NSTX-U

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(EX/P7-21) Evolution of the Turbulence k_r Spectrum near the L-H Transition in NSTX Ohmic Discharges

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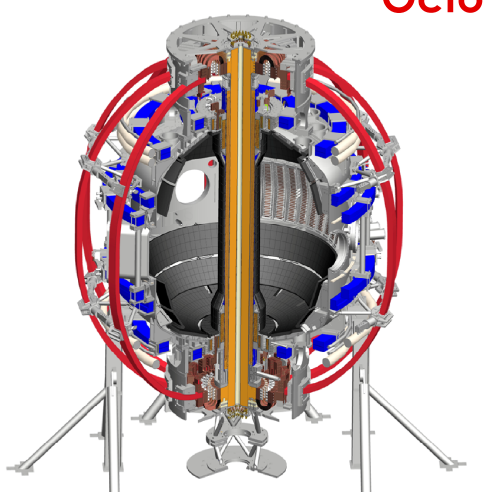

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Abstract

The turbulence characteristics near the L-H transition in NSTX Ohmic discharges are measured using the FMCW reflectometry and backscattering techniques. The unique capabilities of this diagnostic combination, i.e. sensitivity to the density provile as well as fluctuations up to k_r~22 cm^{-1}, are utilized to document the correlation between dynamics of the edge density gradient, turbulence correlation length, and the radial wavenumber spectrum, near the L-H transition in NSTX. During the L-mode phase, a broad band of turbulence (k_r~2-10 cm^{-1}) extends over a significant portion of the edge-core from R=120 to 155 cm (ρ=0.4-0.95). At the L-H transition, turbulence is quenched across the measurable k_r spectral range at the ETB location, where the radial correlation length also drops from ~1.5 to 0.5 cm. Close to the L-H transition, oscillations in the density gradient and edge turbulence quenching become highly correlated. These oscillations are also present in Ohmic discharges without an L-H transition, but are far less frequent. Similar behavior is also seen near the L-H transition in NB-heated discharges.

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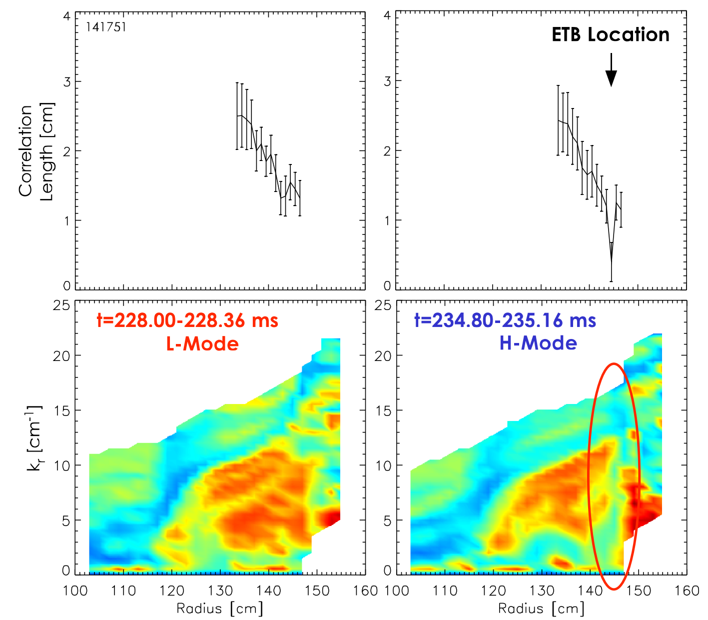
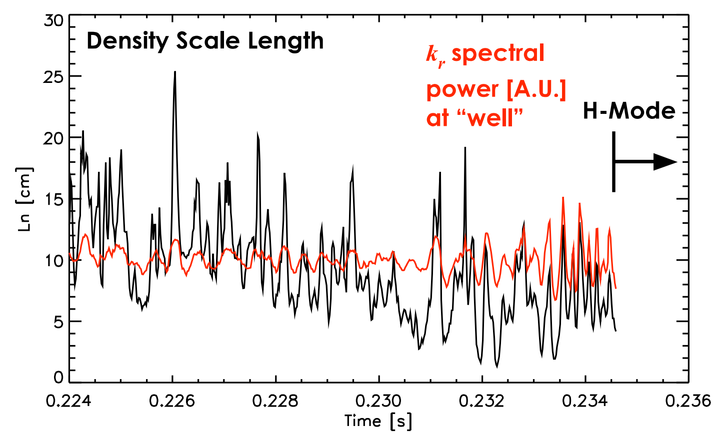
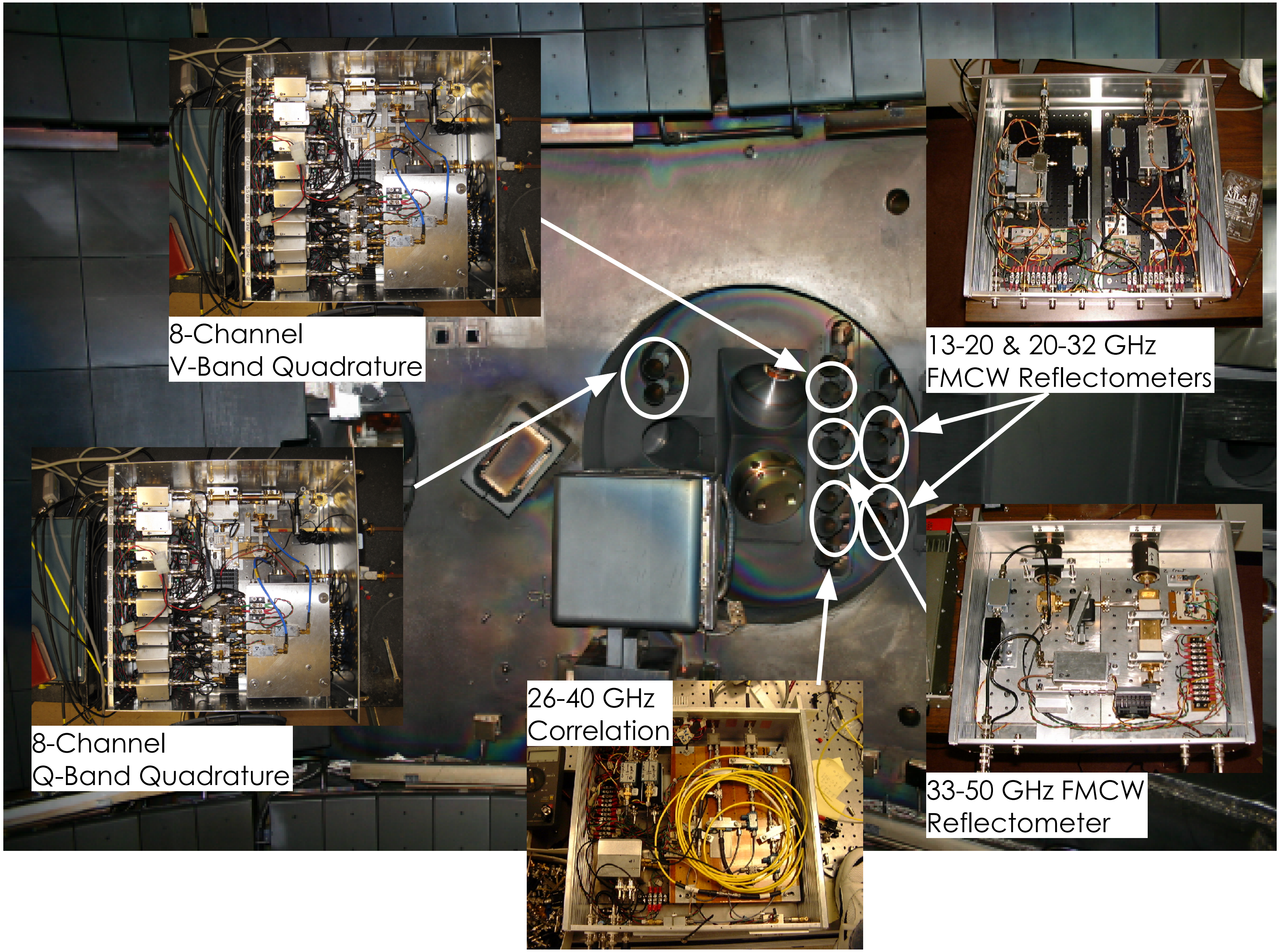
Summary Slide

- FMCW reflectometry and backscattering used to probe broad-k_r turbulence in Ohmic shots
  - Good spatial (<cm) resolution and coverage (ρ~0-1), k_r spectral range (~0-22 cm^{-1}) and time resolution (>10 μs)
  - Observe correlation of Micro-turbulence dynamics with formation of ETB and meso-scale structures
- Key experimental observations:
  - Fast and slow modulation of the k_r spectrum shape and power in L-mode
  - Near the L-H transition, fast quenching of the edge turbulence localized to the ETB location
    - Correlated with oscillatory ("H-mode-like") local steepening of the density gradient at the ETB location
    - Final L-H transition occurs when turbulence correlation length decreases at the ETB location
- Strong interplay between micro-turbulence and density profile near L-H transition
  - Supports observations elsewhere showing coupling between turbulence and ETB formation





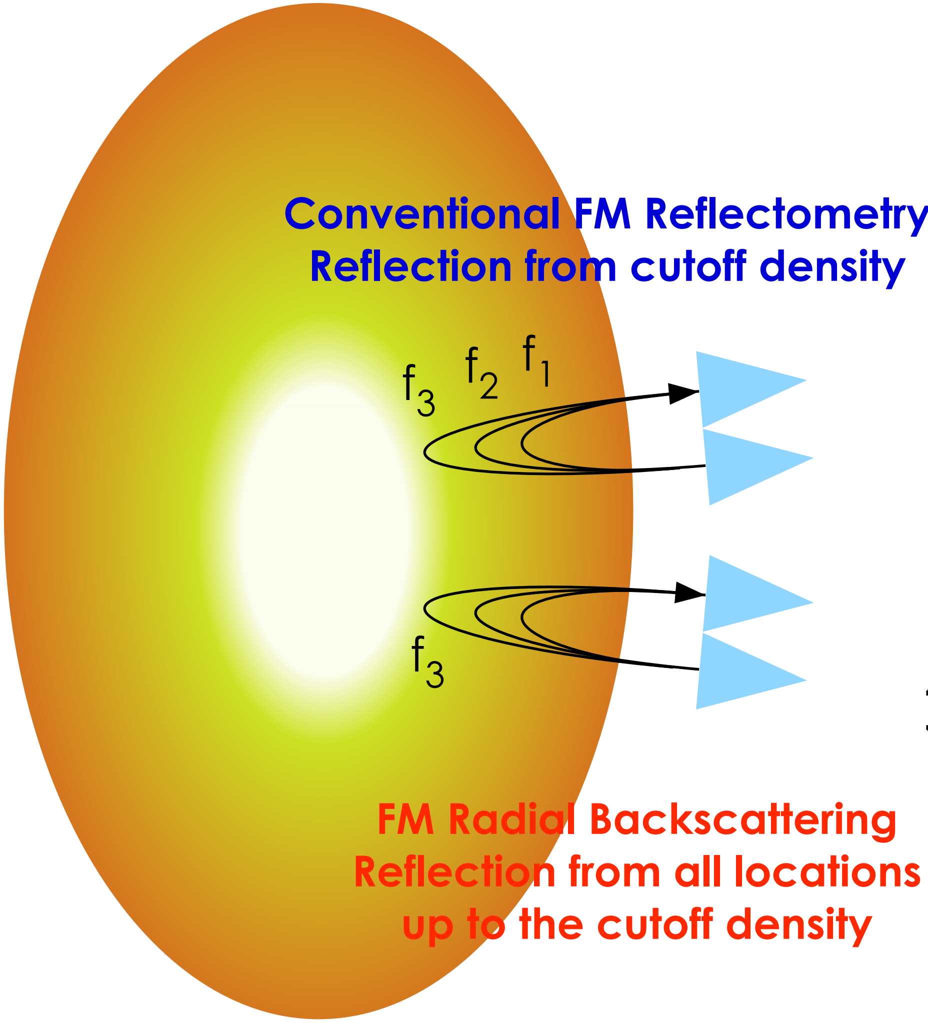
Millimeter-Wave Diagnostics for FY2010 Campaign



Motivation

- Connection between microinstabilities and transport remains a critical issue for fusion plasma devices
  - Formation of meso-scale structures such as zonal flows and streamers thought to influence internal gradients and transport barrier formation (e.g. L-H transition)
- Fluctuation measurements over a broad wavenumber range are necessary
  - Imaging diagnostics (i.e. GPI and BES) capture low-k
  - Doppler backscattering used for intermediate-k
  - Forward- and back-scattering at high-k
- Requires multiple diagnostics to operate simultaneously
  - Each has different response to fluctuation spectrum
  - Different temporal and spatial resolution
  - Viewing same location (radially, toroidally, poloidally)?
  - Background profiles?
- FMCW reflectometry and backscattering techniques can provide many of these capabilities in a single diagnostic

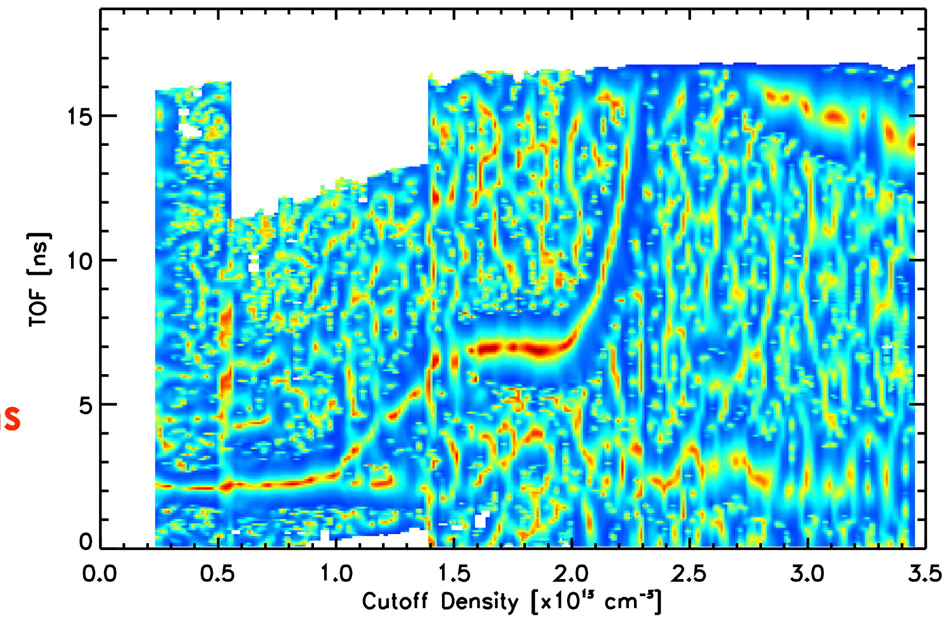
New Tool is Backscattering: Spatially-Resolved k_r Spectrum



- Density profile from cutoff reflection.
- Local k from density profile.
- Probed k_r from Bragg Law:

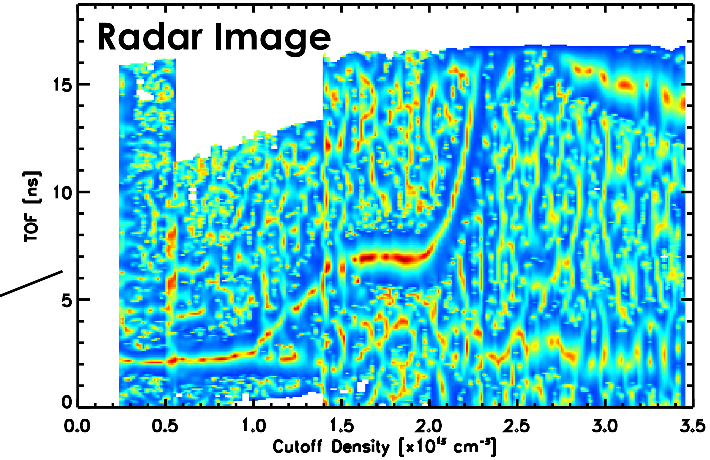
$$k_s(r, f) = 2\,k(r, f)$$

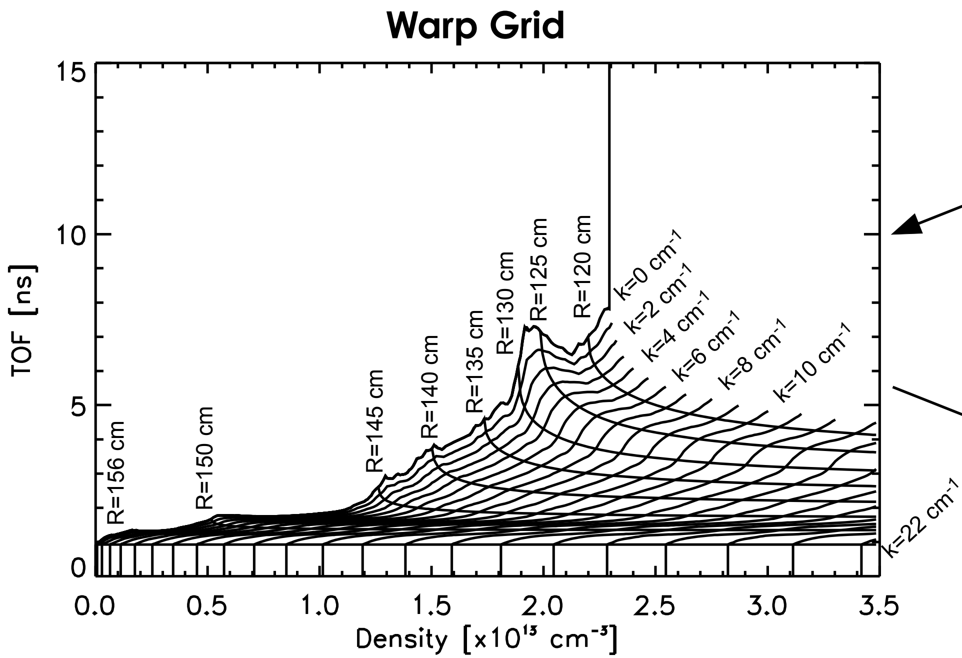
Reflectometry/Backscattering Radar Image

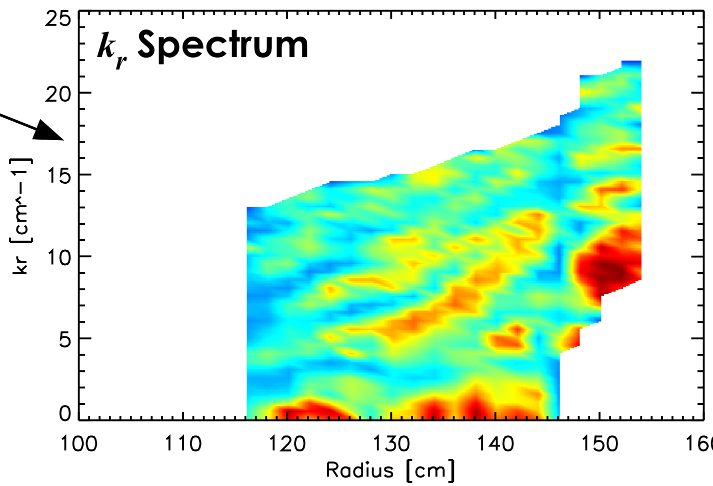


Transformation of Radar Image to k_r Spectrum

- **Similar procedure in the language of image processing.**
  - Image warp.
  - (τ, f) to (k_r, R) map or vice versa are the "warp grids" for forward or backward mapping.







Warp grid created from $n_e(r)$.

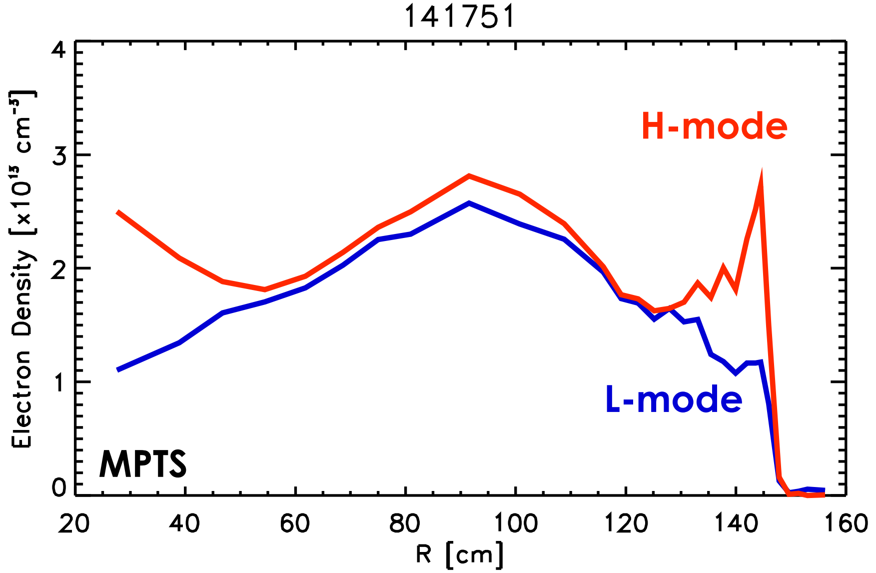
Target L-H Transition in NSTX Ohmic Discharges

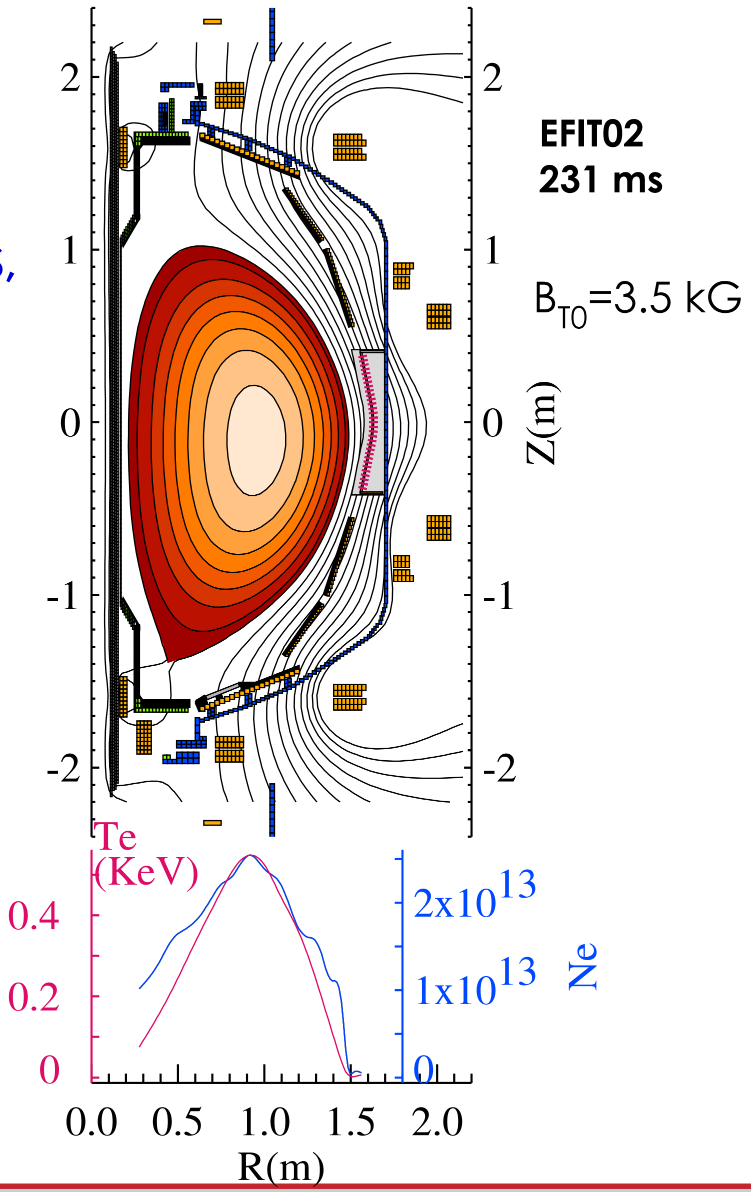
- Revisit FM reflectometry ($\Delta t \leq 10\ \mu s$, $n_e = 0.2\text{-}3.5\text{x}10^{13}\ cm^{-3}$)
  - Density profile evolution: $n_e(R,t)$
  - Radial correlation lengths: $L_{cr}(R,t)$
  - New analysis method: FM Backscatter
    Spatially resolved k_r spectrum from backscattering ($\leq 22\ cm^{-1}$): $k_r(R,t)$
- Shape and evolution of the wavenumber spectrum can indicate details of nonlinear processes governing turbulence and transport
  - Spectral energy transfer and coherent structures
  - Turbulence spreading
  - Transport barrier formation
- L-H transition provides "easy" target
- Observations of interplay between turbulence and zonal flows during L-mode phase of NB-heated H-mode discharges from gas-puff imaging (GPI)
  - ~3 kHz GAM-like oscillations
  - Trigger mechanism(s) for L-H transition remains elusive

Ohmic H-Modes Targets for L-H Transition Studies

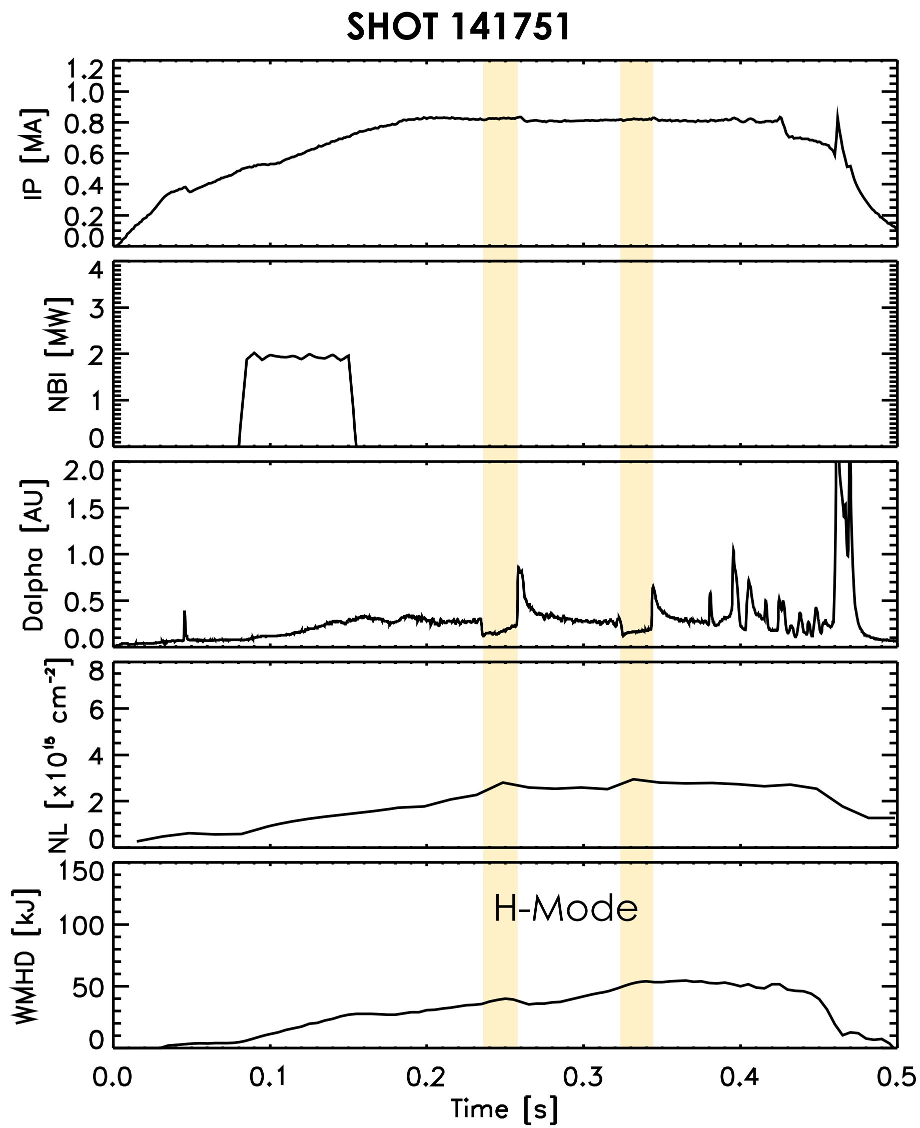
- **Benefits of Ohmic discharges:**
  - No fast particle-driven modes to mask turbulence spectrum
  - No external momentum input
  - Lack of NB-based diagnostics (CHERS, MSE, BES, etc.)
- **Discharge parameters:**

  B_T=3.5 kG, I_p=800 kA, LSN, Deut.
- **Edge density ears in H-mode limits access to core.**

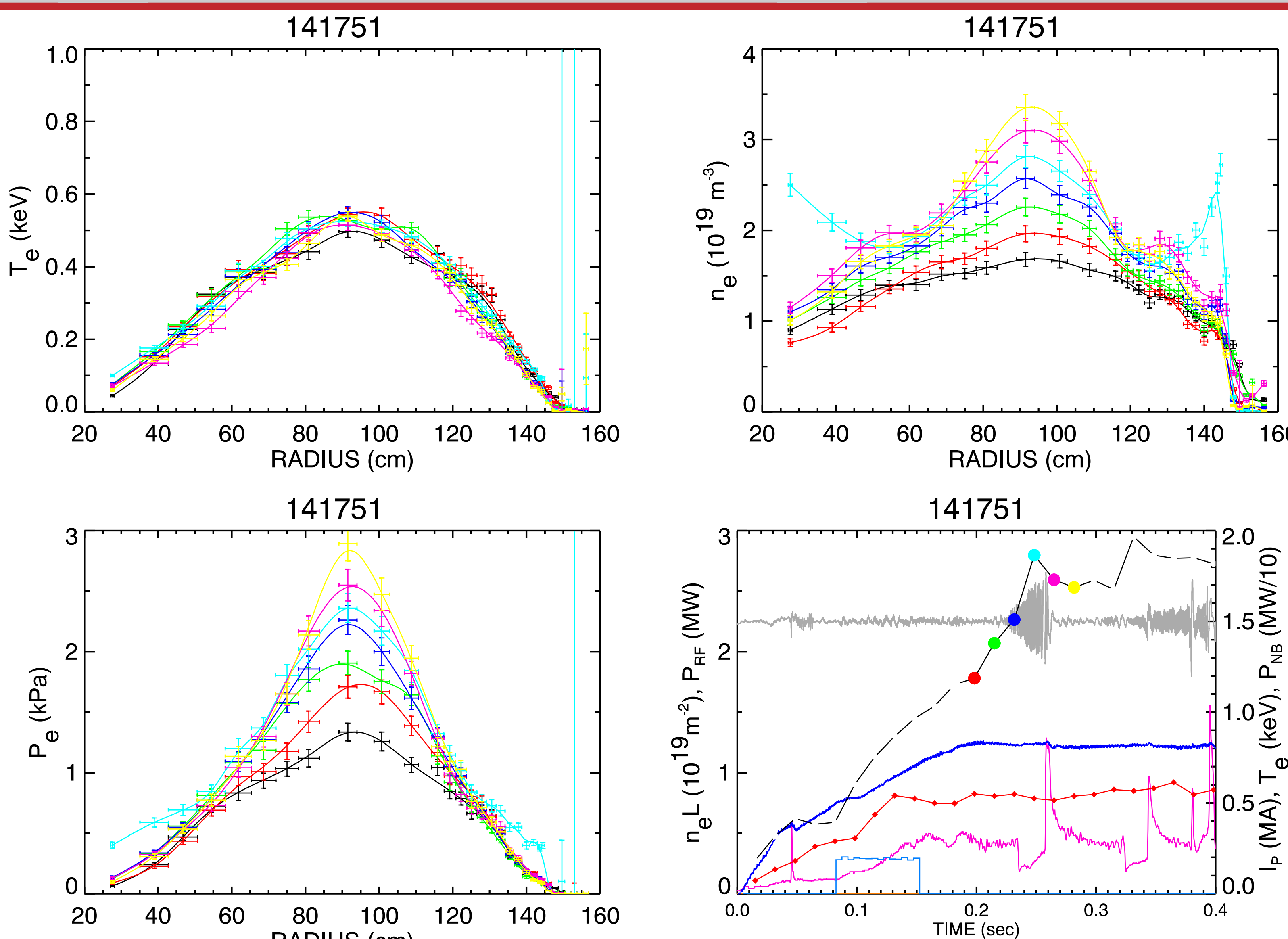




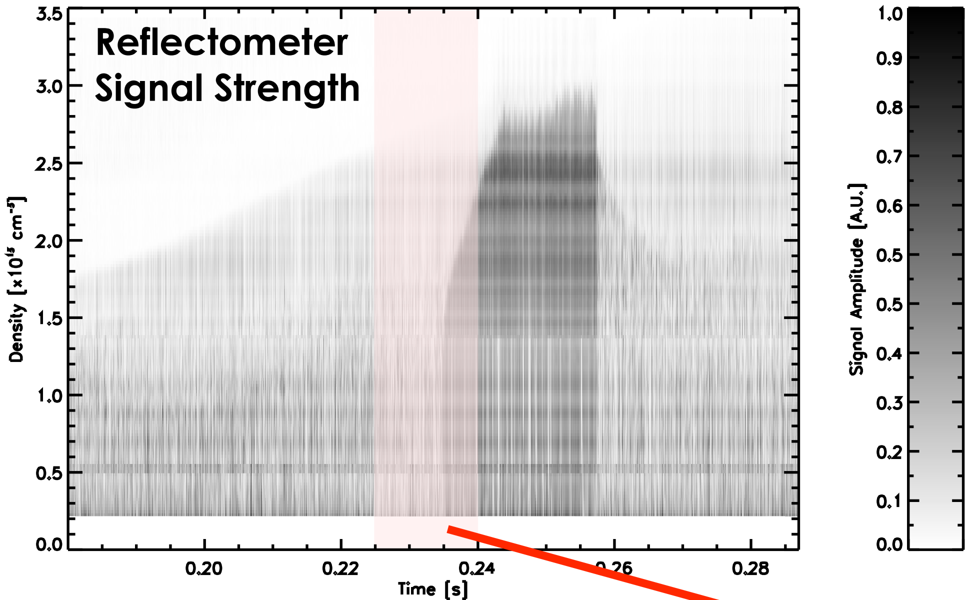
B_T=3.5 kG, I_P=800 kA, LSN, Ohmic Discharges

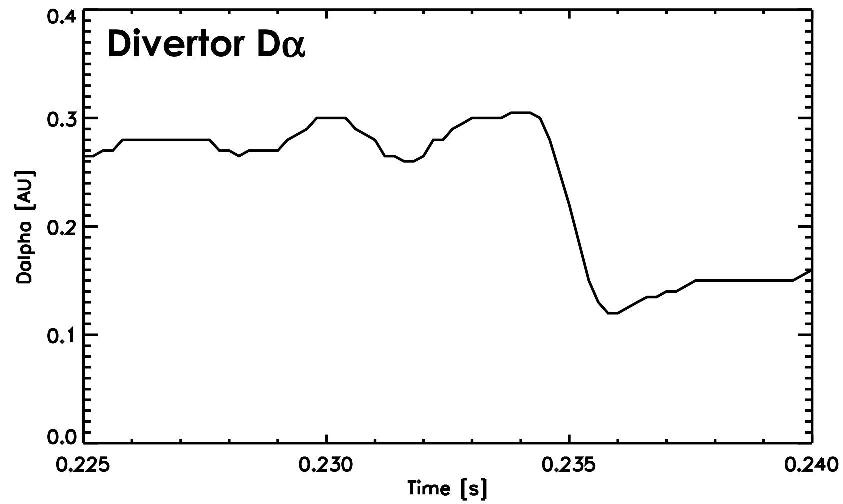


Ohmic H-Mode Discharge Profiles

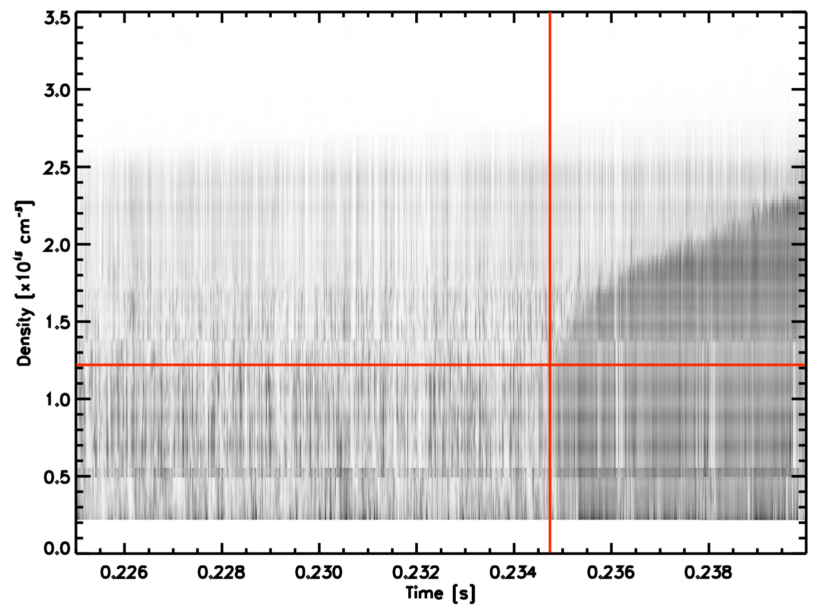


Precise L-H Transition Timing and ETB Position Identified from Signal Strength



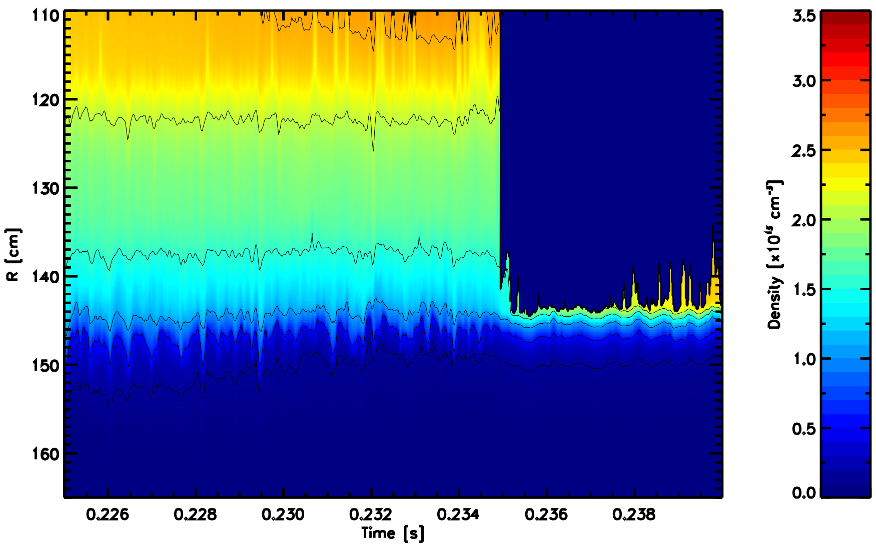


- For H-mode edge,
  - Turbulence reduction -> specular reflection -> stronger signal.
- t=234.64 ms
- n_e=1.2x10^{13} cm^{-3}

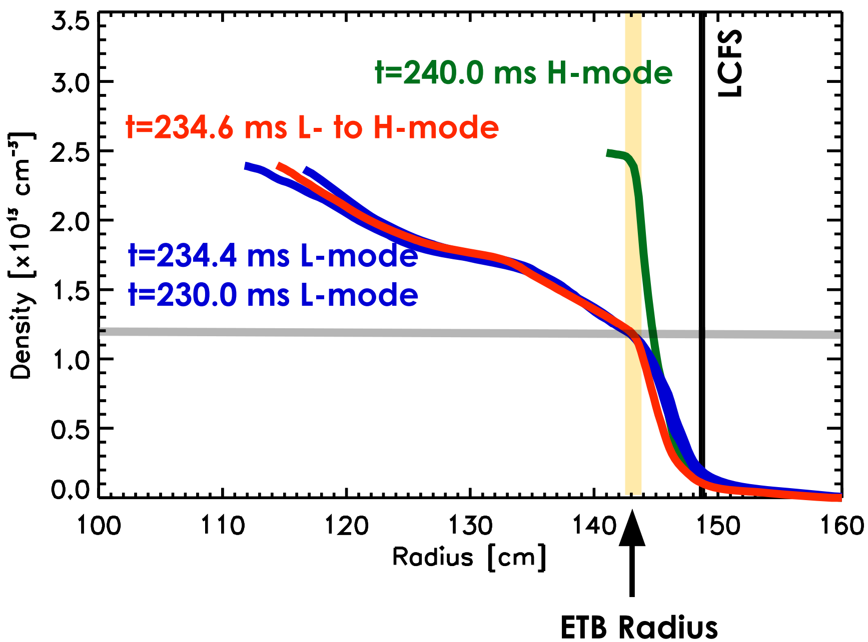


Density Gradient Steepens at ETB Location

Density Profile Contours



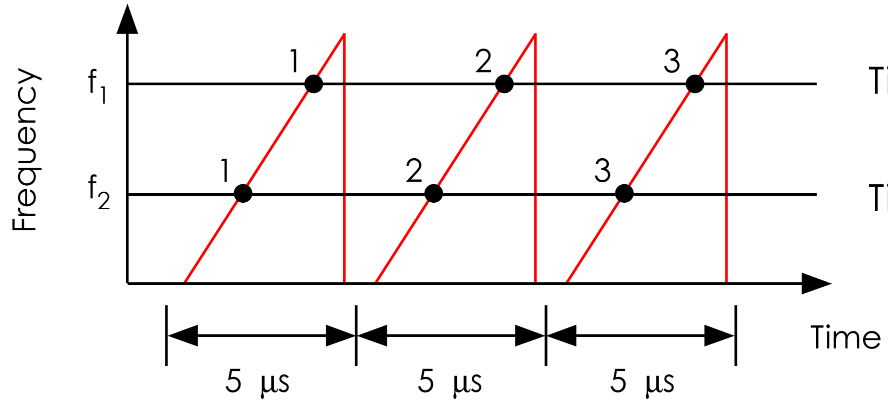
Density Profile Near L-H Transition



- L-H transition occurs at t=234.64 ms
- ETB location is R=143-144 cm
  - Density gradient sharply increases
- Oscillations prior to final L-H transition
  - Density gradient sharply increases

Outline of Quasi-Simultaneous FMCW Correlation Technique

Step 1:

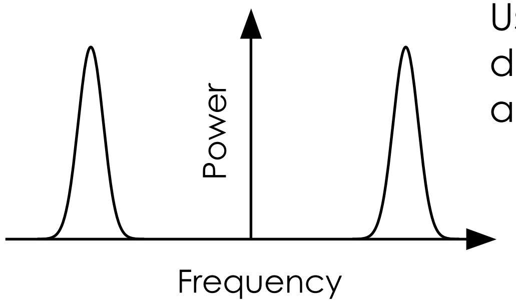


Time series for probe frequency f_1.

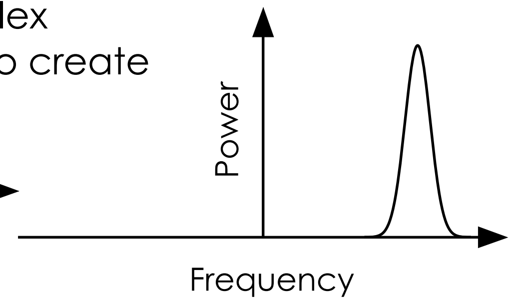
200 kHz equivalent sampling

Time series for probe frequency f_2.

Step 2:



Use CDM (complex demodulation) to create analytic signal.



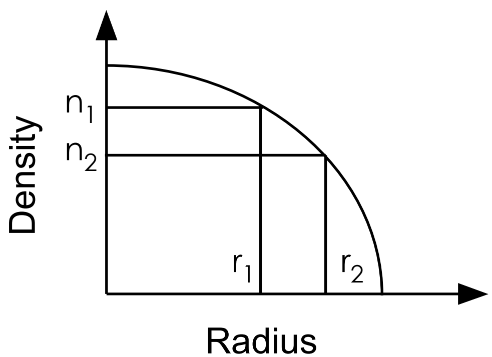
Real homodyne time series: $A(t)\sin(\phi(t))$.

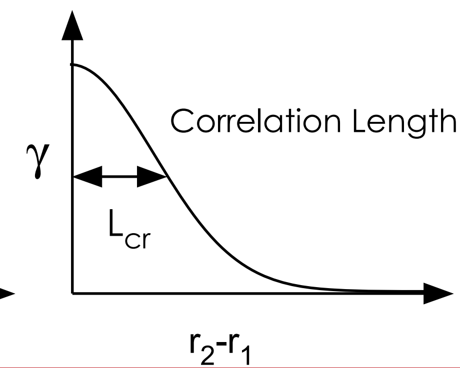
Complex amplitude $E(t)=A(t)\exp(i\phi(t))$.

Step 3:

Normalized cross correlation:

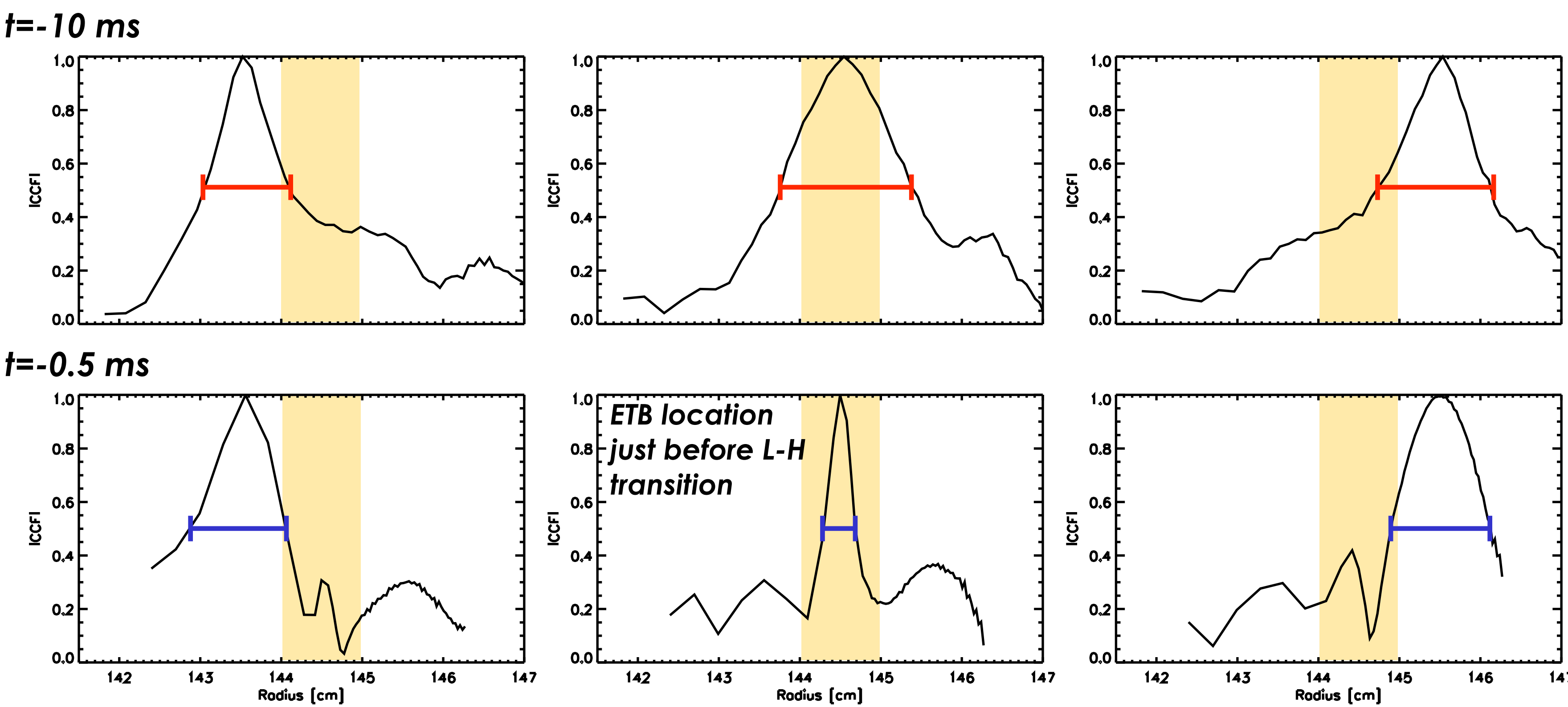
$$\gamma = \frac{|\langle E_1 E_2^* \rangle|}{\sqrt{\langle |E_1|^2 \rangle \langle |E_2|^2 \rangle}}$$



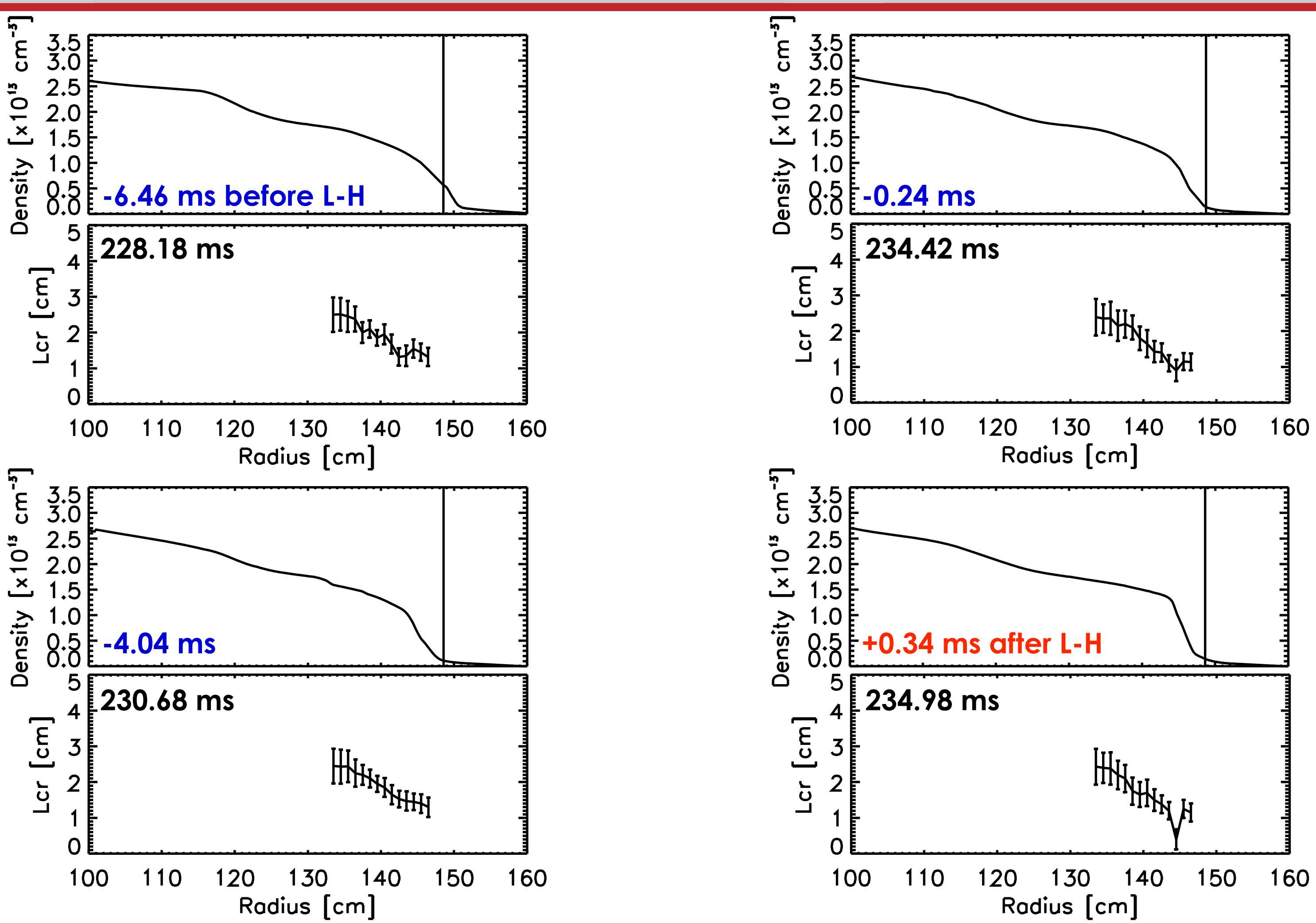


Correlation Length Change Near L-H Transition

- **Turbulence radial correlation length decreases prior (<1 ms) to L- to H-mode transition.**
  - Change only seen localized at ETB location R~144.5 cm.
  - Utilizes FMCW reflectometers for radial correlations with <1 ms resolution.
  - Correlated with drop in spectral intensity from k_r backscattering (next slide).

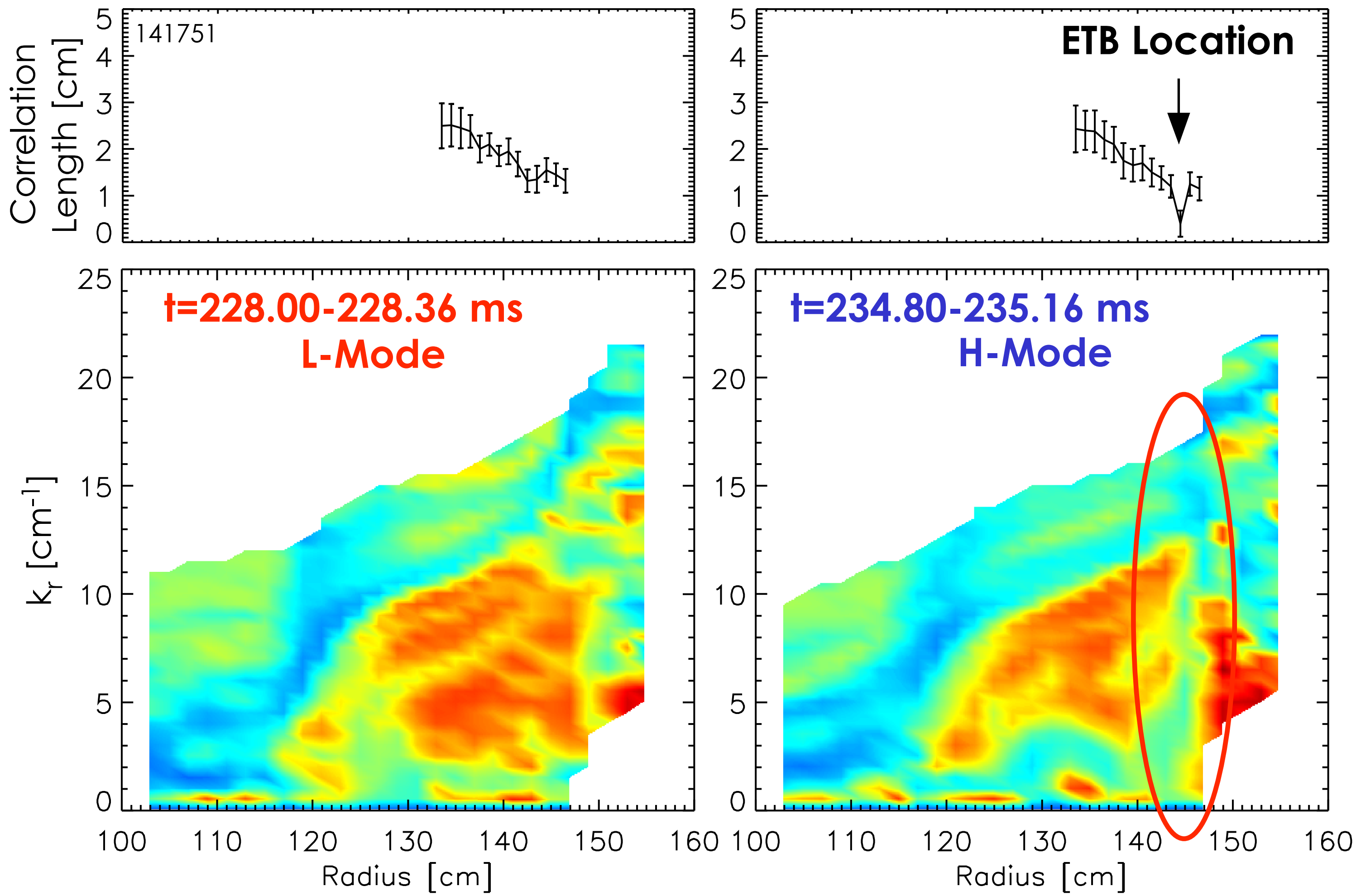


L_{cr} Decreases Locally at ETB Near L-H Transition

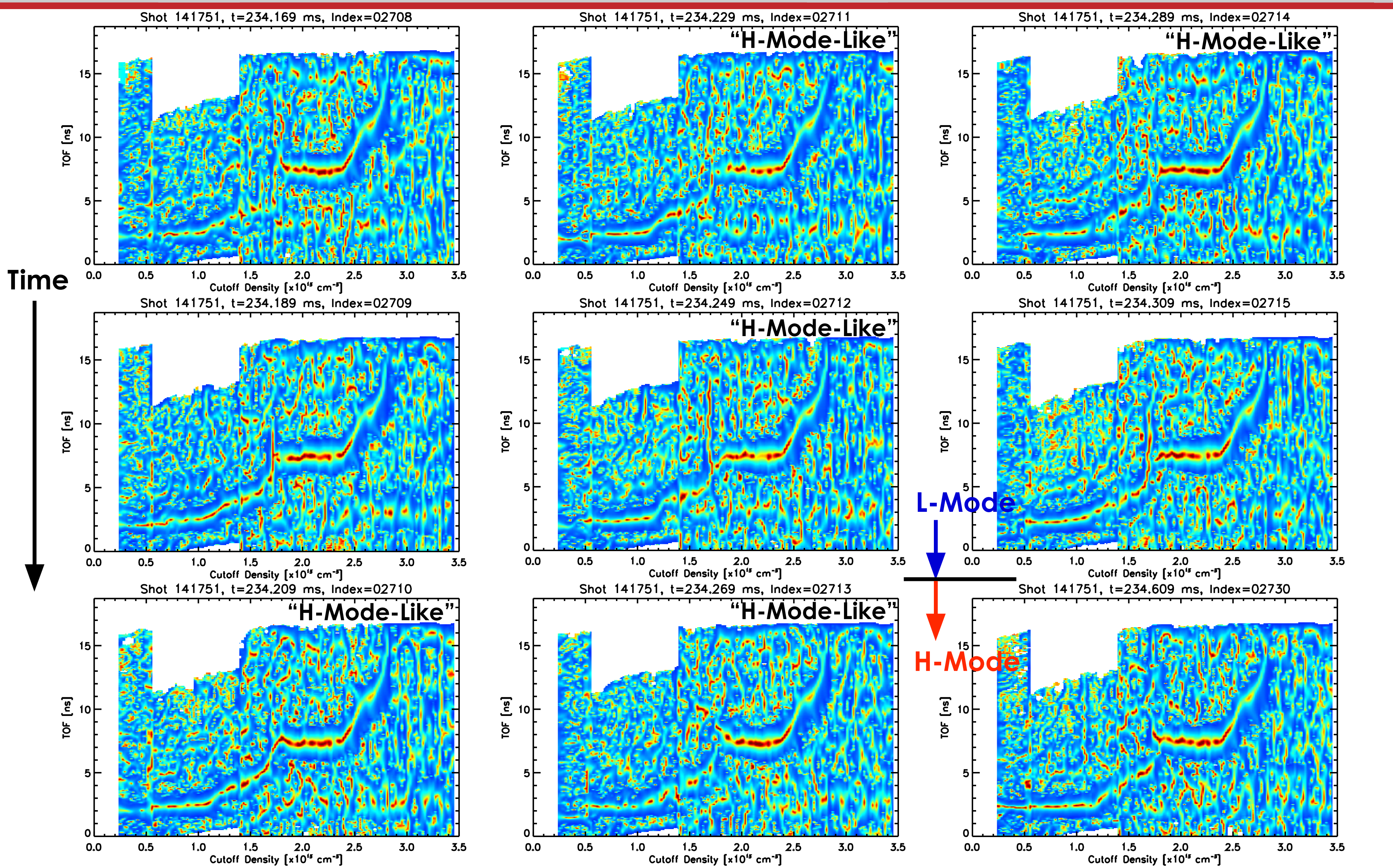


- **(Low-*k* turbulence) radial correlation length drops at L-H transition**
  - Statistical method which requires Δt ≥ 0.36 ms resolution

k_r Spectrum: "Well" at ETB Location Near L-H Transition

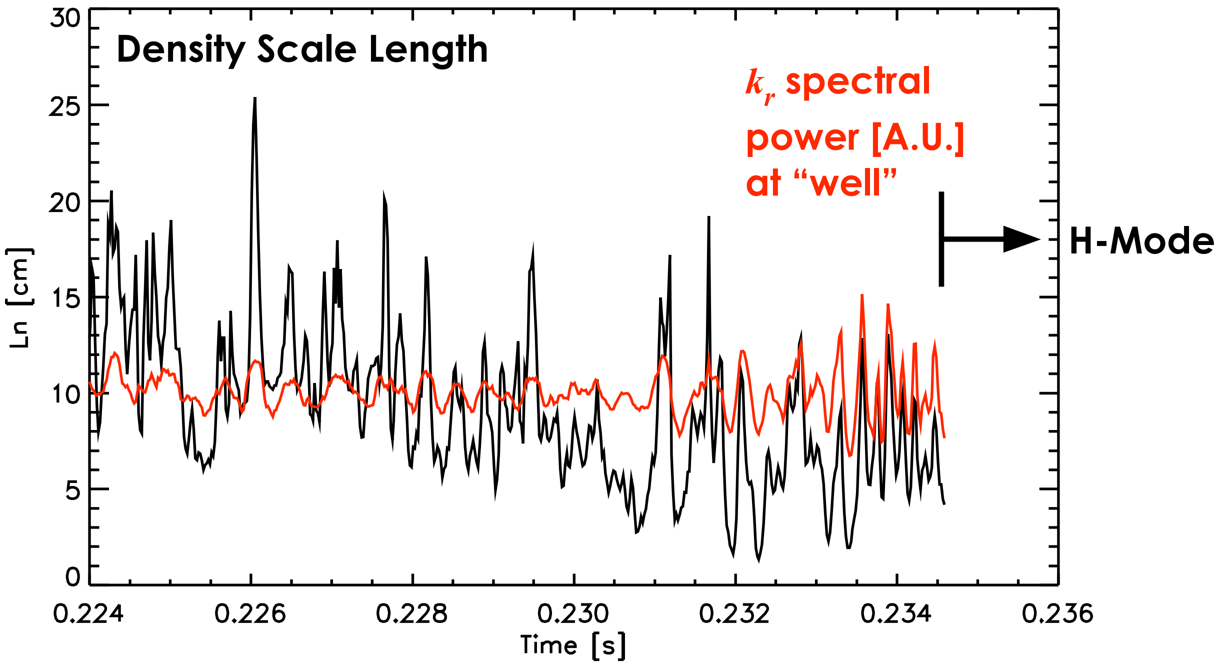


Radar Images Show Edge Density Profile Oscillations During L-Mode Phase



At ETB Radius L_n Correlated With Variations in k_r Spectral Power

- **At *R*=143~144 cm (ETB location), density scale length is correlated with variation of power in k_r spectrum.**
  - Amplitude and degree of correlation increases closer to L-H transition.



  - Could be sign of underlying flow/turbulence dynamics.

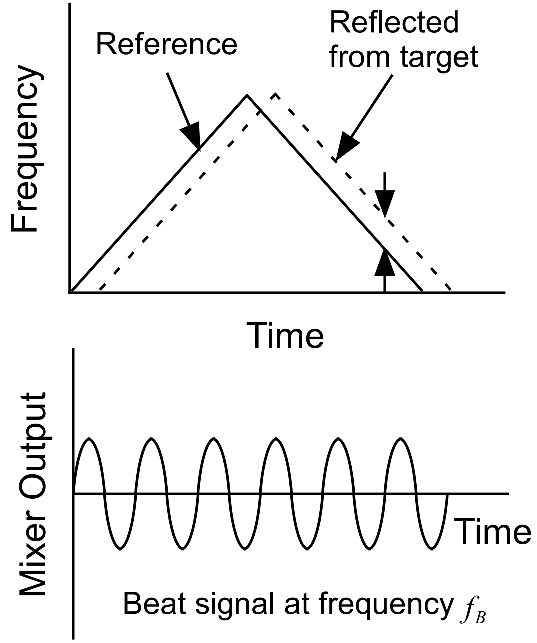
Summary of Observations

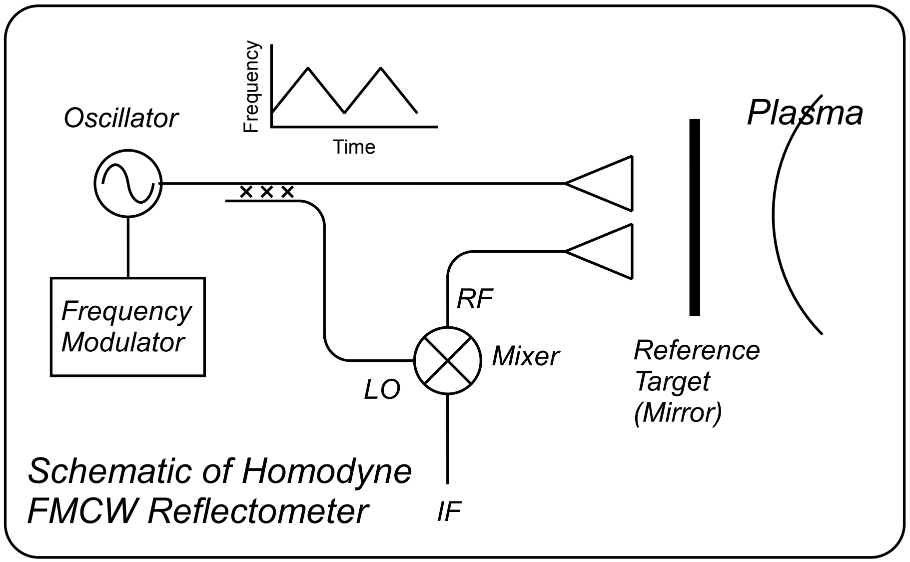
- Evolution of turbulence and density profile characteristics near the L-H transition measured using several mm-wave diagnostics
  - New technique: FMCW backscattering for k_r spectrum measurements
- Localized (to ETB) changes in turbulence at the L-H transition:
  - Drop in $\delta n/n$
  - Reduction in radial correlation length
  - Steepening of the density gradient
  - k_r-spectrum spatial "well" develops
- Oscillations in L-mode phase:
  - Correlation between k_r-spectrum well and steepening/relaxing of edge gradients
  - Could be indicative of flow/turbulence dynamics
    - Further modeling as well as comparison with GPI measurements necessary
- Similar to behavior seen in NB-heated H-mode discharges
  - Oscillations in L-mode phase seem to be fairly ubiquitous

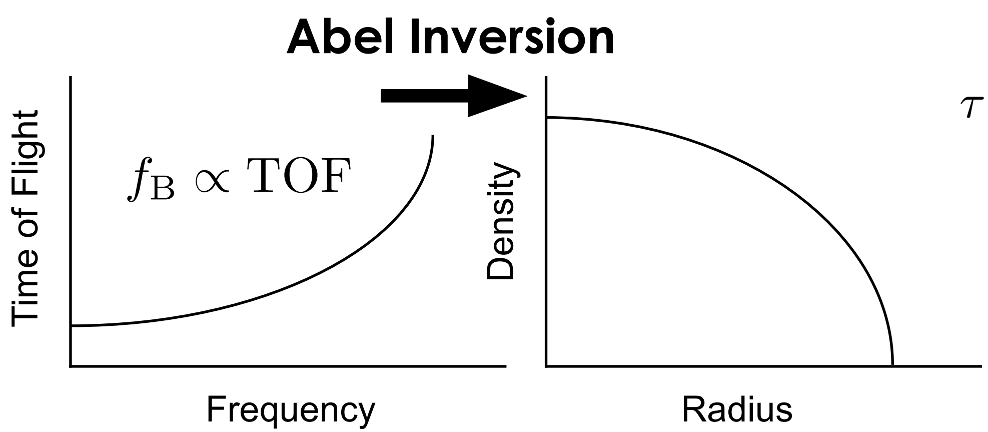
Future Directions

- Backscattering results still qualitative
  - Theoretical and numerical studies under way
    - Spatial and wavenumber resolution, spectral shape, amplitude, etc.
  - Multi-dimensional GPU-based full-wave codes to address the problem in 1-D and 2-D
- "New" method of looking at "old" data
  - FMCW reflectometry a common diagnostic on many devices
  - Advanced signal analysis techniques are necessary to process radar image
- ITER relevance
  - Recent numerical studies have indicated Bragg backscattering could have deleterious effects for profile reflectometry
    - Begin to look at this problem experimentally
- Strength of diagnostic should be in edge-core measurements
  - Broad radial coverage for L-mode plasmas
  - Data mining of past NSTX shots

Review of FMCW (Profile) Reflectometry







$$\phi(f) = \frac{4\pi f}{c} \int_{r_{\rm a}}^{r_{\rm c}(f)} \mu(f, x) dx - \frac{\pi}{2}$$

$$\tau(f) = \frac{1}{2\pi} \frac{d\phi}{df} = 2 \int_{r_{\rm a}}^{r_{\rm c}(f)} \frac{1}{v_{\rm g}(f, x)} dx$$

$$= \frac{2}{c} \int_{r_{\rm a}}^{r_{\rm c}(f)} \left(1 - \frac{f_{\rm p}^2(x)}{f^2}\right)^{-1/2} dx$$

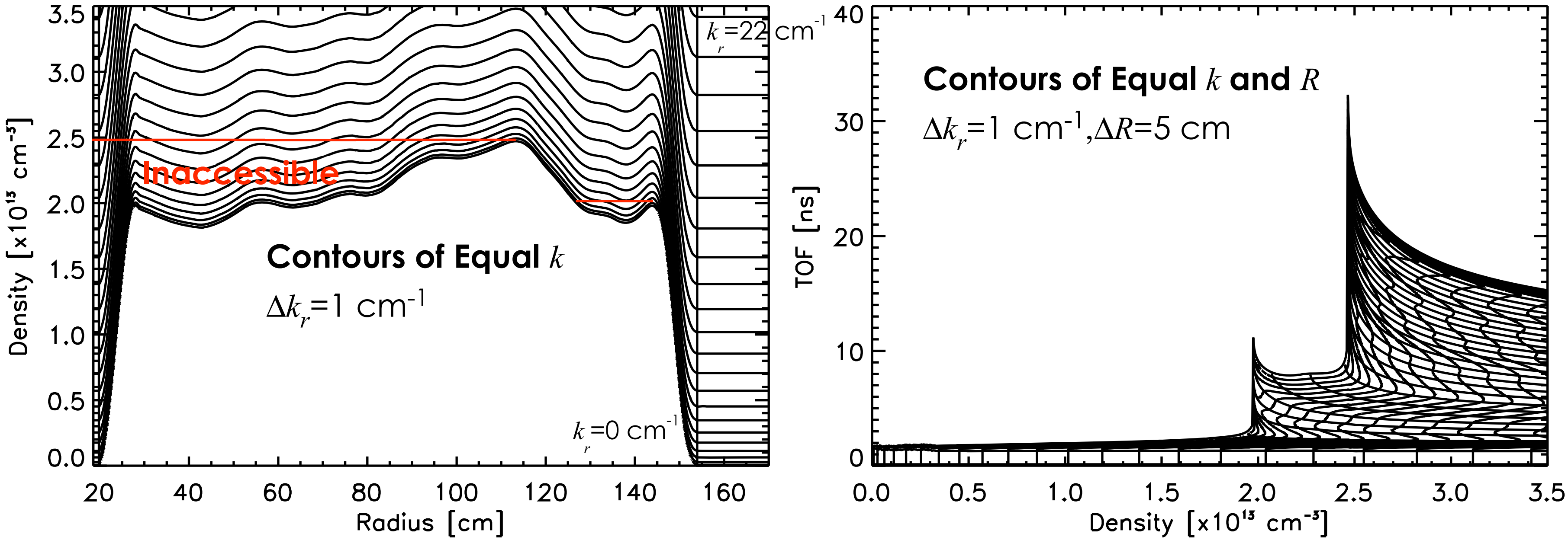
$$x(f_{\rm p}) = \frac{c}{\pi} \int_0^{f_{\rm p}} \frac{\tau(f)}{\sqrt{f_{\rm p}^2 - f^2}} df$$

Signal Processing Technique

- **Prescription for creating backscattered signal intensity image in (k_r,R).**
  - Create (τ,f) image to determine TOF curve for profile inversion.
  - Abel invert $\tau(f)$ to create $n_e(R)$.
  - Using $n_e(R)$, calculate (τ,f) points corresponding to a (k_r,R) grid.
  - Since $f(t)=f_0+\alpha\, t$, localize raw signal in time and frequency $(\Delta t,\Delta f)$. Determine intensity of this signal.
  - Determine corresponding uncertainty $(\Delta k,\Delta R)$.
- **Effectively, this is using the backward mapping.**
  - Most image processing algorithms do this as well to insure even resolution in the transformed image.
  - At higher IFs (better resolution for the original image), may be able to use the forward mapping on the original image directly.
  - Technical difficulties with reflectometer hardware for doing this:
    - > More difficult to maintain linear frequency sweep.
    - > Nonlinearities cause artifacts.
- **For non-monotonic profiles where profile inversion cannot be done, MPTS density profiles can be substituted.**

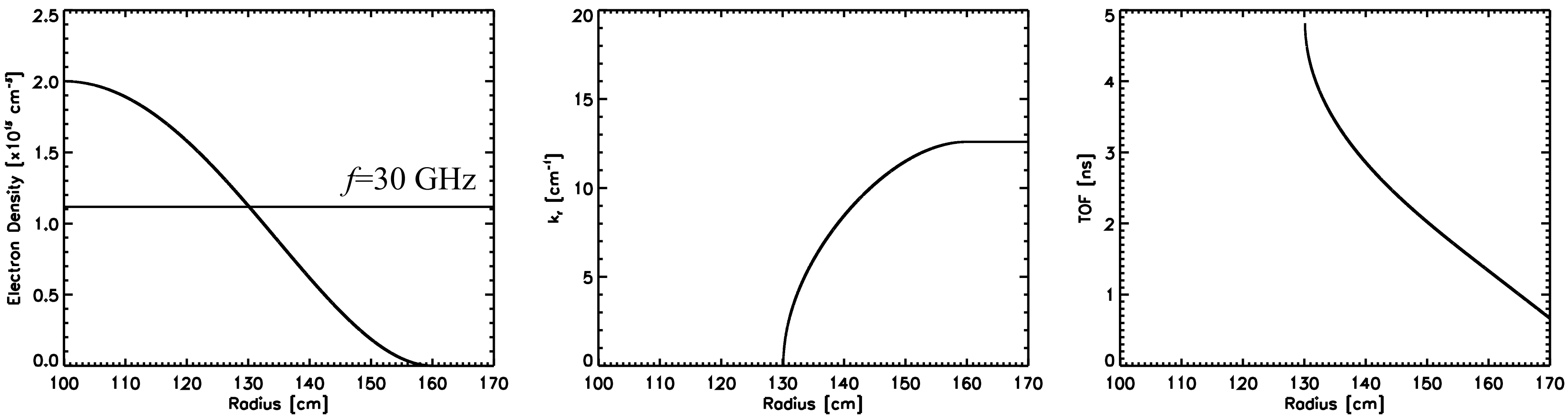
Inaccessible Regions of (τ,f) and (k_r,R)

- **All profiles.**
  - **Upper limit of $k_r(R)=4\pi f_{max}/c\ \mu(n_e(R),f_{max})$.**
  - **Upper limit of $\tau(f)=\tau(n_{e,cutoff}(f))$.**
- **Monotonic density profiles.**
  - **Lower limit of $k_r(R)=0$.**
- **Non-monotonic density profiles.**
  - **No reflection from $n_{e,cutoff}(f)$ hence $k_r(R)=0$ inaccessible.**



Conceptual View of FMCW Backscattering (Single-Frequency Case)

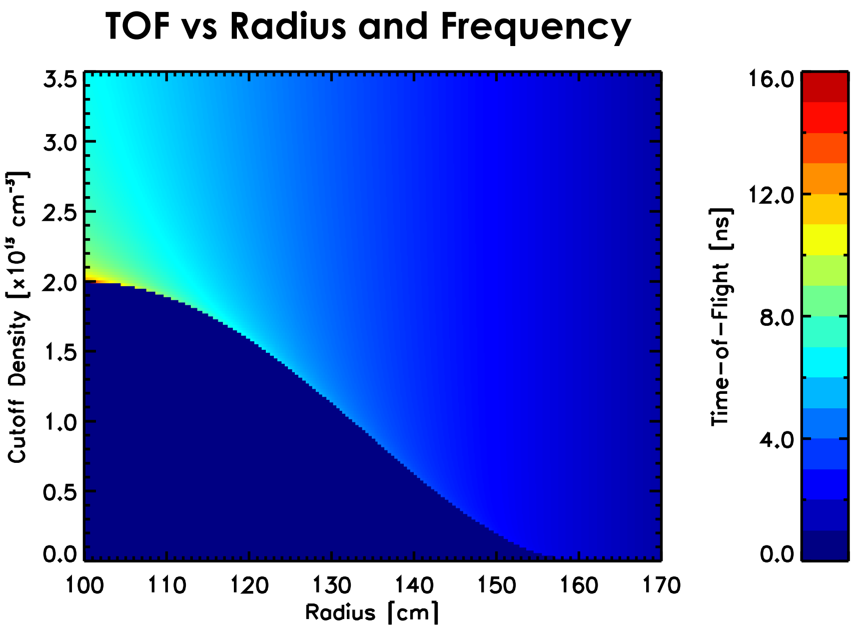
- Assume we know $n_e(R)$ from FMCW reflectometry. Consider wave-packet centered around f.

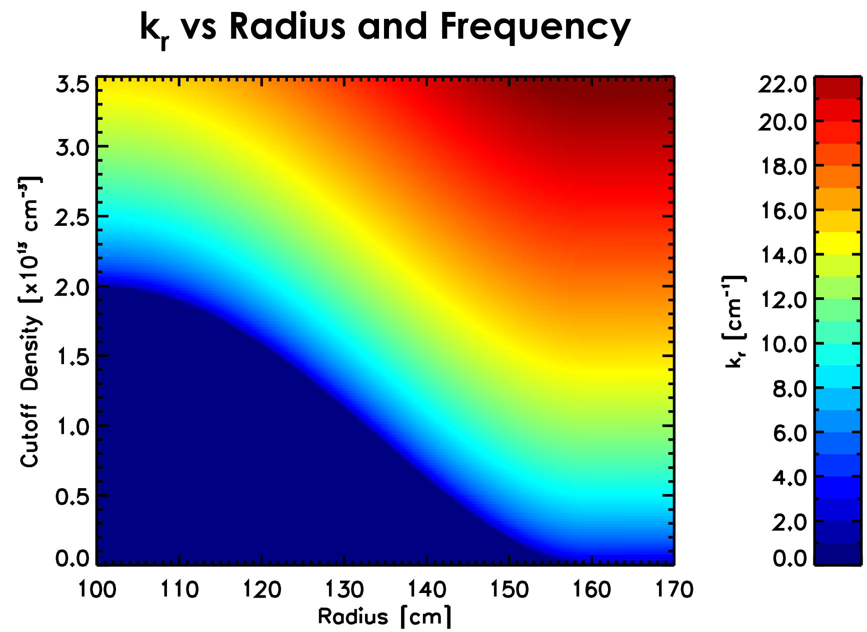


- Assume backscattered reflection from each point along path.
  - Bragg matching condition for backscattering: $k_r = 2\,k_0\,\mu(n_e(R), f)$
  - Time-of-flight (TOF) monotonically increasing towards cutoff.
  - Probes wavenumbers between $k = 2\,k_0 = 4\pi f/c$ (2x vacuum wavenumber) at edge and $k = 0$ at cutoff.

Conceptual View of FMCW Backscattering (Multiple- or Swept-Frequency Case)

- Consider FMCW source (range of swept frequencies or cutoff densities).

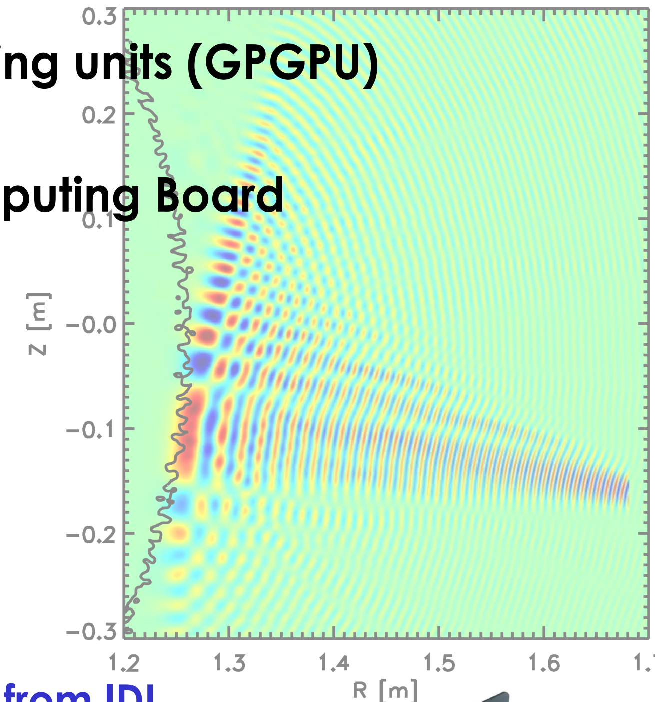




- Provides a signal intensity map from (τ, f) to (k_r, R).
  - One-to-one mapping.
  - If one knows $n_e(R)$, this mapping must be unique (stated here without proof).
- Method is similar to conventional 180° collective backscattering, but
  - Scattered/reflection location is discriminated by time-of-flight and frequency.
  - Probed wavenumber is discriminated by location and frequency.

GPGPU-Assisted Full-Wave Codes

- General-purpose computing on graphics processing units (GPGPU)
  - Utilizes massively parallel architecture of GPU cards
- Examples below with NVIDIA Tesla C870 GPU Computing Board
  - 128 streaming processor cores (16 multiprocessors)
  - Memory size: 1536 MB
  - Double wide, PCI Express x16
  - Power requirement: 171 Watts
  - Compute capability 1.0
- CUDA for C programming environment
  - Wrapper program in IDL for loading inputs
  - Shared library for compiled kernel programs called from IDL
- Significant acceleration of computation speed for 2-D
  - x20 acceleration for typical X-mode computation
  - x15 acceleration for typical O-mode computation
- Modulation of wave source
  - 2-D pulsed radar
  - 1-D pulsed radar and FMCW



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