

Measurement of Electron Density Profile and Fluctuations on HSX

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Measurements of Electron Density Profile and Fluctuations on HSX

The 288 GHz interferometer system on the quasi-helical stellarator HSX views the plasma cross section along 9 adjacent chords with 1.5 cm spacing. At this frequency refraction is manageable but requires correction when doing inversions. The interferometer has sensitivity $n_e dl = 8 \times 10^{11} \text{ cm}^{-2}$ and frequency response of up to 1 MHz. Improved time response permits measurement of high-frequency density fluctuations as well as fast changes to the equilibrium profile. First results from HSX with 2nd harmonic ECH at 28 GHz, using a 5 chord version of the interferometer, indicate that the density profile is quite peaked for both quasi-helically symmetric (QHS) plasmas and those where the quasisymmetry is broken (mirror mode) for $n_e \sim 1 \times 10^{12} \text{ cm}^{-3}$. However, for densities $n_e = 3 \times 10^{11} \text{ cm}^{-3}$, the profile for the QHS plasma (high stored energy) is narrower when compared to the mirror mode (low stored energy). Density profile variation with plasma configuration and resonant heating location using the 9 channel interferometer will be described. For high density HSX plasmas, $n_e = 3 \times 10^{12} \text{ cm}^{-3}$, coherent oscillations are observed in the line-integrated density traces which are out of phase across the magnetic axis. These $m=1$ oscillations are observed at frequencies of 1-2 kHz and result in a periodic displacement of the density profile.

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Interferometer Capabilities

- **Spatial resolution:** 9 chords, 1.5cm spacing and width.
- **Fast time response:** analog: 100-200 μsec , real time
digital: $<10 \mu\text{sec}$
maximum bandwidth 250 kHz [with 2 MHz sampling]
- **Low phase noise:** 24 mrad (1.6°)
 $(\Delta n_e dl)_{\min} = 8 \times 10^{11} \text{ cm}^{-2}$
0.4% level density fluctuations can be measured
- **Density fluctuations:** wavenumber resolution
(i) $k_{\perp} < 2.1 \text{ cm}^{-1}$, (ii) $k_{\parallel} < 0.07 \text{ cm}^{-1}$

Solid State Source

- **Solid State Source:**

- bias-tuned Gunn diode at 96 GHz with passive solid-state Tripler providing output at 288 GHz (8 mW)

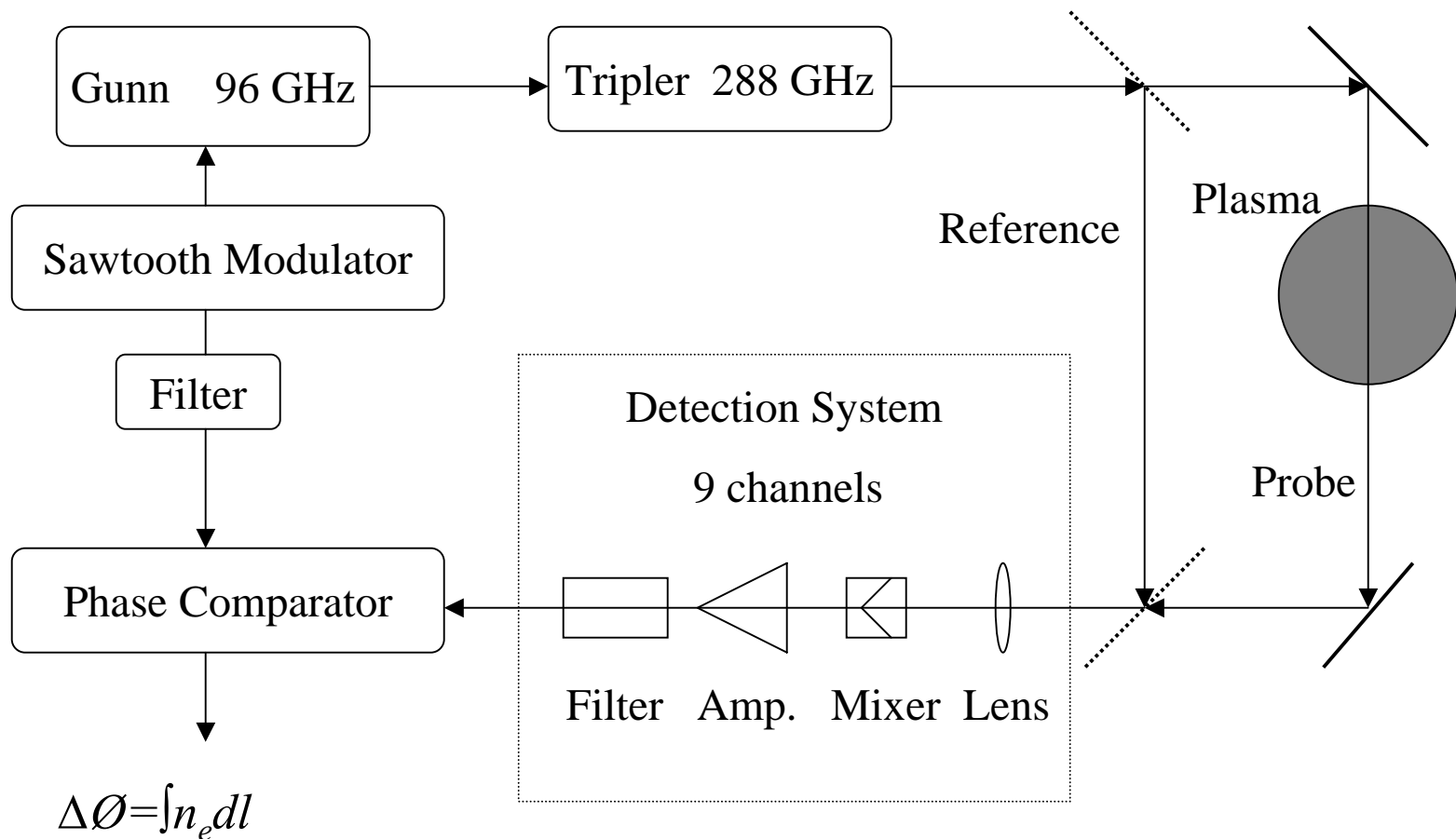
- **Support of Optical System:**

- 2.5 meter tall, 1 ton reaction mass, mounted on structure independent of HSX device. Reduces structure vibration and minimizes phase noise.

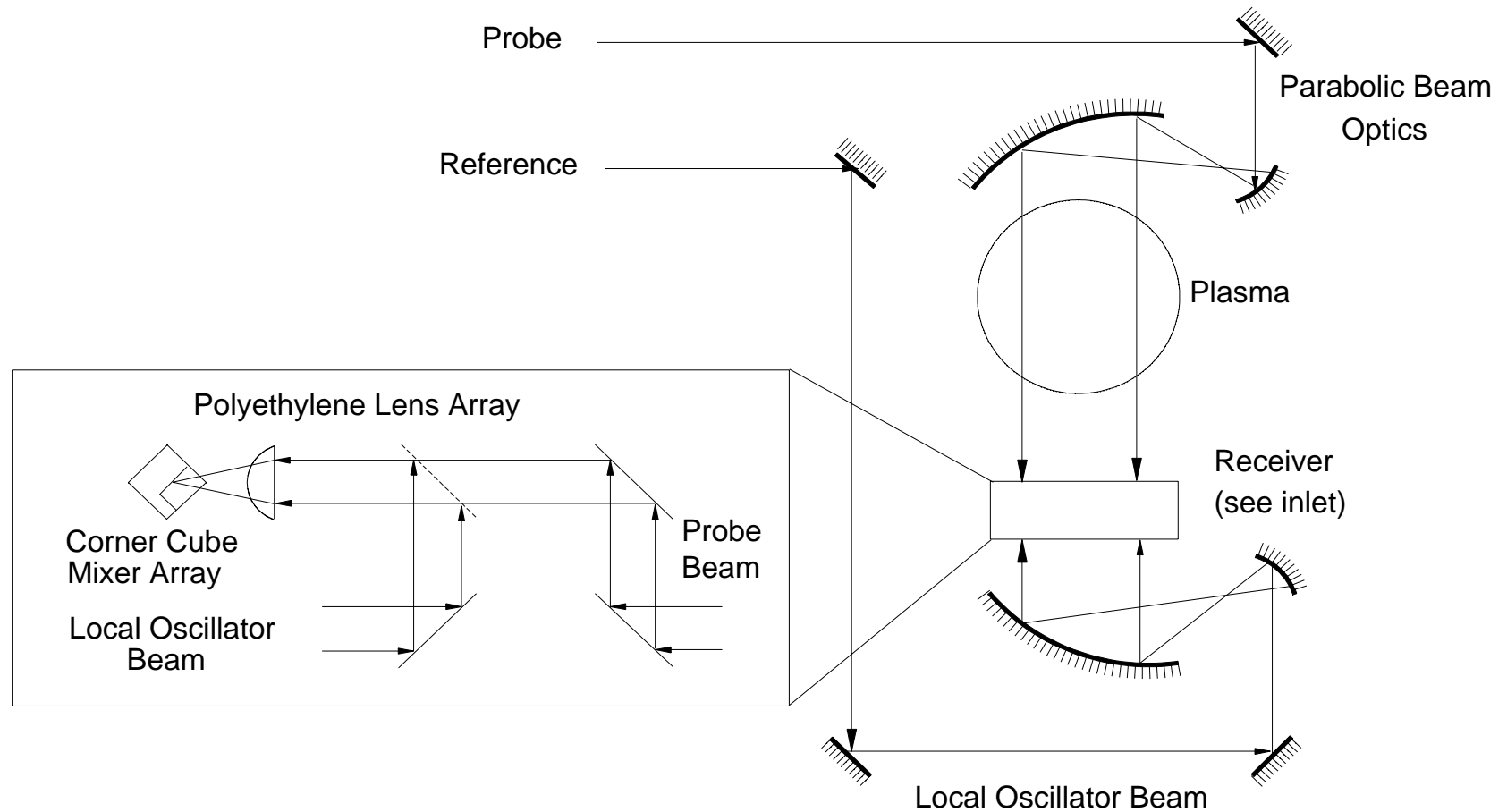
- **Dichroic Filters:**

- mounted on port windows to shield interferometer from 28 GHz gyrotron radiation plus,
- cutoff frequency: 220 GHz
- approximately 10% loss
- attenuation ranging from 92db at 28 GHz to 68 db at 150 GHz.

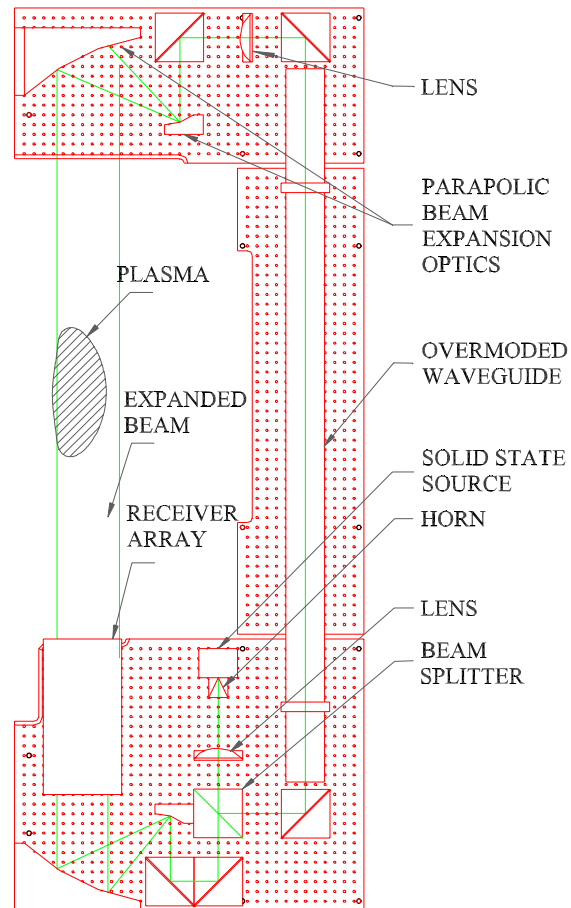
Interferometer Schematic



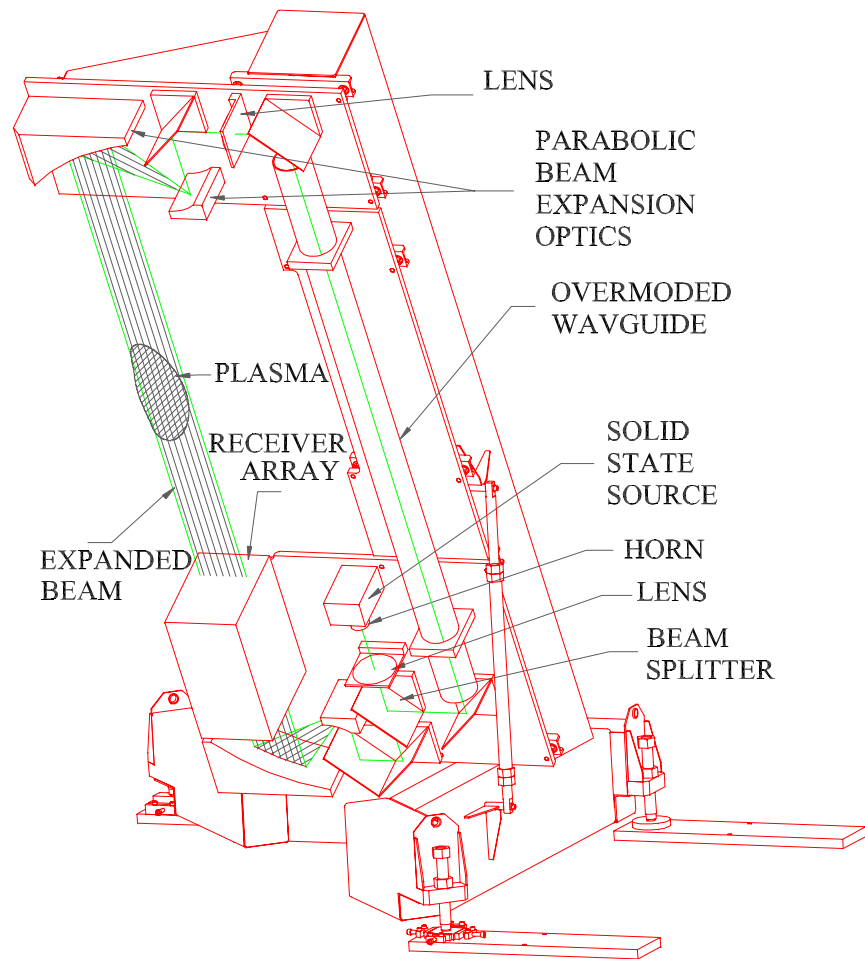
Beam Expansion Optics and Receiver Array

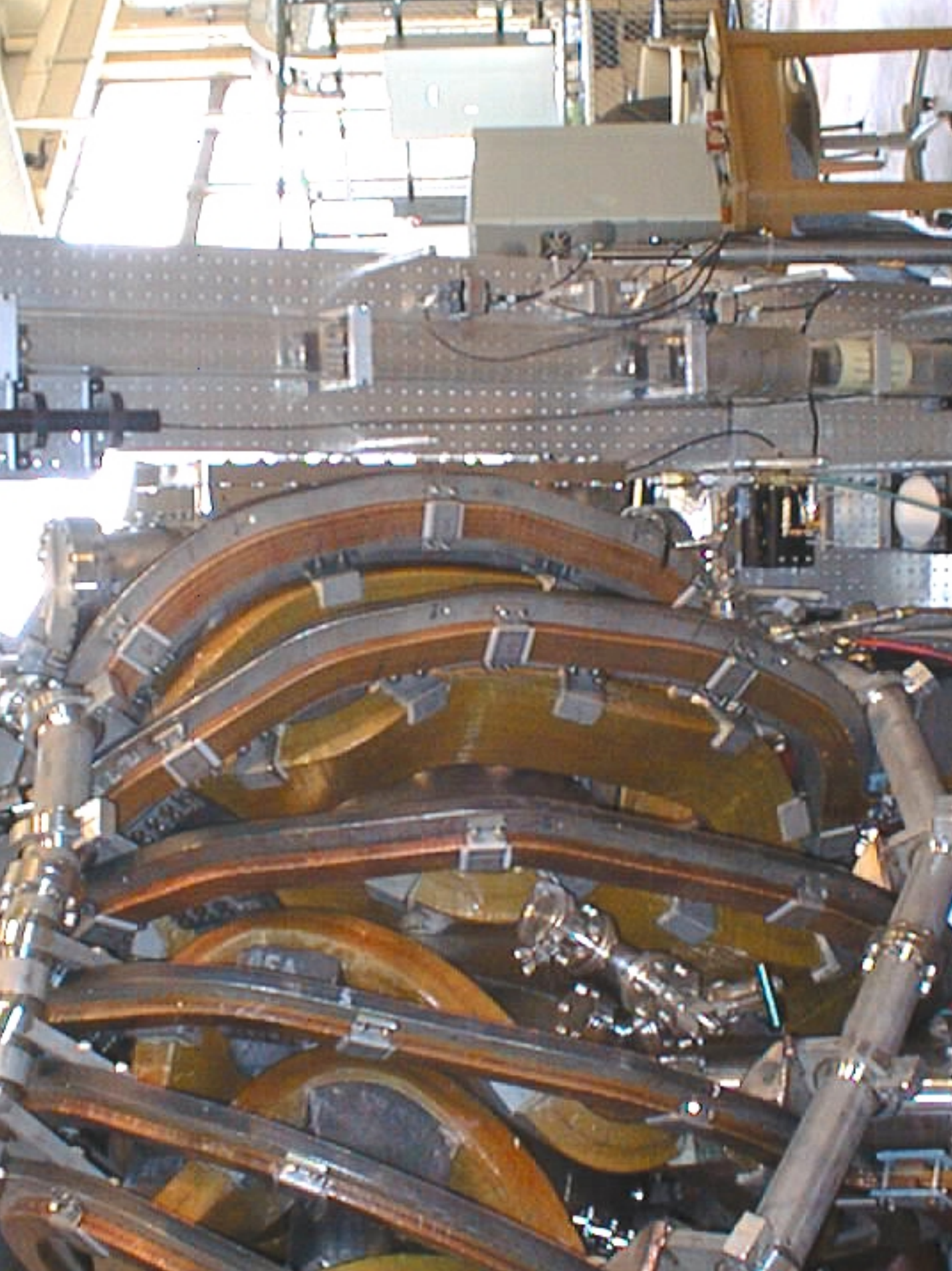


HSX Interferometer Layout

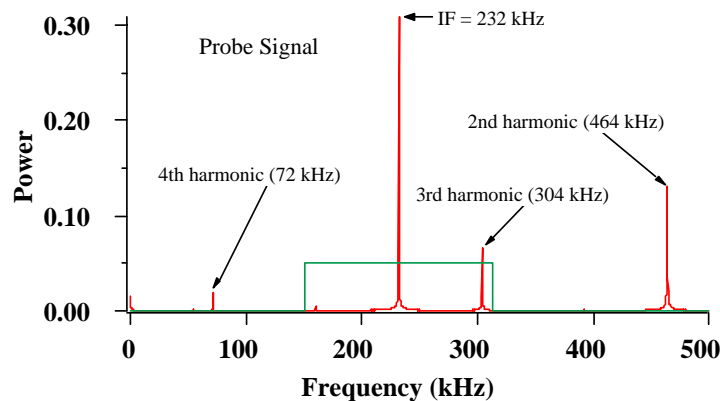
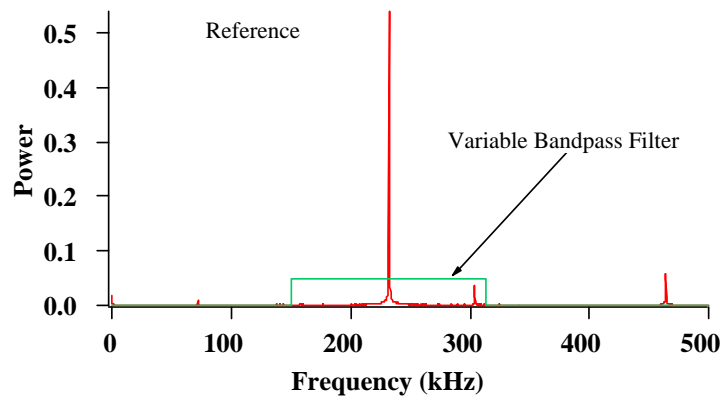


HSX Interferometer System



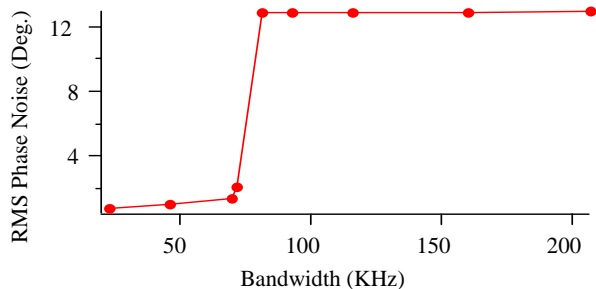
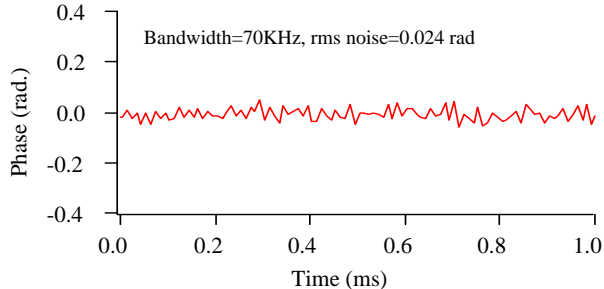
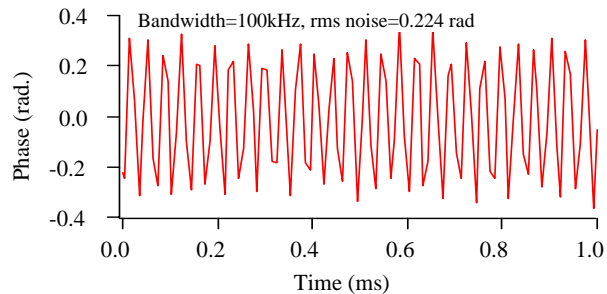


FFT Spectra Analysis



- **768 kHz IF sampled at 1 MHz, aliased to 232 kHz**
- **Sawtooth frequency modulation of source produces harmonics**
- **Unable to remove harmonic components completely with existing electronic filters ($70 \text{ kHz} < \text{passband} < 2 \text{ MHz}$ at 3 db points).**

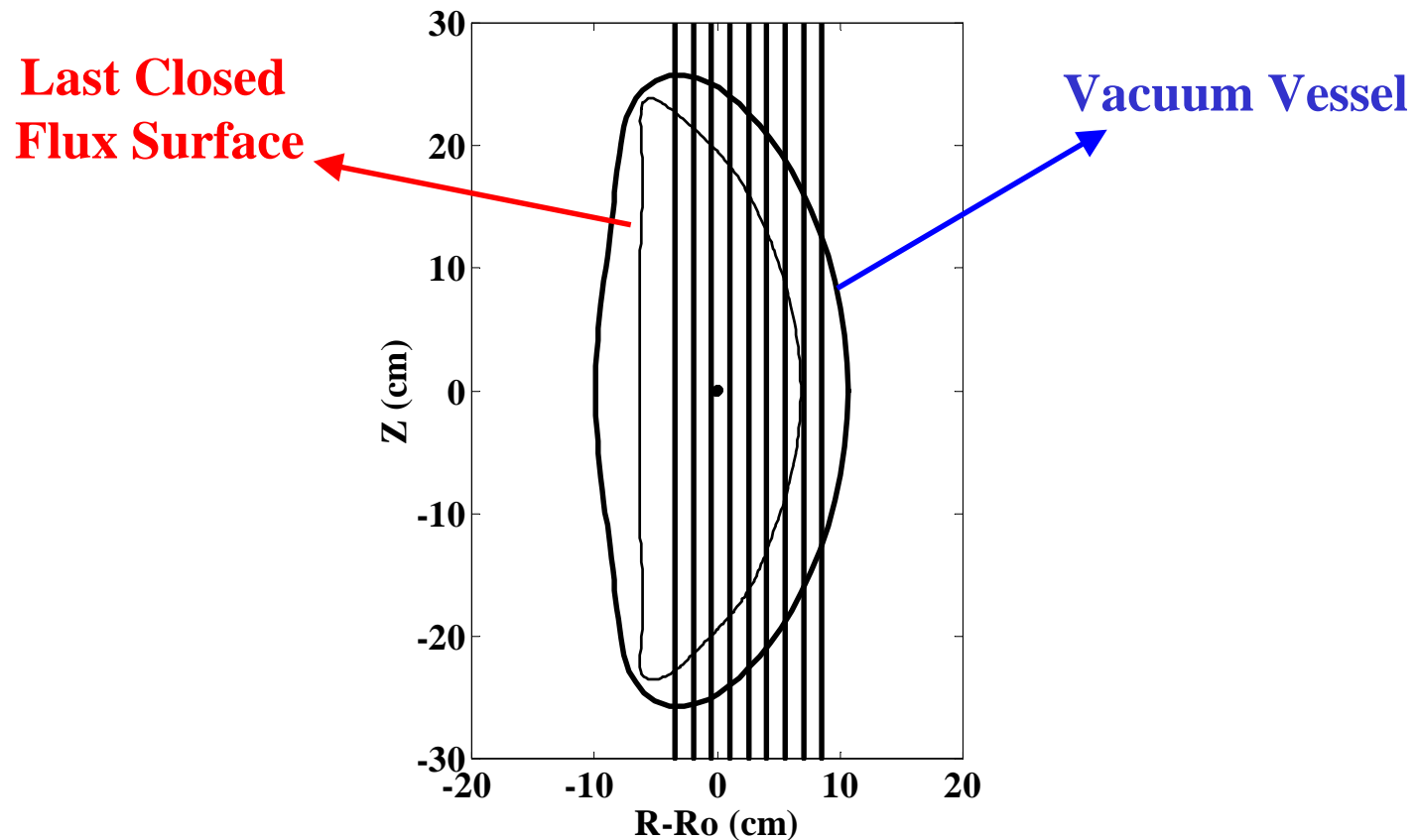
DPC Phase Noise



- Including harmonic content in bandwidth of DPC causes phase oscillation
- Excluding harmonics from DPC bandwidth reduces rms phase noise to 24 mrad (same as analog PC with <10 kHz bw)
- 100 kHz max. bandwidth with 1 MHz sampling
- 250 kHz max. bandwidth with 2 MHz sampling

Chord Lengths

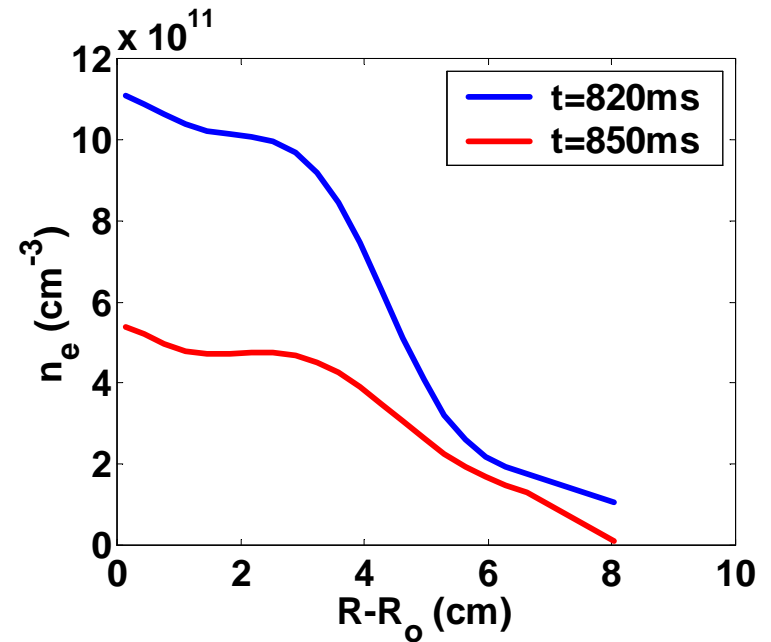
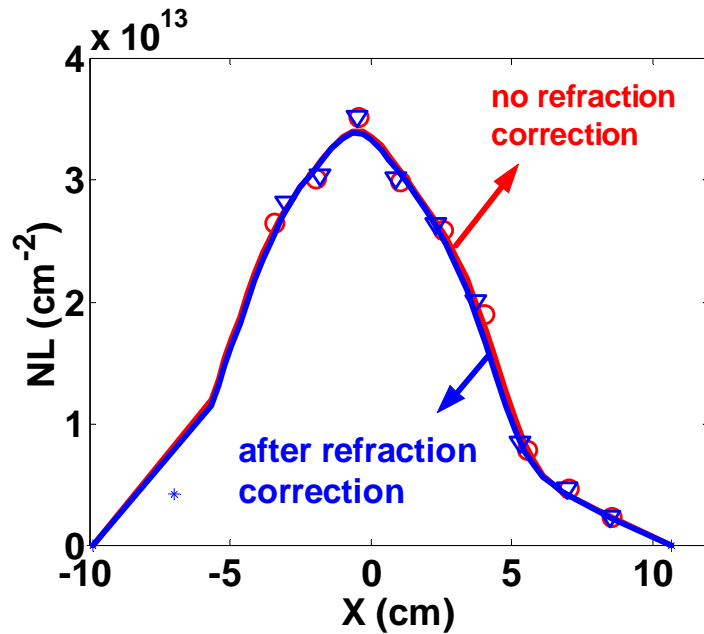
Magnetic Flux Surfaces and Chord Positions



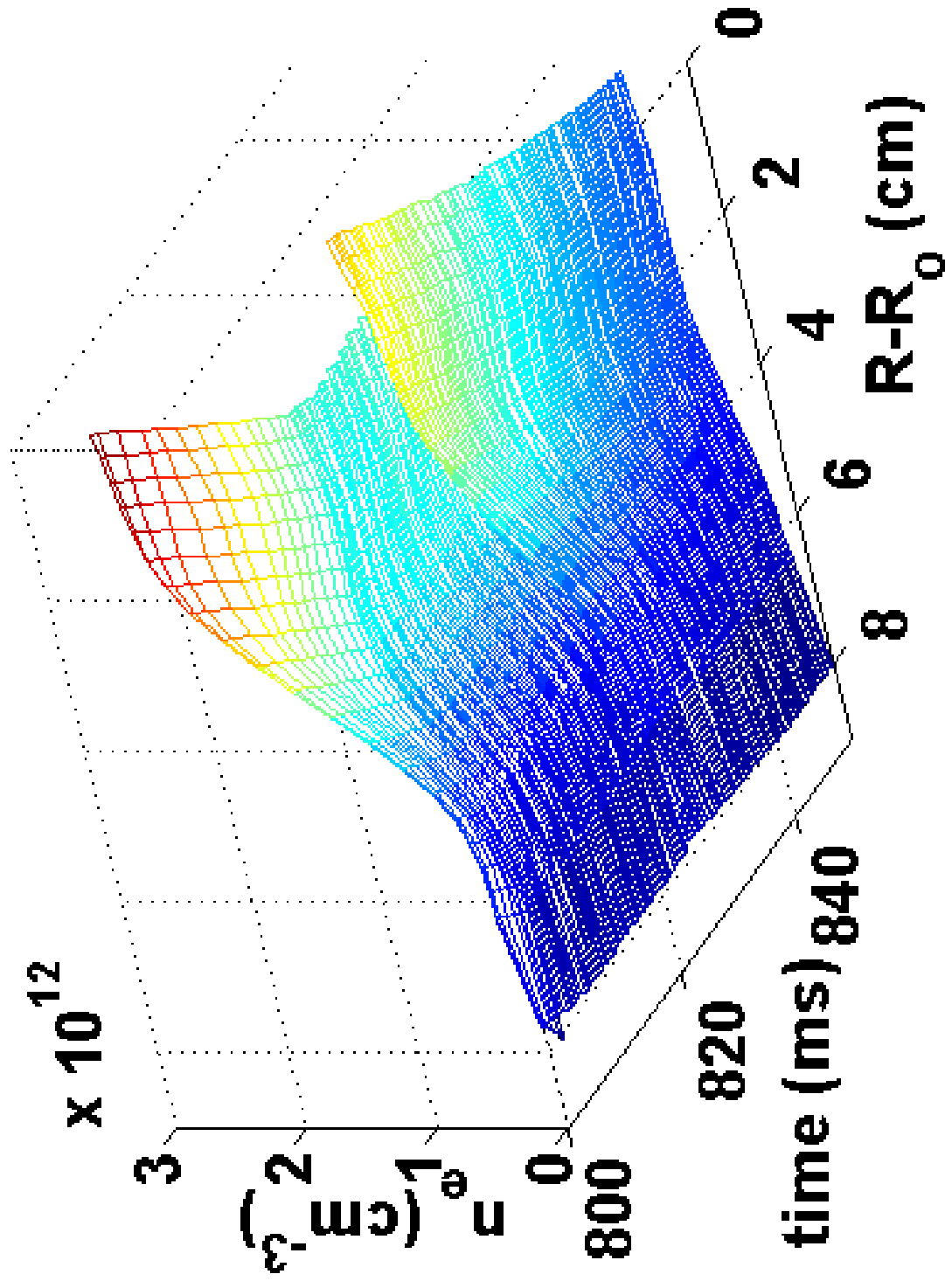
Density Profile Inversion

- **Method:** H. K. Park technique; asymmetric Abel inversion
 - flexible boundary conditions
 - non-circular geometry
 - plasma scrape-off-layer SOL estimate
- **Model:** spline fit to 9 channel line-density profile
 - no Shafranov Shift
- **Path lengths:** calculated for ten vacuum flux surfaces,
- **SOL plasma contribution:** One viewing chord is outside the separatrix. This will provide information on the SOL contributions to other chords.
- **Refraction correction:** necessary for chord length and position

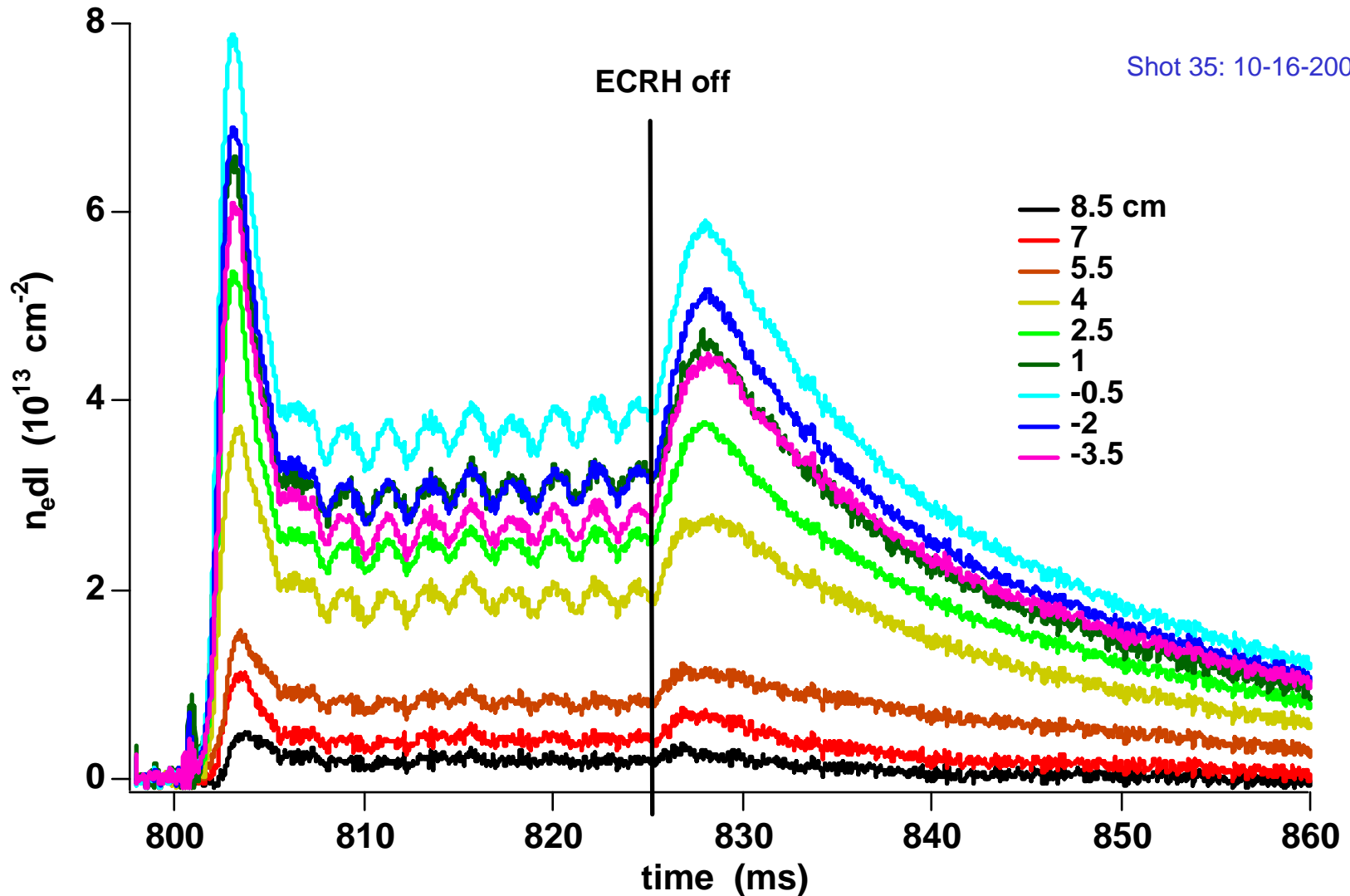
HSX Density Profile



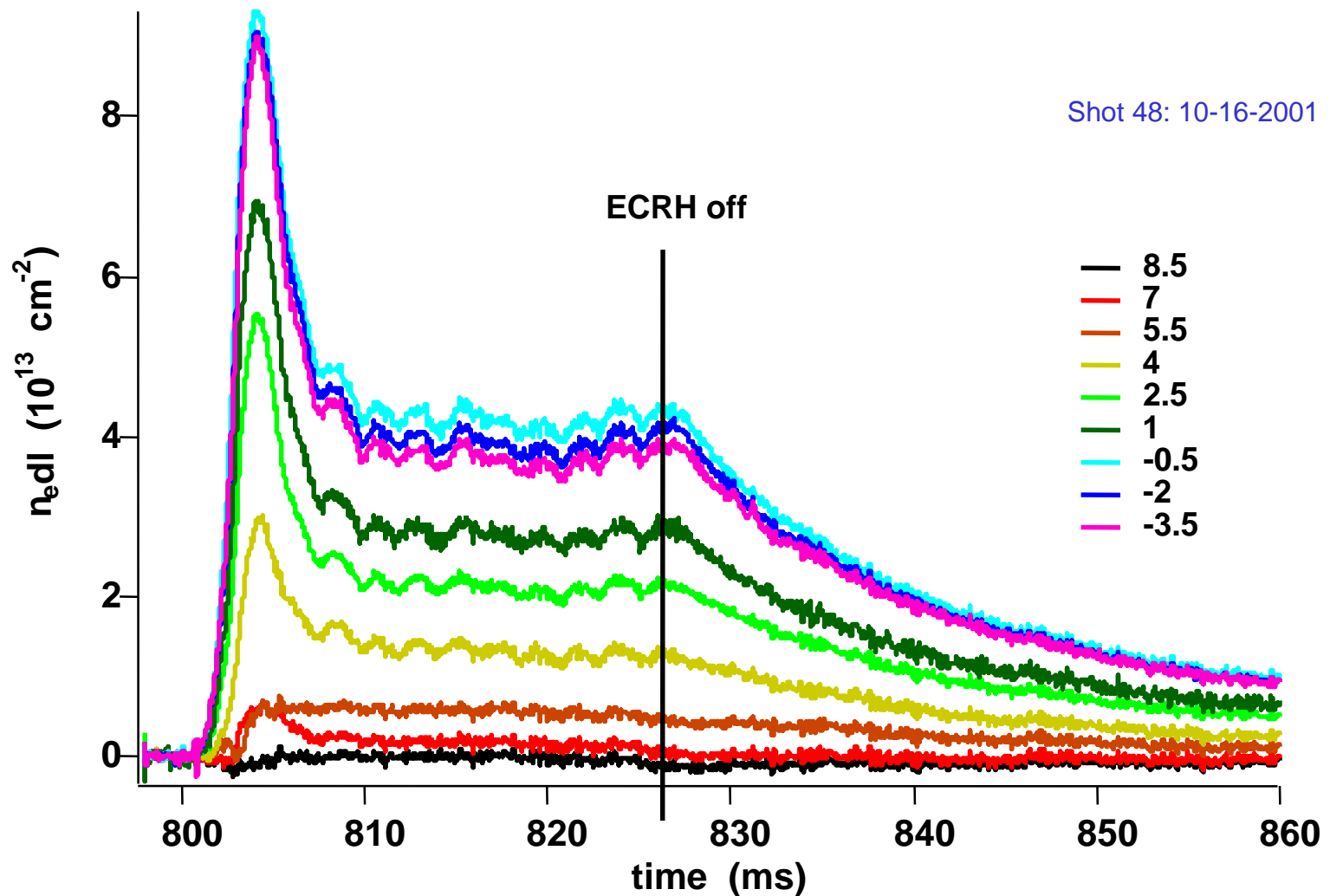
Density Profile Time Evolution



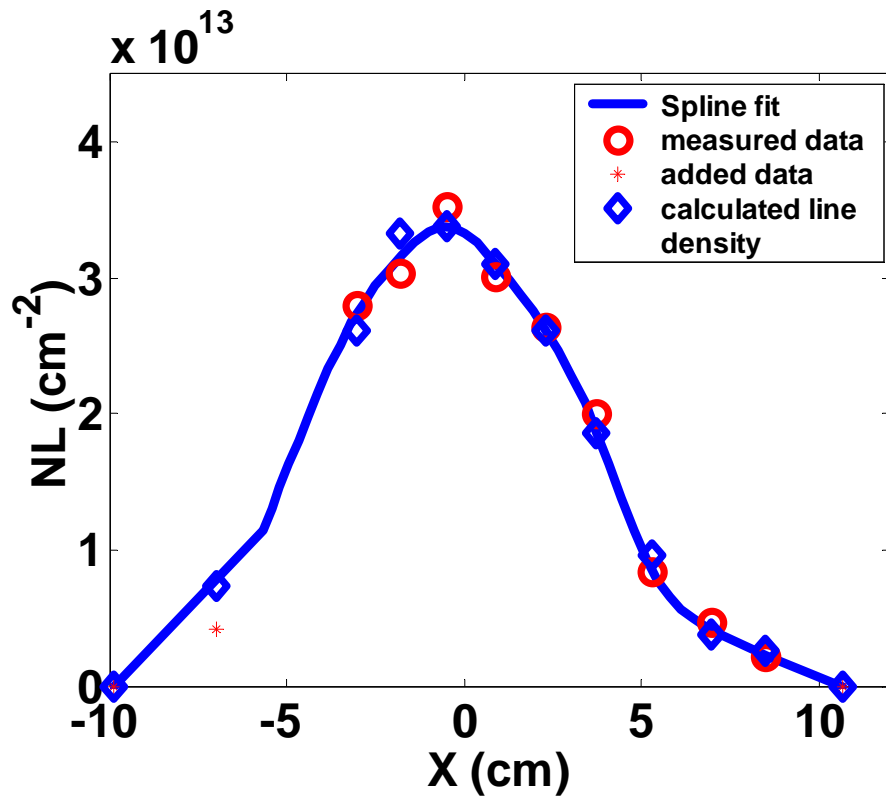
Line-Integrated Data for QHS Plasma



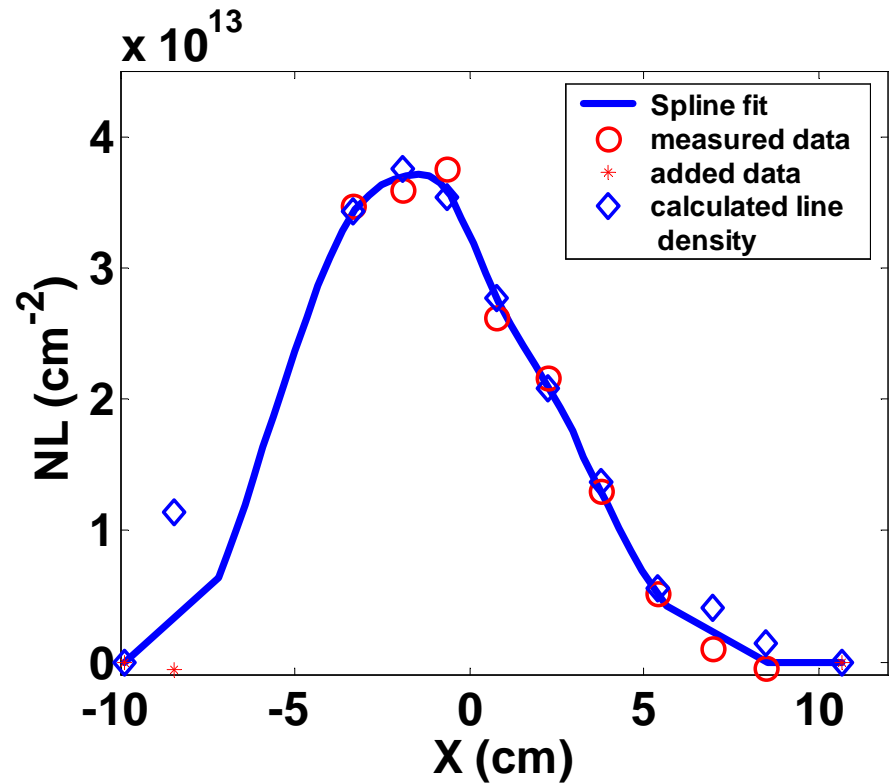
Line-Integrated Data for Mirror Mode



QHS and Mirror Mode Comparison

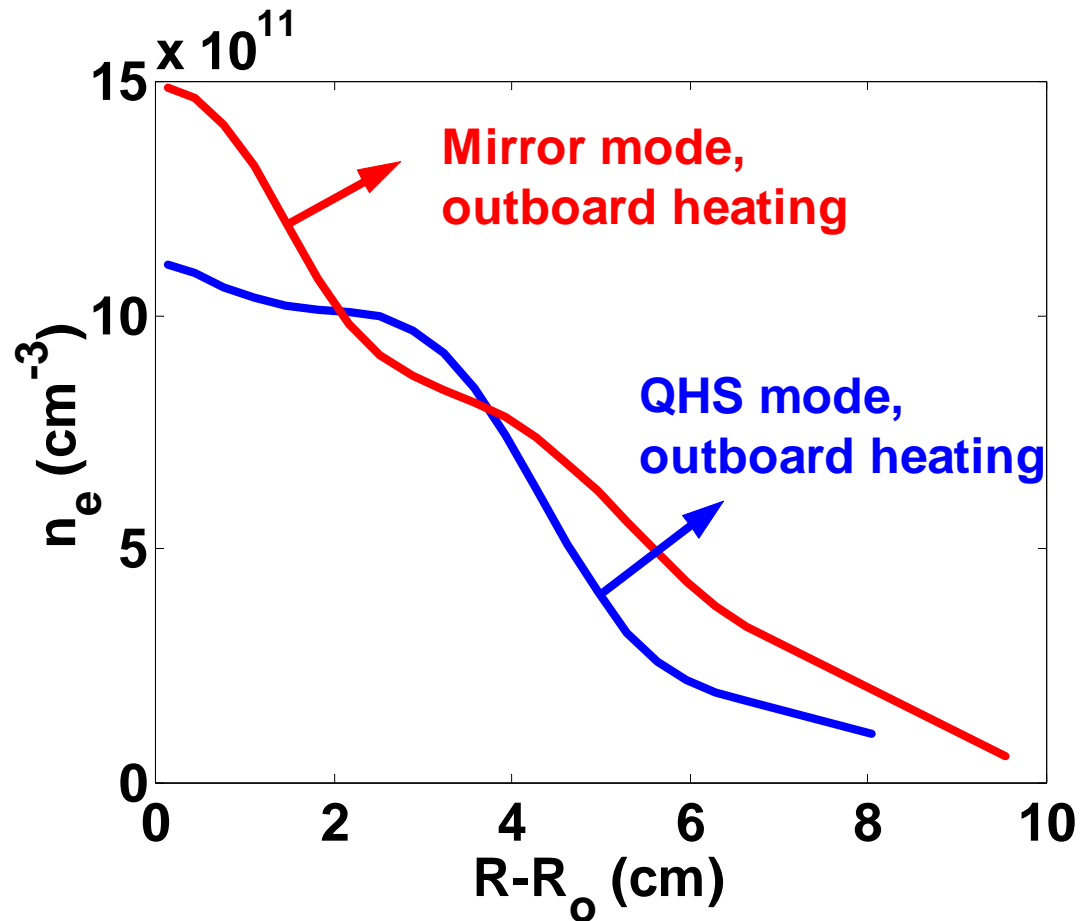


QHS

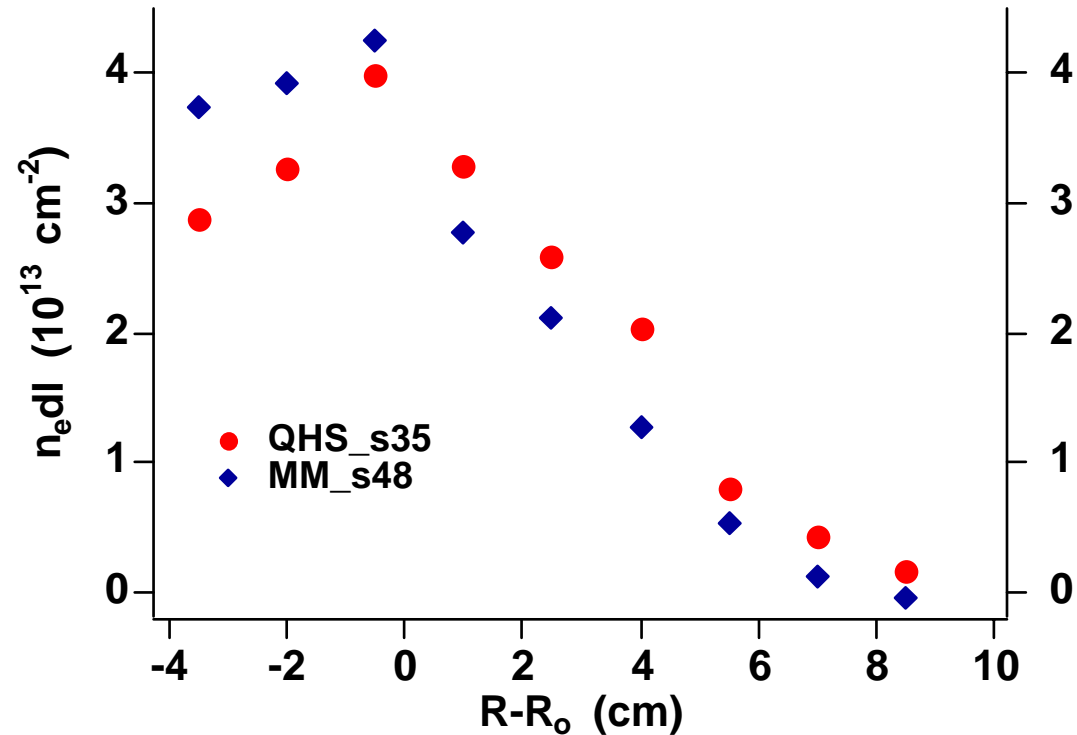


Mirror Mode

Inverted Density Profiles

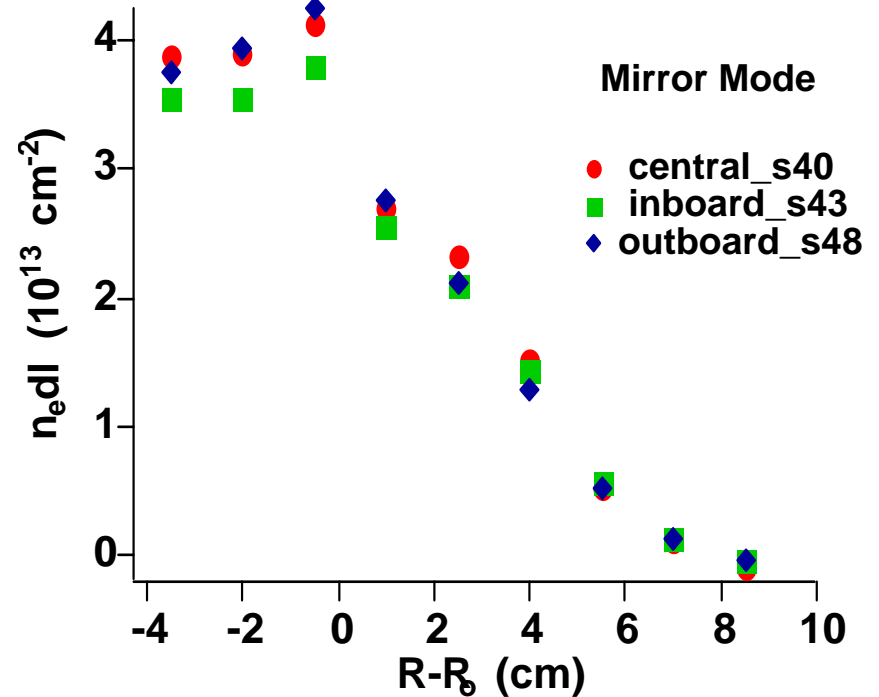
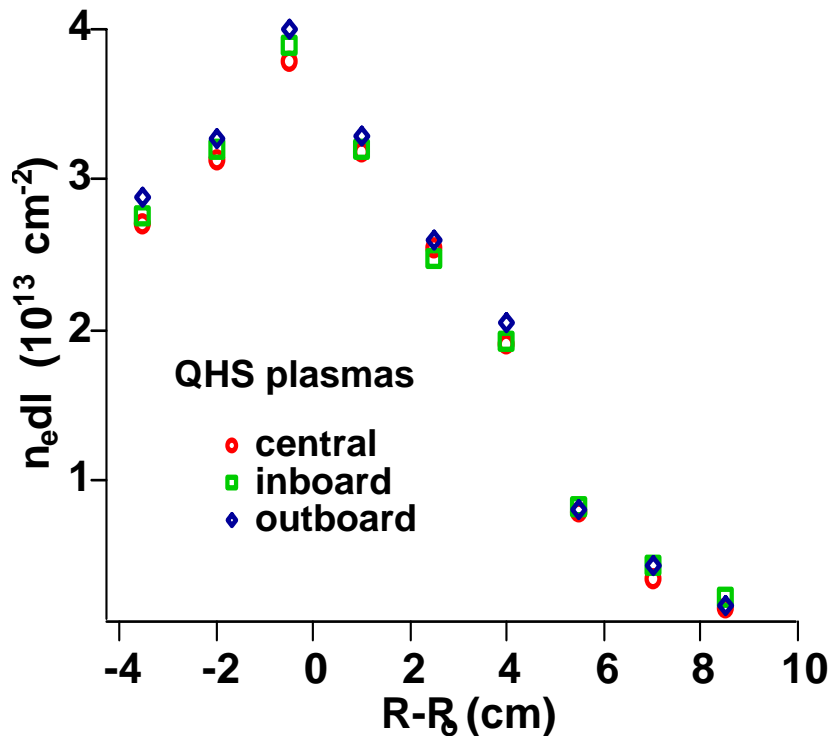


QHS and Mirror Mode Density Profiles



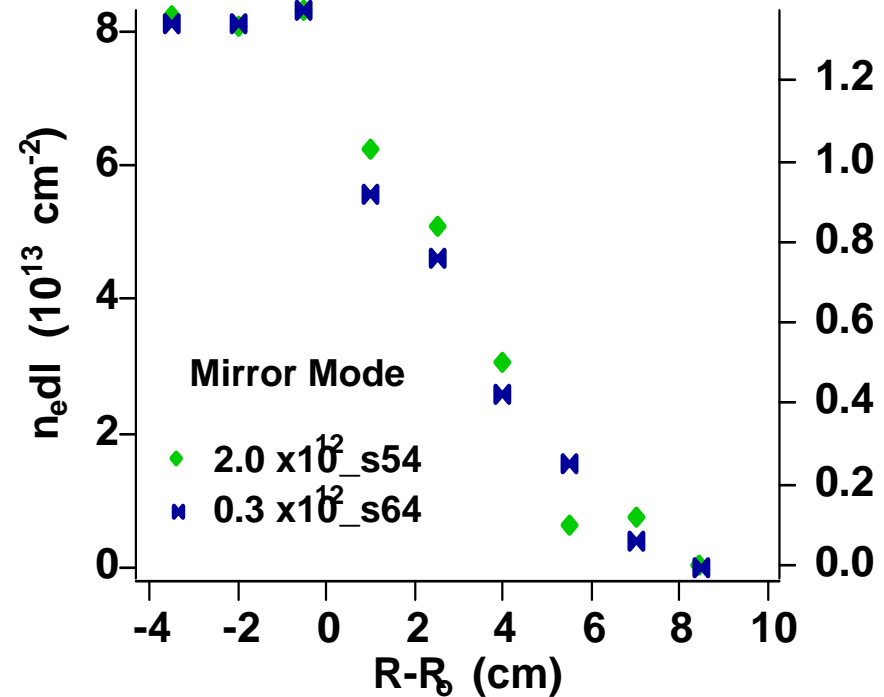
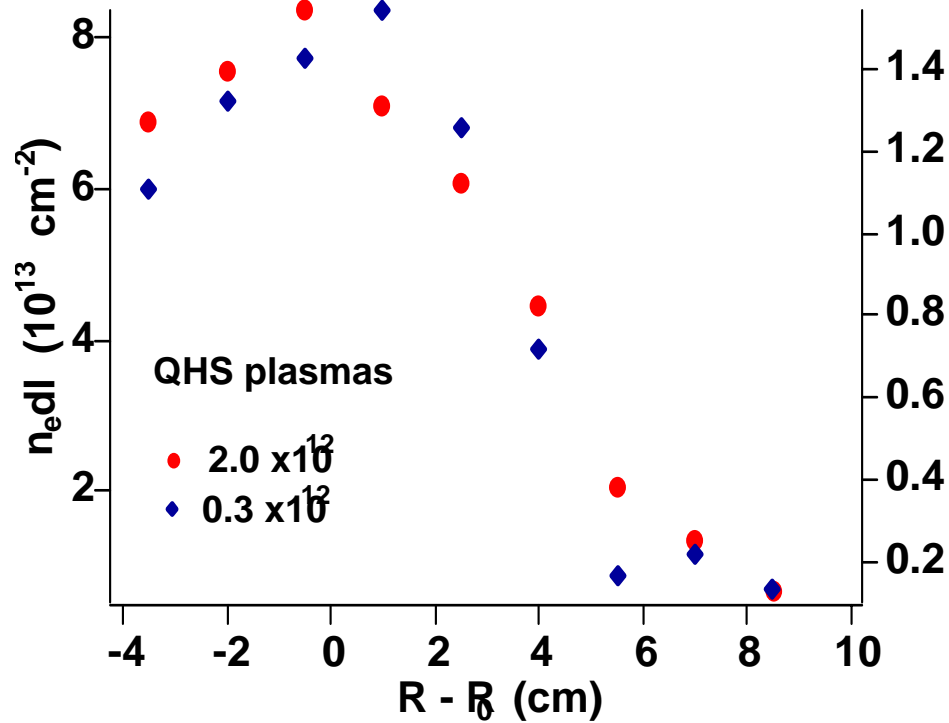
→ mirror mode plasmas have inboard higher density

Profile Changes with ECRH Location



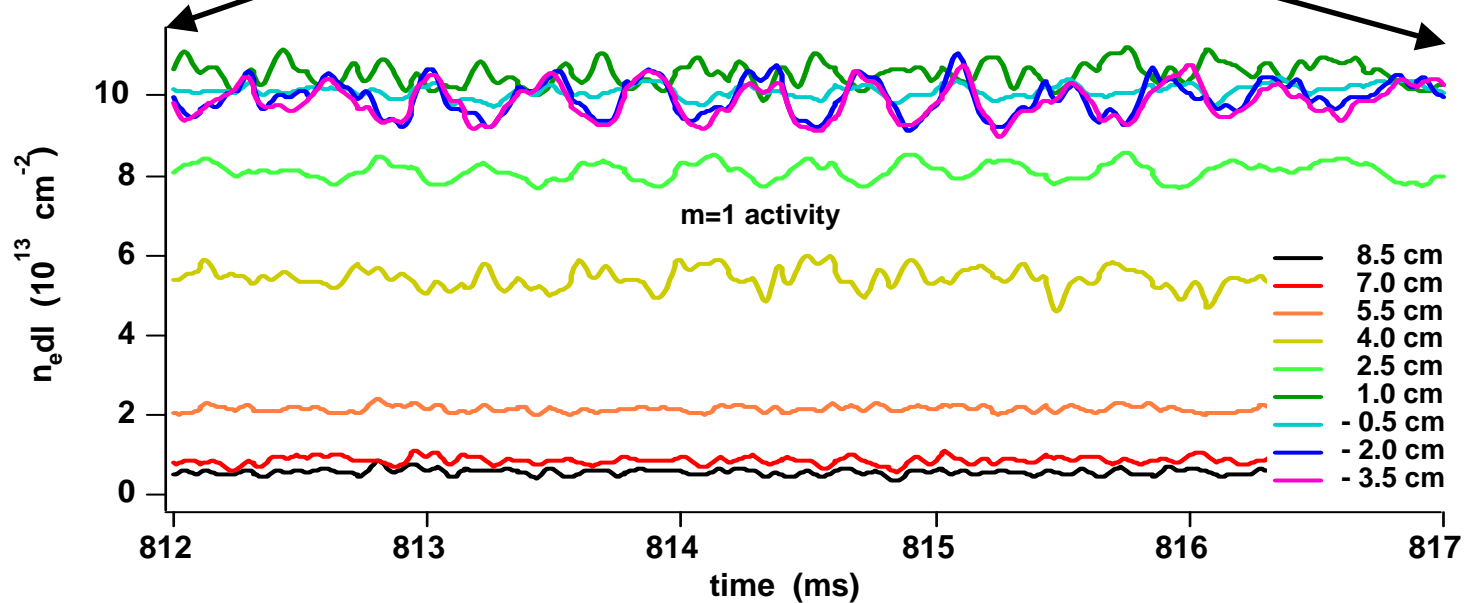
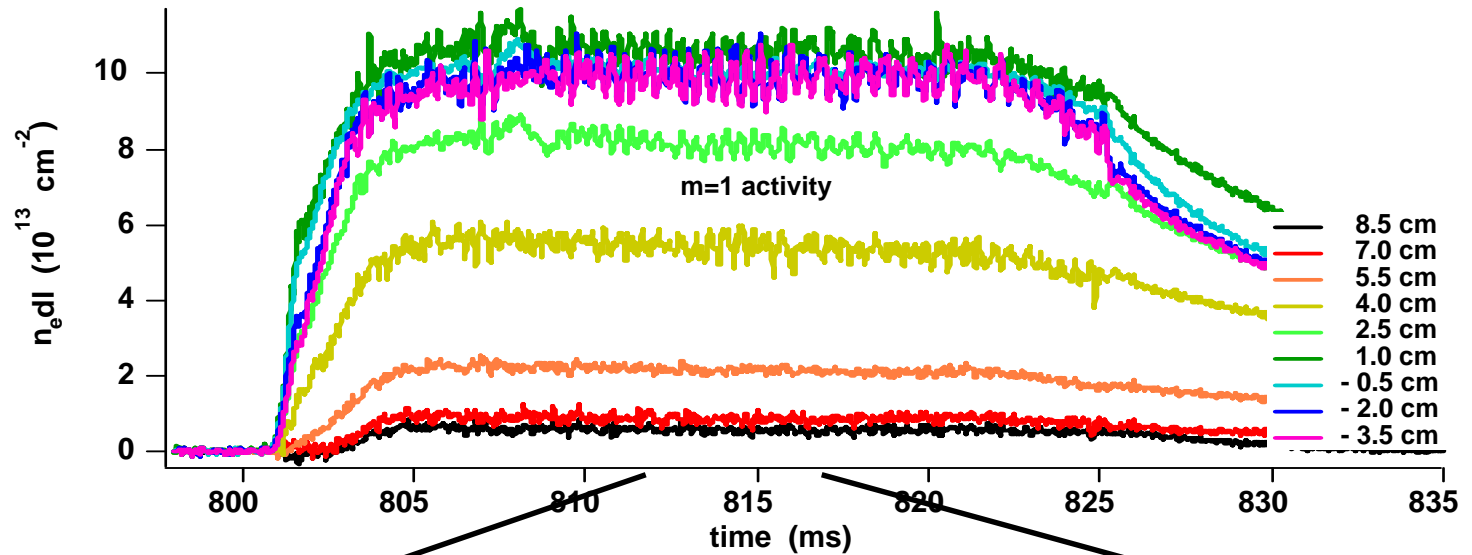
→ profile shape does not vary with heating location

Profile Changes with Density

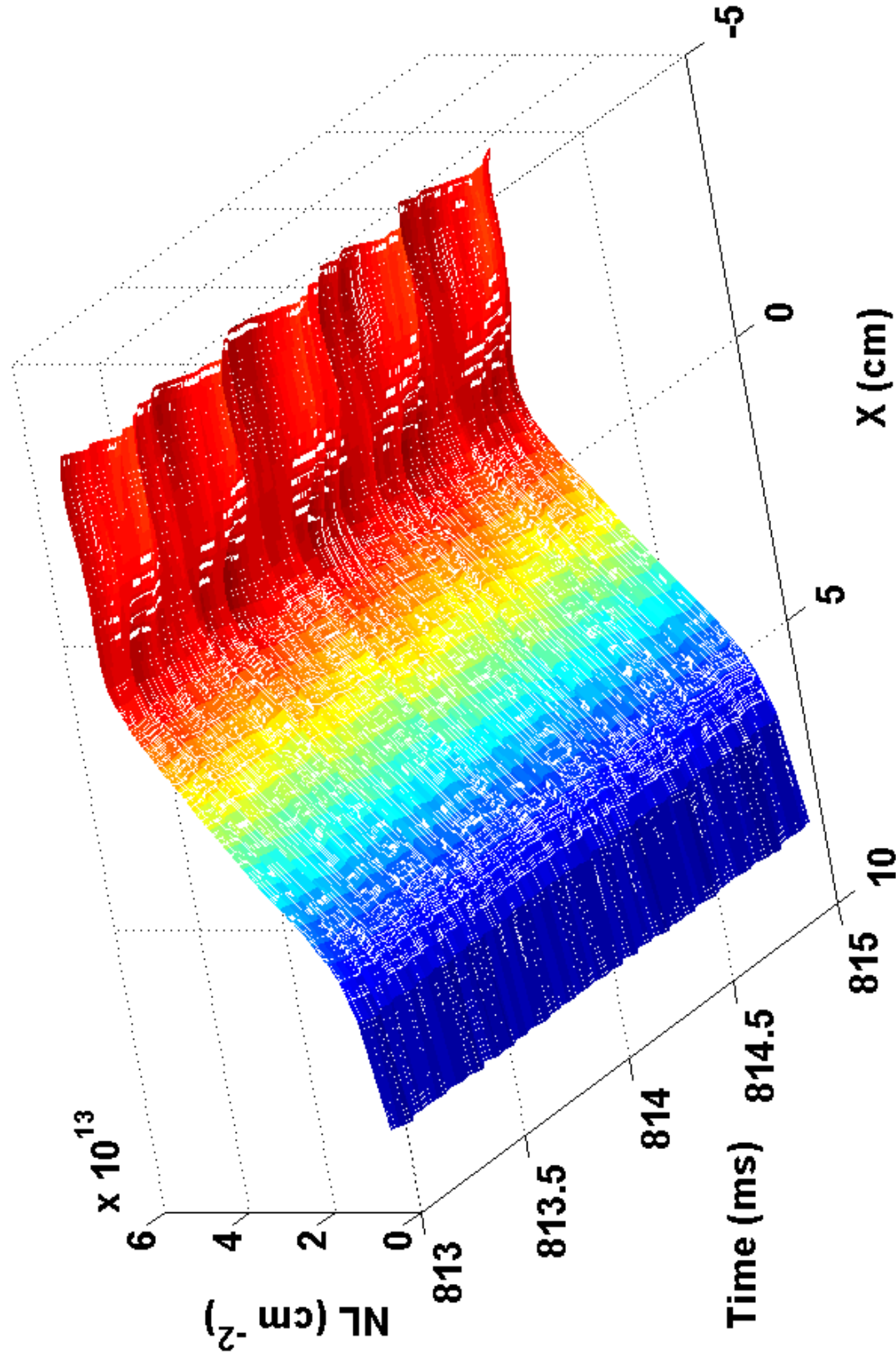


→ profile shape varies little with density

m=1 Density Fluctuations

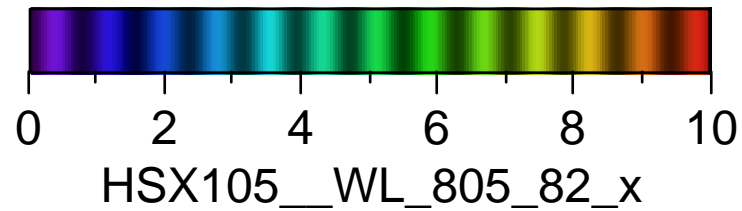
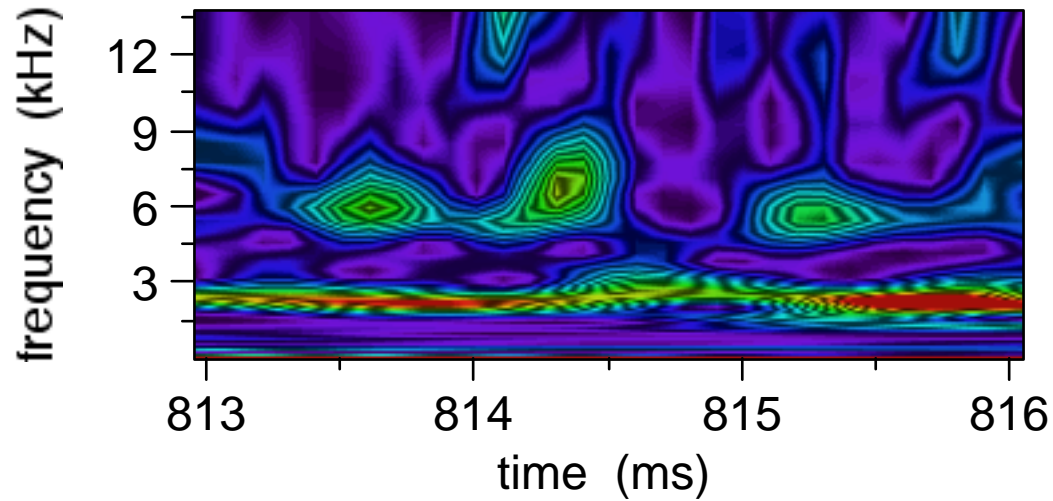


m=1 Density Fluctuations

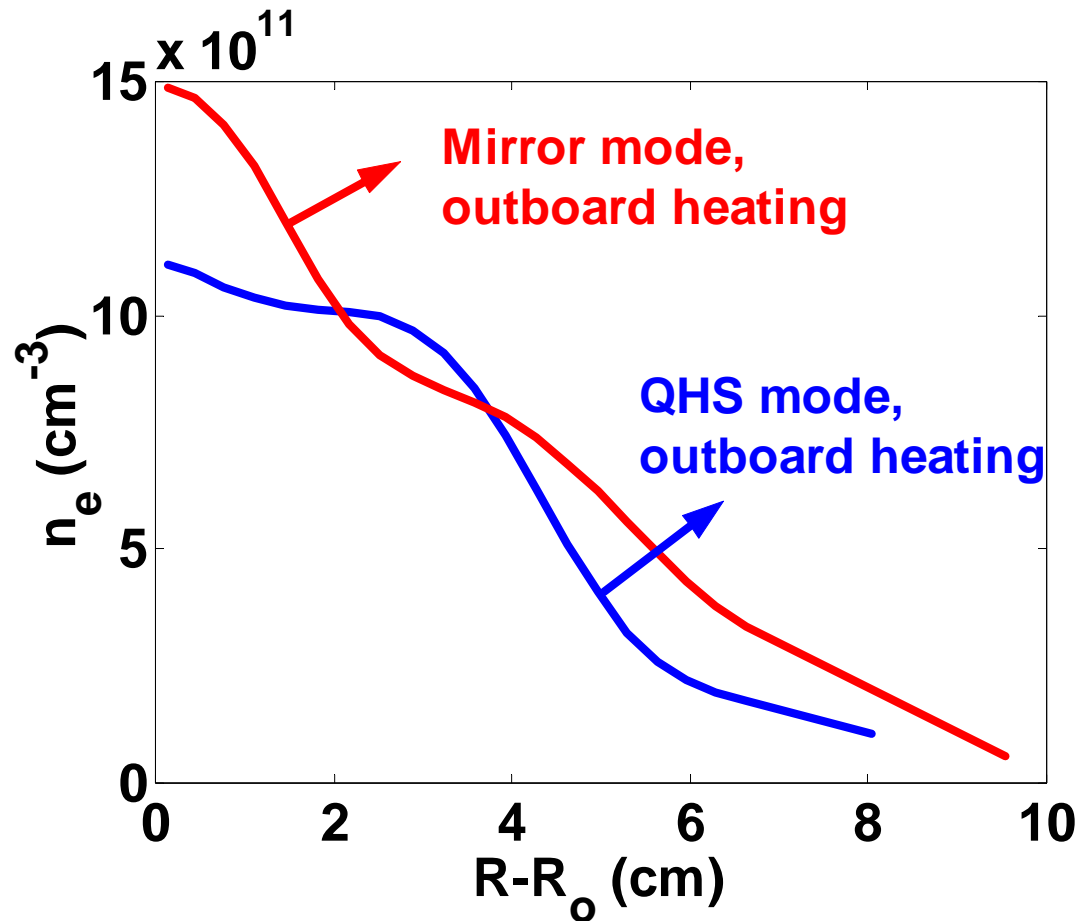


Frequency Spectra

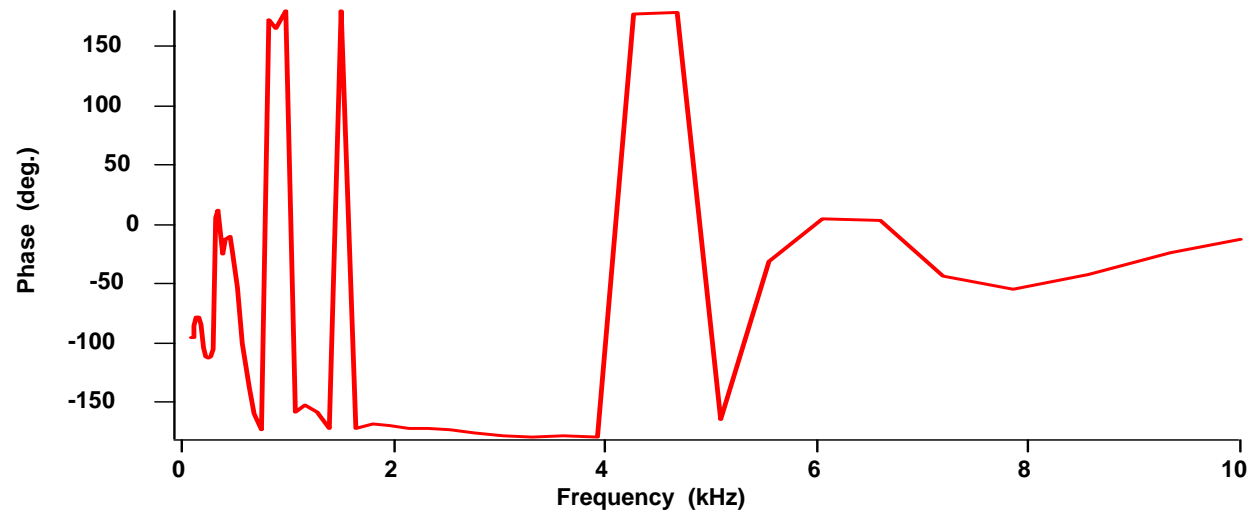
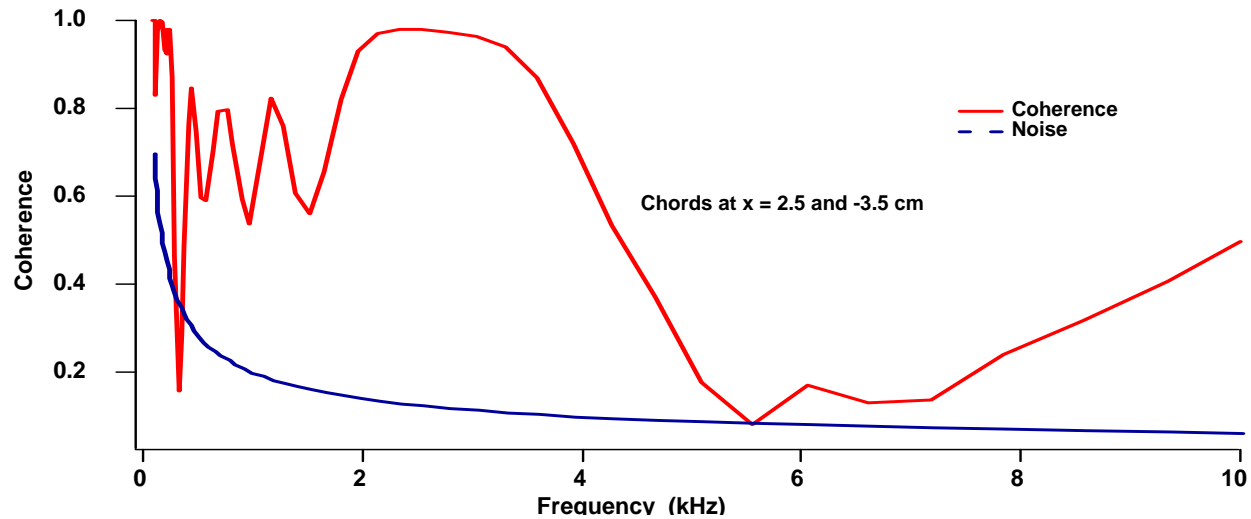
Chord at $x = 1$ cm



Inverted Density Profiles

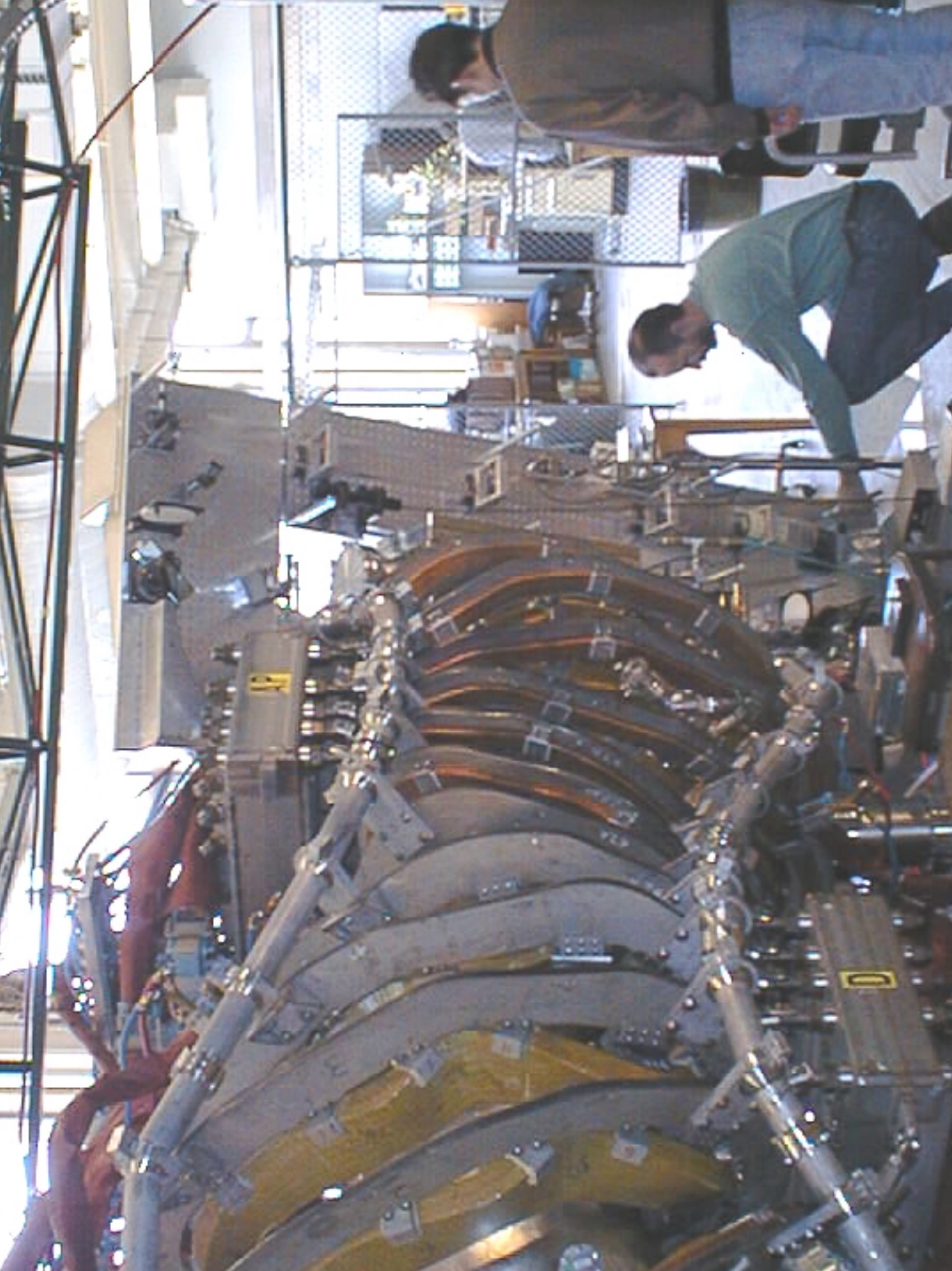


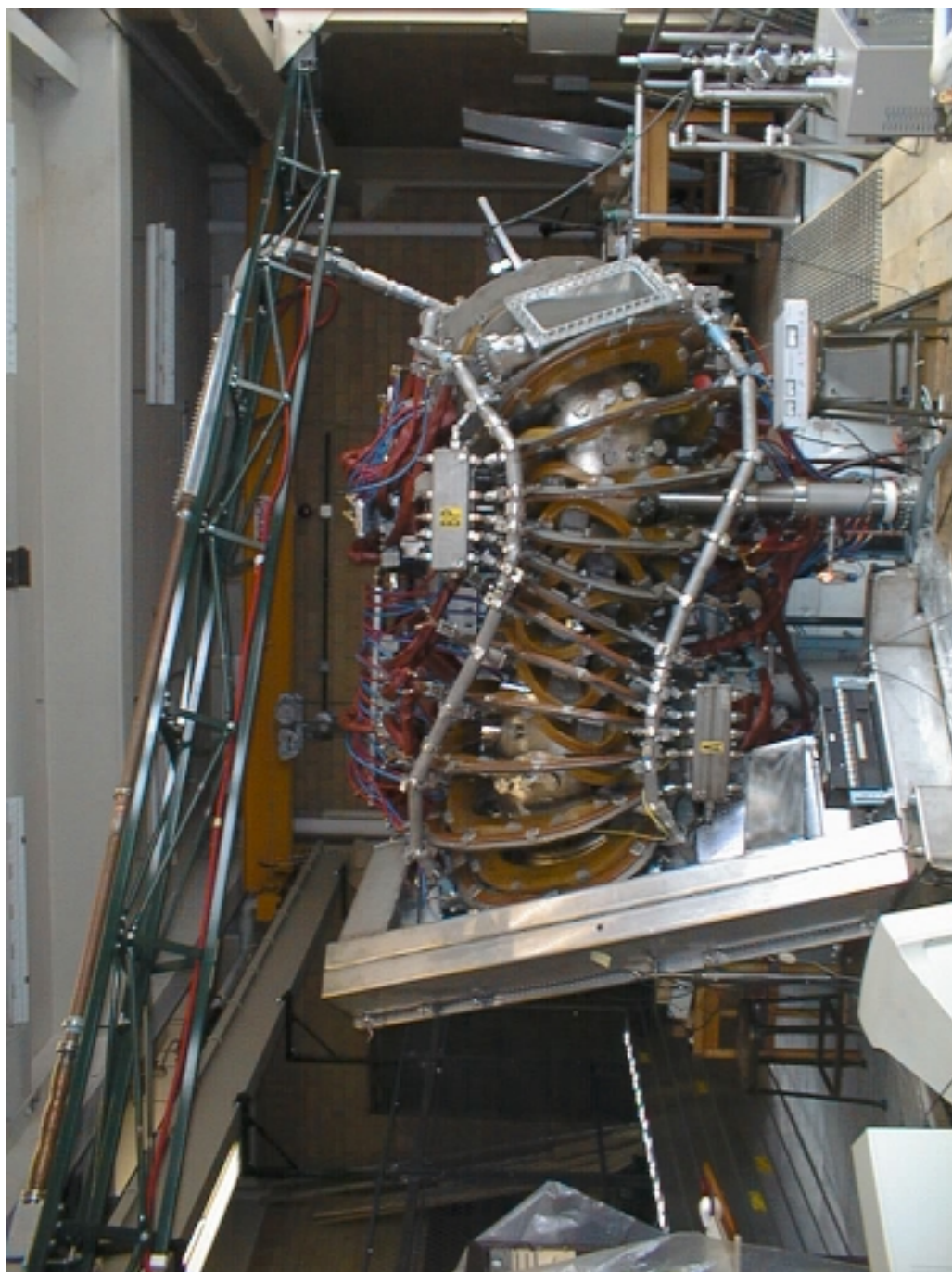
Coherence and Phase



Summary

- Multichannel 288 GHz interferometer system has been installed and is now operating on the HSX stellarator
- Refraction correction to line-integrated data is required
- Initial inversions show a peaked density profile, inversion development still in progress
- Differences between QHS and Mirror Mode plasmas are being evaluated
- Little profile variation found with changing density or ECRH location
- For high density plasmas, large-amplitude $m=1$ oscillations (3 kHz) are often observed





HSX Stellarator

- **Helically Symmetric EXperiment, HSX**
quasi-helically symmetric [QHS] stellarator
major radius: $R=1.2$ m,
average minor radius: $\langle a \rangle = 15$ cm,
 $B_T = 0.5 - 1$ T, $T_e = 1$ keV, and $n_e < 1 \times 10^{13}$ cm⁻³
Heating and breakdown: 28 GHz ECRH, 200 kW
- **Unique toroidal magnetic configuration:** no toroidal curvature and a helical axis of symmetry.
Physics goals:
 - Greatly reduced neoclassical transport with respect to other stellarators and comparable tokamaks.
 - Reduced anomalous transport by low parallel viscous damping in the direction of symmetry.

Data Acquisition System

- **Analog phase comparator:** PCI-MIO-16E-1, 12 bits resolution, maximum sampling rate 75 kHz for 9 channels
- **Digital phase comparator:** PCI-6110 E, 12 bits resolution, max sampling rate 5 MHz for 10 channels
- **Control and manage:** PC and LabVIEW.

Comparison of **Analog** and **Digital** Phase Comparator Output

