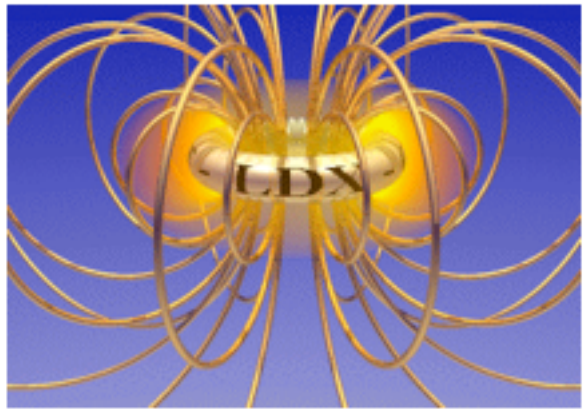


Evidence of "Natural" Density Profiles in a Dipole-Confined Plasma

A. Boxer, J. Ellsworth, Jay Kesner

MIT

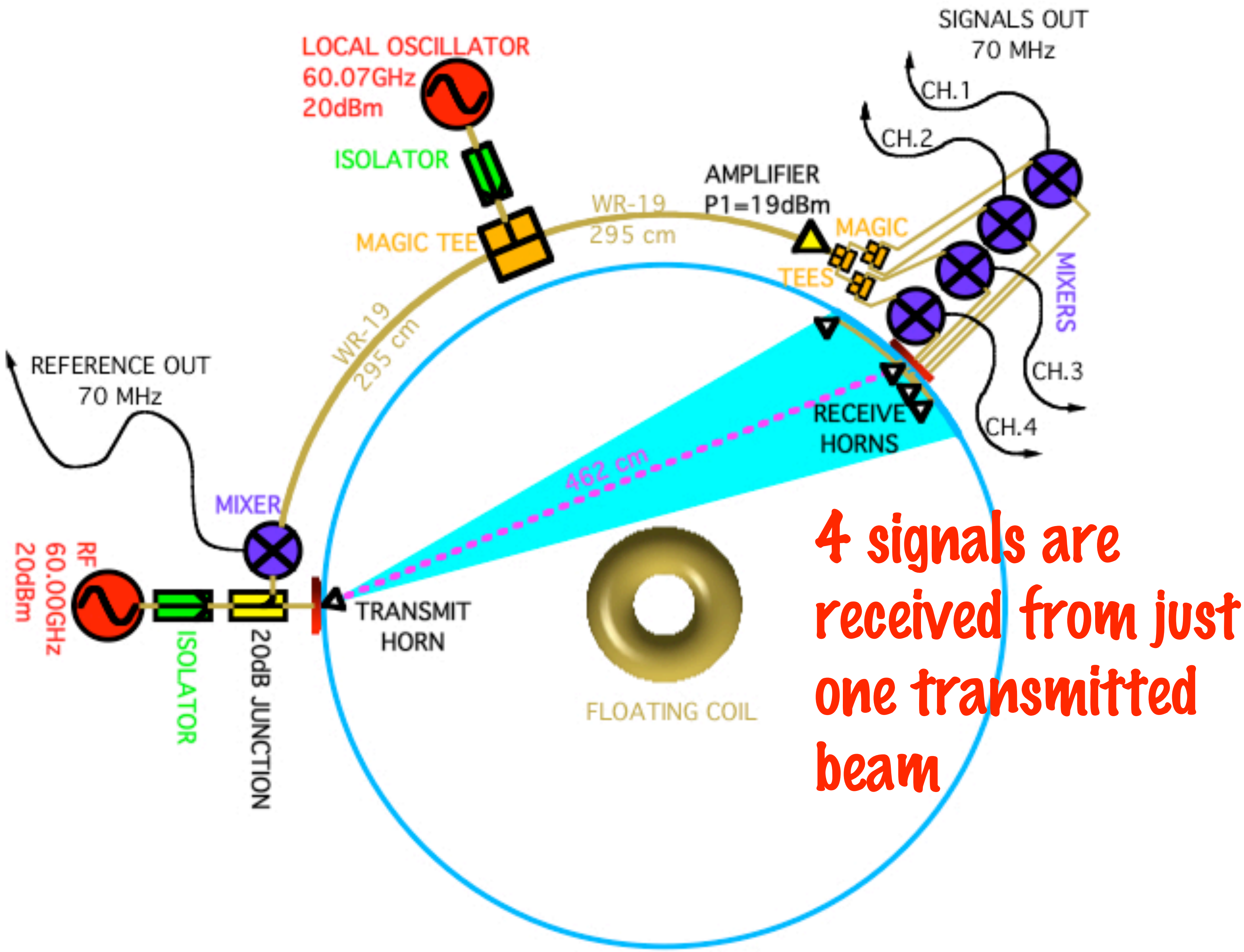
D.T. Garnier, M.E. Mauel

Columbia University

Columbia University

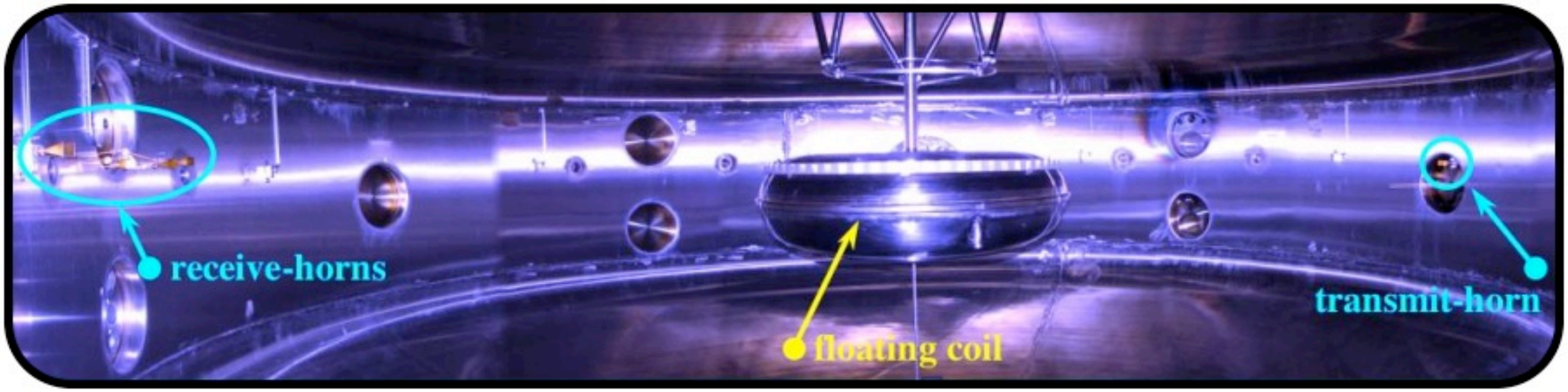
Poster CP6.00084

Presented at the DPP Meeting, Dallas, November 17, 2008

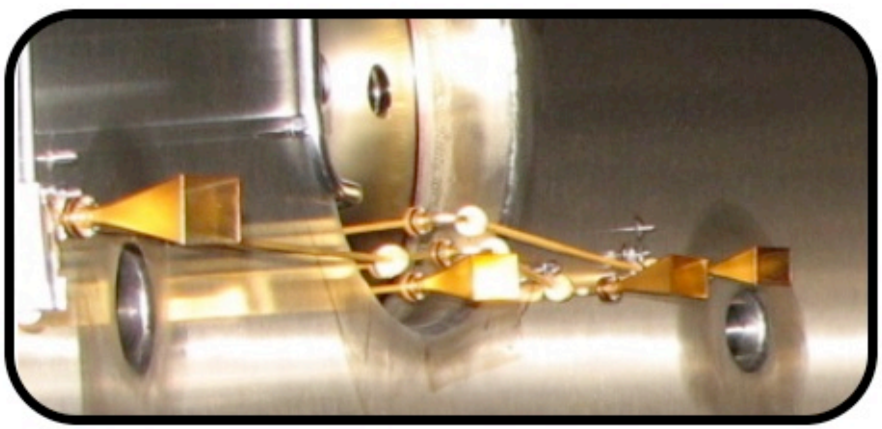


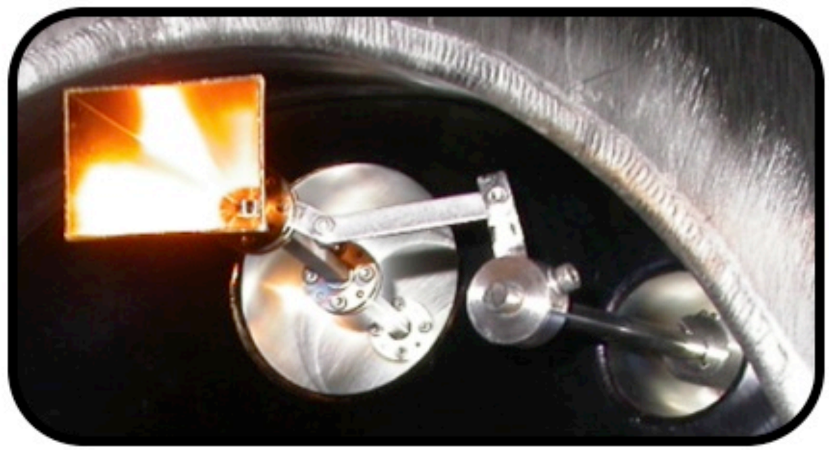
BLOCK DIAGRAM OF THE LDX INTERFEROMETER AS SEEN FROM ABOVE

Interior of the LDX Vacuum Chamber

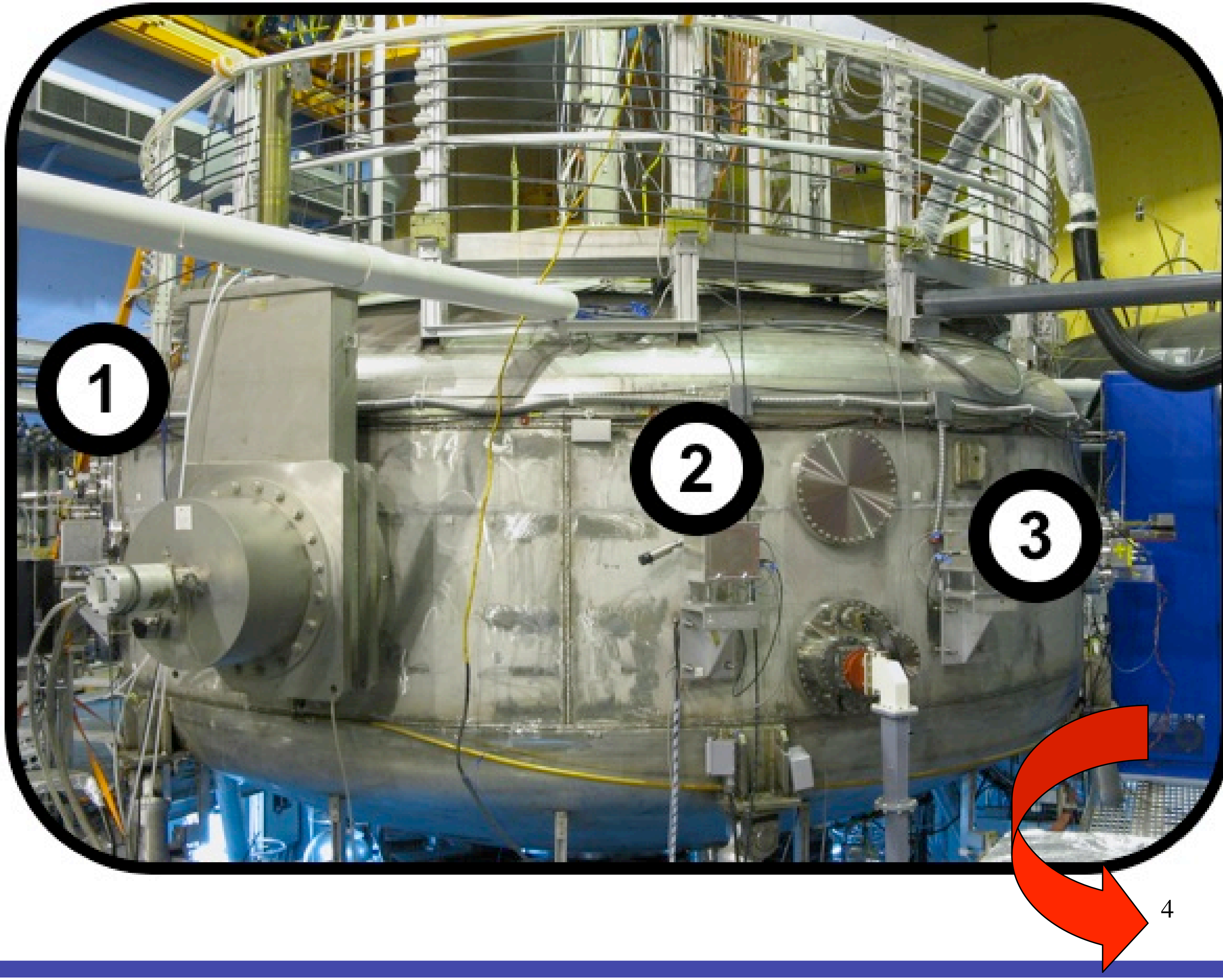


Receive-Horns





Transmit-Horn with Azimuthal Adjust


1
2
3

The LDX interferometer is, in essence, a heterodyne FM radio transmitter and receiver. The fluctuating plasma density modulates the 60 GHz microwave beam just like a voice modulates a radio's carrier signal (RF).

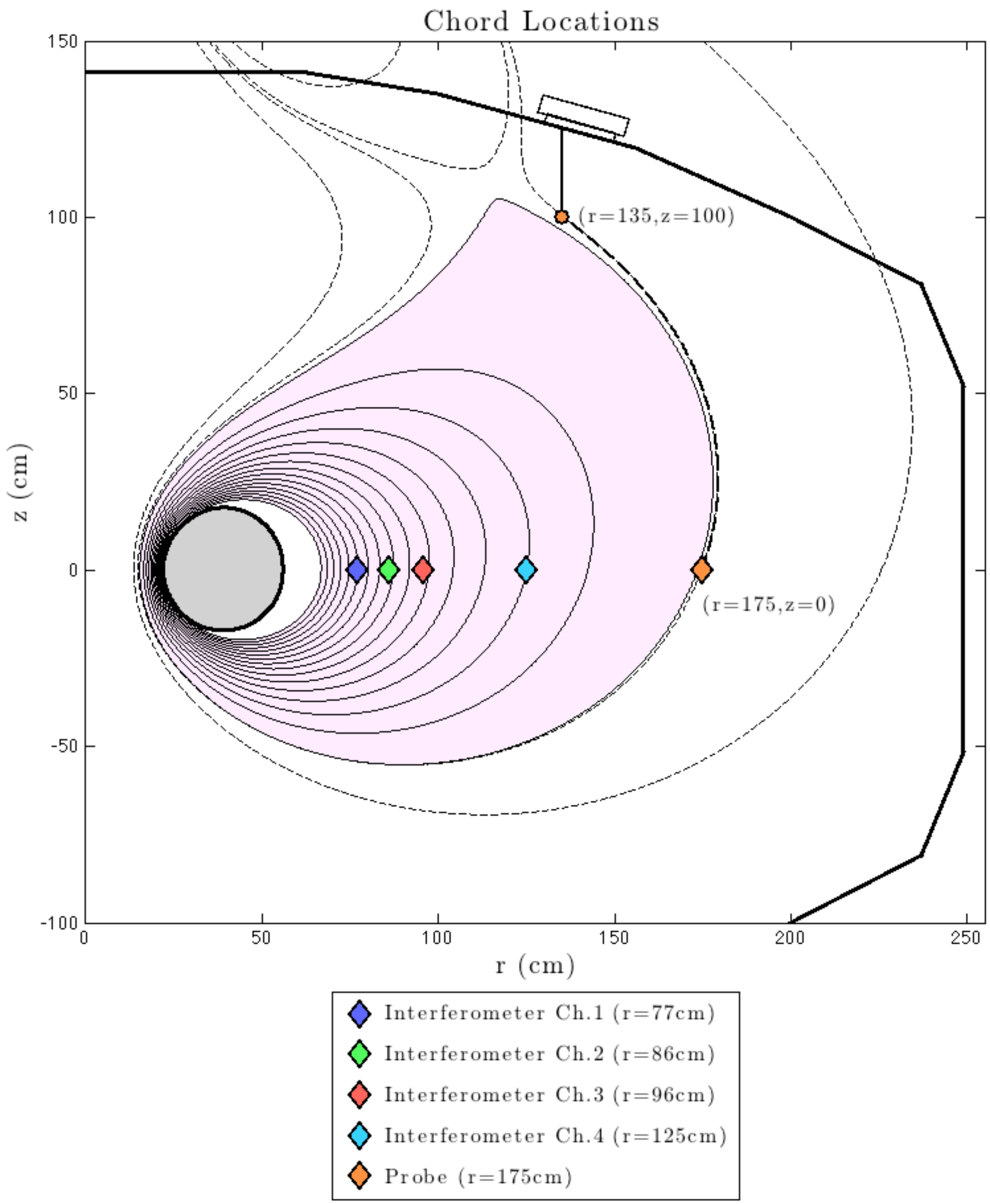
A local oscillator (LO) at the receiver location is mixed with the RF to produce an intermediate frequency (IF) modulated by the signal of interest.

In LDX, these frequencies are:

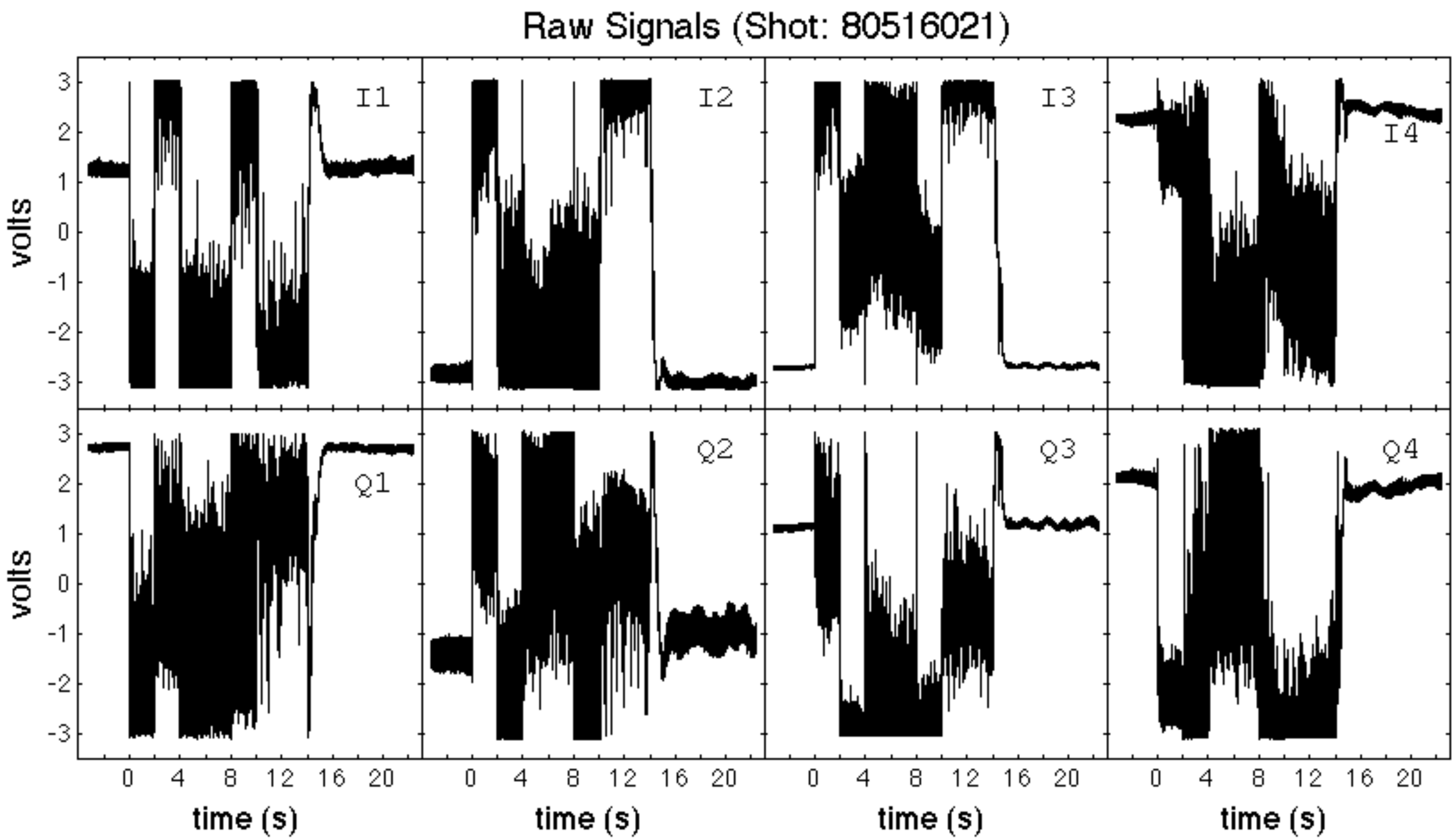
RF = 60.00 GHz
LO = 60.07 GHz
IF = 70 MHz
Density Information < 10 kHz

The advantage of heterodyning is that it greatly improves the phase stability of the interferometer. The signal and reference legs need only to be made equal to within a few wavelengths of the IF (λ_{IF} = 14 ft) instead of a few wavelengths of the RF (λ_{RF} = 5 mm). At sufficiently high IF (> MHz), the phase noise in two free-running oscillators (the RF and the LO) is comparable to two phase-locked oscillators.

C. Domier, "Millimeter-Wave Interferometer for Measuring Plasma Electron Density ". *Review of Scientifc Instruments,* 1988.

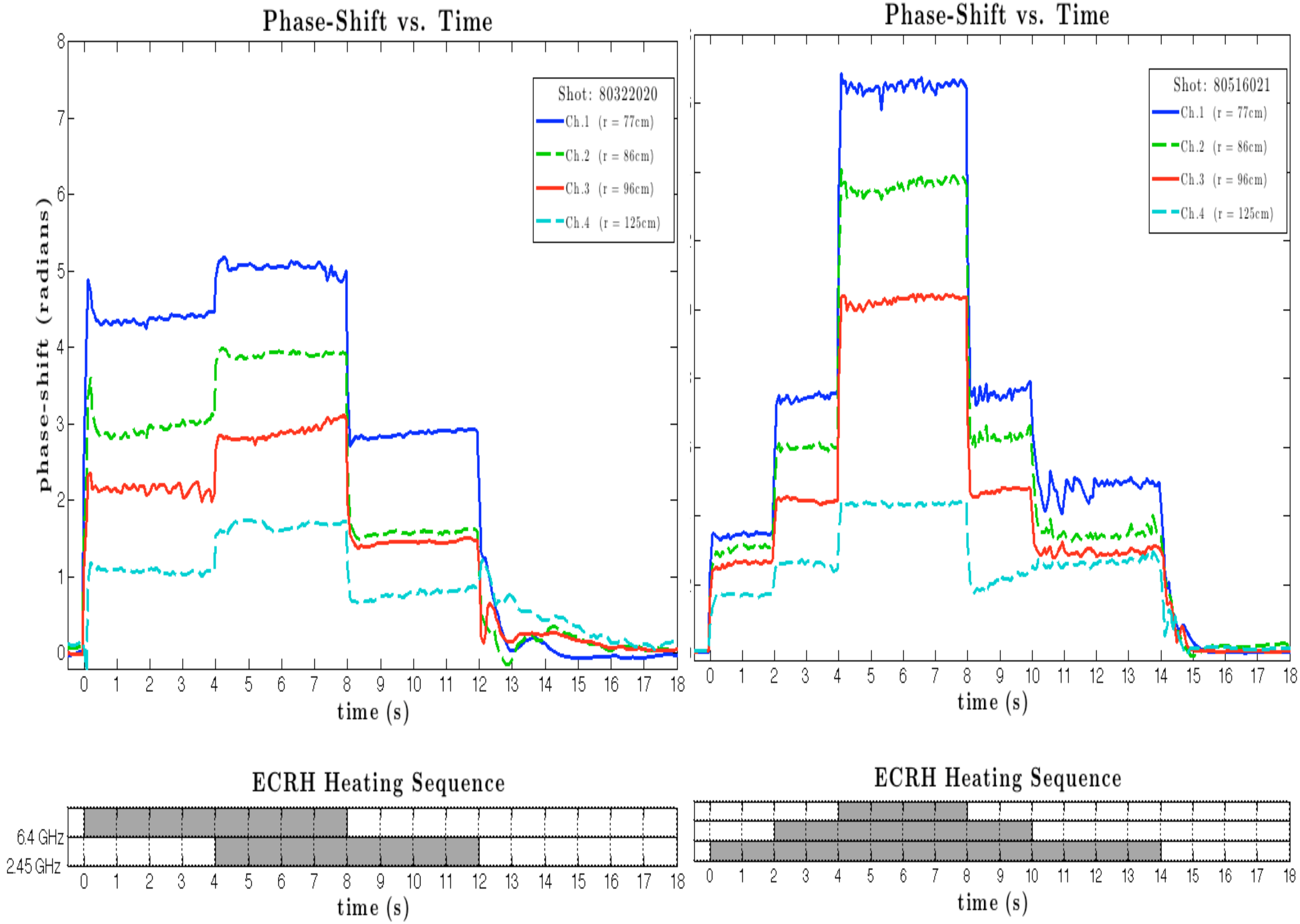


Radial locations of the interferometer chords as seen in a cross-sectional view of the LDX vacuum chamber



Raw Signals (Shot: 80516021)
I1
I2
I3
I4
Q1
Q2
Q3
Q4
volts
volts
3
2
1
0
-1
-2
-3
0
4
8
12
16
20
time (s)
time (s)
time (s)
time (s)

Two typical shots



FROM PHASE SHIFTS TO DENSITY PROFILES

The geometry of LDX offers the opportunity of transmitting the interferometer beam entirely in the O-mode. The dispersion relation is then particularly simple: $N(\omega) = (1 - n/n_c(\omega))^{1/2}$.

Here N is the index of refraction

ω is the wave frequency

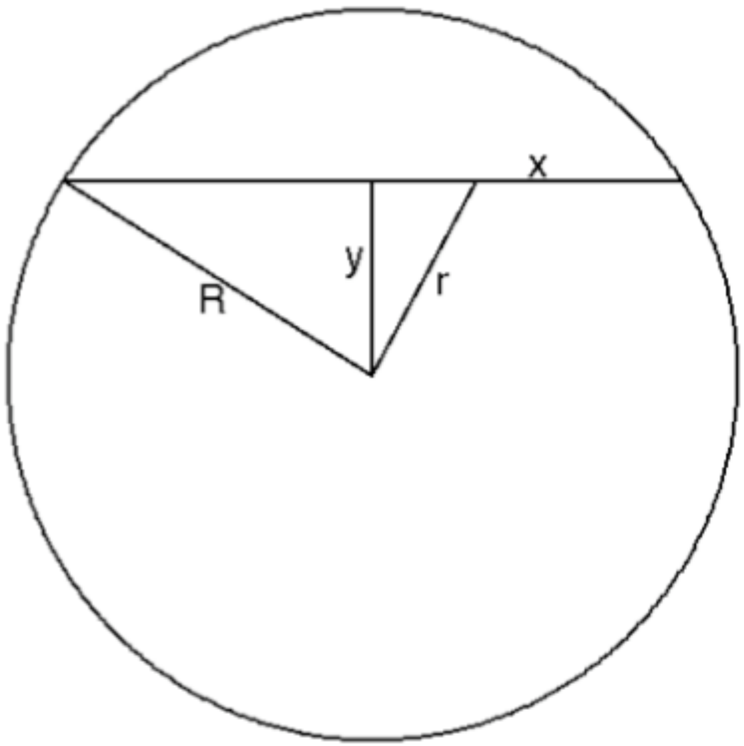
n is the electron density

n_c is the cutoff density of the wave

For the LDX interferometer, n_c(60 GHz) = 4.5 x 10^{13} cm^{-3}. Assuming that the electron density is small compared to this value, phase shifts can be related to the line-integrals for the density by a simple scaling factor.

$$\int n \, d\ell = \frac{-n_c c}{\pi f} \, \Delta\phi$$

$$\approx -7.11 \times 10^{12} \, \Delta\phi \text{ cm}^{-2}.$$

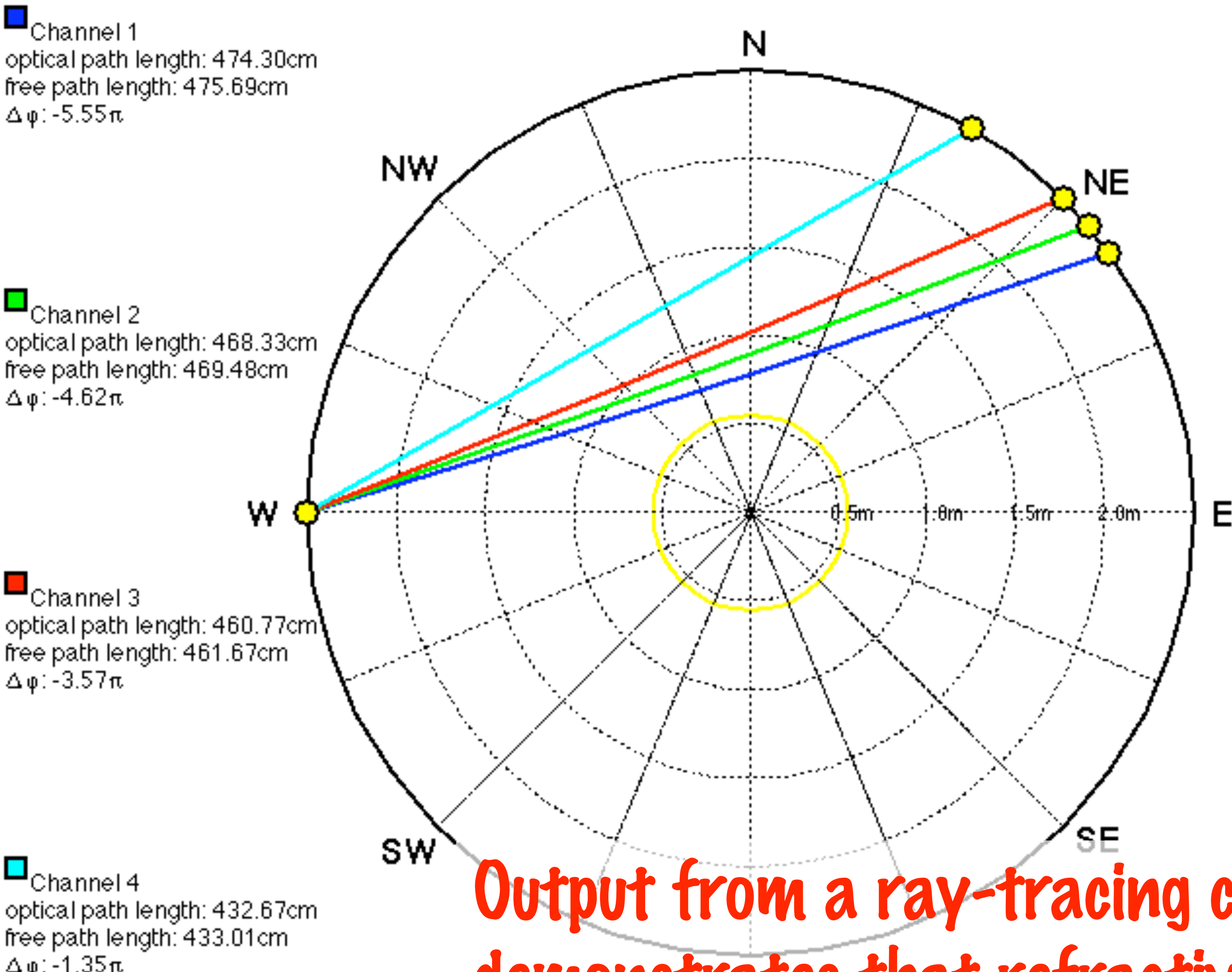


Abel Inversion:

$$f(r) = \frac{-1}{\pi} \int_r^R \frac{dF}{dy} \frac{dy}{(y^2 - r^2)^{1/2}}.$$

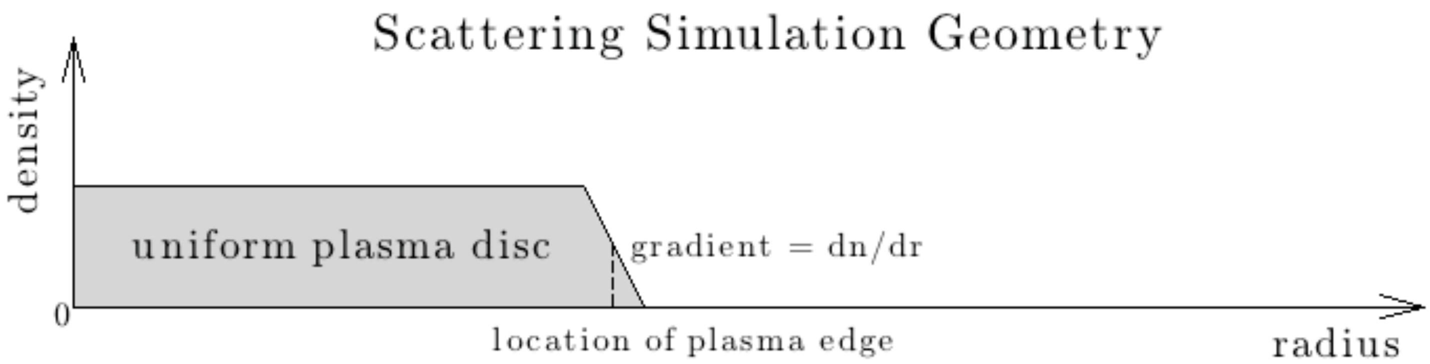
Using Abel inversion to reconstruct the plasma density profile requires two, strong assumptions:

1. The plasma density is axisymmetric.
2. The interferometer rays traverse straight-line paths.

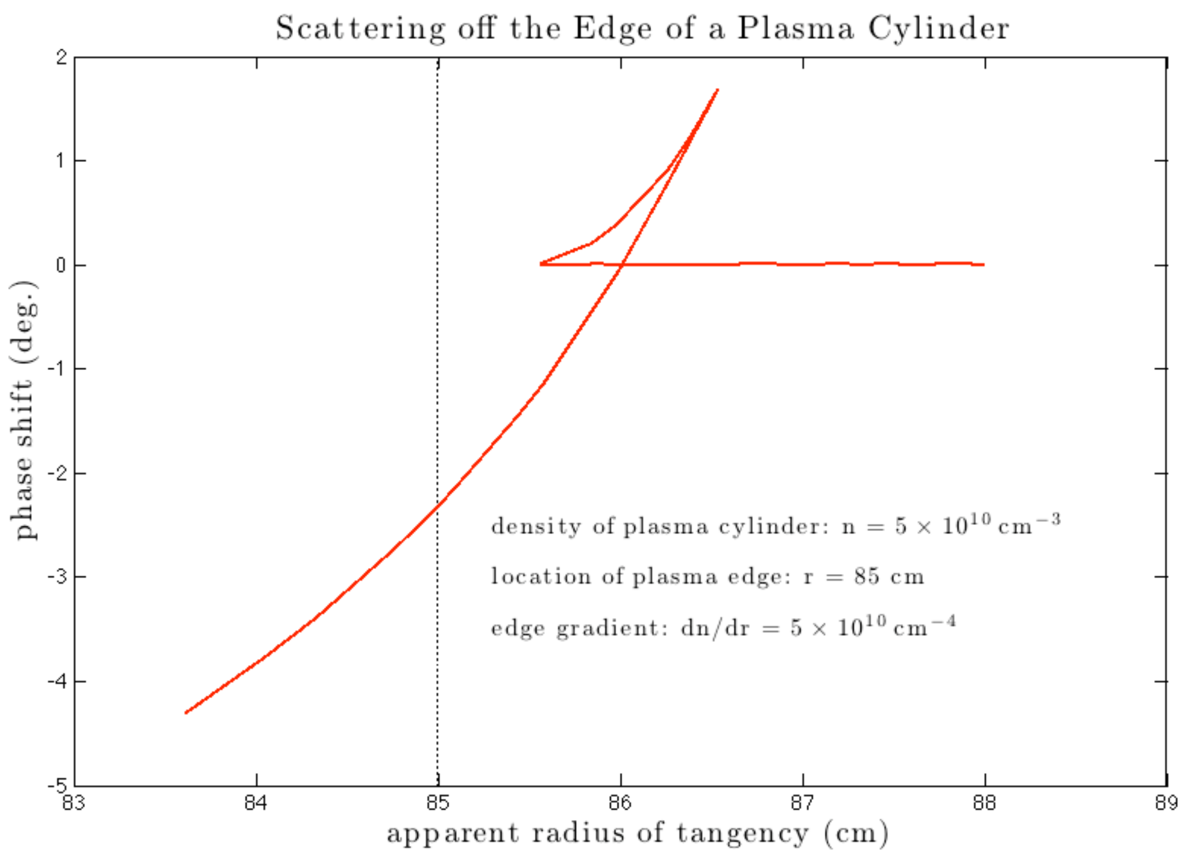


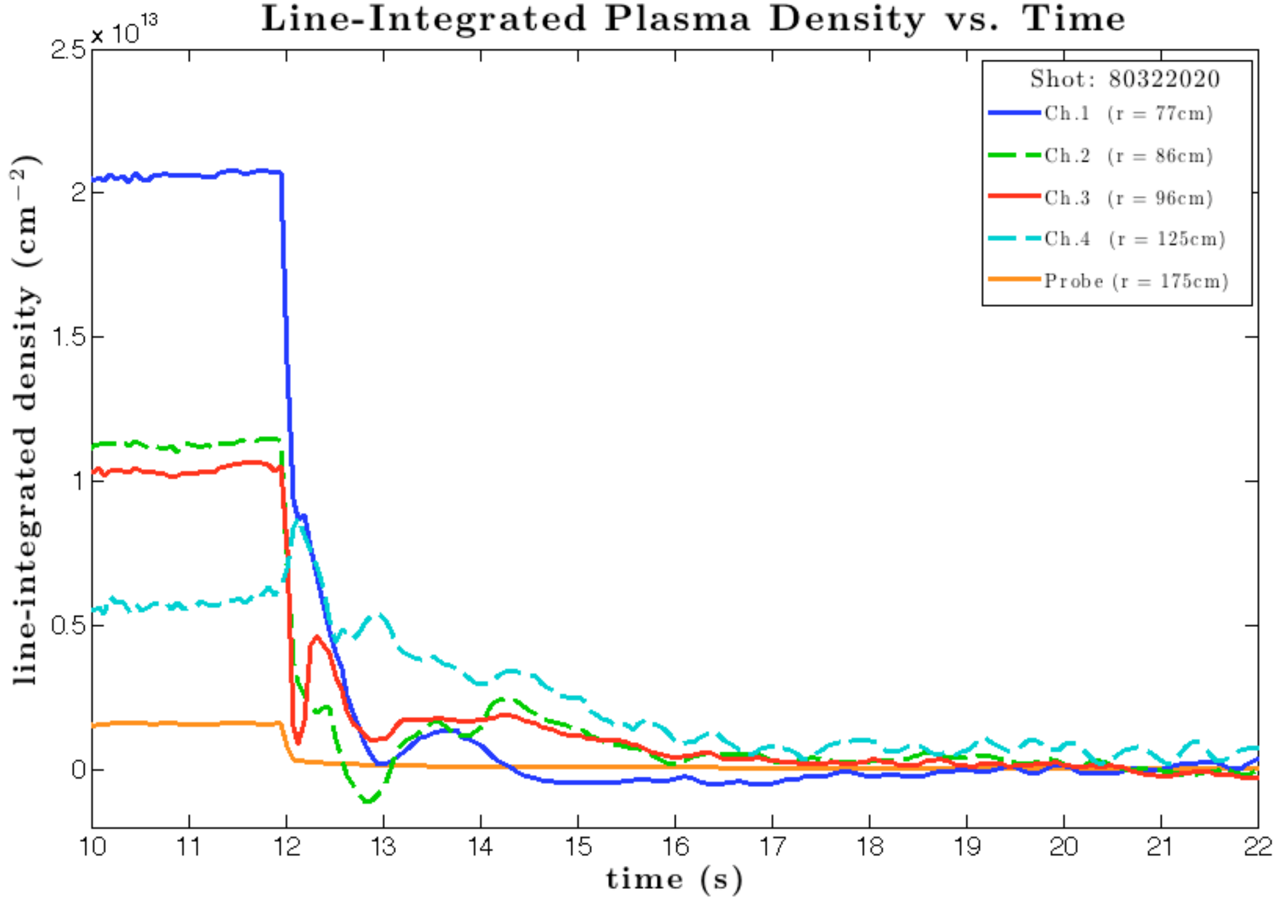
Output from a ray-tracing code demonstrates that refractive effects are generally small

Scatter from sharp plasma-vacuum interface



However, a simple simulation of scattering at a sharp plasma-vacuum interface shows that refractive effects can become large.



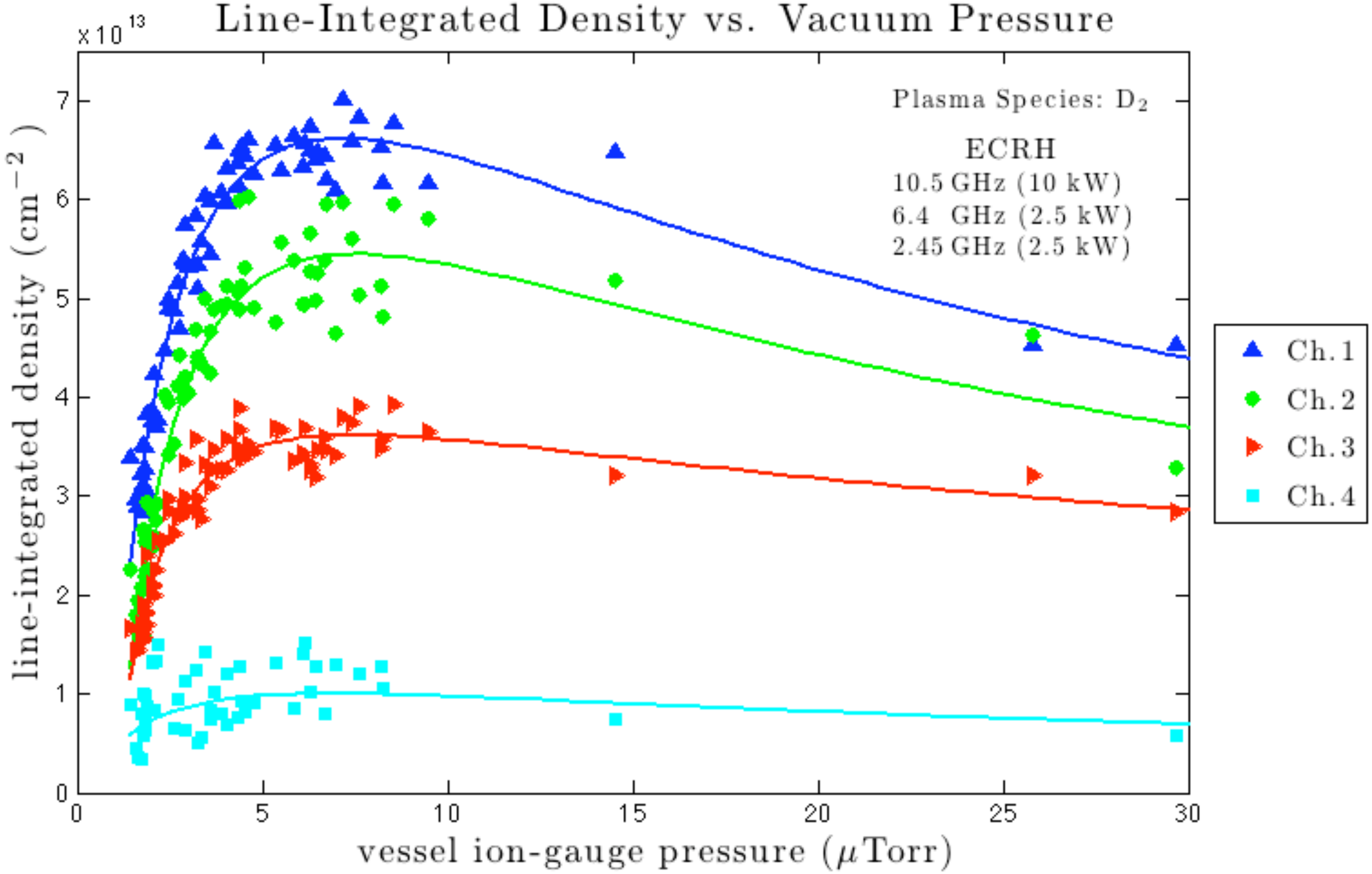


These effects may play a role in the plasma afterglow. Data at these times indicate that original assumptions of Abel inversion (axisymmetric density and straight-line paths) no longer obtain.

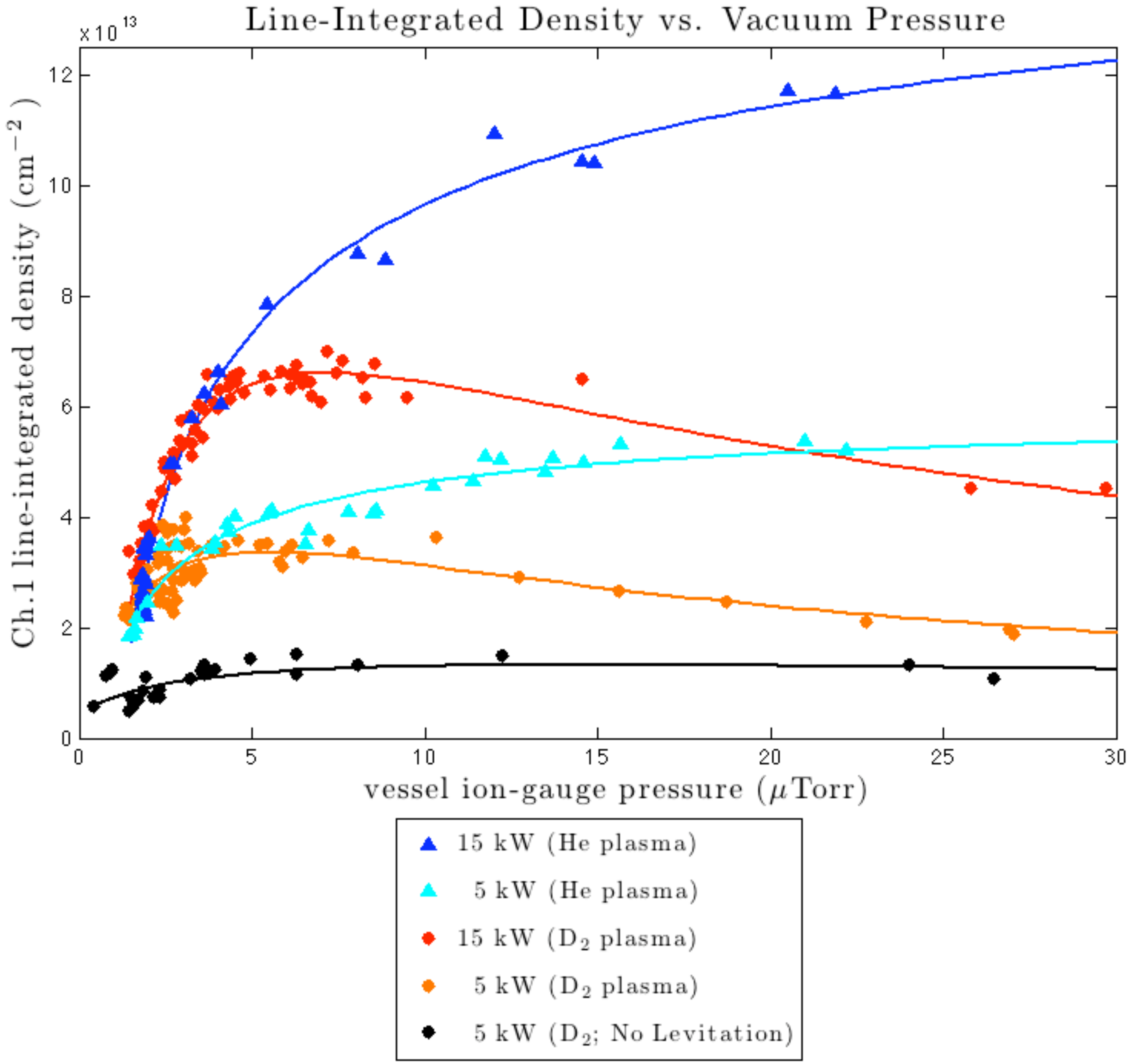
DENSITY PROFILES IN LDX

The density of plasmas in LDX is found to depend upon the following experimental parameters:

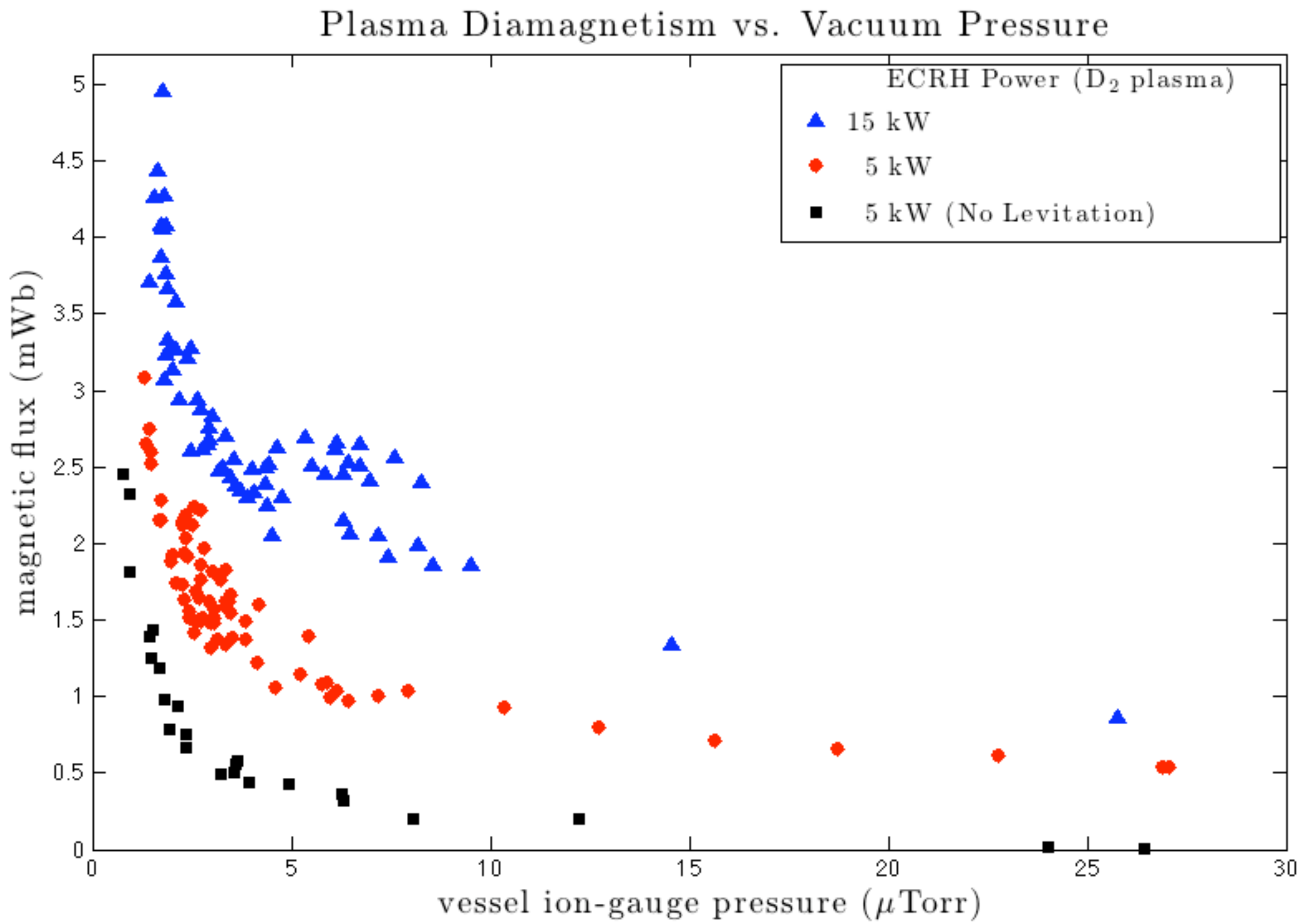
1. ECRH
2. Fueling of neutral particles
3. Levitated vs. mechanical support of the F-Coil
4. Plasma Species



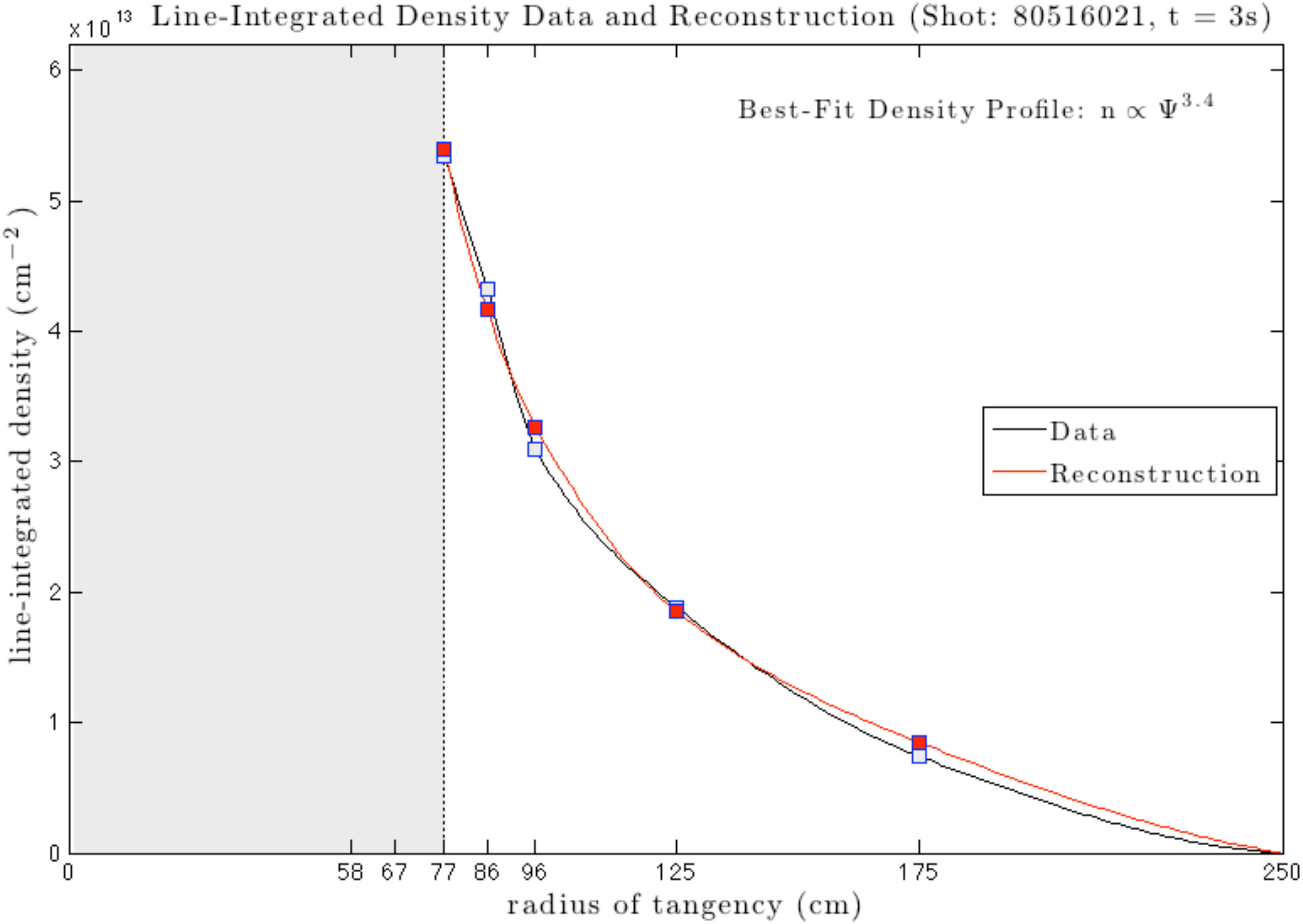
LDX plasmas are largely reproducible once the neutral pressure is taken into account.



DENSITY INCREASES WITH LEVITATION, POWER AND SPECIES MASS

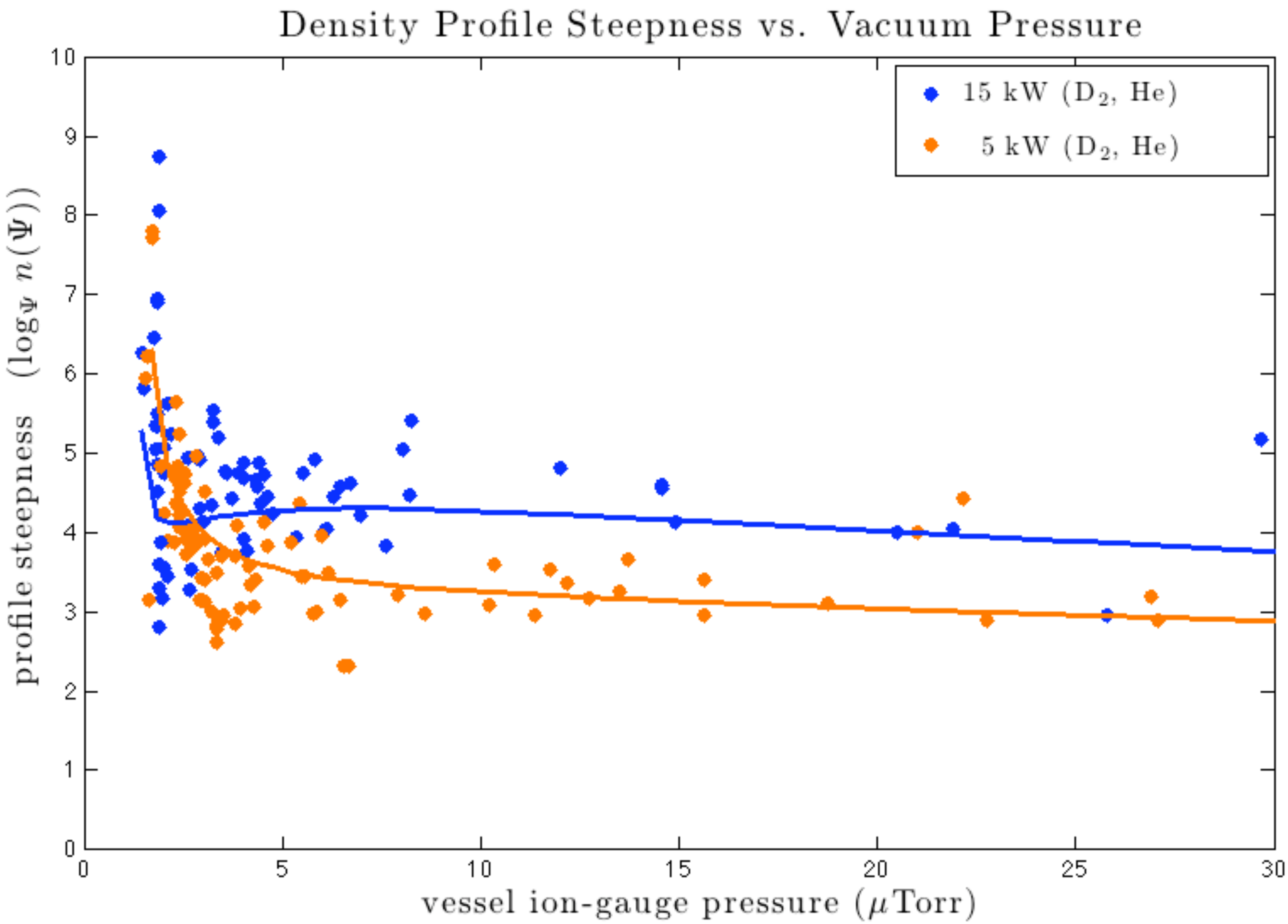


Most of the plasma energy is stored in the smaller, non-thermal population of hot electrons.



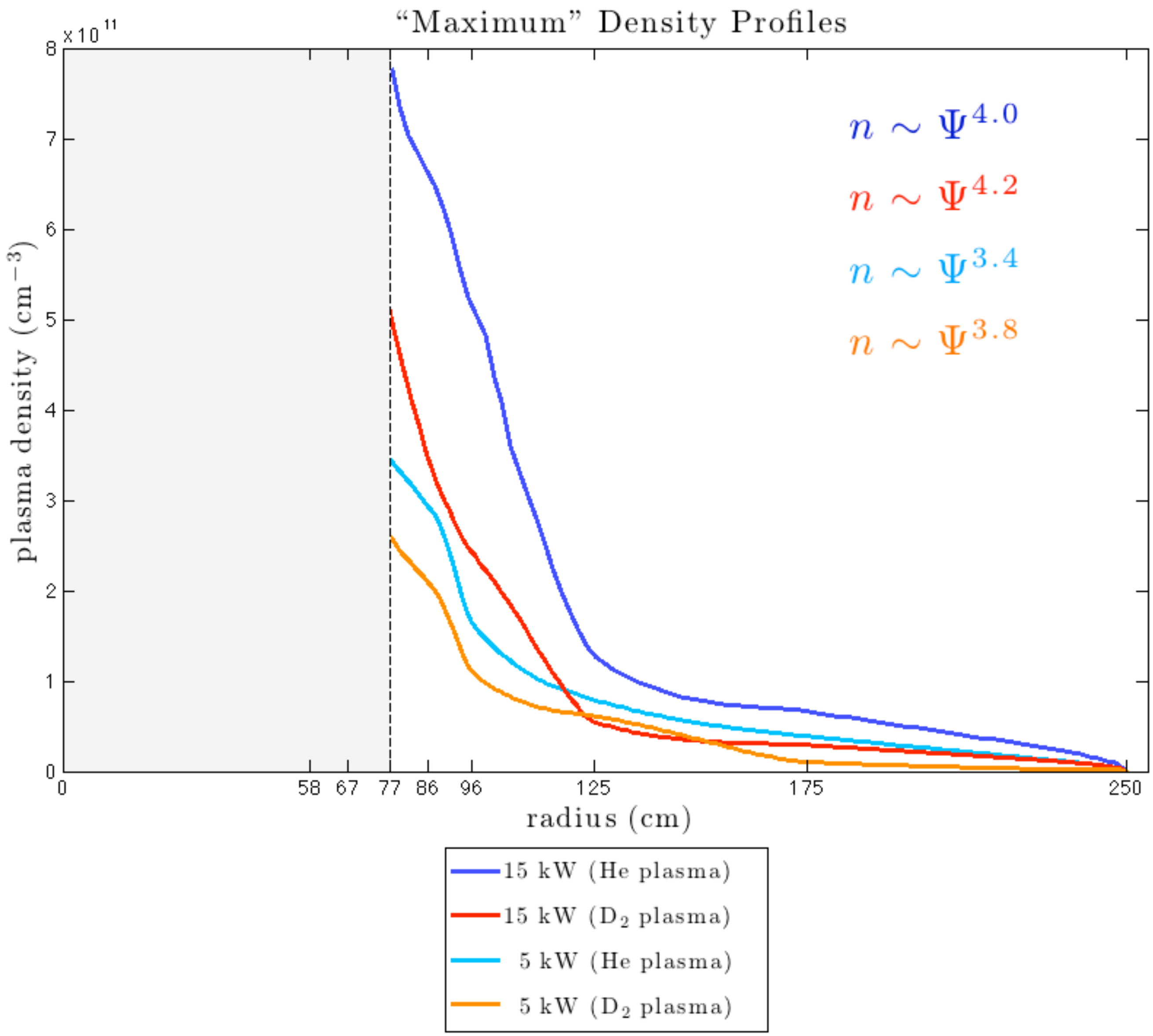
We can fit the density data to functions of the flux, ψ(r).

$\psi^{4.5}$ corresponds to an equal number of particles per flux-tube.



LDX plasma exhibit a "profile consistency" in the density.

KNEE MOVES OUT WITH POWER. LDX APPEARS TO BE UNDERPOWERED

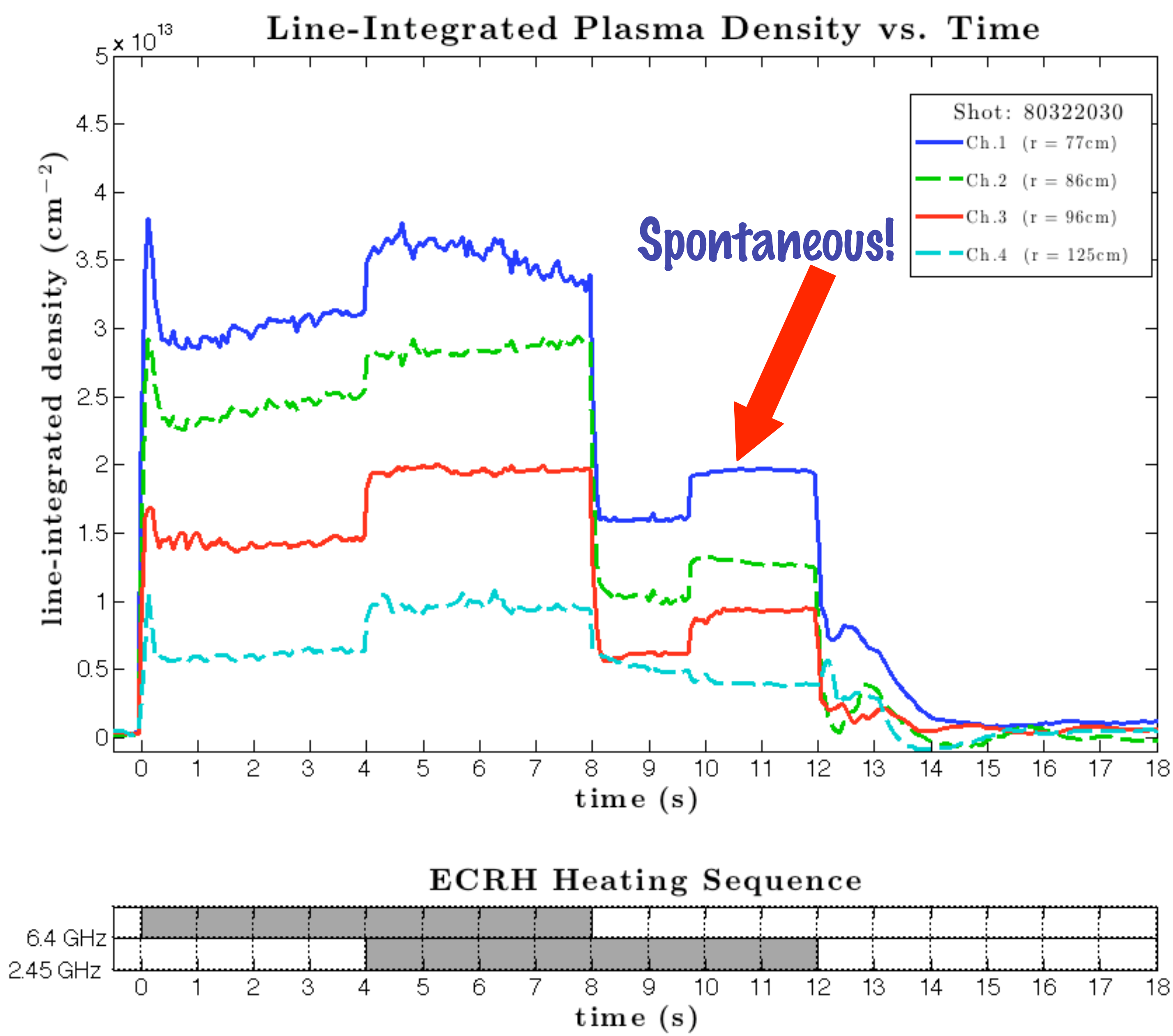


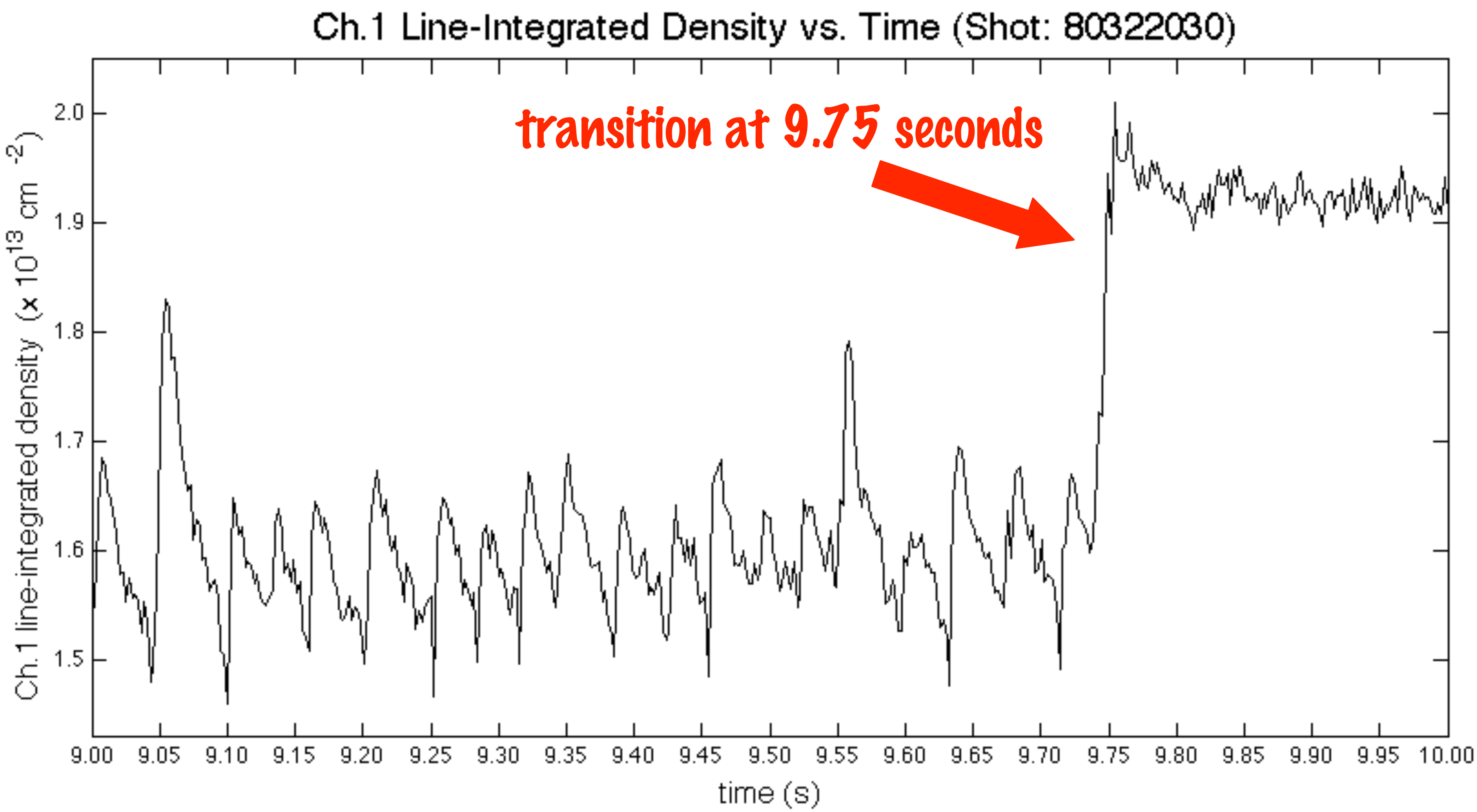
OBSERVATIONS OF PLASMA SELF-ORGANIZATION

It is remarkable that LDX plasmas so often approximate the density profile that is stationary to interchange modes. This result would not be expected by a simple balance of particle sources (localized at the ECRH resonance zones) and sinks. Some additional, convective process must be at work.

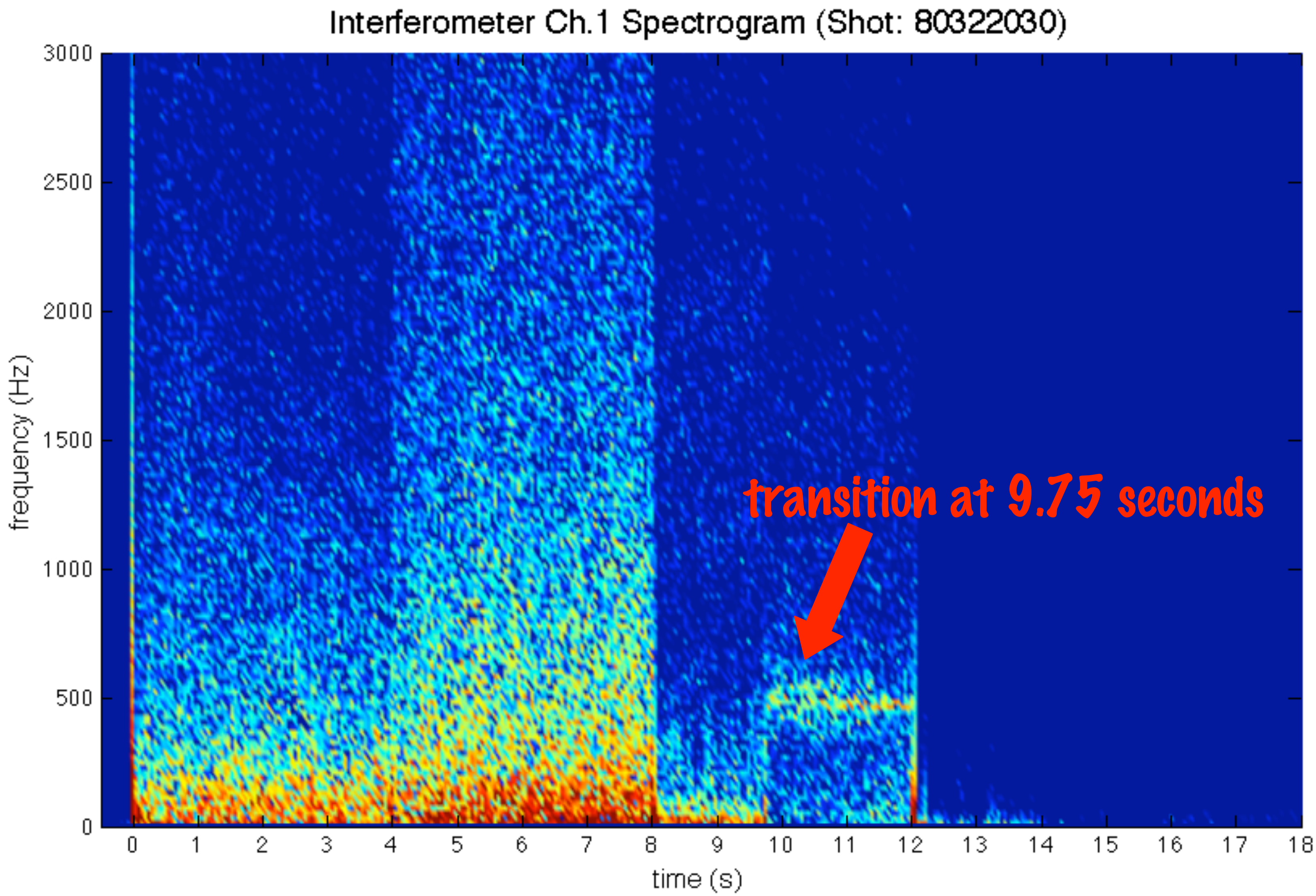
Additional indication that the stationary density profile is somehow “preferred” or “natural” is evidenced by the observation of “spontaneous density transitions”.

OBSERVATIONS OF PLASMA SELF-ORGANIZATION

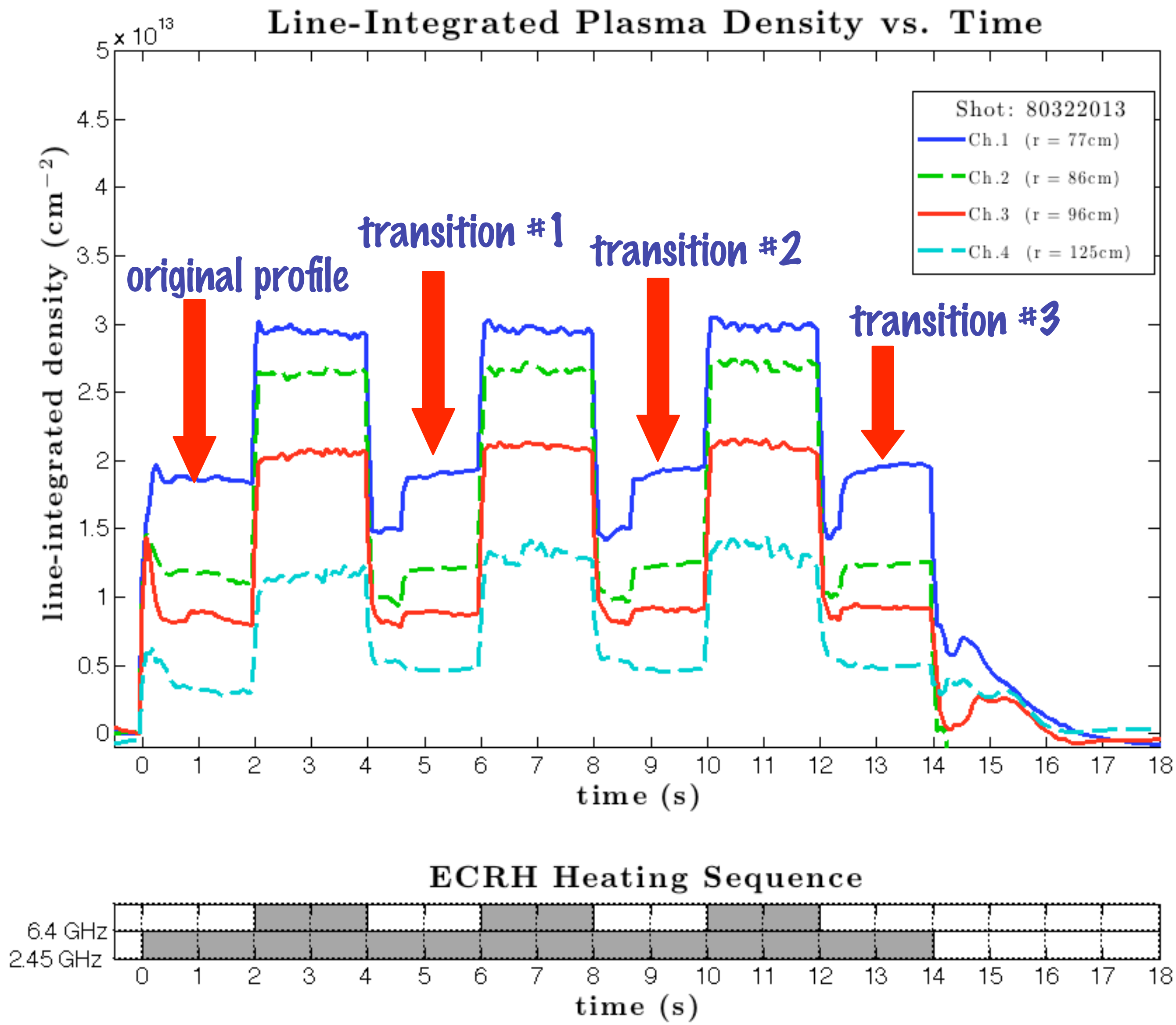




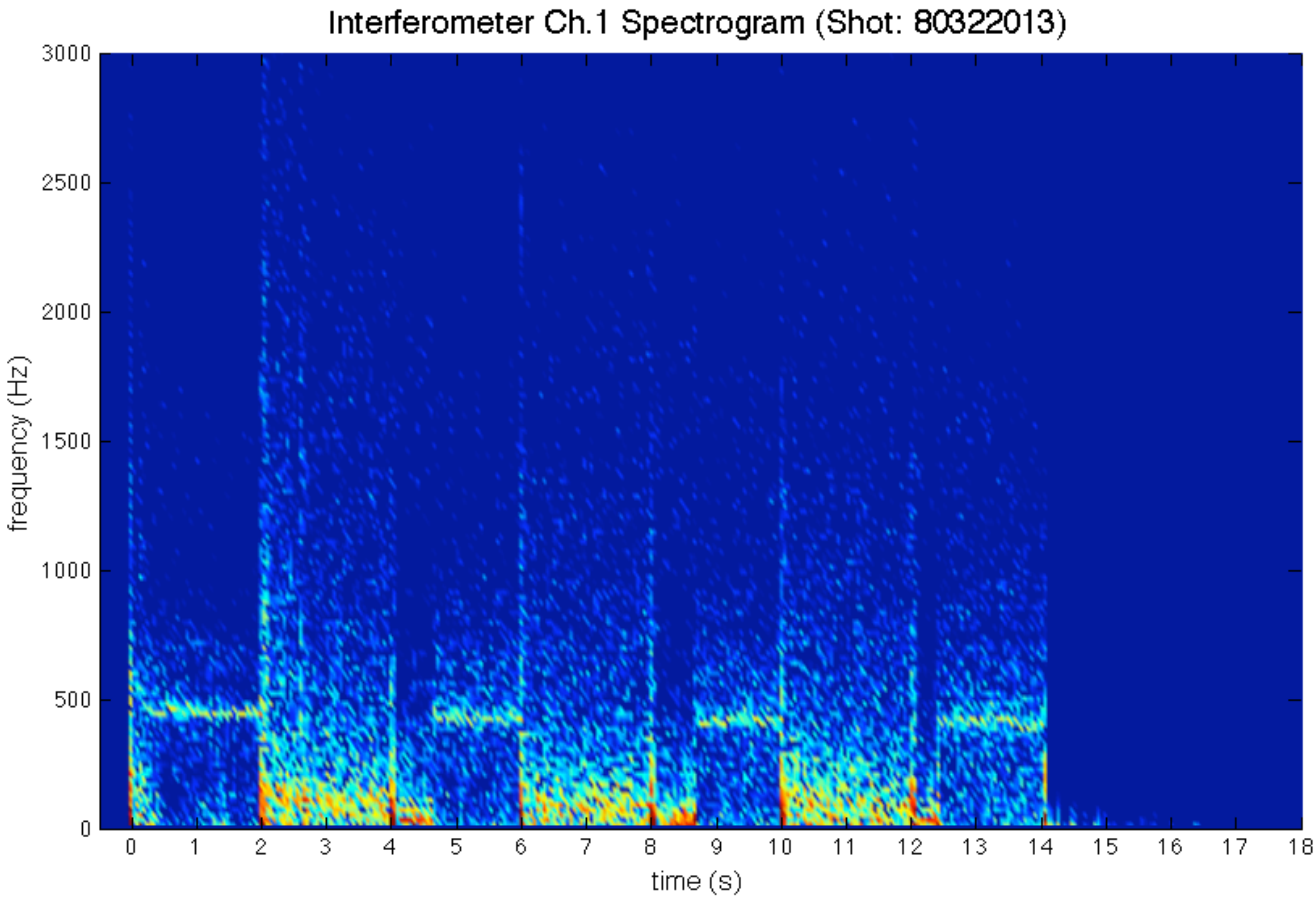
Large, inverse-sawteeth fluctuations (~ 30 Hz) appear on the inner interferometer channels before a transition.



A strong, quasi-coherent mode at 500 Hz appears on the innermost channel (r = 77cm) in conjunction with the density transition.



A modulation shot shows that the transition "restores" the density profile.



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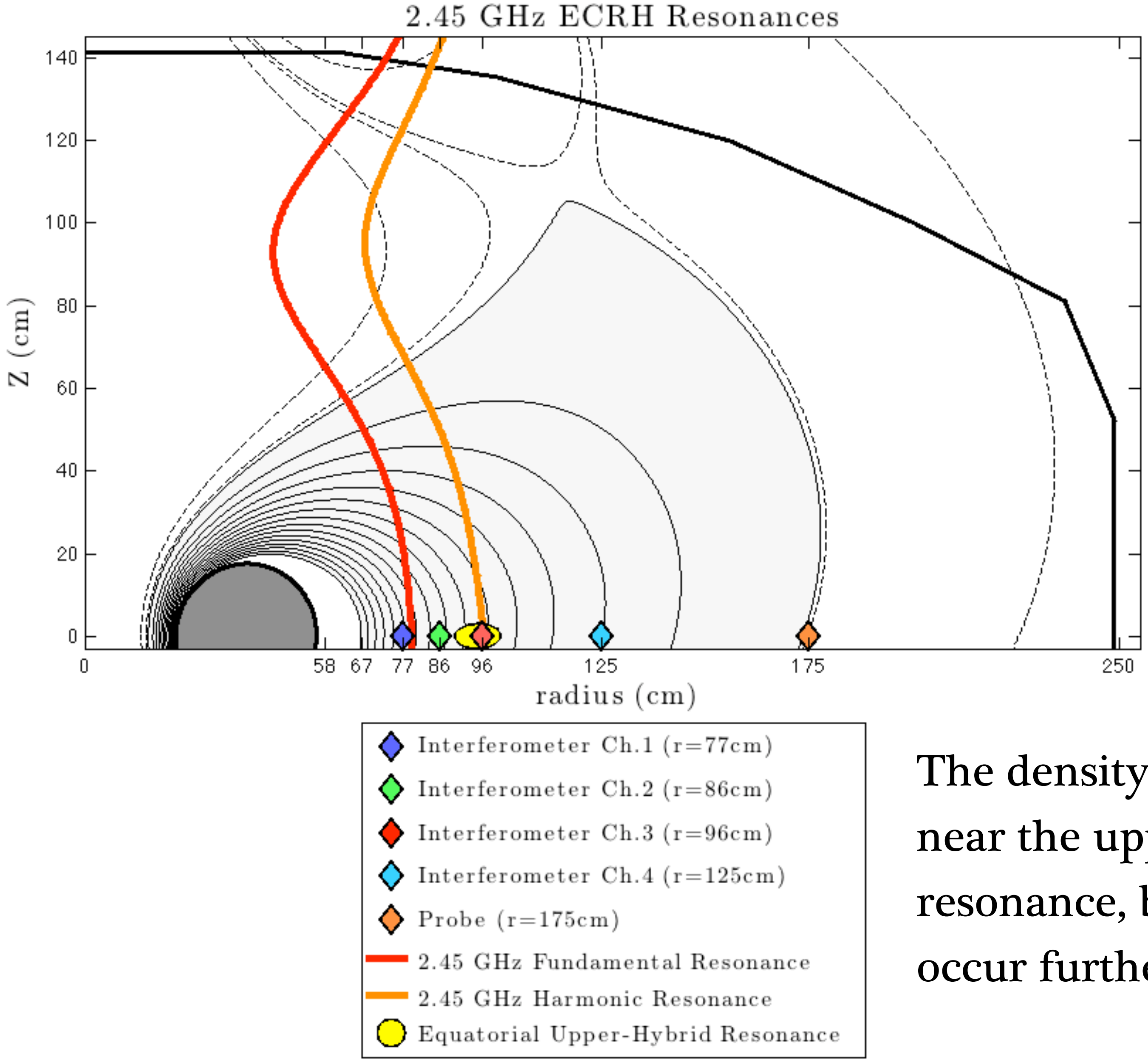
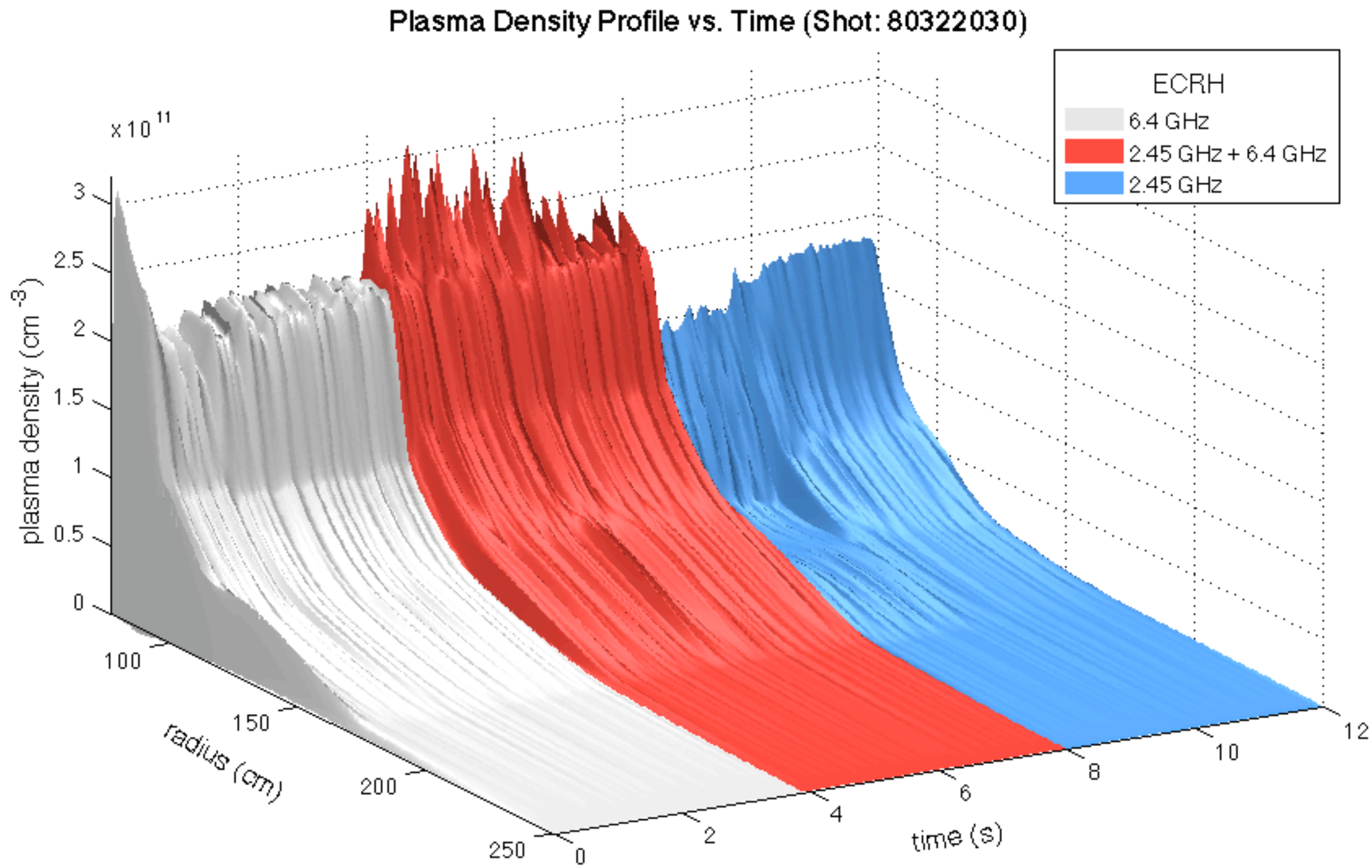
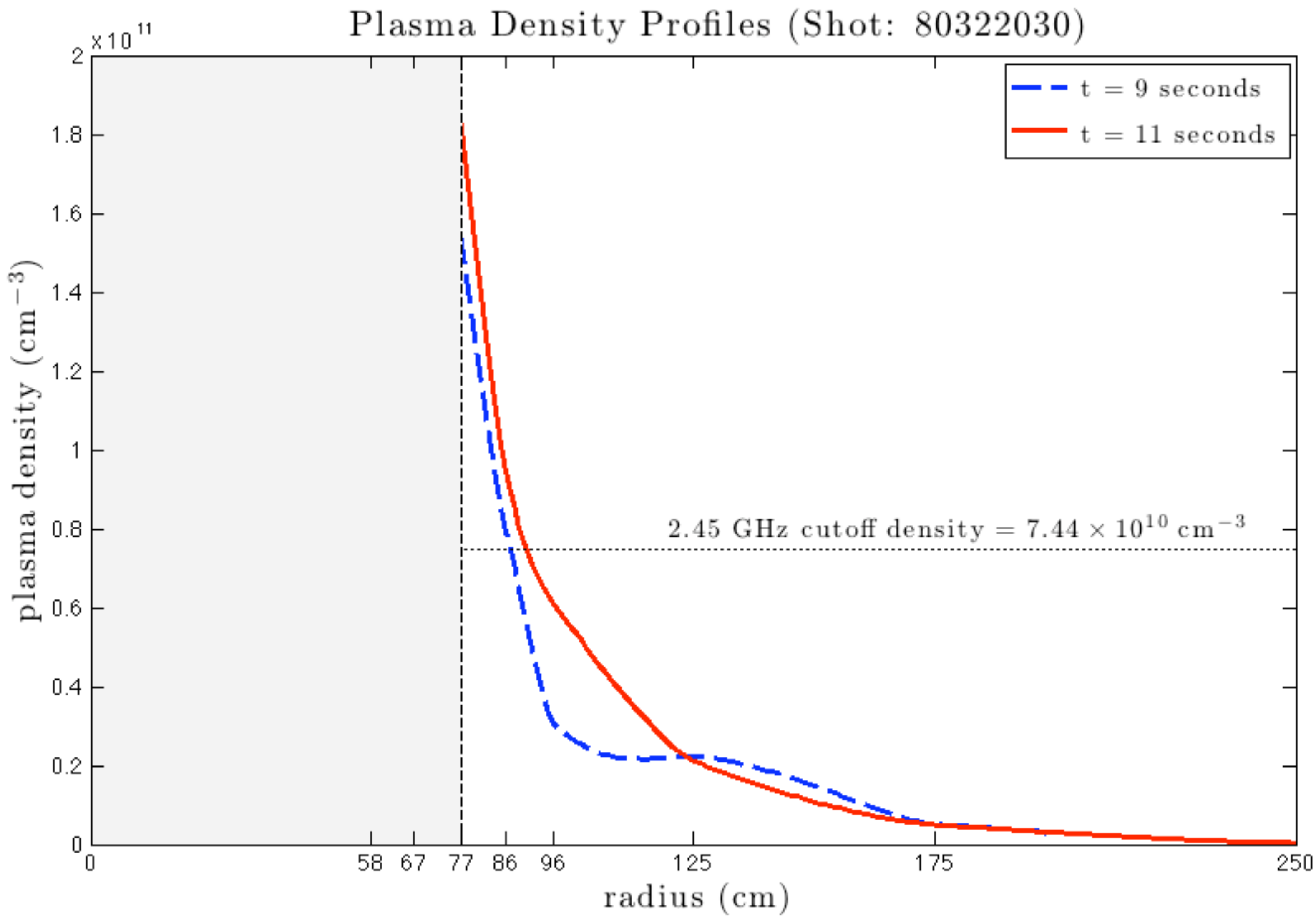


The density transition happens near the upper-hybrid resonance, but the sawteeth occur further inwards

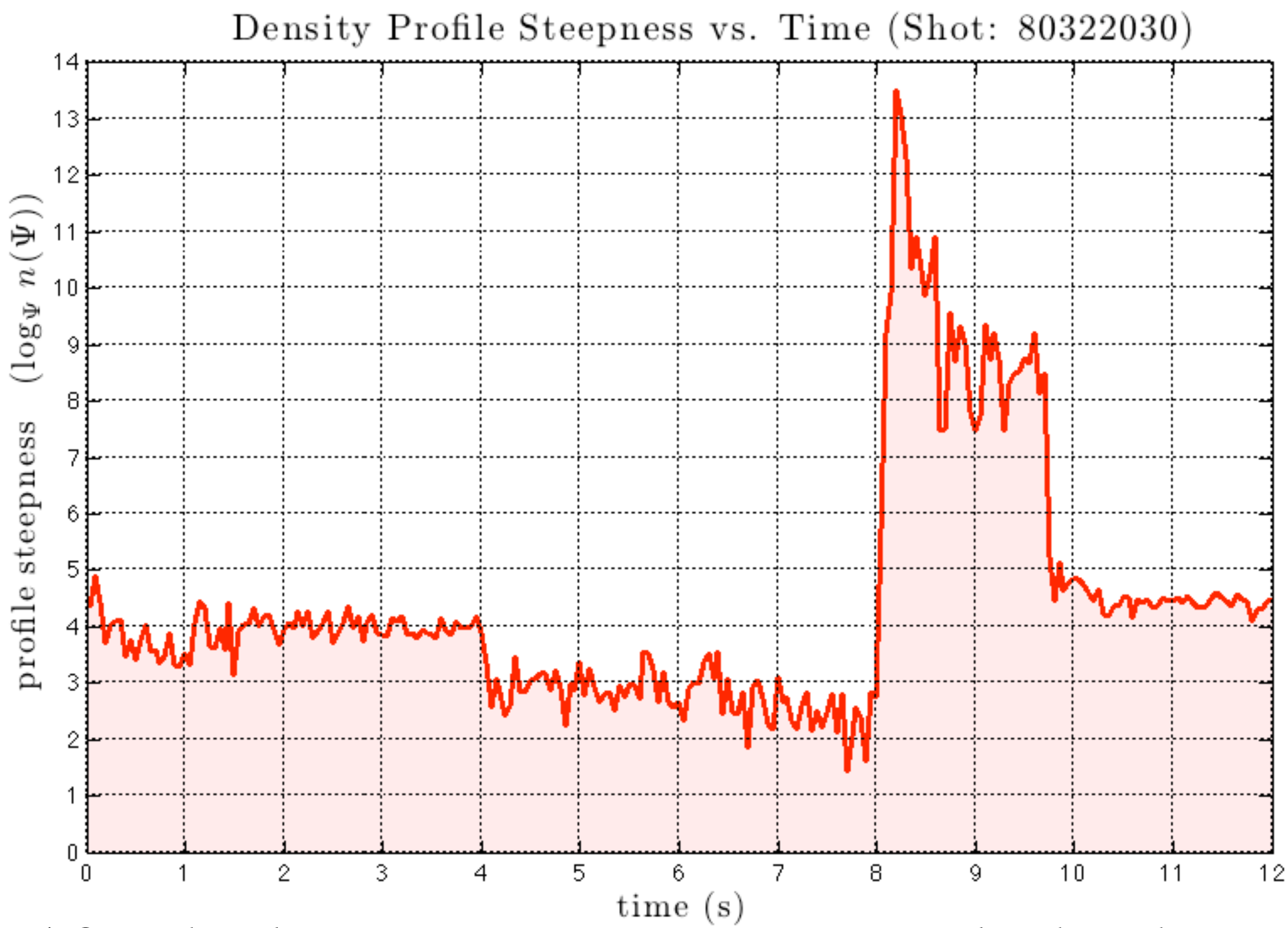


From 8-9.75 seconds, the density has a "hole" near 100 cm that gets "filled-in" after the density transition at 9.75 seconds.

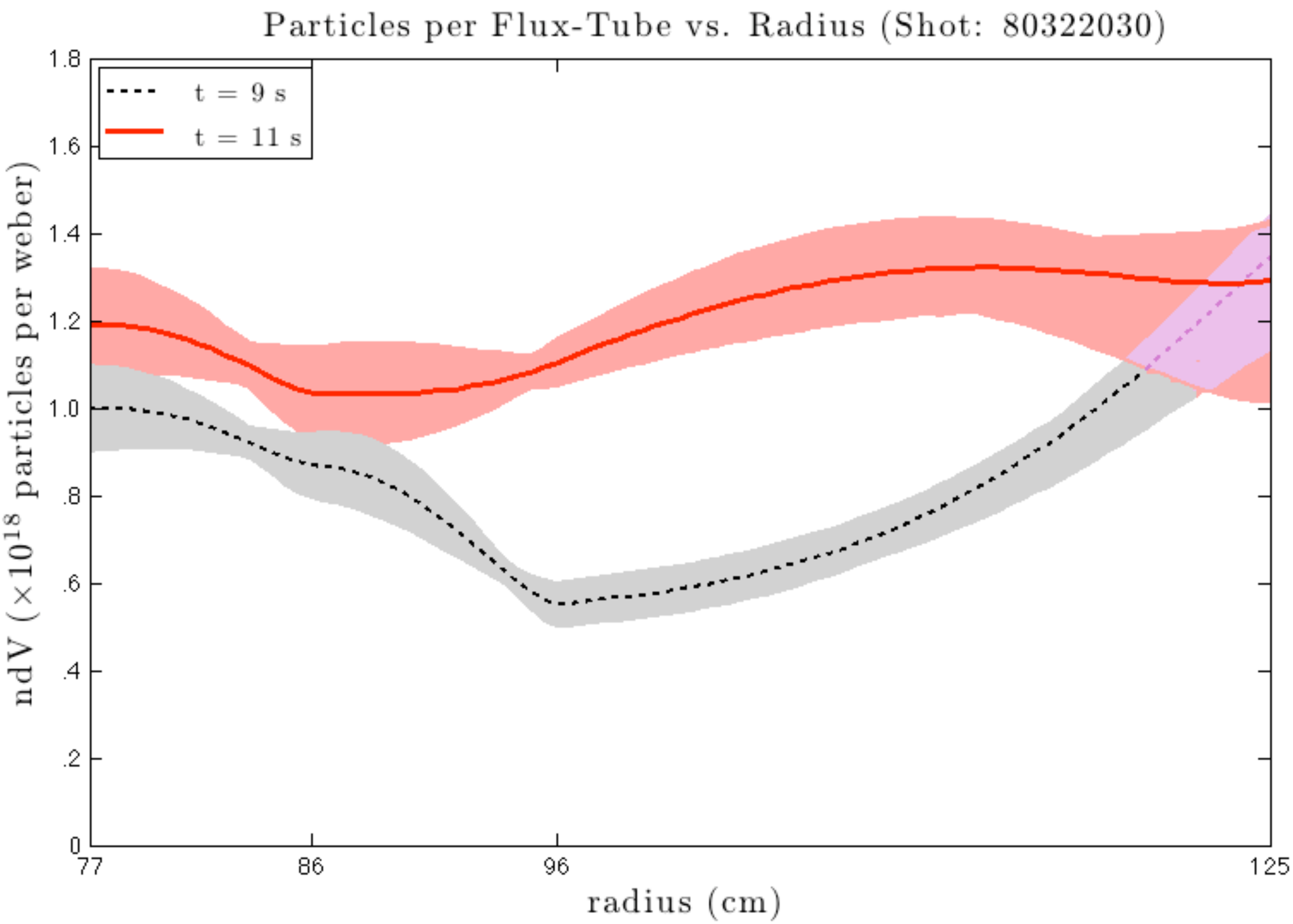
WITH 2.45 GHZ HEATING PLASMAS ARE OVERDENSE



The density is above the 2.45 GHz cutoff both before and after the transition at 9.75 seconds.



After the density transition at 9.75 seconds, the plasma matches exactly the stationary profile of $\psi^{4.5}$.



After the density transition, the number of particles per flux-tube becomes more constant throughout the plasma

CONCLUSION

A microwave interferometer has been been built to measure the density profiles of LDX plasmas.

Density trends have been identified across a range of experimental conditions.

Density profiles in LDX often approximate the form predicted to be stationary to interchange modes.

Density transition events are observed that may be associated with self-organized convection into a stationary profile.

Future experiments in LDX will benefit from increased diagnostics capabilities and increased heating power.

One way to look at the density transitions is as a convective process that acts to bring the plasma into its stationary profiles. In this hypothesis, the 500 Hz mode may be a large-scale convective cell drifting azimuthally around the LDX vacuum chamber. The generation of the mode can be thought of as "self-orgnization" insofar as it represents an *apparent* decrease of entropy ("inverse cascade").

A. Hasegawa, "Self-Organization Processes in Continuous Media " *Advances in Physics,* 1985.

The self-organization hypothesis is supported by the fact that the density profiles after a transition are indeed closer to the equal particle per flux-tube form.