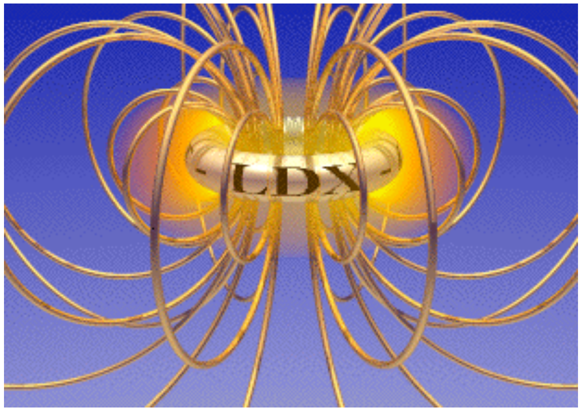

Microwave Interferometer Density Diagnostic for the Levitated Dipole Experiment

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Columbia University

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Presented at APS Philadelphia, Pennsylvania
2 November 2006

LDX Interferometer

•Multiple channels are now operational

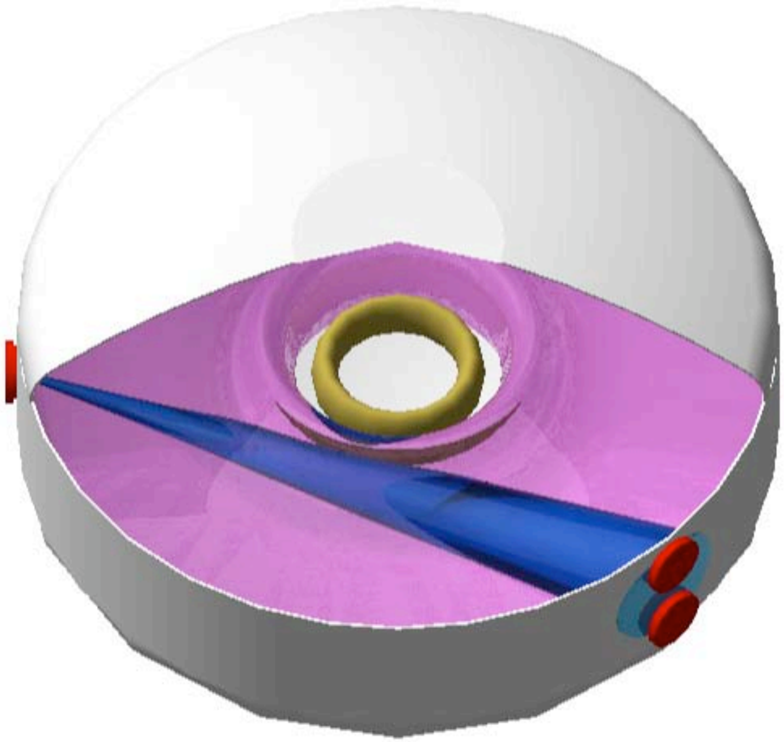
•Highly peaked density profiles have been measured

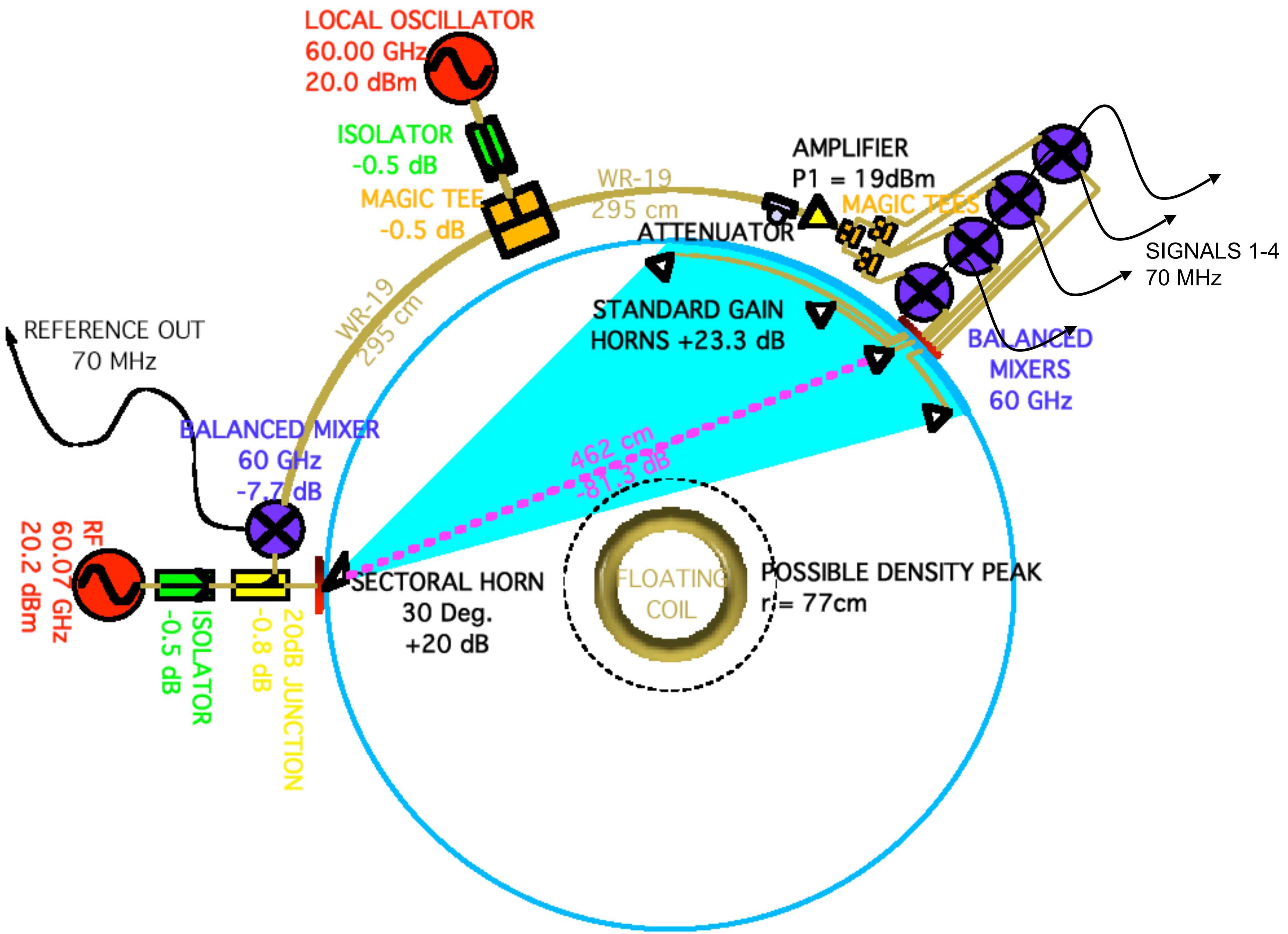
•Peak densities around $2x10^{13}\ cm^{-3}$

•Changes of the profile in response to RF heating and to gas-fueling have been observed

Basic Design

- The basic design follows other microwave interferometers in the literature, in particular *C.W. Domier et. al. Rev.Sci.Instrum.* ***59*** *[1988], 1588*
- An RF beam of 60 GHz puts our interferometer in the microwave spectrum.
- 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*.
- Phase information is obtained along *4 chords*. This information is then reconstructed to produce a radial density profile.





Block Diagram for a 4-Channel Microwave Interferometer

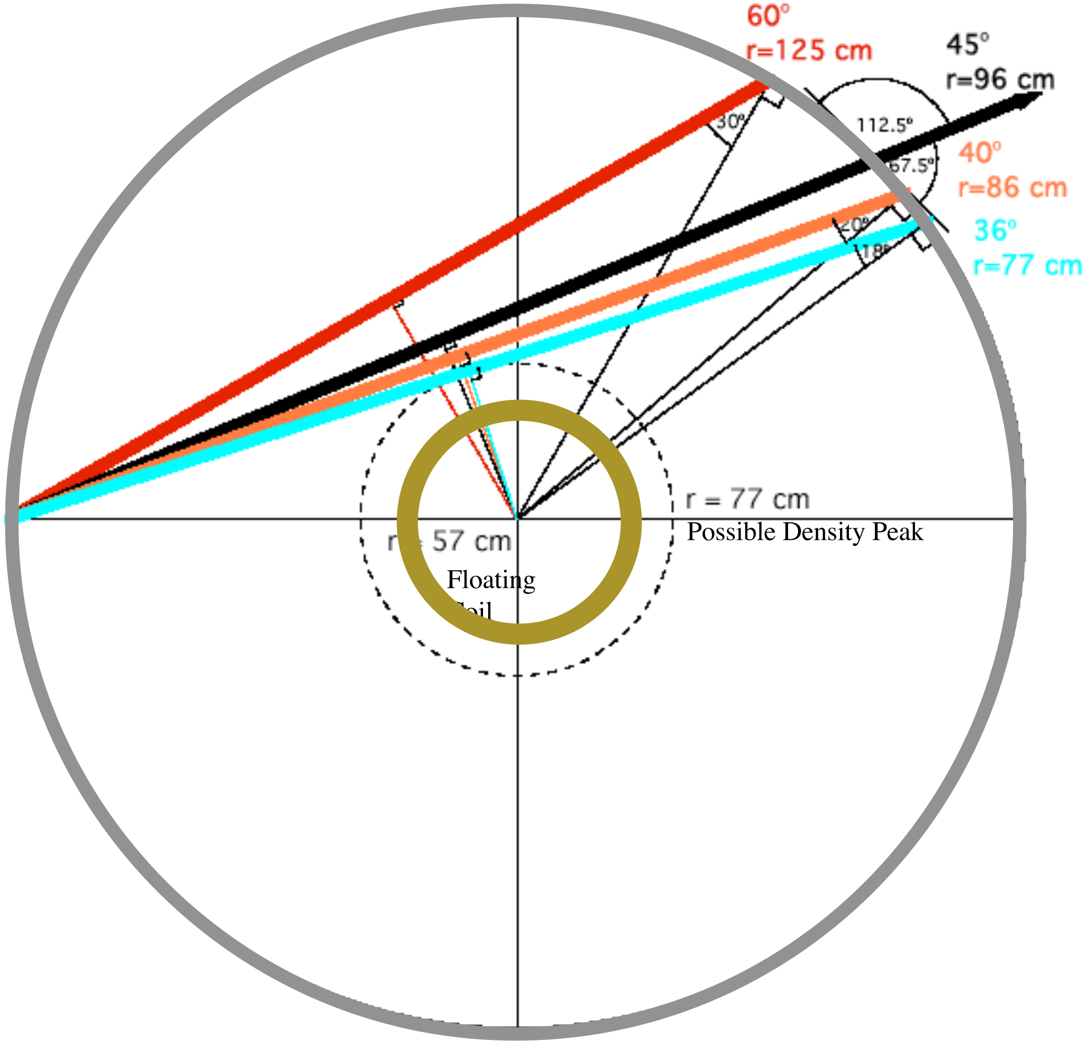
Lines of Sight and Radii of Tangency

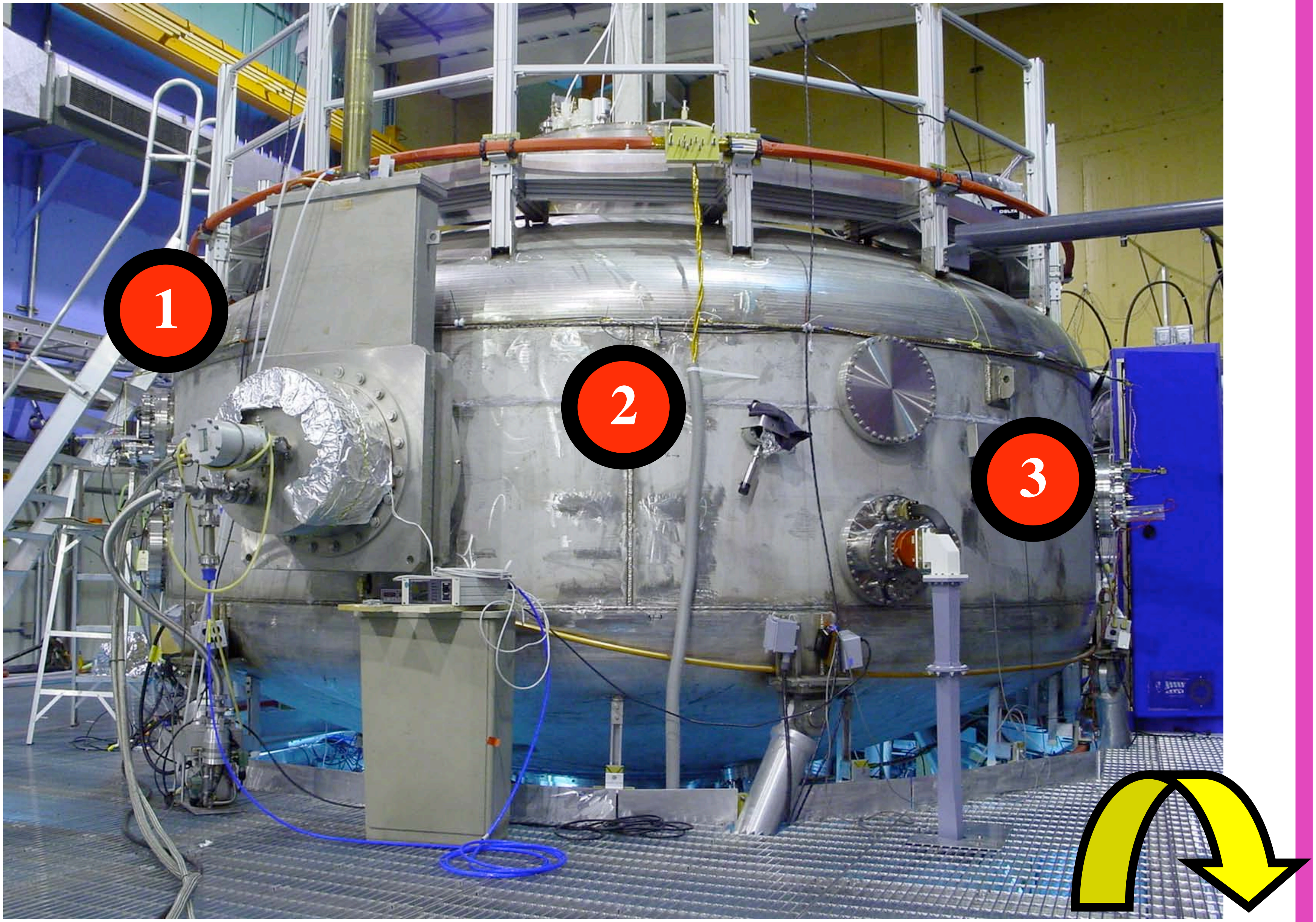
🟦 r_1 = 77cm

🟧 r_2 = 86cm

⬛ r_3 = 96cm

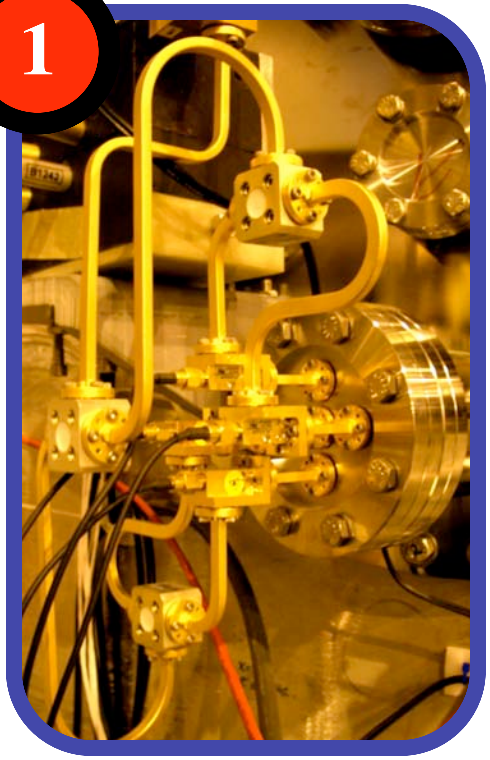
🟥 r_4 = 125cm





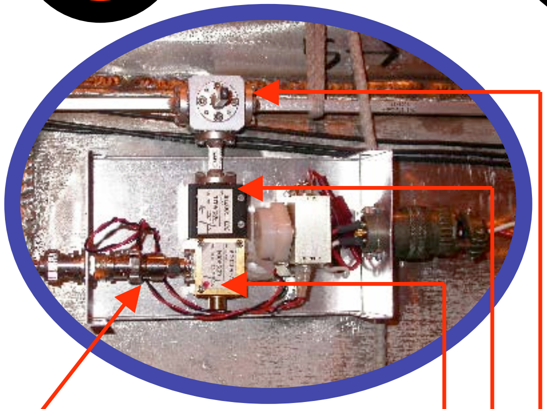
The LDX Vacuum Vessel and Interferometer

1



NORTHEAST PORT

2



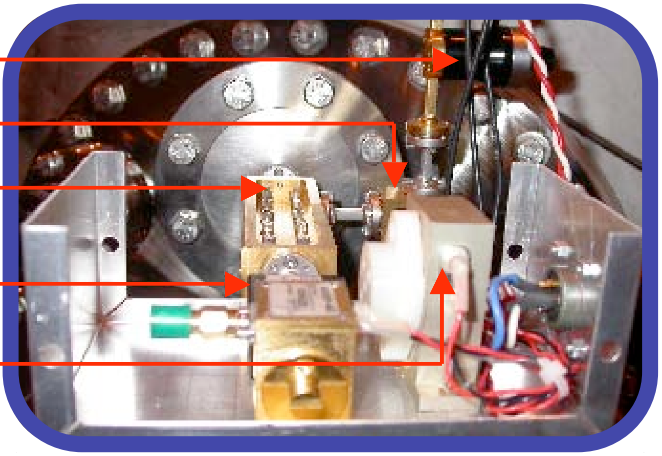
Varactor Tuning
Gunn Oscillator
Isolator
Magic Tee

3

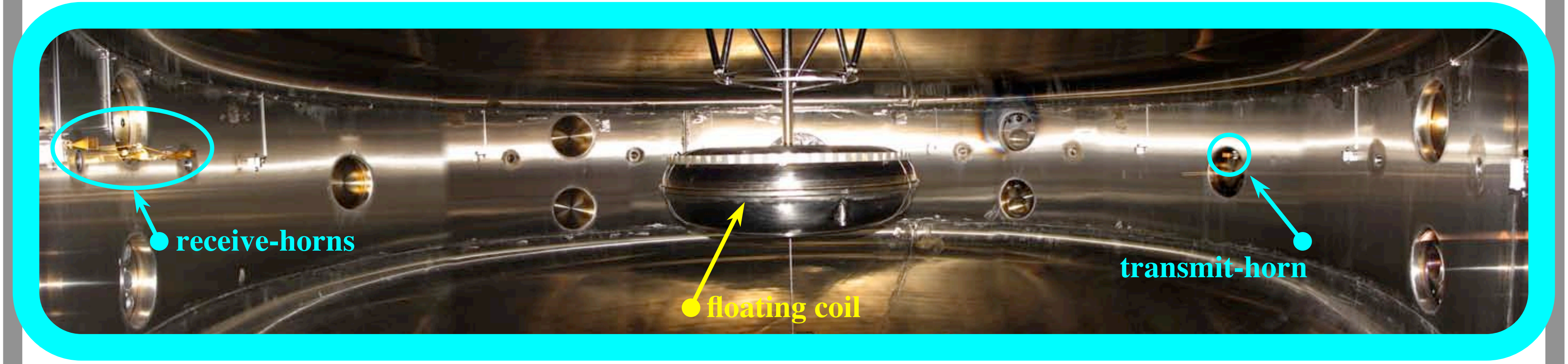
WEST PORT

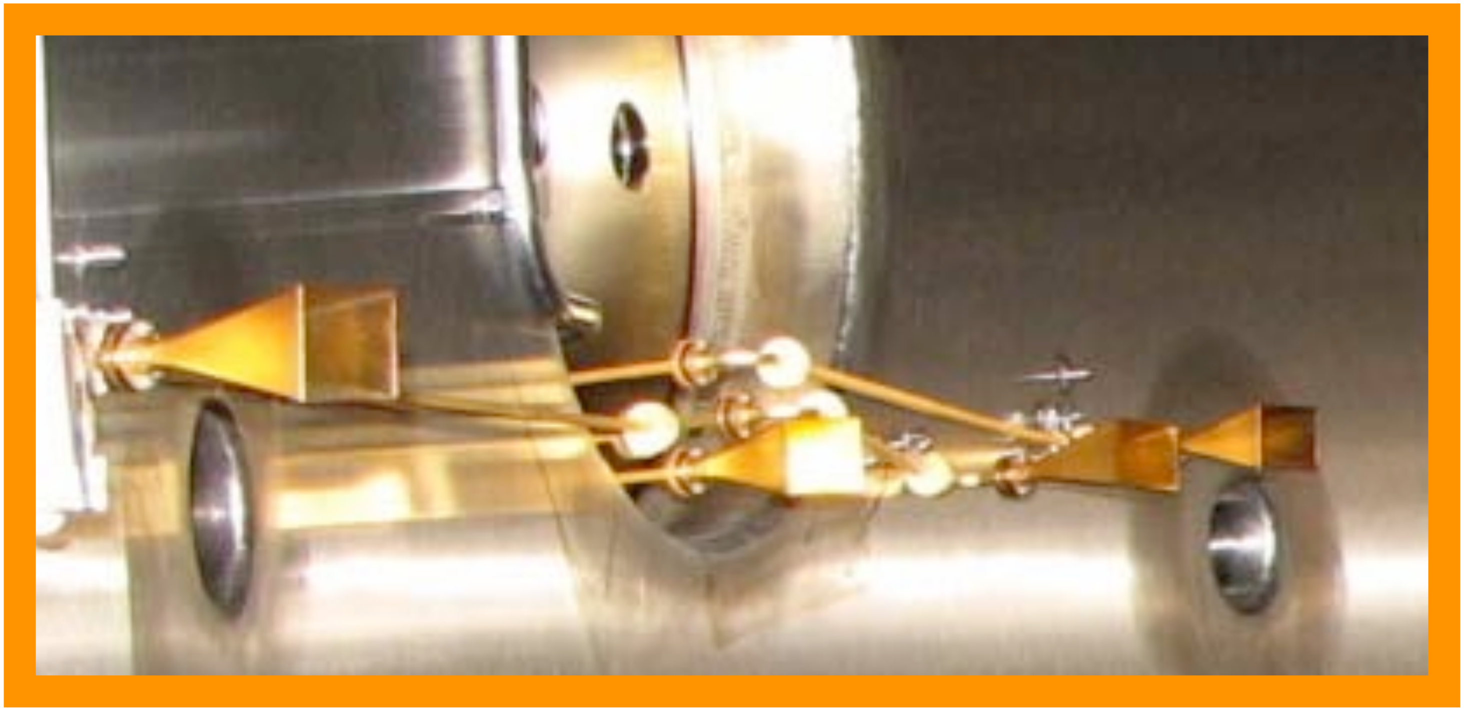
Phase Shifter
60GHz Mixer
20db Junction

Gunn Oscillator
Voltage Regulator



Interior View of the LDX Vacuum Chamber





Receive-Horns:

A Closer View

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)

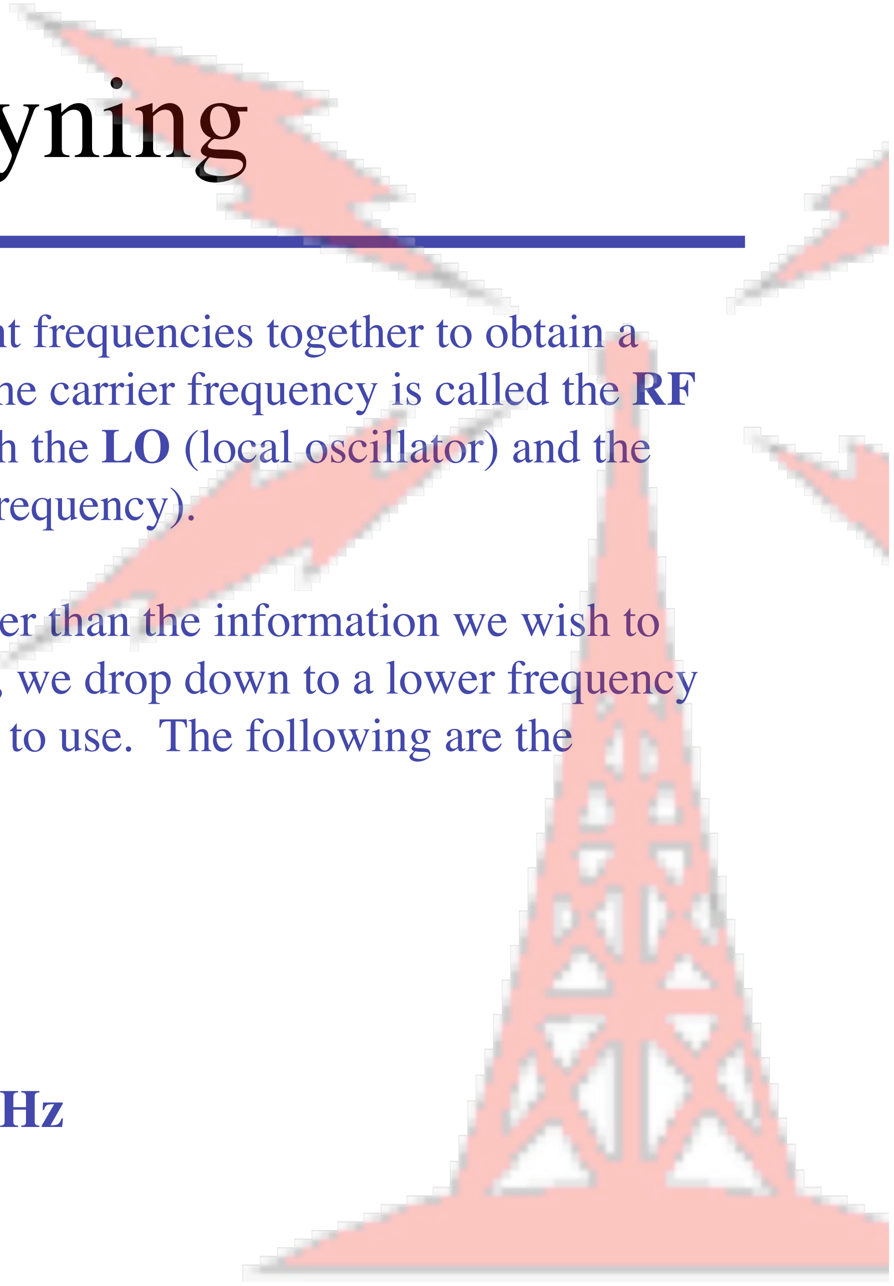
$$\phi = \frac{\omega}{c} \int \left(1 - \frac{n_e}{n_c}\right)^{1/2} dl$$

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

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

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.

Heterodyning

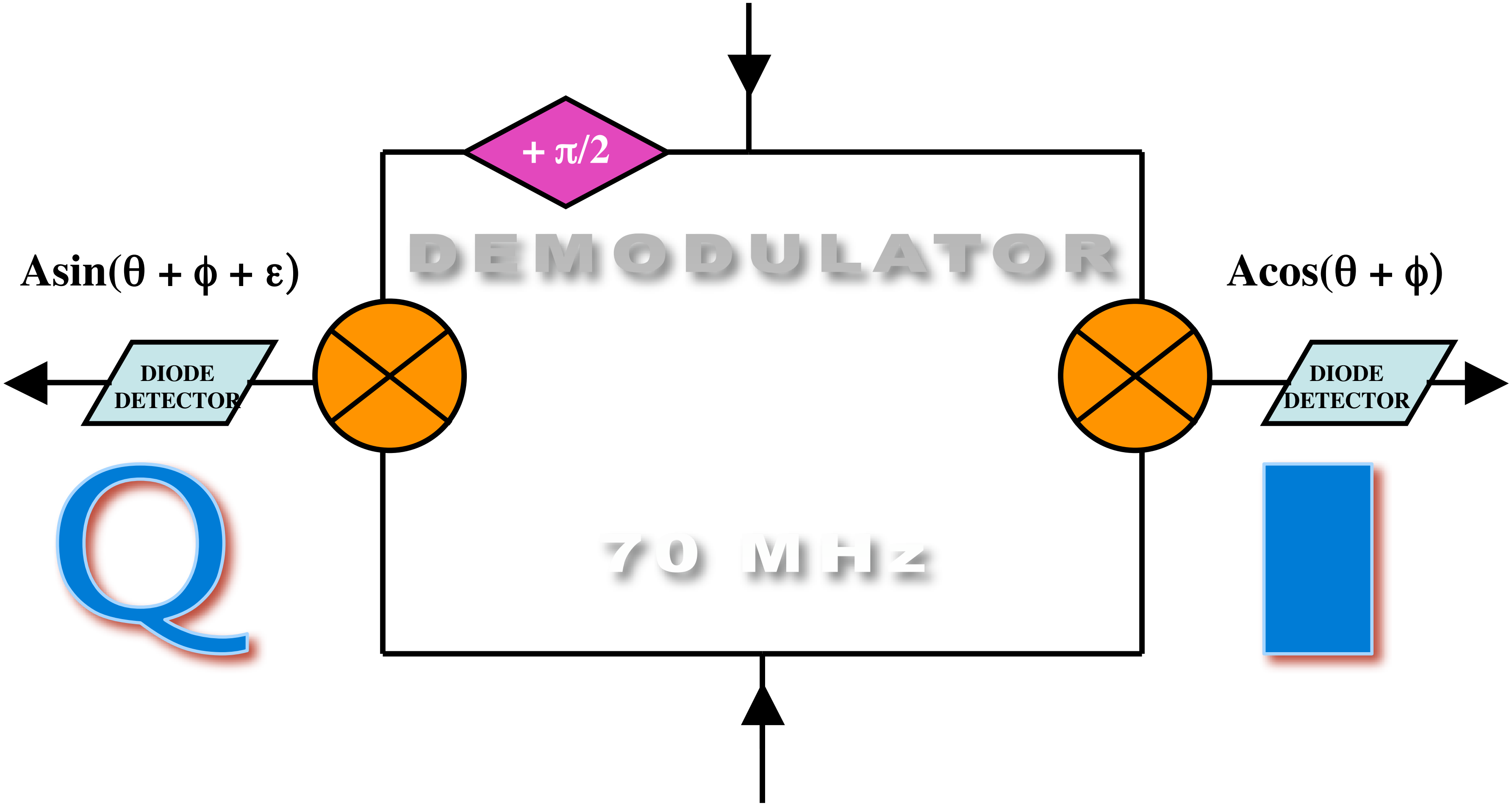


Heterodyning consists of mixing two different frequencies together to obtain a **Beat Frequency**. Following RADIO usage, the carrier frequency is called the **RF** (radio frequency); this frequency is mixed with the **LO** (local oscillator) and the beat frequency is called the **IF** (intermediate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

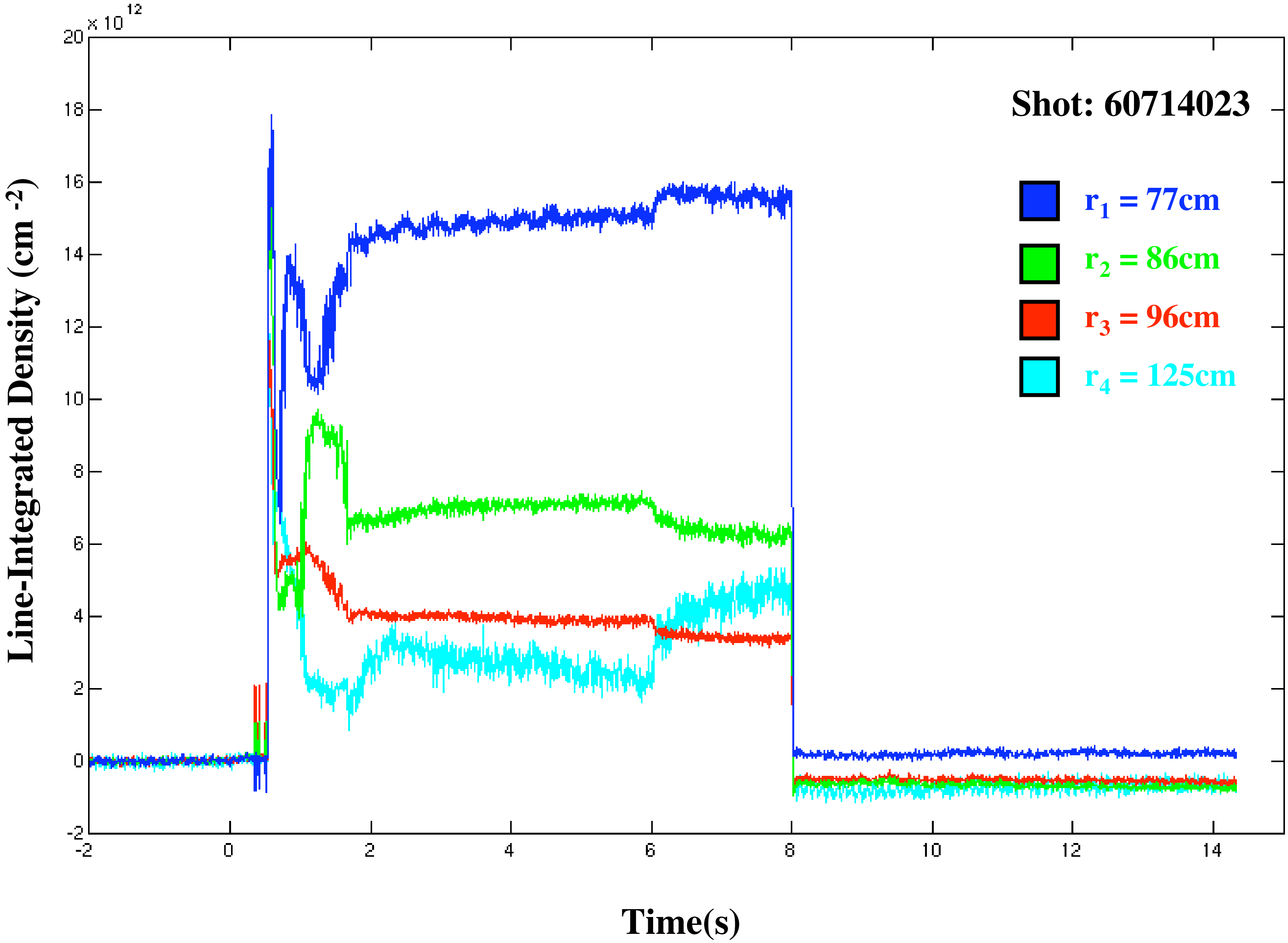
RF = 60.07 GHz
LO = 60.00 GHz
IF = 70 MHz
Frequency of Density Fluctuations **< 1 MHz**

Quadrature Phase Detection



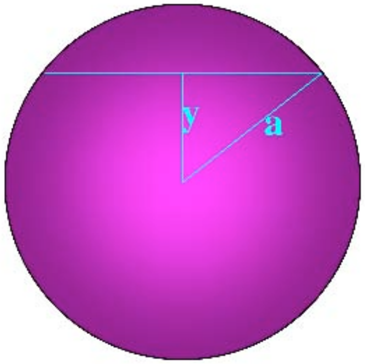
The phase difference between our two 70 MHz signals is detected in **Quadrature**

LDX Interferometer Measures along 4 Chords



Analysis

The data is reconstructed into a density profile by assuming that the profile is of the simple form $f = Ar^{-n}$. For each n we construct a chord function $\chi_n(y)$:



$$\chi_n(y) = A \int_{-\sqrt{a^2-y^2}}^{\sqrt{a^2-y^2}} (x^2 + y^2)^{-n/2}$$

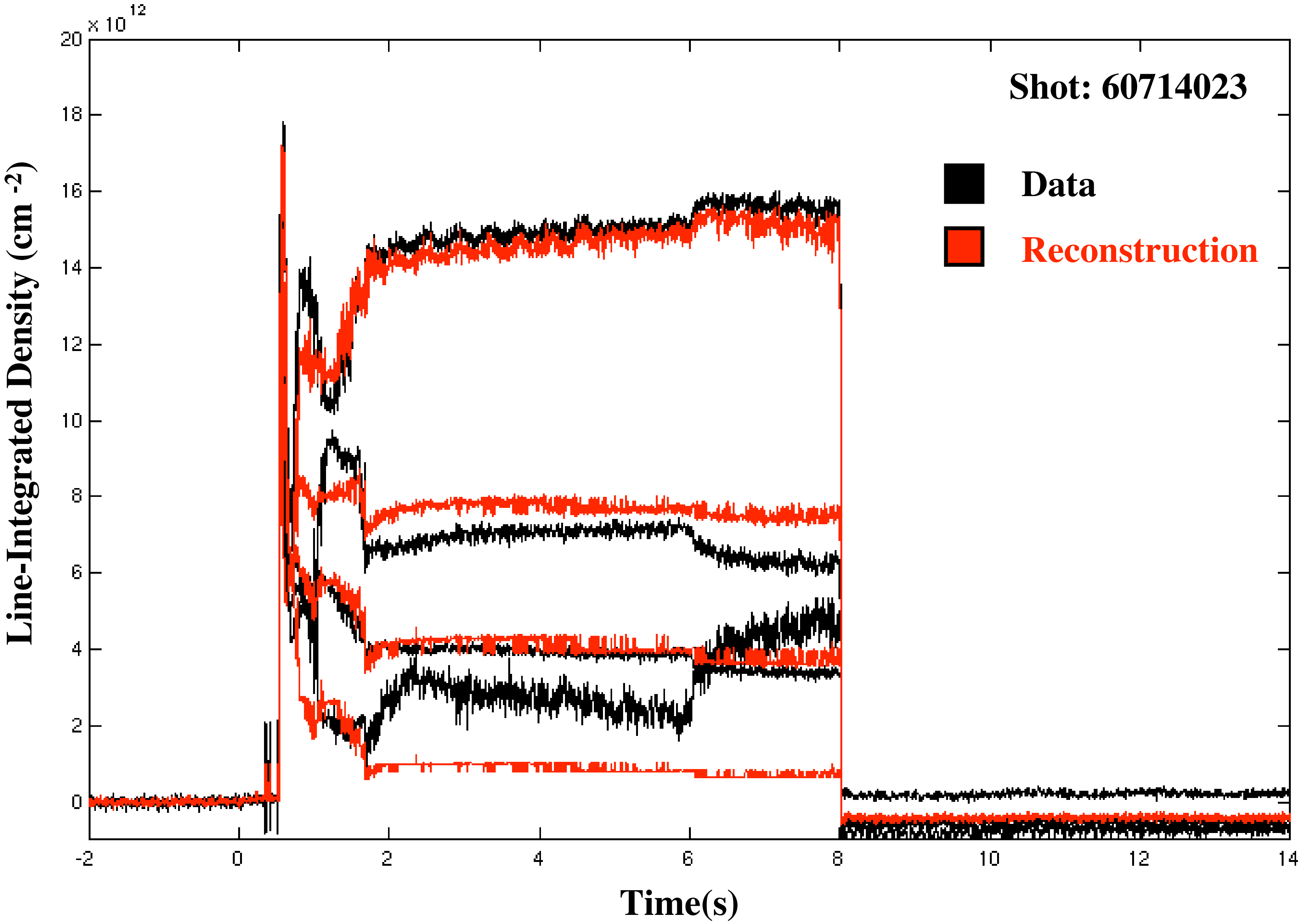
$$\Rightarrow \boxed{\chi_{n+2}(y) = \left(\frac{2A}{n \cdot a^n}\right) y^{n/2} \cdot \gamma(y) + \left(\frac{n-1}{n}\right) \frac{\chi_n(y)}{y}}$$

$$\gamma(y) \equiv \sqrt{\left(\frac{a}{y}\right)^2 - 1}$$

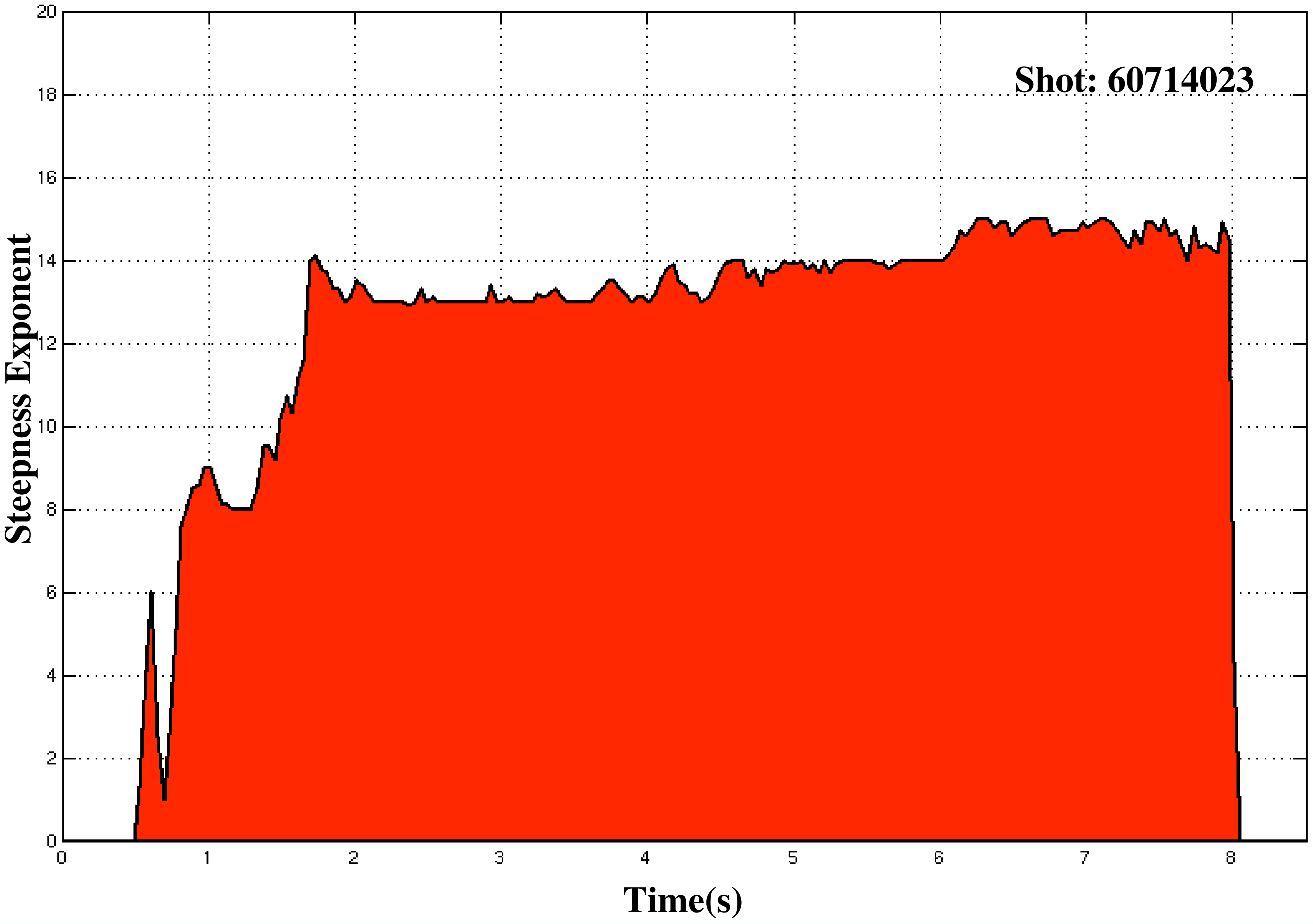
$$\chi_2(y) = 2A \cdot \arctan \gamma(y); \qquad \chi_3(y) = \frac{2A\sqrt{y}}{a}\gamma(y)$$

At each point in time, the optimal fit parameters A and n are chosen by the method of least-squares. We refer to n as the *steepness exponent* and its graph over time gives us the clearest indicator of the dynamics of the density profile in LDX.

$A(t)r^{-n(t)}$ Fits the Data Nicely

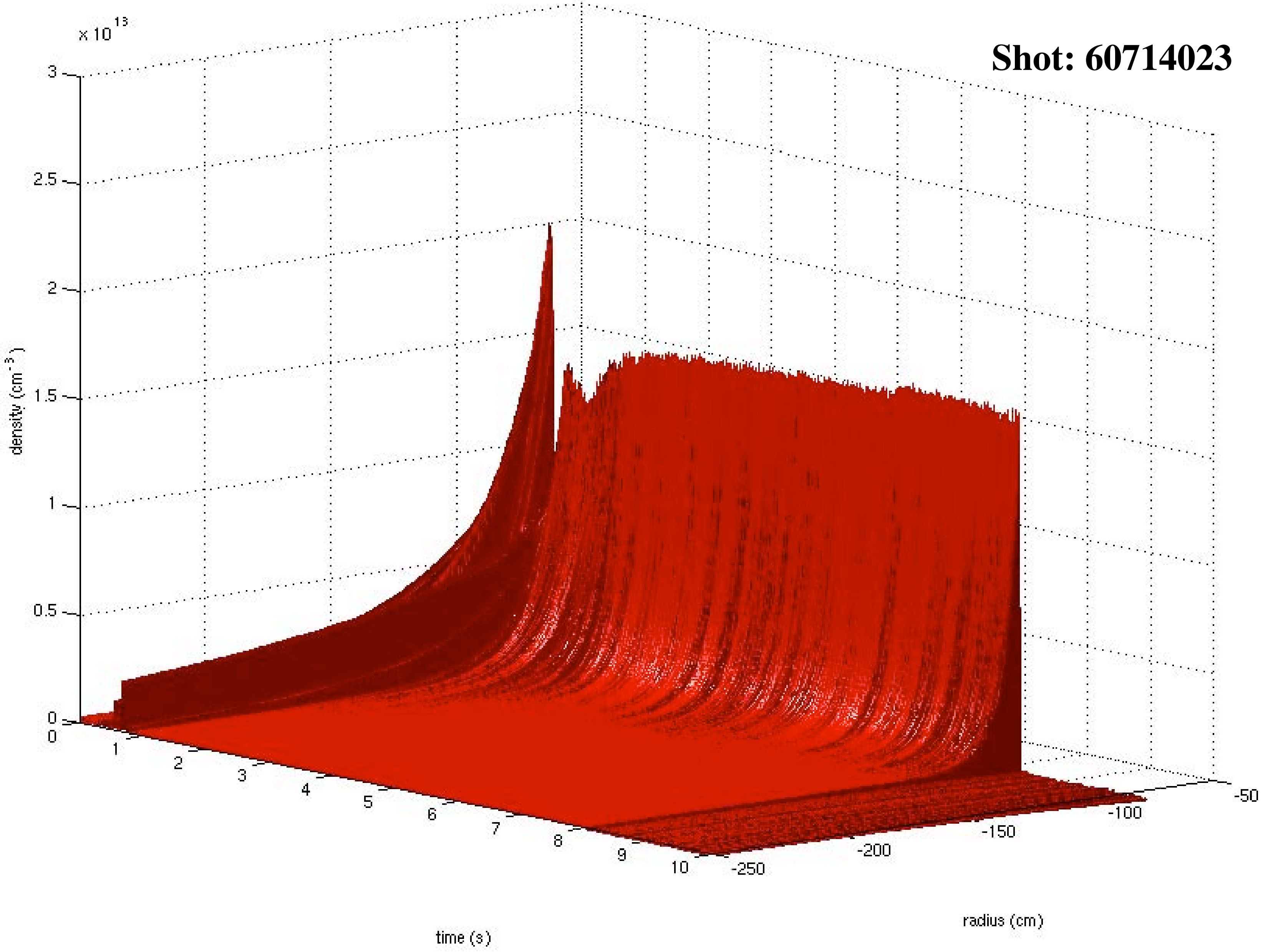


DENSITY PROFILE: 2.45GHz HEATING

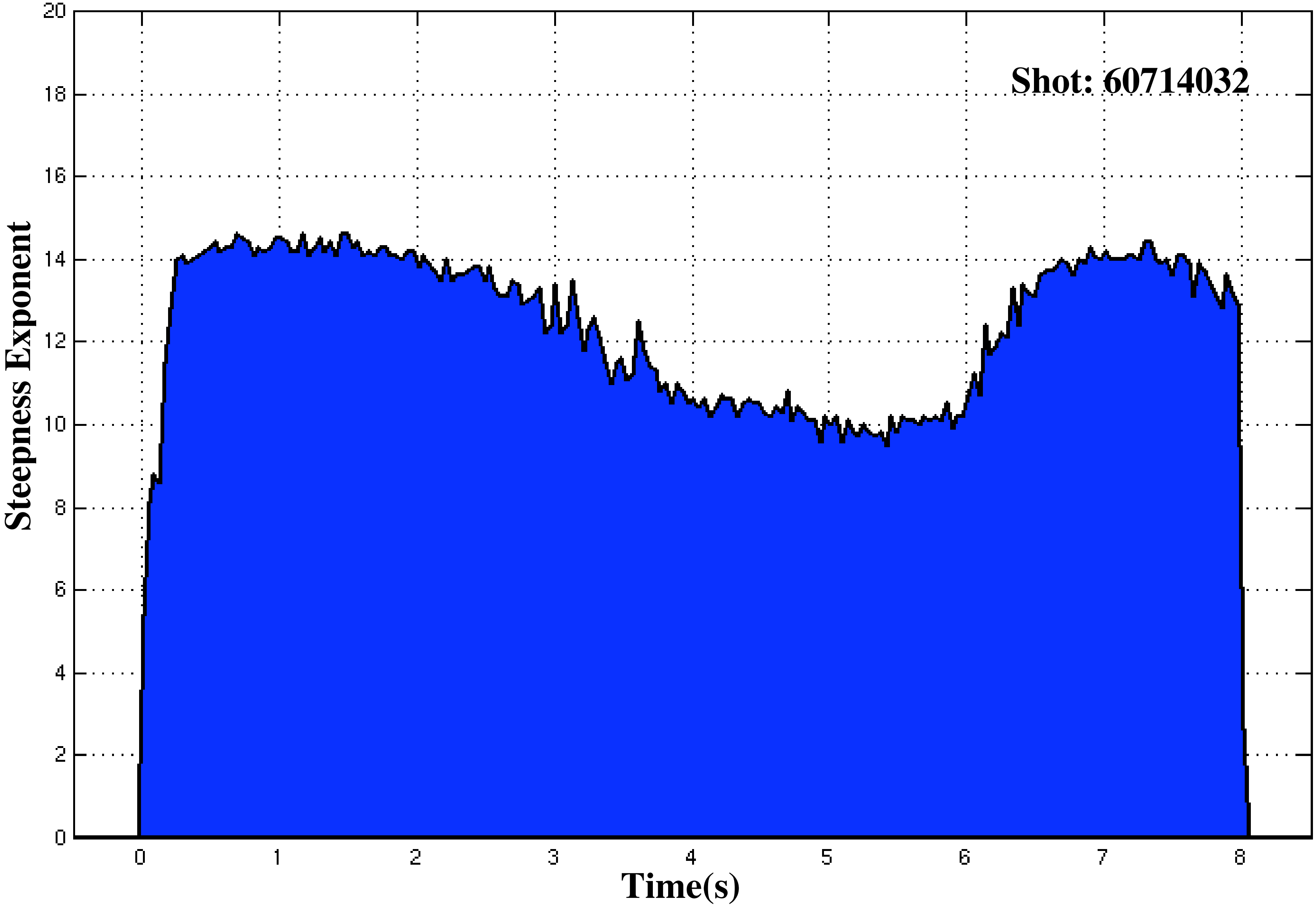


DENSITY PROFILE: 2.45GHz HEATING

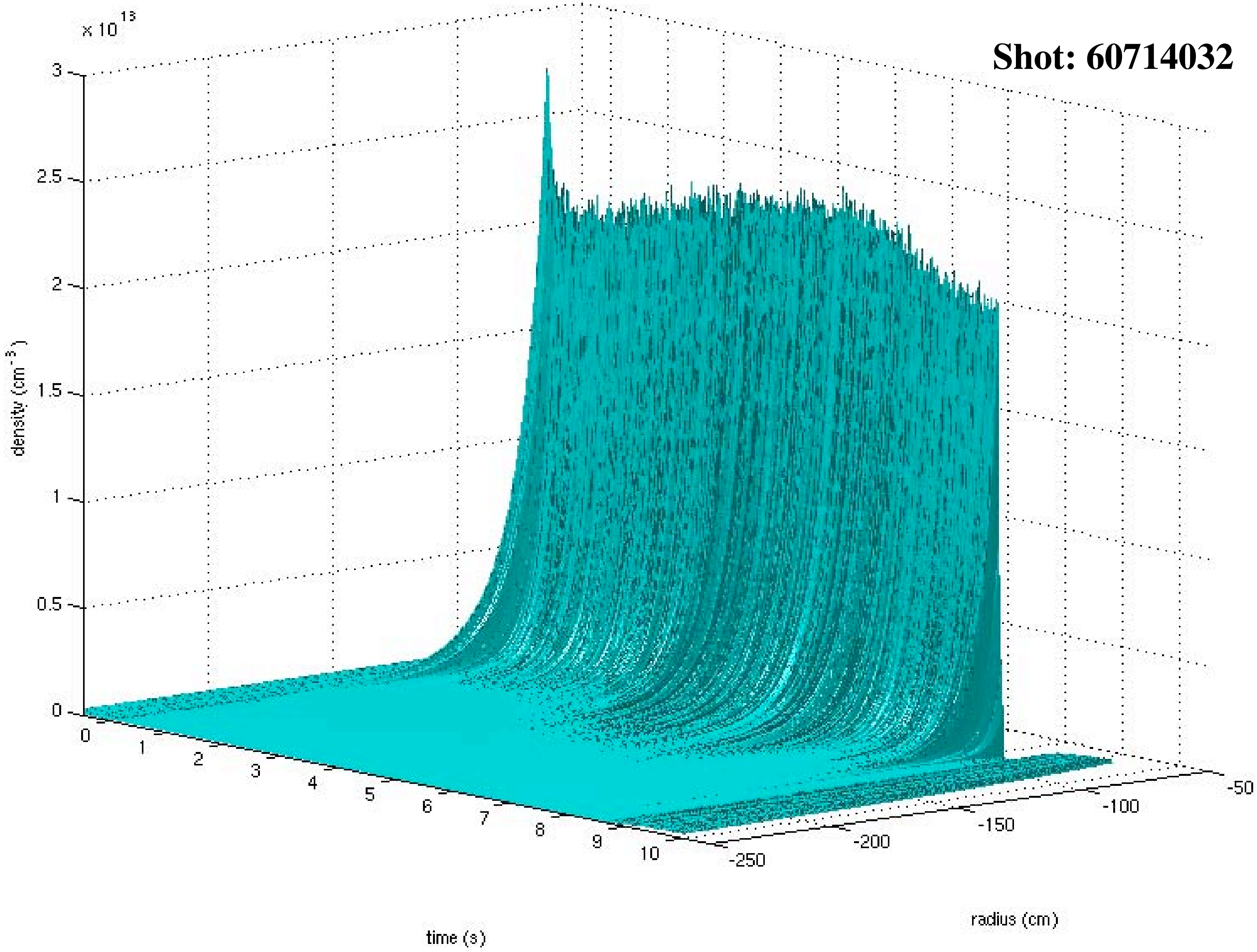
Shot: 60714023



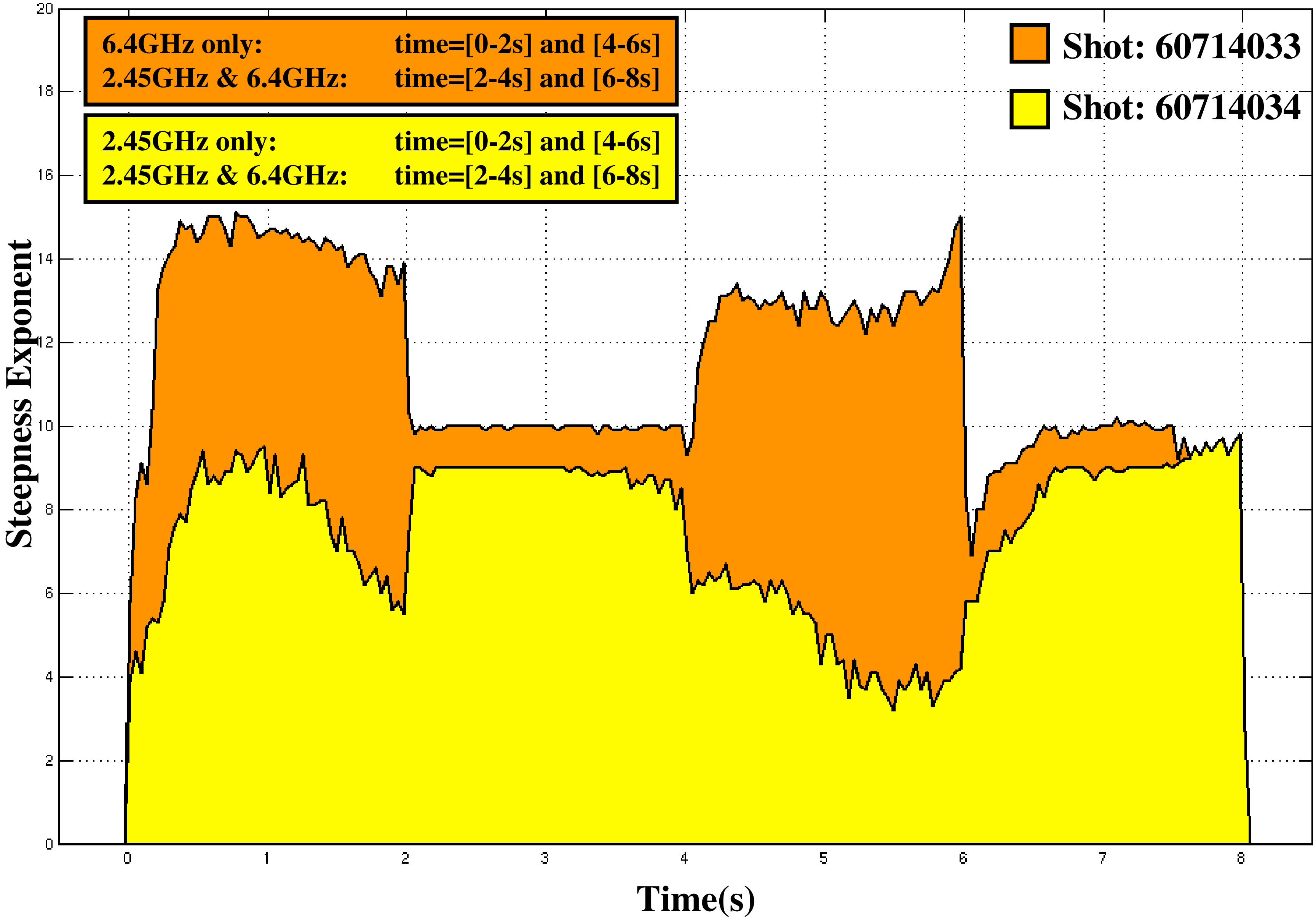
DENSITY PROFILE: 6.4GHz HEATING



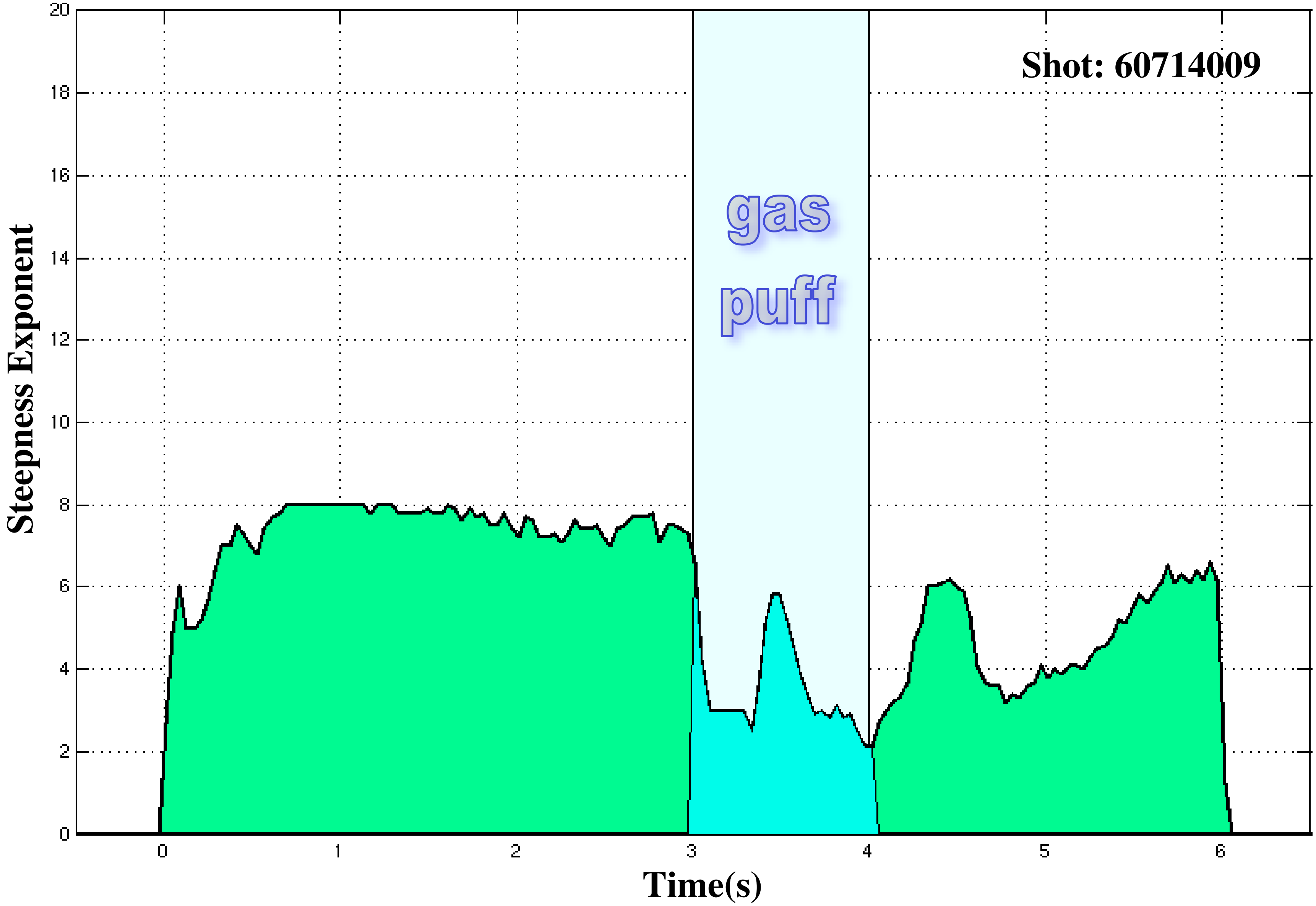
DENSITY PROFILE: 6.4GHz HEATING



DENSITY PROFILE CONTROLLED BY ECRH



DENSITY PROFILE CONTROLLED BY GAS-FUELING

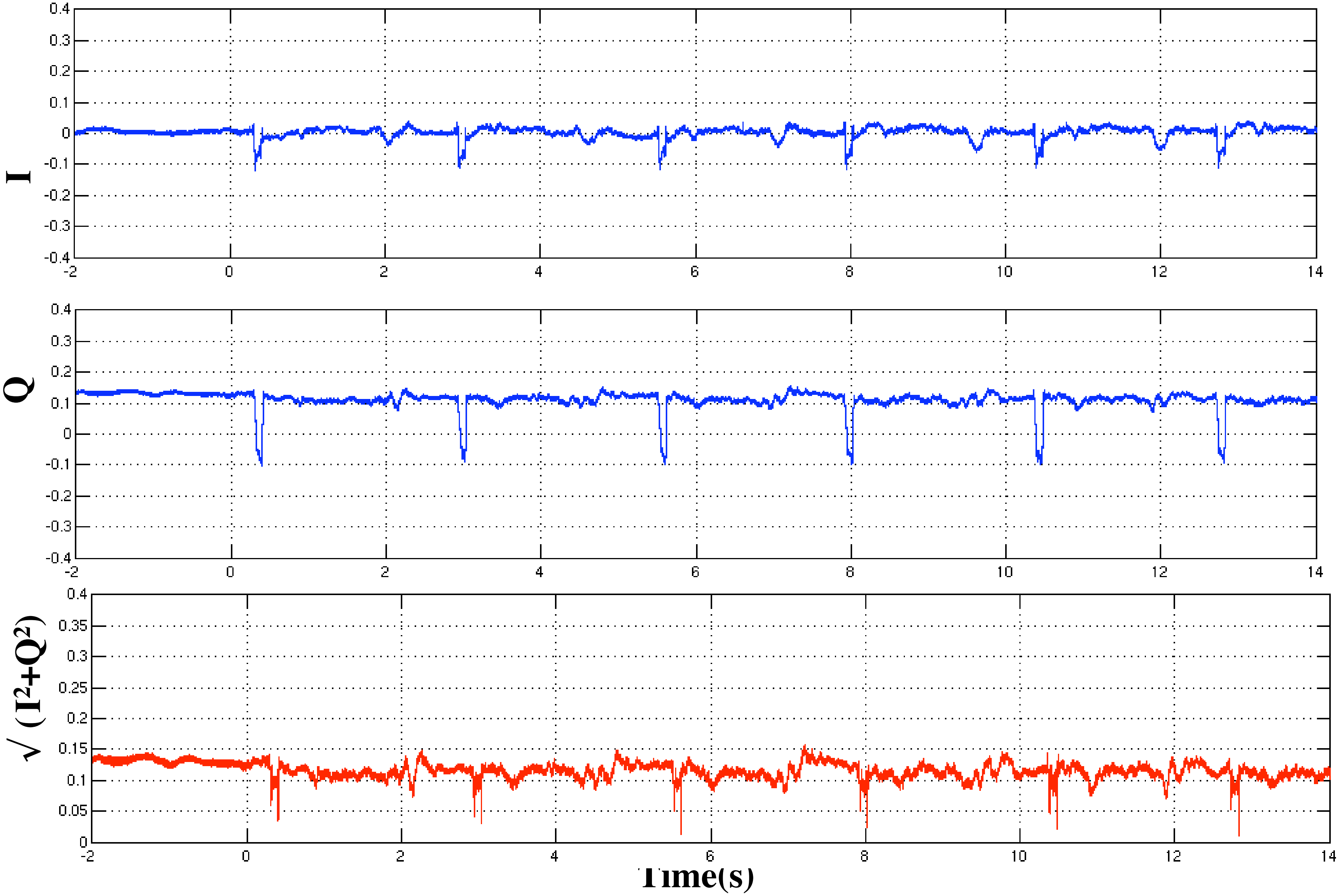


HARDWARE AND CALIBRATION ISSUES

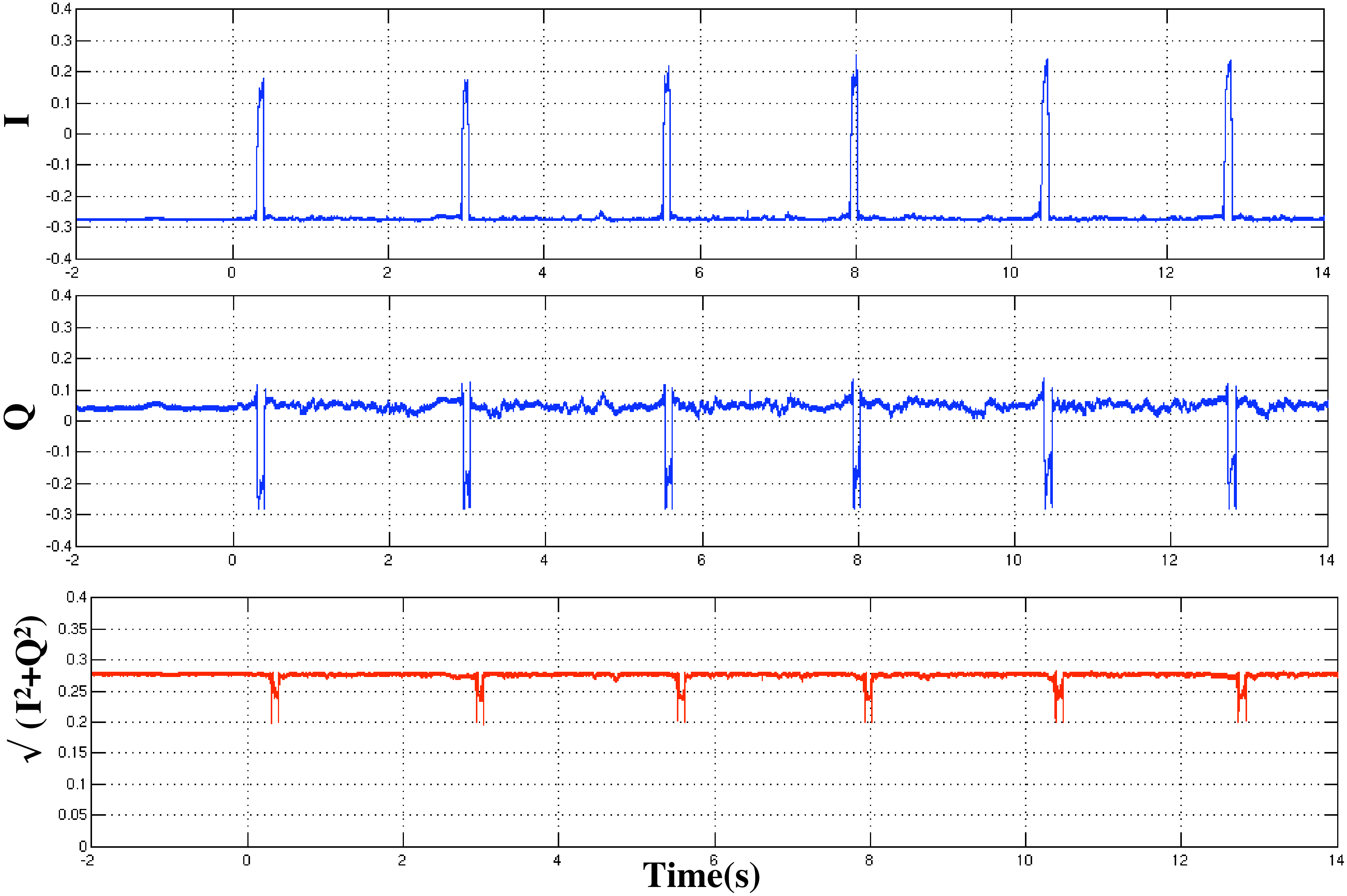
For many shots, the interferometer still gives unreliable data. Most often, this consists of line-integrated density measurements that either go negative or fail to return to a level near zero at the end of a shot. We have spent much effort trying to get the interferometer to calibrate correctly. During up-to-air periods, we have performed calibration-tests by going inside the vessel and dropping slabs of material of known dielectric constants in the path of the beam. These tests have shown that reflected power seems to be causing much of the problems. We are addressing this problem along three avenues:

1. Isolation has been increased at the RF Gunn-Diode from 25dB to 50dB
2. Limiting amplifiers have been installed on all IF signals to normalize their amplitude over time
3. Phase-Locking the two Gunn-Diodes (not yet begun)

OLD CALIBRATION SHOT



CALIBRATION SHOT WITH LIMITING AMPLIFIER



FUTURE WORK

- Phase-lock the two Gunn-diode oscillators and continue calibration improvements.

- Properly treat the refractive effects that a highly peaked density profile will have on the trajectory of our beam.

- Further characterize the dynamics of the density profile as a function of the other plasma parameters.