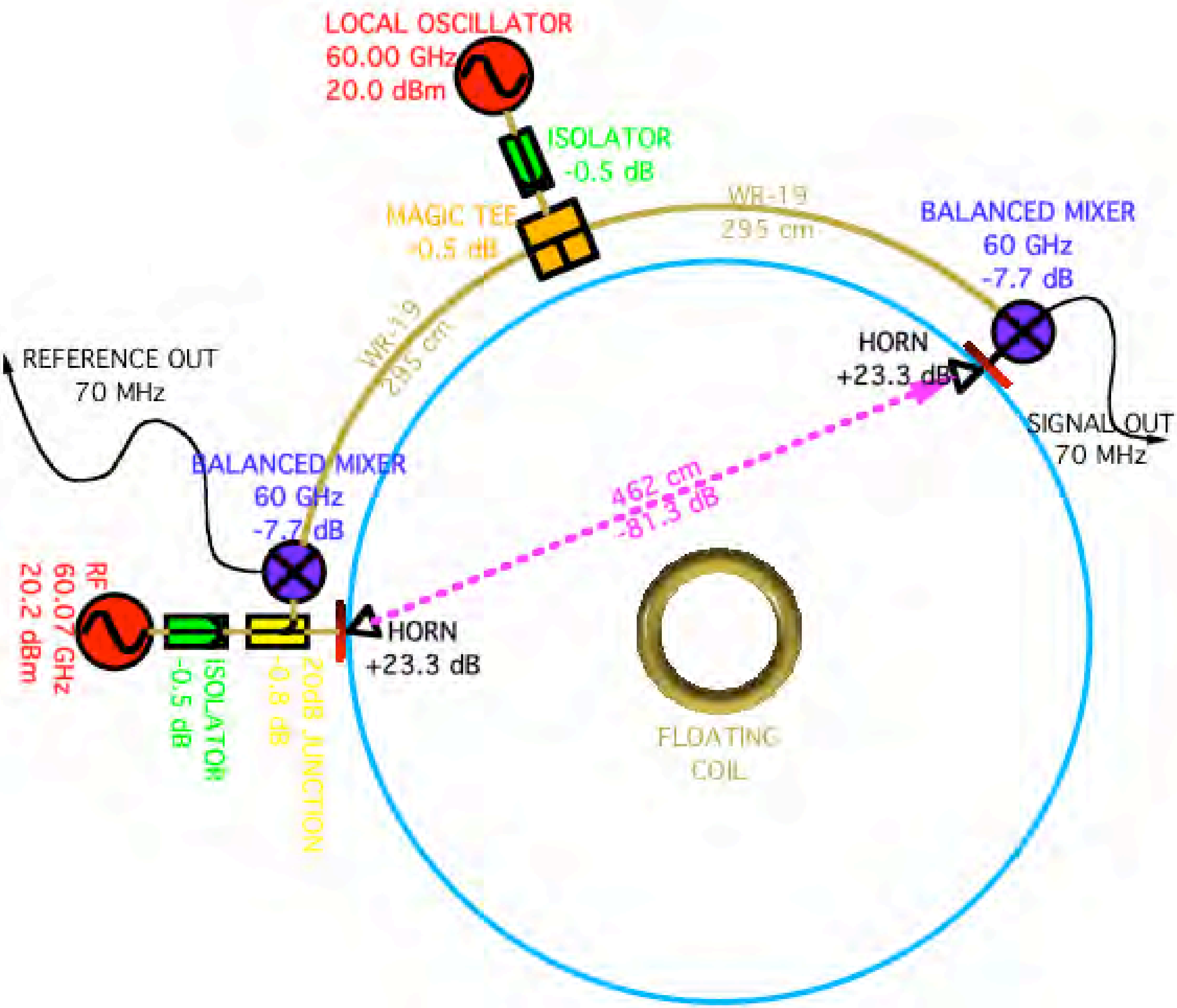
- The primary design is for a one-channel interferometer that will later be upgraded to many channels.

- The basic design follows other microwave interferometers in the literature, in particular *C.W. Domier et. al. Rev.Sci.Instrum.* ***59*** *[1988], 1588*

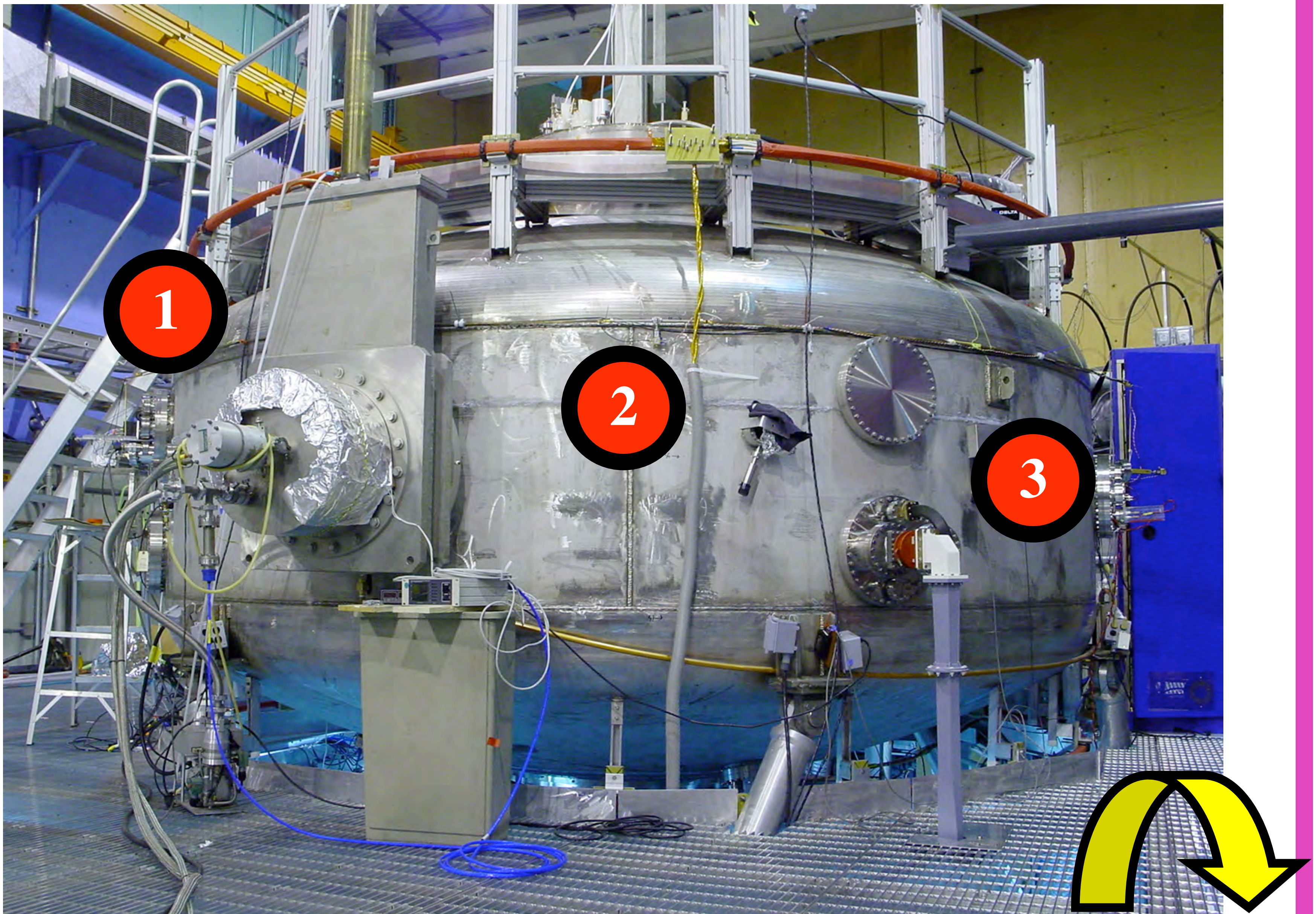
- Our interferometer is a *Heterodyne* system since an additional frequency source, the Local Oscillator (LO), is mixed with the RF to produce an Intermediate Frequency (IF).

- Our interferometer uses two free-running Gunn oscillators for the RF and LO. The IF is chosen to be 70 MHz. Phase-shifts are measured in *Quadrature* from two IF signals.

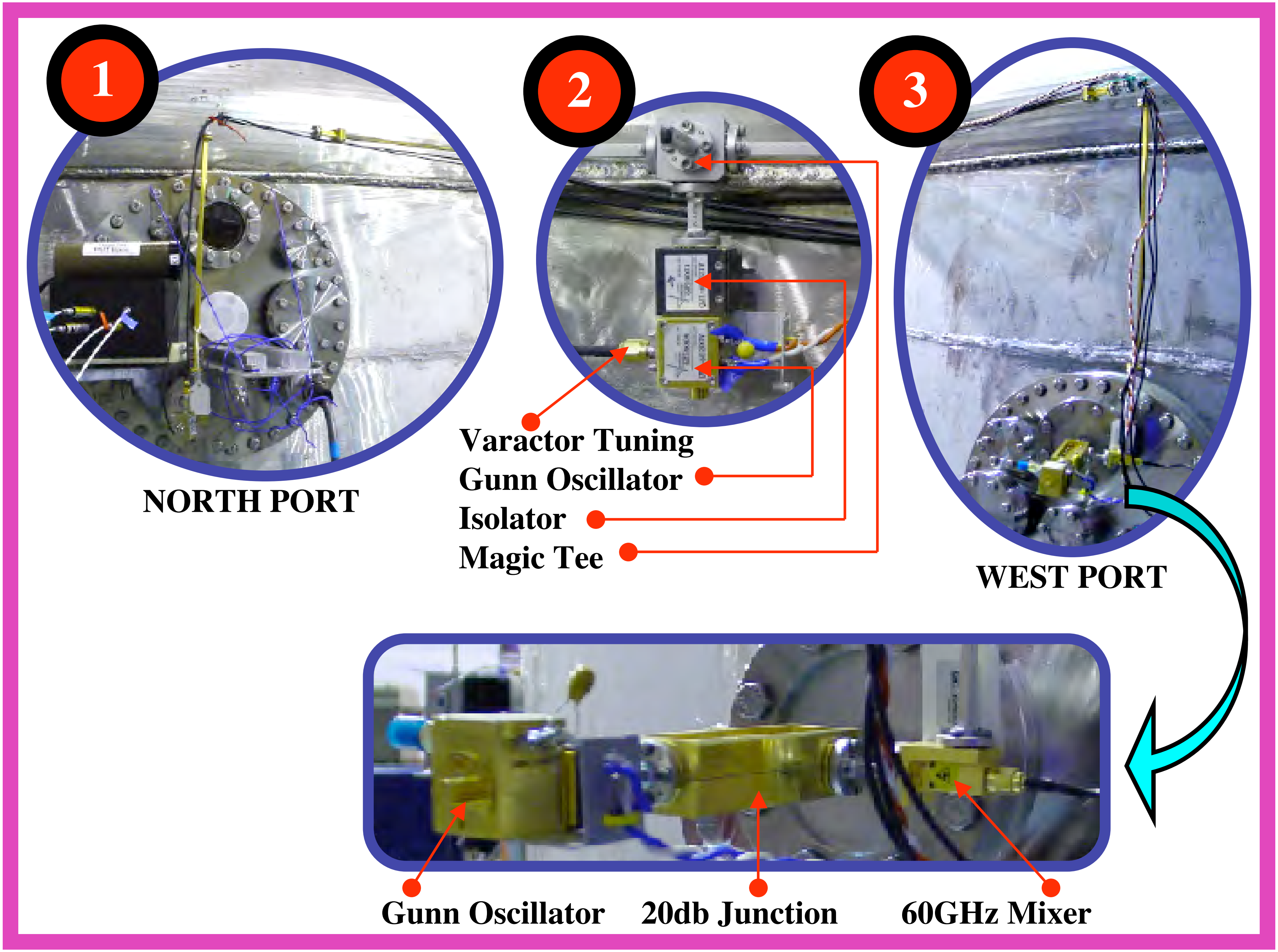




Block Diagram of the LDX Interferometer Showing Power Gains and Losses



The LDX Vacuum Vessel and Interferometer


1
2
3
NORTH PORT
Varactor Tuning
Gunn Oscillator
Isolator
Magic Tee
WEST PORT
Gunn Oscillator
20db Junction
60GHz Mixer

Interferometry Basics

An *Ordinary Wave* propagating through a plasma sees an index of refraction which is a function of the plasma's electron density

$$N^2 = 1 - \frac{\omega_p^{\,2}}{\omega_{RF}^{\,2}} = 1 - n_e/n_c$$

N is the index of refraction

ω_{RF} is the frequency of the probing wave (*RF*)

ω_p is the plasma frequency

n_e is the electron density of the plasma

n_c is the cutoff density for the probing wave

$$n_c = \frac{\omega_{RF}^2 m \varepsilon_0}{e^2} \qquad n_e = \frac{\omega_p^2 m \varepsilon_0}{e^2}$$

If the electron density changes sufficiently slowly when compared to the wavelength, we can use a *geometric-optics* approximation to describe its behavior in space and time

$$\psi \approx \exp i \{\int k \, dl - \omega t\}$$

The total phase-shift is

$$\phi = \int k \, dl = \int N \frac{\omega}{c} dl$$

These formulas allow us to relate a parameter we want to know (the electron density $\mathbf{n_e}$) with a quantity we can measure experimentally (the total phase-shift ϕ)

$$\phi = \frac{\omega}{c} \int \left(1 - \frac{n_e}{n_c}\right)^{1/2} dl$$

In order to separate the phase-shift due to plasma fluctuations from the phase-shift accumulated by traveling through space, we construct an *Interferometer*. The interferometer subtracts a reference beam from the probing beam. The resulting phase-shift (using a small $\mathbf{n_e/n_c}$ approximation) is

$$\Delta\phi \approx \frac{\omega}{2cn_c} \int n_e \, dl = \frac{e^2}{4\pi\varepsilon_0 mcf} \int n_e \, dl$$

Measurements of $\Delta\phi$ taken along multiple chords allows us to reconstruct—by the method of Abel inversion, for example—a radially symmetric density profile. A larger number of chords results in a more detailed reconstructed density profile.

Choosing the RF Frequency: Maximizing Phase-Shift

Two considerations come into play when choosing the RF frequency of an interferometer:

1. Maximizing the phase-shift

2. Keeping refraction under control

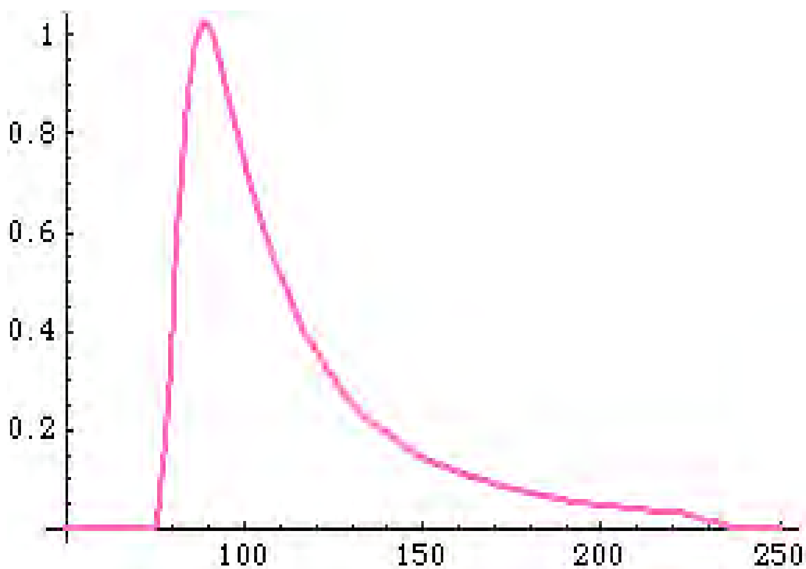
Large phase-shifts allow us to more easily measure smaller changes in density. From the above slide we have the result:

$$\Delta\phi = \frac{e^2}{4\pi\varepsilon_0 m_e c f_{RF}} \int n_e dl$$

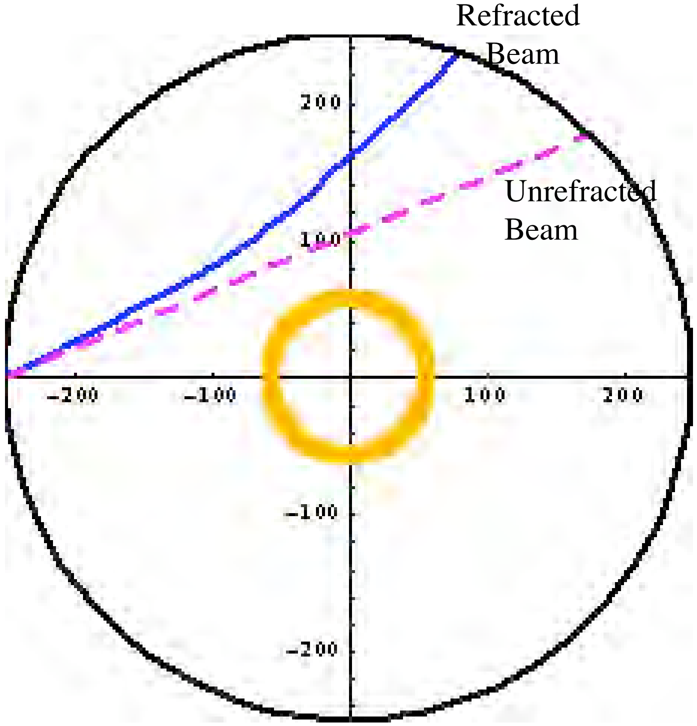
This approximation is only valid for $f_{RF} >> f_{plasma}$, but in general we see that a lower RF frequency will yield a larger phase-shift

Choosing the RF Frequency: Minimizing Refraction

We cannot choose our RF frequency to be lower than the largest possible plasma frequency since this would cause our signal to be **CUT-OFF**. Frequencies are more refracted the closer they get to the cut-off frequency.



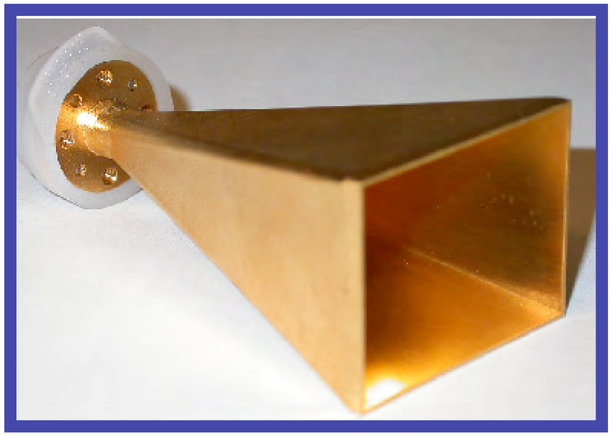
Possible density profile (normalized to peak density)



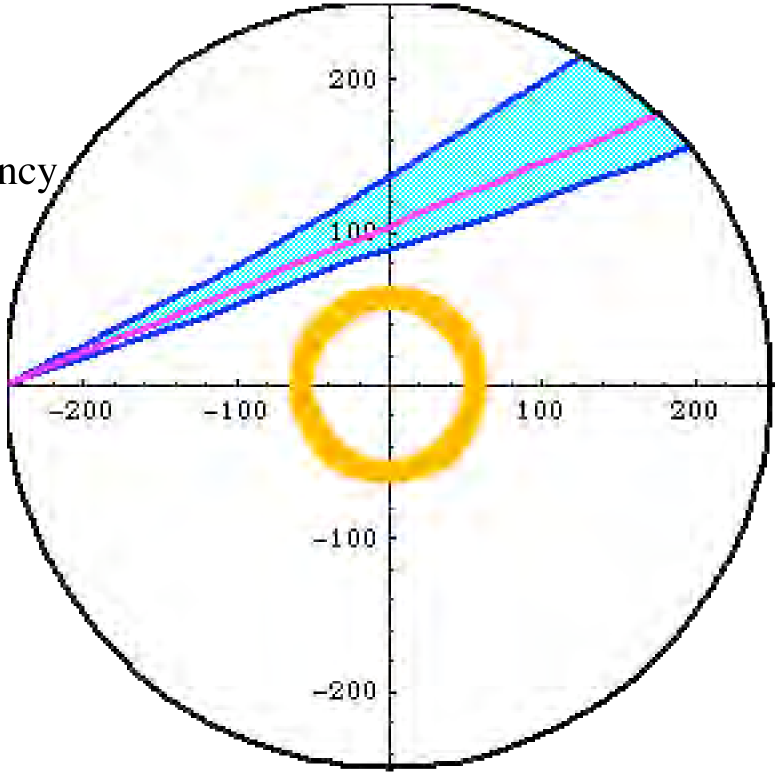
Refractive effects on a beam with $\omega = 3\omega_p$

RF Frequency: 60GHz

- $n_e \approx 3 \times 10^{11}$ cm^{-3} predicted density of the hot electron startup mode in LDX
- $f_p \approx 4.9$ GHz corresponding plasma frequency
- $f_{RF} = 60$ GHz this is 12 x's the plasma frequency
- $\Delta\phi \sim 2\pi$ corresponding phase-shift



A standard gain horn at 60GHz produces a 3db beam-width of 9.5 °



$\omega = 12\omega_p$, width = 9.5°

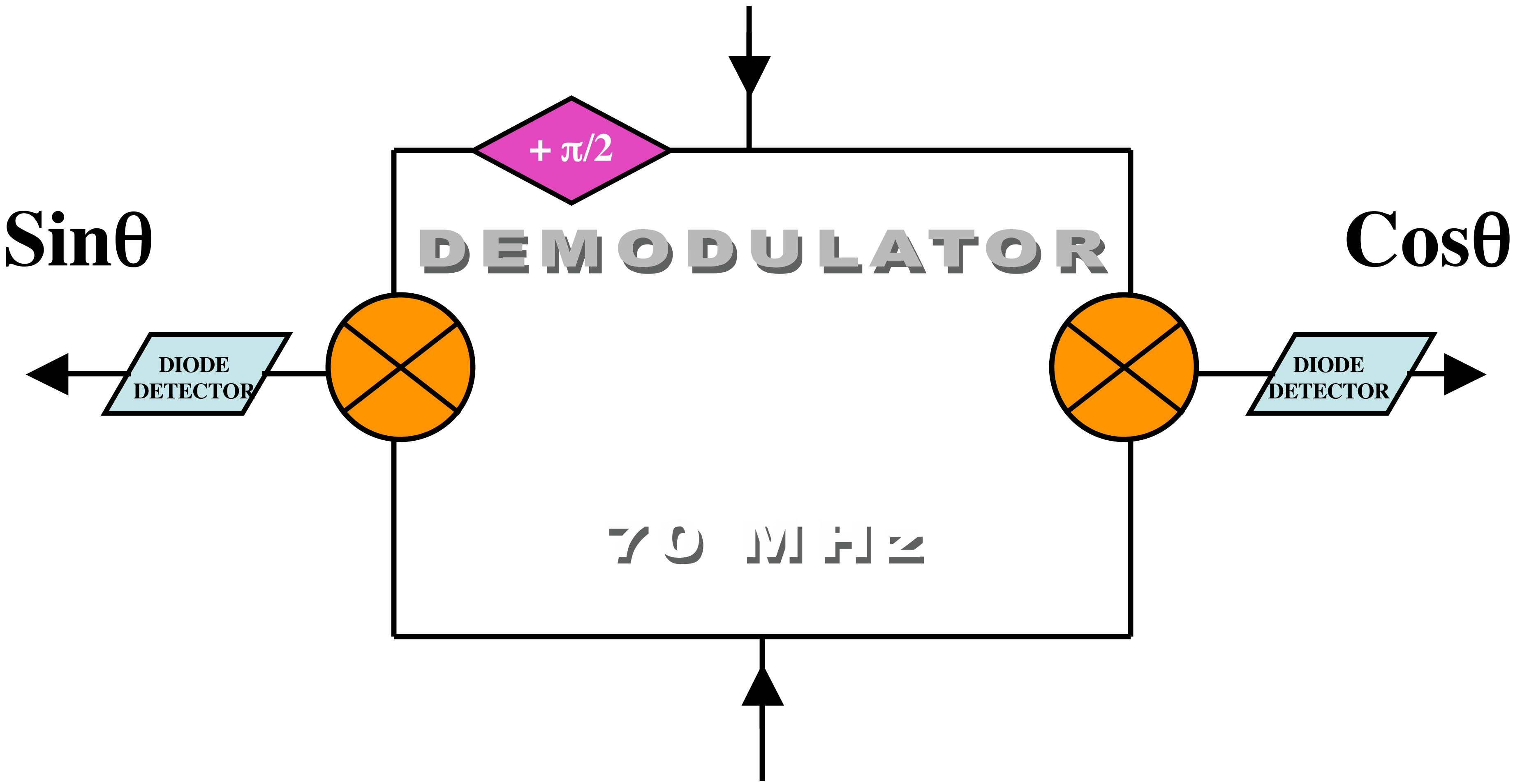
Heterodyning

Heterodyning consists of mixing two different frequencies together to obtain a **Beat Frequency**. Following RADIO usage, the carrier frequency is called the **RF** (radio frequency); this frequency is mixed with the **LO** (local oscillator) and the beat frequency is called the **IF** (intermediate frequency).

As in radio, our carrier frequency is much faster than the information we wish to receive. After the signal has been transmitted, we drop down to a lower frequency (IF) where components are cheaper and easier to use. The following are the frequencies used in LDX:

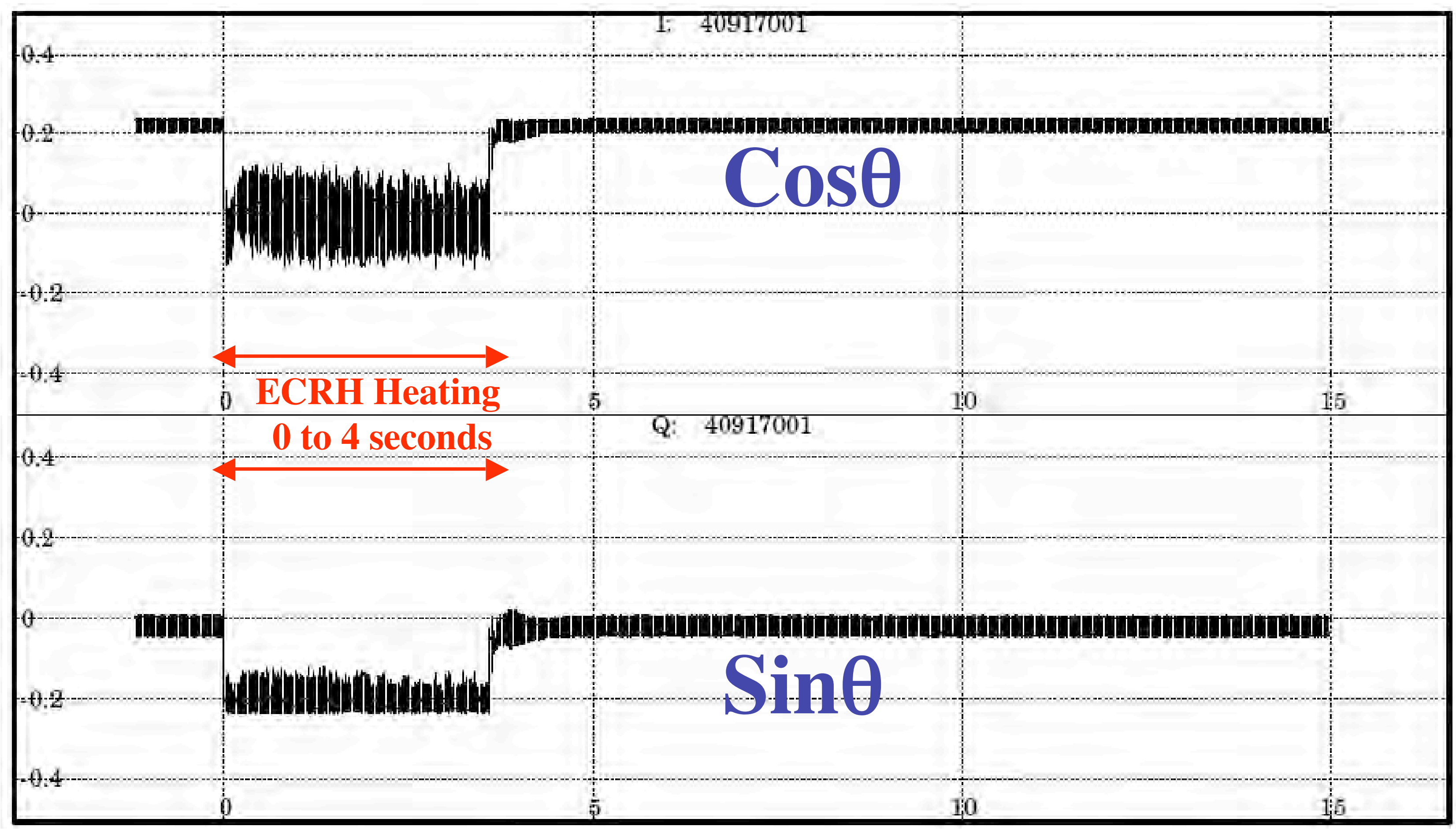
RF = 60.07 GHz
LO = 60.00 GHz
IF = 70 MHz
Frequency of Density Fluctuations **< 1 MHz**

Quadrature Phase Detection



The phase difference between our two 70 MHz signals is detected in **Quadrature**

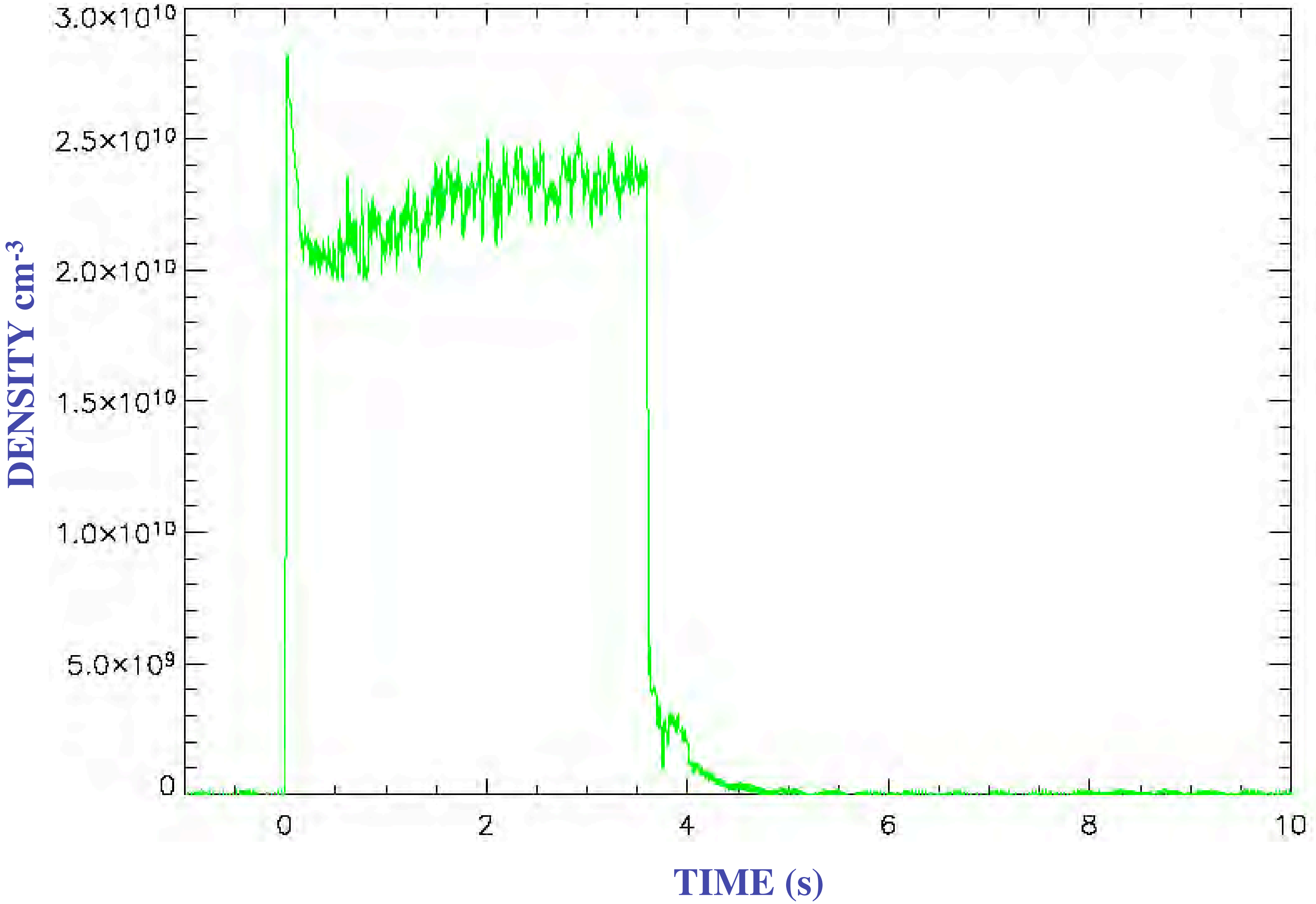
LDX Phase-Shift Data



September 17th, shot #1

LINE AVERAGED DENSITY

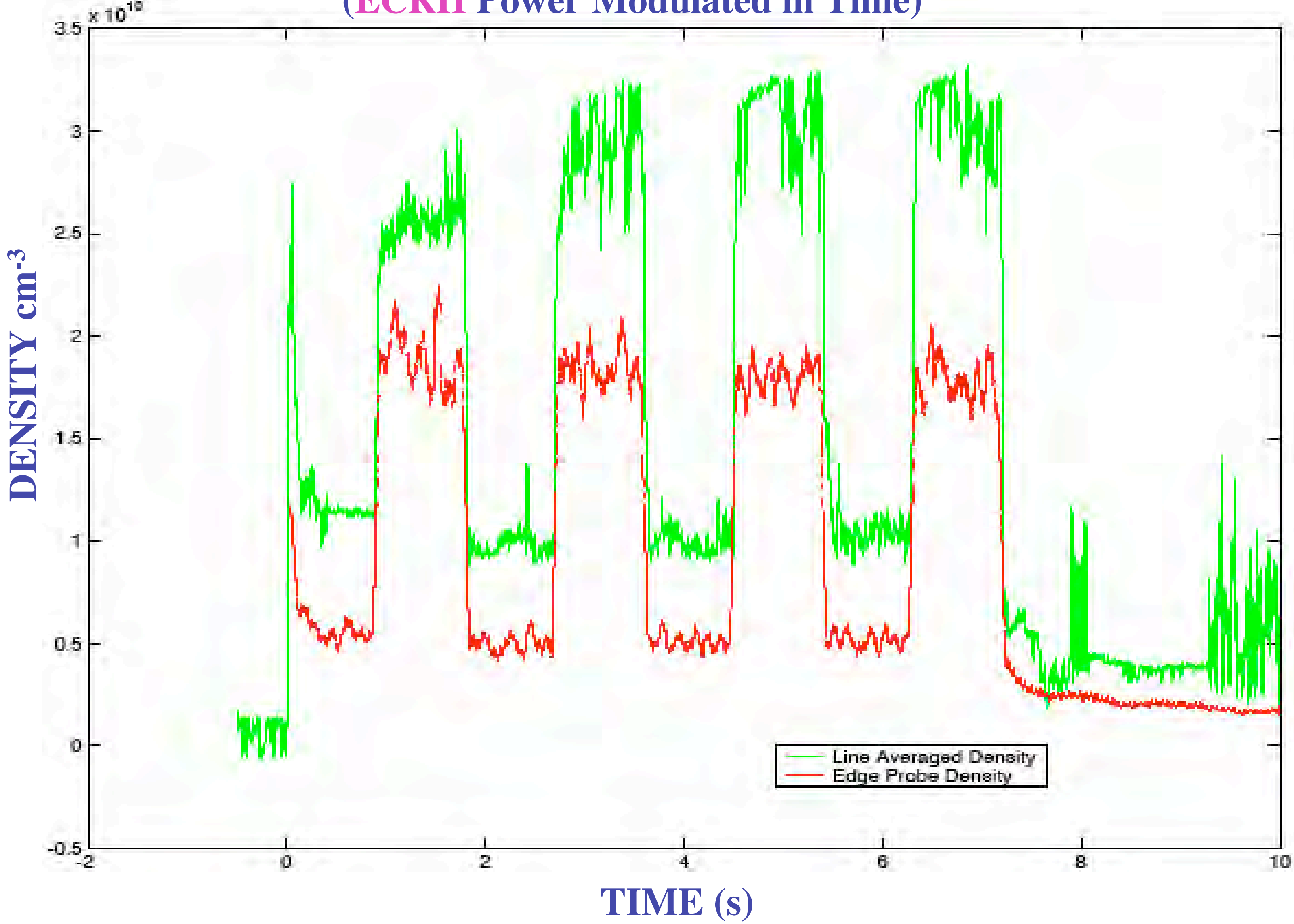
(Smoothed to 60Hz)



September 17th, shot #1

Comparing Core and Edge Pressures

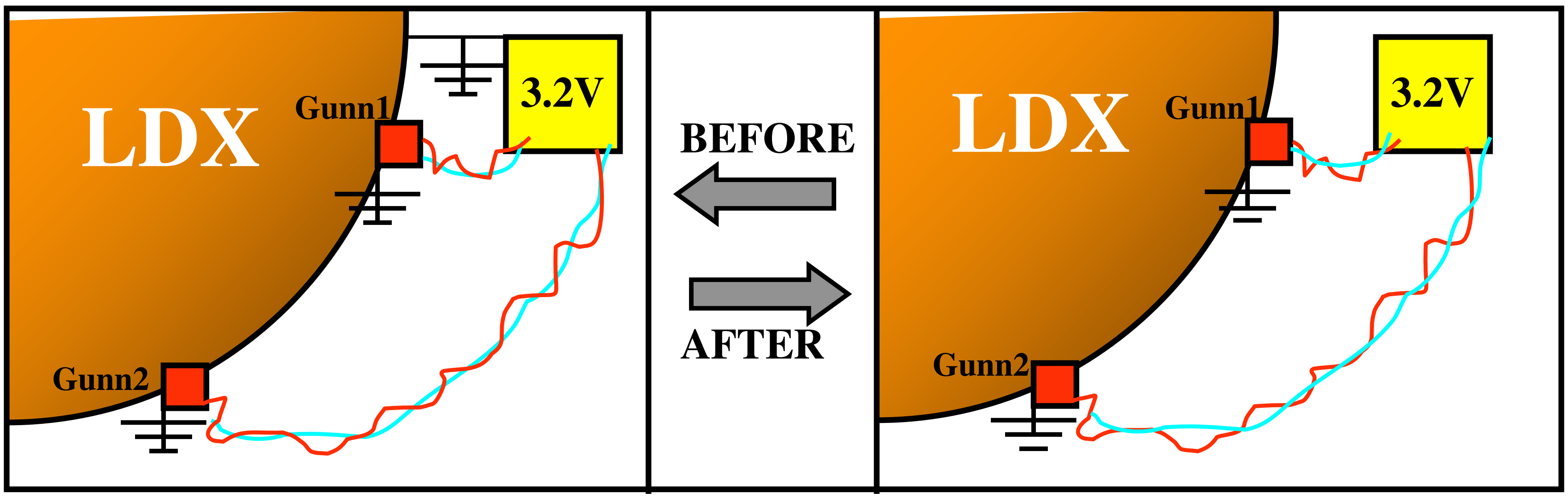
(ECRH Power Modulated in Time)



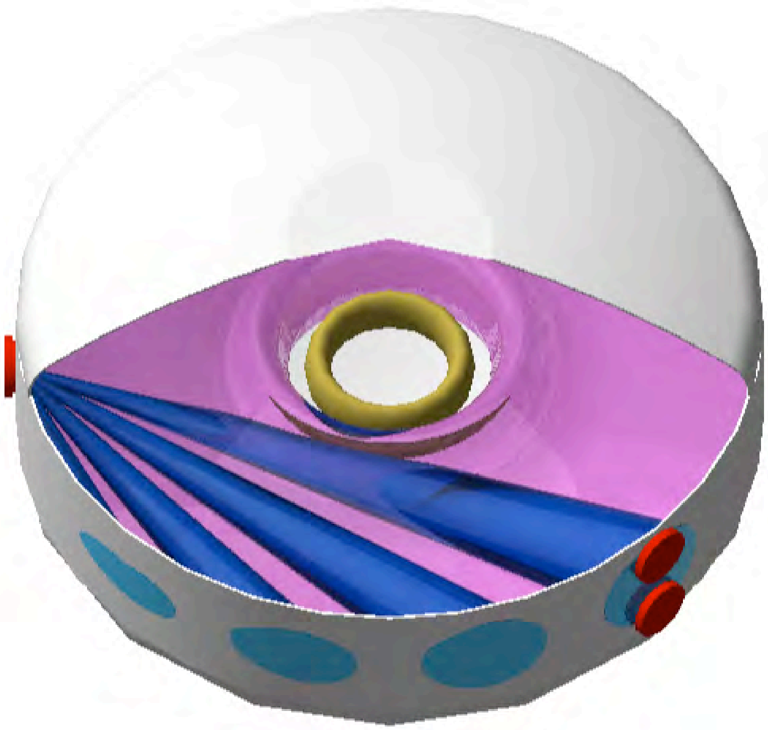
September 17th, shot #19

NOISE NOISE NOISE NOISE

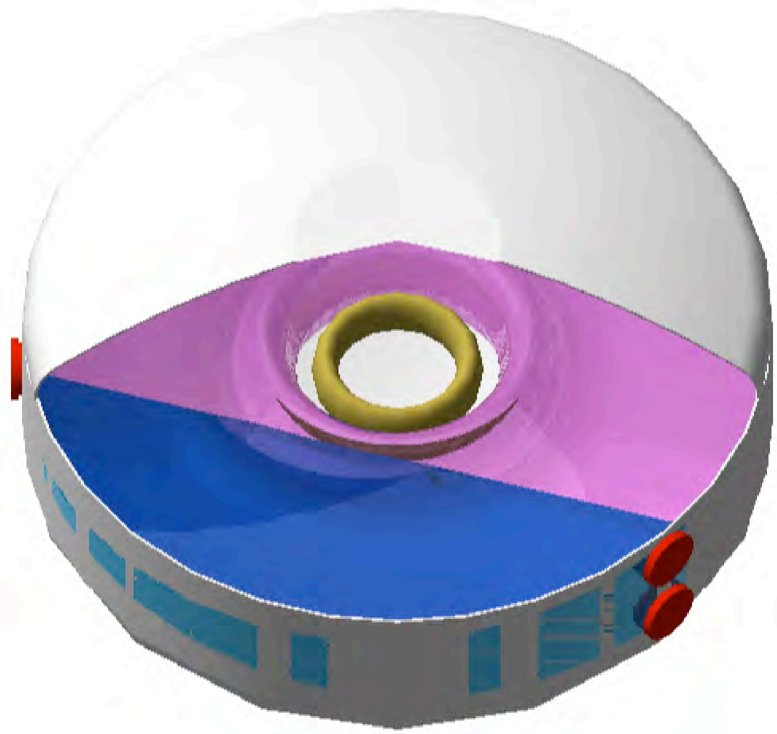
- It’s pretty clear that the inaugural run of our interferometer was far too noisy, especially at 60 Hz.
- Performance seems significantly improved with the removal of a major GROUND-LOOP, but much work needs to be done before our next run in early December.



Possible Multichannel Designs



Multiple Standard Gain Horns



One Sectoral Horn