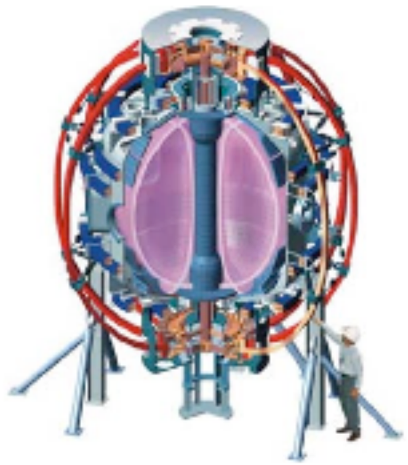
Density fluctuation studies in NSTX using reflectometry and gas puff imaging



by NA Crocker, WA Peebles*, S Kubota*, XV Nguyen*; S Zweben**, T Munsat**, E Fredrickson**, NSTX team**; RJ Maqueda[†]*

**University of California – Los Angeles*
***Princeton Plasma Physics Laboratory*
[†] Nova Photonics

Presented at the 46th Annual

APS Division of Plasma Physics Meeting

Savannah, GA Nov 15-19, 2004

Abstract (Revised)

Density fluctuation studies in NSTX using reflectometry and gas puff imaging[1]

NA Crocker, WA Peebles, S Kubota, XV Nguyen (UCLA); S Zweben, T Munsat, E Fredrickson, NSTX team (PPPL); RJ Maqueda (Nova Photonics)

Reflectometry and Gas Puff Imaging (GPI) are complementary, non-intrusive techniques for observing density fluctuations in fusion plasmas. GPI provides 2-D images of turbulence, whereas reflectometry generates local turbulence measurements from the edge to deep in the core plasma. They have recently been used to obtain simultaneous measurements in NSTX of edge turbulence during L to H mode transitions. Additionally, in conjunction with arrays of Mirnov coils outside a plasma, reflectometry may be used to probe the structure of density perturbations associated with global MHD inside the plasma (e.g. compressional and toroidal Alfvén eigenmodes). Recently, just such global MHD activity has been observed by reflectometry in NSTX. Three quadrature reflectometers that reflect at densities of approximately 1, 2 and 3 x 10^{13} cm^{-3} allow determination of local fluctuation levels and spectra in NSTX. GPI provides high-speed imaging of a 20 cm x 20 cm region centered just inside the separatrix near the outer midplane in NSTX. Preliminary results from reflectometry at 1 x 10^{13} cm^{-3} show that the reflectometer phase fluctuation level undergoes a significant reduction at the L-H transition. GPI also shows a large reduction that occurs nearly simultaneously over a comparable timescale. Reflectometer phase shows peaks in coherence at a variety of frequencies with signals from Mirnov coils in a toroidal array outside the plasma. Variation of the cross-phase at each of these frequencies with coil position allows identification of the toroidal mode number of the associated global mode.

[1]Supported by U.S. DoE Grant DE-FG03-99ER54527

Motivation

- Reflectometry and Gas Puff Imaging (GPI) are complementary, non-intrusive techniques for observing turbulence in fusion plasmas.

- GPI provides 2-D images of edge line emission, which may be interpreted as turbulence images

- Reflectometry generates local density fluctuation measurements from the edge to deep in the core plasma.

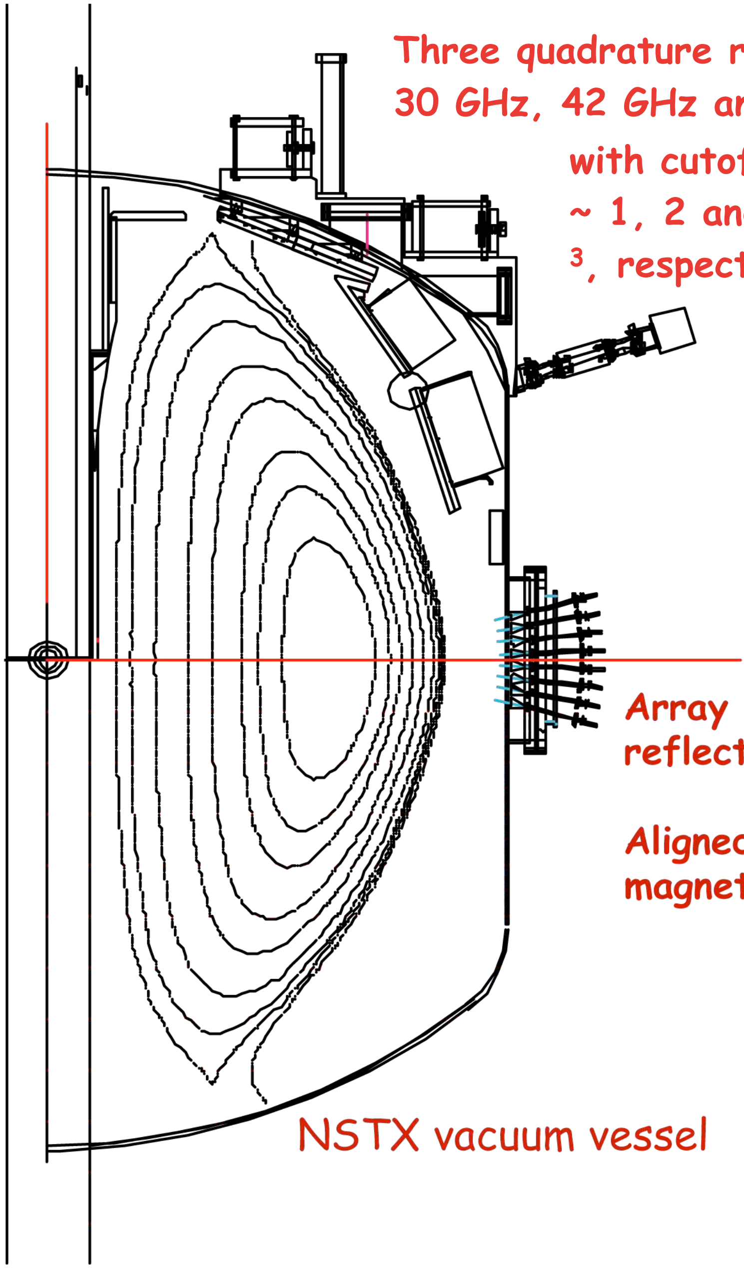
- In conjunction with arrays of Mirnov coils outside a plasma, reflectometry may probe the structure of density perturbations associated with global MHD inside the plasma.

Main Points

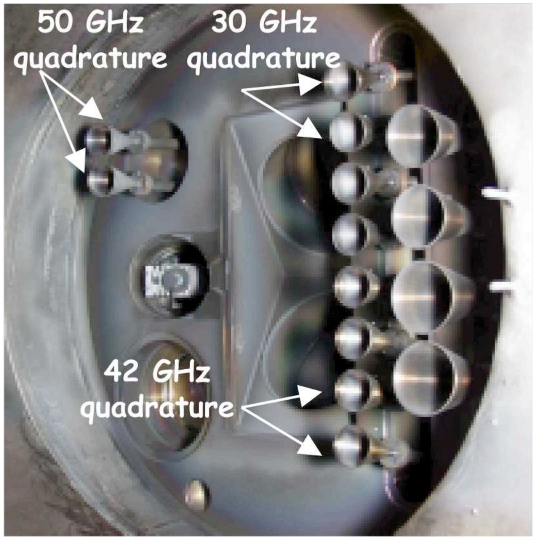
- Reflectometry and Gas Puff Imaging have obtained measurements simultaneously of substantial changes in turbulence during an L-H transition
  - Abrupt change observed in reflectometer phase fluctuations.
  - Fast (but slower) changes seen in GPI images and fast chord measurements of turbulence
- Change in density fluctuation level ($\delta n/n_0$) thru L-H transition difficult to determine from reflectometer measurement
  - Determination of $\delta n/n_0$ in H-mode may be possible. Requires testing of reflectometry models.
  - Determination of $\delta n/n_0$ in L-mode not possible due to interference effects,† but measurement nonetheless suggests it is larger than in H-mode.

    †Problem not intrinsic to L-mode. L-mode-only shots exist where $\delta n/n_0$ can be determined.
- Similar fluctuation spectra, featuring both turbulence and global MHD, seen by reflectometer and GPI
- Toroidal mode number of global MHD modes identified. Internal structure of associated density perturbation may be determined with future work.

Experiments Performed in NSTX



Three quadrature reflectometers in use:
30 GHz, 42 GHz and 50 GHz
with cutoff densities of ~ 1, 2 and 3 x 10^{19} m^{-3}, respectively.



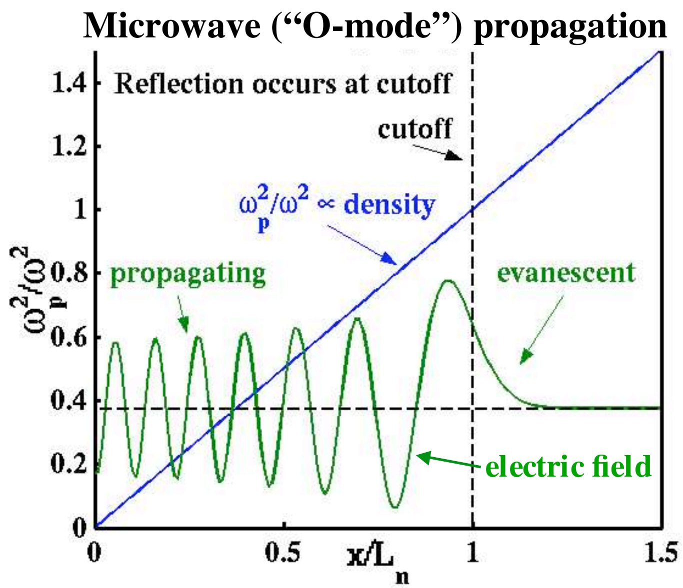
Array of microwave reflectometer horns.

Aligned perpendicular to magnetic flux surfaces.

Device Parameters for These Experiments:

R_0	= 95 cm
a	= 62 cm
I_p	= 0.58- 0.85 MA
B_T	= 0.32-0.44 T
κ	= 1.9
δ	= 0.45

Microwaves can be used to probe density fluctuations in plasma

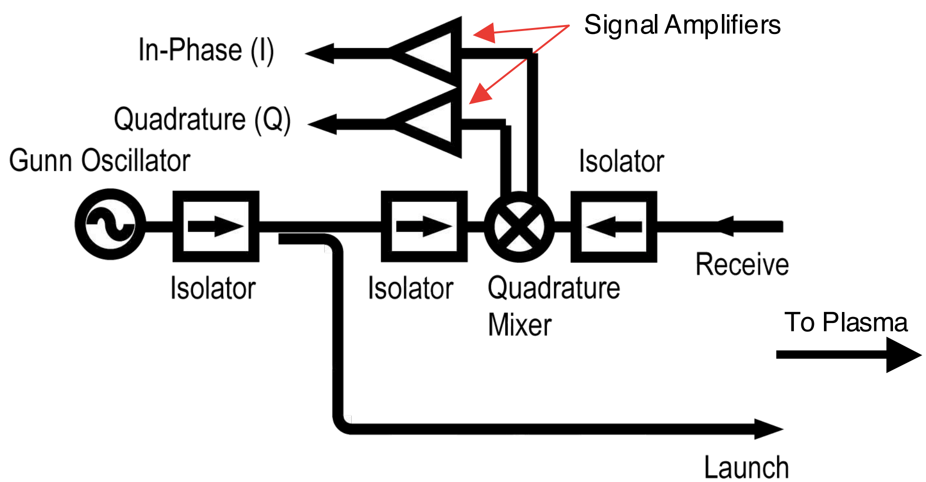


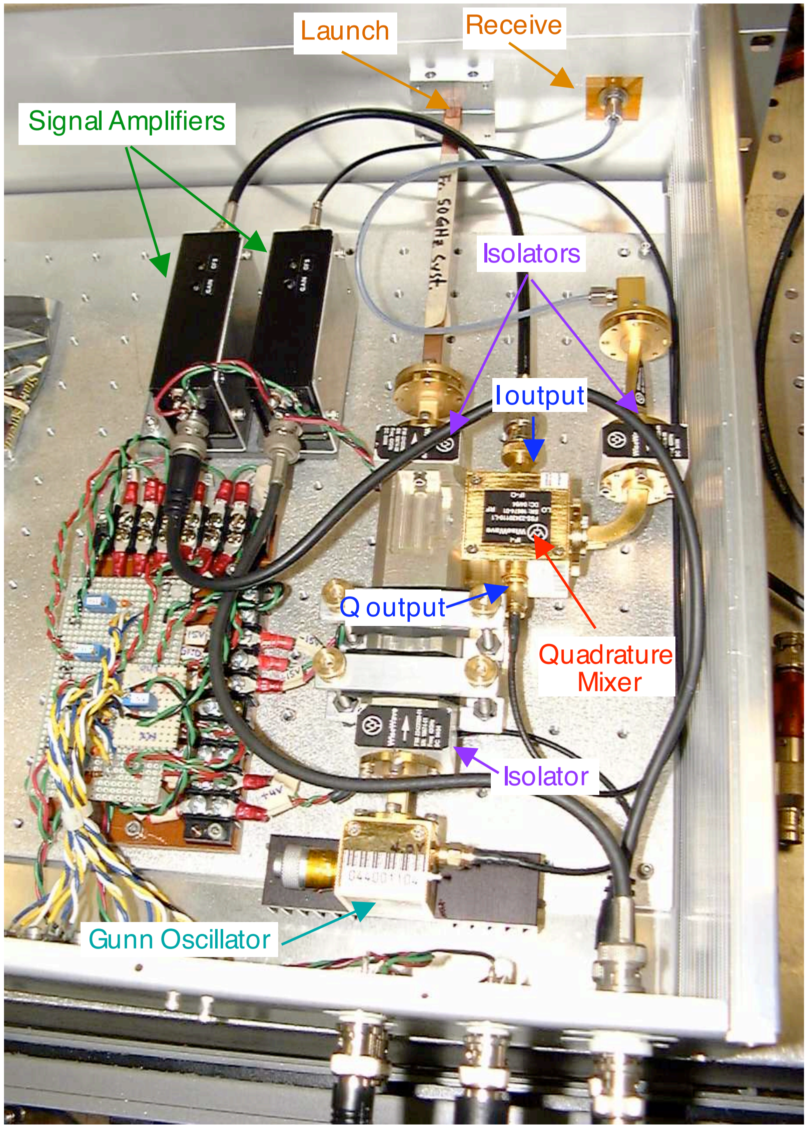
- Microwaves with low enough frequency ($\omega < \omega_p$) will reflect from "cutoff" layer in plasma
  - ω_p^2 is proportional to density: $\omega_p^2 = e^2 n_0/\varepsilon_0 m_e$
  - Dispersion relation for "ordinary mode" ("O-mode") microwaves: $\omega^2 = \omega_p^2 + c^2k^2$
  - $k \rightarrow 0$ as $\omega \rightarrow \omega_p$
  - Microwaves reflect at "cutoff" surface, where $\omega = \omega_p$, $k = 0$
- Wave propagation controlled by density $\Rightarrow$ reflected microwaves carry information about density fluctuations

Quadrature reflectometer probes density fluctuations in NSTX plasma

- **Quadrature reflectometer detects amplitude, $A(t)$, and phase-shift, $\phi(t)$ of microwaves reflected from plasma.**
- **Reflectometer has two outputs:**
  - **"In-Phase": $I(t) = A(t)\cos[\phi(t)]$**
  - **"Quadrature": $Q(t) = A(t)\sin[\phi(t)]$**
- **Fluctuations in output caused by density fluctuations in plasma**

Homodyne quadrature reflectometer circuit.





How do density fluctuations perturb the microwaves detected by the reflectometer?

- There are at least three ways in which density fluctuations perturb the microwaves detected by the reflectometer:

  - May cause "Rigid" motion of the cutoff (i.e. reflecting) surface: causes change in path length from launch to receive horns $\Rightarrow$ change in phase of reflected microwaves

  - May cause scattering: incoming microwaves may scatter off density fluctuations anywhere Bragg condition, $k_{in} + k_{\delta n} = k_{scattered}$, may be satisfied

  - May ripple or roughen cutoff surface when $k_{\delta n} \perp B, \nabla n_0$: causes interference effects, possibly incoherence in reflected microwaves

- The exact way in which these effects contribute to the reflectometer measurement is an active area of research

Many models have been proposed to interpret reflectometry measurements

- **1-D models which neglect scattering indicate $\delta\phi \propto \delta n/n_0$. Proportionality depends on** (see e.g. R Nazikian, et al.; PoP, May 2001)**:**
  - **wave number of density fluctuation, $k_{\delta n}$ (where $k_{\delta n} \parallel \nabla n_0$)**
  - **equilibrium density gradient scale, $L_n = n_0/|\nabla n_0|$**
  - **vacuum wavelength of microwaves, k_{vac}**
- **if fluctuation wavelength long, $k_{\delta n}L_n \leq 1$ (i.e. $|\nabla\delta n|/\delta n \leq |\nabla n_0|/n_0$):**

$$\delta n/n_0 \sim \delta\phi/(2k_{vac}L_n)$$

- **if fluctuation wavelength short, $k_{\delta n}L_n > 1$ (i.e. $|\nabla\delta n|/\delta n > |\nabla n_0|/n_0$):**

$$\delta n/n_0 \sim \delta\phi(k_{\delta n}L_n)^{1/2}/(2k_{vac}L_n)$$

- **For 1-D which models which include scattering, $\delta\phi$ depends on spatial structure of $\delta n/n_0$** (see e.g. BB Afeyan, et al.; PPCF 1995)**:**
  - **Scattering occurs for $2k_{in} = k_{\delta n}$, since $k_{out} = -k_{in}$**

Many models have been proposed to interpret reflectometry measurements (cont.)

- **2-D models account for important effects not included in 1-D models:**
  - **curvature of cutoff surface**
  - **roughening or rippling of surface**
  - **Propagation effects, beam width effects.**
  - **Examples of 2-D models include "random phase screen model" and "distorted mirror model"**

- **Random phase screen model** (see e.g. R Nazikian, et al.; PoP, May 2001) **predicts:**
  - **$\delta n/n_0 \propto \delta\phi$. Proportionality depends on L_n and $k_{\delta n||}$, the component of $k_{\delta n}$ || to ∇n_0**
  - **Severe interference when $\delta\phi$ > ~ 2 radians at cutoff surface or path length from cutoff to receiver > "diffraction length", D.**
    - **$D = 2k_{vac}/\{(1+\delta\phi^2)(\Delta k_{\delta n\perp})^2\}$, where $\Delta k_{\delta n\perp}$ is width of the density fluctuation spectrum for $k_{\delta n} \perp B$, ∇n_0**

- **Distorted mirror model** (see e.g. GD Conway, et al.; PPCF 1996)**:**
  - **relates amplitude and poloidal correlation length of cutoff surface distortions to "coherent" and "incoherent" reflection coefficients and path length to cutoff surface.**

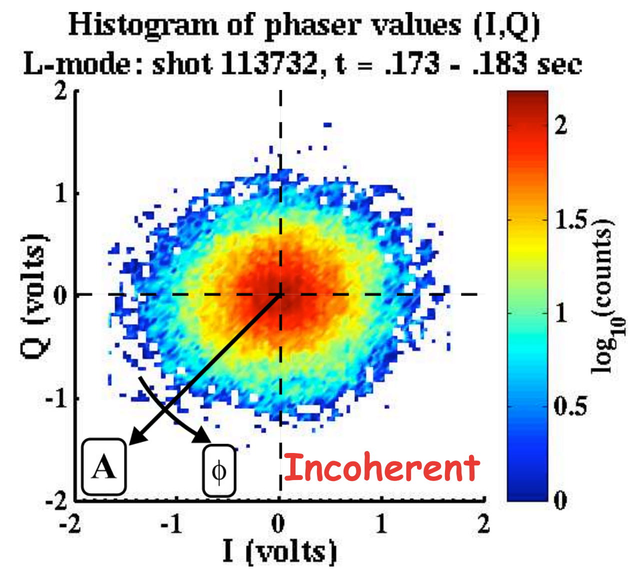
- **UCLA plans to compare reflectometer measurement with alternate $\delta n/n_0$ measurements (e.g. BES in DIII-D) to assess various models**

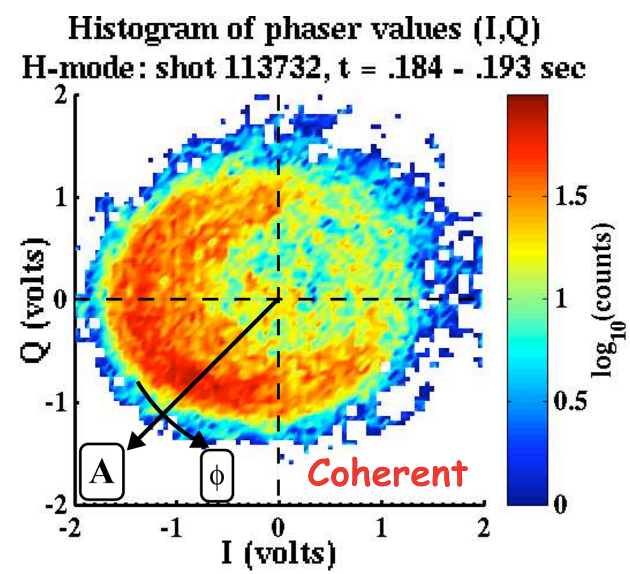
Interference effects can prevent interpretation of reflectometer measurement

- **Microwaves reflected from plasma may be incoherent due to:**
  - Interference from strong random rippling or roughness of cutoff surface
  - Long distance propagation of angularly scattered microwaves

- **When reflected microwaves incoherent (top)**
  - Phaser, given by $A(t)e^{i\phi(t)} = I(t)+iQ(I)$, is randomly distributed around zero amplitude
  - Proportionality between phase and density fluctuations breaks down

- **When reflected microwaves coherent (bottom):**
  - phaser exhibits strong phase fluctuations, weak amplitude fluctuations
  - Phase fluctuations proportional to density fluctuation level $\delta n/n_0$.



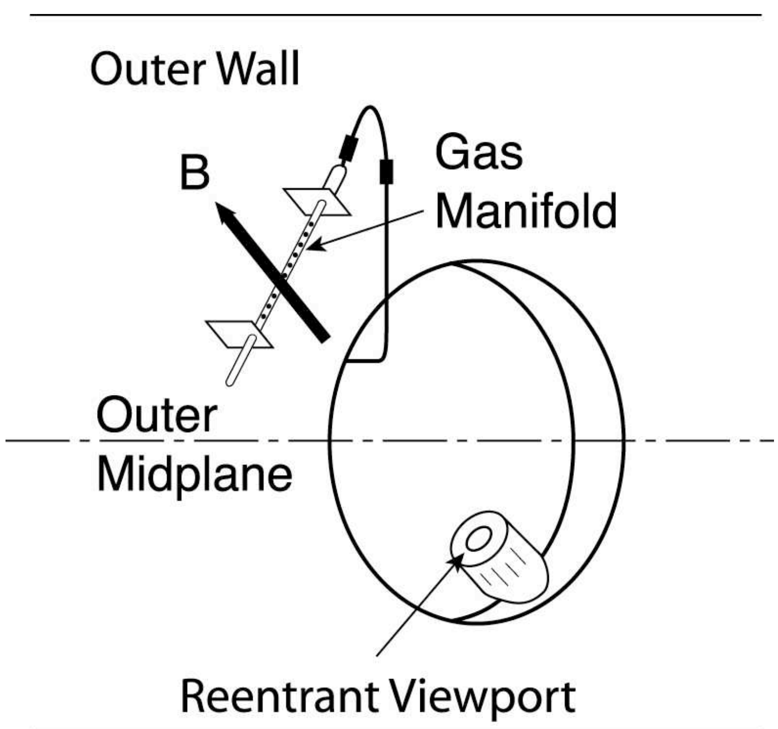


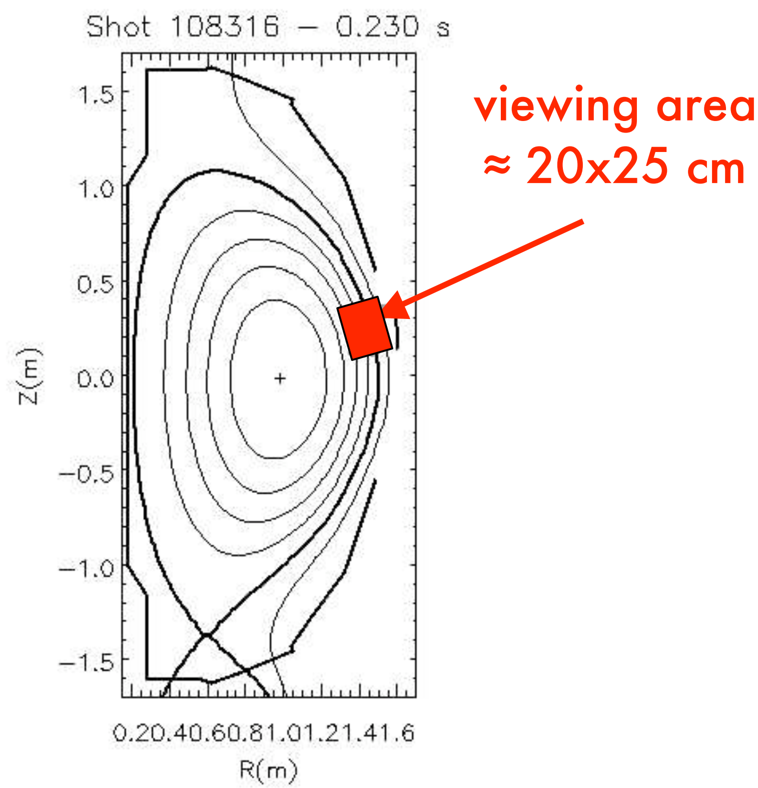
Gas Puff Imaging diagnostic images turbulence in NSTX edge

- Looks at D_α or HeI light from gas puff:

$$I \propto n_o n_e f(n_e, T_e)$$

- View ≈ along B field line to see 2-D structure ⊥ B
- Image coupled to camera with 800 x 1000 fiber bundle

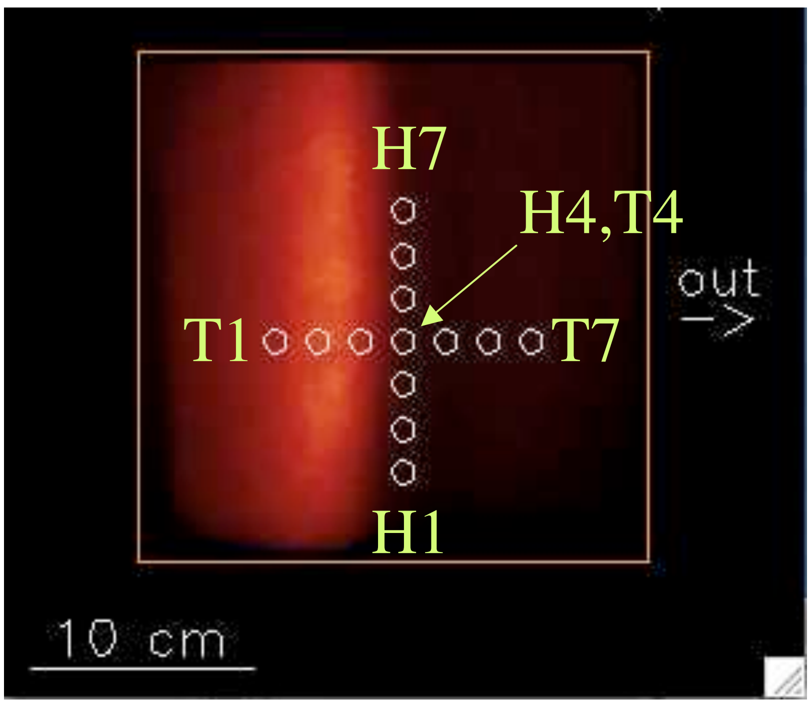




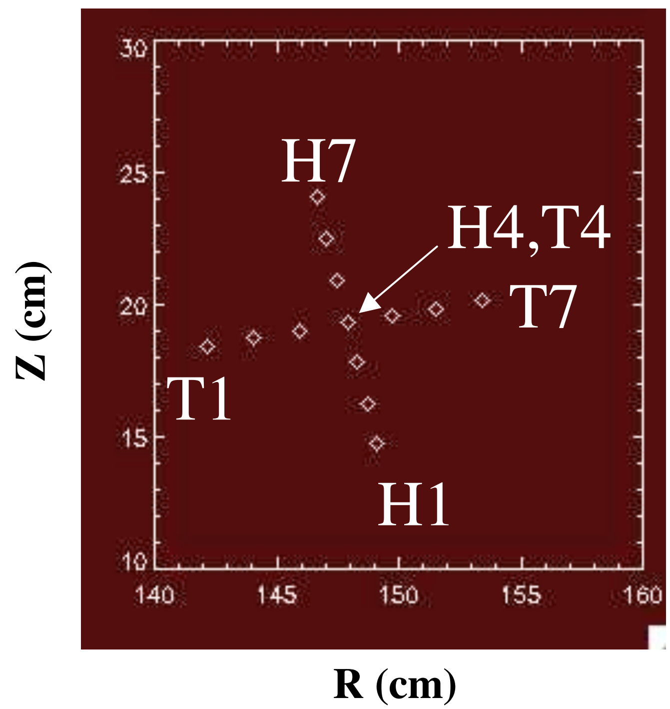
Gas Puff Imaging system has two complementary subsystems

- High spatial resolution, short time records:
  - PSI-5 Camera (300 frames/shot): ≤ 250,000 frames/sec with 64 x 64 pixels per frame
- Limited spatial resolution, long time records:
  - Fast Chords (13 channels/shot): 2 cm spots into PM tubes with 200 kHz bandwidth

Chord locations with respect to PSI-5 Image



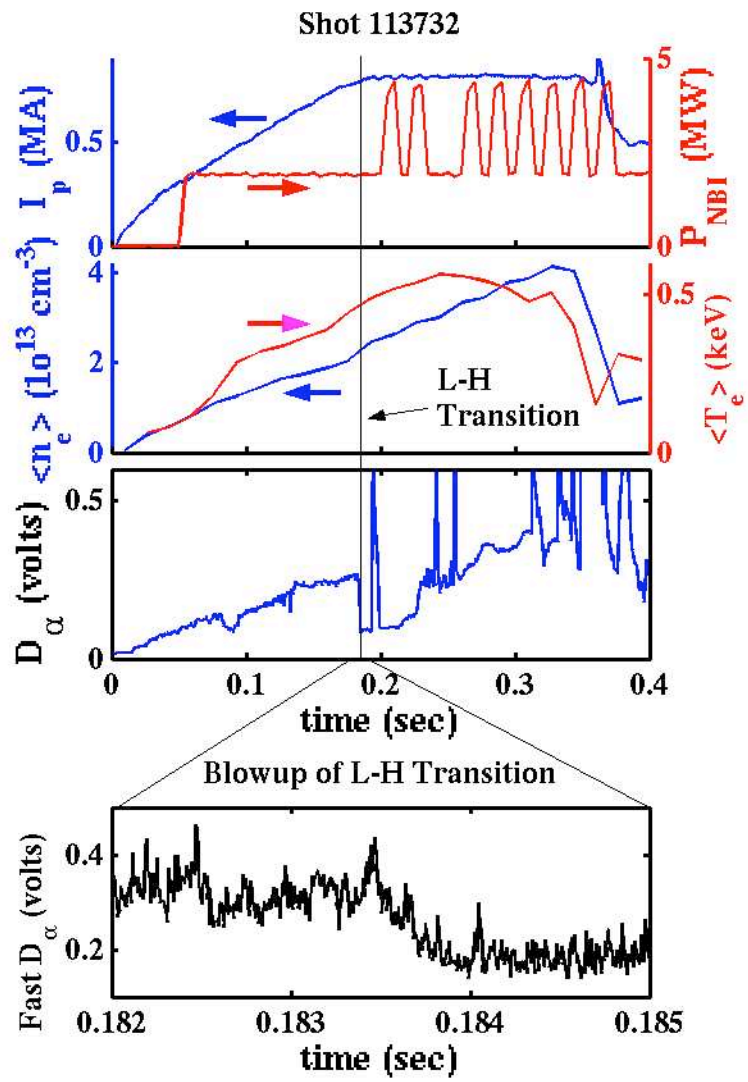
Chord locations with respect to lab coordinates



L-H transition observed in neutral beam driven NSTX shot

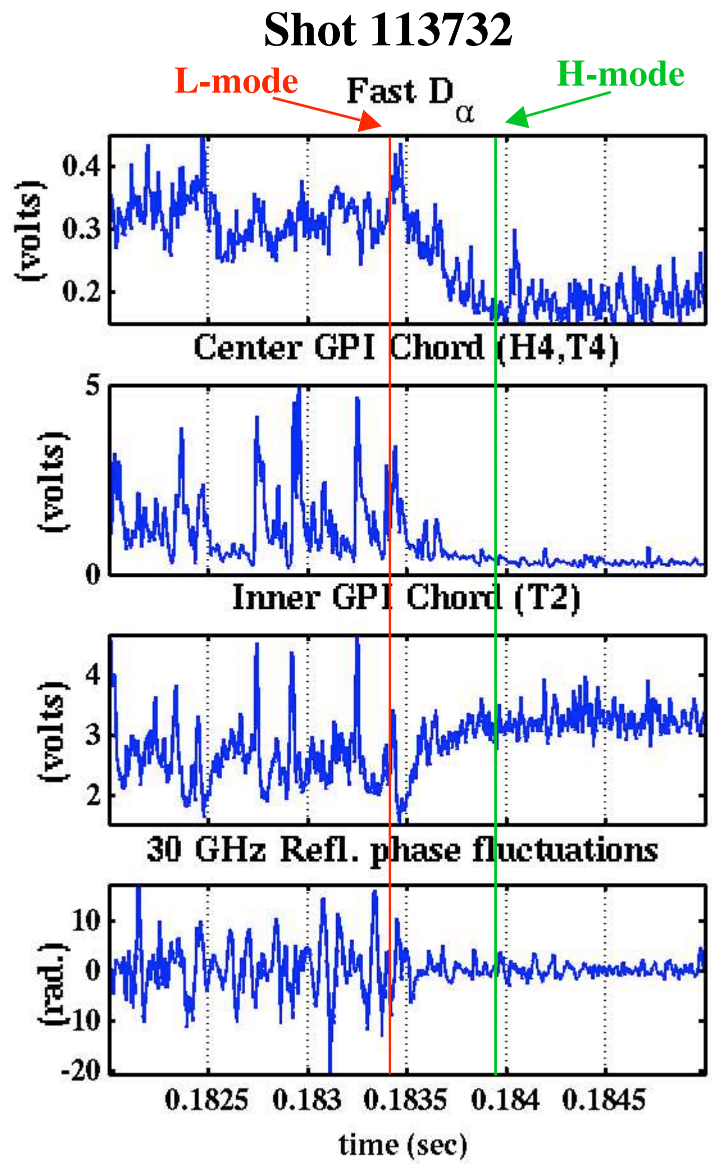
- NSTX Shot 113732 has plasma parameters:
  - Peak plasma current, Ip = 900 kAmp
  - Neutral beam power, P_{NBI} ~ 1/4 – 1/2 MW
  - Peak line avg. density, $\langle n_e \rangle = 4.1 \times 10^{13}$ cm^{-3}
  - Peal line avg. temperature, $\langle T_e \rangle$ = 0.56 keV

- Sudden drop in D_α at t ~ 0.1835 sec corresponds to L-H transition

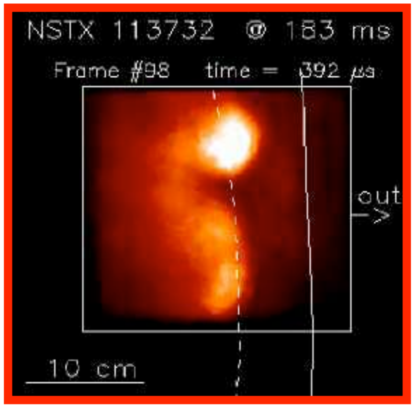


Reflectometry and Gas Puff Imaging obtain simultaneous, complementary measurements during L-H Transition

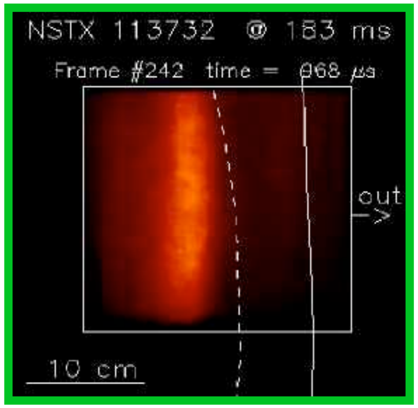
- **Simultaneous measurements of L-H transition:**
  - Fast D_α (top right): Sudden drop indicates transition
  - Center and Inner fast chords (upper and lower middle right): large D_α intensity changes. Chord arrays provide long-time, multi-point spectra
  - 30 GHz reflectometer phase fluctuations (bottom right): sudden amplitude change, faster than D_α intensity change.
  - Fast 2-D imaging of transition (left and right below): can provide short-time, high spatial resolution spectra



L-mode

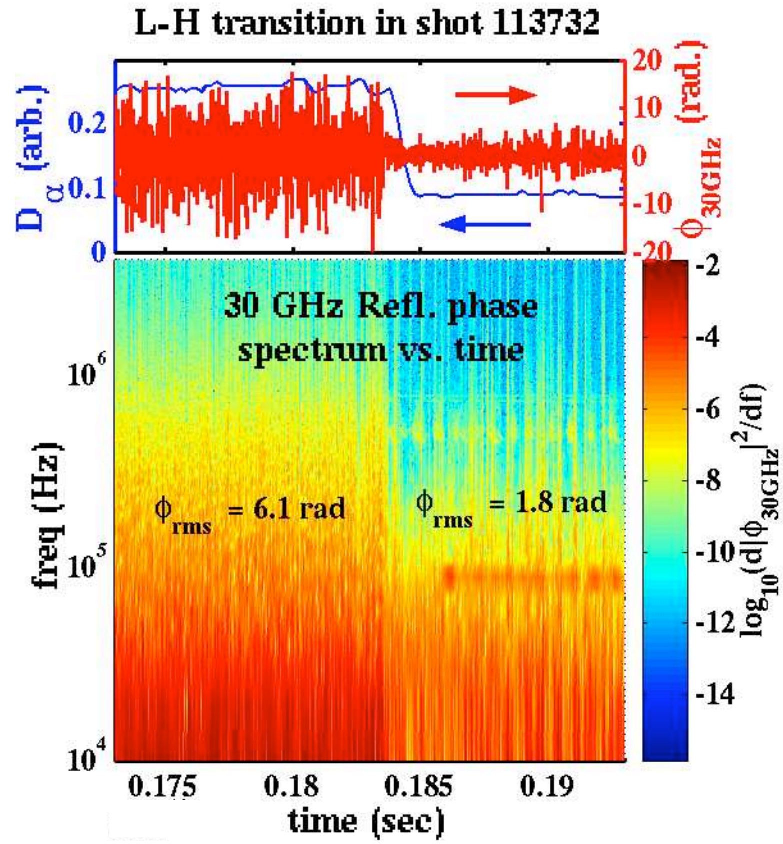


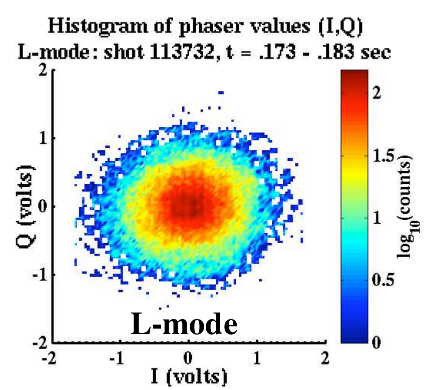
H-mode

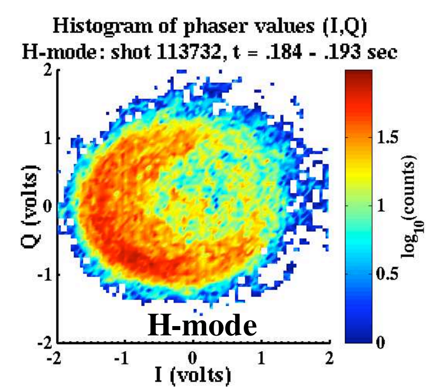


Reflectometer Phase Fluctuations Decrease Abruptly (≤ 100 μsec) at L-H Transition

- **Sharp drop in D_α indicates L-H transition (top right)**
- **Fluctuations in 30GHz reflectometer phase decrease abruptly at L-H transition (top right)**
  - $\delta\phi$ changes from ~ 6.1 radians to ~ 1.8 radians
  - received microwaves incoherent before transition (bottom left), coherent after transition (bottom right)
- **Phase spectrum changes abruptly, as well (middle right), For instance, various coherent modes appear.**
- **Reflectometer phase sensitive to L_n and density fluctuation level, as well as 2-D effects**

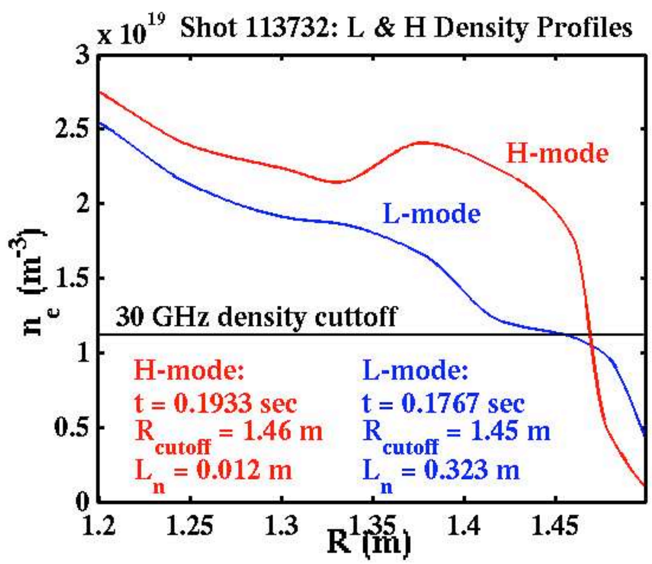






Change in density fluctuation level at L-H transition difficult to determine

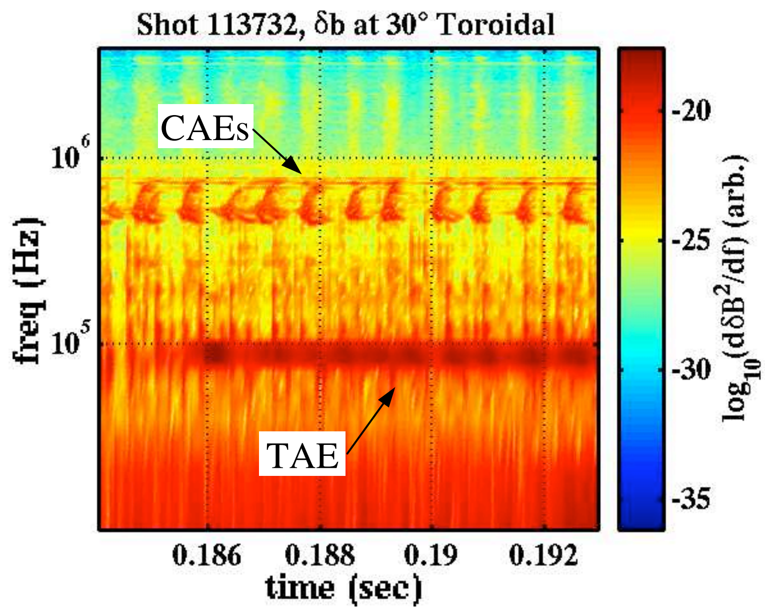
- **In L-mode, can't determine $\delta n/n_0$†**
  - Microwaves at receiver incoherent ⇒ can't determine $\delta n/n_0$.
  - Incoherence may be due to large L_n. Multipoint Thompson Scattering (MPTS) shows L_n ~ 30 cm at t = .177 sec
- **Rapid $\delta\phi$ drop (≤ 100 μsec) during transition suggests $\delta n/n_0$ drops, as well**
  - L_n should change on transport time scale, much longer than 100 μsec ⇒ change in $\delta\phi$ due to change in $\delta n/n_0$
- **In H-mode, from 1-D model, $\delta n/n_0 \sim 0.14$**
  - for 30 GHz reflectometer, $k_{vac} = 2\pi\ \text{cm}^{-1}$
  - assume $k_{\delta n} \sim 1\ \text{cm}^{-1}$
  - from MPTS, L_n ~ 1 cm after transition (t = .193 sec)
  - $k_{\delta n}L_n = 1 \Rightarrow \delta n/n_0 \sim \delta\phi/(2k_{vac}L_n) \approx 1.8/(2*2\pi*1) = 0.14$
  - UCLA plans to compare refl. measurements with alternate $\delta n/n_0$ measurements (e.g. BES in DIII-D) to assess various models



†L-mode shots not intrinsically intractable. $\delta n/n_0$ can be determined in some L-mode-only shots (not shown here).

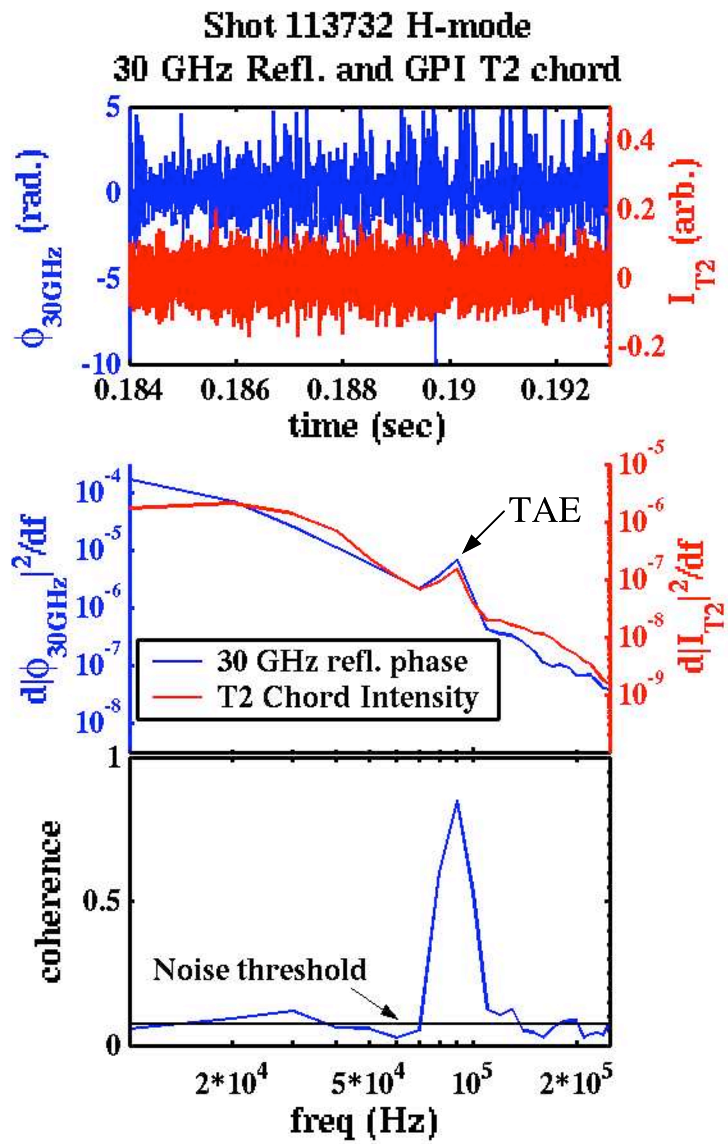
Global MHD modes typically observed in neutral beam driven plasmas in NSTX

- Compressional Alfvén Eigenmodes (CAEs) (see right)
  - Driven by neutral beam ions
  - Multiple coherent modes at resonant frequencies
  - Range of frequencies, f, controlled by ion cyclotron frequency, f_{ci} : $\sim 1/5 \leq f/f_{ci} \leq \sim 1$
- Toroidal Alfvén Eigenmodes (TAEs) (see right)
  - Driven by fast ions energized by neutral beams
  - Low toroidal mode numbers: n = 1 - 5
  - Frequencies in range 50 - 150 kHz
- Energetic Particle Modes (EPMs) (not shown):
  - Also called "fishbone instabilities"
  - frequencies in range ~ 10 kHz - ~ 100 kHz
  - frequency "chirps": sensitive to energetic particle distribution
  - related to shear Alfvén waves



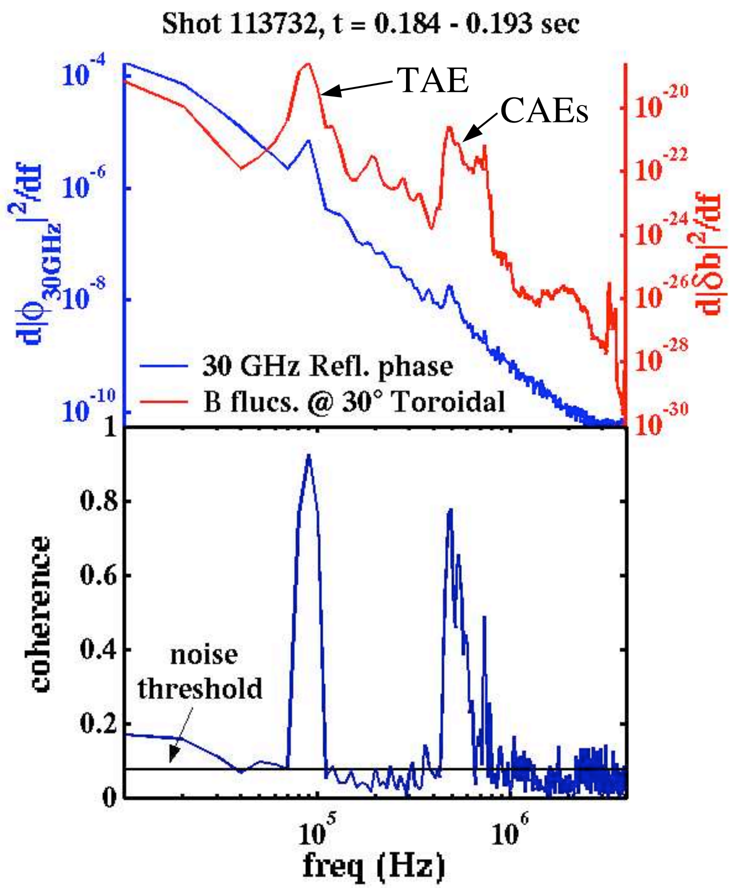
Reflectometer and GPI see similar fluctuation spectra, featuring both turbulence and global MHD

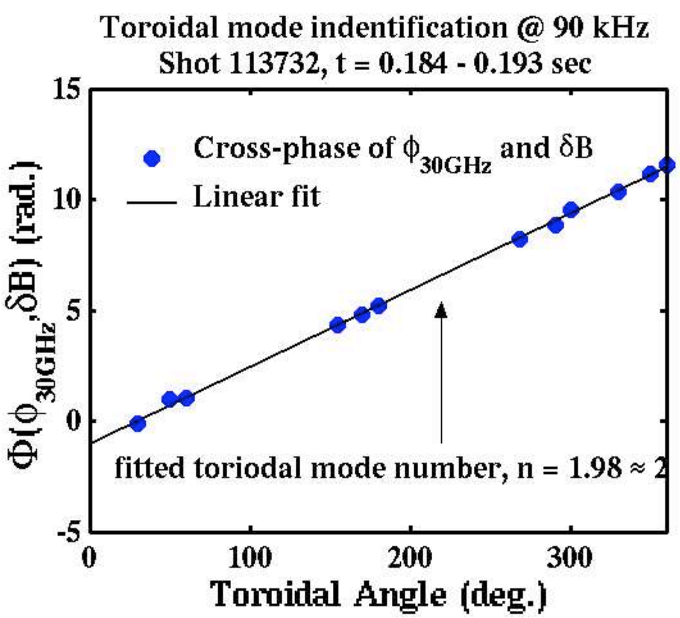
- Simultaneous fluctuation measurements (top right) obtained just after L-H transition for:
  - inner fast GPI chord emission intensity
  - 30 GHz reflectometer phase fluctuation
- Both signals show spectra with similar shapes (middle right)
  - expected if simplest interpretation of signals as density fluctuations applicable.
- Both signals strongly coherent at ~ 90 kHz (bottom right)
  - Indicates that both signals affected by global MHD fluctuation (TAE).
- Both signals not coherent elsewhere:
  - Indicates spectra mostly represent local turbulence



Reflectometers are sensitive to global MHD fluctuations

- Reflectometer phase coherent with global MHD modes
  - δB spectrum from Mirnov coil and 30 GHz refl. phase spectrum show similar peaks (top right)
  - Strong coherence at peaks (bottom right).
- cross-phase of reflectometer phase and coil signals in toroidal array obtained (below)
  - may identify toroidal Fourier mode number of global MHD modes





- Radial structure of $\delta n/n_0$ associated with global MHD mode may be obtained:
  - requires simultaneous measurements with reflectometers at different microwave frequencies.

Conclusions

- **Reflectometry and Gas Puff Imaging have obtained measurements simultaneously of substantial changes in turbulence during an L-H transition**
  - **Abrupt change observed in reflectometer phase fluctuations.**
  - **Fast (but slower) changes seen in GPI images and fast chord measurements of turbulence**
- **Change in density fluctuation level ($\delta n/n_0$) thru L-H transition difficult to determine from reflectometer measurement**
  - **Determination of $\delta n/n_0$ in H-mode may be possible. Requires testing of reflectometry models.**
  - **Determination of $\delta n/n_0$ in L-mode not possible due to interference effects,† but measurement nonetheless suggests it is larger than in H-mode.**

    †Problem not intrinsic to L-mode. L-mode-only shots exist where $\delta n/n_0$ can be determined.
- **Similar fluctuation spectra, featuring both turbulence and global MHD, seen by reflectometer and GPI**
- **Toroidal mode number of global MHD modes identified. Internal structure of associated density perturbation may be determined with future work.**

Future Work

- Compare density fluctuation levels determined from reflectometer phase with alternate $\delta n/n_0$ measurements (e.g. BES in DIII-D) to assess various models

- Find conditions where density fluctuation levels can be determined both before and after L-H transition. Compare GPI with reflectometry
  - L-mode shots not intrinsically intractable. Density fluctuation levels can be determined in some L-mode-only shots (not shown here).

- Measure internal structure of global MHD mode density perturbations:
  - Use different microwaves frequencies simultaneously for radial structure
  - Use toroidal array of Mirnov coils to identify toroidal mode number
  - Explore use of poloidal arrays to determine poloidal structure

Requests For Electronic Copies
(please provide e-mail address)