Reflectometry Characterization of Edge Density Fluctuations During ELMy H-Modes in NSTX*

S. Kubota, N.A. Crocker, A. Diallo[1], S.M. Kaye[1], R. Maingi[1]

University of California, Los Angeles, CA

[1]Princeton Plasma Physics Lab, Princeton, NJ

Abstract

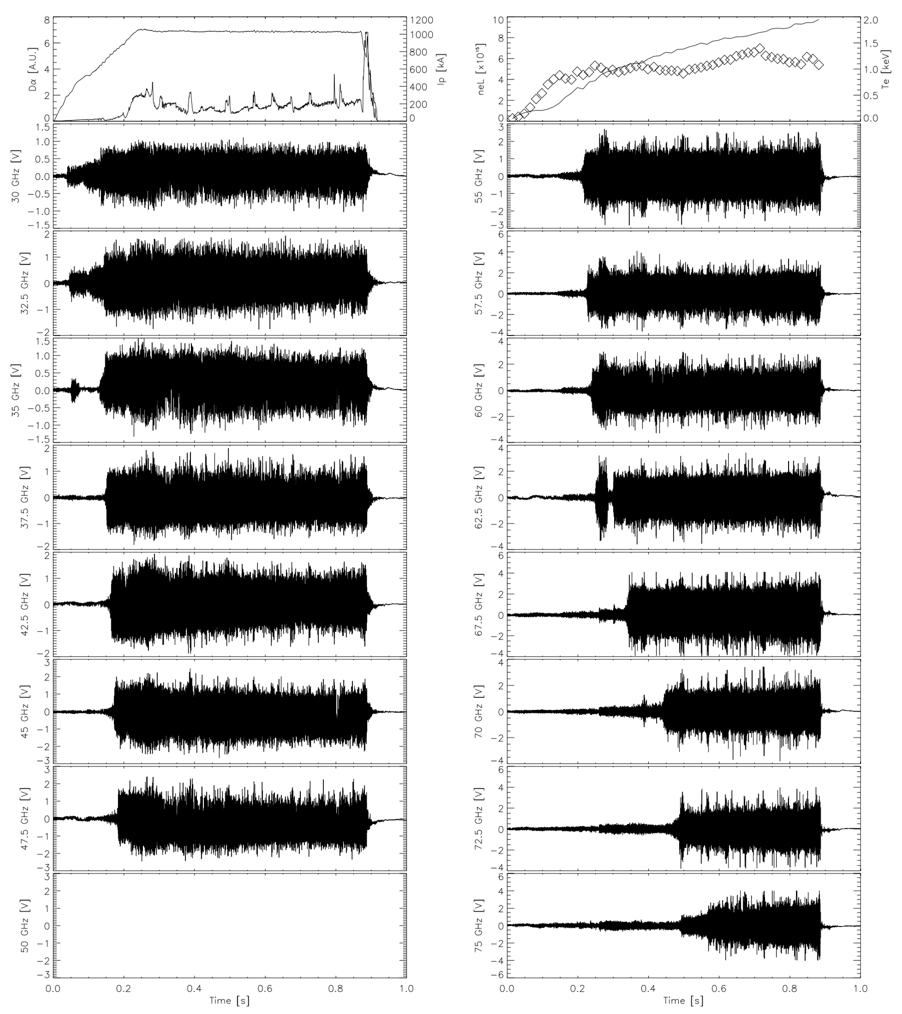
Understanding the role of instabilities that govern the properties of the H-mode pedestal is an important research topic for existing and future magnetic fusion devices. In a previous study (A. Diallo et al., Phys. Plasmas **20**, 012505), fluctuations in the pedestal of ELMy H-modes in NSTX were characterized using BES and reflectometry. With respect to the reflectometry analysis, the fluctuation model used for the 2-D full-wave analysis in that work assumed fully-developed turbulence characterized by Gaussian statistics. In the present work, data from the 30-75 GHz fixed-frequency reflectometer (16 channels, radially and toroidally separated) is used in conjunction with 3-D physical optics and full-wave calculations to determine the spatial structure and additional characteristics of the edge fluctuations. The analysis of the reflectometer data suggests that edge electron density fluctuations are dominated by long-lived (τ_{decorr}~several 100 μs) coherent structures. The largest structures are found to be poloidally localized (width ~3 cm) with a dipole shape, and elongated in the direction of the magnetic field. Further information about the reflectometry analysis, as well as a detailed description of the edge fluctuations, will be presented.

Background

- Previous fluctuation analysis of reflectometry
  - Assumed fully-developed turbulence model
  - Statistical comparison of simulated and experimental data using 2-D O-mode full-wave code (synthetic diagnostic)
- More traditional reflectometry analyses consider additional quantities to generate a fluctuation model
  - Time evolution of signal phase and amplitude
  - Correlation between toroidally separated arrays
- Goal is to couple with 1-D, 2-D and 3-D synthetic diagnostic analysis (WKB, full-wave, geometric optics) for a better understanding of density fluctuations
- This poster details analysis methods being developed for ELMy H-mode shots
  - Full physical interpretation will be presented at a later date

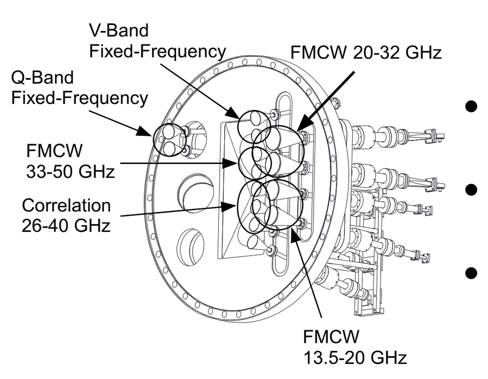
139047 Discharge Parameters & Reflectometer Signals

Q-Band | **V-Band**



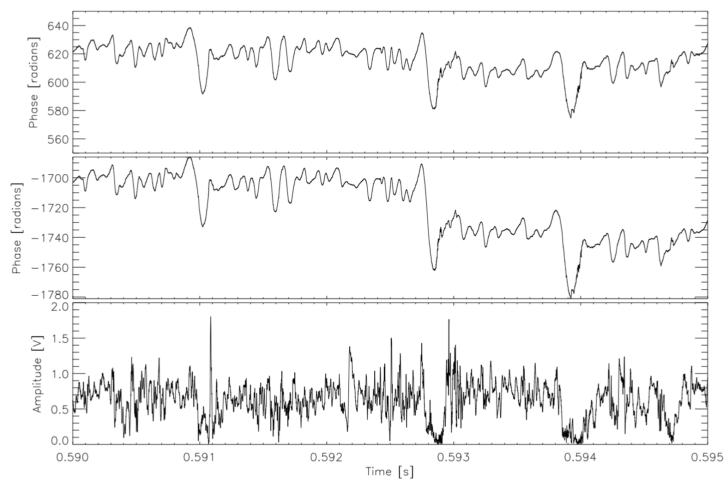
- NB-heated ELMy H-mode
- Type I and Type V ELMs
- Concentrate on a single inter-ELM period

16 Fixed-Frequency Reflectometer Channels on NSTX



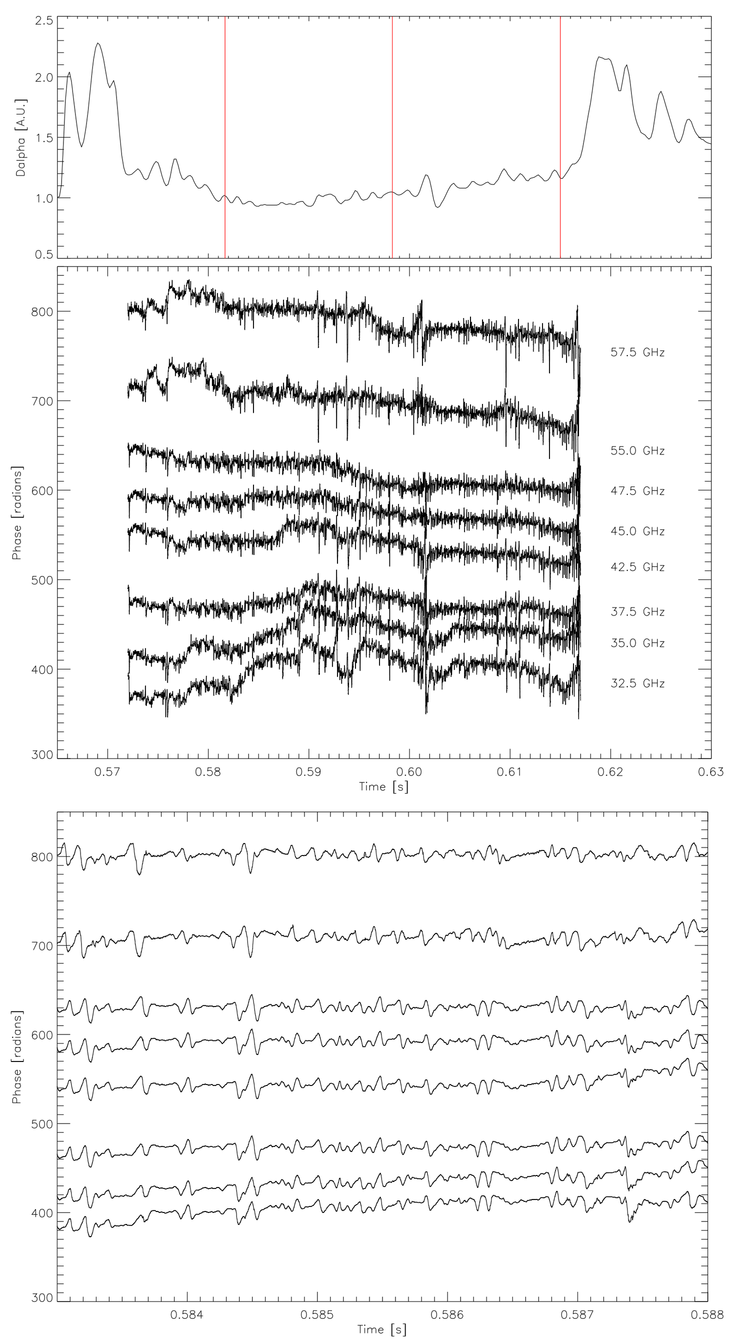
- Q-band frequencies: 30, 32.5, 35, 37.5, 42.5, 45, 47.5, 50 GHz
- V-band frequencies: 55, 57.5, 60, 62.5, 67.5 70, 72.5, 75 GHz
- 14-bit, 10 MHz sampling rate

Reflectometer Signal Properties: Fringe Jumps



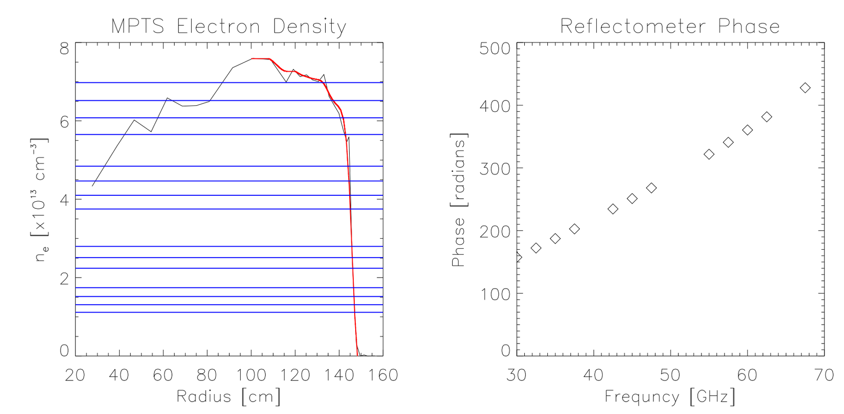
- Fringe jumps, not phase runaway
- Nulls in simple amplitude correlated with signature in the phase
- Implies decrease in the diffraction length (large, narrow perturbations)

Reflectometer Phase Evolution During an ELM Cycle



- Kernel-based algorithm used to remove fringe skips
- Phase value at the fringe skip location not completely accurate
- Individual perturbations highly correlated across all channels
- Hints at narrow field-aligned striations

Electron Density Profile Evolution from Phase



- Phase evolution can be used to track density profile evolution (necessary for determining fluctuation level)
- Density profiles using Abel inversions

Strategy for Reflectometry Data Analysis

Synthetic Diagnostics to Characterize Fluctuations

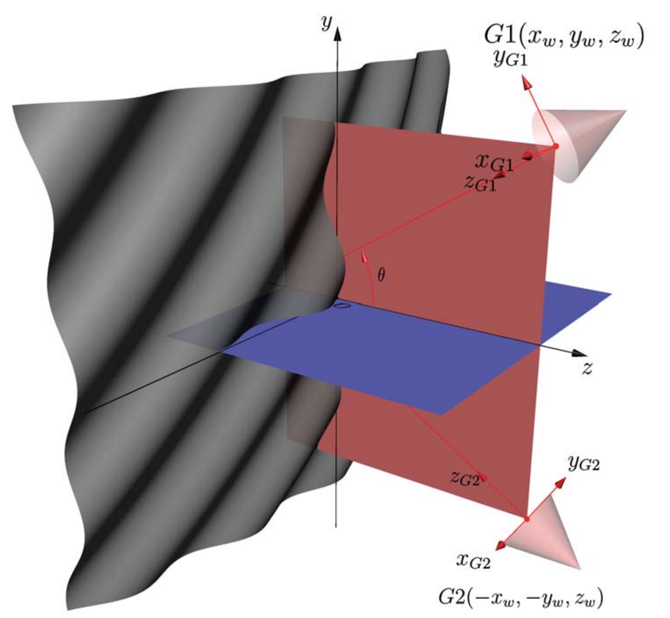
In increasing order of dimensionality and difficulty,

- 1-D methods: phase response using analytic formulas, WKB or 1-D full-wave calculations
- 2-D methods: phase and amplitude response using 2-D physical optics or 2-D full-wave calculations
- 3-D methods: phase and amplitude response using 3-D physical optics or 3-D full-wave calculations

Strategy

- The fluctuation model is the key input for all synthetic diagnostic methods, since the reflectometer response can have a highly nonlinear response
- Synthetic diagnostic outputs should look like experimental signals (model consistency)
- Multiple analysis methods increase confidence in results

3-D Physical Optics Model/Kirchhoff Integral Method



- Follows works by Ejiri and Conway
- The perturbed cutoff surface is modeled by the equation

$$z(x,y) = -\frac{x^2}{2R_x} - \frac{(y-y_s)^2}{2R_y} + \Delta(x,y).$$

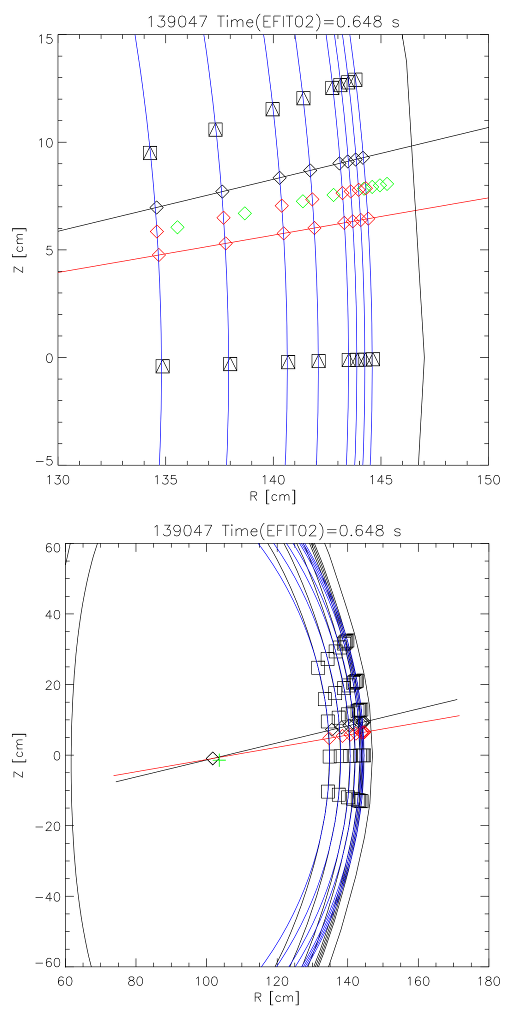
where R_x and R_y are the toroidal and poloidal curvatures of the cutoff surface, respectively, and Δ is the radial excursion of the perturbation.

- The reflectometer signal can be calculated using the Kirchhoff integral with identical launch and receive Gaussian beam patterns:

$$E = \frac{2\cos\theta}{\pi\ w^2}\int dx \int dy \exp\left[-\frac{x_{G1}^2+x_{G2}^2}{w^2}\right]\exp\left[-\frac{y_{G1}^2+y_{G2}^2}{w^2}\right] \times \exp\left[ik(z_{G1}+z_{G2})\right]\exp\left[ik\frac{x_{G1}^2+x_{G2}^2}{2R}\right]\exp\left[ik\frac{y_{G1}^2+y_{G2}^2}{2R}\right],$$

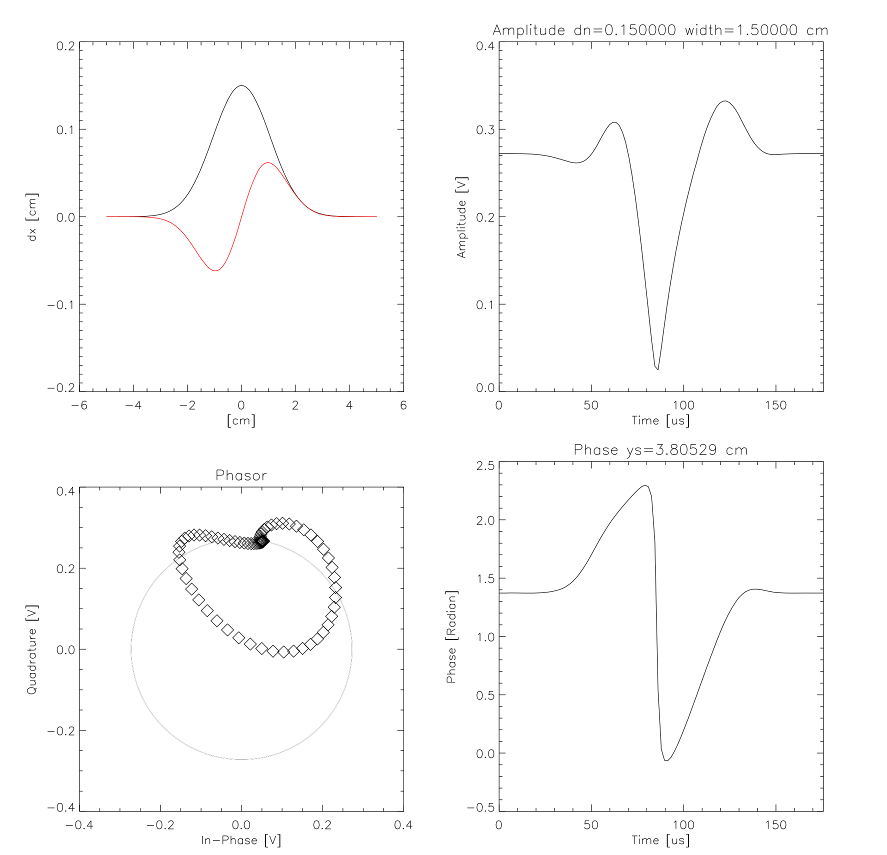
where w is the beam width and R is the beam curvature, respectively, at the cutoff layer. Note that (x_{G1}, y_{G1}, z_{G1}) and (x_{G2}, y_{G2}, z_{G2}) are local coordinates centered at the horn positions.

Cutoff Surface Information



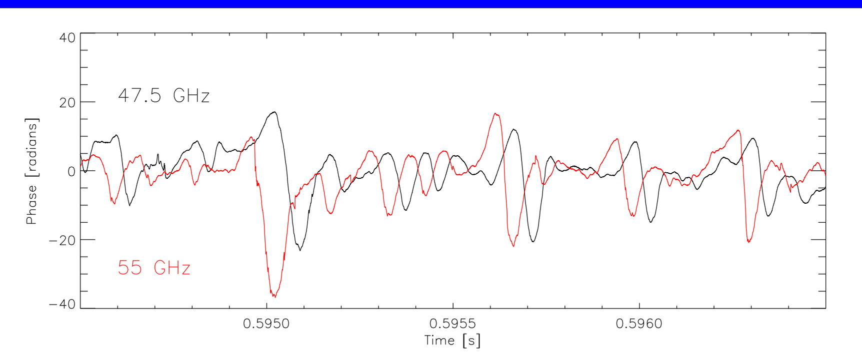
- Cutoff radius from reflectometers and MPTS
- Cutoff surface curvature from EFIT

Response to $\Delta(x,y)$ Modulated Gaussian Pulse*



- Best fit to experimental data
  - Also tried: Gaussian pulse, sine wave
- Pulse full-width of ~3 cm required to produce ~100% modulation of amplitude
- Calculation above for 32.5 GHz at t=0.648 s

Toloidal Correlation of Signals



- Phase signals from toroidally separated arrays are highly correlated
- Time delay of ~50–100 μs

Comments on the Structure of $\Delta(x,y)$

- Observations are consistent with long-lived field-aligned structures that rotate (toroidally or poloidally or both)
- Assuming only toroidal rotation, velocity of ~1.2 km/s in the co-current direction can be inferred from antenna array separation
  - Co-current propagation is consistent with asymmetry seen in Kirchhoff integral response from a modulated Gaussian pulse
- Transit time of pulse in front of array also gives poloidal width of ~2–4 cm
  - ~3 cm poloidal width estimated from best fit model
- Detailed analysis of radial structure to follow

Summary

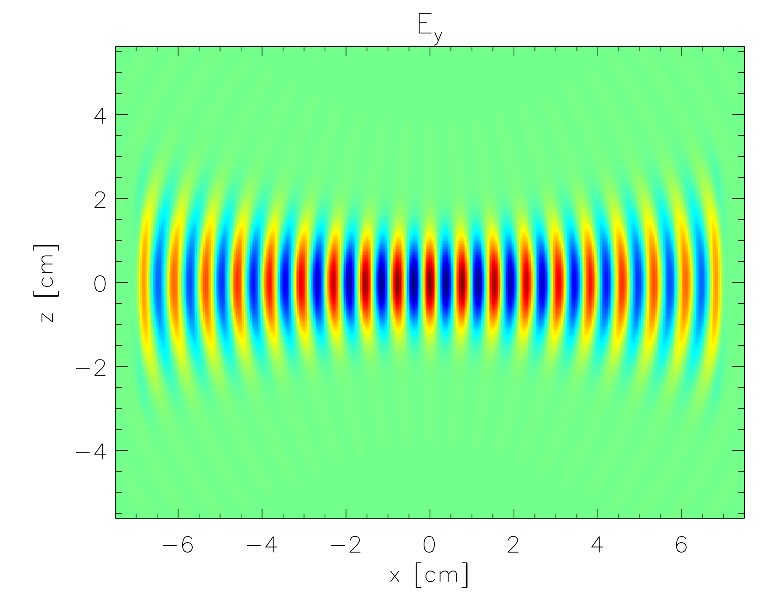
- Traditional reflectometry analysis of fluctuations during an ELM cycle can lead to a wealth of information
  - Evolution of the density profile, fluctuation levels, cycles within the ELM cycle (which may determine the interval of the larger cycle)
- Initial analysis of individual density perturbations using the 3-D Kirchhoff Integral Method
  - Good qualitative and quantitative match with observations
  - More sophisticated analysis methods to follow
- Multiple analysis methods and fluctuation models need to be utilized for full picture of inter-ELM dynamics

Future Work

- Investigate statistical properties of density perturbations and their correlation with background profiles
  - Theories involving the KBM
- Advanced methods for reflectometry synthetic diagnostic analysis
  - Implement 2-D and 3-D full-wave codes for similar analysis to refine the fluctuation model(s)
  - GPU acceleration of the 3-D full-wave code

2-D & 3-D GPU-Accelerated Full-Wave Codes

- General-purpose computing on graphics processing units
  - Utilizes massively parallel architecture of GPU cards
- 2-D full-wave code for reflectometry synthetic diagnostic
  - ×20 acceleration for X-mode
  - ×15 acceleration for O-mode
  - ×18 acceleration for coupled equations
- 3-D propagation in vacuum
  - Poster JP8.00021 "Development of a GPU-Accelerated 3-D Full-Wave Code for Reflectometry Simulations", K. Reuther
  - 381 × 251 × 251 grid size, 1000 steps
- Results
  - K20, 2 minutes 51 seconds
  - M2070, 3 minutes 47 seconds
  - C1060, 5 minutes 23 seconds



Acknowledgement

Supported by U.S. DoE Grants DE-FG02-99ER54527 and DE-AC02-09CH11466.