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Millimeter-Wave Measurements on NSTX

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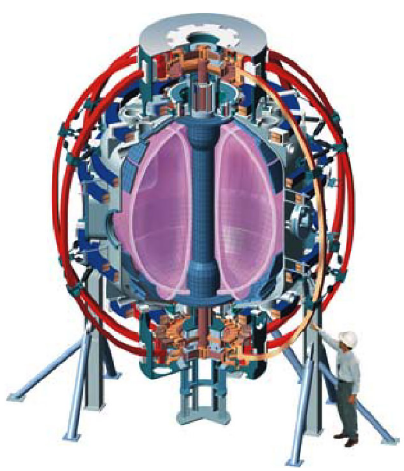

45th Annual Meeting of Division of Plasma Physics
American Physical Society
October 27 – 31, 2003
Albuquerque, New Mexico

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Abstract

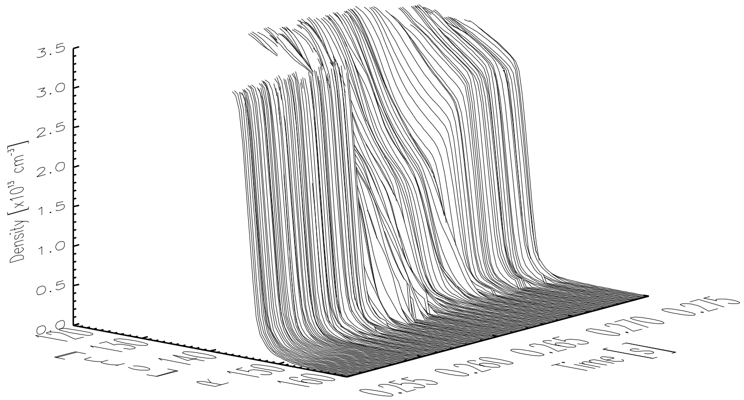
UCLA operates a suite of microwave and millimeter-wave diagnostics on NSTX for measurements of electron density profiles and fluctuations. During the previous campaign the FMCW reflectometers (13.5 to 50 GHz) have operated routinely for documenting the fast density profile evolution. Two new systems recently added are 1) a proof-of-principle magnetic pitch-angle diagnostic utilizing fixed-frequency correlation reflectometers (50 GHz) separated poloidally and toroidally, and 2) a fast single-chord 1 mm interferometer with a radial midplane view. Preliminary measurements from the newer systems will be presented. Additional diagnostics to be installed in the near future are 1) fixed-frequency quadrature reflectometer channels (30 and 50 GHz) for $\tilde{n}_e$ measurements and 2) an edge FMCW reflectometer (5 to 13.5 GHz) in support of EBW heating and current drive research. The design and proposed implementation of these systems will be discussed.

MM-Wave Reflectometery on NSTX: Status and Goals

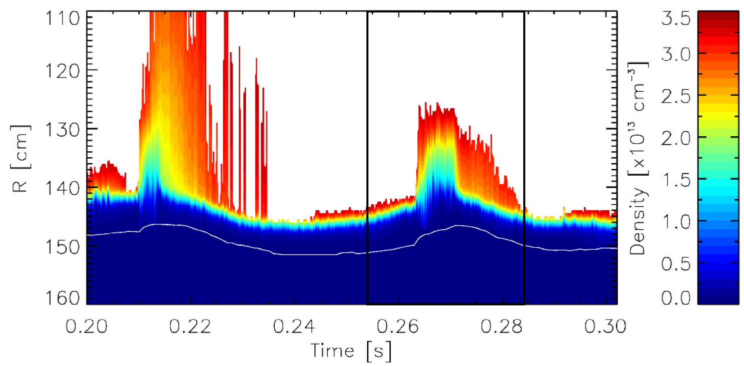
- The following additional systems were added for FY03:
  - Correlation reflectometry using toroidally and poloidally separated locations for magnetic pitch-angle measurements. Augment measurements using MSE and FIReTIP.
  - Single chord milllimeter-wave (1 mm) interferometer with a radial view installed at a midplane port. Additional density monitor, plus the capability of tracking density fluctuations in the ~100 kHz range.
- Previously we have reported on the following millimeter-wave diagnostics for density profile and fluctuation analysis on NSTX.
  - FMCW (frequency-modulated continuous-wave) reflectometry for fast profile measurement discharges. Documented fast changes in the profile during L-H transitions and ELMs.
  - Fluctuation measurements using fixed frequency quadrature system with three simultaneous channels. Reduction in turbulence spectrum during H-mode. Turbulence incerease during ELMs. Fluctuations in CAE (~MHz) range of fre quencies clearly visible.
  - Correlation reflectometry for turbulence radial correlation lengths and magnetic field strength measurements.

Results from FMCW Profile Reflectometry

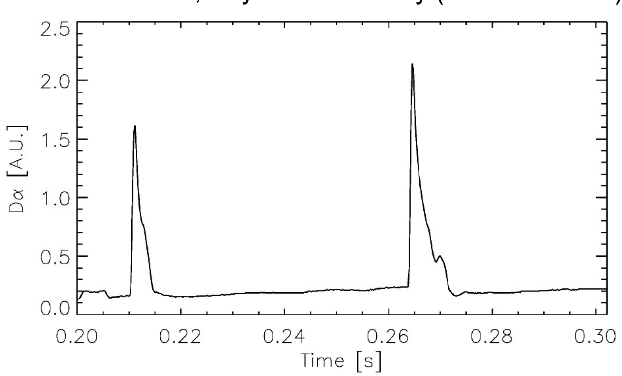
NB-Heated Discharge: H-Mode, Giant ELMs (Shot 108487)

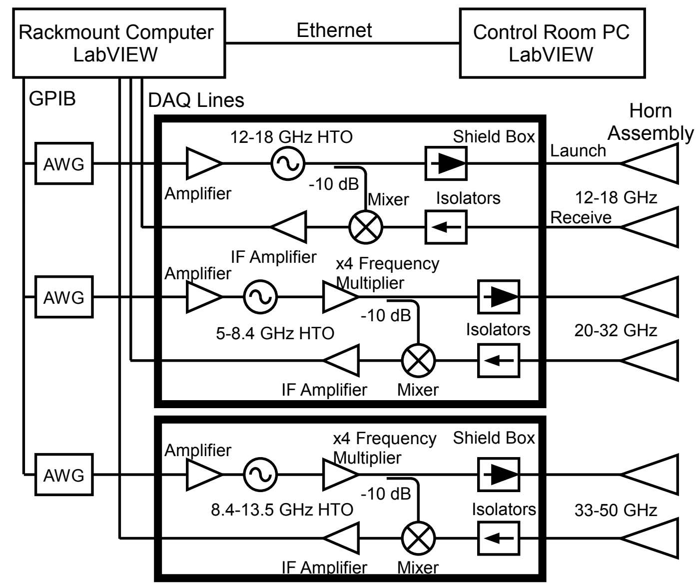


Shot 108487, Density Profile Contour Plot

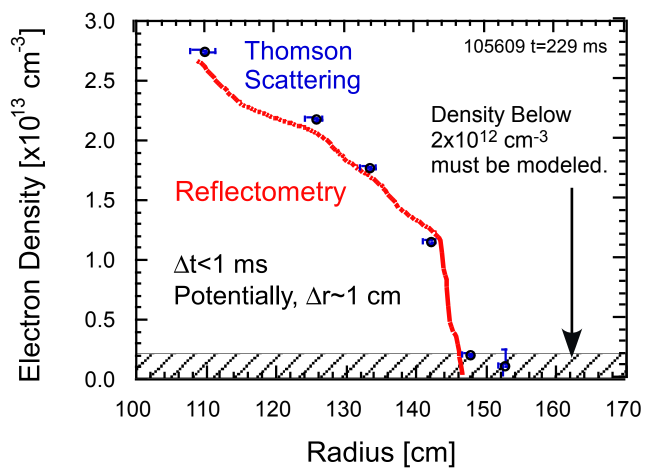


Shot 108487, Bay C Dα Intensity (Lower Divertor)





- 12-50 GHz coverage (1.8×10^{12} to 3.1×10^{13} cm^{-3}).
- Maximum repetition rate of 100 μs/sweep (818 total profiles)
- Use spline fit to Thomson edge profile below $n_e=9\times10^{11}$ cm^{-3}.



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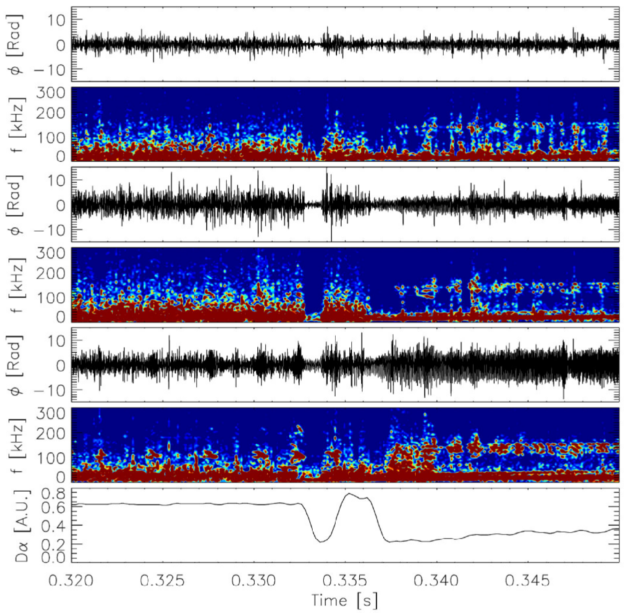
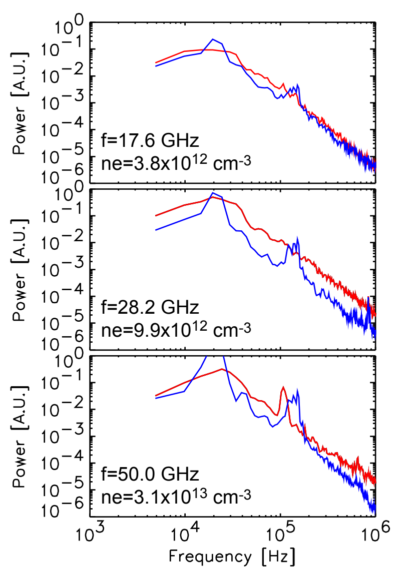
Results from Fixed Frequency Reflectometry

NSTX

Fluctuation Component of Reflectometer Phase and Spectrogram at L-H Transition



Power Spectrum of Phase



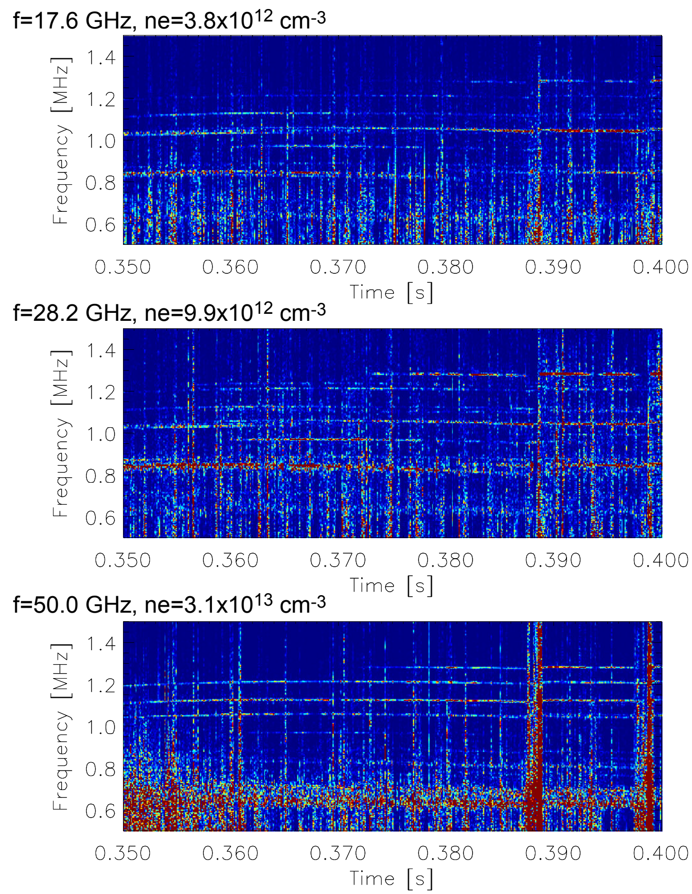
Turbulence Suppression/ Fluctuations at L-H Transition

L-Mode: 0.325-0.330 s

H-Mode: 0.340-0.345 s

Fluctuation Measurements: Compressional Alfven Eigenmodes

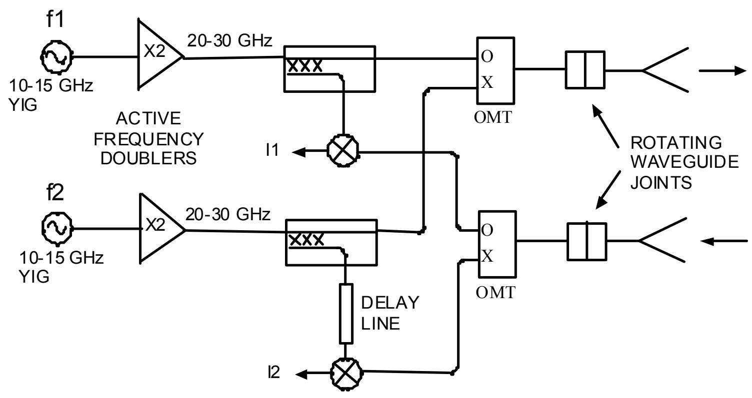
Shot 108824, Reflectometer Phase Spectrograms

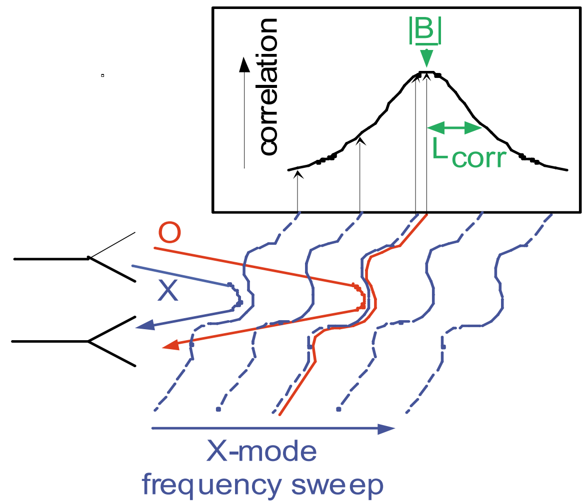


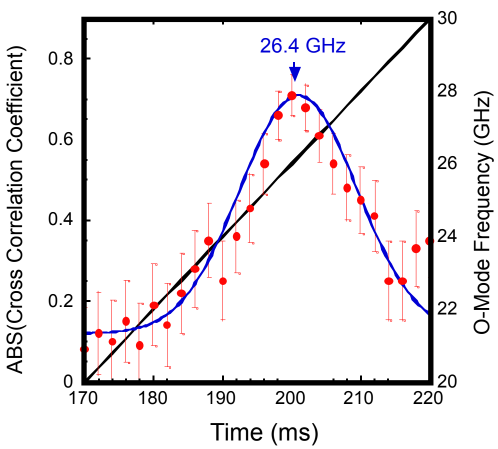
Results from Correlation Reflectometry

Results from O- and X-Mode Swept Configurations

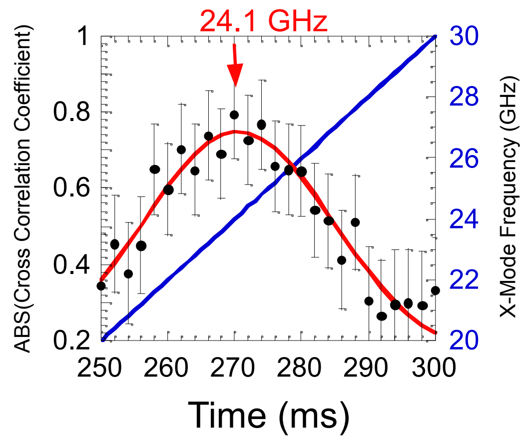
- 20-30 GHz homodyne system
- f1 fixed, f2 slowly swept
- f1, f2 combined in circular w/g via ortho mode transducer (OMT)
- Circuit implemented mainly with high frequency coaxial cable/devices. Transition to w/g at OMTs.
- Cutoff densities $n_e \approx 0.5 \rightarrow 1.0 \times 10^{13}$ cm^{-3} probed
- Cutoff positions in the range R/a $\approx$ 0.85 - 0.95





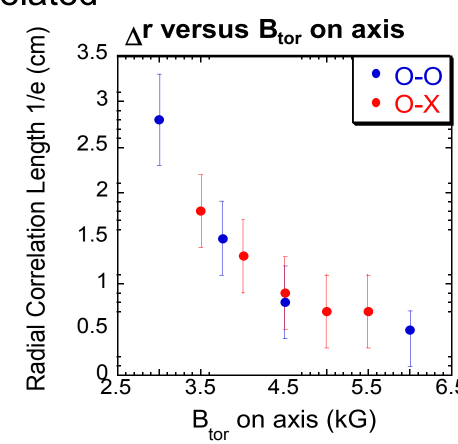


- f_x = 30 GHz
- f_o swept 20-30 GHz
- Gaussian fit gives $f_{o,pk}$ = 26.4 ± 0.15 GHz
- X-mode cutoff location R = 147 cm
- 1D full wave model gives |B| = 2.5 ± 0.15 kG at R =147 cm
- EFIT gives |B| ≈ 2.6 kG at this radius



- f_o = 20 GHz
- f_x swept 20-30 GHz
- Gaussian fit gives $f_{x,pk}$ = 24.1 ± 0.15 GHz
- O-mode cutoff location R = 151 cm
- 1D full wave model gives |B| = 3.0 ± 0.14 kG at R =151 cm
- EFIT gives |B| ≈ 3.0 kG at this radius

- NBI heated L-mode plasmas
- Cutoff layers (30 GHz) 4-8 cm inside LCFS
- L_n varies from ≈ 6 to 16 cm
- Fluctuation frequencies 20 - 500 kHz correlated

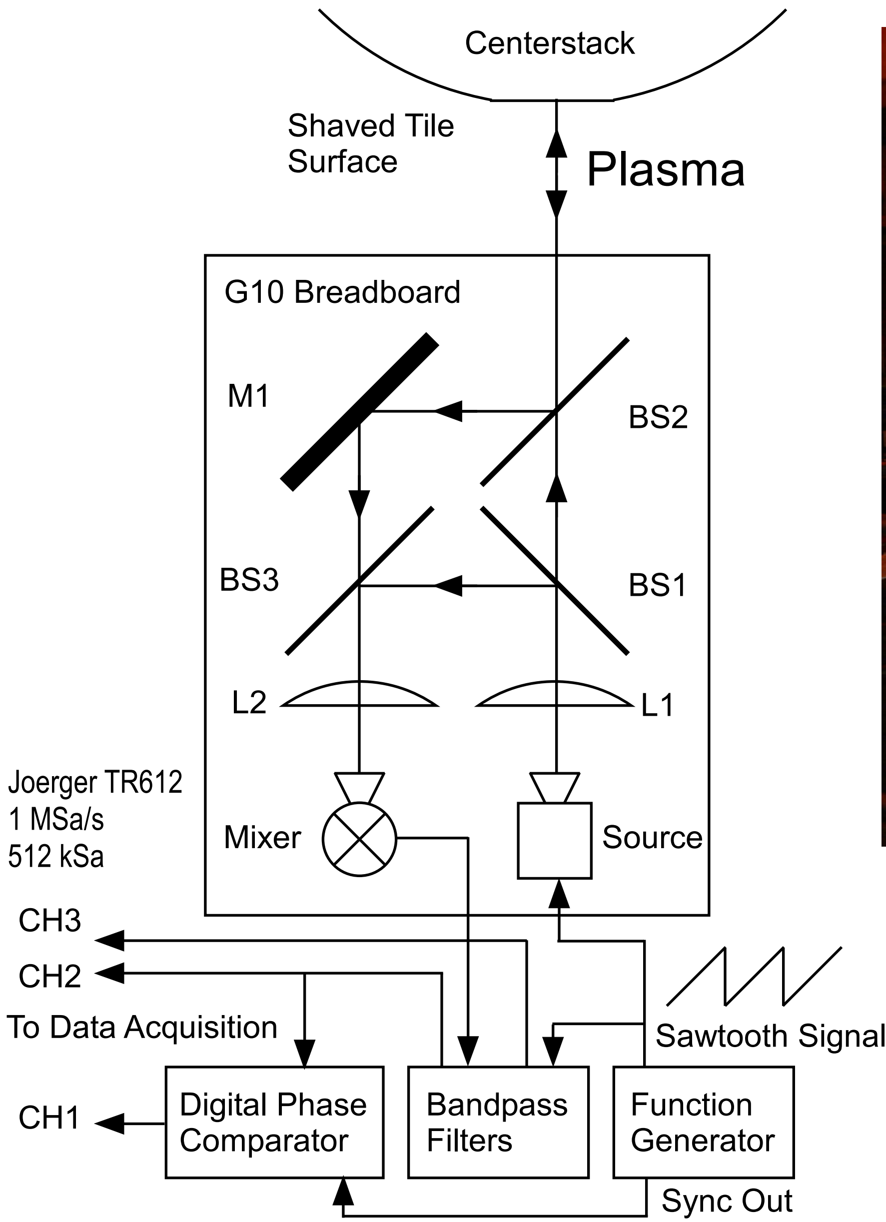


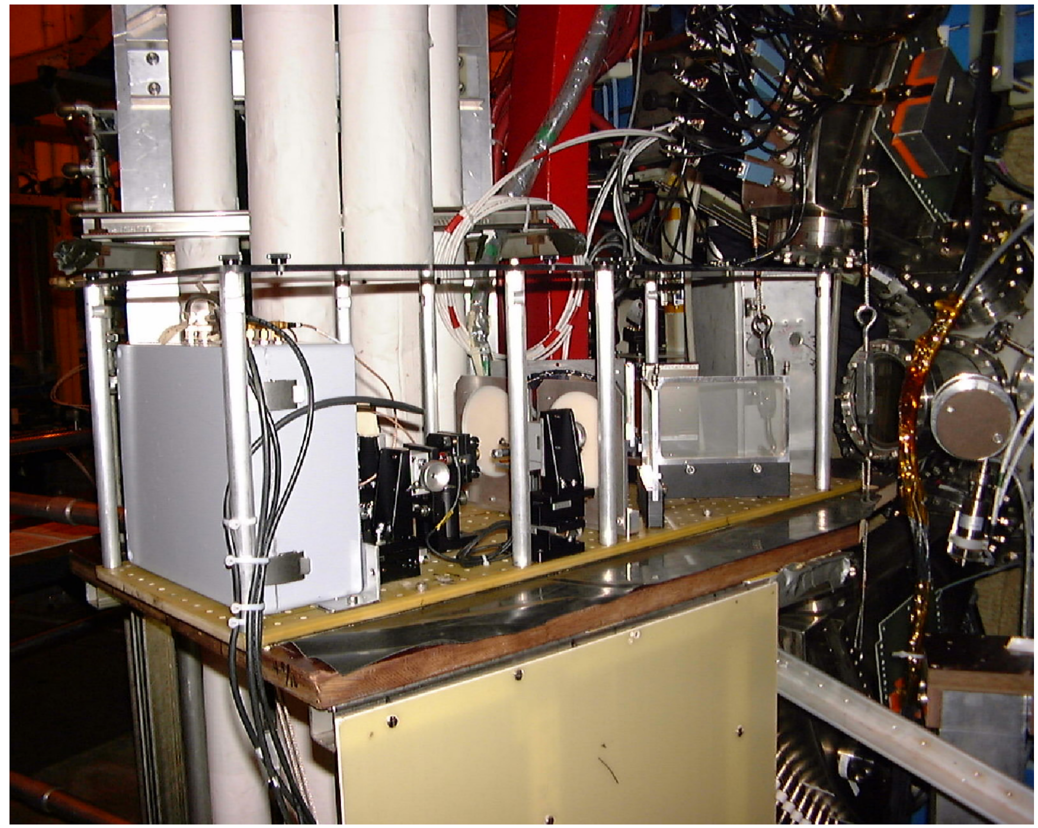
Diagnostics To Be Implemented During FY04

NSTX

- Edge density profile/fluctuation monitor for EBW heating and current drive experiments [KO1.008 G. Taylor].
  - Use of in-vessel 4-18 GHz quad-ridged EBW antenna.
  - Frequency-modulated continuous-wave (FMCW) reflectometer, similar to existing systems on NSTX.
  - Initially will combine two solid-state sources for 5-13.5 GHz coverage (n_e<$2x10^{12}$ cm^{-3}). Possible third source for 5-20 GHz coverage.
  - Full band sweep rate > 50 kHz.
- Dedicated multi-channel reflectometer system for fluctuation measurements.
  - High bandwidth up to 5 MHz.
  - Analysis of CAEs, TAEs, fishbones, H-mode and ELM precursors, turbulence with spatial resolution.
  - Homodyne quadrature systems at 12-18, 30, and 50 GHz (corresponding densities are 0.2-0.4, 1.1, $3.1x10^{13}$ cm^{-3} in O-mode). Possible additional channel at 65 GHz ($5.2x10^{13}$ cm^{-3}).
  - Estimation of $\tilde{n}/n$ from phase measurements.

Location and Layout of 1 mm Interferometry System





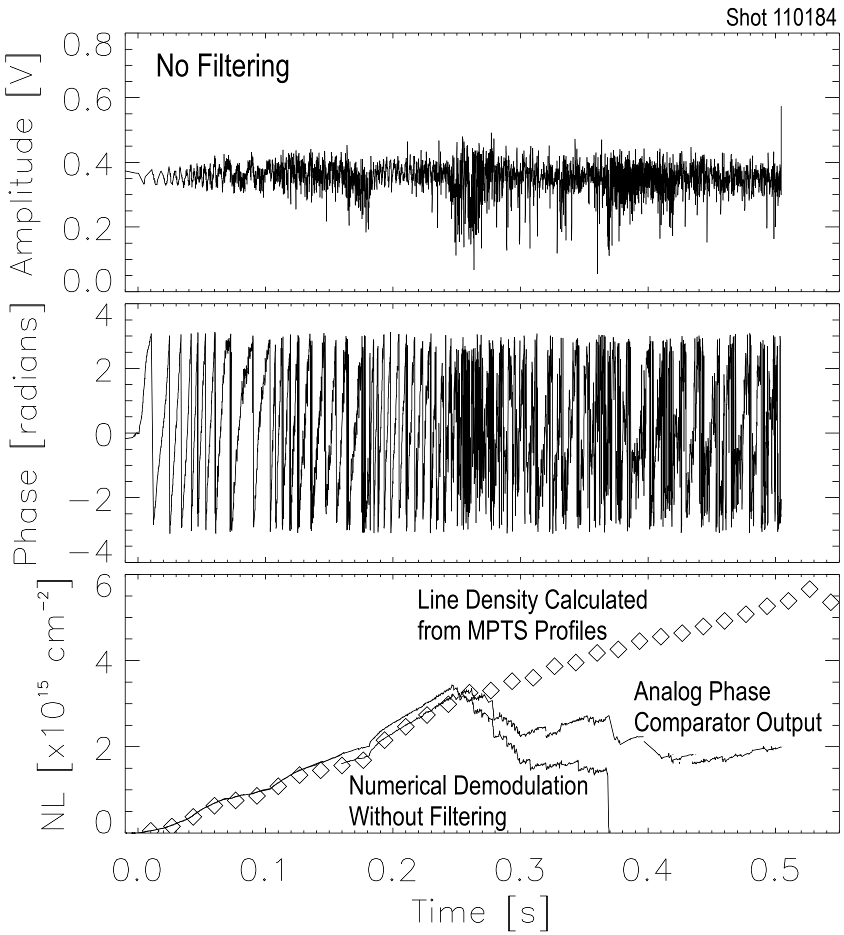
- Quasioptical design. Radial view slightly above midplane (1/2").
- Operating frequency is 288 GHz, using bias-tuned Gunn oscillator at 96 GHz and passive solid-state tripler (~10 mW).
- Function generator (750 kHz sawtooth) modulates Gunn oscillator in the range of ~100 MHz. Synchronized with analog phase comparator. Sawtooth is also filtered and used as input for digital phase comparator.

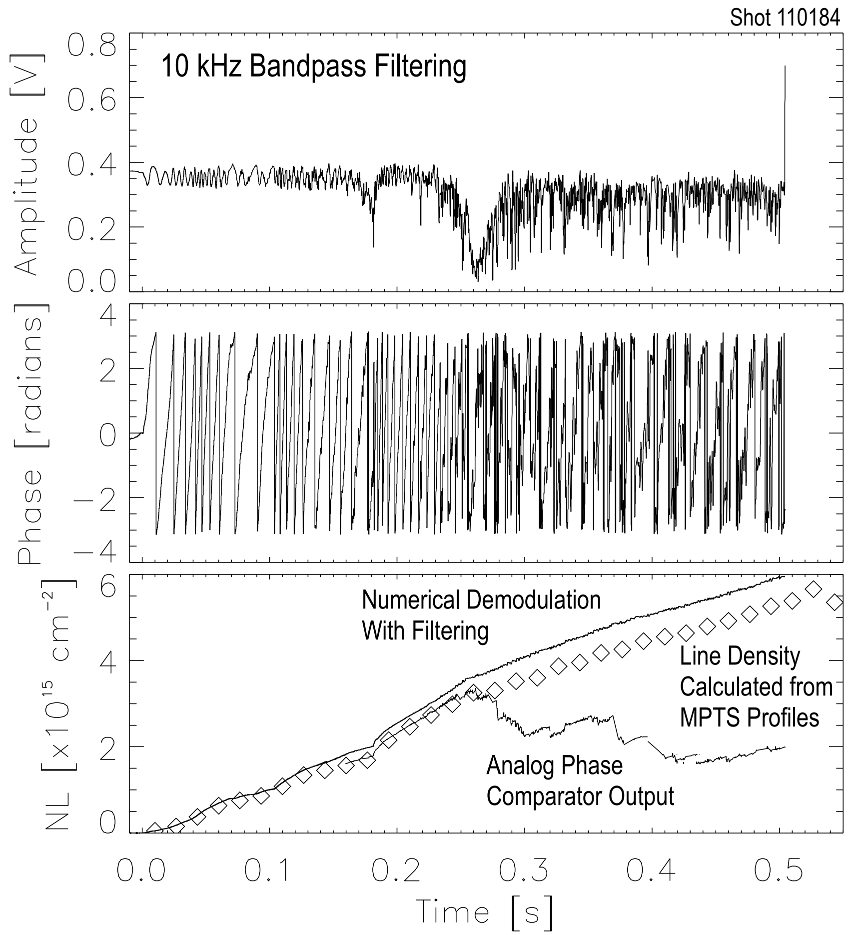
System Description, Capabilities and Status

NSTX

- Similar to systems already in use on DIII-D, Pegasus and HSX.
  - Single chord interferometer with radial view at NSTX midplane.
  - Simple design using quasi-optical components for beam transmission. Single solid-state source and mixer. Heterodyne detection via chirping source frequency.
  - Phase recovery via analog phase comparator (~750 kHz IF, BW ~150 kHz) or digital (software) phase comparator.
- Capabilities of current interferometer system.
  - Wavenumber resolution of fluctuations: $k \leq 1\ cm^{-1}$.
  - Bandwidth: ~150 kHz with analog phase comparator and digital phase comparator (utilizing current data acquistion). Can be much higher using faster digitizers with deep memory.
  - Phase noise: $(\Delta\phi)_{rms} = 0.022$ radians or $(\Delta n_e dl)_{rms} = 2.4 \times 10^{11}\ cm^{-2}$.
- Status.
  - System operational in spring 2003.
  - Limited number of shots so far. Comparison ongoing with MPTS.

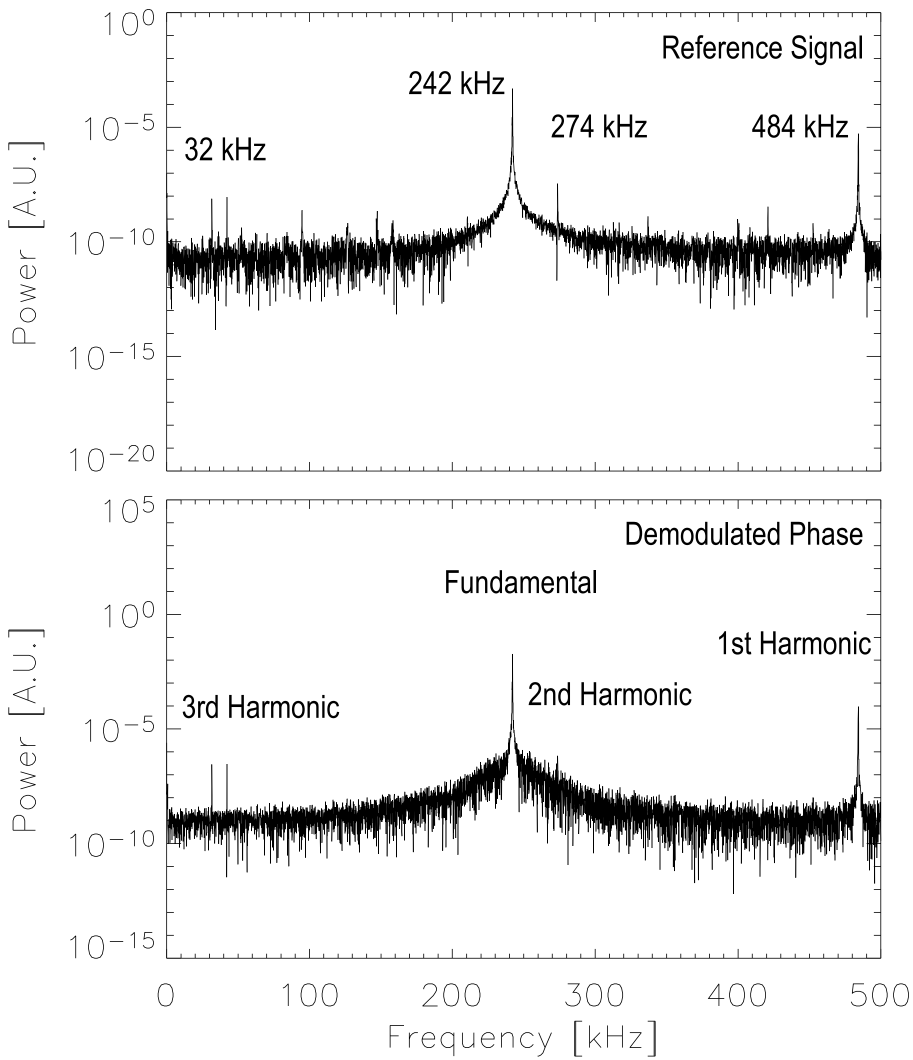
Reconstructed Line Density/Comparison With MPTS

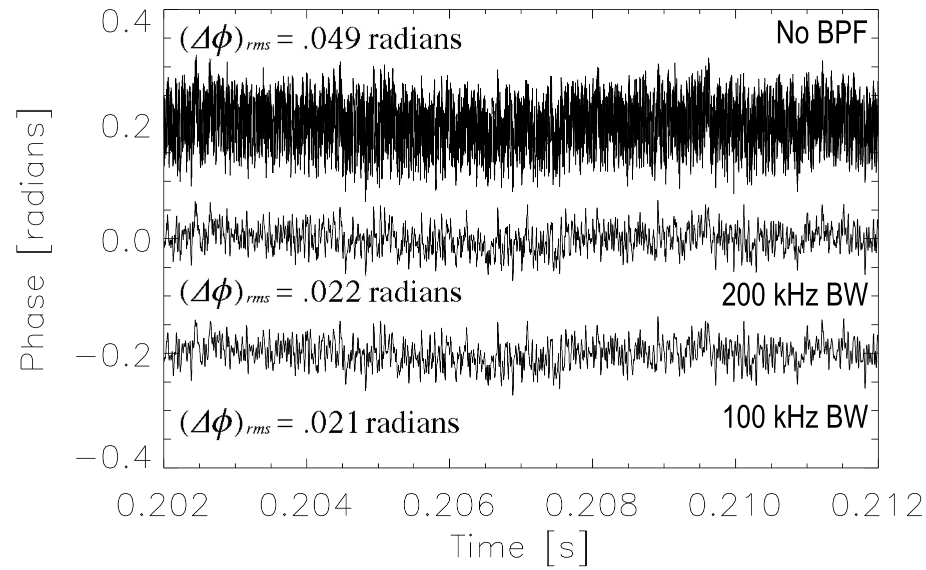




- Plots show analog phase comparator output as well as results from numerical demodulation. Also shown are line densities calculated from MPTS plots.
- Note that raw mixer IF signal at ~750 kHz is undersampled at 1 MSa/s. Hence, analog phase comparator has wider bandwidth and should be expected to perform better.
- Narrow bandpass filtering can reduce effects of fringe jumps due to fast phase fluctuations as well as amplitude drops at the cost of reduced bandwidth.
- Phase comparator and numerical demodulation results agree well with MPTS calculated line densities below ~2 $\times 10^{15}$ cm^{-2}. Comparisons are still ongoing.

Measurement Sensitivity/Phase Noise



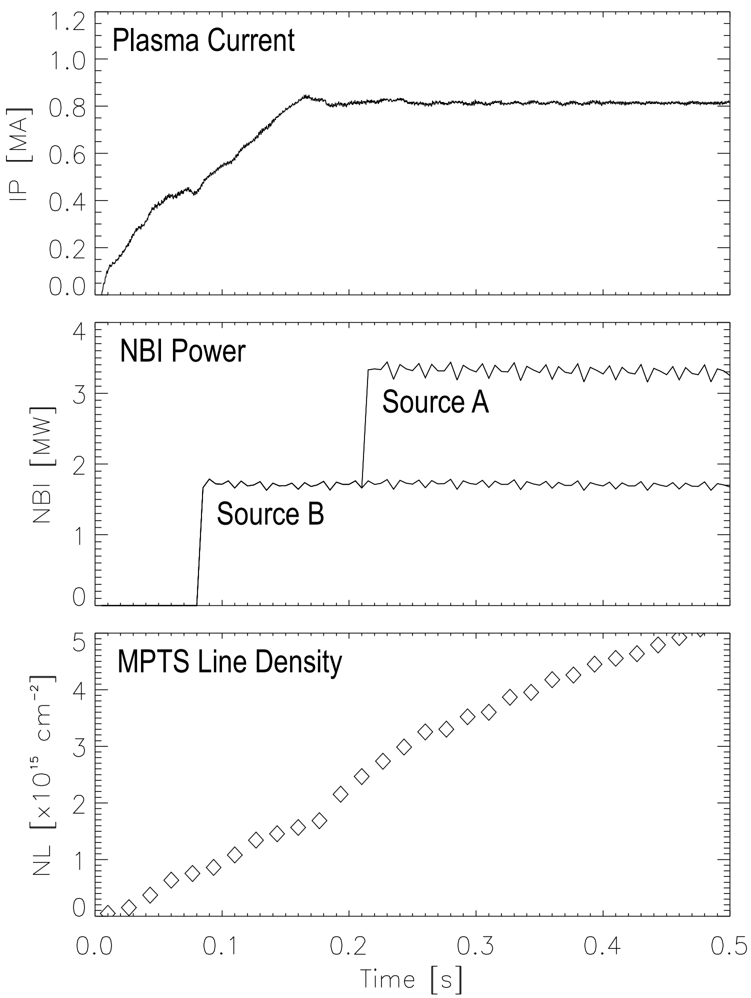


- IF fundamental frequency is 758 kHz. Signals were under-sampled with digitizer acquisition rate of 1 MSa/s.
- Reference sinusoid created by filtering sawtooth signal. Harmonics contribute to phase noise. Main contribution is from aliased 1st harmonic.
- Phase noise can be decreased by bandpass filtering. For 200 kHz bandwidth, this corresponds to:

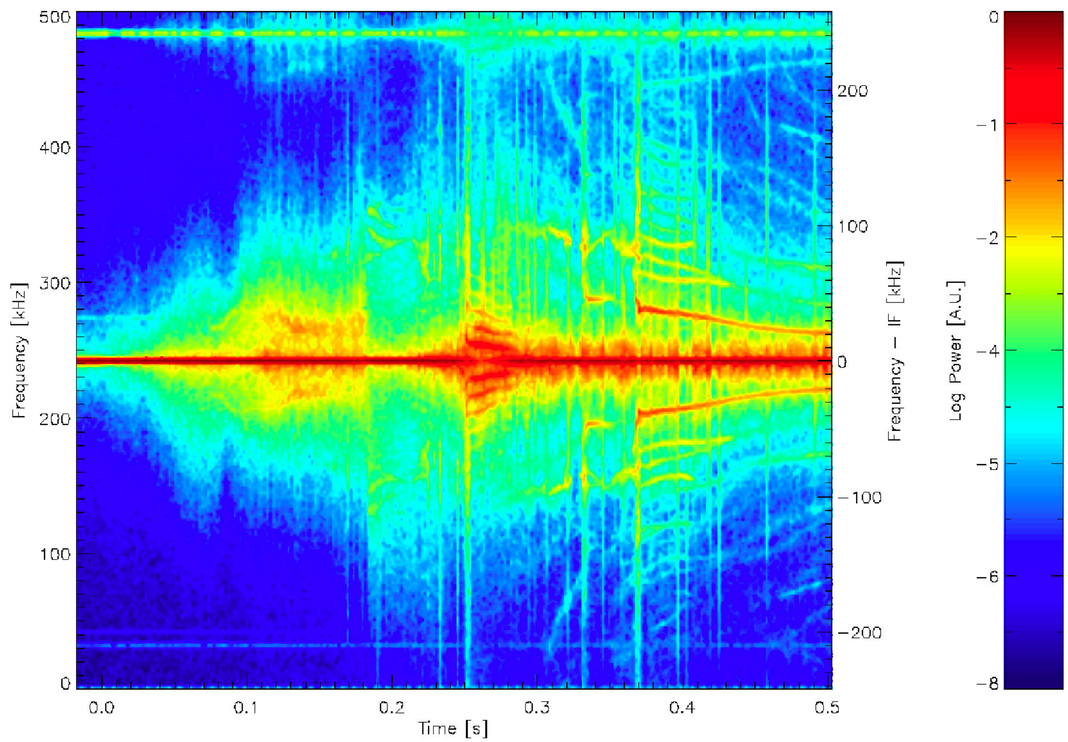
$$(\Delta n_e\, dl)_{rms} = 2.4 \times 10^{11}\ \mathrm{cm}^{-2}$$

IF Signal During Plasma Shot

Discharge Parameters for Shot 110184



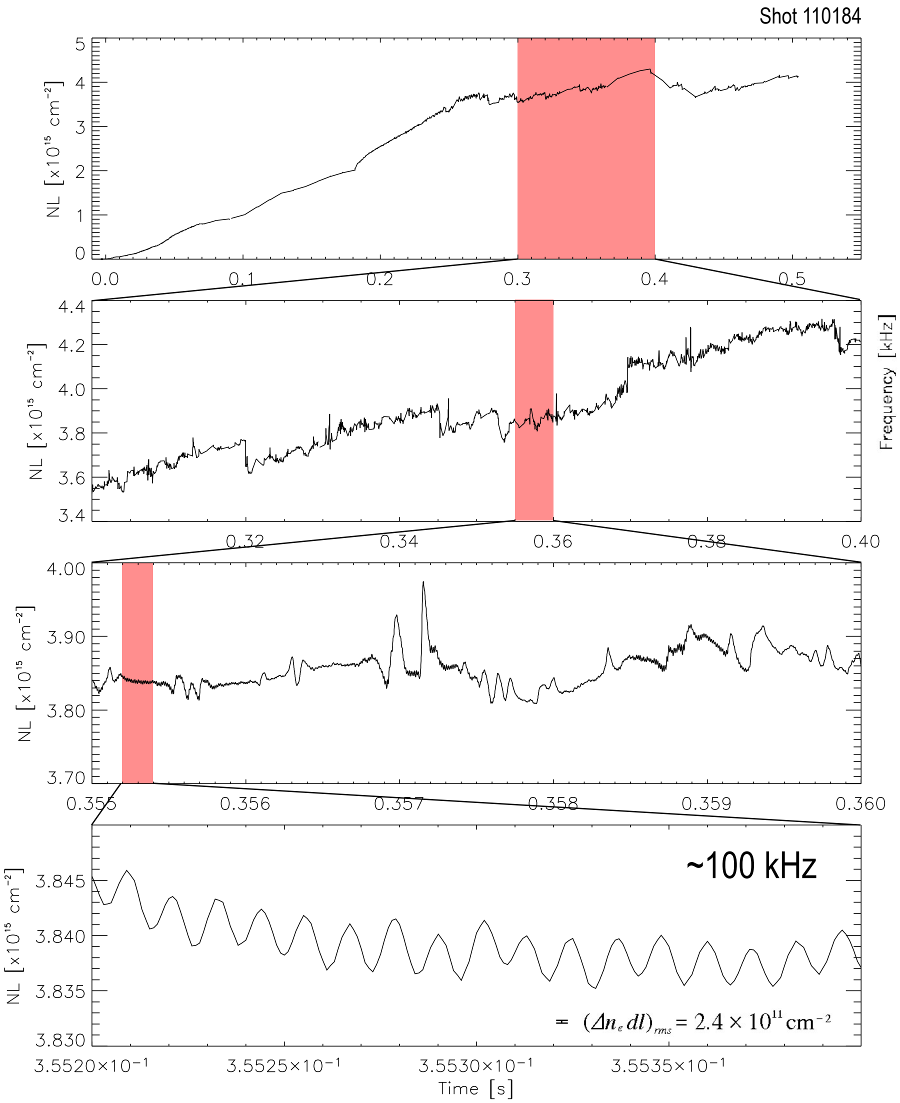
Spectrogram of IF Signal During Discharge



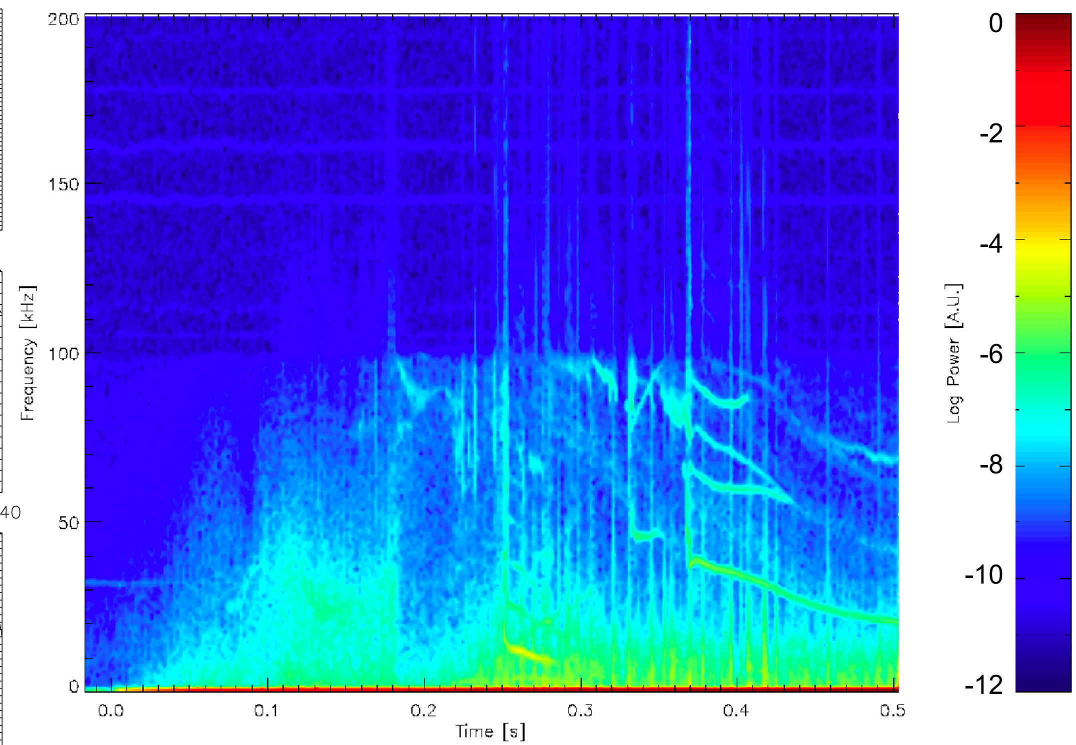
- Strong MHD activity at ~250 ms connected to signal loss.
- Note aliased FM signal, hence multiple harmonics are also evident.

Fluctuating Component of the Line Density

View of Line Density at Finer Scales



Spectrogram of Line Density



- ~70-150 kHz are TAE range of frequencies.
- For ~100 kHz fluctuations on left:

$$\bar{n}_e = 3.00 \times 10^{13}\,\mathrm{cm}^{-2}$$

$$\Delta\bar{n}_e = 2.15 \times 10^{10}\,\mathrm{cm}^{-2}$$

$$\Delta\bar{n}_e / \bar{n}_e = 0.0007$$

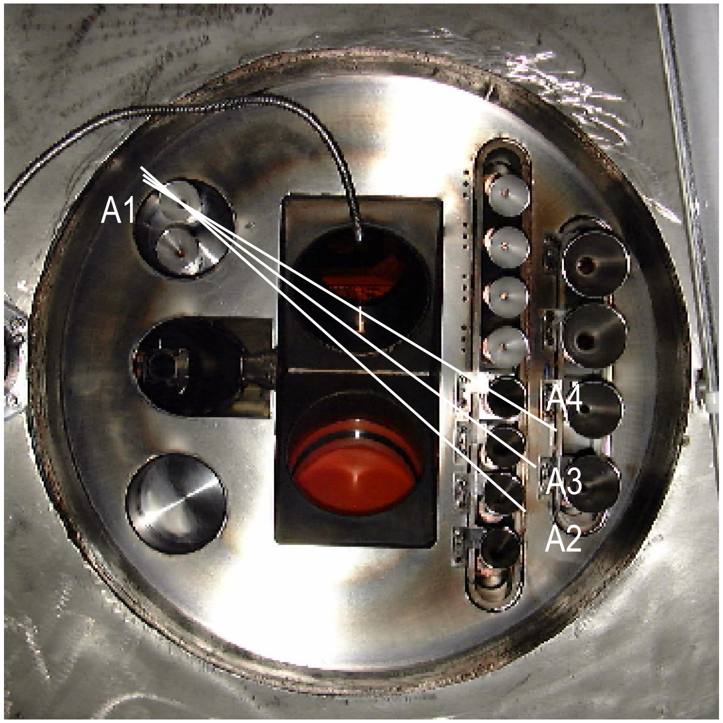
Summary of 1 mm Interferometer Results on NSTX

- Preliminary assessment and issues.
  - Interferometer is operational.
  - Line density monitor: Phase tracking or fringe jumps due to fluctuations or loss of signal (refraction) remain an issue. May be able to overcome jumps due to fluctuations by increasing response bandwidth (higher IF, faster digitizers). Better beam alignment may help with refraction effects (plasma is typically 5 to 15 cm below the midplane). Otherwise, options are to filter (reduce response bandwidth) over slowly varying portions of the discharge, or to use a numerical fringe jump algorithm (difficult to automate different plasma conditions).
  - Results track well with calculations from MPTS. Line density values are similar, but need to look at more shots.
  - Fluctuation monitor: Good sensitivity with wide bandwidth (~150 kHz).
  - These results are for neutral-beam heated discharges. Discharges with HHFW or combined heating may present additional challenges.
- Future plans.
  - Should be operational from day one when experiments resume in spring 2004.
  - Can use PCI-6115 digitizer (4 ch, 10 MSa/s, 8 MSa/ch). What is appropriate sweep frequency and sampling rate for NSTX?

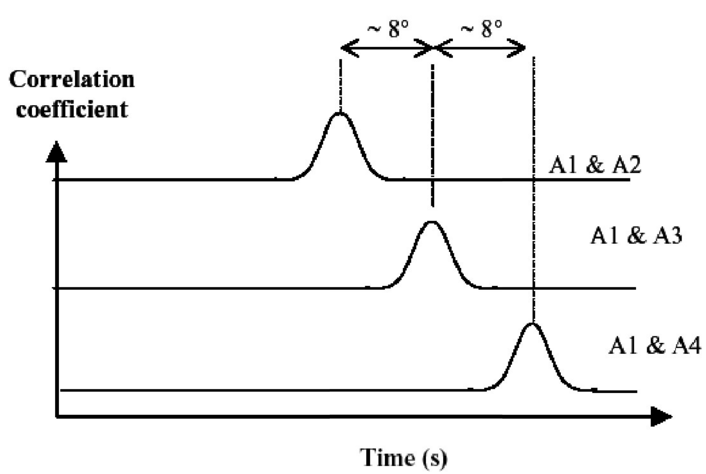
Importance of Internal Magnetic Field Measurements

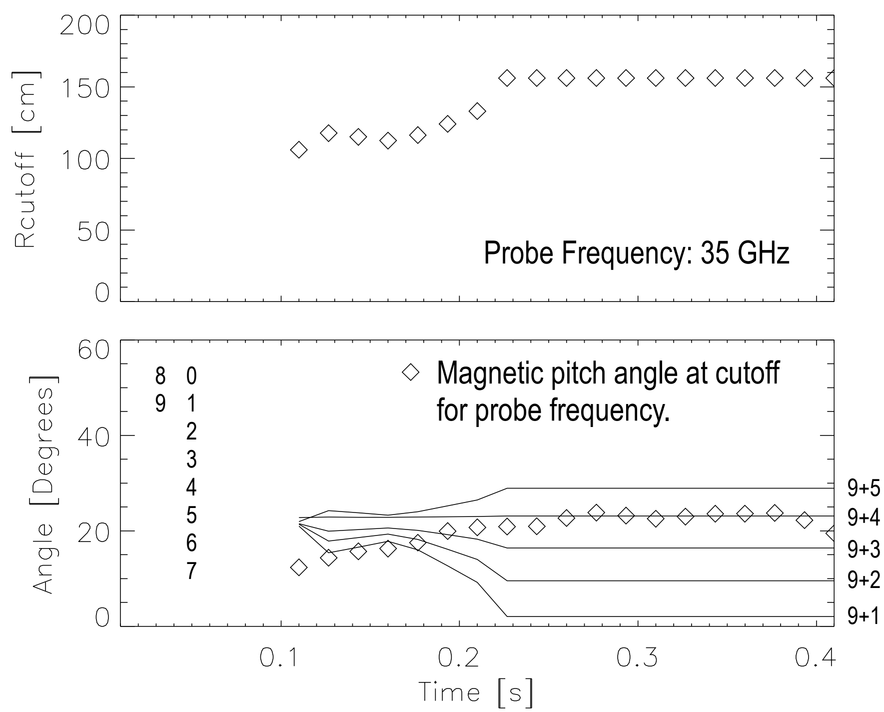
- Internal measurements of the magnetic field and *q* profiles are important for determining plasma equilibrium, stability, and transport properties of toroidal plasmas. Equally important for high field devices such as ITER and low field devices such as the ST.
- Other internal magnetic field diagnostics in development on NSTX.
  - MSE-LIF.
  - Tangential interferometry/polarimetry (FIReTIP). Successful implementation could be several years away.
- Radial correlation reflectometry performed on NSTX.
  - Turbulence radial correlation lengths.
  - PoP experiments for internal B field strength measurements.
- Here we explore the use of correlation reflectometry as a diagnostic for measurement of the magnetic field pitch angle. Method utilizes the concept that for naturally occurring turbulence in such devices, the correlation length along the field lines is large compared to other directions.

Diagnostic Concept of Magnetic Pitch Angle Measurement



Two toroidally separated arrays of vertically oriented reflectometers are utilized to search for the correlation of density fluctuations aligned along the magnetic field.



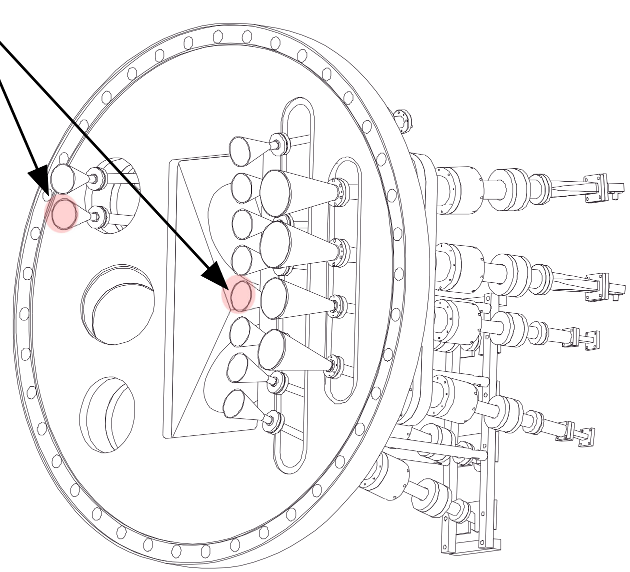


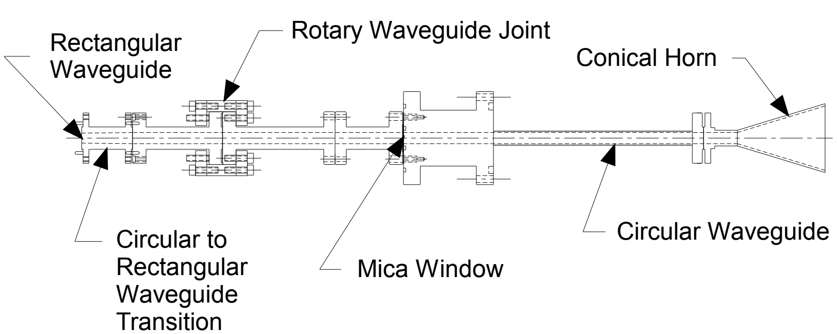
Calculation of magnetic pitch angle and angle between horn pairs using parameters from Shot 110055.

Location of Reflectometer Horn Arrays on Bay J

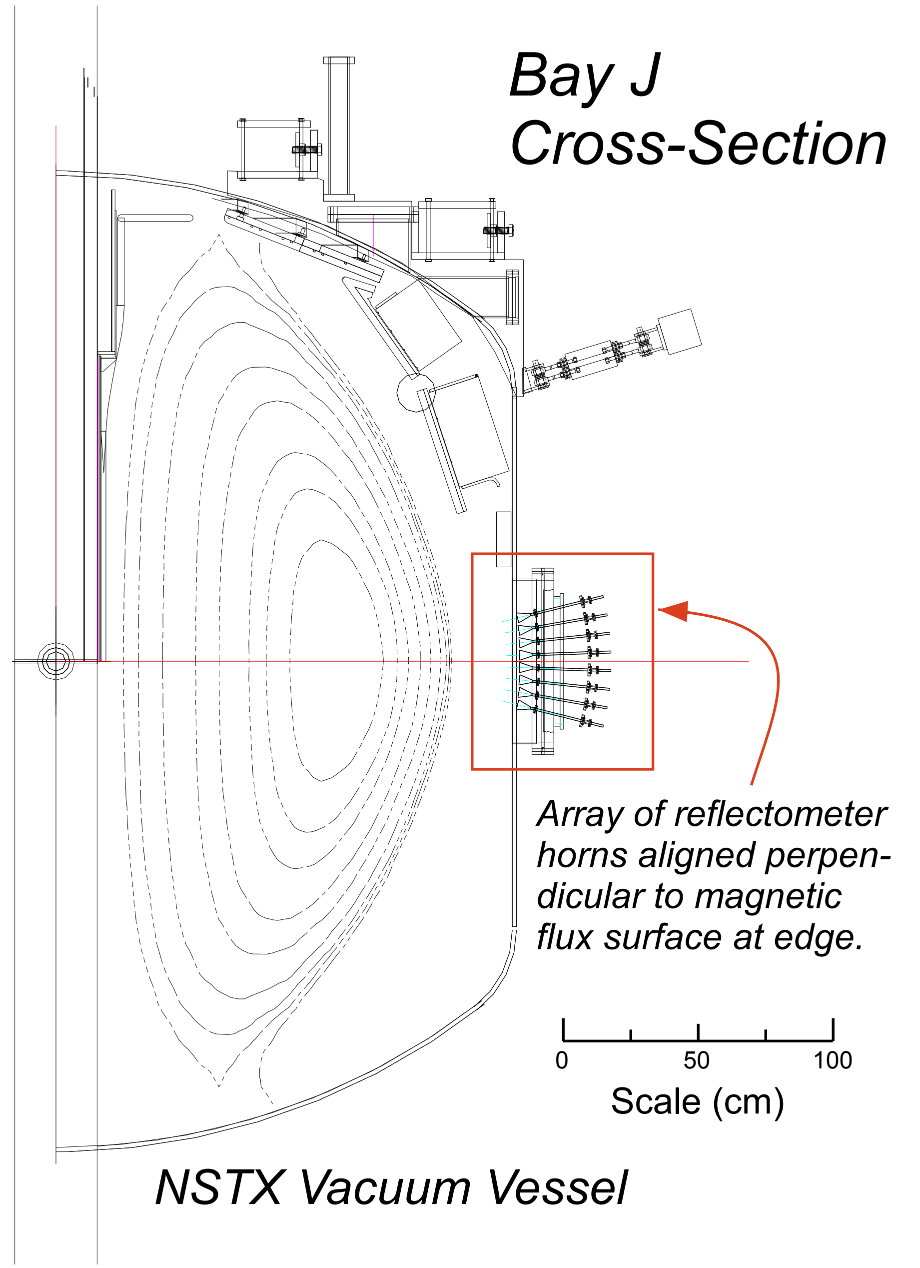
NSTX

Horn pairs used for this experiment.

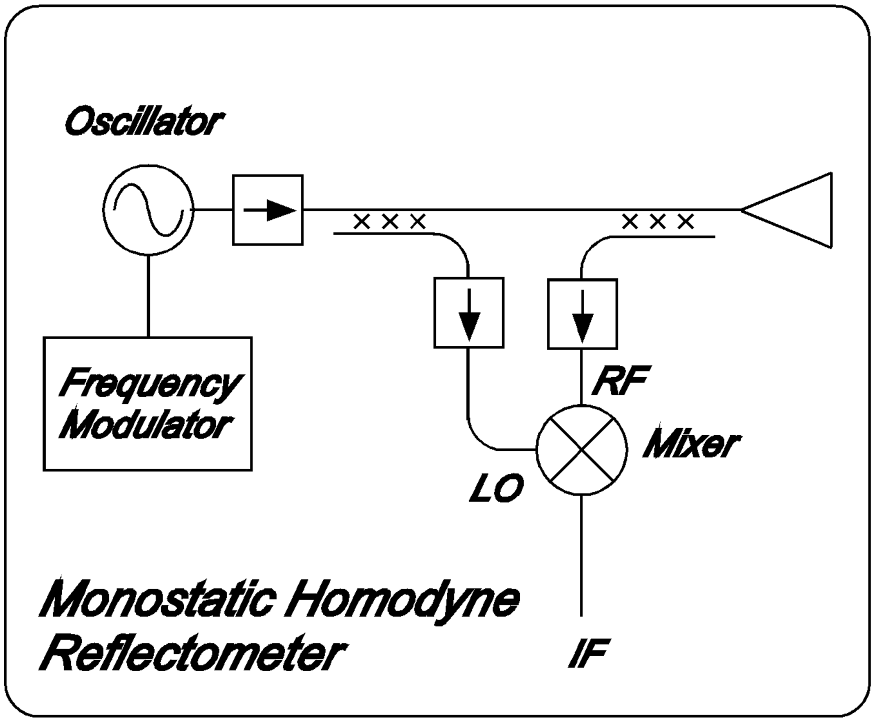


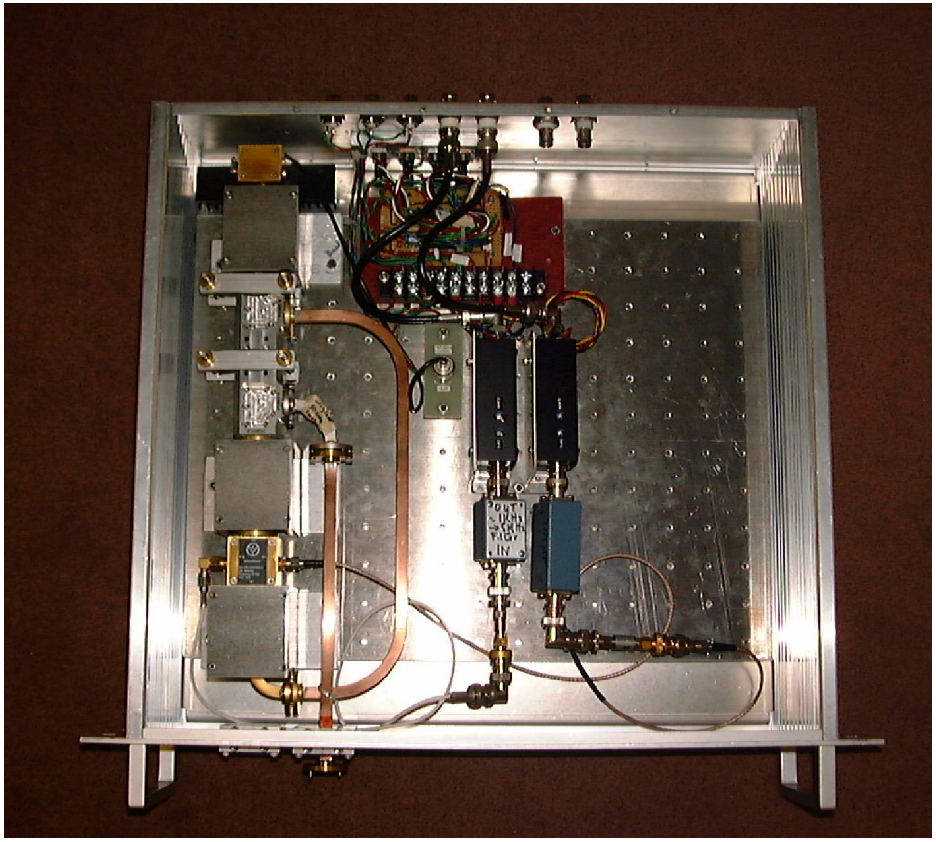


Rotary joint for matching polarization at edge.



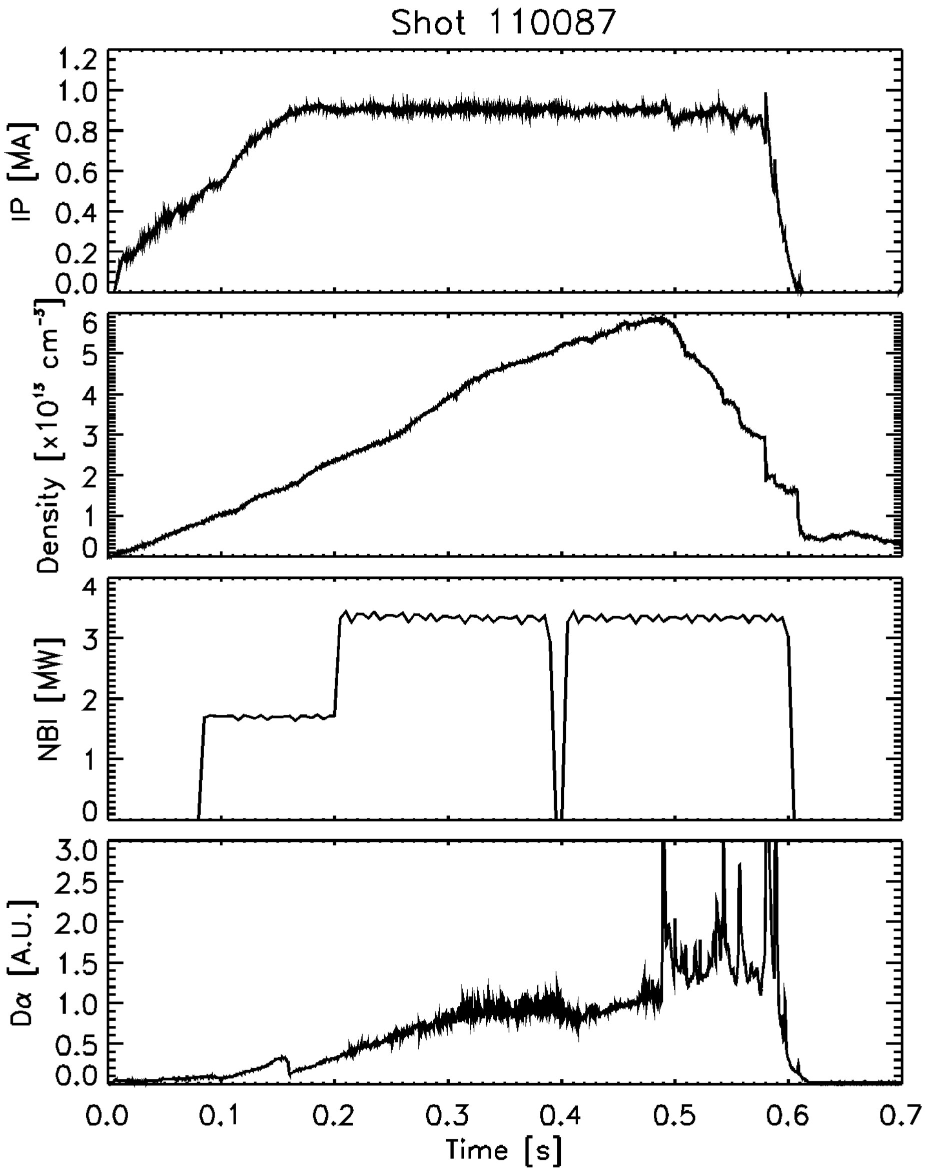
Correlation Reflectometer Circuit Diagram

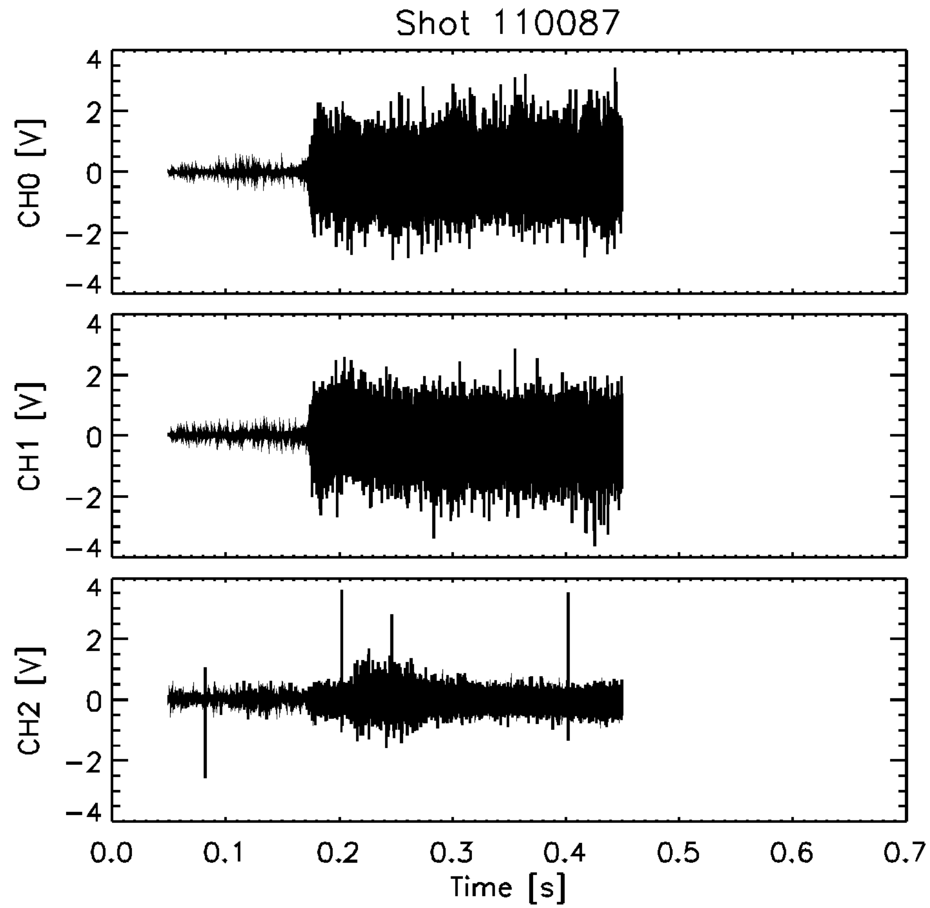




Typical Waveforms and Discharge Parameters

NSTX



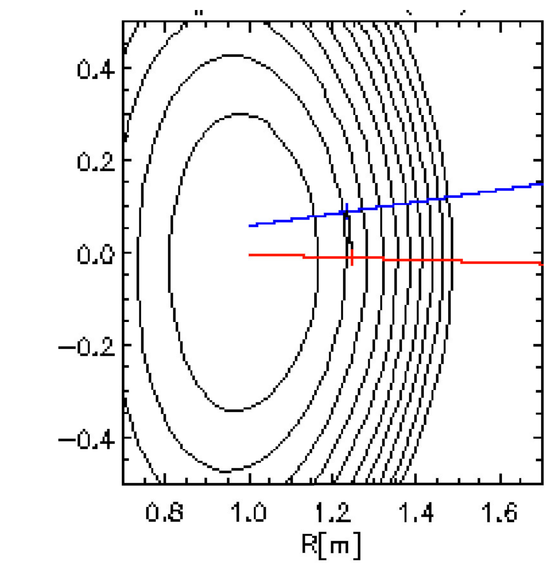


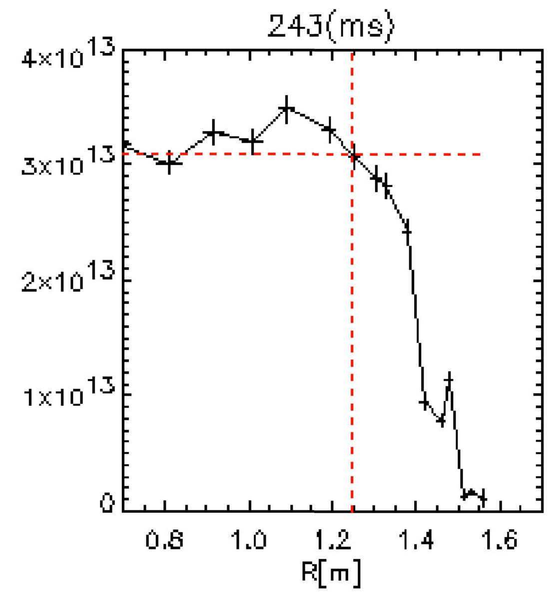
- CH0/CH1 are I/Q signals from reflectometer above midplane.
- CH2 is homodyne signal from reflectometer below midplane.

Analysis Methods: Horn Array/Field Line Alignment

NSTX

- Using EFIT results $\psi(R_i,Z_j,t_k)$, $F(\psi_l,t_k)=RB_t$ for fixed grid points, ψ and F are calculated for an arbitrary (R,Z) at t_k. (B_r,B_t,B_z) are calculated from ψ and F.
- Using the Thomson scattering electron density profiles $n_e(R_m,t_n)$, R of the critical density for 50 GHz and $\psi(R=R_m,Z=0,t_k)$ for the critical density (cutoff) are calculated.
- Intersection of two beams and cutoff layer are calculated. These are the reflection points and are used as starting points of the magnetic field line trace.
- Field lines from the two reflection points are traced back to each other using (B_r,B_t,B_z). Step size is 0.2 mm.
- Find the closest points on the field lines to the other reflection point, and calculate the distance between them. These lines and points are on the same flux surface. Distance between reflection points are ~20 cm.





Analysis Methods: Field Line Trace/Cross Correlation

NSTX

- Auto-correlation and normalized cross-correlation of signals.

  y_0: I-component of CH1.

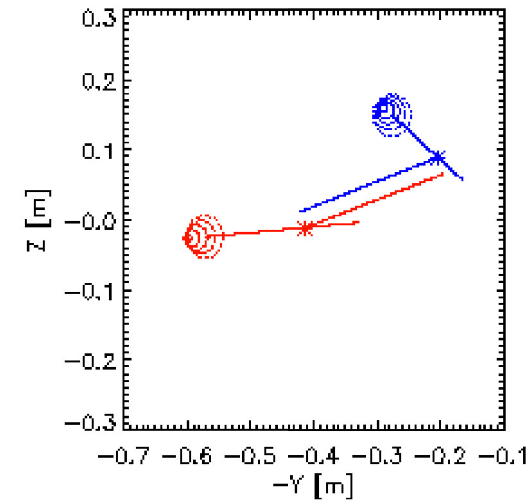
  y_1: Q-component of CH1.

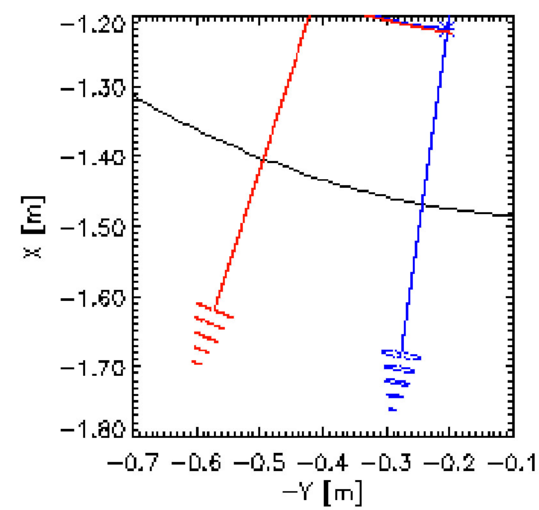
  y_2: Homodyne signal of CH2.

$$\left\langle \tilde{y}_0 \tilde{y}_0 \right\rangle_{\Delta T} \quad : \tilde{y}_0 = y_0 - \left\langle y_0 \right\rangle_{\Delta T}$$

$$\frac{\left\langle \tilde{y}_0 \tilde{y}_2 \right\rangle_{\Delta T}^2}{\left\langle \tilde{y}_0 \tilde{y}_0 \right\rangle_{\Delta T} \left\langle \tilde{y}_2 \tilde{y}_2 \right\rangle_{\Delta T}} + \frac{\left\langle \tilde{y}_1 \tilde{y}_2 \right\rangle_{\Delta T}^2}{\left\langle \tilde{y}_1 \tilde{y}_1 \right\rangle_{\Delta T} \left\langle \tilde{y}_2 \tilde{y}_2 \right\rangle_{\Delta T}}$$

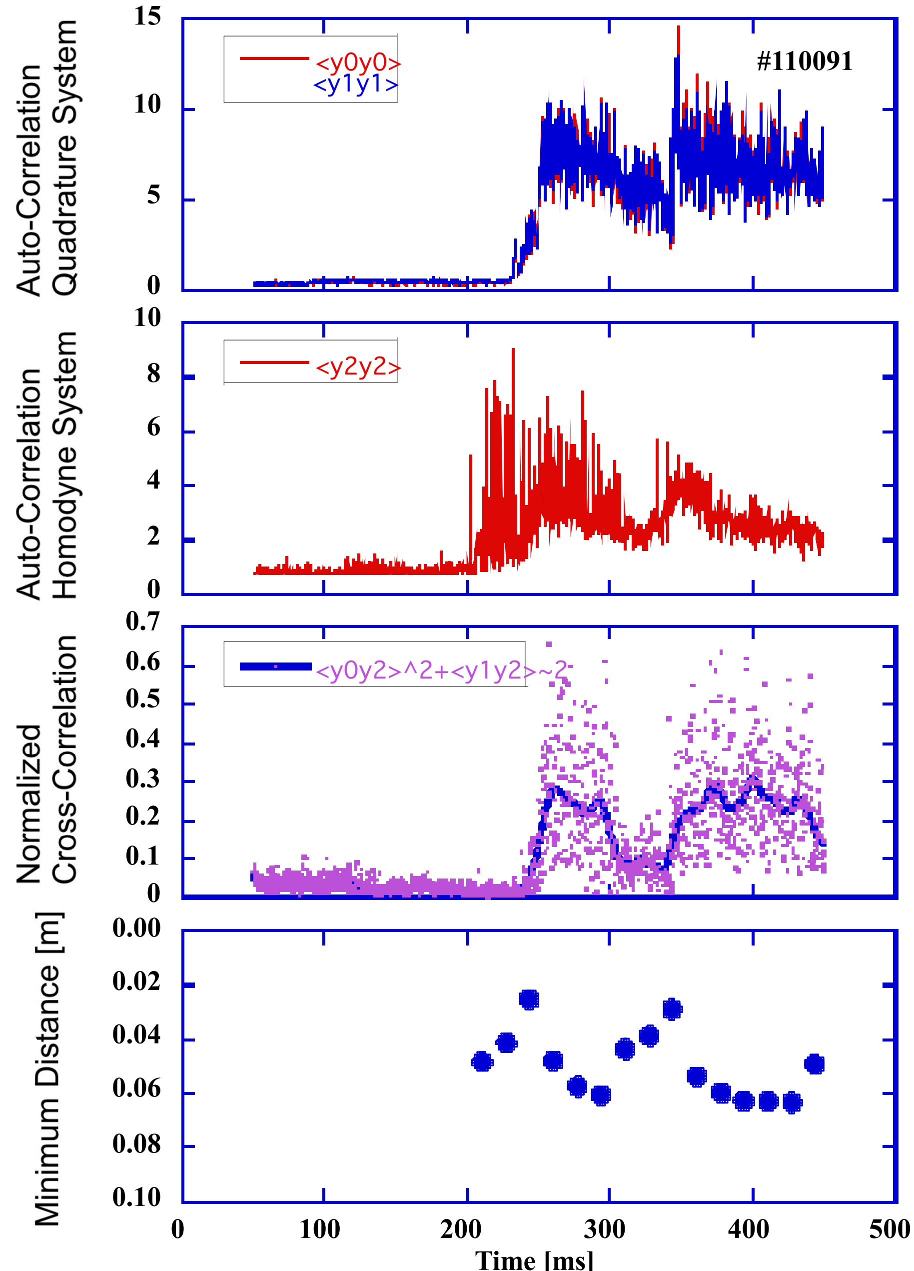
- Hardware (bandpass, 5 kHz-5 MHz) and numerical (highpass, >20 kHz) preprocess filtering. ΔT in the range of 10-50 μs shows, structures. ΔT is chosen to be 20 μs in the following analysis.





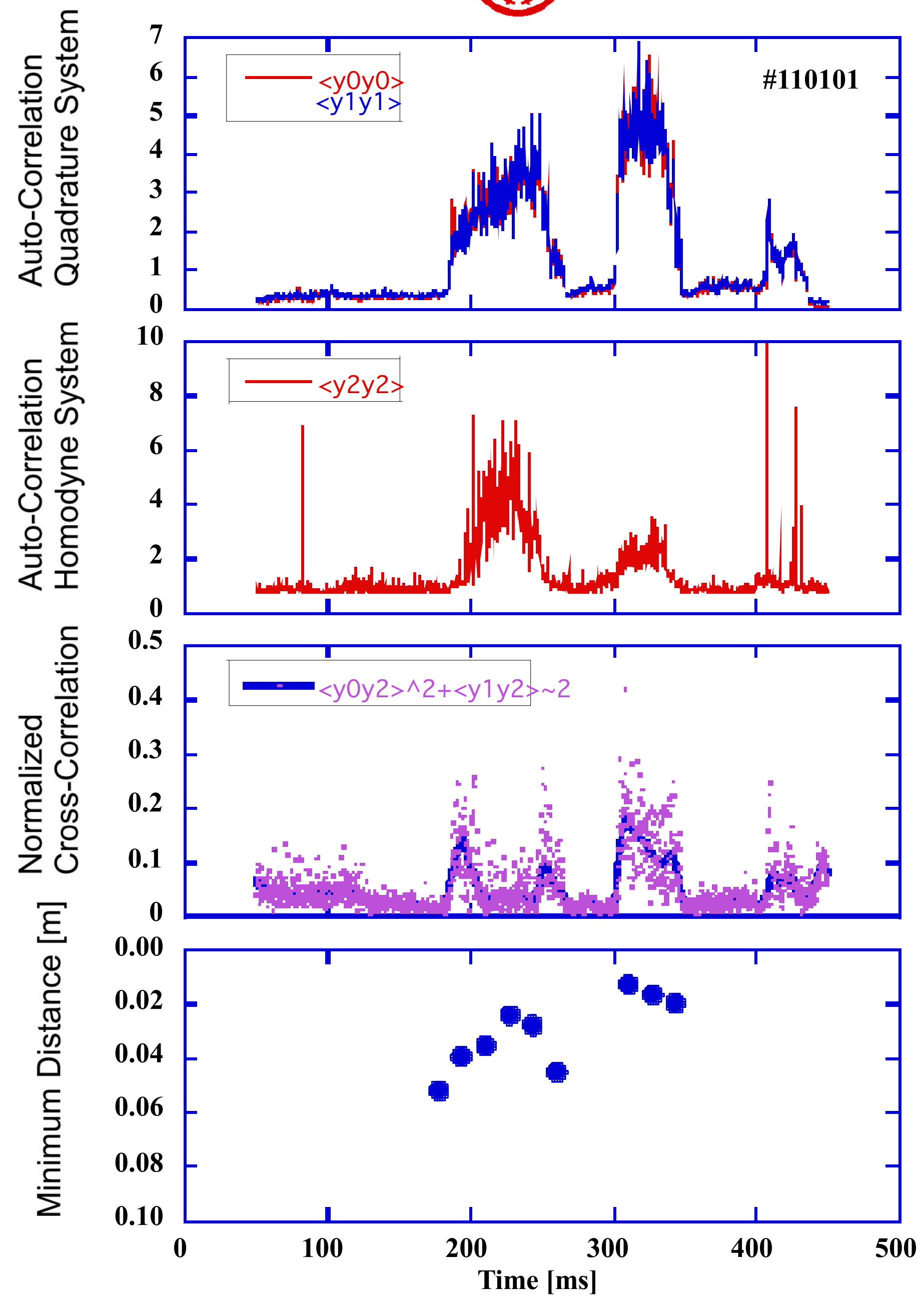
Normalized Cross-Correlation vs. Minimum Distance

- Normalized cross-correlation shows much scattter, but is very large for some points.
- Minimum distances (calculated at the timing of the Thomson scattering data) are typically 1-7 cm. Points without a cutoff are not shown in the bottom figure.
- Maximum correlation is expected to occur at minimum distance.
- Since the profile is rather flat, slight systematic and random errors in the density can cause large errors in the minimum distance.
- Analysis performed with EFIT01 calculations (external magnetics only).
- The above analysis assumes that both reflectometers are operating at 50.0 GHz. Actual frequencies were 49.9 and 50.1 GHz, corresponding to Δn of 2.5×10^{11} cm^{-3}.



Normalized Cross-Correlation vs. Minimum Distance

- Time behavior of normalized cross-correlation is different from auto-correlation.
- When cutoff density appears or disappears, reflected power shows box-like behavior in auto-correlation. Cutoff appears near center and moves outward, disappears moving inwards.
- Peak in cross-correlation appears at beginning and end of box-like behavior. Qualitatively consistent with behavior of minimum distance, but not always quantitatively.



Summary for Magnetic Pitch Angle Diagnostic

NSTX

- PoP exploration of correlation reflectometry as a magnetic pitch angle diagnostic are ongoing. Analysis carried out on a handful of data taken while diagnostic was being commissioned.
- Two sets of O-mode reflectometers (quadrature and homodyne) used to measure at two points separated by ~20 cm.
- Time evolution of normalized cross-correlation shows several peaks, which seem different from the auto-correlation.
- Time evolutions of the normalized cross-correlation and the minimum distance were compared. Calculated minimum distance ranged from 1 to 7 cm.
- Correlation between minimum distance and maximum normalized cross-correlation was not clear cut quantitatively, although qualitatively they are consistent with the plasma behavior.
- More measurements when NSTX operations resume in spring 2004.

Overall Summary

- UCLA now has an array of millimeter-wave diagnostics with diverse measurement capabilities:
  - FMCW reflectometer (density profile and slow fluctuations <10 kHz).
  - Fixed frequency 3 channel quadrature reflectometers (density fluctuation level for high frequency fluctuations <5 MHz)
  - Radial correlation reflectometer for turbulence scale lengths and magnetic field strength.
  - 1 mm interferometer (line density monitor and fluctuations into 100's of kHz range)
  - Magnetic pitch angle measurement using correlation reflectometry (PoP).
- Additional systems to come online during FY04
  - Edge FMCW reflectometer system (densities $< 2\times10^{12}$ cm^{-3}).
  - Dedicated quadrature reflectometer system.
- Experiments for FY04 should allow simultaneous operation of many of above systems. Measurements will complement each other.

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