Reflectometry Measurements of Electron Density Profiles and Fluctuations in NSTX

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Abstract

UCLA operates a suite of millimeter-wave/microwave reflectometers on NSTX for routine measurements of the electron density profile and fluctuations. These homodyne reflectometers have a combined frequency coverage of 12 to 50 GHz (in the bands 12-18, 20-32 and 33-50 GHz) or corresponding O-mode cutoff range of 1.8×10^{12} to 3.1×10^{13} cm^{-3}. Profile measurements are made by configuring the reflectometers for FMCW (frequency-modulated continuous-wave) operation; sweep times of up to 100 us are possible over the entire frequency range. Fluctuation measurements are made by fixing or stepping the launch frequency. The reflectometers have been successful in documenting fast changes in the profile and turbulence characteristics during L- to H-mode transitions, and detecting fluctuations due to compressional Alfven eigenmodes during neutral beam injection. A new addition to the above hardware is a correlation reflectometer in the 20-30 GHz range for radial turbulence correlation length measurements. Recent data from all of the above systems are presented.

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Features of Reflectometry on NSTX

- Minimal access requirements. Requires little modification to existing hardware designs for implementation on ST.
- Non-perturbing measurement capability.
- Can perform multiple tasks.

1) Sensitive, local measurements with high bandwidth and excellent temporal coverage.
2) Density profiles, turbulent correlation length, fluctuation level, magnetic field strength, rf waves, Alfven modes, etc.

- Spatial coverage limited.

1) Peaked profiles will restrict measurements to outer half of plasma.
2) Flat H-mode profiles will further restrict measurement capabilities to edge plasma.
3) Can provide crucial connection between core and scrape-off measurements.
4) Excellent for studying H-mode transitions, ELMs, and other edge phenomena.

Reflectometer Diagnostic Capabilities on NSTX

Current Capabilities

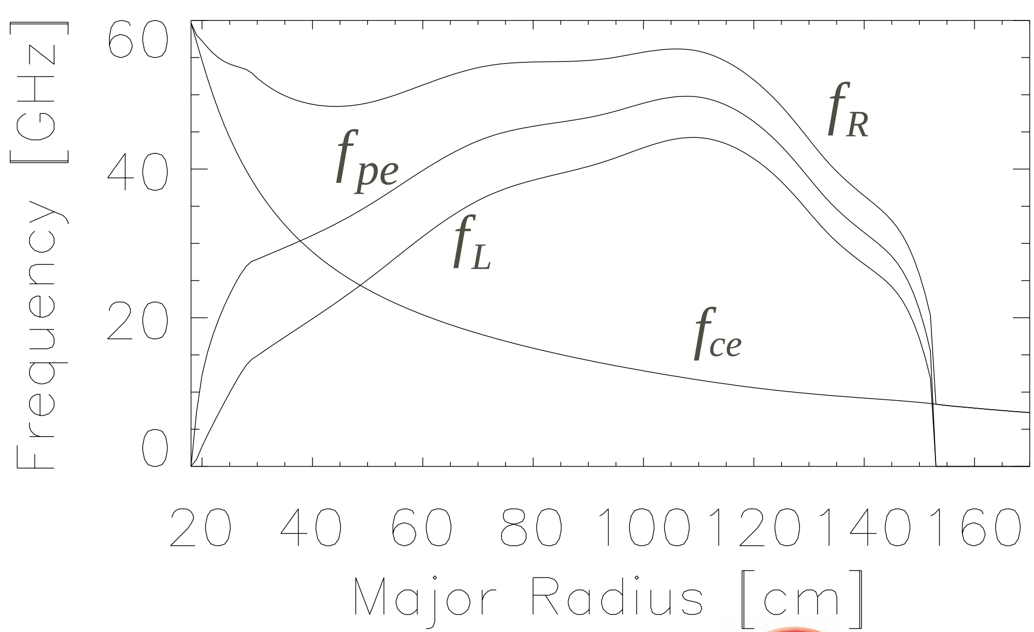
12-50 GHz FMCW reflectometer is operational.

- Edge to core electron density profiles (1.8×10^{12} to 3.1×10^{13} cm^{-3} range for O-mode).
- Fixed- and stepped-frequency fluctuation measurements. Absolute density fluctuation levels in SOL. Homodyne signal for measurements in edge and core.

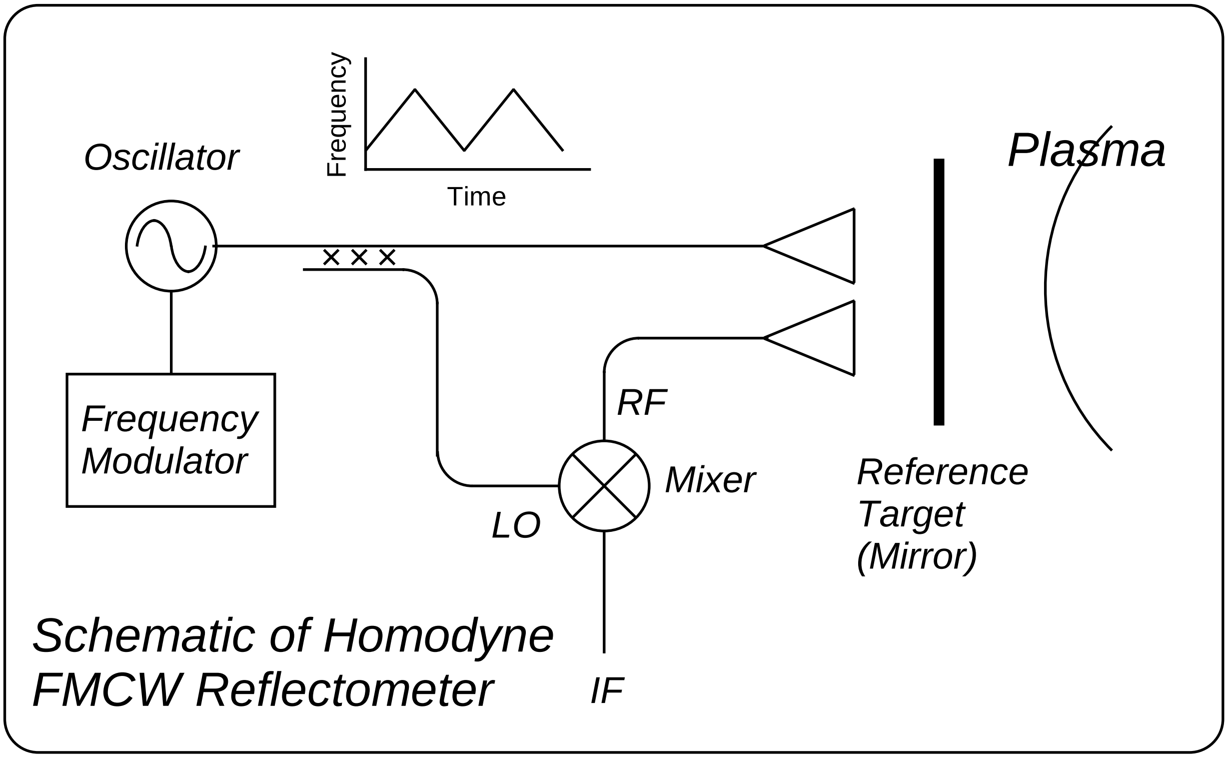
Preliminary Measurements During Summer 2001

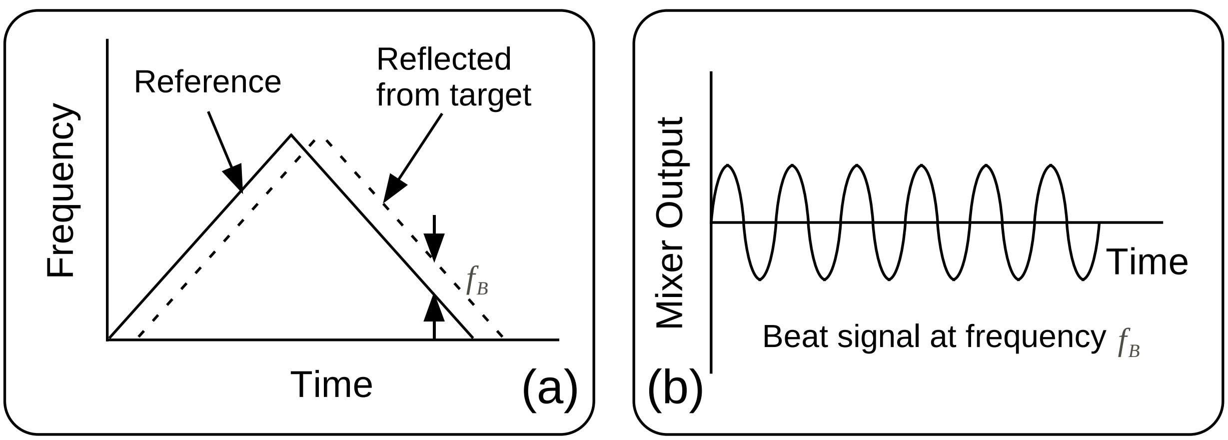
20-30 GHz dual-mode (O-X) correlation system operated.

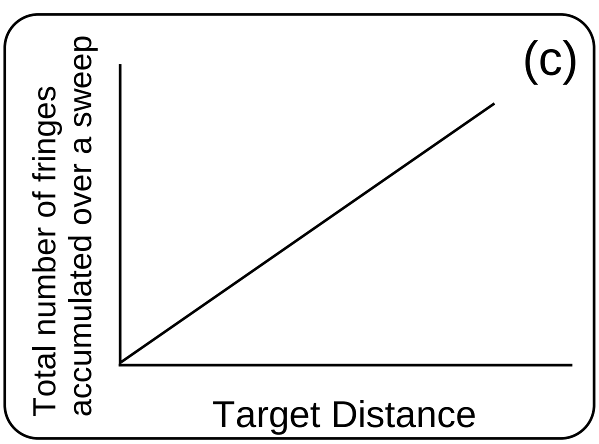
- Internal magnetic field strength measurement.
- Turbulent radial correlation lengths.



Principle of FMCW Reflectometry





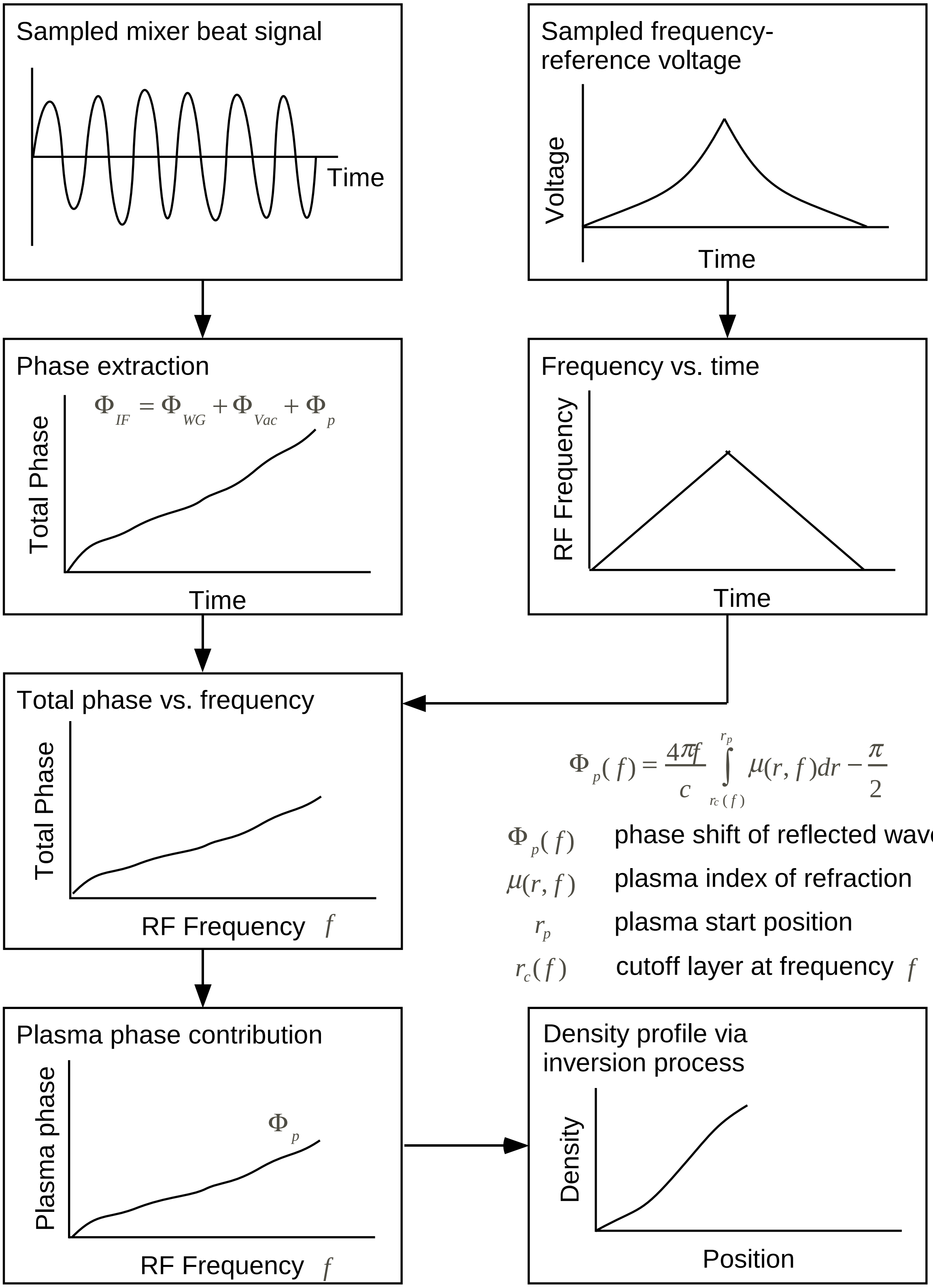


(a) Reflected wave is delayed in time with respect to the reference wave.

(b) With a mirror target, a beat with a constant frequency proportional to the mirror distance is created.

(c) The number of accumulated fringes during a sweep is linearly proportional to the mirror distance.

Density Profile Reconstruction from Phase Curve



$$\Phi_p(f) = \frac{4\pi f}{c} \int_{r_c(f)}^{r_p} \mu(r, f)\,dr - \frac{\pi}{2}$$

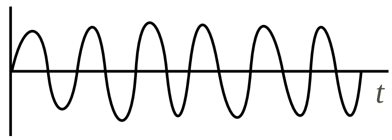
$\Phi_p(f)$	phase shift of reflected wave
$\mu(r, f)$	plasma index of refraction
r_p	plasma start position
$r_c(f)$	cutoff layer at frequency f

Complex Demodulation for Phase Curve Recovery

Time Domain

Digitized mixer signal

$$s(t_n) = A(t_n)\cos\{2\pi f_n(t_n)t_n\}$$



Create complex signal with frequency translated by $-f_0$

$$s(t_n)\exp(-i2\pi f_0 t_n)$$

Low-pass filtered signal

$$q(t_n) = \frac{1}{2}A(t_n)\exp\{i2\pi[f_n(t_n) - f_0]t_n\}$$

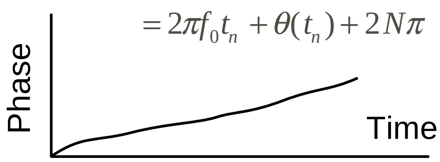
Phase and amplitude

$$\theta(t_n) = \arctan\left\{\frac{\mathrm{Im}[q(t_n)]}{\mathrm{Re}[q(t_n)]}\right\}$$

$$A(t_n) = 2|q(t_n)|$$

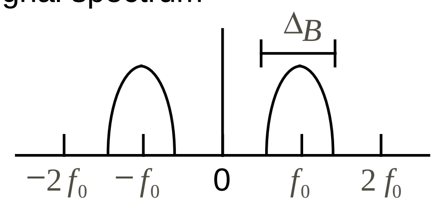
Extracted phase

$$\Phi(t_n) = 2\pi f(t_n)t_n$$
$$= 2\pi f_0 t_n + \theta(t_n) + 2N\pi$$

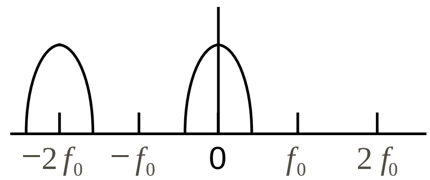


Frequency Domain

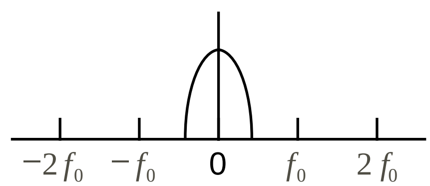
Signal spectrum



Spectrum shifted by $-f_0$



Spectrum after low-pass filtering



Conditions for using complex demodulation (CDM):

1. $f_0 > \Delta B/2$
2. $f(t_n) > f_A(t_n)$, where $f_A(t_n)$ is the amplitude modulation frequency.
3. $\Phi(t_n)$ is monotonically increasing without abrupt changes.

Under these conditions CDM is an efficient method of recovering the time-depedent phase.

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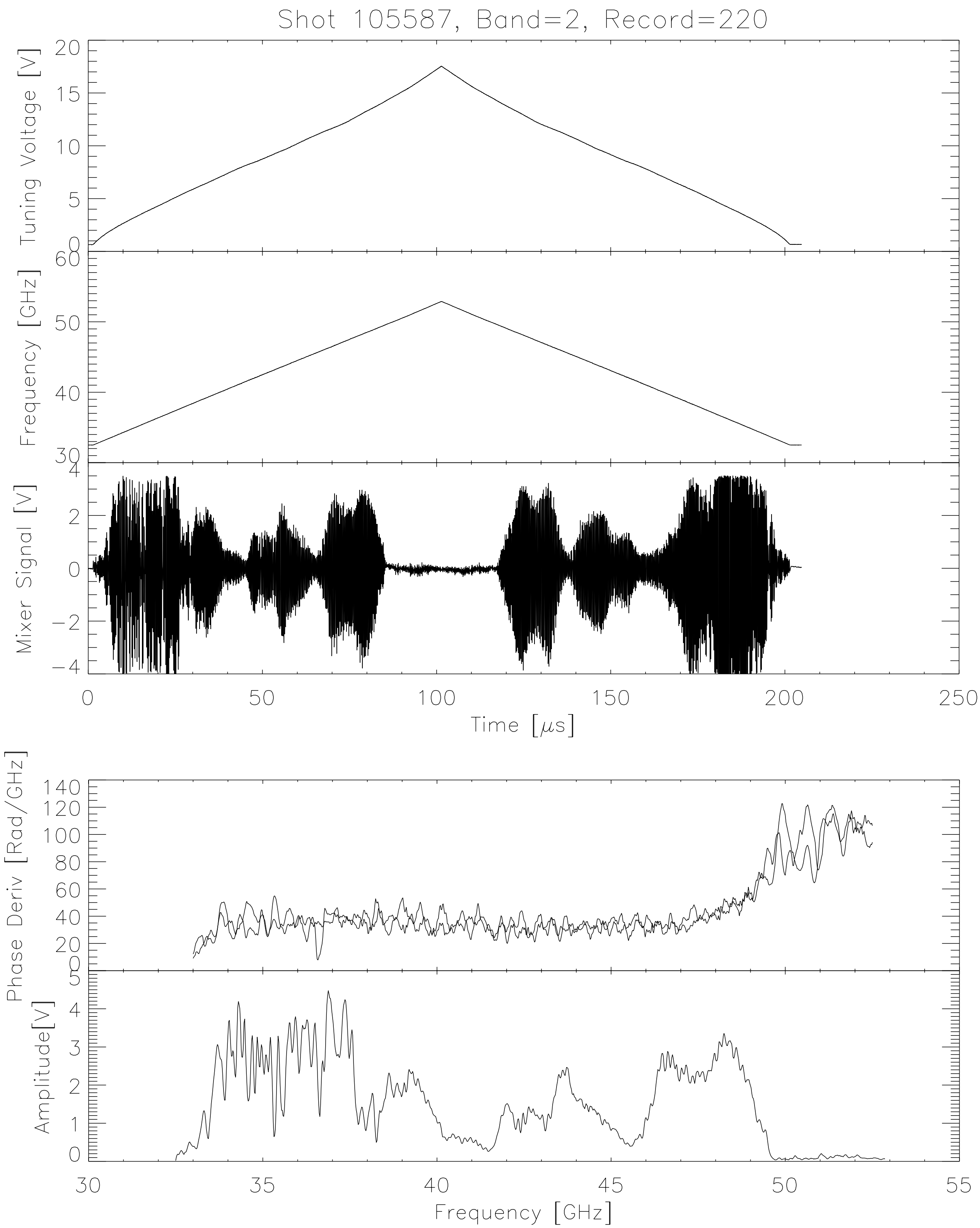
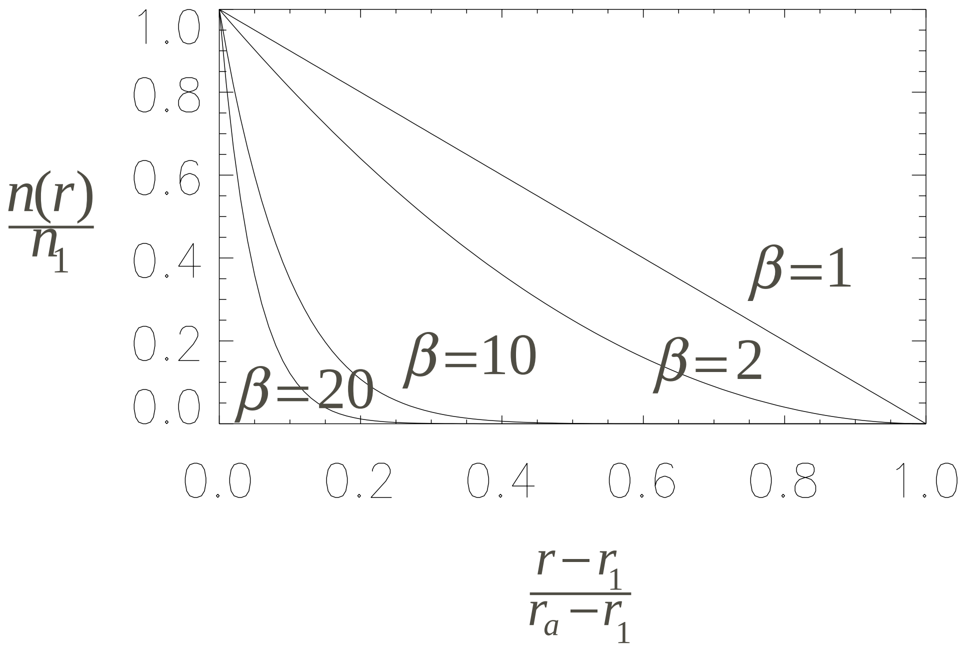
Raw and Processed Reflectometer Data



Edge Profile Modeling Below 12 GHz



Shape function for edge profile: $n(r)=n_1\left[1-\frac{r-r_1}{r_a-r_1}\right]^\beta$

	n_1	Innermost or peak density for edge model.
Variable Parameters	r_1	Cutoff location for density n_1.
	r_a	Edge major radius.
	β	Shaping parameter.

1) n_1 is set to 24 GHz.

2) Parameters are varied to look for best fit to profile between 12 and 24 GHz.

O-Mode Profile Reconstruction by Matrix Inversion

For O-mode, equation for phase curve can be written:

$$\begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \vdots \\ \phi_n \end{bmatrix} = \begin{bmatrix} \Phi_1 - \frac{4\pi f_1}{c}\left(r_{ref} - r_a\right) - A_{11} r_a \\ \Phi_2 - \frac{4\pi f_2}{c}\left(r_{ref} - r_a\right) - A_{21} r_a \\ \Phi_3 - \frac{4\pi f_3}{c}\left(r_{ref} - r_a\right) - A_{31} r_a \\ \vdots \\ \Phi_n - \frac{4\pi f_n}{c}\left(r_{ref} - r_a\right) - A_{n1} r_a \end{bmatrix} = \underbrace{\begin{bmatrix} -A_{11} & 0 & 0 & \dots & 0 \\ A_{22} - A_{21} & -A_{22} & 0 & \dots & 0 \\ A_{32} - A_{31} & A_{33} - A_{32} & -A_{33} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{n2} - A_{n1} & A_{n3} - A_{n2} & A_{n4} - A_{n3} & \dots & -A_{nn} \end{bmatrix}}_{\mathbf{M}} \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ \vdots \\ r_n \end{bmatrix}$$

where

$$A_{ij} = \frac{8\pi}{3c} \left\{ \frac{\left(f_i^2 - f_{j-1}^2\right)^{3/2} - \left(f_i^2 - f_j^2\right)^{3/2}}{\left(f_i^2 - f_{i-1}^2\right)} \right\}$$

Then r_i is recovered via

$$r = \mathbf{M}^{-1}\,\phi\,.$$

1) $d\Phi/df$ is integrated to recover $\Phi(f)$.

2) Assumes piecewise linear density profile between consecutive f_i.

3) Inversion matrix is calculated only once for a regular grid of f_i .

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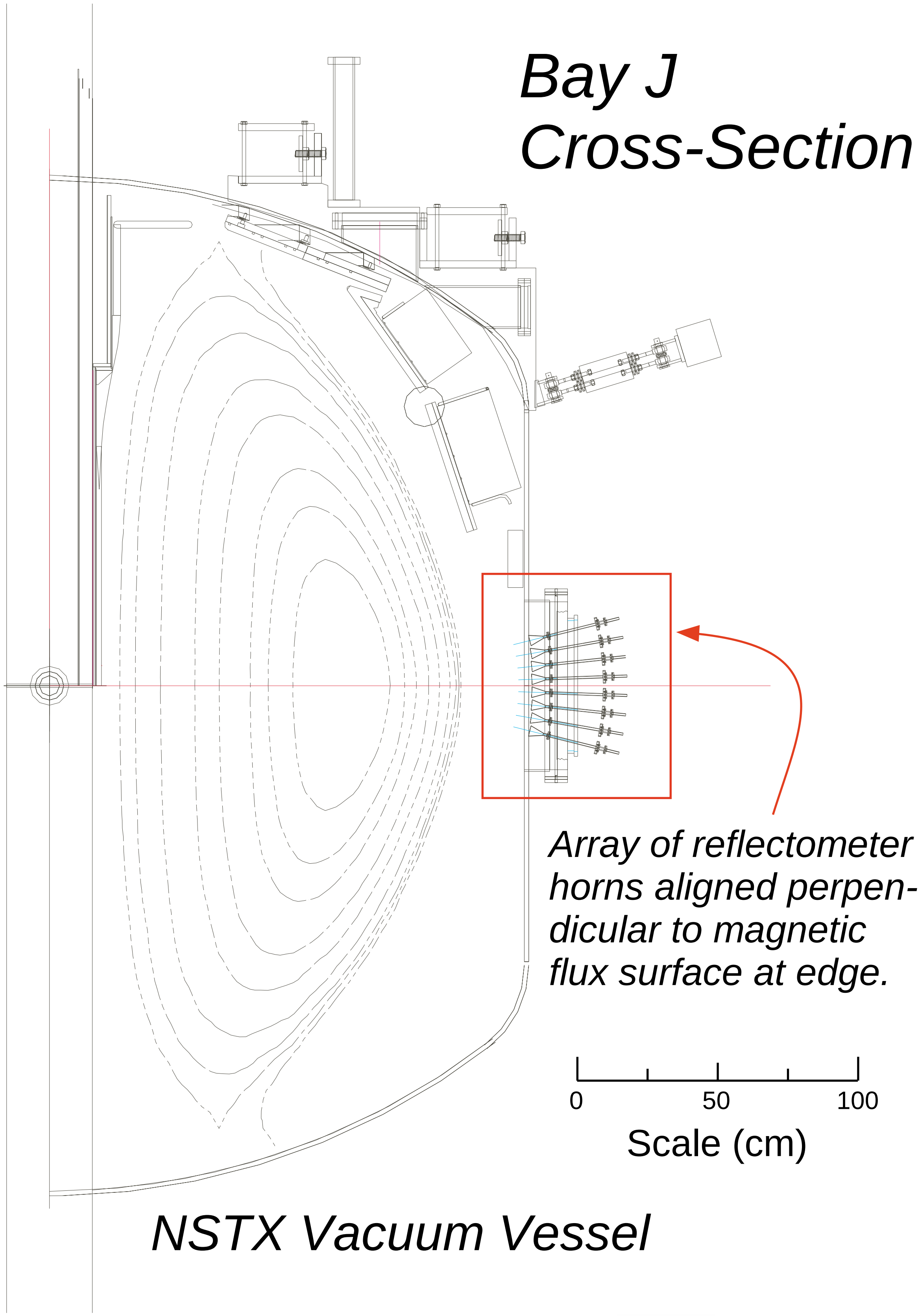
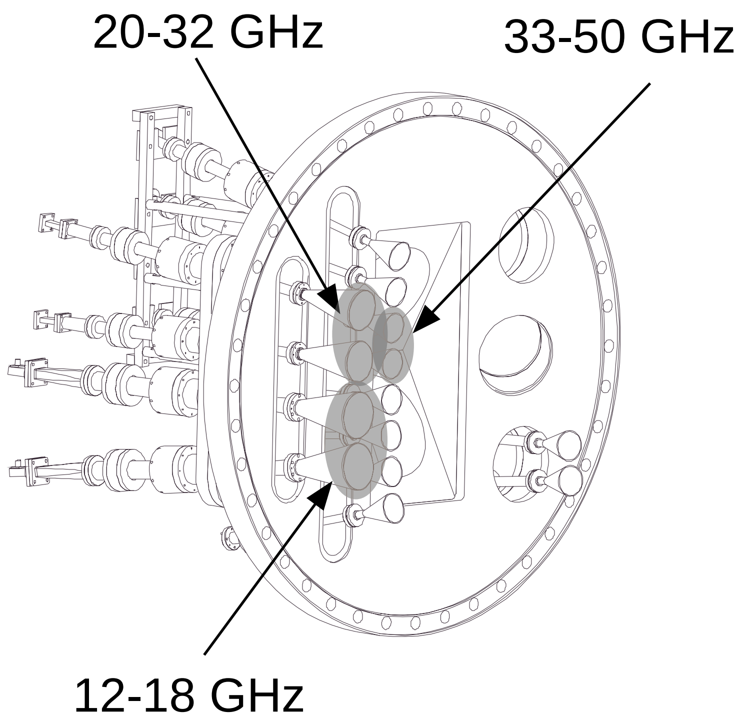
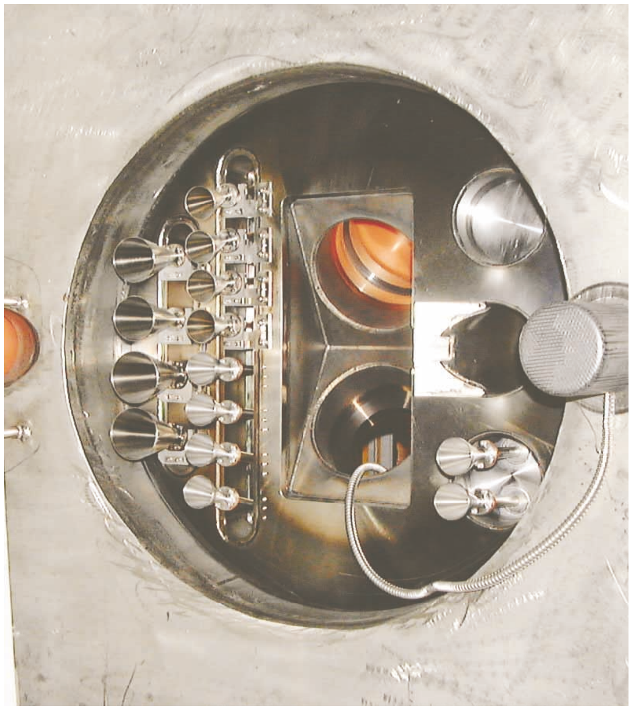
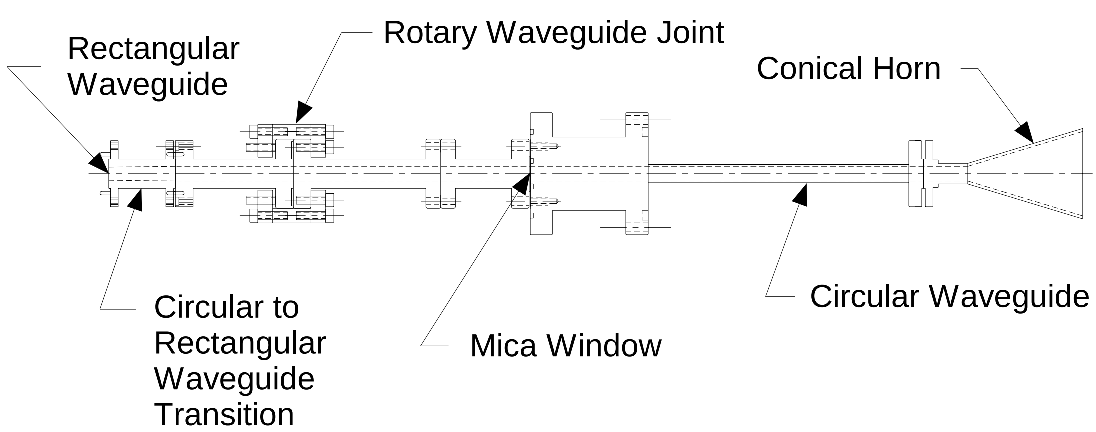
Horn Arrays Near NSTX Midplane



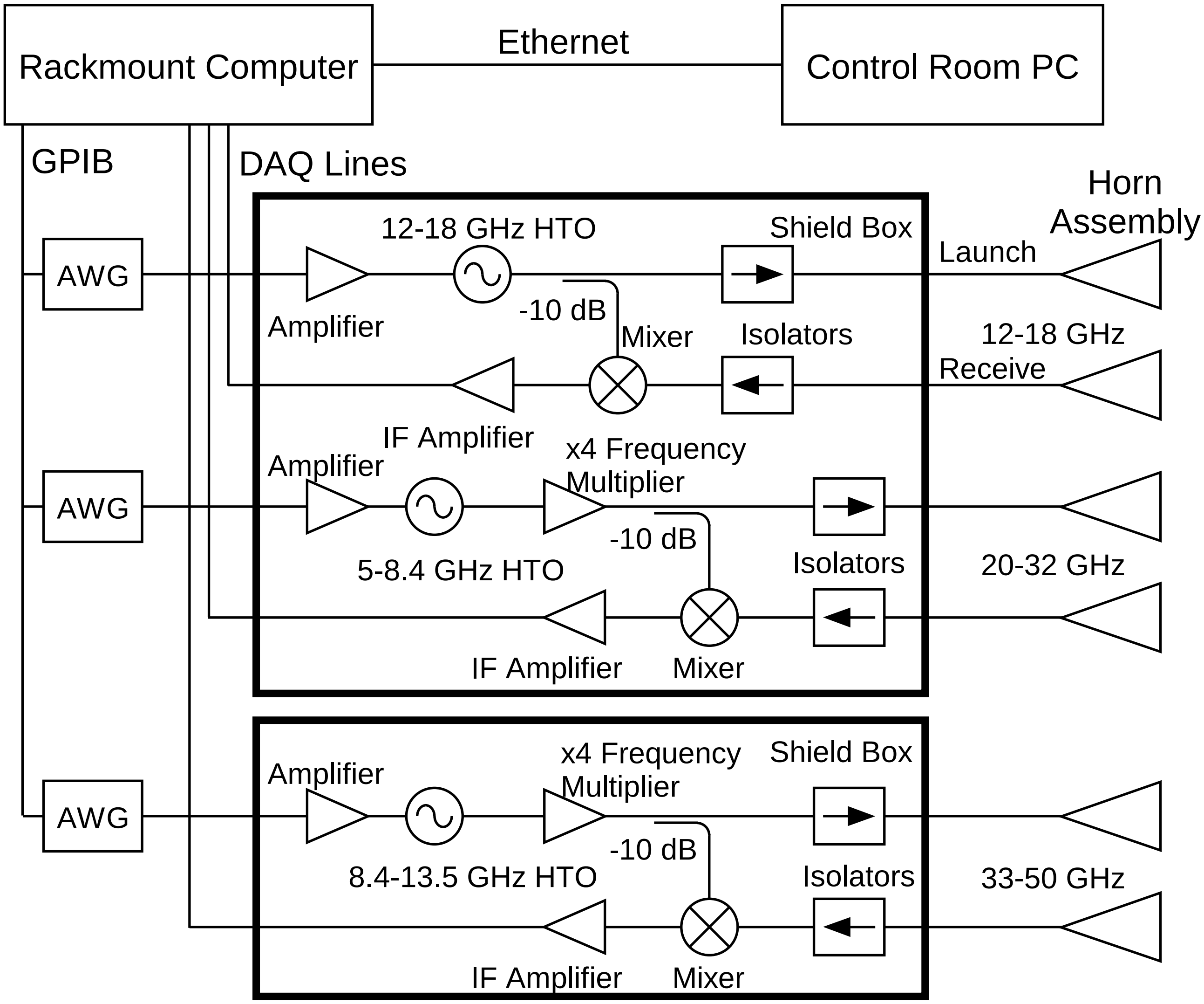
Horn Arrays and Waveguide Assembly

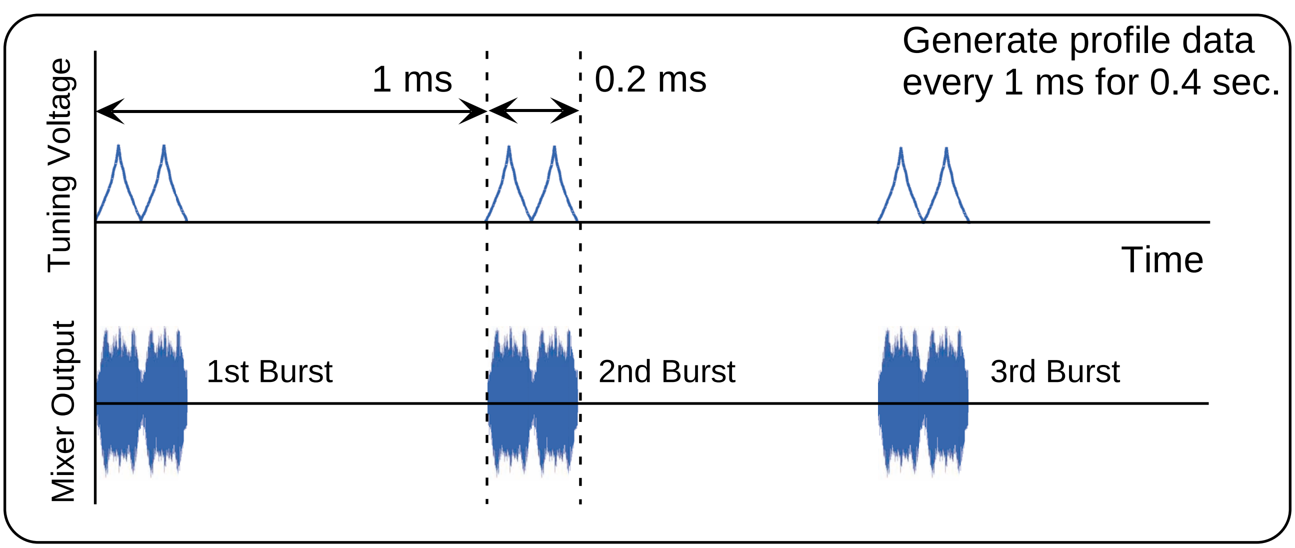






Reflectometer System Layout





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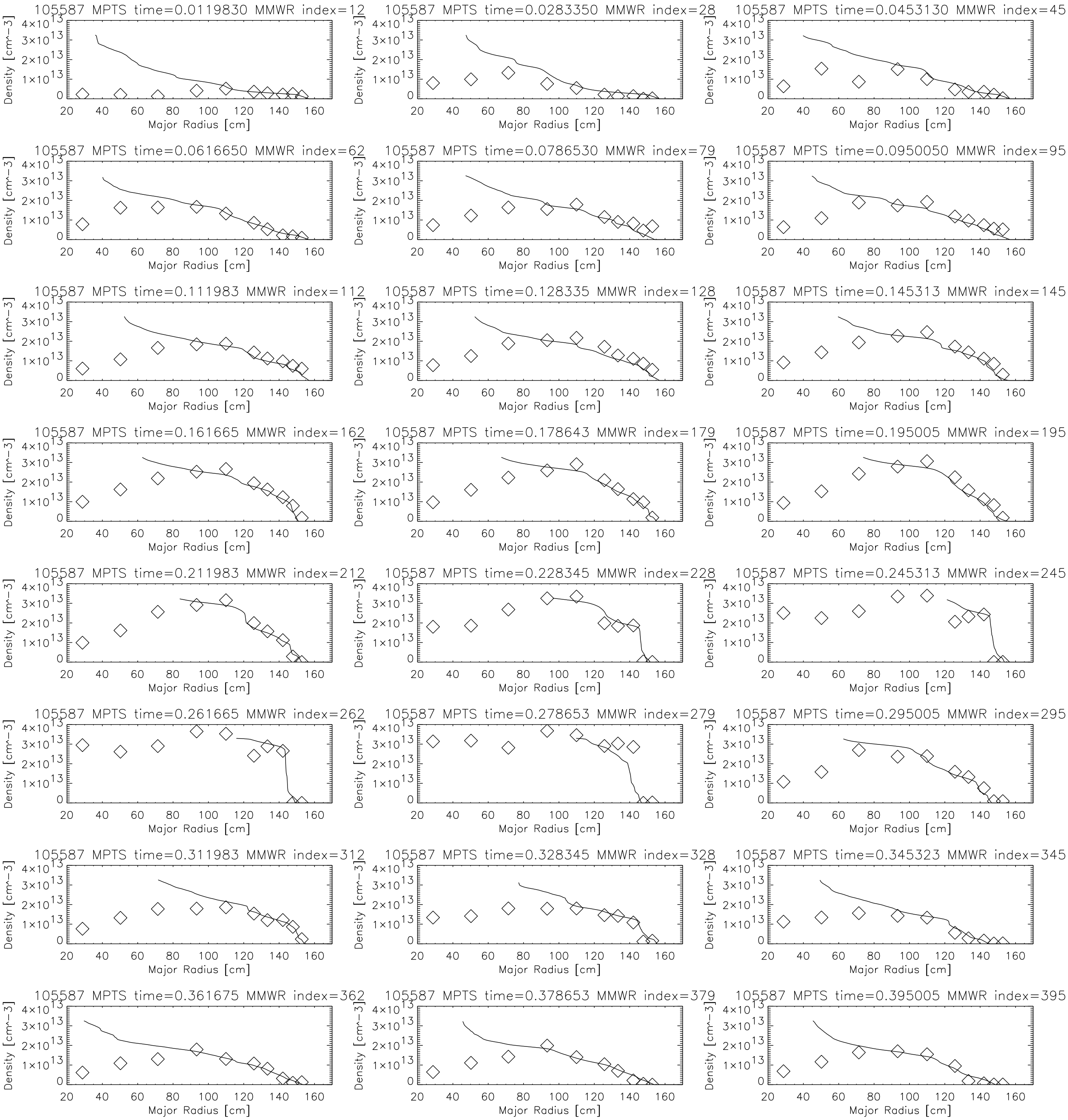
Comparison With Thomson Scattering



◇ Thomson Scattering

— Reflectometry

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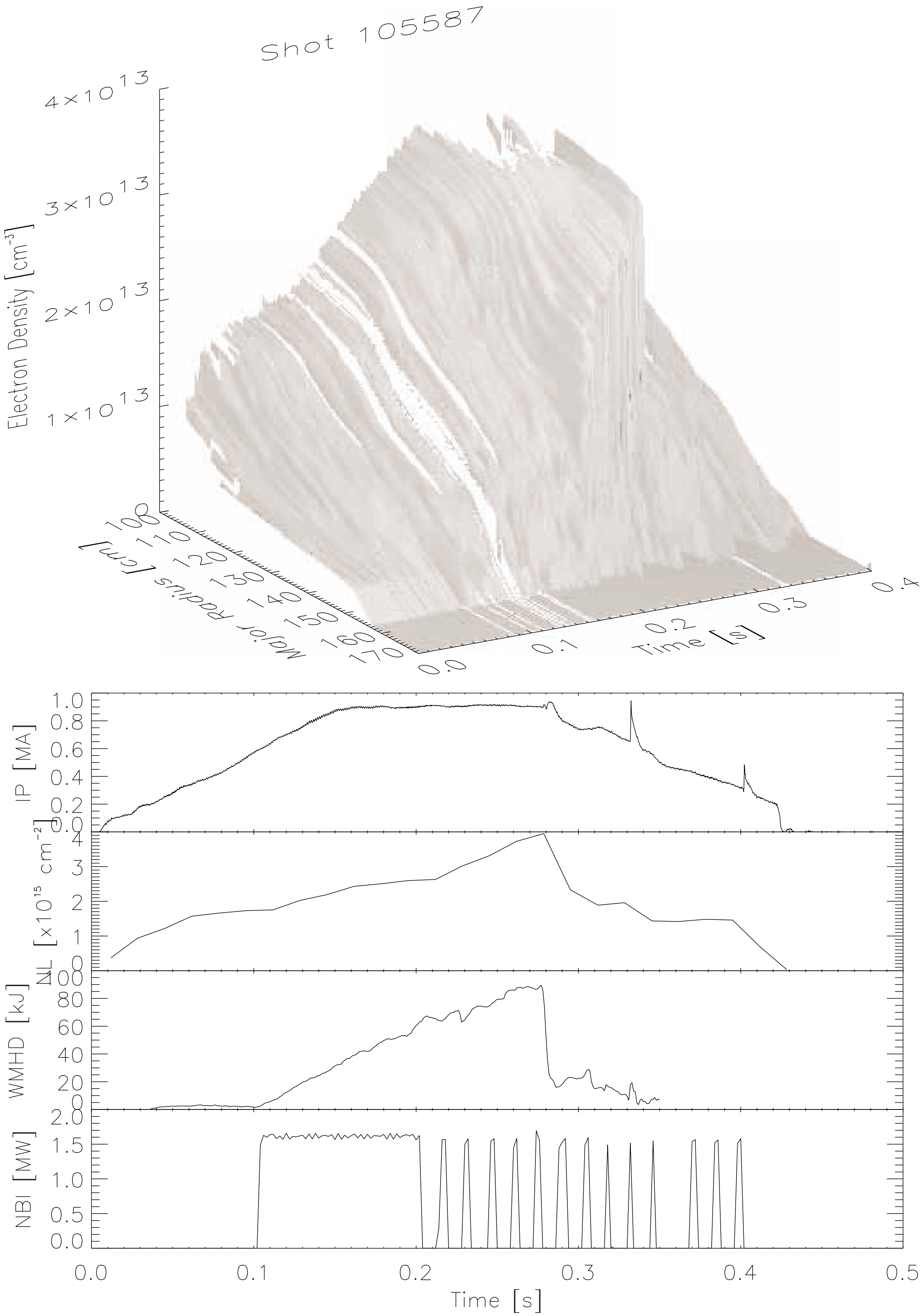
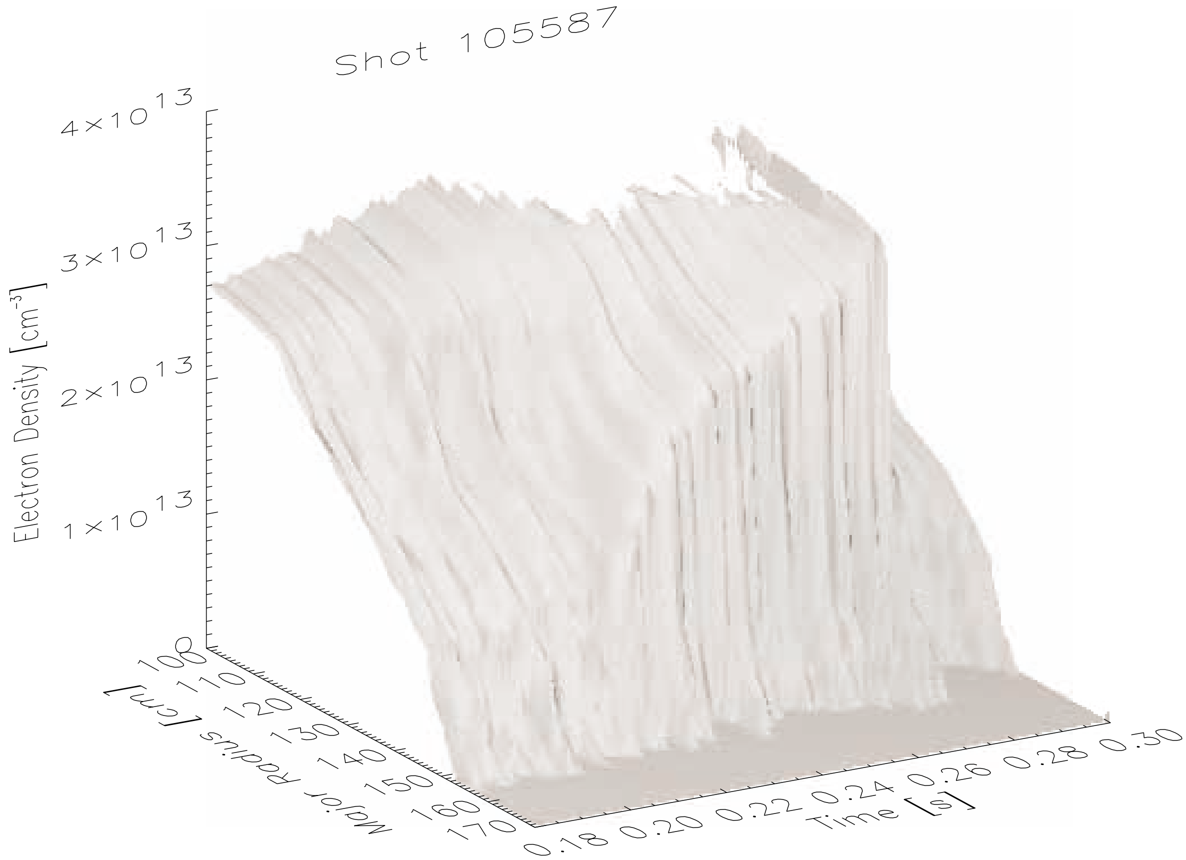
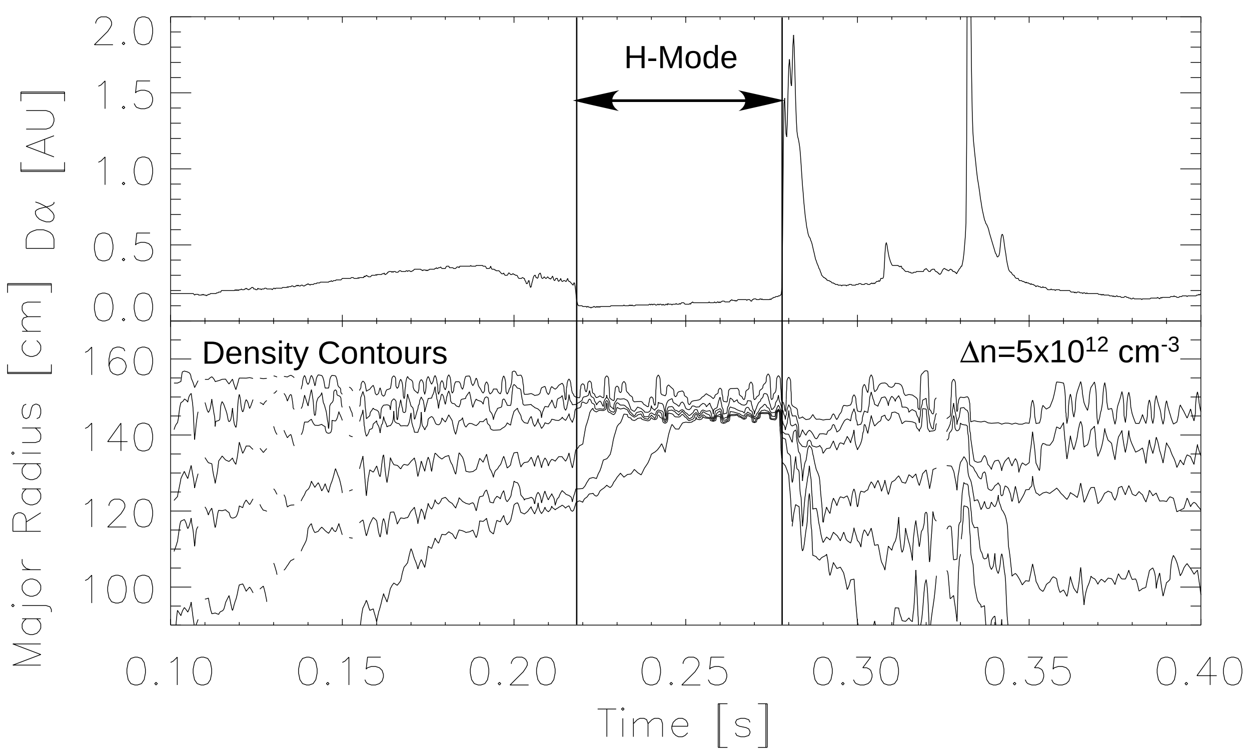
Profile Evolution During Shot 105587



Profile Evolution During L-H Transition





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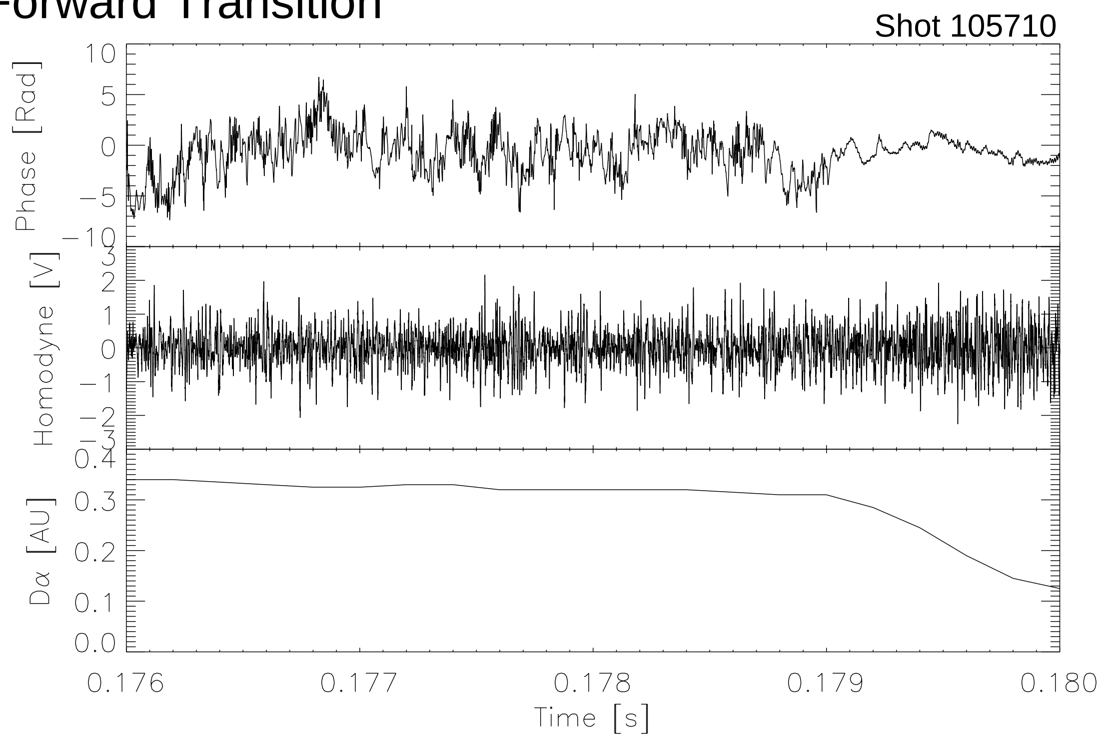
Suppression of Turbulence at L-H Transition

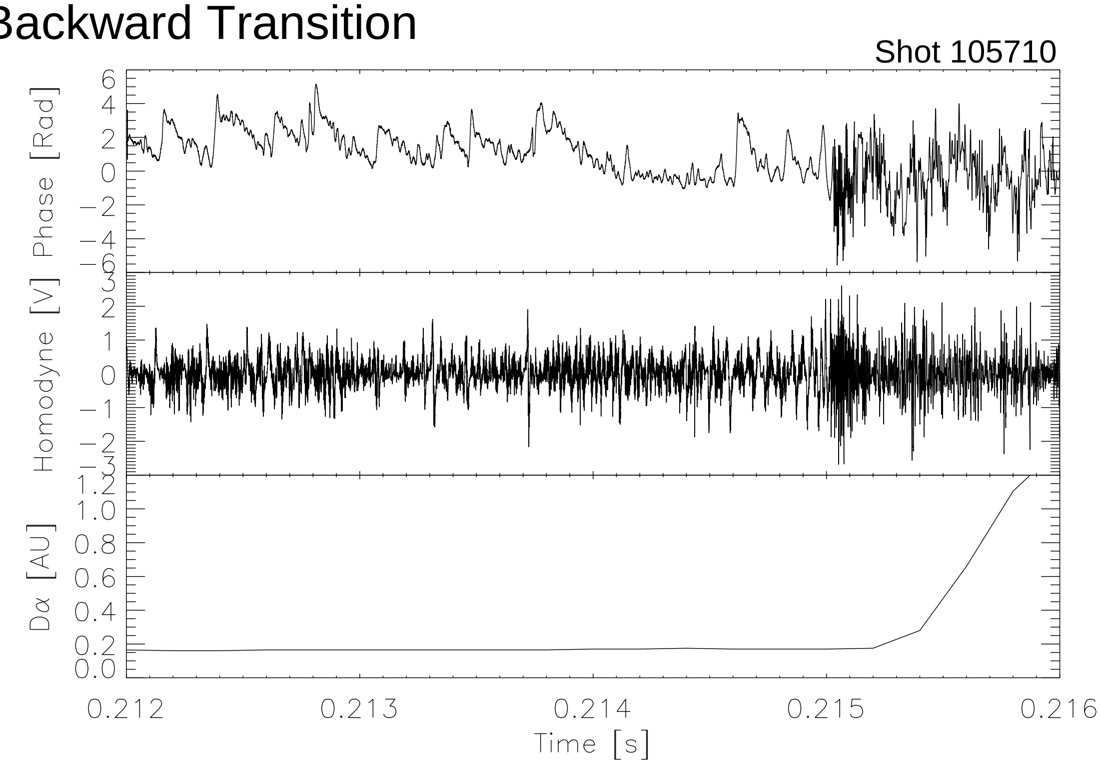
Forward Transition



f=18.0 GHz
n_e=4.0x10^{12}

f=31.1 GHz
n_e=1.20x10^{13}

Backward Transition

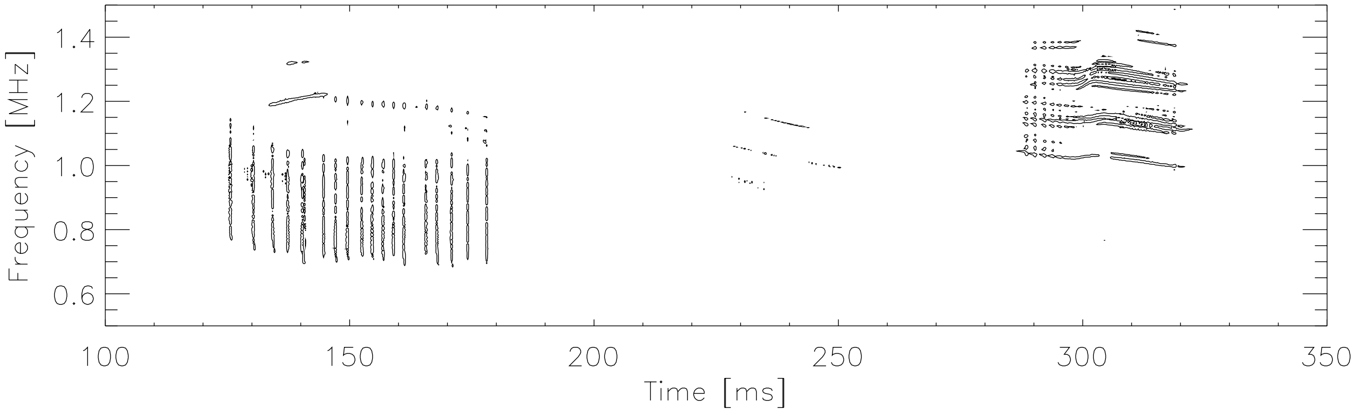


f=16.8 GHz
n_e=3.5x10^{12}

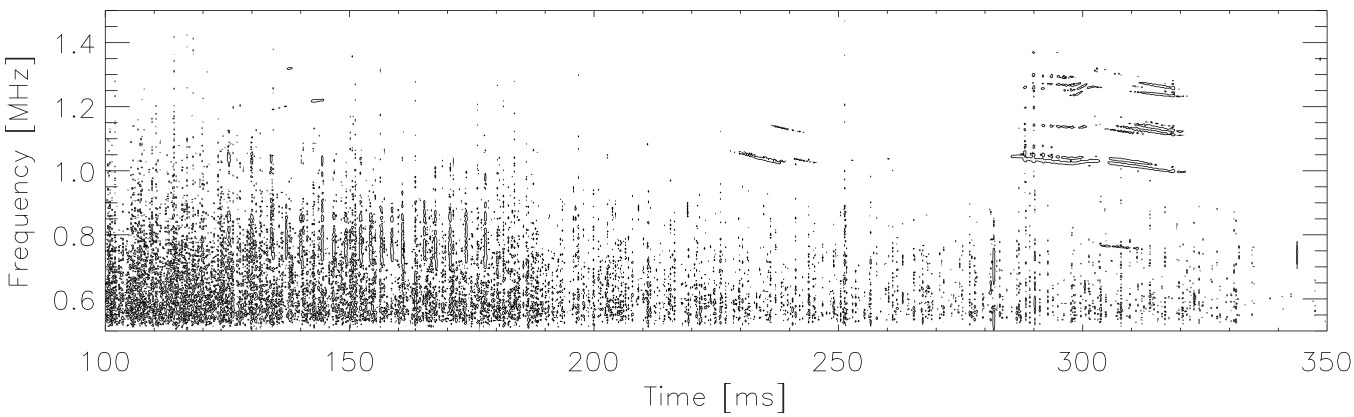
f=29.1 GHz
n_e=1.05x10^{13}

Compressional Alfven Eigenmodes

Raw Mirnov Spectrogram Shot 106233



Reflectometer Phase Spectrogram



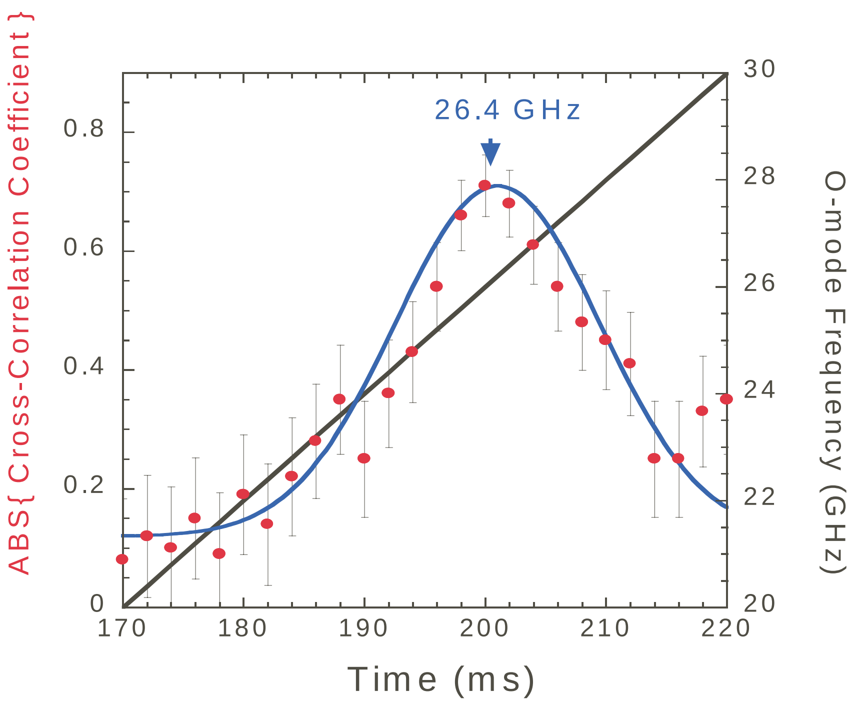
- NBI driven CAE's seen by Mirnov coils and reflectometer.
- Phase fluctuations using I/Q mixer with 12-18 GHz channel.
- f=14.75 GHz, n_e=2.7x10^{12} cm^{-3}.

Results from FMCW Reflectometry

- The 12-50 GHz FMCW reflectometer for NSTX is installed and operational. Data was acquired routinely (shot-by-shot) during Fall 2000-Summer 2001.
- Software for automatic analysis and profile reconstruction is almost ready. Tweaking is still necessary for speed and edge model-ing. Between-shot analysis (~15 min.) is possible.
- The reconstructed density profiles using O-mode reflectometry track well with Thomson scattering results. Further edge profile measurements will lower uncertainty: ORNL edge reflectometer, UCSD fast reciprocating probe.
- Mode contamination due to polarization mismatch or mode-conversion seems not to be an issue. This is also being evaluated numerically.
- Fluctuation measurements using fixed-frequency mode. Turbulence suppression at L-H transition. CAE's detected.

Preliminary O-X Correlation Reflectometry Experiments in NSTX are Encouraging

- A 20-30 GHz correlation reflectometer was modified to operate in a dual mode (O-X) configuration.
- $f_{X\text{-mode}}$=30 GHz
- $f_{O\text{-mode}}$ swept over 20-30 GHz



- EFIT gives |B|~2.4 kG at radius for 26.4 GHz cutoff, R=1.47 m.
- Interpretation of the data using a 1-D model indicates B=2.5+/-0.15 kG.
- Assuming reflection occurs at cutoff gives 2.42 kG.

Preliminary Correlation Length Measurements

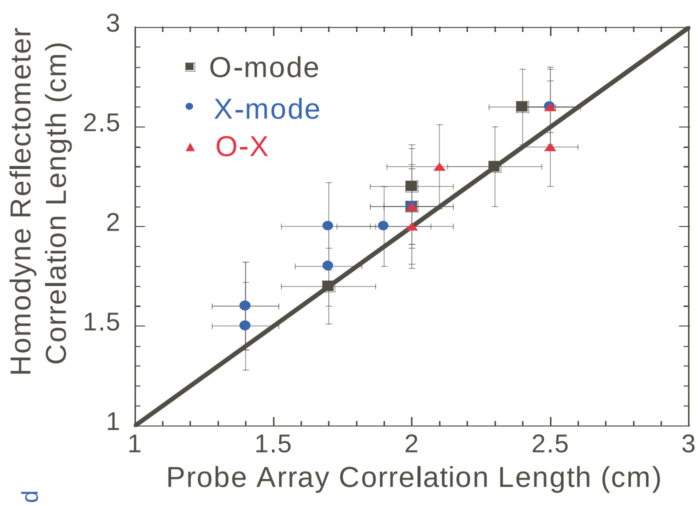
Preliminary turbulent radial correlation length measurements have been made.

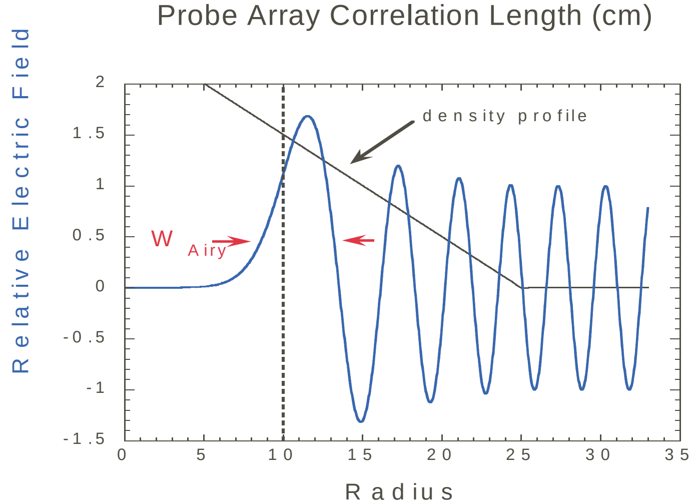
- Measurements to date have been in the 20-30 GHz band ($n=0.5\text{-}1\times10^{13}$ cm^{-3}) using both O-X and O-O correlation.
- Correlation lengths are currently measured over tens of milliseconds - this will be improved during future operation.
- 1/e Δr varies from ~0.7 cm (edge) to 2.8 cm (core). These values are roughly equal to the ion gyro radius.
- It should be noted that UCLA has the capability to determine turbulent correlation lengths in DIII-D, NSTX and ET. Cross-comparison should lead to improved knowledge of the relevant step-size for transport in these devices.
- In addition, comparison with simulation predictions is underway (Leboeuf, Dorland). This should improve overall understanding of transport mechanism as well as benchmarking of codes.

Preliminary Correlation Length Measurements

	LAPD	NSTX
f (GHz)	8 - 18	20 - 30
Δr (1/e, cm)	1.5 - 2.5	0.7 - 2.8
$\Delta r/W_{Airy}$	> 0.8	0.7 - 2.8

- Scaled (to W_{Airy}) correlation lengths measured in NSTX are similar to the range measured previously in LAPD.





Results from Correlation Reflectometry

- Dual-mode correlation reflectometry measure ments have been performed on NSTX over the frequency range 20 to 30 GHz.
- Preliminary analysis indicates correlation lengths of ~1 cm near the plasma edge rising towards the core.
- Preliminary magnetic field measurements in the edge plasma are within 5% of values pre- dicted by EFIT.
- These results are extremely encouraging and development of O-X correlation reflectometry for both magnetic field strength and correlation lengths will continue.
- This approach is complementary to MSE. The technique requires no neutral beam and is insensitive to internal electric fields.

Plans and Future Work

- Profile measurements for densities up to $1x10^{14}$ cm^{-3} via higher frequency operation (up to 90 GHz)?
- Absolute density fluctuation determination via measurement of phase fluctuations using multi-channel reflectometers. 50 and 65 GHz channels will be available during the next run.
- Radial profile of turbulence radial correlation lengths and |B| via an array of dual-mode homodyne correlation reflectometers.
- Measurement of magnetic field pitch angle. Two toroidally separated arrays of vertically oriented reflectometers are utilized to search for the correlation of density fluctuations aligned along the magnetic field.