# Reflectometer Measurements of Edge Density Profile for ICRF Coupling Studies on NSTX

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# Abstract

**Reflectometer Measurements of Edge Density Profile for ICRF Coupling Studies on NSTX** J.B. Wilgen, G.R. Hanson, T.S. Bigelow, D.W. Swain, P.M. Ryan, M.D. Carter, ORNL; J. R. Wilson, PPPL, and the NSTX Team - Plasma loading of the HHFW (High Harmonic Fast Wave) antenna on NSTX is sensitive to details of the electron density profile in the plasma edge region. A microwave reflectometer with access through the HHFW antenna is used to measure the time-dependent edge density profile during ICRF heating experiments. A single broadband reflectometer covering the frequency range of 6-26 GHz provides the capability for probing the density range from below 1.0 $x10^{17}$ $m^{-3}$ up to nearly $1.0x10^{19}$ $m^{-3}$. A pair of circular waveguide launchers is used to provide externally adjustable wave polarization to match the pitch angle of the magnetic field lines at the edge of the plasma. Extraordinary-mode reflectometer data acquired using 100 microsecond sweep times has been used to reconstruct edge-density profiles in front of the HHFW antenna. Using these measured profiles, the loading of the plasma on the antenna has been calculated using the RANT3D code.

Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Dept. of Energy under contract DE-AC05-00OR22725

# Outline

- System description of broadband microwave reflectometer

- Recent reflectometer improvements
  - Sweep time reduced to 100 μsec
  - Use X-mode to reduce starting density
  - Replaced Sin(ϕ) detector with I&Q detector

- Data analysis progress
  - Now providing time-averaged density profiles
  - More flexible profile reconstructions (less assumptions)
  - Working toward limited automation

- Initial look at fluctuation measurements
  - Are now setup for remote control of arbitrary sweep waveforms
  - Can reconfigure from profile to fluctuation setup between shots

- Future plans and some possible options
  - Improved analysis throughput - automation
  - Faster data acquisition sampling rate to reduce sweep time
  - Fluctuation measurements
  - Look at 30-MHz component of reflectometer signal when doing 30-MHz rf heating

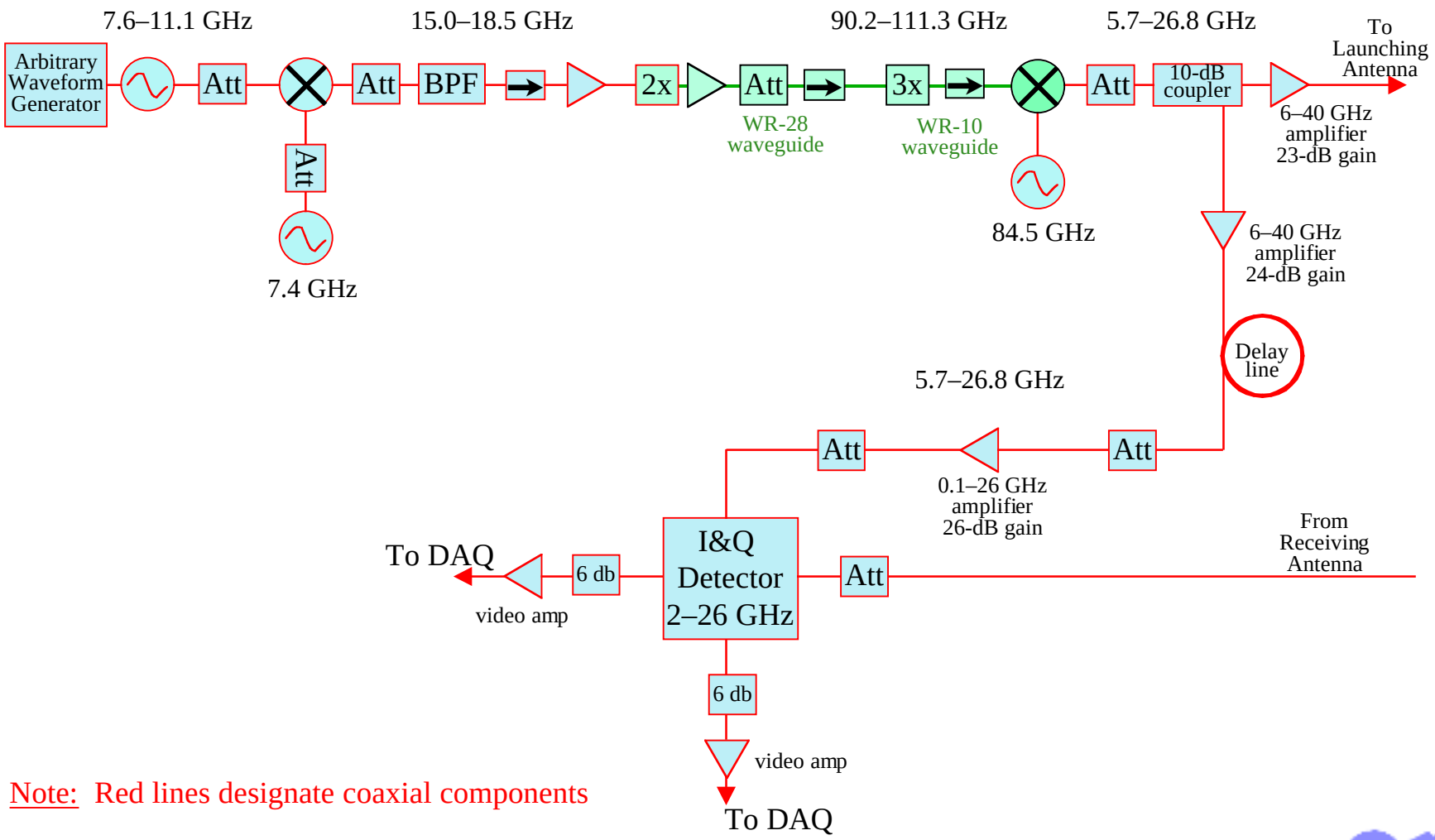
# HHFW Broadband Microwave Reflectometer - Description

- **Purpose:** Measure the edge density profile directly in front of the HHFW antenna, primarily in the scrape-off layer in the gap between the outermost flux surface and the antenna

- Launcher access located between current straps #2 & #3 of HHFW antenna
  - Transmit/receive antennas recessed 1" behind the Faraday screen
  - Launchers are fed by broadband dual-ridged coax-to-waveguide adapters
  - Polarization easily changed by rotation of these adapters to match pitch angle
  - Connect to reflectometer using 40 GHz low loss coaxial cables

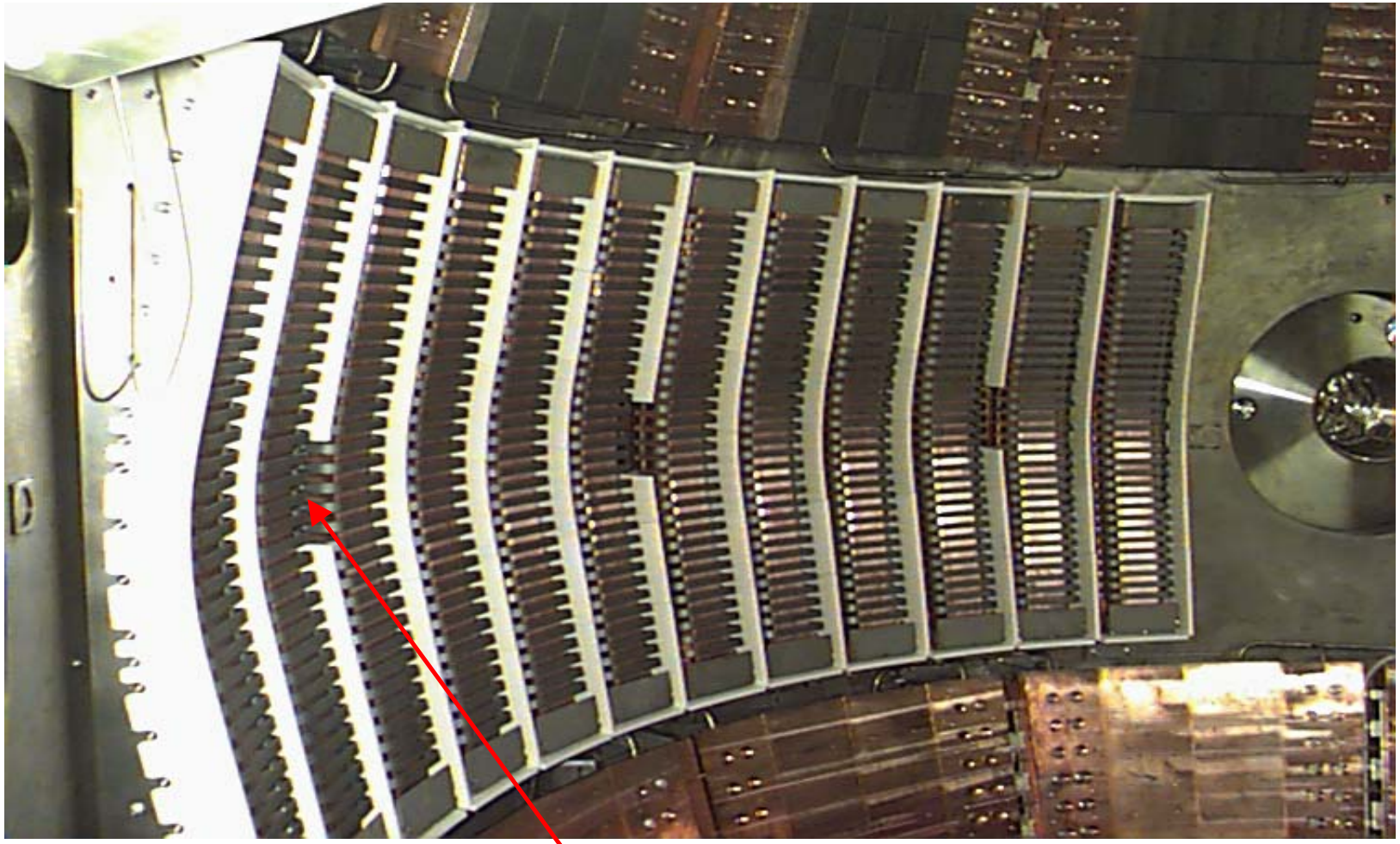
- Status for latest run period (May - July, '01)
  - Sweep time: 100 μsec
  - Frequency range: 5.74 to 26.8 GHz
  - X-mode polarization, sweep starts with $f < f_{ce}$ (for B>0.3 T)
  - Density range: 0.01 to 6.0 x $10^{12}$ $cm^{-3}$
  - Due to the low starting density, the starting point for profile reconstruction is normally located at the leading edge of the Faraday screen (in most cases)

# NSTX HHFW Broadband Reflectometer Microwave Circuit Diagram (5.7–26.8 GHz)




Note: Red lines designate coaxial components

# HHFW antenna installed in the NSTX vacuum vessel showing BN limiters surrounding each strap



Location of ORNL microwave reflectometer used for edge density profile measurements

# Recent Reflectometer Improvements (July 2001)

- Sweep time reduced from 200 to 100 μsec
  - reduced effects of density fluctuations
  - made significant improvements in quality of phase data

- Analog sweep driver replaced by a digital arbitrary waveform generator
  - improved stability eliminates drift in the phase calibration
  - allows remote switching between profile measurement and fluctuation measurement
  - enables linearization of frequency sweep (not yet attempted)

- Replaced Sin($\phi$) detector with a broadband quadrature phase detector
  - improved phase accuracy and fringe tracking
  - frequency range limited to 27 GHz maximum

- Have utilized remote operation of arbitrary waveform generator to obtain some initial fluctuation data in frequency stepping mode

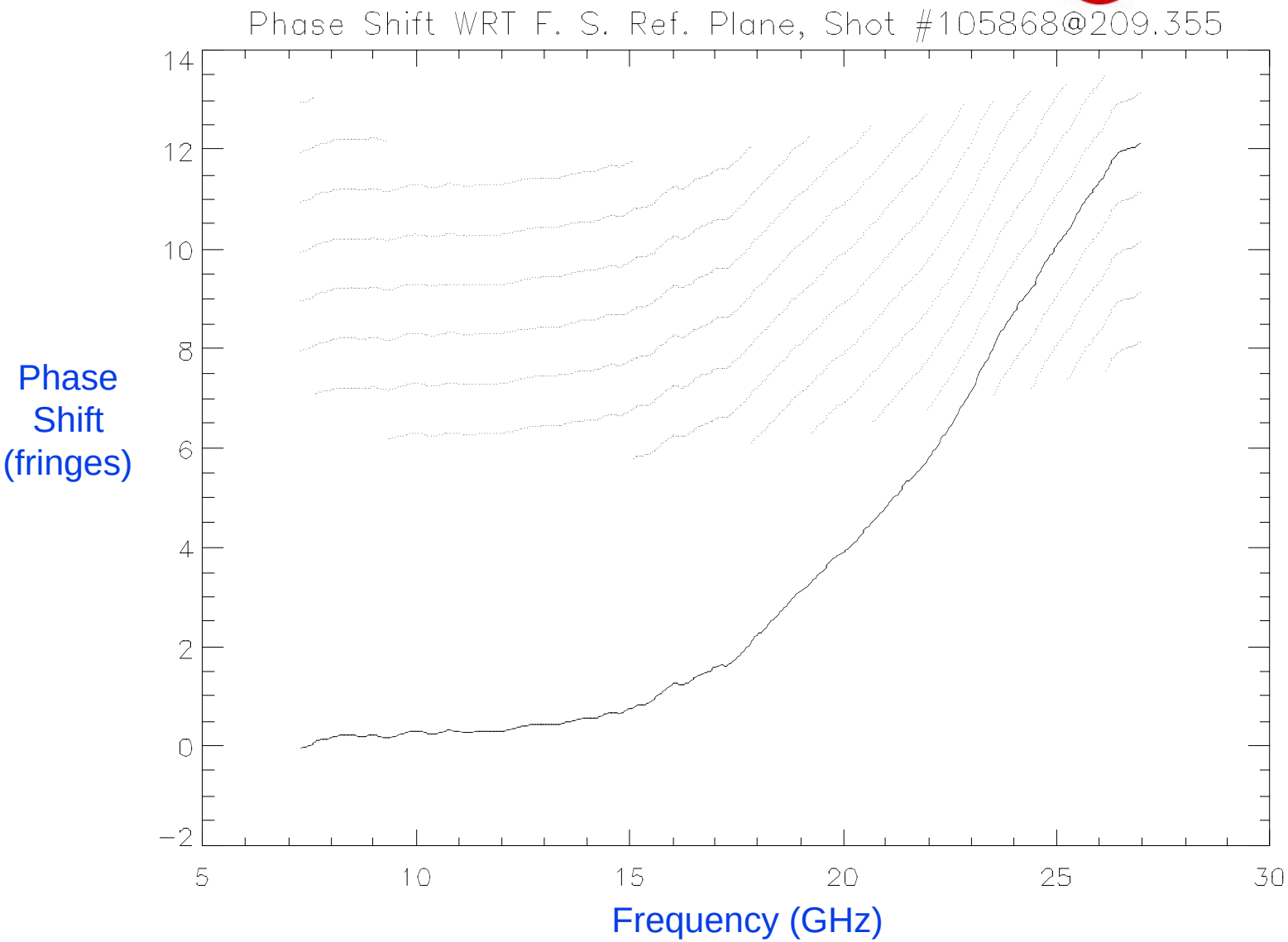
# Recent Progress in Data Analysis

- Now providing time-averaged density profiles by averaging together the phase data from multiple sweeps
  - ICRF antenna coupling depends on an average edge-density profile, spatially-averaged over the entire surface of the HHFW antenna
  - The reflectometer provides a highly localized measurement
  - Time averaging of the locally measured profile provides a better indication of the spatially-averaged density profile
  - Best way to do this is to average the phase data from multiple sweeps

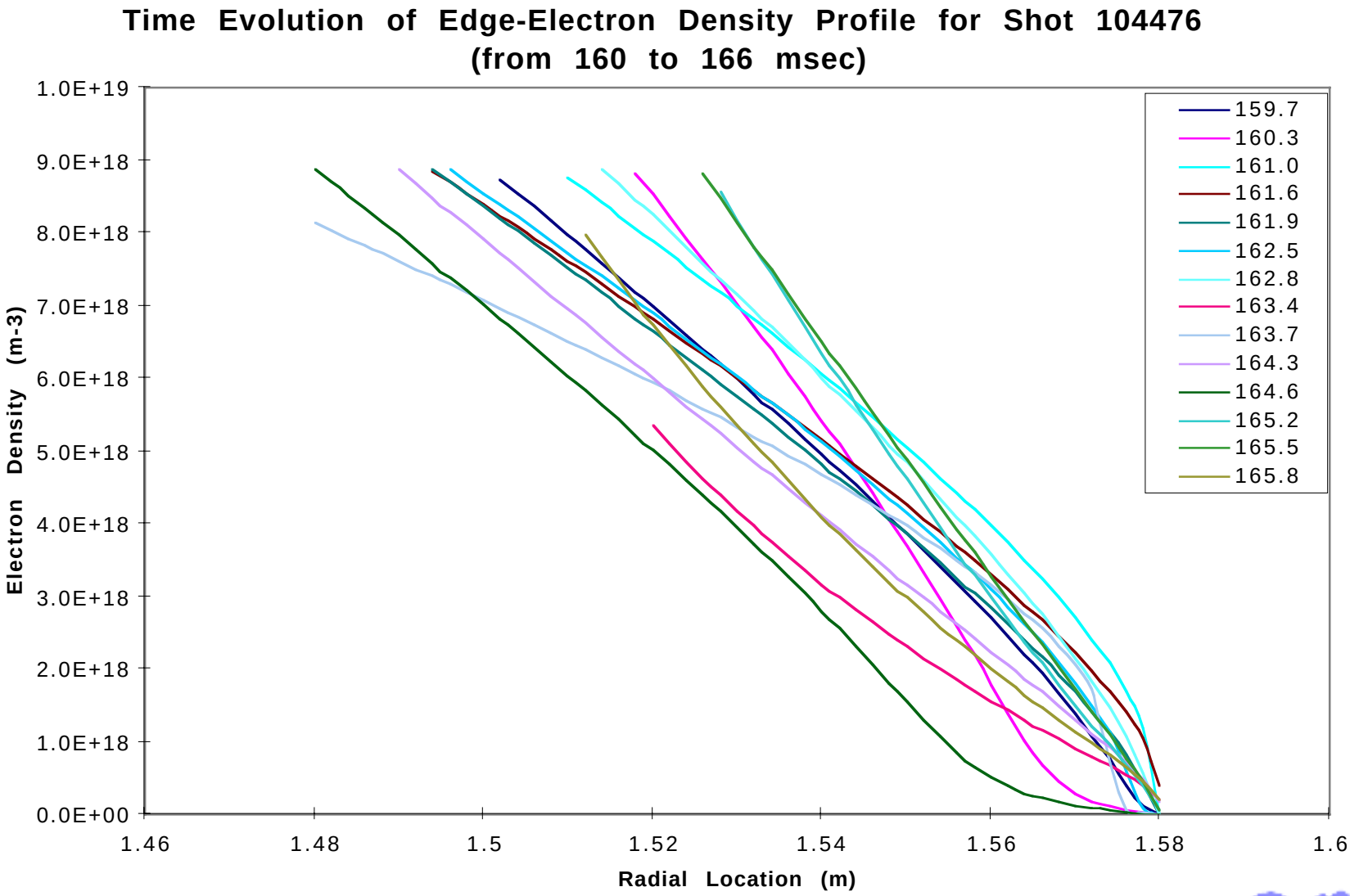
- Faster sweep time (100 μsec) simplifies data analysis - can replace polynomial fitting of phase data with simple smoothing
  - Initially used polynomial fit to smooth out effects of density fluctuations
  - Smoothed phase data more closely follows the raw data
  - Data is no longer artificially distorted by the fit

- Now using EFIT mod-B data to determine frequency range of X-mode data

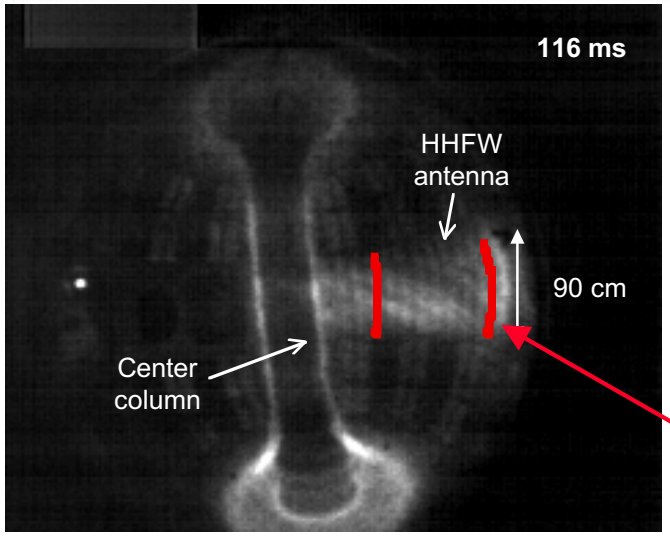
# Example of Typical Unfiltered Phase Data
# 100 μsec Sweep Time

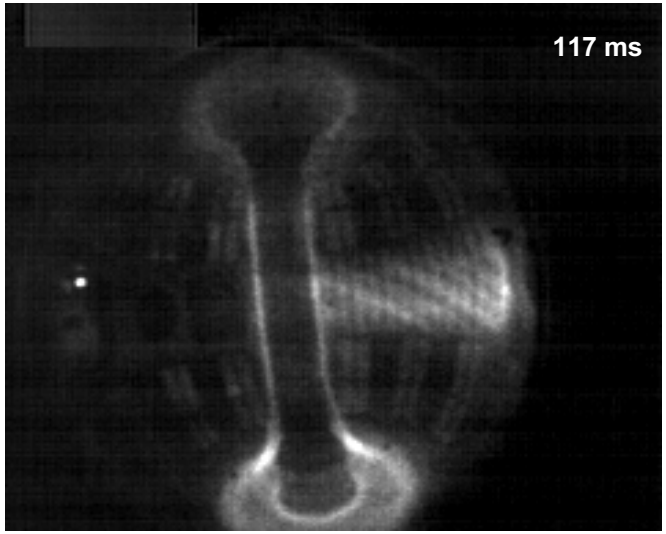


# The Edge-Density Profile Shows Large Fluctuations



# Large Scale Density Fluctuations are Also Observed by Visible Light Camera




Pictures from R. Maqueda[1] of edge turbulent filaments over the HHFW antenna.

"Illuminated" by natural recycling from the Faraday shield.

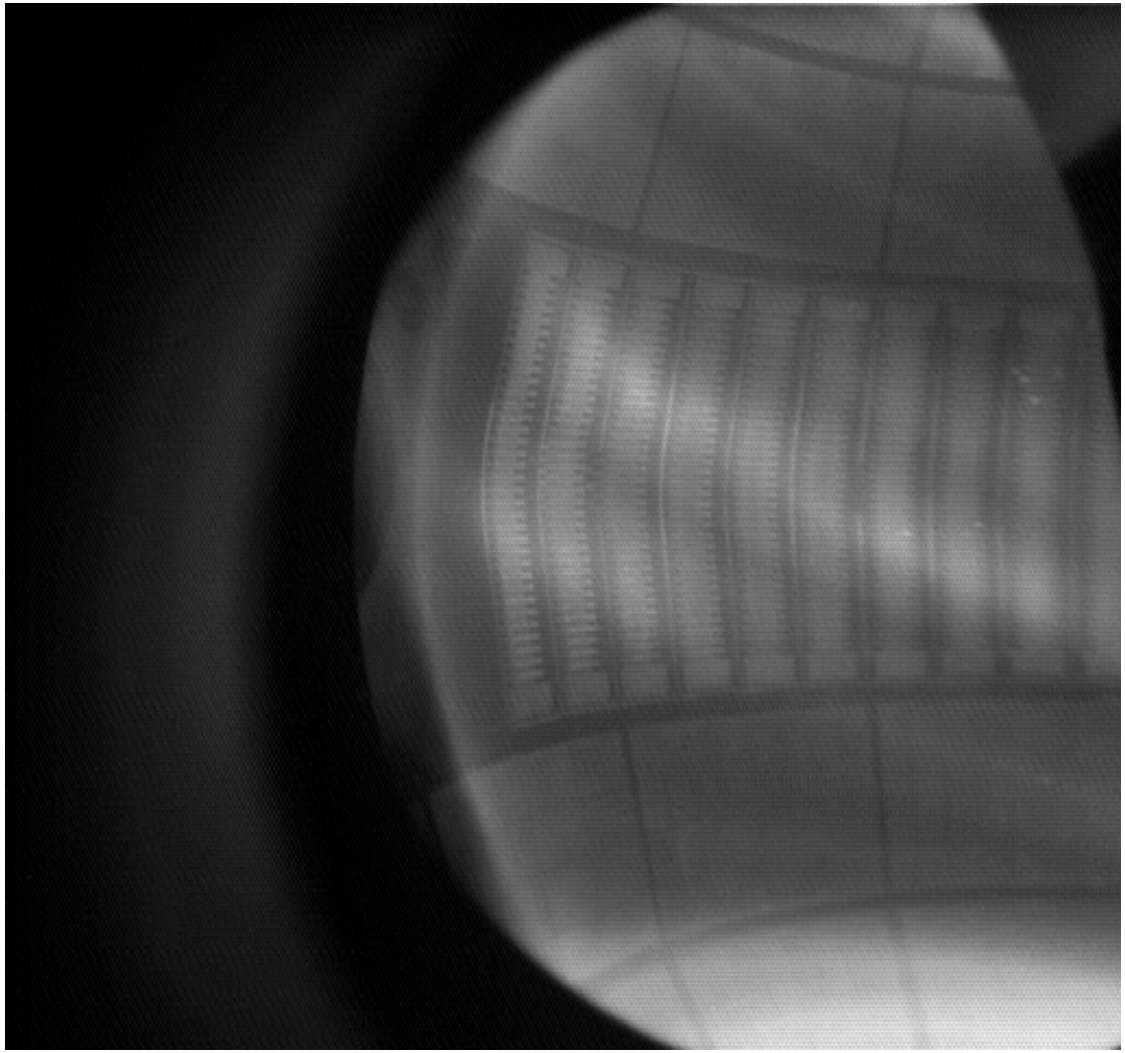
20 μs exposure time, no interference filter.

Red curves show approx. locations of two of the antennas (e.g, antennas 7 and 12) that are connected together in one loop.

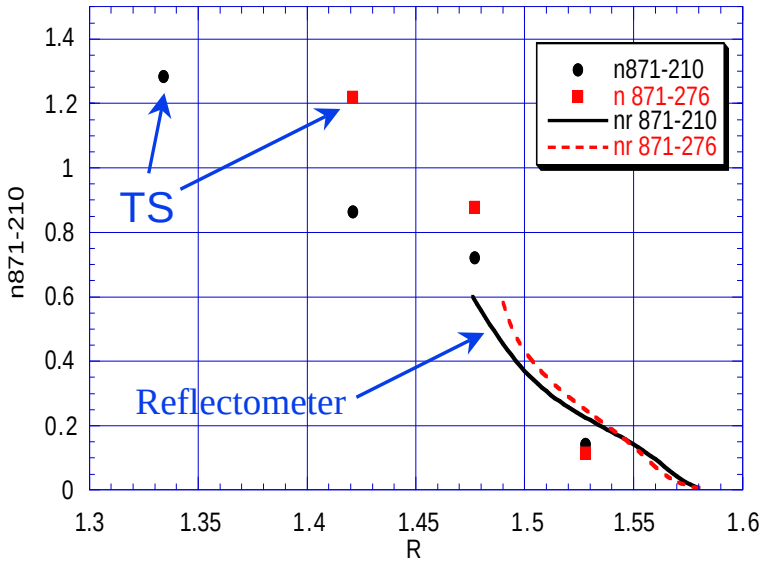
Presence of striations is *independent* of presence of rf. Pictures were taken with $P_{rf} = 0$.

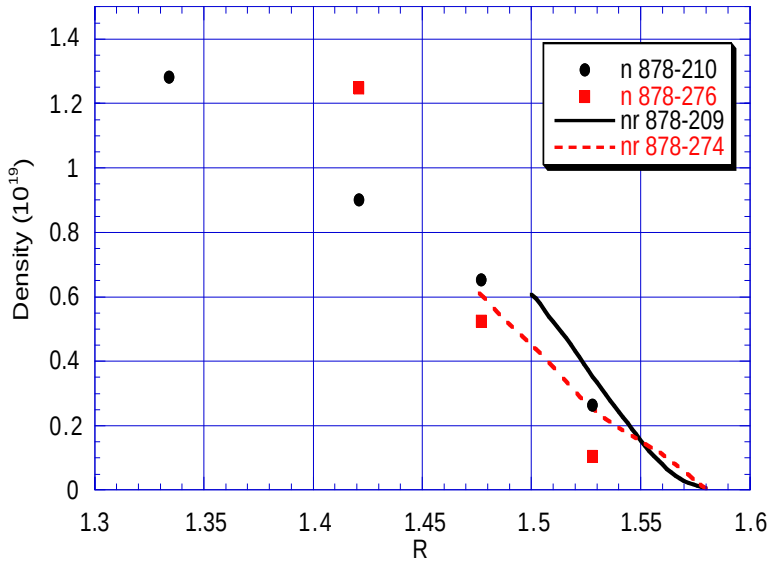
[1] R. Maqueda et al. "Edge turbulence measurements in NSTX by gas puff imaging", *Rev. Sci. Instr.* **72**, 931 (2001).

# Large Scale Fluctuations in Front of the HHFW Antenna as Observed by Visible Light Camera



# Phase-Averaged HHFW Reflectometer Edge-Density Profiles

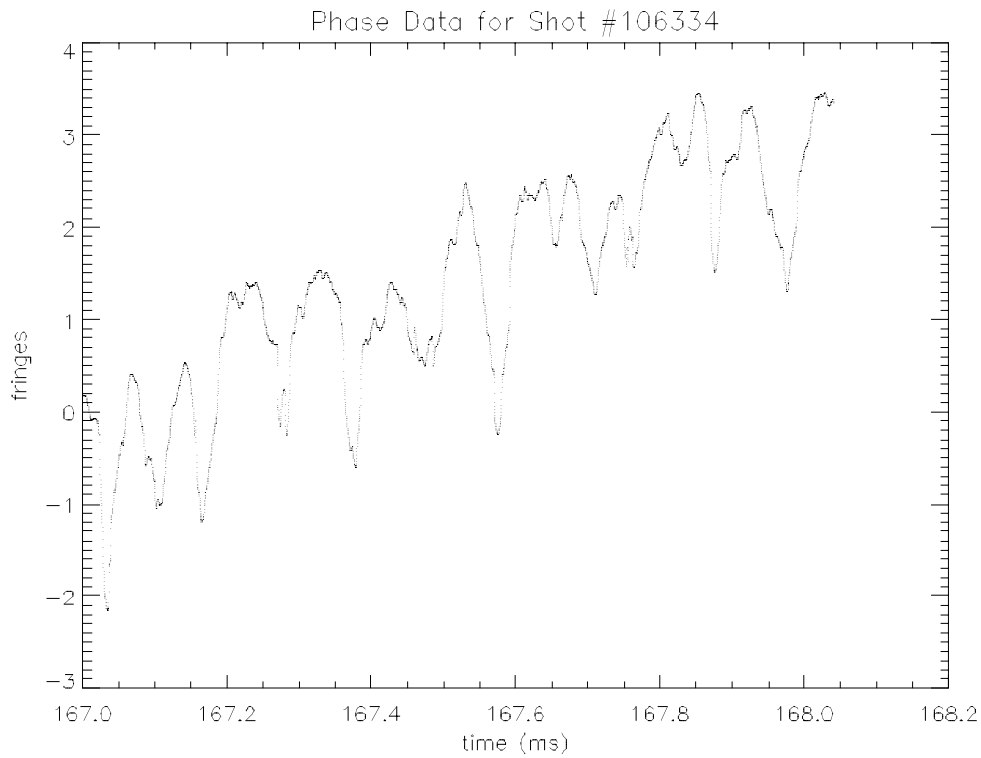



- Comparison of phase-averaged reflectometer profiles with TS data
  - Average phase data from 5-7 sweeps within a 2 msec interval
  - Compare with TS data at 210 msec (blk) and at 276 msec (red)
  - Shots 105871 & 105878 from RF heating experiment on June 13th show reasonable agreement between HHFW reflectometer & TS
  - For other low current shots (300 kA), TS is half the reflectometer density

# Initial Phase Fluctuation Data at 14.2 GHz

f=14.2 GHz
$n_e$=1.3x$10^{12}$ $cm^{-3}$
t = 167-168 ms
Shot # 106334

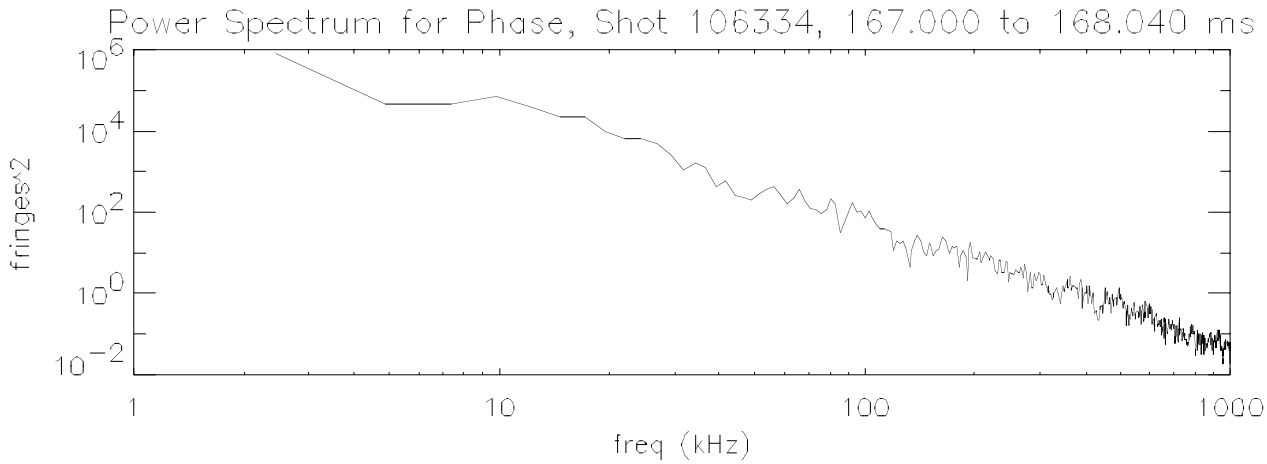


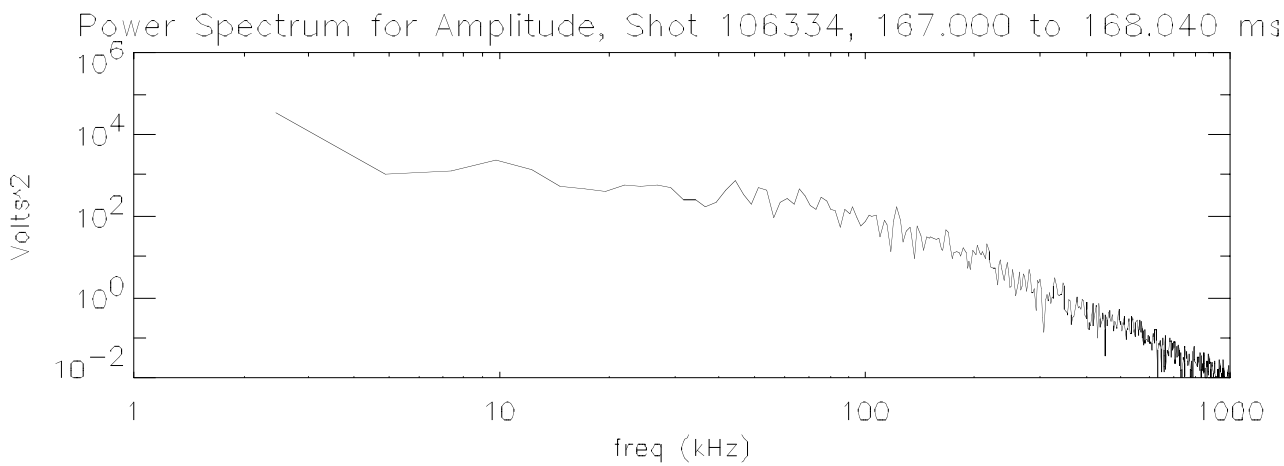

- Phase fluctuations (in fringes) measured at a probing frequency of 14.2 GHz
  - Amplitude of low-frequency phase fluctuation is about 2 fringes peak-to-peak
  - Largest phase excursions are low frequency, about 10 kHz

# Initial Phase Fluctuation Data at 14.2 GHz (con't)

f=14.2 GHz
$n_e$=1.3x$10^{12}$ $cm^{-3}$
t = 167-168 ms
Shot # 106334

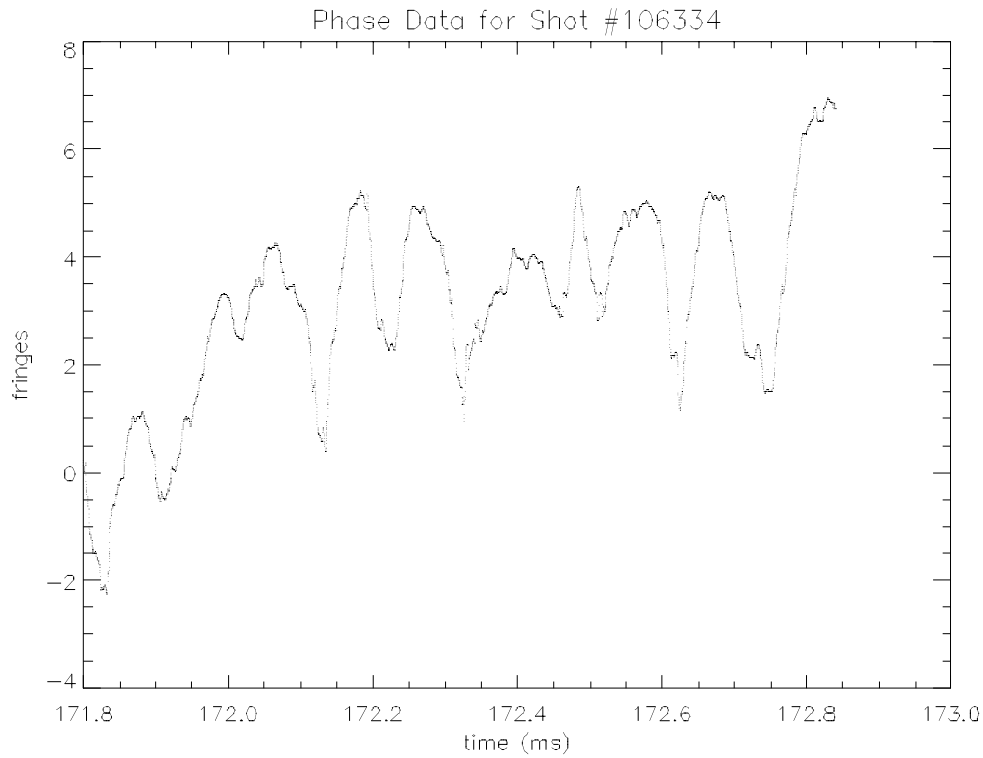
- Power spectrum of phase and amplitude fluctuations measured at 14.2 GHz
  - Phase spectrum peaks at 10 kHz, then falls as $1/f^2$
  - Amplitude spectrum is flatter



# Initial Phase Fluctuation Data at 20.4 GHz

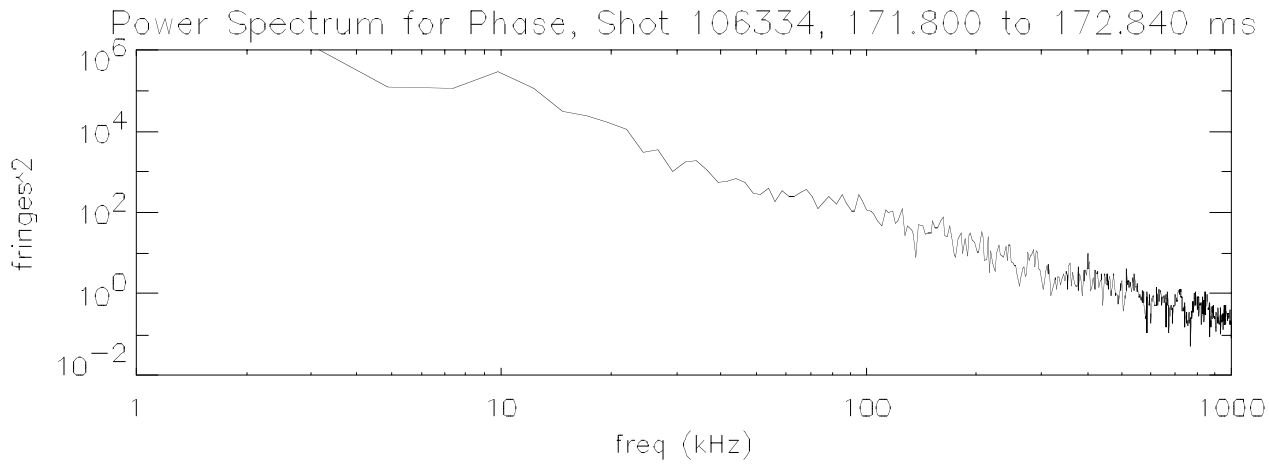
f=20.4 GHz
$n_e$=3.5x$10^{12}$ $cm^{-3}$
t = 172-173 ms
Shot # 106334

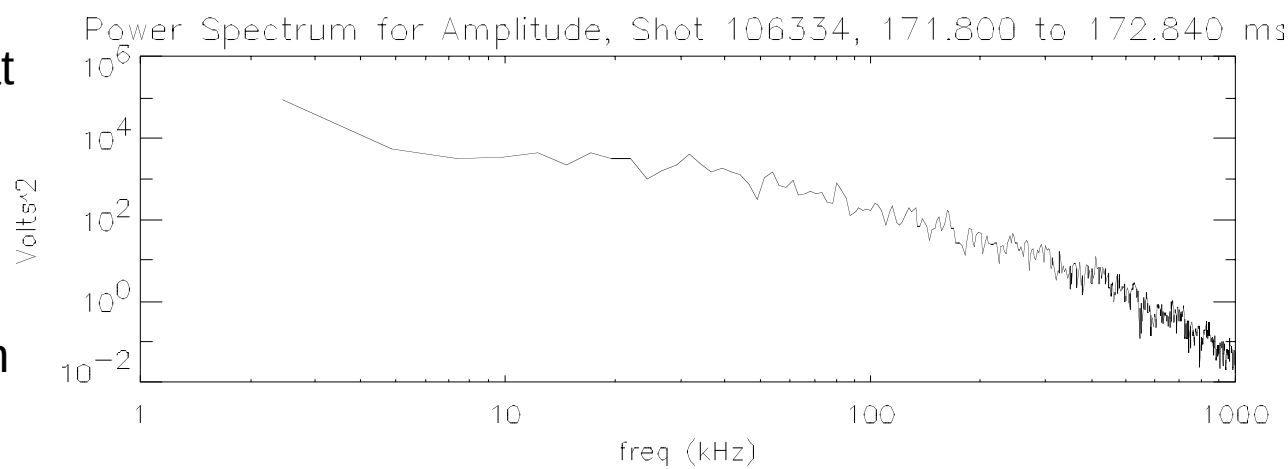



- Phase fluctuations (in fringes) measured at 20.4 GHz for the same condition
  - Amplitude of low-frequency phase fluctuation is about 2-3 fringes peak-to-peak
  - Large amplitude component predominantly low frequency, about 10 kHz

# Initial Phase Fluctuation Data at 20.4 GHz (con't)

f=20.4 GHz
$n_e$=3.5x$10^{12}$ $cm^{-3}$
t = 172-173 ms
Shot # 106334



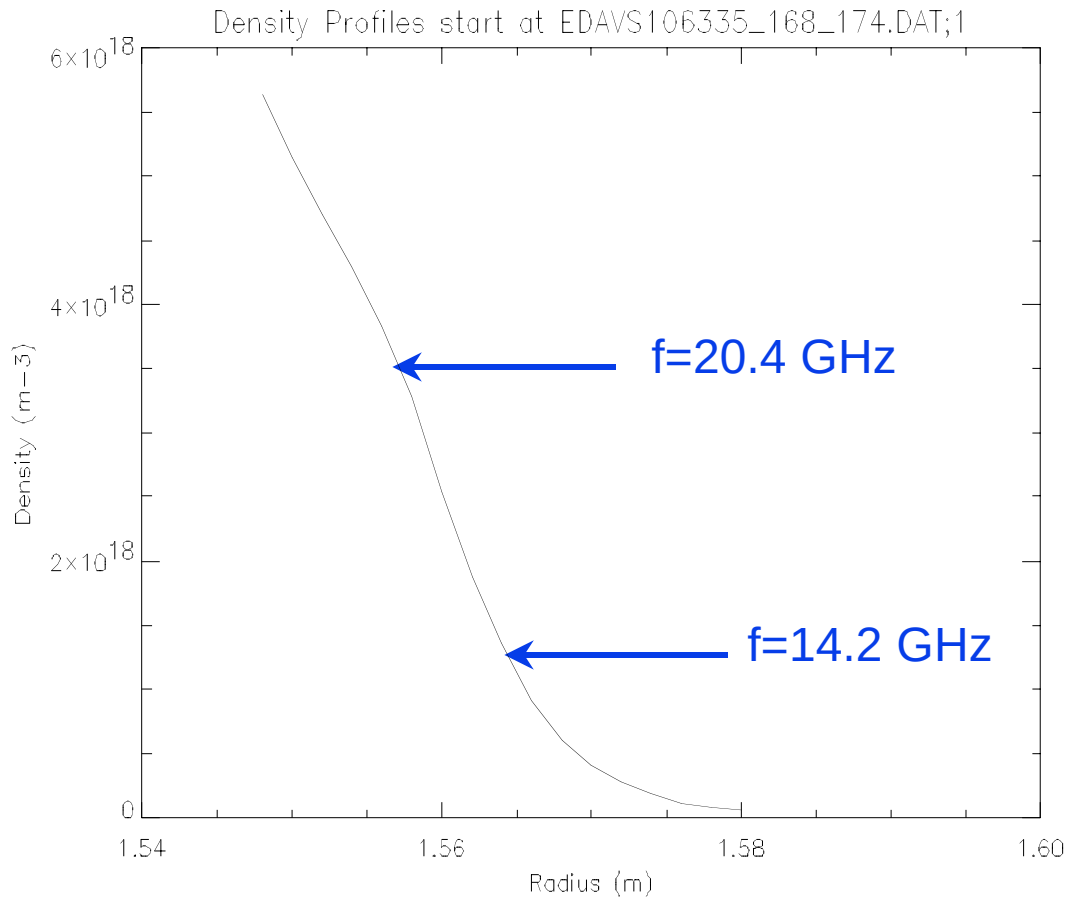




- Power spectrum of phase and amplitude fluctuations measured at 20.4 GHz
  - Phase spectrum peaks at 10 kHz, then falls as $1/f^2$
  - Amplitude spectrum is flatter

# Initial results from fluctuation measurements

## Shot # 106335 (profile)
## t = 168-174 ms

- Phase-averaged density profile obtained by averaging phase data from 16 sweeps
- Using the density scale length, $L_n$, from this average profile, we can estimate the density fluctuation level: $(\delta n/n) \cong \delta\phi * \lambda/(2L_n)$
- Based on the 10 kHz phase fluctuation observed at both 14.2 and 20.4 GHz, density fluctuation is large, $\delta n/n \cong 200\%$ peak-to-peak



# Future plans, options,….

Definitely in the works –

- Improve viability of HHFW reflectometer for measuring edge density fluctuations
  - Need isolation amplifier between I/Q detector and receiving antenna to eliminate problem caused by LO leakage
  - Will increase signal amplitude relative to offset voltages of I/Q detector
  - Will improve S/N for both profile and fluctuation measurements

- Improved fluctuation analysis
  - Goal is to develop good characterization of edge fluctuations (frequency spectrum, radial profile, …)
  - Needs more modeling to determine what the data means, how we can interpret what we measure

Hope to have most of this done in time for the start of the next run in Spring

# Future plans, options,….

Would like to do if funding permits –

- Improve data acquisition from present 5 MHz sampling rate to ~ 25 MHz
  - Allows sweep time to be reduced to 50 μsec, or less, further reducing effects of density fluctuations
  - Will improve reliability of analysis
- Automating the data analysis (phase-averaged density profile)
- Would like to look at 30-MHz component of HHFW reflectometer signal while doing rf heating
  - Measurement (somewhat) of ñ due to rf wave?
  - Need to analyze and figure out how to interpret phase & amplitude changes, to determine what we could infer from this measurement

# Significant Progress has been Made in the Last Year

- Reflectometer upgrades have greatly improved the quality of the phase data
  - Sweep time reduced to 100 μsec
  - Replaced analog driver with arbitrary waveform generator
    - resolved phase-calibration stability issues
    - enabled fluctuation measurements

- Have made significant progress on data analysis:
  - Have started providing phase-averaged density profiles covering the density range from $5 \times 10^{10}$ to $6 \times 10^{12}$ $cm^{-3}$.
  - Quality of phase data is improved – no longer constrained by fit

- Initial look at phase fluctuation data at 14.2 & 20.4 GHz:
  - Phase fluctuations levels are typically 2-3 fringes p-p, mostly in 10 kHz range
  - Density fluctuations are large, but have shorter scale than length of current straps, so that antenna loading depends on average profile

# Development of the Broadband Reflectometer Instrument

# Reflectometer Challenges in NSTX

| Complicating Factor | Resolution Strategy |
| --- | --- |
| Low value of magnetic field with 5 GHz X-mode cutoff | Use broadband reflectometer to cover a large frequency range |
| Large pitch angle of field at edge of plasma | Adjust launch polarization to match pitch angle during Ip flat top |
| Magnetic shear coupling of plasma modes | This is not a serious problem at low frequency (5-20 GHz) |
| X-mode tunneling from cutoff to upper hybrid layer | Compare results with O-mode measurements |
| Electron density fluctuations | Fast frequency sweep (≤100 μs) |

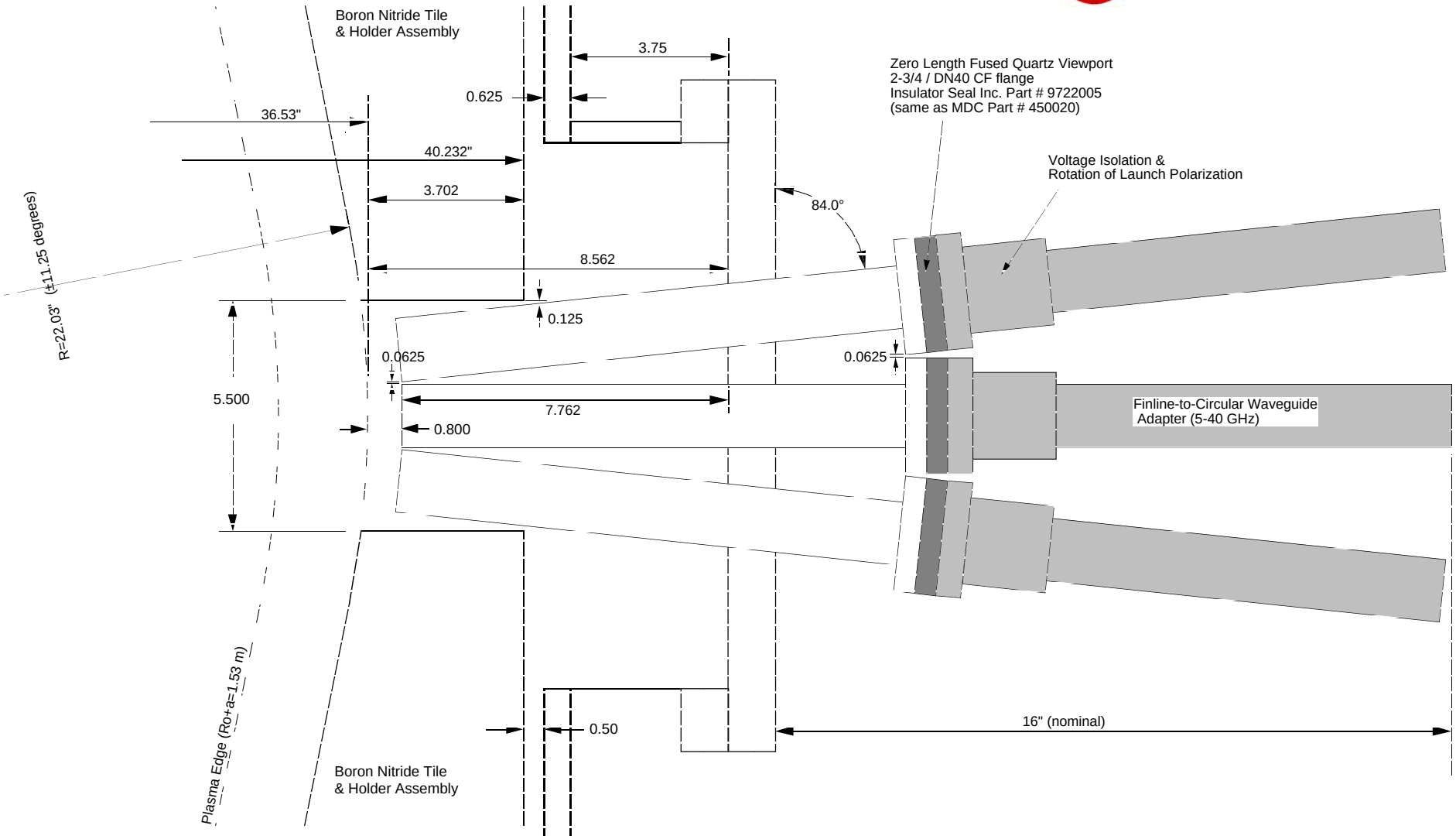
# ICRF In-Antenna Edge-Density Reflectometer

- Purpose: Measure Edge-Density Profile in front of the HHFW Antenna
- Initial Design Parameters
  - Electron Density Range 0.02 to 1.6 $x10^{13}$ $cm^{-3}$
  - Frequency Range Goal 6-36 GHz
  - Wave Polarization Primarily X-mode
- Launcher Requirements
  - Fits Available Space Between Faraday Shields
  - Broadband Launchers (6-36 GHz)
  - Externally Selectable Launch Polarization
  - Capability for Measuring Polarization of Reflected Wave
  - Extendable for Use at Higher Frequencies
- Microwave Electronics - Design Utilizes Existing Hardware from the TFTR ICRF Reflectometer and the ATF Reflectometer

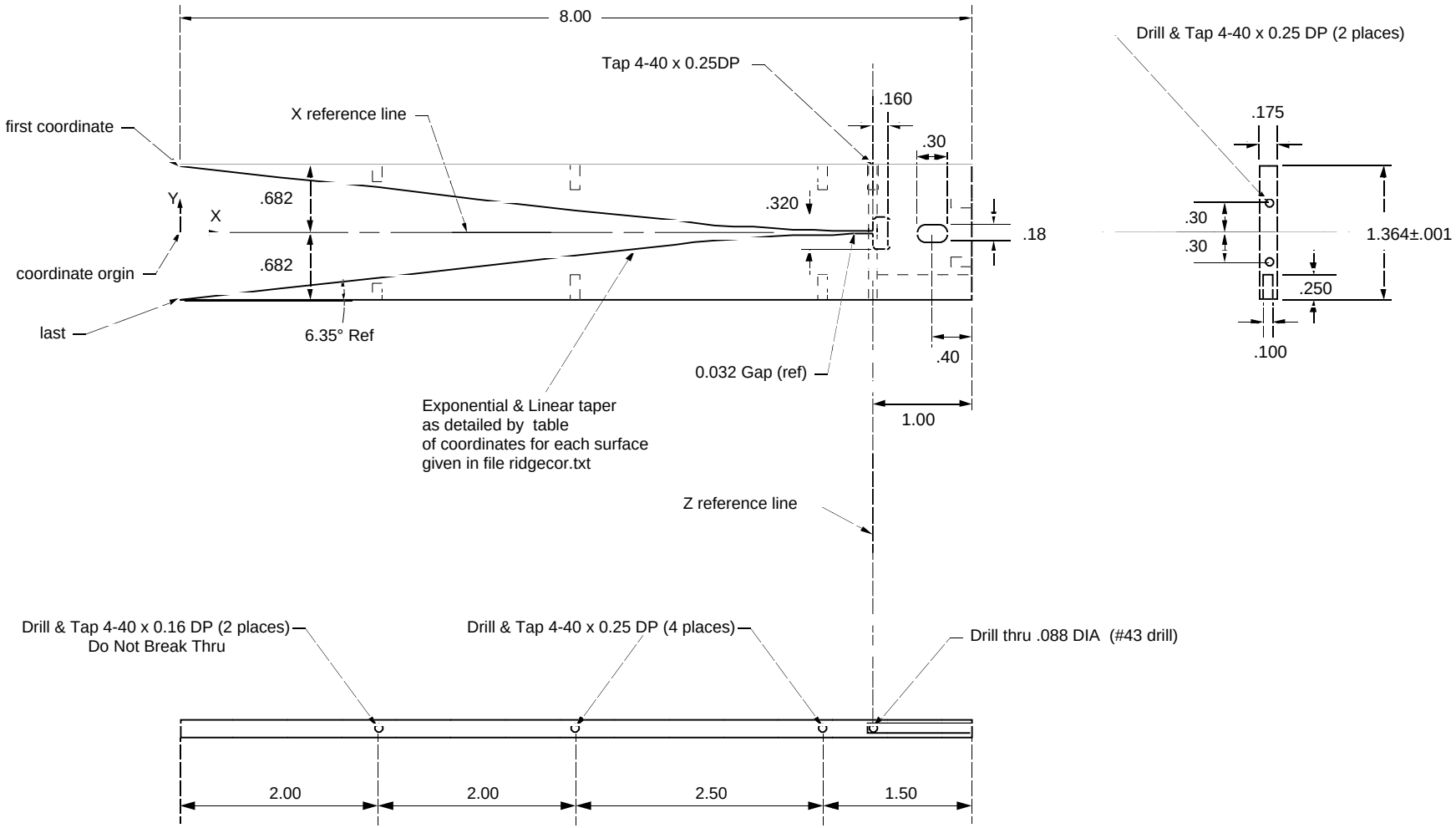
# Development and Performance of Broadband Reflectometer Instrument

- Fabricated vacuum flange with 3 cylindrical waveguide launchers (see sketch, p. 26)
- Fabricated broadband (5-40 GHz) coax-to-dual-ridged waveguide adapters. Performance exceeded expectations (see sketch & data. P. 27-28)
- Assembled and tested the broadband 6-36 GHz reflectometer signal source. Obtained useable sweep range of 6.2 to 36.8 GHz (see sketch & data, p. 29-30)
- Tested the fully assembled reflectometer using a calibration fixture that replicates the vacuum windows & launchers, and also simulates the RF boxes, & Faraday screen elements (see test data & photos, p. 31-32)
- Installed & calibrated the reflectometer instrument on NSTX and obtained initial plasma data during the fall of 1999

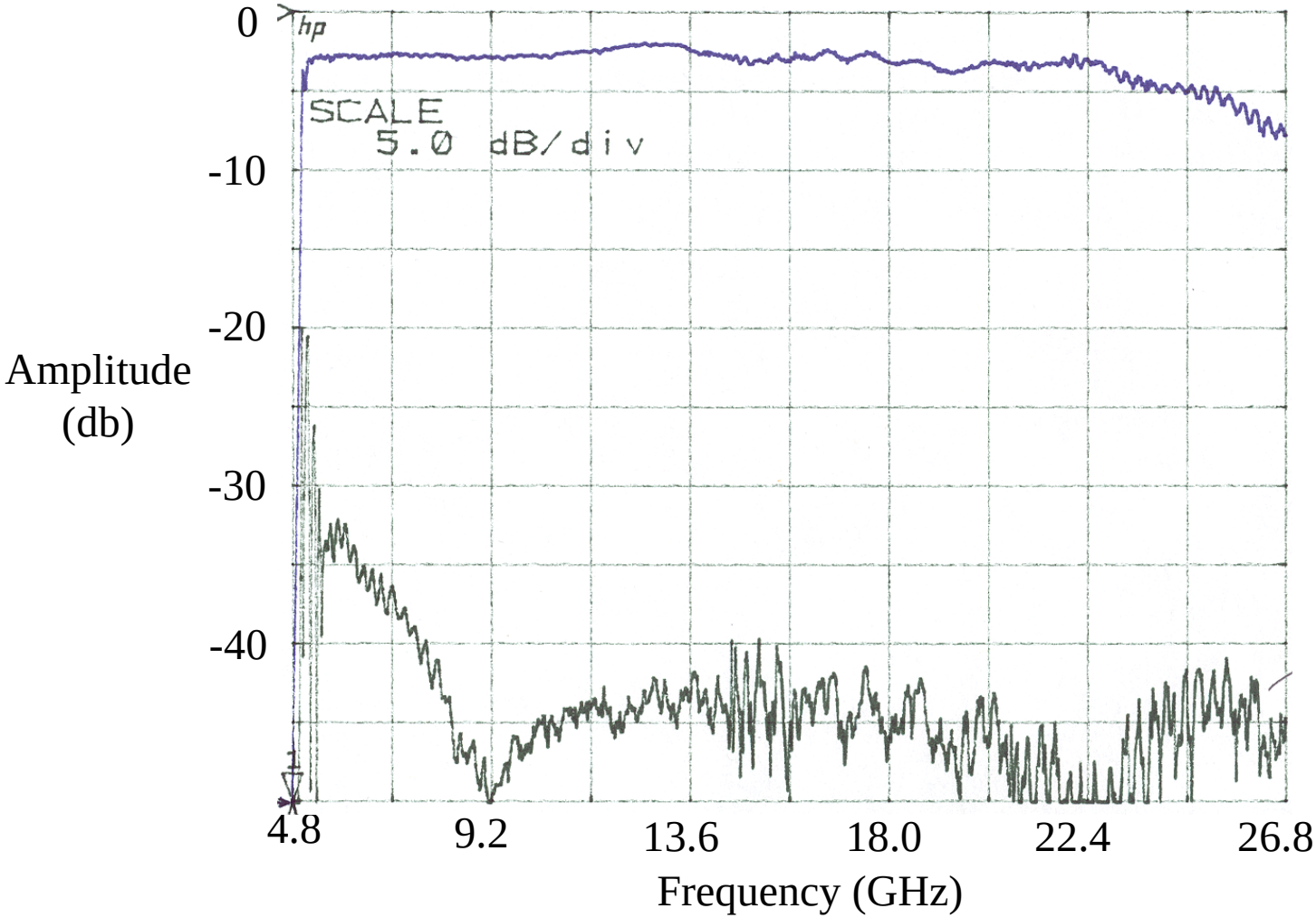
# Sketch of the Launcher Installation on Vacuum Flange



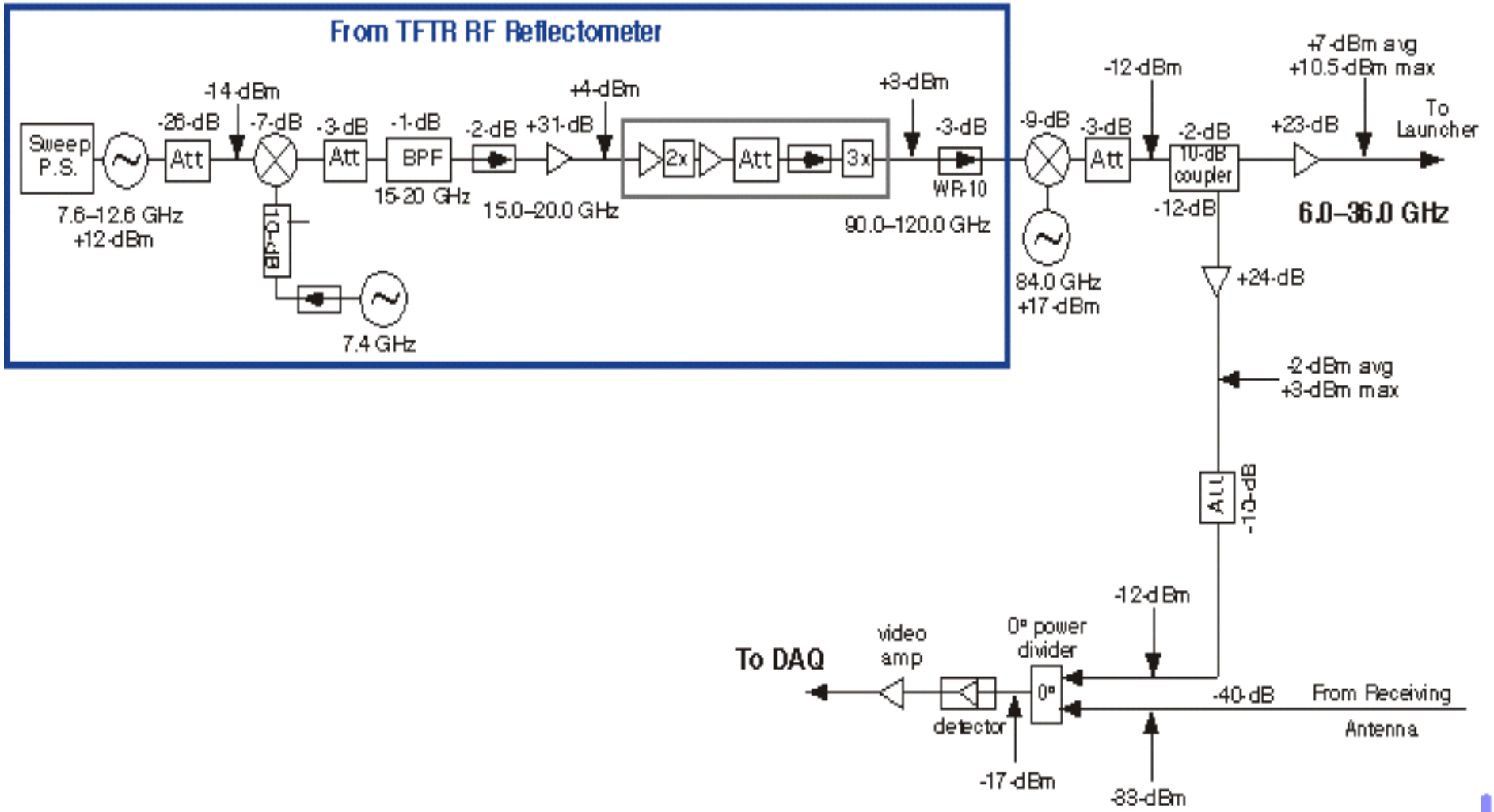
# Sketch of the Dual-Ridged Waveguide-to-Coax Adapters



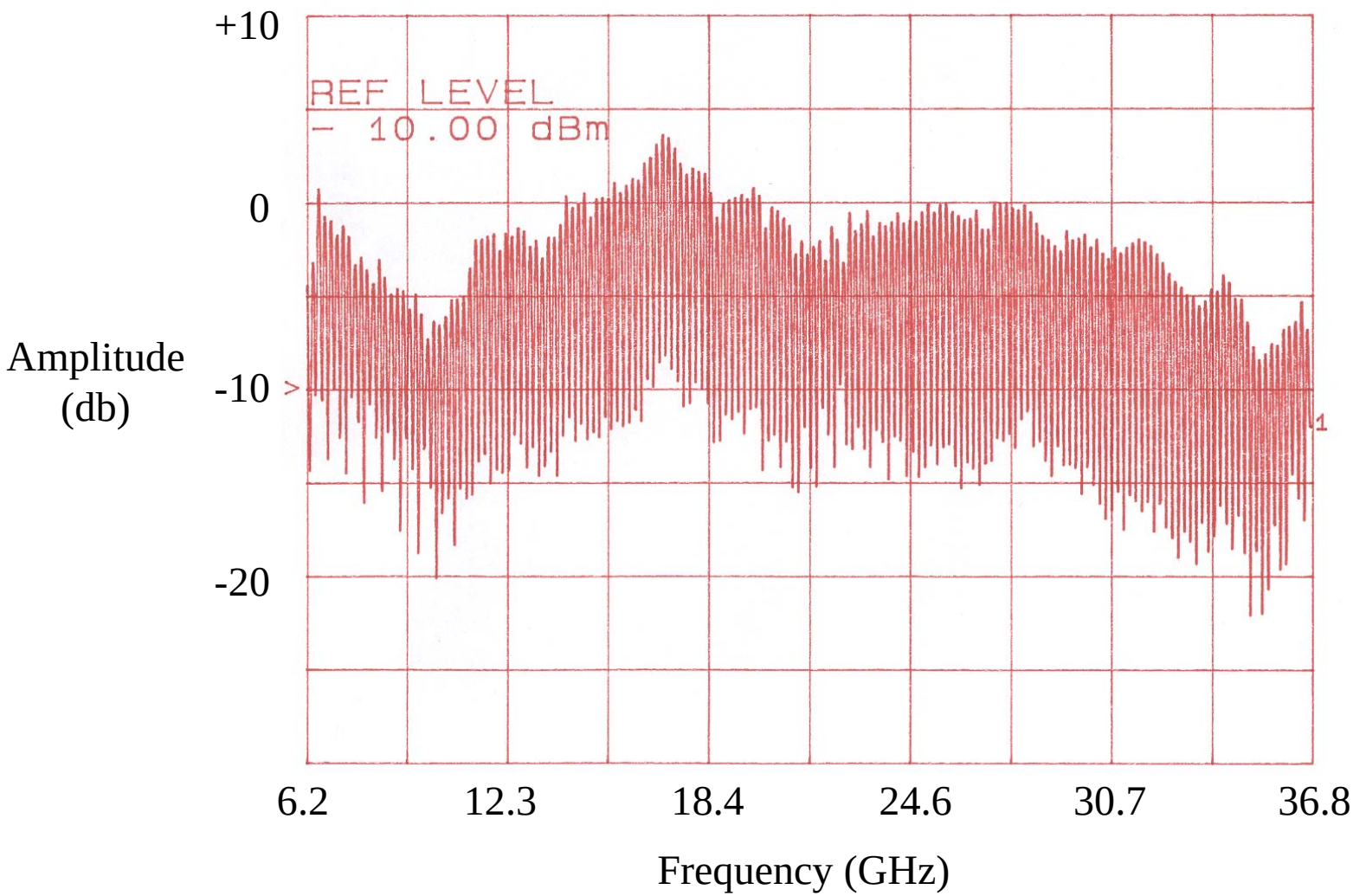
# Insertion Loss and Cross Polarization Between a Pair of Coax-to-Waveguide Adapters



# NSTX HHFW Reflectometer – Original 1999 Version Microwave Circuit Diagram (6–36 GHz)

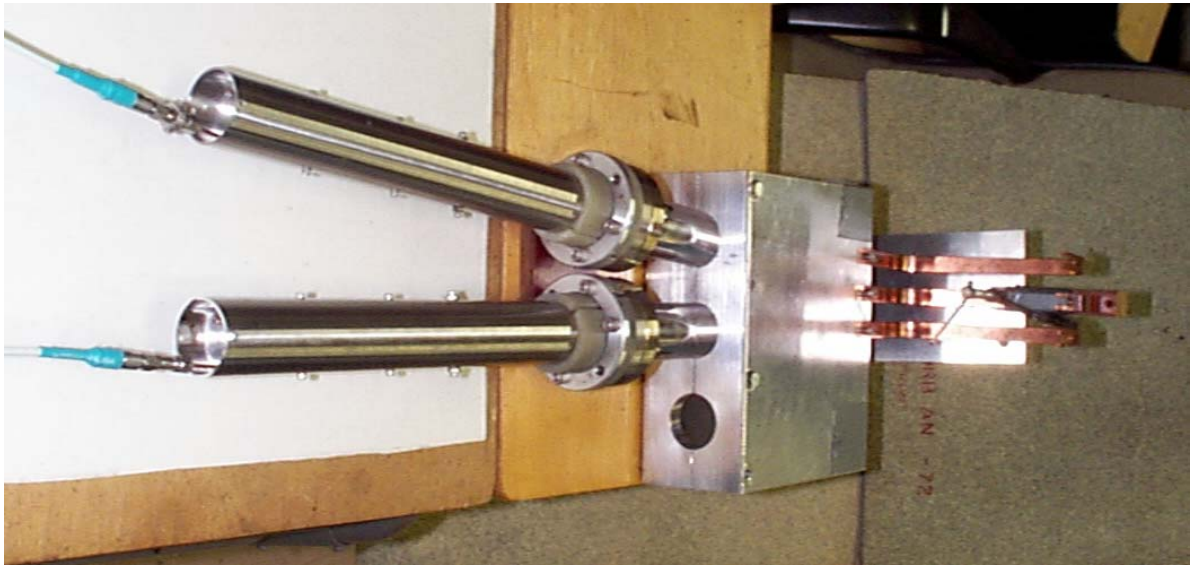


# Test Interferogram Obtained Using a 4 ft Cable and a 20 db Attenuator Pad to Simulate the Plasma Path

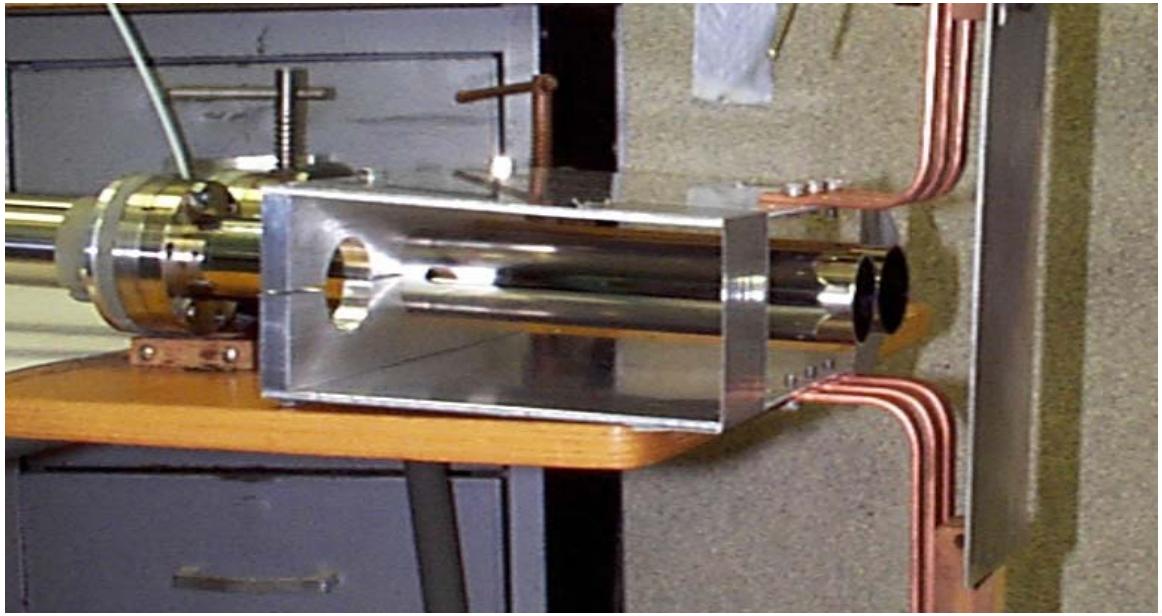
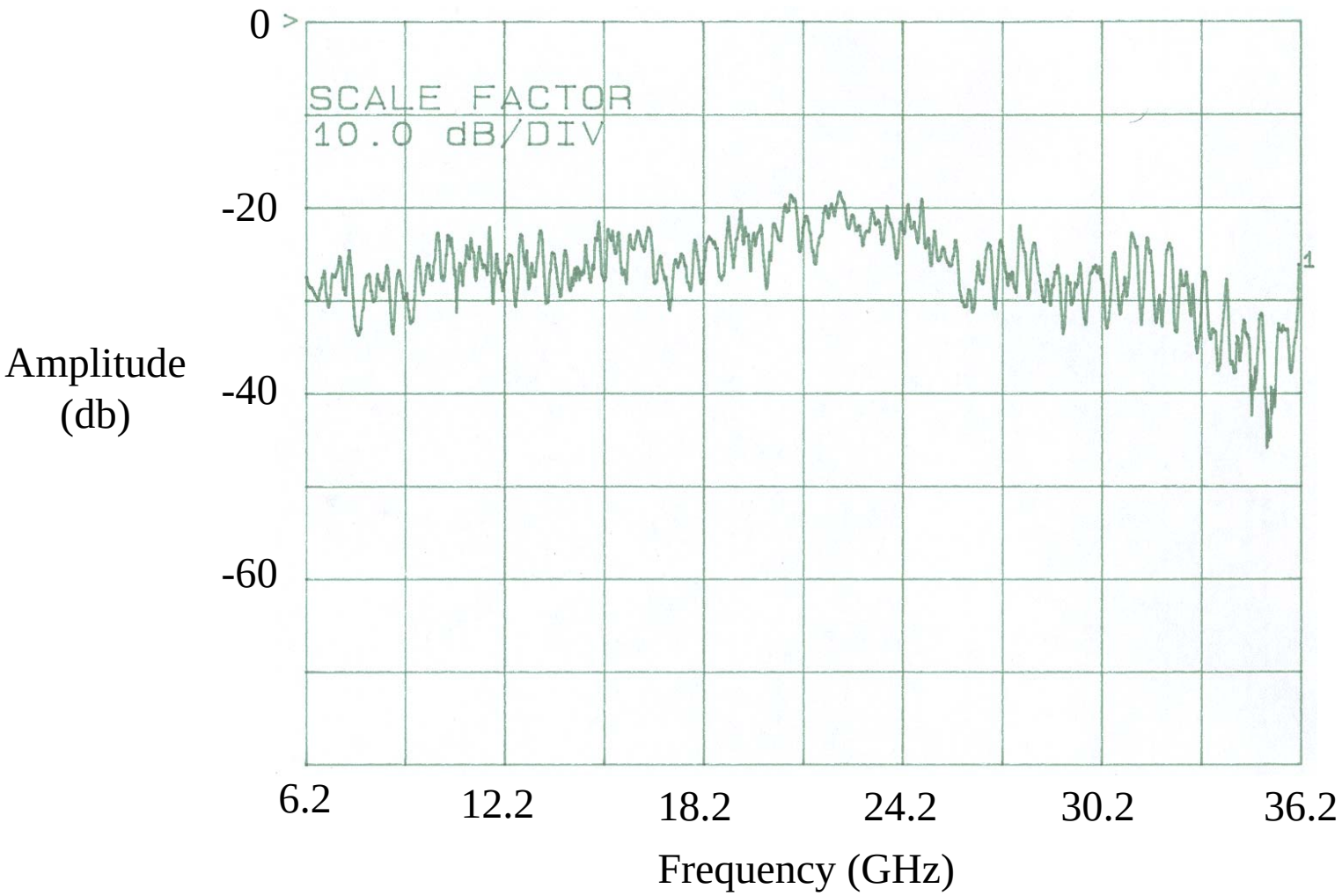


# Phase Calibration Fixture

Coax-to-Waveguide Adapters Mounted on a Calibration Fixture that duplicates the Vacuum Windows & Launchers



Phase Calibration fixture simulates the RF Boxes & Faraday Screen. A flat metal plate is used to define the phase reference plane.



# Launcher Coupling (E-plane) with Reflector Located 4” from Aperture