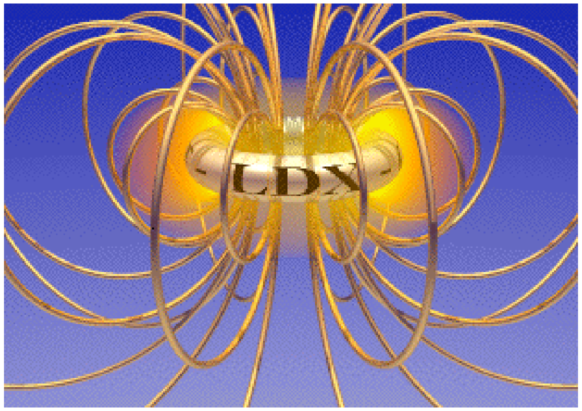

Microwave Interferometer Density Diagnostic for the Levitated Dipole Experiment

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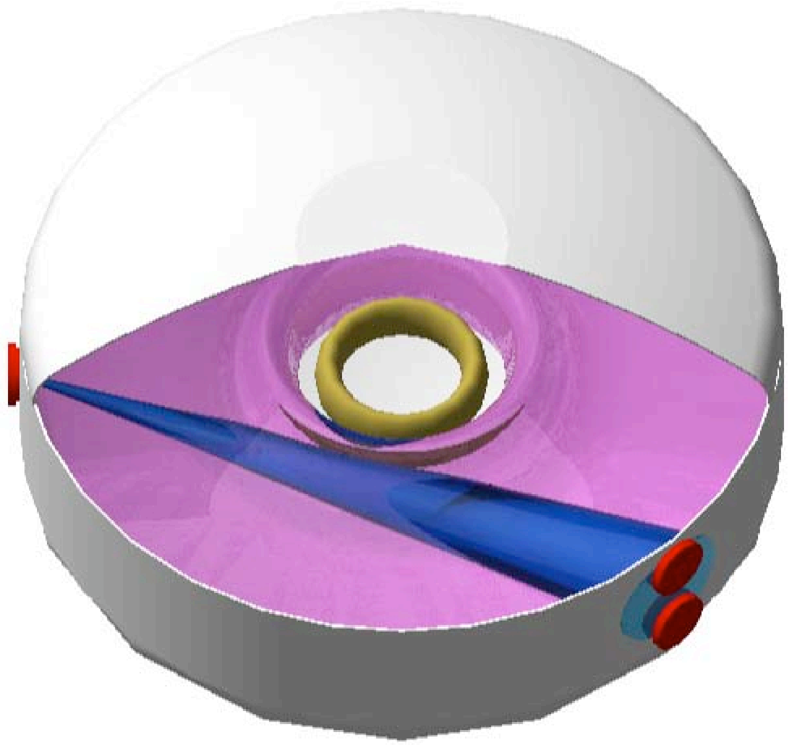
Abstract

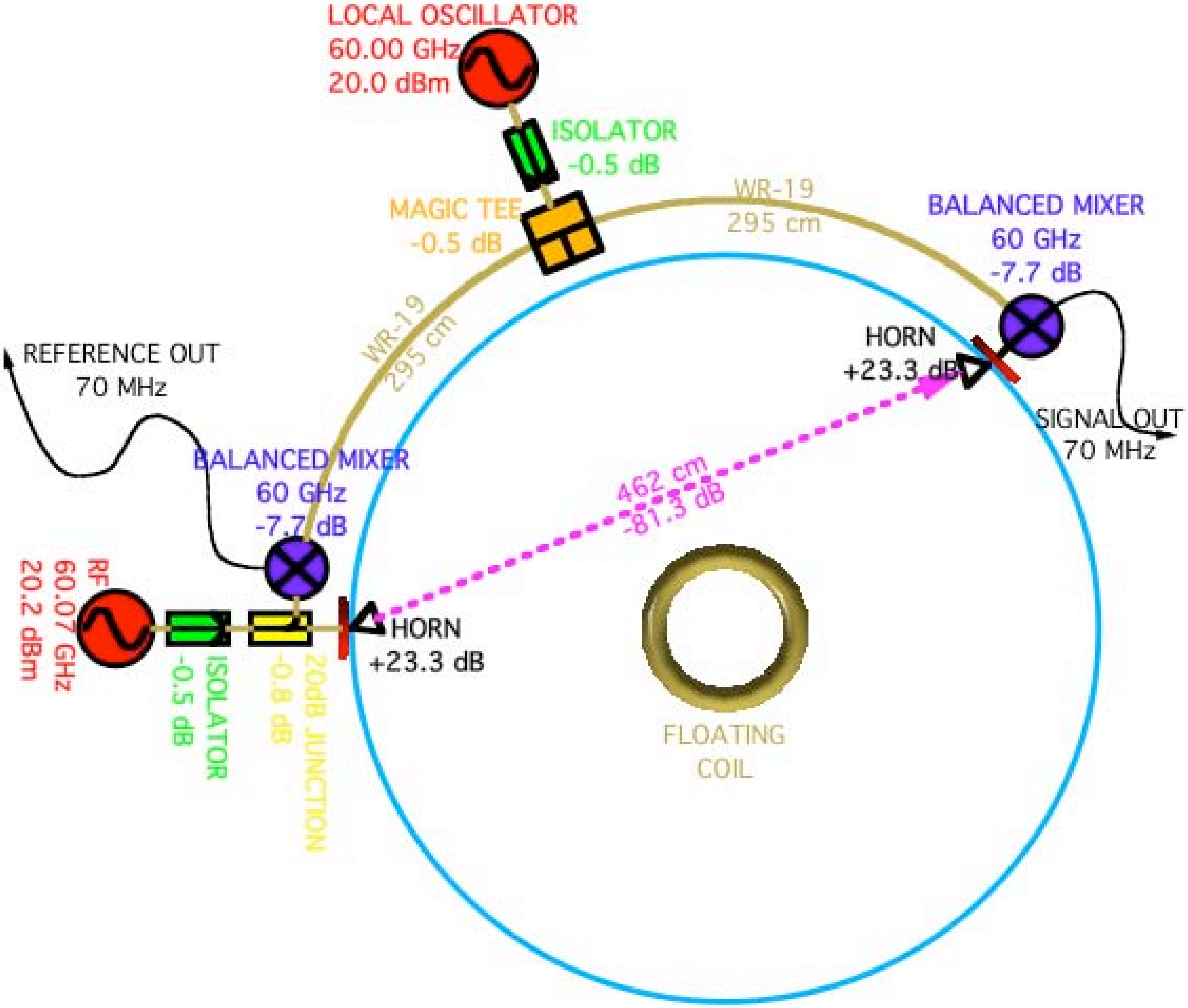
A plasma is collection of charged particles. Knowing how many of these particles are present at any given location--which is to say the density--is vital, then, for even the most basic understanding of a plasma. The density, along with measurements of temperature, pressure and magnetic field, gives us sufficient information to model a plasma's behavior as an electrically conducting gas subject to the laws of of thermodynamics and electromagnetism--laws which together we call magnetohydrodynamics (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. This 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. The microwave interferometer of LDX will be a multi-channel, heterodyne interferometer with a center frequency of 60 GHz and with phase-shifts measured in quadrature. Challenges have arisen in building a reliable one-channel device and these must be addressed before we progress to full multi-channel operation.

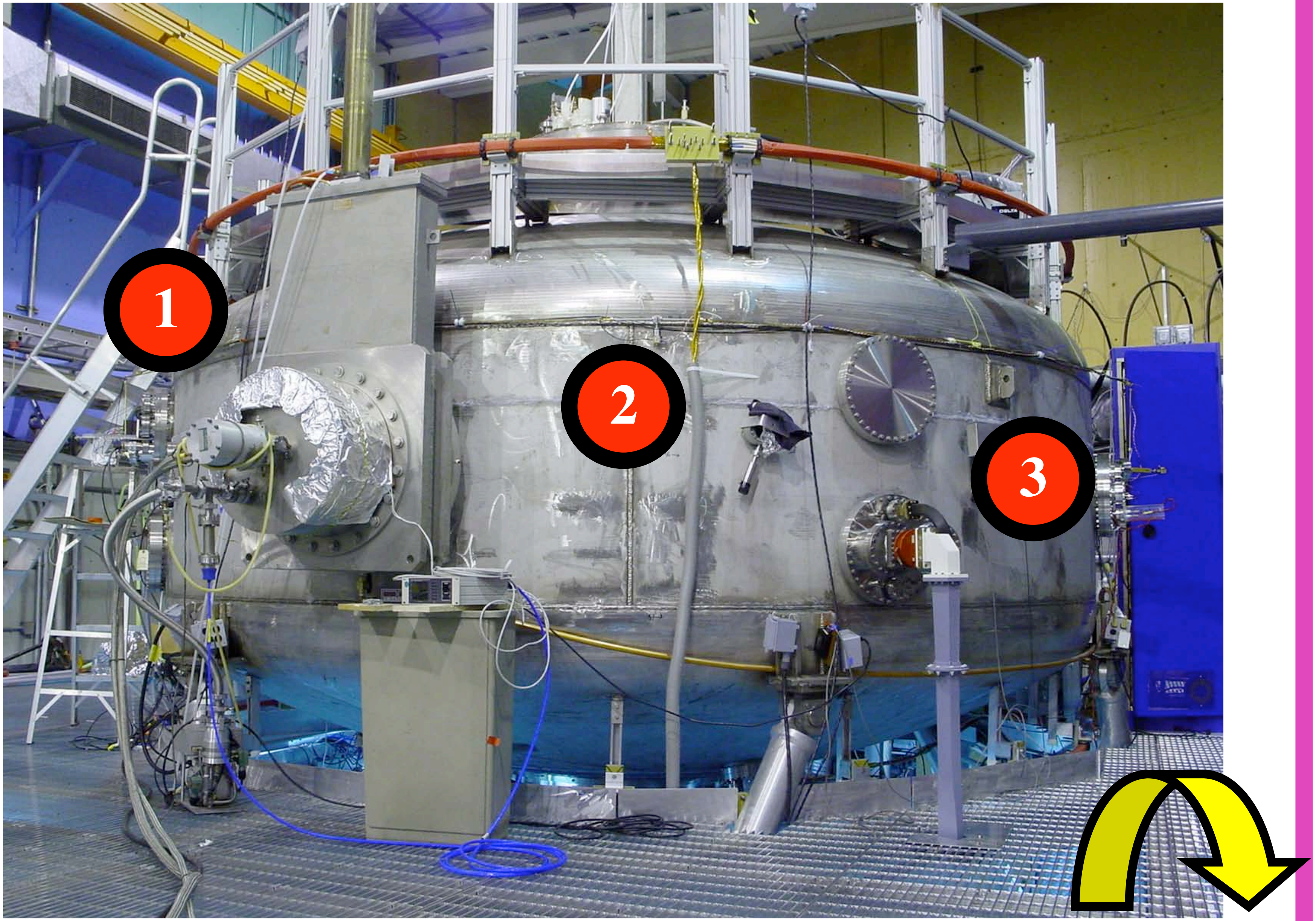
Basic Design

- 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.



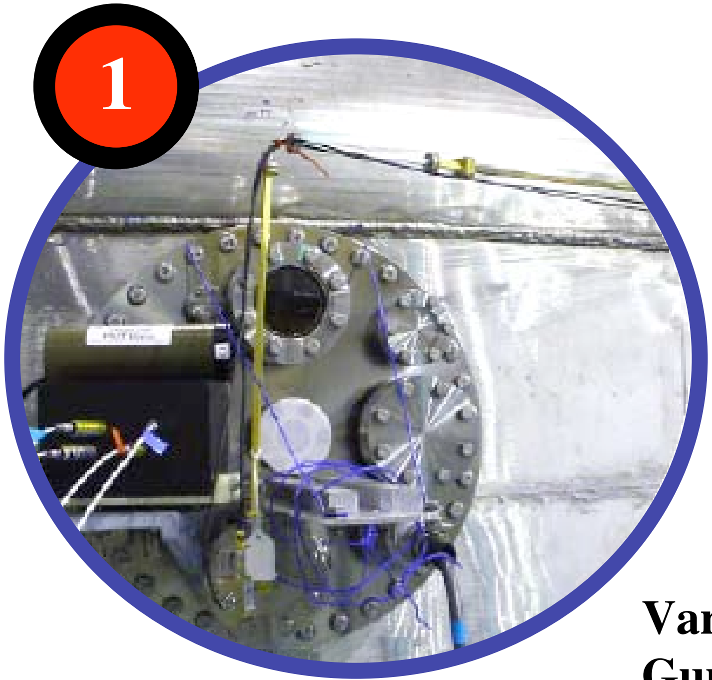


Block Diagram of the Single-Channel LDX Interferometer Showing Power Gains and Losses



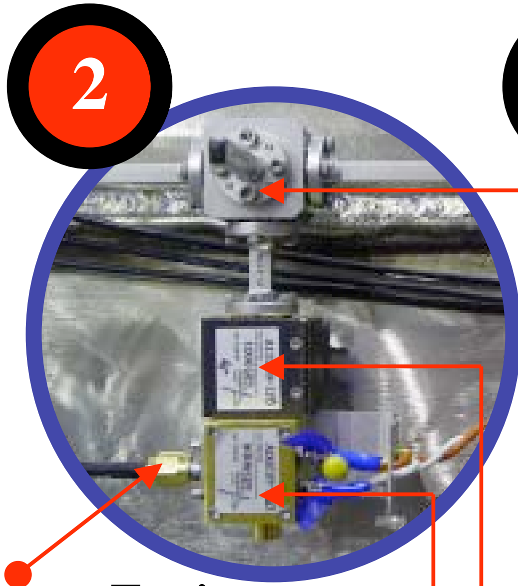
The LDX Vacuum Vessel and Interferometer

1



NORTH PORT

2



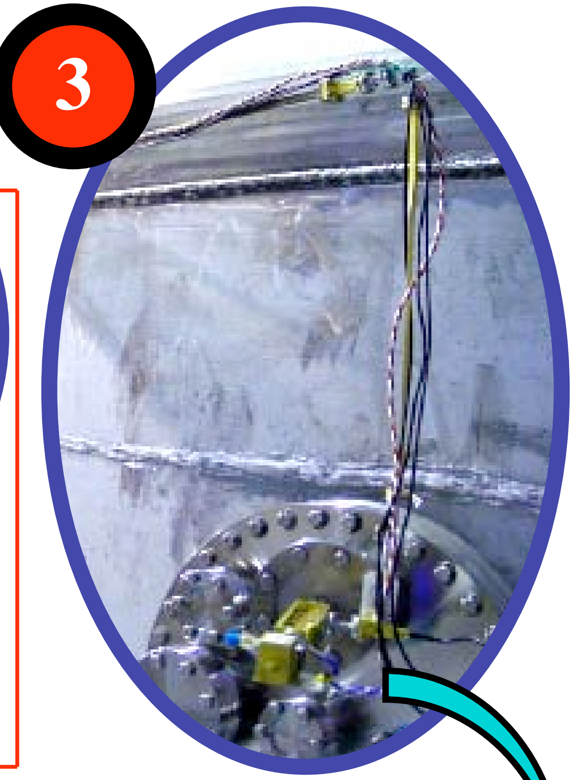
Varactor Tuning

Gunn Oscillator

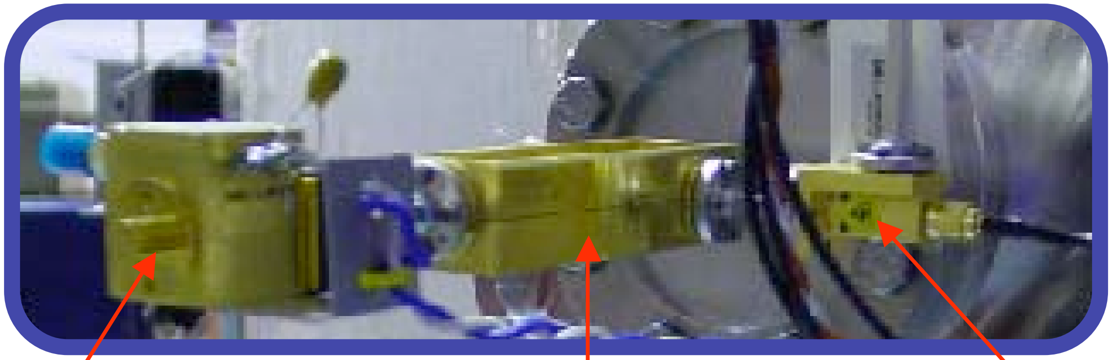
Isolator

Magic Tee

3



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

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

1. Maximizing the phase-shift

2. Keeping refraction under control

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

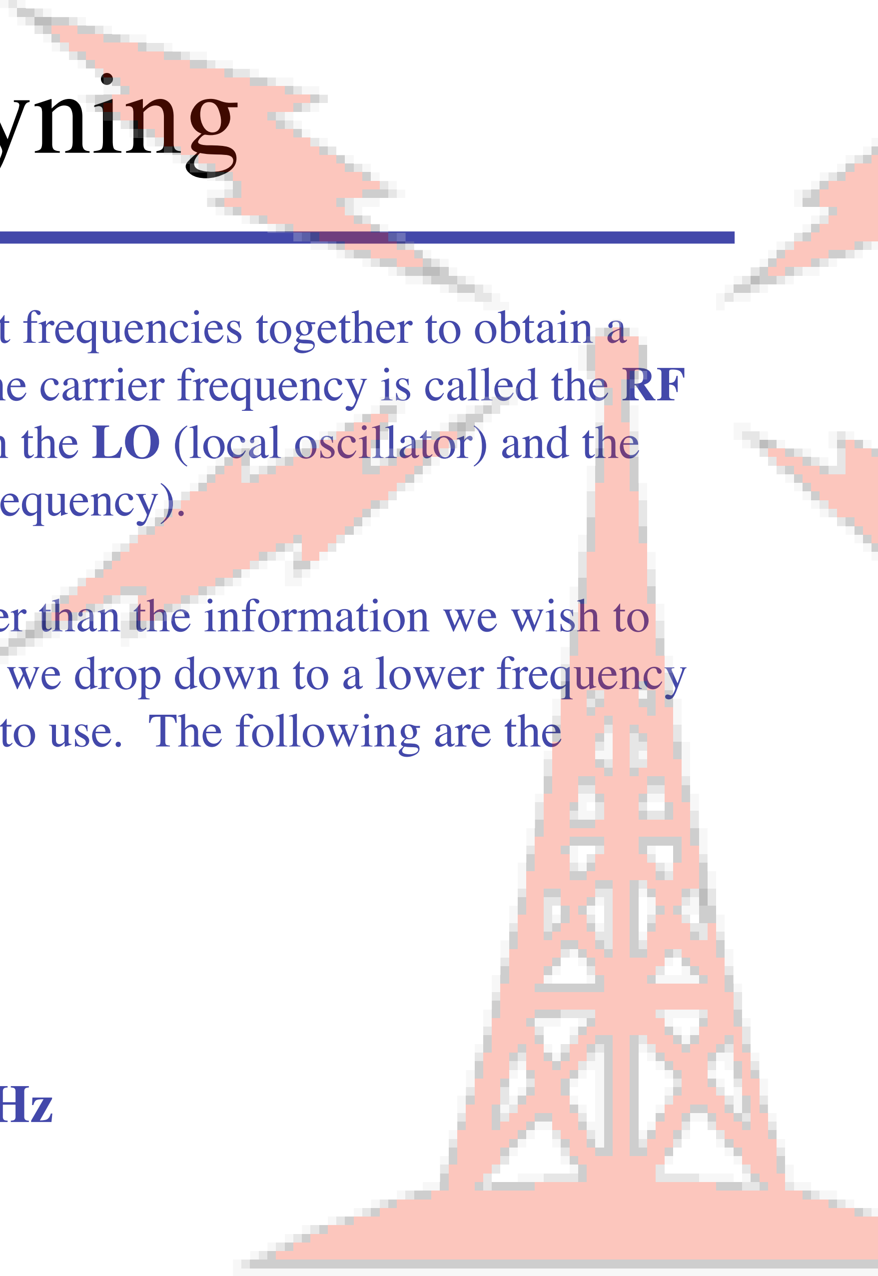
$$\Delta\phi = \frac{-\;e^2}{4\pi\varepsilon_0 m_e c f_{RF}} \int n_e dl$$

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.

2. We cannot get too close to f_{plasma} however, because our beam will become more and more refracted up to the point when $f=f_{plasma}$ at which point our beam is reflected backwards (**cut-off**).

Plasmas in LDX have average densities of the order $10^{10}cm^{-3}$. This corresponds to a plasma frequency of about 2 GHz. Our RF frequency is chosen to be 60 GHz and we measure phase shifts of about 1 fringe (2π).

Heterodyning

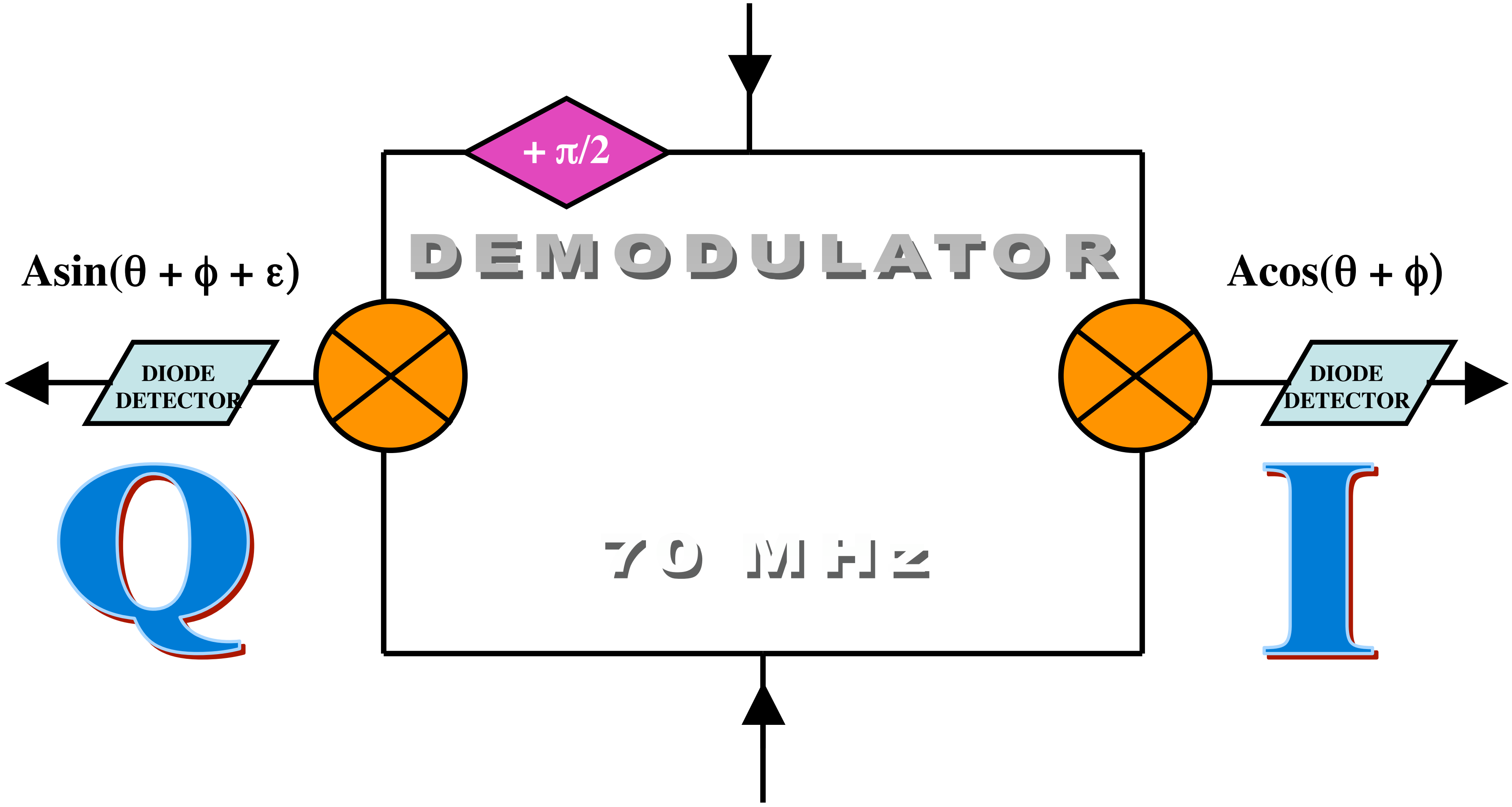


Heterodyning consists of mixing two different frequencies together to obtain a **Beat Frequency**. Following RADIO usage, the carrier frequency is called the **RF** (radio frequency); this frequency is mixed with the **LO** (local oscillator) and the beat frequency is called the **IF** (intermediate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

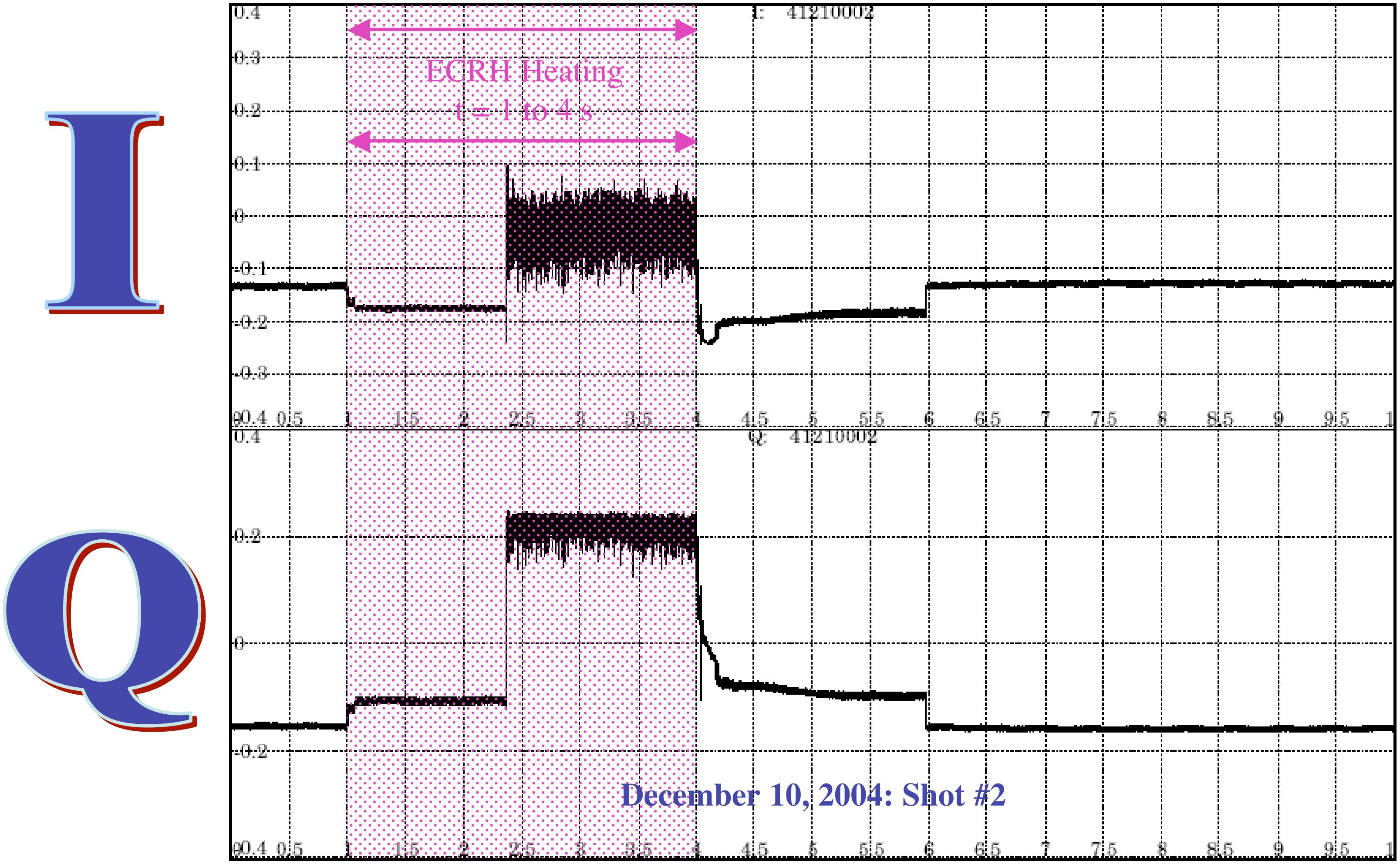
RF = 60.07 GHz
LO = 60.00 GHz
IF = 70 MHz
Frequency of Density Fluctuations **< 1 MHz**

Quadrature Phase Detection



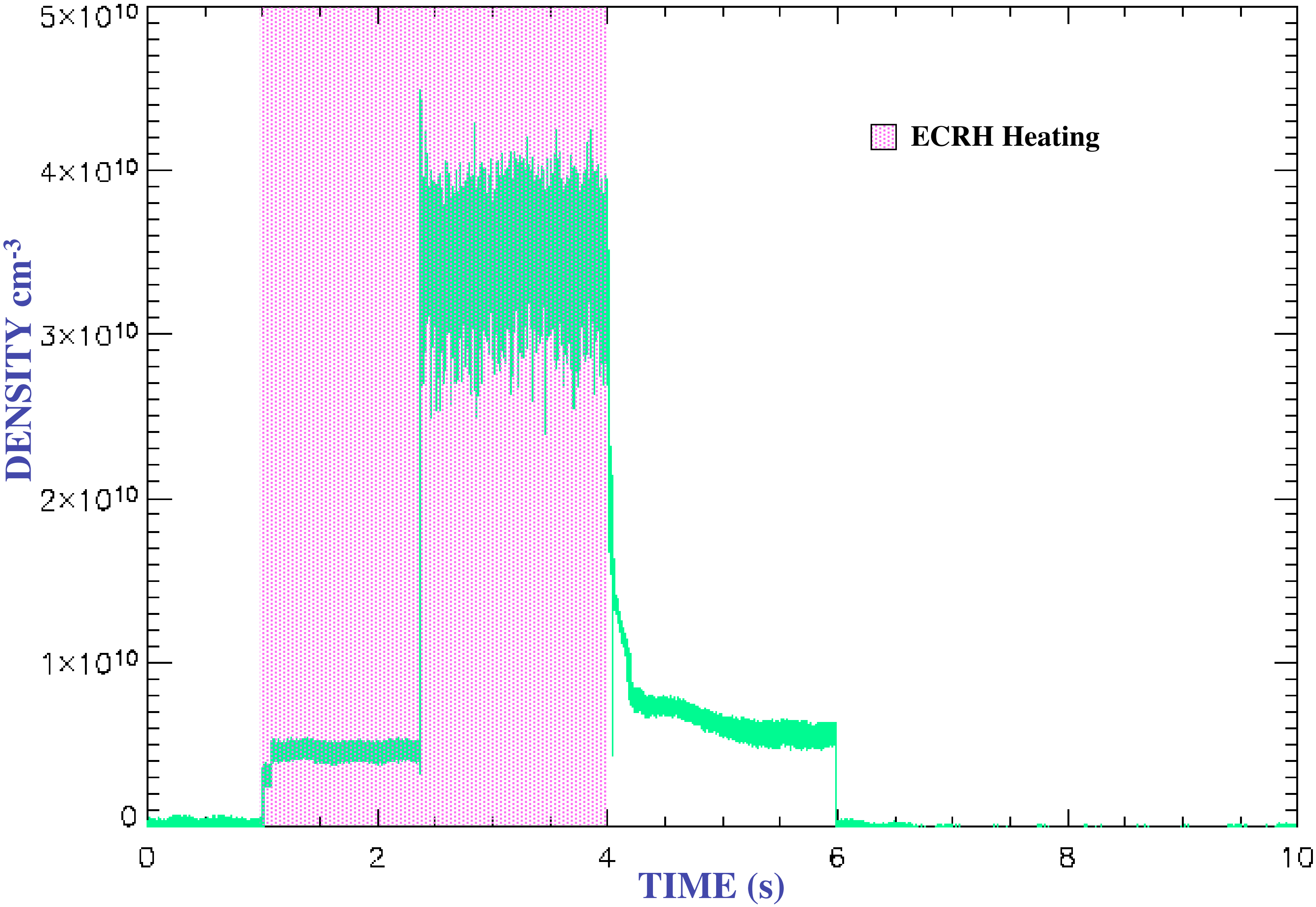
The phase difference between our two 70 MHz signals is detected in **Quadrature**

LDX Interferometer Raw Data



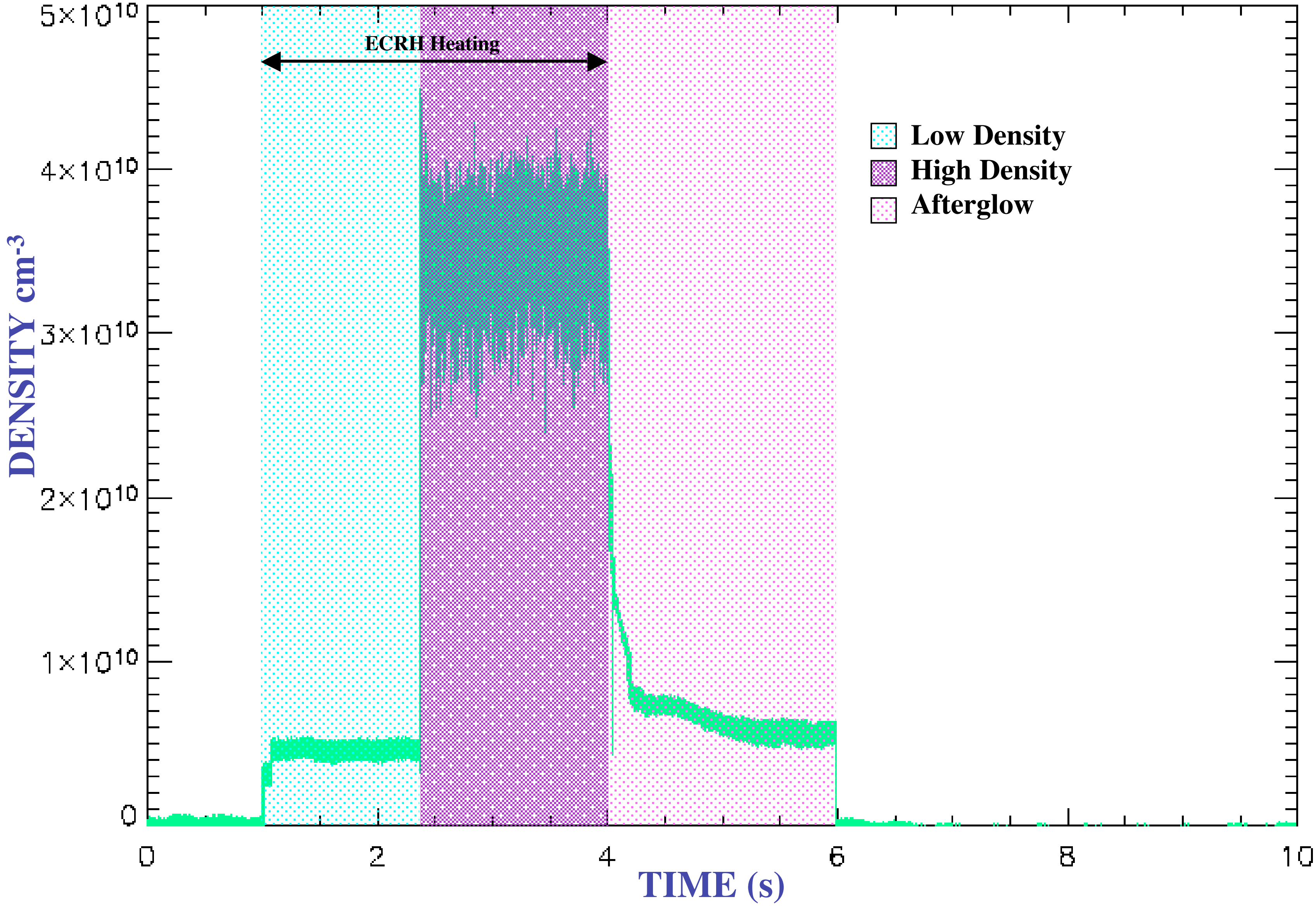
December 10, 2004: Shot #2

LINE AVERAGED DENSITY



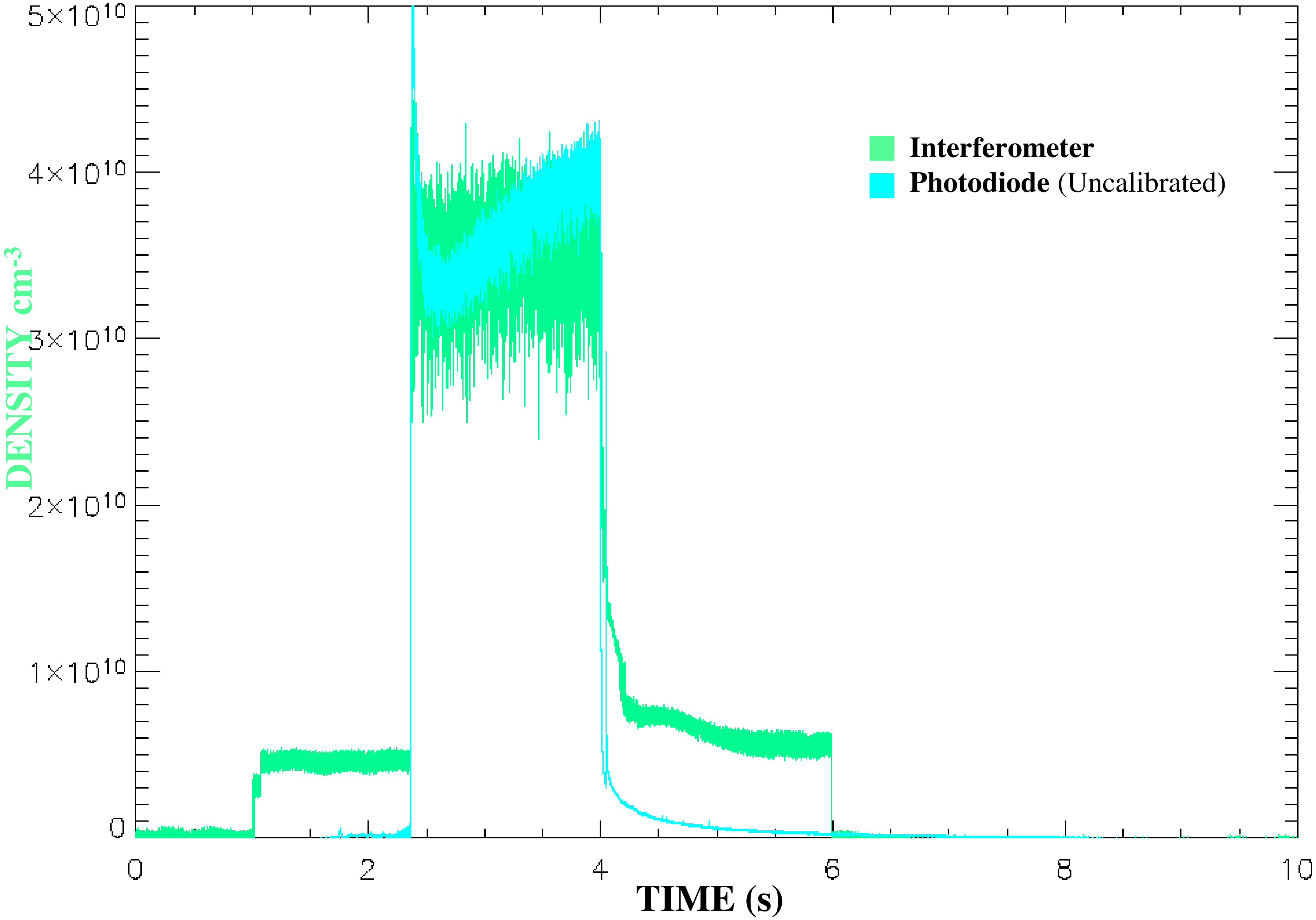
December 10, 2004: shot #2

3 Density Regimes



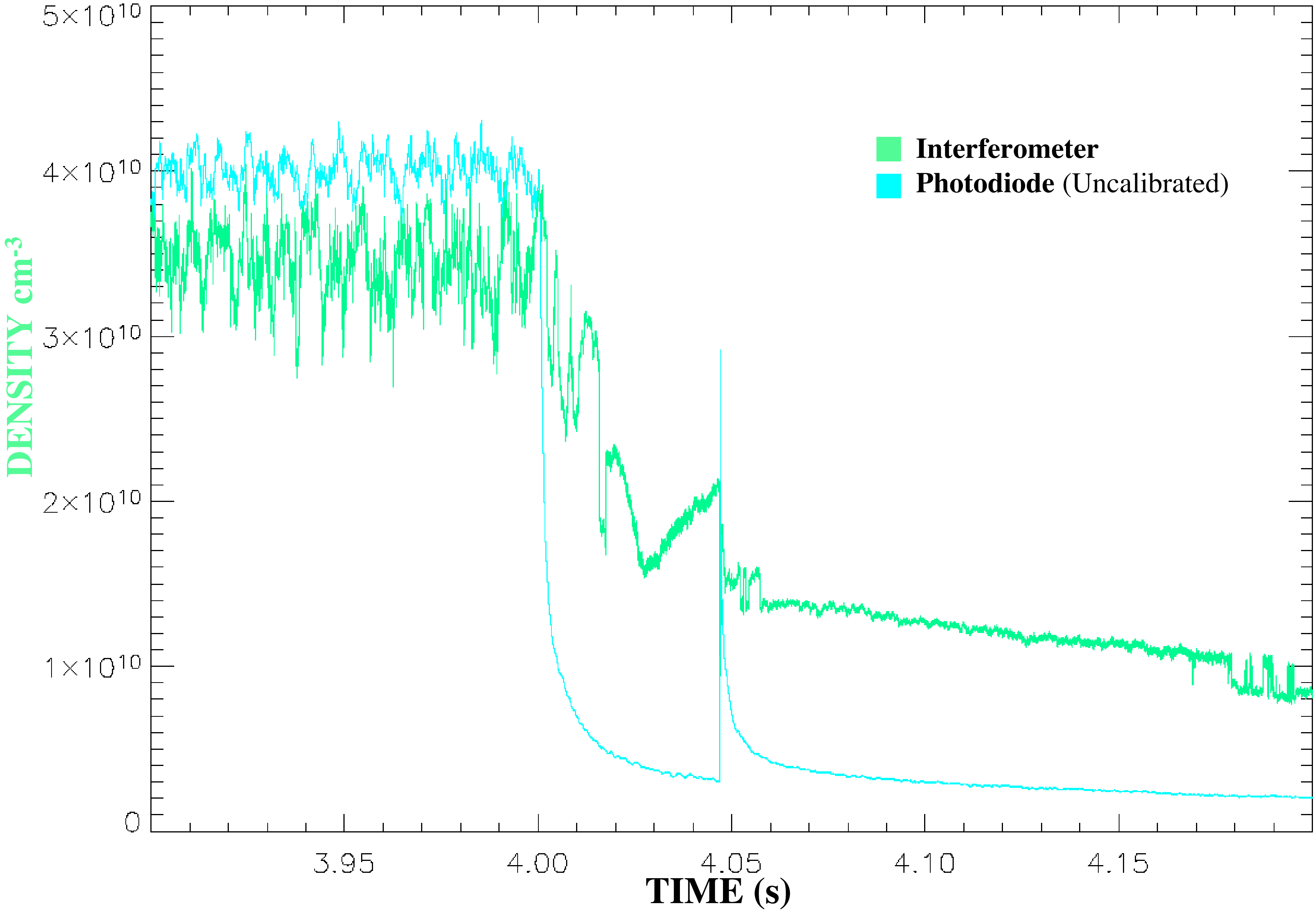
December 10, 2004: shot #2

Interferometer and Photodiode



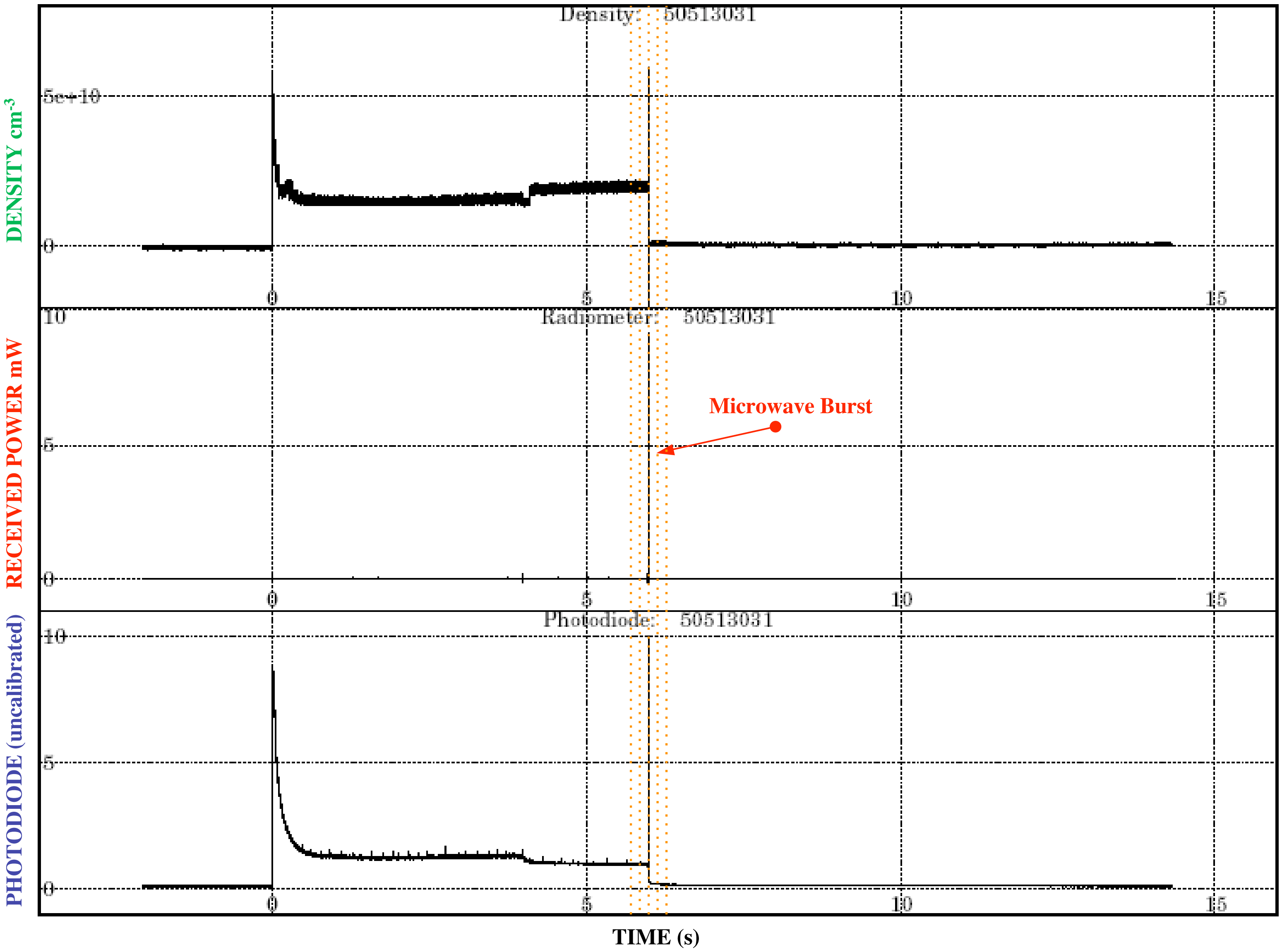
December 10, 2004: shot #2

Transition to Afterglow



December 10, 2004: shot #2

MICROWAVE BURSTS OFTEN ACCOMPANY A COLLAPSE OF PLASMA DENSITY



May 13, 2005: shot #31

Microwave Bursts

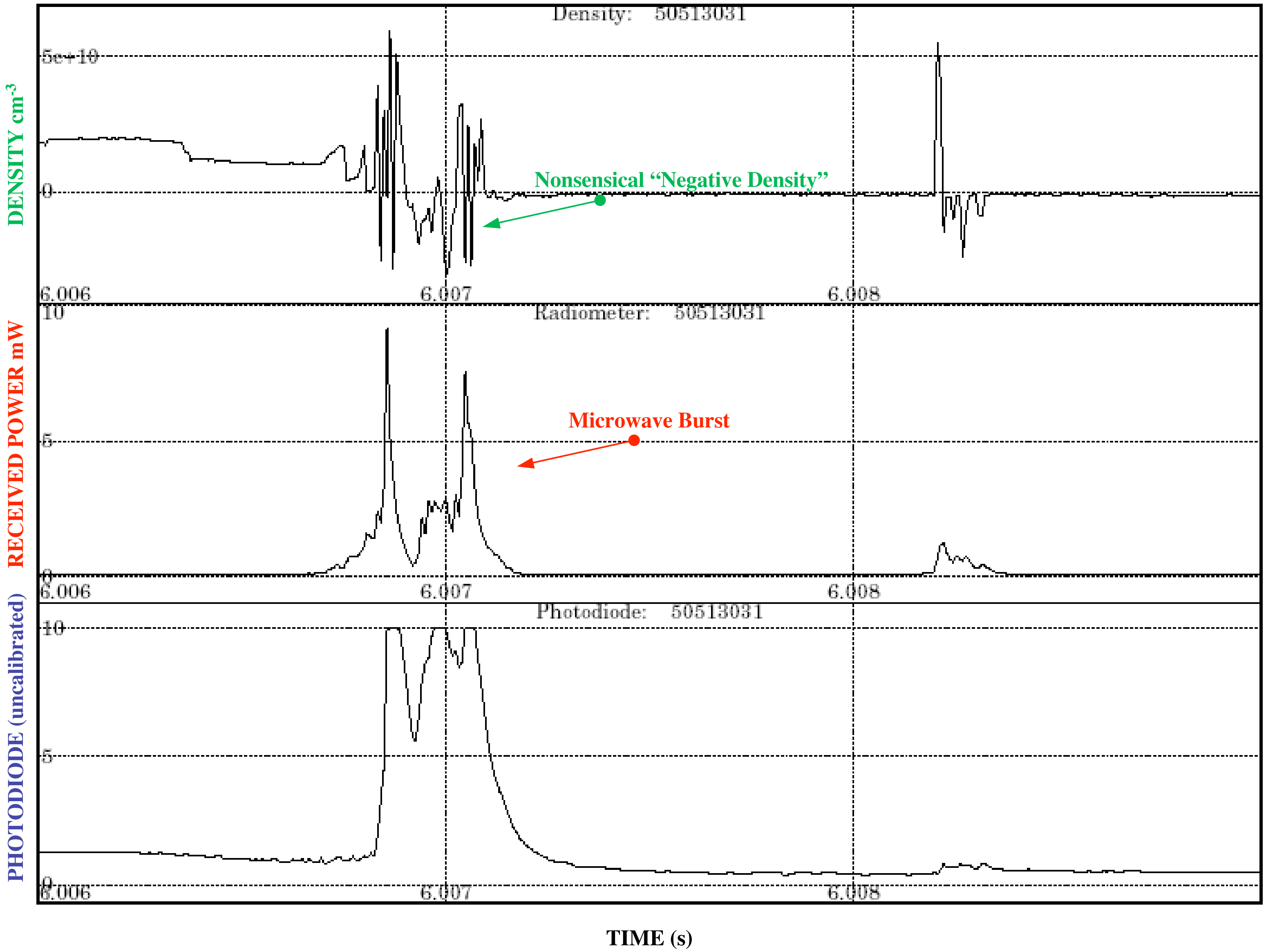
- Microwave radiation emitted by the plasma can be detected with a simple **radiometer**. We have assembled a radiometer by placing a V-Band (50-75 GHz) **standard gain horn** () at one of the vacuum vessel windows and then attaching a **crystal diode detector** to convert the received microwave power to a measurable voltage.

- A large burst of microwaves almost always corresponds to a **large reorganization of the plasma density**. This can be seen in cases where the plasma does not have an afterglow but instead succumbs to a rapid density collapse, as in the previous slide.

- The standard gain horn of the radiometer is the same as the two horns in our microwave interferometer. It follows that microwaves measurable by the radiometer will also affect our interferometer. Quite often this causes rapid phase shifts which show up in our density plots as **nonsensical negative densities**. Sometimes, as in the previous slide, this can be compensated for easily; more often it leads to very bizarre density data.

- The fact that we can observe a mode in the microwave spectrum shows that the Hot Electron Interchange (HEI) mode, which is in the kHz range, is not the only fish in our plasma sea. A likely, higher-frequency mode is the **Whistler Wave** which travels along magnetic field lines. Here on earth, whistlers caused by lightning bolts in the southern hemisphere travel along a magnetic field line and are measurable where that field line hits the earth in the northern hemisphere (and vice-versa, of course).

A Closer Look: Microwave Bursts and Density Collapse



Nonsensical “Negative Density”

Microwave Burst

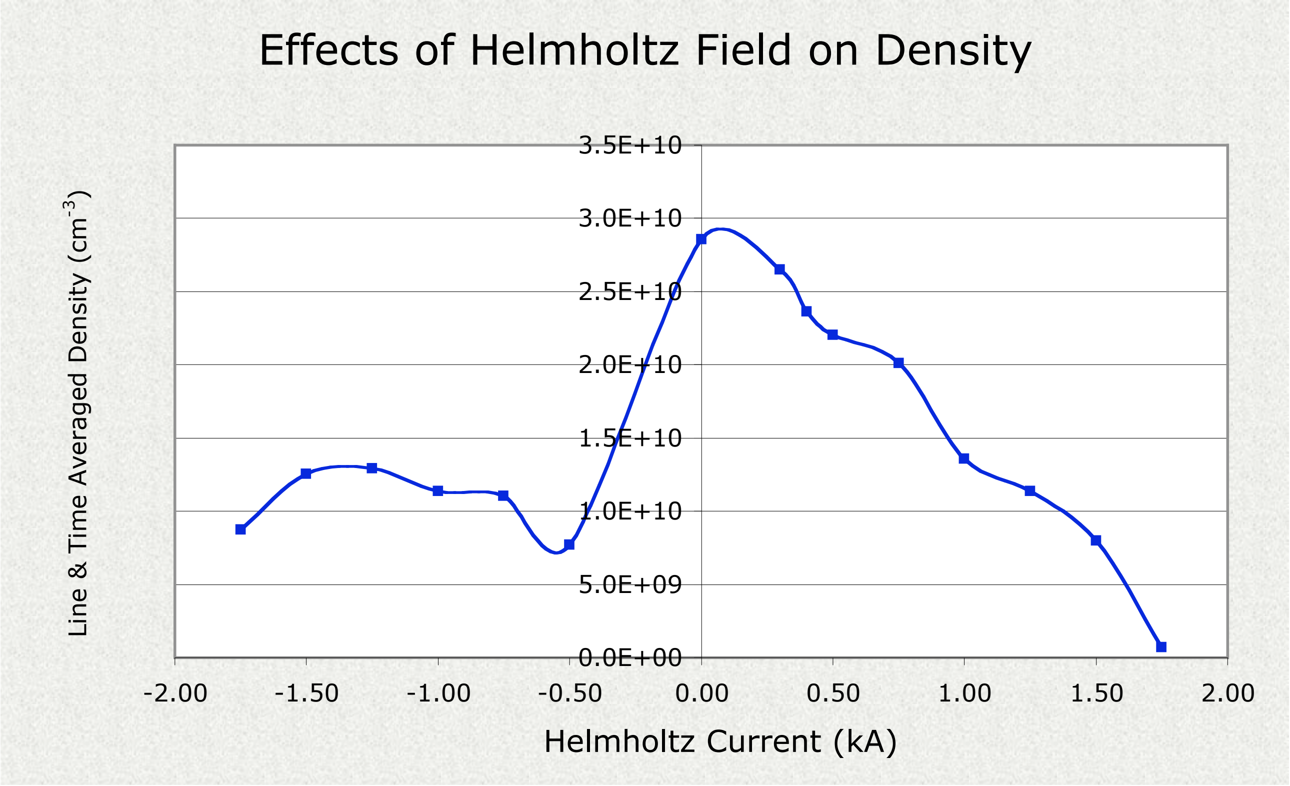
May 13, 2005: shot #31

Decreasing the Plasma Volume

- The LDX plasma can be shaped using the vertical magnetic field of a Helmholtz coil.

- The Helmholtz field moves the last closed field line (which is the boundary of our plasma) inwards towards the floating coil. This decreases our total plasma volume.

- As expected, the line integrated density decreases as the Helmholtz field increases (in either direction).



Present Status

- The LDX interferometer began its operation a little more than one year ago, contemporaneous with the initiation of LDX plasma experiments.

- Over this time we have made some major improvements, most notably in suppressing gigantic noise, spurious phase-hopping and a bad case of random system collapse.

- We are confident that what we measure corresponds closely to the core density and is not just the result of edge effects or ECRH noise. However, our data exhibits a lot of unusual and poorly understood behavior. Partly this is due to the pickup of microwave radiation emitted by plasma, but we also believe there are some systematic errors that have eluded debugging thusfar.

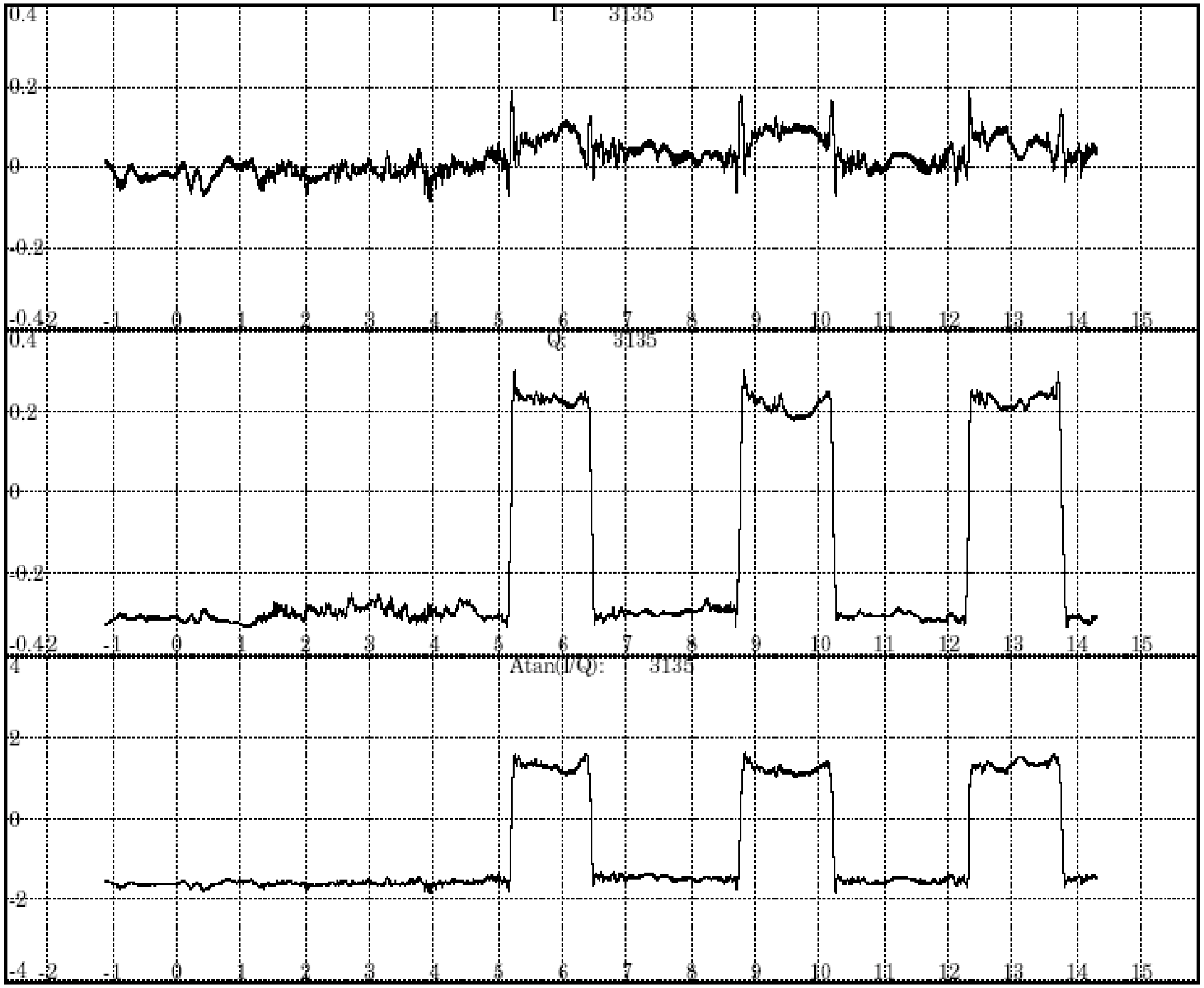
- A recent period of the LDX vacuum chamber being up-to-air has allowed us to perform direct calibration tests. Some of the results are presented in the slides that follow.

Calibration Tests

I

Q

Arctan(I,Q)



Inserted Square of Alumina
6” x 6” x 3/8”
Dielectric Constant ≈ 7

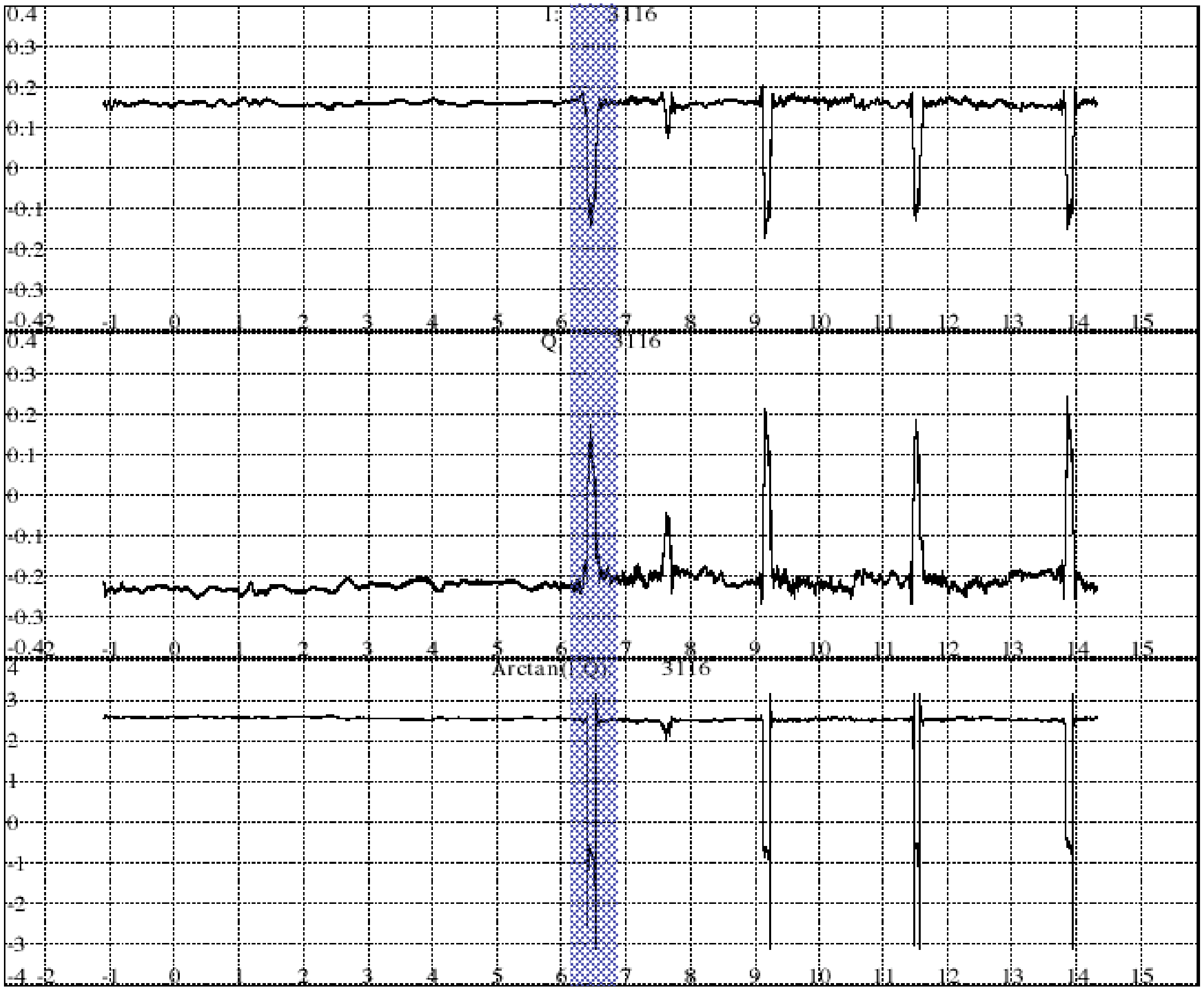
October 17, 2005: TestShot #3135

Falling Dielectric: Too Fast to Measure?

I

Q

Arctan(I,Q)



October 7, 2005: TestShot #3116

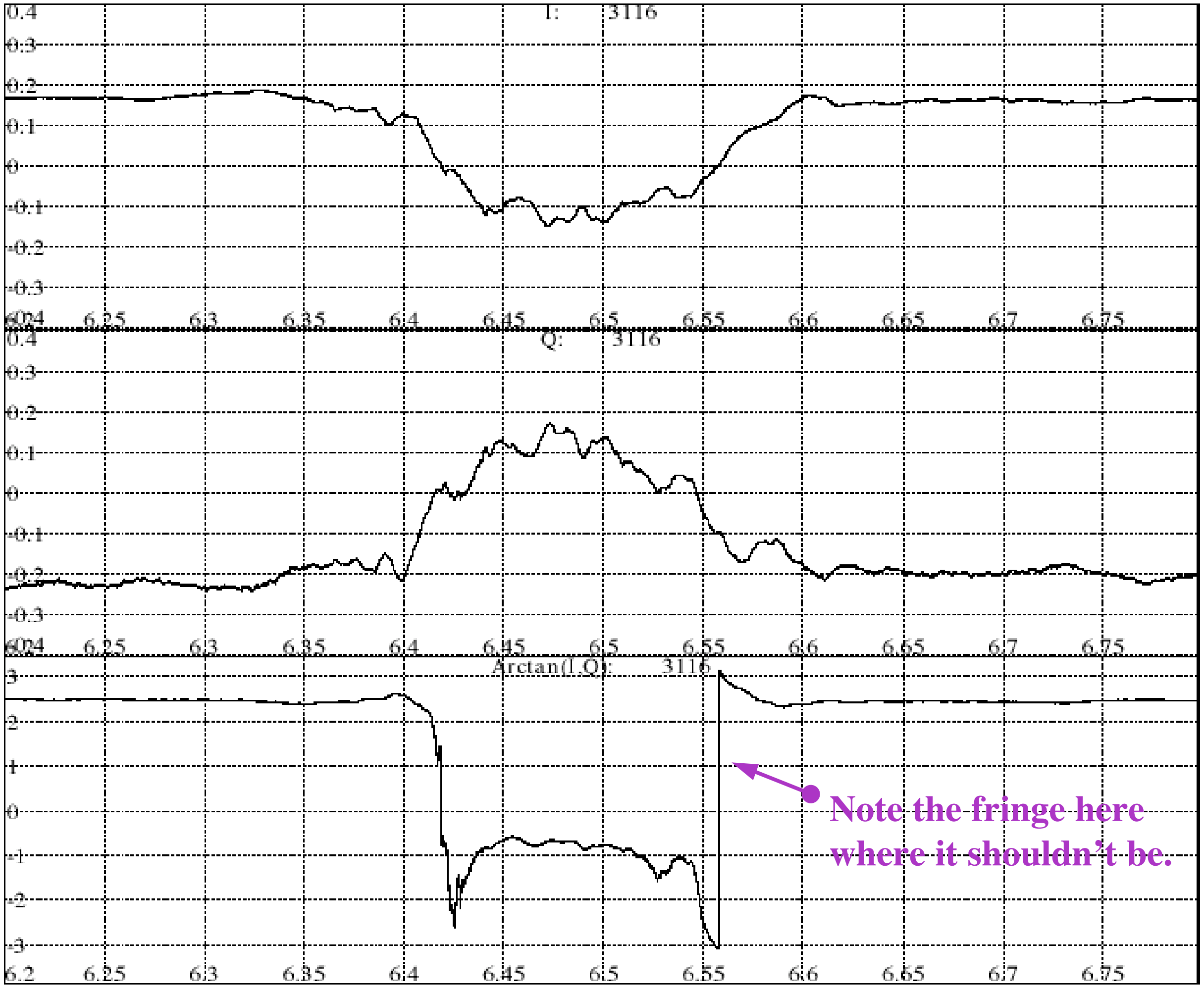
Falling Square of Alumina
6” x 6” x 3/8”
Dielectric Constant ≈ 7

Too Fast? A Closer Look

I

Q

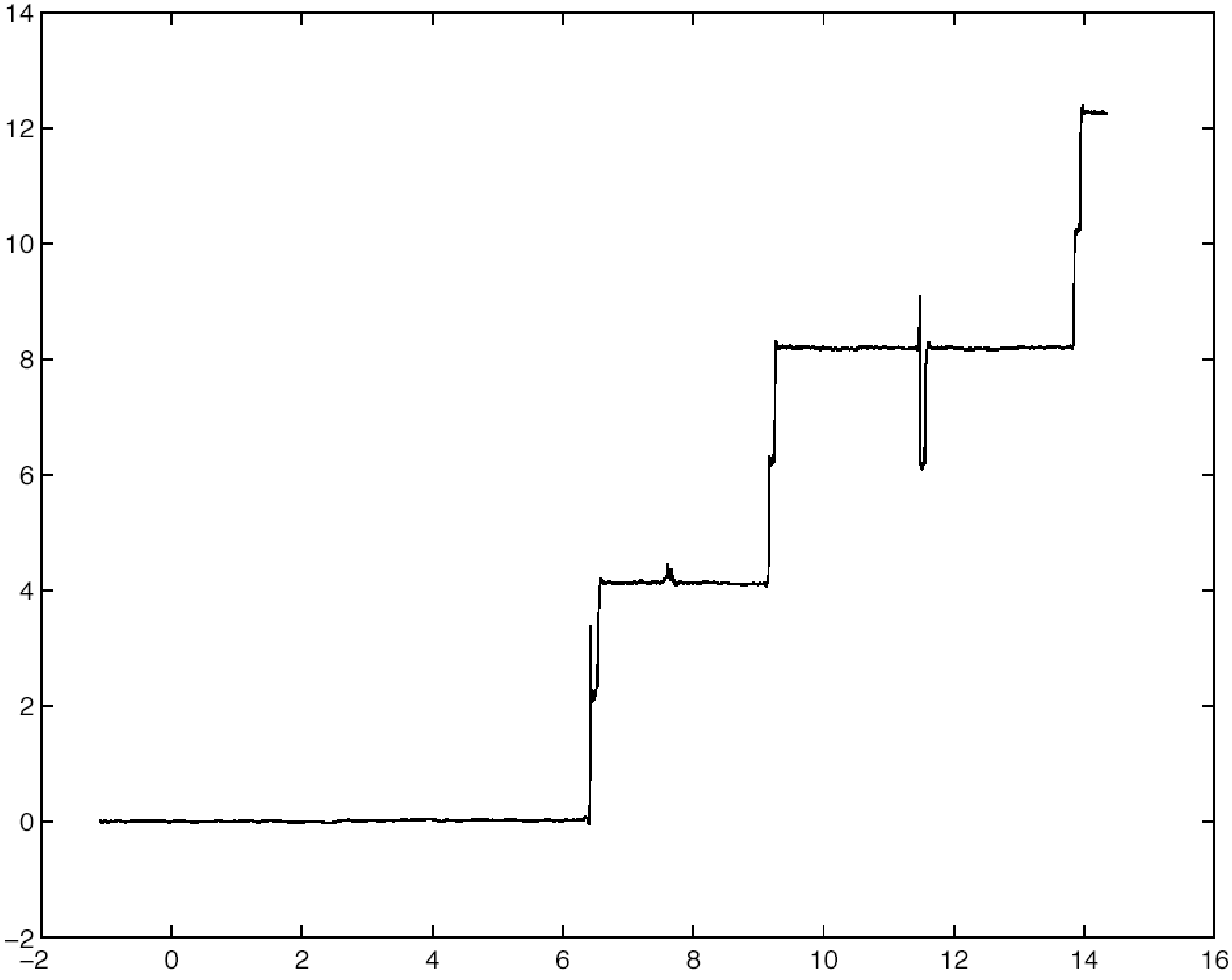
Arctan(I,Q)



Note the fringe here
where it shouldn't be.

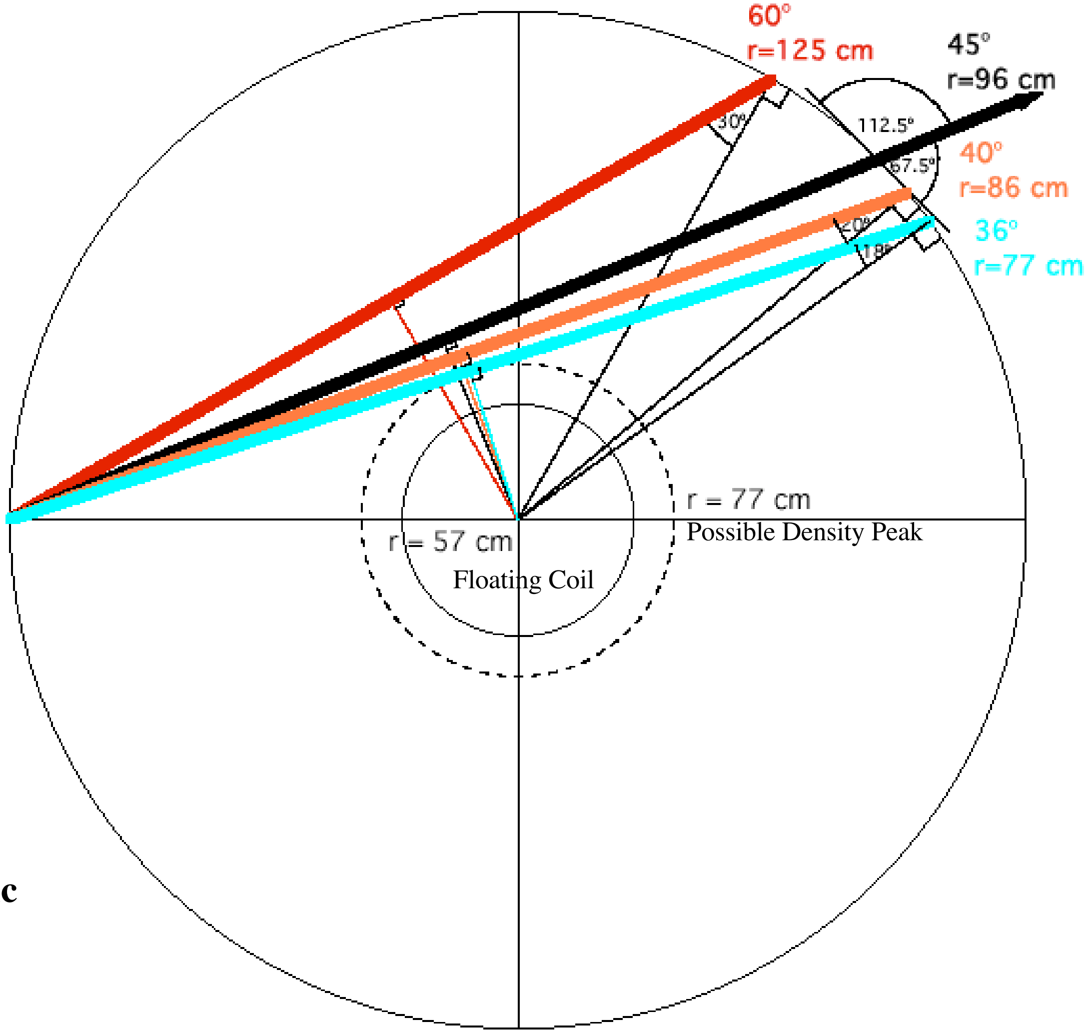
October 7, 2005: TestShot #3116

Nonsensical Reconstructed Phase

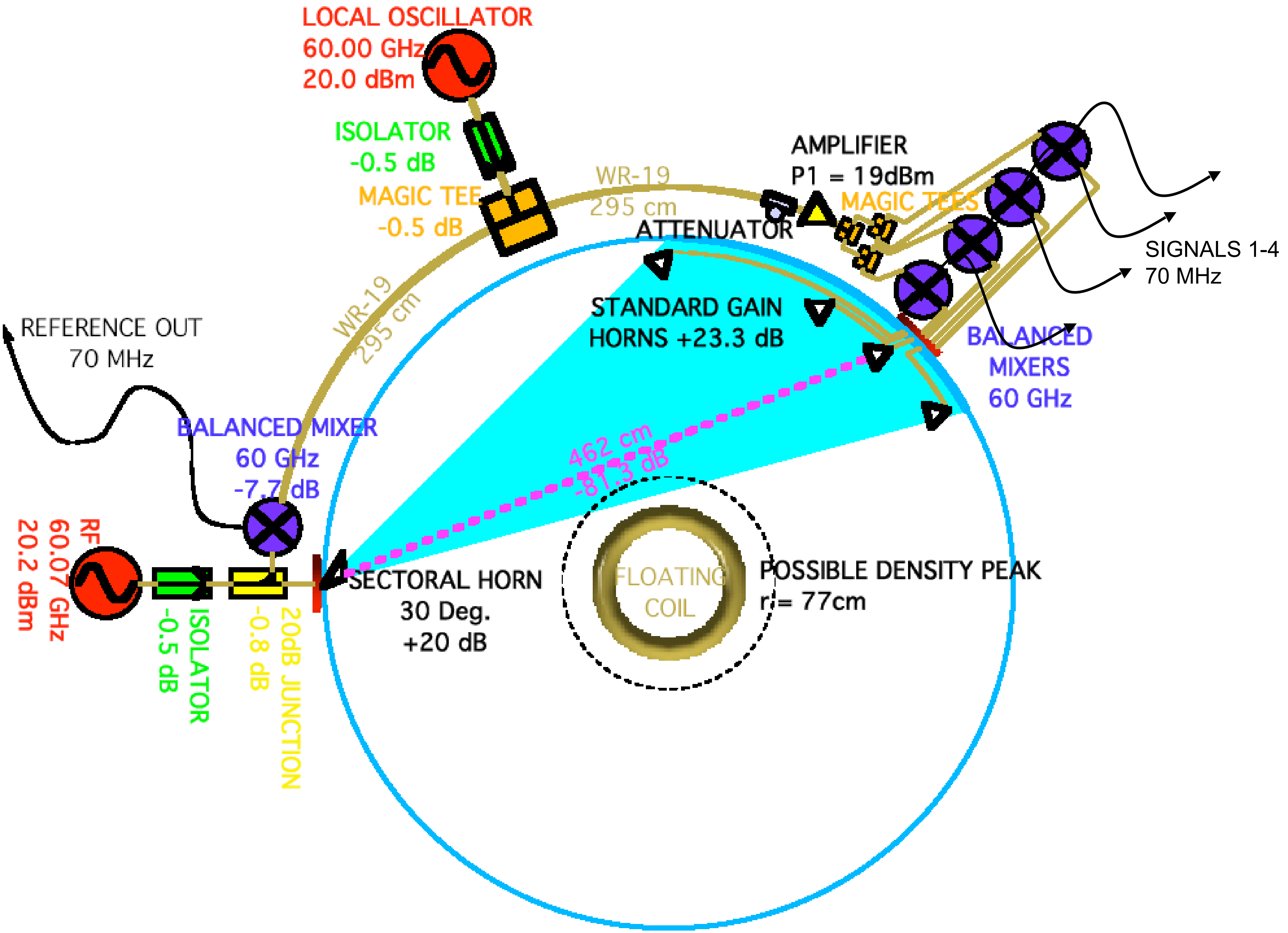


October 7, 2005: TestShot #3116

Future Work: Multiple Channels



Multichannel Schematic Showing Lines of Sight



Block Diagram for a 4-Channel Microwave Interferometer

Future Work: Multiple Channels

PHOTOS OF
STUFF!